Marine Survival of Salmon & Steelhead in the Salish Sea

November 2nd, 2012

HYPOTHESES AND PRELIMINARY RESEARCH RECOMMENDATIONS FOR PUGET SOUND

Prepared by the US Salish Sea Technical Team and contributing authors (see reverse)

Authors in alphabetical order by last name:

US Salish Sea Technical Team
Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences
Barry Berejikian, NOAA Northwest Fisheries Science Center
Josh Chamberlin, NOAA Northwest Fisheries Science Center
Alan Chapman, Lummi Nation
Mike Crewson, Tulalip Tribes
Chris Ellings Nisqually Indian Tribe
Correigh Greene, NOAA Northwest Fisheries Science Center
Julie Keister, University of Washington, Oceanography
Paul Hershberger, US Geological Survey, Marrowstone Marine Field Station
Nate Mantua, University of Washington, Aquatic and Fisheries Sciences
Jan Newton, University of Washington, Oceanography
Sandie O'Neill, NOAA Northwest Fisheries Science Center
Kenneth Warheit, Washington Department of Fish and Wildlife
Mara Zimmerman, Washington Department of Fish and Wildlife

Contributing Experts
Neil Banas, University of Washington, Oceanography
Sayre Hodgson, Nisqually Indian Tribe
Lyndal Johnson, NOAA Northwest Fisheries Science Center
Parker MacCready; University of Washington, Oceanography
Paul McElhany, NOAA Northwest Fisheries Science Center
Jack Rensel, Rensel Associates Aquatic Sciences

Project Management and Facilitation
Iris Kemp, Long Live the Kings
Michael Schmidt, Long Live the Kings**

****for more information, contact mschmidt@lltk.org**

Table of Contents

PREFACE

This report reflects the foundational information for a formal marine survival research proposal for Puget Sound, to be developed by the US Salish Sea Technical Team. In it, the project scope, conceptual framework, hypotheses and preliminary recommendations are described. The content of this report will be presented and discussed at the November 2012 Marine Survival of Salmon and Steelhead in the Salish Sea workshop. An Advisory Panel will convene at the end of the workshop evaluate the presented material and the outcomes of the discussions and use this information to determine the critical elements of a joint US - Canada research program. The Technical Team will then use the results of the workshop to refine the research recommendations and complete a research plan.

INTRODUCTION

Effective salmon and steelhead management requires a thorough understanding of the factors controlling survival at each specific life stage. Current management and recovery efforts rely on understanding and addressing issues affecting freshwater productivity, but they are hampered by an inadequate and fragmented understanding of issues affecting productivity in the marine and estuarine environments. This is a critical knowledge gap since it is known that the marine life stages are of equal importance for salmon and steelhead survival as the freshwater life stages, and the early marine phase is generally considered one of their most critical periods, where the fish are known to experience some of their most rapid growth and highest mortality rates (Duffy et. al. 2010). For Chinook, coho and steelhead in the Salish Sea, this issue is emphasized by long-term declining trends in marine survival and/or abundance, common throughout the Salish Sea region but unique when compared to populations from other areas.[1]

Working with scientists, managers and funders from the public and private sectors, Long Live the Kings and the Pacific Salmon Foundation are facilitating the development of a joint United States and Canada research effort, utilizing intellectual and capital resources from both countries to evaluate salmon and steelhead marine survival in the Salish Sea from an ecosystem context. The objective of this effort is to identify the primary factors affecting the survival of salmon and steelhead in the Salish Sea[2] marine environment. The project includes three phases: 1) comprehensive research planning; 2) coordinated, systematic research; and 3) dissemination and application of the research results to management.

This proposed, collaborative, multidisciplinary, ecosystem-based research effort benefits the science and management community by improving information sharing, promoting data standardization, incorporating existing research and monitoring efforts into a comprehensive and hypothesis driven framework, implementing simultaneous data collection, and taking a basin-wide approach. The research effort is also solutions oriented, intended to systematically: a) identify or help prioritize hatchery, harvest, habitat and ecosystem management actions to increase the survival of Salish Sea wild and hatchery salmon and steelhead (including Endangered Species Act - listed Puget Sound Chinook and

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[1] See page 7, "Evidence that Changes Unique to the Puget Sound/Salish Sea are Affecting Survival".

[2] See page 20 for a description of the Salish Sea.

steelhead) ; b) improve adult salmon and steelhead return forecasting and, thusly, natural spawning, harvest, and hatchery management; and c) help us more accurately evaluate the success of freshwater habitat restoration and hatchery activities by reducing uncertainty around the role of the marine environment in overall productivity. Ultimately, the research results and subsequent management actions may also benefit other Salish Sea marine life, such as ESA-listed southern resident killer whales.

We envision the results of this broad-scale, ecosystem based research approach will provide the mechanistic framework for what factors should be monitored over the long-term to help achieve wild fish recovery and maintain sustainable fisheries. In this manner, the research effort helps fulfill the needs of the ecosystem-based management and recovery efforts being developed for Puget Sound and the Strait of Georgia[3].

The Salish Sea Marine Survival Project is currently in the research planning phase. Through the Pacific Salmon Foundation, participating Canadian scientists have developed a relevant research plan for Chinook and coho in the Strait of Georgia (Pacific Salmon Foundation 2009). In the winter of 2011, the United States Salish Sea Marine Survival Technical Team (Technical Team) was formed and research planning for the US waters of the Salish Sea (Puget Sound)[4] is underway.

This report reflects the foundational information for a formal marine survival research proposal for Puget Sound, to be developed by the US Salish Sea Technical Team. In it, the project scope, conceptual framework, hypotheses and preliminary recommendations are described. The content of this report will be presented and discussed at the November 2012 Marine Survival of Salmon and Steelhead in the Salish Sea workshop. An Advisory Panel will convene at the end of the workshop evaluate the presented material and the outcomes of the discussions and use this information to determine the critical elements of a joint US - Canada research program. The Technical Team will then use the results of the workshop to refine the research recommendations and complete a research plan.

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[3] Sustainable recreational and commercial fishing and the recovery of wild Chinook and southern resident killer whales have been identified as 4 of the 21 indicators of Puget Sound ecosystem recovery by the Puget Sound Partnership (http://www.psp.wa.gov/vitalsigns/index.php).

[4] The US waters of the Salish Sea include Puget Sound and portions of Juan de Fuca Strait and the Southern Strait of Georgia; however, the entire area is often referred to as Puget Sound. See page 20 for more details.

EVIDENCE THAT CHANGES UNIQUE TO THE PUGET SOUND/SALISH SEA ARE AFFECTING SURVIVAL

There is increasing evidence that changes in the Salish Sea marine environment may be significantly affecting the overall survival of salmon and steelhead. The outmigrant-to-adult survival[5] (largely, the period when they are in the marine environment) for many stocks of coho and Chinook has declined, in some cases to less than one tenth of the levels experienced in the 1970's and 80's. Steelhead populations have also declined significantly, with evidence that juvenile mortality during their migration through Salish Sea marine environment is playing a role. And extraordinary variations in sockeye, chum and pink populations are perplexing scientists who work to predict their return as adults for harvest, hatchery broodstock collection, and natural escapement management. Evidence that the effect on survival is derived in the Salish Sea is the disparity in survival and abundance trends when comparing Salish Sea populations to those outside of the region. These trends are described in greater detail for Chinook, coho and steelhead below.

Chinook

The declining marine survival of Salish Sea Chinook is clear when compared with other regions. The Strait of Georgia and Puget Sound hatchery Chinook populations show a consistent, concurrent downward trend in marine survival since the mid 70's (Beamish 2011; Mahnken et. al. 1998) (Figure 1). These populations show less variation when compared to coastal and Columbia River populations over the past 30 years (Figure 2). The Fraser hatchery Chinook populations display greater variation but also appear to be on a declining trend. North Coast Canada and West Coast Vancouver Island populations also display a declining trend but with greater variation, and the Washington, Oregon and Columbia River populations declined slightly in the mid 70's but then rebounded in the mid 80's, appearing more stable with consistent variation over time (interpreted from the Whitehouse & Tompkins 2010 presentation, Appendix 1 in Peterman et al. 2010). In Puget Sound, hatchery Chinook salmon marine survival has been under 1% for most of the past 30 years (Duffy 2009). Inter-annual variation shared among populations throughout the area depicted in Figure 2 can be explained by large-scale climate forces such as El Nino (Mahnken 1998) and the Pacific Decadal Oscillation; however, these do not explain the long-term declining trends observed for Salish Sea hatchery Chinook.

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[5] Also known commonly as smolt-to-adult survival.

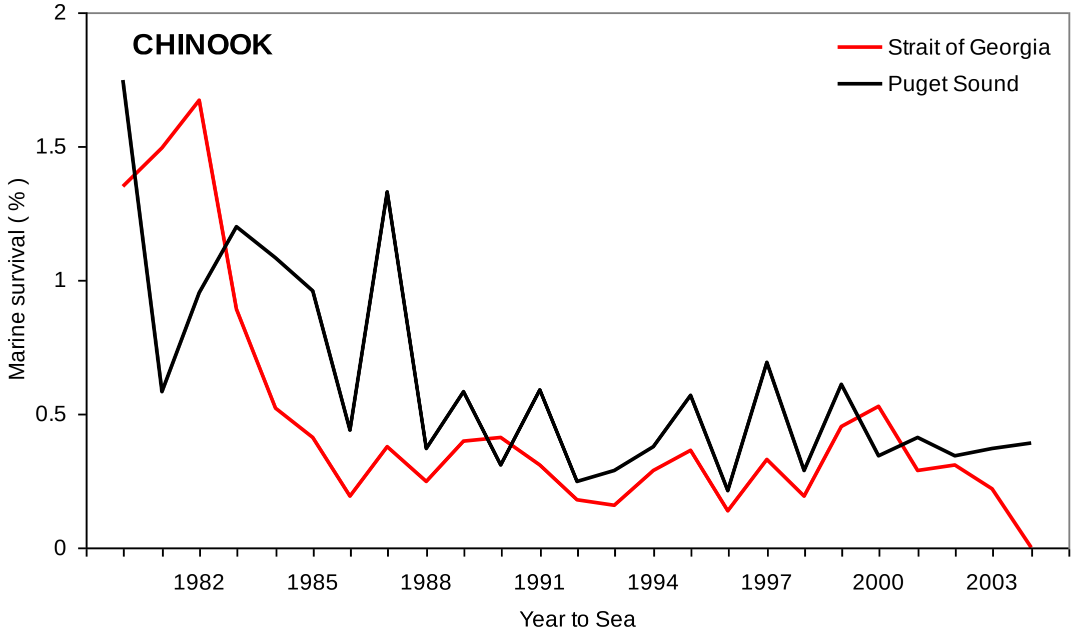


Figure 1. Mean survival of hatchery Chinook released into the Strait of Georgia and Puget Sound from 1980-2004 (Beamish 2011).

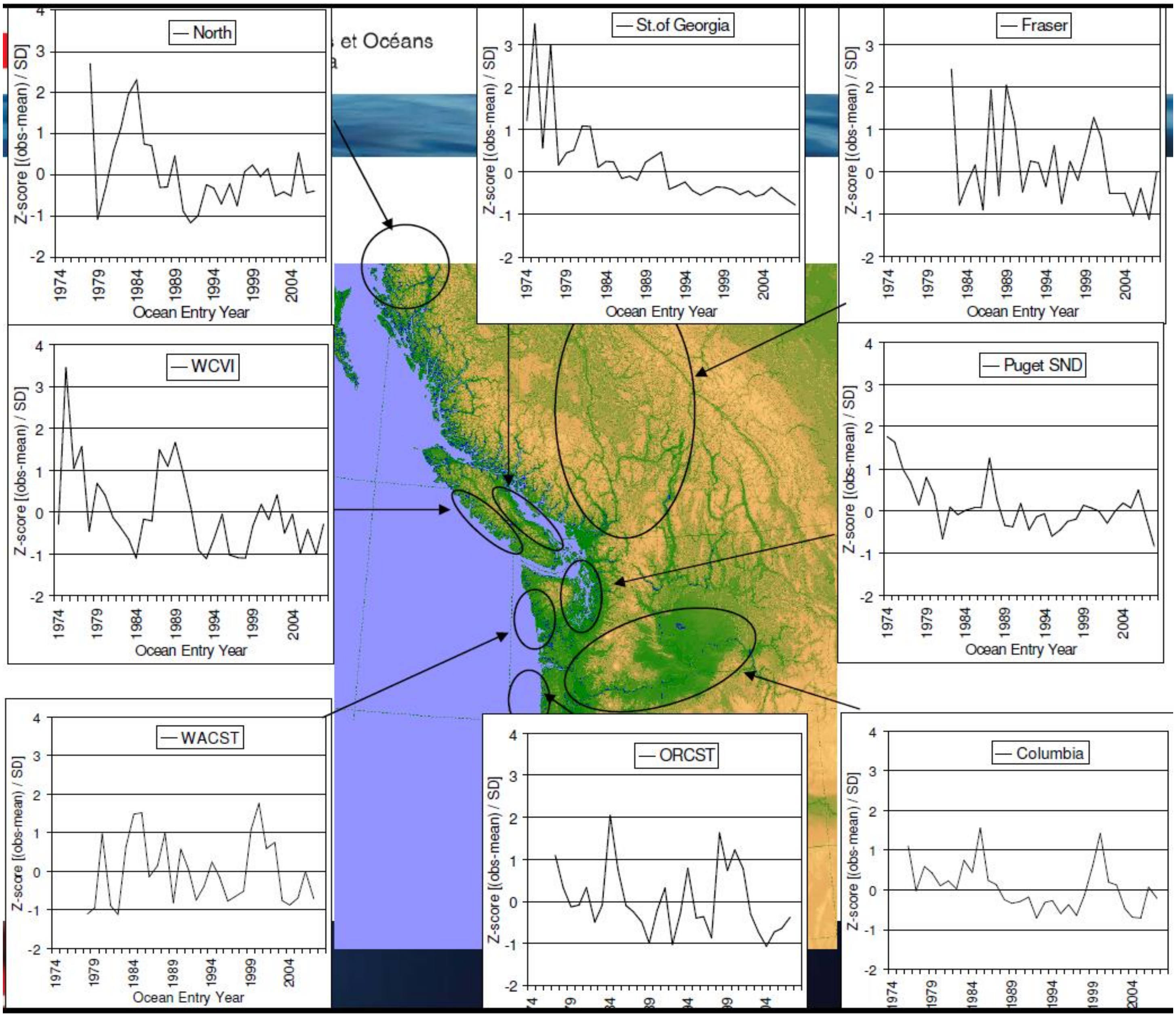


Figure 2. Chinook marine survival: a regional comparison (Whitehouse & Tompkins 2010 presentation, Appendix 1 in Peterman et al. 2010)

Coho

Salish Sea coho salmon display a dramatic decline in marine survival rates over the past 20 to 30 years. The marine survival of Puget Sound hatchery coho populations has decreased concurrently with the marine survival of Strait of Georgia coho populations (Beamish 2011) (Figure 3). This pattern was not mirrored in coastal hatchery populations in Washington, British Columbia, Oregon, or California between 1970-1990 (Mahnken et al. 1998) and when comparing Puget Sound hatchery and wild coho survival to the Washington Coast from 1970 through 2005 (Beetz 2009), suggesting that factors specific to the Salish Sea populations are responsible for the reduction in marine survival (Figure 4, Figure 5). Throughout the 1970s and much of the 1980s, Puget Sound hatchery and wild coho populations exhibited greater marine survival rates than coastal coho populations. Now, marine survival rates in Puget Sound hatchery and wild coho populations are about half of what they once were, while marine survival rates in coastal populations remain the same (Beetz 2009). Within Puget Sound, variations on a theme of decline are present (Figure 6). Coho populations in the Northern Straits, Hood Canal, and South Sound show a steep decline in the mid-late 1980s with little variation in survival rates beyond that point. Whidbey Basin and Central Sound populations decline in the late 1980s-early 1990s and display some variability in marine survival rates after this time period, but do not rebound to the levels of the early 1980s. Two hatchery populations from the Strait of Juan de Fuca (Dungeness River, Elwha River) show a slight peak (~10% survival) in the late 1970s, then decrease and remain consistently low (<1% survival) with little variation. Populations within regions of Puget Sound show localized patterns in marine survival, suggesting that an amount of small-scale regional variation is present; however, this does not explain the overall trend towards decreased survival in the Salish Sea. Reduced marine survival is apparent in hatchery, wild, and net-pen reared coho, although throughout the period of decline, wild coho marine survival rates are consistently greater than that of hatchery and net-pen reared coho (Beetz 2009). This evidence supports the assumption that separate evaluation of wild and hatchery populations is preferable.

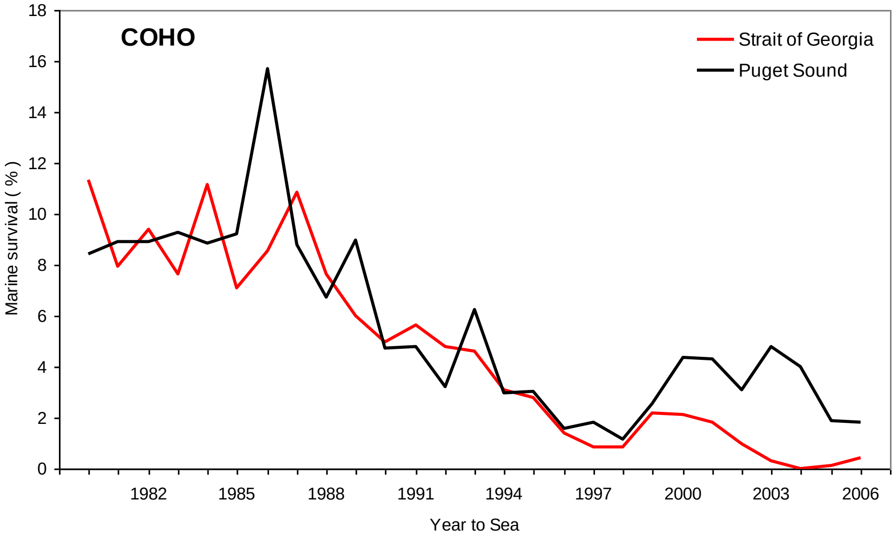


Figure 3. Mean survival of hatchery Chinook released into the Strait of Georgia and Puget Sound from 1980-2006 (Beamish 2011).

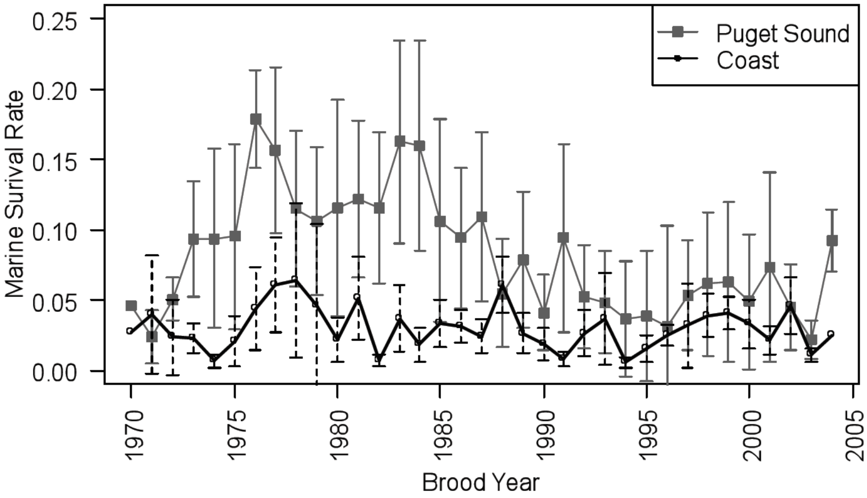


Figure 4. Aggregate MS rate line plot depicting average variations over the 1970-2004 period for each regional group. Error bars are based on the standard deviationamong individual populations within each regional group. MS rate data in this plot has not been transformed i.e. has not been standardized or detrended (Beetz 2009)

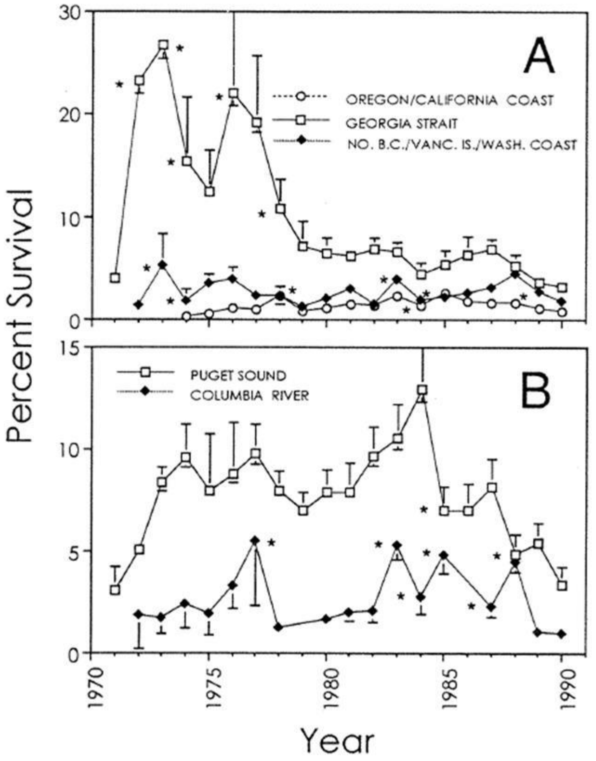


Figure 5. Mean survival (coded-wire tags) of coho salmon released from Pacific coast hatcheries 1970-1990. (A) Georgia Strait estuary, coastal regions of north British Columbia/outer Vancouver Island/Washington, and coastal regions of Oregon/California. (B) Puget Sound & the Columbia River. Error bars are one standard error. Asterisks denote differences (P<0.05) ANOVA, Fisher PLSD between successive means (Mahnken et. al. 1998)

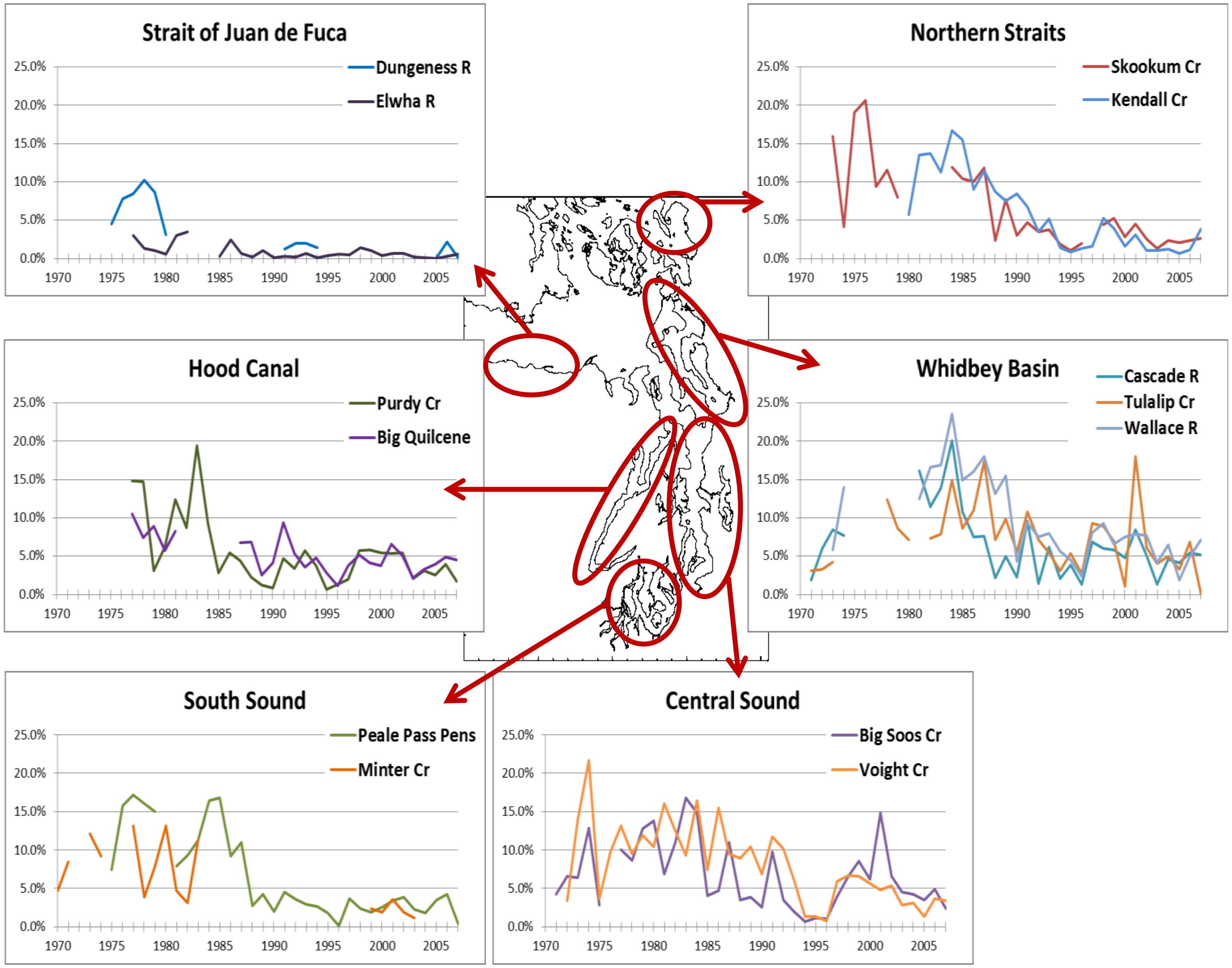


Figure 6. Marine survival trends of Puget Sound hatchery coho stocks from geographically distinct sub-basins in Puget Sound (pers. comm. J. Haymes, Washington Department of Fish and Wildlife, 2011)

Steelhead

Reduced marine survival of over the past 20 to 30 years appears to be a major limiting factor for Salish Sea steelhead trout, and the declining abundance trends of Salish Sea populations compared with coastal populations points to poor survival in the Salish Sea. Steelhead along the Pacific Coast from British Columbia through Oregon, including the Columbia and Snake Rivers share a common pattern of high abundance in the mid 1980's, followed by very low abundance in the early through the 1990's. Subsequently, both interior and coastal populations have rebounded beginning in 2000 (www.psmfc.org/steelhead). The striking commonality in these patterns among populations from a large geographic region points strongly to common ocean effects on survival and adult abundance. Populations entering the southern Strait of Georgia and Puget Sound, which show common migratory pathways (i.e., through the Juan de Fuca Straight; Moore et al. 2010, Welch et al. 2011, Balfry et al. 2011) depart substantially from this pattern. They show the same high peak in the mid 1980's and decline in the 1990's, but no subsequent increases in abundance from 2000 to present (Figure 7 and Figure 8). Striking examples include Central and South Puget Sound populations such as the Puyallup, Nisqually, Cedar, and Green, and southern Strait of Georgia (SoG) populations, including the Keogh River and tributaries of the Thompson/Fraser. Smolt-to-adult survival rate data are much less available, but WDFW has documented much higher rates for coastal than Puget Sound populations since 2000 (Scott and Gill 2008) (Figure 9). The smolt-to-adult/marine survival declines in the Keogh River (SoG) and Snow Creek (Puget Sound)wild winter steelhead populations generally coincide with abundance declines (Figure 10). This correlation between marine survival and abundance provides some confidence that the abundance trends described for other wild steelhead populations are often good indicators of marine survival trends.

British Columbia trends in abundance

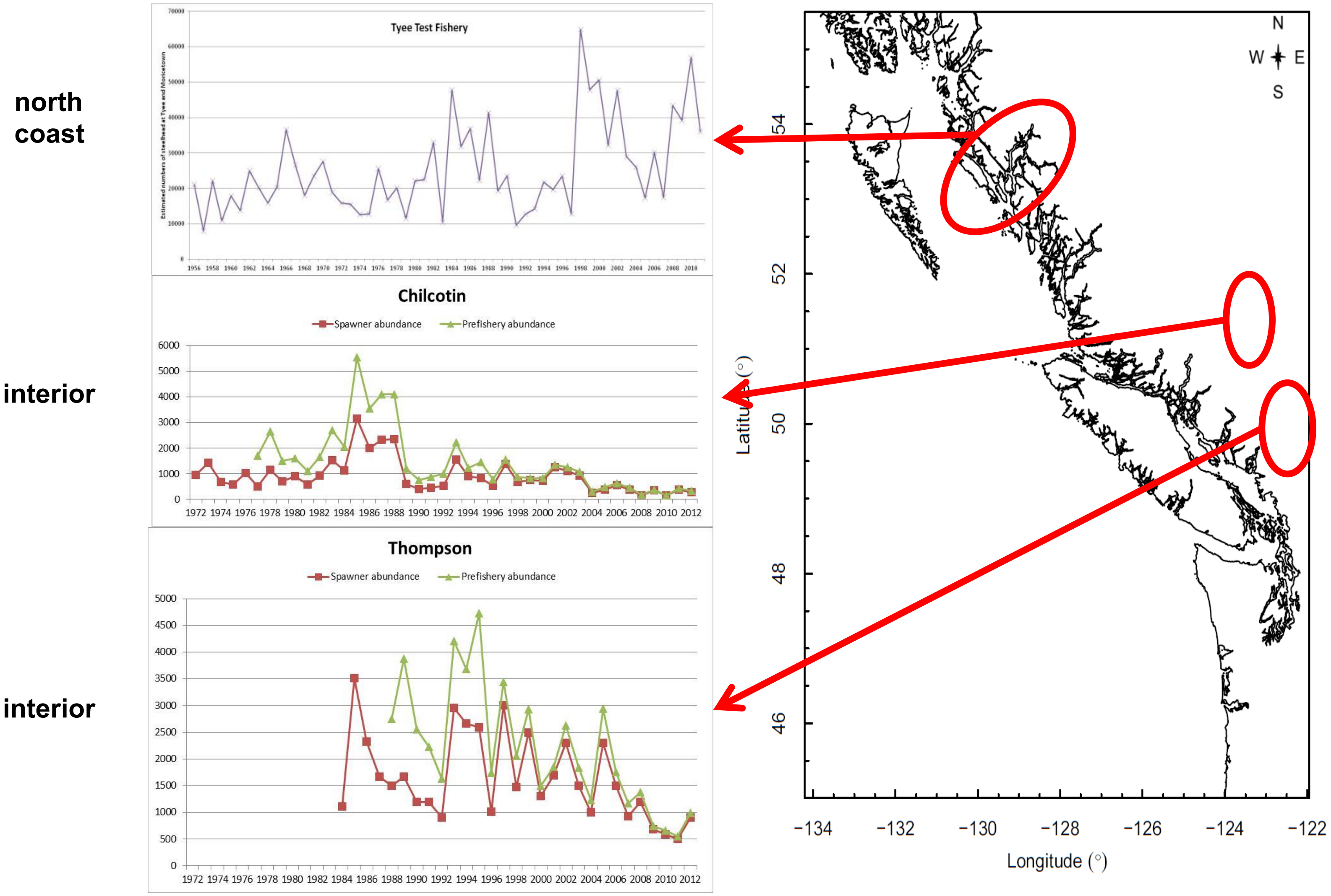


Figure 7. British Columbia trends in steelhead abundance (adapted from Pollard and Beere 2012 presentation - www.psmfc.org/steelhead)

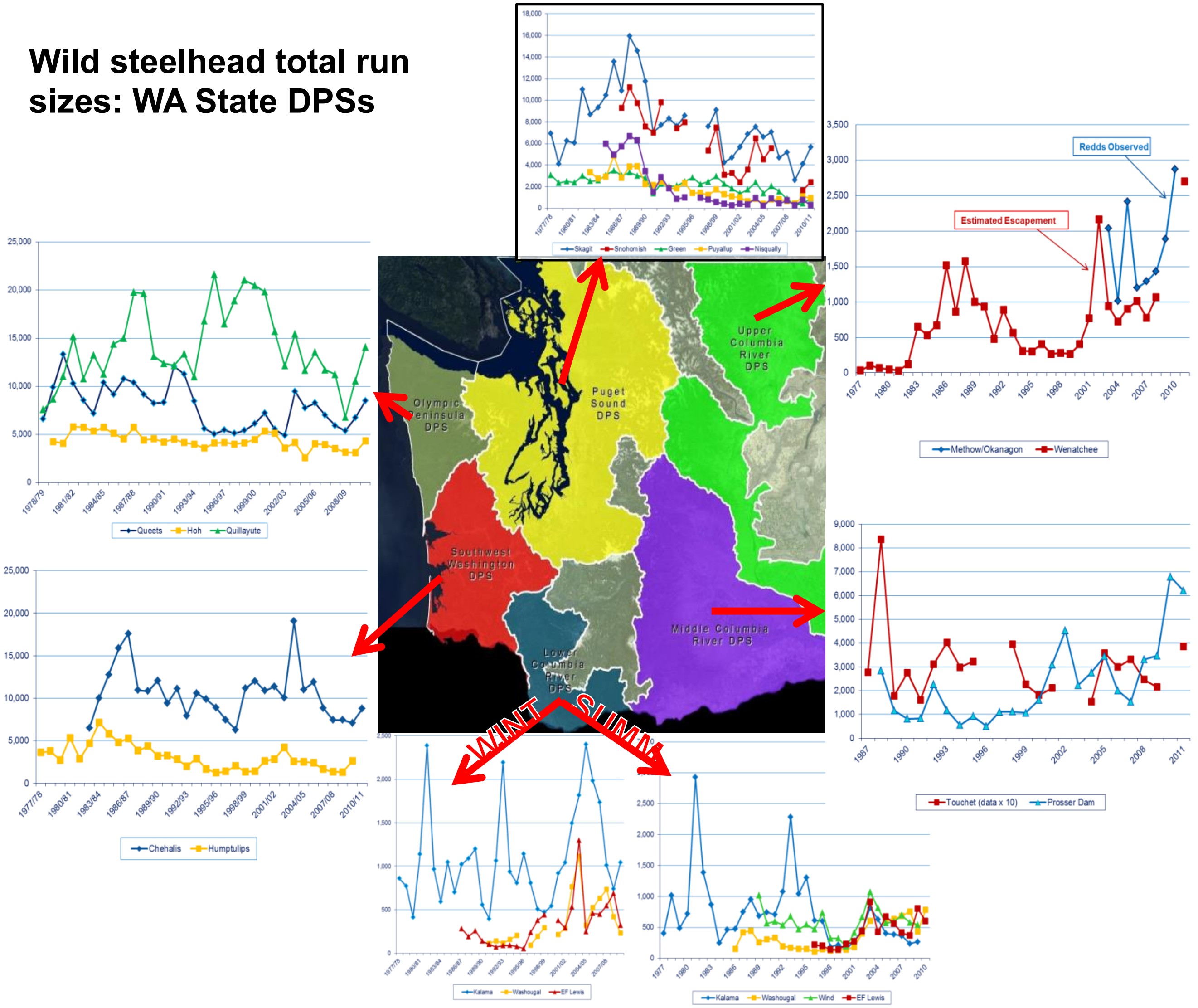
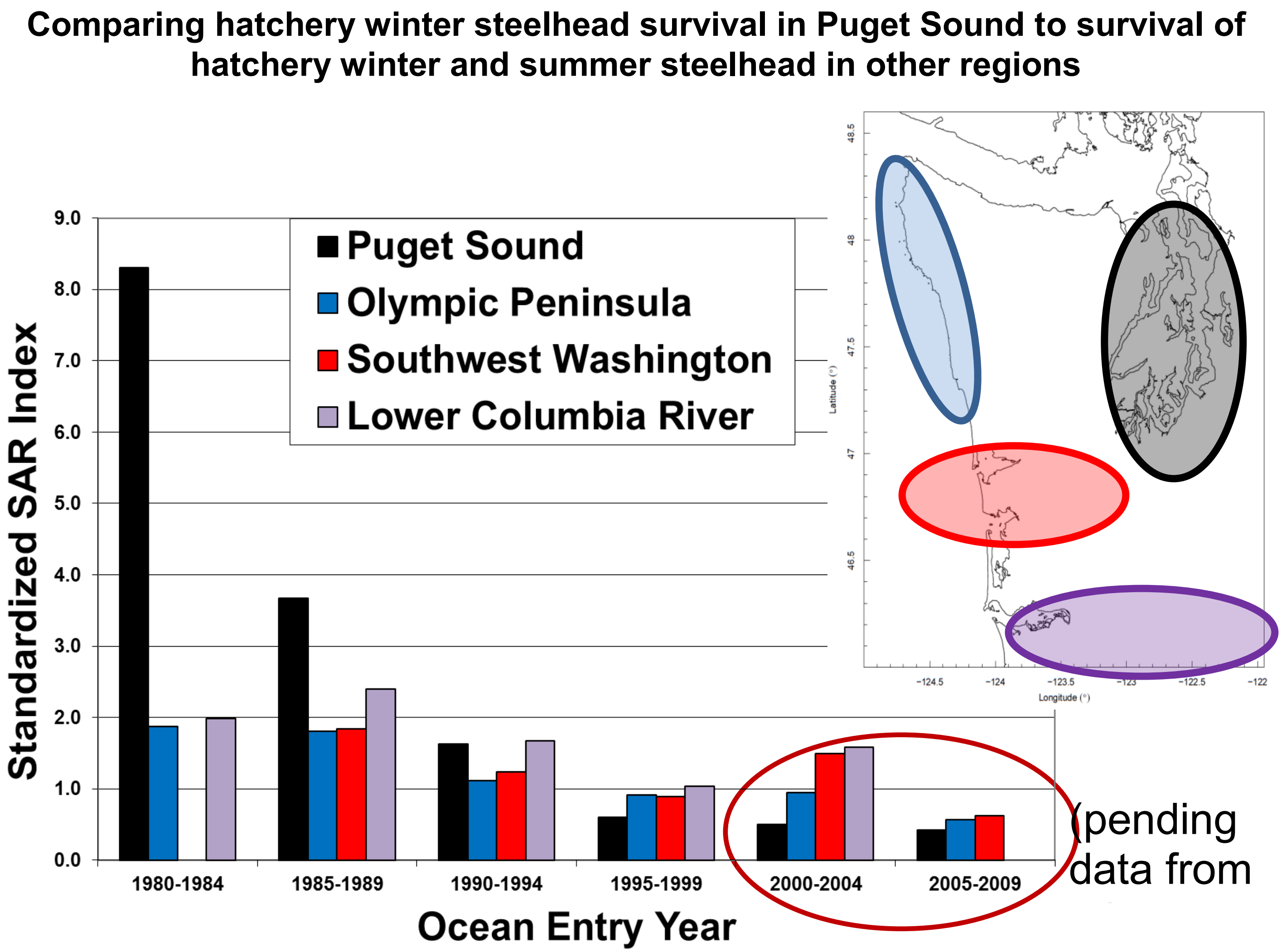


Figure 8. Wild steelhead total run size for Washington State Distinct Population Segments, 1978-2011 (adapted from Leland and Marshall 2012 presentation - www.psmfc.org/steelhead)



Comparing hatchery winter steelhead survival in Puget Sound to survival of hatchery winter and summer steelhead in other regions

Figure 9. Hatchery steelhead survival in Puget Sound vs. other regions, 1980-2009. Years 2001-2009 are incomplete, pending data from other sources (adapted from Scott and Gill 2008).

Wild winter steelhead marine survival in the Salish Sea and its correlation with abundance:

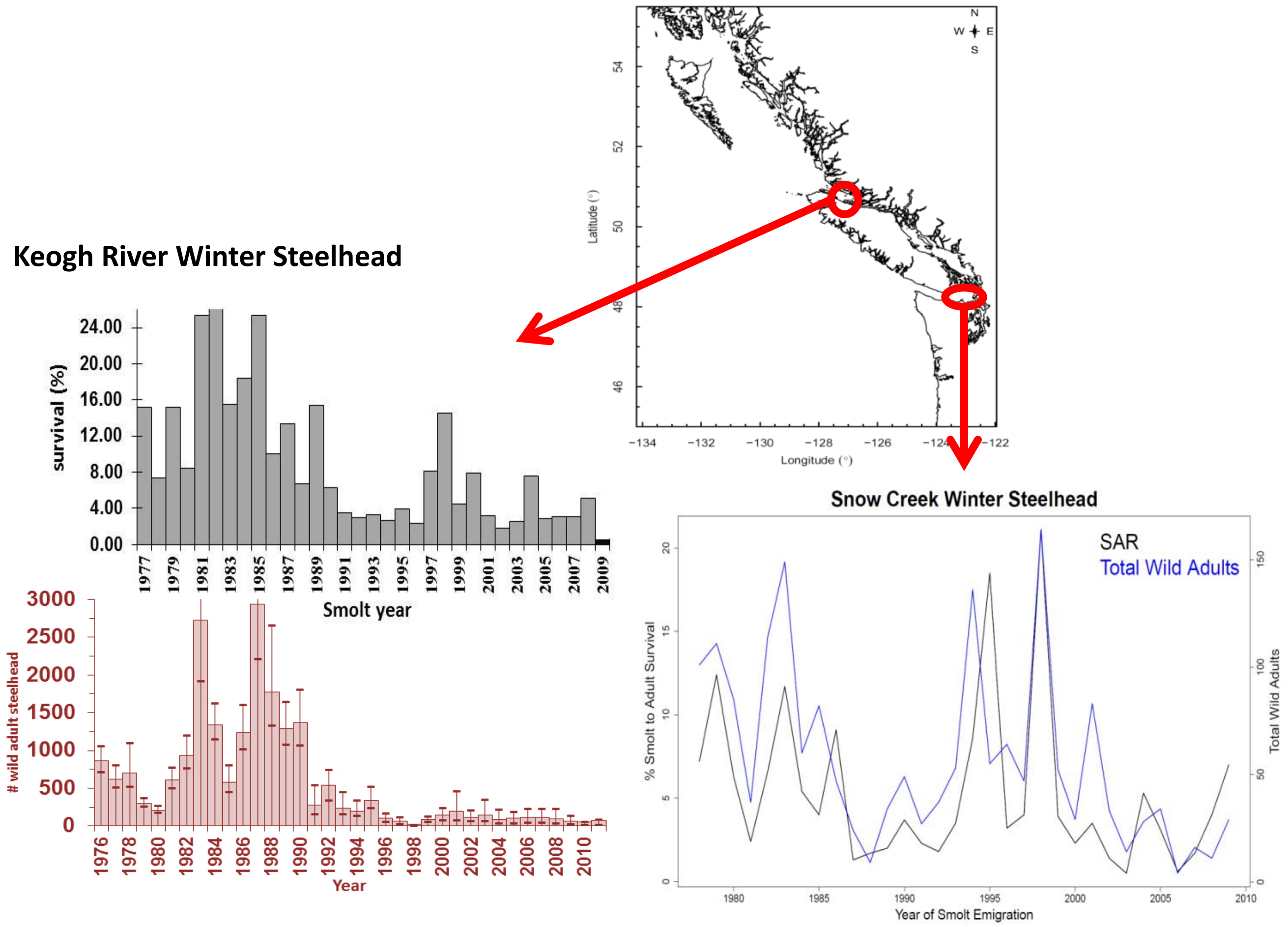


Figure 10. Outmigrant to adult survival (marine survival) of wild Snow Creek and Keogh River winter steelhead and the correlation between outmigrant year marine survival and 4-year-old adult return abundance, late 1970s-2010 (adapted from Pollard and Beere 2012 presentation - www.psmfc.org/steelhead - Keogh River, and pers. comm. Washington Department of Fish and Wildlife, 2012).

OBJECTIVE, SCOPE AND APPROACH

Objective

The primary objective of the Salish Sea Marine Survival Project is to identify the most significant factors affecting the survival of salmon and steelhead while they outmigrate through and reside in the Salish Sea marine and estuarine environment. The proposed work is solutions oriented, intended to systematically:

- identify or help prioritize hatchery, harvest, habitat and ecosystem management actions to increase the survival of Salish Sea wild and hatchery salmon and steelhead (including Endangered Species Act (ESA) listed Puget Sound Chinook and steelhead)
- improve adult salmon and steelhead return forecasting and, thusly, natural spawning, harvest, and hatchery management; and
- help us more accurately evaluate the success of freshwater habitat restoration and hatchery activities by reducing uncertainty around the role of the marine environment in overall productivity.

Ultimately, the research results and subsequent management actions may also benefit other marine life in the Salish Sea food web, such as ESA-listed southern resident killer whales.

From a research perspective, this collaborative, multidisciplinary, ecosystem-based effort will improve information sharing, promote data standardization, and implement simultaneous data collection by integrating existing and proposed research and monitoring efforts into a comprehensive and hypothesis driven framework at an ecologically relevant scale – the entire Salish Sea.

Scope

Because the interaction between salmonids and the Salish Sea is complex, this issue will be approached from an ecosystem context, utilizing experts from multiple disciplines. Chinook, coho and steelhead are the species of greatest concern given their significant declines in outmigrant-to-adult[6] survival (aka. marine survival) since the 1970s. However, chum, pink and sockeye are also included in the research plan given potentially shared survival drivers; interspecies interactions; that future research methods can evaluate multiple species; and the recent, extraordinary variation in survival of these salmon species and its effects on fisheries management. The focus is principally on issues affecting juvenile salmon and steelhead survival while they are in the Salish Sea, from the river deltas to the open ocean: spatially and temporally ranging downriver of traditional freshwater monitoring locations (e.g., smolt traps, hatcheries) to the point where and time when salmon and steelhead leave the Salish Sea. The resident life-history component of specific salmon species may also be investigated as these fish stay within the Salish Sea through adulthood. Understanding the condition of fish entering and leaving the Salish Sea marine environment will be included to determine whether impacts occurring prior to their marine

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[6] Also known commonly as smolt-to-adult survival.

residence are reducing survival in the Salish Sea, or in case impacts occurring in the Salish Sea are reducing survival in the Pacific Ocean, respectively. Factors that don't appear to be driving survival will also be documented as both pieces of information will help inform management decisions.

Geographic Range

The geographic range of this project includes the entire Salish Sea, the body of water that extends from the north end of the Strait of Georgia and Desolation Sound to the south end of the Puget Sound and west to the mouth of the Strait of Juan de Fuca, including the inland marine waters of southern British Columbia, Canada and northern Washington, United States[7] (Figure 11)[8].

Figure 11. Topographic map of the Salish Sea

This research proposal reflects the work of the US Salish Sea Technical Team (herein referred to as the Technical Team) and focuses on the U.S. waters of the Salish Sea. This includes the entirety of Puget Sound and the portions of the Strait of Juan de Fuca and the Southern Strait of Georgia within the borders of the U.S. (Figure 12).[9] For the purposes of this report, we will refer to this entire area as Puget Sound since contemporary resource management efforts also reference the entire area as such[10]. Research proposed for the Canadian waters of the Salish Sea, the Strait of Georgia, is covered in the Pacific Salmon Foundation's Strait of Georgia Chinook and Coho report (Pacific Salmon Foundation 2009)[11].

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[7] http://staff.wwu.edu/stefan/SalishSea.htm

[8] Figure from, http://www.newrelationship.gov.bc.ca/success_stories/aboriginal_gov_relations.html

[9] It should be noted that some of the research recommendations, such as those for Harmful Algae (hypothesis 9) extend beyond the US waters of the Salish Sea, and most all of the research recommendations could be considered in a broader geographic context.

[10] See the Puget Sound Partnership maps at http://www.psparchives.com/resources/maps.htm, and the ESA-listed Puget Sound Chinook salmon, summer chum, & steelhead ESU maps at http://www.nwfsc.noaa.gov/trt/puget.cfm.

[11] The Strait of Georgia Chinook and Coho Proposal can be found at http://www.lltk.org/rebuilding-populations/salish-sea-marine-survival/approach.

Sub-basins of Puget Sound

The Puget Sound study area encompasses seven sub-basins that reflect somewhat distinct domains of varying geology, tidal hydrology, physiography, and oceanography settings in Puget Sound (Simenstad 2011) (Figure 12). The basin designations are based upon the work of the Puget Sound Nearshore Ecosystem Restoration Partnership (PSRNERP). They were used because each basin encapsulates distinct physical processes in the nearshore and offshore, and because the basin designation correlates well with the geographic regions of diversity established for ESA-listed Puget Sound Chinook (Ruckelshaus et. al. 2002) and the major population groups established for ESA-listed Puget Sound steelhead (Hard et. al. 2012). And, this aligns with Puget Sound Partnership Action Areas http://www.psp.wa.gov/aa_action_areas.php

Puget Sound Sub-basin Map - courtesy of PSNERP 2012

Figure 12. Seven sub-basins are based on somewhat distinct domains of varying geology, tidal hydrology, physiography and oceanography (http://www.pugetsoundnearshore.org/strategies.html - adapted from Simenstad et al. 2011).

Timescale and Study Approach

The primary impetus for this research is the unique, long-term downward marine survival and abundance trends of Chinook, coho, and steelhead that have occurred between the 1970s and the present. This trend differs from the more frequent variability in marine survival and abundance of Chinook, coho and steelhead populations from the outer coast and the Columbia River basin (see section, “Evidence that changes unique to the Puget Sound/Salish Sea are affecting survival”, above). Therefore, a retrospective element will be present in this effort. The Technical Team is also concerned about future impacts in response to looming issues such as climate change and ocean acidification. However, the Technical Team proposes to largely implement a mechanistic approach to evaluating the factors that may be affecting salmon and steelhead survival in the present, with the assumption that the information gained from this approach can both explain current situation but also be attributed to past and future situations via modeling, process studies and retrospective analyses.

The study approach is based on other large-scale, ecosystem-based, interdisciplinary research programs such as the Global Ocean Ecosystem Dynamics (GLOBEC) initiative, the estuarine and ocean salmon research program design proposed by Brodeur et al. (2000), and the Columbia River basin juvenile salmon marine ecology program (Jacobsen et. al. 2012). Four concurrent activities are proposed to occur over a 5-year, intensive study period: data syntheses and retrospective analyses; coordinated, simultaneous monitoring; process studies including systematic sampling and controlled experiments; and modeling and integration. Where appropriate, retrospective and other targeted analyses will be prioritized to leverage results for more funding, clarify research directions, and ensure previous studies are not duplicated.

As research is completed over the course of the 5-year intensive research effort and within the year following, the research results will be disseminated and communicated to managers. The Technical Team envisions the results of this intensive research approach will provide the mechanistic framework for what factors should be monitored over the long-term to help achieve wild fish recovery and maintain sustainable fisheries in addition to helping identify specific management actions to improve marine survival. The research structure and its results will also feed into monitoring and adaptive management planning proposed for ESA-listed Chinook (and, likely steelhead and summer chum in the future)[12]. In this manner, the research effort helps fulfill the needs of ecosystem-based management and recovery efforts being developed and implemented for Puget Sound and the Strait of Georgia[13].

All efforts will be highly collaborative—involving federal, state, tribal, academic and nonprofit staff—and will be coordinated intensively at the U.S. – Puget Sound level and broadly with the Canadian efforts, guided by the November 2012 workshop summary report that will identify the critical elements of the U.S. – Canada, Salish Sea research program. One important relationship is with the Puget Sound Ecosystem Monitoring Program (PSEMP), a coordinated monitoring program designed to evaluate progress towards ecosystem recovery and to serve as a foundation to continually improve the scientific basis for management actions in Puget Sound[14].

Hatchery Production in the Context of this Study

Hatchery production assumes an obvious and compelling role in this research effort. Hatcheries can provide sustainable fisheries benefits but may also pose risks to wild populations. From a research perspective, hatcheries can provide us the opportunity to perform large-scale manipulations to evaluate various marine survival factors. For this study, the Technical Team determined that the results of the research implemented could be beneficial to hatchery and wild fish, but with the caveat that, with new information, we may have to make decisions that weigh both wild fish recovery and sustainable fisheries options. Generally, the Technical Team (and the scientists in Canada) concluded that a stronger science basis is needed to make important decisions that both affect the socio-economic welfare of our region and the recovery of wild salmon and steelhead populations.

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[12] As described in the draft April 2012 NOAA Technical Memorandum, “A Common Framework for Monitoring the Recovery of Puget Sound Chinook Salmon and Adapting Salmon Recovery Plans” produced by the Puget Sound Recovery Implementation Technical Team and their support staff (Puget Sound Recovery Implementation Technical Team 2012).

[13] Sustainable recreational and commercial fishing and the recovery of wild Chinook and southern resident killer whales have been identified as 4 of the 21 indicators of Puget Sound ecosystem recovery by the Puget Sound Partnership (http://www.psp.wa.gov/vitalsigns/index.php).

[14] http://www.psp.wa.gov/MP_monitoring_program.php

Throughout this document, efforts will be made to identify the origin of fish in question (hatchery or wild). In some cases,, hatchery-wild interactions are the main focus of a proposed study whereas in other cases proposed studies are tailored toward improving our understanding of one origin over the other or even use hatchery fish survival as a proxy for understanding impacts to both hatchery and wild fish.

THE CONCEPTUAL FRAMEWORK

Development of a conceptual framework is part of a hierarchical process to lay the foundation for a research plan. The order to this hierarchy is: (1) **project objective**, (2) **conceptual framework and assumptions**, (3) **hypotheses and information gaps/research needs**.

Figure 13. Conceptual Framework organization levels defined.

The organizational levels are defined using ecological and genetic criteria:

Ecosystem refers to the interrelated set of biotic and abiotic variables that contribute to energy flow.

Community refers to a group of species that occur in the same area and affect each other's survival, growth, and behavior through a network of interactions.

Population refers to both population and meta-population characteristics. A population is defined as a breeding group of individuals from a single species that occupy a defined area and share a common gene pool that may be genetically different from the gene pools of similar groups. A meta-population is defined as a group of semi-reproductively isolated populations whose dynamics and genetic structure are influenced by limited inter-population migration and local environmental conditions.

Individual refers to the characteristics of each individual fish.

(Largely derived from Zimmerman & Krueger 2009)

The following conceptual framework identifies and organizes the components of a system (Figure 14). In this case, the framework describes the factors that could be affecting salmon and steelhead survival during the component of their life cycle experienced in the Salish Sea. The factors are nested within organizational levels: ecosystem, community, population, and individual (levels defined in Figure 13). The levels are organized in a modified stacked venn diagram to illustrate the overlapping relationships between the levels. Human factors are nested in their own category given their overarching effects at multiple levels. This framework is loosely based upon the conceptual model developed by Zimmerman and Krueger (2009) for examining scientific questions related to the reestablishment of native deepwater fishes in the Laurentian Great Lakes.

The conceptual framework is based on a set of stated assumptions, also described below. The framework and its associated assumptions regarding how the system operates provide a structure for developing the hypotheses of survival drivers. Both are intended to be challenged and revised throughout the research process.

A simpler systems approach to describing the Salish Sea ecosystem would have been to use the bottom-up and top-down model: bottom-up controls being factors or processes affecting food supply and top-down typically meaning predation but has been expanded in many forums to include other factors or processes affecting survival, such as disease and toxics. However, the Technical Team was concerned that this model does not illustrate relationships between bottom-up and top-down controls, and certain factors don't seem to fit well in either of the two categories. For example, predator abundance (top-down) can be affected by salmon prey availability (bottom-up), indirectly where the prey (e.g., zooplankton) affects multiple species at a trophic level targeted by the predator, or directly where the prey source is shared by the salmon and its predator.

Assumptions

The following assumptions represent the basis for the research plan.

A. Salmon and steelhead survival is connected to the condition and the dynamics of their environment.

B. Salmon and steelhead survival can be better understood by examining impacts through a series of inter-connected life stages and associated habitats as well as holistically.

C. Salmonids experience the early marine environment as four habitat types: lower river, estuary (marine entry), nearshore, and pelagic (offshore). Lower river is included because it is the area beyond which existing monitoring occurs.

D. The most informative approach to understanding salmonid survival should include a simultaneous review of hierarchical factors at the individual, population, community, and ecosystem levels as well as human factors.

E. The importance of these hierarchical factors to salmon and steelhead survival vary over space and time.

F. Different factors affect salmonid species and populations in different ways, although shared drivers across species and populations exist.

G. In some cases, hatchery stocks can act as a proxy/indicator for wild salmon or steelhead populations; however, separate hatchery and wild evaluations are typically preferable.

H. Multiple factors are likely at play (for determining growth and survival of juvenile salmon) and many should be assessed simultaneously for cumulative effects

Framework Diagram

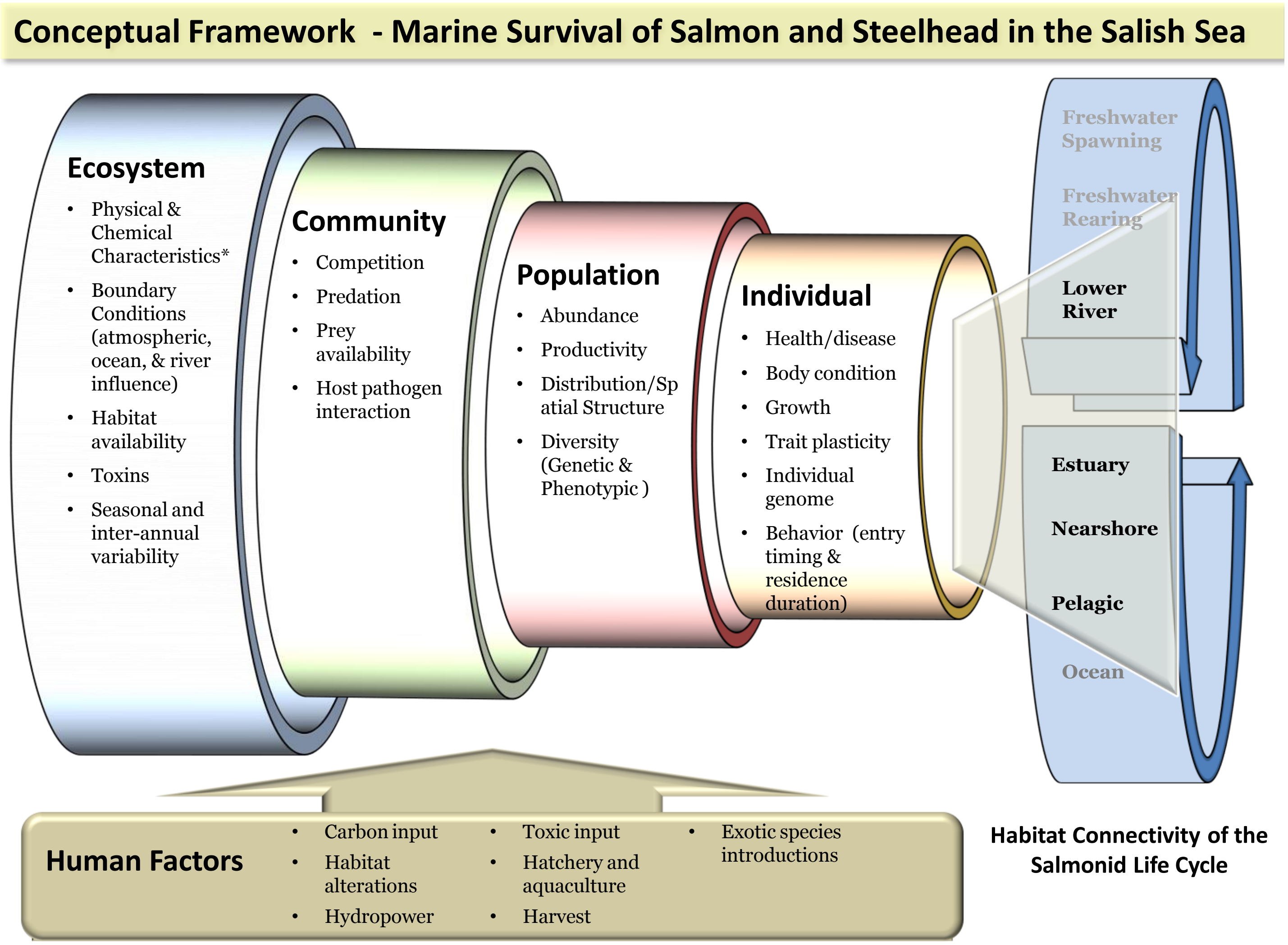

Figure 14. Conceptual Framework of the Puget Sound marine survival research plan.

Framework Diagram Notes:

- Physical & Chemical Characteristics of the Salish Sea include temperature, salinity, pH, dissolved oxygen, CO2, wind, sunlight, nutrients, circulation/currents, etc.
- Boundary Conditions represent the characteristics of the atmosphere, coastal ocean, and rivers; those "boundary" environments that influence the physical and chemical characteristics of the Salish Sea.
- Individual and Population characteristics refer to salmon and steelhead only whereas ecosystem, community and human factors include other relevant species and factors affecting those species.
- The factors intend to describe interactions "within" the four habitats experienced by salmon and steelhead while in the Salish Sea. Boundary conditions are the exception as they represent pressures that influence the characteristics of the Salish Sea.

HYPOTHESES AND RESEARCH RECOMMENDATIONS

Overview

The Technical Team with the help of other contributing authors have drafted hypotheses and preliminary research recommendations required for determining which factors most significantly affect salmon and steelhead marine survival in Puget Sound[15]. The Technical Team assumes that multiple factors are at play and many should be assessed simultaneously for cumulative effects; however, dominating factors will also emerge. It should also be noted that, while the hypotheses cover a broad range of potential factors affecting survival, when investigating in aggregate, efficiencies emerge. With that said, the Team does believe that current information, as described in the hypotheses descriptions and associate research recommendations, can help refine the scope of the research needed; the next step in the process toward completing the formal research plan.

The hypotheses are categorized based upon the levels of the conceptual model described above. They are:

Salmon and Steelhead Individual & Population Characteristics

1. Marine survival does a better job than freshwater survival in explaining productivity trends of salmon and steelhead in the Salish Sea.
2. Ecosystem and community factors affecting salmon and steelhead survival are operating at different levels by area encountered, species, hatchery v. wild, and within species, by life-history.

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[15] It should be noted that some of the hypotheses and research recommendations, such as those for Harmful Algae (hypothesis 9) extend beyond the US waters of the Salish Sea, and most all of the hypotheses and research recommendations could be considered in a broader geographic context.

3. Size-Selective mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood.
4. Outmigration timing influences the magnitude effect of competition, predation, and environmental variation on survival in the Salish Sea
5. Resident-type behavior and the duration of residence influence survival in the Salish Sea.
6. Through a process known as the portfolio effect, diversity among salmonid populations confers temporal stability and long-term persistence of the species within the Salish Sea.

The Role of Ecosystem Factors

7. Changes in circulation and water properties have altered phytoplankton and zooplankton production in ways that degraded salmon food-webs in the Salish Sea from the 1970s to 2000s.
8. Increased C02 concentrations indirectly affect salmon survival or increase their susceptibility to other sources of mortality.

   H-8_A (Indirect) Ocean acidification affects the productivity or nutrition quality of important zooplankton invertebrate prey for salmon (and forage fish).

   H-8_B (Increase susceptibility) Increased CO_2 concentrations affect the nervous system and behavior of salmon and steelhead or affect growth.

   H-8_C (Indirect) Elevated CO_2 concentrations alone and combined with increased temperatures are promoting *Heterosigma* growth, which can affect salmon survival.

   H-8_D (Indirect) Synergistic responses to elevated CO_2/low pH concentrations combined with low oxygen, warming, and eutrophication can occur, as well as the combined effects of ocean acidification and toxics.

9. Harmful algae directly affect salmon survival through acute or chronic mortality and may adversely affect prey availability by food web impoverishment.

   H-9_A Major *Heterosigma* blooms reduce survival of Fraser River Sockeye in specific years over a 20 year period. Survival may be affected by acute or chronic toxicity, food web and salmon prey impoverishment, or a combination of these factors. The algal may affect other salmonid species that encounter *Heterosigma* blooms in other regions of the Salish Sea.

   H-9_B Other harmful algal bloom species that occur in the Salish Sea and NE Pacific Ocean waters kill fish directly through toxicity or physical gill damage.

10. Reduced habitat availability and/or diversity have affected the behavior (and reduced the diversity) of salmon while in the Salish Sea.
11. Toxic contaminant inputs have increased, affecting marine survival of salmon through reductions in growth and resistance to disease.

    H-11_A Exposure to contaminants in estuarine and marine waters reduces the marine survival of juvenile salmon migrating through the Puget Sound to the Pacific Ocean.

    H-11_B Exposure to contaminants in estuarine and marine waters of Salish Sea reduces the marine survival of salmon residing in the Salish Sea

H-11_C Exposure to contaminants in freshwater habitats causes latent reductions in marine survival of juvenile salmon.

The Role of Community Factors

12. Food supply limits growth, and thus survival, during critical periods of early marine rearing.
    - H-12_A Growth is limited by food supply during critical growth periods
    - H-12_B Growth is limited by food quality
    - H-12_C Growth is limited by the metabolic effects of temperature
    - H-12_D Food supply is limited by competition during critical growth periods
    - H-12_E Food supply is limited by reduced production of key prey. Timing, duration, quantity, spatial extent, and/or composition/quality of prey has changed (Insufficient food supply to meet demand or mismatch between demand (outmigrant timing and condition) and prey.
13. Predation by larger fish and marine mammals has increased on salmon and steelhead, respectively. And, the potential effect of bird predation represents a significant knowledge gap.
14. Infectious and parasitic diseases are causing direct and indirect mortality.[16]

The Role of Human Factors

The contribution of human factors is inherently important as it relates back to management actions that can be implemented for wild fish recovery and sustainable fisheries. The Technical Team chose to leave most of the human factors embedded within the hypotheses, above, instead of identifying them separately. These include the effects of habitat alterations, carbon inputs, hydropower, toxic inputs and hatchery and aquaculture production. Bycatch in fisheries was discussed as a driver for juvenile and resident salmon survival (hook and release mortality and purse seine fisheries). However, a cursory review suggests that bycatch may not be significant enough to warrant intensive investigation (pers. comm. N. Mantua 2012). The association of human factors to the above hypotheses will continue to be a top priority in research development and when evaluating the research results.

Evaluating Cumulative Effects

Several of the factors described in the hypotheses above may have additive, compensatory, or synergistic effects on salmon and steelhead survival when combined. Efforts must be made to replicate these phenomena to ensure that the strength of the factors on survival and their relationships with one another are well understood. To do this, several factors will likely have to be evaluated simultaneously through monitoring, process studies, and models. Examples of models with potential are MoSSea[17] (Modeling the Salish Sea) physical circulation and ecosystem modeling up through zooplankton and the Atlantis ecosystem model NOAA fisheries is currently developing for Puget Sound. A more thorough discussion is needed regarding how to evaluate cumulative effects before a research plan is finalized.

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[16] Disease is listed under community factors because the source of disease is host pathogen interactions that are considered to exist at the community level.

[17] http://faculty.washington.edu/pmacc/MoSSea/

Hypotheses Summaries and Research Recommendations

The following sections describe the hypotheses and research recommendations. Abstracts are provided up front for each hypothesis followed by a summary of the research recommendations and a list of existing, relevant monitoring activities, most of which will likely be associated with completing the research proposed. The complete write-ups of the hypotheses and research recommendations, including references, are provided as appendices to this document. While the specifics for implementing the research have not been developed, it is assumed, based on the collaborative approach applied through the research planning process, that this effort will continue to include resources from federal and state agencies, tribes and academia.

Salmon and Steelhead Individual & Population Characteristics

Salmon and steelhead individual and population characteristics can be evaluated to determine where and when is survival most affected, how their characteristics may affect survival, and whether their freshwater experience is affecting survival in the marine environment. Hypotheses 1 through 6 and the associated research recommendations describe the Technical Teams perspective and evaluation approach. Hypotheses 1 and 4 were written solely from the standpoint of wild population analyses; however, they have been expanded in the research recommendations summary that follows this section to include hatchery stocks. Hypotheses 2, 3, 5 and 6 are inclusive of hatchery stocks and wild populations. Chinook, coho, chum, pink and steelhead are proposed for investigation.

1. Marine survival does a better job than freshwater survival in explaining productivity trends of salmon and steelhead in the Salish Sea

Mara Zimmerman, Washington Department of Fish and Wildlife
Correigh Greene, NOAA Northwest Fisheries Science Center

Differences in the temporal pattern of survival for Salish Sea and Pacific coast salmon stocks have focused attention on Puget Sound's marine environment, and some have pointed to low survival in recent years as evidence for problems within Puget Sound and the Strait of Georgia. Interactions within the freshwater and estuary environments may both influence productivity and the temporal patterning of adult returns.

Survival in the freshwater versus marine environment is a natural division for anadromous salmonids as the physiological requirements and the ecological interactions in these environments differ. This section develops a rationale and approach to test the hypothesis that marine survival predicts trends and variation in productivity of salmon and steelhead in the Salish Sea. Productivity is defined as the ratio of spawner produced by parent spawners and represents the cumulative survival through multiple life stages. In this section we are primarily interested in whether survival in the marine environment is a better predictor of trends in productivity than survival in the freshwater environment. Understanding the mechanistic explanations for these relationships is essential but more suitably addressed by subsequent hypotheses in this research plan.

Evidence supporting our hypothesis comes from a number of studies that link environmental factors in marine systems to adult returns, and studies suggesting that due to predation risks, marine systems are inherently more dangerous than freshwater environments. However, any species with extended residency in freshwater will be exposed to substantial freshwater mortality during life stages that are highly vulnerable due to size-dependent mortality. Moreover, in freshwater systems, competition occurs in a more restricted environment, and, as a result, freshwater contributions may influence mortality due to variation in individual growth rates. Ultimately, the first step in testing out hypothesis is to determine the relative contributions of freshwater and marine survival to the trends in salmon and steelhead productivity.

We begin with a general background of freshwater and marine survival of salmon and steelhead. We then use selected long-term data sets for coho and Chinook salmon to develop an approach that addresses our hypothesis. We next develop a rationale for considering spatial components of marine survival and identify data needs that facilitate additional comparisons among other stocks. Finally, we propose a short-term research program, based on a space-for-time substitution, which should further address the contribution of marine survival to salmon and steelhead productivity.

The take-home messages of our summary are:

- Useful analyses to address this hypothesis will be (1) trends in total mortality and variation in total mortality partitioned between the freshwater and marine environment, and (2) correlation between survival rates (freshwater and marine) and resulting adult recruits,
- In our case examples, the proportion of total mortality occurring in the marine environment ranged between 1% and 20%,
- In just one of our case examples, the number of adult recruits is better explained by survival in the marine than the freshwater environment,
- Regional factors make an important contribution to adult recruitment; therefore, spatial comparisons may be as informative as temporal comparisons when explaining salmon and steelhead productivity,
- Data needs to further address this hypothesis include spawner, smolt, and catch abundance partitioned by age class, and
- We propose a 5-year research program which substitutes spatial replication for temporal longevity and is based on life cycle monitoring of populations in representative regions of the U.S. Salish Sea.

2. Ecosystem and community factors affecting salmon and steelhead survival are operating at different levels by area encountered, species, hatchery v. wild, and within species, by life history

Michael Schmidt, Long Live the Kings

The Puget Sound ecosystem does not behave uniformly and neither do the salmon and steelhead entering it. Different species of salmon and steelhead entering and occupying Puget Sound in different areas at different times (e.g., Georgia Strait, Whidbey, North Central Puget Sound, South Central Puget Sound, South Puget Sound, Hood Canal, Strait of Juan de Fuca; and lower river, estuary, nearshore, pelagic), representing different life-history strategies, and as hatchery or wild fish, will experience factors affecting their survival differently (see Figure 6 on page 12, as an example). At the same time, commonalities likely exist. Evaluating marine survival, distribution and residence duration trends of hatchery and wild salmon and steelhead populations across Puget Sound can help isolate where and when survival is affected. This information, in turn, helps direct efforts to determine what factors have the greatest impact on survival. To do this, the temporal and spatial composition of all project investigations should strategically represent the various environments experienced and the species, types (hatchery v wild), and life histories that experience them. Correlations between marine survival and characteristics such as outmigration origin, outmigrant time, outmigrant size, and hatchery v. wild should be evaluated. Existing data should be analyzed to the best extent practicable, and these analyses should be included as part of an intensive, 5-year research effort. Existing acoustic telemetry data could be used to do a cursory evaluation of the distribution and movement of Chinook and coho; however, the resident life-history component for these species confounds efforts to estimate mortality using this method. Distribution, movement and mortality of steelhead will be analyzed using acoustic telemetry data as a component of the steelhead research described in predation hypotheses (number 13).

3. Size-selective mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood.

Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences

Size-selective mortality has been widely reported during the juvenile stages of many fish species, including anadromous salmonids, and can be a predominant force affecting marine survival and adult run size. Size-selective mortality can operate at different life stages for different species and stocks of anadromous salmonids. Strong size-selective mortality for hatchery Chinook salmon in Puget Sound and coho salmon in the Strait of Georgia linked higher adult returns with sizes achieved during early months of marine life, whereas varied responses have been reported for steelhead and pink salmon populations within or adjacent to the Salish Sea. Predation by resident Chinook salmon, anadromous cutthroat trout and bull trout in Puget Sound all show clear evidence that juvenile pink, chum, and Chinook salmon in stomach samples were significantly smaller than conspecifics sampled concurrently in the environment.

Size-selective mortality offers a useful conceptual framework for examining and linking processes that affect growth and survival at different life stages of anadromous salmonids, and for identifying and quantifying when and where critical periods of growth and survival occur. By relating size (weight, fork length, condition) of juveniles to adult returns or smolt-to-adult survival (SARs) at regular intervals or during sequential life stages (i.e., smolt trap and/or hatchery, estuarine, nearshore marine, and offshore marine), we can identify the life stages that most influence size-selective marine survival (critical sizes and critical periods). By collecting scale (or otolith) samples for each of the life stages sampled above, and for returning adults, shifts in the modal back-calculated size at specific life stages can be used to determine the magnitude of size-selective mortality, the periods of critical growth or mortality, and stage-specific relationships between size and survival.

4. Outmigration timing influences the magnitude effect of competition, predation, and environmental variation on survival in the Salish Sea

AND

5. Resident-type behavior and the duration of residence influences survival in the Salish Sea.

Josh Chamberlin, NOAA Northwest Fisheries Science Center

Changes in outmigration timing and residence duration may have significant effect on marine survival in the Salish Sea. Typical outmigration periods for naturally spawned fish in Puget Sound range between February and August depending on species and life history type while hatchery reared fish are generally released from late March to mid June based on species, run, or age class. Several factors, including density dependent mechanisms and variable environmental conditions, can shift the peak outmigration date and change the duration of the outmigration period. Timing of outmigration has significant influence upon the conditions fish experience during the early marine phase. Shifts in outmigrant timing may have a negative effect on juvenile salmon survival if these shifts do not correspond to resource availability in the marine environment or increase encounters with adverse environmental conditions (HAB's). Earlier outmigration periods may reduce fish condition as a result of poor growth and can further reduce growth potential through an increase in predation and competition. Overall, variation in outmigration timing may increase the magnitude effect of predation, competition, and/or environmental variation on overall survival of individuals during the early marine period. Furthermore, extended residence in the Salish Sea may negatively impact overall marine survival of salmon in the region, especially for Chinook and coho. Increased contaminant load, delayed competition for limited and seasonal prey, and increased predation by local marine mammal populations may all contribute to reduced survival and warrant further research.

6. Through a process known as the portfolio effect, diversity among salmonid populations confers temporal stability and long-term persistence of the species within the Salish Sea.

Kenneth Warheit, Washington Department of Fish and Wildlife

Ecological systems are more stable and at lower risk when they are composed of a diversity of interacting component parts (i.e., the portfolio effect). For example, species richness and a diverse assemblage of species interactions are assets for ecological communities, just as a diversity of stocks and bonds is an asset for a financial investment portfolio. We cannot explicitly test the portfolio effect hypothesis for Puget Sound salmonids because we lack long time series for many populations from which we can measure diversity, and we are without an unbiased measure of meta-population stability (due in part to population supplementation from hatcheries). However, we can evaluate a corollary of the portfolio effect, that a reduction in the diversity of the component parts may put the larger whole at risk of decline. Here, as an example, we will examine if a reduction in the diversity of Chinook salmon populations may put the Puget Sound Chinook meta-population at risk of decline. We explore the genetic diversity, adult run timing, and geographic structure of Chinook from 13 different river systems and hatcheries to determine if Puget Sound Chinook have experienced a reduction in diversity during the past several decades. From 1975 through 2010 the Chinook meta-population within Puget Sound has been transformed from a balanced mix of north and south populations with varying run timing to a system that is now dominated by late run hatchery-origin individuals from a single ancestral lineage (Green River). In other words, Puget Sound Chinook salmon have experienced an overall decrease in genetic and run time diversity. At the population and meta-population levels, the portfolio effect hypothesis predicts a decline in the stability of the Chinook meta-population in Puget Sound. Furthermore, extending the hypothesis to the molecular – individual and population levels, a reduction in MHC diversity, for example, may be associated with a decline in individuals' relative resistance to pathogens, putting populations at an increase risk to declines associated with new epidemics.

In the absence of parallel long-term data sets describing life history or geographic diversity of populations, and overall stability of a species or meta-population in the Salish Sea, it will be difficult to ascribe change in salmonid abundances to the portfolio effect. However, our current inability to test for the portfolio effect does not negate the importance of establishing baselines and monitoring diversity among salmonid populations. It is the diverse portfolio that drives health and stability, and a monoculture of genes (for individuals) or populations (for meta-populations) will place individuals at risk of death and populations, meta-populations, or species at risk of extinction. We know too little about the portfolios of salmon and steelhead populations in the Salish Sea, putting us at a disadvantage to better understand why some species and populations may thrive and others, despite management efforts, do not recover, or continue to decline.

Research Summary: Salmon and steelhead individual & population characteristics

There is significant overlap in data collection and analyses to address hypotheses 1-6. Therefore, a comprehensive overview of the proposed research recommendations is provided. This section begins with a summary of the recommended analyses (Table 1). Retrospective data collection; an intensive, 5-year, spatially representative monitoring design; and one process study are recommended for these analyses, including wild populations and hatchery stocks from each Puget Sound sub-basin identified in Figure 12. The structure of the intensive monitoring effort is explained in Table 2, below, and research considerations follow. Finally, a list of existing, relevant monitoring activities is provided (Table 3), several of which the research proposed here will utilize and build upon.

Analyses

The following table describes the recommended analyses. The correlating hypotheses numbers are to the left, followed by the types of analyses and their descriptions.

Table 1. Summary of recommended research: individual and population characteristics

Hypotheses	Analysis Type	Description
(1) Survival, Marine v Fresh (2) Factors operate at diff. levels by region, etc.	Retrospective and Monitoring	Analyze (1) trends in survival and variation in total survival partitioned between the freshwater and marine environment, and (2) correlation between survival rates (freshwater and marine) and resulting adult recruits. Include spatial comparisons to evaluate survival variance within the Puget Sound basin. Continue to compare Puget Sound marine survival to representatives of other regions such as the Washington Coast to help discern between open ocean effects and those unique to Puget Sound.
(4) Outmigrant timing (2) Factors operate at diff levels by... (3) Size-selective mortality	Retrospective and Monitoring	Analyze outmigration timing (and size) trends. Among the Puget Sound sub-basins and at a watershed by watershed scale determine whether certain life-history trajectories (or, for hatchery programs, release strategies) are more successful (when related to marine survival) than others from an outmigrant timing (and size) perspective. Determine the extent to which inter-annual variability in outmigrant timing (and size) is correlated among species and life-history trajectories. Determine whether outmigration timing (and size) has changed over time and whether there is a correlation with changes in marine survival.
(3) Size-selective mortality	Retrospective	Conduct retrospective analysis on scale patterns of returning adults to evaluate relationships in smolt size, size-at-annulus, and patterns in size-at-specific circuli to adult returns or SARs. Compare size distributions at specific life stages from scales of returning adults to size distributions from scales of juveniles sampled at specific life stages in frozen archives (2001-2012).
(2) Factors operate at diff levels by…	Monitoring	Evaluate the distribution and movement of salmon and steelhead via presence and abundance (and mark recapture) as part of the intensive, 5-year fish monitoring effort.
(3) Size-selective mortality	Monitoring	Examine size-selective mortality using two complementary approaches: 1) correlations and linear relationships between body size (fork length, weight, or condition) and SARs or some alternative measure of survival for as many life stages as can be adequately assessed feasibly; and 2) changes in stage-specific size distributions through time and among life stages, based on scale (and potentially otolith) circuli patterns (radius and counts of all circuli associated with specific life stages).
(3) Size-selective	Monitoring	Determine whether there is a size-dependent effect expressed in marine mortality but is a result of effects in the freshwater by

Hypotheses	Analysis Type	Description
mortality (4) Outmigrant timing		including outmigrant trap data as part of this analysis.
(5) Residency	Retrospective and Monitoring	Determine proportions of populations, especially Chinook and coho, that display residency. Perform an otolith microstructure/microchemistry analysis of known residents (capture location & month and contaminant evaluation as independent verification, see row below) vs. spawners. Utilizing existing otolith samples, if available, and collect additional samples during the 5-year intensive monitoring effort to determine the proportion of residents over time and whether there is a correlation between the proportion of residents and marine survival. Determine hatchery vs wild contribution to residency and changes in proportions over time.
(5) Residency (11) Toxics	Retrospective and Monitoring	Analyze microstructure/microchemistry of otoliths and PBT contaminant concentrations of Chinook and populations assumed to be resident and nonresident (based on capture location and timing) to determine if a distinct chemical signal indicative of residency can be developed for otoliths. Recent results indicate that these resident Chinook and coho salmon have elevated levels of PBTs and distinct chemical fingerprints as a consequence of their feeding within the Puget Sound food web. However, PBT chemical fingerprint are more expensive than otolith microchemistry fingerprints.
(2) Factors operate at diff levels by…	Retrospective	Analyze available acoustic tag information to do a cursory evaluation of the distribution and movement of Chinook and coho. The resident life-history component for Chinook and coho confound efforts to estimate mortality using acoustic tags.
(2) Factors operate at diff levels by… (13) Predation	Retrospective and Monitoring	Analyze available and future acoustic tag data to evaluate distribution, movement and mortality of steelhead. See hypotheses 13 for a complete description
(6) Portfolio effect	Process Study and Monitoring	Continue the process of establishing diversity baselines and monitoring diversity among salmon populations. Of special concern for this study are the three priority meta-populations—Puget Sound Chinook, steelhead, and coho.
All	Retrospective and Monitoring	Analyze fish data against ecosystem data collected to determine whether correlations exist. Utilize direct comparisons, modeling, etc.

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Intensive, Short-Term Monitoring

The data collection associated with the proposed 5-year monitoring effort that expands upon existing activities within Puget Sound.

Table 2. Field data collection for the 5-year monitoring effort: individual and population characteristics component.

Habitat	Time Frame	Measurement Tool	Survival, Abundance and Density[1, 2]	Behavior (migration timing and residence duration)	Size Distribution, Body Condition and Growth	Spatial Diversity
Freshwater / Lower River	April-December (varies)	Spawer Survey, Adult weir	redd/live counts + mark-recapture[3]	otolith micro chem	Scale/otolith size-at- age & size-at-circuli	Scale samples (min 50 per population per year for two years) for diversity analysis.
	January-July (daily)	Smolt trap / Hatchery release	counts + mark-recapture CPUE or # per square	Date present (all fish collected)	Sample up to 50 per outing - Body Condition[4] (Energy, IGF-1, %Dry Wt) - Scale/otolith size-at- age & size-at-circuli	
Estuary	Spr-Sum (every other week	Tide channel, Fyke trap	CPUE or # per square meter + mark-recapture counts	Date present (all fish collected)		
Nearshore	Spr-Sum (every other week)	Beach seine				
	April-October (montly)	Surface tow net, lampera net				
Pelagic	April-October (monthly)	Purse Seine				
	July & Sept (monthly)	Midwater trawl (Ricker)				
Marine/ Fresh	Year round (continuous)	Harvest, Hatchery	# fishery mortalities, # to hatchery + mark-recapture	Otolith micro chem from winter test fishery (to establish resident signature), and broad collection	Scale/otolith size-at- age & size-at-circuli	

1. Mark/Tag status is required for all sampling to partition hatchery and wild origin fish.
2. Stock Identification & Hat/Wild composition will be determined by collection location, historic contribution data, cwt, otolith, GSI, ad-fin clip presence/absence
3. Mark recapture is described as the use of marks (e.g., otolith, cwt, gsi, fin clip) to identify population origin to be compared between capture locations, such as smolt traps to beach seines, etc.
4. Length, weight samples will likely exceed 50 samples per outing in several cases due to standard protocol for particular monitoring activites (e.g., hatchery releases and smolt traps).

Research Considerations

The following research considerations are most relevant to the individual and population characteristics analyses but extend to the ecosystem and community factors analyses as well. For both retrospective work and short-term monitoring:

- Ensure that research program represents each Puget Sound sub-basin to the best extent practicable. Consider including 1 wild population and 1 hatchery stock of each priority species that originate in the following Puget Sound sub-basins described previously in Figure 12: San Juans and Georgia Strait (aka., Northern Straits), Strait of Juan de Fuca, Hood Canal, Whidbey, South Central Puget Sound, South Puget Sound. Include pelagic monitoring in North Central Puget Sound even though it does not have representative populations/stocks.
- Build upon existing programs, filling in gaps to fulfill research needs.
- Priority should be given to wild populations and hatchery stocks where the most complete and independent data can be established. Indices are often used to develop estimates of fisheries-related mortality, age composition, spawner abundance, and juvenile outmigrant abundance. At times, the indices are based on proxies or indicator stocks. In many cases, at least for hatchery stocks, the preferred populations to evaluate will likely stocks currently used as indicators for harvest management. For this study, independent data on smolt outmigrant and adult abundance should be simultaneously available for each wild population evaluated, and priority should be given to those with the best fit indicator stocks: preferably those with double-index tag groups[18] for estimating fisheries-related mortality. Wild and hatchery fish should be distinguishable (or the proportions known) so that they don't confound the results.
- See table 2 in appendix A, hypothesis 1 for information about data availability by wild population and table 3 under appendix A, hypothesis 1 for an example of the research composition by wild population. A similar set of recommendations have not yet been develop for hatchery stocks.
- A representation of various habitats and habitat conditions should be considered when establishing the intensive fish monitoring effort (addresses needs in the habitat hypothesis [10]). Also, the locations of all ecosystem monitoring proposed in this study should be coordinated appropriately with the fish monitoring locations.
- Evaluate take ESA - constraints for Puget Sound Chinook and steelhead and Hood Canal summer chum when developing the research. Coordinate sampling needs that result in mortality to the greatest extent practicable.

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[18] Double index tag groups – Release groups that are coded-wire tagged and included both adipose-fin clipped and non-adipose fin clipped fish. The coded-wire tagged fish with their adipose fin intact can provide a better representation of wild fisheries-related mortality due to their differential treatment in mark-selective fisheries that target adipose-fin clipped fish.

Existing, Relevant Monitoring Activities

The monitoring of salmon individual and population characteristics occurs on a broad scale in Puget Sound. The resource co-managers, Washington Department of Fish and Wildlife (WDFW) and the Puget Sound Treaty Tribes perform the bulk of the monitoring; however, NOAA Fisheries, the University of Washington, the counties, nonprofits and other cooperative groups are involved. The following is a general , not comprehensive, list of monitoring and data management activities relevant to executing the research proposed in this report. For a specific evaluation of several of these monitoring activities, please refer to the "Methods and Quality of VSP Monitoring of ESA Listed Puget Sound Salmon and Steelhead" report produced recently for the Puget Sound Ecosystem Monitoring Program (Crawford 2012).

Table 3. Existing monitoring activities related to salmon individual and population characteristics analyses recommended in this report.

Activity Type	Program	Agency	Comments
monitoring	Fish In - Fish Out (Juvenile outmigrant and adult return/natural escapement monitoring)	WDFW, Treaty Tribes and participating orgs	Covers a variety of approaches used to estimate adult and juvenile abundance in the freshwater. This is most typically done via spawning ground surveys and juvenile outmigrant trapping. Pops with most years of data are described in Appendix A, Hyp 1, Table 2.
monitoring & database	Spawning Ground Surveys and database AND information with individual tribes	WDFW, Treaty Tribes	Annual estimates of spawner abundance by river and species for selected populations.WDFW's SalmonScape and their SGS database house a significant portion of this information.
monitoring	Intensively Monitored Watersheds	WDFW, WDOE, NOAA, EPA, Lower Elwha Klallam Tribe, SRSC[19], Weyerhauser	Couples salmon life cycle and habitat monitoring to evaluate population-level response to habitat restoration treatments in the Strait of Juan de Fuca, Hood Canal, and Skagit River estuary.

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[19] Skagit River System Cooperative.

Activity Type	Program	Agency	Comments
monitoring	Juvenile offshore sampling Ricker Cruises	DFO Canada, UW	bi-annual midwater trawls throughout Salish Sea (primarily Strait of Georgia but some time in Puget Sound) to evaluate abundance, growth, diet, etc. Special emphasis on salmon (but other species, including forage fish, are sampled)
monitoring	Juvenile nearshore sampling	Treaty Tribes, NOAA, UW, nonprofits	Some juvenile salmon sampling has and continues to occur in various nearshore and estuary locations throughout Puget Sound, most notably near the Skagit, Snohomish, Stilli, Nisqually, Elwha, and Hood Canal watersheds.
monitoring	Salmon Biotelemetry	NOAA, POST, Kintama Research and others	Acoustic tracking network. Status is ongoing, but funding is limited and recent changes have been made
monitoring database	Hydra - Salmon Biotelemetry Database	Consultant working with NOAA, UW, and others	Independent consultant who created a database to help manage biotelemetry data.
monitoring	Harvest monitoring: Commercial, sport & tribal :	WDFW, Treaty Tribes	Harvest quantities and catch effort using various methods, in the coastal ocean, Puget Sound and the freshwater.
monitoring & database	Coded-wire tagging programs and the Regional Mark Information System (RMIS)	WDFW, Treaty Tribes, PSFMC, NOAA	Mark-recapture program designed to evaluate fisheries distribution, contribution rates to fisheries and escapement, age structure, and survival. PSFMC administers the Regional Mark Processing Center.
monitoring & evaluation	Pacific Salmon Commission Chinook and coho indicator stock programs	PSC, DFO, WDFW, Treaty Tribes, NOAA	Exploitation rate indicator stocks based on CWT analyses (Chinook and coho). Used to evaluate and manage harvest and escapement for Pacific Salmon Treaty. Includes run-reconstruction analyses.
monitoring and database	Salmonid Stock Inventory (SaSI)	WDFW and Treaty Tribes	SaSI is a standardized, uniform approach to identifying and monitoring the status of Washington's salmonid stocks. The inventory is a compilation of data on all wild stocks and a scientific determination of the status of each stock as: healthy, depressed, critical, extinct, or unknown. This information is provided via WDFW's SalmonScape and the inventory technical documents.

Activity Type	Program	Agency	Comments
monitoring and research	WDFW Genetics Laboratory	WDFW	Stock identification, diversity, gene flow, population structure, and mixed stock-fishery and parentage analyses. Contributing to the standardization of allozyme, microsatellite, and SNP markers in Chinook, chum, and coho salmon, steelhead, and bull trout, and a major repository of fish tissue samples (for DNA analysis)
monitoring	NWIFC Genetics Laboratory	NWIFC	Stock identification, diveristy, gene flow, population structure, and mixed stock-fishery and parentage analyses.
monitoring	Otolith and Scale Evaluations	WDFW, NOAA, UW, Treaty Tribes, private consultants	WDFW Otolith Lab regularly performs mark-recapture for hatchery-wild evaluations and evaluate fish life-history, growth and other characteristics. WDFW Scale Lab evaluates fish origin life-history, growth and other characteristics. Other groups in the region also perform otolith and scale evaluations on a regular basis.
monitoring	WDFW Fish Plant Reporting	WDFW and cooperative programs	WDFW tracks the history of hatchery release data (stock, numbers, size, release date, mark presence/absence, etc.) for WDFW and cooperative hatchery programs. Hatchery releases are also included in the RMPC database at www.rmpc.org
monitoring	WDFW Hatchery Escapement Reporting	WDFW and cooperative programs	Enumerates the total number of adult fish returning to hatchery racks or traps. provide information on run timing, information on the results of selective fisheries, and critical data for coded-wire tag (CWT) analysis
monitoring	Treaty Tribes Fish Plant and Escapement	Treaty Tribes	Each of the treaty tribes individually track hatchery releases and adult returns.
monitoring	USFWS Hatchery Release and Escapement Reporting and the Fisheries Resources Evaluation Database (FRED)	USFWS	Encompasses production, releases, returns to Quilcene Hatchery in Hood Canal

The Role of Ecosystem Factors

Ecosystem factors refer to the biotic and abiotic variables that contribute to energy flow (Zimmerman and Krueger 2009). These factors are the foundation upon which the entire ecosystem is built. Certain ecosystem factors may have a stronger influence on salmon and steelhead survival as described in the hypothesis and research recommendation summaries, below.

7. Circulation and bottom-up processes hypothesis: Changes in circulation and water properties have altered phytoplankton and zooplankton production in ways that degraded salmon food-webs in the Salish Sea from the 1970s to 2000s.

Nate Mantua, University of Washington, Aquatic and Fisheries Sciences
Neil Banas, Julie Keister, and Parker MacCready; University of Washington, Oceanography
Jan Newton, University of Washington, Oceanography

This hypothesis states that trends and variations in Salish Sound circulation and affected water properties cause trends and variations in Salish Sea salmon marine survival through bottom-up processes. These bottom up processes may include physically forced variations in the timing of the spring phytoplankton bloom and/or changes in zooplankton development cycles in ways that lead to a mismatch between forage production cycles and smolt migration timing, and/or changes in the amount of high-quality prey at key times of the early marine life history that result in changes in salmon marine survival. Several lines of evidence demonstrate trends and variations in environmental conditions and changes in juvenile salmon food supplies in the Salish Sea. These include surface warming trends and multidecadal variations since the 1920s, a period of surface and subsurface warming in the Strait of Georgia from the 1970s to present. At the same time there has been a shift to an earlier and briefer growing season by the copepod Neocalanus plumchrus that has been ongoing since the 1970s in the Strait of Georgia. This change appears to be related to warming trends. The specific physical forcing of greatest importance is still in question. We have evidence of long-term temperature changes, but it may be that surface water stratification exerts a stronger control. We currently lack the data required to evaluate similar trends in the growing season for Puget Sound copepods. Integrated monitoring programs for hydrography, zooplankton, forage fish and juvenile salmon ecology would fill substantial knowledge gaps surrounding this hypothesis. If this hypothesis is true, zooplankton and forage fish monitoring could provide an early warning system for changes in salmon productivity that could inform hatchery operations to better match smolt production numbers or release timing to expected timing or baseline levels of productivity that may be necessary for increasing smolt-to-adult survival rates.

8. Increased C02 concentrations indirectly affect salmon survival or increase their susceptibility to other sources of mortality.

Michael Schmidt, Long Live the Kings
Paul McElhany, NOAA Northwest Fisheries Science Center
Julie Keister, University of Washington, Oceanography

The properties of Puget Sound, including restricted circulation, incursion of upwelled waters, and lower pH river inputs, put it at high risk of impacts from ocean acidification. Ocean acidification currently plays a small but important role in lowering the pH of Puget Sound, while pH is largely regulated by natural mixing, circulation, and biological processes. As Puget Sound pH is still dominated by natural processes, it is likely that ocean acidification has not altered the local environment significantly enough to be considered a major contributor to recent declines in salmon marine survival. However, there are concerns about future impacts given the predicted trajectory for atmospheric CO_2, and long-term local trends in seawater pH. Chinook, coho, chum, pink, and sockeye salmon and steelhead could all be affected, with the greater impact potentially being on those who reside longer in the Puget Sound environment or whose diet depends on species directly vulnerable to ocean acidification. Increased concentrations of CO_2 in the marine environment can impede the calcification process and influence the physiology of marine organisms by changing their internal acid-base balance—potentially leading to changes in protein synthesis, growth, development, and neurophysiology—and reduced oxygen transport capacity. Invertebrate prey important to salmon and herring diets, including gammarid amphipods, harpacticoid and calanoid copepods, euphausiids, and decapod larvae could be affected. There are also potential direct effects on fish. Recent studies of reef fish exposed to increased CO_2 concentrations in their larval stages have shown behavioral and olfactory sensory abnormalities. Similar studies have not been performed on salmon or forage fish species such as herring. Also, elevated CO_2 concentrations alone and combined with increased temperatures promote heterosigma growth, a harmful algae common to the Salish Sea that has been associated with salmon mortality. Finally, in general, a better understanding of synergistic responses to elevated CO_2 concentrations combined with low oxygen, warming, and eutrophication is a significant concern, as well as the combined effects of ocean acidification and toxics. Research recommendations include: concurrent monitoring of Puget Sound carbon chemistry with the biological investigations proposed in this report; incorporating ocean acidification data into modeling exercises to evaluate synergistic and food web effects; and process studies evaluating the effects of pH/pCO2 variability on salmon and forage fish and their invertebrate prey.

It is important to note that estimates of species risk from ocean acidification are based on projections from laboratory exposure experiments showing response to elevated pCO_2. With the possible exception of Pacific oysters, studies have not shown changes in wild abundance for any species as a direct consequence of changes in ocean chemistry from anthropogenic CO_2. The decrease in ocean pH from anthropogenic CO_2 is well documented and the change in future pH from projected carbon emissions is well understood. However, the biological response to these changes is much less clear. The extremely rapid pace of change in ocean pH and the susceptibility of a wide variety of taxa to changes in ocean carbon chemistry suggest that while the precise effects of ocean acidification on the salmon ecosystem are uncertain, the effects could be substantial.

9. Harmful algae directly affect salmon survival through acute or chronic mortality and may adversely affect prey availability by food web impoverishment

Jack Rensel, Rensel Associates Aquatic Sciences

Worldwide, harmful algal blooms (HABs) are more extensive and pervasive compared to prior decades due in part to human activities and nutrient enrichment of coastal waters, climate change and via ballast water. *Heterosigma akashiwo* (herein *Heterosigma*) is a microflagellate HAB species that appears to have become more prevalent in the Salish Sea since 1989 and now has been recorded in bloom concentrations in all basins of the Salish Sea. *Heterosigma* blooms can kill fish and other fauna and are implicated in poor survival of Fraser River sockeye. Fish survival may be affected by acute and chronic toxicity effects of *Heterosigma*, food web and salmon prey impoverishment related to the blooms, or a combination of these factors. The evidence involves strong correlations between marine survival of sockeye salmon and probable bloom exposure as juveniles, observations of wild fish being killed concurrently with farmed fish in Puget Sound and the known characteristics of the alga in other seas. Chinook, coho, chum, pink, and sockeye salmon and steelhead could all be affected, with the greater probable impact on those stocks that migrate or reside in the Salish Sea during May-early July or in late summer and early fall when large-scale blooms are most common. Blooms vary from a few days to months depending on location and are subject to rapid advection from one area to another. Adverse effects on wild adult salmonids are possible, but not documented yet. Several other HAB species are known to occur or bloom in the Salish Sea and NE Pacific Ocean waters which either kill fish directly through toxicity or gill damage. However, no quantitative data are available to assess the relative importance of these other HAB species to wild stocks of fish at this time.

Research recommendations include: Conduct live cage bioassays in target bloom and reference areas at different depths and with subsequent tissue and toxin analyses; increase the spatial extent, frequency and duration of harmful algae monitoring activities, where appropriate, to cover the migration time of priority salmon and steelhead species (especially associated with the Fraser River plume); coordinate bloom tracking efforts with underwater acoustic telemetry fish tagging and tracking; build from existing volunteer monitoring efforts; evaluate remote sensing technologies for improving bloom detection; standardize harmful algae monitoring protocol and consolidate/quality assess the data.

10. Reduced habitat availability and/or diversity have affected the behavior (and reduced the diversity) of salmon while in the Salish Sea.

Chris Ellings and Sayre Hodgson, Nisqually Indian Tribe

Juvenile salmon are dependent on high quality and diverse habitat as they migrate through Puget Sound. They need the opportunity to access the habitat, and the habitat must have the capacity to support abundant fish populations. The ability of Puget Sound nearshore habitat to support salmon is limited due to the dramatically altered distribution, diversity, abundance, and quality of Puget Sound nearshore habitat relative to the historic condition. Reduced river delta and coastal embayment shoreline lengths, armored shorelines, and loss of tidal wetlands contribute to the simplification, fragmentation and disconnection that has occurred. This may especially impact

Chinook and chum, the species most dependent on nearshore habitat. Reduced habitat availability and diversity may lead to altered behavior such as rearing, growth, and migration patterns, and lead to reduced growth, increased predation, and lower survival rates.

11. Toxic contaminant inputs have increased, affecting marine survival of salmon through reductions in growth and resistance to disease

Sandie O'Neill and Lyndal Johnson, NOAA Northwest Fisheries Science Center

The Puget Sound Lowland is the most densely populated area of Washington and is expected to grow rapidly in the future. Human development of the Salish Sea has resulted in habitat loss and modification. Much attention has been paid to the physical alterations that have occurred but contaminants have also reduced habitat quality. Chemicals released into the Salish Sea from human activities and developments reduce the health and productivity of salmon. In estuarine and marine waters, contaminants may reduce the survival of juvenile salmon migrating through the Salish Sea to the Pacific Ocean, especially for Chinook and chum salmon because of their reliance on estuaries. Reduced growth and disease resistance have been demonstrated for juvenile Chinook salmon exposed to environmentally relevant contaminant levels. Moreover, Chinook, and to a lesser extent coho salmon, that reside in the Salish Sea are exposed to contaminants for much of their marine water phase and accumulate significantly higher contaminant levels than conspecifics that rear in the coastal ocean. The effects of increased contaminant exposure on resident Chinook and coho are unknown, but may include reduced survival and viability of developing eggs and sperm. Exposure to contaminants in freshwater habitats may cause latent reductions in marine survival of juvenile salmon via reductions in growth, increased susceptibility to disease and abnormal development. Toxics are not expected to cause rapid changes in marine survival from year to year but they may contribute to long-term declines in survival, thus they need to be integrated into models of survival.

Research Summary: Ecosystem factors

A comprehensive overview of the proposed research recommendations is provided below (Table 4). Retrospective data collection, monitoring, modeling and process studies are all recommended analyses. All efforts will be closely aligned with those described in the individual and population characteristics and community factors sections. Table 5 and Table 6 follow, describing the ecosystem components of the 5 year, intensive monitoring effort. Finally, a list of existing, relevant monitoring activities is provided (Table 7), several of which the research proposed here will utilize and build upon.

Analyses

The following table describes the recommended analyses. The correlating hypotheses numbers are to the left, followed by the types of analyses and their descriptions.

Table 4. Summary of recommended research: ecosystem factors

Hypotheses	Analysis Type	Description
(7) Circulation, bottom-up	Retrospective	Conduct retrospective analyses of density stratification documented in the Collias reports from 1952-1966 Puget Sound surveys; compare observations from 1952-1966 period with those

Hypotheses	**Analysis Type**	**Description**
		from ORCA buoys from 2005-present; also compare with Department of Ecology monthly survey data to determine if monthly sampling is adequate for documenting seasonal interannual and longer timescale trends and variations in Puget Sound properties.
(7) Circulation, bottom-up	Retrospective	Use existing ORCA records to conduct analyses of phytoplankton production rates, timing, and variability to assess interannual and inter basin variation.
(7) Circulation, bottom-up	Retrospective	Use existing ORCA records to quantify the apparent connection between chlorophyll and stratification in the different basins of Puget Sound. If the connection is meaningful then stratification may be a useful proxy for primary production. Stratification has more historical data than chlorophyll, and its modeling in future scenarios is more robust.
(8) Ocean Acidification	Retrospective	Determine the role of local human influence (current and predicted) on Puget Sound acidification versus global influence to evaluate the degree to which regional efforts could influence change. This should be associated with larger efforts regarding the evaluation of ocean acidification and climate change. [low cost to this effort if covered by other efforts]
(11) Toxics	Retrospective	Conduct a review of the literature to assess potential effects of environmentally relevant exposures of legacy contaminants and chemical of emerging concern (especially xenoestrogens, pharmaceuticals, and personal care products) on salmon. This review should address 1) the available literature for priority chemical contaminants that, based on likely hazard and occurrence, pose the most important threats to salmon; 2) known mechanisms of toxicity, with clear biological connections to salmon individual fitness (lifetime survival and reproductive success); 3) established toxicity thresholds that can inform past, ongoing, and future monitoring in Puget Sound; 4) new technologies, including molecular biomarkers, that can improve the diagnostic power of monitoring for both contaminant exposure and adverse health outcomes in salmon; and 5) a gap analysis to identify where cause-and-effect toxicity studies are needed to most effectively guide salmon conservation and recovery in Puget Sound.
(7) Circulation, bottom-up	Monitoring	Expand the ORCA buoy network to more sites, and sustain observations for at least 5 years in order to increase sample sizes and document spatial and temporal variability in primary production and hydrographic features (water column temperatures, salinity, density structure, nutrients, mixed layer depths, and stratification). This should be done at the same time as the intensive fish monitoring effort described in this report, and the

Hypotheses	Analysis Type	Description
		network should appropriately represent each of the Puget Sound sub-basins described in Figure 12. The locations of the existing ORCAS buoys are in Figure 15, below this table.[20]
(7) Circulation, bottom-up	Monitoring	Add sensors to the buoy network for photosynthetically active radiation (PAR) to all buoys.
(8) Ocean Acidification	Monitoring	Ensure marine carbon chemistry and pH are included in the suite of baseline physical attributes monitored throughout Puget Sound. Carbon monitoring should be coupled with biological monitoring of species potentially vulnerable to ocean acidification that affect salmon growth and survival (e.g. krill and copepods). These data are needed to establish any causative link between acidification and salmon performance.
(7) Circulation, bottom-up **(12) Food**	Monitoring and Modeling	Develop a zooplankton and forage fish[21] monitoring program that can be implemented and sustained over multiple years in order to characterize the space-time zooplankton and forage fish production cycles and their seasonal and nonseasonal variability within and between years. Then link salmon performance and abundance measures to measures of zooplankton and forage fish abundance and community composition in the way NOAA's Northwest Fishery Science Center has done for the OR/WA coast.
(9) Harmful Algae	Monitoring	Increase the spatial extent, frequency and duration of harmful algae monitoring activities where appropriate to cover the migration or residence times of the priority salmon species. For example, expand harmful algae monitoring in southern Strait of George and North Puget Sound in and around the Fraser River plume during spring and late summer/early fall in all years but with special efforts in high risk years easily identified by weather and river discharge patterns. • Build from existing efforts such as monitoring at fish and shellfish farms; the HAMP program in Nanaimo; the Puget Sound, SoundHab and SoundToxin networks; Puget Sound tribal resources. Most of this work is voluntary and, therefore, cost effective but presently not extensive enough to be useful to examine many of the unknowns. • Use remote sensing technologies such as satellite chlorophyll imagery with improved algorithms to deal with river water interference to expedite near real time

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[20] Sites that adequately sample inflowing and outflowing water such as in the Strait of Juan de Fuca are highly desirable to observe short and long term changes and variation (pers. comm. J. Rensel, Rensel Assoc,. 2012)

[21] Forage fish monitoring as part of the intensive 5 year study is described under Community Factors in Table 10.

Hypotheses	Analysis Type	Description
		identification of *Heterosigma* blooms. • Continue to test and adapt remote sensing molecular sampling equipment such as the Environmental Sample Processor (ESP) and other advanced technologies for use in Salish Sea waters. • Standardize harmful algae monitoring protocol and consolidate/quality assess the data. Use existing HAMP data for additional analysis as a springboard to determine priorities for other algal species besides *Heterosigma*.
(9) Harmful Algae	Monitoring	Collect samples from salmon and herring during the bloom period targeted sampling proposed during the 5-year intensive monitoring effort. Ensure that some of the fish sampling locations are coordinated with areas where blooms are occurring.
(10) Habitat	Retrospective and Monitoring	Evaluate the role of habitat conditions on fish movement and distribution, prey availability, competition, predation, diet, health, etc. This can be achieved by considering a representation of various habitats and habitat conditions when establishing the intensive fish monitoring effort, and by utilizing existing habitat condition data established through the Puget Sound Nearshore Ecosystem Restoration Project and other activities.
(11) Toxics	Monitoring	Conduct juvenile salmon contaminant monitoring surveys for Chinook (and possibly chum) salmon to assess field exposure and effects: Funding is also needed to support and expand existing monitoring programs to document the extent and magnitude of contaminants in neritic and offshore water to which salmon may be exposed. In particular, measures of juvenile salmon exposure to xenoestrogen, pharmaceutical and personal care products, and pyrethroids are needed. Where possible, field assessments should assess potential effects of contaminants on salmon health in addition to exposure. Field assessment may include alterations in genes, proteins, and hormones that control growth, immuno-competence and reproductive development, as well as measures of growth and condition, such as lipid content. Such monitoring will better characterize the threat that contaminants pose to juvenile salmon and will provide a measure of the effectiveness of current strategies and near term actions to reduce toxics threats to Puget Sound. This should be done as part of the 5 year, intensive, space-for-time fish monitoring effort described in the body of this report.
(7) Circulation, bottom-up	Modeling	Develop empirically based models for understanding and predicting the spring phytoplankton bloom; well validated models could then be used to both hindcast and forecast spring bloom dates using historical and predicted environmental data. Incorporate the zooplankton monitoring data to make the association between

Hypotheses	Analysis Type	Description
		phytoplankton and zooplankton production and improve ecosystem modeling so that it can produce zooplankton hindcasts and forecasts.
(8) Ocean Acidification (7) Circulation, bottom-up (9) Harmful Algae	Modeling	Incorporate past, current and predicted levels of pCO_2/pH and results regarding ocean acidification effects on marine biota from relevant existing empirical studies and/or future studies in ecosystem modeling exercises to evaluate synergistic (with low oxygen, warming, and eutrophication or combined effects with toxics) and food web effects relevant to salmon and steelhead growth and survival. This includes incorporating the results of the recommended zooplankton studies and looking for correlations with *Heterosigma* blooms.
(11) Toxics	Modeling	Apply modeling techniques to explore population and ecosystem impacts of contaminant exposure scenarios. These methods could be used to determine whether hypotheses associated with contaminant exposure and effects are consistent with the patterns of survival of different species and populations of salmon and trout. Several types of modeling could be used, including population modeling, trophic transfer modeling to examine food-web-mediated impacts, and spatial exposure modeling based on land cover and toxic inputs.
(8) Ocean Acidification	Process study	Study the effects of pH/pCO_2 variability on invertebrate prey of greatest importance locally to salmon and forage fish. An ongoing study of copepods and euphausiids by Drs Julie Keister (University of Washington), Paul McElhany (NOAA), and Shallin Busch (NOAA) directly addresses this need but could be expanded upon to include other species of concern such as gammarid amphipods and decapod larvae and potential synergistic variables such as temperature and oxygen.
(8) Ocean Acidification	Process study	Evaluate the impact of CO_2 on all species of salmon and steelhead (and forage fish) in a laboratory setting. The study should include early marine life stages. Focus on behavioral and sensory impacts.
(9) Harmful Algae	Process study	Conduct portable bioassay assessments using live cages deployed at differing depths during known harmful algae major blooms for hypothesis validation or modification in the Southern SoG and North Puget Sound. Monitor survival in exposure and reference areas and collect gill and organ tissues for histological and toxicological analyses together with cell counts and basic hydrographic profiles.
(9) Harmful Algae	Process study	(A STRAIT OF GEORGIA , FRASER SOCKEYE RECOMMENDATION) Coordinate harmful algae bloom tracking efforts with acoustic tracking of tagged wild sockeye to determine where fish may

Hypotheses	Analysis Type	Description
		encounter mortality. Coordinate with overlapping hypotheses such as food web limitation and with retrospective studies to analyze bloom occurrence with known and conceptual model forcing factors.[22]
(11) Toxics	Process study	Diagnostic laboratory studies to characterize the threat that BPA, exogenous E2, EE2, pharmaceuticals, and other contaminants of emerging concern, pose to salmon growth, reproduction, and survival. These studies would establish mechanisms, thresholds and indicators for toxicity that could be applied in field assessments and toxic reduction effectiveness monitoring, and provide controlled context for investigating interactions between chemical and non-chemical stressors.
(11) Toxics	Process study	Diagnostic studies to investigate the effects of contaminant exposure (especially especially PBDEs, PCBs and xenoestogens) on the smolting steelhead, Chinook and coho salmon during their transition from fresh to salt water. In particular, there is a need to identify toxicant-induced changes in endocrine physiology and target tissue gene expression in these critical physiological systems. Ultimately, indicator genes identified in these studies would be used to examine expression patterns in naturally outmigrating smolts to monitor for physiological stressors (e.g. contaminants) in watersheds throughout Puget Sound. Salmon indicator genes involved in olfactory signaling and the thyroid endocrine axis should also be assessed.
(11) Toxics	Process study	Diagnostic rearing studies to evaluate the contaminants in stormwater on viability, development and growth of salmon embryos.
(11) Toxics	Process study	Diagnostic studies to investigate the direct effects of pyrethroids and other current use pesticides on the growth of steelhead, Chinook and coho salmon and indirect effects on their prey.
(11) Toxics	Process study	Compare PBT concentrations in adult coho salmon returning to southern Puget Sound that were produced using normal hatchery release timing, with those produced using extended rearing to release larger fish at a later time, a strategy intended to increase the tendency of salmon to remain within Puget Sound waters. Archived samples for this study already exist. This comparison should stimulate a comparison of the benefits from producing resident salmon with the possible health risks to humans and marine mammals from consuming them. This should be performed

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[22] While this particular recommendation is out of the scope of this document, it was included as it is a recommendation related to Salish Sea marine survival as a whole.

Hypotheses	Analysis Type	Description
		with the other residency (hyp. 5) research recommendations.

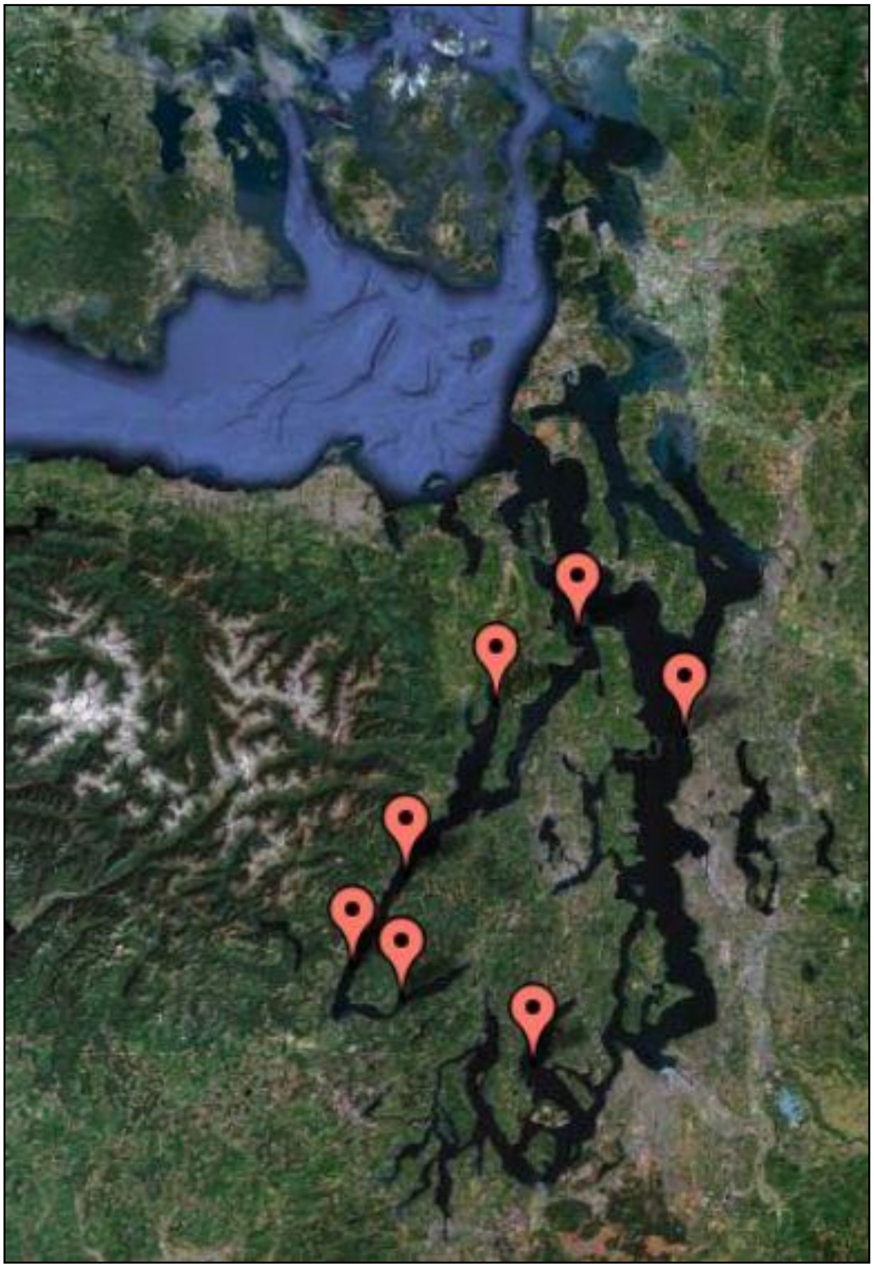

Figure 15. Current locations of ORCA buoys in Puget Sound network[23]

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[23] http://orca.ocean.washington.edu/data.html#

Intensive, Short-Term Monitoring

The following tables describe the data collection associated with the proposed 5-year monitoring effort that expands upon existing activities within Puget Sound.

Table 5. Field data collection for the 5-year monitoring effort: Intensive monitoring of salmon characteristics associated with evaluating ecosystem factors.

Habitat	Time Frame	Measurement Tool	Toxics	Harmful Algae
Estuary	Spr-Sum (every other week	Tide channel, Fyke trap		
Nearshore	Spr-Sum (every other week)	Beach seine	Example: Sample x a min of x per x to evaluate the extent, magnitude and effects of exposure to toxics.	Collect and examine gill scrapes for juvenile salmon known to pass through areas of repeated and extensive Chaetoceros (subgenus Phaeoceros) occurrence
	April-October (montly)	Surface tow net, lampera net		
Pelagic	April-October (monthly)	Purse Seine		
	July & Sept (monthly)	Midwater trawl (Ricker)		

Table 6. Field data collection for the 5-year monitoring effort: Intensive environmental monitoring of ecosystem factors

	Harmful Algae			Water Quality	
Habitat	**Timeframe**	**Measurment Tool**	**Approach**	**Timeframe**	**Measurment Tool**
Nearshore	Spr-Sum (continuous)	Volunteer collection networks and remote sensing equipment	presence, duration, intensity	Year round	Expanded monitoring network focused on documenting the spatial and temporal variability of primary production and carbon chemistry/pH
Pelagic					

Existing, Relevant Monitoring Activities

The monitoring of relevant ecosystem factors occurs on at varying levels throughout Puget Sound. Likely the richest datasets are existing nearshore habitat assessments and water quality data captured by the Washington Department of Ecology, the University of Washington, NOAA, King County, and others. The following is a general , not comprehensive, list of monitoring and data management activities relevant to executing the research proposed in this report. Recently, a report was completed with recommendations for monitoring salmonid habitat for the Puget Sound Ecosystem Monitoring Program (Crawford et. al. 2012). Broadly, there is some overlap between that report and the research recommendations described in this document as trends in habitat conditions can contribute to determining the role of physical habitat in marine survival.

Table 7. Existing monitoring activities related to ecosystem factors analyses recommended in this report.

Activity Type	Program	Agency	Comments
monitoring	**Estuary and Nearshore Habiat Assessments and Monitoring**	Counties, Treaty Tribes, UW, nonprofits	Additional estuary and nearshore habitat assessments and monitoring is periodically being performed, beyond those programs listed below.
monitoring	Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP)	WDFW and Treaty Tribes	Long-term information system that assembles, synthesizes & delivers detailed salmonid distribution and habitat information to users. This information is provided via WDFW's SalmonScape & technical documents.
monitoring	Nearshore Habitat Program (NHP)	DNR	Monitors and evaluates the status of intertidal biotic communities, kelp and eelgrass. This is a component of the Puget Sound Assessment and Monitoring Program (PSAMP).
monitoring	Marine sediment monitoring	WDOE	Evaluates marine sediment quality and benthic macroinvertebrate composition. This is a component of the Puget Sound Assessment and Monitoring Program (PSAMP).
retrospective & future monitoring	Puget Sound Nearshore Ecosystem Restoration Project	USACOE, WDFW and partners	Collaborative study designed to improve our understanding of changes to nearshore ecosystems, significant ecosystem problems, and potential solutions to those problems. As PSNERP restoration projects are implemented, associated monitoring will occur.

Activity Type	Program	Agency	Comments
retrospective	Limiting Factors Analyses	State, tribes, counties	Provided initial assessment of factors limiting salmon production by watershed. Occurred in the late 1990's early 2000's but contains significant habitat data.
retrospective	WEMAP and the National Coastal Condition Assessment	EPA - WDOE	WEMAP = Water column measurements are combined with information about sediment characteristics and chemistry, benthic organisms, & data from fish trawls to describe the current estuarine condition (1999-2004)
assessment	SeaDoc habitat mapping	SeaDoc	SeaDoc and Tombolo are joining together to create a habitat mapping lab for the Salish Sea.
monitoring	**Estuary and Marine Water Quality**	Various	Additional water quality monitoring and assessments occur throughout Puget Sound; however, below are the primary components for the marine waters.
monitoring: effort and data aggregator	NANOOS: the Northwest component of NOAA's Integrated Ocean Observing System	NOAA, WDOE, King County, UW, USGS, DFO, and others	NANOOS is an integrated ocean observing system. NVS compiles efforts and data across a wide range of assets such as buoys, shore stations, and coastal land-based stations. Associated programs include the WDOE Marine water quality monitoring progam, USGS Stream Flow Monitoring, the National Estuarine Research Monitoring Program, UW's ORCA buoy network, NOAA's National Ocean System, NOAAs PMEL Carbon Program and others. See Appendix B for a complete list of NANOOS Assets and what they monitor.
monitoring	Stream flow monitoring	WDOE and USGS	Additional streams are monitored beyond the gages listed as assets in NANOOS
monitoring	CoastWatch West Coast Regional Node	US Dept of Commerce, NOAA, NESDIS	Satellite data for the west coast. Freely accessible & archived. Products include ocean surface wind vectors, SST California frontal products, altimetry data, OSCAR, sea surface roughness, chlorophyll-a anomaly.

Activity Type	Program	Agency	Comments
monitoring, modeling, & data synthesis	Puget Sound Regional Synthesis Model (PRISM) and MoSSea (Modeling the Salish Sea)	UW	PRISM Cruise produce CTD data and evaluate other bio-chemical properties down the axis of the Main Basin, Whidbey Basin and Hood Canal. These PRISM cruises visit many of the same stations visited by some of the earliest Puget Sound measurements gathered in the Collias Atlas (Collias et al., 1974). PRISM and other data are incorporated into models, including the MoSSea model. with the goal of providing the first ever high-resolution, realistic hindcast simulations of the physical circulation in the entire Salish Sea region
database	STORET Data Aggregator	EPA	The STORET Data Warehouse is EPA's repository of the water quality monitoring data collected by water resource management groups across the country.
monitoring	**Harmful Algae:** Sound HAB and SoundToxins Network	NOAA, Consultants, Academia, Private Industry, Tribes, Citizen Volunteers	SoundToxins = a cost-effective monitoring program that could provide sufficient warning of HAB and vibrio events to enable early or selective harvesting of seafood. SoundHAB = coordinated by a volunteer , this list serve system is used by researchers, agency or industry managers, and the mariculture industry to share timely information about harmful algal blooms (HABs) and to help coordinate timely sampling and research effort synergies.
monitoring	**Toxics:** Marine toxic contaminants in Puget Sound fish and shellfish	WDFW	Evaluate and track the complex patterns of contamination across the Sound by using indicator species and life-stages that cover a broad range of feeding habits, movement patterns, and habitats. Toxic chemicals or contaminant-metabolites within organisms covering a wide range of sources, persistence, toxicity, mode of action, and accumulation potential are measured at various spatial and temporal scales to address specific short- and long-term questions. This is a component of the Puget Sound Assessment and Monitoring Program (PSAMP).

The Role of Community Factors

Community factors include the interactions that occur as a result of a group of species existing in the same area. Hypotheses regarding prey availability, competition, predation and disease are described below.

12. Food supply limits growth, and thus survival, during critical periods of early marine rearing

Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences
Julie Keister, University of Washington, Oceanography

The strong relationship between SARs and body size after some period of early marine growth suggests that factors affecting feeding and growth are important for sustaining productive adult returns of salmon. Growth limitation is a potential concern for Chinook, coho, chum and pink salmon in Puget Sound, whereas steelhead and sockeye salmon appear to emigrate rapidly and are thus less likely to be affected by growth limitations. For hatchery Chinook salmon, high variability in size, feeding and growth among years and regions support the hypothesis that food is limiting during a critical growth period through July. Much of the variability in feeding and growth can be accounted for by primarily the contribution of crab larvae and secondarily by neustonic insects to the energy budget of juvenile Chinook salmon. Based on the epi-pelagic temperatures observed in Puget Sound during spring and summer, salmon growth has been relatively insensitive to the thermal regime and very sensitive to feeding rate, a surrogate measure of food supply. In contrast, the Strait of Georgia averages 2^{o}C warmer than Puget Sound during the summer, and temperature could significantly affect salmon growth in this region. Competition could be an important influence on marine survival in certain periods and regions, as suggested by the lower and variable feeding rates associated with reduced marine survival of salmon and comparisons of prey demand among juvenile salmon and forage fish species. Initial bioenergetic simulations of population-level consumption demand indicated that Pacific herring consume 10-40 times more biomass of the key prey species than the juvenile Chinook population during the critical May-July growth period in Puget Sound. This suggests that competition for food in offshore regions is more likely driven by the dynamics of herring, the most abundant consumer, than by competition between hatchery and wild conspecifics or among salmon species within Puget Sound. However, density-dependent growth or hatchery-wild competition within or among salmon species could still potentially occur in localized estuarine or nearshore marine habitats. Very little is known about the temporal-spatial availability of key zooplankton and other prey or the abiotic and biotic factors that influence production cycles of prey in Puget Sound.

The primary research and monitoring needs for the growth limitation hypothesis include: 1) monthly to twice monthly zooplankton sampling, stratified by depth and region to assess the availability of key prey through time and space, and in coordination with sampling for fish growth, scales, diet, and relative abundance; 2) Monthly to twice monthly nearshore (March-August) and epi-pelagic (May-October) sampling for diet, size, and growth of juvenile salmon and forage fishes by region; 3) Quantitative hydroacoustic-midwater trawl survey of epi-pelagic fish [and potentially macro-zooplankton] community during July; 4) Map/model growth potential within-among regions and depths for juvenile salmon and forage fishes 2-3 times during critical spring-summer growth period. Identify hotspots for feeding, growth and interactions with competitors and predators.

13. Predation by larger fish and marine mammals has increased on salmon and steelhead, respectively. And, the potential effect of bird predation represents a significant knowledge gap.

Barry Berejikian, NOAA Northwest Fisheries Science Center
Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences

Predation on juvenile salmon and steelhead is hypothesized as an important factor in their low survival in Puget Sound; however, the most significant hotspots and predators may be different for salmon than for steelhead. Although several fish taxa have been identified as salmon predators, larger salmonids generally appear to be the most important predators during early marine life: subyearling Chinook, yearling coho, and sea-run cutthroat trout and bull trout eating pink and chum salmon in nearshore habitats; predation on age-0 Chinook salmon in nearshore marine habitats by sea-run cutthroat trout; and predation on juvenile pink, chum, and Chinook salmon in offshore habitats of Puget Sound by resident subadult Chinook and coho salmon. Monthly or twice-monthly purse seine sampling among regions in epi-pelagic waters of Puget Sound would provide important samples needed to quantify the temporal-spatial patterns in predation as functions of predator species, predator size, prey size, the role of alternative prey, and environmental mediators (temperature, salinity, turbidity, light, DO). Retrospective analysis of existing acoustic telemetry data on seasonal and diel horizontal and, especially vertical movement and distribution of resident coho and Chinook salmon to determine regions, depths, periods, and potential hotspots of overlap with juvenile salmon and forage fishes.

Predation is hypothesized as the primary cause of the high mortality rates documented for steelhead trout in Puget Sound. Their rapid migrations through Puget Sound suggest that proximal mechanisms such as poor feeding opportunities and low growth rates, starvation, or disease are much less important contributors to high mortality. Admiralty Inlet has been identified as a potential mortality hotspot for migrating Hood Canal steelhead. A meta-analysis of segment-specific survival rates other Puget Sound populations has recently been initiated and will help in identifying spatial patterns in mortality rates and further isolate potential hotspots. The large size of steelhead smolts, their rapid migration, and inverse relationship between harbor seal population abundance and Puget Sound steelhead marine survival point to increased harbor seal predation as plausible hypothesis. Concurrent telemetry tagging of steelhead and harbor seals provides an opportunity to estimate encounter rates. Predators can also be fitted with receivers to detect tagged smolts and tags to track their spatial-temporal patterns with high accuracy.

14. Infectious and parasitic diseases are causing direct and indirect mortality.

Paul Hershberger, US Geological Survey, Marrowstone Marine Field Station

As in marine regions throughout other areas of the world, fishes in the Salish Sea serve as hosts for many pathogens, including crustaceans, nematodes, trematodes, protozoans, protists, bacteria, and viruses. Our knowledge of the pathogen assemblages occurring in Salish Sea salmonids is based largely on health assessments of returning hatchery salmonids. Unfortunately, these assessments are extremely limited in geographical and temporal scope; more importantly, they not designed or intended to provide information regarding the effects of the identified pathogens to the health of affected hosts and populations. An even greater information gap exists in our understanding of diseases affecting wild salmonids. Here, we identify some of the pathogens known to occur in the Salish Sea that are believed to contribute to population-level impacts. Future field surveillances and controlled empirical studies are required to determine whether mortality from the resulting diseases may contribute to the recent population depressions observed in Salish Sea salmonids.

Research Summary: Community Factors

A comprehensive overview of the proposed research recommendations is provided below (Table 8). Retrospective data collection, monitoring, modeling and process studies are all recommended analyses. All efforts will be closely aligned with those described in the individual and population characteristics and ecosystem factors sections. The community factors monitoring activities associated with the 5 year, intensive monitoring effort are then described in Table 9 and Table 10. Finally, a list of existing, relevant monitoring activities is provided (Table 11), several of which the research proposed here will utilize and build upon.

Analyses

The following table describes the recommended analyses. The correlating hypotheses numbers are to the left, followed by the types of analyses and their descriptions.

Table 8. Summary of recommended research: community factors

Hypotheses	Analysis Type	Description
(13) Predation	Retrospective analysis	Retrospective analysis of existing acoustic telemetry data on seasonal and diel horizontal and, especially vertical movement and distribution of resident coho and Chinook salmon to determine regions, depths, periods, and potential hotspots of overlap with juvenile salmon and forage fishes. These data would provide insight into physical and biotic factors that influence the magnitude and dynamics of predation on juvenile Chinook salmon versus other salmon and forage fishes.
(13) Predation	Retrospective analysis	Complete a retrospective analysis of steelhead survival rates throughout Puget Sound to identify areas of greatest mortality and inform the installation of acoustic telemetry receiver arrays (NOAA NWFSC).
(12) Food	Monitoring	Depth-stratified zooplankton sampling (species, presence/absence, abundance, duration) within a spatial-temporal framework and in coordination with the juvenile salmon sampling effort. Juvenile salmon feed predominantly during daylight in shallow nearshore waters initially, and then in the upper mixed layer of marine waters; therefore, prey availability should be sampled from these nearshore-offshore zones and depth layers explicitly. Year-round sampling is

Hypotheses	Analysis Type	Description
		desirable with an emphasis on more frequent sampling (e.g., twice per month) during April-September.
(12) Food	Monitoring	Continue monitoring epi-pelagic diet, size, and growth of juvenile salmon and forage fishes in July and September. Supplement with analogous data in April-August from purse seining during research phase to determine finer-scale resolution on stock-specific growth limitation among species through time and space.
(12) Food	Monitoring	Quantitative hydroacoustic-midwater trawl survey of epi-pelagic fish community during July to determine the species composition, abundance, distribution, biomass, and trophic interactions of juvenile salmon and forage fishes in epipelagic habitats.
(13) Predation	Monitoring	Perform a census of harbor seals, and potentially other marine mammal predators, to evaluate abundance, distribution, and density. Aerial surveys and boat-based line transects or other distance sampling techniques to be applied. Consider including marine bird that are considered predators of concern in a census.
(13) Predation	Monitoring	Identify and quantify the temporal-spatial patterns in predation as functions of predator species, predator size, prey size, the role of alternative prey, and environmental mediators (temperature, salinity, turbidity, light, DO). Highest priority would be purse seine sampling among regions in epi-pelagic waters of Puget Sound monthly in April and May, twice monthly June-September, and monthly in October.
(14) Disease	Monitoring	Assess pathogen and disease prevalence and intensity in the marine environment. Do this as part of the marine survival research program's 5-year intensive fish sampling effort. Incorporate standard virology, bacteriology, and parasitology, using protocols described in the *AFS, Fish Health Section – Blue Book, Procedures for the Detection and Identification of Certain Finfish Pathogens.* Non-standard diagnostics that are specific to marine pathogens in the Salish Sea should also be employed, including appropriate diagnostics required to detect marine bacteria (i.e. *Vibrio spp.*, *Rennibacterium salmoninarum*, etc.), parasites (i.e. *Ichthyophonus sp., Nanophyetus salmonicola*, myxozoans, sea lice, etc.), and viruses (including specific PCR primers for ISAV, ENV, and other marine viruses that are often refractory to standard cell lines).
(12) Food	Modeling	Map/model growth potential within-among regions and depths for juvenile salmon and forage fishes 2-3 times during critical spring-summer growth period. Identify hotspots for feeding, growth and interactions with competitors and predators.
(12) Food	Process study	Determine the dietary value (energy content and fatty acid composition) for key prey: zooplankton, ichthyoplankton, and insects. This study would last two years with data collection occurring

Hypotheses	Analysis Type	Description
		monthly during the spring and summer.
(13) Predation	Process study	Analyze mortality hot spots and predation by harbor seals, and, if needed, other predators using acoustic telemetry. Telemetry receiver arrays would be established in specific areas of south, central and northern Puget Sound/Admiralty inlet and northern Hood Canal in presumed predation hot spots. Hot spots will be identified the first year and two would be chosen for a more detailed assessment of encounter rates between harbor seals and steelhead smolts.
(14) Disease	Process Study	After pathogens-of-concern are identified by field surveillances, effects to the infected host should be addressed by performing well-controlled empirical manipulations in the laboratory using specific pathogen-free hosts. Effects to populations of Salish Sea salmonids can then be addressed by integrating field surveillance data with cause-and-effect relationships between the hosts, pathogens, and environmental variables.

Intensive, Short-Term Monitoring

The following tables describe the data collection associated with the proposed 5-year monitoring effort that expands upon existing activities within Puget Sound.

Table 9. Field data collection for the 5-year monitoring effort: Intensive monitoring of salmon characteristics associated with evaluating community factors.

Habitat	Time Frame	Measurement Tool	Diet	Disease
Freshwater / Lower River	April-December (varies)	Spawer Survey, Adult weir	▨	▨
	January-July (daily)	Smolt trap / Hatchery release	Sample up to 50 per ? - Diet (gut samples), Stable Isotopes	Sample a min of 60 per? - Collect kidney & spleen
Estuary	Spr-Sum (every other week	Tide channel, Fyke trap		
Nearshore	Spr-Sum (every other week)	Beach seine		
	April-October (montly)	Surface tow net, lampera net		
Pelagic	April-October (monthly)	Purse Seine		
	July & Sept (monthly)	Midwater trawl (Ricker)		
Marine/ Fresh	Year round (continuous)	Harvest, Hatchery		sample a min of 60, kidney & spleen, per year, in test fishery

Table 10. Field data collection for the 5-year monitoring effort: Intensive monitoring of other biological factors associated with evaluating community factors.

	Prey Availability (zooplankton)			Prey, Competition,Indicator (forage fish-herring)			Predation by Fish (e.g., Resident Chinook and coho salmon, cutthroat, bull trout, other)		
Habitat	**Timeframe**	**Measurment Tool**	**Approach**	**Time frame**	**Measurment Tool**	**Approach**	**Time frame**	**Measurment Tool**	**Approach**
Nearshore Pelagic	Year round (every other week), with emphasis on April-September.*	Net tows	Depth-stratified zooplankton sampling (species, presence/absence, abundance, duration)	Year round?	Net tows (include in salmon collections but strategically expand to also evaluate forage fish abundance)	Relative abundance, Fork length, weight, distribution, diet, scales, otoliths, tissue for genetics, SIA, FAA, etc. and size structure of herring	May-Aug (every other week) April, Sept, Oct (monthly)	Purse Seine**	Relative abundance, Fork length, weight, distribution, diet, scales, otoliths, CWT, tissue for genetics, SIA, FAA, etc. and size structure of resident salmon
							July, Sept, and occasionally Feb or March (monthly)	Midwater trawl**	

* Calibrate effort nearshore to offshore to coincide with fish presence.
**include in juvenile salmon monitoring but strategically expand.

Existing, Relevant Monitoring Activities

Compared to the monitoring of salmon and steelhead individual and population characteristics and the monitoring of relevant ecosystem factors, the monitoring of relevant community factors is extremely limited. Below is a brief description.

Table 11. Existing monitoring activities related to community factors analyses recommended in this report.

Activity Type	Program	Agency	Comments
monitoring	Fish health monitoring	WDFW, NWIFC, USFWS, Treaty Tribes, USGS	Fish Health monitoring programs primarily focus on tracking fish health issues in hatchery juveniles and adults. The Salmonid Disease Control Policy of the Fisheries Co-Managers of Washington State is the guidance document for monitoring. Co-managers and federal partners also coordinate on much of the fish health monitoring effort.
monitoring & database	National Wild Fish Health Survey	USFWS	National Survey to determine presence of certain aquatic pathogens and the location, and species of wild fish populations that may harbor them.
monitoring	Puget Sound herring stock assessments	WDFW	Critical for determining annual abundance of spawning herring in Puget Sound[24]. Herring are the basic food source for salmon, seals, rockfish, etc.
monitoring	marine birds and mammals monitoring	WDFW	Periodic monitoring of trends in distribution and abundance of marine birds, mammals in Puget Sound. This is a component of the Puget Sound Assessment and Monitoring Program (PSAMP).

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[24] Current monitoring focuses exclusively on spawning grounds. No monitoring of abundance, distribution, feeding, etc. during other life stages.

NEXT STEPS

The content of this report will be presented and discussed at the November 2012 Marine Survival of Salmon and Steelhead in the Salish Sea workshop. An Advisory Panel will convene at the end of the workshop evaluate the presented material and the outcomes of the discussions and use this information to determine the critical elements of a joint US - Canada research program. The Technical Team will then use the results of the workshop to refine the research recommendations and complete a formal plan. The objective is to complete this plan in the spring of 2013 and begin implementing the proposed research soon afterward.

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APPENDIX A: COMPLETE HYPOTHESES AND RESEARCH RECOMMENDATIONS WRITE UPS

Hypothesis 1. Marine survival does a better job than freshwater survival in explaining productivity trends of salmon and steelhead in the Salish Sea

Mara Zimmerman, Washington Department of Fish and Wildlife
Correigh Greene, NOAA Fisheries

Abstract

Differences in the temporal pattern of survival for Salish Sea and Pacific coast salmon stocks have focused attention on Puget Sound's marine environment, and some have pointed to low survival in recent years as evidence for problems within Puget Sound and the Strait of Georgia. Interactions within the freshwater and estuary environments may both influence productivity and the temporal patterning of adult returns.

Survival in the freshwater versus marine environment is a natural division for anadromous salmonids as the physiological requirements and the ecological interactions in these environments differ. This section develops a rationale and approach to test the hypothesis that marine survival predicts trends and variation in productivity of salmon and steelhead in the Salish Sea. Productivity is defined as the ratio of spawner produced by parent spawners and represents the cumulative survival through multiple life stages. In this section we are primarily interested in whether survival in the marine environment is a better predictor of trends in productivity than survival in the freshwater environment. Understanding the mechanistic explanations for these relationships is essential but more suitably addressed by subsequent hypotheses in this research plan.

Evidence supporting our hypothesis comes from a number of studies that link environmental factors in marine systems to adult returns, and studies suggesting that due to predation risks, marine systems are inherently more dangerous than freshwater environments. However, any species with extended residency in freshwater will be exposed to substantial freshwater mortality during life stages that are highly vulnerable due to size-dependent mortality. Moreover, in freshwater systems, competition occurs in a more restricted environment, and, as a result, freshwater contributions may influence mortality due to variation in individual growth rates. Ultimately, the first step in testing out hypothesis is to determine the relative contributions of freshwater and marine survival to the trends in salmon and steelhead productivity.

We begin with a general background of freshwater and marine survival of salmon and steelhead. We then use selected long-term data sets for coho and Chinook salmon to develop an approach that addresses our hypothesis. We next develop a rationale for considering spatial components of marine survival and identify data needs that facilitate additional comparisons among other stocks. Finally, we

propose a short-term research program, based on a space-for-time substitution, which should further address the contribution of marine survival to salmon and steelhead productivity.

The take-home messages of our summary are:

- Useful analyses to address this hypothesis will be (1) trends in total mortality and variation in total mortality partitioned between the freshwater and marine environment, and (2) correlation between survival rates (freshwater and marine) and resulting adult recruits,
- In our case examples, the proportion of total mortality occurring in the marine environment ranged between 1% and 20%,
- In just one of our case examples, the number of adult recruits is better explained by survival in the marine than the freshwater environment,
- Regional factors make an important contribution to adult recruitment; therefore, spatial comparisons may be as informative as temporal comparisons when explaining salmon and steelhead productivity,
- Data needs to further address this hypothesis include spawner, smolt, and catch abundance partitioned by age class, and
- We propose a 5-year research program which substitutes spatial replication for temporal longevity and is based on life cycle monitoring of populations in representative regions of the U.S. Salish Sea.

Contributions of Marine versus Freshwater Survival

When survival in the freshwater and marine environment has been measured, the measures range considerably across years and across species. Freshwater survival is considered to be from egg to outmigrant and marine survival is considered to be from outmigrant to spawner. Both the magnitude and inter-annual variation of survival in these two environments show notable differences among species.

The highest freshwater survival rates are typically observed for those species (chum, pink, ocean-type Chinook) that spend the least amount of time in the freshwater environment (Groot and Margolis 1991). However, in some years, freshwater survival can be very low (~1%) regardless of how long the juveniles reside in the freshwater environment. For example, freshwater survival of pink salmon has ranged between 0.06% and 40% (Heard 1978; Heard 1991) and up to 85.5% in channel habitat (Heard 1991). Freshwater survival of chum salmon is also quite variable with known ranges between 1.3% and 58.9% (Salo 1998). In comparison, the freshwater survival of coho (1-12%; Drucker 1972) and sockeye salmon (10-12%; McDonald and Hume 1984) are lower, on average, and less variable. One potential explanation for the interspecific differences is that egg-to-fry survival is highly variable in all species, but freshwater survival for species with extended freshwater rearing periods (i.e., coho, sockeye, steelhead) is further constrained by competitive interactions in freshwater.

Marine survival rates also range widely among species and among years. For example, marine survival of species that emigrate as subyearlings (e.g., pink, chum, and ocean-type Chinook) is frequently an order of magnitude lower than species (e.g., coho and sockeye) that emigrate after a year or more of freshwater rearing (Groot and Margolis 1991; Pearcy 1992). However, variation in marine survival rates can be greater among years than it is among species. For example, marine survival rates of sockeye salmon are observed to range between 1% and 50% (Burgner 1991; Foerster 1968; McDonald and Hume 1984), pink salmon between 0.3% and 23% (Heard 1978; Heard 1991; Pearcy 1992), and coho salmon between 0.4% and 21% (Beamish et al. 2000; Drucker 1972; Koslow et al. 2002).

A logical way of testing the hypothesis that marine survival drives salmonid productivity is to partition mortality across the life cycle into freshwater and marine components. To illustrate this approach, we review monitoring data from several well-studied salmon populations in U.S. portions of the Salish Sea – coho salmon in the Deschutes River and Chinook salmon populations in the Skagit River. We summarize the total mortality (absolute value and variation) in the freshwater and marine environment and determine whether freshwater or marine survival can be used to explain temporal variation in the number of adult recruits. Even so, the logic of this partitioning assumes that freshwater and marine survival rates are independent of each other. We briefly explore mechanisms such as density dependent migration that may affect marine survival above and beyond mortality related directly to variation in the marine ecosystem (e.g., temperature, dissolved oxygen, prey availability).

Case Study: Deschutes River coho salmon

The Deschutes River flows northwest into Puget Sound near Olympia, Washington. Coho salmon in this watershed are a non-native, naturalized population which originated from Green River (Soos Creek) coho planted between 1949 and 1981. Natural barriers to anadromous fishes are located at rkm 3.2 and rkm 66; however coho salmon have ascended the lower barrier (Tumwater Falls) after a fish way was built in 1954. A self-sustaining population of natural-origin coho salmon established and annual returns of 5,000 to 10,000 coho spawners were maintained through the mid-1990s. In years with strong returns (>1,000 natural-origin adults), hatchery coho have represented less than 5% of the return (mostly from South Sound net pen operations). Hatchery coho have not been released above Tumwater Falls since 1998, once fish origin could be determined from external markings.

A long-term coho monitoring program for Deschutes River coho salmon was initiated by the Washington Department of Fisheries (now WDFW) in 1978. This monitoring program uses a smolt trap, operated at the base of Tumwater Falls, and an adult trap, located at the upstream end of the fish way, to estimate freshwater production and adult returns of coho salmon each year. Marine survival is estimated by coded-wire tagging coho smolts and tracking tag recoveries in coast-wide fisheries as well as at the adult trap. Potential egg deposition (PED) is calculated based on the number and average length of female spawners passed above Tumwater Falls and a length-fecundity relationship derived from Deschutes River coho salmon ($PED = 93.07*FL-3303$, where FL = average female fork length in cm).

Freshwater survival (egg to smolt) of Deschutes River coho salmon has averaged 3.1%, has ranged 10-fold from 0.7% to 7.6%, and has shown no trend over time (Figure 1a). Marine survival of these same brood years has averaged 5.0%, has ranged 48-fold from 0.3% to 14.5%, and has been characterized by chronically low marine survival (< 5%) since 1992. In terms of total numbers of individuals lost, the highest mortality occurs in the freshwater life stage. Of all mortalities from egg to adult recruit, 92.5% to 99.3% occur in the freshwater environment and just 0.7% to 7.5% occurs in the marine environment (prior to fishery interception). The percent total mortality that has occurred in the marine environment has increased over the monitoring period (Figure 1b).

Although the highest mortality of Deschutes River coho salmon occurs in freshwater, the declining trend in adult recruits is better explained by variable survival in the marine than the freshwater environment. The number of adult coho salmon (pre-fishing recruits) was not correlated with freshwater survival

(Figure 2a) but was positively correlated with marine survival of the parent brood year (Figure 2b). The positive correlation between marine survival and adult coho was apparent prior to the population crash but has not been apparent in recent years when marine survival has been chronically low (Figure 2b).

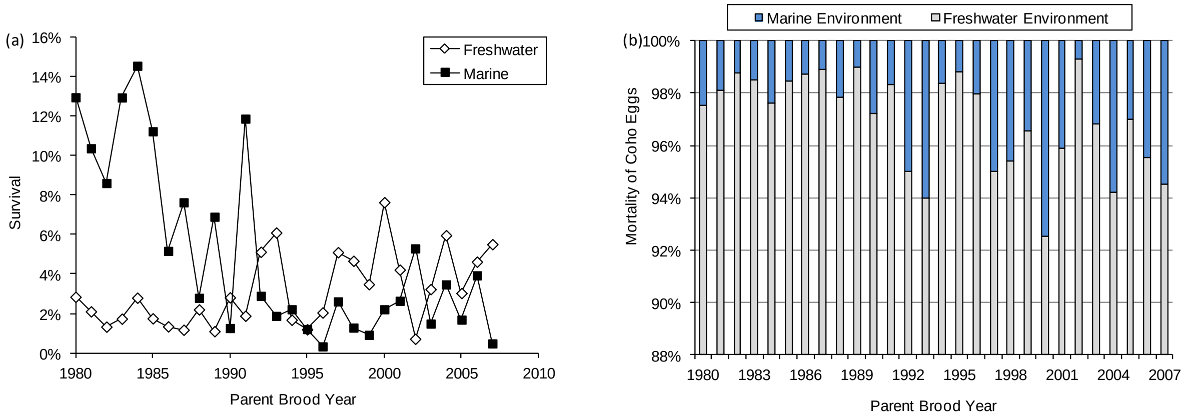

Figure 1. Comparison of freshwater and marine survival of natural-origin Deschutes River coho salmon, parent brood year 1980 to 2007. Data are shown as survival in each environment (a) and as percent of total mortality for each cohort (b). Data provided by WDFW (M. Zimmerman, pers. comm.).

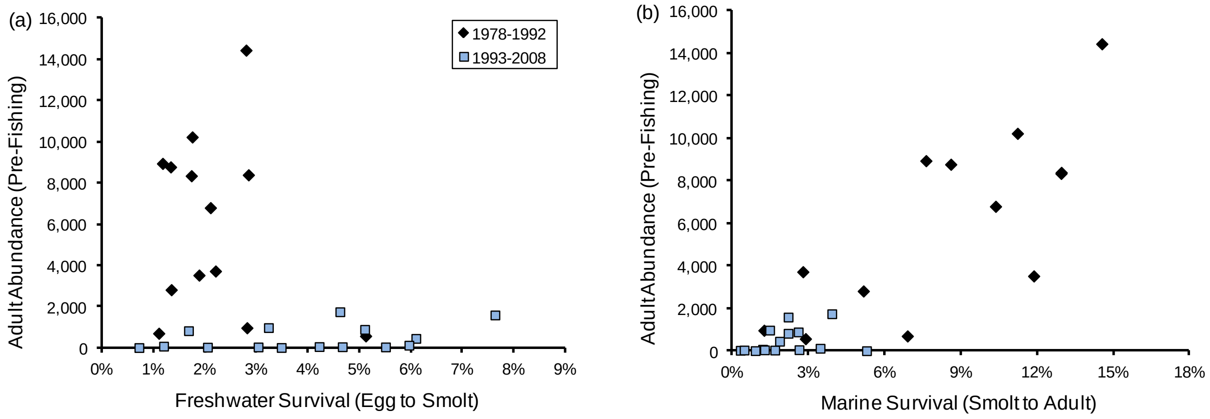

Figure 2. Pre-fishing abundance (ocean age-3) of natural-origin coho salmon from the Deschutes River, Washington as a function of freshwater (a) and marine (b) survival of each parent brood year, 1980 to 2007. Data are color coded by brood year prior to (1978-1992, black diamond) and after (1993-2008, blue square) the population crash and were provided by WDFW (M. Zimmerman, pers. comm. 2012).

Case Study: Chinook salmon populations in the Skagit River

The six spawning populations of Chinook salmon in the Skagit River have had some of the most intensive monitoring in Puget Sound, and therefore represent the best system to examine freshwater and marine mortality in Chinook salmon. Most spawning populations have over 30 years of spawner abundance surveys, with systematic sampling of scales or otoliths for age structure over most of that time period. Outmigrants have been monitored for 20 years at a trap at Mount Vernon, and further monitoring in the estuary, marine shoreline, and nearshore subtidal has occurred for 10-20 years. This integrated set of status monitoring provides a rich dataset to explore patterns of freshwater and marine survival. Spawner counts and outmigrant monitoring allow quantitative estimate of freshwater and estuary/marine survival, and estuary, shoreline, and nearshore cumulative abundance estimates provide relative indices of survival when compared against outmigrant abundance.

In addition, the Skagit River is noted for its juvenile life history variation, which is composed of four general types: 1) yearling migrants, which rear in freshwater until over a year old before migrating into Puget Sound and rapidly into either deep or offshore waters; 2) parr migrants, which rear 3 to 4 months before migrating directly out into Skagit Bay and Puget Sound where they may rear extensively (several months or several years as blackmouth); 3) estuary fry, which migrate downstream as fry and rear in the tidal delta before migrating into Skagit Bay and Puget Sound, where they may rear extensively, 4) fry migrants, which behave like pink salmon and migrate downstream directly into Skagit Bay, where they rear extensively (Beamer et. al. 2000; Hayman et. al. 1996). As most fish (~80-90%) migrate out of the river as subyearlings, it is reasonable to expect that marine mortality in Puget Sound dominates total mortality. Nevertheless, freshwater mechanisms, particularly incubation floods, can have large effects on return rates (Greene et al. 2005).

The multiple types of abundance data in the Skagit allow us to test several hypotheses:

- Outmigrant-adult mortality is higher than freshwater mortality and explains most of the variation in adult returns
- Capacity limitations in freshwater and estuary result in density-dependent migration, leading to smaller body size at marine entry and lower adult returns.

Because source populations cannot be identified during outmigration, we lumped adults from all populations to estimate egg deposition and the total number of returns. These data can be converted into recruits/spawner (i.e., accounting for harvest). For the entire spawner time series, we used these data to determine freshwater vs estuary/marine predictors of productivity. We found that density-dependent signals and incubation floods explained a large portion of the variation in total productivity, but that environmental conditions experienced during marine life stages (estuary rearing through adult return) is nevertheless substantial (Greene et al. 2006).

The period when outmigrants have been monitored provide a more direct determination of the relative contribution of freshwater and estuary/marine survival in a similar way as was done for Deschutes River coho salmon. Unlike Deschutes River Coho, Skagit River Chinook have not exhibited directional changes in either freshwater or marine survival, and marine survival is consistently about an order of magnitude lower than freshwater survival (Fig. 3a). Nevertheless, most (78-94%) of mortality across the life cycle occurs before outmigrants pass the trap at Mt Vernon (Fig 3b). Neither freshwater nor estuary/marine survival strongly predicts adult returns, although both show positive trends (Fig. 4).

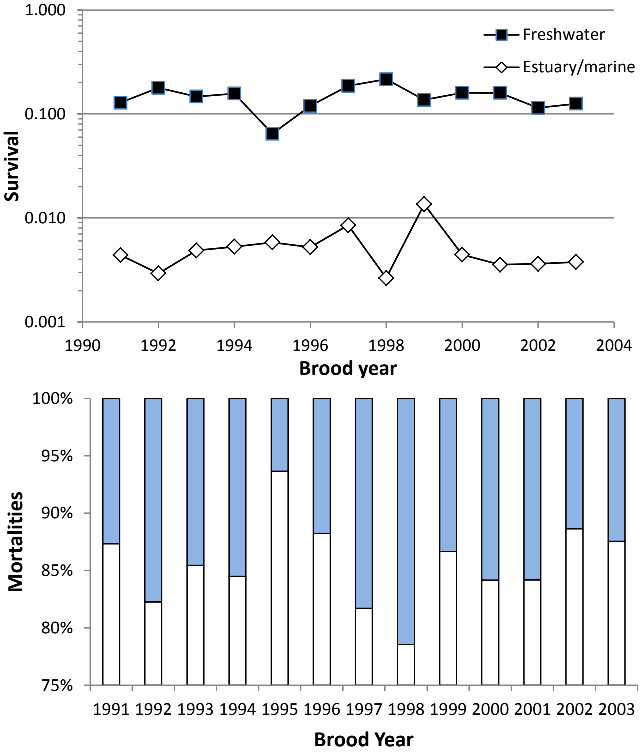

Figure 3. (a) Freshwater and estuary/marine survival and (b) the percentage of mortalities (open= freshwater, filled = estuary/marine) in Skagit River Chinook salmon.

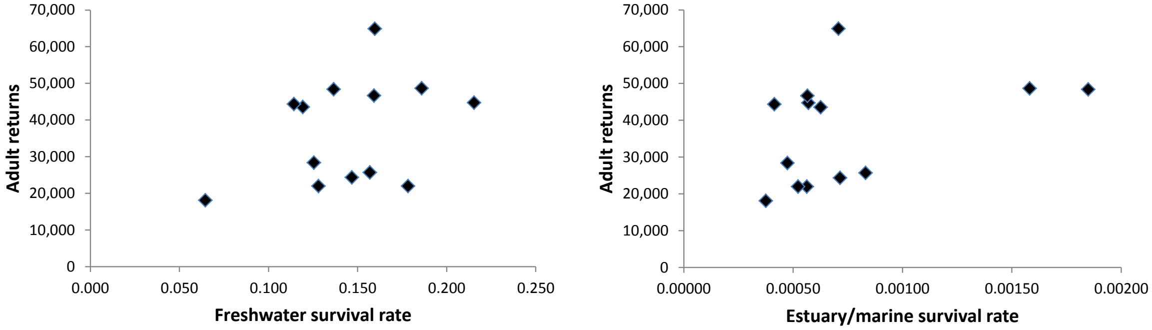

Figure 4. Adult returns as functions of (a) freshwater survival rate and (b) estuary/marine survival in Skagit River Chinook salmon.

In addition to impacts of direct mortality, salmon populations can suffer delayed mortality due to nonlethal effects of outmigration timing or condition. The existence of delayed mortality might cause one to incorrectly assign a greater proportion of the total mortality to estuarine and marine causes based on where the fish died, even though the cause of death is a delayed effect from freshwater. One example of delayed mortality is the concept of density-dependent migration (Reimers 1973, Greene and Beechie 2004). The idea here is that competition for space or food resources results in movement of some individuals downstream. As a consequence, competition would lead to shorter residence in freshwater, earlier timing of outmigration, and smaller outmigrant body size. If marine mortality results from timing mismatches or is size-dependent, then density-dependent migration could lead to delayed mortality.

Monitoring in the Skagit River system allows us to test for the existence and consequences of density-dependent migration. The incidence of fry migrants (i.e., the proportion of fish captured in Skagit Bay shorelines that are fry migrants) increases with cumulative density in the tidal delta (measured over six months), possibly leveling off at the highest cumulative densities. This same pattern is observable in freshwater, although the patterns is complicated by variability in survival due to incubation floods (Zimmerman in prep.).

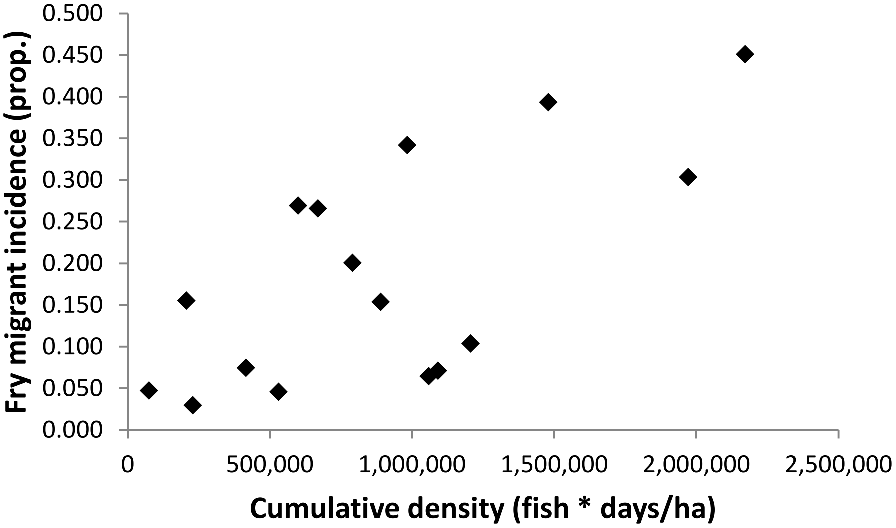

Figure 5. The incidence of Chinook salmon fry migrants captured in Skagit Bay shoreline beach seines is positively correlated with the cumulative density of juveniles rearing in the tidal delta.

Because fry migrants arrive at Skagit Bay early in the season and at very small sizes, it is reasonable to expect that they suffer high mortality. In years when the incidence of fry migrants is high, survival of the population to adulthood might expected to be lower. This is in fact the pattern observed over the 10 years for which adult return rates (recruits/spawnwers) can be calculated, and outmigrant survival can be factored out to obtain total estuary/marine survival (Fig. 6). Due to the relatively small number of available years, Figure 6 can be interpreted in a number of ways. Across all data points, estuary/marine survival is moderately negatively correlated with fry migrant incidence (r = 0.33), with higher variation in estuary/marine survival at lower fry migrant abundance. Alternately the patterns can be interpreted as two different sets of data (high and low fry migrant incidence), each with strong but contrasting correlations. This pattern might occur, for example if fry survived at higher rates in schools, but experienced high mortality or competition at high fry migrant incidence. A third interpretation is that at high levels of fry migrant abundance, adult return rates are tightly constrained by low survival, but that other factors in estuary or marine habitats influence return rates at low fry migrant levels, causing high variability. At this point in time, testing these intriguing hypotheses requires additional data, either from more years or from other river systems.

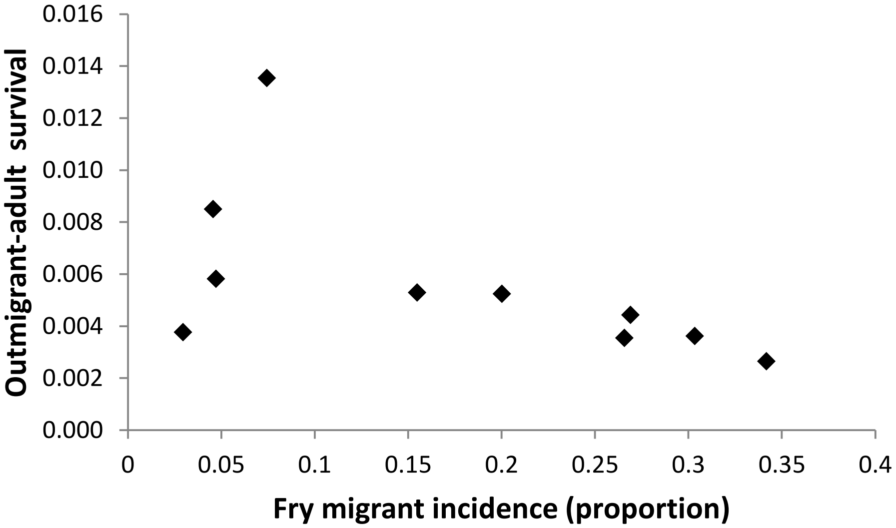

Figure 6. Estuary/marine survival rates as a function of the incidence of Chinook salmon fry migrants captured in Skagit Bay shoreline beach seines.

Regional Factors and Adult Recruitment

We propose that the contribution of marine survival to productivity is not uniform for all salmon and steelhead stocks in the U.S. Salish Sea and, as a result, spatial comparisons will be useful for understanding the relationship between marine survival and productivity. In the U.S. Salish Sea, salmon and steelhead populations have historically exhibited contrasting trends in adult results over time. Different abundance trends, by definition, result from different productivity trends. High productivity (> 1 spawner per spawner) will lead to increasing adult returns and low productivity (< 1 spawner per spawner) will lead to decreasing adult returns.

To illustrate this concept, we examine long-term adult return data sets (1980-2011) for natural-origin coho salmon and steelhead in the U.S. Salish Sea. We selected these data sets because they represent counts at upstream fish traps and are thus some of the most accurate available information on adult spawners. For coho salmon, correlations in adult returns are weak (Table 1, Figure 7a) indicating that regional factors have played an important role in coho salmon productivity. Temporal trends in coho abundance vary among regions. For example, coho returns to South Sound were highest in the late 1980s whereas coho returns to Hood Canal and Whidbey Basin were highest in the early 2000s. In comparison, the peaks and valleys in the two steelhead data sets generally have tracked each other and temporal trends in both watersheds have been declining since 2000 (Figure 7b). The similarities among the steelhead data sets are particularly notable because the adult life history of the two populations differ - Snow Creek are a wild winter-run population whereas the South Fork Skykomish River are primarily a naturalized summer-run population.

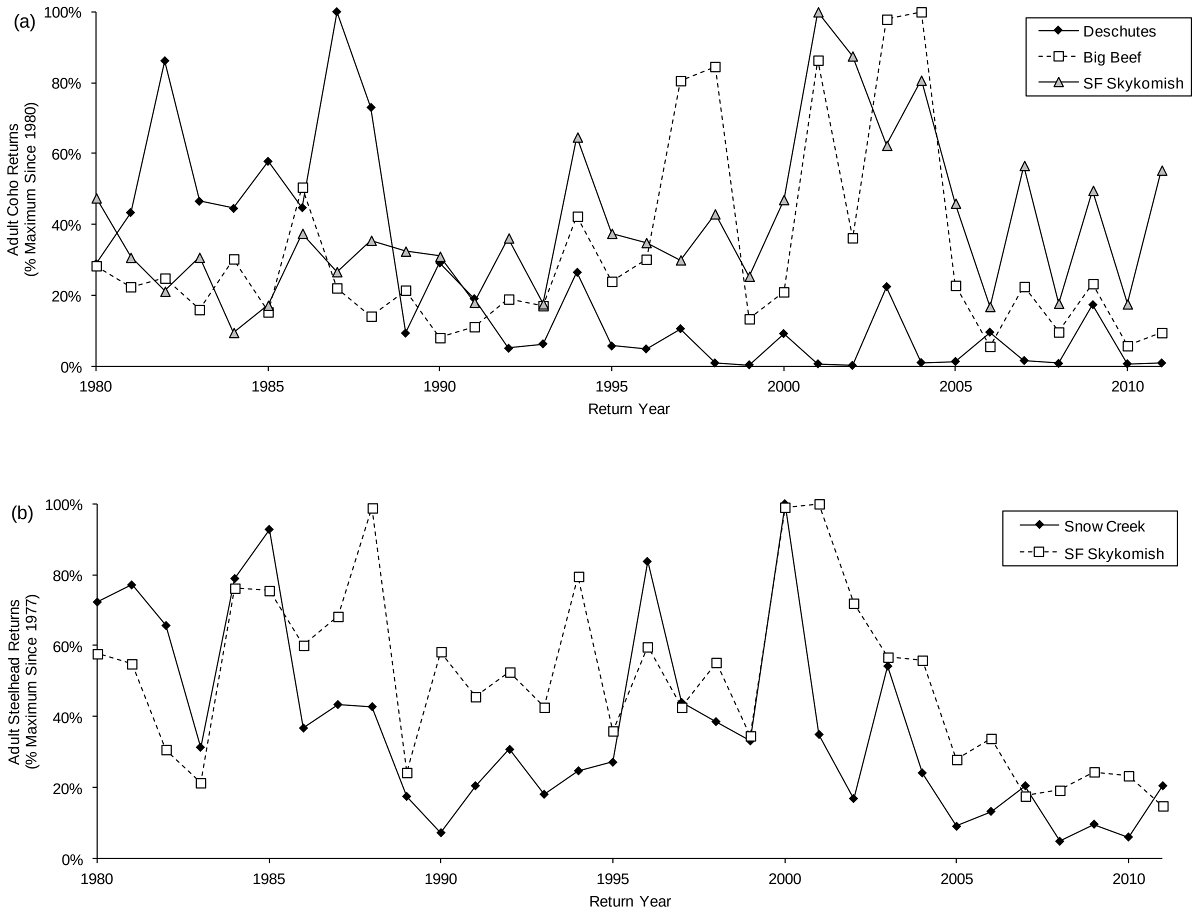

Figure 7. Returns of natural-origin coho spawners (a) to South Sound (Deschutes River), Hood Canal (Big Beef Creek), Whidbey Basin (SF Skykomish River) and returns of natural-origin steelhead spawners (b) to Snow Creek and South Fork Skykomish River. Data are the percent of maximum abundance between 1980 and 2011 as provided by WDFW (M. Zimmerman, pers. comm.).

Table 1. Correlation between adult coho returns to South Sound (Deschutes River), Hood Canal (Big Beef Creek), Whidbey Basin (SF Skykomish River) and Grays Harbor (Bingham Creek) for return years 1980 to 2011. Data are Pearson correlation coefficients. Asterisks indicate the correlation differs from zero (α < 0.05).

	South Sound	**Hood Canal**	**Whidbey Basin**	**Grays Harbor**
South Sound	1.0	-0.17	-0.34	-0.29
Hood Canal		1.0	*0.60	0.19
Whidbey Basin			1.0	*0.39
Grays Harbor				1.0

Data Availability and Needs

Three metrics may be particularly useful to address the role of marine survival in salmon and steelhead productivity trends. These metrics are (1) the proportion of total mortality that occurs in the marine versus freshwater environment, (2) variation in the proportion of total mortality in the marine versus freshwater environment, and (3) correlation between freshwater and marine survival and adult spawner returns. The stock-specific data needed to derive these metrics are spawners, smolts, and catch abundance for each population divided into age categories and attributed back to the parent brood year. Female fecundity is the fourth data component required for this analysis.

Our hypothesis relies on the ability to partition freshwater and marine survival rates. Measures of freshwater and marine survival are derived from the number of adult spawners, an assumed fecundity, and the number of emigrating juveniles. Since juvenile emigrants are typically measured with traps located above the point of saltwater entry, calculations attributed to freshwater or marine environment overestimate the freshwater component and underestimate the marine component. The extent of this bias depends on the mortality that occurs in the reach below the trap and above saltwater entry.

The challenges for deriving the defined metrics from existing data will vary by species. At a minimum, spawner and smolt abundance of wild populations are required. Information gleaned from hatchery stocks can serve as surrogate estimates for fecundity, age structure, and harvest of the wild or natural populations. For most species, the combination of spawner and smolt abundance data are available throughout the Salish Sea region (Table 2). This broad scale coverage has resulted, in part, from the "Fish-In Fish-Out" monitoring framework developed by the Washington State Governor's Monitoring Forum (Crawford 2007).

The longevity of smolt and age data sets are more likely to limit the analysis than spawner abundance or harvest data. Smolt data are sparse for some ESUs, such as Hood Canal summer chum, where funding or logistics have resulted in just a few years of information from a few watersheds. For species with relatively simple life histories, such as pink salmon, age data will not be a problem and the largest challenge will be partitioning catch in mixed stock fisheries. For species of higher commercial value, such as coho and Chinook salmon, harvest models are reasonably well developed and the greatest challenge may be selecting populations where escapement estimates are accurate (Crawford and Rumsey 2011). Deriving the described metrics will be the most challenging for steelhead because smolt data sets are short in length and smolt and adult age data are minimally available.

Table 2. Salish Sea populations for which smolt and adult abundance data are simultaneously available for natural populations through the 2012 outmigration. In some cases, the monitored tributary comprises just a portion of the entire population. Populations are defined according to Technical Recovery Team documents for Chinook, steelhead, and summer chum (Ruckelhaus et al. 2006; Sands et al. 2009).

Species	Population	Tributary	Number of years
Chinook salmon	Skagit (composite)	---	18
	Stillaguamish	---	10
	Skykomish	---	13
	Snoqualmie	---	12
	Cedar River	---	14
	Sammamish River	Bear Creek	14

	Green River	---	13
	Puyallup River	---	13
	Nisqually River	---	4
	Mid-Hood Canal	Duckabush	2
		Hamma Hamma	2
	Dungeness River	---	8
	Elwha River	---	8
Coho salmon	Skagit	---	23
	Stillaguamish	---	7
	Skykomish	---	13
	Lake Washington	Cedar River	14
		Bear Creek	14
	Green River	---	13
	Puyallup River	---	8
	Nisqually River	---	4
	Deschutes River	---	34
	South Sound	Cranberry Creek	14
		Mill Creek	13
		Skookum Creek	11
		Goldsborough Cr.	14
		Johns Creek	6
		Sherwood Creek	9
	East Kitsap	Chico Creek	2
	Hood Canal	Little Anderson	19
		Big Beef Creek	35
		Seabeck Creek	19
		Stavis Creek	19
	Discovery Bay	Snow Creek	32
	Dungeness River	---	8
	Sequim Bay	Jimmecomelately	11
		Bell Creek	3
	Morse Creek	McDonald	7
		Siebert	11
		Ennis	8
	Salt Creek		13
	Pyscht/Twin/Deep	East Twin Creek	13
		West Twin Creek	13
		Deep Creek	16
Pink salmon	Skagit River (odd)	---	10
	Green River (odd)	---	6
	Nisqually River (odd)	---	2
	Duckabush River (odd)	Duckabush	3
	Dungeness River (odd)	---	4
	Elwha River (odd)	---	4
Chum salmon	Skagit River (fall)	---	18
	Nisqually River (winter)	---	4
	Duckabush (summer)	---	2

	Duckabush (fall)	---	2
	Hamma Hamma (summer)	---	2
	Hamma Hamma (fall)	---	2
	Straits JDF (summer)	Salmon Creek	5
	Dungeness River	---	8
	Elwha River	---	8
Steelhead	Skagit River	Finney Creek	1
		Illabot Creek	1
		Bacon Creek	1
	Green River	---	8
	Nisqually River	---	4
	East HC	Big Beef Creek	35
		Dewatto	6
	South HC	Tahuya	6
	West HC	Duckabush	1
		Little Quilcene	4
	JDF Lowland Tributaries	Snow Creek	32
	Dungeness River	---	8
	Salt Creek	---	13
	Pyscht/Independent Tribs	East Twin Creek	13
		West Twin Creek	13
		Deep Creek	16

Research Recommendations

As currently described, most work that can support the analyses described above is retrospective in nature, i.e., targeted analysis of previously collected data. As shown for some examples above, there are limits to what can be concluded from retrospective analyses, particularly for examining regional variation. Recognizing that questions concerning spatial variation are central to the overall research plan for the Salish Sea marine survival project, we propose a space-for-time substitution to examine freshwater and marine survival over a greater number of sites, but for a relatively short period of time. Replication within oceanographic basins would thereby allow us to test whether some basins have higher marine survival than others, over a relatively (5-year) time frame.

The selection of watersheds for this research program builds on existing life cycle monitoring projects conducted by state and tribal biologists. The proposed watershed replicates within each of the four study regions of the Salish Sea are identified in Table 3. The scale of data used in this research program ranges from small tributaries to major rivers. Small tributaries have the benefit of high quality information; however, in most cases, dispersal among adjacent tributaries will be an unknown source of error for the survival estimates. Major rivers are the only source of monitoring information for main stem spawners such as Chinook and pink salmon; however, major rivers have few replications within the selected geographic regions.

In order to support this research program, aspects of the existing monitoring efforts will need to be expanded. Work to be supported under this research program includes retrospective abundance estimations with existing data (e.g., pink salmon juvenile estimates), modification of existing juvenile monitoring projects (e.g., Hood Canal summer chum), and the consistent incorporation of age sampling in juvenile and adult monitoring projects. This research program will also support work to compile juvenile, adult, and catch abundance data for the identified populations (or subpopulations) and analyze the mortality and productivity trends according to the approach outlined in this section. Together, these data will be used to identify the role of marine survival in the overall productivity of salmon and steelhead in different regions of the Salish Sea.

Table 3. Populations and sub-populations to be included in the spatially replicated approach used to evaluate the contribution of marine survival to salmon and steelhead productivity in the U.S. Salish Sea. Sockeye are not included as they are not a focus of this research program.

Species	Whidbey Basin	South Sound	Hood Canal	Straits JDF
Chinook	Skagit Stillaguamish Skykomish Snoqualmie	Nisqually	Duckabush Hamma Hamma	Dungeness Elwha
Pink	Skagit	Nisqually	Duckabush Hamma Hamma	Dungeness Elwha
Chum	Skagit	Nisqually	Duckabush Hamma Hamma	Salmon Creek Dungeness Elwha
Coho	Skagit Stillaguamish Skykomish	Nisqually Deschutes South Sound tribs (6)	Hood Canal tribs (4)	Snow Creek Dungeness River JDF tribs (9)
Steelhead	Skagit tribs (3)	Nisqually River	East HC tribs (3) West HC tribs (2)	Snow Creek Dungeness River Salt Creek Pyscht/Indep. Tribs (3)

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Hypothesis 2. Ecosystem and community factors affecting salmon and steelhead survival are operating at different levels by area encountered, species, hatchery v. wild, and within species, by life history.

Abstract only. See p. 25 of the report.

Hypothesis 3. Size-Selective Mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood.

Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences

Size-selective mortality has been widely reported during the juvenile stages of many fish species, including anadromous salmonids, and can be a predominant force affecting marine survival and adult run size (Sogard 1997; Moss et al. 2005; Cross et al. 2009; Duffy and Beauchamp 2011; Tomaro et al. 2012). Larger size typically confers a survival advantage through periods of high mortality, wherein predation, overwinter starvation, or physiological debilitation are the commonly ascribed agents of mortality (Beamish and Mahnken 2001). The key processes influencing size-selective marine mortality of salmonids are hypothesized to occur primarily during critical periods during marine entry and early marine growth, and again during winter. Therefore, it is important to realize that size-selective mortality can operate either in the short term or impose delayed consequences based on earlier size or growth of individuals. The challenge will be to determine the generality of size-selective mortality, and the spatial-temporal dynamics of processes affecting specific species and stocks of Salish Sea salmon and steelhead across the range of environmental and ecological variability among seasons and years.

Size-selective mortality offers a useful conceptual framework for examining and linking processes that affect growth and survival at different life stages of anadromous salmonids, and for identifying and quantifying when and where critical periods of growth and survival occur. Size selective mortality is generally expressed as disproportionately low survival of the smaller individuals from one period (e.g., hatchery release, smolt trap) to some later period or life stage. Also, within periods that allow survival estimates (e.g., smolt-to-adult returns: SARs), positive correlations between survival and body size at specific life stages within that survival period can provide: 1) empirical relationships between size and survival for specific species or stocks; 2) can infer the relative importance of size attained at different life stages to survival over the total survival period, based on comparisons of the strength of correlation and magnitude of the slope between size and survival.

Supporting Evidence

Size-selective mortality can operate at different life stages for different species and stocks of anadromous salmonids. Strong size-selective mortality has been reported for hatchery Chinook salmon in Puget Sound (Duffy and Beauchamp 2011) and coho salmon in the Strait of Georgia (Beamish et al. 2004), and was associated with sizes achieved during the early months of marine life, whereas varied responses have been reported for steelhead (Ward et al. 1989; Ward 2000) and pink salmon (Beamish 2006) populations within or adjacent to the Salish Sea.

For Chinook salmon, hatchery CWT release groups from the South, Central, and Whidbey basins of Puget Sound in 4 years over 1997-2002 exhibited a strong positive correlation between SARs and mean body mass for juveniles captured in offshore habitats in Puget Sound during July; however, SARs for the same CWT stocks were only weakly correlated with size at hatchery release, and showed a much weaker correlation to mean body mass achieved offshore in September (**Figure 1**; Duffy and Beauchamp 2011). The higher correlation and steeper slope of the relationship in July compared to September indicated that early marine growth leading up to the sizes sampled in July strongly influenced overall marine survival, but that this benefit declined for the juveniles remaining in September. Since the juvenile Chinook doubled or tripled their mass after leaving nearshore habitats Duffy et al. 2005, Duffy and Beauchamp 2011), their growth during 1-2 months (June-July) in the epi-pelagic environment of Puget Sound constituted a critical growth period that influenced total marine survival for these hatchery stocks of Chinook salmon during those years. Quinn et al. (2005) similarly reported a generally positive, but non-significant correlation between size at hatchery release and % marine survival for both Chinook and coho released from Soos Creek and University of Washington, but had no data on effects of subsequent marine growth on survival for these stocks.

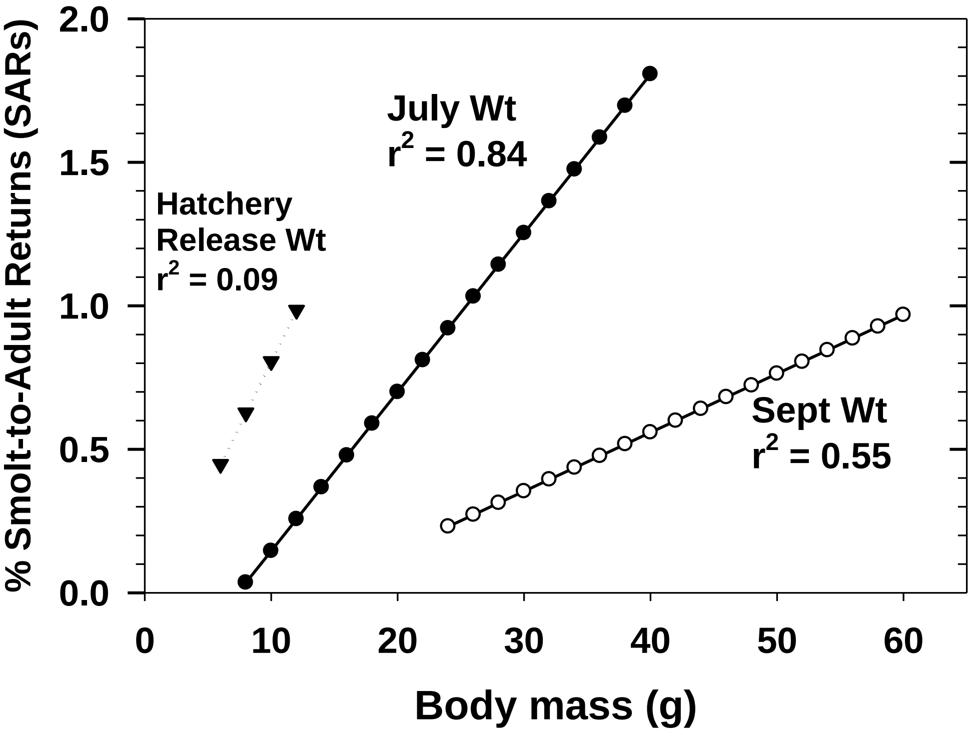

Figure 1. Relationships of SARs to mean body mass of CWT groups of hatchery Chinook salmon at release and when captured during marine offshore life stages in midwater trawls during July and September (modified from Duffy and Beauchamp 2011).

A comparison of the back-calculated sizes of juveniles to those of surviving adults from the same life stages can provide evidence for the timing and magnitude of size-selective mortality (e.g., Moss et al 2005; Cross et al. 2009 for pink salmon in the Gulf of Alaska). Unfortunately, direct comparisons between stage-specific sizes of juveniles versus adults from the same stock and brood year have not been analyzed for Puget Sound Chinook. However, an opportunistic comparison of size among life stages from different stocks or brood years is provided as a suggestive illustration of this approach. The scale radius at specific circuli for returning adult Chinook salmon in 2004 (2001 Brood year) were significantly larger than for juvenile Chinook from the same brood year captured nearshore during 2002; however, the radii at comparable circuli counts were similar between the adults returning in 2004 and juveniles sampled offshore in Puget Sound during summer in 2008 (although wider error bars for the sizes of the juveniles; Beauchamp and Duffy 2011; **Figure 2**). If these comparisons had pertained to the same stock, we could conclude that strong size-selective mortality acted against the smaller, slower growing juveniles that remained longer in nearshore habitats contributing to adult returns. In addition, if the offshore juvenile had also originated from the same stock and brood year as the adults and nearshore juveniles above, we would conclude that size-selective mortality would have been considerably less severe on the offshore juveniles than for neashore juveniles. This would have further suggested that considerable size-selective mortality occurred during or soon after the nearshore-offshore transition, because these smaller fish were reflected in the size distribution of juveniles offshore. However, because these data do not come from the same brood year, this pattern of size-selective mortality must be treated as merely suggestive rather than definitive.

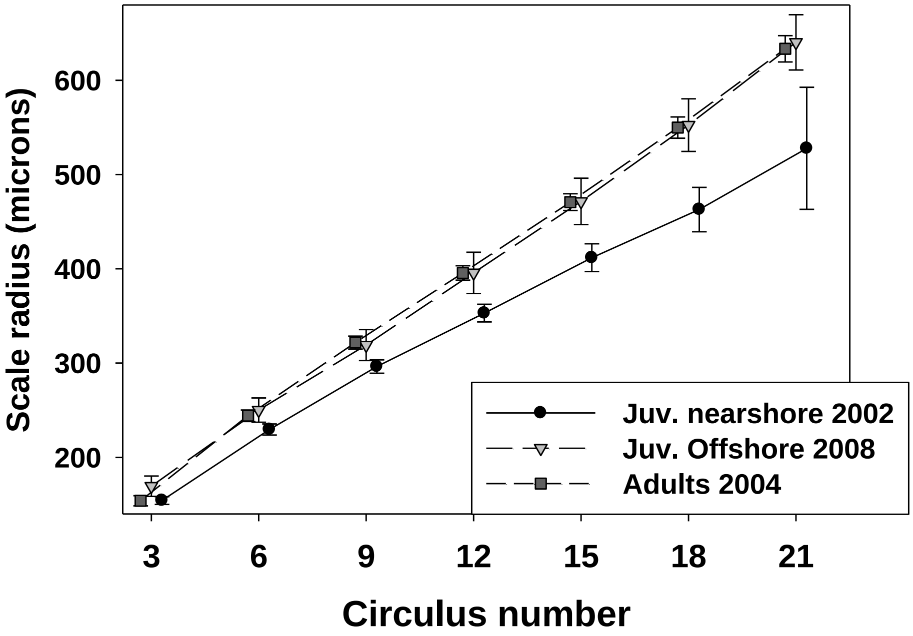

Figure 2. Juvenile Chinook sizes (scale radius at specific circuli) at specific life stages compared among nearshore-rearing juveniles sampled in 2002, offshore rearing juveniles sampled in 2008, and from returning adults collected in 2004. Note that the offshore juvenile samples are from a different brood year, whereas the 2004 adults represent just the first of three ages of adult returns associated with age-0 juveniles from 2002.

For coho salmon in the Strait of Georgia, Beamish et al. (2004) reported that juveniles that grew faster through the first 10 circuli of saltwater growth on their scales survived at a disproportionately higher rate: juveniles larger than the median size contributed 85% of surviving subadults and adults the following year, whereas coho smaller than the median contributed only 15% to the older life stages; **Figure 3**).

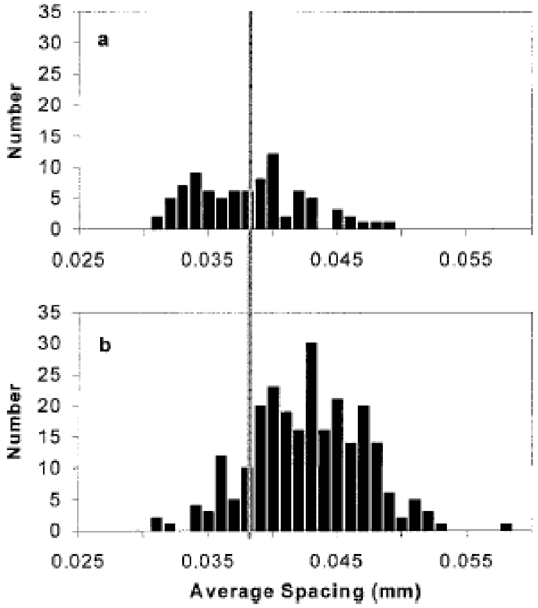

Figure 3. The frequency distribution of early marine growth (represented by spacing of the first 10 circuli of saltwater growth on scales) for: a) juvenile coho and b) surviving subadults and adults during the following year for coho from the Strait of Georgia (Beamish et al. 2004).

Based on acoustic telemetry, ***steelhead*** migrate rapidly through Puget Sound and Strait of Georgia, and appear to experience substantial mortality; however, evidence for a size-selective component to survival during this brief migration period was equivocal (Melnychuk et al. 2007; Moore et al. 2009). Steelhead from the Keogh River, north of the Strait of Georgia showed a strong positive correlation between freshwater smolt length and smolt-to-adult returns (SARs) during 1976-1989, but after 1990, no correlation was detected and SARs declined dramatically from 15% during 1976-1989 to 3.5% during 1990-1995 (Ward 2000; **Figure 4**).

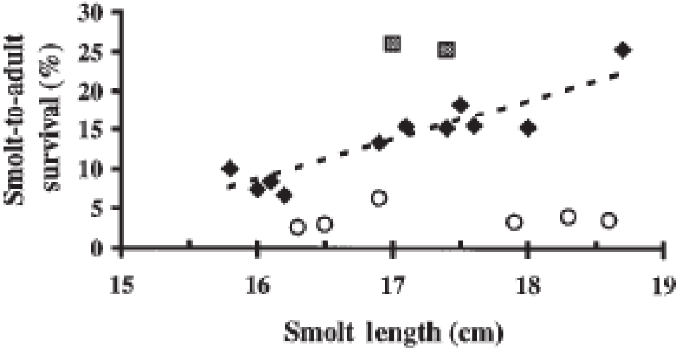

Figure 4. Relationship between fork length of steelhead smolts sampled from a downstream migrant trap and SARs during 1976-1989 (black diamonds) and 1990-1995 (open circles) for the Keogh River, BC. Smolts from 1982 and 1985 that experienced El Nino conditions are indicated by gray squares (Figure from Ward 2000).

Larger salmonids exert size-selective predation on younger salmon. Sea-run cutthroat trout (Duffy and Beauchamp 2008) and resident Chinook salmon (Beauchamp and Duffy 2011; **Figure 5**) eat smaller juvenile salmon on average than are available in the population. These predators are capable of eating prey up to 50% of their body length, but routinely consume prey fishes averaging 25-30% of their body length (Beauchamp et al. 2007; Duffy and Beauchamp 2008; Duffy et al. 2010).

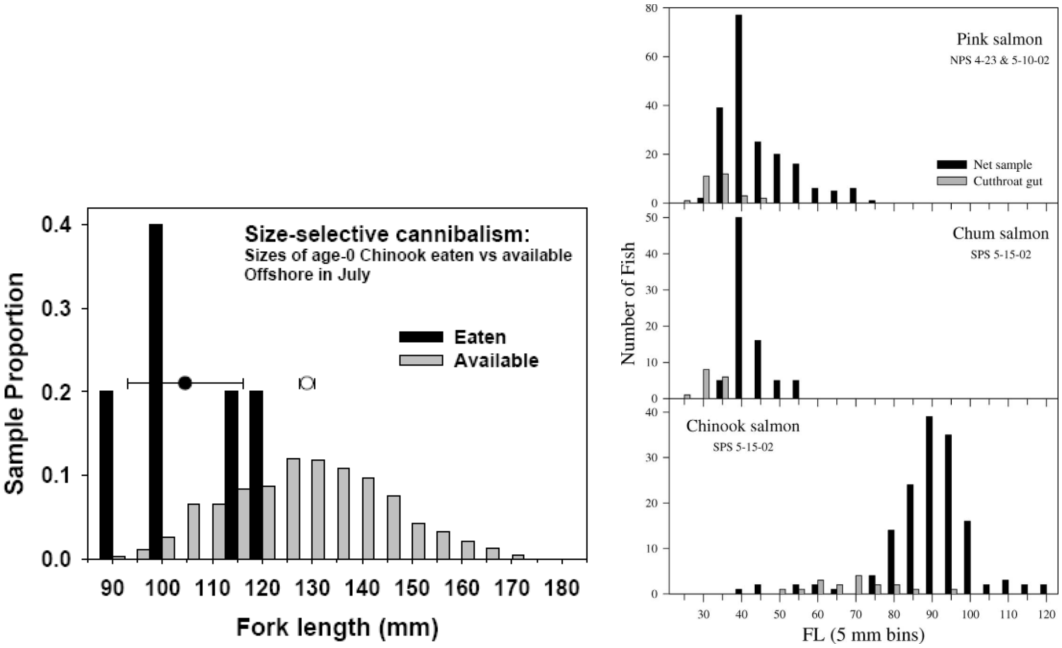

Figure 5. Size distribution and mean fork length (± 2 SE) of subyearling Chinook salmon found in stomachs of resident Chinook salmon versus those concurrently available in offshore regions of Puget Sound during July (Left), and by cutthroat trout in nearshore habitats during April-May.

Data Needs

In Puget Sound, some important unknowns are:

- Where and when do critical growth periods occur for specific species or stocks?
- Do critical periods differ among stocks or species (e.g., ocean-type Chinook salmon from the Skagit River Basin versus south-central Puget Sound populations)?
- Does the resulting size-selective mortality occur primarily within Puget Sound or at later life stages in other regions?
- What are the underlying processes that affect growth during these critical periods, and thus survival to adulthood? (see hypotheses below on growth, food supply, temperature, competition)

For ocean-type Chinook salmon, we need to learn whether these size-selective relationships extend into August (only July and September have been examined) or can be generalized to other years and other stocks of hatchery Chinook. Do these relationships also apply to wild Chinook? And can similar relationships be developed for other species of salmonids in the Salish Sea?

Wild ocean-type Chinook from the Whidbey Basin (Skagit and Snohomish Rivers) appear to remain nearshore for more than a month longer than the hatchery Chinook described above (Duffy et al. 2005; Rice et al. 2011; E. Beamer, unpublished data), and thus appear to miss the presumptive critical growth benefit from epi-pelagic feeding during June-July. Similar analyses of relationships between SARs and juvenile Chinook size at various life stages (i.e., size at hatchery release, smolt trap, estuarine-marine beach seine and tow net samples) would fill an important information gap regarding critical sizes and periods for these Skagit River stocks (hatchery and wild).

Changes in size through time can result from either true growth (i.e., all sampled individuals represent the unbiased growth trajectory for the population at large) or apparent growth wherein the size distribution was altered by size-dependent immigration-emigration, size-selective capture techniques, or size-selective mortality within a growth period of interest (e.g., from smolt trap or hatchery release to some marine sampling event). Distinguishing between real and apparent growth provides much of the essential information needed to identify and quantify the temporal and spatial dimensions of size-selective mortality. Therefore, this approach needs to account for stock of origin (via CWT or genetic techniques like SNPs) and effects of immigration-emigration through specific habitats/regions within key sampling periods.

Two complementary approaches for examining growth size-selective mortality are: 1) correlations and linear relationships between body size (fork length, weight, or condition) and SARs or some alternative measure of survival for as many life stages as can be adequately assessed feasibly; and 2) changes in stage-specific size distributions through time and among life stages, based on scale (and potentially otolith) circuli patterns (radius and counts of all circuli associated with specific life stages).

The relationships between body size or condition and SARs, and estimates of survival at intermediate life stages, identify life stage(s) that are most involved in size-selective mortality, and quantify how variability in size exerts strong influence on marine survival, and ultimately adult returns. The scale-based analysis of change in stage-specific size distribution through time can diagnose whether size-selective mortality occurs within specific life stages (e.g., within the Salish Sea) or simply influences survival over subsequent periods based on the sizes achieved during current or earlier life stages. These analyses can help identify whether salmonid survival is influenced more by growing conditions or direct mortality (i.e., predation, disease, environmental stress) while occupying the Salish Sea.

Research Recommendations

Conduct retrospective analysis on scale patterns of returning adults to evaluate relationships in smolt size, size-at-annulus, and patterns in size-at-specific circuli to adult returns or SARs. Compare size distributions at specific life stages from scales of returning adults to size distributions from scales of juveniles sampled at specific life stages in frozen archives (2001-2012).

Sample and record size distributions (fork length and weight) and collect scales from juvenile salmon, with emphasis on tracking growth trajectories and size distributions of known-origin through time at:

- Hatchery release
- Smolt traps
- Estuarine (beach seines and tidal traps
- Nearshore marine (beach seines)

- Nearshore-offshore transition (surface tow net)

Offshore (midwater trawling by DFO July & Sept; purse seining monthly April/May through September/October)

Management Implications

The following is a list of conceptual strategies that could be applied in response to the research results if the hypothesis was found to be correct.

- Inform prioritization strategies for specific habitat restoration and determine whether specific restorations should emphasize the habitat's function in supporting migration, feeding and growth, survival, or some combination.
- Inform hatchery strategies for optimal size and time at release for different stocks and species.
- Potentially use the relationships of SARs to stage-specific juvenile size as an element in run size forecasting
- Knowledge of stage-specific, size-selective mortality will help parse out where important bottlenecks to overall survival occur in freshwater versus early marine life, and can determine the importance of size or growth within and among life stages. This would inform both hatchery practices and habitat restoration.

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Hypothesis 4. Outmigration timing influences the magnitude effect of competition, predation, and environmental variation on survival in the Salish Sea.

Josh Chamberlin, NOAA Northwest Fisheries Science Center

Following periods of higher survival in the late 1970's, survival of Pacific salmon (*Oncorhynchus* spp.) in Puget Sound rapidly declined and has remained relatively low into recent years. The transition from the estuarine to the nearshore and pelagic marine environments of outmigrating juvenile salmon has been characterized as a critical period for determining the overall survival of salmon in the region (Beamish and Mahnken 2001). The timing of this transition period may have significant influence on the overall survival of a particular cohort of outmigrants. For example, growth rates during the early marine transition can significantly affect survival (Beamish et al. 2008; Healey 1982; Holtby et al. 1990). Fish that are able to grow faster and attain a larger size sooner have been found to have higher survival rates than their slow growing counterparts in Puget Sound and beyond (Duffy and Beauchamp 2011; Tipping 2011). The match/mismatch between juvenile fish and their prey during this critical period can affect survival, or recruitment, to later life stages (Cushing 1975; Cushing 1990). Shifts in outmigration timing may have cascading effects on the overall survival of juveniles during the early marine transition via interactions between fish condition (increased predation) and growth potential (increased competition, match-mismatch hypothesis).

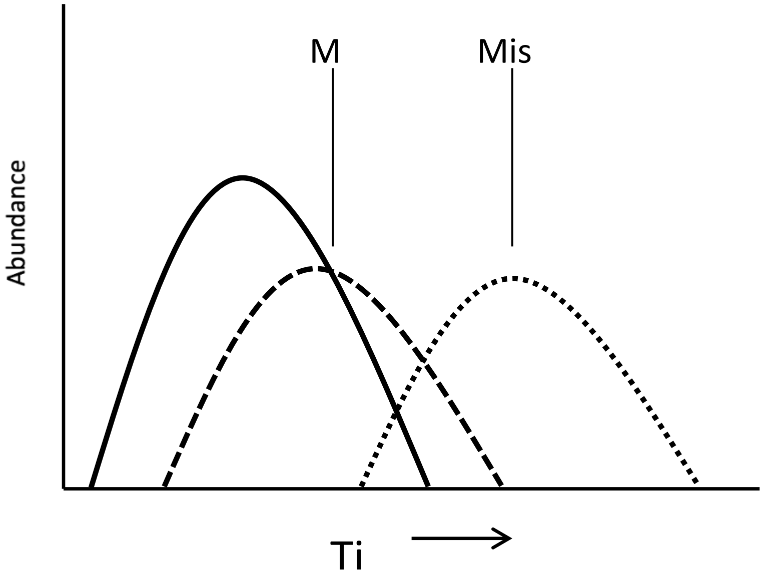

Figure 1. Conceptual diagram of match/mismatch hypothesis adapted from Cushing (1975,1990) showing how shifts in outmigration timing (dashed lines) can affect the conditions fish experience based on the timing of environmental variation (solid line).

Timing of outmigration has significant influence upon the conditions fish experience during the early marine phase. The match-mismatch hypothesis states that the overlap between juvenile fish and their prey is critical for achieving growth necessary for increased survival (Cushing 1975; Cushing 1990). Saito (2009) found a positive correlation between increased growth and condition for chum salmon when outmigration coincided with peak abundances of zooplankton in Nemuro Strait. Early studies in Hood Canal suggest that abundances of zooplankton were low in winter and early spring and steadily increased into June and late summer which would coincide with typical outmigration periods for juveniles in the region (Bollens et al. 1992). Therefore, shifts in outmigrant timing may have a negative effect on juvenile salmon survival if these shifts do not correspond to resource availability in the marine environment (Hypothesis 10). To examine this hypothesis in the Salish Sea will require an understanding of environmental variables that drive the timing of freshwater outmigration, marine productivity, and the correlations between them. For example, freshwater variables such as stream temperature, if correlated with marine temperatures, may actually help to synchronize juvenile migration with a productive marine environment (Holtby et al. 1989).

Typical outmigration periods for naturally spawned juvenile salmon in Puget Sound range from February to August. However, considerable inter- and intra-annual variation has been observed depending on species and life history composition within a given watershed (Beamer and Larsen 2004; Groot and Margolis 1991; Hypothesis 13). Outmigration timing for hatchery populations occurs between late April and early June in most systems throughout Puget Sound. Release timing has remained relatively static for decades largely due to size at release goals based upon past studies/observations documenting increased survival of individual fish. However, differences in release timing do exist depending on species, age class, and run type. Species that migrate upon emergence (chum, pink, some Chinook) leave freshwater earlier than the larger outmigrants that spend months to several years rearing in freshwater (Topping and Zimmerman 2011; Weinheimer et al. 2011; Kinsel et al. 2008). Several factors, including density dependent mechanisms and variable environmental conditions, can shift the peak outmigration date and change the duration of the outmigration period. Abundant populations may experience shifts in outmigration timing due to abundances that exceed the carrying capacity of natural rearing habitats (Greene and Beechie 2004). Heavy rainfall and increased occurrence of flooding events can physically displace fish within streams and estuaries and may limit the amount of habitat with slow moving current ideal for rearing juvenile salmonids. (Greene et al. 2005). Outmigrant timing is also correlated with steam temperatures during incubation, especially for those species that migrate immediately following emergence (Kiyohara and Zimmerman 2012; Holtby et al. 1989; J. Weinheimer, WDFW, unpublished data) Data from the Snohomish River estuary suggest that juvenile salmon leave earlier in years when water temperatures are warmer than average and rear longer when water temperature remain cold (K. Fresh, NWFSC, unpublished data).

Environmental variables also drive the marine habitat productivity, which typically increases in early spring (Pearcy 1992, Hypothesis 5). Detritus, an important nutrient base for the estuary food web, has a fairly predictable availability (Sibert 1979, Sibert et al. 1977). In comparison, plankton blooms in nearshore and pelagic habitats are driven by winds, currents, and salinity (Winter et al 1975), variables that are far less predictable on an annual basis. Warming trend in global climate overlay productivity cycles in all habitats and may cause directional shifts in the timing of spring blooms in future decades (Chittenden et al 2010). If the productivity of marine habitats is driven by different mechanisms, then the effects of environmental variables are not universal and should be considered with respect to habitat and species residency in that habitat. For example, Chinook and chum salmon have extended rearing periods in estuary habitat (weeks to months) in comparison with pink and coho salmon and steelhead, which move offshore more quickly (Moore et al. 2010; Pearcy 1992).

If shifts in outmigration timing are decoupled from productivity in Salish Sea environment, fish condition in the marine environment may be reduced (Hypotheses 3 and 12). While it is difficult to corroborate an link between size at entry and overall survival (Henderson and Cass 1991; Quinn et al. 2005), growth during the early marine period is critical for survival to subsequent life stages (Duffy and Beauchamp 2011; Holtby et al. 1990). Reduced fish condition resulting from poor growth can further reduce growth potential through an increase in predation and competition. Size selective predation by coastal cutthroat trout *(O. clarkii clarkii*) on juvenile salmon has been documented in Puget Sound during the peak outmigration periods of April and May (Duffy and Beauchamp 2008). Reduced fish condition may also affect competition between and among species of salmon and other pelagic fishes. Ruggerone and Goetz (2004) showed evidence of a shift from predation- to competition-based mortality for Chinook salmon (O. tshawytscha) in response to increasing abundances of pink salmon (*O. gorbuscha*) in Puget Sound. Along with increased abundances in the nearshore habitat, a reduction in fish condition will likely affect the predation/competition dynamic for juvenile salmon.

In addition to the match-mismatch between outmigrating juvenile salmon and their prey, the potential for increased encounters with adverse environmental conditions in the nearshore due to shifts in timing may also negatively impact overall survival. Reduced survival of sockeye salmon (*O. nerka*) smolts and abundance of Pacific herring (*Clupea pallasii*) in the Fraser River was strongly correlated with blooms of *Heterosigma* akashiwo in the Strait of Georgia (Rensel et al. 2010). Harmful algal blooms (HAB) of the dinoflagellate *Alexandrium catenell* are predicted to occur earlier and have a longer duration in Puget Sound due to changing climate conditions (Moore). Understanding the effects of specific HAB's on juvenile salmon and their prey the likelihood for overlap as outmigration periods may be important for explain trends in salmon survival throughout Puget Sound.

Data Needs

The following questions must be addressed

Determine to what extent inter-annual variability in outmigrant timing is correlated among species (and life-history trajectories)? To what extent are environmental drivers of outmigration timing species specific? Is the outmigrant timing of some species more responsive than others to inter-annual variability in the freshwater environment?

Evaluate life history diversity at the watershed scale. What life-history trajectories are more successful than others, from the perspective of outmigrant timing?

Evaluate whether there is a size-dependent effect expressed in marine mortality that result from effects in the freshwater (e.g., density dependent migration). Do this by incorporating outmigration timing and size data as part of evaluation described in hyp 3 (critical size).

Research Recommendations

In conjunction with the data collected to address the other hypotheses listed, in both retrospective analyses and the proposed 5-year intensive monitoring effort, include outmigration timing information. Outmigrant size data is also critical and will be collected in conjunction with addressing hypothesis 3 (critical size).

Cross-Referenced Hypotheses

> Hypothesis 3. Size-Selective Mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood.

Hypothesis 6. Through a process known as the portfolio effect, diversity among salmonid populations confers temporal stability and long-term persistence of the species within the Salish Sea.

Hypothesis 7. Changes in circulation and water properties have altered phytoplankton and zooplankton production in ways that degraded salmon food-webs in the Salish Sea from the 1970s to 2000s.)

Hypothesis 9. Harmful algae directly affect salmon survival through acute or chronic mortality and may adversely affect prey availability by food web impoverishment.

Hypothesis 10. Reduced habitat availability and/or diversity have affected the behavior of salmon while in the Salish Sea.

Hypothesis 12. Food supply limits growth, and thus survival, during critical periods of early marine rearing

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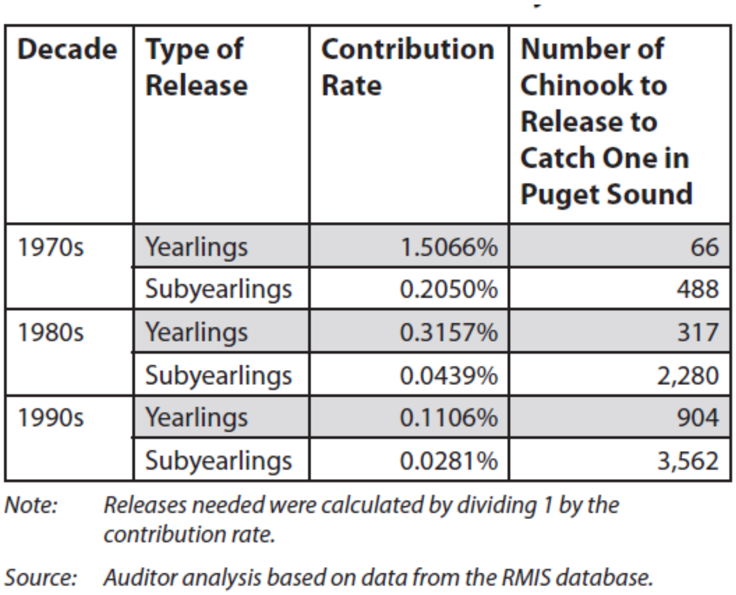
Hypothesis 5. Resident-type behavior and the duration of residence influences survival in the Salish Sea.

Josh Chamberlin, NOAA Northwest Fisheries Science Center

In addition to the typical ocean migration patterns of Pacific salmon, several species (Chinook, coho, chum, pink) are documented to spend extended periods of time residing within the Salish Sea (Haw et al. 1967; Pressey 1953). Chinook and coho, in particular, may spend the entire marine portion of their life cycle as residents before returning to their natal rivers to spawn. Recent analysis of CWT data suggests that 24% of CWT recoveries in Puget Sound from 1973-1990 were defined as residents based upon location and month of recovery (Chamberlin et al. 2011). In addition, an independent fishery assessment model for Puget Sound estimated that 29% of sub-yearling, and 45% of yearling, hatchery releases displayed a resident behavior (O'Neill and West 2009).As survival declined during the mid 1980’s so did the proportion of residents caught in the Puget Sound recreational fishery (Table 15.). During this period, the relative proportion of residents to non-residents showed an overall decline even though total hatchery release numbers steadily increased (Chamberlin and Quinn, unpublished data; Figure 15.). However, inter-annual variation in the trends indicates the mechanisms driving a resident-type behavior and the potential effects of residence duration on marine survival within the Salish Sea are poorly understood.

Extended residence in the Salish Sea may negatively impact overall marine survival of salmon in the region. O’Neill and West (2009) observed elevated PCB levels in the tissue of Chinook that displayed a resident behavior suggesting an increased risk of contaminant exposure during residence in Puget Sound (Hypothesis 12.2) . Competition between Chinook and other small pelagics (e.g. herring) in Puget Sound during the early marine period has been documented (Duffy and Beauchamp 2011, Hypothesis 10.2) though competitive interactions between resident Chinook, resident coho, and other large pelagic species during sub-adult life stages remains unknown. Furthermore, the increased predation risk associated with a resident type-behavior may be similar to the hypothesized effect on local steelhead populations due to the increased abundance of resident marine mammal populations(Hypothesis 11). Overall, the potential negative effects of residency on survival of salmon in the Salish Sea should be identified as a major information gap that warrants further research.

Table 15.1. Historical contribution rates and releases needed for one Chinook to be caught in the Puget Sound recreational fishery (WSAO 2010).



Decade	Type of Release	Contribution Rate	Number of Chinook to Release to Catch One in Puget Sound
1970s	Yearlings	1.5066%	66
	Subyearlings	0.2050%	488
1980s	Yearlings	0.3157%	317
	Subyearlings	0.0439%	2,280
1990s	Yearlings	0.1106%	904
	Subyearlings	0.0281%	3,562

Note: *Releases needed were calculated by dividing 1 by the contribution rate.*

Source: *Auditor analysis based on data from the RMIS database.*

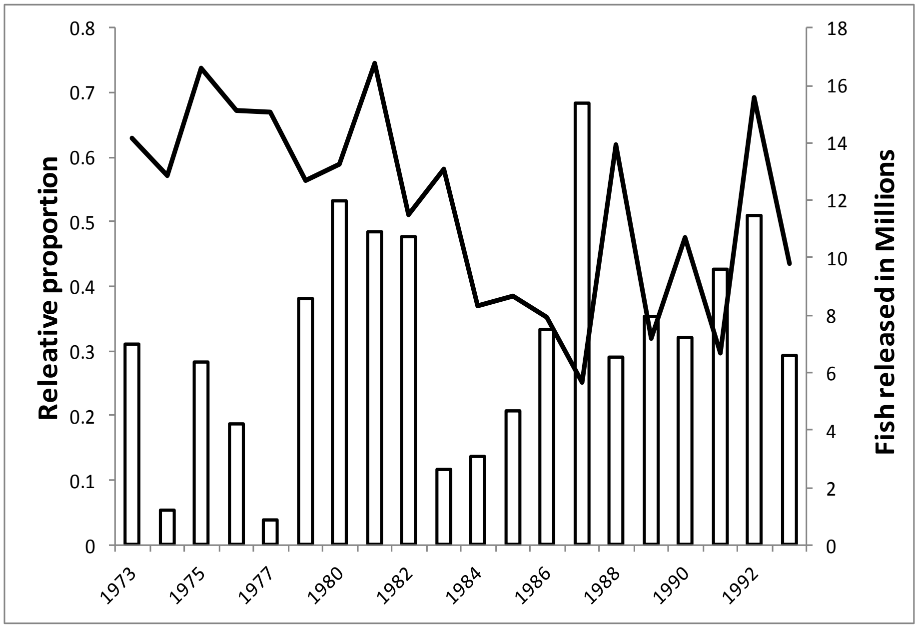


Figure 15.3. Relative proportion of resident: non-resident Chinook recoveries in Puget Sound recreational fishery (black line) and # of fish released (millions) between 1973-1993 based on CWT data.

Data Needs and Research Recommendations

- Determine proportions of populations that display residency . Perform an otolith microstructure/microchemistry analysis of known residents (capture location & month and contaminant evaluation as independent verification) vs. spawners. . Utilizing existing otolith samples, if available, and collect additional samples during the 5-year intensive monitoring effort to determine the proportion of residents over time and whether there is a correlation between the proportion of residents and marine survival. Determine hatchery vs wild contribution to residency and changes in proportions over time.
- Determine mechanisms driving resident behavior: Individual life history type, growth rates, outmigration location, environmental variation, etc.
- In conjunction with the efforts described in hypotheses 9, 11, 12, 13 and 14, include some level of adult sampling to evaluate behavior, diet, predation, toxic buildup, and disease in salmon, in particular Chinook and coho, identified as residents.

Cross-Referenced Hypotheses:

- Hypothesis 9. Harmful algae directly affect salmon survival through acute or chronic mortality and may adversely affect prey availability by food web impoverishment.
- Hypothesis 12d. Food supply is limited by competition within/among species of salmon & forage fish
- Hypothesis 13. Predation by larger fish and marine mammals has increased on salmon and steelhead, respectively. And, the potential effect of bird predation represents a significant knowledge gap.
- Hypothesis 14. Infectious and parasitic diseases are causing direct and indirect mortality.

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Hypothesis 6. Through a process known as the portfolio effect, diversity among salmonid populations confers temporal stability and long-term persistence of the species within the Salish Sea.

Kenneth Warheit, Washington Department of Fish and Wildlife

Background

Ecological systems work at a diversity of temporal and spatial scales, and units within these systems can form a nested hierarchical structure (Figure 1). Although each of the levels within this hierarchy may have emergent properties, the structure itself is formed as a collection of parts from a lower level of the hierarchy (e.g., individuals are collections of molecules, populations are collections of individuals, species are collections of populations, and so on). Ecological stability and persistence of a particular unit within the ecological hierarchy may depend on the diversity of that unit's component parts. For example, the major histocompatibility complex (MHC) is a multigene family that codes for a variety of immunological responses in vertebrates (Edwards and Hedrick 1998). Some MHC genes are among the most diverse functional genes in the vertebrate genome, and there is strong evidence that this diversity is maintained by pathogen-mediated balancing selection (Edwards and Hedrick 1998, Radwin et al. 2010). Individuals heterozygous at MHC loci may be more resistant to disease and have lower parasite loads than individuals without this diversity (but see Dionne et al. 2009). Populations that lack diversity at MHC genes will be ill-equipped to combat outbreaks of new diseases. Furthermore, since pathogens in one local area may be different from those in another area, populations may become locally adapted at their MHC genes (Eizaguirre and Lenz 2010). That is, based on individuals' relative resistance to pathogens, populations adapted to pathogens in one location may be maladapted to pathogens in another location.

The relationship between diversity and ecological stability has been studied most intensely at the ecological community level. For example, MacArthur (1955) showed theoretically that the number of interacting species (or the number of food web components) within an ecological community confers stability to that community. Tilman (1996) showed empirically that year-to-year variability in plant community biomass and ecosystem processes was lower in communities with high species richness. However, Tilman (1996) also showed that the composition of species does not need to be constant for species richness to remain high, and variability in community and ecosystem processes to remain low. Here, the decline in abundance of one species may be offset by the increase in abundance of a competing species. Therefore, it is the compensatory process and species richness (i.e., high diversity, not just high abundance) that provided community and ecosystem stability.

Tilman and others (Tilman et al. 1998, Lehman and Tilman 2000) developed further the concept of biodiversity and stability in ecological communities, and noted that the statistical averaging of abundances of the constituent species (as in the compensatory process above) dampens the relative fluctuations of species abundance across all species within a stable community. Lehman and Tilman (2000) referred to the stability that results from the statistical averaging of component parts (species) within a larger whole (communities) as the "portfolio effect," drawing parallels between ecological processes and the management of assets (stocks and bonds) within a financial investment portfolio. Figge (2004) and Koellner and Schmitz (2006) more formally linked the idea that biodiversity and stability of ecological units (Figure 1) to portfolio theory and the management of risk. Ecological systems are more stable and at lower risk when they are composed of a diversity of interacting component parts. That is, species richness and a diverse assemblage of species interactions are assets for ecological communities, just as a diverse portfolio of MHC genes is an asset for an individual or population.

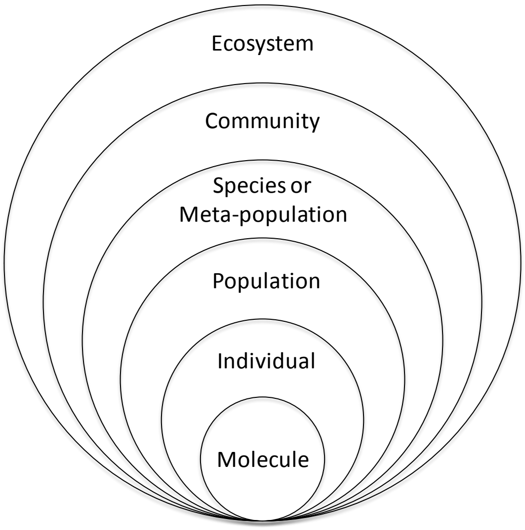

Figure 1. An example of a nested hierarchical structure of ecological systems.

Evidence Supporting the Hypothesis

Portfolio Effect and Salmonids: Salmonids show natal philopatry and will return (home) to natal streams to spawn (Quinn 2005). They also exhibit adaptation at a local scale (e.g., individual streams or rivers) (e.g., Taylor 1991, Quinn 2005). Homing and local adaptation can promote divergence among populations within a larger geographic area (e.g., Puget Sound), and this divergence can be revealed by an analysis of genetic markers (e.g., Hedrick 2000), or a survey of life history traits, phenotypes, or behaviors (Quinn 2005). The Bristol Bay sockeye complex provides a unique opportunity to study the portfolio effect: commercial fishery catch and escapement into specific river systems have been recorded for over 50 years (Hilborn et al. 2003), the behavioral, spatial, and life history diversity of the populations are well known (Quinn 2005, Habicht et al. 2007, Seeb et al. 2011, Gomez-Uchida et al. 2011), and the freshwater habitat is relatively unaltered by anthropogenic effects, including hatcheries. Greene et al. (2010) and Schindler et al. (2010) showed that within the Bristol Bay sockeye complex recruits per spawner and annual returns showed increasing stability with increasing life history (Greene et al. 2010) or spatial (Schindler et al. 2010) diversity, both affirming predictions drawn from the portfolio effect hypothesis. In fact, Schindler et al (2010) emphasized that the life history and genetic diversity among the Bristol Bay sockeye populations not only stabilized returns to the entire Bristol Bay sockeye complex, but was also responsible for low interannual variability in the commercial fishery over several decades.

Portfolio Effect and the Stability of Chinook salmon in Puget Sound: Greene et al. (2010) used a per cohort index of the age structure of freshwater and marine residency as measure life history diversity. Alternatively, Schindler et al. (2010) used a hierarchy of spawning geography, from individual streams, to larger rivers, and eventually to regional population complexes with the Bristol Bay area as a measure of population diversity. For their measures of meta-population stability, both Greene et al. (2010) and

Schindler et al. (2010) used population abundance; more specifically, recruits per spawner and annual adult return rates, respectively. For Puget Sound Chinook (*Oncorhynchus tshawytscha*) we can compile population-based information on some life history parameters such as freshwater residency, but it would be difficult to obtain sufficient data across all populations and time periods. Furthermore, our population abundance data (e.g., terminal run size) are greatly affected by hatchery operations. Hatchery operation policies and agreements control the number of hatchery plants, which to some degree controls the hatchery adult run size. Therefore, hatchery releases in systems with large-scale hatchery operations, as in most Puget Sound Chinook-bearing rivers, will bias the stability – diversity relationship. Therefore, without long time series for many populations from which we can measure diversity, and without an unbiased measure of meta-population stability we cannot explicitly test the portfolio effect hypothesis for Puget Sound Chinook. However, a corollary of the portfolio effect hypothesis is that a reduction in the diversity of the component parts puts the larger whole at risk. Here, a reduction in the diversity of Chinook populations may put the Puget Sound Chinook meta-population at risk of decline. In what follows, we explore the genetic diversity, adult run timing, and geographic structure of Chinook from 13 different river systems and hatcheries to determine if Puget Sound Chinook have experienced a reduction in diversity during the past several decades.

Puget Sound Chinook Genetic Diversity: We obtained genetic samples from 24 collections representing 13 different river system, and aggregated these collections into three groups: (1) Early Run, consisting of populations with spring or summer adult run timing, (2) Late Run – Green River ancestry (Late Run – GR), consisting of populations with late summer or fall adult run timing and whose ancestry is primary from the Green River (natural- and hatchery-origin individuals whose ancestry is from broodstock transfers from Soos Creek Hatchery, Green River), and (3) Late Run (Late Run – No GR), consisting of populations with late summer or fall adult run timing and whose ancestry is not from the Green River (Table 1, Figure 2). Except for the Samish River collection, the Late Run – GR aggregate is limited geographically to south Puget Sound and Hood Canal, while the Early Run aggregate is restricted to north Puget Sound (Figure 2).

Table 1. Collection locations and identity of samples used in this analysis. Under collection Source, H = hatchery- and N = natural-origin individuals

Collection	Collection Source	Watershed	Aggregate
NF_M_Nooksack	H	Nooksack River	Early Run
SF_Nooksack	N	Nooksack River	Early Run
SamishFall	H	Samish River	Late Run - GR
Marblemount_H_Sp	H	Skagit River	Early Run
U_Skagit_Su	N	Skagit River	Early Run
Suiattle_R	N	Skagit River	Early Run
U_Sauk_R_SpSu	N	Skagit River	Early Run
L_Skagit_R_Fa	N	Skagit River	Late Run - No GR
NF_Stillaguamish	H/N	Stillaguamish River	Early Run
SF_Stillaguamish	H/N	Stillaguamish River	Late Run - No GR
Skykomish_H_SU	H/N	Snohomish River	Early Run
Grovers_Cr_H	H	Grover's Creek	Late Run - GR
Issaquah_Cr_SuFa	H/N	Lake Washington Tributaries	Late Run - GR
Bear_Cr_SuFa	N	Lake Washington Tributaries	Late Run - No GR

UW_H_SuFa	H	Lake Washington	Late Run - No GR
Cedar_R_SuFa	N	Cedar River	Late Run - No GR
Soos_H	H	Green River	Late Run - GR
S_Prairie_Cr	H/N	Puyallup River	Late Run - GR
Nisqually_R_SuFa	N	Nisqually River	Late Run - GR
Clear_Cr_H	H	Nisqually River	Late Run - GR
SF_Skokomish_R	H/N	Skokomish River	Late Run - GR
NF_Skokomish_R_Fa	N	Skokomish River	Late Run - GR
GeorgeAdams_H	H	Skokomish River	Late Run - GR
Hamma_Hamma_R	N	Hamma Hamma River	Late Run - No GR

Geographic coordinates were set for each collection based on the physical location of each hatchery or the point in the river where the samples were obtained. If no collection location was provided, the geographic coordinate for that collection was estimated as some centrally placed reach along the river or stream. We calculated pairwise geographic distances between each collection using Google Earth Pro by tracing routes along rivers and through central corridors in Puget Sound.

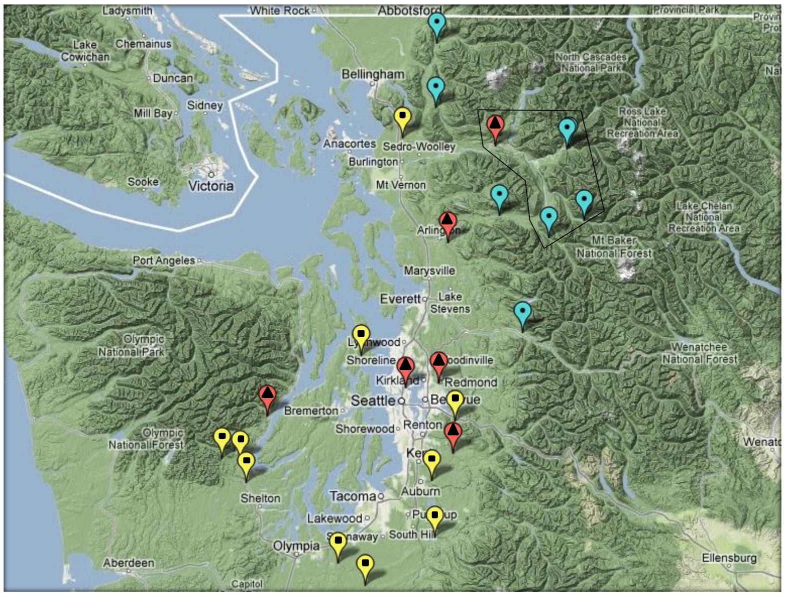

Figure 2. General locations for the 24 collections in Table 1. Yellow symbols with filled squares are Late Run – GR, red symbols with filled triangles are Late Run – No GR, and blue symbols with filled circles are Early Run collections. Polygon encloses the five Skagit River collections (Upper Skagit and Marblemount collections are nearly superimposed in the upper right of the polygon).

We genotyped all samples using 68 single nucleotide polymorphism (SNP) loci, summarized data as population allele frequencies, and subjected the frequencies to a principal component analysis. We generated genetic distances among all pairwise populations based on the Euclidian distances between pairs of populations across the first four principal components, which were the only components with significantly stable coefficients across 1000 bootstrap runs.

Three patterns are evident when we plot pairwise genetic distances against pairwise geographic distances (Figure 3). First, along the geographic distance range, the genetic distances between Early Run populations were greater than those between Late Run – GR populations. Second, on average, genetic distances increased with geographic distances for Early Run populations, but genetic distances remained relatively constant and low for Late Run – GR populations. Third, the distribution of Late Run – No GR populations resembles a combination of the Early Run and Late Run – GR populations, and their genetic distances are generally greater than the genetic distances between Late Run – GR populations.

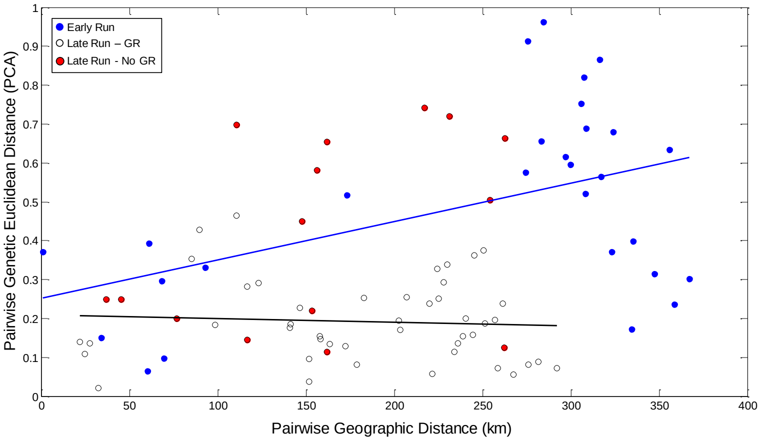

Figure 3. Within-aggregate pairwise comparisons of geographic and genetic distances. Blue and black lines are the least squares regressions for the Early Run and Late Run – GR comparisons, respectively.

We compared the pairwise genetic distances among the populations within a single large watershed (Skagit River; Table 1 and Figure 2) with the pairwise genetic distances among the populations with the Late Run – GR aggregate. Despite covering nearly four times the linear geographic distance the genetic diversity among the Late Run – GR populations was significantly less than the genetic diversity among the populations within the Skagit River watershed, although there were no differences in the genetic diversity (i.e., expected heterozygosity) within each of these populations (Figure 4).

Although the Late Run – GR aggregate is genetically less diverse than the Early Run aggregate (Figure 3) and among the populations within the Skagit River watershed (Figure 4), its abundance has increased relative to the Early Run abundance, from 1975 through 2010 (Figure 5). The increase in relative abundance of the Late Run – GR populations appears to be fueled only by the hatchery-origin component of these populations (Figure 6). From 1975 through 2010 the Chinook meta-population within Puget Sound has been transformed from a balanced mix of north and south populations with varying run timing to a system that is now dominated by late run hatchery-origin individuals from a single ancestral lineage (Green River). In other words, during the past 35 years Puget Sound Chinook salmon have experienced an overall decrease in genetic and run time diversity. [See also Ruckelshaus et al. (2006) for putative extinction of early run populations from south Puget Sound and Hood Canal; and Rice et al. (2011) for broader seasonal distributions of density for unmarked (natural-origin) northern

Puget Sound juvenile fish compared with marked (hatchery-origin) juveniles throughout Puget Sound and unmarked juveniles from central and southern Puget Sound]. In Puget Sound, the decline in among-population diversity associated with hatchery operations is not limited to Chinook salmon. Eldridge et al. (2009) showed a decline in the genetic distances among Puget Sound coho (*Oncorhynchus kisutch*) populations that were subjected to hatchery operations and translocations. In addition, Chambers Creek hatchery steelhead (*O. mykiss*) have been propagated throughout western Washington State, including Puget Sound (Scott and Gill 2008), although a detailed analysis of hatchery-origin effects has not been completed (WDFW, in progress).

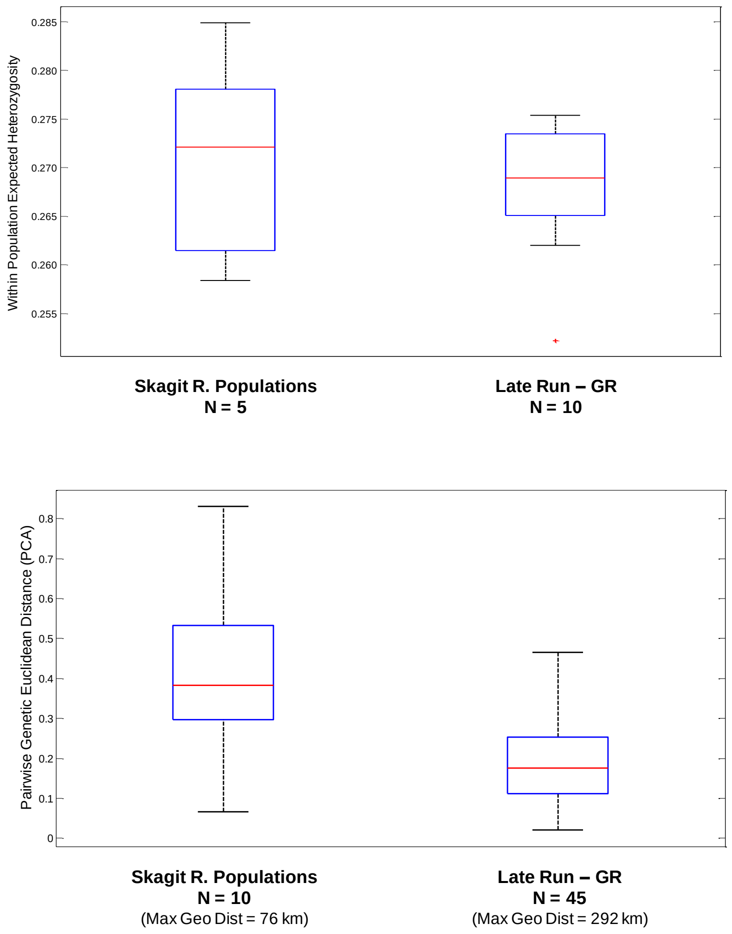

Figure 4. Within-population genetic diversity (measured as expected heterozygosity; top panel) and pairwise genetic distances (bottom panel) for the five populations within the Skagit River (Figure 2) and the Late Run – GR populations. Center red line within each box is the median value, top and bottom of the boxes are 75 and 25 percentile, respectively, and top and bottom "whiskers" are the 99 and 1 percentile, respectively. Red pluses are the outliers.

At the population and meta-population levels, the portfolio effect hypothesis predicts a decline in the stability of the Chinook meta-population in Puget Sound. Furthermore, extending the hypothesis to the molecular – individual and population levels, and if low MHC diversity can be predicted from the homogenizing effects of Green River hatchery plants, and the loss of mate choice in hatchery broodstock, reduced MHC diversity may be associated with a decline in individuals' relative resistance to pathogens and lower reproductive success, putting populations at an increase risk to declines associated with new epidemics (Evans et al. 2011; see also Miller et al. 2011).

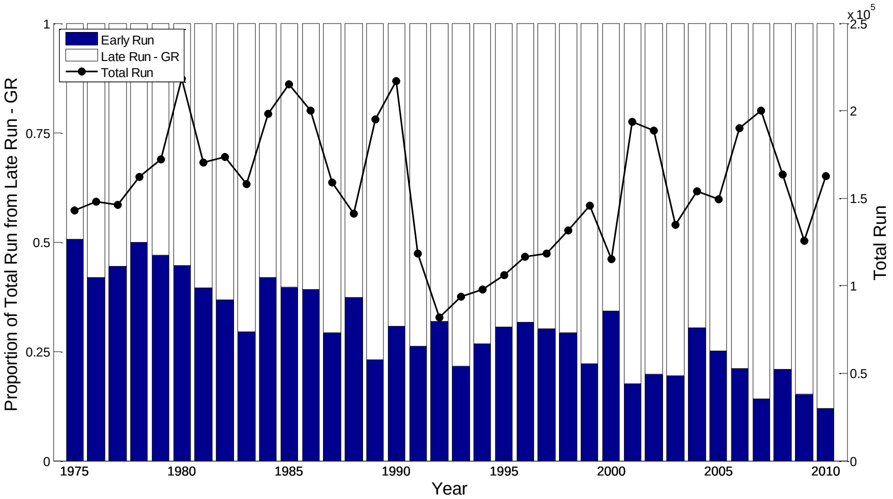

Figure 5. The proportion of the total run that was composed of Early Run and Late – GR populations (bar plot, left y-axis), and total run size (line plot, right y-axis) for years 1975 through 2010. Total run is defined as all fish entering freshwater prior to freshwater fisheries. Early Run includes Nooksack, Skagit, Stillaguamish, and Snohomish Rivers, and aggregates the Lower Skagit and SF Stillaguamish (Late Run – No GR) within the Skagit and Stillaguamish Rivers, respectively. Late Run – GR includes Lake Washington tributaries (Bear Creek [Late Run – No GR] and Issaquah Creek Hatchery), and Samish, Green, Puyallup, Nisqually, and Skokomish Rivers. The total run into all Puget Sound freshwater is composed of roughly 75% of the total run from the populations included here.

Data Needs and Research Recommendations

In the absence of parallel long-term data sets describing life history or geographic diversity of populations, and overall stability of a species or meta-population in the Salish Sea, it will be difficult to ascribe change in salmonid abundances to the portfolio effect. However, our current inability to test for the portfolio effect does not negate the importance of establishing baselines and monitoring diversity among salmonid populations. It is the diverse portfolio that drives health and stability, and a monoculture of genes (for individuals) or populations (for meta-populations) will place individuals at risk of death and populations, meta-populations, or species at risk of extinction. We know too little about the portfolios of salmon and steelhead populations in the Salish Sea, putting us at a disadvantage to better understand why some species and populations thrive and others, despite management efforts, do not recover, or continue to decline.

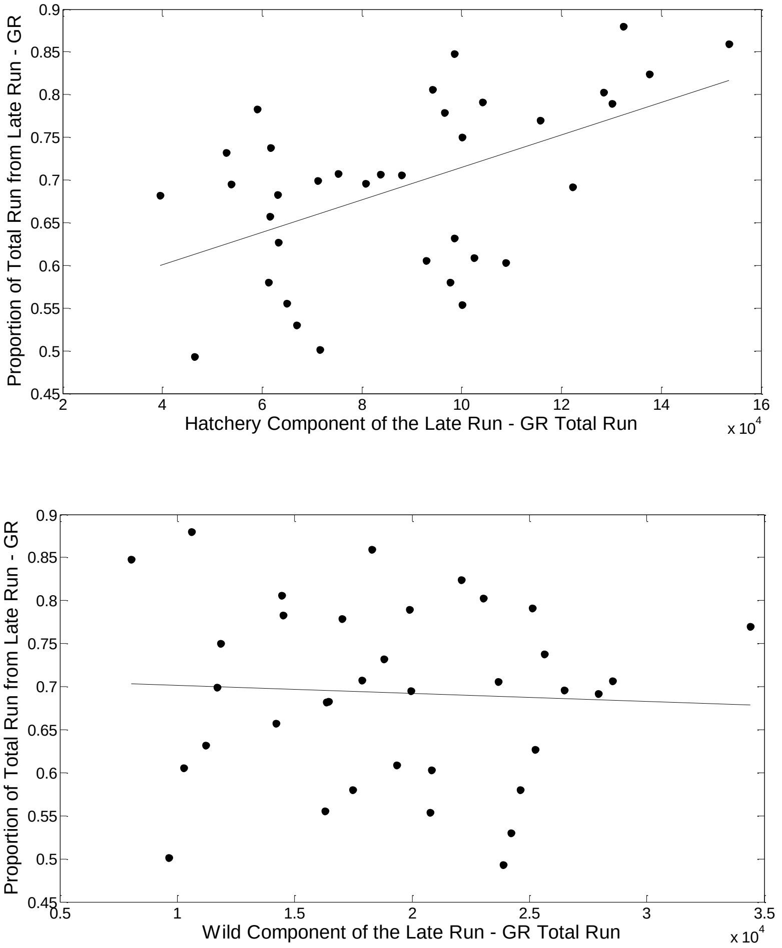

Figure 6. The Late Run – GR proportion of the total run (from Figure 5) as a function of either the hatchery (top panel) or wild (lower panel) component of the Late Run – GR total run.

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Hypothesis 7. Circulation and bottom-up processes hypothesis: Changes in circulation and water properties have altered phytoplankton and zooplankton production in ways that degraded salmon food-webs in the Salish Sea from the 1970s to 2000s.

Nate Mantua, University of Washington, Aquatic and Fisheries Sciences
Neil Banas, Julie Keister, and Parker MacCready; University of Washington, Oceanography
Jan Newton, University of Washington, Oceanography

Background

This hypothesis states that trends and variations in Salish Sea circulation and water properties affect Salish Sea salmon marine survival through bottom-up processes. These bottom up processes may include physically forced variations in the timing and species composition of the spring phytoplankton bloom and/or changes in zooplankton development cycles in ways that lead to a mismatch between forage production cycles and smolt migration timing, and/or changes in the amount of high-quality prey at key times of the early marine life history that result in changes in salmon marine survival.

Several lines of evidence demonstrate trends and/or variations in environmental conditions and/or changes in juvenile salmon food supplies in the Salish Sea. This evidence includes:

- Warming water temperatures in the Salish Sea from the 1920s to present, along with large year-to-year variations and 20 to 30 year periods of relatively warm (1920s-1940s, 1980s-2011) and cool conditions (1950s to 1970s)
- A shift to an earlier and briefer growing season by the copepod *Neocalanus plumchrus* that has been ongoing since the 1970s in the Strait of Georgia that appears to be related to warming trends. This copepod had historically been the dominant component of the Strait of Georgia zooplankton biomass in April and May, but now reaches its annual peak well before most juvenile coho, Chinook and sockeye salmon enter the Strait of Georgia (note that data required to evaluate similar trends in the growing season for Puget Sound copepods are not available).

Salish Sea Circulation Basics

The Salish Sea is composed of multiple estuarine basins with a layer of relatively fresh water flowing toward the ocean, and a deep layer of primarily oceanic water flowing landward. The flow referred to here is the tidally-averaged or “subtidal” current. The tidal currents are faster, but it is the subtidal currents that persistently move water through the sub-basins and which control the residence time. This “estuarine circulation” is consistently present throughout the year and is unlikely to be significantly disrupted in different years, though its timing and intensity do show interannual variation. Subtidal currents exert a dominant control on the residence time of the system because these are much larger than the river flows. For example, the exchange flow at Admiralty Inlet is about 30 x 10^3 m^3 s^{-1}, thirty times larger than the average of all the rivers flowing into Puget Sound (Sutherland et al. 2011 and references therein). It also dominates the biogeochemical function of the system because the water flowing in at the mouth of the Strait of Juan de Fuca, sourced near the shelf break at 200 m in the NE Pacific, is the largest source of nutrients such as nitrate into the inland waters. Conceptually the ecosystem in the Salish Sea is relatively isolated from that on the coast. The reason is that the primary production within it occurs in the surface layers, which on average are flowing out of the system.

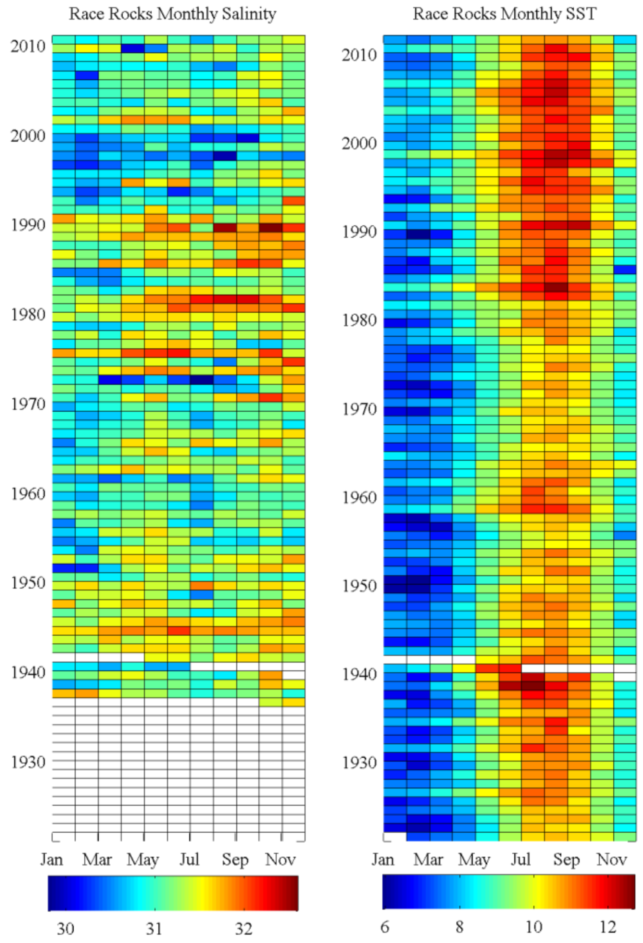
The role of boundary conditions in driving Salish Sea circulation variations has been explored by Babson et al. (2006) and Moore et al. (2008). The ocean, direct atmospheric forcing, and freshwater runoff from the land all play a role. Babson et al. (2006) found that variations in salinity of the deep ocean source water, though not large, were the dominant control on Puget Sound salinity. Moore et al. (2008) found that local weather conditions played a larger role in controlling surface water temperature than did any of the global climate patterns examined (ENSO, PDO, NPGO). There are known to be large inter-annual variations in the degree of bottom water hypoxia in Hood Canal, a site of observed fish kills. Newton (2005) attributes this to the specific weather of different years, especially when it allowed an early spring bloom of phytoplankton in the surface waters.

Stratification and phytoplankton blooms

The role of river input is also important, however, because of its effect on Salish Sea density stratification. While external salinities may be more important to driving residence time, the freshwater influence from rivers affects stratification in measurable ways (Newton et al., 2003). During the 2000-2001 drought, the percent change in stratification varied throughout the Puget Sound region, ranging from no effect (~0%) in the well–mixed channels at Admiralty Inlet and Dana Passage to nearly 75% in Budd Inlet and Commencement Bay. The mean reduction in stratification at these stations was 56%.

Stratification intensity, timing, and depth of the pycnocline, all related to this effect, are all factors in the timing of phytoplankton blooms. This is because the timing of phytoplankton blooms is known to be influenced by the depth of the mixed layer relative to where net community photosynthesis is positive. If cells are mixed out of the euphotic zone, photosynthesis cannot occur and the population growth rate is not large enough to result in a bloom. The onset of sufficient stratification with enough light to fuel a bloom regulates the timing of the bloom. Implications for match or mis–match of phytoplankton blooms with zooplankton and other heterotrophs' emergence could influence biota recruitment success and trophic transfer (Cushing, 1990; Cushing and Horwood, 1994).

Figure 1: Monthly averages of the observed daily high-tide bucket samples for (left) salinity and (right) water temperature at the Race Rocks lighthouse in the Strait of Juan de Fuca.



Supporting Evidence

Multidecadal variations and century long trends in temperature

There are only a handful of sustained, multidecadal time series of properties for Puget Sound water properties that serve as indicators for circulation trends and variations in Puget Sound. Daily daytime high tide bucket samples for surface water temperature and salinity at Race Rocks provides one continuous set of observations that date back to the early 20th century (see Figure 1). These records indicate multidecadal variations in surface temperatures, some extremely warm years that coincide with tropical El Niño events in the early 1940s, 1958, 1983, and 1998, and a near century-long warming trend. Salinity variations and trends at Race Rocks are not well correlated with those for temperature, and show a period with mostly above average salinity from the late 1970s through the 1980s, mostly low salinity in the 1990s, and then a period of mostly intermediate salinity in the 2000s.

Moore et al (2008) showed that the temperature and salinity at Race Rocks is well correlated with the leading pattern of seasonal to interannual variations in Puget Sound salinity and temperature, respectively, as observed in the once-monthly water column profile data from the Washington Department of Ecology.

Warming trends at Race Rocks parallel trends in observed surface air temperatures from locations around the Puget Sound lowlands, while salinity variations are correlated with variations in freshwater discharge in Puget Sound rivers in winter, and correlated with the strength of coastal winds that drive upwelling in summer (Moore et al. 2008).

Masson and Cummins (2007) documented warming trends through the entire water column at a site in the Strait of Georgia over the period 1970–2005 that were coherent with large-scale climate forcing and water temperature trends in the NE Pacific Ocean west of Vancouver Island (Figure 2). Like the Race Rocks surface temperature record, water temperatures in the Strait of Georgia were predominantly warmer than average in the 1980s through early 2000s. Strong coherence between surface and deep-water temperature anomalies is a prominent and interesting feature of the Nanoose Bay record, likely caused by the intense mixing driven by tidal currents in Haro Strait. By removing the linear trends from the temperature data, residual temperature anomalies highlight short-term extremes that are sometimes associated with tropical El Niño and La Niña events, and sometimes associated with more local/regional atmospheric forcing (Figure 2b).

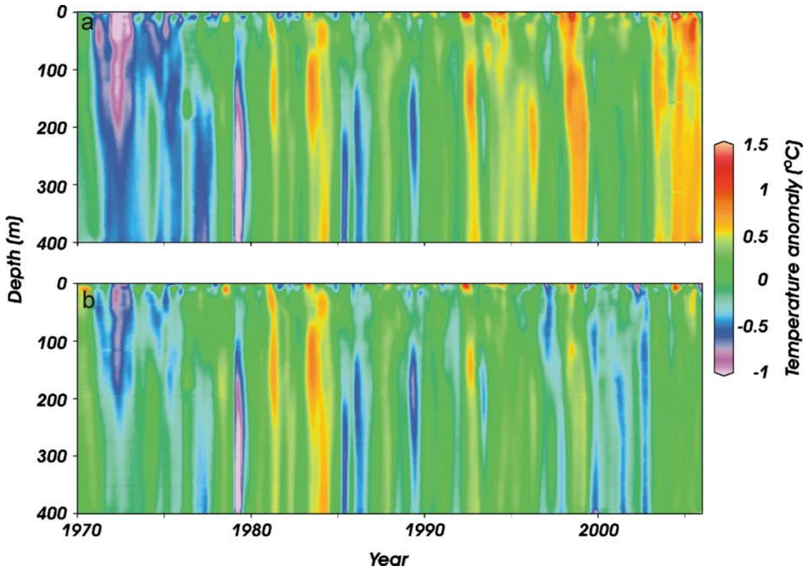


Figure 2: (a) Temperature anomalies measured at the Nanoose station in the Strait of Georgia, and (b) the anomalies with the secular trend removed at each depth level. Figure reproduced from Masson and Cummins (2007).

Large scale climate forcing and its variability through time

The Aleutian Low atmospheric pressure cell is the most prominent atmospheric driver of climate variability in the NE Pacific and Pacific Northwest. Major changes in the intensity of the Aleutian Low over the North Pacific were associated with the 1976-77 climate shift that saw a persistently more intense Aleutian Low and a stronger counterclockwise surface wind circulation in the decade after 1976 compared with the decade prior (Trenberth 1990; Trenberth and Hurrell 1994). In the period between 1989 and 2011 the intensity of the Aleutian Low and associated counterclockwise winds over the North Pacific have, on average, been weaker than they were in the 1980s, with substantial year-to-year variability in the 1990-2011 period (Figure 3).

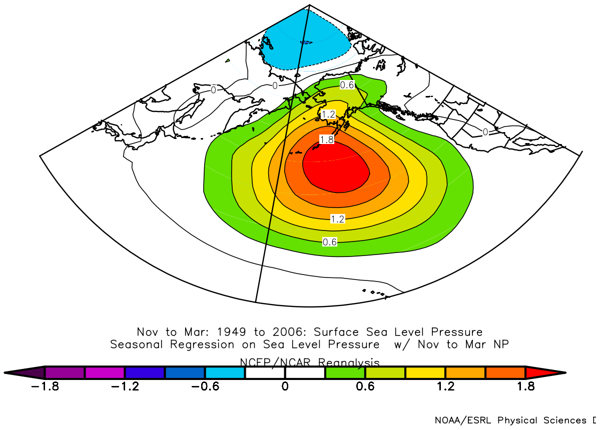
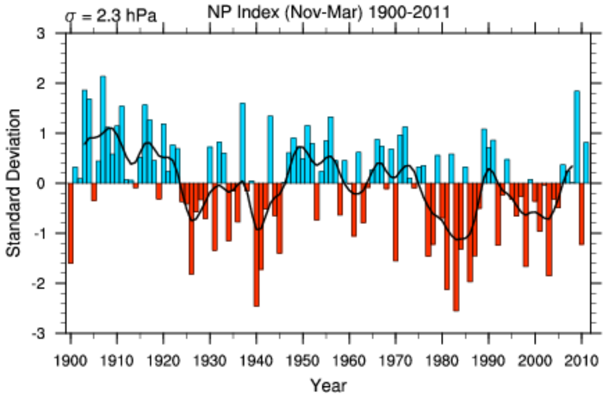


Figure 3: (Top) Spatial pattern of Aleutian Low sea level pressure variations tracked by the “North Pacific” (NP) index of Trenberth and Hurrell (1994) (image created using NOAA’s online plotting tool at http://www.esrl.noaa.gov/psd/data/correlation/.



(bottom) Time series of the Nov-Mar NP index from 1900-2011. Figure obtained from

http://www.cgd.ucar.edu/cas/jhurrell/indices.info.html#np.

Substantial fractions of the interannual to interdecadal variability in the climate of the Pacific Northwest and the oceanography of the NE Pacific Ocean and Salish Sea are related to three large-scale patterns of climate variability: El Niño-Southern Oscillation (ENSO), the Pacific (inter)Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO).

ENSO is Earth’s dominant source of year-to-year climate variations (Rasmussen and Wallace 1983). This phenomenon is understood to be a natural part of climate that spontaneously arises from interactions between tropical trade winds and ocean surface temperatures and currents near the equator in the Pacific. While the essential physics of ENSO are thought to be contained within the tropical Pacific sector, ENSO variations exert especially strong impacts on the northeast Pacific Ocean through atmospheric teleconnections that influence the strength and location of the Aleutian Low, primarily from October through March (Alexander et al. 2002), and through oceanic teleconnections that involve coastally trapped internal waves that can influence the depth of the pycnocline, nearshore currents, and coastal sea levels (Parres Sierra and O’Brien 1989). During warm phases of ENSO, coastal SSTs in the northeast Pacific Ocean and in the Salish Sea are typically warmer than average, while the cool ENSO phase is associated with cooler SSTs in the Salish Sea and northeast Pacific Ocean. ENSO variations are most prominent at periods of 2 to 7 years (Figure 4).

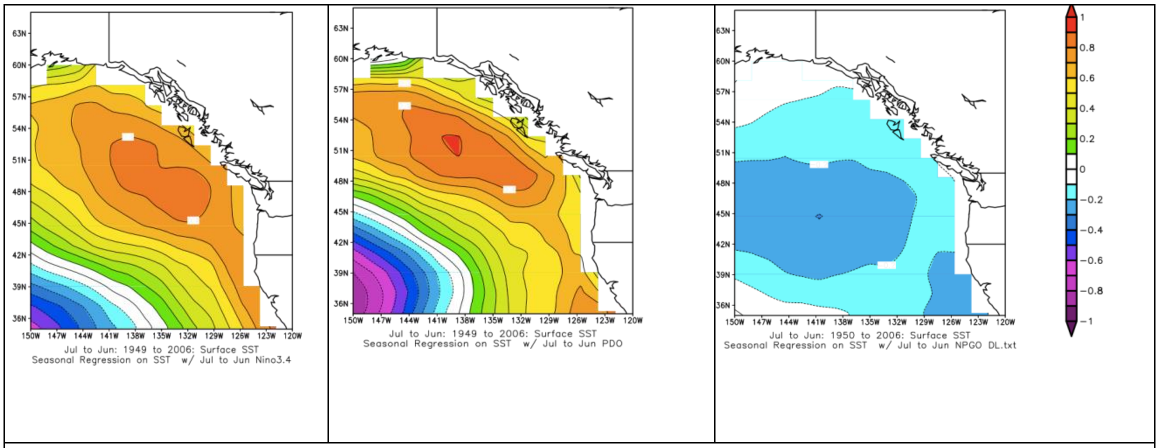


Figure 4: Patterns of SST variability associated with positive phases of the ENSO (left), PDO (middle), and NPGO (right) created by regressing July-June averages of gridded SST fields onto each of the 3 climate indices, respectively. Shading depicts the pattern of temperature change (in °C) associated with a +1 standard deviation value of the indicated climate index. Time series plotted in the lower panels show the standardized monthly index values for each of the large-scale climate patterns over the 1950-2010 period. Maps were generated with NOAA's Earth System Library Research tool at http://www.esrl.noaa.gov/psd/data/correlation/

The PDO is defined as the leading pattern of monthly North Pacific sea surface temperature (SST) variations over the 20th century, wherein periods with cooler-than-average SSTs in the central and western North Pacific Ocean tend to occur with warmer-than-average SSTs in the northeast Pacific Ocean, and vice-versa (Figure 4)(Mantua et al. 1997). This pattern is closely associated with the leading pattern of variability in monthly sea surface height in the northeast Pacific Ocean (Cummins et al. 2005). The PDO has been characterized as an ENSO-like pattern of Pacific climate variability that tends to vary over multiple years and decades, and its variability is closely associated with the interannual and interdecadal variability of the Aleutian Low (Zhang et al. 1997). There appears to be no timescale for PDO variations that predominates, but it has most of its variability at decadal to interdecadal time scales. PDO variations are thought to be a consequence of atmospheric forcing on the north Pacific Ocean caused by the random and intrinsic variability of the Aleutian Low in combination with more systematic atmospheric and oceanic teleconnections related to ENSO (Newman et al. 2003; Schneider and Cornuelle 2005). During warm phases of the PDO, SSTs in the NE Pacific and Salish Sea tend to be warmer than average, whereas cool PDO phases have cooler SSTs (Figure 4).

The NPGO is defined as the 2nd-most dominant pattern of sea-surface height and SST variations in the northeast Pacific Ocean, and is well correlated with variations in salinity, nutrients, and chlorophyll-a measured in long-term observations in the California

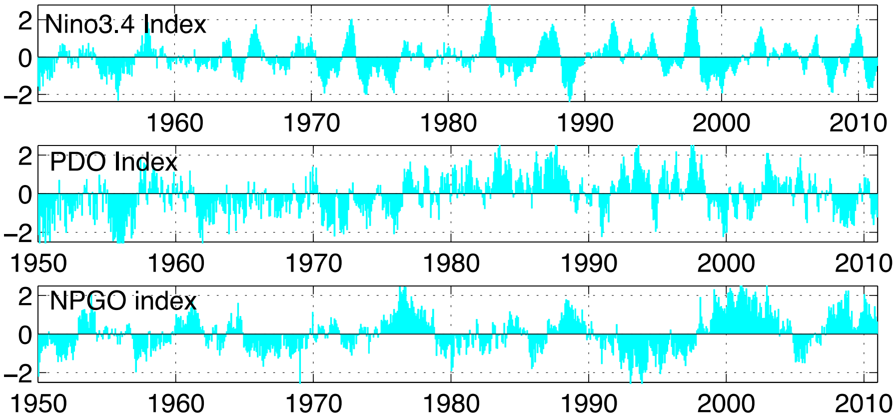


Figure 4: Monthly indices for ENSO (the Nino3.4 index), the PDO, and the NPGO, from 1950-2010.

Current System and Gulf of Alaska along Line-P (DiLorenzo et al. 2008). Variability in the NPGO pattern exhibits a near decadal time scale and has been related to intrinsic variability in atmospheric forcing over the North Pacific (Chhak et al. 2009). Recent research suggests that so-called “central Pacific” El Niño events are linked with atmospheric teleconnections to the NPGO (Di Lorenzo et al 2010). During positive phases of the NPGO, SSTs near Canada’s west coast tend to be cooler than average, and negative phases are warmer (Figure 3).

In the historical record from 1900-2010 the PDO pattern varied across periods ranging from interannual to interdecadal, with a tendency for elevated variance at periods of 15-to-25 and 50-to-70 years, but had no distinct periodicities (Minobe, 1999). Paleoclimate reconstructions for PDO behavior over the past few centuries find sustained interannual to interdecadal variability across a range of timescales, with no fixed bands of preferred periodicities. Monthly indices for ENSO, the PDO, and NPGO highlight the different time scales of variations associated with these 3 phenomena (Figure 4). ENSO variability is most prominent at periods ranging from 2 to 8 years. The PDO pattern varies at timescales ranging from interannual to multidecadal. The NPGO pattern tends to vary at periods around 10 years.

Di Lorenzo et al. (2010) showed that decadal fluctuations in the NPGO are characterized by a pattern of SST anomalies that resemble the central Pacific warming (CPW) pattern of recent El Niño events.

Data Needs

Historical observations for the physical and chemical properties of Puget Sound are relatively scarce, and historical observations for phytoplankton and zooplankton are even less available. However, there are some historical observations taken over limited time periods, like the Collias data set, that can be used for this purpose. More recently, the deployment and sustained operation of ORCA profiling buoys at multiple locations in Puget Sound now provides continuous time series of water column observations that include flourometers for estimating chlorophyll concentrations and the standing stock of phytoplankton.

Research Recommendations

- Conduct retrospective analyses of density stratification documented in the Collias reports from 1952-1966 Puget Sound surveys; compare observations from 1952-1966 period with those from ORCA buoys from 2005-present; also compare with Department of Ecology monthly survey data to determine if monthly sampling is adequate for documenting seasonal interannual and longer timescale trends and variations in Puget Sound properties.
- Use existing ORCA records to conduct analyses of phytoplankton production rates, timing, and variability to assess interannual and inter basin variation.
- Use existing ORCA records to quantify the apparent connection between chlorophyll and stratification in the different basins of Puget Sound. If the connection is meaningful then stratification may be a useful proxy for primary production. Stratification has more historical data than chlorophyll, and its modeling in future scenarios is more robust.
- Expand the ORCA buoy network to more sites, and sustain observations for at least 5 years in order to increase sample sizes and document spatial and temporal variability in primary production and hydrographic features (water column temperatures, salinity, density structure, nutrients, mixed layer depths, and stratification). This should be done at the same time as the intensive fish monitoring effort described in this report, and the network should appropriately represent each of the Puget Sound sub-basins described in Figure 12 on page 20. The locations of the existing ORCAS buoys are in Figure 15, on page 49 in the main body of this report.
- Add sensors for photosynthetically active radiation (PAR) to all buoys.
- Develop a zooplankton and forage fish monitoring program that can be implemented and sustained over multiple years in order to characterize the space-time zooplankton and forage fish production cycles and their seasonal and nonseasonal variability within and between years. Then link salmon performance and abundance measures to measures of zooplankton and forage fish abundance and community composition in the way NOAA's Northwest Fishery Science Center has done for the OR/WA coast.
- Develop empirically based models for understanding and predicting the spring phytoplankton bloom; well validated models could then be used to both hindcast and forecast spring bloom dates using historical and predicted environmental data. Incorporate the zooplankton monitoring data to make the association between phytoplankton and zooplankton production and improve ecosystem modeling so that it can produce zooplankton hindcasts and forecasts

Management Implications

The following is a list of conceptual strategies that could be applied in response to the research results if the hypothesis was found to be correct.

- Improved monitoring of key environmental indicators (like freshwater runoff and boundary salinity) and ecosystem indicators (like zooplankton and/or forage fish) could provide an early warning system for changes in salmon productivity (and productivity for other higher level predators).
- Hatchery operations could be altered to better match smolt production *numbers* or *release timing* to expected timing or baseline levels of primary and secondary productivity that may be necessary for increasing smolt-to-adult survival rates.

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Hypothesis 8. Increased C02 concentrations indirectly affect salmon survival or increase their susceptibility to other sources of mortality

Michael Schmidt, Long Live the Kings
Paul McElhany, NOAA Northwest Fisheries Science Center
Julie Keister, University of Washington, Oceanography

H-8_A (Indirect) Ocean acidification affects the productivity or nutrition quality of important zooplankton invertebrate prey for salmon (and forage fish).

H-8_B (Increase susceptibility) Increased CO_2 concentrations affect the nervous system and behavior of salmon and steelhead or affect growth.

H-8_C (Indirect) Elevated CO_2 concentrations alone and combined with increased temperatures are promoting *Heterosigma* growth, which can affect salmon survival.

H-8_D (Indirect) Synergistic responses to elevated CO_2/low pH concentrations combined with low oxygen, warming, and eutrophication can occur, as well as the combined effects of ocean acidification and toxics.

Relevant Species of Salmon and Steelhead

Chinook, coho, chum, pink, and sockeye salmon and steelhead could all be affected, with the greater impact potentially being on those who reside longer in the Puget Sound environment or whose diet depends on species directly vulnerable to ocean acidification.

Supporting/Refuting Evidence

As a deep, semi-enclosed estuary in an urbanized area, the properties of Puget Sound, including restricted circulation, incursion of upwelled waters, and lower pH river inputs, put it at high risk of impacts from ocean acidification. (Feely et al 2010)—the ongoing decrease in the pH of the Earth's oceans, caused by the uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere (Calderia et al. 2003). The current patterns of low pH are largely a result of natural mixing, circulation, and biological processes. Ocean acidification is playing a smaller but important role of further lowering the pH, accounting for an estimated 24-49% of the pH decrease in the deep waters of the Hood Canal sub-basin of Puget Sound relative to estimated pre-industrial values (Feely et al 2010). However, over the next several decades, ocean acidification could become the dominant process for lowering the pH, accounting for 49%-82% of the pH decrease in subsurface waters for a doubling of atmospheric CO_2 (Feely et al 2010).

As the Puget Sound system is still dominated by natural processes, it is likely that ocean acidification has not altered the local environment significantly enough to be considered a contributor to recent declines in salmon marine survival. However, data are not sufficient for a quantitative analysis of the relationship between local pH changes and changes in salmon survival, especially in the context of all the other co-factors that affect salmon survival. Although there is uncertainty about any role of pH in

recent marine survivals, there are concerns about future impacts given the predicted trajectory for atmospheric CO_2, and long-term local trends in seawater pH. Slightly to the north in Vancouver Harbor, Strait of Georgia, but still within the Salish Sea, long-term records indicate a decrease in pH since the late 1970's from a mode of 7.9 to 7.6 in 2010, and a significant increase in within-year variability, from 7.9-8.0 to 7.3-7.9 (Marliave et al. 2011) (Figure 1). Although not completely illustrated on the figure below, variability in pH from 1954-1974 ranged from 7.8-8.1.[25] Recent work in Puget Sound indicate the pH levels below 7.6 are also common in the summer (Feely et. al. 2010), and pH conditions are highly variable[26].

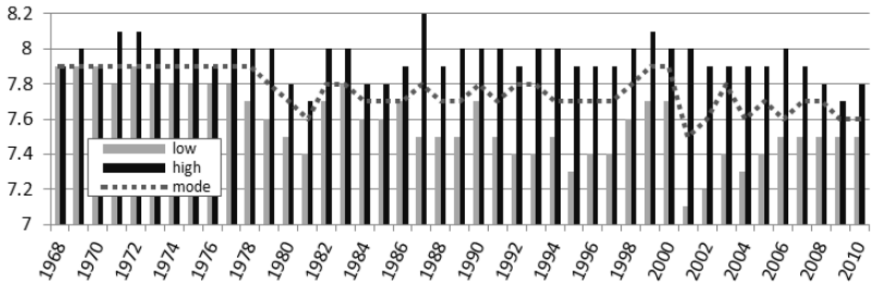

Figure 1. Modal pH and extreme range (min 5 measures for low or high value) for Vancouver Harbor from 1968-2010 (Marliave et al. 2011).

Increased concentrations of CO_2 in the marine environment impede the calcification, shell-forming process many marine organisms depend upon to survive. While, locally, the shellfish industry is under the greatest apparent threat, calciferous invertebrates that are prey to salmon and to the forage fish that salmon depend upon also may be at risk. Calcification isn't the only concern. CO_2 changes can also influence the physiology of any marine organism by changing its internal acid-base balance—leading to changes in protein synthesis, growth, and development—and reduced oxygen transport capacity (Fabry et al. 2008, Portner et al.). Salmon and forage fish invertebrate prey that have low metabolic rates such as amphipods and euphausiids are deemed susceptible to these impacts (Fabry et al. 2008), as are pteropods (Busch et al. in prep). Based upon the history of salmon and herring diet analyses done in Puget Sound, the invertebrates of greatest importance, and thusly of greatest concern, are gammarid amphipods, harpacticoid and calanoid copepods, euphausiids, and decapod larvae (see appendix C).

Direct impacts of increased CO_2 on salmon and forage fish may also be a concern. Recent studies of reef fish exposed to increased CO_2 concentrations in their larval stages have shown behavioral and olfactory sensory abnormalities (Nilsson et al. 2012). Similar studies have not been performed on salmon or forage fish species such as herring. Also, elevated CO_2 concentrations alone and combined with increased temperatures promote *Heterosigma* growth (Fu et. al. 2008), a harmful algae common to the Salish Sea that has been associated with salmon mortality (see hypothesis 9 in this report). Finally, in general, a better understanding of synergistic responses to elevated CO_2 concentrations combined with low oxygen, warming, and eutrophication is a significant concern (Feely et. al. 2010), as well as the

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[25] The data in this paragraph is based upon sweater records taken by Vancouver Aquarium from 1954-present.

[26]

combined effects of ocean acidification and toxics. For example, lowering pH affects the speciation of copper, which can lead to increase and in in more toxic forms (Millero et al. 2009).

It is important to note that estimates of species risk from ocean acidification are based on projections from laboratory exposure experiments showing response to elevated pCO_2. With the possible exception of Pacific oysters, studies have not shown changes in wild abundance for any species as a direct consequence of changes in ocean chemistry from anthropogenic CO_2. The decrease in ocean pH from anthropogenic CO_2 is well documented and the change in future pH from projected carbon emissions is well understood. However, the biological response to these changes is much less clear. The extremely rapid pace of change in ocean pH and the susceptibility of wide variety of taxa to changes in ocean carbon chemistry suggest that while the precise effects of ocean acidification on the salmon ecosystem are uncertain, the effects could be substantial.

Hypothesis 8_A Ocean acidification affects the productivity of important zooplankton invertebrate prey for salmon (and forage fish).

Few studies have been conducted on the impacts of ocean acidification on zooplankton. While zooplankton have shown impacts to development and reproductive success, the results have been mixed and impacts are most frequently apparent at pCO_2 levels above the range proposed for future global CO_2 scenarios (PICES 2011, Kawaguchi et al. 2010, Nicol 2008 newsletter, Dupont & Thorndyke 2009, Kurihara et al. 2004, Kurihara & Ishimatsu 2008, Watanabe et al. 2006). However, these studies tested zooplankton in response to elevated but constant pCO_2 levels (reflecting global averages) and not the highly variable pH/pCO_2 environment inherent to coastal ecosystems and zooplankton behavior. pH/pCO_2 concentrations are not only variable overtime in the Puget Sound/Salish Sea environment as described above. Large vertical gradients in pH and pCO_2 also occur across the thermocline in stratified areas (e.g. see figure 2), so vertical movement of organisms can lead to large variation in the pH conditions they experience.

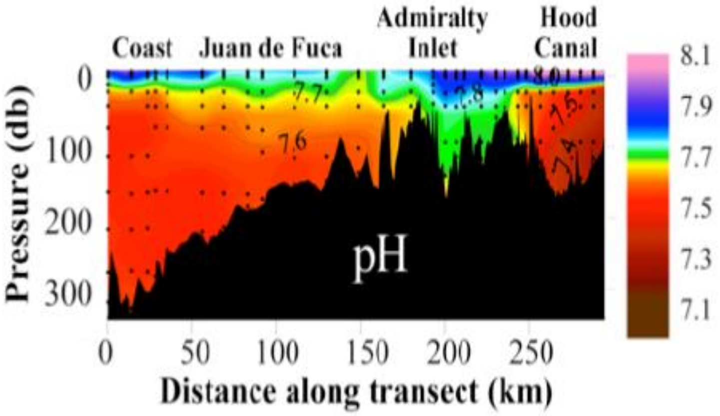

Figure 2. pH along a transect in Puget Sound from the WA coast (left) through Hood Canal (right), August 2008. Very low pH water (<7.5) occurred below 50m depth in Hood Canal [from Feely et. al. 2010]

Beyond direct affects to zooplankton, the association between impacts to zooplankton and affects on salmon and steelhead has not been well studied. For example, Aydin found that a 10% decline in pteropod production can lead to a 20% reduction in the body weight of mature pink salmon (as cited in Fabry et. al. 2008). Studying changes to prey quality and quantity and their associated impact will likely occur elsewhere as part of this study (see hypotheses 7 and 12), however, associations back to ocean acidification could be made via modeling exercises (see research recommendations, below).

Hypothesis 8_B Increased CO2 concentrations affect the nervous system and behavior of salmon and steelhead or affect growth

Studies suggest adult marine fish are highly tolerant to increase CO_2 concentrations, especially in regards to direct mortality (Michaelidis et al 2007, Hayashi et al 2004, Kikkawa et al 2004 and 2006 – as cited in Fabry 2008). The locomotory muscles of active animals, such as epipelagic fish, have high activities of anaerobic metabolic enzymes and, consequently, have a high capacity for buffering internal pH changes (Castellini and Somero 1981, Seibel et al. 1997, Seibel and Walsh 2003 – as cited in Fabry 2008). Additionally, the tolerance of marine fish may relate to a high capacity for internal ion and acid–base regulation via direct proton excretion (Ishimatsu et al. 2004) and an intracellular respiratory protein that results in a high oxygen carrying capacity and substantial venous oxygen reserve (Fabry 2008). Although adult marine fish generally display little sensitively to the changes in pH expected from ocean acidification, larval fish can have negative effects. Experiments on silversides showed decreased larval growth and survival at reduced pH (Baumann et al. 2011). Larval fish have a higher surface to volume ratio than adult fish, may rely more on diffusive processes and have less well developed acid-base regulatory mechanisms, making them more responsive to external pH. Since salmon eggs and fry develop in fresh water they are not exposed to ocean acidification during these developmental window.

However, studies of reef fish exposed to higher CO_2 levels (700-900 uatm predicted to occur in the sea by the end of the century) in their larval stages have shown behavioral and sensory abnormalities (Nilsson et al. 2012). Changes include increased boldness and activity, loss of behavioral lateralization, altered auditory preferences and impaired olfactory function (Nilsson et. al. 2012 refs 1-5). One specific result was the decreased ability for these fish to avoid predators (see Nisson refs). Nisson et al. (2012) found that that high CO_2 directly stimulates a receptor in the fish brain called GABA-A, leading to a reversal in its normal function and over-excitement of certain nerve signals. Most teleost fish exhibit complete, or near-complete, compensation of acidosis by HCO3 accumulation and Cl- efflux, and this could make them much more susceptible to the effects of CO_2 on GABA-A receptor function (Nilsson et a. 2012). Therefore, it could be that aquatic animals with the best-developed acid-base regulation will also be most susceptible to disruption of GABA-A receptor function by rising CO_2 (Nilsson et a. 2012). Overall, this research suggests that species and early life-stages of marine fish with very high rates of oxygen consumption, including highly active pelagic species, are likely to be among the most susceptible to changes in ambient CO_2 because their high rates of gas exchange can be expected to result in particularly low blood pCO_2 that approaches ambient pCO_2 (Nilsson et. al. 2012).

Additionally, studies of farmed Atlantic salmon have found that growth rates decreased (Martens et al. 2006) and condition factors were reduced (Fivelstad et al. 1999) when exposed to elevated levels of CO_2 as juveniles. In the Fivelstad study, the mean weight and length of fish in the high CO_2 group were significantly greater and the condition factor was significantly reduced, compared to the control group after 123 days of exposure. The Martens study monitored their fish after exposure through entire life, after their study period was complete. While there were some changes in bone development through smoltification, no causative mechanism was identified and farmed salmon exposed to CO_2 vs. controls showed no differences in harvest weight and body composition at the end of their growout period (Martens et al. 2006).

Similar research has not been performed on juvenile pacific salmon and steelhead. While juvenile salmon are not in their larval stage in the marine environment, exposure to elevated CO_2 levels may occur in the freshwater environment, resulting in abnormalities that don't affect survival until the fish enter the marine environment. Alternatively, juvenile salmon migrating into and through Puget Sound are experiencing significant physiological changes (e.g., during smoltification) which may increase their risk of impact. That said, the rivers entering Puget Sound where salmon and steelhead originate are low pH (Feely et al 2010), so it could be assumed that, in their egg, larval and juvenile stages, they are adapted to such environments.

Hypothesis 8_C Elevated CO2 concentrations alone and combined with increased temperatures are promoting Heterosigma growth, which can affect salmon survival

A study by Fu et al 2008 has shown that elevated CO_2 alone or in concert with temperature stimulates *Heterosigma* growth. This is a concern given the presence and known toxicity of *Heterosigma* to salmon. Potential *Heterosigma* affects on salmon are discussed in hypothesis 9.

Hypothesis 8_D Synergistic responses to elevated CO2/low pH concentrations combined with low oxygen, increased temperatures, and eutrophication can occur, as well as the combined effects of ocean acidification and toxics.

Studies on variety of taxa demonstrate additive or synergistic interactions between the effects of acidification and other stressors such as elevated temperature, low oxygen, low food availability or light availability (in the case of primary producers [ref[27]]. These sorts of interactive studies generally have not been undertaken for the species most relevant to salmon survival (e.g. salmon or salmon prey). Salmon will not experience acidification as an isolated stressor and synergistic responses are considered a significant concern (Feely 2010).

Research Recommendations

The following recommendations are in response to the hypotheses provided above. They are in order of priority. Any research proposed through this effort should be strongly coordinated with ongoing studies, NOAA's ocean acidification program, and any research endeavor that results from the recommendations of Washington's Ocean Acidification Blue Ribbon Panel[28], to be released this fall, 2012 The Panel is focused on documenting the current state of scientific knowledge about ocean acidification, determining ways to advance our scientific understanding of the effects of ocean acidification, and

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[27] To be added in a later version. Ran out of time.

[28] http://www.ecy.wa.gov/water/marine/oceanacidification.html

recommending actions to respond to increasing ocean acidification, reduce harmful effects on Washington's shellfish and other marine resources, and adapt to the impacts of acidified waters. [29]

- (monitoring) Ensure marine carbon chemistry and pH are included in the suite of baseline physical attributes monitored throughout Puget Sound.

- (monitoring) Carbon monitoring should be coupled with biological monitoring of species potentially vulnerable to ocean acidification that affect salmon growth and survival (e.g. krill and copepods). These data are needed to establish any causative link between acidification and salmon performance.

- (process study) Study the effects of pH/pCO_2 variability on invertebrate prey of greatest importance locally to salmon and forage fish. An ongoing study of copepods and euphausiids by Drs Julie Keister (University of Washington), Paul McElhany (NOAA), and Shallin Busch (NOAA) directly addresses this need but could be expanded upon to include other species of concern such as gammarid amphipods and decapod larvae and potential synergistic variables such as temperature and oxygen. At the same time, the study approach could be reviewed to determine whether an appropriate array of biological variables are included to ensure that alternations that could be magnified in individuals and populations over time, that, in turn, may affect ecosystem function are captured (PICES 2011). This to address concerns that most studies use metrics to quantify effects from ocean acidification that are acute and obvious (e.g., mortality, morphology, embryological development, egg hatching success, alterations in community composition) (PICES 2011). For example, ocean acidification mediated changes in zooplankton quality (or, phytoplankton quality if going one step below) could be an important indirect mechanism through which ocean acidification acts on marine food webs (Rossol et al. 2012)

- (modeling) Incorporate past, current and predicted levels of pCO_2/pH and results regarding ocean acidification effects on marine biota from relevant existing empirical studies and/or future studies in ecosystem modeling exercises to evaluate synergistic (with low oxygen, warming, and eutrophication or combined effects with toxics) and food web effects relevant to salmon and steelhead growth and survival. This includes incorporating the results of the recommended zooplankton studies and looking for correlations with *Heterosigma* growth.

- (process study) Conduct laboratory studies of potential direct effects of acidification on salmon. Studies would examine behavioral and sensory responses as well as other metrics such as metabolic effects (hypercapnia) or developmental impacts during smoltification and early marine life stages.

- Determine the role of local human influence (current and predicted) on Puget Sound acidification versus global influence to evaluate the degree to which regional efforts could influence change. This should be associated with larger efforts regarding the evaluation of ocean acidification and climate change. [low cost to this effort if covered by other efforts]

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[29] Ibid.

Management Implications

Efforts to change the long-term trajectory of ocean acidification and its impacts locally may be difficult without the effort being global in scale to reduce anthropogenic carbon inputs. However, the results of the research proposed above may help forecast and prepare for certain impacts, and possibly affect the trajectory of ocean acidification if local human influence is a greater driver than global influence. Management responses could include:

1. Modify hatchery production to produce salmon less susceptible to ocean acidification impacts (either because they aren't directly affected or prefer prey types that are less affected). Or, change the release size and timing so that they are less susceptible. (*Benefits hatchery fish only*)

2. Establish local efforts to reduce the role of local human influence on ocean acidification.

3. Scale fisheries expectations (harvest and hatchery production) based upon future scenarios that include predicted impacts of ocean acidification.

4. Reduce manageable stressors (e.g. toxic loading) that exacerbate potential ocean acidification effects.

The management recommendations of the Washington State Blue Ribbon Panel on Ocean Acidification should also be reviewed.

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Hypothesis 9. Harmful algae directly affect salmon survival through acute or chronic mortality and may adversely affect prey availability by food web impoverishment.

Jack Rensel, Rensel Associates Aquatic Sciences

Overview

Worldwide, harmful algal blooms (HABs) are more extensive and pervasive compared to prior decades due in part to human activities and nutrient enrichment of coastal waters, climate change and via ballast water. *Heterosigma akashiwo* (herein *Heterosigma*) is a microflagellate HAB species that appears to have become more prevalent in the Salish Sea since 1989 and now has been recorded in bloom concentrations in all basins of the Salish Sea. *Heterosigma* blooms can kill fish and other fauna and are implicated in poor survival of Fraser River sockeye. Fish survival may be affected by acute and chronic toxicity effects of *Heterosigma*, food web and salmon prey impoverishment related to *Heterosigma* blooms, or a combination of these factors. The evidence involves strong correlations between marine survival of sockeye salmon and probable bloom exposure as juveniles, observations of wild fish being killed concurrently with farmed fish in Puget Sound and the known characteristics of the alga in other seas. Chinook, coho, chum, pink, and sockeye salmon and steelhead could all be affected, with the greater probable impact on those stocks that migrate during May-early July or in late summer and early fall when large-scale blooms are most common in the Salish Sea. Adverse effects on wild adult salmonids are possible, but not documented yet. Several other HAB species are known to occur or bloom in the Salish Sea and NE Pacific Ocean waters which either kill fish directly through toxicity or gill damage. However, no quantitative data are available to assess the relative importance of these other HAB species to wild stocks of fish at this time.

Research recommendations include: Conduct live cage bioassays in target bloom and reference areas at different depths and with subsequent tissue and toxin analyses; increase the spatial extent, frequency and duration of harmful algae monitoring activities, where appropriate, to cover the migration time of priority salmon and steelhead species (especially associated with the Fraser River plume); coordinate bloom tracking efforts with underwater acoustic telemetry fish tagging and tracking; build from existing volunteer monitoring efforts; evaluate remote sensing technologies for improving bloom detection; standardize harmful algae monitoring protocol and consolidate/quality assess the data.

Two hypotheses are advanced here:

H-9$_A$ Major *Heterosigma* blooms reduce survival of Fraser River Sockeye in specific years over a 20 year period. Survival may be affected by acute or chronic toxicity, food web and salmon prey impoverishment, or a combination of these factors. The algal may affect other salmonid species that encounter *Heterosigma* blooms in other regions of the Salish Sea.

H-9$_B$ Other harmful algal bloom species that occur in the Salish Sea and NE Pacific Ocean waters kill fish directly through toxicity or physical gill damage.

Relevant Species of Salmon and Steelhead

Sockeye, Chinook, coho, chum, steelhead and to a lesser degree pink salmon could all be affected, with the greater probable impact on those that migrate through areas of the Salish Sea that most commonly experience large-scale blooms during May-early July or in late summer and early fall.

Supporting/Refuting Evidence

Hypothesis 9A Major Heterosigma blooms have been strongly correlated with poor survival of Fraser River Sockeye over a 20+ year period. Survival may be affected in bloom years by acute or chronic toxicity, food web and salmon prey impoverishment, or a combination of these factors. The algal may affect other salmonid species that encounter Heterosigma blooms in other regions of the Salish Sea.

Supporting Evidence

Worldwide, harmful algal blooms (HABs) are more extensive and pervasive compared to prior decades due in part to human activities and nutrient enrichment of coastal waters, climate change and introduction of new algal species via ballast water. There is a huge body of literature that defies summary in a few short pages, but a recent review article examines HABs along the North America West Coast, the history, trends, causes and impacts (Lewitus et al. 2012). A subset of that paper deals with *Heterosigma akashiwo,* a microflagellate that is considered by phycologists and HAB experts as among the most versatile and allelopathic HAB species. The alga may adversely affect salmon through acute or chronic toxicity, food web and salmon prey impoverishment, or a combination of these factors. The case study presented by Rensel et al. (2010) here is for the Fraser River sockeye, a most valuable and complex set of salmon stocks that are shared between Canadian and U.S. fishers and the subject of much research and debate. *Heterosigma* has occurred in the Salish Sea since at least 1967 (Taylor and Haigh 1993) but appears to have become more prevalent since about 1989 (Kennedy and Kreiberg 1991, PBS 1999, Rensel 2007) and now has been recorded in bloom concentrations in all basins of the Salish Sea.

Extremely poor salmon returns of Fraser River sockeye in 2009 after the 2007 smolt outmigration was the subject of much scrutiny by the Fraser River Panel and the Cohen Commission and others. Catch and escapement rebounded significantly in 2010, breaking a 20-year pattern of decline and emphasizing that some controlling fish mortality factor(s) may be episodic in nature. Rensel et al. (2010) provided a review of both *Heterosigma* bloom ecology in the vicinity and the Chilko stock of Fraser River Sockeye and articulated the hypothesis and supporting data that in some years there are major linkages between blooms of the alga and the salmon survival. Marine survival of Fraser River sockeye salmon was strongly correlated with blooms of the harmful raphidophyte microflagellate *Heterosigma akashiwo* in the Southern SoG and North Puget Sound.

In addition to farmed fish kills, observations of dead wild salmonids and marine fish in shallow inlets of South Puget Sound or along beaches of deeper areas of North Puget Sound coincided with every observed, major *Heterosigma* bloom since 1989. Recurring wild fish kills related to *Heterosigma* blooms have also occurred in bays and coastal areas of North Carolina, Georgia, Delaware, and Texas.

Heterosigma has been termed the most versatile and allelopathic harmful algal bloom species for many reasons including its antagonistic effects on organisms with sizes ranging from bacteria to fish (Smayda 1998, 2006) and its ability to rapidly vertically migrate in the water column (Hershberger et al., 1997a; Bearon et al., 2004).

Taylor and Haigh (1993) note that *Heterosigma* have regularly appeared in late spring in English Bay, Vancouver, B.C. since 1967 when routine annual phytoplankton surveys were first initiated. This was several years before commercial aquaculture net pens were used in Salish Sea waters. A few large and persistent blooms were documented in Departure Bay and the SoG in the 1990s as HABs and effects on aquaculture was a research priority at that time (Pacific Biological Station, 1999). More frequent and large but relatively brief *Heterosigma* blooms in Puget Sound commenced in 1989. There were multiple year gaps with no major blooms in Puget Sound other than North Puget Sound (Rensel, 2007), which contrasts with frequent and extended major blooms in B.C. waters in the post 1989 era. Routine recording of cell density throughout B.C. waters began in 1999 with the initiation of the Harmful Algae Monitoring Program (herein HAMP, operated first by DFO and then privately by N. Haigh).

Fraser River sockeye salmon abundance began to decline after peaking in the late 1980s, coinciding with commencement of major, basin-wide, Salish Sea *Heterosigma* blooms. Marine survival of Chilko stock Fraser River sockeye salmon averaged 2.7% in years when smolt seawater entry coincided with major *Heterosigma* blooms vs. 10.9% in the same timing in years when no bloom or only minor-blooms occurred. Separate evidence that juvenile sockeye salmon marine mortality occurs in the SoG and North Puget Sound was found by comparing young of the year herring survey catch to marine survival of Chilko stock. This yielded a highly significant correlation ($r = 0.89$, $p = 0.0001$) for smolts entering seawater from 1997 through 2008. *Heterosigma* blooms that annually began in late June or later have in recent years commenced earlier, as early as late May or early June, coinciding more completely with juvenile sockeye salmon migration through Salish Sea waters. Fraser River discharge was significantly larger and earlier in major bloom years compared to minor or non-bloom years and appears to be a primary forcing factor.

Heterosigma is euryhaline, growing at 5 psu salinity but significantly faster at 10 psu or above, depending on strain, as determined with four different Puget Sound strains (Fredrickson et al. 2011). Etiology of fish mortality from *Heterosigma* exposure is uncertain and possibly variable but is thought to involve gill damage and respiratory failure caused by algal production of reactive oxygen species (ROS), including hydrogen peroxide, hydroxyl free and superoxide radicals (Oda et al., 1997). It is also possible that different clones or strains of *Heterosigma* have different toxin-producing capabilities that may be expressed in different locations and times. For example, brevetoxins (i.e., HAB toxins that disrupt normal neurological functions of fish or other fauna) have been found in some Japanese strains. Salmonid fishes including chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), and chum salmon (*O. keta*), rainbow trout (*O. mykiss*) and Atlantic (*Salmo salar*) salmon are all susceptible to the alga with varying survival rates in different blooms (e.g., Hershberger et al., 1997b; Pacific Biological Station, 1999; Anderson et al., 2001). Sockeye salmon (*O. nerka*) may be at enhanced risk of gill injury or other adverse effects from harmful algae as they have numerous and closely spaced gill rakers used to strain the water for plankton. Other salmonids including those reared in B.C. fish farms (Atlantic and chinook salmon) have fewer and more widely-spaced gill rakers, in line with their differing feeding patterns.

Below is a shortened version of Rensel et al. (2010) where previously unpublished HAMP data of Heterosigma density/timing/distribution, DFO published data and observations (Pacific Biological Station

1999), Puget Sound farmed or wild fish kill data and publications are combined and compared to marine survival of Fraser River sockeye salmon in the post 1989 period.

Methods: HAMP database regions include, from north to south: (A) Broughton Archipelago and Queen Charlotte Strait, (B) Johnstone Strait and Quadra Island areas, (C) Sechelt and Jervis Inlets and (D) Southern SoG (Fig. 1). Region D was sampled along western nearshore waters from Departure Bay to Saltspring Island, in one of several known juvenile sockeye salmon migration pathways. Water bottle samples from 1, 5 and 10 meters depth were preserved with Lugol's iodine solution. All HAB species were enumerated using a Sedgwick-Rafter counting slide and a standard transmitted light microscope by N. Haigh, who has managed the HAMP program since its initiation in 1999. *Heterosigma* cell counts are ranked by density as follows: 0 = no cells, 1 = low number of cells (i.e., not bloom levels, 0 to 10 cells/ml), 2 = moderate numbers of cells (possible to certain blooms, 11 to 999 cells/ml) and 3 = large numbers of cells (blooms of >1,000 cells/ml).

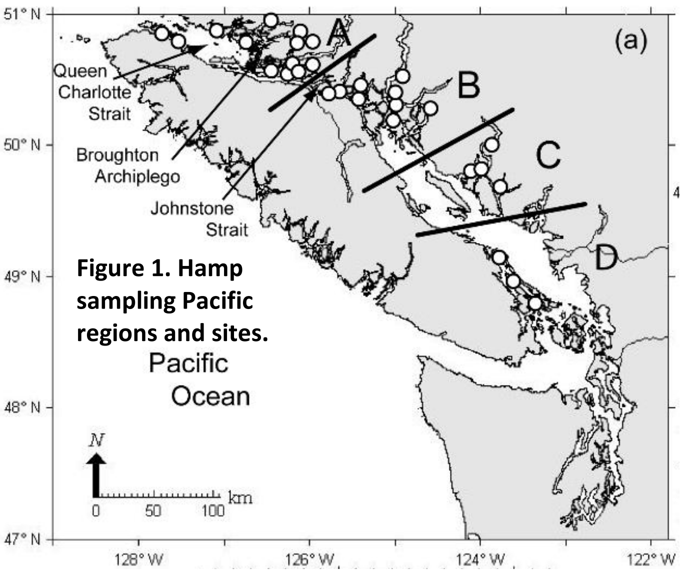
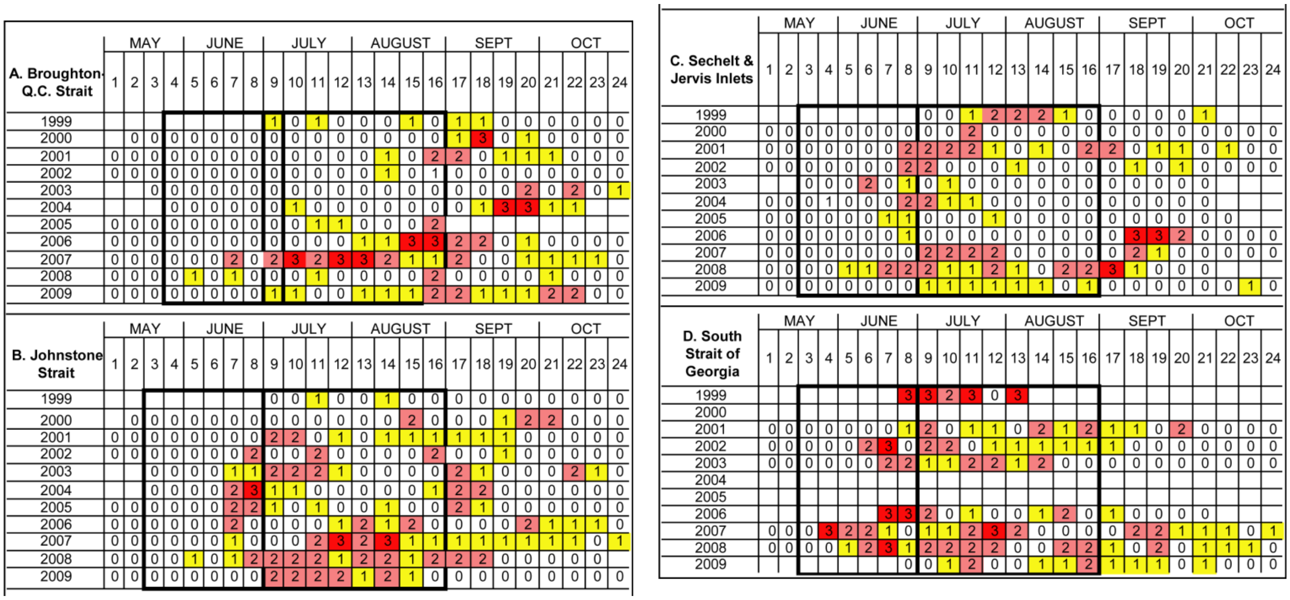


Figure 1. Hamp sampling Pacific regions and sites.

The concentration of cells causing salmon mortality is uncertain and perhaps variable but is thought to occur in the level 2 range (e.g., Rensel and Whyte 2003). A "bloom index" was constructed by summing different bloom rankings for known sockeye migration periods and regions, only level 2 and 3 rankings were utilized. Data from three annual periods were compiled separately: (1) May through October, (2) mid-May through June for juvenile sockeye migration timing, and (3) July and August for adult sockeye migration timing in the Salish Sea. Months were divided into four periods each, herein termed "weeks". A primary metric to estimate the possible interaction of *Heterosigma* blooms with Fraser River sockeye was annual marine survival data for Chilko Lake stock sockeye salmon. Marine survival is defined as number of returning adults divided by the number of smolts migrating out of Chilko Lake, where adults are the total age-four adult run that includes the total fishery catch plus the observed spawning escapement plus the estimated freshwater adult en route loss (i.e., fish that entered the river and were estimated in the lower river by hydroacoustic methods but are assumed to have died before spawning). The period of mid-May through the end of June was selected as representative of the time that juvenile fish would be sequentially migrating into and through Regions D and B, from south to north, based on literature (Groot and Cooke, 1987) and advice from Pacific Salmon Commission (PSC, M. Lapointe), with an extra week for lag time to pass through Region A. For returning adult Chilko stock sockeye, we estimated that the annual migration passes through Regions A, B and D in July and August, based on the literature and PSC unpublished data (M. Lapointe, pers. comm. 2009). Statistical associations, using Pearsons correlations, were tested between the sum of annual bloom index levels 2 and 3 for juvenile and adult migration periods (described above) and the Chilko sockeye marine survival rate estimates. Daily Fraser river discharge during the juvenile migration period was compared using Student-t tests.

Results and Discussion: *Heterosigma* blooms in sampled regions of British Columbia waters were remarkably frequent, particularly during the mid-June through October period. Table 1 illustrates weekly bloom index ranking with black rectangles for juvenile (left) and adult (right) migration timing.

Table 1. Weekly *Heterosigma* bloom rankings for four HAMP sampling regions of British Columbia.



A. Broughton-Q.C. Strait	MAY				JUNE				JULY				AUGUST				SEPT				OCT			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999									1	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0
2000		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	0	1	1	1	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
2003			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	1
2004				0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	3	3	1	1		
2005	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2								
2006	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	2	2	0	1	0	0	0	0
2007	0	0	0	0	0	0	2	0	2	3	2	3	3	2	1	1	2	0	0	1	1	1	1	0
2008	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	2	0	0	0	0	1	0	0	0
2009	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	2	2	1	1	1	2	2	0	0

B. Johnstone Strait	MAY				JUNE				JULY				AUGUST				SEPT				OCT			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999									0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
2000		0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	2	2	0	0	0
2001	0	0	0	0	0	0	0	0	2	2	0	1	0	1	1	1	1	1	1	0	0	0	0	0
2002	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	2	0	0	1	0	0	0	0	0
2003			0	0	0	0	1	1	2	2	2	1	0	0	0	0	2	1	0	0	0	2	1	0
2004			0	0	0	0	2	3	1	1	0	0	0	0	0	1	2	2	0	0	0	0	0	0
2005	0	0	0	0	0	0	2	2	1	0	1	0	0	1	0	0	2	1	0	0	0	0	0	0
2006	0	0	0	0	0	0	2	0	0	0	0	1	2	1	2	0	0	0	0	2	1	1	1	0
2007	0	0	0	0	0	0	1	0	0	0	2	3	2	3	1	1	1	1	1	1	1	1	0	1
2008	0	0	0	0	1	0	1	2	2	2	2	1	2	2	1	2	2	2	0	0	0	0	0	
2009	0	0	0	0	0	0	0	0	2	2	2	2	1	2	1	0	0	0	0	0	0	0	0	0

C. Sechelt & Jervis Inlets	MAY				JUNE				JULY				AUGUST				SEPT				OCT			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999									0	0	1	2	2	2	1	0	0	0	0	0	1			
2000	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	2	2	2	2	1	0	1	0	2	2	0	1	1	0	1	0	0
2002	0	0	0	0	0	0	0	2	2	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0
2003			0	0	0	2	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0			
2004	0	0	0	1	0	0	0	2	2	1	1	0	0	0	0	0	0	0	0	0	0			
2005	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0		
2006	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	3	2	0	0	0	0
2007	0	0	0	0	0	0	0	0	2	2	2	2	0	0	0	0	0	2	1	0	0	0	0	0
2008	0	0	0	0	1	1	2	2	2	1	1	2	1	0	2	2	3	1	0	0	0			
2009	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	1	0

D. South Strait of Georgia	MAY				JUNE				JULY				AUGUST				SEPT				OCT			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999								3	3	2	3	0	3											
2000																								
2001	0	0	0	0	0	0	0	1	2	0	1	1	0	2	1	2	1	1	0	2	0	0	0	0
2002	0	0	0	0	0	2	3	0	2	2	0	1	1	1	1	1	1	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	2	2	1	1	2	2	1	2	0	0	0	0	0	0	0	0	0	0
2004																								
2005																								
2006							3	3	2	0	1	0	0	1	2	0	1	0	0	0	0			
2007	0	0	0	3	2	2	1	0	1	1	2	3	2	0	0	0	0	2	2	1	1	1	0	1
2008	0	0	0	0	1	2	3	1	2	2	2	2	0	0	2	2	1	0	2	0	1	1	1	0
2009								0	0	1	2	0	0	1	1	2	1	1	1	0	1	0	0	0

The largest frequency of detection occurred in the South Strait region where 48% of the sampling weeks throughout the May through October period tested positive for *Heterosigma*. Region B, Johnstone Strait averaged 35% cell detection, followed by Regions A and C with 29% and 24% occurrence, respectively (Table 2). For estimated juvenile sockeye migration timing, mean annual level 2+3 bloom index increased from north (Region A) to south (Region D) with 40% of the sampled weeks in Region D, South SoG, for the mid-May through June period ranked as bloom levels 2 or 3. When ranked by potentially fish-killing *Heterosigma* bloom levels 2 and 3 during adult sockeye timing, the South SoG was also highest; 30% of the sampled weeks were observed to be bloom levels 2 or 3 followed by 24% occurrence in Region B. These data indicate significantly more frequent occurrence of level 2 and 3 blooms in the South SoG, compared to all other regions for both juvenile and adult timing.

Table 2 Heterosigma percent weekly occuence, regions A - D, HAMP database, for time periods with no missing data

Migration Timing, Bloom Levels	Region	Percent Detection
May thru Oct. Bloom Levels 1, 2, 3	A	29%
	B	35%
	C	24%
	D	48%
Juvenile Sockeye Salmon Timing, Bloom Levels 2, 3	A	3%
	B	18%
	C	18%
	D	40%
Adult Sockeye Salmon Timing, Bloom Levels 2, 3	A	13%
	B	24%
	C	15%
	D	30%

Bloom index level 2 and 3 occurrences were summed for each year's estimated juvenile or adult sockeye migration period by region and compared to the Chilko sockeye salmon marine survival rate for relevant smolt seawater entry or adult return years. For juvenile fish, the correlation coefficient between South SoG *Heterosigma* bloom index in smolt year and Chilko marine survival rate was -0.83 (p = 0.04, n = 6). No other regions had significant correlations for juvenile migration periods and all areas were not significant for adult timing. To increase sample size we utilized weekly data from the Pacific Biological

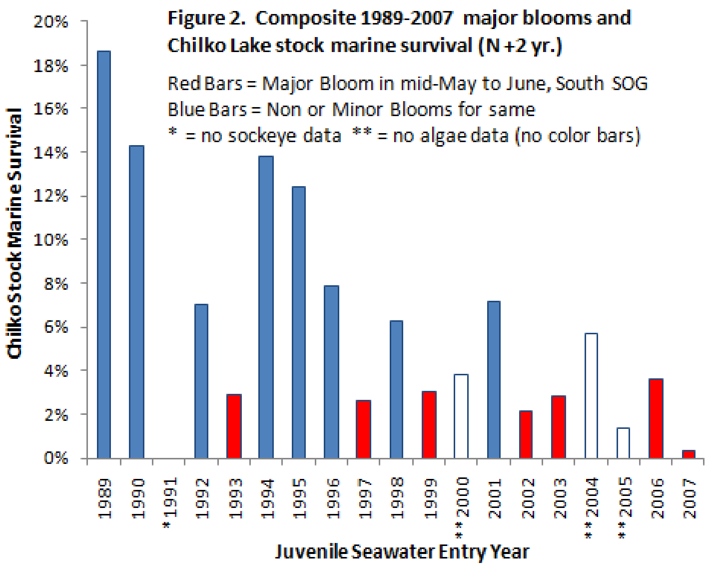


Figure 2. Composite 1989-2007 major blooms and Chilko Lake stock marine survival (N +2 yr.)

Red Bars = Major Bloom in mid-May to June, South SOG
Blue Bars = Non or Minor Blooms for same
* = no sockeye data ** = no algae data (no color bars)

Station in the Southern SoG (PBS 1999) in the 1990s. *Heterosigma* blooms lasting four months were documented in 1993 and 1997 in large areas if not the entire SoG and the latter year had May and June data, but not the former. Chilko stock juvenile sockeye salmon entering the sea during these two years produced the two lowest marine survivals rates for the 1989-1999 period (2.9% and 2.6%, respectively). For comparison, marine survival averaged 12.3% during non-bloom or minor bloom years of the same time period. Adding 1997 data to the correlation analysis described above and using only years with no missing juvenile migration weekly data (n = 5), the correlation coefficient between “bloom index” and Chilko stock marine survival was -0.88 (p = 0.05). Finally, we reconfigured the same data into four bloom levels by splitting bloom level 2 in two levels (11 to 499 cells/ml and 500 to 999 cells/ml) and for complete data years in the SoG found the correlation to improve (r = -0.91, p = 0.03, n = 5).

Figure 2 summarizes major blooms in the juvenile sockeye salmon migration period that occurred during the HAMP (1999+) and PBS (1989-1999) observations (Rensel et al. 2010). During the 19 year period of 1989-2007 marine survival of Chilko Stock averaged 10.9% in non-bloom or minor bloom years versus 2.7% in years with major blooms during juvenile migration in the Southern SoG. 1989 and 1991 were reportedly major bloom years (Taylor and Haigh, 1993) but no timing or data were reported for the former and no sockeye marine survival data were collected for the latter. Year 2003 was equivocal with regard to bloom status, major or minor.

If mortality of sockeye smolts was occurring in the SoG during bloom years, resident fish that inhabit near-surface water may also be expected to be affected concurrently. We examined young of the year (YOY) September herring survey catch data published by Schweigert et al. (2009) extending from 1992 to

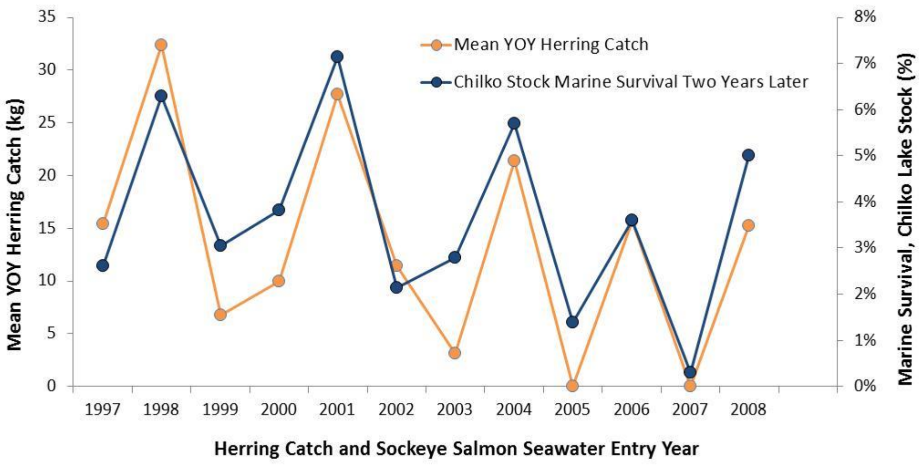


Figure 3. Strait of Georgia herring survey catch and Fraser River sockeye Chilko stock marine survival after 2 year in marine waters, updated from Rensel et al. 2010.

2007 (1991 purposely excluded for method differences, 2008 data point provided by J. Schweigert, pers. comm.). Beginning in 1997 and extending through the herring data set to 2008 there was a highly significant correlation between YOY herring catch and Chilko sockeye salmon marine survival (r = 0.89, p = 0.0001, Fig. 3).

Including earlier years (1992-1994) in the analysis resulted in a non-significant correlation (e.g., r = 0.26 for 1992-2007 p = 0.36) but using the period 1995-2007 resulted in statistically significance (r = 0.66 p = 0.02) and increased to r = 0.93 for 1998-2007 period. The reasons for this shifting pattern are not known. During the period of declining productivity of Fraser sockeye salmon (since mid-1990s through 2009), these data suggest that marine survival rates are principally determined within the Strait of Georgia and likely within the first six weeks of sockeye seawater rearing. The concept of significant early marine mortality of sockeye salmon is not new (e.g., Furnell and Brett, 1986). However, these data are remarkably strong, supporting the notion that most Chilko stock sockeye salmon mortality occurred in the SoG in the first six weeks of seawater life.

To evaluate effects of varying Fraser River discharge volume on *Heterosigma* blooms during the juvenile sockeye salmon migration period, we plotted river discharge from years of known major blooms versus non-bloom or minor-bloom years in the SoG for the 1989 through 2009 period. Mean and confidence interval discharge plots and a Student's t-test of two data sets indicate significantly greater river discharge (p < 0.001) in the May-June period of major *Heterosigma* bloom years versus other years (Fig. 4). These data suggest a probable linkage between May-June *Heterosigma* blooms and larger/earlier than normal peak river discharge. Earlier than normal peaking of Fraser River flows is driven by warmer than normal weather that also enhances the probability of *Heterosigma* blooms through cyst germination acceleration and establishment of stronger vertical density gradients.

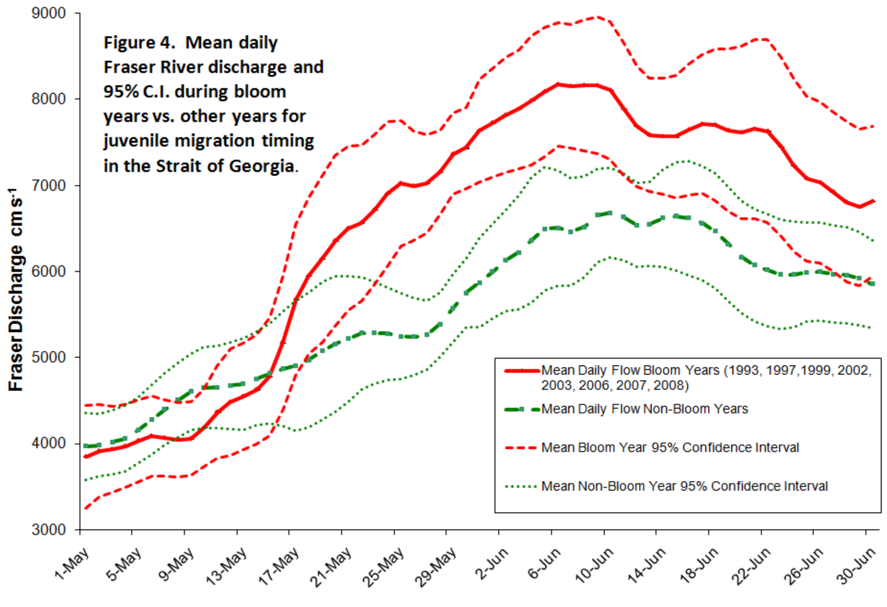


Figure 4. Mean daily Fraser River discharge and 95% C.I. during bloom years vs. other years for juvenile migration timing in the Strait of Georgia.

Based on these results, we suggest that *Heterosigma* is at least partially responsible for acute or chronic toxicity of the sockeye salmon, food web and prey impoverishment, or some combination of these factors in the SoG and contiguous waters of North Puget Sound. Adult sockeye may be affected too, but our data are insufficient to assess this due to differences in migration paths and algal sampling locations. In the past scientists have not investigated wild fish interaction with *Heterosigma*, but assumed that the wild salmon would swim under or around blooms (Taylor and Harrison, 2002) although this was conjecture (P.J. Harrison, pers. comm. 2009). *Heterosigma* blooms do concentrate very near the surface at times, such as in quiescent summer periods during daylight hours that would allow fish to pass underneath. But at other times and locations in B.C. they may be mixed throughout the water column (Gaines and Taylor, 1986) as well as in Puget Sound (Rensel, 2007). Moreover, *Heterosigma* can vertically migrate at night to the shallow (~10 m) nutricline, a depth range that corresponds with the reported maximum depth distribution of juvenile sockeye salmon throughout the Strait (Groot and Cooke, 1987). Since moribund and dead salmon sink rather than float and exposure to the alga may induce chronic effects in addition to acute mortality, the losses may easily go undetected over broad areas. Means to further investigate and possibly mitigate blooms of *Heterosigma* in the Salish Sea, a literature review of modes of toxicity, verticial distribution of the sockeye salmon and the alga and related topics are addressed by Rensel et al. (2010).

Additional Supporting Data and Background

Additional information not mentioned above or requiring embellishment:

- In major *Heterosigma* blooms, typically all other nanoplankton and larger phytoplankton are extirpated from the water column, sometimes just near the surface but not uncommonly in North Puget Sound to many tens of meters depth (Rensel 2007). Extirpation, injury or death of normal food web constituents is known to occur with *Heterosigma* blooms in other locations worldwide, which raises the possibility in the Salish Sea. So in addition to possibly causing acute mortality or adverse sublethal effects to wild juvenile fish, survival could be indirectly affected through food web impoverishment, or a varying combination of all these factors.

- Massive blooms of *Heterosigma* in the Salish Sea are somewhat predictable for monitoring or mitigation within approximately a week (the period of relatively accurate weather forecasting). Blooms occur during warm to hot sunny periods, increase during neap tides, and are thought to commence in sheltered bays with vertically stratified water columns that heat more rapidly in the spring that the main basins. In persistently cool and windy or overcast weather and years, the alga may not bloom or blooms may be rapidly terminated by such conditions.

- In the Strait of Georgia prior studies by UBC scientists indicate that *Heterosigma* blooms may persist for long periods of the late spring through early fall, sometimes for many months and extend throughout the entire Strait into Northern Puget Sound. Blooms also occur in inlets of the west coast of Vancouver Island and the mainland of B.C. and Washington State with the exception of the most physically energetic channels and passages (N. Haigh, HAMP data and pers. comm., Rensel 2007).

- In Puget Sound, the available data suggests that *Heterosigma* blooms have never exceeded a week in duration and are often the result of a remote bloom (e.g., SoG or Samish Bay origin) being transported by estuarine flow or wind driven currents. Blooms have occurred in every basin of Puget Sound but the occurrence is better documented in the main basins and channels versus bays, inlets and poorly flushed backwaters. No systematic phytoplankton monitoring is conducted or data archived in many large subareas of Puget Sound and parts of the Salish Sea in B.C. Fish farms in Washington State only monitor during high HAB risk periods at fish farms and in areas surrounding farms by aircraft surveys that are often validated with water sample collections and cell counts for ground truthing purposes. Their data is no longer archived or reported as it is in B.C.

- Dead wild fish have been noted during most major blooms in Central and North Puget Sound that concurrently killed farmed fish but no investigations or tagging has been conducted to assess the significance. Wild salmon and marine fish mortalities have repeatedly been observed in shallow waters of upper Case Inlet in South Puget Sound during *Heterosigma* blooms (Hershberger et al. 1997, T. King, pers. comm., posted SoundHAB archives). Rensel et al. (2010) examine evidence of how fish kills can occur in our relatively cool marine waters resulting in fish that sink rapidly and do not refloat. Slow rates of bacterial gas formation in fish body cavity, and pelagic and demersal predation as well as carcass transport into the deep, generally cooler subsurface layer appear to be contributing factors.

- Wild juvenile Pacific salmon and steelhead are thought to be susceptible to *Heterosigma* blooms, as they occupy the upper water column where the algal concurrently grows and vertically migrates. Returning adult salmon such as sockeye are also surface oriented, particularly nearer natal river mouths and nearby migration pathways. Larger fish are more subject to blood hypoxia from gill damage caused by HABs and some HAB neurotoxin than smaller fish.

- Nutrient sensitive, vertically stratified water columns found in some bays and backwaters of the Salish Sea are prime areas for *Heterosigma* bloom initiation. A few areas are generally known, but none have been investigated in detail. Some of these areas are heavily influenced by riverine discharge, but bloom initiation areas exist in other areas such as backwaters of central Puget Sound (Kitsap County) that have no major river systems but are subject to vertical stratification from insolation. Benthic cyst beds (i.e., where the alga overwinters in a dormant form in fine sediments) are known to occur although few data are available.

- The role of nutrient flux change in the Salish Sea is uncertain with regard to *Heterosigma* bloom frequency, extent and duration. However, long term water temperature increases in the SoG, along with warmer winter and spring weather over many decades favors earlier cyst germination and bloom formation that could more nearly match May and June outmigrating salmon smolt timing. As shown above, many blooms in the past have not commenced until late-June or early July, and thus not overlapping with smolt migration, but the above analysis indicates the probable effects of earlier blooms into the migration or residency timing of salmonids.

Refuting Evidence

There have been no studies refuting the concept that HABs or *Heterosigma* can cause mortality to wild fish. In British Columbia there are no experienced HAB scientists working for agencies at present and the problem is viewed by some as an issue that only affects fish farms only. Others acknowledge a possible role for *Heterosigma* to produce mortality of wild salmon or effects on the food web (e.g., Beamish et al. 2012), but point out that the geographical extent of sampling is limited. This is true for British Columbia in part because of the large coastal areas involved, except for prior documented cases, but in major bloom events in Washington State aerial surveys are conducted by fish growers and allow some general estimates of the extent of the blooms are available. *Heterosigma* has a unique coloration appearance when viewed from an airplane that is apparent to a trained observer, and ground truth surveys are conducted both at fish farms and remote areas.

Also there is uncertainty about the mechanisms involved and the significance and consistency of fish kills caused by the alga. In coastal waters of British Columbia occasionally a bloom of *Heterosigma* will drift through a fish farm and no fish mortality occurs. And in some areas (e.g., Scotland) blooms are rarely toxic to fish, while in New Zealand, Chile and some other locations the blooms are usually toxic. Thus it is possible that these blooms may not result in mortality of wild salmon in all cases. However, every major bloom in Washington State has resulted in significant net pen fish mortality, sometimes despite the air lift pumping of deep water into pens. In only one case in Washington State (Connell et al. 2001) were returning adult hatchery fish held in saltwater tanks apparently unaffected by exposure to pumped seawater containing high concentrations of the alga, although few details are available.

The apparent inconsistency of toxic effects in some cases may be related to the existence of at least six different ecotypes (strains) of the alga that have differing physiological characteristics such as growth rate or salinity preferences, so that toxin production may vary too (see Rensel et al. 2010 for more discussion and literature). Alternatively, low environmental levels of nutrient availability or other stressors may initiate toxin production, such as generally lower water temperatures and enhanced vertical mixing in North Puget Sound versus the SoG during late spring and summer. *Heterosigma* cells that have been treated with an antibiotic (i.e., axenic, bacteria free cultures) have never killed fish in the laboratory. Because bacteria associated with *Heterosigma* are apparently required for toxin production, differing bacteria may have different propensities to elicit toxin production from the alga. Studies of the ecophysiology and toxicity of *Heterosigma akashiwo* in Puget Sound are currently underway by NOAA NWFSC workers (Trainer, unpublished progress report).

Other factors undoubtedly contribute to juvenile and adult salmon mortality with varying rates over differing spatial and temporal distributions. At this point, correlations are the best that researchers can muster to gain insight into the possible strength of contributing factors and have been heavily relied on by some others in the Fraser River sockeye debate. Correlation does not prove cause but compared to any other proposed causes of major variation of marine survival none approach that of the Fraser River sockeye x *Heterosigma* relationship described herein. The Fraser River sockeye case may or may not be a unique situation in the Salish Sea, other salmon runs have not been monitored for concurrent marine survival of the fish and harmful algal bloom dynamics interactions.

Hypothesis 9B Other harmful bloom species are known to occur in the Salish Sea and NE Pacific Ocean waters that either kill fish directly through toxicity or gill damage or create considerable physiological stress or injury.

Other species of harmful algae implicated in fish or invertebrate kills in the Salish Sea include *Chaetoceros* (subgenus Phaeoceros), *Cochlodinium fulvescens*, *Dictyocha* spp., *Chrysochromulina* spp., *Chattonella* sp., *Corethron criophilum* and *Alexandrium catenella*. However, only the HAMP database in British Columbia contains data for all these species throughout the Salish Sea and in four more regions along the outer coast of Vancouver Island where *Heterosigma* blooms are also frequent. Some of these species, especially *Chaetoceros* (Phaeoceros) and *Chattonella* sp. are very likely to contribute to mortality of wild fish in the Salish Sea. The former because of its frequency and virulence at low concentrations throughout the water column as well as occurrence in spring and summer/fall periods of salmon migration and the latter is associated with a high degree of fish toxicity and apparent worldwide expansion in range and severity of effects. Not all HAB species pose a problem to salmon and steelhead. For example, results from oral exposure experiments and observations from multiple and highly toxic bloom events have provided strong evidence that forage fish or their fish predators are not behaviorally affected by domoic acid producing diatoms of the genus *Pseudo-nitzschia* even though forage fish on the US West coast regularly contain high levels of the toxin and act as vectors to seabirds and marine mammals (Lefebvre et al. in press).

In the list of HAB species that could affect wild fish in the Salish Sea only *Chaetoceros* (Phaeoceros) is sufficiently well documented to be summarized here:

Supporting Evidence, *Chaetoceros* (subgenus Phaeoceros)

The marine diatom genus *Chaetoceros* is separated into 2 subgenera by the presence (*Phaeoceros*) or absence (*Hyalochaete*) of long, partly hollow setae or primary spines that contain chloroplasts. *Phaeoceros* species, such as *C. concavicornis* and *C. convolutus* have more robust setae and frustules than *Hyalochaete* species and the setae are armed with short but extremely sharp secondary spines that point toward the distal ends of the primary setae (Cupp, 1943). The chain-forming *Phaeoceros* species are responsible for mortality of wild and farmed fish (Bell 1963, Rensel 1992, 1993a, Yang and Albright 1992, Albright et al. 1993), commercial crab species (*Tester* and Mahoney 1995) and probably at least compromise many other aquatic species that use gills to respire (see review in Appendix of Rensel 2007).

Rensel (1992, 1993a) used scanning electron microscope techniques to show that penetration of salmon gill tissue by *C. concavicornis* was uncommon. Rather, chains of cells tended to lodge between the secondary lamellae and be present in the surrounding gill mucus. Associated fish blood-gas studies showed that affected salmon had severe blood-hypoxia as a result of mucus production during acute exposure or physiological damage to the gills after longer-term exposure. Longer chains of *C. concavicornis* caused significantly lower blood-oxygen partial pressures compared to fish exposed to shorter chains. Longer setae associated with longer chains were apparently more likely to become wedged in the gills and stimulate mucus cell release, lesions and epithelial damage. Salmon respond to *C. concavicornis* exposure by an immediate and periodic cough response that diminishes slightly in frequency over time (Rensel, 1992, 1993a). This is similar to fish coughing caused by many environmental irritants and chemicals (Heath, 1987). Coughing and mucus production act in concert to help clear the gills of the diatoms. Long strings of mucus were seen trailing from the gills of live fish during the 1987 Cypress Island fish kill. Short-term laboratory exposure to as few as 10 cells per ml of *C. concavicornis* caused a rapid increase in mucus cell discharge on the gills as well as a severe hypoxia and elevated carbon dioxide content in the blood of Atlantic salmon (Rensel, 1992; 1993a). Long-term exposure to <5 cells/ml of harmful *Chaetoceros* in net pens has been reported to increase disease and through secondary infection and direct mortality of farmed salmon (Albright et al. 1993). It is clear that very low concentrations of these diatoms can kill salmon, hence the term "bloom" is not always appropriate when referring to harmful *Chaetoceros*-caused fish kills.

It is likely that harmful *Chaetoceros* have caused mortalities of wild and hatchery-released fish, but these effects occur at very low concentrations that are unnoticeable to all but those doing cell counts with a microscope (e.g., no change in affected water appearance, turbidity, dissolved oxygen, or usually even chlorophyll *a* concentration). South Hood Canal and Dabob Bay/North Hood Canal are areas where these harmful diatoms often occur (Rensel et al., 1989; Rensel Associates and PTI Environmental Services, 1991, Taylor and Horner 1994). During the fall of 1990 a mixed water column in north Hood Canal containing *Chaetoceros concavicornis* to at least 40-m depth correlated with the otherwise unexplained mortality of migrating adult Chinook salmon observed by Dept. of Ecology staff (Rensel Associates and PTI Environmental Services, 1991). A protracted bloom of this species in North Puget

Sound in the fall of 1987 (Rensel et al. 1989, Rensel 1990) resulted in chronic mortality of small and large Chinook salmon at Cypress Island net pens. Brood stock that survived had 100% infertility of fertilized salmon eggs resulting in an insurance claim (Rensel, unpublished data). During this bloom the alga was distributed throughout surface and subsurface waters at densities sufficient to cause the observed losses and problems. In southern Hood Canal, mortality of juvenile salmon in seawater pumped from a subsurface depth was due to harmful *Chaetoceros*; this suggests the possibility of a recurring problem for wild smolts moving through the area. Harmful *Chaetoceros* occur in spring and again in September or October, concurrently with migrating juvenile and adult salmon in the Salish Sea, although they may be present at any time of year in Pacific Northwest waters (R. Horner, unpublished data; Rensel, 1992). Occasionally high concentrations are found such as in October 1991 in Dabob Bay with cell numbers near 10^5 cells/L (J. Postel, unpublished data cited in Taylor and Horner 1994). Several fish kills from C. concavicornis have occurred throughout the Salish Sea at fish farms in the past few decades but most are not researched as to extent, depth and severity other than what data is available from the HAMP database.

Refuting Evidence, *Chaetoceros* (subgenus Phaeoceros):

The extent that these other harmful algae influence wild salmon is not possible to estimate, support or refute at this time without additional studies (see Research Recommendations)

Research Recommendations

Heterosigma Monitoring: Strait of Georgia and North Puget Sound

Monitoring is complicated by the variable temporal occurrence of these blooms that range from a few days or a week (in all areas) to months (in the Strait of Georgia). SoundToxins relies on volunteer sampling and analysis with limited coordination funds. The program could benefit from formal quality assurance checks, expansion of spatial and temporal coverage, recruitment of other participants and funds to provide regular posting of results for students, researchers, the public and agencies to use. No routine assessments are made of harmful algae in the south Strait of Georgia except near Nanaimo where volunteer but professional monitoring is conducted by the HAMP program and in nearby North Puget Sound at fish farms. To test the *Heterosigma* effect on sockeye salmon hypothesis, this area must be monitored, with stratified sampling in high risk periods a means to reduce cost. The use of livefish bioassays in bloom and reference areas of the SoG and North Puget Sound at differing depths could be conducted to verify mortality in the same waters and timing that wild sockeye smolts are present. Collection of gill and organ tissues for histological and toxicological analyses would be conducted concurrently. Similarly, coordination of acoustic tagging of sockeye smolts with bloom tracking would expedite understanding of migration pathways through blooms and locations of potential mortality.

There presently are no HAB research experts active in British Columbia. Some training and practice is needed to conduct cell counts of *Heterosigma* in water samples, especially of preserved samples, but expert services are available with the HAMP program in Nanaimo. Costs of monitoring program in the Southern SoG could be minimal, as there would be no need to extensively sample in rainy, cool springs when the fish outmigrate as it is highly unlikely an extensive *Heterosigma* bloom would occur. Volunteer identification of *Heterosigma* in live samples is easier than in preserved samples. Cell counts of samples from major blooms are expedited by the lack or low numbers of other plankton species present in some cases. At these times, monitoring capability is greatly expanded by use of a CTD equipped with a *in vivo* fluorometer, as long as samples are taken to calibrate a chlorophyll x cell abundance ratio for the specific sampling period and locations (Rensel 2007).

There are no fish farms in the South SoG to provide routine samples as there are near some other areas of the Salish Sea, so sampling would be required by small boat(s) in the subject river plume and edge area. Plume area may range from a few hundred to over a thousand km^2, so selection of sampling locations is a difficult issue, but could be informed by review of prior satellite chlorophyll imagery distributions, corrected to deal with the issue of interference from river source particulates and shifts in CDOM absorption. Similarly, the area is too large to safely assume that smolts are using historical migration pathways, but acoustic tagging is probable for other efforts and near real time data could be provided to add to the remote sensing data to provide sampling stations of opportunity.

Heterosigma Cell Monitoring: Other Areas

In other regions of the Salish Sea different arrangements are made for routine monitoring. The HAMP program in B.C. is focused on fish farming areas and provides a highly useful and quality work product, but large areas without fish farms are not routinely monitored. There are extensive data of other HAB species occurrence besides *Heterosigma* that are available in the HAMP database and could be used as a springboard to determine the highest risk species, locations and timings and to evaluate trends. The service is paid for by fish farmers but data is often summarized and posted on line by HAMP staff.

In Puget Sound, there are few fish farms and shellfish culture areas tend to be clustered, leaving other areas unmonitored. These areas include smaller basins and backwater areas. Even if monitoring was conducted routinely in all areas of Puget Sound, there is no one protocol for sampling and analysis or reporting and no one agency has leadership in keeping records, producing reports, contributing to international HAB data compilation efforts, etc. Various contributors participate two list serve systems related to HAB issues: SoundHAB is hosted by Woods Hole Oceanographic Institution and sponsored by NOAA's Center for Sponsored Coastal Ocean Research (CSCOR) for professional researchers, agency staff and aquaculturists to notify each other about bloom events and look for synergies among contributors. SoundToxins network is coordinated by NOAA NWFSC and Washington Sea Grant to train volunteer phytoplankton analysts and has numerous sites in Puget Sound sampled by shellfish culturists, shellfish hatcheries, NGOs and others. SoundHAB is designed to be a notification and coordination network and has publically accessible archives but no formal data collection. SoundToxins has a data collection network and web site designed for long-term data collection but relies on non-professional, volunteer analysts who receive basic training in phytoplankton analysis. These networks are cost effective because they are volunteer based, but information is not collected or distributed on a regular basis and there are broad areas where resources are threatened but no monitoring occurs.

There is a potential role for Tribes in many expediting monitoring of HABs and some like the Jamestown S'Klallam Tribe and Nisqually Tribe are actively involved in such efforts. Tribal biologists who have local knowledge, close contact with Tribal fishers and other member and routine contact with local resources are in a good position contribute significantly to monitoring efforts. Infrastructure for communication or potential data submission and archiving is already in place with SoundToxins network.

Monitoring: Remote Sensing and Surrogate Indicators

As discussed above, use of instrument package buoys or high quality satellite imagery of SST or chlorophyll are potentially useful means to detect heightened risks of *Heterosigma* blooms. It is not uncommon to have >20 ug/L chlorophyll *a* concentrations during blooms. That is sufficient to at least trigger an alert that some species is blooming and follow up with water samples for phytoplankton species identification, particularly at specific high risk times and weather conditions known to lead to *Heterosigma* blooms. An example of an existing program is the Stilliguamish Tribal effort, now in its second year, to monitor the Port Susan estuary with a fluorometer equipped CTD (K. Kilabrew, pers. comm). Tribal biologists are not only interested in *Heterosigma* occurrence using the general approach mentioned above (i.e., chlorophyll and other parameters with the capability to spot sample for phytoplankton species composition should bloom conditions occur), but are interested in timing and abundance of normal primary productivity to further understand the dynamics of the Stilliguamish River estuary. It is emphasized that chlorophyll is a poor indicator of *Heterosigma* occurrence when conducted through remote sensing such as a CTD mooring, unless the extra steps are taken for sample collection, cell counts or at least examination of other forcing factors that contribute to *Heterosigma* bloom initiation and spread. More advanced field processing instrumentation is available to assist with this step as discussed next.

Monitoring with Advanced Instrumentation

Two relatively new technologies are becoming available that may greatly influence efficacy of HAB monitoring. First, the Environmental Sample Processor (ESP) is an advanced and autonomous biological sensing platform that conducts in situ collection and molecular analysis of water samples and telemeters the results to shore in near real-time (Fig. 5). The ESP can remotely detect and quantify the abundance of target organisms (e.g., phytoplankton including HABs and bacteria) using genetic probes that are printed onto an array. The probes generate a signal in the form of light when target organisms are detected, and an image of the array is taken using a camera and telemetered to shore for interpretation by experts. The intensity of the light signal is directly proportional to the abundance of the target organism. An advantage of this technology is that it allows for sustained surveys in remote locations with interactive capability that enables adaptive sampling. It is a developing technology and miniaturization holds great promise for its future. Genetic probes have been developed for *Heterosigma* detection and quantification and were tested again most recently in 2012 in an extended deployment at Friday Harbor Laboratory. The ESP originator (Monterey Bay Aquarium Research Institute), their commercial partners along with NOAA-NWFSC staff are interested in using several (possibly three) ESP units in North Puget Sound and the South Strait of Georgia to help investigate the *Heterosigma* x sockeye salmon hypothesis and other water quality issues. Such an effort cannot be conducted without some grant funding, but in kind contributions will be available from aquaculturists, NGOs and others interested in this application.

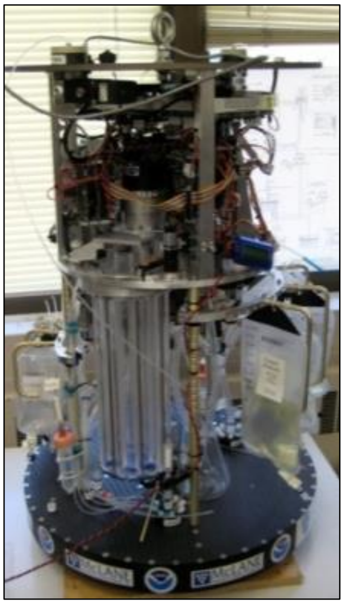


Figure 5. ESP unit without oceanographic deployment shroud at the NOAA NWFSC laboratory in Seattle.

Second, commercial production of a promising instrument for relatively inexpensive but high quality identification and enumeration of nano and micro-phytoplankton has just begun in late 2012. An imaging-in-flow cytometer known as the FlowCytobot, developed at Woods Hole Oceanographic institute, uses open source software to train the unit to enumerate phytoplankton accurately, after being programmed through regional specific training (Oslon and Sosik 2007). The video and cytometry based unit, for large and small size fractions respectively, can operate unattended for months at a time while computing, recording and transmitting data ashore. Such an instrument could contribute profoundly to understanding of HAB occurrence in the Salish Sea and would provide an archive of phytoplankton species composition and abundance, the primary base of the aquatic food web, that is sorely lacking in the region. Other hypotheses in this report point out the necessity of understanding zooplankton abundance as a controller of salmonid productivity and survival. Zooplankton are dependent on the nutritional quality of phytoplankton as prey and those assemblages cannot be assumed to remain constant or accurately characterized by bulk, surrogate measurements such as chlorophyll *a* concentrations. Phytoplankton community composition shifts to less desirable or more prevalent toxic forms are possible and currently we would be challenged to detect the change. With impending climate change effects on aquatic biota, it would be advantageous to finally begin to routinely characterize and quantify the community composition of water column primary productivity in the Salish Sea.

Other HAB species than *Heterosigma*

Routine monitoring of phytoplankton is required to detect blooms or occurrences of the other HAB species mentioned above. As for *Heterosigma*, monitoring could target known migration and residency timing of priority salmonid stocks to reduce costs. If a bloom is occurring, fish sampling of commercial or sport caught fish in the field or in the case of hatchery fish, as adult salmonids return to collection weirs, could be conducted. Simple microscope wet mounts of gill scrapes can indicate if certain species like *Chaetoceros* concavicornis, C. convolutus or *Dictyoch*a spp. are present on the gills and therefore causing stress or cohort mortality as they do with cultured salmonids, marine fish and invertebrates. Affected fish gills produce mucous to dislodge these cells, so the sampling has to be done soon after leaving seawater or while still in seawater. Such monitoring is difficult to plan, as these HABs may occur episodically, as monitoring has been infrequent in Washington State waters of the Salish Sea. Target areas would be hatchery runs that migrate through areas known to experience periodic fish killing or stressing harmful algae blooms (e.g., C. concavicornis in Hood Canal, Port Orchard, the Whidbey Basin and main channels of North Puget Sound) although the actual distribution of these other species is not well established.

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Hypothesis 10. Reduced habitat availability and/or diversity have affected the behavior (and reduced the diversity) of salmon while in the Salish Sea

Chris Ellings and Sayre Hodgson, Nisqually Indian Tribe

Supporting Evidence

The diverse suite of Puget Sound nearshore habitats link freshwater and terrestrial systems with the marine landscape (Fresh et al. 2011). Nearshore habitat supports multiple functions for Pacific salmon as juveniles migrate out of their natal rivers towards marine feeding grounds. Fresh (2006), citing Simenstad and Cordell 2000 characterizes these functions as: 1) feeding and growth, 2) avoidance of predators, 3) the physiological transition from freshwater to saltwater, and 4) migration to ocean feeding habitats. In order for salmon to realize nearshore habitat function, they must have the opportunity to be able to access the habitat and the habitat must have the capacity to support fish once accessed (Simenstad and Cordell 2000). The opportunity and capacity attributes of Puget Sound nearshore habitat for salmon are impaired due to the dramatically altered distribution, diversity, abundance, and quality of Puget Sound nearshore habitat relative to the historic condition.

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) conducted an extensive Puget Sound nearshore habitat change analysis which documented dramatic anthropogenic alterations of nearshore ecosystems (Simenstad et al. 2011). Some of the most dramatic changes, synthesized by Fresh and others (2011) are: 1) 27% loss of large river delta shoreline length for the 16 largest deltas, 2) 46% loss of coastal embayment shoreline length, 3) about 27% of the shoreline of Puget Sound is armored, and 4) tidal wetlands have declined by 56% for the 16 largest Puget Sound deltas. The cumulative impacts of nearshore habitat alterations are losses in connectivity, increased fragmentation, and simplification of nearshore habitat (Fresh et al. 2011). The myriad of nearshore habitat impairments have resulted in reduced opportunity for salmon to utilize the habitat and constricted the capacity of nearshore habitat to support critical salmon functions. The hypothesis that reduced nearshore habitat availability and diversity have affected the behavior, and potentially the diversity, of salmon is most relevant for Chinook and chum, the species with the strongest link to nearshore habitat (Fresh 2006).

Chinook salmon are considered the most estuary and nearshore dependent of the Pacific salmon. Chinook can express multiple life history strategies that utilize estuarine and nearshore habitat in different ways. For example, Beamer et al. (2005) developed the following life history classification scheme for Skagit River Chinook salmon:

- Fry Migrants – These fry emerge from egg pockets and migrate quickly downstream to Puget Sound. Fry migrants do not rear extensively in tidal delta habitat so no tidal delta rearing structure is observed on their otolith. Some fry migrants take up residence in pocket estuary habitat.
- Tidal Delta Rearing Migrants – Tidal delta rearing fry emerge from egg pockets and migrate downstream at the same time as fry migrants. Instead of directly entering Puget Sound, they reside in tidal delta habitat for a period ranging from several weeks up to several months.

- Parr Migrants – These fry emerge from egg pockets and rear for a couple of months in freshwater to achieve a similar size as their tidal delta rearing cohorts over the same time period. Parr migrants do not reside in tidal delta habitats.
- Yearlings – These fry emerge from egg pockets and rear in freshwater for a period over one year. Yearlings do not reside in tidal delta habitats for an extended period of time like tidal delta rearing migrants. Yearlings are rarely found in shallow intertidal environments, but are most commonly detected in deeper subtidal or offshore habitats.

After rearing in the tidal delta, Chinook can be found utilizing a variety of nearshore habitat from late spring to early summer, with peak abundances in May – early July (Fresh et al. 1979; Duffy 2003; Ellings and Hodgson 2007). After leaving their natal delta Chinook can distribute broadly into estuarine and nearshore habitat throughout Puget Sound. For example, Ellings and Hodgson (2007) analyzed over 230 coded wire tags (CWT) from hatchery Chinook captured in the Nisqually estuary located in South Puget Sound and found that over 26% of those tagged fish were from hatcheries outside of the Nisqually watershed, with some of the CWT recoveries from hatcheries in Central and North Puget Sound watersheds including the Puyallup River, the Duwamish River, and Snohomish River. Fry migrant Chinook utilize very specific embayment habitat types called pocket estuaries in early spring (Beamer 2003; Ellings and Hodgson 2007). These very particular habitat types appear to be incredibly important early marine rearing areas for this specific life history strategy (Beamer 2003).

Chum salmon fry leave freshwater quickly after emergence (Salo 1991). Chum can be found rearing throughout delta and nearshore habitats from March- July with peak abundance in May and June (Duffy 2003; Brennan et al. 2004; Fresh et al. 2006; Ellings and Hodgson 2007). Chum, like Chinook appear to move offshore as they increase in size (Fresh 2006)

Chinook and chum utilize nearshore and estuarine habitat in Puget Sound extensively during their early marine rearing phase. The opportunity for salmon to access high quality nearshore habitat and the capacity of existing nearshore habitat to support salmon continues to decline (Fresh et al. 2011) however; the extent to which reductions in opportunity and capacity have altered the behavior of estuary and nearshore rearing salmon is unclear. Toft et al. (2007) found reduced densities of juvenile salmon along Puget Sound shorelines under overwater structures and found increased densities at the edges of overwater structures and on shorelines with deep riprap (compared to sand beaches, cobble beaches, and shallow riprap shorelines), indicating that these habitat alterations can alter fish behavior, though it is unclear whether fish select these areas with high densities or were concentrated there due to interrupted movement or loss of shallow-water habitat. These changes in distribution could lead to impacts on competition, feeding and susceptibility to predation. Alterations to Puget Sound shorelines may also reduce input of terrestrial-derived prey for salmon with potential impacts on the habitat's overall capacity to support juvenile salmon and reduced growth and survival (Toft et al. 2007).

Data Needs

Fresh (2006) lists the following 7 gaps and critical uncertainties in our knowledge about salmon in nearshore ecosystems:

- How do juvenile Chinook salmon use the habitats associated with the shoreline areas of Puget Sound?

- How do juvenile salmon move around in Puget Sound (movement, distribution, residence time in different habitat types) and how does this differ among populations?
- What are the linkages between habitat use and population viability parameters (e.g., productivity)? Are there differences in how different populations, different races (e.g., summer vs. fall chum salmon) and different life history strategies use shoreline/littoral habitats?
- What factors affect the residence time of juvenile chum salmon in deltas?
- How do hydrodynamic processes affect distribution and movements of juvenile salmon within Puget Sound?
- What is the capacity of nearshore habitats to support salmon?

Some additional gaps we have identified include:

- What role does the quality, quantity, and distribution of estuary and nearshore habitat play in supporting various life histories of Chinook and other salmon?
- Do local habitat degradation and other nearshore stressors lead to indirect impacts such as altered migratory pathways or increased predation?
- How do timing and use patterns of estuary and nearshore habitat in Puget Sound compare to the range of patterns expressed by the species in other regions with high quality habitat (as an indicator of potential historic patterns here)?

Research Recommendations

Activities that address the hypothesis include retrospective analyses and future monitoring of juvenile fish movement and distribution patterns, comparison of prey availability, competition, predation and behavior impacts in different habitat conditions, and long-term status and trends monitoring. These activities should incorporate information on differences between life history types. Pairing up the habitat data and condition analyses of the Puget Sound Nearshore Ecosystem Restoration Project with the results of the biological monitoring proposed as part of the marine survival research program's 5-year intensive monitoring effort—including salmon (and forage fish) survival, distribution and movement; and prey monitoring—will likely address several of the data needs listed above. To achieve this, a representation of various habitats and habitat conditions should be considered when establishing the intensive fish monitoring effort.

Management Implications

The following is a list of conceptual strategies that could be applied in response to the research results if the hypothesis was found to be correct.

- Prioritizing key habitats for protection and restoration.
- Using scientific studies documenting the importance of the habitat to justify increased protection (e.g. update with stronger regulations over time) and restoration.
- Restore (or enhance when restoration is not feasible) degraded key habitats such as estuaries (all sizes), eelgrass/kelp beds, and forage fish spawning areas. This includes actions such as

removing shoreline armoring and fill, replacing culverts at creek mouths with larger structures, reconnecting feeder bluffs or adding beach nourishment, etc.

- Designating priority areas or corridors for increased protection and restoration.

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Hypothesis 11. Toxic contaminant inputs have increased, affecting marine survival of salmon through reductions in growth and resistance to disease

Sandie O'Neill and Lyndal Johnson, NOAA Northwest Fisheries Science Center

The Puget Sound Lowland is the most densely populated area of Washington and is expected to grow rapidly in the future. Human development of the Salish Sea has resulted in habitat loss and modification. Much attention has been paid to the physical habitat alterations and climate-driven processes that may be responsible for the recent declines in marine survival of salmon but contaminants have also reduced habitat quality and also affect salmon survival.

Core Hypothesis

Chemicals released into the Puget Sound from human activities and developments reduce the health and productivity of salmon. Contaminant inputs to the Salish Sea and its watershed are hypothesized to effect marine survival of salmon directly and indirectly as follows:

H-11_A Exposure to contaminants in estuarine and marine waters reduces the marine survival of juvenile salmon migrating through the Puget Sound to the Pacific Ocean.

H-11_B Exposure to contaminants in estuarine and marine waters of Salish Sea reduces the marine survival of salmon residing in the Salish Sea

H-11_C Exposure to contaminants in freshwater habitats causes latent reductions in marine survival of juvenile salmon.

Background

Susceptibility of Puget Sound ecosystem to contaminant inputs

Puget Sound is unique among US estuaries in being a deep fjord-like structure that contains many urban areas within its drainage basin. Sills limit the entry of oceanic water into Puget Sound, thus it is poorly flushed compared to other urbanized estuaries of North America. Toxic chemicals that enter Puget Sound stay longer in the system, and so biota are exposed to higher levels of contaminants for a given input, compared to other large estuaries. This hydrologic isolation also puts the Puget Sound ecosystem at higher risk from other types of pollutants that enter the system, such as nutrients and pathogens. The contaminant problems in Puget Sound are exacerbated by biological isolation; many species remain resident within Puget Sound and so are exposed to contaminants for longer periods and at higher concentrations than might otherwise occur.

Toxics contaminants enter Puget Sound via surface runoff, wastewater treatment, atmospheric deposition, and groundwater. Industrial pollutants are generally found near discharges but they also concentrate in depositional zones that can be distant from point sources. Because of their anadromous life-history, salmon and steelhead (henceforth, for simplicity, "salmon") may be exposed to contaminants in freshwater, estuarine and marine waters. Juvenile salmon can encounter a wide range of water quality conditions, from relatively clean to highly contaminated, as they migrate from freshwater to saltwater in Puget Sound. During this life stage, as they transition from fresh to saltwater, they are particularly sensitive to stressors such as toxic contaminants. Once in the saltwater, they may continually be exposed to contaminants that accumulate in the urbanized bay of Puget Sound and in the coastal water of the North Pacific adjacent to developed and urbanized landscapes.

Contaminants in the Puget Sound

Broadly speaking, there are two classes of contaminants:

- persistent, bioaccumulative and toxic (PBT); and
- toxics that tend to be soluble and less persistent than PBTs.

This distinction is important in the context of salmon because these two categories behave differently in the environment and exert their effects differently.

Persistent, bioaccumulative and toxic (PBT) contaminants

These contaminants include well-known legacy chemicals such as polychlorinated biphenyls (PCBs), the chlorinated pesticide DDT, dioxins, and some heavy metals, and as well as recently emerged chemicals used as flame retardants: polybrominated diphenyl ethers (PBDEs).

PBTs are fat-soluble, persist in the environment, accumulate in animals with age, and biomagnify through the food chain so they can concentrate in fishes, including salmon. PBTs are not easily metabolized and therefore fishes and other animals *carry the risks* from these contaminants with them through their entire life cycle. PBTs are subject to global transport and they continue to cycle in the environment decades after their peak use. Environmental concentrations of legacy PBTs, including PCBs, DDT, and dioxins, peaked in the 1960s - 1970s, then declined rapidly from late the 1970s through mid 1980s because of regulations at the national and international level. However, they have shown little decline since then, and are still at concentrations that cause adverse effects in aquatic resources. Flame retardants are not regulated by EPA, although certain forms of PBDEs have been banned in Washington (RCW 70.76) and Oregon ORS 453.005-135). PBDEs increased exponentially from the 1970s but currently appear to be declining in some fish species in the Salish Sea (West et al. 2011).

Non-persistent contaminants

The second class of contaminants tends not to accumulate in fish because they are either less persistent, less fat-soluble, or do not move readily through the environment. Non-persistent contaminants include compounds with adverse affects such as polycyclic aromatic hydrocarbons (PAHs) and copper, and newer chemicals of emerging concern such as pharmaceuticals, natural hormones, currently used pesticides, bisphenol A (BPA), and surfactants (e.g. PFOS). Some of these contaminants may be fairly localized with usage or discharge and can affect fish during sensitive developmental stages. Some of the non-persistent chemicals of concern for Puget Sound are discussed below.

<u>PAHs</u> are toxic and carcinogenic chemicals that occur naturally in coal, crude oil and gasoline and in products made from fossil fuels, such as coal-tar pitch, creosote and asphalt. PAHs enter streams, rivers, and estuaries through industrial discharges, stormwater runoff from highways and other paved surfaces, and atmospheric deposition. PAHs are metabolized by salmon and other fish Varanasi et al., 1989), so

they do not accumulate in fish tissues, but nonetheless can be highly toxic to fish. Sediment cores from the Puget Sound region reveal that maximum PAH concentrations occurred between 1945 and 1960, then decreased for the next 20 to 30 years (MacDonald and Crecelius, 1994). However, a recent study by Washington State Department of Ecology comparing surface sediment collected in 2000 to results from 1989 through 1996 at 10 long-term Puget Sound sites showed that PAH levels were significantly higher in samples collected in 2000 than they were historically at 5 of the 10 sampling (PSAT, 2004). Early declines in PAH concentrations can be attributed to the switch from coal to oil and natural gas for home heating, improvements in industrial emissions controls, and increases in the efficiency of power plants (Gschwend and Hites, 1981). More recent, PAH increases have been linked to increasing urban sprawl and vehicle traffic in urban and suburban areas (Lefkovitz et al. 1997; Van Metre et al. 2000, in press).

In the 1970s and 1980s, after chlorinated pesticides such as DDTs were banned because of their adverse environmental and health effects, a number of new, less persistent pesticides were developed and licensed. These compounds, referred to as current-use pesticides, include herbicides, insecticides, and fungicides, and do not tend to accumulate in the environment because they are highly water-soluble and have a short soil half-life. While agriculture application accounts for over 75% of pesticides used, urban usage is increasing.

Copper is widely used in building materials (e.g., copper roofs and treated lumber), automobile parts (e.g., brake pads), and pesticides (Davis et al., 2001). Consequently, copper is often a pervasive contaminant in urban and agricultural watersheds where juvenile salmon rear prior to oceanic migration. It can enter aquatic environments in urban stormwater and agricultural runoff.

Other chemicals threatening ecological health include bisphenol A (BPA), the synthetic hormone 17-a ethynylestradiol (EE2), and exogenous sources of the hormone 17-b estradiol (E2). These xenoestrogens, commonly detected in water and sediments, can disrupt hormonal and metabolic processes at low concentrations.

Summary on Contaminants' Potential Impacts to Salmon

PBTs and non-persistent contaminants can reduce the productivity of salmon populations. PBTs could predispose salmon to mortality through a range of sublethal effects. Non-persistent contaminants can be difficult to monitor but these toxicants may also reduce salmon survival. Both classes of contaminants could also reduce salmon productivity indirectly, through effects on food quality and availability. Toxics, on their own, may help to contribute to long-term trend in marine survival but generally will not cause large year-to-year variation.

The Toxic Contaminant Hypotheses

General Approach to Ecotoxicological Investigations

The potential effects of toxic contaminants on marine survival of salmon in the Salish Sea were evaluated through a broad interdisciplinary approach. For each hypothesis presented below, we provide exposure assessments that are tightly linked to the detection of effects at several levels of biological organization, including biochemical changes, growth, reproduction, larval and embryonic development and immunocompetence and disease susceptibility.

H-11$_A$ Exposure to toxic contaminants in estuarine and marine waters of Puget Sound reduces the marine survival of juvenile salmon migrating through the Salish Sea to the Pacific Ocean

Supporting Evidence

Species and Populations Most at Risk

Juvenile salmon integrate contaminant conditions from across the freshwater/saltwater interface, the primary receiving waters for stormwater-borne and other contaminants. Impairment of water quality in these highly productive habitats represents a significant threat to salmon populations. Chum salmon, and ocean-type Chinook salmon, the predominant life-history type in Puget Sound, considerably more time, in estuaries than other salmon species, and thus are more susceptible to contaminant exposure during their out-migrant phase. Additionally, Chinook salmon will accumulate higher PBT contaminant burdens than other salmon because of their higher trophic status.

Justification for Research: Field Assessments of Contaminant Exposure

Systematic, comprehensive monitoring of juvenile salmon for contaminant exposure has not occurred in Puget Sound; however, sampling conducted by WDFW and NWFSC indicates that many juvenile Chinook salmon from Puget Sound urban populations are exposed to several PBT and non-persistent contaminants. Exposure to PBTs such as PCB and PBDEs are often above estimated effects thresholds or at concentrations at which know effects occur (Table 1). More limited PBT exposure assessments have been completed for chum, coho and pink salmon. Generally, concentrations of PBTs in coho and pink salmon are lower than those observed for Chinook salmon from the same locations, whereas concentrations in Chinook and chum salmon are similar (Stehr et al., 2000; Olson 2007). Such differences are likely related to habitat use, diet and metabolism. Assuming the estuary is an important source of contaminants for out-migrant salmon, higher contaminant exposures in Chinook and coho salmon are consistent with the more prolonged period of estuarine exposure in these species (Quinn 2005).

Table 1. Concentrations of PCBs and PBDEs in whole body samples of juvenile Chinook salmon from Puget Sound estuaries, and percentages of samples exceeding health effects thresholds for PCBs and PBDEs. NA = no data available.

Site	N	Mean ± SD concentration of PCBs (ng/g lipid)	Mean ± SD concentration of PBDEs (ng/g lipid)	% of samples with PCBs > 2400 ng/g lipid	% of samples with PBDEs > 1400 ng/g lipid
Skagit	12	2000 ± 2000 [2]	1300 ± 3500 [1]	23%	7.70%
Snohomish	6	4000 ± 1700 [2]	2400 ± 1100 [1]	85%	86%
Elliott Bay	6	14000 ± 13000 [2]	560 ± 390 [1]	100%	0%
Duwamish	13	4800 ± 2200 [2,3]	560 ± 770[1]	86%	17%
Commencement Bay	21	1700 ± 1100 [4]	NA	24%	NA
Nisqually	1	1500 [4]	NA	0%	NA
Squaxin Pass	6	5200 ± 270 [5]	570 ± 330 [5]	100%	100%
Skokomish	1	980 [3]	NA	0%	NA

[1]Sloan et al. 2010; [2]unpublished NWFSC data; [3]Johnson et al. 2007; [4]Olson et al. 2008; and [5]WDFW unpublished data

Additionally, exposure to non-persistent PAHs has been examined in juvenile Chinook, coho, and chum salmon from 5 hatcheries and their respective estuaries of five river systems of Puget Sound: the Green-Duwamish, the Puyallup-Hylebos/Commencement Bay, the Nisqually, the Snohomish, and the Skokomish (McCain et al. 1990; Olson et al., 2007; Stehr et al., 2000; Stein et al., 1995). Salmon collected from the Duwamish and Commencement Bay/Hylebos Waterway estuaries adjacent to Seattle and Tacoma showed elevated levels of PAH metabolites in bile in comparison to fish from hatcheries or from the less-urbanized Nisqually and Skokomish systems.

Justification for Research: Effects of Contaminant Exposure on Salmon Growth

Growth is impaired for out-migrant juvenile salmon while migrating through urban estuaries and bays of Puget Sound (Casillas et al. 1995 a,b,1998). The growth rates of juvenile Chinook salmon collected from urban estuaries (e.g., Hylebos and Duwamish Waterways) and held in the laboratory for 90 days, were lower than those for fish from the corresponding hatcheries or from nonurban estuaries. Furthermore, concentrations of plasma hormones involved in the regulation of growth in fish, such as thyroxine (T4), triiodothyronine (T3), and insulin- like growth factor (IGF), were altered in salmon from urban estuaries in comparison with hormone levels in hatchery or non-urban fish (Casillas et al., unpublished data). Thus exposure to contaminants may interfere with the endocrine modulation of growth in juvenile salmon, reducing overall growth.

Additionally, laboratory exposure experiments using sediment extracts from contaminated Puget Sound sites and model toxic compounds indicated that exposure to toxic contaminants may suppress growth or alter the metabolism of juvenile Chinook salmon (Casillas et al., 1998, Meador et al. 2006). In studies by Casillas et al. (1998), there was some uncertainty regarding the concentrations of PAHs required to suppress growth of juvenile salmon because fish exposed to PAHs alone at concentrations comparable to those present in the Hylebos Waterway did not exhibit consistent reductions in growth in all treatment groups, although growth was reduced consistently in fish exposed to sediment extracts containing PAHs in combination with PCBs and other contaminants. Meador et al. (2006) dosed juvenile Chinook salmon with PAHs at 5 different concentrations in feed encompassing PAH concentrations measured in stomach contents of juvenile salmon from Pacific Northwest estuaries. Significant differences in mean fish weight, and whole body lipids were detected at the two highest doses. At the lowest doses, variability in fish weights increased significantly. Additionally some significant alterations in plasma chemistry enzymes were observed at the second lowest and higher doses. These studies indicate effects of PAHs on fish growth and energy balance but also suggest that other compounds present in contaminated Puget Sound estuaries, such PCBs, are contributing significantly to growth reductions that have been observed in field collected fish; however, more work is needed to determine the relative importance of various compounds in generating this effect.

Justification for Research: Effects of Contaminant Exposure on Immuno-competence

Exposure to environmentally relevant concentrations of PAHs, PCBs and PBDEs suppress the immune system, rendering salmon more vulnerable to naturally occurring pathogens (Arkoosh and Collier, 2002; Arkoosh et al. 1994, 1998, 2001, 2010). Arkoosh et al. (1998) demonstrated that Chinook salmon from an urban estuary were more susceptible to bacteria-induced mortality from naturally occurring marine pathogen than were fish from the corresponding hatchery upstream from the urban-estuary, and fish from a nonurban estuary and its corresponding hatchery (Figure 1).

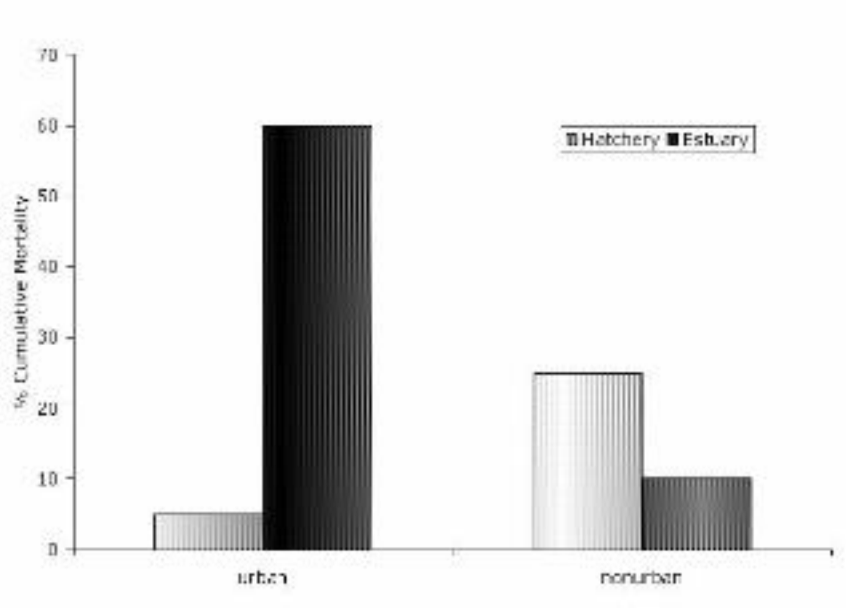

Figure 1. Percent cumulative mortality of juvenile Chinook salmon from an urban and nonurban estuary and their corresponding hatcheries four days after exposure to the marine pathogen *V. anguillarum.* (Adapted from Arkoosh, M.R. et al., *Trans. Am. Fish. Soc.*, 127, 360–374, 1998.)

Follow-up laboratory exposure studies with sediment extracts and contaminant model mixtures determined that contaminants such as PCBs and PAHs, apart from other estuarine variables specifically associated with the Duwamish and Hylebos Waterways, could independently suppress immune function and increase disease susceptibility in juvenile Chinook salmon (Arkoosh et al., 1994, 2001). More recently, studies have documented that exposure to PBDEs also influence disease resistance (Arkoosh et al. 2010). Though an adverse health effects threshold for PBDEs has yet to be determined, Arkoosh et al. (2010) demonstrated that juvenile salmon fed an environmentally relevant concentration of PBDE congeners were more susceptible to the marine pathogen *Listonella anguillarum*.

Justification for Research: Effects of contaminant exposure on reproductive development

There is evidence that juvenile Chinook salmon are exposed to estrogenic contaminants in estuarine and nearshore waters that can affect their reproductive development. Peck et al. (2011) documented higher plasma levels of estrogen-inducible yolk protein, vitellogenin (VTG), in field caught Chinook salmon at sites such as Elliott Bay and the mouth of the Snohomish River than non-exposed hatchery control fish. Juvenile Chinook with elevated VTG during a sensitive early life stage could experience delayed reproductive effects such as those observed in independent studies on flounder or rainbow trout (Hashimoto et al. 2000 and Bennetau-Pelissero et al. 2001)

Data Needs and Research Recommendations

Exposure and effects data for some newly emerging chemicals of concern, including xenoestrogens, pharmaceuticals and personal care products, are very limited for marine systems, including Puget Sound, but are necessary to assess the risk that they pose for the health of salmon in the Salish Sea. Additionally data on trends in contaminant body burdens of juvenile salmon are lacking. To date, most of the assessments of contaminant exposure in field-caught Chinook salmon from Puget Sound have been limited to nearshore estuarine waters, sampled with beach seines. To more fully evaluate contaminant exposure, additional sampling of contaminant exposure in neritic and offshore areas of Puget Sound are needed.

Retrospective

- Conduct a review of the literature to assess potential effects of environmentally relevant exposures of legacy contaminants and chemical of emerging concern (especially xenoestrogens, pharmaceuticals, and personal care products) on salmon. This review should address 1) the available literature for priority chemical contaminants that, based on likely hazard and occurrence, pose the most important threats to salmon; 2) known mechanisms of toxicity, with clear biological connections to salmon individual fitness (lifetime survival and reproductive success); 3) established toxicity thresholds that can inform past, ongoing, and future monitoring in Puget Sound; 4) new technologies, including molecular biomarkers, that can improve the diagnostic power of monitoring for both contaminant exposure and adverse health outcomes in salmon; and 5) a gap analysis to identify where cause-and-effect toxicity studies are needed to most effectively guide salmon conservation and recovery in Puget Sound.

Monitoring

- Conduct juvenile salmon contaminant monitoring surveys for Chinook (and possibly chum) salmon to assess field exposure and effects: Funding is also needed to support and expand existing monitoring programs to document the extent and magnitude of contaminants in neritic and offshore water to which salmon may be exposed. In particular, measures of juvenile salmon exposure to xenoestrogen, pharmaceutical and personal care products, and pyrethroids are needed. Where possible, field assessments should assess potential effects of contaminants on salmon health in addition to exposure. Field assessment may include alterations in genes, proteins, and hormones that control growth, immuno-competence and reproductive development, as well as measures of growth and condition, such as lipid content. Such monitoring will better characterize the threat that contaminants pose to juvenile salmon and will provide a measure of the effectiveness of current strategies and near term actions to reduce toxics threats to Puget Sound. This should be done as part of the intensive, space-for-time fish monitoring effort described in the body of this report.

Process studies

- Diagnostic laboratory studies to characterize the threat that BPA, exogenous E2, EE2, pharmaceuticals, and other contaminants of emerging concern, pose to salmon growth, reproduction, and survival. These studies would establish mechanisms, thresholds and indicators for toxicity that could be applied in field assessments and toxic reduction effectiveness monitoring, and provide controlled context for investigating interactions between chemical and non-chemical stressors.

Modeling

- Apply modeling techniques to explore population and ecosystem impacts of contaminant exposure scenarios. These methods could be used to determine whether hypotheses associated with contaminant exposure and effects are consistent with the patterns of survival of different species and populations of salmon and trout. Several types of modeling could be used, including population modeling, trophic transfer modeling to examine food-web-mediated impacts, and spatial exposure modeling based on land cover and toxic inputs.

Cross-Referenced Hypotheses:

- Hypothesis 3: Size-selective mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood. – *Increased contaminant input to Puget Sound may reduce growth of salmon, especially in urban bays*.

- Hypothesis 12: Food supply limits growth, and thus survival, during critical periods of early marine rearing. – Increased contaminant input to Puget Sound, especially the Main Basin, may affect the quality of salmon's food supply.

- Hypothesis 13. Predation by larger fish and marine mammals has increased on salmon and steelhead, respectively. And, the potential effect of bird predation represents a significant knowledge gap. – *Contaminant related reductions in growth, swimming swimming speed, and immune-competence, may increase predation by larger fish and marine mammals.*

- Hypothesis 14: Infectious and parasitic diseases are causing direct and indirect mortality. - Contaminant related reductions immune-competence may increase susceptibility to infectious and parasitic diseases.

H-11$_B$ Exposure to toxic contaminants in estuarine and marine waters of Salish Sea reduces the marine survival of salmon residing in the Puget Sound

Supporting Evidence

Species and Populations Most at Risk

Adult salmon accumulate the majority (> 96%) of PBTs while feeding in the marine environment rather than in their freshwater and estuarine habitats (Cullon et al. 2009; O'Neill and West 2009), as over 98% of their growth occurs in saltwater (Quinn 2005). Species and populations of Pacific salmon vary considerably in their marine distribution and, depending on where they feed, can be differentially exposed to PBTs. Coastal waters near dense human populations tend to receive higher inputs of land-based sources of PBTs than offshore areas.

In general, **sub-adult and adult Chinook and coho salmon have more coastal marine distributions and are more are readily exposed to contaminants in coastal waters than other species.** In contrast, when sockeye, pink, and chum salmon enter the marine environment, they rapidly migrate northward and westward through coastal waters of North America and are found in the open waters of the North Pacific, Gulf of Alaska and Bering Sea by the end of their first year at sea (Quinn 2005). Consequently, the amount of time they spend feeding in more contaminated coastal environments is limited, as is evident by their lower POP concentrations.

Some Chinook and coho salmon spend all or most of their time in marine waters with Puget Sound and associated parts of the Salish Sea, and are termed "residents". O'Neill and West (2009) estimated that average residency rates of subyearling and yearling Puget Sound Chinook salmon was 29% and 45%, respectively, but noted considerable year to year variation. More recently, Chamberlin et al. (2011) provided comparable estimates of percent residency for Puget Sound Chinook salmon. As detailed below, these fish are higher in POP concentrations than conspecifics feeding along the continental shelf.

Justification for Research – Field Assessments of Exposure

Various studies have measured low to moderate concentrations of POPs in many populations of free-ranging adult Pacific salmon, underscoring the widespread distribution of these contaminants (See Table 2). A meta-analyses of these data reveal that **throughout their geographic range, the observed levels of POPs in adult Pacific salmon appears to be primarily determined by geographic proximity to contaminated marine environments (and contaminated prey).** However, biological traits such as trophic status, lipid content, duration of exposure (life span and fish age), species-specific metabolism and detoxification may also exacerbate or mitigate the degree to which POPs are accumulated in Pacific salmon.

Measured average concentrations of PCBs and PBDEs were highest for Chinook (29 ng/g and 7.3 ng/g), intermediate for coho (14 ng/g and 0.2 ng/g), less for sockeye (7.6 ng/g and 0.15 ng/g), and lowest for pink and chum salmon (<3 ng/g PCBs and < 0.2 ng/g PBDEs; Table 2). Similarly, average DDT values were elevated in Chinook and coho salmon (15.7 and 18.1 ng/g) compared to sockeye (8.60 ng/g) and lowest for pink and chum salmon (<2.0 ng/g).

Table 2a. Lipid and POPs Concentrations (ng/g wet weight) of adult and subadult Chinook salmon sampled in terminal areas. Terminal areas include coastal marine water and river mouths through which fish migrate en route to their natal stream.

Species	Region	Sub-region	Population	Sampling Location	Sex	n	Tissue Analyzed	Lipids (%)	PCBs	DDTs	PBDEs	Citation
Chinook	Alaska	unknown	unknown	unknown		2	muscle wo/skin	NR	5.6	NR	0.95	4
		Aleutian Islands	unknown	unknown		3	muscle w/skin	7.6	5.0	22	0.71	14, 15*
		SE Alaska/ Gulf of Alaska/ Berring Sea	unknown	unknown		35	muscle wo/skin	9.7	11	7.1	0.53	21
		SE Alaska	unknown	unknown		3	muscle w/skin	NR	8.0	NR	0.50	5*, 6*
		South Central	River	Kenai River	F	10	muscle wo/skin	NR	9.1	9.8	NR	13
		Alaskan Chinook salmon average						**8.7**	**7.7**	**13.0**	**0.67**	
	British Columbia	unknown	unknown	unknown		3	muscle w/skin	NR	17	NR	4.20	0
		BC North Coast	Skeena			30	whole body	NR	7.3	7.3	0.08	11
		Fraser River	Thompson	Johnstone Strait		6	muscle wo/skin	10	9.1	1.5	NR	1
				Johnstone Strait		13	whole body	NR	9.4	6.6	0.80	11
			Thompson	Fraser River		7	muscle wo/skin	12	8.6	7.7	1.54	17**
			Shuswap	Fraser River		2	muscle wo/skin	3.0	9.8	5.5	NR	17**
			Harrison	lower Fraser River		6	muscle wo/skin	5.4	47	4.3	17.7	1
		Fraser River Chinook salmon AVERAGE (excluding Harrison)						**8.3**	**10**	**5.7**	**1.67**	
		British Columbia Chinook salmon Average						**7.6**	**15**	**5.5**	**4.87**	
	Washington	Puget Sound	Nooksack River	Nooksack River		28	muscle wo/skin	3.5	37	NR	NR	12
			Skagit River	Skagit River		29	muscle wo/skin	4.8	40	NR	NR	12
			Duwamish River	Duwamish River		65	muscle wo/skin	7.3	56	NR	NR	12
			Nisqually River	Nisqually River		20	muscle wo/skin	3.8	41	NR	NR	12
			Deschutes River	Deschutes River		34	muscle wo/skin	1.7	59	NR	NR	12
			PS mixed	marine waters		28	muscle wo/skin	4.8	76	NR	NR	12
			Duwamish River	Duwamish River		3	whole body	6.4	35	18.3	6.43	1
			Deschutes River	Deschutes River		4	whole body	4.3	56	NR	NR	1
			Deschutes River	Deschutes River		10	muscle wo/skin	1.0	49	NR	NR	8
			Issaquah Creek	Issaquah Creek		10	muscle wo/skin	0.6	49	NR	NR	8
			PS mixed	Puget Sound rivers		36	whole body	NR	43	29.1	18.9	11
			PS mixed	marine waters		34	whole body	NR	91	16.4	42.2	11
		WA Coast	Makah	Makah Hatchery		10	muscle wo/skin	1.5	19	NR	NR	8
		WA Coast	Quinault	Quinault Hatchery		10	muscle wo/skin	1.8	16	NR	NR	8
		Puget Sound Chinook salmon Average						**3.8**	**53**	**21.3**	**22.5**	
		Washington Coast Chinook salmon Average						**1.7**	**17**	**NR**	**NR**	
		Washington Chinook salmon Average						**3.5**	**48**	**21.3**	**22.5**	
	Oregon	unknown	unknown	unknown		3	muscle w/skin	NR	10	NR	2.10	5*, 6*
		Columbia River	unknown Fall	Columbia River		17	whole body	NR	18	19.9	3.69	11
			unknown Spring	Columbia River		20	whole body	NR	33	34.8	9.77	11
			mixed fall Chinnook			15	muscle w/skin	7.0	37	21.0	NR	18
			mixed spring Chinook			24	muscle w/skin	9.0	38	22.0	NR	18
			fall Chinnook	Clackamas River		4	whole body	9.4	15	NR	2.30	16
			Clackamas River	Clackamas River		3	muscle w/skin	8.8	13	NR	1.80	16
			Clackamas River	Clackamas River		3	muscle wo/skin	6.1	10	NR	1.50	16
		Oregon Chinook salmon average						**8.1**	**22**	**24.4**	**3.53**	
	California	Sacramento /San Joaquin	unknown	Point Reyes		29	whole body	NR	14	33.6	2.56	11
	Chinook salmon Average							**5.6**	**29**	**15.7**	**6.22**	

Table 2b. Lipid and POPs Concentrations (ng/g wet weight) of adult and subadult sockeye salmon sampled in terminal areas. Terminal areas include coastal marine water and river mouths through which fish migrate en route to their natal stream.

Species	Region	Sub-region	Population	Sampling Location	Sex	n	Tissue Analyzed	Lipids (%)	PCBs	DDTs	PBDEs	Citation
Sockeye	Alaska	unknown	Alaska	unknown		2	muscle wo/skin	NR	3.6	NR	0.21	4
		Aleutian Islands	unknown	unknown		13	muscle wo/skin	5.8	*130*	6.9	NR	3
		Kodiak	unknown	unknown		3	muscle w/skin	NR	5.0	NR	0.10	5*, 6*
		Gulf of Alaska/ Berring Sea	unknown	unknown		24	muscle wo/skin	8.2	13	12.0	0.22	21
		Gulf of Alaska/ Berring Sea	Copper River	Copper River		97	muscle wo/skin	5.5	37	12.2	NR	19**
		SE Alaska	unknown	unknown		3	muscle w/skin	NR	13.3	NR	0.10	5*, 6*
		Alaskan sockeye salmon average						**6.5**	**14.4$^{\#}$**	**10.4**	**0.16**	
	British Columbia	unknown	unknown	unknown		3	muscle w/skin	NR	8.0	NR	0.10	5*, 6*
		Fraser River	Early Stuart	Port Renfrew	F	3	soma	16	*13*	NR	NR	7**
			Early Stuart	Yale, Fraser River	F	5	muscle wo/skin	4.0	3.9	NR	NR	7**
			Early Stuart	Yale, Fraser River	M	6	muscle wo/skin	5.0	6.9	NR	NR	7**
			Adams	Fraser River (mouth)		5	muscle wo/skin	8.8	7.7	6.6	NR	17**
			Weaver Creek	Harrison River	F	3	muscle wo/skin	1.4	6.8	NR	NR	7**
			Weaver Creek	Harrison River	M	2	muscle wo/skin	1.1	3.6	NR	NR	7**
			Weaver Creek	Weaver Creek	F	2	muscle wo/skin	1.5	5.3	NR	NR	7**
			Weaver Creek	Weaver Creek	M	1	muscle wo/skin	1.1	4.0	NR	NR	7**
			Weaver	Fraser River (mouth)		8	muscle wo/skin	3.9	6.8	5.4	NR	17**
		West Coast VI	Great Central Lk.	Barkley Sound	F	6	muscle	6.1	1.7	NR	NR	7**
			Great Central Lk.	Barkley Sound	M	3	muscle	6.6	1.6	NR	NR	2**
			Great Central Lk.	Robertson Creek	F	2	muscle	1.0	1.5	NR	NR	2**
			Great Central Lk.	Robertson Creek	M	3	muscle	1.0	2.4	NR	NR	2**
		British Columbian sockeye salmon Average						**4.4**	**5.2**	**6.00**	**0.10**	
	Sockeye salmon Average							**4.8**	**7.6$^{\#}$**	**8.6**	**0.15**	

Table 2c. Lipid and POPs Concentrations (ng/g wet weight) of adult and subadult steelhead and coho, pink and chum salmon sampled in terminal areas. Terminal areas include coastal marine water and river mouths through which fish migrate en route to their natal stream.

Species	Region	Sub-region	Population	Sampling Location	Sex	n	Tissue Analyzed	Lipids (%)	PCBs	DDTs	PBDEs	Citation
Steel head	Oregon	**Columbia River**				21	muscle w/skin	**6.0**	**34**	**21.0**	**NR**	18
Coho	Alaska	unknown	unknown	unknown		2	muscle wo/skin	NR	1.6	NR	0.32	4
		Kodiak	unknown	unknown		3	muscle w/skin	NR	4.0	NR	0.10	5*, 6*
		seak/goa	unknown	unknown		14	muscle wo/skin	2.9	2.0	1.5	0.19	21
		SE Alaska	unknown	unknown		3	muscle w/skin	NR	4.0	NR	0.10	5*, 6*
		Alaskan coho salmon Average						**2.9**	**2.9**	**1.5**	**0.18**	
	British Columbia	**unknown**	unknown	unknown		3	muscle w/skin	**NR**	**6.0**	**NR**	**0.30**	5*, 6*
	Washington	Puget Sound	unknown	marine waters		32	muscle wo/skin	3.1	35	NR	NR	10
			PS mixed	mixed rivers		##	muscle wo/skin	3.1	27	NR	NR	10
			PS mixed			##	muscle wo/skin	3.3	NR	11.7	NR	20
		Washington coho salmon average						**3.2**	**31**	**11.7**	**NR**	
	Oregon	**Columbia River**	Umatilla River	Umatilla River		3	muscle w/skin	**2.5**	**35**	**41.0**	**NR**	18
	Coho salmon Average							**3.0**	**14**	18.1	**0.20**	
Pink	Alaska	Kodiak	unknown	unknown		3	muscle w/skin	NR	3.0	NR	0.10	5*, 6*
		northern Alaska	unknown	unknown		7	canned	6.3	2.6	1.8	NR	22
		SE Alaska/GOA	unknown	unknown		12	muscle wo/skin	3.5	1.3	0.6	0.22	21
		SE Alakka	unknown	unknown		3	muscle w/skin	NR	2.0	NR	0.10	5*, 6*
		Alaskan pink salmon Average						**4.9**	**2.2**	**1.2**	**0.14**	
	British Columbia	**unknown**	unknown	unknown		3	muscle w/skin	**NR**	**3.0**	**NR**	**0.30**	**5*, 6***
	Pink salmon Average							**4.9**	**2.4**	**1.2**	**0.18**	
Chum	Alaska	Kodiak	unknown	unknown		3	muscle w/skin	NR	2.0	NR	0.10	5*, 6*
		SE Alaska	unknown	unknown		3	muscle w/skin	NR	3.0	NR	0.10	5*, 6*
		Berring Sea	unknown	unknown		18	muscle wo/skin	4.8	3.2	1.9	0.16	21
		Alaskan chum salmon Average						**4.8**	**2.7**	**1.9**	**0.12**	
	British Columbia	**unknown**	unknown	unknown		3	muscle w/skin	**NR**	**2.0**	**NR**	**0.20**	**5*, 6***
	Chum salmon Average							**4.8**	**2.6**	**1.9**	**0.14**	

1. Cullon et al. 2009. Environ. Toxicol. Chem.28:149-161.

2. Debruyn et al. 2004. Environ. Sci. Technol. 38: 6217-6224.

3. Hardell et al. 2010. PLoS ONE 5(8):e12396. doi:10. 1371/journal.prone.0012396; median values shown

4. Hayward et al. 2007; average of reported values in Table 4

5. Hites et al. 2004a. Science 304:226-229; estimated from Figure 2

6. Hites et al. 2004b. Environ. Sci. Technol. 38: 4945-4949, estimated from Figure 2.

7. Kelly et al. 2007. Environ. Sci. Technol. 41:3083-308; estimated from Table 1; NOTE: Up river sampling location was not included

8. Missildine et al. 2005. Environ. Sci. Technol.

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***** estimated values from figure
****** estimated value from reported lipid weight
#excluded value as an outlier

The importance of marine distribution as a factor affecting PBTs accumulation was particularly evident for Chinook salmon populations. Although, Chinook salmon generally had higher concentrations of PBTs than other Pacific salmon species, the levels varied considerably; populations feeding in close proximity to land-based sources of contaminants had higher concentrations. The Alaskan Chinook populations distributed mostly along the remote waters of Alaska (Weitkamp 2010) had the lowest average PCBs and PBDE levels). Intermediate levels of PCB and PBDEs were measured in California and Oregon populations that are generally distributed northward from the natal stream. In contrast, the highest DDT concentrations were measured in Chinook salmon from California, a region with historically high inputs of DDTs (citation). Highest PCB and PBDE concentrations were observed in fish from Puget Sound and the Harrison River, a tributary of the Fraser River, that are primarily distributed within the Salish Sea and along the west coast of Vancouver Island (Weitkamp 2010; DFO citation). Other Fraser River populations of Chinook salmon with more northerly distributions had much lower PCBs and PBDEs concentration (Cullon et al. 2009). Resident Chinook salmon from Puget Sound carry heavier burdens of PBTs than other Pacific coast populations and than other Puget Sound-origin Chinook salmon that rear along the coast (O’Neill et al. 2006; O’Neill and West 2009).

The elevated PBTs levels in Puget Sound Chinook salmon may be high enough to impair the health of the fish. Toxicological studies on juvenile salmonids, examining effects ranging from enzyme induction to mortality, have indicated an adverse health effects threshold for PCBs of 2400 ng/g lipid (Meador et al. 2002). Approximately 22% of the maturing and subadult Chinook salmon samples collected from Puget Sound had PCB concentrations above this threshold (O'Neill and West 2009). Moreover, the elevated PBTs in resident Chinook will result in elevated contaminant levels in gonads, possibly high enough to affect affect egg and embryo viability. The lipid content in the muscle tissue of adult salmon in marine waters decreases rapidly as they approach freshwater and reproductive maturity (Brett 1995; Ewald et al. 1998; Hendry and Berg 1999). During this reproductive phase, PBTs are not metabolized with the fat or transformed and eliminated (deBruyn et al. 2004), but rather are mobilized and redistributed to fatter tissues such as the gonads (Ewald et al. 1998; Kelly et al. 2007; Veldhoen et al. 2010). Therefore, whole body PBTs concentrations in Pacific salmon generally do not decline with reductions in fat content during maturation, so the contaminants are transferred to embryos, and to the ecosystem receiving the salmon carcasses.

Data Needs and Research Recommendations

Chinook and coho salmon show variable migration patterns but the prevalence of residency in Puget Sound and the factors affecting this behavior, in contrast to migration to the coastal or open ocean waters, are not well known. Research is needed to clearly identify resident and non-resident fish, which will enable several kinds of studies.

Process Studies

- Analyze microstructure/microchemistry of otoliths and PBT contaminant concentrations in of Chinook and coho salmon populations assumed to be resident and nonresident (based on capture location and timing) to determine if a distinct chemical signal indicative of residency can be developed for otoliths. Recent results indicate that these resident Chinook and coho salmon have elevated levels of PBTs and distinct chemical fingerprints as a consequence of their feeding within the Puget Sound food web. However, PBT chemical fingerprint are more expensive than otolith microchemistry fingerprints.

- Compare POP PBT concentrations in adult coho salmon returning to southern Puget Sound that were produced using normal hatchery release timing, with those produced using extended rearing to release larger fish at a later time, a strategy designed to increase the tendency of salmon to remain within Puget Sound waters. Archived samples for this study already exist. A comparison of PBTs in hatchery fish with normal and extended rearing practices should stimulate a comparison of the benefits from producing resident salmon with the possible health risks to humans and marine mammals from consuming them.

Cross-referenced Hypotheses

- Hypothesis 3: Size-selective mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood.
- Hypothesis 4: Outmigration timing influences the magnitude effect of competition, predation, and environmental variation on survival in the Salish Sea
- Hypothesis 5. The affect of a resident-type behavior and the duration of residence on survival in the Salish Sea.
- Hypothesis 12: Food supply limits growth, and thus survival, during critical periods of early marine rearing
- Hypothesis 13. Predation by larger fish and marine mammals has increased on salmon and steelhead, respectively. And, the potential effect of bird predation represents a significant knowledge gap.
- Hypothesis 14: Infectious and parasitic diseases are causing direct and indirect mortality.

H-11$_C$ Exposure to toxic contaminants in freshwater habitats causes latent reductions in marine survival of out-migrant juvenile salmon and steelhead

Evidence of Supporting Hypothesis

As in marine systems, salmon exposure to contaminants in freshwater habitats may reduce survival. Pertinent to this proposal are sub-lethal contaminant exposures in freshwater that reduce salmon growth and, by extension, subsequent size-dependent survival when they migrate to the ocean. Likewise, sub-lethal contaminant exposure in freshwater that impairs immunocompetence may subsequently reduce marine survival, particularly as they make the parr-smolt transformation and enter marine waters. Contaminant exposures the disrupt the smoltification process may alter time at entry into saltwater as well subsequent growth nd immuno-competence.

In freshwater systems, contaminants of concern for salmon health include many of the same contaminants that affect salmon productivity in marine systems (i.e., PCBs, PAHs and PBDE as discussed for H_1). Additional contaminants that may impair salmon health in freshwater include current use pesticides that do not persist long in the environment, and some metals. Copper is a particular concern as it is more bioavailable in freshwater than in saltwater.

Species and Populations Most at Risk

In developed watersheds, juvenile salmon hatching and rearing in freshwater and migrating from freshwater to estuarine environments are exposed to many contaminants. Small rivers and streams in watersheds with developed landscapes are particularly vulnerable to contaminant input because the volume of contaminated runoff is large compared to the volume of the receiving waters. All salmon species may be exposed in fresh water systems; however, coho salmon, and steelhead that have a stronger affinity for small streams, may be exposed to higher contaminant levels.

Justification for Research: Effects of Contaminant Exposure on Salmon Growth

Pesticides: There is ample evidence that juvenile salmon and steelhead in some Puget Sound basin streams are exposed to current use pesticides at levels high enough to cause neurobehavioral toxicity. Low-level exposures to two classes of current-use pesticides, organophosphates and carbamates, directly affect behaviors that are important for salmon survival. Organophosphate and carbamate pesticides inhibit the activity of the acetylcholinesterase (AChE), an enzyme involved with nervous system function. AChE inhibition, may, in turn, disrupt several fish behaviors, including swimming, feeding, homing and predator avoidance (Scholz et al. 2000; Sandahl et al. 2005). Additionally, pesticides commonly occur as mixtures, sometimes producing greater-than-additive (i.e. synergistic) effects (Laetz et al. 2009). Interference with such basic and important life activities could clearly have adverse effects on salmon growth, survival, and reproductive success. Baldwin et al. (2009) developed a model that explicitly linked sublethal AChE inhibition to feeding behavior, food ration, growth, and size at migration, which in turn was then used to estimate size- dependent survival during migration and transition to the sea. Individual survival estimates were then used to calculate population productivity and growth rate. Baldwin et al. (2009) concluded that short-term (i.e., four-day) exposures that are representative of seasonal pesticide use may be sufficient to reduce the growth and size at ocean entry of juvenile Chinook salmon, and, by extension, subsequent size-dependent marine survival. Additionally, some pesticides target aquatic insects that are prey for salmon (reviewed by Macneale et al., 2010). Furthermore, measured pesticides in Puget Sound streams have recently been shown to be toxic to aquatic macroinvertebrates (Weston et al., 2011), suggesting that pesticides can have indirect effects on juvenile salmon growth via food webs.

Copper: Short-term-exposure to low levels of copper reduces the olfactory capacity of salmon and, therefore, their ability to detect important olfactory cues from nearby prey and predators (Baldwin et al. 2003; Sandahl et al. 2007, McIntyre et al. 2008). Copper disrupts olfaction and olfactory-mediated behaviors in Chinook, coho and chum salmon, steelhead, Atlantic salmon, and rainbow trout (reviewed by Tierney et al. 2010, see also Baldwin et al. 2010). These findings support extrapolation of copper toxicity data across species and are relevant to both hatchery and wild fish. In addition to these behavioral effects, modeling by Mebane and Arthaud (2010) suggested that body size reductions due to chronic early life stage exposure to sublethal copper concentrations could reduce juvenile salmon survival and population recovery trajectories.

Justification for Research – Effects of Embryonic and Larval Exposures to PAHs on Development and Growth

The impacts of PAHs on the development of wild Puget Sound salmon have not been well characterized, although laboratory exposure studies have shown developmental abnormalities in Pacific Northwest salmon species exposed to PAHs (Ostrander et al., 1988, 1989). The effects of PAHs on early development were also investigated extensively in salmon and other fish after the 1989 *Exxon Valdez* oil spill in Prince William Sound, Alaska. Field and laboratory studies in several species, including Pacific herring and pink salmon, demonstrated a common syndrome of oil-induced embryo toxicity characterized by pericardial and yolk sac edema, jaw reductions, and curvature of the body axis (Carls et al.,1999; Couillard, 2002; Heintz et al., 1999; Marty et al., 1997; Pollino and Holdway, 2002), generally resulting in embryo death. Delayed mortality in marine waters also occurred in fish with no external malformations, as indicated by the reduced oceanic survival of pink salmon exposed to weathered crude oil as embryos and released as smolts (Heintz et al., 2000). Exposure to the lower molecular weight tricyclic PAHs that are the most common components of weathered crude oil possibly results in of impaired cardiac function (Heintz et al., 2000; Incardona et al., 2004, 2005). Tricyclic PAHs are also common in urban stormwater runoff.

More recent research suggests that that the stage of development at which fish are exposed to PAHs may determine the effects. Low level exposures to PAHs affect the developing cardiovascular system, causing heart failure or permanent heart defects (Incardona et al. 2006, 2009). Hicken et al. (2011) further demonstrated that nearly a year after embryonic PAH exposure, adult zebrafish showed subtle changes in heart shape and a significant reduction in swimming performance, indicative of reduced cardiac output. More recently, the types of reduced cardiac output observed in zebrafish have been extended to pink salmon, which also show heart deformities as juveniles following embryonic PAH exposures (Incardona, unpublished results). Delayed physiological impacts on cardiovascular performance at later life stages provide a potential mechanism linking reduced individual survival to population-level ecosystem responses of fish species to chronic, low-level oil and stormwater pollution. Thus exposure concentrations within the range often found in the environment, may cause subtle cardiovascular effects in fish that otherwise appear normal. This work highlights the importance of sublethal, potentially long-term effects of PAHs (Peterson et al., 2003). Petroleum levels in stormwater runoff from developed land in the Puget Sound region may potentially affect normal embryonic development of salmon.

Justification for Research - Immunological Alterations

In addition to water-borne exposure pathways, juvenile rainbow trout (*Oncorhynchus mykiss*) exposed to PAHs in their diet at environmentally relevant concentrations had reduced disease resistance and expression of immune-regulating genes, and were more susceptible to a naturally occurring freshwater pathogen (Bravo et al., 2011).

Information Gaps and Research Recommendations

Contaminant exposure information on juvenile salmon in freshwater is available for some classes of contaminants (i.e., PCBs, PBDE, PAHs, DDT), however, trend data is lacking. Additionally, information is lacking on the extent to which juvenile salmon are exposed to chemical of emerging concerns, including xenoestrogens, pharmaceuticals, personal care products, and newer use pesticides like pyrethroids. These emerging contaminants have been detected in freshwater streams in Puget Sound and in discharge from waste water treatment plants. It is not yet known the extent to which juvenile salmon

salmon are exposed to these chemicals in freshwater habitats, and what effects such exposure might have on long-term survival.

Laboratory studies are underway to investigate effects of PBDEs on disease resistance post smoltifications (i.e., studies led by Mary Arkoosh), however, additional biological endpoint such as smolting should also be evaluated. PBDEs, for example, are structurally similar to thyroid hormones involved in regulating smoltification and juvenile salmon exposed to mixtures of PBDEs found in Puget Sound may have alterations in smoltifcation process and timing. Impacts on thyroid signaling by these compounds have been documented for a number of species (Lema et al. 2008, Birnbaum and Staskal 2004).

Monitoring

- Juvenile salmon contaminant monitoring surveys for Chinook and coho salmon and steelhead is assess field exposure and effects: Funding is needed to support and expand existing monitoring programs to document the extent and magnitude of contaminants as they transition from freshwater to saltwater. In particular, measures exposure of juvenile salmon to xenoestrogen, pharmaceutical and personal care products, and pyrethroids are needed. Where possible, field assessments should included potential effects on contaminants on salmon health. Field assessment may include alterations in genes, proteins, and hormones that control growth, smoltification, immuno-competence and reproductive development. Such monitoring will better characterize the threat that contaminants pose to juvenile salmon and will provide a measure of the effectiveness of current strategies and near term actions to reduce toxics threats to Puget Sound.

Process Studies

- Diagnostic studies to investigate the effects of contaminant exposure (especially especially PBDEs, PCBs and xenoestogens) on the smolting steelhead, Chinook and coho salmon during their transition from fresh to salt water. In particular, there is a need to identify toxicant-induced changes in endocrine physiology and target tissue gene expression in these critical physiological systems. Ultimately, indicator genes identified in these studies would be used to examine expression patterns in naturally outmigrating smolts to monitor for physiological stressors (e.g. contaminants) in watersheds throughout Puget Sound. Salmon indicator genes involved in olfactory signaling and the thyroid endocrine axis should also be assessed. These physiological systems are ideal as bioindicators because they are extremely sensitive to environmental cues and environmental stressors, are critical for survival of the organism, are relatively well-characterized, and are likely susceptible to PBDE toxicity (Lema et al. 2008, Birnbaum and Staskal 2004, Lower and Moore 2007).

- Diagnostic rearing earing studies to evaluate the contaminants in stormwater on viability, development and growth of salmon embryos.

- Diagnostic studies to investigate the direct effects of pyrethroids and other current use pesticides on the growth of steelhead, Chinook and coho salmon and indirect effects on their prey.

Modeling

- Apply modeling techniques to explore population and ecosystem impacts of contaminant exposure scenarios. These methods could be used to determine whether hypotheses associated with contaminant exposure and effects are consistent with the patterns of survival of different species and populations of salmon and trout. Several types of modeling could be used, including population modeling, trophic transfer modeling to examine food-web-mediated impacts, and spatial exposure modeling based on land cover and toxic inputs.

Cross-Referenced Hypotheses

- Hypothesis 3: Size-selective mortality is an important process regulating survival at one or more life stages of salmon and steelhead: Larger body size at certain life stages confers higher survival to adulthood. – *Increased contaminant input to Puget Sound may reduce growth of salmon, especially in urban bays*
- Hypothesis 4: Outmigration timing influences the magnitude effect of competition, predation, and environmental variation on survival in the Salish Sea. – *Increased contaminant inputs may alter smoltification processes and outmigration timing.*
- Hypothesis 14: Infectious and parasitic diseases are causing direct and indirect mortality. - Contaminant related reductions immune-competence may increase susceptibility to infectious and parasitic diseases

Management Implications

Given current regional projections for population growth and coastal development, the loadings of chemical contaminants to Puget Sound will increase dramatically in the years ahead, unless serious measures are taken to address this issue now. However, chemicals fall into the category of *stressors that we can control*.

These three steps, namely source characterization and quantification, source control and reduction, and biologically-based monitoring and assessment, are essential if we are to protect Puget Sound from the waste products of its surrounding, and growing, human population. Four categories of strategies to reduce the toxic threat to the Puget Sound have been identified by the Puget Sound Partnership:

- prevent releases,
- control inputs of released toxics,
- restore/remediate contaminated sites and
- facilitate natural attenuation of toxic contaminated sites.

P**revention strategies** to reduce the sources of toxic chemical entering Puget Sound include: implement and strengthen authorities and programs to prevent toxic chemicals from entering the Puget Sound environment; promote the development and use of safer alternatives to toxic chemicals; adopt and implement plans and control strategies to reduce toxic releases into the Puget Sound from air emissions; provide education and technical assistance to prevent and reduce toxic releases; and increase compliance with and enforcement of environmental laws, regulations, and permits.

Control strategies to reduce pressures on the Puget Sound ecosystem from runoff from the built environment include: manage urban runoff at the basin and watershed scale; prevent problems from new development at the site & subdivision scale (e.g. Low Impact Developments); fix problems caused by existing development (e.g. stormwater retrofits); control sources of pollutants in runoff; provide focused stormwater-related education and training; and assess effectiveness of actions and effects on the environment. Additional control strategies to reduce pressures on the Puget Sound ecosystem from wastewater have also been identified.

Restoration/ remediation strategies to address and clean up cumulative water pollution impacts in Puget Sound include: complete total maximum daily load (TMDL) studies and other necessary water cleanup plans for Puget Sound to set pollution discharge limits and determine response strategies to address water quality impairments; and clean up contaminated sites within and near Puget Sound.

Large-scale sediment remediation combined with local and watershed and upland-site control can reduce legacy contaminant threat to juvenile Chinook salmon. Whether these have an affect on legacy contaminants in pelagic fish such and Pacific herring and sub-adult Chinook salmon and coho salmon is uncertain. Federal, state, tribal, and local cleanup activities are occurring throughout the Puget Sound region, including major cleanup locations in Bellingham, Bremerton, and Elliott Bay and the Lower Duwamish Waterway. Unfortunately, many of these efforts are very protracted. For example, in 2001 the Lower Duwamish was declared a Superfund, with 440 in-water acres identified for clean-up. To date, less than 10 acres have been remediated. The Puget Sound Action Agenda supports enhancement of these efforts. The Puget Sound Action Agenda also supports near-term actions for stormwater retrofits of developed lands and the evaluation of using Low Impact Development (LID) for newly developed lands.

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Hypothesis 12. Food supply limits growth, and thus survival, during critical periods of early marine rearing

Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences
Julie Keister, University of Washington, Oceanography

Abstract

The strong relationship between SARs (smolt-to-adult returns) and body size after some period of early marine growth suggests that factors affecting feeding and growth are important for sustaining productive adult returns of salmon. Growth limitation is a potential concern for Chinook, coho, chum and pink salmon in Puget Sound, whereas steelhead and sockeye salmon appear to emigrate rapidly and are thus less likely to be affected by localized growth limitations. For hatchery Chinook salmon, high variability in size, feeding and growth among years and regions support the hypothesis that food is limiting during a critical growth period from marine entry through July. The contribution of crab larvae and secondarily neustonic insects to the energy budget of juvenile Chinook salmon can account for much of the variability in their feeding and growth. Salmon growth in Puget Sound has been relatively insensitive to the mid-spring-summer thermal regime, but very sensitive to feeding rate, a surrogate measure of food supply. In contrast, the Strait of Georgia averages 2°C warmer than Puget Sound during the summer, and temperature could significantly affect salmon growth in this region. Competition could be an important influence on marine survival in certain periods and regions, as suggested by the lower and variable feeding rates associated with reduced marine survival of salmon and comparisons of prey demand among juvenile salmon and forage fish species. Initial bioenergetic simulations of population-level consumption demand indicated that Pacific herring consume 10-40 times more biomass of the key prey species than the juvenile Chinook population during the critical May-July growth period in Puget Sound. This suggests that competition for food in offshore regions is more likely driven by the dynamics of herring, the most abundant consumer, than by competition between hatchery and wild conspecifics or among salmon species within Puget Sound. However, density-dependent growth or hatchery-wild competition within or among salmon species could still potentially occur in localized estuarine or nearshore marine habitats. Very little is known about the temporal-spatial availability of key zooplankton and other prey or the abiotic and biotic factors that influence production cycles of prey in Puget Sound.

The primary research and monitoring needs for the growth limitation hypothesis include: 1) monthly to twice monthly zooplankton sampling, stratified by depth and region to assess the availability of key prey through time and space, and in coordination with sampling for fish growth, scales, diet, and relative abundance; 2) Monthly to twice monthly nearshore (March-August) and epi-pelagic (May-October) sampling for diet, size, and growth of juvenile salmon and forage fishes by region; 3) Quantitative hydroacoustic-midwater trawl survey of epi-pelagic fish [and potentially macro-zooplankton] community during July; 4) Map/model growth potential within-among regions and depths for juvenile salmon and forage fishes 2-3 times during critical spring-summer growth period. Identify hotspots for feeding, growth and interactions with competitors and predators.

Sub-hypotheses-

H-12_A Growth is limited by food supply during critical growth periods

H-12_B Growth is limited by food quality

H-12_C Growth is limited by the metabolic effects of temperature

H-12_D Food supply is limited by competition during critical growth periods

H-12_E Food supply is limited by reduced production of key prey. Timing, duration, quantity, spatial extent, and/or composition/quality of prey has changed (Insufficient food supply to meet demand or mismatch between demand (outmigrant timing and condition) and prey.

Supporting Evidence

***Hypothesis 12a. Growth is limited by food supply during critical growth periods* -** Higher growth and survival rates (SARs) of juvenile hatchery Chinook during 2001 compared to 2002 (**Figure 1)** were supported by higher feeding rates, especially on key prey groups like crab larvae and adult or terrestrial insects (**Figure 2**).

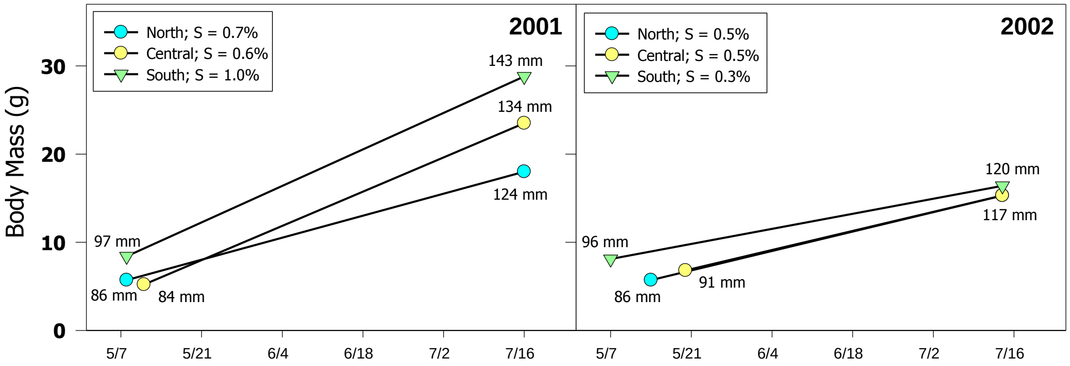

Figure 1. Change in size and associated SARs for CWT groups of hatchery Chinook salmon from north (Whidbey Basin), central and south regions of Puget Sound during years of higher growth and survival (2001) and lower growth and survival (2002) from Duffy (2009).

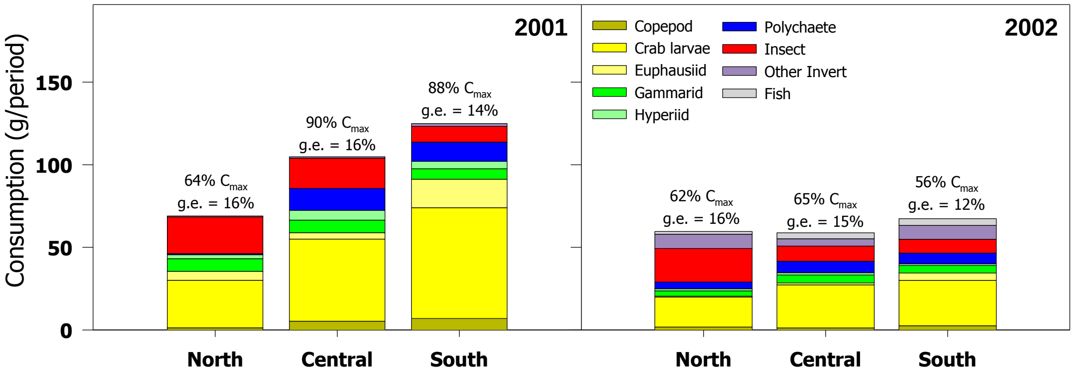

Figure 2. Bioenergetics modeling estimates of feeding rates (% Cmax) and the mass of major prey types consumed by juvenile Chinook salmon from different regions of Puget Sound during high (2001) and low (2002) growth and survival years. Note important contribution of crab larvae (1^{o} zoea) and terrestrial or adult insects to variability in feeding rates among regions and years (Duffy 2009).

Variability in growth, feeding, and SARs among regions and years for hatchery Chinook, and the higher SARs associated with higher growth and feeding suggest that food limitation in Puget Sound influences marine growth and survival. Less than 10 functional taxonomic groups represent recurrently important prey in nearshore and offshore marine diets for juvenile Chinook salmon. At any one time, only 4-5 of these prey groups contribute 90% of the biomass and energy consumed to fuel growth.

Although diets for all juvenile salmon species and herring have been periodically described from 1970 to the present, differences in processing, analyzing, and reporting these data preclude rigorous quantitative comparison. However, qualitative summaries indicate a general similarity in the key prey utilized by juvenile salmon species over the past 40 years.

Hypothesis 12b. Growth limited by food quality-Although the composite energy density of diets varied among years by approximately 20% for juvenile Chinook salmon during the presumptive critical offshore growth period in July, there was no apparent relationship between energetic quality of the diet and marine growth or survival (**Figure 3;** Beauchamp and Duffy 2011). In general, feeding rate influenced growth more than prey energy content, so variability in availability of key prey (as reflected by feeding rate) was more important to salmon growth than variability in the energetic quality of the diet. In addition to energy, prey also contribute other forms of essential nutrition, such as protein, vitamins, and essential fatty acids (EFAs) which could also limit growth or survival. Much less is known about these dynamics in Puget Sound.

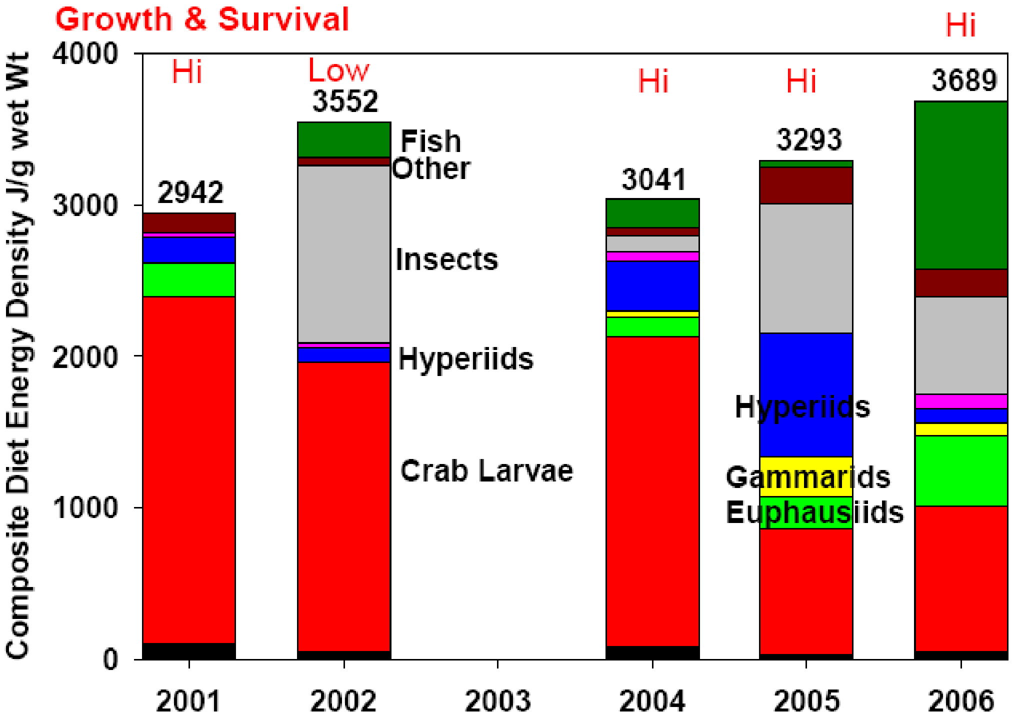

Figure 3. Interannual variability in energy densities and the relative contribution of each of the major prey groups to the composite diet for juvenile Chinook salmon feeding in the pelagic zone of Puget Sound during July. The juvenile marine growth and subsequent ocean survival associated with each year is indicated by "Hi" or "Low" above each bar, along with the mean composite energy density value.

Hypothesis 12c. Growth limited by metabolic effects of temperature – Models based on observed diet, growth, temperature, and bioenergetics estimates of feeding rates suggest that variability in feeding rate (a surrogate for food supply) had a much greater effect on growth than the direct metabolic effects of temperature over the range of temperatures observed in epi-pelagic habitats during this period (**Figure 4**). This suggests that growth of Chinook (and coho salmon) should be relatively insensitive to normal temperature fluctuations during spring-summer in Puget Sound. In contrast, summer temperatures in the Strait of Georgia average 2°C warmer than in Puget Sound, and extend over the steeply declining limb of the temperature-dependent growth curves for Chinook and coho salmon; consequently, direct temperature effects on growth would likely be considerably greater in the Strait of Georgia than in Puget Sound (**Figure 4**).

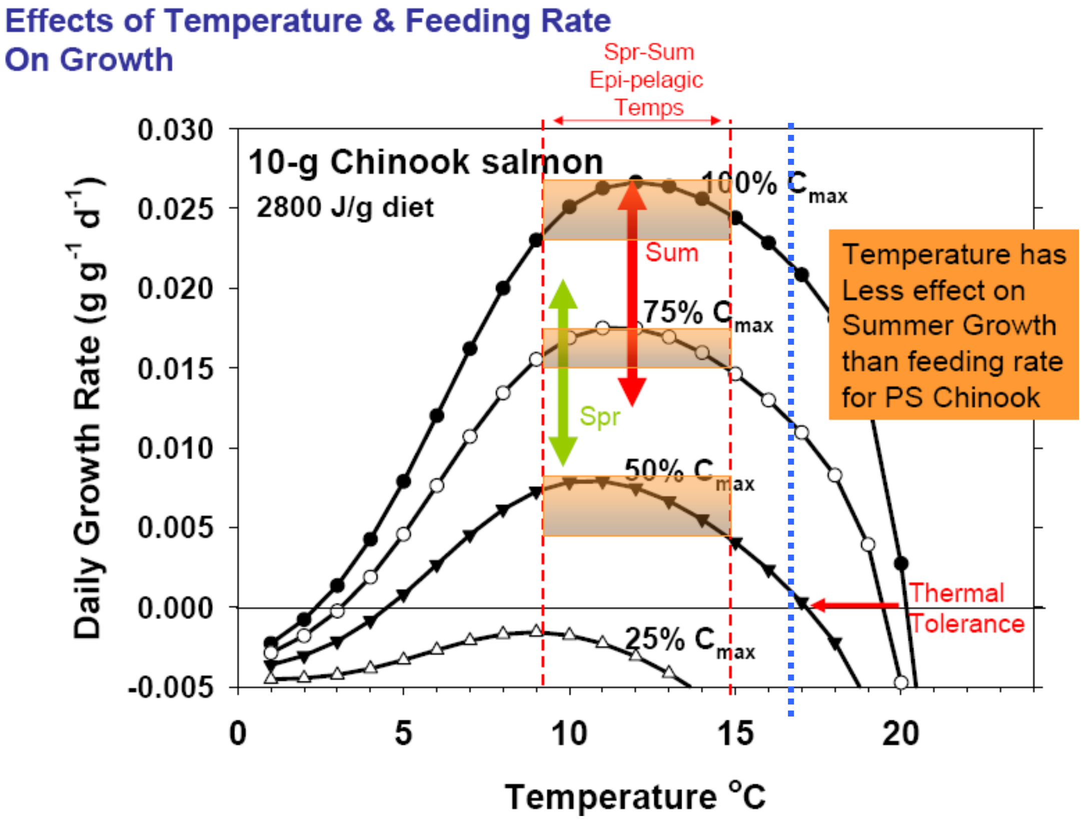

Figure 4. The relationship between daily growth rate and temperature for a 10-g Chinook salmon feeding at its physiological maximum feeding rate (100% Cmax) and at incremental reductions in feeding rate (75%, 50%, and 25% Cmax). The vertical arrows span the observed range of inter-annual feeding rates during spring (May-July, green arrows) and summer (July-September, red arrows) estimated by bioenergetics analyses (Duffy 2009). The dashed red vertical lines indicate the minimum and maximum epi-pelagic temperatures encountered during the spring-summer feeding period in Puget Sound. Shaded areas indicate the variability in growth response to the full spring-summer range in thermal conditions associated with 100%, 75% & 50% feeding rates. Note that growth rates varied much more in response to estimated variability in feeding rates (arrows) than to observed temperature variability for a given feeding rate (shaded regions). Dotted blue line represents the average upper temperature in Strait of Georgia.

Hypothesis 12d. Food Supply is limited by competition during critical growth periods-Considerable diet overlap for key prey occurs among juvenile Chinook, coho, pink salmon, and herring, and less overlap with chum salmon in Puget Sound (Beauchamp and Duffy 2011). Pacific herring are more abundant than juvenile salmon in Puget Sound and exhibit strong spatial-temporal overlap (**Figure 5**).

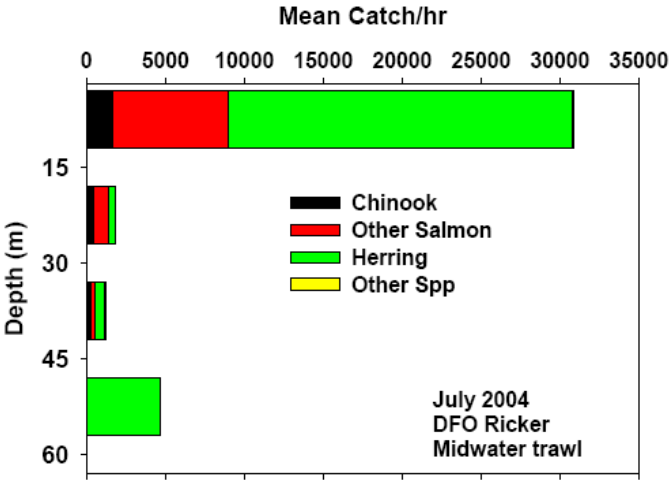

Figure 5. The mean catch rate of different pelagic fishes in depth-stratified midwater trawls indicated that most of the daylight planktivorous community is concentrated in the upper 15 m of the water column and was dominated by Pacific herring followed by juvenile salmon during the critical period of offshore growth for Chinook salmon in July. The highly schooling herring are likely underestimated compared to juvenile salmon.

During the critical growth period for hatchery Chinook, diet overlap with Pacific herring for key prey has been variable but often quite high among years (**Figure 6a**). Moreover, the estimated population-level consumption by herring for key prey averaged 10-40 times higher than for juvenile Chinook salmon in the Whidbey through southern basins of Puget Sound during the critical May-July growing period (**Figure 6b**; Beauchamp and Duffy 2011).

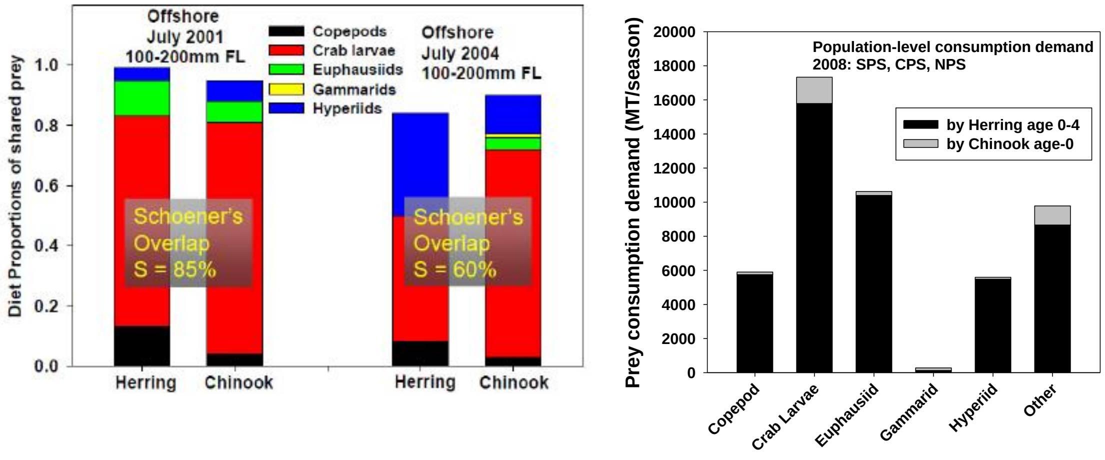

Figure 6. A-<u>Left Panel</u>-Diet overlap between juvenile Chinook salmon and herring offshore in Puget Sound during July 2001 and 2004. B-<u>Right Panel</u>-Population-level consumption demand between subyearling Chinook salmon (hatchery and wild combined) and herring in Puget Sound during the presumptive critical May-July growth period for Chinook salmon. The herring population consumed 10-40 times more biomass of key prey (Beauchamp and Duffy 2011).

Although population-level consumption demand by juvenile coho, chum, and pink salmon have not been quantified, the prey biomass they consume would logically fall between the demand by Chinook and herring, based on their relative abundance, diet overlap, and consumption potential. Juvenile sockeye salmon and steelhead appear to migrate rapidly out of Puget Sound after marine entry, so they are considered relatively insensitive to variability in growth potential within Puget Sound.

These preliminary analyses were generated from a single year and pooled over all regions of Puget Sound, so competitive bottlenecks that might occur at finer temporal-spatial scales would not be detected. Nonetheless, the initial indication from this coarse-grain analysis suggests that competition for food in offshore regions is more likely driven by the dynamics of herring, the most abundant consumer, than by competition between hatchery and wild conspecifics or among salmon species within Puget Sound. Hatchery-wild competition within or among salmon species could still potentially occur in localized estuarine or nearshore marine habitats. Production cycles and temporal-spatial patterns of availability for key prey are not currently known, but the lower and variable feeding rates associated with reduced marine survival of salmon and comparisons of prey demand among juvenile salmon and forage fish species suggest that competition could be an important influence on marine survival in certain periods and regions.

Hypothesis 12e. Food supply is limited by reduced production of key prey. The timing, duration, quantity, spatial extent, and/or composition/quality of prey has changed (Insufficient food supply to meet demand or mismatch between demand (outmigrant timing and condition)—Environmental factors can directly and indirectly affect the biomass, species composition, and distribution of zooplankton and ichthyoplankton. Numerous studies of zooplankton variability in estuaries and temperate marine systems worldwide have demonstrated that climate variability and anthropogenic inputs affect planktonic communities, but mechanisms vary among habitats and how the controls may operate in Puget Sound is not known. The dominant factors that control zooplankton are likely to include nutrient inputs (which affects phytoplankton biomass and species composition), temperature (which affects physiology), circulation including river flow, stratification, and mixing (which indirectly affect nutrients and advection). These are all known to be strong controls on the biomass and species composition of zooplankton in other regions and are likely to be important in Puget Sound.

Too few zooplankton studies have been conducted in Puget Sound to allow interannual comparisons of seasonality, biomass, or distributions. Only a handful of locations have been sampled over a full year cycle and most of those studies were conducted in the 1960s-1980s using methods that are not directly comparable among studies. A few patterns have emerged from the sampling that has been done. For example, the timing and magnitude of the spring bloom is important: differences in river flow and stratification affect the timing of seasonal cycles, particularly between Main Basin (later growth cycles) and the more sheltered Whidbey and Hood Canal basins (earlier). Different plankton assemblages dominate in different regions with larger taxa such as euphausiids inhabiting deeper regions and smaller taxa dominating shallower regions. Crab larvae that are important in juvenile salmon diets are patchy in time and space; their timing and distributions are not well understood.

In the Georgia Basin, a strong decline in the largest copepod, *Neocalanus plumchrus*, has occurred over the past decade and the timing of peak production has shifted 50 days earlier (El Sabaawi et al. 2009). *Neocalanus* is not an important species in the shallower Puget Sound and it is not known whether changes in the dominant large-bodied species here (particularly *Calanus pacificus*) have occurred, but if so, consequences to juvenile salmon may be expected. In the California Current, zooplankton biomass and quality as prey changes with the PDO and ENSO and are correlated with salmon survival (Peterson

2011). Similar environmentally-correlated changes in zooplankton species composition has been observed in the Strait of Juan de Fuca (Keister unpublished data); correlation with salmon survival has not been attempted.

Data Needs

- Seasonal production dynamics and the resulting spatial-temporal supply of key prey for juvenile salmon, herring, and other forage fishes are largely unknown as are the climatic, oceanographic and biotic factors that influence prey for salmon.
- The relationship between spatial-temporal prey availability, feeding, and growth is not understood for juvenile salmon or forage fishes.
- Dynamics of food supply versus consumer demand for key prey taxa among months and regions.
- Abundance, biomass, and distribution of the epi-pelagic assemblage of juvenile salmon and forage fishes.
- Improved ability to track growth performance and survival by stock or release group via genetic stock identification (e.g., SNPs) and CWT.

Research Recommendations

- Depth-stratified zooplankton sampling (species, presence/absence, abundance, duration) within a spatial-temporal framework and in coordination with juvenile salmon sampling. Juvenile salmon feed predominantly during daylight in shallow nearshore waters initially, and then in the upper mixed layer of marine waters; therefore, prey availability should be sampled from these nearshore-offshore zones and depth layers explicitly. Year-round sampling is desirable with an emphasis on more frequent sampling (e.g., twice per month) during April-September.
- Determine the dietary value (energy content and fatty acid composition) for key prey: zooplankton, ichthyoplankton, and insects. This study should last two years with data collection occurring monthly during the spring and summer.
- Continue monitoring epi-pelagic diet, size, and growth of juvenile salmon and forage fishes in July and September. Supplement with analogous data in April-August from purse seining during research phase to determine finer-scale resolution on stock-specific growth limitation among species through time and space.
- Quantitative hydroacoustic-midwater trawl survey of epi-pelagic fish community during July to determine the scope of competitors for key food types during critical growth periods.
- Map/model growth potential within-among regions and depths (e.g., Brandt et al. 1992) for juvenile salmon and forage fishes 2-3 times during critical spring-summer growth period. Identify hotspots for feeding, growth and interactions with competitors and predators.

Management Implications

The following is a list of conceptual strategies that could be applied in response to the research results if the hypothesis was found to be correct.

- By determining how the early marine growth environment for juvenile salmon changes through time and space, managers will develop an understanding for the dynamic carrying capacity of the Salish Sea and the relative importance of food production cycles versus natural recruitment or hatchery inputs of potential competitors. By identifying regions and times that are especially productive, or conversely, are particularly vulnerable to exceeding carrying capacity, expectations for growth and survival could be adjusted and would inform run forecasting and hatchery release strategies.
- By developing explicit linkages between spatial-temporal food availability and early marine growth of salmon, we can potentially identify bottlenecks in production of key prey species and thus inform future restoration efforts that target habitat and water quality or quantity. Developing indices of survival might be possible once relationships between prey variability and growth are better understood.

Hypothesis 13: Predation by marine mammals and larger fish has increased on steelhead and salmon, respectively. And, the potential effect of bird predation represents a significant knowledge gap.

Barry Berejikian, NOAA Northwest Fisheries Science Center
Dave Beauchamp, University of Washington, Aquatic and Fisheries Sciences

Hypothesis 13_A Predation by marine mammals has increased on juvenile steelhead

Supporting Evidence

Reduced marine survival of over the past 20 to 30 years appears to be a major limiting factor for Salish Sea steelhead trout, and the declining abundance trends of Salish Sea populations (all with similar patterns) compared with coastal populations points to poor survival in the Salish Sea (see the Evidence section of this report on page 7 for more information). Published early marine survival estimates for steelhead come primarily from acoustic telemetry studies in Hood Canal. An estimated 2.7% to 34.1% of the smolts entering Hood Canal survive to Pillar Point in the western Strait of Juan de Fuca (Mean = 16%; Moore et al. 2010ab, Moore et al., unpublished; data represent two wild populations monitored for five consecutive years and an additional wild population in one year, N = 11). Early marine survival rates are similar to those reported for the SoG steelhead populations (Welch et al. 2011). Survival rate estimates are conservative because tag loss, tag effects, and potential detection inefficiencies in the Juan De Fuca receiver array may each inflate estimates of natural mortality. However, even a doubling of the average estimated survival rate would suggest that the more than 60% of the smolt-to-adult mortality occurs within the first three weeks following seawater entry. Numerous telemetry studies have been conducted within Puget Sound over the past 7 or 8 years, and preliminary migratory behavior and survival data are very comparable to results from Hood Canal data; and these data are now being included in a Puget Sound-wide analysis.

Potential mechanisms

Predation is hypothesized as the primary cause of the high mortality rates in Puget Sound. Steelhead smolts spend approximately 14-17 days in Hood Canal and travel at rates (straight-line) of approximately 8-10 km/day; Moore et al. 2010a). After passing the Hood Canal bridge and entering Admiralty Inlet, their migration rates approximately triple to 26-27 km/day through the Strait of Juan de Fuca. The rapidity with which steelhead migrate to the Pacific Ocean suggests that proximal mechanisms such as poor feeding opportunities and low growth rates, starvation, or disease are unlikely important contributors to high mortality. For example, there is no evidence of size selective mortality in tagged migrant steelhead over a body mass range of 30 to 90 grams (Moore et al. 2010, Melnychuck 2007), which excludes only the bottom 10% of the total wild smolt size-frequency distribution. Even very high growth rates of 1% body mass gain per day would equate to an average size smolt of 45 g, increasing to a body mass of 52 g during the two week residence in Puget Sound. All of the smolts tagged for the telemetry studies appeared healthy and in good condition and exhibited no external signs of pathology, so any disease would have to impact the smolts within a short period. Monitoring of Hood Canal steelhead smolts suggests mortality rates (mortalities per km) are greater in Admiralty Inlet than for earlier or later segments in the migration (Figure 1).

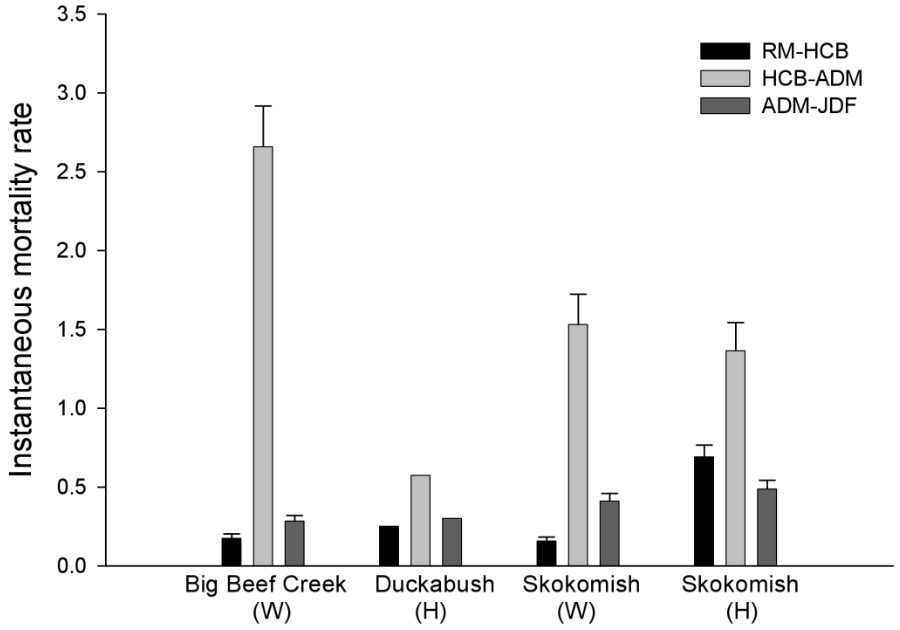

Figure 1. Example of segment-specific mortality, calculated as numbers of presumed mortalities per distance travel (based on straight line distances) from points of release to the river mouths (black bars), river mouths to the Hood Canal Bridge (black bars), Hood Canal bridge to northern Admiralty Inlet (light grey) and northern admiralty inlet to Pillar Point at the western Juan de Fuca Strait (dark grey). H and W refers to hatchery and wild populations, respectively.

Predation pressures on steelhead are likely exerted by a variety of mammalian, avian and piscine predators, however, there have been no investigations into predation on steelhead smolts in Puget Sound, so we are left with developing hypotheses based on circumstantial information. Puget Sound harbor seal populations have increased approximately three-fold between the 1970's and 1999 (Jeffries et al. 2003), and concomitant increases have been reported for the Strait of Georgia (DFO 2010). Puget Sound and Hood Canal steelhead smolts must migrate past dozens of harbor seal haul-out areas en route to the Pacific Ocean, which likely presents a higher encounter rate with predators than for coastal populations. As an example of potential predation impact for Hood Canal, a population of 1,000 harbor seals (c.f. Jeffries et al. 2003), with a daily mean diet composition of 0.5% steelhead smolts and consumption rates = 2 kg/individual/day (Howard et al. 2009) could consume half of the estimated 40,000 smolts from Hood Canal during the course of the approximate two-month outmigration period.

Data Needs

Survival estimates from Puget Sound populations (other than Hood Canal) – A meta-analysis of segment-specific survival rates for outmigrating Puget Sound steelhead has recently been initiated, and will help to identify, on a coarse scale, regions of Puget Sound where survival is low. Following this analysis, a coordinated Puget Sound-wide study can be conducted to identify specific areas of high mortality and estimate encounter rates between steelhead and harbor seals.

Identify mortality or predation 'hot spots'. Areas of greatest mortality or predation 'hot spots'. The Puget Sound-wide analysis of mortality patterns will help in identifying spatial patterns in mortality rates and indicate potential hot spots. Mortality rates appear to be greatest in Admiralty Inlet, but this is confounded by extra mortality potentially associated with the Hood Canal Bridge (Moore et al. in prep). The question is whether Admiralty Inlet and other constrictions (e.g., Tacoma Narrows, Deception pass) or areas of high harbor seal density provide conditions for high predation rates.

Quantify predator-prey encounter rates. Unfortunately, direct observation of predation on salmon or steelhead smolts are very rare, and would be very impractical, difficult ,and costly to conduct. Moreover, the primary predators of steelhead smolts migrating through Puget Sound are completely unknown. Harbor seals and harbor porpoise are the two marine mammals exhibiting abundance increases over the period of steelhead abundance declines (Jeffries et al. 2003, B. Hanson pers. Commun). Concurrent telemetry tagging of steelhead and potential predators provides an opportunity to estimate encounter rates. Predators can also be fitted with receivers to detect tagged smolts and tags to track their spatial-temporal patterns with high accuracy.

Research Recommendations

Research to identify hot spots and encounter rates with predators would likely be phased. The first step will be to complete a retrospective analysis of steelhead survival rates throughout Puget Sound. This analysis will help to identify areas of greatest mortality, and inform the installation of telemetry receiver arrays to identify potential hot spots and predators associated with them. Initial work may also include a census of harbor seals in Puget Sound, which has not occurred since 1999 (Jeffries et al. 2003). Census of other predators associated with other predation hypotheses may also inform and shape the work described here.

Following this analysis, a coordinated Puget Sound-wide study can be conducted to identify specific areas of high mortality and estimate encounter rates between steelhead and harbor seals. Such a study would involve tagging steelhead throughout Puget Sound (e.g., Nisqually, Puyallup, Green, Skagit or Snohomish, and Hood Canal), and estimating survival through specific segments of Puget Sound. Telemetry receiver arrays would be established in specific areas of south, central and northern Puget Sound/Admiralty inlet and northern Hood Canal in presumed predation hot spots. Steelhead smolts would be tagged and released from each of the River systems to estimate survival through each of the segments, and some tagged fish would be barged and released on either side of the hot spot arrays to estimate mortality associated with migration through each area. Hot spots will be identified the first year and two would be chosen for a more detailed assessment of encounter rates between harbor seals and steelhead smolts.

Harbor seals would be fitted with transmitters to identify their locations before during and after the outmigration period. Mobile transceivers used to study predator-prey interactions in marine environments will be affixed to harbor seals to estimate their foraging times and durations, foraging range from haul outs and encounter rates of steelhead with specific predators. Depending on results from the first year of concurrent tagging of steelhead and seals, other predators (e.g., harbor porpoise) may be investigated or additional year(s) of harbor seal tagging may be required.

Data would be analyzed using a combination of mark-recapture models recently applied to estimate steelhead survival in Puget Sound (Moore et al. 2010) and temporal-spatial patterns of predators and steelhead smolts will be quantified using the Aquatracker software developed by NWFSC scientists (Moore et al, in review). If harbor seals are not found to be the primary predator, additional predator-prey interaction studies can be cost effectively implemented in subsequent years (this project both establishes the infrastructure to do so and will identify predator hot spots that focuses efforts).

The infrastructure needs would be substantial, but some of it is already in place. Receiver arrays would need to be maintained at the Strait of Juan de Fuca, Admiralty Inlet. These arrays are already in place, but the Admiralty Inlet array would need to be recovered, re-batteried, and re-deployed. A receiver line can easily be deployed at the Hood Canal Bridge, and two additional receiver arrays will need to be deployed (one in South Puget Sound, near Pt Defiance and another in Central Puget Sound). Many telemetry receivers are available for this work. Collection of smolts by various entities is occurring throughout Puget Sound, and the expertise needed for tagging currently exists. A focused effort to target, capture, and tag harbor seals would be needed.

Hypothesis 13$_B$ Fish predation of juvenile salmon has increased

Like steelhead, acoustic telemetry can be used in similar fashion for yearling Chinook and coho smolts. However, for the smaller ocean-type Chinook and other subyearling salmon smolts, only the largest individuals can accommodate these tags. Given the strong size-selective component of mortality, using non-representative size distributions would confound results of acoustic telemetry studies of subyearling smolts.

Supporting Evidence

The evidence for significant predation mortality of juvenile salmon by piscivorous fishes comes from diet analysis and bioenergetics simulations of predation rates. Although several fish taxa have been identified as salmon predators, larger salmonids generally appear to be the most important piscine predators during early marine life in Puget Sound: subyearling Chinook, yearling coho, and sea-run cutthroat trout and bull trout eat pink and chum salmon in nearshore habitats (Parker 1968, 1971; Hargreaves and LeBrasseur 1985; Duffy 2003; Duffy and Beauchamp 2008; Duffy et al. 2010); sea-run cutthroat trout feed on age-0 Chinook salmon in nearshore marine habitats (Duffy and Beauchamp 2008); in offshore habitats of Puget Sound, measurable predation by resident subadult Chinook and coho salmon on juvenile pink, chum, and Chinook salmon has been documented (Duffy et al. 2010; Beauchamp and Duffy 2011). However, populations of resident Chinook appeared to have decreased over the same time period as the declines in marine survival of Chinook, coho and steelhead.

Predation by non-salmonid fishes have also been reported, but their potential impact During 1988-1989, Beamish et al. (1992) reported that ≤2% of spiny dogfish sampled from a large aggregation contained hatchery Chinook or coho salmon, coincident with their release into the Big Qualicum River, central Strait of Georgia. The authors believed the resulting predation mortality was large, given the high abundance of spiny dogfish in the area. When not associated with hatchery releases (or natural outmigration pulses?), reports of predation by spiny dogfish on salmon have been anecdotal. Hake and jack mackerel consumed measurable amounts of juvenile salmon off the mouth of the Columbia River, but were not deemed to be a major source of mortality, although the authors cautioned that limitations of their study could have underestimated predation mortality (Emmett and Kruzikowsky 2008).

Larger salmonids exert size-selective predation on younger salmon (See Hypothesis 3). These predators are capable of eating prey up to 50% of their body length, but routinely consume prey fishes averaging 25-30% of their body length (Beauchamp et al. 2007; Duffy and Beauchamp 2008; Duffy et al. 2010; **Figure 2**). When diet data are combined with the size structure (**Figure 2**) and assumed abundance of resident Chinook salmon in Puget Sound, we conclude that predation by larger salmonids can impose a biologically significant amount of mortality on juvenile Chinook salmon and perhaps other species (Beauchamp and Duffy 2011). Bioenergetic model simulations of predation by resident Chinook salmon (marine age-1 and older) indicated that, although herring were the primary prey fish eaten throughout the year, predation by resident Chinook could account for an estimated loss of 7-62 million pink/chum salmon during April-May and 1-9 million subyearling Chinook salmon during June-August in Puget Sound. The lower range of these predation rates were considered under-estimates, because diet data were lacking for predatory Chinook during the May-June peak immigration and offshore transition periods for subyearling Chinook, conversely, the upper estimates relied on what the authors considered to be reasonable assumptions regarding predator abundance and temporal diet composition, but these assumptions need to be confronted with empirical data, especially for temporal diet composition of piscivores throughout the early marine growth period for juvenile salmon (Beauchamp and Duffy 2011).

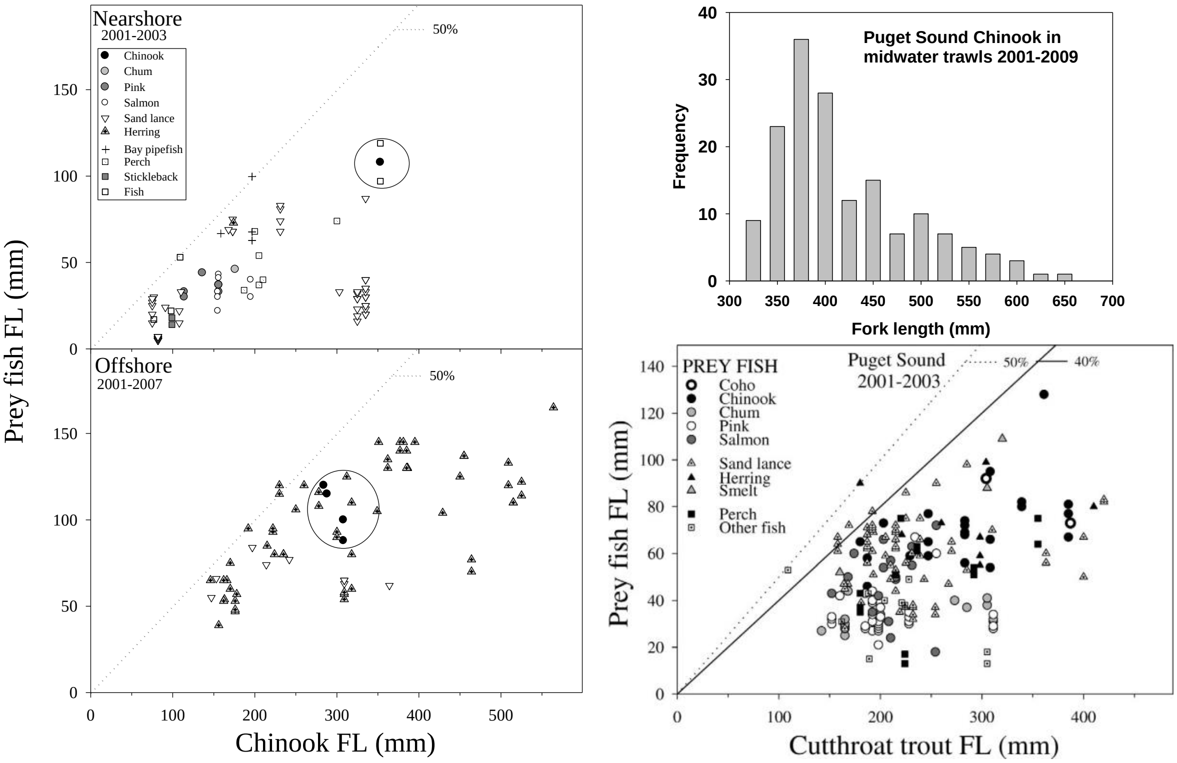

Figure 2. Size of prey fish species found in the stomachs of juvenile and subadult Chinook salmon in Puget Sound (Left panel) from nearshore (top) and offshore habitats (Duffy et al. 2010), a similar relationship for sea-run cutthroat trout in nearshore habitats (Lower right; Duffy and Beauchamp 2008); and the composite length frequency of sub-adult resident Chinook salmon captured in Puget Sound with midwater trawls during July and September, 2001-2009 (Beauchamp and Duffy 2011).

Data Needs

- Juvenile Chinook, pink, and chum salmon have been recorded in nearshore diets of sea-run cutthroat and bull trout, and juvenile Chinook salmon in marine nearshore habitats, and for resident Chinook or coho diets that were examined opportunistically from offshore samples in July and September. However, piscivore diets have not been methodically sampled during the peak nearshore-offshore transition and offshore rearing in Puget Sound, when expected predation would be heaviest on juvenile salmon. Predation mortality estimates are highly sensitive to changes in timing, duration, and magnitude of juvenile salmon in the diet, and to the average mass of salmon consumed by piscivores.
- How does the proportional weight contribution of juvenile salmon species and forage fishes change in the offshore diet of piscivorous fishes through time and by region through the April-October marine rearing period?
- Relationship between size and growth of juvenile salmon and the timing and magnitude of predation by different piscivores among marine habitats through time.
- Temporal trends in the magnitude of predation mortality is not known. Predation rates on juvenile salmon can change in response to changes in abundance or size distribution of predators, distributional shifts by predators or prey which affect their temporal-spatial overlap, change in abundance of juvenile salmon or alternative prey, and changes in environmental conditions that mediate predator-prey interactions such as light intensity, water transparency-turbidity, temperature, and hypoxia in epi-pelagic waters. Long term trends in abundance and size distribution of potential predators like anadromous salmonids, gadoids, etc. should be reconstructed. In addition, an examination of long term changes in the relative light environment and transparency of the nearshore and epi-pelagic zones would address the question of whether environmental conditions have become more or less conducive for visual predators (i.e., piscivorous fish and birds) to feed on juvenile salmonids.

Research Recommendations

- Identify and quantify the temporal-spatial patterns in predation as functions of predator species, predator size, prey size, the role of alternative prey, and environmental mediators (temperature, salinity, turbidity, light, DO).
- Highest priority would be purse seine sampling among regions in epi-pelagic waters of Puget Sound monthly in April and May, twice monthly June-September, and monthly in October.
- Retrospective analysis of existing acoustic telemetry data on seasonal and diel horizontal and, especially vertical movement and distribution of resident coho and Chinook salmon to determine regions, depths, periods, and potential hotspots of overlap with juvenile salmon and forage fishes. These data would provide insight into physical and biotic factors that influence the magnitude and dynamics of predation on juvenile Chinook salmon versus other salmon and forage fishes.

Hypothesis 13$_C$ The potential effects of piscivorous birds on salmon survival is unknown

This is an area that should be discussed further.

Management Implications

Accounting for predation on juvenile salmon will determine the relative importance of this process on overall marine survival, will quantify where and when predation mortality occurs, who is responsible, and identify processes that influence the magnitude of predation (e.g., growth, availability of alternative prey, environmental-oceanographic conditions, etc.) that could become useful for mitigating predation losses.

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Hypothesis 14. Infectious and parasitic diseases are causing direct and indirect mortality.

Paul Hershberger, US Geological Survey, Marrowstone Marine Field Station

Introduction

Populations of wild animals often undergo dramatic changes in abundance or zoogeography; however, the causes of these fluctuations are typically difficult to determine. The problem is magnified for populations of wild fishes that often cannot be directly observed. For these populations, unanticipated increases in mortality are usually only detected through the absence of a large portion of predicted biomass or significant lack of age cohorts at some stage of the life cycle. At this point, hypotheses are commonly proposed for the proximate cause(s) of the mortality that often include: habitat loss, over-harvest, predation, starvation, disease, etc. However, assigning causality to any of these factors is extremely difficult for wild populations; therefore, a weight of evidence approach is typically employed, whereby all lines of evidence are measured against each other.

The influence of infectious and parasitic diseases as population-limiting factors is often underestimated or ignored by ecologists (Scott 1988), even though the definition of parasites includes the "… decrease in either the survival or reproduction of host populations" (Anderson and May 1978). Across broad scales, diseases are a significant component of natural mortality in fully-functioning ecosystems, and population-level impacts are not necessarily precipitated by anthropogenic factors. Unfortunately, determining the fraction of natural mortality attributable to infectious diseases or parasites, and detecting changes in this level, are both extremely challenging, especially in populations that are difficult to study directly. In contrast, effects of disease are relatively easily observed in human populations, where seven of the top ten causes of adult mortality are due to infectious or non-infectious diseases (WHO 2003).

In terrestrial animal populations, infectious diseases have been shown to be associated with significant losses (Smith et al. 2006) or large scale oscillations (Hudson et al. 1998). However, our understanding of disease impacts on fish populations is generally limited to mortality events that are common in hatchery and aquaculture facilities or to periodic case history reports describing large scale epizootics accompanied with massive fish kills. In a particularly well-documented example, several lines of evidence indicate that an introduced herpesvirus caused large fish kills in populations of the native pilchard (Sardinops sagax) in southern Australia (Murray et al. 2003). These losses resulted in trophic cascades that included direct host mortality and breeding failure of birds that depended on the pilchards for forage (Dann et al. 2000). Unfortunately, most disease-related losses in wild fishes are not so easily visualized, especially when host populations are distributed over a broad geographical areas, when the infections are chronic, or when the losses are asynchronous due to variations in dose, time of exposure or environmental conditions.

As in marine regions throughout the world, fishes in the Salish Sea serve as hosts to a broad range of pathogens, including myxozoans (e.g. *Parvicapsula, Henneguya* and *Kudoa* spp.), coccidians (e.g. *Goussia* spp.), monogenean and digenean trematodes (e.g. *Gyrodactulus* and *Nanophyetus* spp.), bacteria (e.g. *Rennibacterium, Vibrio* and *Tenacobaculum* spp.), viruses (e.g. infectious hematopoietic necrosis virus and viral hemorrhagic septicemia virus), parasitic crustaceans that are collectively referred to as sea lice (e.g. *Lepeopthirius Calanus*, and *Argulus* spp.), and other parasites (e.g. *Ichthyophonus* spp.). Typically, a delicate balance between host, pathogen, and environmental conditions results in perpetuation of these pathogens in low infection prevalence and intensity; however, periodic natural and anthropogenic perturbations can result in the manifestation of epizootic diseases that can be accompanied by host mortalities and population-level impacts.

Supporting Evidence

Infectious and parasitic diseases can drive population oscillations (Hudson et al 1998) and shifts in age structure (Ohlberger et al 2011) to wild animal populations; unfortunately, analogous disease impacts to populations of wild salmonids are poorly investigated, largely owing to a paucity of disease surveillance data. In the Salish Sea, disease impacts have been investigated more thoroughly in sympatric species including Pacific herring, where disease-related mortalities represent a leading hypothesis accounting for age structure shifts in Puget Sound (Hershberger et al 2002) and population declines and failed recoveries in Prince William Sound (Marty et al. 1998, 2003, 2010). Among salmonids, some high-profile diseases, including IHN (Traxler et al 1997) and BKD (Rhodes et al. 2011) are known to occur in the Salish Sea; however, concerted efforts to investigate their impacts to populations of wild and free-ranging salmonids have not been undertaken. Additionally, other lesser-known pathogens, including VEN (Evelyn and Traxler 1978), *Nanophyetus* (and other trematodes), myxozoans, and numerous species of sea lice also occur among salmonids in the Salish Sea and anecdotal observations indicate high infection / infestation prevalence and intensity.

Data Needs and Research Recommendations

Pathogen surveillance. The vast majority of all current pathogen and disease surveillances among salmonids in the Salish Sea occurs in association with state, tribal, and federal enhancement facilities, where the health of pre-release juveniles and pre-spawn adults is routinely assessed during their freshwater life history phases. As such, obvious gaps currently occur in our understanding of pathogens and diseases that commonly occur during the marine phases of the salmonid life history. Additionally, the health profiles of wild (non-hatchery) salmonids are less poorly documented and are generally limited to periodic descriptions of epizootic disease situations. Therefore, concerted fish health surveillances are required that envelop the entire life history cycle of salmonids in the Salish Sea. These surveillances should incorporate standard virology, bacteriology, and parasitology, using protocols described in the *AFS, Fish Health Section – Blue Book, Procedures for the Detection and Identification of Certain Finfish Pathogens*. Additionally, marine surveillances should employ non-standard diagnostics that are specific to marine pathogens in the Salish Sea, including appropriate diagnostics required to detect marine bacteria (i.e. *Vibrio spp*., *Rennibacterium salmoninarum*, etc.), parasites (i.e. *Ichthyophonus sp., Nanophyetus salmonicola*, myxozoans, sea lice, etc.), and viruses (including specific PCR primers for ISAV, ENV, and other marine viruses that are often refractory to standard cell lines).

Cause-and-effect. Although disease surveillances are necessary for determining the prevalence and intensity of pathogens at multiple life history stages and geographic locations, field surveillances of pathogen prevalence and intensity are inadequate for determining effects on infected hosts and populations. After pathogens-of-concern are identified by field surveillances, effects to the infected host should be addressed by performing well-controlled empirical studies in the laboratory using specific pathogen-free hosts. Effects to populations of Salish Sea salmonids can then be addressed by integrating field surveillance data with cause-and-effect relationships between the hosts, pathogens, and environmental variables.

Management Implications

Management of diseases in wild fish populations requires adaptive approaches that are designed around specific host / pathogen relationships. This approach is similar to that employed by the World Health Organization and the Centers for Disease Control, which base disease management in human populations on epidemiological characteristics that are specific to individual diseases. For example, malaria is generally controlled through mosquito mitigation; AIDS is controlled through education, prophylactics, and prevention; and cholera is often controlled through the filtration of drinking water. Unlike in hatchery and confined fishes, application of vaccines and pharmaceutical treatments are typically not practical on large temporal or geographical scales such as the Salish Sea. Rather, the key to mitigating disease impacts to populations of wild fishes involves the active management of affected and closely-related resources.

Hypothetical disease situations and possible management options:*

Disease Situation	**Management Options**
1) Parasitic disease caused by an intermediate host (i.e. *Nanophyetus* sp. or other digeneans)	- Manage the intermediate host - Adjust hatchery releases to mismatch the timing of the intermediate host
2) Epizootic viral disease outbreaks that occur during periods of low herd immunity (i.e. VHS or IHN)	- Develop management options for the host population that encourage herd immunity (i.e. selective fisheries on susceptible cohorts, or restricted harvest of resistant cohorts)
3) Chronic disease resulting in pre-spawn mortality of adult salmonids (i.e. BKD, ichthyophoniasis, or *Parvicapsula*)	- Adjust the effective population size when setting salmonid escapement goals to account for adequate recruitment after disease-related mortality occurs.

*Note: these are generalized hypothetical examples, intended to illustrate the existence of tangible disease mitigation options for wild fish populations. Any management options for specific disease issues identified in salmonids from the Salish Sea should be based on empirically-demonstrated epizootiological relationships between regional host, pathogen, and environmental variables that are specific to each disease.

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APPENDIX B: NORTHWEST REGIONAL OCEAN OBSERVING SYSTEM (NANOOS), SALISH SEA ASSET LIST

Table 1: NANOOS asset list and water quality characteristics measured. [30]

Name	Type	Region	Provider	Measurements
NERRS PDBBPWQ	Fixed Shore Platform	Padilla Bay	NERRS	Oxygen Concentration, Oxygen Percent Sat., pH, Salinity, Turbidity, Water Depth, Water Temperature
NERRS PDBBYWQ	Fixed Shore Platform	Padilla Bay	NERRS	Oxygen Concentration, Oxygen Percent Sat., pH, Salinity, Turbidity, Water Depth, Water Temperature
NERRS PDBFMET	Land Station	Padilla Bay	NERRS	Air Temperature, Barometric Pressure, Dewpoint Temperature, Wind Direction, Wind Speed
NERRS PDBJLWQ	Fixed Shore Platform	Padilla Bay	NERRS	
APL-UW NPB-1	Buoy	Puget Sound	APL-UW	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., Photosyn. Active Rad., Salinity, Water Density, Water Temperature, Wind Direction, Wind Gust, Wind Speed
APL-UW NPB-2	Buoy	Puget Sound	APL-UW	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., Salinity, Solar Radiation, Water Density, Water Temperature, Wind Direction, Wind Gust, Wind Speed
FHL-UW Friday Harbor	Fixed Shore Platform	Puget Sound	FHL-UW	Air Temperature, Photosyn. Active Rad. - Atm., Rain, Relative Humidity, Salinity, Solar Radiation, Water Temperature, Wind Direction, Wind Speed
HCDOP Cruises	Cruise	Puget Sound	HCDOP	Chlorophyll, Nitrate, Oxygen Concentration, Photosyn. Active Rad., Pressure, Salinity, Transmittance, Turbidity, Water Density, Water Temperature
ICM Marrowstone	Buoy	Puget Sound	ICM-Mobilisa	Air Temperature, Barometric Pressure, Relative Humidity, Wind Direction, Wind Gust, Wind Speed

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[30] http://www.nanoos.org/nvs/nvs.php?section=NVS-Assets

Name	Type	Region	Provider	Measurements
ICM Poulsbo	Buoy	Puget Sound	ICM-Mobilisa	Air Temperature, Blue-Green Algae, Chlorophyll, pH, Redox Potential, Relative Humidity, Salinity, Turbidity, Water Depth, Water Temperature, Wind Direction, Wind Gust, Wind Speed
ICM Worden	Buoy	Puget Sound	ICM-Mobilisa	Air Temperature, Barometric Pressure, Blue-Green Algae, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., pH, Redox Potential, Relative Humidity, Salinity, Turbidity, Water Depth, Water Temperature, Wind Direction, Wind Gust, Wind Speed
KC Alki	Buoy	Puget Sound	King County	Chlorophyll, Nitrate, Oxygen Concentration, Oxygen Percent Sat., pH, Salinity, Turbidity, Water Temperature
KC NSAJ02	Fixed Shore Platform	Puget Sound	King County	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., pH, Rain, Relative Humidity, Salinity, Solar Radiation, Turbidity, Water Depth, Water Temperature, Wind Direction, Wind Speed
KC NSGE01	Buoy	Puget Sound	King County	Chlorophyll, Nitrate, Oxygen Concentration, Oxygen Percent Sat., pH, Salinity, Turbidity, Water Temperature
KC SEAQYSI	Fixed Shore Platform	Puget Sound	King County	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., pH, Rain, Relative Humidity, Salinity, Solar Radiation, Turbidity, Water Temperature, Wind Direction, Wind Speed
KC YCQMH01	Fixed Shore Platform	Puget Sound	King County	Chlorophyll, Nitrate, Oxygen Concentration, Oxygen Percent Sat., pH, Salinity, Water Depth, Water Temperature
NDBC New Dungeness	Buoy	Puget Sound	NDBC	Air Temperature, Average Wave Period, Barometric Pressure, Dewpoint Temperature, Dominant Wave Period, Water Temperature, Wave Height, Wave Mean Direction, Wind Direction, Wind Gust, Wind Speed
NDBC SISW1	Land Station	Puget Sound	NDBC/C-MAN	Air Temperature, Barometric Pressure, Wind Direction, Wind Gust, Wind Speed
NDBC WPOW1	Land Station	Puget Sound	NDBC/C-MAN	Air Temperature, Barometric Pressure, Wind Direction, Wind Gust, Wind Speed
NOS Friday Harbor	Fixed Shore Platform	Puget Sound	NOS/CO-OPS	Water Level, Water Temperature

Name	Type	Region	Provider	Measurements
NOS Port Townsend	Fixed Shore Platform	Puget Sound	NOS/CO-OPS	Air Temperature, Barometric Pressure, Water Level, Water Temperature, Wind Direction, Wind Gust, Wind Speed
NOS Seattle	Fixed Shore Platform	Puget Sound	NOS/CO-OPS	Air Temperature, Barometric Pressure, Water Level, Water Temperature, Wind Direction, Wind Gust, Wind Speed
NOS Tacoma	Fixed Shore Platform	Puget Sound	NOS/CO-OPS	Air Temperature, Barometric Pressure, Water Level, Water Temperature
NOS Tacoma MET	Fixed Shore Platform	Puget Sound	NOS/CO-OPS	Wind Direction, Wind Gust, Wind Speed
ORCA Dabob Bay	Buoy	Puget Sound	ORCA-UW	Air Temperature, Barometric Pressure, Chlorophyll, CO2, CO2 Air, Oxygen Concentration, Oxygen Percent Sat., Salinity, Water Density, Water Temperature, Wind Direction, Wind Gust, Wind Speed
ORCA Hansville	Buoy	Puget Sound	ORCA-UW	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., Salinity, Water Density, Water Temperature, Wind Direction, Wind Gust, Wind Speed
ORCA Hoodsport	Buoy	Puget Sound	ORCA-UW	Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., Salinity, Turbidity, Water Density, Water Temperature, Wind Direction, Wind Gust, Wind Speed
ORCA Twanoh	Buoy	Puget Sound	ORCA-UW	Air Temperature, Barometric Pressure, Chlorophyll, CO2, CO2 Air, Oxygen Concentration, Oxygen Percent Sat., Salinity, Solar Radiation, Water Density, Water Temperature, Wind Direction, Wind Gust, Wind Speed
PRISM Cruises	Cruise	Puget Sound	PRISM-UW	Ammonium Concentration, Chlorophyll, Nitrate, Nitrite Concentration, Oxygen Concentration, Phaeophytin Concentration, Phosphate Concentration, Photosyn. Active Rad., Pressure, Salinity, Silicate Concentration, Transmittance, Turbidity, Water Density, Water Temperature
PSI-PCSGA Lummi	Fixed Shore Platform	Puget Sound	PSI	Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., pH, Redox Potential, Salinity, Water Temperature

Name	Type	Region	Provider	Measurements
Taylor-PCSGA Dabob	Fixed Shore Platform	Puget Sound	TaylorShellfish	Oxygen Concentration, Oxygen Percent Sat., pH, Redox Potential, Salinity, Water Temperature
USGS Green	River Gage	Puget Sound	USGS	Discharge, River Stage Height
USGS NF Stillaguamish	River Gage	Puget Sound	USGS	Discharge, River Stage Height
USGS Nisqually	River Gage	Puget Sound	USGS	Discharge, River Stage Height
USGS Nooksack	River Gage	Puget Sound	USGS	Discharge, River Stage Height, Water Temperature
USGS Puyallup	River Gage	Puget Sound	USGS	Discharge, River Stage Height
USGS Skagit	River Gage	Puget Sound	USGS	Discharge, River Stage Height
USGS Skokomish	River Gage	Puget Sound	USGS	Discharge, River Stage Height
USGS Snohomish	River Gage	Puget Sound	USGS	Discharge, River Stage Height
WADOE Manchester	Fixed Shore Platform	Puget Sound	WADOE	Oxygen Concentration, Oxygen Percent Sat., Pressure, Salinity, Water Density, Water Temperature
WADOE Mukilteo	Fixed Shore Platform	Puget Sound	WADOE	Oxygen Concentration, Oxygen Percent Sat., Pressure, Salinity, Water Density, Water Temperature
WADOE Squaxin	Fixed Shore Platform	Puget Sound	WADOE	Oxygen Concentration, Oxygen Percent Sat., Pressure, Salinity, Water Density, Water Depth, Water Temperature
San Juans PEF Survey	Cruise	Puget Sound, Strait of Juan de Fuca	FHL-UW	Ammonium Concentration, Chlorophyll, Conductivity, Nitrate, Nitrite Concentration, Oxygen Concentration, Oxygen Percent Sat., Phaeophytin Concentration, Phosphate Concentration, Phytoplankton, Pressure, Salinity, Silicate Concentration, Water Density, Water Temperature, Zooplankton
WADOE Marine Flights	Flight	Puget Sound, SW WA Coast	WADOE	Ammonium Concentration, Chlorophyll, Nitrate, Nitrite Concentration, Oxygen Concentration, Oxygen Percent Sat., Pathogens, pH, Phaeophytin Concentration, Phosphate Concentration, Pressure, Salinity, Silicate Concentration, Transmittance, Water Density, Water Temperature

Name	Type	Region	Provider	Measurements
EC 46131	Buoy	Strait of Georgia	Env. Canada	Air Temperature, Barometric Pressure, Dominant Wave Period, Water Temperature, Wave Height, Wind Direction, Wind Gust, Wind Speed
EC 46146	Buoy	Strait of Georgia	Env. Canada	Air Temperature, Barometric Pressure, Dominant Wave Period, Water Temperature, Wave Height, Wind Direction, Wind Gust, Wind Speed
NOS Cherry Point	Fixed Shore Platform	Strait of Georgia	NOS/CO-OPS	Air Temperature, Barometric Pressure, Water Level, Water Temperature, Wind Direction, Wind Gust, Wind Speed
NOS Cherry Point 2	Fixed Shore Platform	Strait of Georgia	NOS/CO-OPS	Air Temperature, Wind Direction, Wind Gust, Wind Speed
VENUS GeorgiaC	Seabed Cabled Platform	Strait of Georgia	VENUS	Oxygen Concentration, Pressure, Salinity, Sound Speed, Water Density, Water Temperature
VENUS GeorgiaE	Seabed Cabled Platform	Strait of Georgia	VENUS	Oxygen Concentration, Pressure, Salinity, Sound Speed, Water Density, Water Temperature
VENUS GeorgiaEDDL	Seabed Cabled Platform	Strait of Georgia	VENUS	Pressure, Salinity, Sound Speed, Water Density, Water Temperature
ICM PortAngeles	Buoy	Strait of Juan de Fuca	ICM-Mobilisa	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., Pressure, Relative Humidity, Salinity, Turbidity, Water Temperature, Wind Direction, Wind Gust, Wind Speed
ICM Sequim	Buoy	Strait of Juan de Fuca	ICM-Mobilisa	Air Temperature, Barometric Pressure, Chlorophyll, Oxygen Concentration, Oxygen Percent Sat., Pressure, Relative Humidity, Salinity, Turbidity, Water Temperature, Wind Direction, Wind Gust, Wind Speed
NDBC Neah Bay	Buoy	Strait of Juan de Fuca	NDBC	Air Temperature, Average Wave Period, Barometric Pressure, Dominant Wave Period, Water Temperature, Wave Height, Wave Mean Direction, Wind Direction, Wind Gust, Wind Speed
NOS Neah Bay	Fixed Shore Platform	Strait of Juan de Fuca	NOS/CO-OPS	Air Temperature, Barometric Pressure, Water Level, Water Temperature, Wind Direction, Wind Gust, Wind Speed
NOS Port Angeles	Fixed Shore Platform	Strait of Juan de Fuca	NOS/CO-OPS	Water Level, Water Temperature
USGS Elwha	River Gage	Strait of	USGS	River Stage Height, Surface Current Speed,

Name	Type	Region	Provider	Measurements
		Juan de Fuca		Turbidity, Water Temperature

APPENDIX C: JUVENILE SALMON FEEDING HABITS IN PUGET SOUND

The following is a description of what we currently know about what salmon (and herring) eat in the estuary, nearshore and pelagic habitats of Puget Sound. This literature review was completed at the request of the Technical Team.

Salmonid feeding in Puget Sound has been a topic of interest since the mid-1970s, although most studies have been short-duration and spatially-limited. Prey preferences appear to differ by habitat, time, and size within each species. It is therefore difficult to pinpoint the most critical prey source for a species, as the dominant source typically shifts over time, size range, habitat, and often between years. Available literature on salmon feeding habits in Puget Sound was reviewed and patterns in feeding by species and by habitat summarized. The feeding habits are summarized in text by species below. A descriptive table follows describing consumption by species, by habitat.

Summary by species

Chinook (literature from 1965-2007)

Chinook progress from feeding on epibenthic gammarid amphipods and neustonic drift insects (mainly dipterans and chironomids) to feeding on pelagic crustacean larvae (mainly brachyuran crab larvae) and small fish (sandlance and herring). An angler survey showed fish 571 ± 78 mm FL to be almost entirely piscivorous (mostly herring – though it should be noted that herring is also primary bait used by anglers and thus may bias the sample). However, other studies with small blackmouth samples also document reliance on invertebrate prey, e.g., decapod larvae (typically, the gut will contain a few fish or many invertebrates). Polychaetes, euphausiids, calanoid copepods, and hyperiid amphipods are also common though generally do not predominate either gravimetrically or numerically. Cumaceans and barnacle larvae appear periodically. In comparison to other salmonid species, Chinook have more diverse diets and appear to be more selective (note, though, that only a very few studies have addressed that question and almost none of them did neuston sampling). The diet is most similar in composition to coho. There is some uncertainty in the literature over whether Chinook or coho depend more on fish, and whether hatchery vs. wild diets are significantly different. A potential shift towards increased importance of insects and reduction in fish prey from 1970s to 2000s is documented.

Coho (literature from 1965-2004)

Coho progress from epibenthic to pelagic feeding, but appear to have less dependence on epibenthic habitats (possibly due to their larger size upon estuarine entry). Smaller coho tend to feed on planktonic crustaceans (e.g., crab larvae), pelagic gammarid and hyperiid amphipods, mysids, and euphausiids; larger coho feed on fish (herring, sand lance, pink, chum, Chinook, gadids, and cottids are all documented). Drift insects, calanoid copepods, cumaceans, and isopods also appear. Most studies note similarity between coho and Chinook diets; one notes similarity between coho and chum.

Chum (literature from 1965-2004)

Chum show stronger dependence on epibenthic prey sources than the other species: they rely on gammarid amphipods and harpacticoid copepods heavily at smaller sizes nearshore and appear to be highly selective and size-selective for these prey. Chironomids also are important. At larger sizes and more offshore areas, they shift to larvaceans (*Oikopleura* sp.) and calanoid copepod prey. They appear to be selective for larger calanoids. Euphausiids, hyperiid amphipods, decapod larvae, fish larvae, barnacle larvae, and insects also appear in the diets. It's worth noting that the study which records the largest chum sizes (290 ± 13, purse seine samples) also documents brachyuran crab larvae as dominating numerically, gravimetrically, and by frequency of occurrence.

Pink (literature from 1970-2002)

Pink salmon have the fewest literature sources. Their diets are more similar to that of chum than to coho/Chinook, feeding epibenthically on harpacticoids and gammarids then progressing to calanoid copepods and larvaceans. Ostracods, polychaetes, insects, cladocerans, and barnacles are also documented, though not consistently. Varying sources state that pinks eat more invertebrate eggs than chum and that they feed more neritically. One source notes bryzoan larvae in the guts and lack of frequency in larvaceans as prey. Only the most recent source documents ostracods, and in that source they have some importance. It is unclear, however, whether this represents a true shift in feeding.

Detailed Description of Feeding Habitat by Habitat and Species over time (1975-present)

The following table was designed in the manner of web-based tag clouds. Clouds are visual interpretations of how common a particular topic is: the larger the font size, the more often the topic is referenced. This is a useful tool for describing how often particular prey items were observed in salmon diets over various studies, in attempt to describe how common particular prey items were for salmon during particular time periods and in particular habitats. The prey are also listed in order of importance to each species diet, within each habitat, during each time period. Both frequency of occurrence across studies and actual measurements within studies were used to prioritize the prey, done in a qualitative manner. The color code describing the measurements from individual studies is as follows: green=numeric percentage, blue=gravimetric percentage, purple=IRI percentage, orange=frequency of occurrence, red=other/unknown.

The table begins on the following page.

Habitat	Species	Time Period	Prey
Estuary	Chinook	1975-1979	gammarids (28% w, 20.7% IRI), insects (27.3% w), fish (19.2% w, 7% IRI), cumaceans (6% w, 6.9% IRI), harpacticoids (3% IRI), crab larvae, *Corophium* (4% w), mysids (13.2% IRI), shrimp (13.8% IRI), polychaetes, hyperiids, copepods
		1980-1984	gammarids (41% f, 31-66% IRI), insects, mysids, calanoids (25-45% IRI), crab larvae, cumaceans, spiders, harpacticoids, decapod zoea, euphausiids, sandlance, fish, chironomids, diptera, crustaceans, fish larvae, barnacle larvae
		1985-1989	chironomids (42-70% IRI), insects, gammarids, mysids, cumaceans
		1995-1999	polychaetes (8% IRI, 9% n, 23% w), insects, crab larvae, cladocerans
		2000-present	insects (36% IRI), polychaetes , spiders, crab larvae, euphausids, hyperiids, fish, gammarids, barnacle exuviae, larvaceans
	Coho	1975-1979	gammarids (24% w, 41% f), mysids (26% w, 32% f), insects (23% w, 2.2% - 15.9% IRI), diptera (47% f), cumaceans (18% w), harpacticoids, hyperiids, *Corophium* (9% w, 38% f), isopods (0.8% w), epibenthic crustaceans (31.5% - 80.6% IRI), euphausiids, ostracods, crustacean larvae, decapod larvae (81% n, 32% w), fish, herring, polychaetes, sand lance,
		1980-1984	gammarids, fish (3% IRI), *Corophium* (32% IRI), chironomids (13% IRI), cumaceans, insects, fish larvae, crab larvae, euphausids
		1995-1999	chironomids (50% w), insects, isopods
		2000-present	gammarids, fish, crab larvae, insects, pink, chum, sand lance, herring, juvenile flounder, euphausiids, polychaetes, copepods (unsp)
	Chum	1970-1974	harpacticoids (66-97% n, 34% - 89% n, 57% f), gammarids (34% n, 15% f), barnacle nauplii (6% f), insects, cladocerans, invertebrate eggs, mysid larvae, calanoids, bivalve larvae, larvaceans
		1975-1979	gammarids (21% w), harpacticoids (4% w, 34% IRI), calanoids (1.1 - 57% IRI), insects (5% w, 26.3% IRI), mysids, euphausiids, cumaceans, diptera (>80% w), oligochaetes, crustacean larvae, chironomids, brachyuran crab larvae, decapods, larvaceans, ostracods
		1980-1984	harpacticoids (76-86% IRI, 41% f), calanoids (54% n, 40% w, 12% f), chironomids (61% f), gammarids (28% f), larvaceans, cumaceans, diptera, aphids (26% f), *Corophium* (20% f), euphausiids, cyclopoids, decapod zoea, mysids
		1985-1989	chironomids (49% - 96% IRI), stonefly nymphs, gammarids, dipterans, cladocerans, spiders, *Chaoborus* , beetles, springtails, gammarids, harpacticoids, leafhoppers, aphids, bees, wasps, grasshoppers, fish larvae, mites, springtails, cyclopoids, caddisflies, mayflies, insects
		1995-1999	chironomids, mysids (85% w), diptera, *Corophium* , spiders, isopods, cladocerans (65-75% IRI), larvaceans (30% w)
		2000-present	calanoids, harpacticoids, cyclopoids, insects, larvaceans, gammarids, crab larvae, cumaceans, invertebrate larvae, copepods (unsp), isopods
	Pink	1970-1974	harpacticoids (28% - 96% n, 36% f), gammarids (31% n), invertebrate eggs, mysid larvae, calanoids, barnacle larvae, bivalve larvae, larvaceans
		1975-1979	calanoids (63% IRI), harpacticoids , larvaceans, gammarids, cumaceans, harpacticoids, decapod larvae, tanaids
		1980-1984	gammarids, harpacticoids, calanoids, cumaceans, cyclopoids, dipterans, euphausiids, copepods (unsp)
		2000-present	harpacticoids, calanoids, ostracods, insects, euphausiids, larvaceans, fish eggs, cladocerans, polychaetes

Habitat	Species	Time Period	Prey
Nearshore	Chinook	1975-1979	insects, crab larvae, herring, sand lance, gammarids (20.7% IRI), fish (7% IRI), shrimp larvae, chum fry, polychaetes, mysids (13.2% IRI), cumaceans (6.9% IRI), shrimp (13.8% IRI), harpacticoids (3% IRI), hyperiids, decapod larvae (55% n), euphausids (32% w, 10% f)
		1980-1984	gammarids, mysids, insects, cumaceans, spiders, harpacticoids, decapod zoea, euphausiid zoea, fish, sandlance
		1985-1989	gammarids, calanoids, insects, spiders, cephalopods, fish, ctenophores
		2000-present	insects (>50%w, 36%IRI), polychaetes, crab larvae, euphausiids, hyperiids, gammarids, fish, larvaceans, spiders, caprellids, barnacle exuviae, plant matter, herring, sandlance, calanoids
	Coho	1975-1979	gammarids, hyperiids, euphausiids (80% n), crab larvae, larval fish, calanoids, ostracods, insects (2.2% - 15.9% IRI), mysids, harpacticoids, crustacean larvae, decapod larvae (81% n, 32% w), polychaetes, herring, fish
		1980-1984	sand lance, gammarids, harpacticoids, dipterans, cumaceans
		2000-present	decapod larvae, gammarids, insects, pink, chum, sand lance, herring, juvenile flounder, euphausiids, polychaetes, amphipods (unsp), barnacle exuviae, copepods (unsp), plant material
	Chum	1970-1974	harpacticoids (66-97% n, 34% - 89% n, 57% f), gammarids (34% n, 15% f), insects, cladocerans, barnacle nauplii (6% f), invertebrate eggs, mysid larvae, calanoids, bivalve larvae, larvaceans
		1975-1979	calanoids (1.1% - 57% IRI), harpacticoids (34% IRI), gammarids, euphausiids, hyperiids, insects (26.3% IRI), larvaceans, crustacean larvae, mysids, decapods, ostracods, crab larvae, fish larvae, herring larvae, sandlance larvae
		1980-1984	harpacticoids (76-86% IRI), larvaceans, calanoids, gammarids, hyperiids, euphausiids, shrimp zoea, decapod zoea, cumaceans, mysids, chironomids, cyclopoids
		1985-1989	copepods (unsp), insects, spiders, cephalopods, fish, ctenophores, larvaceans
		2000-present	calanoids, harpacticoids, cyclopoids, insects, larvaceans, gammarids, decapod larvae, cladocerans, invertebrate eggs, cumaceans, hyperiids, spiders, polychaetes, isopods
	Pink	1970-1974	harpacticoids (28% - 96% n, 36% f), gammarids (31% n), invertebrate eggs, mysid larvae, calanoids, barnacle larvae, bivalve larvae, larvaceans
		1975-1979	calanoids (63% IRI), harpacticoids, larvaceans, gammarids, cumaceans, decapod larvae, tanaids, copepod larvae, bryzoan larvae
		2000-present	harpacticoids, calanoids, ostracods, insects, euphausiids, larvaceans, fish eggs, cladocerans, polychaetes
Offshore	Chinook (>200-649 mm)	1975-1979	herring (44%f, 60%w), fish (80%w, 96%w), euphausiids, gammarids, mysids
		1980-1984	decapod larvae, larval fish, fish, insects, euphausiids
		1995-1999	euphausiids, decapod larvae, fish, larval fish, insects, amphipods (unsp), herring
		2000-present	crab larvae, euphausiids, hyperiids, fish
	Coho (375-527 mm)	1975-1979	fish (72%w, 30%f), gammarids (11%w), crab larvae (10%w), euphausiids (4%w), herring, juv chk, sandlance, gadids, cottids
		1995-1999	fish (20% unk), euphausiids, crab larvae, amphipods (unsp)
	Chum (277-303	1975-1979	crab larvae (68%n, 90%w, 83%f)
		1995-1999	euphausiids, crab larvae, amphipods
	Pink (251-245 mm)	1975-1979	euphausiids, crab larvae

Discussion

For all salmon species, diets appear to differ by habitat, time, and size. These factors are almost certainly linked in many cases – as the season progresses, the fish grows larger and shifts habitat. The habitat shift is likely a product of multiple factors: the larger fish has access to larger prey and is less vulnerable to predation. There is some suggestion in the literature (particularly for chum) that a habitat shift may also occur because of over-grazing of the prey stock – in the specific case of chum, nearshore harpacticoid copepods. It is therefore difficult to pinpoint the most critical prey source for a species, as the numerically/gravimetrically/IRI dominant source typically shifts over time, size range, habitat, and often between years.

There are diel feeding differences, noted especially for coho, Chinook, and chum. For example, Chinook eat euphausiids in daytime, decapods at dusk, and copepods at dawn; coho eat more insects and fish in daytime, cumaceans exclusively at night, and gammarids throughout; chum eat epibenthic prey during/after dusk, planktonic prey during daylight. At different times of day/dusk/night, feeding preference changes (potentially as prey availability shifts, e.g., diel migration of calanoid copepods, or as predation risk shifts). Some literature sources note that the fish appear to move between nearshore and offshore habitats over the diel period. There are also seasonal (winter/spring) differences in feeding and digestive rate for those species that become resident (Chinook, coho - see Fresh et al. 1978).

Each species appears to be selective for its preferred prey sources. However, prey preferences tend to differ by species and by size within species (e.g., in one study, small Chinook avoided gammarids while large Chinook selected for them; small Chinook ate calanoid copepods proportional to their abundance while large Chinook avoided them). Studies which did have concurrent zooplankton sampling (mainly studies about chum) found high selectivity but were fairly small-scale in terms of sampling area. Additionally, there is some disagreement in certain studies' conclusions about prey preference, possibly due to the confusing factors of fish size and habitat.

Data on pelagic feeding are most lacking for all species. Additionally, many of the literature sources focused on only a relatively small near-to-shore area, which makes large-scale basin comparisons challenging.

Other species (included in salmon literature sources; often with very small sample sizes)
Herring: Primarily neritic feeding, mostly on calanoid copepods and euphausiids. Amphipods, decapod crab larvae, chaetognaths, and cyclopoid copepods also occur. In areas of extensive eelgrass beds, herring will also feed on harpacticoid copepods. Gut contents tend to be well digested and there is a relatively high percentage of empty stomachs (much higher than that for salmon species).

Cutthroat trout: sand lance and gammarid amphipods

Sand lance: calanoid copepods; in eelgrass habitats, harpacticoid copepods

Sockeye: Euphausiids, juvenile shrimp, decapod larvae

Surf smelt: calanoid copepods, urochordates, carideans, euphausiids, cyclopoid copepods, larvaceans, harpacticoid copepods

Steelhead: calanoid copepods, crab larvae, insects, crustaceans, euphausiids, ostracods. One incidence of fish larvae (15 in one gut); one incidence of herring.

Spiny dogfish, hake, tomcod: euphausiids, mysids, gammarids

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