NOVEL ASSESSMENT TECHNIQUES, MONITORING RECOMMENDATIONS, AND NEW TOOLS FOR ECOSYSTEM-BASED MANAGEMENT RESULTING FROM THE

SALISH SEA
MARINE SURVIVAL PROJECT

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LONG LIVE THE KINGS

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INTRODUCTION

Changes in the Salish Sea marine environment may be significantly affecting the survival of salmon and steelhead. The smolt-to-adult return (SAR) or marine survival, for many stocks of Chinook and Coho salmon has declined, in some cases to less than one tenth of the levels experienced in the 1970's and 1980's (Zimmerman et al. 2015; Ruff et al. 2017). Steelhead populations have also declined significantly, with evidence that juvenile mortality during their migration through the Salish Sea is playing a critical role (Kendall et al. 2017). When comparing Salish Sea population survival and abundance trends to those outside the region, there is evidence that the effect on survival is occurring within the Salish Sea (Zimmerman et al. 2015; Ruff et al. 2017; Kendall et al. 2017). To identify the most significant factors affecting the survival of outmigrating salmonids through the Salish Sea, Long Live the Kings and the Pacific Salmon Foundation developed a joint Washington State (U.S.) and British Columbia (CA) research effort known as the Salish Sea Marine Survival Project (SSMSP) (Pearsall and Schmidt et al. 2021).

The SSMSP leverages human and financial resources from the United States and Canada to determine the primary factors affecting the survival of juvenile salmon and steelhead in the Salish Sea from an ecosystem context. The project undertook a comprehensive study of the physical, chemical, and biological factors impacting their survival. Over 60 organizations, representing diverse philosophies and encompassing most of the region's fisheries and marine research and management complex, worked together on this massive transboundary effort. The SSMSP presented an opportunity to rethink how we assess our Salish Sea ecosystem from a salmonid perspective and try novel techniques to address critical information gaps. In doing so, the results and new tools developed from this project provide guidance for improving our region's ecosystem monitoring framework and ecosystem-based management tools.

1. Marine survival, also called smolt-to-adult survival, is the survival rate from when juvenile salmon migrate downstream to the marine environment to when they become adults and are captured in fisheries or return to rivers and hatcheries to spawn.

STRUCTURE

This technical report illustrates the novel assessment approaches developed through the project, then describes the project's monitoring recommendations, and provides information about new potential tools for ecosystem-based management. The report follows the salmonid and ecosystem assessment structure established during the project:

A. **Fish Survival, Behavior, and Condition**

B. **Bottom-Up Processes** — weather, water conditions, and productivity that determine the food for salmonids and therefore result in the variation in size and growth rate. Also included are factors affecting the relationship between salmonids and their prey, such as competition.

C. **Top-Down Processes** — ecological processes that are not associated with food supply. 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 and contaminants).

NOVEL ASSESSMENT TECHNIQUES

Several assessment techniques were developed or refined over the course of the SSMSP. These new and novel techniques could substantially improve how we assess salmon and their marine ecosystem. Below are brief descriptions.

A. Fish Survival, Behavior, and Condition

Microtrolling: an economical method to nonlethally sample and tag juvenile salmon at sea

To improve current fish sampling practices, Duguid and Juanes (2017) developed a new methodology called microtrolling. Microtrolling uses small vessels and modified recreational fishing gear to nonlethally capture, sample, and tag juvenile Chinook and Coho salmon. This methodology uses small fishing hooks to avoid penetrating the eye, gill, or other critical area of the fish and increase the likelihood of capturing smaller fish than previous hook and line sampling programs (Duguid and Juanes 2017). Microtrolling is economical, nonlethal, enables high-frequency sampling events at multiple depths, and its small-scale nature creates opportunities for stakeholder engagement in the research process (pers. comms. W. Duguid 2020). Microtrolling for other salmon species has not been tested, but microtrolling could be applied across tagging and sampling events.

Reciprocal transplant experiment to distinguish different effects on steelhead marine survival

Freshwater effects and effects from the local marine environment contribute to high mortality of outmigrating steelhead smolts in the Salish Sea (Moore and Berejikian 2017). Previous between-population comparisons of marine survival have been confounded because each population enters Puget Sound from a different location (pers. comm. M. Moore 2020). Moore and Berejikian (2017) conducted a reciprocal transplant experiment with steelhead smolts from two different rivers to separate the influences of freshwater effects from effects of local marine conditions on the survival of the two populations. Steelhead smolts from both rivers were tagged with acoustic telemetry transmitters and released back into their natal river or transported and released into the other river (Moore and Berejikian 2017). Results from this study have been vital in advancing further research on early marine mortality of steelhead.

B. Bottom-up Processes

Geoduck shells as a proxy to determine historical primary production patterns

Tracking long-term primary production trends in the Salish Sea has been challenging because of a lack of historical datasets to pull from. To overcome this challenge, Greene et al. (in review) conducted the first dendrochronological approach to evaluate long-term changes in primary production by measuring growth rings and stable isotopes in geoduck shells. Greene et al. (in review) discovered geoduck growth tracked primary productivity patterns and was strongly correlated with local sea surface temperature and the Pacific Decadal Oscillation (pers. comm. C. Greene 2020). Geoduck clams are long-lived (some live greater than 100 years), allowing researchers to use annual geoduck growth indices in the context of other relevant ecosystem indicators to retrospectively model chlorophyll-α concentrations (Greene et al. in review). This novel approach in examining long-term primary production patterns via natural markers creates the opportunity to draw inferences about environmental conditions since the 1950s.

Satellite and aerial imagery as tools to understand long-term trends and ecosystem changes

Three SSMSP studies used satellite imagery and one study used aerial photography to understand long-term trends and changes. Brandon Sackmann leveraged historic and current satellite imagery to characterize long-term trends in near-surface water quality at a high spatial resolution in Puget Sound to develop water quality indicators. Suchy et al. (2019) developed a methodology that uses MODIS Aqua satellite products and region-specific algorithms to examine the relationships between environmental drivers and satellite-derived chlorophyll-α in different subregions of the Strait of Georgia between 2003 and 2016. Satellite imagery for the 14-year timeframe enabled Suchy et al. (2019) to assess the long-term spatiotemporal variability of primary production. This methodology is cost-effective for observing phytoplankton at high sampling frequencies, informs long-term monitoring at various scales, and provides high-resolution satellite imagery that can be used to map at regional scales by applying imagery-processing techniques (pers. comms. M. Costa 2020).

Satellite and aerial photography can also tell us about changes to physical marine habitat. Schroeder et al. (2019) was the first study on the west coast of the United States to use remote sensing via satellite imagery to map bull kelp habitat changes over time (13 years) at a very high resolution. Remote sensing to assess habitat change is a valuable tool for long-term monitoring and mapping of ecosystem change at a local scale. The robust methodology they used allows for flexible mission planning and provides high spatial resolution and tonal detail (pers. comms. M. Costa 2020). Eelgrass provides valuable habitat for salmon, steelhead, and their prey yet little is known about eelgrass habitat extent and connectivity over time in the Salish Sea. Nahirnick et al. (2019) were the first researchers to use historical aerial photographs and unoccupied aerial system imagery to assess changes in eelgrass coverage and shape index over an 84-year timeframe within the Salish Sea. This methodology merged various technologies to map shoreline development, which is a leading factor in eelgrass fragmentation throughout the Salish Sea (Nahirnick et al. 2019).

C. Top-down Processes

Retrofitted PIT tag scanners on harbor seals to detect consumed PIT-tagged salmon smolts

Austen Thomas with the University of British Columbia's Marine Mammal Research Unit developed and applied new technologies to yield the first direct measure of predation events by harbor seals on salmon. Thomas and his colleagues passive integrated transponder (PIT) tagged a small portion of outmigrating juvenile Coho at Big Qualicum Hatchery and attached satellite-linked, head-mounted PIT tag scanners and data loggers to 20 harbor seals to record their locations, behaviors, movements, and predation on tagged salmon smolts (pers. comm. A. Thomas 2020). The head-mounted PIT tag scanner tracked head movement and acceleration patterns which pinpointed predation events in time and space. This novel technology produces salmon consumption rates as a direct measure of predation with increased confidence compared to other studies that have used scat data to reconstruct consumption estimates (pers. comm. A Thomas 2020).

DNA metabarcoding and hard part scat analysis of harbor seals to determine species and age of prey

The physical identification of fish hard parts in seal feces has been the primary methodology for determining what and how much harbor seals are eating. As an alternative to the traditional morphological prey identification, Thomas et al. (2017) utilized DNA metabarcoding with hard part scat analysis to determine the species and age of prey items in harbor seal diets. The merger of DNA metabarcoding and hard parts analysis enables estimation of proportional diet contributions of adult and juvenile salmon by harbor seals. These estimates are then combined with a bioenergetics model and seal population size to estimate the number of smolts and adult salmon of each species that are eaten by harbor seals, reducing the per sample cost of DNA diet analysis (Thomas et al. 2017, Nelson et al. in review). This methodology offers high taxonomic resolution and increasingly quantitative information about the proportions of species consumed by pinnipeds (Thomas et al. 2017).

Molecular diagnostic tool to detect Nanophyetus salmincola and treatment options

Hershberger et al. (2019) developed the first molecular diagnostic tool for detecting Nanophyetus salmincola (N. salmincola) in water, tissues, and other substrates. N. salmincola is a freshwater pathogen that can have adverse effects on outmigrating salmonids. High loads of this pathogen can be associated with microscopic lesions in kidney, gill, muscle, and heart tissue of a fish (Chen et al. 2018), and inflammation and fibrosis (Hershberger et al. 2019). The new benchtop tool is unique because, with just water samples, it can determine where and when fish are exposed to and infected with N. salmincola within watersheds to identify hotspots and refugia, and it can determine the seasonality of the parasite shedding from the first intermediate host (Hershberger et al. 2019). Hershberger et al. (2018) evaluated the ability of formalin, hydrogen peroxide, and seawater to kill N. salmincola cercariae and determined formalin is a good treatment option to reduce the impact of N. salmincola on salmonids reared at hatcheries.

Genomics to understand the role of infection and diseases in marine survival in salmonids

Kristi Miller's molecular genetics laboratory within Fisheries and Oceans Canada has been applying a series of novel molecular and ecological approaches to understand the role of infection and disease outbreaks in salmonid declines. The program she leads has developed an innovative suite of host biomarker tools to resolve the earliest stages of stress and disease development. One of the most impactful biomarker panels can identify a viral disease state from a non-destructive gill biopsy sample (Teffer and Miller 2019). This tool has led to the discovery of over a dozen uncharacterized viruses and viral strains in wild and hatchery-raised salmon in British Columbia (Nekouei et al. 2019). This research program has also developed a molecular tool that applies a series of curated biomarker panels to identify specific stressors and disease states, as well as signatures associated with poor survival (Mordecai et al. 2020). They are now employing this technology to explore the complex interactions between stress and disease, and to identify where along the coast salmon are most compromised (pers. comm. K. Miller 2020). Miller's laboratory continues to progress cutting edge research in genomics to further our understanding of the role infection and disease play in marine survival of salmon and steelhead.

Contaminant fingerprints and other chemical tracers to identify contaminant sources and pathways to juvenile salmonids

Downstream migrating juvenile salmonids are particularly sensitive to toxic contaminants that can make them more susceptible to disease and/or predation (O'Neill et al. 2015, Chen et al. 2018). The prevalence and intensity of contaminants in migrating juveniles informs potential risk of growth, metabolic function, and mortality issues. It also informs us about the ecological pathways and sources of contaminants so that corrective actions can be taken to reduce the contaminant threats. Sandra O'Neill and collaborators at Washington Department of Fish and Wildlife and the Washington Department of Ecology have developed novel approaches to assess contaminant exposure in migrating juvenile salmonids by examining contaminant fingerprints, in conjunction with stable isotopes (O'Neill et al. 2020a) and biofilms (O'Neill et al. 2020b, Hobbs et al. 2019). Researchers analyzed tissue samples to identify specific persistent organic pollutant (POP) fingerprints in downstream migrating salmonids. Complementary tracer data were also used to assess the location and source of contaminant exposure for these juveniles with multiple contaminant sources (O'Neill et al. 2020a). This research was the first to use contaminant fingerprints to elucidate information about contaminant sources and movement patterns of juvenile salmonids on a small-scale (<30 km), indicating the robustness of the technique at discriminating contaminant sources along a contaminant gradient (O'Neill et al. 2020a). Contaminant fingerprints in biofilm samples were also used to identify sources of POPs to steelhead smolts (O'Neill et al. 2020b, Hobbs et al. 2019).

FISH AND ECOSYSTEM MONITORING RECOMMENDATIONS

This section summarizes the monitoring recommendations that should be continued and/or expanded beyond the SSMSP. These recommendations are in addition to the other ecosystem and fish monitoring already ongoing throughout the Salish Sea. We begin with a comprehensive snapshot (Table 1) followed by brief descriptions as to why each recommendation is important. Ultimately, all the monitoring elements proposed provide critical data for adult salmon return forecast models, models for ecosystem management, and data that could be used for guiding salmon and steelhead recovery actions (NMFS 2007, NMFS 2019), Southern British Columbia Chinook recovery planning, West Coast Vancouver Island marine risk assessments and strategic planning under the Wild Salmon Policy, monitoring the Puget Sound Ecosystem Vital Signs and indicators, and guiding ecosystem recovery actions.

Table 1. *Fish and Ecosystem Monitoring Recommendations*

DESCRIPTION	ACTION	LOCATION	SEASON	DATA TO COLLECT	INFORMS
Fish Survival, Behavior, and Condition					
Marine survival time series	Maintain	Salish Sea	Annually	Chinook: Coded-wire tag (CWT) releases & recoveries or Parentage-based tagging (PBT) | Coho: CWT or PBT releases & recoveries or smolt outmigration, adult return | Steelhead: Adult return abundance, age compositions, smolt abundance, PBT	• Marine survival trends relative to ecosystem processes • Adult return abundance forecasting
Wild smolt trapping	Expand	Salish Sea	Winter Spring Summer	Fish counts, body mass, fork length, PBT for stock identification	• Freshwater & marine survival estimates • Migration patterns (e.g., outmigration timing) • Abundance & productivity estimates • Genetic introgression (annually)
Steelhead early marine mortality	Expand	Salish Sea	Spring	Body mass, fork length, smolt age composition, tissue sample for genetic analysis, temperature, depth, migration routes via receiver detections, travel time	• Spatially explicit smolt mortality locations & rates • Outmigrant behavior patterns • Links to ecosystem processes
Stage-specific mortality	Expand	Strait of Georgia Puget Sound (possibly)	Spring Summer	<u>Chinook and potentially Coho</u>: PIT tag data counts that provide information on location, origin, & species; Fit-Chip data which is a predictor of salmon condition	• Freshwater & marine survival estimates • Migration patterns, distribution, & residency • Adult return abundance forecasting • Evaluation of hatchery release experiments • Management decisions around smolt readiness • Fish condition in different environments in relation to disease and stress

DESCRIPTION	ACTION	LOCATION	SEASON	DATA TO COLLECT	INFORMS
Juvenile salmon & herring midwater sampling	Expand	Salish Sea	Summer	Species, stock (where practicable), body mass, fork length, sampling location, scales/otoliths, IGF-1, diet, CWT	• Size & growth trajectories during critical growth periods • Marine survival estimates • Diet data for periodic diagnostic analysis • Links to ecosystem processes, competition, & actions such as increased hatchery production
Bottom-Up Processes					
Citizen Science Program	Maintain	Strait of Georgia	Year-round	Water temperature, salinity, turbidity, conductivity, depth, dissolved oxygen, chlorophyll-α, nutrients, plankton	• High resolution spatiotemporal variations in oceanographic conditions, lower trophic levels, & harmful algal blooms • Relationships between the physical environment & the productivity of key species
ORCA Buoy Network	Maintain	Puget Sound	Year-round	Water temperature, salinity, density, pH, dissolved oxygen, nutrients, chlorophyll-α	
Zooplankton Sampling Program	Maintain	Puget Sound Strait of Georgia	Year-round	Latitude/longitude, station depth, target tow depth, taxa, biomass, winds, currents, weather, wire angle, length of tow time	• Regional abundance & biomass variations • Relationships between physical conditions, prey, forage fish & salmon growth & survival • Crab larval recruitment, jellyfish & herring larvae interactions, benthic invertebrates & zooplankton interactions, invasive species, contaminants, eDNA, etc.
Top-Down Processes					
Pinnipeds	Expand	Salish Sea	Spring Summer	Abundance, length, weight, sex, age; diet (DNA & hard parts) & sex from fecal sample	• Population size, distribution, & demographics • Fish consumption species, quantity, age class, & size
Contaminants	Expand	Salish Sea	Spring Summer	Fork length or size, weight, age, origin, & lipid content for each fish; chemical tracer data (POP & CEC concentrations, contaminant fingerprints, stable isotopes) via fish tissue samples	• Ongoing risks of contaminant exposure to fish growth, metabolic function, disease resistance, & survival • The introduction of contaminant monitoring in Strait of Georgia • CEC monitoring in Puget Sound • Contaminant source tracing

A. Fish Survival, Behavior, and Condition

Maintain marine survival time series for Chinook, Coho, steelhead and expand wild smolt trap monitoring

Chinook, Coho, and steelhead marine survival timeseries were created as part of the SSMSP to assess salmonid marine survival trends (Zimmerman et al. 2015; Ruff et al. 2016; Kendall et al. 2017) and relate them to ecosystem change (Sobocinski et al. 2020, Sobocinski et al. In Press 2021). These marine survival time series datasets for Chinook and Coho salmon and steelhead should be maintained, updated annually, and made broadly available. To maintain marine survival timeseries, smolt trap monitoring throughout the Salish Sea must be maintained and expanded to provide wild fish data. Monitoring via smolt traps informs freshwater and marine survival estimates, migration patterns, abundance and productivity estimates, annual genetics introgression, and the competition, predation, and reproductive fitness of hatchery and wild populations (pers. comm. J. Anderson 2020).

Monitor steelhead early marine mortality at index sites using acoustic telemetry

Acoustic tracking of juvenile steelhead smolts provides critical data on early marine mortality locations and rates, outmigrant behavior patterns, and on predator interactions (Moore et al. 2015, Berejikian et al. 2016). Further, this information can help researchers define specific mechanistic relationships between mortality and migration behavior, as well as the factors that affect both. The early marine mortality of at least three index populations, each representing a Puget Sound distinct population segment, should continue to be monitored. This is consistent with the recommendations put forth in the Puget Sound Steelhead Recovery Plan (NMFS 2019). The Nisqually, Skagit, and Skokomish wild steelhead populations currently have the longest time series. Time series data should be collected and maintained for other steelhead populations to expand monitoring throughout Puget Sound. However, there are currently no early marine mortality time series for Strait of Georgia populations.

Calculate segment-specific survival of salmon using PIT tag methodology

One of the greatest limitations to understanding juvenile salmonid mortality in the Salish Sea is tracking their behavior and movement once they leave freshwater. Pellet (in prep) developed a new PIT tagging methodology to estimate the survival of cohorts of Cowichan Chinook by early marine life stage. Leveraging a new microtrolling methodology (see Novel Assessment Techniques section), Pellet applied PIT tags to fish at multiple locations for six months following ocean entry (Pellet in prep). This method requires fewer tags than only applying in river as survival to return naturally increases at each marine segment. Early results are promising, illustrating high mortality soon after marine entry, and substantial winter mortality (Pellet in prep). This helps researchers narrow in on specific ecosystem processes affecting survival and allows for comparisons of return rates between wild and hatchery salmon to better inform management decisions. This segment-specific survival assessment piloted on the Cowichan River Chinook population should be expanded to other systems throughout the Salish Sea. Currently, several systems on the East Coast of Vancouver Island are being outfitted, as well as one system on the West Coast of Vancouver Island, to elucidate survival bottlenecks in several additional Chinook, Coho, and steelhead populations in British Columbia. Some Puget Sound Chinook populations should also be considered by subbasin (South, Central, North Puget Sound, and Hood Canal).

Sample juvenile salmonid and forage fish in midwater depths

Midwater sampling of juvenile salmon and key forage fish species should occur annually, at least once each summer. Sampling is already occurring consistently in the Strait of Georgia; however, in Puget Sound it has been sporadic. Sampling during this critical period for juvenile Chinook and Coho salmon provides us insight into early marine survival and growth rates (Duffy and Beauchamp 2011, Beamish et al. 2010a). Given the significant relationship between size of Chinook salmon in the first summer and overall marine survival, continued monitoring of summer size would inform adult return forecasting and salmon management and recovery (Duffy and Beauchamp 2011). These data also help researchers diagnose the ecosystem processes that influence early marine growth and survival.

Further, there has been limited focus on young-of-year herring in Puget Sound. Sampling juvenile herring and other important forage fish helps researchers better assess forage fish abundance in Salish Sea water and the physical drivers of abundance (Boldt et al. 2018). Given the weak link between adult spawning biomass and larval recruitment of herring, age class sampling data is crucial.

B. Bottom-up Processes

Continue the Strait of Georgia oceanographic sampling via citizen scientists

The Pacific Salmon Foundation, Fisheries and Oceans Canada, and Ocean Networks Canada initiated the Strait of Georgia Citizen Science program in 2015. The intent has been to leverage citizens with boats and time to help assess oceanographic conditions on spatial and temporal scales that had never been done before (Esenkulova et al. 2017). Citizen scientists collect data on phytoplankton, zooplankton, temperature, salinity, density, dissolved nutrients, fluorescence, oxygen, and turbidity (Esenkulova et al. 2017). Every two weeks from February to October, citizens sample for phytoplankton at about 80 sites along with nutrients and environmental data from about 30 sites throughout the Strait of Georgia (Esenkulova et al. 2017). The data collected by citizen scientists can be found at the Ocean Networks Canada (https://oceannetworks.ca/) and Strait of Georgia Data Centre (http://sogdatacentre.ca/) websites. This Citizen Science Program should be continued over the long term to provide data to assess the relationships between the physical environment and the productivity of key species.

Maintain the Puget Sound oceanographic monitoring via the ORCA buoy network

As part of the SSMSP, the University of Washington updated their Oceanic Remote Chemical Analyzer (ORCA) buoy network to document spatial and temporal variability in weather, phytoplankton biomass, and hydrographic features. The ORCA buoy network is an autonomous moored profiling system that provides real-time oceanic and atmospheric conditions (University of Washington 2009). Since 2000, the ORCA system has provided near-continual high-resolution water quality data from locations throughout Puget Sound (e.g., Hood Canal and Carr Inlet) which are aggregated and stored via the online NANOOS platform (University of Washington 2009). These data can be used to fill gaps in our knowledge about relationships between the physical environment and the productivity and vitality of salmon and other species higher up the food web. This network should continue to be maintained.

Continue zooplankton sampling in the Strait of Georgia and Puget Sound

Continuous and consistent zooplankton sampling needs to be maintained throughout the Salish Sea. Zooplankton are the cornerstone of the food web and the fundamental link between our physical environment and the fish, crustaceans, marine mammals, and other organisms we care so much about. Thus, zooplankton are a robust indicator of ecosystem health. Zooplankton sampling was expanded in the Strait of Georgia by the Department of Fisheries and Oceans in 2015 during the SSMSP. In Puget Sound, a collaborative sampling program was initiated in 2014 to fill this critical monitoring gap. The Puget Sound program includes 12 tribal, county, state, federal, academic, and non-profit entities sampling zooplankton up to every two weeks throughout Puget Sound's six subbasins (Keister et al. 2017). This year-round zooplankton sampling program provides subbasin-specific abundance, biomass, and community composition data which informs researchers on seasonal and interannual dynamics of the prey base for salmonids and forage fish, as well as crab larval recruitment (pers. comm. J. Keister 2020). Long-term sampling illustrates how physical changes are translating to a biological response (e.g., nutrient and climate impacts). Additionally, zooplankton sampling provides a platform for assessing invasive species, contaminant pathways and transport through the food web, jellyfish and herring larvae interactions, benthic invertebrates, and zooplankton interactions, eDNA sampling of the ecosystem, and marine plastics sampling (Keister et al. 2017).

C. Top-down Processes

Monitor harbor seal abundance and diet, and assess sea lions and harbor porpoise

Currently, researchers have fragmented data regarding pinniped abundance trends, distribution, demographics, foraging behavior, and fish consumption (e.g., the species, age, and size of fish) (pers. comm. S. Jeffries 2020). Pinnipeds are near the top of the trophic pyramid and given their increased abundance and presence in Puget Sound, they have the potential to significantly influence the abundance and size structure of their prey. Harbor seals are also generalists and tracking their prey composition can inform us about environmental changes. Aerial surveys of seal haul-outs and scat or fecal sampling should be performed annually for abundance and diet data. Demographic data should also be collected periodically. This data can then be used to estimate harbor seal population size, distribution (by haul-out and foraging hotspots), demographics, and fish consumption by species and age class. Finally, sea lion data is sparse as well as harbor porpoise data: both types of pinnipeds are increasing their presence and should be monitored more frequently.

Extend geographic coverage of existing juvenile salmonid contaminant monitoring and add monitoring for Chemicals of Emerging Concern (CECs), as well as broaden species assessed

Existing contaminant monitoring programs for juvenile salmonids should be maintained in Puget Sound, extended to include the Strait of Georgia, and the suite of contaminants assessed in all regions should be expanded to include CECs including pharmaceuticals (e.g., antibiotics, heart medications, antidepressants), personal care products (e.g., soaps, detergents, anti-bacterial agents), and industrial compounds of concern (e.g., perfluorinated compounds, plastics, surfactants). With support from LLTK, pilot contaminant exposure assessments have documented that legacy organic pollutants are a concern for juvenile Chinook salmon, and to a lesser extent steelhead in Puget Sound. Additionally, a recent pilot study of CECs in juvenile Chinook salmon measured CEC levels high enough to potentially impair salmon health, and possibly their marine survival, while rearing in some Puget Sound watersheds. Ongoing funding for monitoring legacy contaminants in juvenile Chinook salmon has been secured for Puget Sound, but not other species. However, funding for CEC monitoring in juvenile salmonids remains a high priority funding gap. Canada's Department of Fisheries and Oceans is currently assessing contaminant exposure in juvenile and adult Chinook salmon, although long-term funding has not been identified. Contaminant monitoring in juvenile salmonids provides information to evaluate the ongoing risks of contaminant exposure on their growth, metabolic function, disease resistance, and survival. Knowing which contaminants pose the greatest sublethal effects to juvenile salmonid survival and the watersheds and habitats within those watersheds that are most threatened is necessary information to remediate adverse contaminant effects and improve salmon recovery.

NEW TOOLS FOR ECOSYSTEM-BASED MANAGEMENT

It is inherently difficult to assess species interactions with their ecosystems. There are numerous pathways and connections between elements. Making things more problematic, the Salish Sea is highly dynamic and heavily influenced by freshwater input as well as the adjoining Pacific Ocean. Models for assessing relationships between ecosystem components have come a long way. Through the SSMSP, we have focused on supporting some comprehensive approaches that not only help us better understand the drivers of salmonid survival but provide promise for improving our region's movement toward ecosystem-based management.

A suite of ecosystem indicators was developed and refined for Puget Sound. These indices were compared to Chinook and Coho marine survival trends (Sobocinski et al. 2020, Sobocinski et al. In Press 2021) and steelhead early marine mortality (Moore et al. in review), to highlight suites of factors that may have more or less influence on salmon and steelhead survival. The results of this work can be used to high-grade specific indicators that should be maintained, which can then be used in salmon adult return forecast models to improve harvest management and in other assessment models to guide ecosystem recovery.

While previous models have been developed to evaluate short-term productivity patterns for the Salish Sea, so far there have primarily only been correlative studies to evaluate the relationship between long-term changes in the ecosystem and the productivity and survival of higher trophic level organisms, notably salmon (pers. comm. V. Christensen 2020). Two end-to-end ecosystem models are under development in Puget Sound and the Strait of Georgia that will allow evaluation of cumulative effects, including the array of top-down and bottom-up drivers considered within the SSMSP.

As described in Morzaria-Luna et al. (in prep), a team at LLTK, NOAA, and CSIRO-Australia have developed a deterministic, numerical biogeochemical and biophysical model of Puget Sound in the Atlantis framework (Fulton et al. 2011, Audzijonyte et al. 2019, see https://research.csiro.au/atlantis/). The model simulates the structure and function of the marine ecosystem in a three dimensional, spatially explicit manner, forced by models of physical oceanography (ROMS), nutrient loading, and time series of catch and salmon hatchery production. Code development at CSIRO Australia has facilitated over 30 Atlantis models globally (Weijerman et al. 2016, Olsen et al. 2018), including applications in the California Current just offshore of Puget Sound and the Salish Sea (Kaplan et al. 2017). Atlantis can be used to explore how bottom-up and top-down ecosystem processes affect the size, abundance, and distribution of species and stocks of concern. The model allows scientists and managers to test ecological hypotheses, identify primary gaps in our understanding of the marine ecosystem, assess the effects of climate change through various scenarios, and assess the biological and economic tradeoffs associated with alternative scenarios for recovery and management strategies (Morzaria-Luna et al. in prep). While this model was first developed to assess the factors affecting salmon marine survival, it is also being used to evaluate Southern Resident killer whale recovery actions, the ecological role of jellyfish, how contaminants move through the food web, and how climate change impacts the Puget Sound ecosystem.

Villy Christensen and his research team at the University of British Columbia developed a coupled hydrographic and biogeochemical model of the Salish Sea, and linked it to a spatial food web model to evaluate how the combination of changes in environmental productivity, food web structure, and human impacts have changed in the Salish Sea over recent decades. Like the Puget Sound Atlantis model, this ensemble will be used to evaluate how bottom-up and top-down processes have changed since 1979 and how that may be affecting salmon marine survival.

CONCLUSION

Long Live the Kings and the Pacific Salmon Foundation initiated the Salish Sea Marine Survival Project to address critical information gaps limiting the recovery of our region's salmon and steelhead. While we have learned a great deal about what drives salmonid growth and survival in the Salish Sea, our education is not complete. Ecosystems are complex and dynamic, and to continue to manage scarce resources like salmonids in this environment we must continue to collect data, evolve our strategies, and use this information to guide our actions.

Therefore, this research approach was designed at its outset to integrate with and improve upon our region's monitoring and adaptive management framework, with an eye toward effective ecosystem-based management for years to come. We hope the monitoring recommendations, techniques, and tools described in this document are adopted by those responsible for managing our precious salmon and steelhead, along with the Salish Sea they swim in.

For additional information on the SSMSP or to review any of the publications, please visit the project website: www.marinesurvivalproject.com.

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