SALISH SEA
MARINE SURVIVAL PROJECT

CANADIAN PROGRAM SUMMARIES



COMPILED BY

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Pacific Salmon Foundation, 2020

LONG LIVE THE KINGS

PACIFIC SALMON FOUNDATION

marinesurvivalproject.com

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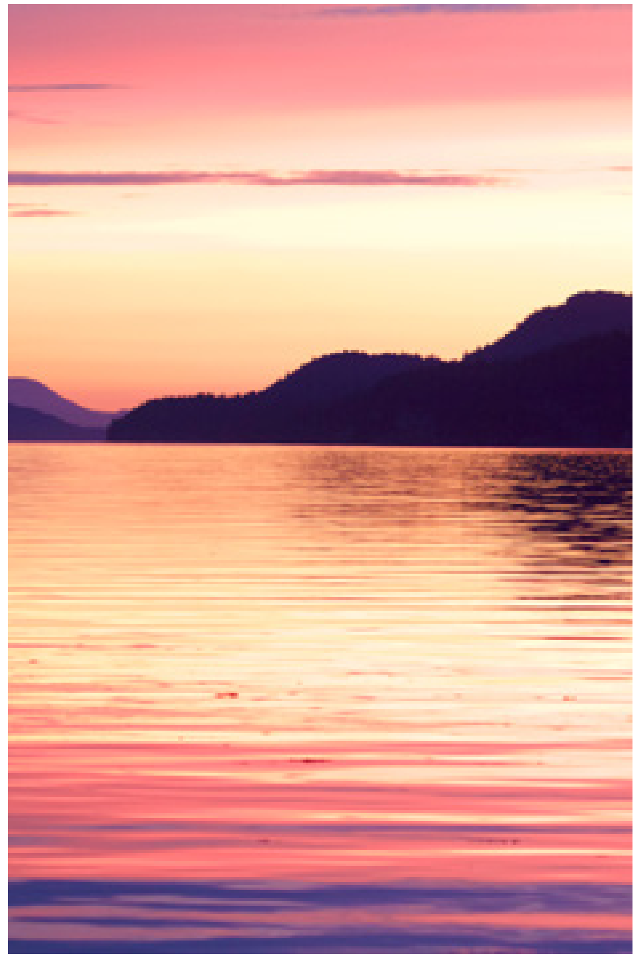


Painting 'Untouchable' by Joshua Hansen. Cover photos by Eiko Jones, Jeremy Koreski, Ryan Miller and Mitch Miller

PREFACE

We admit some significant pride in our accomplishments and deep appreciation to our friends and funders who enabled the Pacific Salmon Foundation to undertake the Salish Sea Marine Survival Project (SSMSP). Now a decade since its inception, and after hundreds of inter-related projects (**www.marinesurvivalproject.com**), we have written project summaries geared to the general population that shares the sea amongst us (about 75% of BC residents live around the Canadian portion of the Salish Sea). Originally a Canadian initiative to address changes in the abundance of Pacific salmon production in the Strait of Georgia, our efforts were greatly strengthened with the inclusion of U.S. partners through the Long Live the Kings organization (Seattle, WA). We asked participants to commit to a short, very intensive and comprehensive period of research as opposed to past practice of single studies on one species over larger times/spaces; and they all enthusiastically responded. We gratefully acknowledge their total commitment to this project.

While we have learned lots, we never know everything — which is why we also acknowledge the invaluable network of researchers, community leaders, foundations, environmental organizations, First Nations, companies, and educators that has evolved during this project. When we initiated our research in 2014, 20 years had passed since the decline of Chinook and Coho salmon production and communities surrounding the Canadian Salish Sea were severely impacted. We hope this network of common interest can be sustained to prevent such a time lag again. We fully believe that the expansion of community-based science will contribute to maintaining this network and an awareness of change in the Salish Sea — as change will certainly continue. Citizen Scientists from your local communities were instrumental in collecting oceanographic information, mapping forage fish beaches, collecting juvenile Chinook and Coho salmon, and restoring near-shore habitats and estuaries. And the Sitka Foundation and the University of British Columbia have provided a secure archive for historical and new information about the Salish Sea (**www.sogdatacentre.ca**) that is open access for all users.

While dozens of scientific publications will be written about this research, we acknowledge that our supporters don't typically read scientific journals during their relaxation time. So, we have prepared short summaries of studies and methods written specifically for folks who share our deep interests and concerns about Pacific salmon and the Salish Sea. We have included a summary of results which will evolve as we complete analyses and publications over the coming years. Further, the Pacific Salmon Foundation will continue to support research and community projects to improve our understanding of this marine ecosystem surrounded by human pressures as we all look to maintain and restore our Pacific Salmon for generations to come.

No introduction to the SSMSP would be adequate without an acknowledgement of the support from our Board of Directors, donors, other Foundations, participating agencies, and governments. While PSF and our science team could design what should be done, we certainly wouldn't have had funds to sustain the initiative without their invaluable support. In October 2013, the Pacific Salmon Commission, Southern Endowment Fund committed $5 million dollars over 5 years for this project. PSF built on this generous contribution, ultimately raising over $12M to allow for successful implementation of this 5-year integrated ecosystem-based program. This was achieved as a result of the wonderful support of many donors and partners, including early, enthusiastic and continuous support from the Pacific Salmon Endowment Fund Society. A fuller recognition of all our donors is provided in the Introduction.

This has been the largest international research project ever undertaken in the Salish Sea targeted at concerns about production of Pacific Salmon. We hope you enjoy the summaries and look forward to our future collaborations.

Brian E Riddell, PhD.
Past CEO/President, PSF
Science Lead, SSMSP

Mike Meneer
CEO/President, PSF

For an in-depth and enjoyable read about the Salish Sea, see: ***The Sea Among Us***, (2014) R. Beamish and G. McFarlane, Harbour Publ. Co. Ltd. Madeira Park, BC 384 p. Published with the support of the Pacific Salmon Foundation

EXECUTIVE SUMMARY

The Salish Sea Marine Survival Project (SSMSP) was designed as an intensive, short-term study of the Salish Sea to simultaneously examine the major components of the salmon ecosystem; evaluate the marine survival of Chinook, Coho and steelhead; and identify the primary determinants of survival/production of these species. *In a nutshell*, our findings are as follows:

BIOLOGICAL OCEANOGRAPHY:

Changes in environmental variables (sea surface temperature, salinity, winds, and light/cloud cover) and zooplankton relate to changes in Chinook and Coho marine survival rates; confirming that annual variation in weather translates into food availability; this subsequently affects the survival and growth of juvenile salmon, and ultimately becomes a major determinant of adult returns/abundance for Chinook and Coho Salmon in the Salish Sea. These studies also introduced a new Citizen Science Oceanography program in the Strait of Georgia that involves local citizens in monitoring of their local marine waters. We recommend on-going monitoring in the Strait in order to forecast change in salmon production, particularly under climate change.

BOTTLENECKS TO SALMON SURVIVAL:

Chinook salmon in the Cowichan River were intensively studied as a proxy for other systems surrounding the Strait of Georgia, and included a comparison of wild and hatchery-produced juveniles. Minimum water flows,[1] the condition of riparian and estuary habitats and hatchery release locations were critically important to juvenile salmon survival in the river; low flows of water resulted in higher losses of juvenile salmon by predators; and wild-produced juveniles survived at twice the rate of the hatchery fish. A surprising finding was the high level of predation by herons, particularly on hatchery fish. A novel tagging program identified that the early marine entry period and then the first winter at sea appear to limit production (i.e. are bottlenecks to survival). We recommend a broader application of such studies throughout the Strait, further study of the first winter at-sea, and a study of the effectiveness of salmon production from hatcheries.

NEARSHORE HABITAT RESTORATION AND RESEARCH:

Healthy estuaries[2] and nearshore habitats serve as nursery areas essential for sustaining production and biodiversity of forage fishes and Pacific Salmon. Coastal development and climate impacts have resulted in degraded estuaries and loss of connectivity of nearshore habitats (including marsh, kelp and eelgrass). Under climate change, warming waters and storm surge will pose increasing risks to these habitats. Our work underscores the need for increased protection and restoration of these vital habitats including reduction of shore-line hardening, marine debris clean-up, and improvements to connectivity of nearshore habitats. These activities can engage many people in community stewardship.

JUVENILE SALMON IN THE SALISH SEA:

The survival and growth of juvenile Chinook and Coho Salmon through their first summer in the Salish Sea is a strong indicator of adult returns to be expected in subsequent years (1 year for Coho, and 1-3 years for Chinook). Genetic analyses of juvenile Chinook and Coho Salmon within the Strait revealed that groups of juvenile Chinook Salmon consistently rear in specific areas but that Coho were widely mixed throughout during their first summer at sea, and that location of rearing was related to patterns of survival. These studies reinforce the importance of oceanographic processes in their survival and growth. Changes in abundance and diversity of Pacific Herring in the Strait of Georgia (in particular age-0 herring, a major prey item), is likely a major determinant of the growth and survival of Chinook and Coho Salmon. We recommend actions to protect and maintain diversity in herring populations.

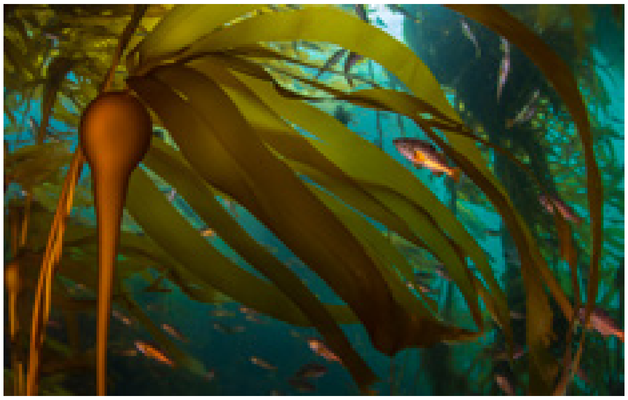
PREDATION STUDIES:

Predators are a major source of mortality on juvenile Chinook and Coho Salmon in the Salish Sea. Our research demonstrated the significance of harbour seals and birds as juvenile salmon predators, and that habitat conditions can significantly increase exposure to predators, particularly in disrupted estuaries associated with log booms. We recommend the development of management actions to reduce exposure of juvenile salmon through habitat restoration, water flow regulation, and removal of log booms in estuaries.

PATHOGENS AND DISEASE:

The southern Strait of Georgia has been identified as an infection 'hotspot' for Pacific Salmon during summer months, with higher infection overall in the Strait of Georgia as compared to the outer Pacific coast. The presence of a dozen pathogens has been associated with poorer body condition and survival for Chinook, Coho, and Sockeye salmon (50 different pathogens were documented in BC salmon). This study was also the first to demonstrate the presence of Piscine orthoreovirus (PRV) and associated diseases in BC's aquaculture salmon (Atlantic and Chinook Salmon). However, the risk that PRV presents to BC's wild Pacific Salmon continues to be debated. PSF has supported a move to closed containment salmon aquaculture in BC, based on outcomes of this research and the present state of Pacific Salmon in BC. Under projections for climate change, we recommend continued research into pathogens and disease as a source of mortality, and tools developed during the Strategic Salmon Health Initiative may be invaluable to these studies.

The ultimate goal of the SSMSP has been to determine whether weak Chinook, Coho and steelhead survival is locally or globally driven and to develop action-oriented research and management recommendations. The complex and highly-migratory life history of Pacific Salmon makes resolving the primary determinants of their marine survival difficult — particularly as humans have extensively altered every habitat they depend upon.



We have developed a broad list of recommended actions and next steps to address local impacts but it also appears likely that much of the variation in salmon production is driven by annual variation in weather and resulting biological oceanographic conditions in the Salish Sea. Resource managers will need to monitor interannual changes in marine conditions for salmon and respond effectively as required.

In summary, the Salish Sea Marine Survival Project has made a significant contribution to understanding our wild Pacific Salmon, and should enable implementation of management actions to benefit Chinook and Coho Salmon production. Ultimately, these actions will benefit Pacific Salmon and marine diversity in Canada's Salish Sea. We hope the community networks developed to complete the Salish Sea Marine Survival Program will be sustained including the international partners crucial in this boundary sea.

The Pacific Salmon Foundation thanks all those involved … the advisors, the researchers and financial supporters!

1. BC's Water Sustainability Act (2014) requires the implementation of minimum ecological flows to protect BC's fishery resources, but these flows remain undefined.

2 Those interested in further reading could see: Levings, C.D. 2016. Ecology of Salmonids in Estuaries around the World: Adaptations, Habitats, and Conservation. UBC Press, Toronto.


Strait of Georgia
Salish Sea
Juan de Fuca Strait
Puget Sound
Pacific Ocean

INTRODUCTION

BACKGROUND CONTEXT

In 2009, the Pacific Salmon Foundation (PSF) was asked to investigate why the production of Chinook and Coho Salmon within the Strait of Georgia crashed during the 1990s and has not recovered. The Strait of Georgia is British Columbia's (BC) inland sea located between Vancouver Island and the provincial mainland. The Strait of Georgia Basin and tributaries are home to three-quarters of the population of BC, many of whom use the area for a wide variety of recreational and commercial activities.

In the past, fisheries for Coho and Chinook were amongst the most valuable in Canada, but that changed dramatically in the mid-1990s. Catches that annually had numbered in the hundreds of thousands to a million fish decreased to a mere tenth or less of those levels and have not recovered despite continued investments in hatchery programs and significant reductions in fishing pressures (Figure 1). Regrettably, these losses have not been explained or addressed[1]; and the public is increasingly concerned about the future of salmon, the health of our inland sea, and the continued economic impacts on local communities. Monitoring of hatchery salmon released into the Strait of Georgia and Fraser River has clearly demonstrated a significant decrease in the ocean (marine) survival rate of these fish but the cause(s) of this decline has not been determined.

The PSF developed a scientific program[2] to determine what presently limits the production of Chinook and Coho Salmon and what mitigation actions may be undertaken to increase production. Promoting the restoration of these fisheries could be invaluable to British Columbia, and studies of the early marine life of Pacific Salmon were understood to be a natural extension of the Foundation's core programs working in freshwater streams and with local communities.

However, the Strait of Georgia is also part of a larger ecological zone contiguous with the Puget Sound and the Strait of Juan de Fuca; in combination this region is referred to as the **Salish Sea**. As in Canada, the American portion of the Salish Sea is also a human population center with extensive development, and many similar problems for Pacific Salmon. Many fisheries in these joint waters are considered under the Pacific Salmon Treaty (1985) between the United States and Canada (**www.psc.org**). Decreased production of salmon in the Salish Sea has severely limited fishing opportunities and presents numerous issues under the Treaty. To address these issues, in October 2013, an endowment fund under the Treaty agreed to fund 25% of an international research program modelled after the Strait of Georgia program, and named the **Salish Sea Marine Survival Project (SSMSP)**. The SSMSP was developed to identify the factors determining annual production of Chinook, Coho Salmon and steelhead trout in the Salish Sea. It was initiated in response to the declines in Chinook, Coho and steelhead production, but also because of other ecological changes in the Salish Sea, and increasing evidence that the overall survival of juvenile salmon at sea is largely determined in the first few months after entry to the marine environment (a scientific hypothesis referred to as the "critical period" hypothesis).

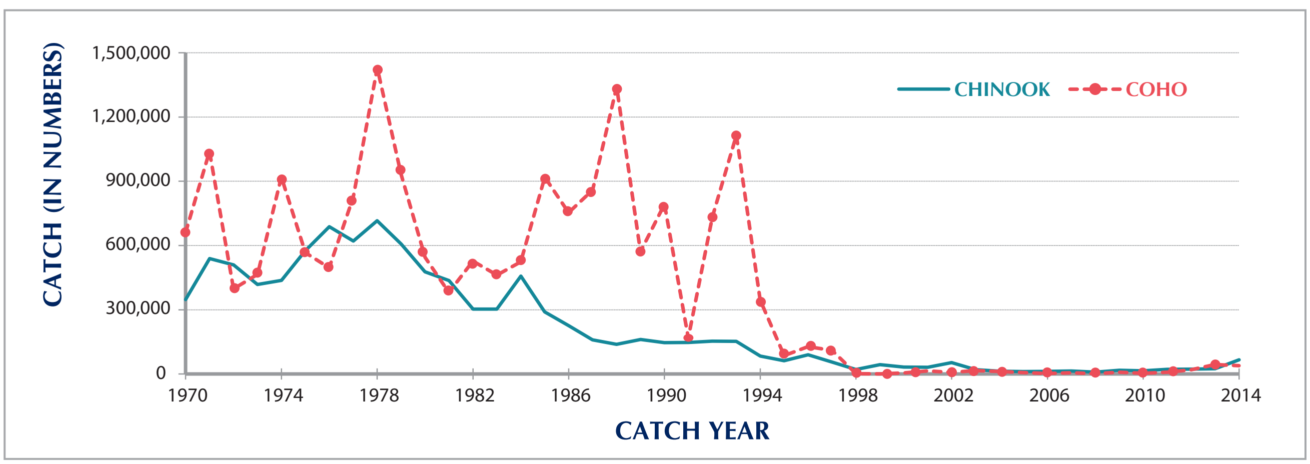


Figure 1. Landed catch of Chinook and Coho Salmon in the Strait of Georgia and Strait of Juan de Fuca, 1970 to 2014. Previous to 1995, catches included recreational fishing and commercial troll; after 1995, catch is limited to recreational catch as troll gear is prohibited for Chinook and Coho in this region.

1. The most recent effort to examine the Strait of Georgia and its biodiversity has been reported in the scientific journal *Progress in Oceanography* (2013), volume 115.
2. The Strait of Georgia Chinook and Coho Salmon proposal (2009). Available at: www.marinesurvivalproject.com

The SSMSP was designed as a 5-year, $20 million ecosystem-based, interdisciplinary study involving government, universities, private consultants, local communities and not-for-profit groups. The Project was coordinated by the non-profits, Seattle-based Long Live the Kings (LLTK) and Vancouver-based Pacific Salmon Foundation (PSF). The project was carried out for 5 years 2014-2018, and analysis, reporting, publication and synthesis continue over 2019 and 2020.

OBJECTIVES OF THE SSMSP

The primary objective of the Salish Sea Marine Survival Project was to determine the principal factors affecting the survival of juvenile salmon and steelhead[1] in the Salish Sea. In Canada these studies were intended to:

- Re-build production of wild Pacific Salmon and steelhead through a program that is ecosystem-based, considers hatchery effectiveness, and engages communities;
- Promote sustainable fisheries and increase their value to BC communities; and
- Provide a foundation for long-term monitoring of Salish Sea and salmon health.

Ultimately, the research results and subsequent management actions may also benefit other marine life in the Salish Sea, such as the southern resident killer whales[2].

SCOPE AND 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 (i.e., the inland marine waters of southern British Columbia, Canada and northern Washington State).

The interaction between salmonids with environments in the Salish Sea is complex. This study was approached from an ecosystem context requiring experts from multiple disciplines. Chinook, Coho and steelhead are the species of greatest concern given significant declines in their smolt-to-adult[3] survival (the primary measure of marine survival) since the mid-1990s. However, chum, pink and sockeye were included to the extent practicable given the recent extraordinary variation in survival of these species, and the associated effects on local fisheries and communities.

HYPOTHESES (CAUSE AND EFFECT)

Science advisors to the SSMSP agreed that the primary ecological processes to investigate included:

A. Bottom-up processes — annual environmental conditions that determine the food for salmon and therefore result in the variation in size and growth rate of juvenile salmonids.

B. Top-down processes — biological processes that directly determine the survival of salmonids. Predation is likely the direct cause of mortality, but fish condition may be compromised by other biological factors, increasing their susceptibility to predation (e.g., disease, hatchery versus wild competition).

C. Additionally, indirect factors exacerbating these ecological processes, including habitat loss and contaminants.

What distinguish the SSMSP from previous efforts are the scope of topics considered simultaneously and the breadth of collaboration involved. Put simply, the SSMSP endeavored to study everything at once that could be hypothesized to impact the annual production of Pacific Salmon within the Salish Sea (Figure 2); as opposed to individual interests in separate species, years and locations.

Our intention is to determine whether the causes of weak Chinook, Coho and steelhead survival are locally (e.g., runoff, wastewater, marine mammal management, habitat availability, hatchery production) or globally-driven (climate change, ocean acidification, ocean cycles). Better understanding of local impacts has the potential to inform action-oriented management decisions to improve salmon production in the Salish Sea; whereas better understanding of globally-driven impacts will further our knowledge about how best to adapt to the changing environment.

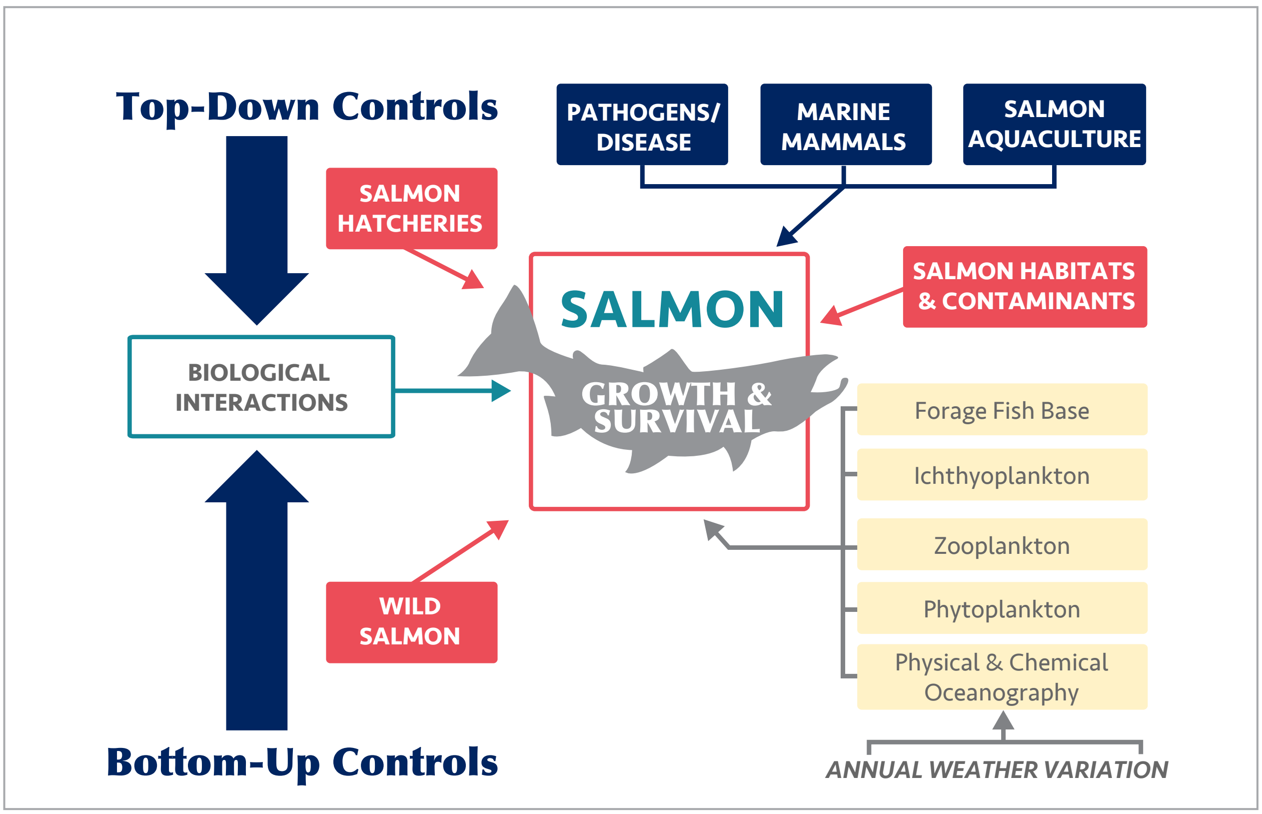


Figure 2. A schematic of the factors addressed annually within the Salish Sea Marine Survival Project. In aggregate, studies within each of these components made up the SSMSP.

1. The original focus in Canada was on the loss of Chinook and Coho catches, but in Puget Sound, Steelhead trout are also a significant concern. Production of steelhead trout in southern BC has also declined in recent decades but has not received the same attention as declines of Chinook and Coho Salmon.
2. The Southern Resident Killer Whale population is listed as 'endangered' under Canada's Species at Risk Act (http://www.registrelep-sararegistry.gc.ca/default.asp?lang=En&n=A9748209-1). See map: http://staff.wwu.edu/stefan/SalishSea.htm
3. A "smolt" is the stage of a juvenile salmon's life when it is physiologically capable of adapting to saltwater. In this stage, the juvenile becomes silvery (losing it dark bars) and begins migration out of freshwater habitats.

PROGRAM DEVELOPMENT

The original concept for the SSMSP program was developed in 2009 by Dr. Brian Riddell (CEO (now retired), PSF), Dr. Isobel Pearsall (Project Coordinator, PSF) and a Canadian Science Team (Table 1).

Table 1. Canadian SSMSP Science Team

NAME	AFFILIATION*	ROLE
Brian Riddell Research Scientist	CEO/President, Pacific Salmon Foundation	Project Lead
Isobel Pearsall Project Coordinator	Research Scientist, Pacific Salmon Foundation	Responsible for project oversight, managing staff and volunteers, science coordination and project planning. Lead for Strait of Georgia Data Centre, PSF/UBC
Richard (Dick) Beamish, Fisheries Research	DFO Science (retired)	Extensive experience in fish, fisheries, and the Strait of Georgia
Ken Denman, Oceanography and Climate	DFO Science (retired)	Adjunct Professor, School of Earth and Ocean Sciences at University of Victoria, and past Chief Scientist with Ocean Networks Canada
Ian Perry, Fisheries Oceanography	DFO Science, Research Scientist	Head of Zooplankton Ecology and Ecosystems, DFO Science, and Adjunct Professor, UBC
Andrew Trites, Marine Mammalogist	Professor, UBC	Director, Marine Mammal Research Unit at UBC, and Research Director of the North Pacific Universities Marine Mammal Research Consortium
Tony Farrell, Fish Physiology	Professor, UBC	Canada Research Chair in Fish Physiology, Culture and Conservation (since 2010)
Carl Walters, Fisheries and Modelling	Professor Emeritus, UBC	Zoology and Fisheries, specialist in fisheries stock assessment, adaptive management and ecosystem modelling
Marc Trudel, Fish Ecology	DFO Science, Research Scientist	Head, Salmon Marine Interactions Section at the Pacific Biological Station. Adjunct Department of Biology, UVic
Kristi Miller-Saunders, Molecular Genetics	DFO, Research Scientist	Head, Molecular Genetics Laboratory at Pacific Biological Station, and an adjunct Professor in the Department of Forest Sciences at UBC
Mel Sheng, Salmon Enhancement	DFO, Salmonid Enhancement Program, Biologist (retired)	Operations Section Head for DFO's South Coast Area, Salmon Enhancement Program
Villy Christensen, Ecosystem Modelling	Professor, UBC	Professor in Ecosystem Modelling at the Institute for the Oceans and Fisheries, leader and developer of the Ecopath project, Principal Investigator, Global Ocean Modelling
Brian Hunt, Biological Oceanography	Assistant Professor, UBC	UBC Hakai Professor in Biological Oceanography at the Institute for the Oceans and Fisheries

*affiliations at the time of SSMSP

The Science team was convened in 2011 and assisted with the development of the SSMSP, building the joint objectives and key hypotheses, and guiding the Canadian research projects.

FUNDING AND SUPPORT

In October 2013, critical seed funding allowed PSF and LLTK to begin the project. The Southern Fund Committee of the Pacific Salmon Endowment Fund committed $5 million dollars over 5 years for this project. The Pacific Salmon Commission is the international body formed by the United States and Canada in 1985 to oversee implementation of the Pacific Salmon Treaty. Pacific Salmon Treaty Commissioner and Fund Committee member, Larry Rutter, announced the award at LLTK's October 2013 Benefit Dinner. PSF built on this generous contribution, ultimately raising over $12M to allow for successful implementation of this 5-year integrated ecosystem-based program. This was achieved as a result of the wonderful support of many donors and partners, including continuous support from the Pacific Salmon Endowment Fund Society associated with PSF, the PSF Board and Major Donor Circle (Figure 3).

James A. Allard, The Aqueduct Foundation, Armstrong Family Foundation, Dick Bradshaw, Brian Denny, Judy Hager, Rivers Holdings Ltd, Tula Foundation, Rudolph North and the North Growth Foundation

Figure 3. Donors of $50K and above to Canadian SSMSP projects.

This compendium is made up of a number of short chapters that provide information and results to date for key projects within the SSMSP. We would like to thank the SSMSP community of researchers and partners for their hard work on these projects, and for provision of text, data, graphs and images for these reports. A full list of our researchers and partners is provided at the end of this booklet.

All data and reports from the SSMSP will be made publicly available via the Strait of Georgia Data Centre (**www.sogdatacentre.ca**) and the SSMSP website (**www.marinesurvivalproject.com**). Further information on the project and the various activities, including copies of technical reports and links to project publications can be accessed at the latter site. Researchers in the program are also preparing scientific papers and intend to publish a compendium of papers summarizing the SSMSP.

Cite document as:

Salish Sea Marine Survival Project – Canadian Program Summaries
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Vancouver BC Canada V6J 4S6.

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SALISH SEA
MARINE SURVIVAL PROJECT

METHODOLOGIES

THE VALUE OF CITIZEN SCIENCE PROGRAMS

BACKGROUND

PSF funded a number of citizen science programs during SSMSP. By 'citizen science' we are referring to the involvement of the interested public in information collection usually within their communities and local activities. There is great value to partnering with citizen science programs, including maximizing information collected in cost-effective ways, developing informed and scientifically competent citizens, and increased understanding by members of the pubic and local communities. Three ongoing SSMSP citizen science programs are described below.

Figure 1. Citizen Science Sampling Locations 2016-present.

Figure 2. A citizen scientist lowering a CTD (Conductivity-Temperature-Depth) in the Strait of Georgia.

PROJECTS

1. Citizen Science Oceanography Program

What is it?

Members of the public collect important oceanographic data about the Strait of Georgia to help us better understand the decline in Pacific Salmon abundance. The project is a partnership between the Pacific Salmon Foundation, Fisheries and Oceans Canada, UBC and Ocean Networks Canada (ONC). Through this program, data have been collected at a spatial and temporal level that has never been accomplished before, and the entire Strait can be sampled within one day!

How it works

The PSF Citizen Science program began in 2015 and was the brainchild of Dr. Eddy Carmack — a retired scientist from the Institute of Ocean Sciences, DFO. It involves volunteers using their own fishing vessels to do oceanographic surveys of the Strait of Georgia approximately every two weeks (Figure 1).

An instrument is lowered through the water to collect and store electronic measurements of conductivity, temperature and depth (CTD) (Figure 2). Conductivity values can be used to calculate salinity. Two auxiliary sensors are also used to measure fluorescence (an indicator of plankton productivity and algal growth) and oxygen content (which helps trace the movement and flushing of water). All this information is then transmitted using a custom designed smart phone application and uploaded to an oceanographic data management system at the University of Victoria, where the data are checked and then archived. The data, once verified and archived, are freely available to anyone.

Four other elements of the work are done by hand to assess water quality. Water samples are taken for nutrient analysis, phytoplankton and zooplankton samples are collected, and turbidity is measured. Nutrients can be limiting factors in plankton growth, while low turbidity is an indicator of healthy water. Plankton is analyzed for occurrence of harmful algae blooms, as well as being Nature's base of the ocean food chain.

In one day, these citizen scientists collect data and water samples from more than 100 sites with automatic transmission of the data via a mobile app called Community Fishers. The app, developed by ONC, allows fishers and volunteer citizens to upload the oceanographic data to ONC's world-leading data management system, Oceans 2.0. From there, the data are archived, processed and visualized for scientists and the public around the world.

Why it's important

Collecting oceanographic measurements this way allows us to be "everywhere at once" and make accurate, consistent data comparisons like never before. Dedicated and trained local citizens are also significant in this era of over-committed staff and shrinking budgets. Finally, the data will help us better understand what is impacting the survival of Pacific Salmon in our local waters.

This collaborative program is ongoing, providing oceanographic information at a temporal and spatial scale not achievable with large traditional research vessels. The data collected are allowing us to assess annual variation in physical/chemical oceanography, develop ecosystem models, validate satellite imagery and understand spatial and temporal changes in productivity of the Strait of Georgia (Figure 3).

2. Coho and Chinook Adult Diet Program

What is it?

PSF is also supporting a citizen science program coordinated by the University of Victoria (UVic), which aims to use food consumed by Coho and Chinook Salmon in the Strait of Georgia to better understand changes in marine ecosystems. This program addresses two key research gaps: the limited research on salmon diets in the Canadian Salish Sea since the 1980s, and winter diets which have never been described. The program involves recreational anglers as 'citizen scientists' to collect diet data year-round throughout the Canadian Salish Sea. The main objectives of the program are to develop an economical, long-term program to monitor the Salish Sea ecosystem, to characterize spatial and seasonal variation in Chinook and Coho diets, and to possibly develop an informative indicator of the abundance of small forage fishes within the Strait.

How it works

Forage fish are the fishy bedrock of the Strait's ecosystem, feeding most predatory marine creatures including salmon. But, while there are studies on commercially fished species like herring, a giant gap exists in our understanding of other forage fish species that are also important. The Adult Diet Program uses salmon stomachs and volunteers to fill that gap. Stomachs of adult fish are collected and then processed by students and staff at UVic. Anglers freeze the stomachs of salmon they caught, fill out a data card for each fish, and drop stomach contents off at designated tackle shops. By engaging multiple volunteers with small vessels, the team is able to collect data from all over the Strait throughout the year.

To date, over a thousand stomachs have been analyzed, and results so far indicate that Pacific Herring are by far the most important prey for both Chinook and Coho, providing a food source year-round. In June, small, recently born herring feed juvenile Chinook (Figure 4). But some observations indicate that these 'young-of-year' herring are getting too big for some juvenile Chinook to feed on, potentially having a negative impact on marine survival. Another finding observed a recent surge in anchovy populations in the southern Strait, with anchovies comprising up to 30 per cent of the adult salmon diet in areas of abundance.

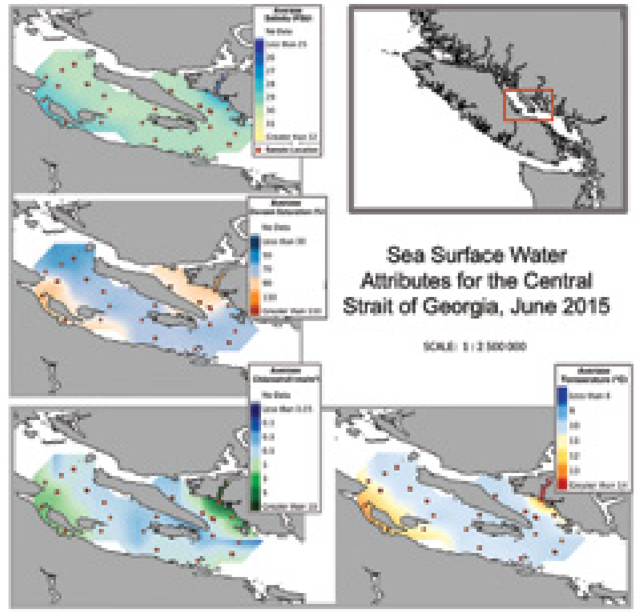


Figure 3. Oceanographic attributes, maps, animations and data available at the Strait of Georgia Data Centre www.sogdatacentre.ca.

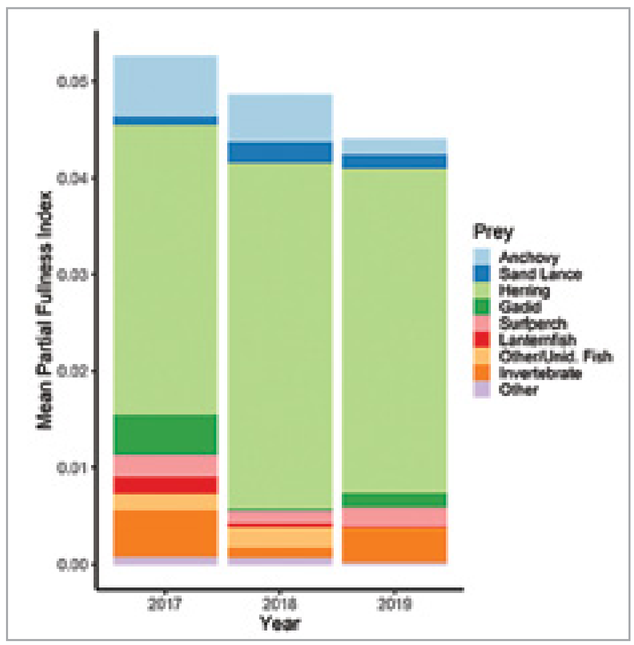


Figure 4. Index of mean partial fullness scores for Chinook Salmon in the Salish Sea from 2017-2019. Data from the Adult Diet Study, provided by Will Duguid, UVic.

Why it's important

While the data collected will be some of the first information obtained on the winter diets of Coho and Chinook, the insight it will give on the state of forage fish could prove equally valuable. Information from this cost-effective, citizen science study could help us make important decisions around the protection of particular forage fish stocks and spawning habitats. As well, having good quality data on forage fish patterns comes with significant benefits to salmon.

3. Forage Fish Beach Monitoring

What is it?

As noted above, forage fish are of tremendous importance to the marine food webs of the Strait of Georgia but their populations are very difficult to enumerate and monitor. Their populations display natural fluctuations in abundance as a result of natural cycles in the marine environment, but anthropogenic activities such as overfishing and habitat degradation exacerbate these fluctuations.

Forage fish and their spawning habitats are protected under Section 35 of the Federal Fisheries Act but minimal data are available regarding location of forage fish spawning habitat along the coast of BC.

The Mount Arrowsmith Biosphere Region Research Institute (MABRRI), together with a number of partners, has implemented a citizen science program for monitoring shorelines around the Strait of Georgia (Figure 5). This builds on much of the past and current work carried out by Ramona De Graaf of the BC Shore Spawners Alliance (BCSSA).

How it works

MABRRI is training citizen science groups around the Strait of Georgia to identify active forage fish spawning sites through the collection of sediment samples from locations with known favourable habitat characteristics. Sites are chosen using MABRRI's existing predictive mapping for the eastern coastline of Vancouver Island, from Bowser south to Sooke, and the Gulf Islands. MABBRI analyses the samples in the lab and classifies each beach as positive, potential or negative. Beach characteristics are also recorded to test the accuracy of the predictive mapping. All data are stored in the Strait of Georgia Data Centre. (Figure 6).

Figure 5. MABRRI training to assess beaches for forage fish spawning and embryonic development.

Why it's important

It is critical to maintain forage fish populations in order to regenerate wild Pacific Salmon to sustainable populations. Generally, Pacific sand lance (PSL) and surf smelt use inter-tidal zones of beaches on Vancouver Island for spawning and embryonic development. The BC Land Act prevents modifications being made in areas below high tide, with exceptions made when leases or licenses are obtained. However, shoreline owners and property owners are not generally informed about locations of spawning habitat when pursuing development, rendering conservation efforts difficult.

The project is allowing us to fill existing data gaps as to where and when forage fish are spawning, specifically PSL and surf smelt. Further, hosting this data in PSF's database, the Strait of Georgia Data Centre, will allow the data to be accessible to any party at all times. These data can ultimately be used to make educated decisions with regards to beaches, including potential policy and management modification that could be made to benefit the spawning activity in identified regions. Ideally the data will be consulted prior to any new coastal development, as well as any actions that could result in harm to forage fish spawning habitat.

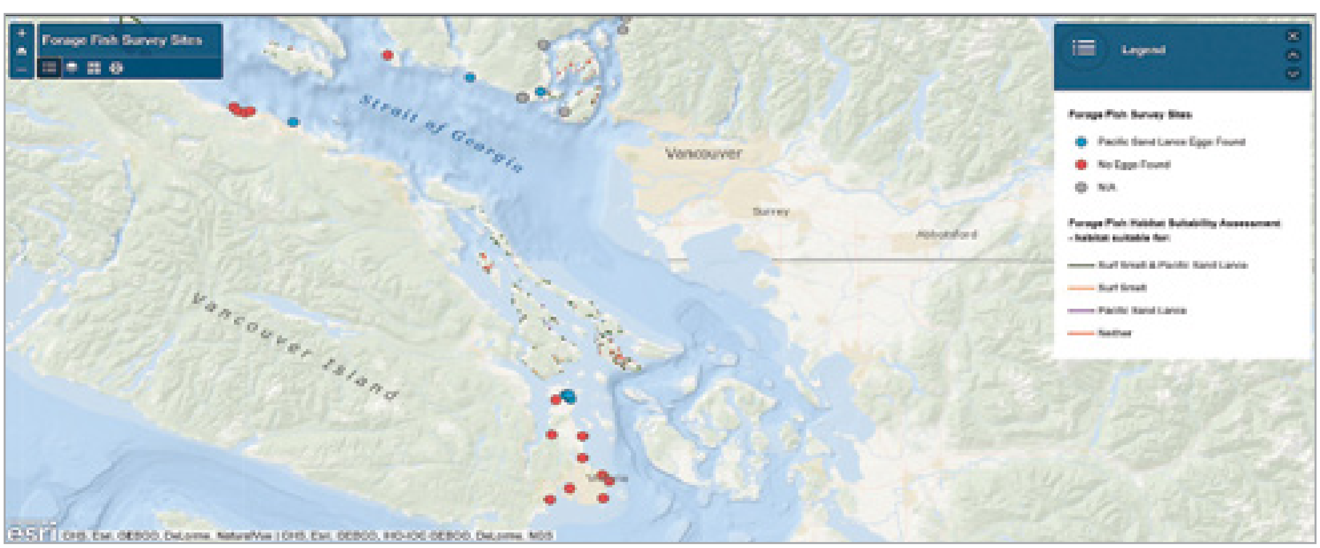


Figure 6. Interactive mapping of beaches surveyed around the Strait of Georgia, with information on positive and negative beaches for surf smelt or Pacific sand lance. Figure provided by the Strait of Georgia Data Centre, www.sogdatacentre.ca.

USE OF NOVEL TECHNOLOGIES

TECHNOLOGIES

1. Using microtrolling to understand salmon mortality

Traditional methods to collect fish in the marine environment use large vessels which cost thousands of dollars per day and are limited in their ability to access specific habitats and high-current areas. But, Will Duguid, (University of Victoria) and Kevin Pellett developed a method coined 'microtrolling' that uses personal boats and miniature recreational hook-and-line gear to non-lethally capture juvenile Chinook or Coho Salmon during their first marine summer. The method greatly reduces costs, allows sampling at fine habitat scales and provides fish with minimal injury (Figure 1).

Mortality of juvenile Pacific Salmon in their first marine months is hypothesized to be a critical period in determining the survival of salmon. But to test this hypothesis requires measuring survival during short time periods, which has been a major challenge in the past. Pilot studies of microtrolling in Cowichan Bay at the beginning of SSMSP showed that this method proved effective for systematically sampling juvenile Chinook Salmon in many micro-habitats. And when coupled with tagging methods that allow us to uniquely identify each tagged fish, these tagged "groups" provide a novel program to measure survival differences between these groups of juvenile salmon.

Duguid uses microtrolling to investigate juvenile Chinook distribution, diet and growth in the southern Gulf Islands in late summer to early autumn. His study focuses on how juvenile salmon use their environment, and whether they are concentrated in biological 'hotspots' that support optimal rearing conditions for salmon.

2. Use of Passive Integrated Transponders (PIT) Tags

Salmon biologists believe the mortality rate of juvenile salmon is very high for the first few months at sea and then declines as salmon grow. But, in reality, our ability to measure the mortality rate in a specific time period is very limited. Typically, it is measured by estimating the number of juveniles migrating to sea (or counted at release in hatcheries) and comparing that number to the estimated catch and spawning return of these fish. So we can estimate the total survival during the life span of a group of fish, but we don't know when the mortality events are occurring.

However, SSMSP participant, Kevin Pellett, came up with a novel method to allow us to pinpoint the key periods of mortality and possible bottlenecks. By PIT tagging a large number of hatchery and wild Chinook at different time periods: in freshwater, at early ocean entry (collected by beach seines when fish are still very close to shore), when the juveniles are larger and have moved into the open bay (collected using purse seines) and later in their first summer and fall when they have moved offshore. In any of the periods/locations, these fish can be collected using microtrolling, tagged, and released (Figure 2). The tags can be detected at a series of antennas located in the mainstem of the lower river and in side-channels. These can detect when juveniles leave freshwater and also when the adults return.

Instead of having just one measure of total survival, we can thus create multiple "release" groups and compare their survival using the information from the PIT tags (which are unique to every fish). During SSMSP, the BC Conservation Foundation applied PIT tags to more than 56,000 juvenile Chinook in the Cowichan River to compare the survival of different groups of fish.

- **Microtrolling, a non-lethal, low-cost method of capturing juvenile salmon, was invented in the Strait of Georgia and is now being employed in Puget Sound by USGS.**
- **Coupled with the application of PIT tags to juvenile fish, microtrolling allowed for the first direct estimates of marine survival during the early marine rearing periods.**

Figure 1. Miniature gear used for microtrolling. Photo by Will Duguid.

Figure 2. BCCF staff PIT tagging juvenile Chinook on a purse seine in Cowichan Bay.

3. Determining harbour seal predation on juvenile salmon

Harbour seals can consume a large number of juvenile Chinook and Coho Salmon when the fish first enter marine waters. But their rate of predation may not be as large as people speculate. Past estimates were based on only a couple of years of sampling scats from Cowichan Bay and other areas of the Strait of Georgia. Those studies used the hard parts that remained in the scat as means to identify the species eaten. The problem is that we were unable to determine the age, species, origin or numbers of salmon in these samples. A new research technique was developed through the Salish Sea Marine Survival Project to directly estimate the rate of predation on a release of hatchery Coho Salmon from Big Qualicum Hatchery.

This research study — conducted by the Marine Mammal Research Unit at University of British Columbia (UBC) under Dr. Andrew Trites in cooperation with BC Conservation Foundation — involved using DNA techniques to identify prey in seal scats, the development of 'seal beanies' to detect Passive Integrated Transponder (PIT) tags placed in salmon, and the application of customized 3-D backpacks to track the activity, including the feeding behaviour, of these seals (Figure 3).

The seal beanies are the creation of Austen Thomas and Brian Battaile, who were both PhD students at UBC during SSMSP. Thomas and Battaile designed a circular antenna for the beanie that could detect a PIT tag as a seal consumed it. When a seal fed on a tagged salmon and then hauled out of marine waters to rest, the tag's information captured by the beanie was automatically transmitted to a satellite, then down to Austen's lab at UBC. PIT tags emit a unique ID meaning salmon can be individually counted when consumed.

▸ This initiative used the first-ever application of 3-D backpacks and the customized 'seal beanie.' Although seal beanies are commonly used to track seals, Thomas' innovation allowed us to study the interaction between seals and juvenile salmon, and provided the first ever direct measure of predation rates on individual salmon.

Figure 3. Seal experts outfit an anaesthetized seal. No seals were harmed during the project. Photo by Dennis Frost.

In 2015, PSF funded the deployment of 20 beanies on seals near Big Qualicum Hatchery, in Deep Bay, and in other local seal rookeries. The seals living near the Big Qualicum River hatchery had the opportunity to feed on 36,900 Coho smolts containing PIT tags. Seals began feeding on tagged Coho during the first night after their release from the hatchery. The data were immediately transmitted back to UBC. After years of development, the system worked perfectly. Results of the study showed that only some of the seals appeared to be specialised feeders on juvenile salmon, that they fed mostly at dusk, and overall, only 6.1% of the tagged Coho were preyed upon by these local seals.

Figure 4. An outfitted seal heads back to sea. Photos by Dennis Frost.

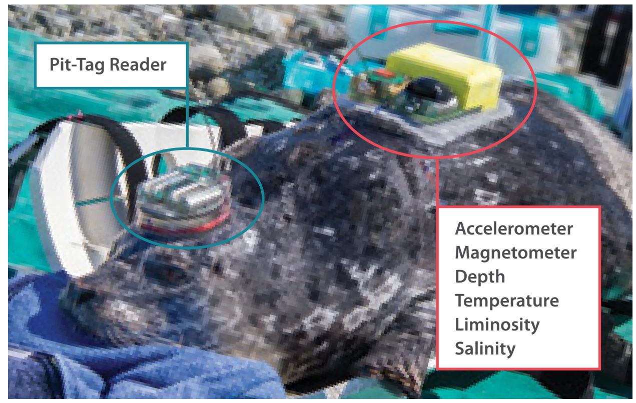


Figure 5. A close-up of the beanie and 3D-backpacks.

4. Using Citizen Scientists to assess oceanographic conditions

One of the serious challenges in studying marine waters is how to determine what is happening in different places at the same time—in other words being 'everywhere at once.' Typically, large oceanographic vessels conduct annual surveys in limited number of places a few times a year. Dr. Eddy Carmack, a retired scientist from the Institute of Ocean Sciences in Sidney, BC, came up with the idea of equipping small private vessels that would follow specified sampling schedules and locations to capture the dynamics of the Salish Sea. This "citizen science" fleet became our answer to how to essentially be "everywhere at once" and capture the fine-scale dynamics of the Strait of Georgia.

Vessels from local communities were contracted and then outfitted with the equipment necessary to conduct surveys (Figure 6). This "mosquito fleet" has been operating since 2015, sampling 2 -3 days per month in 8-10 overlapping areas of the Strait. In one day, these citizen scientists collect oceanographic data, plankton and water samples from about 60 sites (Figure 7). The data collected are then transmitted automatically via a mobile app called Community Fishers. The app, developed by Ocean Network Canada (ONC), allows fishers and volunteer citizens to upload data to ONC's world-leading data management system, Oceans 2.0. From there, the data are archived, processed and visualized for scientists and the public around the world (Figure 8).

Figure 6. Steveston Citizen Scientist Billy McMillan lowers a secchi disk into the water to test for turbidity or water murkiness. Murkiness can block light and prevent plants that support salmon prey from growing.

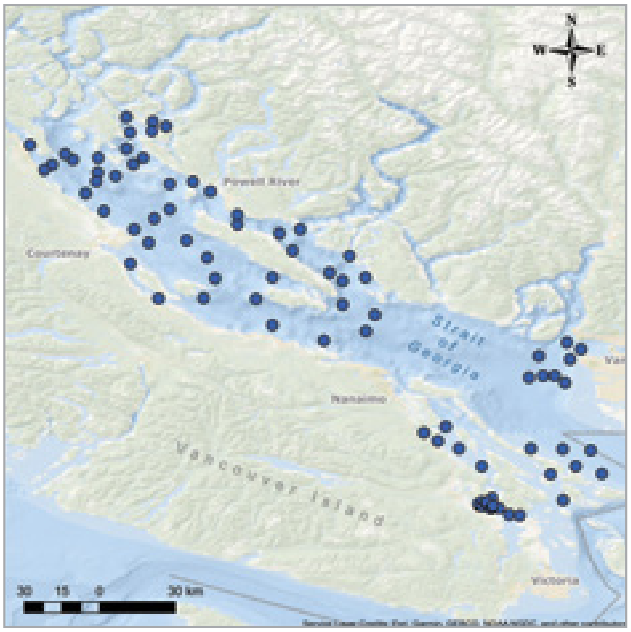


Figure 7. PSF Citizen Science Oceanographic Sampling Stations 2017-present

▸ **This compilation of oceanographic data is the most comprehensive ever collected in our Salish Sea! The data are freely available from ONC's data management system Oceans 2.0 and from the Strait of Georgia Data Centre.**

Figure 8. Information flow from the wi-fi enabled CTDs to the ONC's database.

Figure 9. The SSHI achieved a milestone in 2015 when the BioMark was approved for use in Phase 2b of the project.

▶ **New technology — the Fluidigm BioMarkTM HD System can analyze samples on a scale never before conducted on fish. Up to 90 individual fish and 47 microbes (duplicated) can be examined simultaneously! This break-through allows for statistically reliable sampling for pathogens in fish for the first time.**

5. Powerful Genetic Technologies — Genomics

During SSMSP, new genetic tools were developed to assess if a fish is developing an active disease, allowing for detection before clinical signs of the disease are evident. The Strategic Salmon Health Initiative (SSHI) is a collaboration between Genome BC, the Department of Fisheries and Oceans led by Dr. Kristi Miller-Saunders, and the Pacific Salmon Foundation. This study has successfully demonstrated the application of a new technology from Dr. Miller's lab. During the past few years, over 28,000 samples of wild Pacific Salmon, hatchery-reared Pacific Salmon and aquaculture-reared Atlantic Salmon have been collected and analyzed using state of the art genomics methods to examine microbes (Figure 9). This study is the largest such survey ever conducted on Pacific Salmon.

The data analyses have focussed on **1)** developing models to relate infectious profiles with ocean survival and productivity in Chinook, Sockeye and Coho Salmon; **2)** assessing the variation in infectious profiles in aquaculture fish from four farms; **3)** producing models to assess potential for farm-wild exchange of infective agents across all salmon species surveyed, assessing pathogenic potential of top agents of interest through linkage with physiological changes at the molecular and cellular levels; and **4)** looking at hatchery-wild interactions for Coho and Chinook.

6. Use of Acoustic Telemetry

Acoustic tags transmit unique signals that are received and recorded by receivers suspended in the sea. If a fish tagged with an acoustic tag passes a receiver within approximately 300 metres, the receiver records that event. By strategically placing lines of receivers across the seafloor, researchers can trace the migration path of individually tagged fish (Figure 10). As part of the SSMSP, PSF has enhanced the use of acoustic tags and receivers within the Strait of Georgia.

Until 2015 the existing acoustic receiver arrays allowed for fish detections in the lower Fraser River, in Juan de Fuca Strait, in north-central Strait of Georgia, and in northern Queen Charlotte Strait (yellow lines on Figure 10). While these arrays have been very useful, they could not provide sufficient resolution to assess the residence time; migration patterns, rate and timing; and survival of juvenile Pacific Salmon within the Strait of Georgia.

To address these issues, PSF deployed 43 new receivers in the Discovery Islands (northern end of the Strait of Georgia/Salish Sea) and Johnstone Strait near Sayward, BC in 2015. Of these, 41 were loaned from OTN and the other two were loaned from Kintama Research. Figure 11 shows the yellow flotation collars used to protect the receivers.

Figure 10. The red coloured arrays were those arrays implemented by KIntama Research and are additional to the arrays managed by the Ocean Tracking Network (OTN), which are coloured yellow.

Figure 11. Acoustic receivers (with yellow flotation collars) deployed during SSMSP. Photo by Dennis Frost.

These new arrays have dual receivers and can pick up both 69KHz and 180KHz frequencies, which are emitted by larger Vemco V7 tags (69 kHz) and new, smaller V4 (180 kHz) tags, respectively. The V4 tag is half the size of the V7 and weighs only 0.24 gm in water. The smaller tag is preferred for juvenile salmon and during SSMSP, Kintama Research was able to establish the high detection efficiency of the new arrays and the utility of the small V4 tags. The high detection efficiency of V4 tags opens up the possibility of carrying out tagging studies on numerous other salmonid stocks, and allows for tagging much smaller fish (down to 9-10g) than has been previously possible.

PSF, in collaboration with Kintama Research and UBC (Dr. Scott Hinch and students) as well as others, used acoustic telemetry to address a number of key questions, and to assess the behavior (migration rates and patterns) and survival of individual juvenile salmon in the Strait of Georgia, the Discovery Islands and Johnstone Strait (studying Sockeye, steelhead, and yearling Chinook Salmon).

Figure 12. The high detection efficiency of the new arrays for the small V4 tags allows fish as small as 10g to be tagged, opening up the possibility of telemetry studies of Chinook and other smaller salmonids. Photo by Erin Rechisky, Kintama Research.

7. Use of Satellite Imagery

The Salish Sea is a highly productive marine ecosystem. Every year we see a spring diatom bloom in the Strait, which generally starts around the end of March, and sometimes a second bloom in the summer. The timing of phytoplankton blooms and associated increases in zooplankton, which feed on the phytoplankton, is highly variable in the Salish Sea as a result of many factors such as ocean temperature, wind speed, cloud cover and ocean surface stratification caused by river inputs. The processes that produce the food for fishes are referred to as "bottom up" processes in ecological jargon.

In some years, a "mismatch" may occur when phytoplankton blooms occur either earlier or later than usual resulting in less zooplankton production available for young fish to feed on. This can impact survival of the young salmon. Such interannual variability in phytoplankton and zooplankton has likely contributed to the variability in production of Chinook and Coho Salmon between years, and to its general decline since the 1980s.

In order to address the impacts of bottom-up processes on salmon, detailed and long-term data on phytoplankton, zooplankton and oceanographic/environmental conditions are needed but often lacking. Satellites and other optical sensors aboard vessels and on buoys can provide this information at the needed spatial and temporal scales.

Satellites detect a signal which is a function of the particles and dissolved matter in seawater, and this can be used to estimate properties of the water such as phytoplankton biomass, water turbidity and even the type of phytoplankton such as harmful algae. Operational ocean colour satellites such as MODIS-Aqua and Sentinel-3 provide a great opportunity for continuous data acquisition at high temporal resolution — and a great opportunity for future monitoring.

During the Salish Sea Marine Survival Project, researchers at the University of Victoria (UVic) used satellite imagery to determine bloom timing and hotspots of productivity, and how they translate to changes moving through the food web via zooplankton, and ultimately, juvenile salmon. Almost 15 years (from SeaWifs and MODIS) of spatial-temporal satellite-derived phytoplankton data and zooplankton samples were analyzed in relation to environmental data that have long time series (SST, Fraser River discharge, turbidity, wind, cloud cover) and large-scale climate indices.

A second major project was to examine the change in kelp distribution over the past twenty years in areas of the Strait of Georgia. This project used historical satellite imagery.

Figure 13. A hyperspectral above-water reflectance sensor used on BC Ferries. This sensor was used to validate satellite imagery, by gathering information on above-water reflectance. Photograph from Dr. Maycira Costa, UVic.

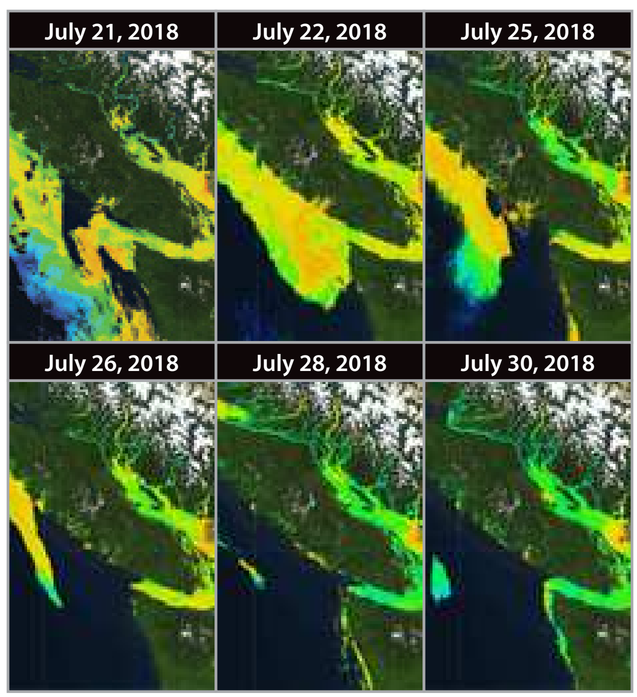


Figure 14. Satellite imagery of the development of the summer bloom in the Strait of Georgia. Images provided by Dr. Maycira Costa, University of Victoria.

8. Pulling It All Together Using Ecosystem Models

A group of scientists led by Dr. Villy Christensen at the University of British Columbia has taken on the task of evaluating long-term trends in salmon survival as part of the Salish Sea Marine Survival Project. The group have learned a great deal from reconstructing ecosystem history using complex food web models for about 50 ecosystems around the world. They concluded that if you wish to replicate historic trends, you need to understand:

1. the interactions in the food web, including how predator and prey impacts each other and how their populations have changed over time;
2. how the environmental productivity, driven by atmospheric and oceanic conditions, has changed over time; and
3. how human impacts and impacts on habitat have changed.

A core aspect of the research is that it requires long-term data. While the research that is supported by SSMSP to a large extent is focused on the present, this ecosystem modelling activity along with the SSMSP data centre (www.sogdatacentre.ca) gathers past data in an attempt to understand the reasons for the reduced marine survival of Coho and Chinook in the Strait of Georgia. But such historic information is sporadic at best — even with a 40-year time horizon — making it necessary to rely on data analysis and synthesis to fill in any blanks. In other words: we need computer models to reconstruct the past, back to when marine survival of salmon smolts was higher.

Through this initiative, UBC researchers are developing a coupled hydrographic and biogeochemical model of the Salish Sea, and linking this to a spatial food web model in order to evaluate how the combination of changes in environmental productivity, food web structure and human impacts (notably through fishing) has changed in the Salish Sea over recent decades. The overarching hypothesis is that the environmental productivity of the Salish Sea is changing over time (e.g., inter-decadal) and that such changes can be amplified through the food web, potentially leading to stronger effects on upper-trophic level species such as Chinook and Coho Salmon.

How do we know if a model is an accurate representation of the actual events? The best means to test complex computer models is to actually build similar but independent models — and that's what we are doing. Besides the UBC model, the National Oceanographic and Atmospheric Administration (Seattle, WA) is building a duplicate model to also explain changes to salmon productivity in the Salish Sea.

- **Complementary "end-to-end" ecosystem models integrate annual weather and water properties, food web structure, fish data and human impacts.**
- **They will be used to cumulatively assess factors affecting salmon survival and trends.**
- **Their long-term value may be as decision support tools for Salish Sea ecosystem and salmon recovery. Integrating what we know to help us manage change over time.**

WHAT CAN WE LEARN FROM OTOLITHS?

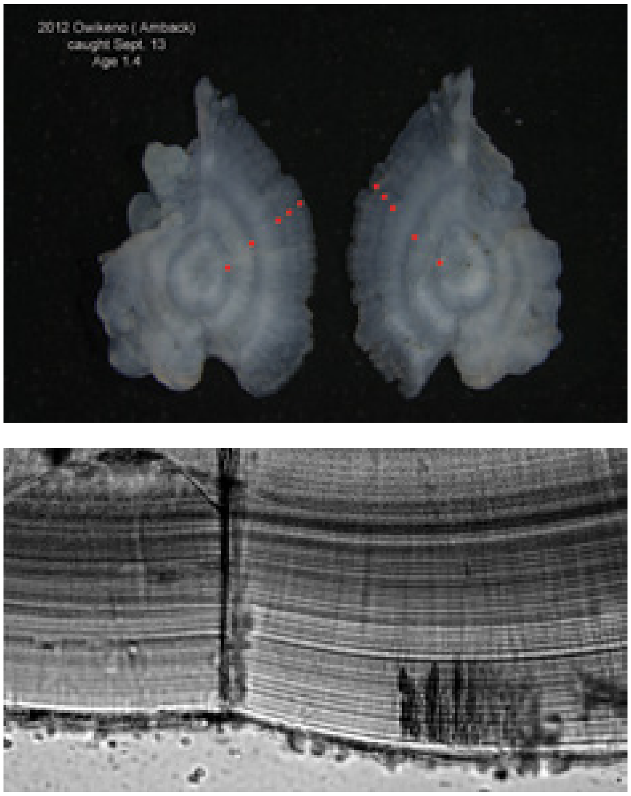


Figure 1. Top: Example of a sockeye otolith with identification of each annulus (red dots) that demark the slower winter growth. Note that the number of annuli from the centre of the otolith (the focus) to an edge of the otolith provides the age of the fish. This sockeye spent 1 year in freshwater, and experienced 4 winters at sea, for a total age of 5 years. Bottom: photograph shows the daily growth rings visible under higher magnification. Images provided by Chrys Neville, Cam Freshwater, Jeff Till and Stephen Wischniowski, DFO

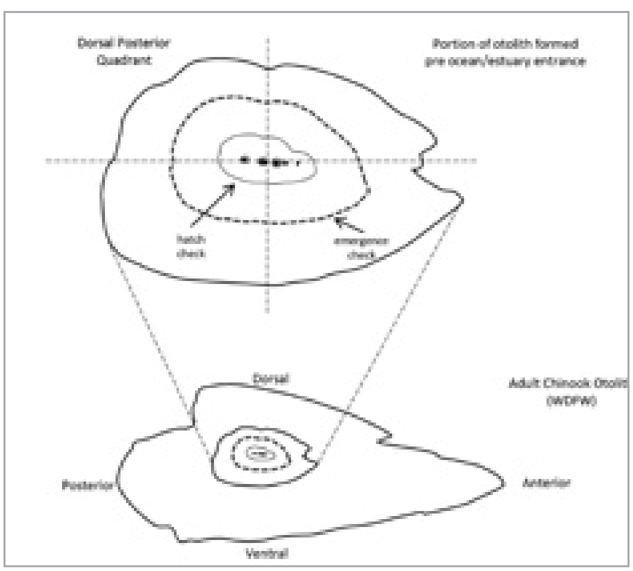


Figure 2. Depiction of an adult Chinook otolith, showing the hatch and emergence checks, as well as the portion of the otolith formed in freshwater and the ocean life history components. Figure provided by Lance Campbell, WDFW.

WHAT ARE OTOLITHS?

Otoliths are ear bones found in all teleost (bony) fish and play an important role in balance, orientation and hearing. They consist of three pairs (left and right sides) of small carbonate bodies called lapilli, asterisci and sagittae. In Pacific Salmon, the first two of these are very small but the sagittae (~5 mm) are larger and are the ones most often studied. Otoliths are actually crystals and formed by a precipitation of protein and calcium carbonate on the exposed surfaces. When examined under a microscope, they show a pattern that looks like the rings of trees. There are a number of concentric zones of differing sizes, and depending on the amount of organic material in each ring they may be opaque or transparent. As juvenile Pacific Salmon move from freshwater into estuarine and then marine environments, the otoliths display bands of different widths and particular visible "checks" which mark periods of change or stress. Ultimately, the otolith with its variable bands and check marks provides an invaluable record of a fish's age, and growth and residence in different habitats.

As a fish grows, the width of the otolith also grows as a result of the precipitation noted above. The amount of precipitation depends on temperature and food availability, resulting in different widths of the bands. Wider bands if a fish grew a lot in a particular environment. These bands are actually deposited daily providing a daily record of a fish's growth and habitat conditions; however, to see the daily growth rings/bands requires high levels of amplification under a microscope (Figure 1 bottom, shows an example of daily growth rings in salmon).

Thermal Marking Studies at Hatcheries

The relationship between temperature and precipitation resulting in formation of daily growth rings has been utilized across the Pacific nations to identify the hatchery-of-origin of various salmon species. In Canada, the Salmon Enhancement Program (SEP) utilizes thermal otolith marks to mass-mark juvenile salmon by creating abrupt changes in water temperatures during incubation which results in a pattern of dark rings in the microstructure of the otoliths. Hatcheries use specific sequences of temperature changes to result in unique patterns for marking the otoliths of their fish. Thermal marking is useful for situations when hatchery salmon juveniles are too small for coded wire tag (CWT) applications or if a release group is particularly large, making it impractical to mark all of them. Thermal marking of otoliths has been important to identify the hatchery origin of adults and for comparative hatchery studies, ultimately providing information on estimates of hatchery contributions in a fishery or fish returning to the rivers, as well as on high seas distribution and migratory characteristics of Pacific Salmon.

WHAT WERE OTOLITHS USED FOR DURING SSMSP?

Otolith Growth Rings: Annual Growth and Age

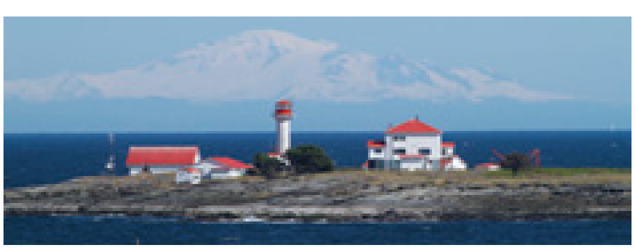
Otoliths are a very reliable tool for determining the age of a fish. In Pacific Salmon annual growth shows up as two distinct bands: a wide ring of dark material (spring and summer growth) and a narrow ring of relatively clear material (fall and winter growth). Biologists can estimate the age of the salmon by counting annuli similar to the way one can count rings on a tree to determine its age. During the Salish Sea Marine Survival Project, many studies used juvenile otoliths to assess size, growth rates and size at estuarine entry of juvenile Chinook and Coho. Other studies looked at returning adult otoliths and used back calculations to assess the influence of size–selective mortality on previous life history stages (e.g., the relationship between size at estuary entry or growth rates of juveniles and subsequent survival).

Otolith Microchemistry: Where Did the Fish Live?

The chemical composition of each layer of an otolith depends on what was in the water around the fish at the time the calcium carbonate was laid down. Quantities of elements such as strontium and calcium can be measured from core to the edge of the otolith to reveal the migration history of the fish, since different environments have different amounts of these rare elements which get incorporated into the otolith. This means that the different parts of the otolith have a unique chemical signature that researchers can use to determine where salmon have been over their lifetime. Also, because different river systems many contain different compositions of these chemical elements, microchemistry techniques can be used to discriminate among stocks or even determine lake or river of origin.

Otolith Shape and Size: Fish Identification and Predation Studies

Otoliths in different species of fish have a distinct shape which can often be diagnostic for that species. Therefore, biologists can look at the shape and size of undigested otoliths in stomach contents or droppings from other predators (avian, fish or mammalian) to reconstruct the species of fish eaten by a predator. Additionally, the size of the otolith can be used to determine the size of the fish eaten.



SSMSP Studies Using Otoliths

During SSMSP, large numbers of otoliths were collected from juvenile and adult salmon to allow us to examine estuarine habitat use, life-history patterns and the relationship between early marine growth and survival of Chinook Salmon. Otoliths from adult Chinook returning to systems have been compared with the otoliths of the juveniles from those same systems to determine which juvenile life history contributed to adult returns. This included determination of whether smaller fry or larger parr were contributing more or less to adult returns, and whether growth rates, estuary residence or other factors were
also important to survival.

Studies done by Lance Campbell and colleagues (Washington State, Department of Fish and Wildlife) have shown that small Chinook fry (35-60 mm) survive to contribute to several populations in Puget Sound and to the Cowichan River in Canada. As adults, these small fry appear to make up as much as 35% of the returning adults to many systems, with the remainder of the returns derived from larger juveniles that leave the systems as larger parr (>60 mm). They also noted that survival of the small fry appears to be greater from systems with intact and less compromised estuaries, which are important rearing habitat for these small fish. This possible relationship between survival and estuary habitat condition could also be related to pathogen and contaminant exposure in the more degraded estuaries. Other studies by Lance have also shown that Coho Salmon that utilize estuarine rearing strategies are important to Coho returns in Puget Sound, an important finding given that the traditional estimates using stream habitat capacity will often underestimate the importance of the estuary-rearing components.

As part of SSMSP and in some of our ongoing studies, such as the Adult Chinook and Coho diet studies spearheaded by Will Duguid at the University of Victoria, otoliths have been collected from stomach contents of salmon to provide information on the species consumed by the various Pacific Salmon.

NEXT STEPS

SSMSP results have focused on the importance of connected and healthy estuaries to both Chinook and Coho life history diversity and survival. We suggest that more work needs to be done to assess the variations in estuary habitat usage, residence and growth of Coho and Chinook in additional Canadian systems as in the Cowichan River. Understanding the length of residence and growth of juvenile salmon in different BC estuaries, and most importantly, the contribution of these fish to the adult populations returning, will help guide and focus future habitat restoration efforts.

SALISH SEA
MARINE SURVIVAL PROJECT

PROJECT BULLETINS

OCEANOGRAPHIC CONDITIONS DURING SSMSP: THE STRAIT OF GEORGIA

OCEANOGRAPHIC CONDITIONS DURING "THE BLOB" 2014-2017

Canadian Salish Sea Marine Survival Project (SSMSP) pilot studies began in 2014 and the full program was implemented in 2015 through 2018. Over these 4 years, we have seen some unusual oceanographic changes occurring along the west coast of North America. These changes had major impacts in the North Pacific Ocean and will likely provide some interesting comparisons during the SSMSP studies and analyses!

In late 2013, scientists started to notice unusually warm sea surface temperatures in the Gulf of Alaska; and by the fall of 2014, these warmer waters extended along vast portions of the Canadian and US coasts. Warming persisted during most of 2015 and into 2016. This mass of warm water, the size of Canada, was named the "Blob" and exhibited sea surface temperatures up to 2.5 degrees Celsius above the 1981-2010 average — an unprecedented observation.

The development of this warm water has been attributed largely to an unusual weather pattern which featured higher-than-normal pressure over the ocean (Figure 1). This ridge of high pressure reduced the number and intensity of storms reaching land, resulting in reduced precipitation along the west coast, and diversion of cold Arctic air into the middle and eastern parts of Canada and the US. The increased temperatures on the surface of the ocean caused the air just above to heat up and stagnate, resulting in greatly weakened coastal winds which were no longer able to push the warm top layer of the Pacific Ocean away from the shoreline. The result was a greatly reduced rate of heat transfer from the ocean to the atmosphere, and slower movement of cooler water into the area of the Blob. This situation was exacerbated by an El Niño event in 2015.

What initially caused this ridge of high pressure is still under some debate. However, using climate modeling, researchers have recently concluded that this climate event was 53 times more likely to have happened, particularly in the Arctic, as a result of human-induced climate change.

PSF'S CITIZEN SCIENCE OCEANOGRAPHY PROJECT

The Citizen Science Oceanography Project, initiated under SSMSP, examined changes in the Strait of Georgia at particularly high spatial and temporal resolution over this very dynamic period of time 2015-2018. Temperature variations were greatest in the upper few meters of water, ranging from as cold as 6°C in March to over 20°C in summer months.

Temperatures below 17°C are best for juvenile salmon early rearing. Given that surface waters were warmer than this in July and August for all three years, it appeared that waters as deep as 10 m in the summer were not good habitat for salmon. However, in all three years, there were regional variations with favourable water temperatures found in highly mixed areas of the Strait, particularly in the northern Strait where tidal flow through Discovery Passage causes extensive mixing. Temperature was also shown to vary significantly between the years, especially at the deeper depth ranges, with 2017 colder at depth (approximately 1.5°C cooler) than 2015 and 2016.

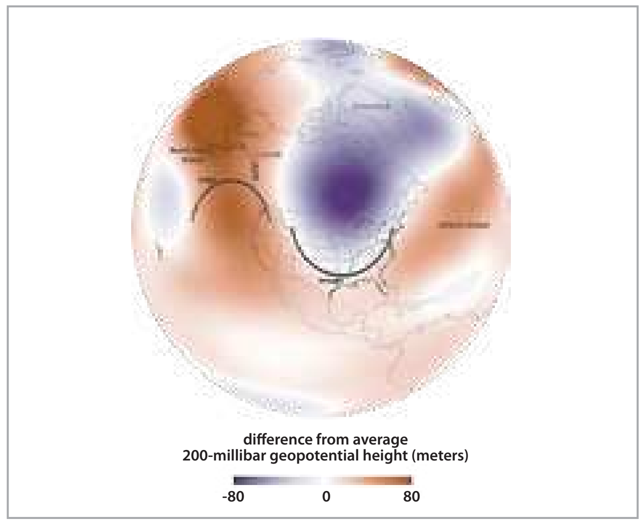


Figure 1. The persistent ridge of high pressure has affected weather patterns. Image derived from NOAA.

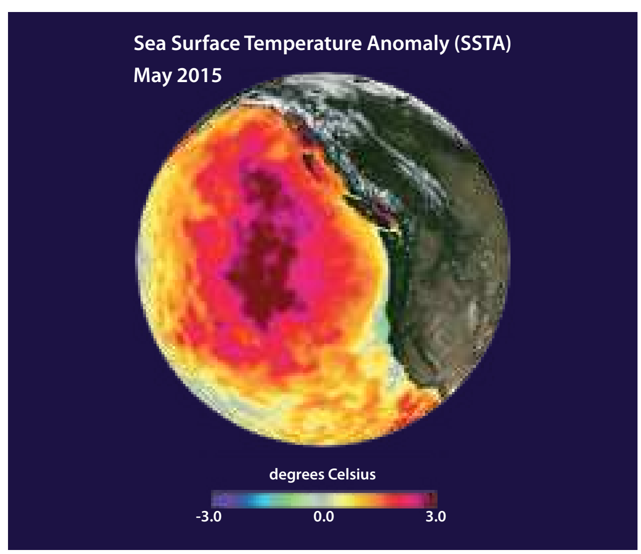


Figure 2. This image shows unusually high sea-surface temperatures in the Pacific Ocean in May 2015 as compared to the 2002–2012 average. Image is from the American Geophysical Union.

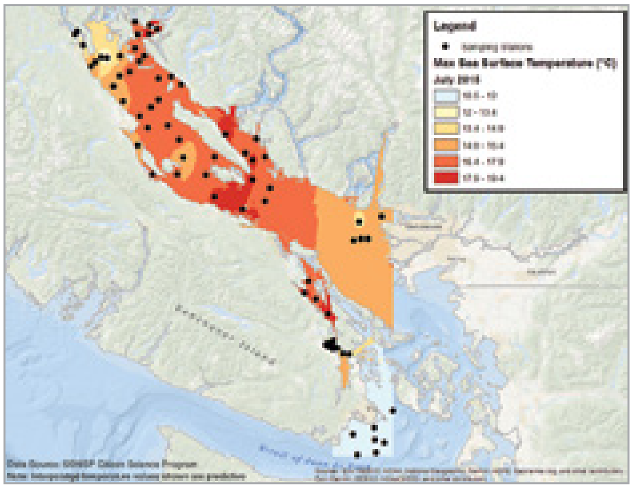


Figure 3. Maximum surface temperatures in the Strait of Georgia July 2015. Data from PSF Citizen Science Program.

Water temperature can also affect dissolved oxygen but in all years surface waters were well oxygenated (> 6 ppm dissolved oxygen). However, oxygen levels were variable between years and at depth. Dissolved oxygen concentrations less than about 6 ppm concentrations decreased growth/increased stress in juvenile salmon. Based on this level, large portions of the deeper water column in the Strait were not good habitat for juvenile salmon for much of the year for all 3 years. The most notable year was 2015 with deep-water oxygen levels approaching a hypoxic limit at 100 m depth around Lund in September and October, and with the critical 6 ppm contour as shallow as 10m in Powell River and Lund at the end of the summer in 2015. Levels of dissolved oxygen in the water column below which most animals will die occurs at concentrations of about 2ppm. While all measurements were above this level for all 3 years, it is known that deeper waters in the Strait have dropped below this hypoxic limit at times.

Given that juvenile Chinook appear to have very defined rearing areas within the Strait, relating regional environmental conditions to growth and survival of the various stocks caught will be illuminating. These data are also being utilized by the Strategic Salmon Health Initiative to understand whether there is a relationship between levels of stress and expression of disease.

IMPACTS OF WARMING CONDITIONS IN THE STRAIT

Warmer water temperatures and increased stratification, both in the North Pacific Ocean and in the Strait, are generally predicted to result in more frequent phytoplankton blooms, more frequent and severe harmful algae blooms and a longer season of blooms. In addition, ocean acidification, another effect of climate change, may increase the toxicity of some harmful algal blooms.

Phytoplankton dynamics in the Strait during 2015 were quite unusual, with mechanically harmful algal species present in abundance. Another unusual observation was a lack of toxic *Heterosigma* blooms over 2015-2017, a species that frequently shows up in the Strait and can kill fish. In 2016, there was an exceptional phytoplankton bloom which turned the water in many areas of the Strait a beautiful tropical turquoise colour (Figure 4). This coccolithophore bloom was not toxic.

Reduced productivity as a result of reduced upwelling is another prediction associated with warming waters. Evidence of this was seen in the Strait of Georgia with nutrients (nitrate and phosphate) trending downwards over 2015 to 2017, with particularly reduced levels of nitrate in 2017 (nitrate is essential for phytoplankton growth).

Other impacts in the Strait included above-average biomass for most zooplankton groups for 2015-2017, which would be good for forage fish and salmon. However, abundances of gelatinous zooplankton, not good fish food, also increased.. The very warm conditions over the winters of 2014-2016 at mid- and bottom depths in the Strait of Georgia had potential negative implications for some important zooplankton. The large, lipid-rich copepod, *Neocalanus plumchrus,* overwinters in the deep Strait of Georgia and has experienced periodic population collapse when deep water winter warming occurs. Early indications in the SSMSP are that *Neocalanus* biomass is now well below average in the Strait of Georgia. This species is considered an important food resource for young of the year fish in the Strait.

Figure 4. Unusual coccolithophore bloom in the Strait of Georgia. August 19 2016. Figure from NASA.

There was a great deal of concern that these conditions would result in widespread salmon recruitment failures but this did not appear to occur. Impacts to Pacific Salmon have been interesting and complex. Unusually high winter flows and/or temperatures in freshwater systems led to variable impacts, while the subsequent summer droughts combined with record breaking summer temperatures resulted in widespread losses of summer migrating salmon adults and rearing juveniles for many populations. Summer droughts also led to high mortalities for "summer-run" adult sockeye returning to spawning grounds in the Okanagan River (>90% en route mortality), Vancouver Island's Sproat River (hundreds of pre-spawn losses) and the Fraser River (various populations exhibiting 20-50% pre-spawn losses).

During SSMSP, we saw very high losses of Cowichan Chinook in-river, likely associated with the low spring flows and easier access for herons and other predators. We also saw negative impacts to kelp populations in the Strait, as temperatures rose well above optimum temperatures for kelp reproduction in many areas.

On the positive side, Coho are showing increased residency in the Strait of Georgia (as evidenced by winter catches by a citizen science group, the Avid Anglers), something that has not been seen since the 1990s. Another unexpected result was the increase in size of Coho juveniles in the Strait, which have been much larger than average. So despite increased temperatures, conditions in the Strait have been conducive to high growth rates and we believe resulted in higher residency rates. Chinook have also shown high growth rates and have been in good condition, as have all other salmon species and herring. Chinook Salmon appear to show consistent differences in distributions that likely result in different stocks experiencing different environmental and growth conditions.

Additionally, there has been a large increase in abundance of Northern Anchovy in the Strait of Georgia. The occurrence of these fish in very large numbers in the Strait is unique in the 18-year history of the DFO trawl survey.

Adult anchovy prefer to spawn in water temperatures that range from 13°-18° C and most reside in warmer Pacific waters. Larval anchovy have been observed in the diets of Coho and Chinook Salmon, and larger juveniles and adults may also provide an alternative prey source for seals and other predators, possibly lessening negative impacts on salmonids and herring. Large catches of multiple age classes of anchovy were encountered in the southern Strait of Georgia in both summer and fall DFO trawl surveys, providing evidence that this species is successfully reproducing in the Strait.

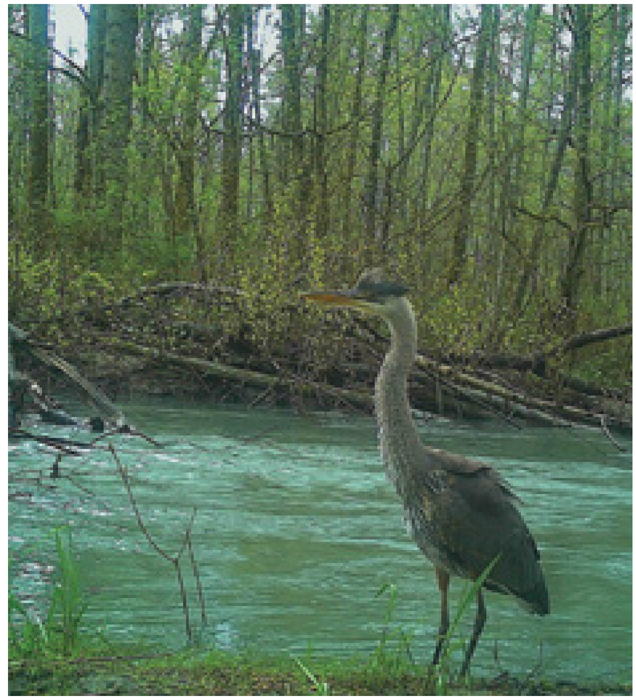


Figure 5. Heron predating on juvenile Chinook in the Cowichan River- herons prefer to forage in shallow waters, less than 25cm depth and foraging success declines rapidly with deeper waters. Photo from BCCF.

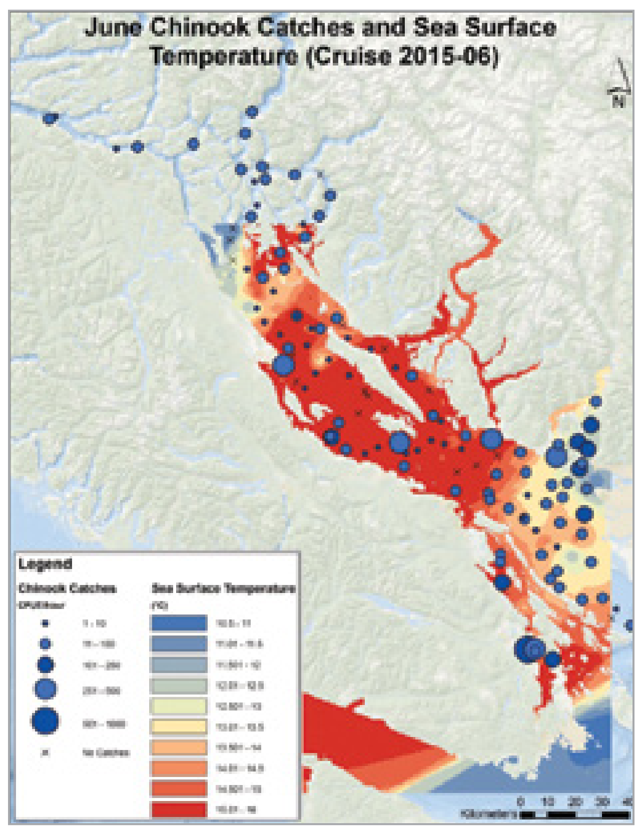


Figure 6. Chinook Salmon have stock specific distributions through the early marine period with over 60% of a stock remaining within these regions. They appear to remain in these areas regardless of the ocean conditions. It is likely that feeding and growth vary greatly depending on the particular conditions experienced in these rearing areas. Figure provided by Chrys Neville, DFO.

At the same time, many other changes have occurred: dogfish are more widely distributed, young of year herring are larger and pollock are more abundant. The larger size of young herring may have a negative impact, due to limits of the mouth size of juvenile Chinook and Coho since many may be unable to switch to feeding on these important prey.

CONDITIONS SINCE 2017

During 2017, physical oceanographic processes associated with the marine heat wave reverted to more normal conditions. The 2017 Strait of Georgia spring bloom had close to average start timing, and phytoplankton community composition in the Strait also showed a return to a more normal distribution. However, although surface temperatures in the Strait of Georgia from May to September 2017 were below the observations for 2015-16, they were still above average for the previous 30 years. These continued higher temperatures may have contributed to some ongoing impacts in the Strait. For example, biomass of most zooplankton groups, including jellies, remained above average; spring spawning biomass of Pacific Herring showed near historic high levels; and Northern Anchovy continued to be abundant in the Strait of Georgia.

Since 2017, new heat waves have been observed again in the North Pacific. Warming of both offshore and coastal waters has led to changes in the food web and coast wide decreases in Chinook Salmon as well as low returns of Fraser River Sockeye Salmon.

SUMMARY

In summary, the story is complex. Warming waters in the Strait of Georgia over the course of SSMSP are conditions that are outside of our experience, and that likely have created a mixture of positive and negative outcomes for salmon. We did see some negative impacts on stocks that entered the Pacific Ocean during the presence of the Blob, with results such as a coast-wide decline of Sockeye Salmon returns in 2017, and generally negative outcomes for BC's central and south coast salmon. However, increasing Coho residency led to many anglers in the Strait being able to take advantage of the first Coho fishing opportunity around the Strait of Georgia in some years.

Our challenge now is to try and understand the relative consequences of these complex conditions. Having the SSMSP studies occur during years when the early marine period appeared to provide particularly good feeding and rearing conditions for Coho and Chinook within the Strait, but likely negative impacts outside of the Strait, is a key consideration for our analyses and understanding.

Figure 8. Herring are a primary fish prey for Coho and Chinook: but YOY herring are at or above the pretty length threshold for most Chinook. Photo by Will Duguid, UVic.

Figure 7. Northern Anchovy displaying an unusual increase in the Strait of Georgia since 2015. Image provided by Ryan Miller.

SATELLITE IMAGERY AND ITS VALUE TO THE SALISH SEA MARINE SURVIVAL PROJECT

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ What are the interannual differences in the timing of the spring bloom and bloom duration in the Northern and Central regions of the Strait of Georgia? ▸ How do plankton respond to climate drivers? ▸ How do variations in phytoplankton relate up the food web to zooplankton, and ultimately, to salmon? ▸ How have kelp distributions changed historically in the Strait?	▸ Satellite-derived chlorophyll (Chl_a) climatology from 2003-2016 was constructed to determine interannual differences in the timing of the spring bloom, bloom duration and anomalies in the Northern and Central regions of the Salish Sea. ▸ Data from ferries, PSF citizen science vessels and the DFO-IOS database were used to validate satellite data. ▸ Environmental drivers (Photosynthetically Active Radiation, Fraser River discharge, Sea Surface Temperature etc.) collated for 2003-2016. ▸ Historical satellite imagery for Kelp: ground-truthing from kayaks.	▸ Bloom timing varies from year to year. ▸ Some regions of the Strait of Georgia have seasonal hotspots with area of particularly high concentrations of Chl_a. ▸ Environmental drivers influence Chl_a differently in the Northern vs Central subregions. Chl_a anomalies in the Northern region were tightly coupled with large-scale North Pacific climate indices, but the Central region was influenced more by localized factors. ▸ Satellite imagery may be used (under certain conditions) to assess changes in kelp distribution in the Strait.

BACKGROUND

The Salish Sea is highly productive, especially during spring when resident and migratory fish populations are either spawning or entering the region. The high productivity is closely linked to phytoplankton and the subsequent zooplankton blooms, and the former is characterized by the annual spring diatom bloom which generally starts around the end of March. The timing of phytoplankton blooms and associated increases in zooplankton, which feed on the phytoplankton, is highly variable in the Salish Sea as a result of a combination of biophysical factors such as ocean temperature, wind speed, cloud cover and ocean surface stratification caused by river inputs (or "bottom-up" processes).

In general, a "mismatch" year when phytoplankton blooms occur either earlier or later than usual results in fewer zooplankton prey being available for young fish to feed on, which lowers the chance of the fishes survival. As a result, interannual variability in phytoplankton and zooplankton likely contributes to the variability in salmon production (e.g., Chinook and Coho) over the last 50 years, and its general decline since the 1980s.

In order to address the impacts of bottom-up processes on salmon, detailed and long-term data on phytoplankton, zooplankton and oceanographic/environmental conditions are needed, but often lacking. Satellites and other optical sensors aboard vessels and buoys can provide this information at the needed spatial and temporal scales.

Satellites detect a signal which is a function of the particles and dissolved matter in seawater, and this can be used to estimate properties of the water such as phytoplankton biomass, water turbidity and even the type of phytoplankton such as harmful algae. Operational ocean colour satellites such as MODIS-Aqua and Sentinel-3 provide a great opportunity for continuous data acquisition at high temporal resolution — and a great opportunity for future monitoring.

USE OF SATELLITE IMAGERY

During the Salish Sea Marine Survival Project, researchers at the University of Victoria (UVic) used satellite imagery to examine the link between phytoplankton and zooplankton using long-term data from specific regions within the Salish Sea. Almost 15 years (from SeaWifs and MODIS) (Figure 1) of spatial-temporal satellite-derived phytoplankton data and zooplankton samples were analyzed in relation to environmental data that have long time series (SST, Fraser River discharge, turbidity, wind, cloud cover) and large-scale climate indices. SeaWifs and MODIS are two principal Earth Observation sensors.

A second major project was to examine the change in kelp distribution over the past twenty years in areas of the Strait of Georgia. This project used historical satellite imagery acquired by SPOT and WorldView. SPOT and WorldView are two principal Earth Observation satellites.

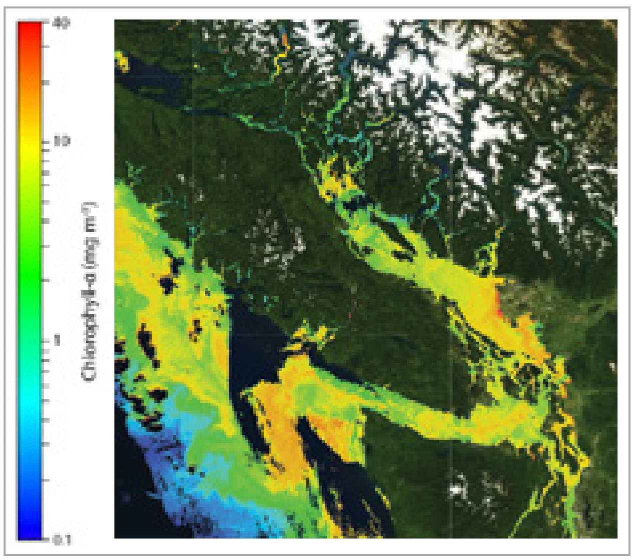


Figure 1. This image shows an example of satellite-derived Chlorophyll-a information. The signal of Chl-a is used as a proxy for the phytoplankton bloom. This image shows a strong bloom presence in the centre of the Strait of Georgia during July 2018. Figure provided by Dr. Maycira Costa, UVic.

SUMMARY OF RESULTS TO DATE

Identify the seasonal patterns and interannual variability in phytoplankton

Spatio-temporal satellite-derived chlorophyll (Chl_a) was constructed over the time period 2003-2016 to determine interannual differences in the timing of the spring bloom and in the northern and central regions of the Strait of Georgia (Figure 2). Figure 3 shows the spatial extent of Chl_a in the "northern" and "central" Strait.

Over time, the highest median Chl_a concentrations were observed in the central region of the Strait of Georgia in spring 2005 and 2015, and fall of 2008. Similar peak timings were also observed in the northern region of the Strait, but to a lesser degree. Low Chl_a concentrations were observed in spring 2011 in both regions.

Spatially, further analyses of the satellite data has indicated that there are hotspots, areas that show particularly high concentrations of Chl_a. For example, the highest concentrations of Chl_a in the spring were located in the southern portion of the central region near the mouth of the Fraser River. During summer, the highest Chl_a concentrations tended to occur in coastal areas of the central region and on the eastern side of Texada Island.

Satellite imagery was also used to calculate the timing of the spring bloom. Bloom initiation was defined as the 8-day week where Chl_a was greater than a threshold value equal to the annual median plus 5%, and concentrations during one of the two following weeks were higher than 70% of the threshold value. The average spring bloom initiation throughout the time series was the end of March (Day 88). Earlier-than-average bloom initiation years were 2005 and 2015, whereas 2007 and 2008 had later-than-average blooms (Figure 4).

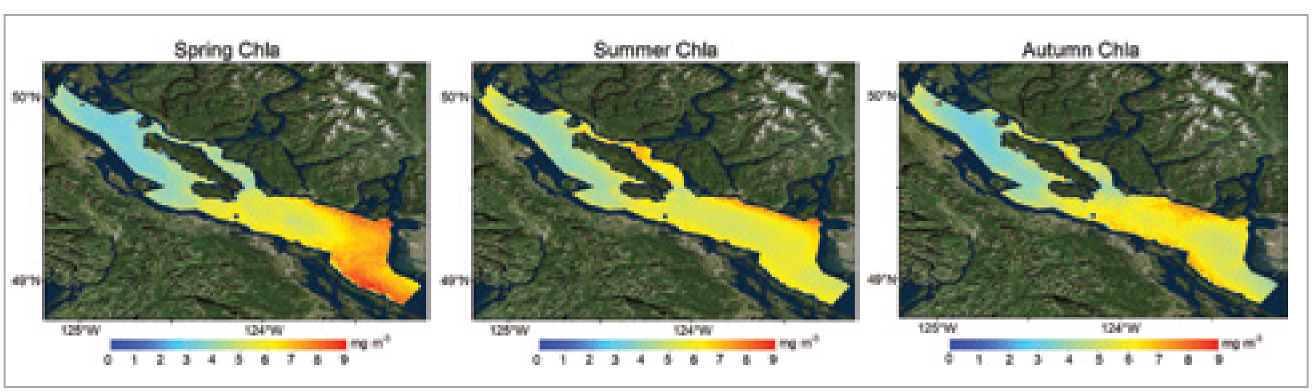


Figure 2. Spatial maps showing chlorophyll a concentrations for spring, summer and fall 2003-2016 in the Strait of Georgia. Figure provided by Dr. Karyn Suchy, UVic.

Investigate the response of phytoplankton to different climate drivers

What causes the differences in bloom timing/abundance? Data for the following environmental drivers were collated: satellite-derived sea-surface temperature (SST) and photosynthetically active radiation (PAR), river input (with a focus on Fraser River discharge), wind speed and wind direction (with a focus on Halibut Bank in the central region and Sentry Shoal in the northern region), and Conductivity-Temperature-Depth (CTD) data (for calculation of a stratification parameter). Regression analysis was carried out in order to determine which environmental drivers best explained variations in Chl_a in the northern vs. central regions of the Strait of Georgia.

Results showed that a combination of increased Fraser River discharge and weak winds likely results in favourable bloom conditions in the Salish Sea. Positive anomalies in stratification in spring 2005 and 2015 corresponded with negative wind anomalies and thus allowed for the development of the anomalously high Chl_a concentrations very early in these years (i.e., during the week of February 18). Median monthly Chl_a in the northern region was positively, and significantly, correlated with monthly Fraser River discharge, SST and PAR; and negatively correlated with wind speed. In the central region, chlorophyll was significantly, positively correlated with Fraser River discharge and PAR; and negatively correlated with wind speed.

Analysis of the relationships between annual median Chl_a anomalies and larger-scale climate indices revealed significant positive relationships between annual Chl_a anomalies in the northern region and the Pacific Decadal Oscillation or PDO, a significant negative relationship between northern Chl_a anomalies and the southern Oscillation Index or SOI, and a nearly significant negative relationship between northern Chl_a anomalies and the North Pacific Gyre Oscillation (NPGO) (Figure 5).

No significant relationships were observed between annual Chl_a anomalies in the central region and any of the climate indices, suggesting that Chl_a in the central region is most strongly influenced by local and annual weather patterns.

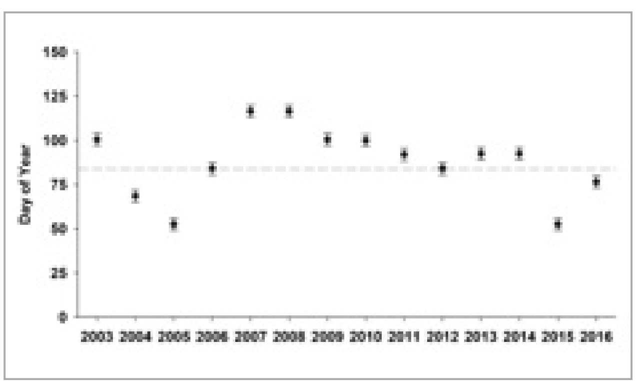


Figure 4. Satellite-derived spring bloom start dates from 2003-2016 in the central Strait of Georgia. Grey line indicates average start date.

Figure 3. Spatial extent of the northern and central regions of the Strait of Georgia. Figure provided by Dr. Karyn Suchy, UVic.

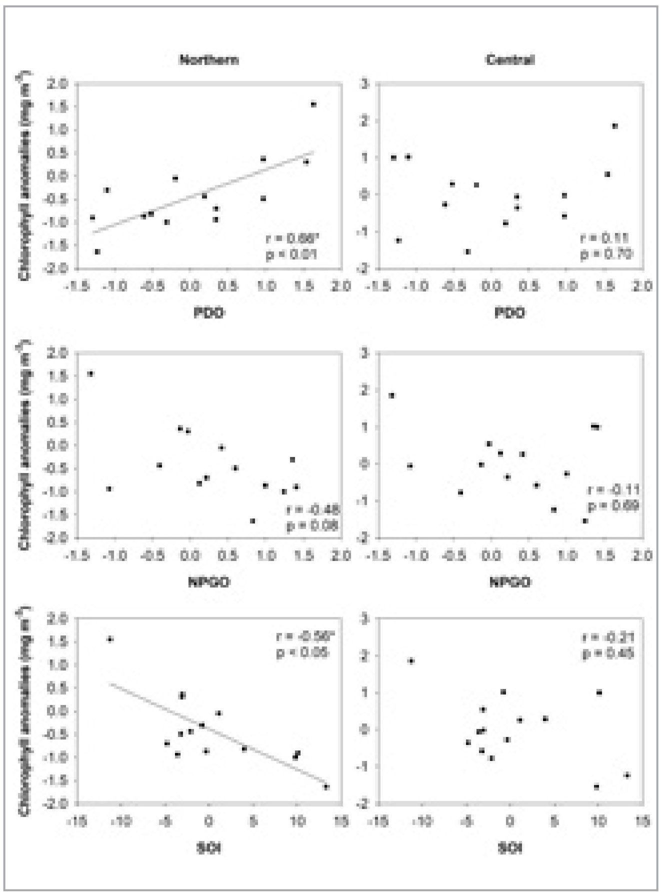


Figure 5. Relationships between annual median chlorophyll a anomalies and climate indices (PDO, NPGO, SOI). Figures 4 and 5 provided by Dr. Karyn Suchy, UVic.

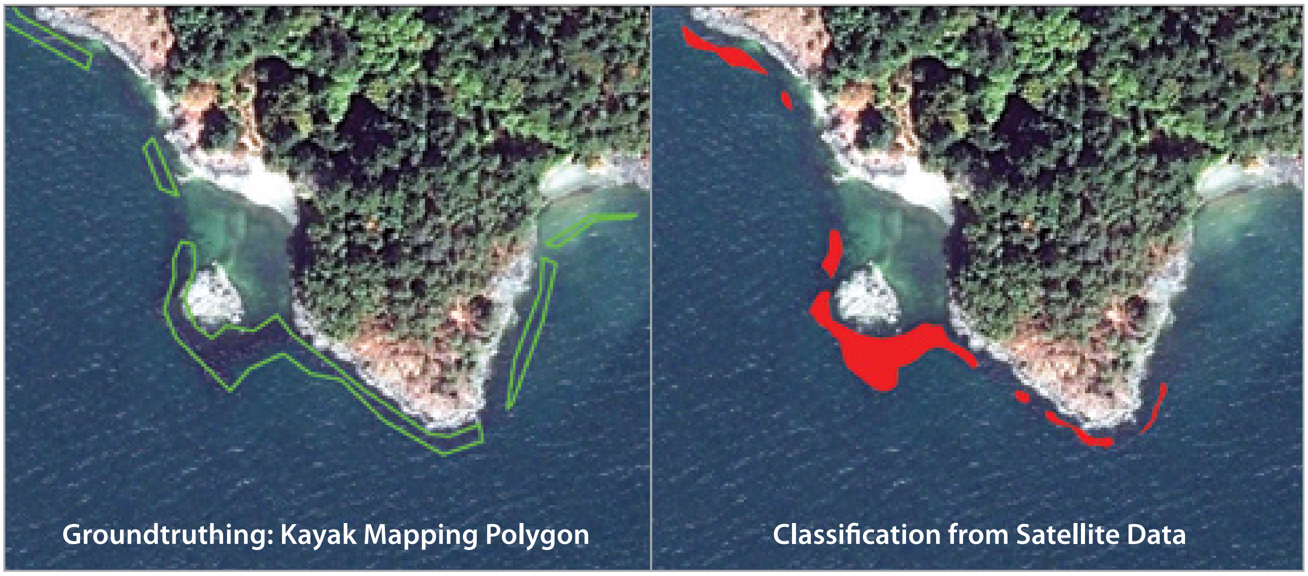


Figure 6. Results of satellite classification (red) and ground-truthing polygons from kayaks (green lines) have 81% overall accuracy. Note some inaccuracies are due to error in the ground-truthing data, which was collected by kayak and GPS. Figure from Sarah Schroeder.

Kelp Studies

Satellite imagery has also proved useful for mapping kelp distributions. High resolution satellite imagery acquired by SPOT and WorldView has been validated by kayak surveys. Results show that the technique has good accuracy when image collection conditions are suitable. When tides are low and kelp beds are dense or mostly on the surface, kelp can be detected with high accuracy (Figure 6).

However, conditions in historical imagery including tide, date and surface conditions are not optimized for remote sensing of kelp and thus kelp detected in these images does not necessarily represent the true maximum extent of kelp present in that year. For this reason, researchers using satellite images will denote kelp presence or absence in defined regions rather than trying to quantitatively assess the extent of kelp. Further refinements to the methodology for analyzing temporal data are being explored to improve the ability to validate historical classifications.

SIGNIFICANCE AND NEXT STEPS

Next steps for the phytoplankton studies will be the linkage of further elements up the food chain to salmon —namely, addition of information on zooplankton, focussing on those species most important in salmon diets. Results will provide insight into how variations in both phytoplankton and zooplankton may impact growth and survival of juvenile salmon in the Strait of Georgia.

ZOOPLANKTON IN THE STRAIT OF GEORGIA

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ What are the seasonal patterns of zooplankton species composition, abundance and biomass in the northern Salish Sea areas? ▸ How do these properties vary with changes in physical conditions? ▸ How do variations in these properties influence the marine growth and survival of juvenile salmon in these areas?	▸ Zooplankton collections throughout the Strait of Georgia 2015-2018 from DFO surveys to provide a 'backbone' of stations, smaller charter vessels to 'fill in' times between the DFO surveys and Citizen Science vessels to sample selected locations at higher frequency (e.g., approximately weekly). ▸ Collections of zooplankton are from vertical net hauls taken during the day or night using Bongo or SCOR nets with 236 μm black mesh.	▸ Total zooplankton biomass in Central and Northern Strait of Georgia has been increasing since 2010. ▸ Biomass of crustacean zooplankton (good fish food) showed a U-shaped pattern over time, with lowest biomasses during 2002-2009 ▸ Statistical models relating physical conditions and zooplankton biomass to Chinook and Coho annual marine survivals are showing clear relationships; and zooplankton prey, salinity and sea surface temperature stand out as key explanatory variables

KEY OBJECTIVES

The short-term goal of the Zooplankton Program has been to identify the seasonal patterns of variability in zoo/ichthyoplankton species composition, abundance and biomass in the Strait of Georgia and Juan de Fuca Strait, and how these patterns relate to changes in environmental conditions.

Long-term, the aim is to identify the effect that changes in seasonal patterns of the species composition, abundance and biomass of the zoo/ichthyoplankton in these areas have on the growth and early marine survival of juvenile salmon and, ultimately, their influence on the overall number of adults that return to local populations.

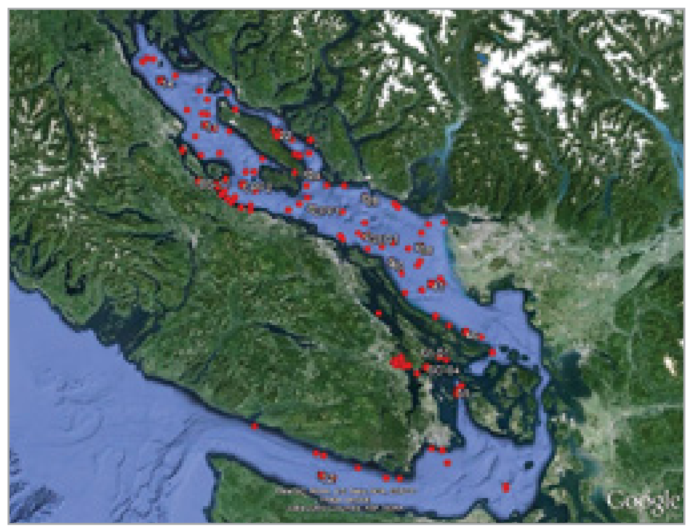


Figure 1. Zooplankton sampling locations during the Salish Sea Marine Survival Project. Map provided by Kelly Young, DFO.

Figure 2a) Top. Zooplankton collected from the Central Strait of Georgia (Station GEO1) for 2017. Note the dark green samples corresponding with major spring/summer blooms. Photo by Kelly Young, DFO. 2b) Bottom. Photographs of zooplankton, larval crab, euphausiid and amphipod species that are common in juvenile salmon diets. Photos by Moira Galbraith, DFO.

WHY ARE ZOOPLANKTON IMPORTANT?

Zooplankton are the basis of the food web for juvenile salmon and the direct connection between bottom-up physical processes and salmon survival and growth. During the Salish Sea Marine Survival Project, a comprehensive zooplankton and ichthyoplankton sampling program was carried out to determine the biomass/abundance of zooplankton species in the Strait of Georgia and Juan de Fuca areas, as well as to examine seasonal status and trends of species composition. This program leveraged existing DFO resources and programs sampling zoo/ichthyoplankton in the Strait, and added additional surveys to sample in areas and at times that are currently not covered by the DFO surveys. The increased sampling intensity over the course of SSMSP (2014-2018) has been continued since, and the data collected continue to provide information regarding ecosystem variability and prey quantity and quality for outmigrating juvenile salmon and other species.

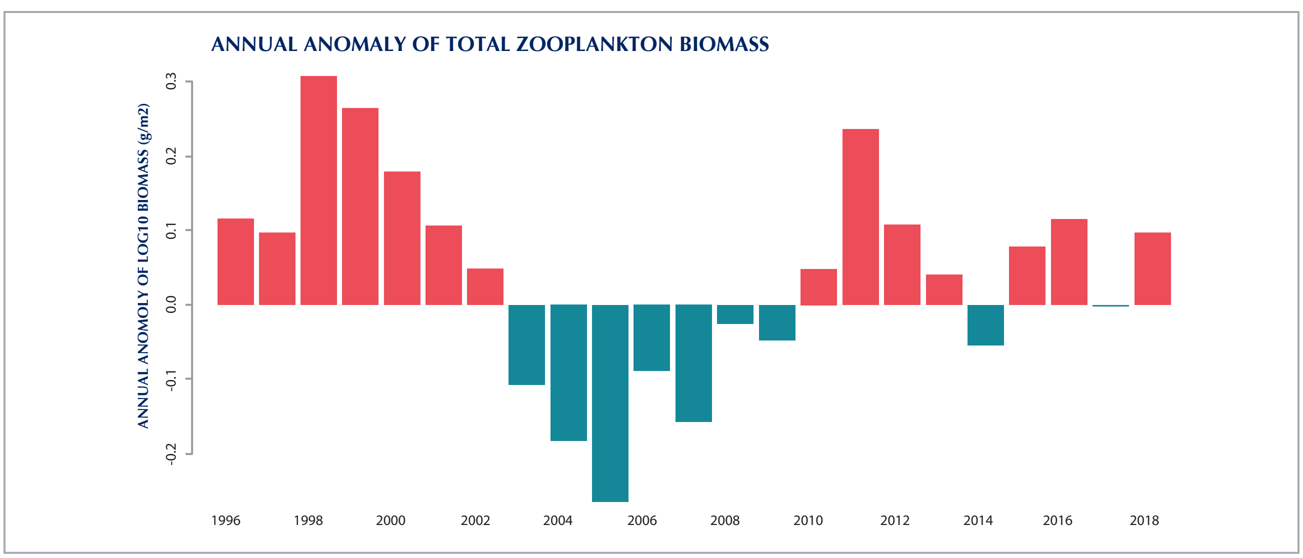


Figure 3. This graph shows the difference of the annual biomass from average conditions of total zooplankton in the Strait of Georgia. The baseline period for the anomalies is 1996 to 2010. Graph provided by Dr. Ian Perry, DFO.

SUMMARY OF RESULTS TO DATE

This project studied the relationships between salmon conditions (abundance, marine growth, survival) with their food sources. It identified the bi-weekly patterns in abundance, biomass and locations of zoo/ichthyoplankton, including species thought to be major prey items.

Preliminary analyses indicated significant relationships between certain physical conditions in the Strait of Georgia, the biomass of some zooplankton taxa which appear to be key food items for juvenile Coho and Chinook Salmon, and the marine survival of Coho and Chinook populations which enter the northern Salish Sea. Regions within the Salish Sea with higher and lower than average plankton concentrations ('Hotspots' and 'Lowspots') are being identified on a biweekly basis throughout the Salish Sea for comparisons with juvenile salmon distributions, timing and growth.

Key findings include:

- Total zooplankton biomass in Central and Northern Strait of Georgia has generally been above average since 2010 (Figure 3);
- In general, crustaceans showed a U-shaped pattern over time, with lowest biomasses during 2002-2009; several crustacean zooplankton species are important diet components for juvenile salmon in the Salish Sea. In contrast, many species of gelatinous plankton (which are not good as fish food!) have been increasing since 1995;
- A number of physical variables appear to be important to patterns in zooplankton including: the annual magnitude of the flow from the Fraser River, the average vertical water temperature measured off of Nanoose Bay, the annual wind stress measured at Sand Heads at the mouth of the Fraser River and the timing of the spring phytoplankton bloom in the Central Strait each year; and
- Results of modelling the annual marine survival of several Chinook and Coho stocks which enter the Strait of Georgia are showing promising relationships. For example, marine survivals of Cowichan River Chinook Salmon are strongly related to sea surface salinity measured at Entrance Island, sea surface temperature measured at Chrome Island and the annual anomaly of the total zooplankton biomass in the year these animals first enter the ocean (Figure 4).

NEXT STEPS

A consistent zooplankton monitoring program in the Salish Sea can assist with projections of future abundances of juvenile salmon. The initial funding for this project from the Pacific Salmon Foundation has re-energized interest and sampling of the lower trophic levels in the Salish Sea, and their connections with environmental drivers and connections to juvenile salmon. The positive early results from this program enabled the DFO research team to obtain support for the use of DFO funds and ship time to continue this sampling throughout 2018 and to the present.

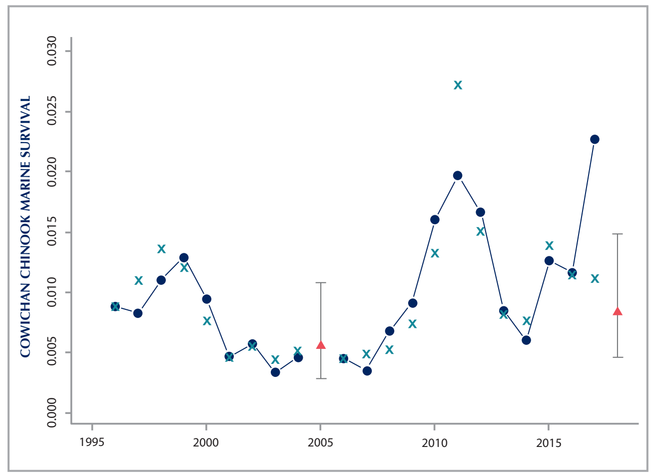
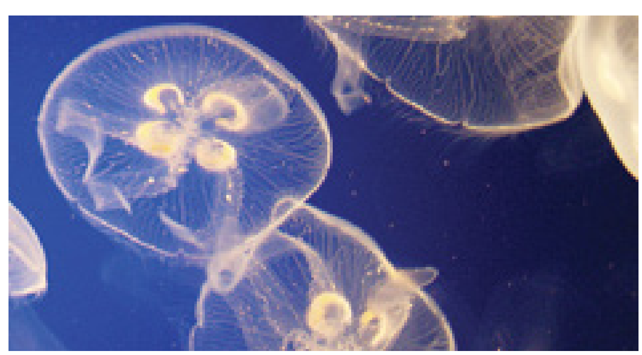


Figure 4. Cowichan River Chinook marine survivals — solid line and dots are estimated marine survival rates from a stock assessment model. Blue crosses are the Chinook marine survival rates fitted to a model with Sea Surface Salinity at Entrance Island, Sea Surface Temperature at Chrome Island and the annual anomaly of the total zooplankton biomass as the predictor variables. Red triangles represent marine survivals and their 95% confidence intervals for Cowichan Chinook Salmon predicted from this model for missing years 2005 and 2018. This model can be interpreted to mean that the marine survival of Cowichan Chinook Salmon is better when the salinity is lower, the sea temperature is warmer and total zooplankton biomass is higher in the years when the fish enter the Strait of Georgia. Note that years 2011 and 2017 were fit poorly by this model – this suggests that other factors which are not included in this model may have been important in these years. Graph provided by Ian Perry, DFO.



THE IMPORTANCE OF FRESHWATER CONDITIONS TO REARING PACIFIC SALMON

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ What is habitat use and behaviour of fry and fingerlings in Cowichan River? ▸ Are there significant hatchery-wild interactions in freshwater? ▸ Are there significant freshwater predators of Chinook and are losses related to flow?	▸ Sampling surveys in the Cowichan River and Estuary. ▸ Rotary Screw trap studies to assess freshwater mortality 2014-2016. ▸ PIT tag studies to assess freshwater and early marine mortality 2015-2017. ▸ Activated trail cameras, PIT tags and antennas to examine potential predators.	▸ Adequate discharge, presence of over-hanging vegetation and instream riparian vegetation cover were critically important for Chinook fry rearing. ▸ Freshwater survival was very low in some years (as low as 20%) and was related to river flows and in-river predation. ▸ There was a high level of freshwater predation by herons on Cowichan Chinook. ▸ Overall survival rates of hatchery fish were much lower than for wild Chinook although they appear to be similar for the first several months.

KEY QUESTIONS

A number of studies have been carried out on the Cowichan River to further our understanding of Cowichan Chinook early life history from the river to the inner estuary. Studies examined habitat use by Chinook, relative survival and interaction of hatchery and wild Chinook, variation in survival and predation with river flow, and ultimately the effect of freshwater rearing conditions on early marine survival. These studies have been carried out primarily by BC Conservation Foundation (BCCF), DFO and UBC.

Figure 1. A Rotary Screw Trap (RST) is used to carry out mark-recapture studies of smolts and to estimate abundance of smolts.

HOW?

1. Chinook were sampled using a variety of observations and gear in the river and estuary

2. Rotary Screw Trap studies 2014-2016

In the last 6 years, research has been undertaken to monitor the spatial and temporal distribution and ratio of hatchery to wild Chinook entering the Cowichan Estuary and through their first months in the ocean. This information has been used to estimate the early marine survival of hatchery and wild Chinook Salmon from this system. The Rotary Screw Trap (RST) operated by DFO and Cowichan hatchery staff during 2014 -2016 allowed for a mark-capture population estimate of hatchery fish reaching the lower Cowichan River and their in-river survival (Figure 1).

3. PIT tag methodology 2015-2017

In addition to the rotary screw trap, PIT tagging methods were also used to compare freshwater survivals between years, segments of the river and between hatchery and wild fish.

4. Trail Cameras

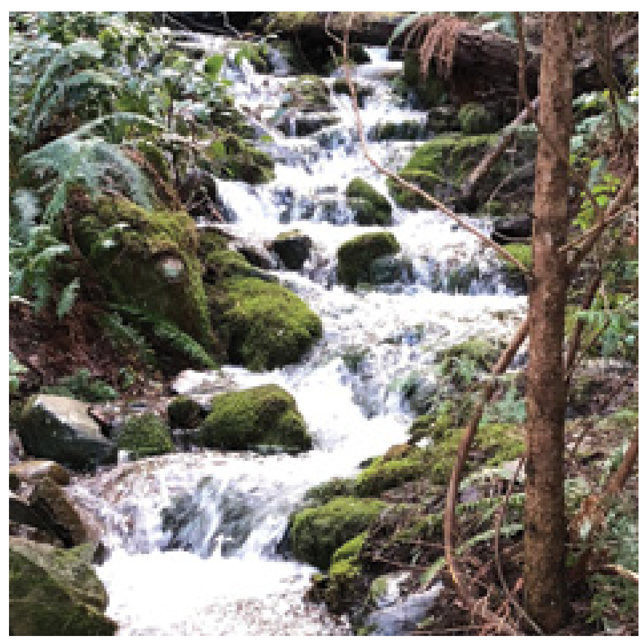
During 2017, the effect of predation on juvenile Chinook survival during their downstream migration was investigated using a combination of PIT tags and trail cameras. Tag detection antennas were used to target their potential predators with the goal of detecting tags (fish) consumed by predators. Predator species and numbers were documented using motion-activated trail cameras.

SUMMARY OF RESULTS TO DATE

Behaviour

- Cowichan Chinook fry distributed themselves from upper river spawning areas to occupy all suitable edge habitat, from natal to intertidal reaches, until a minimum size was attained for outmigration.
- Mainstem and large side channel edge habitats with suitable velocities and intact over-hanging vegetation and/or instream riparian vegetation cover were widely utilized for Chinook fry rearing, particularly early in the season (Figure 2).
- Chinook fry were observed in virtually all intertidal habitats including blind-end channels (although at lower densities than freshwater habitat). The historic loss of these habitats may be a limiting factor, particularly in years following increased escapements with higher production and potential for fry displacement to the estuary. Many such channels in the Cowichan's inner estuary are cut off or poorly connected due to diking and/or erosion protection.
- Beach/purse seine catches in Cowichan Bay increase dramatically in May and June as fingerlings emigrate from the river. The fingerlings migrating from the river choose to occupy habitats either along the beach or out in the middle of the bay depending on their size. This may have implications for competition between hatchery and wild fish if the former enter the marine environment at a larger size and crop down food resources in the bay before wild fish move into that habitat. Evidence for size selective habitat use can be found by comparing the proportion of hatchery fish in 2015 beach and purse seine catches where twice as many hatchery fish were captured in offshore habitats.

Figure 2. Nootka Rose—a preferred riparian vegetation cover for rearing fry.



Freshwater Survival

- Several downstream survival estimates for Chinook were created from RST and PIT tag data collected in 2014-2017. For 2015, the RST survival estimate for hatchery fish from the lake release to the bottom of the river was 14%, and for wild fish was only 27%. These results indicate significant in-river mortality. Historically, in the absence of in-river mortality estimates, this mortality was included in marine survival estimates. This would result in an under-estimate of the 'true' marine survival estimates of this important stock.
- In 2016, groups of Chinook smolts were tagged and released at multiple locations along the river to determine if survival improves with shorter migrations (Figure 3). Survival rates were again very low from the upper river (approx. 25%) and showed a linear decline along the river (Figure 4) for both wild and hatchery fish.
- In 2017, in-river survival was much higher for Chinook (71%). River discharge was six times higher during 2017 compared to 2016 (Figure 5). Thus, there appears to be a relationship with river discharge.

The study was repeated one more time in 2018 under moderate flow conditions and losses were again found to be significant from upper river sites (Figure 6a). Two independent detection locations 5 km apart showed similar results. Survival data from each release was also converted to an estimate of abundance (fish remaining) at each site from an initial release of 1,000 (Figure 6b). Losses in the upper portion of the river (Road Pool to Stoltz, ~30 km) were found to be 10X higher per km than through the lower 17 km.

In-River Predation Studies 2017

In April 2017, 5,494 hatchery Chinook were PIT tagged and released at various locations along the Cowichan River. PIT Tag antennas (with motion-activated trail cameras) were set up at four investigation sites to detect tagged fish consumed by predators (e.g., North American River Otter, North American Raccoon, Pacific Pine Marten and Common Merganser). PIT tag antennas were monitored for six weeks, post-release. Based on photo and video images, a minimum of 197 predators crossed through an operational PIT tag detection field but not a single tag was detected in any predator.

However, PIT tag scans were completed underneath the Pacific Great Blue Heron rookery at Cowichan Bay (100 nests in 2017) and 428 PIT-tags were detected in the guano. Pit tags from all four years of tagging in the Cowichan River were present. Over 50% of the recovered tags were from 2016, a very low-flow year (Figure 7). In total, 71% of the PIT tags at the Cowichan Bay Heron rookery were from hatchery-reared Chinook smolts—and 90% of the recovered tags were from smolts released in the river.

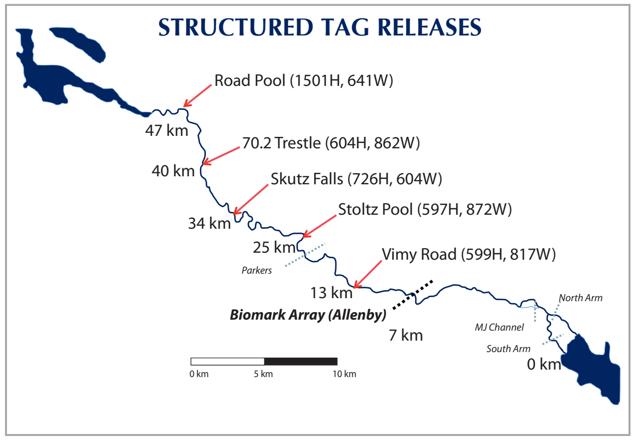


Figure 3. Locations of smolt release along Cowichan River for assessment of river segment mortality. Figure provided by Kevin Pellett, DFO.

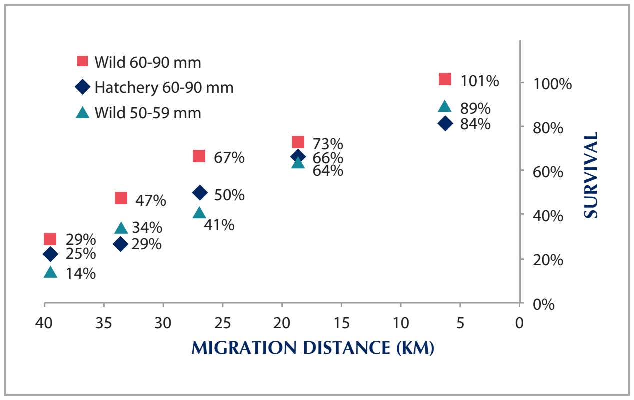


Figure 4. Survival rates for wild (2 size bins) and hatchery Chinook smolts from different release sites along Cowichan River, 2016. PIT tagged fish are recorded when they pass over the Biomark array at the bottom of the river (River Km 0). Figure provided by Kevin Pellett, DFO.

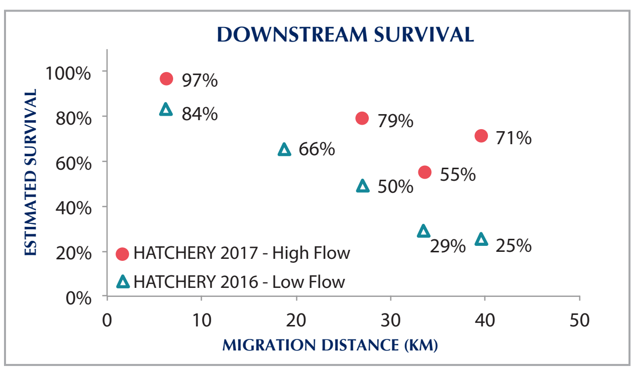
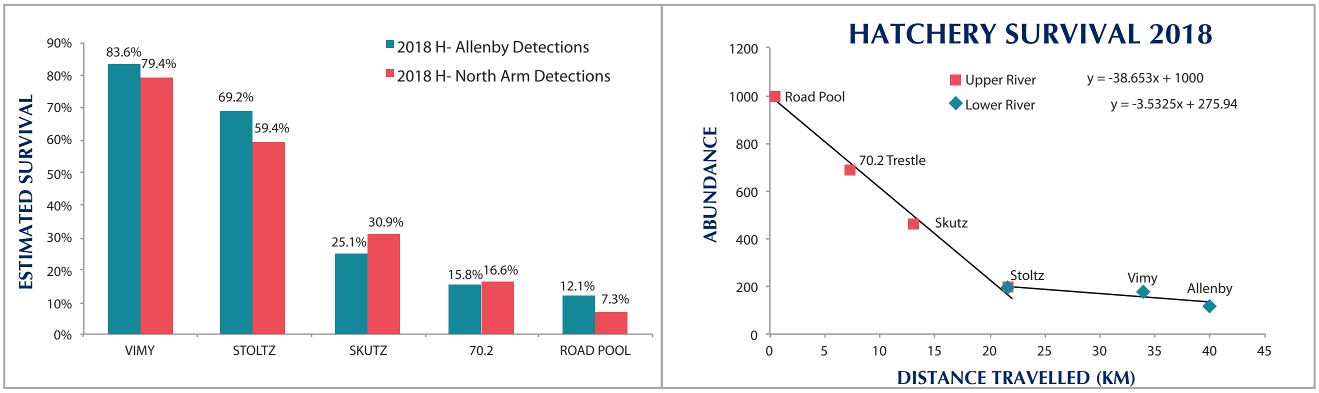


Figure 5. Relationship between estimated freshwater survival rates for hatchery fish in Cowichan River during a low flow (2016) and higher flow (2017) year. Figure provided by Kevin Pellett, DFO.

Predation rate estimates in 2016 were 5.4% and 1.9% on hatchery and wild fish, respectively. Heron predation rates are likely underestimated as herons typically defecate as they take flight. The relationship with low flows is likely due to the fact that herons cannot forage successfully at a maximum depth over ~0.5m.



Figures 6a and 6b. Downstream survival data collected for hatchery fish released at 5 locations in spring 2018. Two independent detection sites 5 km apart produced similar survival estimates (6a, left) while the conceptual decline in abundance for a group of 1000 fish released in the upper river is displayed on the right (6b). Figures provided by Kevin Pellett, DFO.

SIGNIFICANCE AND RECOMMENDATIONS

The results of these studies have led to a change in hatchery practices. DFO now releases Chinook smolts at the hatchery or lower in the river, rather than at the top of Cowichan River.

Other results will direct future lower river and estuary rehabilitation projects targeting Chinook recovery. These may include:

- In-stream restoration of side channels with moderate to high flows, and improving existing shoreline habitats (e.g., riparian planting);
- River flow manipulations and/or predator management on Cowichan River;
- PIT tag studies to assess in-river survival and predation should be carried out in additional years and on other river systems;
- Evaluation of hatchery practices, release strategies and locations. Lower survival of hatchery fish, which are larger but less familiar with predators suggests that changes in hatchery practices should be considered and evaluated; and
- Address minimum ecological flow needs for natural production of Cowichan Chinook Salmon.

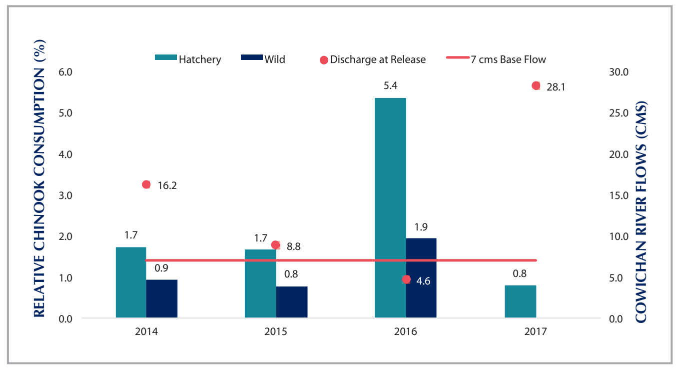


Figure 7. Great Blue Heron consumption estimates of juvenile Chinook in comparison to river discharge (red dots) on hatchery release date. Cowichan, 2017. No wild spawned juvenile Chinook were tagged in 2017. Figure provided by Jeramy Damborg, BCCF.

THE IMPORTANCE OF NEARSHORE HABITATS FOR PACIFIC SALMON

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ What is the value of nearshore habitats to juvenile salmon? ▸ What is the impact of anthropogenic stress on these habitats? ▸ How can we mitigate these impacts and allow for successful restoration?	▸ Numerous SSMSP studies have examined kelp, eelgrass and marsh habitats in the Strait of Georgia. ▸ Data include: snorkel surveys; aerial photos, drone and satellite imagery; use of stable isotopes to examine source of salmon diet; examination of otoliths to determine loss of Chinook life history variants in degraded estuaries; and genetic studies of kelp and eelgrass.	▸ Estuaries play an important role for protection and rearing of juvenile salmon, especially of smaller fry, and allow for diversity in salmon production. ▸ Estuary degradation appears related to anchorage scour, shoreline activities and alterations, and contaminants. ▸ Reproductive capacity of bull kelp is reduced at warmer temperatures.

WHY?

Nearshore marine habitats are of great ecological and economical importance. Eelgrass meadows are among the most productive and sensitive nearshore habitats, providing shelter and food to numerous species including salmon, and forage fish such as sand lance and herring. They also improve water clarity by filtering polluted runoff, reduce negative impacts of ocean acidification and protect shorelines from erosion by absorbing wave energy.

Another critical role of eelgrass meadows includes mitigation of climate change. Eelgrass absorbs carbon from the atmosphere through photosynthesis and buries it in underlying sediments, isolating it from further circulation in the carbon cycle, often for thousands of years. This sequestration process is often referred to as the production of "blue carbon". In BC, roughly 400 km^2 of salt marsh and eelgrass meadows stash away as much carbon as BC's portion of the boreal forest or the equivalent of the emissions from 200,000 cars.

Eelgrass habitats are threatened by human activities and have been documented as decreasing in area and abundance throughout many areas of the Strait of Georgia. It is hypothesized that this decline could contribute to the poor marine survival of Coho and Chinook Salmon juveniles in recent decades. However, there is a lack of understanding of the relative threats that are causing the decrease of eelgrass beds in this region.

Similarly, bull kelp habitats have been shown to provide important feeding and refuge conditions for Chinook and Coho in the Strait. They form extensive forests in rocky habitats along the subtidal zone of the coast of British Columbia. Bull kelp forest habitat has been in steady decline within many areas around the Strait of Georgia for the last several decades. The reasons for the decline, which have resulted in patchy kelp habitat in many parts of the Salish Sea, are unclear and still being studied. This phenomenon is seemingly widespread on the Pacific coast of North America.

HOW?

Numerous SSMSP projects have focussed on Strait of Georgia nearshore habitats. These include studies to examine:

1. The use of kelp, eelgrass and other estuarine habitats by juvenile salmon;
2. The role of eelgrass versus non-eelgrass habitats for juvenile salmon diets;
3. The importance of intact estuarine habitat for juvenile Chinook life history diversity;
4. The impact of human disturbance on diversity of eelgrass beds and biodiversity;
5. The effects of temperature stress and herbivore grazing as limitations to bull kelp distribution;
6. The use of satellite imagery, aerial imagery, and drones to examine changes in the extent of bull kelp and eelgrass beds; and
7. The impact of temperature stress on kelp populations.

Restoration and monitoring efforts for both bull kelp and eelgrass throughout the Strait have been ongoing over the course of SSMSP.

Figure 1. Crabs attached to kelp. Photo by Sarah Schroeder.

Figure 2. Fyke net used to capture salmon smolts in the Fraser estuary. Photo by Raincoast Conservation Foundation.

FINDINGS TO DATE

1. Usage of Nearshore Habitats by Juvenile Salmon

SSMSP snorkel and underwater video studies in the Cowichan estuary, Denman/Hornby Island and a number of other coastal regions around the Strait have observed the use of kelp and eelgrass beds by individuals and schools of juvenile salmon, forage fish and resident fish species (e.g., shiner perch, rockfish) and invertebrates (e.g., crabs, caprellid amphipods).

Similarly, sampling in marsh channels, eelgrass and sand flats in the Fraser estuary across Roberts and Sturgeon banks showed highest total abundance and diversity of fish in eelgrass, followed by sand flat and marsh habitats. Of the estuarine habitats available, Chinook Salmon were found to particularly utilize the marsh channels but other estuarine and nearshore habitat types appear to be utilized in high density years. In the Fraser estuary , the most abundant Chinook were small ocean-type Harrison Chinook which showed high residency and dependence on estuarine habitats for growth.

Juvenile Chinook and Coho Salmon diets contain harpacticoid copepods, a species which is highly associated with eelgrass habitats. One SSMSP study of stable isotope signatures in juvenile salmon showed high overlap with eelgrass stable isotope signatures, suggesting a large portion of salmon diet comes from eelgrass carbon where eelgrass is present. These results highlight the value of eelgrass in providing nearshore foraging opportunities for juvenile salmon.

2. Value of Nearshore Habitats

A number of SSMP studies assessed the value of estuarine and nearshore habitats. Several studies showed evidence of decreased species richness and increasing simplicity of eelgrass fish communities in highly disturbed regions (e.g., sites within Fraser Estuary, Comox Estuary, southern Vancouver Island). Rockfish species, in particular, were an indicator species of low disturbance regions (sites within Clayoquot Sound, Barkley Sound, Central Coast and Skeena Estuary), whereas threespine stickleback were most associated with high disturbance regions. The higher diversity (within and among sites) of the fish community and the importance of commercially-valuable rockfish species within the community at low disturbance sites exemplifies the need to maintain and restore eelgrass habitats.

In the Cowichan River, the estuary was particularly important to smaller fry as compared to stream-rearing Chinook that left the river at a larger size. High mortality rates for river-reared smolts in some years suggest that estuary-reared counterparts could have a survival advantage in some years and may be an important component of annual Chinook production. Estuaries in general provide an important role for protection and rearing, especially of smaller fry, and allow for diversity in salmon production.

Figure 3. Beach seining in Cowichan Bay for juvenile Chinook Salmon.

Other studies in the Cowichan noted that hatchery-reared smolts were larger than wild smolts, ate larger prey, spent very little time in the estuary, and disappeared from the bay earlier, due to emigration or mortality. The larger body size may be a disadvantage for hatchery smolts if it necessitates their leaving the estuary prematurely to meet food needs. The onset of piscivory (when smolts begin to feed on forage fish) began at a fork length of approximately 74 mm, which was less than the average fork length of the hatchery (clipped) fish in this study. Leaving the safety of nearshore habitats, especially those providing eelgrass and kelp cover, may expose hatchery fish to increased predation risk and account for the lower survival rates of hatchery fish compared to wild fish.

Copepods were conspicuously absent from the diet of young Chinook Salmon in Cowichan Bay. Continued log-booming activities in the north-western part of Cowichan Bay and the Cowichan River estuary have altered the substrate. The constant shedding from logs and lack of sunlight make the substrate inhospitable to eelgrass and the many organisms that live in eelgrass ecosystems including harpacticoid copepods, a favoured prey of Chinook Salmon smolts. Decomposing bark and wood on the bottom of the ocean also release toxins, such as log leachates, which are lethal to fish. Eliminating log booming (in shallow marine environments) and restoring eelgrass beds would improve salmon habitat quality in Cowichan Bay, and more broadly.

Washington Department of Fish and Wildlife (WDFW) staff learned that small juvenile Chinook migrating out of North Puget Sound rivers (Nooksack and Skagit) and from the Cowichan River early in the season have a much greater chance of surviving to return as adults when compared to populations from Mid and South Puget Sound (Cedar, Green, Puyallup). Mid and South Puget Sound watersheds have limited estuary habitat compared to North Puget Sound rivers, which may account for the low survival of fry-sized fish in those populations (Figure 4). This work is currently being extended to include more Strait of Georgia systems which will allow for a more complete transboundary analysis, and may reveal whether a relationship between survival rates and presence of intact estuary habitats holds for the whole Salish Sea. If this is the case, there will be an extremely strong case for increased protection and restoration of estuaries.

3. Losses of these Important Habitats

Globally, seagrass ecosystems are declining in area by about 5% per year due to anthropogenic stresses, including decreased water quality and increased water temperatures. SSMSP researchers have been assessing the overall decline or degradation of eelgrass nursery areas in the Strait of Georgia over the period from 1932-2016 using historic aerial photographs and Unmanned Aerial Vehicle (UAV) or drone imagery. They found that increasing fragmentation and loss of eelgrass beds were associated with shoreline activities (boats, docks, log booms and armouring) and increased housing density in the three estuaries chosen for study. The results suggest an overall deterioration of coastal environmental health in the Salish Sea due to increased use of the coastal zone, as well as declines in water quality due to urbanization.

Other studies have identified reductions or loss of kelp beds in many regions of the Strait of Georgia, particularly in the northern and central Salish Sea, while other beds appear to persist (e.g., in Sansum Narrows, Dodds Narrows, Mayne Island, Saratoga Beach and Burrard Inlet side of Stanley Park). At present, the majority of kelp mapping is conducted manually via transects and aerial photography. Though effective, the strategy is labour-intensive, requires large time investment and is limited by the areas surveyed. Under SSMSP, there has been a recent breakthrough as one study has highlighted the utility of satellite imagery for mapping kelp beds, delineating the distributional changes and losses of kelp is ongoing.

4. Limiting Factors for Kelp and Eelgrass

SSMSP funded restoration projects for both kelp and eelgrass in many areas around the Strait. These projects have also elucidated many of the limiting factors to survival of these species. Kelp shows distinct responses in terms of decreased reproductive activity when waters are warm, and rising ocean temperatures are thought to be a major contributor to kelp declines.

Eelgrass restoration activities have been successful in many areas of the Strait, but are hampered due to the damage by anchors and anchor chains, dock building and shoreline hardening. Restoration is also hampered if large quantities of marine debris fragment the eelgrass beds.

NEXT STEPS

1. Estuaries are essential for salmon production. Work to continue estuary rehabilitation and protection in the Strait of Georgia is highly recommended.
2. Removal of marine debris from estuaries is required to allow for successful restoration.
3. Signage providing information about extent of local eelgrass and kelp habitats, as well as creation of eco-friendly mooring buoys, could reduce damage to these important habitats.
4. Studies are required to determine effective strategies to mitigate high levels of contaminants, including hydrogen sulfide, in estuarine sediments that would otherwise be suitable for eelgrass productivity.
5. An ongoing study evaluates the effects of temperature stress on kelp populations in the Salish Sea. There appear to be kelp populations that are adaptable to local temperature regimes: work is being carried out to assess thermal tolerance with the hope that warm water-adapted populations could be more effective for restoration activities, particularly under climate change.
6. Research is needed to find possible genetic strains of eelgrass resistant to wasting disease (*Labyrinthula zosterae*), a mold disease related to increased sea surface temperatures.
7. Research is needed to define areas of eelgrass and kelp on the entire coast of BC. A mapping of the extent of local kelp and eelgrass habitats, and protection of these habitats is highly recommended.

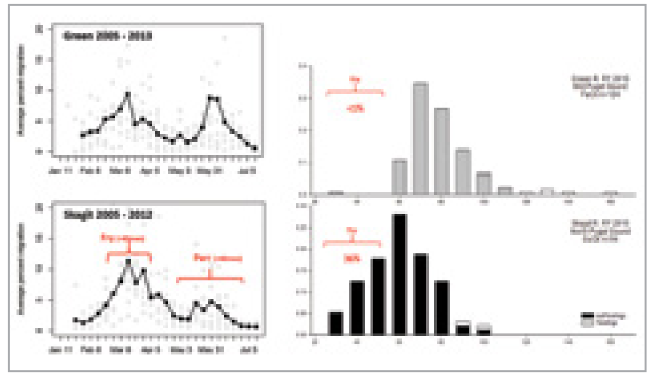


Figure 4. Chinook smolts leave both the Green and Skagit Rivers early as small fry and later as larger parr. However, returning adults to the more developed Green River are only derived from those smolts that left as parr. The fry component did not appear to survive. Similar results were apparent in a number of other degraded estuaries. Figure provided by Lance Campbell, WDFW.

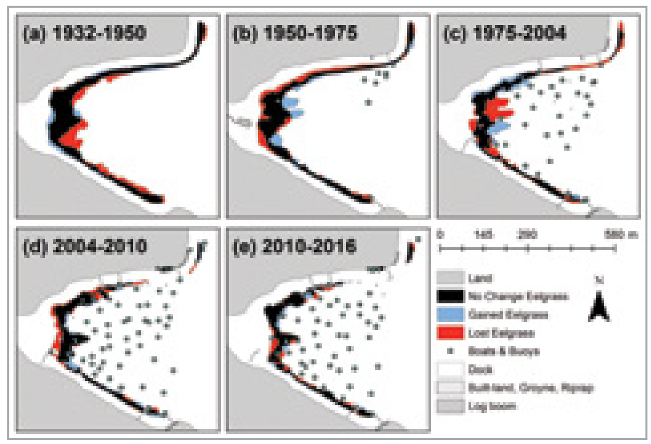


Figure 5. Changes in spatial distribution of eelgrass between two consecutive mapping years in Horton Bay along with shoreline activities. Eelgrass is seen to progressively deteriorate as boat traffic increases and more docks are built. Figure provided by Natasha Nahirnick.

KELP LIMITING FACTORS

- **Prolonged (>35 days) temperatures >16° C.**
- **Grazing pressure from sea urchins and kelp crabs.**
- **Competition from other algae for substrate.**

EELGRASS LIMITING FACTORS

- **Salinity over 42 ppt, high turbidity (lack of light), pH outside of 7.3 to 9.0, temps outside of 5° C to 30° C.**
- **Substrates with high levels of hydrogen sulfide (from long term log booming).**
- **Direct damage due to anchorages and presence of marine debris.**

COWICHAN PIT TAG PROGRAM

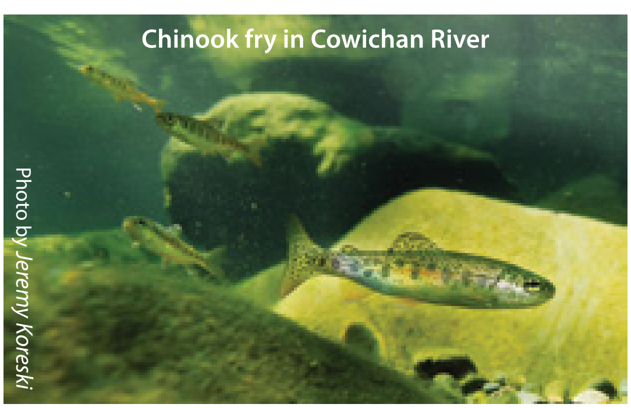
QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ When is the bottleneck to survival in juvenile Chinook Salmon? ▸ What is the difference between hatchery and wild survival?	▸ Over 56,000 PIT tags applied to juvenile Chinook in Cowichan River, Cowichan Bay (beach seining, purse seining) and Sansum Narrows (by microtrolling). ▸ Compare returns from each tagged cohort returning to the Cowichan River using an antenna in the river.	▸ There appear to be two key mortality periods: downstream migration of smolts to the ocean and then during the first winter. ▸ Hatchery fish survival is about 35-40% of that of wild fish across all stages. ▸ The mechanism controlling this difference likely occurs after their first summer at sea.

THE IMPORTANCE OF PIT (PASSIVE INTEGRATED TRANSPONDER) TAGS

PIT tags are tiny (rice-grain size) electronic tags that are cost-effective, easily applied and have a unique code.

These very small glass tags (no battery, 2.1 mm x 12 mm) are applied world-wide for wildlife and fisheries research. They are injected into the animal but then require an antenna to instantaneously charge and read the unique code within each PIT tag. Antennas may be hand-held wands or large antennae arrays that animals must move past. The tag can be automatically detected and decoded as a fish crosses an antenna, which eliminates the need to kill or handle the fish during data retrieval. The tag code can be linked to information gathered at the time of tagging (i.e., tagging location, source (hatchery or wild) and size at tagging). During SSMSP, we installed such an array across the bottom of the lower Cowichan River and used smaller portable antennas in other locations.

In the Salish Sea Marine Survival Project, these tags were essential for identifying individual juvenile Chinook and Coho Salmon (including hatchery or wild), monitoring downstream migration rates and survival, separating freshwater survival from marine, qualifying predation, assessing critical size/time hypotheses, tracking growth and survival of individuals, and estimating survival between life-stages including as mature fish returning to the Cowichan River.



HOW WERE PIT TAGS USED?

Over 56,000 PIT tags were applied to juvenile Chinook in Cowichan River, Cowichan Bay (beach seining, purse seining) and Sansum Narrows (by microtrolling) between 2014 -2017 (Figure 1). Both wild (32,915) and hatchery (23,270) fish were tagged. More hatchery fish were tagged in-river, while more wild fish were marked in the marine environment.

Since 2014, Chinook returning to the Cowichan River have been scanned for PIT tags using automated antennas ("arrays") installed at the counting fence at the Skutz Falls fishway, and since 2016, at a full stream Biomark array placed at the bottom of the river. Hatchery broodstock have also been scanned for tags using hand-held scanners since 2016. Monitoring has resulted in the detection of 582 unique tags between 2014 and 2018. Data were expanded based on antenna detection efficiency, and survival estimates created based on tag returns from all years, pooled by location. These data allow us to compare survival among the four different cohorts, and to compare survival between wild and hatchery fish, as well as the relationship between size, time of ocean entry, growth, residency and survival.

PIT tags have also been used in SSMSP predation studies, both to examine levels of in-river predation in the Cowichan River, as well as to determine predation by seals on Big Qualicum Coho.

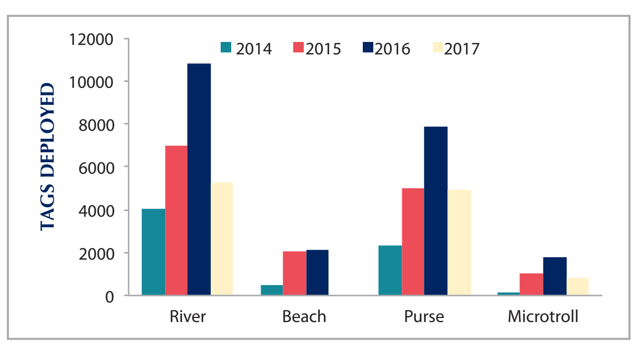


Figure 1. PIT tags applied to hatchery and wild Cowichan Chinook 2014-2017. Graph provided by Kevin Pellett, DFO.

SUMMARY OF RESULTS TO DATE

Results to date suggest survival increases with distance from the estuary, and that wild fish have a consistently higher survival than hatchery conspecifics by a factor of approximately 3:1 (Figure 2).

The surprising finding was the still very low survival of fish caught in September-October of their first year at sea. These fish were captured and tagged by microtrolling (using modified troll gear to capture small Chinook) around the Southern Gulf Islands. This suggests that significant mortality occurs during the first winter and beyond. Thus, there is evidence of two key critical periods, one at marine entry, and the second over the first winter at sea.

Kevin Pellett, DFO, produced preliminary "decay curve" models starting with 1,000 fish, illustrating how numbers would compare over time given the survival estimates determined above for the 2015 tag cohort. The curves for wild (Figure 3) and hatchery (Figure 4) are shown below. The data are based on PIT tag returns through 2019 which are essentially complete, while Age 2 data (green dots) are estimated from coded wire tag returns in the fishery. The curves are similar, though the initial drop in abundance of wild fish is steeper than for hatchery fish. The reason for this is unknown, though it may be related to the short period that hatchery fish remain in the river and estuary environment and their initial greater body size.

Other key findings to date include the following:

- Freshwater mortality appears to be confined to the downstream migration of smolts and not in-situ rearing. Mortality increases with both migration distance and declining flow, and can be over 75% during low flow years. This appears related to heron predation, and hatchery fish were more vulnerable to this predation (perhaps due to naivety). This has led to changes in hatchery practices, and hatchery releases now occur in the lower river.

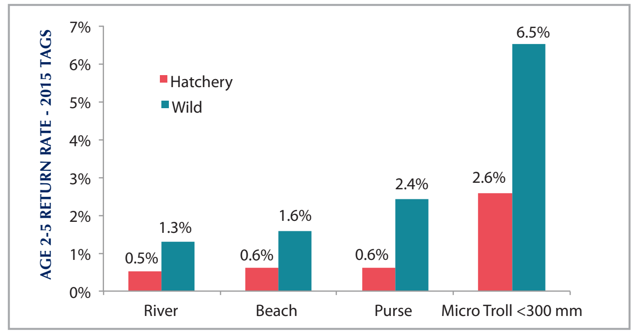
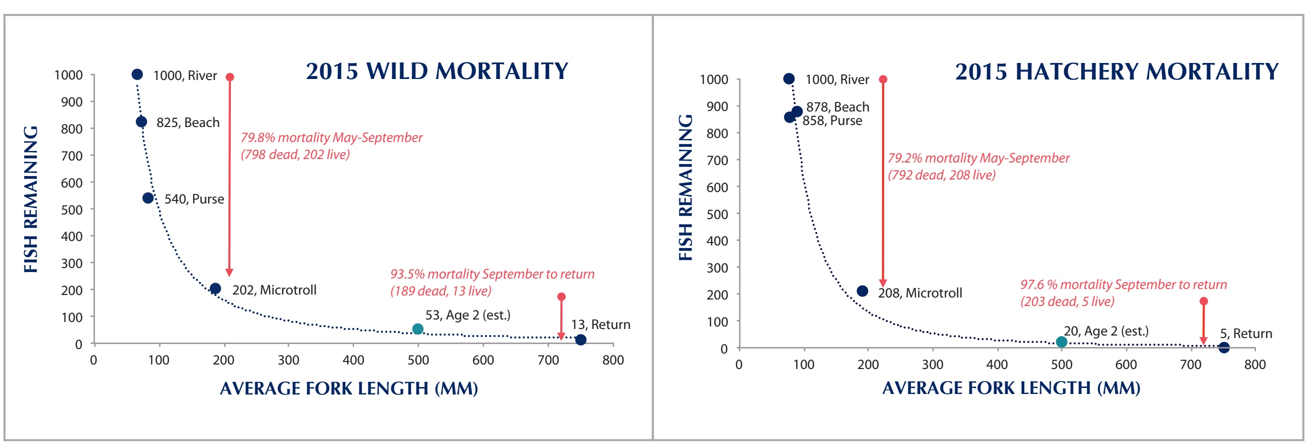


Figure 2. Summary of return data by location for hatchery and wild Chinook tagged in 2015. Graph provided by Kevin Pellett, DFO.

- Outmigration timing for both hatchery and wild Chinook appears to be related to size. Hatchery fish were larger than wild fish in every year and generally migrated to the ocean within five days of release. Wild fish tended to reside longer in-river before migrating with the longest residency correlated to the smallest fish.
- Size does not appear to influence downstream survival of either hatchery or wild Chinook. Cursory investigations of size-selective mortality suggest all size classes are represented in tag returns (of recovered fish) from all stages.

NEXT STEPS AND SUGGESTIONS

- Data collection will be continued until November 15, 2020 when all surviving Cowichan Chinook that were PIT tagged during SSMSP will have returned to the Cowichan River.
- This project highlights the importance of the first winter in the ocean, a period that has been studied very little anywhere. Future research should focus on this period of Chinook life history.
- Given the efficacy of methods and new information gathered during the Cowichan programs, expansion of these studies is now taking place in other river systems.



Figures 3 (left) and 4 (right). Chinook mortality "decay curves" showing how abundance of 1000 fish in the river changes throughout their life cycle based on PIT tag survival data. Graphs provided by Kevin Pellett, DFO.

WHAT IS MICROTROLLING?

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ Do critical mortality period(s) exist for juvenile Chinook Salmon? ▸ Does juvenile Chinook Salmon habitat quality and utilization vary at scales below what is resolved by current sampling programs? ▸ How are diet and growth linked to juvenile Chinook Salmon survival?	▸ Catch per unit effort for over 30,000 georeferenced, depth-specific hook deployments over 4 years (in most cases including thermistor-derived temperature-at-depth data). ▸ Detailed biological data (diet, length, genetic stock identification, scale-based growth trajectories) for over 1,600 juvenile Chinook Salmon and 150 juvenile Coho Salmon. Of these 1,333 Chinook Salmon were tagged with PIT tags allowing biological parameters to be related to eventual survival.	▸ Microtrolling is an effective, economical tool to sample juvenile Chinook and Coho Salmon beginning in late summer of their first year at sea, and in specific environmental conditions. ▸ Diet and growth of juvenile Chinook Salmon varies predictably at fine spatial scales with implications for predation exposure and survival.

THE NEED FOR MICROTROLLING

As juvenile Chinook or Coho Salmon disperse from estuaries and move deeper in the water column it becomes more challenging to study them. While midwater trawling with a large net can catch these fish, vessel time is very costly. Trawl-caught fish are also not landed in a condition where they can be used for tagging studies. The Salish Sea Marine Survival Project presented the need for an economical method to non-lethally sample and tag juvenile Chinook Salmon at the end of their first summer at sea. Microtrolling was developed to fill this need.

WHAT IS MICROTROLLING AND HOW WAS IT USED?

Microtrolling employs a small vessel and recreational fishing gear (Scotty Electric Downriggers) to mimic the methods of a commercial salmon troller at a miniaturized scale. Up to 12 lines (6 per side) are deployed simultaneously with very small lures (generally 2.5 cm or less) to target salmon in their first (~12-30 cm) or second (~30-50 cm) year at sea. Gear is retrieved frequently, generally every 10 minutes or less, and salmon are landed into a live well. The location and depth of capture is recorded for each fish.

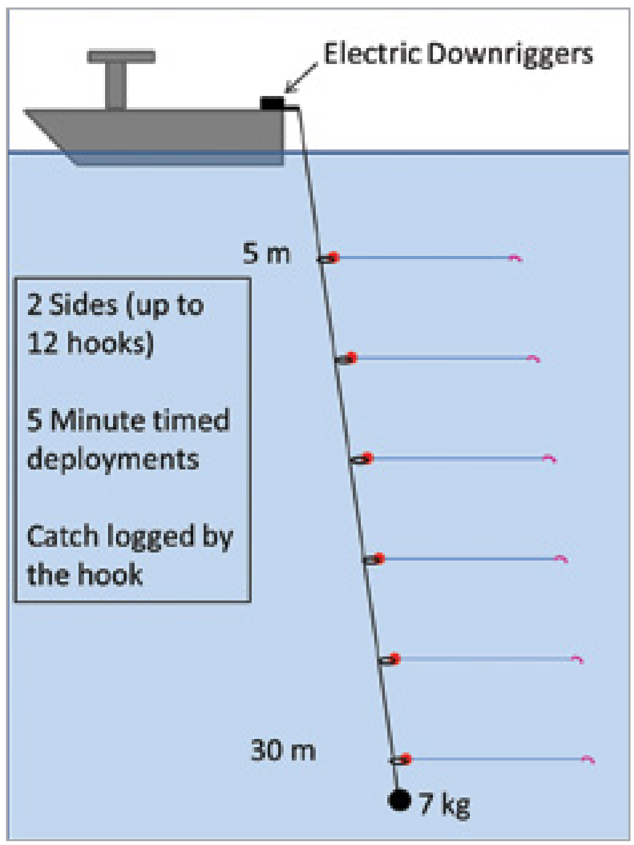


Figure 1. Microtrolling gear and set up. Graph provided by Will Duguid.

Microtrolling has been used for a number of purposes as part of the SSMSP

- BC Conservation Foundation (BCCF) and University of Victoria researchers used microtrolling to apply PIT tags to juvenile Chinook Salmon to investigate mortality periods of Cowichan River Chinook. Effort was concentrated in the Southern Gulf Islands from August to October 2014-2017. Juvenile Chinook were tagged and tissue samples (fin clips or scales) were taken for genetic stock identification to determine which fish would be expected to return to the Cowichan River.
- University of Victoria researchers employed a standardized (gear, depth, deployment time) microtrolling protocol to investigate fine scale variation in distribution, diet and growth of juvenile Chinook Salmon in the Southern Gulf Islands. Deployment of hooks coupled with temperature loggers at standardized depths allowed detailed depth distribution and thermal stratification data to be collected. Fish diets were sampled non-lethally by gastric lavage (stomach flushing) and growth rate was analyzed by measuring the width of circuli (growth rings) on scales.
- Microtrolling was used by Kintama Research Services, University of Victoria and DFO to economically capture juvenile Chinook Salmon for an acoustic tagging study in the Southern Gulf Islands in 2017.

SUMMARY OF RESULTS TO DATE

Microtrolling has proven to be an effective method for capturing juvenile Chinook Salmon in good condition for tagging. Since 2014, over 4,000 juvenile Chinook Salmon have been PIT tagged by 2-3 person crews operating out of small (5-7 m) boats. This tagging effort has been a key component of the ongoing Cowichan Chinook Salmon PIT tagging program which is providing new insights on hatchery and wild Chinook Salmon survival

Microtrolling has also allowed diet, distribution and growth of juvenile Chinook Salmon in late summer of their first year at sea to be analyzed at a spatial and temporal scale not possible before. Summer growth of juvenile fish in Cowichan Bay is remarkable (Figure 3). Researchers have found that size, diet and growth rate of juvenile Chinook Salmon can vary between closely adjacent locations (<4 km apart) (Figures 4 & 5).

Larger, faster growing Chinook Salmon appear to spend more time in areas where juvenile Pacific Herring are available. In fact, sampling the same region throughout late summer and fall has revealed that only larger juvenile salmon appear able to consume juvenile Pacific Herring, while smaller salmon rely on crab larvae and other planktonic organisms. Co-occurrence of larger, faster growing juvenile Chinook Salmon with juvenile Pacific Herring also has potential to bring them into contact with predators which are targeting herring schools.

Figure 2. Microtroll-captured juvenile Chinook Salmon (211 mm) with small spoon in its mouth. Photo by Will Duguid.

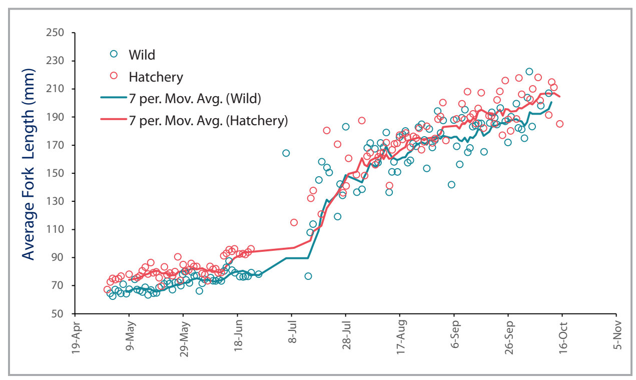


Figure 3. Average size per day by origin for PIT tagged fish (2014-2019) in Cowichan Bay. (Caveats: early season fish only big enough to tag (>60 mm) are shown, no tagging done in July and microtrolling may exclude smaller fish especially in August). Fish in August and September are caught by mictrolling. Figure credit: Kevin Pellett, DFO.

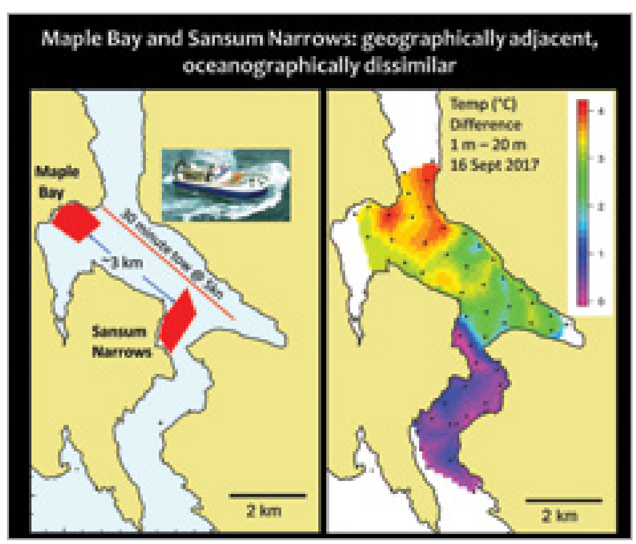


Figure 4. Microtrolling locations in Sansum Narrows and Maple Bay, locations located ~3 km apart. Figure provided by Will Duguid.

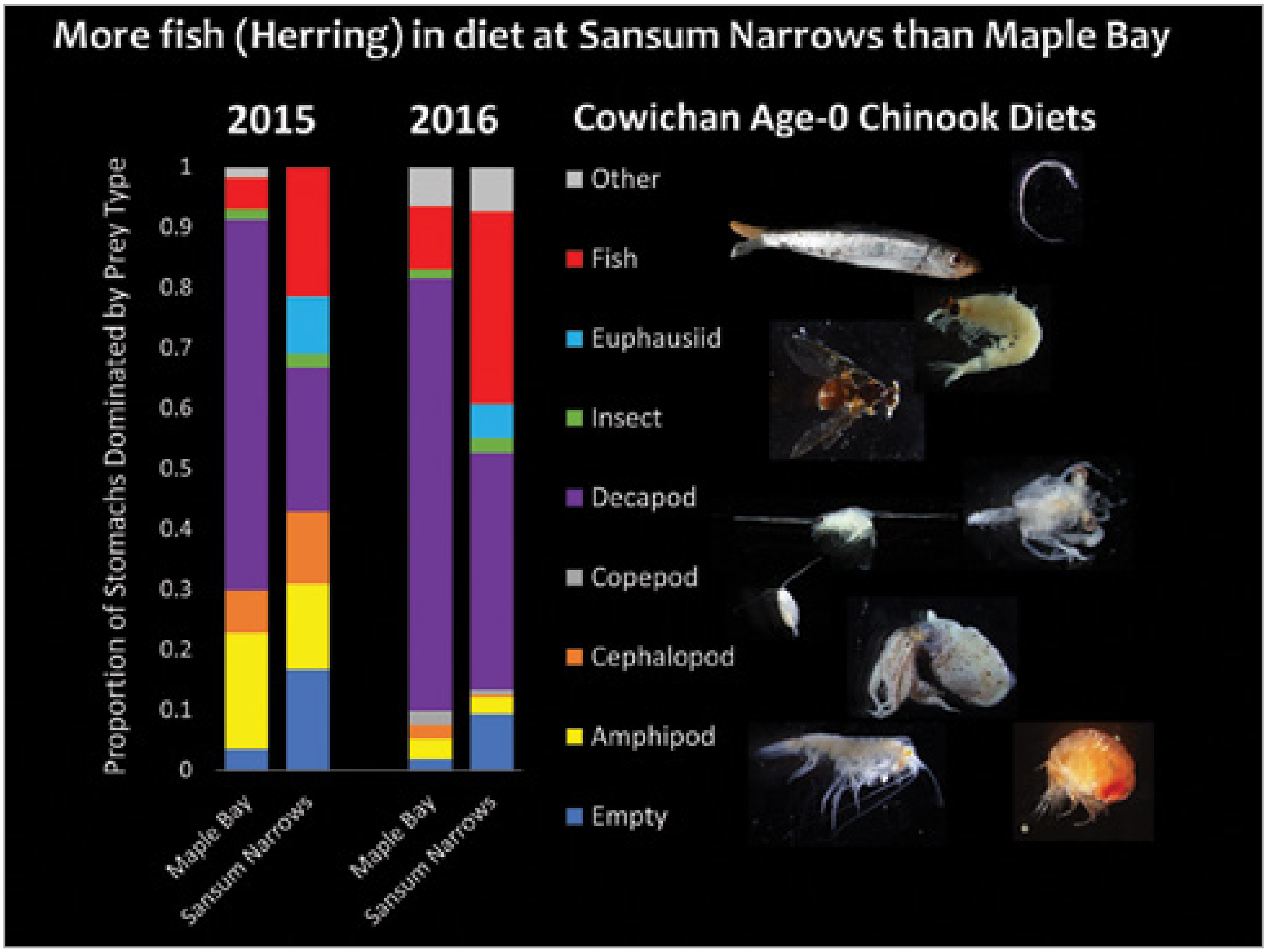


Figure 5. Varying diets of microtroll-caught Chinook Salmon from Sansum Narrows and Maple Bay. Fish in Sansum Narrows were larger and their diets contained a higher proportion of Pacific Herring, which also resulted in higher growth rates for these juvenile Chinook. Figure provided by Will Duguid.

NEXT STEPS AND SUGGESTIONS

- Microtrolling has the potential to allow investigation of subjects that until now have been overlooked in studies of Salish Sea salmon survival, such as the condition, habitat and survival of fish over the first winter in the ocean. The results of Cowichan PIT tagging and acoustic tagging studies have indicated that important mortality occurs after the first summer at sea; the latter study (and a number of studies in Puget Sound) have also indicated considerable residence of Salish Sea Chinook Salmon through at least the first winter at sea.
- Ongoing and future studies at PSF using microtrolling will allow us to economically sample juvenile Chinook Salmon through their first winter in the Salish Sea, characterizing over-winter habitat and assessing fish condition and health and diet composition and quality. Microtrolling will be used in a new study to PIT tag multiple stocks of East Coast Vancouver Island Chinook Salmon during and after their first winter at sea, to partition out the importance of first winter mortality in regulating recruitment success of Salish Sea Chinook Salmon.

Figure 6. Will Duguid, UVic, who co-developed and used microtrolling extensively for his PhD studies.

THE IMPORTANCE OF HERRING AND OTHER FORAGE FISH TO PACIFIC SALMON

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ Determine an index of herring recruitment and prey availability to salmon and other predators. ▸ Explore factors affecting herring distribution and survival. ▸ Determine the relationship between recruitment of herring and marine survival of Coho and Chinook Salmon.	▸ 1992-2019 DFO juvenile Pacific Herring and Nearshore Pelagic Ecosystem Survey. ▸ DFO trawl survey data including stomach content data for juvenile Coho and Chinook. ▸ Year-round hook and line observations of Chinook and Coho diets from Salish Sea Anglers. ▸ Diet, size and growth of juvenile Chinook caught by microtrolling in the Gulf Islands.	▸ Condition of juvenile herring in the Strait has been high since 2007. Length-weight residuals (condition) increased during 1997-2012 and were positive in 2005 and 2007-2017. ▸ During the Salish Sea Marine Survival Project, only the largest juvenile Chinook appeared to be capable of feeding on age-0 herring. ▸ Feeding on herring appears related to higher growth over the first summer/fall, which may improve winter survival ▸ Anchovy have been abundant in the Strait and have provided an alternate food source since 2014.

BACKGROUND

Healthy forage fish populations are crucial for Coho and Chinook which switch from feeding on invertebrates to fish during their first summer at sea. Abundant forage fish may also help reduce predation pressure on juvenile salmon because other fish, marine mammals and birds consume forage fish too. The forage fish community of the Salish Sea is dominated by Pacific Herring, Pacific Sand Lance, and various species of smelt. Anchovy have also been abundant periodically, including since 2014 (the period of the Salish Sea Marine Survival project).

In the Strait of Georgia (SOG), both juvenile Chinook and Coho Salmon switch to feeding on herring during their first summer. The relationship is complex: while abundant Pacific Herring may inhibit juvenile Chinook Salmon growth through competition, larger juvenile Chinook Salmon may experience enhanced growth when Pacific Herring small enough to utilize as prey are abundant. Understanding the factors affecting the recruitment dynamics and growth of herring in the SOG may be key to understanding the variability in the marine survival of Coho and Chinook Salmon in the SOG.

The main objectives of this program were to estimate the relative abundance and distribution of juvenile herring and other pelagic fish in the Strait of Georgia, create an index of potential prey availability to Coho and Chinook, and determine why the forage fish community varies over time and space.

HOW?

The DFO has a monitoring program in the Strait of Georgia for juvenile Pacific Herring and the nearshore pelagic fish community. It also samples the zooplankton community, as well as the physical water column properties (e.g., temperature, salinity, oxygen). This yearly survey (in September-October) uses a purse seine to sample 10 transects after dusk and at night when herring are near the surface. The program has been carried out during 1992-2019 (except 1995) (Figure 1).

SUMMARY OF RESULTS TO DATE

1. The age-0 herring index may be a leading indicator of numbers of recruits joining the SOG herring population 2.5 years later and the amount of prey available to predators in the Strait.
2. An index of the relative biomass of age-0 herring in the SOG was lower and stable during 2013-2019 compared to the peaks within the time series (1992-2017) (Figure 2). This index peaked every 2-3 years with the peaks occurring in even years during 2004-2012; however, this pattern stopped after 2013. The reason for the alternating peaks is unknown.
3. Age-0 herring were heavier for a given length (i.e., in better condition) in 2007-2019 compared to previous years (Figure 3).
4. Abundance and condition of age-0 herring in the fall is related to many factors including their prey, timing of availability of prey, and other factors including herring spawn biomass and water temperatures.
5. When ocean conditions are good for age-0 herring (i.e., higher abundance of herring), they also appear to be good for juvenile salmon (all species).
6. Anchovy have been abundant, observed in stomach contents of juvenile Chinook and successfully spawning in the Strait since 2014. In addition to acting as competitors or prey, abundant anchovy could potentially reduce predation pressure by harbour seals on juvenile Chinook and Coho. Abundance of anchovy appears related to periods of elevated ocean temperature. Little is known of the biomass of Sand Lance or Surf Smelts in the Strait, though much information exists on habitat requirements and preferred spawning habitats.

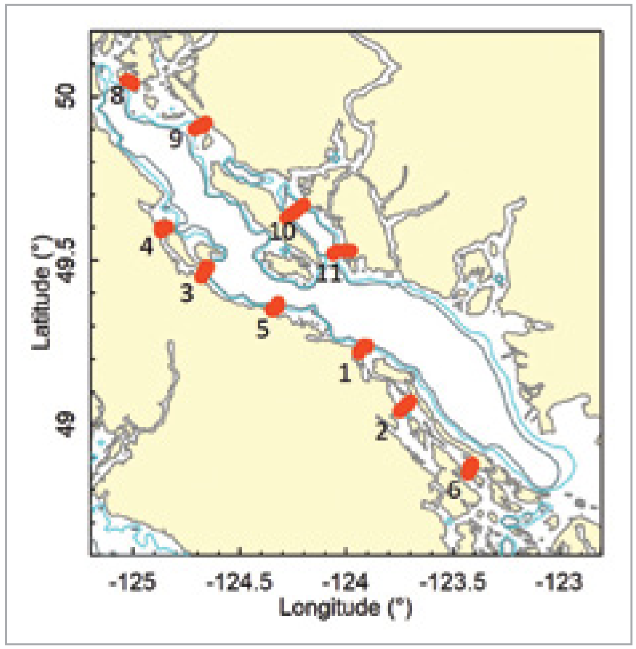


Figure 1. DFO's Strait of Georgia juvenile herring core survey transects (#1-11, there is no #7). Figure provided by Jennifer Boldt, DFO.

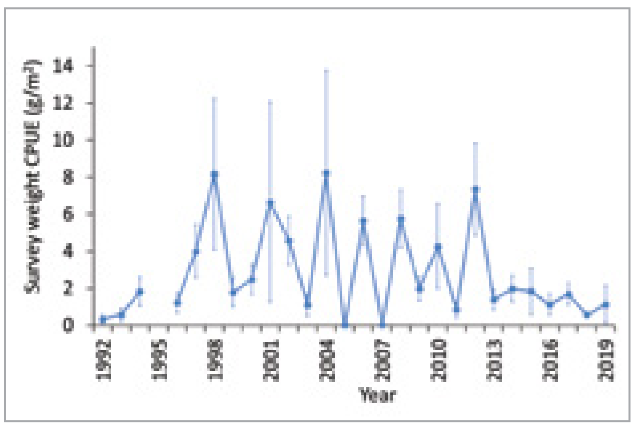


Figure 2. Mean catch weight per-unit-effort (CPUE) of age-0 Pacific Herring caught in DFO's Strait of Georgia juvenile herring survey 1992-2019 (no survey in 1995).

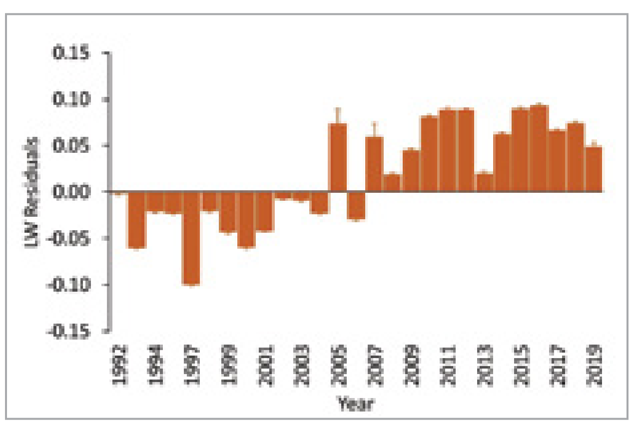


Figure 3. Mean age-0 Pacific Herring condition (length-weight (LW) residuals) from DFO's Strait of Georgia juvenile herring survey, 1992-2019 (no survey in 1995).

SIGNIFICANCE AND NEXT STEPS

- Pacific Herring and other forage fish such as Northern Anchovy, Sand Lance and Surf Smelt are important prey for Coho and Chinook, as well as marine mammals, and seabirds. The above-average age-0 herring condition since 2007 indicates that fish are heavier for a given length and may contain more energy for predators.
- SSMSP results suggest that, to have a good chance of surviving their first winter, juvenile Coho must be large enough to eat the cohort of age-0 herring that are available to them. Our studies showed that Coho sampled 2012-2014 in the Strait of Georgia grew more at the north end of the Strait than at the lower end, and that this appeared to be related to the amount of herring in the diet. Other studies focusing on Cowichan River Chinook in 2015 and 2016 showed that only the largest juvenile Chinook Salmon were able to consume age-0 Pacific Herring. The ratio of age-0 herring size to juvenile salmon size in late summer may be impacted by temperature, prey availability, and competition effects on both juvenile salmon and juvenile herring earlier in the season. This predator to prey size ratio could be a key regulator of survival for juvenile Chinook and merits further study.
- Continued warming of the Salish Sea may lead to greater abundance and persistence of anchovy, with potentially important consequences for the ecosystem as a whole.
- Understanding trends in the populations of small pelagic fish species and factors that affect their abundance and condition requires long-term monitoring of the nearshore pelagic ecosystem. PSF recommends the continuation of the critically important DFO Juvenile Herring Survey. Information on other important forage fish such as Sand Lance and Surf Smelt are not routinely collected, but we recommend identification and protection of spawning habitats, and the development of biomass surveys, for these forage fish species. An ongoing PSF funded study of year-round adult Chinook and Coho Salmon diets will provide new insights into the ecology of Salish Sea forage fish.

Photo by Ryan Miller

JUVENILE SALMON STUDIES IN THE STRAIT OF GEORGIA

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ Where and why do juvenile Chinook and Coho die in the Strait? ▸ What are the characteristics of the survivors? ▸ Is there a relationship between early marine growth and survival or residency? ▸ Can this mortality be mitigated?	▸ DFO Juvenile salmon Trawl Survey 1998-present in Strait of Georgia in June and September. Puget Sound also surveyed in some years. ▸ 3 years of freshwater juvenile sampling on Vancouver Island and Fraser River, beach and purse seining in Cowichan Bay and purse seining off Big Qualicum River. ▸ Species identification and enumeration. Biological data, DNA processing, CWT/fin clip/PIT tag tracking, condition, diet, energy density and otoliths/scales for age and growth analysis. ▸ Adult returns in east coast Vancouver Island and selected Fraser River stocks sampled for otoliths and scales.	▸ Chinook have stock specific areas for rearing during their residence in the Strait of Georgia over the first marine summer. This may account for similar survival patterns for populations from proximal river systems. ▸ Coho abundance in the Strait and early marine survival have been increasing since 2009. ▸ The condition of juvenile Coho and Chinook as they enter their first marine winter is related to subsequent survival. ▸ Some Coho Salmon are remaining resident in the Strait of Georgia similar to pre-1993. This may be related to their early marine growth and condition in the fall.

OBJECTIVES OF STUDY

This project directly assesses the bottom-up and physiological factors limiting the recruitment of Chinook Salmon and Coho Salmon during their early marine life in the Strait of Georgia (SOG). The project is divided into two specific components:

1. A cohort analysis to determine which segment of the population survive the early marine residency period; and

2. An analysis to determine how ocean conditions affect the growth and bioenergetics of juvenile Chinook and Coho.

In order to determine whether or not there is a specific component of the population that disappears over time during their first year at sea, salmon smolts are collected as they leave freshwater and subsequently in the marine environment by the DFO trawl survey (Figure 1). Coho and Chinook (both hatchery and wild) were sampled in the Cowichan, and around the Qualicum and Puntledge rivers and the lower Fraser River, as both juveniles and adults. Researchers compare characteristics of adults to those in juveniles to determine those important to their survival.

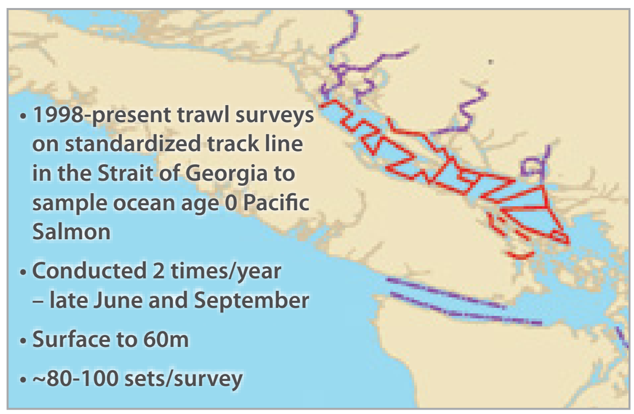


Figure 1. The DFO Trawl Survey 1998-present. Figures 1 through 4 provided by Chrys Neville, DFO.

These studies examine the relationships between ocean entry time and size, growth, bioenergetics, diet, fatty acids (in both zooplankton prey and juvenile salmon), presence/absence of competitors and presence of microbes and early marine survival. Early marine survival is the survival of salmon over the first few months after entry into the Strait of Georgia from their natal rivers, and is depicted in Figure 2.

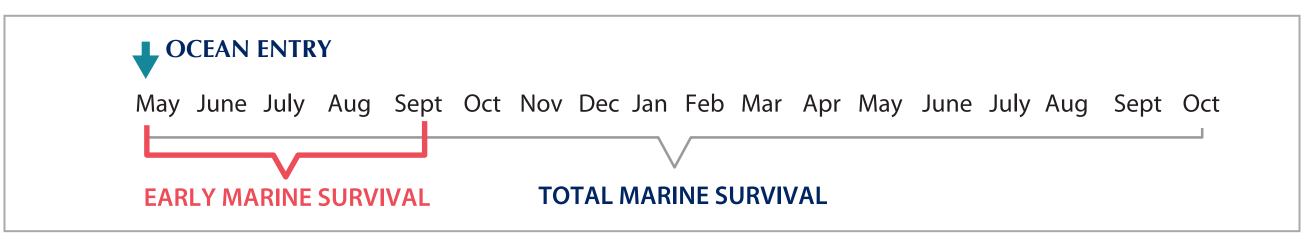


Figure 2. The period of early marine survival occurs within the first few months after ocean entry for Coho Salmon.

SUMMARY OF KEY RESULTS TO DATE

Chinook

DFO summer trawl catches were declining and below the long-term survey average from 2010 to 2014 (Figure 3 top). Since 2016 the CPUE (catch per unit effort) has been average. In the fall (September/October) surveys have been variable since 2013 with below average CPUE except for 2014 and 2018 (Figure 3 bottom).

The CPUE indicates that there are often similar numbers of juvenile Chinook in the Strait of Georgia in the early summer and fall. However, DNA analysis indicates that the Chinook populations present change significantly over the season. The stock mixture sampled in June is still present in September, but because South Thompson Chinook enter the Strait later (primarily July), they are the dominant group of Chinook (50-70%) captured in September. The reduction in number of the early ocean entry Chinook stocks between summer and fall is a combination of mortality and migration out of the region. However, results from acoustic tagging studies and the low number of these stocks captured outside of the Strait of Georgia in late summer and fall suggests that mortality during the early marine period in the Strait of Georgia is the primary factor.

In July, the distribution of Chinook Salmon has been very consistent (Figure 4 top). About 70-80% of Chinook Salmon are captured near their natal streams.

- BQR/Puntledge along ECVI
- Cowichan in Gulf Islands
- South Thompson in Howe Sound

In September, the distribution of Chinook remains consistent with that seen in July, although there are now far more South Thompson fish in the SOG (Figure 4 bottom).

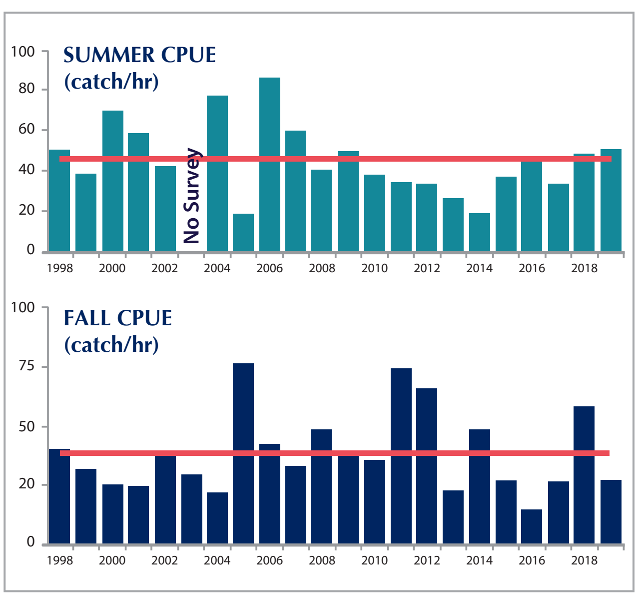


Figure 3. CPUE (r) of juvenile Chinook Salmon captured in trawl surveys 1998-2017. Top figure shows summer CPUE and bottom figure shows fall CPUE.

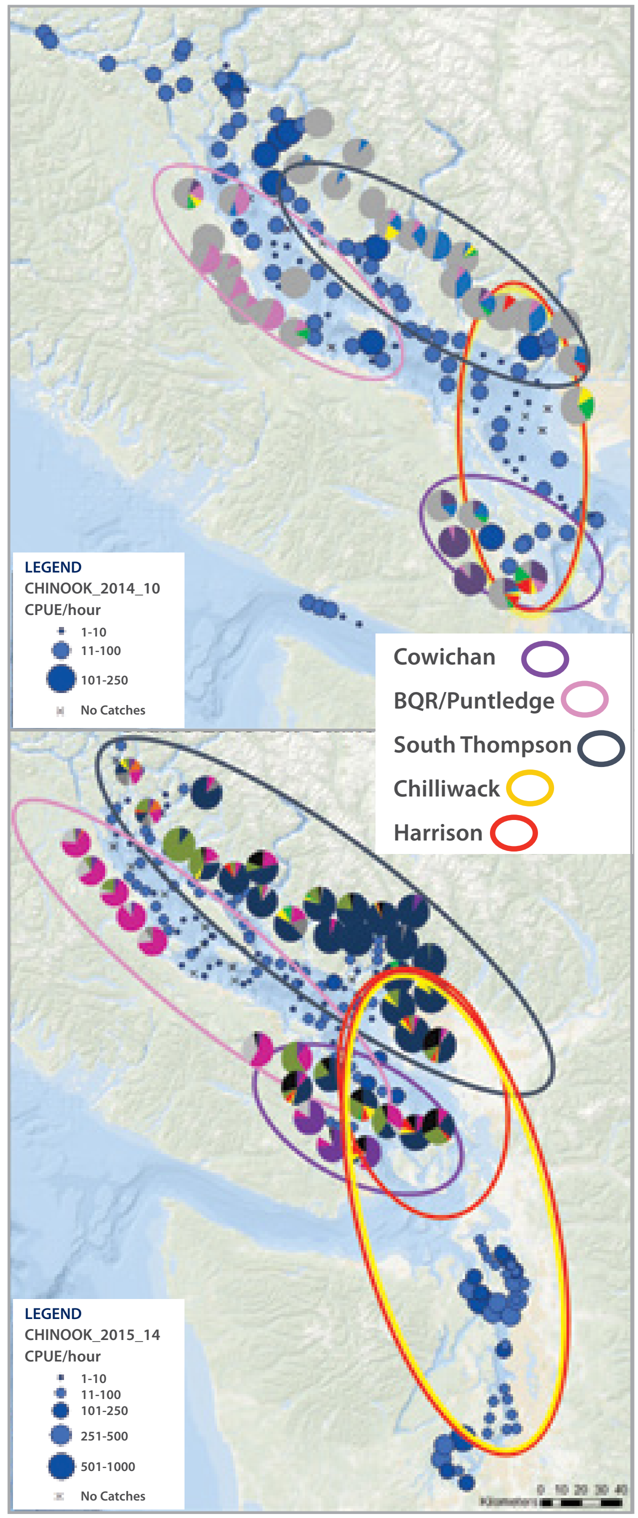


Figure 4. Chinook distribution in July (top) and September (bottom).

An analysis of historical Salish Sea Chinook survival data indicated that survival rates varied significantly between populations, but were similar for populations derived from closely-located river systems. This would make intuitive sense given that these populations were likely rearing in very similar areas in the Strait, and experiencing comparable oceanographic conditions.

A surprise in the results were the low numbers of Harrison/Chilliwack Chinook Salmon captured in the Canadian survey area. This stock is the dominant stock of Chinook Salmon in the Fraser River and would be expected to represent about 40% of the Chinook captured, however, it represented only about 5% of the catch. Associated surveys in the US San Juan Islands and in Puget Sound indicate that as juveniles, Chinook rear in the southern Strait of Georgia (US zone) and in Puget Sound.

Coho

The CPUE of Coho Salmon has increased since 2009 (Figure 5). The size and condition of the juveniles has also increased. Along with this change has been a change in the residency behaviour of Coho Salmon in the Strait. After the early 1990s Coho Salmon no longer appeared to stay in the Strait over winter. Beginning in about 2013, Coho Salmon (age 2+ years) were found to be present in the Strait of Georgia in the late spring when the recreational fishery opened. This was suggested to be due either to Coho overwintering in the Strait or returning to the Strait in the late winter.

In 2017/2018 some Coho Salmon remained in the Strait of Georgia over their first marine winter. This information was gathered by the hook and line efforts of a local SOG sport fishing/research group called the "Avid Anglers" who fish year-round. It is the first time in over 20 years that there was an abundance of Coho Salmon in the Strait of Georgia in the winter. It may indicate that the behaviour we saw in the 1970s and 1980s is returning and that there may possibly be more food for the juveniles in the Strait of Georgia.

Although it is difficult to determine if there is higher food availability for Coho in the Strait, studies are examining the early marine growth of these Coho Salmon to determine if they are growing better. Field results indicate that since 2013, the Coho juveniles in their first ocean year in September have been larger each year (Figure 6). The fish that were in the Strait in February 2018 were 30-35 cm (12-14 inches), or about the size of the Bluebacks in the 1970s.

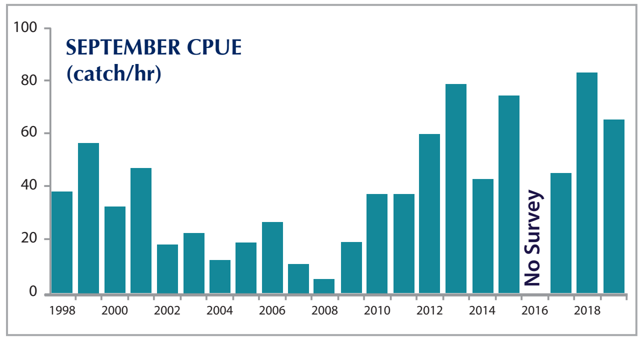


Figure 5. CPUE for juvenile Coho Salmon in the Strait of Georgia in September.

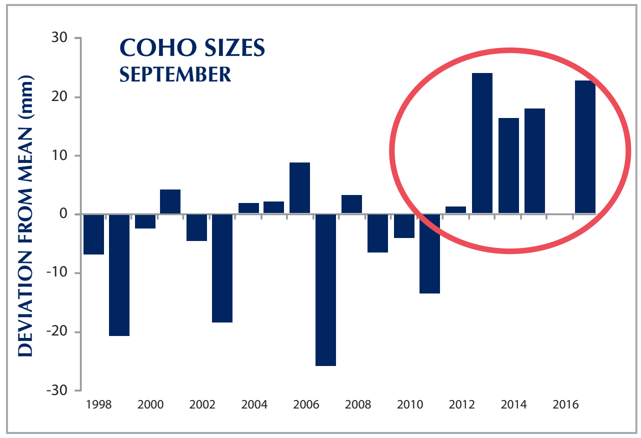


Figure 6. Size of Coho juveniles in the Strait of Georgia in September. Positive deviations from the mean (for 1998-2016) indicate larger fish. Juveniles have been generally larger by September since 2013. Figure provided by Chrys Neville, DFO.

NEXT STEPS

There are a number of important questions this study is working to answer:

- Are growth patterns, health status, or condition of juveniles rearing in different regions significantly different?
- How do these conditions change across years with different oceanographic conditions?
- Can we identify the fish that will survive based on their early marine growth, distribution or condition?
- If fish are not changing distribution patterns based on oceanographic conditions how does this impact survival?
- What implications does this have on hatchery production or other actions intended to increase salmon survival and availability to sport and commercial fisheries?

Analyses for this project are ongoing. The DFO trawl survey provides one of the best long-term data series for juvenile Coho and Chinook stock distributions, growth, survival and state of health as well as valued and additional information on the Strait of Georgia marine ecosystem. We suggest that it is crucial that DFO continues this program and makes these data more available in the future.

TELEMETRY STUDIES: FOLLOWING SALMON ON THEIR JOURNEY IN RIVERS AND OCEANS

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ What is migration survival of Pacific Salmon through freshwater and segments of the Strait of Georgia? ▸ What are travel speeds and routes taken out of the Strait? ▸ What are causes of mortality?	▸ Since 2010, ~2,500 out-migrating Chilko Sockeye smolts and ~300 Seymour steelhead have been acoustically tagged and tracked from freshwater through coastal regions. ▸ Gill biopsies of 200 wild Chilko Sockeye and 160 Seymour Steelhead to examine links between health and survival. ▸ Predation studies of bull trout in Chilko Lake.	▸ Survival rates vary geographically and are segment- and route-specific. ▸ Cumulative mortality of Chilko Sockeye was ~ 50% over the ~ 700 km freshwater migration, and reached ~ 90% over the subsequent 300 km marine migration. ▸ Travel speeds vary among species. ▸ Pathogens and immune function were important to migration success, with higher predation on smolts infected with pathogens.

HOW?

This research was undertaken to assess how individual physiological states relate to migration rates, behaviour and survival of juvenile salmon travelling through the Strait of Georgia and Discovery Passage areas of the Salish Sea. Using small acoustic transmitters, the behaviour and fate of Chilko Sockeye (2016 and 2017) and Seymour steelhead (2015) smolts was tracked from release through the Salish Sea. The condition of these smolts was assessed prior to transmitter implantation and release through the use of biomarkers for pathogen presence and load, presence of immune- or stress-related responses and growth potential to better understand the links between body condition during initial outmigration may influence survival and behaviour in the early marine environment.

Until 2015, the existing acoustic receiver arrays allowed for fish detections in the lower Fraser River, in Juan de Fuca Strait, in north-central Strait of Georgia (NSoG) and in northern Queen Charlotte Strait only. PSF, working with Kintama Research (Nanaimo, BC), established new acoustic receiver arrays in Discovery Islands and Johnstone Strait in 2015, and also evaluated the detection efficiency of V9, V7 and the much smaller V4 Vemco acoustic tags. The addition of the new arrays and the high efficiency of V4 tags opens up the possibility of carrying out tagging studies on much smaller fish than has been previously possible (Figure 1).

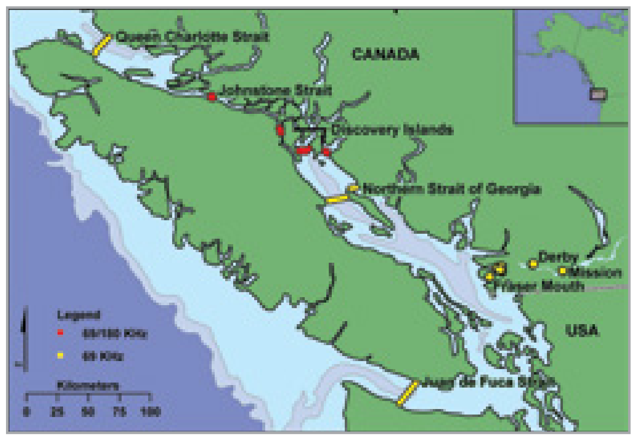


Figure 1. The red coloured arrays in the figure above were those arrays implemented by Kintama Research and are additional to the arrays managed by the Ocean Tracking Network (OTN)-coloured yellow. The red-coloured arrays in the Discovery Islands are 69 and 180KHz and can detect the new small and high frequency V4 tags in addition to larger tags. Figure provided by Kintama Research.

SUMMARY OF RESULTS TO DATE

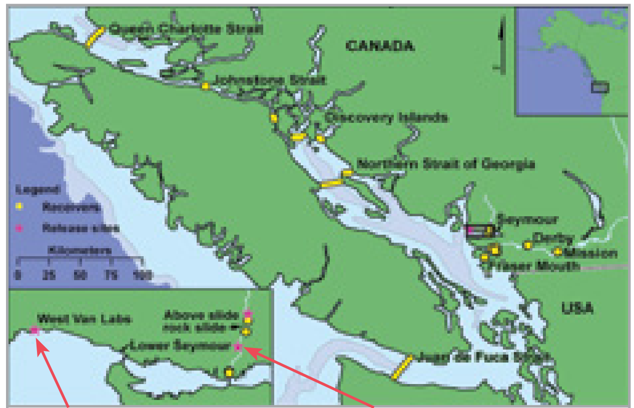
1. Evaluate the migration and survival rates of juvenile salmon in the Strait of Georgia, the Discovery Islands and Johnstone Strait (Sockeye and steelhead) 2015-2017.

Seymour steelhead 2015: In 2015 age-1 hatchery steelhead smolts were tagged at the Seymour River Hatchery in North Vancouver and released at two locations to test route- and location-specific survival across outmigration (Figure 2). Survival to the Queen Charlotte Strait array was higher for fish released at West Vancouver (27.3%) than fish released in the lower Seymour (9.1%) (Figure 3). Thus, transporting fish ~18 km resulted in a 3-fold increase in survival. Seymour River and Burrard Inlet were noted as regions of particularly low survival for migrating smolts. We are not sure why, but these areas may be predation hotspots. Travel rates were about 2-3 times faster through the same marine regions as they found with Sockeye smolts — see below (e.g., 15-20 km per day in the Strait of Georgia, 40-50 km per day in the Discovery Islands, 30-40 km per day at northern Vancouver Island). Their faster speeds are probably due to their much larger body sizes compared to Sockeye smolts.

Chilko Sockeye 2010-2014: Age-2 Chilko Sockeye have been tagged with V7 tags, released at the outlet of Chilko Lake and tracked as they cross a number of arrays (Figure 4). Survival patterns were as follows (Figure 5):

- Release to 14 km (B): 63 – 90% survival
- Release to Fraser River Mouth (G): 21-48% survival
- Release to Queen Charlotte Strait (K): 3-10% survival

Chilko Sockeye 2016: In 2016, with the availability of the small V4 tag, it was possible for the first time to tag smaller age-1 Sockeye smolts (important as these make up the majority of the Chilko Sockeye smolts) (Figure 6). Surprisingly, survival of age-1 fish was higher than that of age-2 smolts, at least in the Chilko River. However, age-1 fish had lower tag burdens, potentially influencing this result. The patterns of mortality were similar in each, with higher mortality in upper Chilko and Chilcotin Rivers (which appear to be a potential mortality hotspot), low mortality in the more turbid waters of the Fraser River and then higher mortality again when smolts enter the Strait of Georgia (Figure 7). Travel rates of smolts in the upper Chilko River was relatively slow at about 10-20 km per day though they were faster in the Chilcotin River at about 100 km per day. In the Fraser River, smolts migrated more quickly at about 180-190 km per day (in all sections there were no differences between the ages). In the marine segments smolts travelled at 10 km per day (Strait of Georgia) and 15 km per day (Discovery Islands) — only one year olds were abundant enough to assess these travel rates. Please see **http://kintama.com/animator/dep/Chilko2016_sockeye/** for an animation of the movements of tagged Chilko Sockeye during 2016.



Marine Release at West Van (n=160) and River Release at Seymour River (n=83).

Figure 2. Release locations for Seymour steelhead study. Figure provided by Steve Healy.

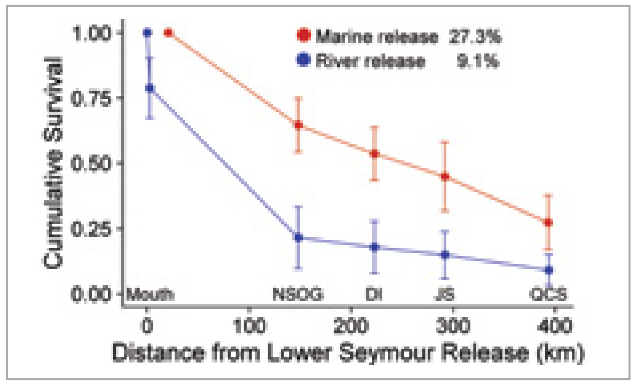


Figure 3. Relative survival of Seymour steelhead released in Seymour River vs West Van. Figure provided by Steve Healy.

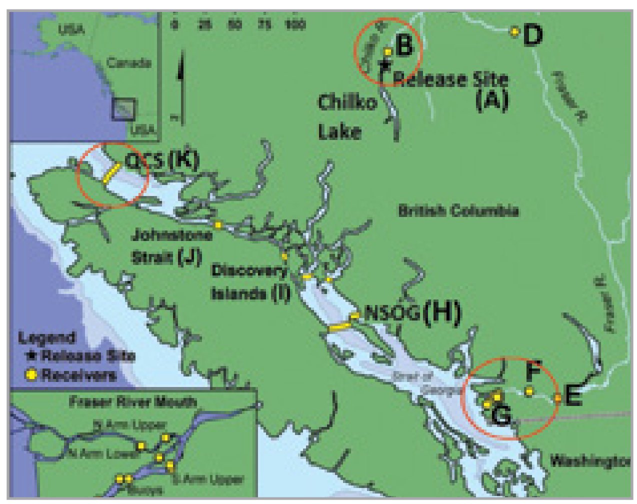


Figure 4. Release site (A) and array locations for Chilko Sockeye studies (A-K). Figure provided by Scott Hinch.

Contents of a single bull trout stomach. Up to 69 sockeye smolts were found in a single trout. Photo by Nathan Furey.

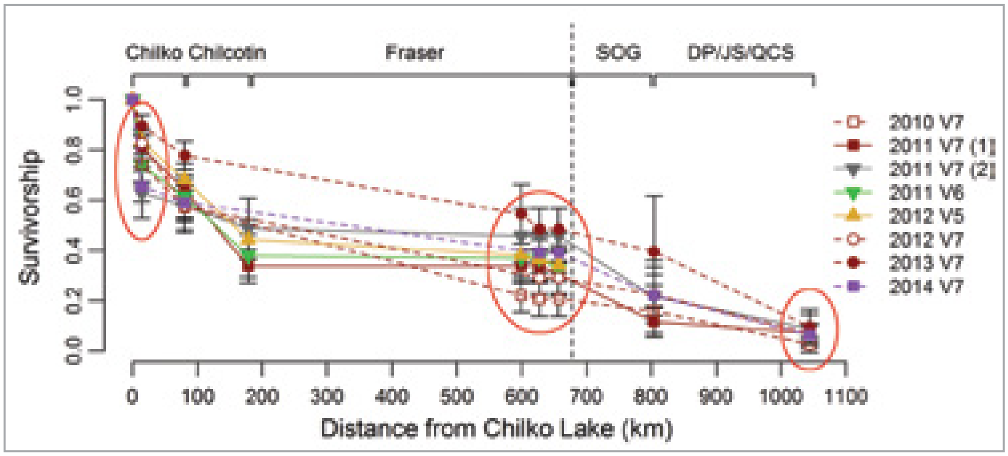


Figure 5. Survivorship patterns for Chilko Sockeye studied 2010-2014 using a variety of different acoustic tags. Figure provided by Scott Hinch.

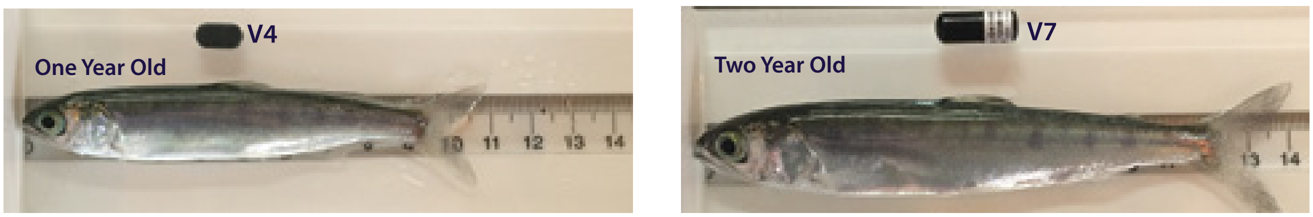


Figure 6. Relative sizes of age-1 and age-2 Chilko sockeye smolts, and the different acoustic tags used for study. Figure provided by Christine Stevenson.

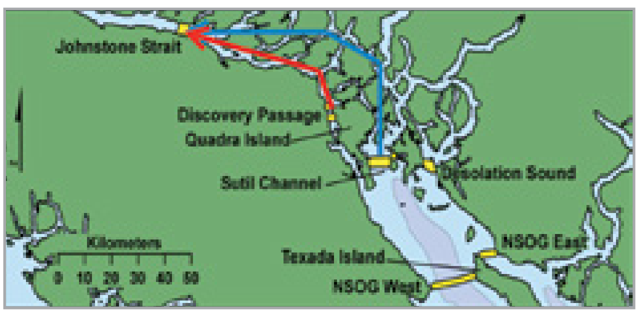


Figure 8. Route specific survival of Seymour steelhead: Discovery Passage: 97.7%, Sutil Channel: 46.2%. Figures 8 and 9 provided by Steve Johnston.

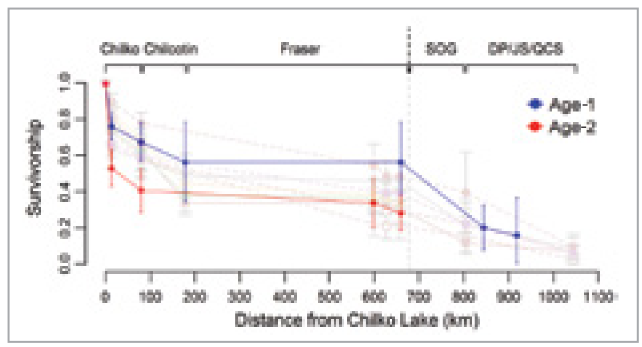


Figure 7. Relative survival patterns of age-1 (blue) and age-2 (red) Chilko Sockeye smolts. Light grey lines and symbols show survival of age 2 tagged fish from previous years (see Figure 5). Figure provided by Christine Stevenson.

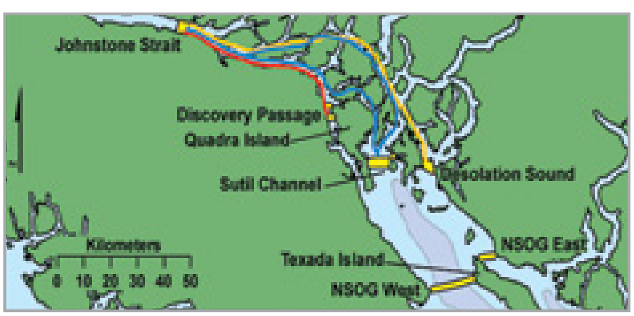


Figure 9. Migration pathways of Chilko Sockeye through the Discovery Islands 2016-2018.

Route through Discovery Islands	2016 27 - V4 tagged smolts	2017 108 - V4/V7 tagged smolts	2018 117 - V5/V7 tagged smolts
Discovery Passage	10	32	27
Sutil Channel	9	49	81
Desolation Sound	1	15	9

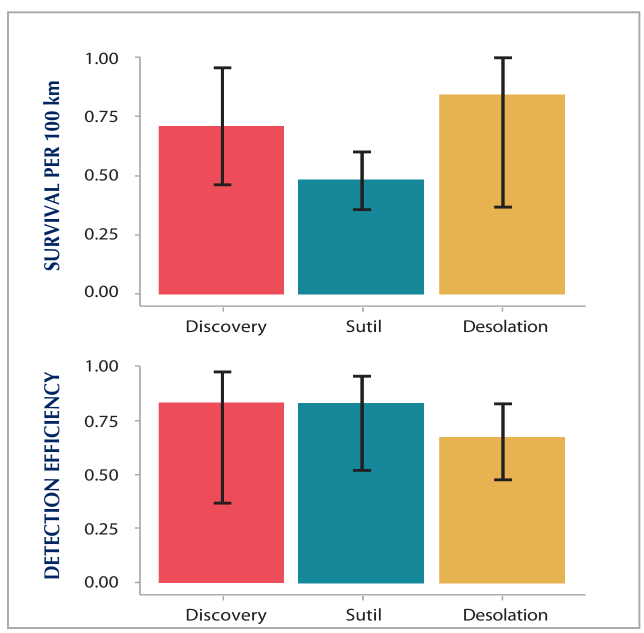


Figure 10. Modelled Sockeye smolt survival rate per 100 km and detection efficiency expressed for three primary migration routes through the Discovery Islands. Figure provided by Steve Johnston.

2. What is the relationship between survival rates and the migration route through the Discovery Islands?

Seymour steelhead 2015: New acoustic receivers around the Discovery Islands revealed that smolts primarily migrated (77%) through the westernmost route (Discovery Passage — red line in Figure 8), and those that did benefitted from ~97% survival per 100 km compared to ~47% per 100 km for Sutil Channel to the east (blue line in Figure 8).

Chilko Sockeye 2016-2018: For Chilko Sockeye, preliminary results from 2016, 2017 and 2018 tagging show that Sockeye preferentially use Discovery Passage and Sutil Channel on their way to Johnstone Strait (Figure 9).

Survival rates associated with these different routes were assessed in 2018 with smolts captured within the Discovery Islands, tagged with V5 and V7s tags, and transported south to the central northern Strait of Georgia, near Mittlenatch Island (Figure 10). Survival was modelled using Cormack-Jolly-Seber model variants and indicated that Desolation Sound (84% per 100 km) had the greatest rate of survival per 100 km, while Discovery Passage (71% per 100 km) expressed lower survival rates than those observed with hatchery steelhead smolts. Sutil Channel captured the largest proportion of released migrants (~69%) in 2018 and expressed the lowest survival rate (48% per 100 km) among observed routes.

OTHER IMPORTANT FINDINGS

1. Researchers at UBC & DFO found that pathogens and immune function were important to migration success.
   a. Chilko Sockeye smolts that carried the naturally occurring IHNV (infectious haematopoietic necrosis) virus were less likely to survive to reach the ocean. Interestingly, bull trout in the upper Chilko River selectively predated on smolts carrying this pathogen as well as smolts with other immune issues. Bull trout exhibited binge feeding, consuming up to 20 times their maximum ration in smolt prey. This is some of the first direct evidence that piscivores are selectively predating on prey that are infected with pathogens, and providing an "ecological service" benefitting Sockeye by reducing the likelihood that smolts could spread pathogens.
   b. Preliminary analyses have found other links between immune- and stress response-related genes and mortality for Chilko Sockeye Salmon smolts tagged in 2016. Thus, it appears that expression of several genes may be predictive of survival during juvenile migration.
2. Kintama Research also conducted a small acoustic telemetry pilot study on hatchery-origin Chilko River (Spring) Chinook, to estimate freshwater survival and migration timing. Freshwater survival to the Fraser River mouth (49%) was comparable to other species which migrate the same distance downstream. However, their downstream migration rate (only 18 km/day) was dramatically slower than that of wild Chilko Lake Sockeye, which migrate rapidly to the ocean after exit from Chilko Lake (100-170 km/day). Thus, Chinook smolts took more than one month on average to reach the SOG, in contrast to wild Chilko Lake Sockeye which generally take under a week.

SIGNIFICANCE & NEXT STEPS

Survival Rates and Routes

Survival rates for both Seymour steelhead and Chilko Sockeye vary geographically and are both segment- and route-specific. There is relatively poor survival close to natal areas and different species/ages appear to respond similarly. This low survival is likely attributed to high levels of predation in freshwater. It is apparent that the physiological state of smolts is also important, and these studies provide some of the first direct evidence that piscivores target physiologically compromised prey. Survival is higher in the turbid Fraser River, but drops again when smolts enter the marine waters of the Strait of Georgia. There is some evidence that the routes taken by these fish through the Discovery Islands region to exit the Strait of Georgia are important to survival.

Travel rates

Smolts travel slowest in clear freshwater areas and fastest in the turbid mainstem of the Fraser River. This is likely related to predator avoidance. They travel more slowly through the Strait, but their rate of travel increases through the Discovery Islands, likely due to the impact of currents and tides in this region. There are large differences among species with respect to travel rates: Chilko River Chinook smolts took more than a month to travel from freshwater to marine entry into the Strait of Georgia, whereas this trip takes only one week for Chilko Sockeye. Meanwhile, steelhead smolts travel 2-3 times faster than Sockeye smolts likely due to their larger size.

Next steps include retrospective analyses on ~10 years of acoustic telemetry studies to determine how migratory behaviour and survival are influenced by oceanographic conditions in the Salish Sea. Lastly, individual fish-based models (IBM) will be developed to simulate smolt migrations to test what navigation and/or orientation behaviours smolts use in the early marine environment. Together these studies will help our understanding of salmon smolt migrations and the trends in productivity and survival.

WHAT WE HAVE LEARNED ABOUT HARBOUR SEALS AND IMPACTS ON JUVENILE SALMON?

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ How many Chinook and Coho smolts are consumed in the Strait of Georgia by harbour seals? ▸ What is the impact of seals on salmon production? ▸ How can we mitigate the impact of seals?	▸ Seal scat collections from the Strait of Georgia for 2012-2018. ▸ PIT tagging of Big Qualicum hatchery Coho for a seal feeding study using head-mounted PIT tag scanner "beanies". ▸ GPS backpacks to look at seal feeding strategies.	▸ Seals may be taking more than 40% of juvenile Coho and Chinook in the Strait, but these estimates need to be reassessed and updated given recent studies showing significant year to year variability in seal diet. ▸ Harbour seals appear to target Coho, Chinook and sockeye smolts in the spring, while largely ignoring juvenile chum and pink smolts—but primarily take adult pink and chum in the fall. ▸ Seal predation on smolts in estuaries occurs primarily at dusk. ▸ Only a small portion of the seal population specialises in feeding on smolts exiting rivers and entering salt water.

OBJECTIVES OF STUDY

The long-term goals of this research are to:

1. Estimate the numbers of Chinook and Coho smolts consumed in the Strait of Georgia by harbour seals;
2. Evaluate their impact on salmon production; and
3. Propose ways to mitigate the impact of seals.

BACKGROUND

Since the 1970s, native stocks of Chinook and Coho Salmon have declined throughout the Strait of Georgia (SOG), despite sizable reductions in harvest from commercial and recreational sources. Coinciding with the decline of these species were rapid increases in populations of pinnipeds native to the SOG, primarily harbour seals (Figure 1). Adult salmon are a significant dietary component of seals and sea lions in the SOG, particularly in estuaries where adult salmon return to their natal steams. There is also direct scientific evidence of seals preying on out-migrating juvenile salmon during the spring. Such predation in combination with habitat loss, fishery removals, declining prey abundance and climate regime shifts may explain declines in salmon abundance in the SOG. Some scientists suggest that predation on salmon by marine mammals may also be impeding recovery.

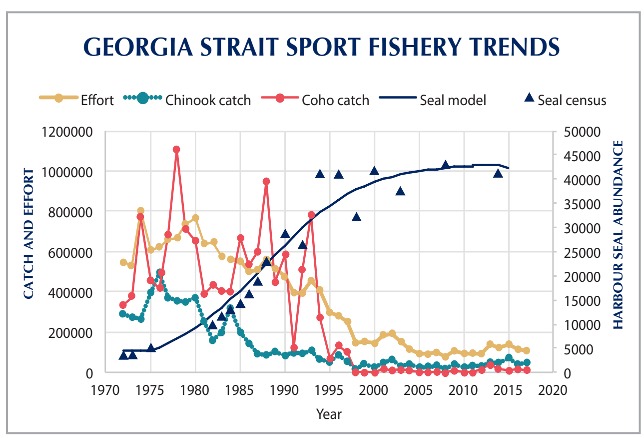


Figure 1. Harbour seal census counts (dark blue triangles) and modelled data (dark blue line) by UBC, together with sport fishery catches and effort. Graph provided by Carl Walters.

HOW?

Three key studies have been carried out:

1. **Scat analysis 2012-2018:** Researchers have been assessing the impact of seals on salmonids in the Strait of Georgia by counting the number of predators, quantifying predation events from visual observations and determining diets from morphological and genetic analysis of fecal samples. Initial studies were done at a few sites, including Cowichan Bay and a small number of estuaries. Data collected 2012- 2014 were subsequently used in a model developed by PhD student Ben Nelson to test the impact of pinnipeds on Pacific Salmon in the Strait of Georgia (Figure 2). Since 2015, scat collections have been expanded to a number of non-estuary haul-outs in the Strait, to provide a more realistic estimate of overall impacts of predation. One of the criticisms of the seal diet work was that the DNA method used had not been validated or compared with other techniques. Thus, 2016 estimates of diet derived from DNA meta-barcoding and hard-part frequency-of-occurrence were compared with a third method, biomass reconstruction.
2. **PIT tag study 2015:** Researchers directly measured predation near Big Qualicum River by capturing 20 adult harbour seals and equipping them with a satellite-linked PIT tag scanner that is designed to quantify the number of PIT tagged fish ingested by harbour seals. PIT tags were implanted in 36,900 Coho smolts at the Big Qualicum hatchery more than one month prior to the release of 381,800 total Coho smolts in early May 2015. The Pit-Tag Readers were affixed to the heads of harbour seals, and the internal PIT tag scanner was activated when seals attempted to capture fish (head-strikes), thereby detecting the presence of PIT tagged fish in the mouths of the seals. PIT tag detections were logged by the instrument and then transmitted via the ARGOS satellite network, providing the number consumed and the unique PIT tag code.

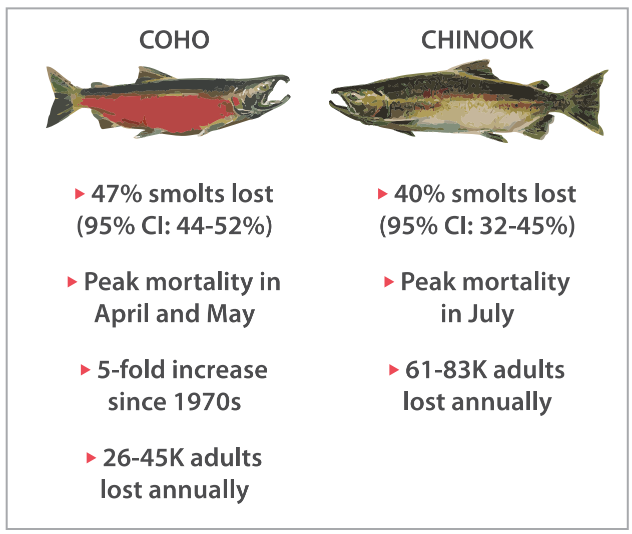


Figure 2. Estimates of the impacts of seal predation on Coho and Chinook based on scat analyses for 2012-2014 from a number of estuary sites in the Strait of Georgia. These values are under review. Figure provided by Ben Nelson.

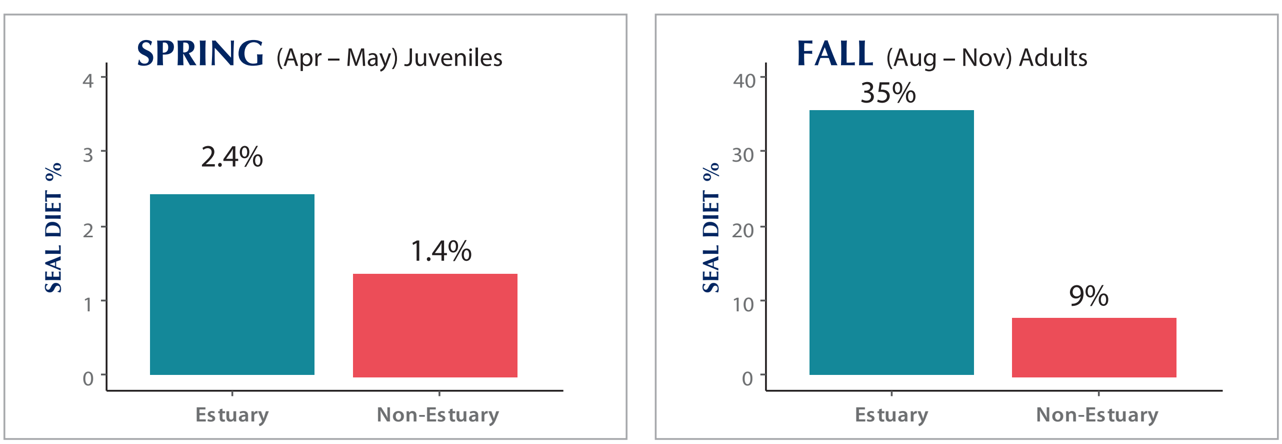


Figure 3. Age-specific salmon proportions in the diets of harbour seals from estuary and non-estuary sites in the Strait of Georgia in 2016: Left graph, proportions for juvenile salmon in spring (April-July); Right graph, proportions for adult salmon in fall (August- November). Figure provided by Sheena Majewski, DFO.

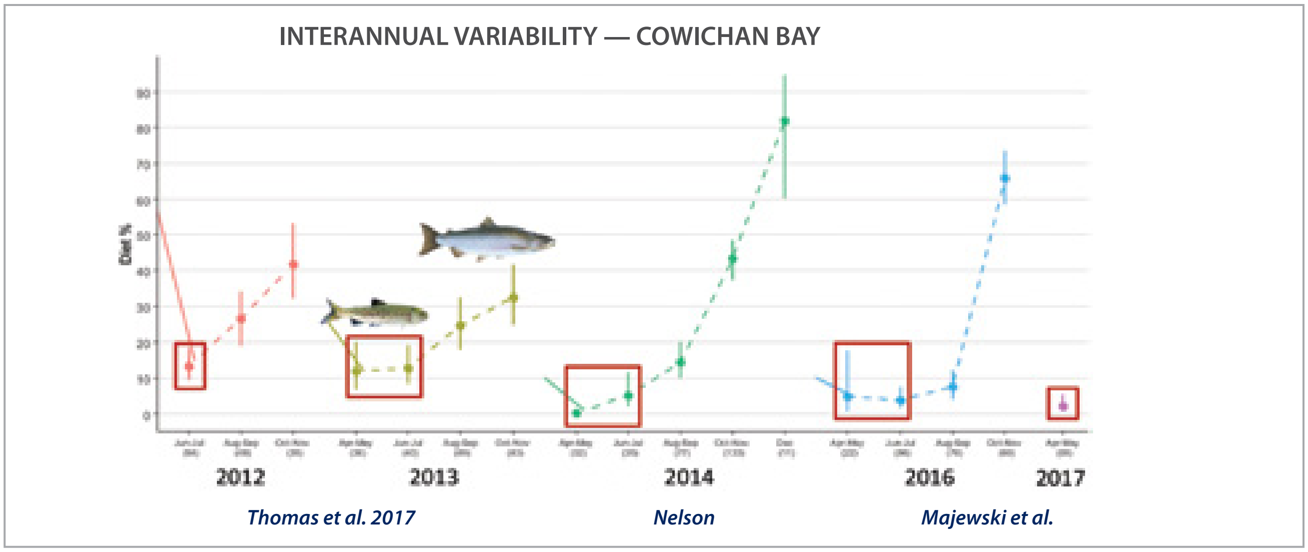


Figure 4. Bi-monthly proportion of salmon in the diet of harbour seals in Cowichan Bay from 2012-2016. Data from 2012-2013 (Thomas, 2015), 2014 (Benjamin Nelson, unpublished) and 2015-2016 (Majewski and Nordstrom, unpublished). Figure provided by Sheena Majewski, DFO.

3.GPS/3D accelerometer study 2015: A second tag incorporated a GPS and 3D accelerometers and allowed for reconstruction of the fine scale movements of individuals to determine locations and ways in which seals were feeding. These data were used to create maps of spatial predation risk needed to identify predation 'hot spots' during the critical period of smolt outmigration. The same 20 seals with PIT tag scanners were also equipped with these tags: 9 seals were tagged in the mouth of the Big Q River and 11 were tagged in a nearby rocky haul-out site. The purpose of this design was to determine a Coho smolt predation rate for the seals that likely specialize on out-migrating smolts versus those seals that fed in other areas and represent the larger portion of the seal population.

SUMMARY OF RESULTS TO DATE

1.Scat analysis 2012-2018: Initial analysis of scat data from Cowichan Bay for 2012-2013 showed that about 12% of the spring diet of seals was made up of juvenile salmon, mostly Chinook, Coho and Sockeye. This suggested a preference for these three species over Chum and Pink, despite the high numbers of Chum available in the Strait at that time of year. Fall diets were made up of 30% salmon, mostly adult Chum.

These data were further analysed based on an average yearly estimate of Coho smolt production of 15.5 million for the period 1998-2007. A seal consumption model predicted that the harbour seal mean annual consumption of Coho for 2012 and 2013 was as follows:

2012: 6.2 million Coho smolts eaten,
40% of the population

2013: 10.3 million Coho smolts eaten,
67% of the population

Based on an estimated 2010 Chinook smolt production of ~66 million, the model predicts that the harbour seal mean annual consumption of Chinook for 2012 and 2013 was as follows:

2012: 26.1 million Chinook smolts eaten,
39.5% of the population

2013: 28.3 million Chinook smolts eaten,
43.0% of the population

Thus, it appears likely that harbour seal predation is responsible for a significant amount of natural mortality in the early marine stage for both Chinook and Coho Salmon.

Most predation appeared to occur when juvenile fish were between 100-150 mm in length. Most Coho mortality occurred in April and May as they entered the Strait at this size range: while most Chinook mortality appears to occur in July when they have grown to the preferred size range. Diet data collected between 2012 and 2014 yielded the model estimates in Figure 2.

These high rates of predation required validation using additional diet data from non-estuary sites. Age-class specific salmon consumption inside versus outside estuaries in 2016 showed minor differences in diet percentages in spring (Figure 3) with lower predation rates on salmon in non-estuary sites, but these studies need additional validation. Salmon contribution to diets was significantly higher in estuaries in the fall, consisting primarily of adult chum in both habitats. However, a longer time series for Cowichan Bay suggests that the greatest variability may be temporal differences in the proportion of salmon consumed in the diet (Figure 4).

Finally, analysis of the DNA meta-barcoding method has shown that this method yields biomass estimates that are similar to the currently accepted gold standard of diet analysis (Hardparts biomass reconstruction — a quite laborious process) while also providing better taxonomic resolution (down to species) for the salmon portion of diet.

2. **PIT Tag Study 2015:** Based on the timing of PIT tag detections, seal predation on smolts in estuaries occurs primarily at dusk and the following hour (Figure 5). During the 4 nights of peak outmigration, it appeared that seals consumed ~1kg Coho smolts per seal each night. This equalled about half of their daily energy needs, indicating that smolt consumption was only part of the daily foraging pattern. Extending the PIT tag detection data to the ~96 seals using the river, seals consumed ~6.19% of the outmigrating smolt population. Note that this estimate is substantially lower than the estimate provided above. The two estimates may be reconciled as follows: 6% of the juvenile salmon entering the Strait (from hatcheries) may be eaten by estuary specialists (as in this study). Another 34% of mortality of smolts may occur from high numbers of seals feeding throughout the Strait of Georgia, giving a total of 40% overall seal-related mortality.
3. **GPS/3D accelerometer study 2015:** Reconstructing the high-resolution movements of the seals and quantifying feeding using counts of prey chasing events (PCEs) detected by accelerometry — revealed that the Big Qualicum estuary was a feeding hotspot for 47.0% of the seals, but was relatively small (accounting for 3% of prey chasing events) compared to the largest feeding area outside the estuary (26% of prey chasing events). Comparing the foraging behaviours of smolt specialists with non-specialist seals revealed 4 different foraging strategies. One consisted of seals (17.6%) that fed on Coho smolts and ignored Chinook in the river mouth, while a second group of seals (17.6%) appeared to target larger fish that preyed on Chinook smolts near the estuary. The two other seal groups did not feed in the estuary in association with the concentrated numbers of smolts, but either remained resident (52.9%) and fed near their main haulouts, or were transient (11.8%) and left the study area. These results suggest a high degree of individual foraging specialization — and show that a small number of seals were specialized in consuming Coho smolts, but did not respond to a later large pulse of smaller-bodied hatchery Chinook smolts during their outmigration.

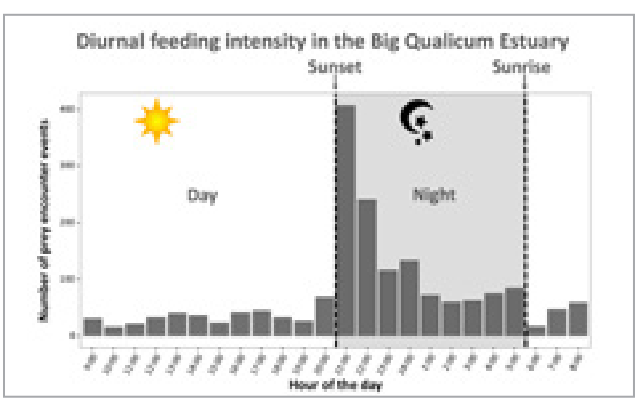


Figure 5. Diurnal feeding intensity by seals on Coho Salmon smolts in the Big Qualicum River estuary. Graph provided by Hassen Allegue.

SIGNIFICANCE

- Preliminary results from estuary scat data have indicated that 20% of harbour seals in the Strait of Georgia may be eating up to half of the Chinook and Coho smolts that enter the Strait of Georgia. Ongoing work will evaluate the influence of sampling habitat (estuary vs non-estuary) as well as the annual variability in the proportions of salmon in diets. These evaluations may alter the current estimates of consumption.
- Harbour seals primarily consume adult salmon of lesser conservation concern in the fall (i.e., Chum and Pink salmon; August–November). But during the spring, seals prefer juvenile salmon of greater conservation concern (i.e., Coho, Chinook, Sockeye; April–July).
- Behaviour observations have included seal usage of log booms as haul-outs, and salmon use of log booms as refuges. Other SSMSP studies suggest the specialized foraging by some seals on smolts may be enabled by large pulses of large hatchery fish entering the Salish Sea each spring during a short window of time.

NEXT STEPS

- DFO is continuing a harbor seal diet monitoring program to extend the Strait of Georgia time-series.
- Marine mammal scientists are refining aerial surveys and seal population numbers, and reviewing diet compositions.
- Further work also needs to be carried out on sea lion diets and movements to fully assess the impact of pinniped predation on salmon survival.
- SSMSP scientists are synthesizing the available information and working to design mitigation strategies. These may include changes to hatchery release strategies and size of smolts at release, as well as changes to log boom placement within estuaries.
- We also suggest that long--term monitoring is critical for assessing impacts of predation, particularly for species with large degrees of natural variability in production such as salmonids.

HOW DO HARMFUL ALGAE IMPACT JUVENILE SALMON?

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ Are there harmful algal blooms (HABs) in the Strait of Georgia and do they affect wild salmon? ▸ Does direct mortality of juvenile salmon increase as prevalence and intensity of harmful algae increase? ▸ Are zooplankton impacted by competition between primary producers of high and low (i.e., harmful algae) nutritional value?	▸ Thousands of water samples collected 2015-2018 by the PSF Citizen Science Program provided information on harmful algal blooms in the Strait of Georgia and associated water quality. ▸ Behavioural and histopathological observations of juvenile Chinook captured during blooms. ▸ Comparison of phytoplankton community composition with the zooplankton caught by the intensive SSMSP zooplankton sampling program.	▸ Phytoplankton community composition is strikingly different year to year and may have significant impacts on the food web. ▸ HABs, of both toxic and mechanically harmful species, are common in the Strait. ▸ There was a correlation between algal blooms, and both feeding activity and conditions of juvenile salmon in Cowichan Bay.

BACKGROUND

The harmful algae program was developed during 2014 with a pilot study in Cowichan Bay. This program was fully implemented in 2015-2018 with collections of phytoplankton samples taking place throughout the Strait of Georgia via the PSF Citizen Science Oceanography Program. Samples have been regularly collected from ~80 stations from February to November from surface waters (0 m) and at depths (5, 10, 20 m) from 10 priority stations. Phytoplankton data collected include: biomass estimation, identification and enumeration of dominant species, % of constituent groups (diatoms, dinoflagellates, silicoflagellates, raphidophytes, nanoplankton, zooplankton) and identification and enumeration of harmful algae. Water quality data collected concurrently with the phytoplankton samples is being used to determine the conditions that appear to promote the development of harmful algal blooms (HABs).

Chinook caught by purse seine in Cowichan Bay during HABs have been examined at the histopathology lab at Pacific Biological Station in Nanaimo to determine if exposure to harmful algae affected body tissues.

SUMMARY OF RESULTS TO DATE

- Multi-year in situ phytoplankton data clearly showed that phytoplankton dynamics in the Strait are a sensitive measure of oceanographic changes. Phytoplankton biomass and composition were strikingly different between years 2015-2018, and appear to be closely associated with nutrients and environmental parameters (Table 1). There is a clear synchrony in phytoplankton dynamics across the Strait, however there are significant differences among locations. This could have direct significance for young Chinook in specific rearing areas.
- Data collected allow evaluation of the relationship between harmful algal occurrence and environmental parameters. Two species of HABS, Heterosigma and Alexandrium, were associated with relatively colder temperatures (i.e., abundances of these HABs were higher in 2018 compared to the warm years of 2015-2017). Heterosigma also was associated with high stratification and low salinity (fresher) waters. Shown below are "windows of opportunity" for two taxa, showing occurrence at specific temperature/salinity ranges (Figure 1).

Table 1. Oceanographic conditions and phytoplankton communities during SSMSP

YEAR	CONDITIONS IN THE N.E. PACIFIC	SPRING BLOOM	SUMMER PHYTOPLANKTON COMMUNITIES	HABs
2015	Year of the "Blob" and strong El Nino	extremely early	dominated by diatoms	calm, some mechanically harmful blooms
2016	El Nino transitioning to La Nina	normal	diatoms, dinoflagellates, lot of silicoflagellates	toxic blooms, mechanically harmful blooms
2017	La Nina	normal	diatoms, dinoflagellates, silicoflagellates	toxic blooms, mechanically harmful blooms

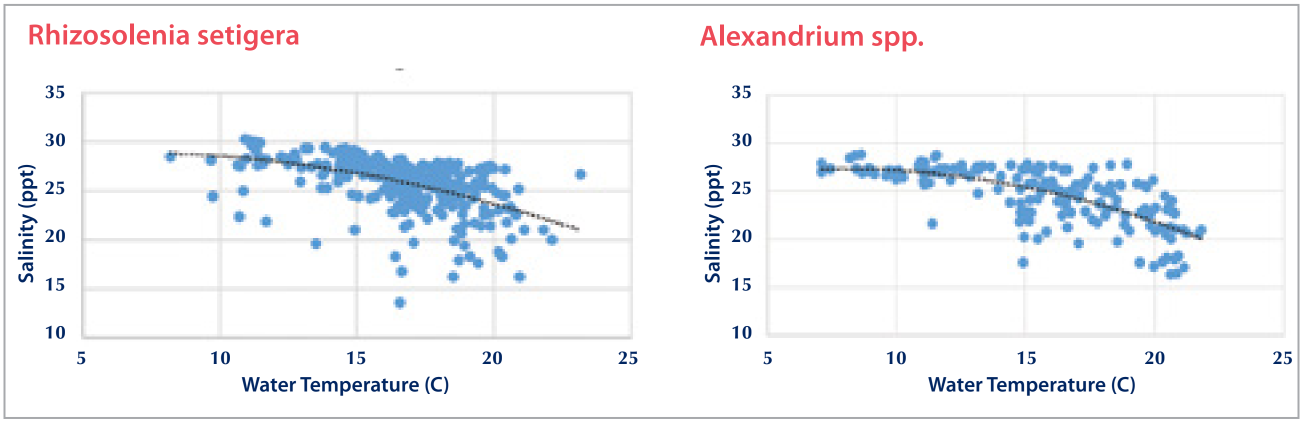


Figure 1. Occurrence of two harmful algal species as related to environmental conditions of salinity and water temperature. Graphs provided by Svetlana Esenkulova, PSF.

- This study captured evidence of the direct effects of HABs on wild juvenile salmon in the Strait of Georgia. From the 2014-2017 Cowichan Bay juvenile salmon study, we observed reduced feeding in juvenile salmon (empty stomachs in >50% of fish caught) and changes in their diet during high algae biomass events; evidence of gill damage confirmed by specific histopathology following high levels of mechanically harmful diatoms; and liver and brain damage, and signs of starvation during moderate toxic algae levels. During the 2014 *Heterosigma akashiwo* bloom in Cowichan Bay, we observed lethargic behaviour in chinook and a dramatic increase in post tagging (PIT tags) mortality during purse seine activities.
- High resolution Citizen Science monitoring confirmed the absence of major *Heterosigma akashiwo* blooms in the Strait during 2015-2017. This is an unexpected result as over 15 years prior, *H. akashiwo* bloomed in the Strait every year. However, blooms of *H. akashiwo* were recorded in 2014 during the pilot juvenile salmon studies in Cowichan Bay and in 2018 by the PSF Citizen Science Program. These contrasting results could help in determining the possible role of *H. akashiwo* blooms on overall juvenile salmon survival in the Strait.
- Preliminary results based on the Citizen Science sampling of phytoplankton and zooplankton in the Malaspina Strait area indicate that biomass of large calanoid copepods and euphausiids was significantly positively correlated to the relative abundance of diatoms. These analyses of the important links between phytoplankton and zooplankton communities are ongoing.

▸ See our Facebook site: "Phytoplankton-Citizen Science Program".

SIGNIFICANCE

- Thousands of water samples were collected over 2015-2018, and we now have unprecedented, high-resolution data on phytoplankton dynamics in the Strait of Georgia.
- Multi-year data on harmful algae species and their environmental preferences are being analyzed. Preliminary results indicate a strong link between HABs and environmental conditions of the Strait.
- SSMSP has provided the first documented evidence of the direct effects of HABs on juvenile salmon in the Strait of Georgia. We observed effects of harmful algae on juvenile salmon in Cowichan Bay in 2014-2016 and the effects were similar to those confirmed from pen-reared salmon worldwide.

Figure 2. Noctiluca scintillans *bloom from southern Vancouver Island, May 2018. Blooms produce ammonia and cause hypoxia. Credit: Dr. M. Costa UVic.*

DISEASE IMPACTS IN PACIFIC SALMON: THE STRATEGIC SALMON HEALTH INITIATIVE

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ What pathogens/diseases may be reducing the survival of BC salmon? ▸ What is the role of potential exchanges of pathogens between wild/hatchery and cultured salmon?	▸ High throughput infectious agent monitoring to quantitate 47 infectious agents in over 31,000 wild, hatchery and cultured salmon assessed from freshwater through the first 9 months of marine life. Including 3,500 samples from net-pen salmon aquaculture. ▸ Host physiological profiling at molecular, protein and cellular levels to study disease processes. ▸ High throughput sequencing for viral discovery. ▸ Acoustic tracking and stress holding studies conducted to assess linkages between pathogens, disease development and fate.	▸ Tracking and holding studies in juvenile and adult salmon identified pathogens linked with fate of individual salmon. ▸ Environment is a key driver of pathogen exposure; temperature is the most important driver of infection. ▸ 15 viruses discovered that had not previously been documented in Pacific Salmon. ▸ Piscine orthoreovirus (PRV) is linked to disease in BC farmed Atlantic and Chinook Salmon, and is infecting wild salmon. ▸ Analyses with 8-10 years of data resolved pathogens associated with reduced survival in Sockeye, Chinook and Coho Salmon.

OBJECTIVES OF STUDY

The main objective of the Strategic Salmon Health Initiative (SSHI) is to determine what pathogens/diseases, if any, may reduce the productivity and performance of BC salmon (hatchery-produced and wild), their evolutionary history and the potential role of pathogen exchange between cultured salmon and other BC Pacific Salmon.

The SSHI project specifically addresses the hypothesis that infectious disease reduces early marine survival of salmon in the Salish Sea. The project also addresses the potential that salmon aquaculture interactions may contribute to risk of disease in migrating Pacific Salmon.

HOW?

Researchers applied novel genomic approaches to study the presence of pathogens and associated 'disease' expression in wild and hatchery-reared Pacific salmon, and open-net pen cultured Atlantic and Chinook Salmon. Prior studies had suggested that health of salmon can be highly predictive of future survival as salmon adapt to new environments. A sampling program established in 2008 facilitated collection of juvenile salmon from freshwater through the first 9 months of marine residence. SSHI researchers were able to assess shifts in pathogen and disease profiles within and between years for over a decade. A new technology using a high throughput system assessed 47 known pathogens (viral, bacterial, fungal and protozoan) in 80 fish at once (Figure 1); in total over 31,000 salmon were profiled. Molecular physiological assessments based on the activity of salmon genes detected disease-related processes associated with infection and survival. Secondary processing of fish showing signs of viral disease enabled discovery of novel (previously uncharacterized) viruses. Histopathology and In-situ hybridization enabled characterization of cellular damage in the host, establishment of infectivity for novel viruses and co-localization of specific agents within damaged tissues. Molecular profiling of gill biopsy samples from acoustically tracked salmon identified pathogen and disease linkages with fate.

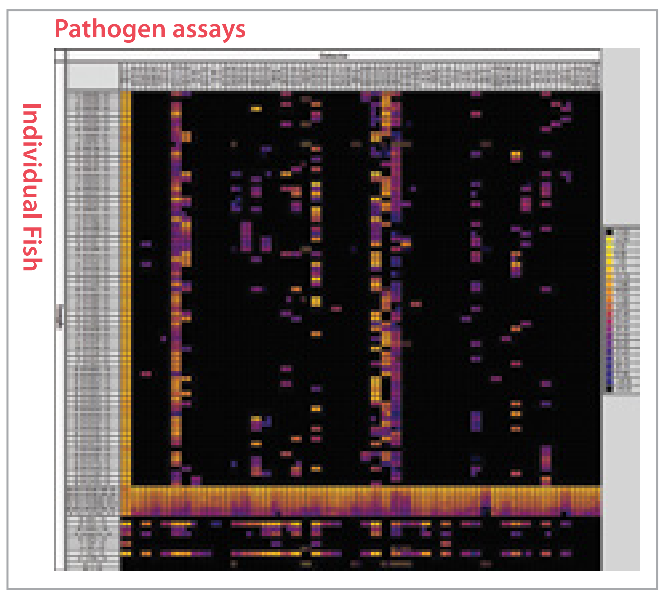


Figure 1. Heatmap showing duplicate detections of 47 pathogens in wild-caught salmon. Image provided by Karia Kaukinen, DFO.

SUMMARY OF RESULTS TO DATE

- Over 50 infectious agents have been observed in juvenile salmon in the Salish Sea. Analytical models derived from 8-10 years of infectious agent monitoring, acoustic tracking and predation studies that relate agents with fate, and physiological assessments have been applied to reveal infectious agents showing the greatest impacts during downstream freshwater migration and in the Salish Sea.
- The most notable parasites include *Myxobolus arcticus, Ichthyoptherius multifiliis, Ichthyophonus hoferii, Paranucleospora theridion, Loma* and all three species of *Parvicapsula*. Notable bacteria include *Tenacibaculum maratimus*, Rickettsia-like organism and *Flavobacterium psychrophilum*. Notable viruses include infectious haemotopoetic necrosis virus (IHNV), piscine orthoreovirus (PRV) and erythrocytic necrosis virus (ENV). We are continuing to study the 15 novel viruses discovered in the SSHI (e.g., Figure 2).
- Linkages with fate vary by salmon species, season, age and environment. Some infectious agents correlated with marine survival come from freshwater, confirming earlier understanding that health and condition at the time of ocean entry can impact subsequent survival. This finding provides a potential means to enhance survival by carefully monitoring and optimising the health and condition of hatchery fish.
- Models relating infection probabilities with environmental (e.g., temperature, sea surface salinity, depth sampled, distance from aquaculture, stock latitude) and intrinsic (origin—hatchery or wild, life-history type, stock) factors reveal that temperature in the Salish Sea is a major driver of infection (Figure 3). In fact, the majority of infectious agents are more prevalent in years of higher coastal marine temperatures. Stress challenge studies (mostly on adults) have also revealed many pathogens with effects enhanced under elevated temperatures.
- Pathogen impacts on survival may arise through direct effects, where fish die from disease, or indirect effects, where infection affects physiological performance and behaviour, enhancing risk of predation and susceptibility to other stressors. It is likely that the latter is the more important for wild fish, where even modest compromise in performance (especially swimming and visual) can lead to death.
- Tracking studies of Chilko Lake sockeye smolts identified linkages between IHNV and migratory survival. Subsequent study showed that smolts with IHNV detection had 16-24 times greater odds of being consumed by bull trout. In the marine environment, Rhinoceros auklets preferentially consume smolts infected with *Parvicapsula* parasites. This research demonstrates linkages between infection state and risk of predation, and the potential role that predators may play in removing infected individuals, thereby increasing the health of the populations.

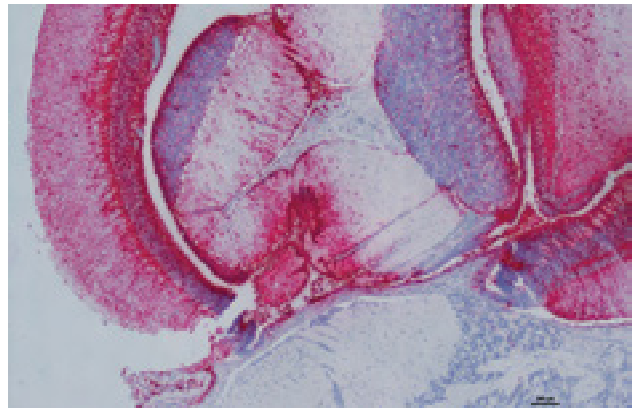
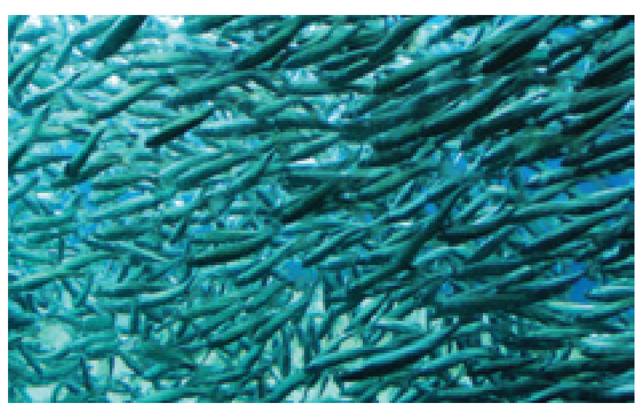


Figure 2. Investigating infectivity of CTV-2 (red), localised to the optic lobe of an Atlantic Salmon brain. Credit: Emiliano Di Cicco.

- After the discovery of HSMI (Heart and Skeletal Muscle Inflammation) on an Atlantic Salmon farm in BC, SSHI researchers began conducting further analysis on Pacific Salmon to determine if the virus, PRV, is associated with, and ultimately causative of, disease in Pacific Salmon. Analysis of Chinook Salmon from farm audit data suggested an association between PRV and jaundice/anemia (jaundice syndrome), a disease highly similar to PRV-caused diseases in Rainbow Trout in Norway, and Coho Salmon in Japan and Chile, as well as a disease originally described in farmed Atlantic Salmon in eastern Canada (hemorrhagic kidney syndrome). In 2018, the SSHI provided evidence that the same virus (PRV) is likely causing different expression of diseases in Atlantic and Chinook Salmon in BC, increasing the evidence that PRV transmission from farmed salmon poses a risk to wild Chinook Salmon. Genetic analyses currently being finalized show PRV exchanges between aquaculture and wild salmon do occur on the BC coast. Moreover, research in 2019 on physiological associations with infective agents in wild-caught Chinook Salmon revealed the strongest linkages for PRV. PRV-infected Chinook showed both a powerful immune response and histological changes consistent with early development of jaundice/anemia. It is important to note that PRV is far more common, and perhaps more relevant, in Chinook Salmon on the west coast of Vancouver Island than in the Salish Sea, with disease manifestation (farmed and potentially wild) occurring over cool fall/winter periods.



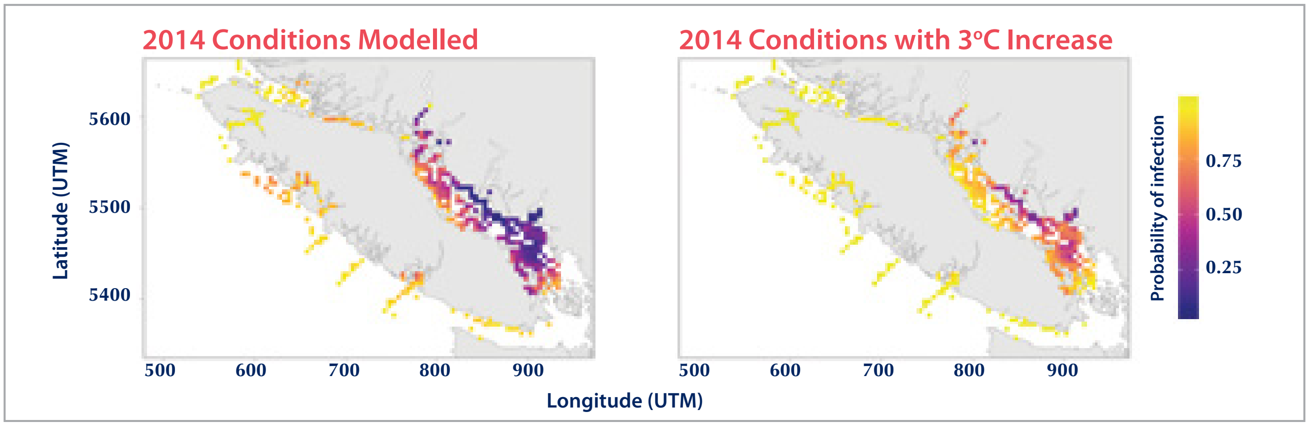


Figure 3. Model estimates of probability of infection with parasite Paranucleospora theridion *under an average sea surface temperature (left) and a 3°C rise (right). Lighter color=higher probability. Credit: Art Bass.*

- In the SSHI, farmed salmon (live- and dead/dying) were collected over one entire production cycle on four farms in Johnstone Strait. The first documented case of HSMI in BC was described as lasting almost a year on one of these farms. A second study has revealed the infective agents most closely associated with dead/dying salmon. The bacterium *Tenacibaculum maratimum*, the causative agent of mouth rot, was consistently associated with dead/dying salmon across all four farms.

- What is as important as the identification of pathogens that have been detected are those NOT detected. Most of the agents reportable to the World Organization of Animal Health (OIE) and/or the Canadian Food Inspection Agency (CFIA) that are highly virulent and can impact trade **were not detected in over 12,000 salmon surveyed**. These include Infectious salmon anemia virus, *Oncorhynchus masou* virus, Infectious pancreatic necrosis virus, and the parasite *Myxobolus cerebralis*. Moreover, the two emerging viruses causative of heart diseases **other than HSMI**, salmon alphavirus (reportable) and piscine myocarditis virus, were also not detected.

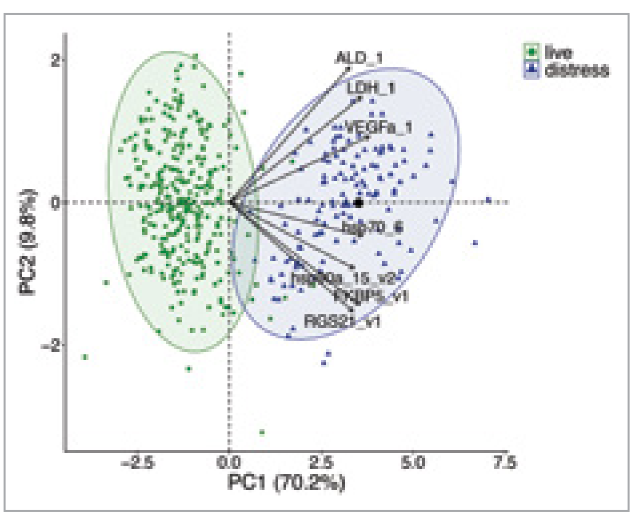


Figure 4. Salmon Fit-Chips include a panel of genes (biomarkers) co-activated in distressed fish that will die naturally within 72 hours (right cluster). Graph from Aimee Lee Houde.

NEXT STEPS

- **Cumulative effects:** An overarching need for the SSMSP syntheses is an understanding of cumulative stressors (e.g., do harmful algal blooms and low dissolved oxygen act synergistically with disease development to ultimately cause mortality?) A new molecular tool, salmon Fit-Chips, is poised to address this need, as it uses validated biomarker panels of host genes to identify specific stressor and disease states in individual fish, all based on a gill biopsy sample. Included in this tool are genes predictive of imminent mortality (Figure 4). Application of Fit-Chips to the same juvenile salmon surveyed in the SSHI will not only reveal the cumulative and synergistic interplay between stress and disease, but will identify the environments where salmon are the most compromised and likely to die.

- **Risks from salmon farms:** Models are currently under development to evaluate the risks to migratory salmon of pathogen transmission from high density salmon farms. Even with the unprecedented large dataset on wild and farmed salmon, this is perhaps the most difficult question to answer. Early models have explored whether agents found in Chinook salmon were more frequently detected within 30 km of active farms. Future models will apply the full weight of data from all salmon species to tackle this question. Undeniably, two agents showing pathogenic potential in wild salmon and observed more prevalently on farms have come to the fore; piscine orthoreovirus and *Tenacibaculum maratimum*, but whether these pose the greatest risk of farm to wild transmission is still to be validated.

- **Challenge studies:** SSHI will host a workshop of leading world experts to utilize SSHI data and published information to rank infective agents by their potential to cause disease in wild salmon. It was the intent that the highest ranked, most understudied agents would be followed up with infection challenge studies (whereby naïve fish are exposed in the laboratory to pure cultures or concentrations of an agent) in the next phase of SSHI. Some of the newly characterized viruses are certainly in line for follow-up challenge research.

STUDIES OF HATCHERY SALMON

BACKGROUND

PSF supported a number of projects that were designed to assess hatchery-wild interactions in the Salish Sea, as well as to improve understanding of the behaviour, marine distribution, habitat use and survival of hatchery-produced salmon. Some of these studies also investigated how to produce hatchery fish that survive at higher rates in the marine environment, which may then allow for reductions in hatchery production while at the same time sustaining or improving adult salmon production.

PROJECTS

1. Delayed Release of Hatchery Coho and Chinook Salmon in the Strait of Georgia

Past studies on the influence of time and size at release of juvenile Coho and Chinook Salmon on their juvenile survival and subsequent return as mature fish indicated that a later sea entry and larger body size increased marine survival. Large late releases of Coho may also result in a greater proportion of Coho residing in the Strait of Georgia (i.e., 'inside' distribution) during their second summer at sea where they may be more available to the local fisheries.

Trials on late releases of large hatchery Coho and Chinook Salmon, funded by the SSMSP, were conducted for three years (2014-2016) at Quinsam and Big Qualicum hatcheries on the East Coast of Vancouver Island. Funding supported the extended rearing, feeding and coded wire tagging of smolts at these facilities, as well as the coded wire tagging of a late large release of Coho at the Seymour River Hatchery in the lower mainland. Similar trials on late releases of large hatchery Coho at Chilliwack and Inch Creek were conducted concurrently by the DFO Salmon Enhancement Program (SEP).

At these hatcheries, Coho and Chinook juveniles were reared and released at a later date, typically late June, along with a traditional production group which were released in May for comparisons. Seymour Hatchery released all of their Coho smolts in June. Although later releases of Coho and Chinook were at a larger size than the traditional May releases, their growth during the extended rearing period was controlled such that the target size at release would be representative of their estimated size in the marine environment had they been released in the traditional May period.

Results to date suggest Big Qualicum and Quinsam Coho and Chinook stocks may be benefiting from later/larger releases with up to a three-fold increase in survival over traditional releases for Coho, and as much as 6 times greater survival for Big Qualicum BY 2015 Chinook. In contrast, mainland populations of Coho from Inch Creek did not show any change in survival between the two strategies but data have yet to be compiled for Chilliwack Hatchery Coho in 2015-2016. Returns beyond 2019 will allow for more detailed evaluations, providing more clarity on the potential benefits of large late Coho and Chinook release strategies.

Table 1. Survival of Brood Year (BY) 2013-2016 Coho and BY2014 and 2015 Chinook from traditional and delayed juvenile releases.

		COHO SURVIVAL				CHINOOK SURVIVAL	
SITE	RELEASE STRATEGY	BY 2013	BY 2014	BY 2015	BY 2016	BY 2014	BY 2015
Big Qualicum River	Traditional	-	1.54%	2.53%	-	0.54%	0.16%
	Delayed	-	2.88%	6.48%	-	1.10%	1.11%
Quinsam River	Traditional	-	0.95%	1.63%	1.96%	0.32%	0.40%
	Delayed	-	2.67%	5.01%	2.82%	0.63%	0.64%
Inch Creek	Traditional	3.28%	4.08%	5.94%	4.51%		
	Delayed	4.10%	3.54%	6.25%	-		
Chilliwack River	Traditional	-	3.20%	*	*		
	Delayed	-	2.60%	*	*		
Seymour River	Delayed	6.70%	*	*	*		

* Results not yet available

2. Impacts of Release Locations: Cowichan River Chinook Hatchery Salmon Projects

The Cowichan River Chinook population was historically one of the larger Chinook stocks in the Salish Sea. PSF has supported several studies relating to Cowichan River Chinook, including studies of relative survivals of both hatchery and wild fish in both freshwater and marine environments.

Rotary screw trap (RST) studies conducted during the downstream migration of hatchery smolts, which in 2015 and 2016 were released 40 kms upstream of the mouth of Cowichan River (i.e., at Road Pool), found that only 20% of the releases could be accounted for in the RST located in the lower river. Based on the 2015 findings, DFO and Cowichan hatchery also agreed to carry out paired release trials of CWT Chinook during 2016, one at the upper river and one at the lower river.

Coded wire tags (CWTs) were applied to 4 release groups of Cowichan hatchery Chinook. These fish were released on two dates in April and two dates in May to make for 2 early and 2 late Cowichan Chinook releases in-river. Both early and late groups also were released at two different locations: the Road Pool (40 kms upstream and labelled the standard release site on Figure 2) and approx. 20 kms downstream. The smolts were supplemented with river water 2-3 hours per day, 2-3 times per week for a month period before release to assist with imprinting. The survival estimates were lower for the upstream releases (Road Pool) versus the downstream releases for both the early and later releases (see Table 2 below). It was recommended that the lower release sites be used in all future Cowichan Hatchery release plans.

Further PIT tag and in-river predator studies carried out in the Cowichan River during SSMSP have suggested that the freshwater losses may be a result of predation from herons and other predators, exacerbated when there are low flows in the river; this may be a result of heron predators which like to forage in shallow waters less than 15cm deep (see Freshwater Studies summary). An interesting observation was that 75% of the smolts taken by herons were found to be hatchery fish, indicating possibly different behaviour or predator responses by these Chinook.

Based on these findings it was suggested that high hatchery losses could be reduced by simply moving the point of hatchery release, a finding that has resulted in a change in hatchery practices: Chinook from the Cowichan hatchery are no longer released in the Cowichan headwaters, but instead, are released in the lower river or directly from the hatchery.

Figure 1. Rotary screw trap used to catch juvenile Chinook on Cowichan River

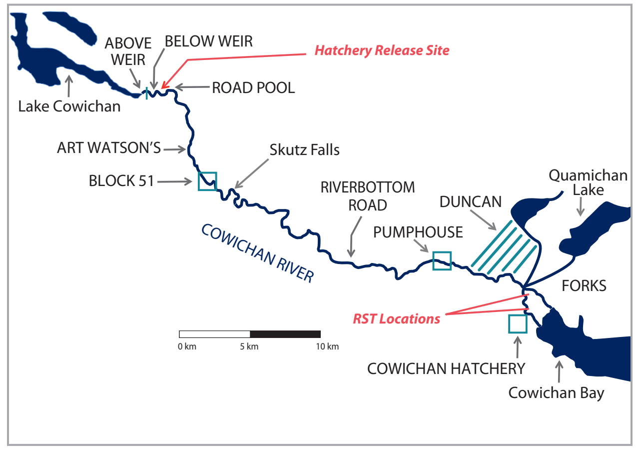


Figure 2. Release sites for Cowichan Hatchery Experimental Releases

Table 2. Comparison of freshwater survival of juvenile Chinook down Cowichan River: comparing different release locations and timing (early versus late releases).

RELEASE LOCATION (River km)	RELEASE DATE	HATCHERY CWT RELEASE NO.	POPULATION ESTIMATE AT RST IN LOWER RIVER	% SURVIVAL
Stoltz (25.7)	27 April	94,530	29,465	31.20%
Road Pool (46.5)	9 May	94,034	10,093	10.70%
Horseshoe Bend (31.7)	24 May	194,315	91,815	47.30%
Road Pool (46.5)	20 June	193,748	29,422	15.20%
Total		576,627	160,796	27.90%

Other studies in the Cowichan River noted that hatchery-reared smolts were larger than wild smolts, ate larger prey, spent very little time in the estuary and disappeared from the bay earlier, due to emigration and mortality. The larger body size may be a disadvantage for hatchery smolts if it necessitates their leaving the estuary prematurely to meet energy needs. For example, the onset of piscivory (fish diet) for Cowichan Chinook begins at a fork length of approximately 74 mm, which was less than the average fork length of the hatchery fish found in Cowichan Bay. These large Chinook may spend more time seeking less abundant larger prey and increasing their exposure to other predators.

Leaving the safety of nearshore habitats, especially those providing eelgrass and kelp cover, may expose hatchery fish to increased predation risk and may contribute to the low survival rates of hatchery fish as compared to wild fish.

3. Efficacy of Hatcheries: Use of Parental-based Tagging of Hatchery Coho Salmon

PSF, together with Genome Canada and DFO, assisted in funding the EPIC4 program **(www.sfu.ca/epic4/)**, one component of which is applying parental-based tagging (PBT) of hatchery Coho stocks in Southern BC in order to genotype (the genetic composition of a parent) the majority of hatchery Coho smolts released into the Salish Sea. This technology allows researchers to estimate contribution to fisheries, and ultimately the family-specific survival rates of hatchery Coho Salmon, which may enable genetic selection programs that have never been tried as a tool to increase the effectiveness of hatchery Coho production.

Currently, hatchery-bred Chinook and Coho Salmon are monitored by means of coded-wire tags (CWT) implanted in juveniles prior to release from the hatchery, although only a small portion of releases are tagged.

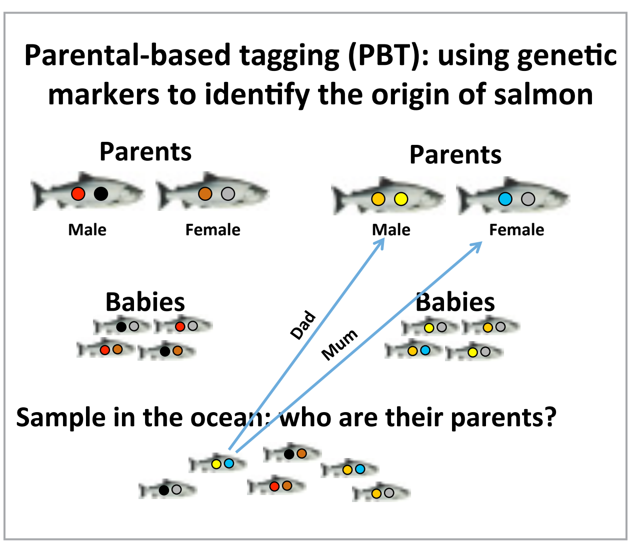


Figure 3. Depiction of how PBT works. Graphic by EPIC4. Credit: Terry Beacham, DFO.

Figure 4. SSHI research collecting samples from the Strait of Georgia. Photo by Mitch Miller.

However, with PBT, essentially those hatchery Coho are "tagged" and identifiable as to when and where they were released. This information makes it possible to understand the impact of different hatcheries on salmon populations and how well hatchery fish survive in the wild, and allows us to compare productivity of hatchery versus wild fish. Similar work is now being carried out for Chinook.

4. Effects of Fish Health and Condition: The Strategic Salmon Health Initiative (SSHI)

Within the SSMSP, the SSHI has provided the tools to assess the health and condition of fish, including their: **1)** infectious health; **2)** state of smolt readiness; and **3)** presence of stress. These tools have been developed for application on non-destructive gill tissue in a tool called the Salmon Fit-Chip. In addition, biomarkers (DNA based) predictive of imminent mortality and state of inflammation, also often predictive of poor survival, have been developed.

Application of these tools by hatcheries could help to:

- Optimize hatchery practices to minimize stress on the fish;
- Precisely identify when fish are ready to emigrate from freshwater to the ocean (smoltify);
- Identify and mitigate exposure to infective agents; and
- Develop means to optimize the health and condition of juvenile salmon for their release to improve their chance of survival.

Research within the SSHI has revolutionized how the health and fitness of Pacific Salmon in any environment can now be monitored and evaluated with a statistically reliable sample size!

NEXT STEPS

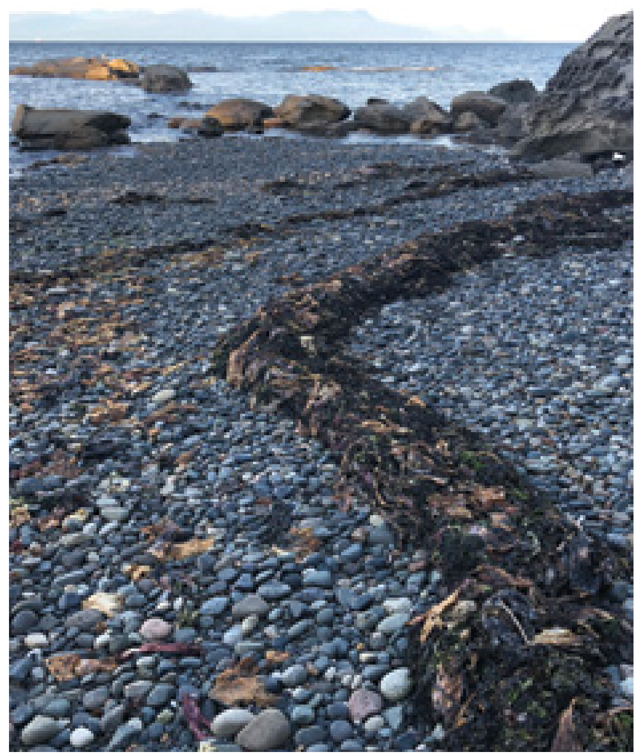
PSF is undertaking a science-based review of hatchery programs in the DFO Pacific Region including community hatcheries and major facilities operated by DFO. This project will examine the effectiveness of current production, identify scientific advancements in recent years that may be applied to increase effectiveness, and ultimately inform the joint production of hatchery-based and wild Pacific Salmon for BC communities and ecosystems.

THE VALUE OF ECOSYSTEM MODELING

QUESTIONS ADDRESSED	DATA	CONCLUSIONS
▸ How has the environment of the Salish Sea changed in the last 50 years, and why? ▸ How do anthropogenic impacts interact with environmental changes in the Salish Sea? ▸ How has predation, competition, and habitat changed in the last 50 years? ▸ What are the impacts on juvenile salmon, particularly for Chinook and Coho Salmon?	▸ Huge amounts of environmental, biological, ecological and fisheries data collated and derived from the Strait of Georgia Data Centre and other databases. Data include the PSF Citizen Science data set, as well as many long- term data sets such as the DFO Juvenile Salmon Trawl data, the Strait of Georgia Zooplankton dataset, catches of salmon and release of salmon from hatcheries in the Salish Sea.	▸ Model development is ongoing.

SUMMARY OF THE GOALS OF THE SSMSP ECOSYSTEM MODELING PROGRAM

While previous studies have evaluated short-term productivity patterns for the Salish Sea, there have so far only been correlative studies to evaluate the relationship between long-term changes in environment and the productivity of higher trophic levels organisms (notably salmon) in the Strait of Georgia ecosystem. However, many studies have shown that changes in primary production (phytoplankton) can be amplified through the food web — a 10-20% change in primary production can lead to a 40-80% change higher up in the food web, perhaps years later. This modelling program aims to represent such changes and to examine if this has occurred in the Strait of Georgia.



A group of scientists within the University of British Columbia has taken on the task of evaluating such long-term trends as part of the Salish Sea Marine Survival Project (SSMSP). The group has learned a great deal from reconstructing ecosystem history using complex food web models for about 50 other ecosystems around the world. They concluded that if you wish to replicate historic trends, you need to understand: the interactions in the food web, including how predator and prey impact each other and over time, how primary (phyto-plankton) and secondary (zooplankton) productivity is driven by atmospheric and oceanic conditions, and how human and habitat impacts have changed with time.

A core aspect of this research is that it requires long-term data. So, while the SSMSP research is to a large extent focused on the present, this ecosystem modelling (along with the SSMSP data centre, **www.sogdatacentre.ca**) must gather extensive past data also. But such historic information is sporadic at best, making it necessary to rely on data analysis and synthesis to fill in the blanks. Or in other words: we need computer models to reconstruct the past, back to when marine survival of salmon smolts was higher.

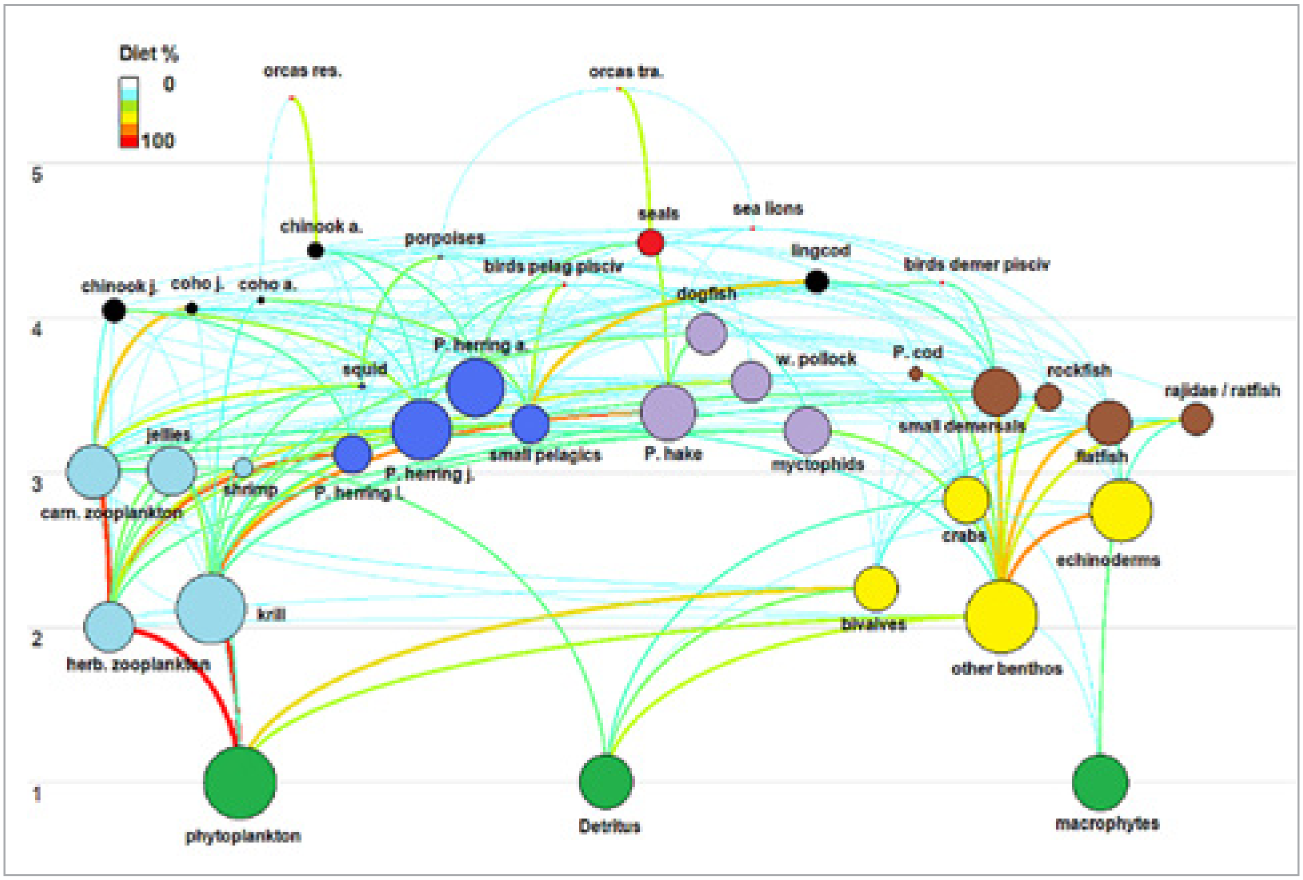


Figure 1: A schematic of the food web of the Strait of Georgia. Circles represent functional groups of species, the size of the circles represent biomass (log-scaled) and the lines indicate trophic (i.e., feeding) relationships. Figure provided by V. Christensen.

To address the questions listed at the beginning of this summary (what, when, where and how did change occur?), this program needs to develop a suite of models for the Canadian Salish Sea, including:

1) A hydro-dynamic model that describes the physical environment of the Salish Sea at a fine time and spatial scale, considering historic weather, river runoff and ocean conditions (hour by hour and day by day);

2) A biogeochemical model that estimates plankton productivity;

3) A food web model that describes how predator and prey populations interact, how they occur spatially and how they have been impacted by humans, notably through fishing and habitat changes; and

4) A behaviour model that follows historic releases of Chinook and Coho Salmon smolts (hatchery and wild) as they come out of the rivers and evaluates how their survival may have been impacted by predators and prey during their first year in the Strait.

The initial hydro-dynamic and biogeochemical models have been developed and progress is ongoing. Once the food web model is complete, the hydrographic/biogeochemical and food web models will be inter-connected. This will then allow for evaluation of the relative impact of changes in environmental productivity, food web structure and direct human impacts on the population trends for salmon and other key ecosystems groups in the Salish Sea.

This activity will be central for the SSMSP's primary research objective of assessing if "bottom-up processes driven by annual environmental conditions are the primary determinants of salmon production via early marine survival."

SIGNIFICANCE

This modelling approach will allow us to examine how environmental productivity, food web conditions (predator and prey factors) and human impacts have impacted salmon survival/production over time. However, understanding and then testing our understanding of predator/prey systems in this ecosystem is complex, as Figure 1 suggests!

In Puget Sound, an independent ecosystem model is being developed. The Atlantis model is another 3D 'end-to-end' modeling approach that includes oceanographic, chemical, ecological (competition and predation) and anthropogenic processes. Atlantis is intended as a strategic management tool to evaluate hypotheses about ecosystem response, to understand cumulative impacts of human activities and to rank management options. Developing a second independent model is one of the only means to really test our understanding of these complex marine ecosystems.

During SSMSP and continuing with Adult Chinook and Coho diet studies at the University of Victoria and PSF, otoliths have been collected from stomach contents of adult salmon and from the scat of harbour seals and other mammalian and bird predators to provide information on their diets that we can observe today.

SALISH SEA
MARINE SURVIVAL PROJECT

SUMMARY

FINAL SUMMARY

The primary objective of the Salish Sea Marine Survival Project was to:

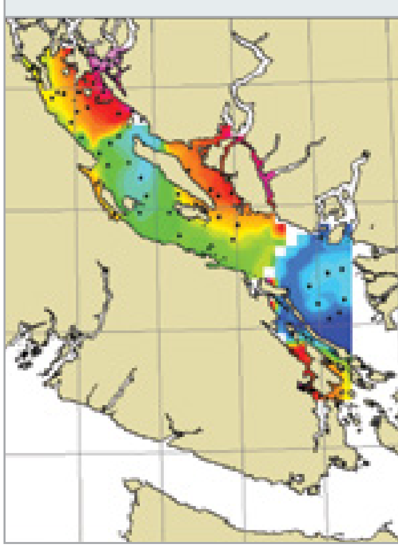
DETERMINE THE PRINCIPAL FACTORS AFFECTING THE SURVIVAL OF JUVENILE SALMON AND STEELHEAD IN THE SALISH SEA.

In Canada the objectives of these studies were intended to:

1. **Re-build production of wild Pacific Salmon and steelhead through a program that is ecosystem-based, considers hatchery effectiveness, and engages communities;**
2. **Promote sustainable fisheries and increase their value to BC communities; and**
3. **Provide a foundation for long-term monitoring of the Salish Sea and salmon health.**

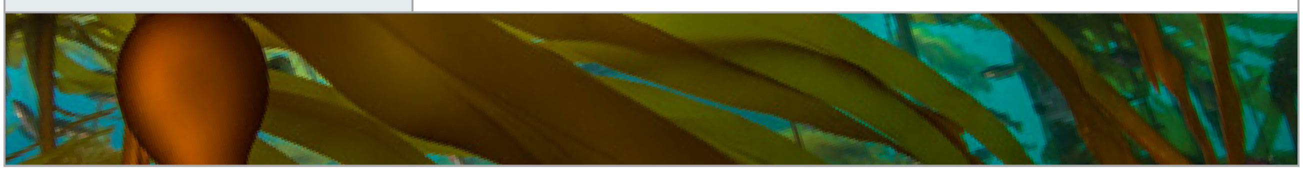
The Salish Sea Marine Survival Project has made a significant contribution to our understanding of wild Pacific Salmon, and our findings will allow for implementation of a number of management actions which will benefit Chinook and Coho production. Ultimately, we believe that the research results and subsequent management actions may also benefit other marine life in the Salish Sea, such as the southern resident killer whales. Key findings from our SSMSP studies are summarized in Table 1.

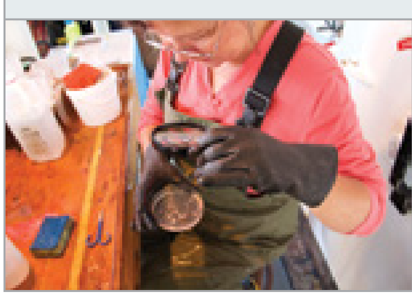
Table 1: SSMSP Findings in a Nutshell

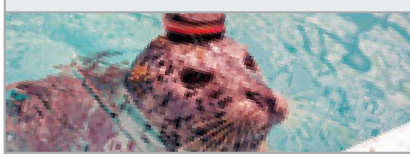
RESEARCH TOPIC	OUTCOMES
Biological Oceanography	
Studies examined water quality, temperature, turbidity, oxygen levels, salinity, ocean acidity, nutrients and chlorophyll levels — and how variations affect marine life from phytoplankton up to forage fishes. Data were derived from moorings, buoys, satellite imagery, the PSF Citizen Science Oceanography Program, and DFO research cruises for zooplankton and herring. 	▸ Changing oceanographic conditions directly alter plankton community structure, abundance and distribution, and the changes to the phytoplankton community have direct effects on higher trophic levels, such as changes in composition and abundance of zooplankton and larval fish assemblages; changes to zooplankton prey quality; impacts on harmful algal blooms; and abundance of forage fish such as herring. ▸ Warming waters and impacts of the North Pacific "Blob" in the Strait of Georgia over the course of SSMSP were conditions that are completely out of our experience, and which created a mixture of positive and negative outcomes for salmon. There were negative impacts to kelp populations, but at the same time, increased abundance of Northern anchovy in the Strait, and increased growth of juvenile Coho and Chinook. ▸ This study has informed us on the drivers of spring bloom in the Strait of Georgia. The amount of Chlorophyll 'a' in the Northern Strait is strongly linked with large-scale ocean climate indices (e.g. Pacific Decadal Oscillation) whereas in the Central Strait it is more strongly influenced by localized factors (e.g. Fraser River discharge) and thus indirectly related to climate indices. Certain areas of the Strait of Georgia are production 'hotspots" for phytoplankton and zooplankton. ▸ Temperatures below 17°C are best for juvenile salmon early rearing; given that surface waters were warmer than this in July and August for 2015-2017, it appeared that waters as deep as 10 m in the summer in most regions of the Strait were not good habitat for juvenile salmon. ▸ However, there were regional variations, with favorable water temperatures in highly mixed areas of the Strait (e.g. Campbell River and the Gulf Islands). ▸ Harmful algal blooms (both toxic and mechanically harmful species) are common in the Strait and they affect wild juvenile salmon with impacts similar to those previously confirmed in BC salmon farms e.g. reduced feeding, changes in diet, histopathological changes showing damage in the liver, brain, gills etc., and signs of starvation.

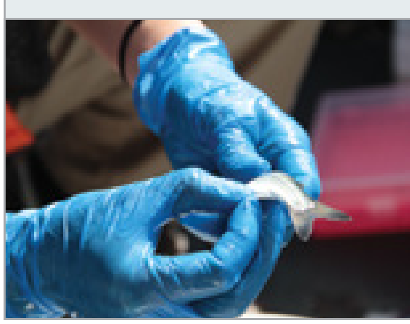
RESEARCH TOPIC	OUTCOMES
Biological Oceanography (continued)	
	▸ Surface waters of the Salish Sea in the winter are corrosive as a result of lowered pH; impacts on the marine food web are being assessed. ▸ In general, there appear to have been two key time periods for zooplankton: 1996-2006, a period of generally declining zooplankton biomass and increasing salinities, and 2007-2018, a period of increasing zooplankton biomass and decreasing salinities. Although this recent increase in biomass should be good for forage fish and salmon, much of it was made up of an increasing abundance of gelatinous zooplankton ("jellyfish — not good fish food). Marine survival of three Strait of Georgia Chinook and one Coho population were best explained by models including zooplankton, sea surface salinity and other variables representing the flow from the Fraser River. ▸ Age-0 herring were heavier for a given length in 2007-2017 compared to herring sampled prior to 2007. This may have implications for juvenile Chinook and Coho, which are piscivorous. The increase in body condition of Young-of-Year (YOY) herring since 2000 has likely resulted in only the largest juvenile Chinook able to prey on age-0 herring due to mouth gape limitations.
Cowichan River Chinook Salmon Studies	
A significant number of studies of Cowichan Chinook were carried out during SSMSP, in freshwater and marine environments, including studies of: freshwater survival rates as related to flow conditions and predators; freshwater habitat requirements; application/ installation of Passive Integrated Transponder (PIT) tags to assess relative survival of groups tagged at different times in their life history, to pinpoint bottlenecks to survival; development of a new sampling methodology called microtrolling; and a comparison of hatchery and wild Chinook survival rates. 	▸ Mainstem and large side channel edge habitats with suitable velocities and intact over-stream and/or instream riparian vegetation cover were critically important for Chinook fry rearing. ▸ SSMSP saw a novel usage of PIT tags, strategically allocating PIT tags to salmon groups at different ages and locations to allow for a comparison of survival rates between groups (determined when fish return to natal streams as adults). Tagging groups from freshwater through their first year in marine waters allowed an examination of the differential survival rates as the fish grew and migrated seaward. ▸ Freshwater survival was surprisingly low some years (less than 30%) and appears to be related to level of discharge on the Cowichan River and possibly the result of predation. A high level of predation by herons, particularly on hatchery fish, was an unexpected finding. ▸ Microtrolling was a new SSMSP innovation to catch smolts using miniaturized trolling gear during their first summer/fall in marine waters. ▸ There appear to be two key mortality periods, during downstream migration of smolts to the ocean and then during the first winter. ▸ Hatchery fish survive about 35-40% as well as wild fish across all stages and it is believed that the mechanism controlling this difference likely occurs after their first summer at sea. ▸ These projects highlighted the importance of the first winter in the ocean, a period that has been little studied in the past.
Nearshore Habitat Restoration and Research	
Numerous SSMSP projects assessed the usage of estuary and nearshore habitats, specifically marsh, eelgrass and kelp beds by juvenile salmonids.	▸ Estuaries are important for protection and rearing of juvenile salmon, especially of smaller fry, and allow for diversity in salmon production. ▸ Forage fish need specific habitat to lay their eggs, and these shoreline habitats require far more protection.

RESEARCH TOPIC	OUTCOMES
Nearshore Habitat Restoration and Research (continued)	
Focus was on mapping changes over time and assessment of anthropogenic impacts on biodiversity and resilience of these habitats; studies to assess the importance of nearshore habitat connectivity; as well as assessments of the environmental requirements for successful restoration. Novel SSMSP projects included the utility of satellite imagery, aerial imagery, and drones to examine changes in the extent of bull kelp and eelgrass beds; use of stable isotopes to examine source of salmon diet; examination of otoliths to determine loss of Chinook life history variants in degraded estuaries; and other studies to examine thermal tolerance in kelp, as well as the effects of temperature stress and herbivore grazing as limitations to bull kelp distribution.	▸ Globally, seagrass ecosystems are declining in area. SSMSP researchers have been assessing the overall decline or degradation of eelgrass nursery areas in the Strait of Georgia and found that estuary degradation is related to anchorage scour, shoreline activities ((boats, docks, log booms and armouring), development, alterations and contaminants. Results suggest an overall deterioration of coastal environmental health in the Salish Sea due to increased use of the coastal zone as well as declines in water quality due to urbanization. ▸ Studies showed evidence of decreased species richness and increasing simplicity of eelgrass fish communities in highly disturbed regions (e.g. sites within Fraser Estuary, Comox Estuary, southern Vancouver Island). ▸ In the Cowichan River, the estuary was particularly important to smaller fry as compared to stream-rearing Chinook that left the river at a larger size. High mortality rates for river-reared smolts in some years suggest that estuary-reared counterparts could have a survival advantage in years of low flow, and may be an important component of annual Chinook production. ▸ Kelp shows decreased reproductive activity when waters are warm, and rising ocean temperatures are thought to be a major contributor to kelp declines. ▸ Eelgrass restoration activities have been successful in many areas of the Strait, but are hampered due to many anthropogenic impacts in estuaries as well as climate change impacts.



Juvenile Salmon in the Salish Sea	
Beyond estuaries and the nearshore habitats, juvenile salmon are widely distributed in open marine waters. SSMSP research built on existing DFO trawl surveys conducted twice annually, and conducted consistently since 1998. These surveys are the key source of juvenile salmon (and other fishes) data on abundance, distributions, and body conditions over time and space for 20 years! 	▸ Genetic analyses of Chinook and Coho samples enables researchers to identify the local populations that our samples originated from. Critical new understandings have emerged for Chinook salmon: different populations consistently use different areas of the Strait of Georgia; and Chinook present in late summer differ from the early summer and are dominated by the South Thompson summer Chinook population. Further, one of Canada's largest Chinook populations (the Harrison River Fall white Chinook) rear in upper Puget Sound more than in the Strait of Georgia. ▸ Coho salmon are more broadly distributed through the Strait of Georgia and analyses are revealing the importance of their early marine survival as the determinate of subsequent adult returns. ▸ For both Chinook and Coho salmon, these observations are consistent with statistical analyses of coded-wire tagging on hatchery fish that pre-date these DNA results. ▸ An important observation has been that Coho salmon have recently been remaining within the Strait through fall and winter and have been in excellent body condition during these years. ▸ Of the other fishes, Pacific Herring are by-far the dominant species during these surveys.

RESEARCH TOPIC	OUTCOMES
Predation Studies	
Salmon have a number of predators and several studies focussed on the role of predation, particularly from harbour seals, on the survival of juvenile salmon. Novel methods were developed during SSMSP including the development of PIT tag scanner "beanies" affixed to the heads of seals to allow for the first direct estimation of predation (in this case, by PIT tagging of Big Qualicum hatchery Coho); collections of seal scat from the Strait of Georgia for 2012-2018 to assess diet using DNA, hardparts, and novel metabarcoding methods; and GPS backpacks to study seal feeding strategies. Studies were done to determine how many Chinook and Coho smolts are consumed in the Strait of Georgia by harbour seals. 	▸ Harbour seal abundance has increased 7X in the Salish Sea since receiving protection under the Marine Mammal Protection Act of 1972. SSMSP analyses suggest this harbour seal abundance trend is negatively related to changes in productivity or marine survival of Chinook, Coho and steelhead. ▸ Harbour seals appear to target Coho, Chinook and Sockeye smolts in the spring, while largely ignoring juvenile Chum and Pink smolts — but primarily take adult Pink and Chum in the fall. For smolts, this may be due to the comparatively larger size at outmigration. ▸ Seal predation on smolts in estuaries occurs primarily at dusk. Only a small portion of the seal population specialises in feeding on smolts exiting rivers and entering saltwater. In the seal "beanie" experiment, only a portion (~18%) of the seals appeared to target the releases of hatchery Coho at the mouth of the Big Qualicum and took about 6% of the release, while ignoring a subsequent release of smaller Chinook smolts. ▸ While juvenile salmon are a minor component of the overall seal diet (<5% juvenile salmon and ~2% juvenile Chinook in the spring diet), the high abundance of seals and their energetic demands can still result in a significant total impact. Results to date suggest that seals may be taking about 40% juvenile Coho and Chinook in the Strait of Georgia, but there is significant year to year and spatial variability. Additionally, most sampling focused on estuary environments, where those salmon species may be more commonly taken than in nearshore sites not associated with estuaries.

Strategic Salmon Health Initiative (PSF, DFO Science, and Genome BC)	
This is the largest study of pathogens in BC salmon (wild, hatchery-reared, and aquaculture) and applied new genomic tools to study viruses, bacteria, fungi and protists. The study addressed whether pathogens/disease is contributing to the reduced productivity of juvenile salmon in the Salish Sea and return migrants in the Fraser River, and investigated the potential interaction of aquaculture salmon with wild/hatchery salmon in BC's coastal waters. 	▸ We developed and applied new technologies to the surveillance of pathogens in BC salmon. We identified 15 previously uncharacterized viruses, and conducted surveillance on 60 infectious agents known to infect salmon globally (including 9 newly discovered). Fifty pathogens were confirmed in BC salmon. ▸ Predation studies with bull trout (Chilko Lake) and Rhinoceros Auklets (coastal BC) demonstrate that predators disproportionately feed on salmon infected with pathogens. ▸ This study was the first to demonstrate the presence of Piscine orthoreovirus (PRV) and associated diseases in BC's aquaculture salmon (Atlantic and Chinook salmon). Modeling shows that PRV infection in wild Chinook salmon is associated with farm exposure and negatively correlated with ocean survival. ▸ Models based on almost a decade of juvenile surveillance depict ocean temperature as the most important driver of infection risk to BC salmon. Models have also identified over a dozen pathogens associated with condition and/or year-class strength for Chinook, Sockeye and Coho salmon. ▸ Our analyses tested 31,000 fish; we did not detect any "Reportable pathogens" not known previously to exist in BC (IHN known previously). ▸ During this research, genomic tools were developed to recognize specific disease and stress response states, and may assist in hatchery production and understanding of cumulative effects in Nature.

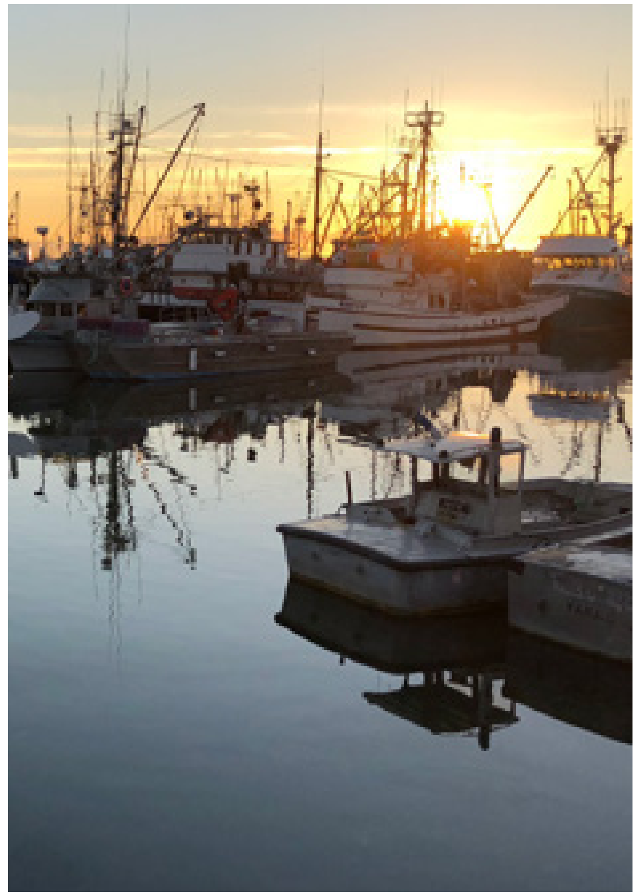
Progress with respect to our key Canadian objectives is as follows:

OBJECTIVE #1: Re-build production of wild Pacific Salmon and steelhead through a program that is ecosystem based, considers hatchery effectiveness and engages communities.

One of the greatest achievements from the SSMSSP has been the development of an integrated and broad community of researchers, across disciplines and borders. The SSMSP has facilitated a high level of integration and collaboration between researchers, in government or academic groups, both in Canada and internationally through its program funding, annual workshops and working groups.

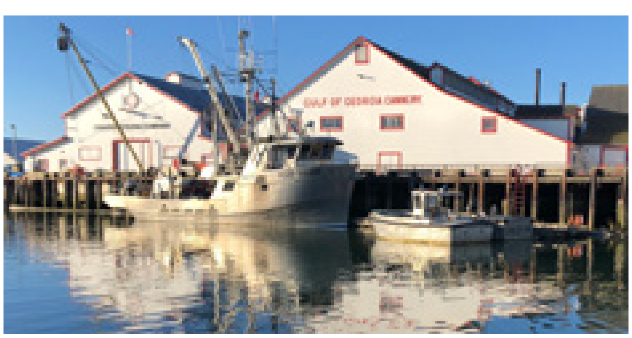
While we continue to see poor survival from local hatchery programs, PSF has undertaken a review of hatchery effectiveness. In recent years, there have been huge advances in our ability to study salmon in the hatchery environment using DNA-based tools (Parental-based tagging) and genomics (EPIC Coho study[5] and Strategic Salmon Health Initiative). These advances enable future studies that could improve the survival of hatchery-reared salmon to provide more sustainable fisheries, supplement production of wild Pacific Salmon and assess interactions between hatchery and wild salmon.

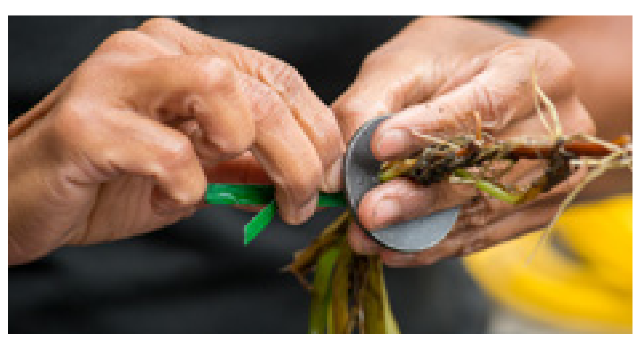
Most notably over the duration of the SSMSP it is apparent that an "ecosystem-based" model of production for Chinook and Coho Salmon is the appropriate level of consideration. While there is certainly a significant mortality during the early months at sea, it is not sufficient to account for the variation in survival rates observed between years or populations. Our studies suggest that mortality occurring through a sequence of life stanzas or periods, some with greater impacts than others, is the appropriate interpretation. Essentially it is a complex full-life history or chain of events that ultimately determines the production of Chinook and Coho Salmon observed from a year — with the weakest link in the chain having the greatest effect. Some of these effects can be mitigated locally but others, like climate change, are more global and will require us to compensate for these long-term changes.



OBJECTIVE #2: Promote sustainable fisheries and increase their value to local BC communities.

The accomplishments under Objective 1 also pertain to Objective 2. Additionally, media coverage of the project — particularly related to the Citizen Science Oceanography program and the Strategic Salmon Health Initiative — raised public awareness and appreciation of wild Pacific Salmon in communities across BC And, since inception, the project has seen a growing roster of charitable fishing derbies to support the Project. These derbies have provided opportunities to educate people at the local level about the importance of sustainable fisheries and how we can support them. However, direct evidence of value to communities will require the implementation of management actions and the accrual of biological benefits to salmon production over time.





5. Enhancing Production in Coho: Culture, Community, Catch (see: www.sfu.ca/epic4/)

OBJECTIVE #3: **Provide a foundation for long-term monitoring of the Salish Sea and salmon health.**

The Strait of Georgia Data Centre, (**www.sogdatacentre.ca**), a partnership between Sitka Foundation, University of BC and PSF provides a vital repository of historical data to inform monitoring and restoration of the Strait. The Citizen Science Oceanography Program has allowed us to collect an unprecedented amount of annual oceanographic data at spatial and temporal scales not previously attainable and at a fraction of the cost of traditional research vessels. The program has also provided the framework for ongoing monitoring of the Strait's ever-changing environmental conditions and its impacts on salmon, particularly when supplemented with innovative applications of remote sensing and ocean moorings through collaborations with BC Ferries, Ocean Networks Canada and others.

The SSMSP has resulted in the expansion of many monitoring programs and creation of new ones, including:

- Continued DFO focus on seal and sea lion diet analysis throughout the Canadian Salish Sea;
- An augmented DFO zooplankton sampling program (a critical development to assess annual variation);
- Extension of oceanographic and salmon studies into Johnstone Strait through collaboration with the Tula Foundation on Quadra Island; and
- A significant expansion of nearshore habitat restoration, monitoring and marine debris removal through Coast Restoration Fund support to Seachange, Project Watershed (Comox) and Raincoast Conservation in the Fraser River estuary.

The SSMSP project (SSHI, Strategic Salmon Health Initiative[7]) has enormously improved our understanding of pathogens in BC salmon (wild, hatchery and aquaculture), and supported the Genome Canada project 'EPIC4' studying natural genetic variation in Coho Salmon and the effects of hatcheries on Coho. Both of these research projects are completing the research phase and progressing to applications, including tools to monitor the health and condition of our salmon. For example, researchers in the SSHI have created a genomic 'fit chip' that can assess the health of salmon, and they propose to develop a similar capacity to assess cumulative effects on individual salmon.

As PSF completes the SSMSP and synthesis of results, we are also considering how to address key gaps and promote continued research. This will allow will also allow for collaboration with government and stakeholders for implementation of effective management actions and continued collaboration between U.S. and Canada on shared issues and science needs.

7. The Strategic Salmon Health Initiative will be completed in March 2021

CONCLUDING REMARKS

The Salish Sea Marine Survival Project (SSMSP) was designed as an intensive, short-term project of the Salish Sea ecosystem to study the major components of the salmon ecosystem simultaneously; evaluate the marine survival of Chinook, Coho and steelhead; and identify the primary determinants of survival/production of these species. As our findings accumulate, we have begun to develop a picture of what is happening to our juvenile salmon and steelhead as they traverse the Salish Sea marine environment. The details of many of the Canadian SSMSP studies and methods were summarized in the previous chapters; here we begin a synthesis of our results.

The journey for salmon and steelhead begins and ends in rivers but they spend the majority of their lives in the ocean. Consequently, the determinants of abundance may occur in freshwater, estuaries and the ocean; and likely some portion within each. In this life cycle diagram, the abundance of salmon that returns from the ocean began years before (in the brood or spawning year for the parents) and varies with the number of spawning adults and survival of the eggs to emerging juveniles (Figure 1). Juvenile use of freshwater streams varies by species from a few months to a few years and survival is habitat (flows, food availability and shelter) and predator dependent. As juveniles prepare to emigrate to the sea, they transform into 'smolts' (juveniles that are physiologically able to enter salt/marine waters) and begin a downstream migration to the estuary and ocean. Smolts use estuaries as transition habitats but to varying degrees, again depending on the species, and gradually move into nearshore waters. This transition to fully marine waters (identified in the diagram by the red, dashed circle and red arrow) is hypothesized to be the ***'critical period'*** in the determination of salmon abundance from each brood year, and occurs over several weeks. The juveniles that survive continue migration through marine waters until they begin to mature and return to their freshwater stream of origin. As these adults return, they now face fisheries and other predators, and physiologically must revert back to freshwater environments. Ultimately their life-cycle ends when adults return to their 'home' streams to spawn and die (Pacific Salmon only spawn once, but steelhead can spawn multiple times). The complex and highly-migratory life of Pacific Salmon makes resolving the primary determinants of their annual abundance very difficult, particularly when humans have extensively altered every habitat that they depend upon. But evidence to date suggests that the 'critical period' is a primary determinant of annual variation in adult returns, and for local populations of Chinook, Coho and steelhead, that the Salish Sea has the greatest effect. However, this critical period reflects the current conditions of habitats, competition and predation in both freshwater and marine environments, but its magnitude may not have been so pronounced under more pristine conditions or if we could mitigate impacts.

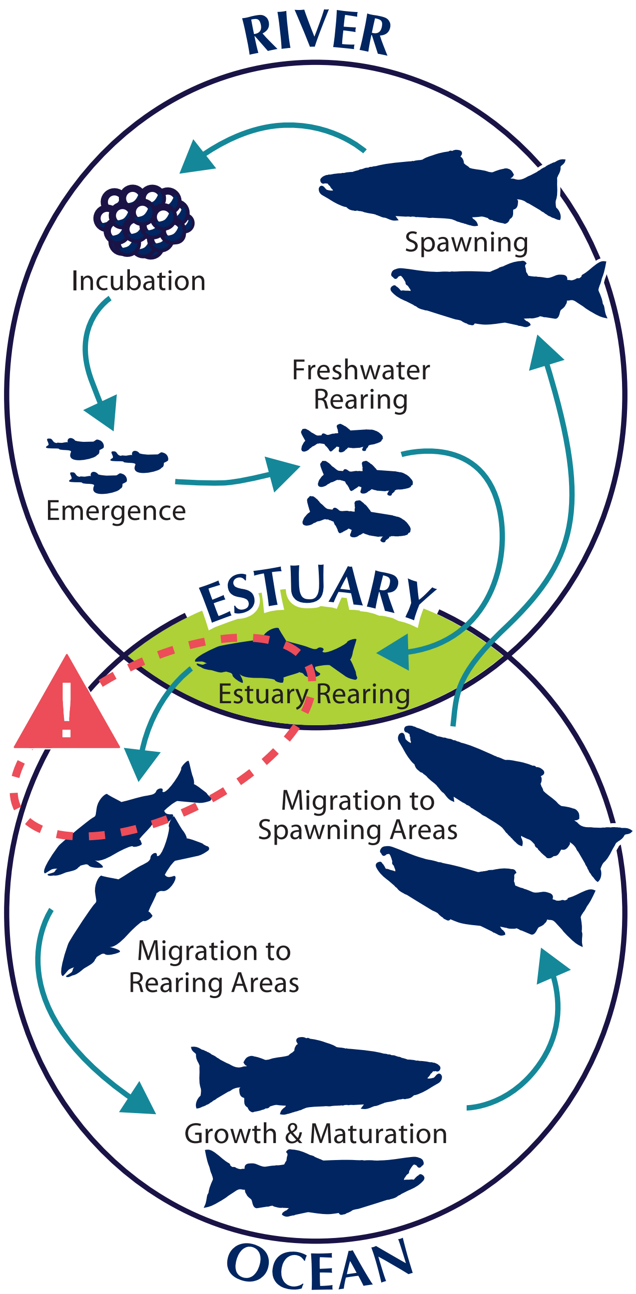


Figure 1. Generic life cycle diagram for Pacific Salmon. The danger icon shows the period that has been hypothesized to be the "critical period".

Our measures of marine survival for Chinook, Coho, and steelhead are determined by the number of smolts entering the sea divided by the subsequent number of adults that return to coastal waters in fisheries or that avoid fisheries to return to hatcheries or natural streams. The marine survival of tagged hatchery-produced Chinook, Coho and steelhead for over 40 years in the Salish Sea have been invaluable in monitoring survival and measures of variability between populations, but as presented below the variation between populations, species and years is substantial (Figure 2).

While the trends in marine survival declines are apparent, the variability between populations within any year is equally important to our analyses of determinants. Our review of historical data on survival of multiple populations of Chinook[1] Salmon in the Salish Sea indicated that Chinook survival rates varied significantly within the Sea and populations from nearby rivers tended to show similar patterns of survival. However, Coho[2] Salmon demonstrated similar survival patterns within a year throughout the Sea, regardless of river of origin. These observations are consistent with our sampling of oceanographic conditions within the Sea, and with the distribution patterns of juvenile Chinook and Coho Salmon determined from trawl catches and DNA analyses to identify populations of origin. Importantly, Chinook Salmon revealed consistent patterns of distribution between years with specific populations consistently rearing in different areas of the Salish Sea. Coho Salmon were more widely distributed and mixed. Within the Canadian Salish Sea, we are unable to assess steelhead patterns of survival due to inadequate data but their abundance has been declining. Further, for both Chinook and Coho Salmon, the patterns of survival in the Salish Sea differed from the patterns in outer coastal populations but were not consistently lower than those other populations.

In considering the primary determinants of salmon production, we have repeatedly returned to the concept of a 'critical period' as hypothesized at the beginning of the SSMSP, and whether one critical period is sufficient to explain variations between years and trends over time. Certainly within the duration of the SSMSP, we saw clear evidence of mortalities throughout the salmon life cycle:

- Extensive mortality of Fall Chinook Salmon juveniles within the Cowichan River associated with extreme low flows during the spring of 2015 and 2016 (higher survival during normal flows in 2017);
- Effects of degraded/lost habitats in estuaries;[3]
- Survival of all sizes classes tagged in the nearshore and subsequently returning to the Cowichan River but at differing rates for hatchery and wild fish; and
- Unprecedented environmental conditions in the North Pacific Ocean that would affect the maturing portions of the Pacific Salmon at sea.

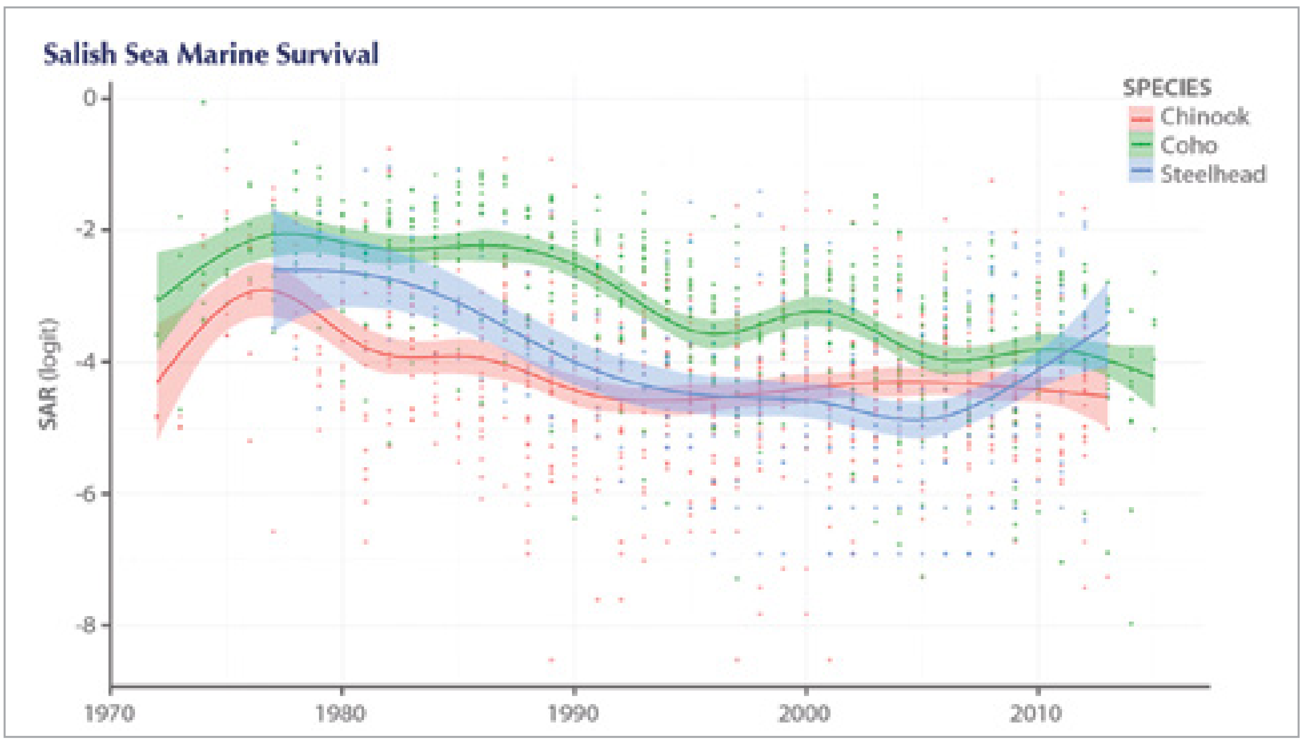


Figure 2. Plot of marine survival estimates for hatchery-reared Chinook, Coho, and steelhead in the Salish Sea since 1972 Ocean Entry Year (OEY), presented as individual estimates by species, location and year (preliminary analysis by Dr. Kathryn Sobocinski (Western Washington University, Bellingham, WA).

1. Ruff, C. P. et al. 2017. Fisheries Oceanography, 2017: 1-13.
2. Zimmerman, M.S. et al. 2015 Marine and Coastal Fisheries, 7: 116-134.
3. C.D. Levings. 2016. Ecology of Salmonids in Estuaries around the World. UBC Press, Toronto, Ont. (OL638.S2L49)

In support of the 'critical period' during early marine life, are:

- Coherence of survival patterns across multiple populations when in a common environment;
- Demonstrated targeted predation by seals and birds during this transition stage;
- Greater survival of the faster growing individuals; and
- Survival of tagged larger Chinook (in September/October) was 2.25 times greater than survival of smaller Chinook tagged in May.

When all our results to date are considered, a more comprehensive interpretation of Chinook and Coho production at a population level may be a chain of events and each link in the chain may vary in strength between years. The effect of a following link may be positive (compensatory) or negative (depensatory) but only within bounds determined by the net effect of the previous links. Essentially all bottom-up and top-down factors identified in the Introduction had some effect.

Chinook and Coho that survive to the early marine phase grow very rapidly during the first months, show behaviours that enhance energy consumption and display variation in migration patterns between populations. Variation in survival between individuals within a population provides the opportunity for adaptation to changing environmental conditions and sustaining local populations. The 'critical' aspect of the early marine phase for individuals may be to achieve a growth threshold/condition in their first summer at sea in order to survive the subsequent fall/winter conditions.

Based on our observations, what management actions may be taken to improve production of Chinook and Coho Salmon? A wide variety of actions could improve production but given the diversity of factors that act sequentially through the salmon life cycle, many of the actions would also have to be taken simultaneously. Restoration projects should therefore be broad-based, coordinated and monitored in order to assess limiting factors and track net gains in restoration. These actions may include:

- Protection of environmental flows in freshwater systems (under BC Water Sustainability Act, 2014);
- Estuary restoration and management of log-booms;
- Management of salmon predators during the vulnerable early migration period;
- Nearshore habitat restoration, particularly for marine grasses and kelps;
- Forage fish restoration and habitat protection/restoration;
- Artificial enhancement projects to supplement natural production and diversity, assuming we can achieve a net gain in production and population diversity; and
- Harvest management impacts appropriate for the productivity rate in naturally spawning populations.

However, under the 'critical period' hypothesis, much of the variation in salmon production will be driven by annual variation in weather and resulting biological oceanographic conditions in the Salish Sea. The actions above may ameliorate (reduce) the magnitude of variation but are unlikely to compensate for these large scale effects. In which case, the ability to predict consequences (by understanding the ecological interactions) and to take necessary management responses is a required outcome of our research. To integrate multiple environmental changes within the Salish Sea, a continuing study within the SSMSP is the development and testing of two ecosystem-based computer models by the University of BC (Dr. V. Christensen) and the National Oceanographic and Atmospheric Administration (Dr. C. Harvey). These independent models are being developed to test our understanding of mechanisms driving this salmon ecosystem. Once completed, these tools will enable researchers to go back in time to assess the causes of changes in production and to provide forward projections (forecasts) of how current environmental conditions may change and affect salmon production. Such models are the only means to objectively test our understanding of the Salish Sea, effects on salmon production and future expectations.

NEXT STEPS FOLLOWING FROM THE SALISH SEA MARINE SURVIVAL PROJECT?

While researchers continue to collect tag returns and complete laboratory analyses for the SSMSP, the Pacific Salmon Foundation has determined a small set of projects that merit continued support to protect the Salish Sea and local salmon populations.

1. Strait of Georgia Data Centre sogdatacentre.ca (in collaboration with UBC and the Sitka Foundation)

The Strait of Georgia Data Centre provides a vital repository and archive of current knowledge based on many past studies and will ultimately house all the results from the SSMSP. Having a central hub to store data from numerous government, academic and not-for-profit organizations is an important benefit and provides a central deposit for environmental and ecological data for the Salish Sea.

2. Nearshore and Estuary Habitat Restoration

SSMSP has highlighted the importance of estuaries and nearshore habitats for the early marine life of juvenile salmon, identified the widespread loss of eelgrass beds associated with coastal development since the 1930s, supported research and restoration of vital kelp and eelgrass habitats and has partnered with the Stewardship Centre for BC for their Green Shores program. Green Shores is a program to reduce hardening of marine shorelines and restore beach function to promote forage fish reproduction while reducing shoreline erosion. Support for three programs will continue:

- Dr. Maycira Costa (UVic) and colleagues will use satellite remote sensing to determine past and current kelp distributions, and assess how distributions varied over time in response to environmental and anthropogenic factors. Identification of resilient beds of kelp is the groundwork needed to identify areas of protection for future responses to climate change;
- Dr. Sherryl Bisgrove (SFU) and colleagues will carry out studies of thermal tolerance of kelp within the Salish Sea, and cultivation of varieties of kelp that may be important for restoration under climate change. The SFU team will create a biodiversity bank for marine plants allowing for the preservation of varieties which may mitigate the effects of climate change within the Salish Sea; and
- PSF will undertake a much-needed review of U.S. and worldwide programs in estuary restoration amidst climate change. There has been extensive estuary restoration, shoreline modification and contaminant research in the Salish Sea that we can draw upon.

3. Chinook and Coho "Bottlenecks" to Production (BC Salmon Restoration and Innovation Fund)

The application of PIT (Passive Integrated Transponder) tags and installation of in-river antennae greatly enhanced our ability to study in-river and marine survival of hatchery and wild Chinook Salmon. Working with the BC Conservation Foundation, PSF will expand on this study and implement PIT arrays in a number of additional river systems to provide information on survival bottlenecks (limitations) for Coho, Chinook and steelhead in both freshwater and early marine environments.

4. PSF Citizen Science Programs

Within the SSMSP, the Citizen Science Oceanography Program enabled the collection of an unprecedented amount of annual oceanographic data at spatial and temporal scales not previously attainable and at a fraction of the cost of traditional research vessels. The program has also provided the framework for ongoing monitoring of the Strait's ever-changing environmental conditions and its impacts on salmon, particularly when supplemented with innovative applications of remote sensing and ocean moorings through collaborations with BC Ferries, Ocean Networks Canada and others.

Other PSF supported citizen science programs will include:

- **Adult Pacific Salmon Diet Project:** The SSMSP has brought into focus the lack of data in the winter, a period that may be critically important for juvenile Chinook and Coho survival. This citizen science program, led by University of Victoria researchers, will gather long-term data on diets, (e.g., forage fish availability over space and time), and subsequent relationships with salmon survival.
- **Forage Fish Monitoring:** Supporting the work by the Mount Arrowsmith Biosphere Region Research Institute and the World Wildlife Fund, this project will enhance mapping of beach and nearshore spawning areas for forage fish such as Pacific Sand Lance and Surf Smelt. These species are two examples of forage fish that are critical sources of prey for roughly 45 species in the Strait of Georgia, including wild salmon.

5. Assessment of Hatchery Effectiveness (a BC Salmon Restoration and Innovation Fund project)

Results to date from the SSMSP highlight the continued poor survival from Strait of Georgia hatchery programs. PIT tag results for Chinook Salmon in the Cowichan River estimate that survival of hatchery fish from the Cowichan hatchery were only 37% of wild fish. Following from these studies, PSF is carrying out an independent assessment of hatchery programs within BC. The program is in collaboration with DFO's Salmonid Enhancement Program, the Provincial government and community organizations. PSF will also engage an expert panel from other jurisdictions to review our work and gain from the experience of others. Our expectation is to complete the analyses and reviews by fall 2021.

6. Education and Communication related to Salmon Conservation

Finally, PSF will expand work in education and communication related to salmon conservation. Many lessons are being learned from the numerous SSMSP projects, including information on new technologies and novel methodologies. Local community groups involved in restoration activities often comment on the lack of public education. PSF will implement a multi-faceted approach to broaden communication and education, utilizing public lectures to local communities, Science and Restoration Forums, dissemination of information online; targeted video production and the development of education modules. A PSF outreach project will assist in maintaining a BC focus on Pacific Salmon and stimulate an on-going dialogue with academia, local communities, local governments, industry, First Nations and provincial and federal governments.

▸ **Through the SSMSP, PSF has built a network of people and agencies around the Salish Sea; we now hope to sustain these interactions to protect and restore the Canadian Salish Sea for future generations.**

ACKNOWLEDGEMENTS

Thank you to our SSMSP community! Below are the names of Canadian SSMSP scientists and technicians whose work we are summarizing in this document. Names are provided with affiliations relevant to the time period of SSMSP.

Citizen Science Programs: Citizen Scientists (Ed Oldfield, John Sinclair, Evan Hogarth, Andre Alarie, John Field, Michael Jackson, John Dafoe, Bill Fraser, Lance Stewardson (Mainstream), Brian Kingzett (Deep Bay Field Station), Barry Peters (DFO-ret), Ted Newell, Warren Johnny, Erica Blake (DFO), Susan Servos-Sept, Dave Ewart (SEP ret), Nicole and Ryan Frederickson, Billy McMillan, Jim Rossi, Fred and Debbie King, Lee-Ann Ennis-Hodges, Chris Clarke, Mike Dilts, Roger Elliot, Brian Dearden, Ryan McQuillan, Kevin Swoboda), Mike Dempsey (DFO-IOS), Eddy Carmack (DFO-IOS), Jane Eert (DFO-IOS), Svein Vagle (DFO-IOS), Ryan Flagg (ONC), Marlene Jeffries (ONC), Benoit Pirenne (ONC), Jessica Stigant (ONC), Maia Hoeberechts (ONC), Adrian Round (ONC), Tanner Owca (ONC), Stefanie Mellon (ONC), Moira Galbraith (DFO-IOS), Kelly Young (DFO-IOS), Linda White (DFO-IOS), Colin Novak (PSF), Svetlana Esenkulova (PSF), Shapna Mazumder (UVic), Mary Steele (DFO-IOS), Mark Belton (DFO-IOS), Tamara Russell (DFO-IOS), Sarah Ann Quesnel (DFO-IOS), Rich Pawlowicz and students (UBC), Avid Anglers BC, Will Duguid & colleagues (UVic), Haley Tomlin (VIU), Alanna Vivani (VIU), Graham Sakaki (VIU), Jaclyn Barrs (WWF) and many others.

Oceanographic Studies: Sophia Johannessen (DFO-IOS), Richard Thomson (DFO-IOS), Robie Macdonald Emeritus, DFO-IOS),Ken Denman (ONC), Louis Hobson (Emeritus, UVic), Stephanie King (Sea This Consulting), Jim Gower (DFO-IOS), Terence Learmonth (Sea This Consulting), Svein Vagle (DFO-IOS), Helen Gurney-Smith (VIU), Eric Peterson (Tula Foundation), Wiley Evans (Hakai), Alex Hare (Hakai), Jennifer Boldt (DFO-PBS), Chrys Neville (DFO-PBS), Mary Thiess (DFO-PBS), Mike Dempsey (DFO-IOS), Eddy Carmack (DFO-IOS), Jane Eert (DFO-IOS), Sarah Zimmermann (DFO-IOS), Glenn Cooper (DFO-IOS), Charles Hannah (DFO-IOS), Maycira Costa (UVic), Tyson Carswell (UVic), Ocean Networks Canada staff.

Remote Sensing Studies: Maycira Costa (UVic), Akash Sastri (ONC), Justin Dell Beluz (UVic), Tyson Carswell (UVic), Andrea Hilborn (UVic), Sarah Schroeder (UVic).

Zooplankton Studies: Ian Perry (DFO), Karyn Suchy (UVic/PSF), Evgeny Pakhomov (IOF-UBC), John Dower (UVic), Moira Galbraith (DFO-IOS), Brian Hunt (IOF-UBC), Kelly Young (DFO-IOS), Nina Nemcek (DFO-IOS).

Freshwater Studies: BCCF (Kevin Pellet, James Craig, Craig Wightman, Shawn Stenhouse, Jeramy Damborg, Jamieson Atkinson), Mel Sheng (DFO-PBS), Steve Baillie (DFO-PBS), Don Elliott (Cowichan Tribes), Tim Kulchyski (Cowichan Tribes), Cheri Ayers (Cowichan Tribes), Wayne Paige Jr. (Cowichan Tribes), Wayne Paige Sr. (Cowichan Tribes), Dr. J. Taylor, Dave Key (Key Mill Construction Ltd.), Cowichan Hatchery staff, and many others.

PIT Tag Studies: Kevin Pellet (BCCF/DFO), BCCF staff (Kevin Pellet, James Craig, Craig Wightman, Shawn Stenhouse, Jeramy Damborg, Jamieson Atkinson), Will Duguid (UVic), Avid Anglers, Cowichan Tribes members.

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Microtrolling: Will Duguid (UVic), Kevin Pellett (BCCF/DFO), Jeramy Damborg (BCCF), Jamieson Atkinson (BCCF) and the Avid Anglers.

Herring and Forage Fish Studies: Jennifer Boldt (DFO-PBS), Matt Thompson (DFO-PBS), Carol Cooper (Zotec Services), Doug Henderson (Skipper and Fisher Contractor), Charles Fort (DFO), Marc Trudel (DFO-PBS), Emma Pascoe (UVic), Stephane Gauthier (DFO-IOS), Kyle Garver (DFO-PBS), John Dower (UVic), Will Duguid (UVic), Francis Juanes (UVic) and many others.

Juvenile Salmon Studies: Richard Beamish (DFO-ret), Marc Trudel (DFO-PBS), Chrys Neville (DFO-PBS), Carol Cooper (DFO-PBS), Svetlana Esenkulova (PSF), Cedar Chittenden, Dave Preikshot (Madrone Environmental), Lana Fitzpatrick (DFO-PBS), August Jones (PSF), Will Duguid (UVic), Kevin Pellett (BCCF/DFO), Francis Juanes (UVic), Rana El-Sabaawi (UVic), Azit Mazumder (UVic), Ian Forster (West Van. Lab.), Strahan Tucker (DFO-PBS), Stewart Johnson (DFO-PBS), Oline Luinenberg (PSF), Colin Novak (PSF), Svetlana Esenkulova (PSF), Elan Downey (CAHS), Brian Hunt (UBC), David Costalago (UBC), Jacob Weil (UVic), Jim Irvine (DFO-PBS), Dennis Woloshuk and the crews of the Ocean Venture, the Ricker, and all other vessels used.

Hatchery Programs: Mel Sheng (SEP-DFO), Dave Willis (SEP- DFO), Ryan Galbraith (SEP- DFO), Matt Foy (SEP- DFO), Esther Guimond (SEP-DFO), Jason Mahoney (SEP-DFO), Ben Nelson (UBC).

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Modeling Studies: Villy Christensen (IOF, UBC), Carl Walters (IOF, UBC), Greig Oldford (IOF, UBC), Vijay Kumar (IOF, UBC), Susan Allen (UBC), Elise Olson (UBC).

Strait of Georgia Data Centre: Terry Curran (PSF), Ben Skinner (PSF) and many others.

Video and Photography: Mitch Miller (Michael Miller Media), Ryan Miller (Ryan Miller Photography).

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