Introduction to using environmental indicators to inform salmon management

Online workshop hosted by the Pacific Salmon Secretariat, Coho Technical Committee, and Committee on Scientific Cooperation
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A. Overall purpose of workshop

It is now well recognized that global climate change poses a key threat to Pacific salmon and their fisheries. The impacts of global climate change are already apparent and can be seen in the changing abundance and productivity of salmon across the North Pacific. All other factors driving salmon trends are enmeshed within the physical, economic, and social factors involved in global climate change and can't be disentangled from it. Challenges to Pacific salmon posed by global climate change will come from many quarters. Understanding where, when, and how global climate change impacts (both positive and negative) will affect Pacific salmon will vary tremendously across their North Pacific range. As a result, there is an urgent need to develop a strategic approach for future Pacific salmon management and assessment frameworks to be resilient and adaptive to environmental stressors.

The productivity of individual salmon populations is affected by environmental conditions in both freshwater and marine environments, by factors such as temperature, flow, water quality, prey availability, and predator abundances. Pacific Salmon Commission (PSC) fishery regimes for Chinook (other than those for transboundary rivers) and coho (south of Cape Caution in BC) are driven by abundance forecasts that frequently involve consideration of the influence of physical conditions by relating salmon metrics, such as stage-specific survival, to environmental indicators of what is happening in a very complex environment. For example, the Pacific Decadal Oscillation (PDO) captures complex patterns of sea surface temperature across the Northeast Pacific Ocean with a single index value (http://research.jisao.washington.edu/pdo/). The PDO is correlated with a wide range of biological measures along the West Coast of North America, from zooplankton community composition to marine survival of many salmon populations.

Use of environmental data like the PDO as quantitative or qualitative indicators of salmon response to conditions can be informative. However, identifying environmental indicators that may be useful in predicting the response of individual salmon populations can be a challenging undertaking, particularly under conditions of rapid environmental change and uncertainty of extreme events. This is due to the need to understand where and when population mortality is strongly influenced by environmental variation, coupled with the availability of appropriate data and statistical models to evaluate the relationships.

To begin to address these issues under the Pacific Salmon Treaty (PST) umbrella, the Coho Technical Committee (CoTC) and Committee on Scientific Cooperation (CSC) jointly hosted a half day virtual workshop on May 11, 2021, on "*Introduction to using environmental indicators to inform salmon management*". This workshop was designed specifically for the PSC family in order to increase the use of environmental data in the management of salmon under the PST. The workshop provided a broad overview of topics relevant to using environmental indicators to inform salmon management and some of the considerations involved in their use. In addition, the latest PST (2020; https://www.psc.org/publications/pacific-salmon-treaty/) includes text in several chapters (specifically Chapter 3-Chinook, Chapter 4-Fraser River sockeye, and part of Chapter 5-southern coho, south of Cape Caution) requiring consideration of environmental variations in the management of salmon, therefore there is a legal mandate for this inclusion.

The workshop was intentionally introductory, in the sense that it provided background information necessary to begin to use indicators. It included presentations on salmon marine distributions, potential data sources, future conditions, use of traditional knowledge, and provided examples of the use of environmental indicators for salmon management. We took this introductory approach because we assumed that the level of knowledge regarding the use of environmental data among the PSC family was not consistent – while some people are well versed in advanced methods, others have little experience using environmental data. In this regard, we saw this as the first workshop in a series of workshops, seminars, or follow-up meetings that will address more complex issues such as statistical methods, validation, or management approaches to deal with environmental uncertainty. Based on the results of the post workshop questionnaire (Section H), our assumption was correct and the vast majority of respondents felt the level of information provided was "about right".

B. Workshop objectives

The workshop had three objectives:

1. Address requirements of new Coho Annex for south of Cape Caution (and PST chapters 3 for Chinook and 4 for Fraser River sockeye) to be:

   "responsive to changes in productivity associated with environmental conditions"

2. Share background information and perspectives on the use of environmental indicators to inform management, specifically:
   - salmon marine distributions,
   - data sources,
   - future conditions, and
   - using western science and traditional knowledge.
3. Provide three examples of using environmental indicators in salmon management:
   - NOAA salmon stoplight chart,
   - Fraser River sockeye scorecard, and
   - hypothesis testing for forecasting Salish Sea salmon.

The workshop schedule was as follows:

Introductions, background information

1:00-1:10 Introduction – Marisa Litz (WDFW) and Brendan Connors (DFO)
1:10-1:20 Environmental change and the PST – Gary Morishima (Quinault Nation)
1:20-1:45 Where salmon go in the ocean – Laurie Weitkamp (NWFSC)
1:45-2:05 Sources of environmental data – Chris Harvey (NWFSC)
2:05-2:30 Climate change and Pacific salmon – Nate Mantua (SWFSC)

2:30-2:40 **BREAK**

Using environmental indicators to inform management

2:40-3:05 The role of Indigenous Knowledge in fisheries management – Andrea Reid (UBC)
3:05-3:30 NOAA salmon stoplight chart – Brian Burke (NWFSC)

3:30-3:55 State of Canadian Pacific salmon – Sue Grant (DFO)
3:55-4:20 Hypothesis-based testing of multiple indicators – Kathryn Sobocinski (WWU)

4:20-4:30 **BREAK**

Panel and group discussion
4:30-4:55 Facilitators - John Holmes (DFO) and Brian Beckman (NWFSC)
4:55-5:00 Wrap up

C. Workshop participants

A total of 157 people participated in the workshop, including presenters. As part of the registration process, we asked audience members questions regarding which country they represented, who they worked for and job title, and what they hoped to learn at the workshop. Results from this survey indicated slightly more than half of workshop participants were from the USA. Approximately 30% of respondents identified as serving in executive/manager/policy roles while 70% identified as serving in science roles (scientist, biologist, technician).

A little over 60% of workshop participants sometimes or always use indicators in their PSC roles, while 40% rarely or never use them. Regarding how they used environmental indicators, 35% used indicators to quantitatively inform pre-season forecasts and 35% used indicators to qualitatively inform forecasts, with smaller percentages using them for in-season management or retrospective analyses. Of those participants who do not use indicators, ~20% of respondents reported not using indicators because of conflicting information and another 20% reported not using indicators because of inadequate information regarding risk and uncertainty. Other reasons provided for not using indicators included indicators not being available for timely action, not knowing where to find indicator time series, limited success when they tried, temporal and/or spatial scale mismatches, and management systems which are risk averse to climate change.

D. Summary of presentations

Where salmon go in the ocean

Presenter: Laurie Weitkamp, NWFSC, NMFS

Extended abstract

Knowing where salmon go in the ocean is a necessary first step for the selection of environmental indicators. Of particular importance is the salmon’s location during critical periods, when mortality is high and strongly influenced by environmental variation. Two generally accepted critical periods are the first spring/summer and the first winter in marine waters (Beamish and Mahnken 2001). While we have a fairly good understanding of where salmon are during their first marine summer/fall and during their last marine spring/summer, far less is known about their location in between these periods.

This talk describes the general ocean migration patterns for all five species of Pacific salmon throughout their ocean residence. There are three phases of ocean residence: (i) their first spring/summer, where fish are small and mortality is high and variable, (ii) subsequent winters/summers, where mortality is lower and less variable and growth occurs during the summer to avoid winter starvation, and (iii) their last spring/summer, when fish are large and mortality is typically low and constant, but individuals are still reliant upon prey for final growth and gonad development.

Ocean migration patterns for pink, chum, and sockeye salmon are fairly similar, though there is variability present among sockeye stocks. Upon ocean entry, juveniles of these species swim in a counter clockwise direction along the continental shelf during their first summer. Sometime during the fall, they head south to the open waters of the Gulf of Alaska where they spend the winter. During subsequent summers and winters chum and sockeye salmon move between the Bering Sea and Gulf of Alaska, while pink salmon return to spawn after a single winter in the ocean. During these subsequent summers spent in the Bering Sea, spatial overlap with populations of chum salmon originating from the western North Pacific occurs. Limited capture of these fish by coastal fisheries suggests these species do not spend a lot of time on the continental shelf before returning to their home streams.

Coho salmon display one of two behaviors during their first summer: either they follow the pink-chum-sockeye pattern of moving counter-clockwise along the shelf, or they remain on the shelf near their ocean entry point. Coho winter in the Gulf of Alaska, although there are resident populations in the Salish Sea and perhaps other areas. They spend a month or more on the continental shelf before returning to freshwater, making them highly susceptible to fishing pressures when compared to species other than Chinook. Chinook salmon generally remain resident on the continental shelf for some or all of their ocean residency, although some fish move offshore in the Gulf of Alaska and others into the Bering Sea in summer. Those that move into the Bering Sea are susceptible to be caught by U.S. federally managed pollock and groundfish trawl fisheries. As they return and migrate across the continental shelf, individuals may be caught by the different fisheries along the continental shelf from central Alaska to their home stream.

One exception to this movement pattern is Columbia River spring Chinook, which rapidly move counter clockwise on the shelf during their first summer of marine life. During their subsequent winters/summers, they move between the Bering Sea and locations further south. During their last spring, they return immediately to the Columbia River, without spending much time on the continental shelf. Ocean migration patterns for steelhead are different from the other salmon species, as they move directly offshore during their first summer and don’t spend much time on the continental shelf. During their subsequent winters and summers, they are distributed across the entire North Pacific, especially the summer steelhead. When they do return to freshwater, they travel directly to their home streams. Thus, environmental indicators used for this species are not appropriate for other species, and vice versa. Within each broad pattern there is considerable individual and stock-specific variation. New analyses based on genetic stock identification (rather than tags) are being published with increasing frequency, allowing greater understanding of these spatial patterns.

Take-home messages

- Knowing the location of the salmon in the ocean is important because it is the first step to indicator selection and is especially important during phases of high marine mortality when environmental drivers are most influential.
- Most mortality occurs during the first spring and summer after leaving the freshwater environment. The majority of environmental indicators currently in use are focused on this period.
- The second critical period is the first winter in the ocean, yet little is known about the distribution of the salmon during this time.
- There is substantial variation in the movement patterns of salmon species and stocks during the different phases of their ocean residency, making them uniquely susceptible to different environmental indicators.
- Recent work on genetic stock identification is a promising technology to augment tagging data for determining the variability in spatial distributions of these species.

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Question and Answer

Q: Do Fraser spring Chinook have similar marine distribution as Columbia?

[Laurie Weitkamp:] The two best studies of the distribution of juvenile Chinook salmon stocks along the West Coast are by Trudel et al. 2009 (using CWTs) and Tucker et al. 2011 (using genetics). Unfortunately, Trudel et al. only caught 27 Chinook released from the Strait of Georgia (which includes Fraser spring Chinook among many others), which had the lowest catch per million hatchery released (1.3) of any region (by comparison they caught 1,330 Columbia Chinook at 6.7 per million released). They recovered 7 individual ocean age 0 Strait of Georgia Chinook, all off the West Coast of Vancouver Island. Their conclusion was that Strait of Georgia Chinook (which includes Fraser spring Chinook) were not moving rapidly and Columbia River spring Chinook were in a class by themselves.

Tucker et al. (2011) did catch more Fraser Chinook salmon, although they too were dwarfed by Columbia River Chinook. They found yearling Fraser Chinook were caught off the West Coast of Vancouver Island or Central BC coast in fall and winter, suggesting they were just leaving the Strait of Georgia. Taken together, both studies suggest that Fraser spring Chinook salmon do not move rapidly along the continental shelf, although the small size of these populations (especially compared to abundant Columbia and Puget Sound Chinook salmon) make detecting their movements difficult.

Q: Are the ocean patterns general enough that we could start to narrow down the ocean conditions where they are at the time they are there?

[Laurie Weitkamp:] It depends on both the behavior of the fish and the spatial domain represented by the indicator. For fish behavior, individuals from a given stock don't all stick together but are typically spread over a large area. For example, in the Fisher et al. (2014) paper on the migration of Columbia Chinook and coho, Fig 3J shows tagged juvenile coho salmon spread from southern Oregon to Kodiak Island in August, although the highest concentrations are along the West Coast of Vancouver Island and the Kenai Peninsula; this is still a lot of real estate! While this might be an extreme case, other studies show salmon from a particular stock are widely dispersed, such as juvenile Chinook (e.g., Tucker et al. 2011), coho (Beacham et al. 2016) and sockeye salmon (Beacham et al. 2014) spread between the Strait of Juan de Fuca and SE Alaska. This dispersion also happens for adult salmon (Weitkamp and Neely 2002, Weitkamp 2010, Beacham et al. 2019, Shelton et al. 2019, Freshwater et al. 2021). Accordingly, salmon from a particular stock are rarely isolated to any particular small area.

However, many environmental indicators (e.g., temperature, salinity, upwelling) generally apply over relatively large areas. For example, sea surface temperatures across the California Current are correlated, and even copepods recorded at a single station along the Newport Line track the dynamics at other stations (Dumelle et al. 2021). Perhaps the big exception to these patterns are indicators associated with inland fjords or seas, such as the Salish Sea or parts of SE Alaska, where conditions within the fjord are different than those outside it, resulting in different survival trends salmon within fjords vs. coastal regions (e.g., Teo et al. 2009, Zimmerman et al. 2015).

Q: Laurie, if you had to prioritize which species needs most additional work on for ocean distribution, do you have a recommendation?

[Laurie Weitkamp:] The short answer is that every stock is important to some group of people, and we really don't have a good understanding of where salmon are after they leave coastal regions as juveniles until they show up in fisheries as maturing adults.

That said, we understand the least about small stocks that might have large importance in freshwater or are the 'weak stocks' that determine marine fisheries, such as the many populations that receive protection under the US Endangered Species Act or those that have been petitioned to be listed under the Canadian Species at Risk Act. Unfortunately, these populations are miniscule and therefore difficult to locate in the ocean. This forces us to use neighboring larger populations to infer migration patterns, which may or may not apply.

Comment: There's a nice new paper from Ole Shelton et al. in Fish and Fisheries on climate variability and at-sea distribution in Chinook CWT stocks.

[Laurie Weitkamp:] Yes, nice paper and analysis. While they do show changes in distributions as ocean temperatures warm, in some ways it's surprising that the distributions didn't change more than they did! I still think that salmon follow ancestral feeding routes that are largely hard wired (genetic) because they've been successful over 1000s of generations (Weitkamp 2010, Tucker et al. 2012). Ole's paper showed that there is some response to temperature, but the dominant pattern for each population was still maintained despite substantial warming in the future—it's not like they all were moving to the Bering Sea.

Q: What has been the biggest surprise regarding open ocean distribution of different salmon species from the two late winter cruises so far?

[Laurie Weitkamp:] My first surprise was the abundance of coho salmon caught on the high seas—the 2nd most abundant salmon caught in both years. I always considered coho to be a largely coastal species, but part of my impression was due to limited knowledge of winter distributions on the high seas. In addition, the winter surveys that had been conducted in the Gulf of Alaska in recent years by the Japanese only fished during the day and we caught most coho (and sockeye) at night (but chum during the day). I've always had a fondness for coho (started my career with them) so it was great to see so many out in the Gulf of Alaska!

The second surprise was the lack of pink salmon in our study area, which ranged from 47-56.5°N and 128-148°E (roughly 700,000 km^2 in 2019). We thought we'd be inundated with pinks and hardly saw any! Pinks are the most abundant salmon in the North Pacific, yet made up only 17% of the total catch of salmon across both years. The highest catches in both years were at the southernmost transects, so perhaps there was a large abundance of pink salmon south of our study area. If they weren't farther south, then I don't know where they are—farther west somewhere?

Q: Have we learned anything further on the 2019 Columbia River coho on what might have contributed to the high loss of a cohort given the prior year's jack return was substantial? And secondly, with the unique ocean migration pattern for Col River spring Chinook, is this specific to upriver spring Chinook or all Col River spring Chinook?

[Laurie Weitkamp:] I have not heard anything else about the 2019 return of Columbia coho salmon. The adults (but not jacks) of that year-class were out in the 2019 marine heat wave so they would have been exposed to warm temperatures during their last year in the ocean and all that comes with it (a mix of cold and warm water species across the entire food web). Perhaps there was high mortality during their 2nd year in marine waters (Oregon Coast natural coho returning in 2019 also had relatively low abundance and survival). Both these groups of coho are unique because they return to their home streams from the south (moving northwards) and are mainly caught off Oregon and California. (By contrast, coho from the WA coast and Salish Sea return home from the north).

For the second part of the question, yes, all Columbia River spring Chinook move rapidly counter clockwise along the Continental shelf towards Alaska, although some move faster than others. The best description of this is the paper by Fisher et al. (2014), which showed that at least some individual lower, mid- and upper- Columbia springs, Willamette springs, and Snake spring/summers reach SE Alaska by June. Estimated ocean migration rates were over 25 km/d for some individuals, although mean stock-specific migration rates ranged from 7 km/d (upper Columbia spring) to 3-5 km/d (lower and mid-Columbia, Willamette, yearling upper Columbia summer). By contrast, migration rates for Columbia River fall Chinook were slower (1-3 km/d) and included southerly (rather than northerly) movement for Upper Columbia fall Chinook.

Sources of environmental data

Presenter: Chris Harvey, NWFSC, NMFS

Extended abstract

Suites of robust, complementary indicators are valuable for tracking the state and trends of ecosystem attributes and overall ecosystem conditions. In this presentation, Dr. Harvey provided a broad introduction to the National Oceanic and Atmospheric Administration's (NOAA) California Current Integrated Ecosystem Assessment (CCIEA) program (https://www.integratedecosystemassessment.noaa.gov/index.php/regions/california-current). He described their approach, data sets, and tools that might allow for the development of time series of ecological indicators for use in the California Current.

The CCIEA program tracks indicators of conditions in the California Current ecosystem and provides annual updates to audiences such as the Pacific Fishery Management Council. The indicator suite includes indicators of climate and oceanographic conditions, ecological integrity, and human activities and wellbeing; most of these indicators are empirical measures, but an increasing number are derived from skilled oceanographic models. The indicators can be summarized across a range of spatial and temporal scales, and many have been contextualized to the life history of salmon stocks.

Annual reports generated by the CCIEA for the California Current have some similarities to products produced by Fisheries and Oceans Canada (DFO) for the British Columbia Coast (State of the Pacific Ocean https://www.dfo-mpo.gc.ca/oceans/publications/index-eng.html#soto-pac-tech) and by NMFS for the Gulf of Alaska, eastern Bering Sea and Aleutian Islands (https://www.fisheries.noaa.gov/alaska/ecosystems/ecosystem-status-reports-gulf-alaska-bering-sea-and-aleutian-islands). There is also considerable overlap with California Cooperative Oceanic Fisheries Investigations (CalCOFI)'s State of the California Current annual report (https://calcofi.org/). However, the CCIEA program also includes a number of freshwater indicators for the West Coast of the US and includes human impacts and drivers, which the other reports do not include.

The CCIEA Team has built an indicator data portal on their website and are presently developing data dashboards that are tailored to the needs of specific end users (https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-indicator-status-trends). This web portal contains some very useful tools for data aggregating and construction of data plots.

Presently, annual reports are used as general descriptive context as a backdrop for management decisions, although the CCIEA Team is working to refine them further for use in other elements of NOAA's IEA framework, including identifying mechanistic driver-response relationships, estimating ecosystem thresholds, quantitative risk assessments, and assessing the effectiveness of management strategies.

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Question and Answer

Q: Are some of these indicators, like snowpack/flow or nearshore indices, available for stocks outside of the California current/ecosystems? Thinking for Canadian indicators.

[Chris Harvey:] This was answered in the chat by people with knowledge of publicly available snowpack and streamflow data in Canada (links below). The CCIEA does not track indicators for stocks outside of the California Current.

https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-data-tools/snow-survey-data

https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-data-tools/real-time-water-data-reporting

Q: Lengthy time series by definition already exist, any thoughts what might exist that hasn't been "discovered" yet?

[Chris Harvey:] "Lengthy" is a relative term of course, but most of the more advanced time series analyses that can explore relationships between different variables and temporal autocorrelation, become more statistically powerful as they get to be 15 years long, or more. So, new time series will likely be added to the menu as different monitoring programs mature. Length of the time series will become more relevant as we experience extreme events or regime shifts, so that we can see how individual indicators and combinations of indicators respond to a wider range of contrasting conditions, shifting baselines, or decoupling of environmental drivers.

Another emerging set of potential "indicator" time series is from oceanographic models that are getting better and better at reproducing observations, filling in gaps, and forecasting future conditions. These models are making it possible to credibly reconstruct oceanographic conditions going back to the early 1980s throughout the water column, and may be a source of information for mechanisms affecting key marine life stages of salmon and other species.

Climate change and Pacific salmon

Presenter: Nate Mantua, NOAA/NMFS Southwest Fisheries Science Center

Extended abstract

Salmon are exposed to climate forcing throughout their lifetime: from their spawning, incubation and rearing in freshwater systems to estuarine, nearshore marine, and open ocean – all highly dynamic habitats subject to seasonal patterns, to which salmon respond predictably as they have adapted through unique life history patterns. Yet sub-seasonal, interannual and decadal variability can be quite unpredictable, and how these types of variability might change in this century was the focus of Nate's presentation.

Research in the 1990s described decadal changes in 20th century salmon production and catch of west coast salmon stocks, characterized by periods of prolonged stability interrupted by rapid shifts. These fluctuations were correlated to a pattern of climatic conditions (Aleutian Low, PDO) defining warmer and colder regimes on the West Coast of North America over multidecadal scale, resulting also in regional differences in catch between northern and southern latitudes (Beamish and Bouillion 1993, Hare and Francis 1995, Mantua et al. 1997).

However, research during the last 25 years has shown that climate and salmon production is more complex than a two-state regime, and there are different types and states of variability. One of them for example, resulting from the spin up of both the Alaskan Gyre and Subtropical Gyre of the West Coast (known as NPGO) sets wind and ocean current patterns favoring the advection of nutrient and cold-waters (lipid-rich) copepods to inshore waters, increasing survival during the critical early stages of marine residence. Over the last few decades, the fraction of the variance in salmon survival/production explained by the NPGO has increased, whereas that associated with PDO has declined. Also, before the 1990s, the NPGO and PDO climatic patterns were mostly uncorrelated, but since then, they have been strongly negatively correlated (Kilduff et al. 2015)

Additional evidence of non-stationarity in the relationship between climate processes and salmon production (chum, pink, sockeye) comes from the Gulf of Alaska, where before 1988/89 there was a strong correlation between winter SST and the abundance of salmon, but since then, the production of salmon has remained high regardless of the SST during the winter (Litzow et al. 2018).

Marine heatwaves - extreme and persistent warm periods in the waters of the in the Northeast Pacific (https://www.fisheries.noaa.gov/tags/marine-heatwave), have recently become a new dominant feature, with the warmest years in the Bering Sea, Gulf of Alaska and the California Current system, during the 2014-2020 period. The socioeconomic impact of this climate pattern with warm and poor ocean conditions is seen from collapses in fisheries to magnified precipitation patterns with increased droughts in California.

And in this context of climate extremes, salmon production systems are evolving under conditions of lost or degraded natural freshwater and estuarine habitats, changes in hatchery production practices favoring the release of larger smolts in narrow windows of time, resulting in increased synchrony among the populations. Food webs are also changing, as evidenced by increases in top predators (whales, pinnipeds, and birds), and boom-bust cycles in production of forage fish (e.g., Pacific sardine and Northern anchovy). Competition between recently abundant pink salmon in Western Alaska, Washington, and British Columbia sockeye has been particularly bad for sockeye production during warm ocean years (Connors et al. 2020).

Predictions of future climate show warmer and wetter conditions for salmon watersheds, particularly at higher latitudes, and on the windward side of the mountains, conditions leading to profound changes on snow accumulation and river run-off timing. Major snowpack losses will occur at lower elevations and in those areas closer to the ocean (in northern latitudes as well as in areas like the Olympic Mountains and the Cascade Mountains, where the snowpack accumulation is very sensitive to changes in temperature). The oceans in addition to being warmer (with suitable ocean thermal habitat for salmon species already shrinking in the summer in the Gulf of Alaska for example), are going to become more acidic and less oxygenated, and these changes in the North Pacific Ocean are accelerating in the coming decades (Welch et al. 1998, Aziz et al. 2011). Vulnerability of salmon species to these changes is increasing, and the impact is going to be sooner and more severe for those more inland populations (Spring type Chinook, coho salmon, sockeye) with a life history that exposes them more to the summer conditions in the river. The impact is going to be less so for pink and chum, as their distribution is more coastal, at lower altitudes, and as they spend less time in the river during their rearing period (Crozier et al. 2019, Crozier et al. 2021).

Take-home messages

- Ocean changes are occurring fast, warm events are more common and intense, and have major impacts on ecosystems and fisheries.
- We are headed to a "No Analog Future", for which we don't have historical reference, hence we should prepare the best we can for novel and major ecosystem and fisheries management challenges.
- We have opportunities to make space for climate change by alleviating existing stressors, and by taking actions that restore habitat and life history diversity for salmon, so that they have more opportunities to adapt in the face of rapid climate change.

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Question and Answer

There was no time left for Q&A during Nate's time slot and no questions were received in the Chat.

The role of Indigenous Knowledge in fisheries management

Presenter: Andrea J. Reid, Centre for Indigenous Fisheries, UBC

Collaborators: L.E. Eckart, J.F. Lane, N. Young, S.G. Hinch, C.T. Darimont, S.J. Cooke, N.C. Ban A. Marshall, J. Popp, D. McGregor, and J. Miller

Extended abstract

The co-management of threatened, endangered, or at-risk ecological communities is complicated. While the relationship between Indigenous and non-Indigenous sovereigns and stakeholders is improving, there continue to be areas of inertia that inhibit moving towards consensus in approaching ecological crises. This is unfortunate as there are limited amounts of energy and resources to be applied to a growing list of ecological crises, and boundaries prompted by history, culture, and perspective continue to inhibit areas of possible synergy that could contribute to positive outcomes. The primary purpose of this Insight Lecture is to be reminded that Indigenous and non-Indigenous participants in co-management inhabit the same landscape with each other and the aquatic systems that occupy their attention. This will work

towards identifying pathways for building consensus and where we can become larger than the sum of our parts when addressing increasingly complicated issues that threaten our aquatic systems.

We need to improve relationships now to improve fisheries management. We need to do things differently, we need to change. Fish are more than just fish, they are linked to culture and social/ecological systems. Present management decisions are based solely on Western science. There is space for Indigenous Knowledge in science systems. Indigenous science increases the worldview and interests of the community, and who we are as individuals needs to be recognized.

This introduces the concept of 'two eyed seeing': an Indigenous framework to transform fisheries research and management. It embraces learning to see from one eye with the strengths of Indigenous Knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together for the benefit of all (as envisaged by Elder Dr. Albert Marshall). Part and parcel to that is 'getting story ready', which requires that we: 1) understand colonial impact, 2) appreciate Indigenous Knowledge systems, 3) value relationships, and 4) learn the core of knowledge. We are accountable to those with whom we have relationships.

It is important to seek the answer to a fisheries question/problem from the appropriate Indigenous Knowledge base. Each issue or problem is different and needs to be treated as such. For example, knowledge of whales and salmon in Icy Straits would be most appropriately posed to the Tlingit elders of Hoonah, whereas information about Nass River sockeye would be most appropriately posed to Nisga'a Nation folks.

Take-home messages

- Sympatric coexistence of Indigenous and Western science in modern fisheries management needs to be recognized and embraced to effectively utilize and maintain aquatic systems, including salmon.
- Each issue or problem is different and needs to be treated as such. Seek the answer from the appropriate Indigenous knowledge base.
- Use 'two eyed seeing' and 'get story ready'.

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Question and Answer

Q: Andrea, what is your advice on how to help or encourage colleagues to get "story ready"? How do I best encourage them to be more comfortable, accepting with this and less resistant? I know, a GIANT question, but I would be so appreciative of any of your insights.

[Andrea Reid:] Great question, and the answer(s) depend a bit on who the colleagues in question are. I'd be happy to chat a.reid@oceans.ubc.ca.

Q: Thank you for a very interesting talk, Dr. Reid. Years ago an Ahousaht elder (Stanley Sam) told me (a UBC/Western trained scientist) that he recalled Ahousaht elders predicting upcoming good or poor salmon years at the time of the winter solstice based on where the sun rose over the mountains southeast of Ahousaht. (I'm still not sure how many years one might see the sunrise in December on the west coast of Vancouver Island, but over generations maybe often enough?) I didn't give much thought to Stanley's "story" until a few years later when I first heard about how salmon production might be related to the slight tilt of the earth, as a previous presenter mentioned today. I can see how the tilt of the earth could be observed in the exact location of the solstice sunrise. Do you or others know of similar knowledge stories? Stanley is no longer with us, but there may still be other Ahousaht or Nuu-chah-nulth elders that recall this knowledge. Thank you again for your thoughtful presentation.

[Andrea Reid:] Wonderful comments and thoughts. Thank you for sharing. I think this is one of many examples where IK gets treated like 'story', an anecdote, something that feels easy to dismiss as evidence… that is until we understand the 'why' component and then accept it as valid. Knowledge holders in my nation will monitor glaciers in the territory and make predictions about the state of salmon returns – which at first blush might sound unrelated (at least to a non-salmon scientist) but of course makes perfect sense when we think about the thermal influences of glacial melt on these cold-water animals.

Q: How can we best accommodate and use traditional knowledge given Nate's statement we could be entering a "no analog" future? In other words, what elements of indigenous knowledge are most applicable to a highly dynamic future?

[Andrea Reid:] Another great question! Fikret Berkes' book Sacred Ecology (2018) I think makes abundantly clear how Indigenous knowledge systems are fundamentally steeped in adaptive management principles. They have coped with and been responsive to tremendous change over time since time immemorial, and because they are guided by language/story/laws that span many generations, these knowledges aren't limited to just a myopic view of the present. There is much that we can learn not only from the knowledge itself (as data / information), but epistemologically from the knowledge systems (as ways of knowing) as they are inherently dynamic and adaptive which is supremely helpful and informative, especially as we face an increasingly uncertain future as you noted!

The NOAA Salmon Stoplight Chart

Presenter: Brian Burke, NOAA Fisheries/NWFSC

Collaborators: Jennifer Fisher, Sam Zeman, Kym Jacobson, and Cheryl Morgan

Extended abstract

The NWFSC has been sampling juvenile salmon and their marine ecosystem for 24 years and we have used much of the resulting data to create a 'stoplight chart' of ocean indicators. This stoplight chart provides a qualitative visual tool to depict whether specific environmental indicators are favorable (green), neutral (yellow) or unfavorable (red) for Columbia River Chinook and coho salmon survival. These indicators range from ocean basin scale indicators (e.g., Pacific Decadal Oscillation [PDO], El Niño index), to physical (e.g., salinity, temperature) and biological (e.g., copepod and larval fish community metrics), indicators at regional scales including counts of juvenile salmon in ocean surveys. This stoplight chart has been used extensively throughout the Columbia River Basin and the greater Pacific Northwest by scientists, salmon managers, and the public to inform predictions of salmon returns.

I used this chart as an example of creating a set of indicators to help manage salmon, specifically asking the questions, "Are these the best set of indicators for a given application?" and "What level of cross-correlation exists in the table, and what effect does that have any conclusions drawn from the table?" Too many indicators, especially those that are strongly correlated can affect conclusions drawn from the indicator set. This is because many methods, ranging from simple ranks to Principal Components Analysis, produce results that reflect the strongest signal from all indicators. In this way, groups of indicators that are highly correlated overwhelm the results, with considerably less influence from indicators that aren't correlated. Ideally, variables are all informative in a predictive sense and correlations among variables are minimized so summary metrics represent all variables

I highlighted several issues to be aware of when creating a set of indicators, including mechanistic links between indicators and responses, cross-correlations among habitats, carryover effects from one habitat to another (for migrating species like salmon), and non-stationarity. For this first issue, it is best to have indicators that reflect mechanisms that directly influence salmon growth or survival (e.g., prey or predator abundances). Unfortunately, few of these types of indicators are available. Instead, most indicators reflect physical water properties or low trophic levels and thus are several steps removed from the mechanisms that affect salmon growth and survival. Because of this ‘distance’, several competing pathways may link the indicator to salmon, with direct directions of influence. In addition, some large-scale ‘drivers’ such as the PDO influence both freshwater and marine habitats (Gosselin et al. 2021), making disentangling the effects of these drivers on specific phases of the salmon life cycle particularly challenging.

For the issue of carryover effects, it’s important to remember that things that happen in previous life stages influence how salmon behave in the current life stage (e.g., Gosselin et al. *In press*). For example, experiences in freshwater influence the size and timing of juvenile salmon at marine entry, which subsequently influences susceptibility to predators and availability of particular sizes of prey. For the third point, an increasing body of evidence is showing that relationships between salmon and environmental indicators are not static but change over time (e.g., Malick 2021, Nate Mantua’s talk). This ultimately leads to the failure of indicators to inform predictions of salmon returns, but determining that these relationships are eroding can be challenging.

Finally, I gave an example of using indicators for projecting adult salmon returns and supported the idea of embracing emerging technologies and quantitative tools. As a simple example, think about model prediction and consider other methods (one step ahead using mean absolute error) instead of AIC to select the best model. Other new tools can bring to light things that aren’t obvious (example of changes in jack: adult return ratios). One such technique is Dynamic Linear Models to explicitly include non-linearity. Using new techniques can detect changes in conditions that may otherwise be overlooked.

Take-home messages

- Be (stock) specific in selecting indicators. Different stocks go to different places or times and therefore indicators that work for one stock may not work for another.
- Mechanistic indicators are best (if you can find them). Less likely to stop working and have a direct and understandable link to survival.
- Consider both indicator performance and information redundancy. Having many correlated indicators skews the picture.
- Embrace quantitative tools and technologies. Hiring a modeler is money well spent.

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Question and Answer

Q: Are the stock-specific stop light charts and data available online as the aggregate is? Same site?

[Brian Burke:] Not yet. Hope to have it within a month or so.

Q: There seems to be a dance between bottlenecks each year (e.g., low flow and high temps in freshwater versus dead zones off the coast). Can modeling incorporate meta-analysis to predict which bottleneck is in effect in each year for each stock and environment so we know which environmental model to use that year?

[Brian Burke:] It's really hard to do. Closest is to use tools that incorporate everything in one analysis. Alternately, use model averaging where you have a suite of models that focus on different processes and each gives an estimate. Then, the bottleneck will be outlier. Could take average or look at outliers to better understand what's going on or focus future research. Not easy to solve this question!

Fraser River sockeye: Chasing predictions in a rapidly changing climate

Presenter: Sue C.H. Grant, DFO

Collaborators: Bronwyn L. MacDonald, Catherine G.J. Michielsens, M. Lapointe, A-M. Huang, M. Trudel, J. King, D. Patterson, K. Robinson, D. Selbie, L. Pon, C. Neville, K. Benner, C. Neville, K. Benner, J. Boldt, I. Perry, J. Tadey, S. Latham, S. Decker, B. Leaf

Extended abstract

Climate change has emerged as a key driver of current and future Canadian Pacific salmon trends. Rapid increases in global and regional temperatures have coincided with a reduction in Canadian catch. Average Canadian catch has reduced by half in the last 35 years reaching 11 million, compared to the previous 75 years of 25 million. The last six years have been particularly low at 4 million, coinciding with Northeast Pacific Ocean heatwaves that largely persisted from late-2013 and continue now in 2021. Catch in the last two years (2019 and 2020) have been extremely small, averaging 2.5 million.

Fisheries management has reduced fisheries catches to respond to declining salmon productivity and abundances, and also to protect an increasing number of stocks in mixed stock fisheries that are facing an imminent risk of extirpation.

Climate change is embedded in all other factors affecting salmon. It has resulted in Northeast Pacific Ocean warming and marine heatwaves, shifts in marine food webs, and warmer river conditions, lower snowpacks by early summer, increasing deforestation from forest fires and pine beetles, and invasive species. These climate related changes in freshwater interact with human alteration of habitat, human water use, salmon disease, etc.

This presentation highlights the importance of integrating information from experts from different disciplines across the salmon life history, both in freshwater and the marine environment, to improve the use of environmental indicators for fisheries management. This is increasingly important that the complexity of interactions and relationships between salmon and their ecosystems is emphasized through integrative processes.

This scientific integration process is illustrated for Fraser River sockeye salmon, where a variety of different methods that rely on environmental indicators has resulted in some important lessons.

The journey of forecasting and how to incorporate environmental indicators started for Sue in 2007 when she took over the forecast of Al Cass. At the time, forecast models were selected based on retrospective analyses and some included environmental covariates like sea surface temperature, PDO, and discharge. At the time, not much attention was paid to recent declines in productivity as it was assumed that they would eventually revert back to historical averages.

In 2008, the forecast process started to rely more on experts with knowledge of the environmental and stock-recruitment data and Fraser salmon. Understanding environmental conditions and how conditions compared to conditions in previous return years was emphasized in the forecast process.

In 2009, the Bill Peterson (NOAA) stoplight approach was adopted to supplement the quantitative forecast approach. This approach seemed to capture the poor migration conditions of 2007 and 2008. For 2009 returns, the indicators predicted improved conditions compared to 2007 and 2008 returns. Unfortunately, sockeye returns to the Fraser River in 2009 represented the lowest productivity on record and there had been no warning signs from the marine or freshwater environment through the stoplight approach, nor from the marine and freshwater experts. This might have been due to the fact that indicators may only be relevant in certain years: some years there may be survival bottlenecks in particular life-stages or habitats, other years might be more cumulative survival mechanisms interacting across life stages. The record low returns resulted in the Cohen Inquiry into the extremely poor returns and declining trends for Fraser Sockeye.

For the 2010 forecast, the recent lower productivity period was recognised, and new models were introduced to account for lower and time-varying productivity. This included using sibling models as indicators where available, and generating forecasts in cases where a large five year old return was expected and survival in the previous year was exceptionally poor. These criteria were established since sibling model relationships can be highly uncertain. Sibling relationships only included post-1980 time series since age of maturity increased in these latter years. The lower productivity forecast scenario that relied on these new models was recommended for fisheries management. However, there was no advance warning provided by marine or freshwater experts regarding the record high return in 2010.

After the two extreme low- and high-return years of 2009 and 2010 and no warning on environmental conditions or salmon condition in advance, a new qualitative integration process was initiated. This process integrated both freshwater and marine experts to examine and discuss the data and information collected across the life history stages of Fraser sockeye during annual meetings. These meetings, which lasted for several days, tried to put the story together of the conditions encountered during the entire salmon life history as well as observations of fish health at various developmental stages. The process also looked at variations between different stocks, in terms of the different spawning, rearing and migration conditions they encountered.

Over the years, these meetings became more rigorous with discussions among experts on environmental processes affecting various life stages, aimed to break down silos between the scientific expertise and knowledge across the entire life cycle. The discussions allowed researchers to look at cumulative effects of poor conditions across all life history stages, as well as identify bottlenecks like landslides or flooding events, or extremely poor environmental or salmon conditions in a particular life stage.

The end result of this Fraser Sockeye integration process was a list of key observations across all of the life history stages, with indications whether the impact was expected to be positive, negative or neutral, the level of confidence in that effect, and its impact on overall survival. All of the information was combined into an overall recommendation plus an indication of confidence, which in recent years has mainly resulted in a recommendation to expect negative impacts on survival. Recommendations were provided in combination with quantitative forecasts, which remained uncertain. These recommendations coincided with very low productivity for Fraser Sockeye in the past decade. An attempt was made to translate this integrated process into a stoplight approach, but the required details and nuances did not lend themselves to this effort.

Climate change is going to continue, even under the best-case scenario of future greenhouse gas emissions. Solving wicked problems like climate change requires lots of different thinking from people with a wide variety of expertise. We are encountering environmental conditions previously not observed and also more extremes, resulting in increased uncertainty. This will require assessments that rely on an integrated process to combine information on environmental and biological indicators across all life history stages as well as more precautionary management approaches. Wild salmon numbers are declining, and an increasing number of stocks are at risk of extinction.

We have to start looking forward, not just for the next season but across the next 10 to 30 years, assess which salmon stocks are vulnerable to climate change, and perform management strategy evaluations under different projections of climate change to assess the impact on salmon and the ecosystem. This will allow us to align management systems to this new future. These management systems should be more adaptive and flexible, instead of rigid and complex, so that they don't break under climate change. We need to stop managing salmon by looking in the rear-view mirror as the future will look very different under climate change.

Take-home messages

- Selecting environmental indicators and using them in forecast processes has not always led to improved predictions as illustrated for Fraser River sockeye salmon. Environmental conditions due to climate change are dramatically being altered. Relationships between environmental variables and salmon survival will increasingly break down, and we should expect surprises.
- To examine the impact of climate changes and other factors embedded within this overarching driver on salmon stocks, it is important to rely on an integrated process that includes the expertise of both freshwater and marine scientists to examine and discuss the data and information collected across the different salmon life history stages.
- We should re-examine where our scientific and management efforts should be placed. Is forecasting and predicting next year's returns the highest priority given the large decreases in catch in recent years, or do we need more radical urgent thinking required under climate change? For example:
    - How do we create more flexible and adaptable management systems required under a rapidly changing climate?
    - How do we determine which salmon populations have the best chance under climate change to align fisheries, habitat, and hatcheries management now towards that future, as opposed to past salmon production and distributions?
- Processes like forward looking salmon vulnerability assessments to climate change (CCVAs) and management strategies that are forward-looking under climate change are required.
- Climate change requires looking forward longer term as historical data and relationships may no longer be applicable.
- Fisheries management systems should be adaptive and flexible to be able to adjust to change.
- The future is going to look very different under climate change, and we are already observing large changes.

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Question and Answer

Q: How much the change in catch was due to management versus environmental change?

[Sue Grant:] Catch has been reduced to ensure sufficient spawners on the spawning grounds and this has been in response to overall declines in abundance as well as to protect weaker stocks that are designated as endangered or at risk and caught in mixed stock fisheries.

Ecosystem indicators across the seascape: Integrating estuarine and marine processes to understand salmon survival

Presenter: Kathryn Sobocinski, Western Washington University

Collaborators: Correigh Greene (NOAA Fisheries), Michael Schmidt (Long Live the Kings), Neala Kendall (WDFW), Joe Anderson (WDFW)

Extended abstract

Independent populations of coho and Chinook salmon have declined over the last 50 years, prompting extensive examination of mortality in different life stages. Previous studies have identified declining trends in marine survival, specifically within the Salish Sea, an urbanized estuary that has received relatively little attention compared to freshwater and ocean habitats. This ecosystem is highly complex and thus, there are a number of potential factors that may be influential to salmon survival. These may include boundary conditions (e.g., freshwater/ocean or atmosphere/ocean), oceanographic conditions of the Salish Sea (e.g., stratification or salinity), predator and competitor abundances, anthropogenic impacts (e.g., harvest, contaminants, habitat loss), or salmon characteristics (e.g., outmigration abundance and timing, size, or growth). Efforts to understand causes of decline in species of concern often involve retrospective evaluation of multiple possible causes based on trends in relevant ecological indicators. These indicators provide insight into the state of the environment and must be hypothesis-driven, theoretically sound, integrative, respond predictably to ecosystem change, relevant to management concerns, change over time, and available at relevant scales (i.e., local, regional, and global). It is understood that environmental conditions at global and regional scales are influential to local scales, and vice versa. For example, anthropogenic impacts locally can cause

carry-over effects beyond local waters (e.g., pollutants). Estuaries and inland waters, like the Salish Sea, are influenced by larger-scale ocean processes that are continually changing.

We used a hypothesis testing framework to examine declines in marine survival for coho and Chinook) salmon in the Salish Sea using data collected since 1970. Before moving to a more quantitative approach, a qualitative network model was used to explore various hypotheses regarding the factors driving marine survival based on the current understanding. This allowed for the narrowing down of predictor variables used to predict marine survival. We explored seven potential explanations for declines: changes in predator buffering related to abundance and timing, density-dependent or -independent food availability, water quality, timing of freshwater delivery to Puget Sound, and anthropogenic impacts.

We compiled ecosystem indicators—time series of relevant and available ecosystem components—for each of these hypotheses and used generalized additive models (GAMs) to examine relationships with survival from multiple coho and Chinook salmon stocks. We also developed additional composite models using the most informative indicators based on variable importance weighting (VIW) from the seven hypothesis groups. We examined how these models explained overall trends in marine survival, as well as survival in three temporal stanzas (before, during, and after a major decline, based on statistical breakpoint analysis).

Across the entire time series, best fitting models explained 30-40% of the variation in the salmon survival dataset. Best fitting models were from multiple hypotheses, including predation (abundance and timing), competition, water quality, and anthropogenic impacts; the freshwater delivery hypothesis was the least supported. Different models performed best (lowest error) during different stanzas of the coho salmon marine survival time series and the two VIW models were generally the top performing models, but performance varied in different years. Indicators with the strongest support included seal abundance, herring abundance, timing of hatchery salmon releases, and indicators related to water properties like stratification and temperature.

These findings suggest that multiple processes embedded in several of our hypotheses influence marine survival but that the best performing indicators vary by time period. Therefore, a suite of indicators is suggested for understanding marine survival in salmon. It is important to consider the selection of indicators based upon hypotheses, however there are limitations to a purely statistical approach. Although correlated variables can explain variance, they may not be the most important factors to consider as the mechanisms behind them are not well-articulated. Further, indirect and interaction effects are not captured well. A number of important data streams are not currently available (e.g., forage fish, zooplankton, fish predators), limiting model quality at this time. Future efforts should consider these factors when selecting relevant indicators and aim to incorporate these data as they become available.

Take-home messages

- Salmon have a complex life history and therefore can be considered ecosystem integrators.

- When evaluating reduction in survival, it is important to consider indicators across the salmon's life history.
- Correlation between variables may not be useful if the underlying mechanism(s) is (are) not understood.
- All best performing models explained 30-40% of variation in the dataset.
- Freshwater input indicators typically did the worst at explaining variance.
- Seal abundance was supported (correlates with time series, also mechanistic work supporting predation hypotheses).
- Hatchery release timing and abundance should be considered more fully as there are some negative relationships with survival; more protracted release timing resulting in higher survival.
- Same suite of indicators may not perform well over the entire time series and therefore it might be better to use a suite of best predictors. Over time new time series become available that can be added to forecast models (zooplankton, ocean sampling).

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Question and Answer

Q: How do we consider the evolutionary plasticity of these animals in the context of abiotic and biotic shifts moving forward? How can this influence our forward thinking for forecasting or management?

[Kathryn Sobocinski:] It would seem we want to maintain the genetic diversity of wild fish to the extent possible to give them the best chance at adapting to shifting conditions.

E. Panel discussion: Introduction to using environmental indicators to inform salmon management

Moderators: Brian Beckman, NOAA/NWFSC, and John Holmes, DFO/PBS

Panelists: Gary Morishima (Quinault Nation), Laurie Weitkamp (NOAA/NWFSC), Chris Harvey (NOAA/NWFSC), Nate Mantua (NOAA/SWFSC), Andrea Reid (UBC), Brian Burke (NOAA/NWFSC), Sue Grant (DFO), Kathryn Sobocinski (WWU)

The intent of the panel discussion was to open a dialogue on the use of environmental indicators in support of salmon management in a changing environment. This conversation is not expected to be definitive on environmental indicators, rather it is envisioned to provide a diversity of views in the hope that workshop participants begin thinking more seriously about how environmental indicators might be used within the PSC to achieve the commitments made by the Parties in the PST.

All of the presentations in this workshop were hugely informative and provided many ideas and concepts for participants to consider. The Workshop Organizers developed a series of questions based on the presentations to guide a follow-up conversation exploring some of the ideas raised by the Presenters. Each of the speakers was sent these questions before the workshop so that they could prepare some thoughts on any of the questions that they wished and provide their input as the questions were posed during the panel discussion. The text below is an edited version of the discussion that occurred.

What are the characteristics of "good" environmental indicators to support assessments and management?

[Nate Mantua:] I think that it's important to custom tailor indicators or indicator sets to the question as much as possible. If the question relates to a specific stock, then make the indicator(s) appropriate to that stock. For example, I was part of a project translating the results of a retrospective modeling study that looked at the life cycle of fall run Chinook salmon in the Central Valley to explain the history of escapement over a 30 year period.

The project identified several factors in the early life history affecting spawning escapement for the parent generation including incubation temperature for the eggs, winter flow related to the rearing and out migration survival rates, and an index of seabird diets at the ocean entry point because seabird colonies on the Farallon Islands are located just outside the Golden Gate bridge where these fish first enter the sea. These factors plus the harvest rate applied to the returning stock help in understanding past influences on the stock. Important characteristics of indicators include ease of updating and clarity (i.e., the meaning of the indicator and range of values is understood), a strong mechanism linking the indicator(s) to the issue, and integrative across the lifecycle so that it's not just focused on one piece of the complex life cycle. For example, these characteristics can be observed in studies trying to explain smolt to adult return rates on the west coast for hatchery dominated stocks, where the freshwater production system is under our control. Consequently, we know how many smolts go out every year, their size at release and when they are released as all of these factors are under our control. This example was applied to a composite stock that's both natural origin and hatchery origin. We also heard from a number of speakers that indicators should be flexible enough that change can be incorporated because using indicators in a forecasting mode is bound to fail at some point because of a surprise event. We need to be able to understand these surprises and how they affect failure so that we can learn from it. It's not surprising that indicators in predictive mode fail because salmon have really complex life histories that are exposing fish to an incredible range of habitats and the bottlenecks that they face can be really different in any given year. We need to be prepared to operate in this sort of environment.

[Sue Grant:] I think it’s important to focus your indicators on the stock of interest and it’s important to think about the objectives for integrators. If indicators are used simply to produce annual predictions for next year and turning the crank on these complex management systems, then we may miss big changes occurring due to greenhouse gas emissions and unless we rain in these emissions we're on this pretty big trajectory. So trying to integrate our knowledge of ecosystems and put it all together should be considered. Because if we focus on prediction next year we're in danger of missing the bigger picture with our science. The presentations today provided a lot of insight on connectivity and integration between components of the ecosystem. However, the annual prediction approach leads to a short-term focus on bottlenecks, which could be a slump or a landslide one year, a flood in another year, or the marine environment. So it’s important for us to evaluate the questions we are addressing with indicators. Annual predictions are necessary, but we also need to look at the bigger picture and indicators may provide a way to do so.

How important is it to understand the mechanisms underlying observed relationships between environmental indicators and salmon abundance/survival before using them to inform salmon management?

[Brian Burke:] In the Columbia basin we use correlates of survival in our management to a large extent and so variables like PDO have been used by countless managers because it's correlated with many events in the north Pacific. PDO was a good predictor of salmon returns for years, their condition and ocean conditions. However, PDO is not performing well as a predictor in recent years, which has sparked questions about its value as a predictor. While PDO was used as an indicator of survival, there was no mechanistic linkage between PDO and salmon survival. This example highlights the need to understand the drivers of survival when considering an indicator. One theory is that the first few months that the fish are in the ocean is a critical period for growth and survival and another theory is that the first winter is important and that's when cohort strength is set. However, in some years it might not be the ocean or a specific time period that affects cohort strength. For example, in the early months of 2015 many smolts were sampled in the Columbia River estuary, but few if any were caught outside in the ocean less than a month later. There seems to be an extremely fine temporal period that drives the cohort levels or it could be sometime in December in Alaska. If indicators are used, then we need to understand the mechanism by which the indicator is correlated with a stock of interest and recognize that correlation changes over time.

[Kathryn Sobocinski:] I think one thing that is important to realize is that there's a certain amount of exploration that can happen without knowing the mechanisms that might set some research priorities outside of management that may better inform management. Seal predation in Puget Sound and the Salish Sea is a good example because it's popped up a number of times and now there's a number of mechanistic studies underway that are starting to give some weight to the fact that seal production may be considerable. This idea wasn’t fully developed in the beginning, but in the last five or seven years there's been a number of additional mechanistic studies that have really provided support for this finding. There is feedback that can happen across the various disciplines that will ultimately inform management as the mechanistic gaps are identified and research conducted to address them.

[Andrea Reid:] I agree with Katherine's comments and I don't think we always need complete mechanistic understanding. This kind of understanding is useful and something that we want to work towards in many contexts. But given the gravity of the situation and the crises that salmon fisheries are facing in many contexts, we are going to need to make decisions when information is limited in many cases. I really liked Don Hall’s question in the Q & A, talking about a specific indicator on the west coast of Vancouver Island and I think there are many times when we might not understand the mechanistic understanding, but we can still take some knowledge and guidance from what is being provided by it.

What is more informative for salmon assessment and/or management: monitoring ecological indicators such predator and/or prey abundances or oceanographic indicators such as sea surface temperatures, PDO, and/or upwelling?

[Laurie Weitkamp:] I think that using biological indicators for assessment and management is appropriate in the sense that they already integrate the responses of salmon to physical conditions, so they provide some level of translation even if you don't know the relevance of a biological indicator to your species of interest. I think biological indicators are telling you something by how they're responding to the physical condition so they eliminate some of the noise and they're informative, although they can also be very unpredictable as well.

[Nate Mantua:] There's something really interesting that happened off the west coast of California, in the last five years, that has bearing on this question. Anchovy abundances became very high after being very low just six seven years ago and the conceptual models are the paradigms for understanding anchovy in the California current. Prior to this period of abundance, our understanding was that anchovy abundance increased during cold strong upwelling associated with sustained cold PDO periods. However, recently, cold upwelling associated with cold PDO periods is not the driver of their current abundance that has resulted in anchovy being the dominant forage fish for a number of top predators, ranging from salmon and halibut up the food chain to San Francisco Bay seabirds and marine mammals even humpback whales. We would not predict this kind of abundance by tracking sea surface temperature or upwelling based on the existing paradigm of anchovy in the California Current. The ecosystem integrates lots of different things that are happening in ways that we don't have the capacity to predict all the time, or even to translate. It’s critical to develop a number of ecological indicators for different parts of the food web and understand how they interact from who’s eating whom and where these events happen. But, consider that these super abundant anchovies that are an important forage species appear to be contributing to a thiamine deficiency in Chinook salmon in California, impacting the reproductive success of the spawners; while spawning fish are fat, this nutritional deficiency in their eggs, if it persists, will have a huge negative impact on the productivity and abundance of this stock. We have not seen this condition on the west coast in the past, which points to the issue of ecological surprises as the ocean changes rapidly and in many ways unpredictably. What's next, what are we going to see that’s different from our historical understanding? These examples force us to think that we have limited capacity to track everything that's important in real time and making predictions is especially difficult and that there is a need for more holistic and integrative approaches that are also more fundamentally focused on what makes these populations of salmon persist and thrive. This is a challenge to the Western science reductionist approach to understand everything in order to manage in a really mechanistic way. It's hard not to look at West Coast salmon management and observe that it’s failed repeatedly in recent decades because we have crises on top of crises at present. There are lots of contributing factors, but we really are at a point where it's time to step back and think about how we can protect these animals and communities that are connected to them in the face of such incredible environmental change with climate change and ocean acidification likely to get much, much worse going forward than what we've experienced in the past.

Audience Questions:

“It's a dance between bottlenecks, each year, for example, low flow, high fresh water temperatures versus ocean dead zones during migration. Can the modeling incorporate a kind of meta analysis to try to use environmental indicators to predict which bottleneck is in effect for a particular stock and/or any brood year so maybe then you know which environmental model to use that year?”

[Brian Burke:] This is a hard question to address. I think the closest we could come is either using tools that incorporate all of those things in one analysis or do some sort of model averaging of a suite of models that provide a prediction for the next year, with bottlenecks being an outlier in this later approach. So you could take the average of all your model predictions, or you could pay a little bit more attention to outliers, arguing that the outlier has the potential to drive the dynamics for the entire cohort and use this finding to conduct additional research to address these kinds of questions. However, it remains a conundrum that we have to address all the time and it's not easy to address.

"How do we consider the evolutionary plasticity of these animals in the context of abiotic and biotic shifts moving forward, how can this influence our forward thinking for forecasting or management?"

[Laurie Weitkamp:] That's a perfect topic for a future workshop.

F. Comments by the Organizing Committee

Brief synthesis – mixed case was presented at the workshop for the use of environmental indicators for forecasting salmon returns and informing management. There was some success for some stocks and less predictive results were found for other stocks. A number of speakers discussed climate change and the non-stationary relationships between environmental indicators and salmon survival, suggesting that one can't assume stable (predictive) relationships between the environment and salmon survival into the future. Differing viewpoints were expressed in regard to the development of specific indicators; some speakers suggested the development of local scale indicators representing mechanistic relationships were important while others asserted that an array of indicators representing correlative relationships could be useful. An overwhelming message was that environmental variability is increasing and that the past may no longer be a good indication of how salmon will respond to environmental variation in the future.

Narrow view – some caution should be exercised when considering investments in the development of environmental indicators for salmon forecasting. There is no guarantee of success and there are some suggestions that even currently successful indicators may fail in the future. The development of a quantitative framework for incorporating indicators into a forecast or assessment framework can be time consuming and face barriers including lack of technical skills and costs of collecting data relevant to individual indicators. Well established environmental indicators for most stocks don't exist, but are expected to vary both spatially and be species and life history specific.

Wider view – the environments that salmon utilize over the course of their life cycle are changing and becoming more variable. There is a need, in at least a qualitative sense, to monitor the environment in order to anticipate changes in salmon distribution and survival (e.g., recruitment failures). Broader scale indicators of the physical environment exist for the NE Pacific (climate indices such as PDO, NPGO, Aleutian Low and physical indices such as satellite sea surface temperature). More local scale data exists in some areas (buoy temperature and salinity data, Canadian lighthouse temperatures).

The utility of indicators for specific PSC management and assessment frameworks depends on both the biology of the salmon species in question, the habitats they utilize (e.g., California Current vs. Strait of Georgia vs. Gulf of Alaska vs. Bering Sea), and the specifics of the management and harvest regimes for that stock. Thus, general recommendations across chapters and species are not possible and trying to develop them would be ill-advised.

The CSC has been tasked with synthesizing the extent to which current PSC assessment models and management frameworks incorporate environmental information and/or account for environmental change (e.g., declines in productivity). Using this information, the CSC will develop recommendations and options for if and how PSC management approaches could be adapted to be more robust to environmental change and detect changes in abundance. This effort will provide a starting point for assessing the vulnerability of PSC assessment and management approaches to environmental change and variability. This effort requires support from Technical Committees and Panels to identify current barriers and needs to consider environmental information, if any, and what support is required to overcome them. However, this does not preclude individual Panels or Technical Committees from exploring the utility of environmental indicators for their own purposes.

G. Recommendations for follow up

The following recommendations were generated from Workshop Presentations and Panel Discussion, responses to the post-workshop questionnaire, and discussions within the Workshop Organizing Committee.

Urgent Need to Develop a Cohesive Strategy to Address Environmental Change

As several of the talks emphasized**,** rapid and increasingly severe impacts of Global Climate Change are already affecting Pacific salmon populations and fisheries. These impacts are expected to become stronger and more unpredictable in the future. In order to be proactive to these changes, the PSC should initiate the development of a strategic approach to climate change, to ensure adequate stewardship of salmon and fisheries under the PST now and in the future.

Short-term efforts could also be undertaken to sustain the momentum initiated by the CoTC-CSC workshop in May 2021. For example, the PSC could sponsor a series of regular seminars on topics ranging from Monitoring Systems (e.g., sentinel stocks, environmental stop lights, data collection, analysis, management, and access) to Indigenous and Local Knowledge and Governance. The PSC could also commission production of a special compendium of papers on environmental change and salmon. These efforts could be supported by financial resources provided by PSC endowment funds and include synthesis and reporting to provide information for PSC deliberation and action. The PSC could also request that its Technical Committees and Panels incorporate measures to address environmental change in annual work plans.

Examine current practices

- Assess how robust current management systems are to environmental change (see CSC task below).
- Systematically evaluate if and how environmental indicators could be included in the work of Technical Committees by:
    - Identify which components of the Committee's assessment work could be quantitatively and/or qualitatively informed by environmental indicators;
    - Prioritize components according to the expected benefits of incorporating environmental indicators into them; and
    - Document next steps to advance further consideration and operationalization (e.g., additional analytical work, inventory of indicators and analytical methods, securing funding for additional analytical work and/or training, incorporation into work plans, etc.).
- Provide input and additions to the templates provided by the CSC that inventory to what extent climate change is accounted for in the stock assessment and fisheries management advice by:
    - Review the template for accuracy and completeness
    - Provide any supplementary narrative, such as barriers to including environmental covariates in the work of the Technical Committees (TCs)

Share information

- Encourage collaboration and coordination across technical committees and panels to accelerate accounting for environmental indicators in assessment and to avoid duplication of effort.
- Share case studies of successful (and unsuccessful) approaches to incorporating environmental indicators into salmon assessment and management (e.g., via regularly scheduled presentations from Technical Committees to the rest of the PSC family).
- Inventory readily available methods that can be adjusted for application by the Technical Committees.

Build technical capacities

- Encourage the organization of capacity-building workshops for Technical Committee members with regard to incorporating and/or considering environmental indicators in assessment work.
    - Apply for endowment funding to incorporate environmental covariates in the work of the Technical Committees (e.g., to implement the methods presented at the May 2021 workshop on environmental indicators and more prescriptive methods that may be identified in the future).
- Identify opportunities for Indigenous Knowledge and ways of knowing to help support the identification and use of environmental indicators by PSC processes.

Recommendations regarding future workshops

- Future workshops may consider:

    - Fewer talks and more time for Q & A and discussion
    - Breakout rooms with activities to increase participant engagement
    - If virtual, no more than four hours/day for no more than 2 consecutive days (avoid meeting fatigue)
    - Keep workshops virtual, inexpensive, and flexible
    - Hosted retransmission of recording (for those who missed it) with group discussion/breakout rooms/panel following rebroadcast
    - Develop an action plan to keep momentum going. This might include having an active blog or regularly scheduled (bi-monthly, quarterly) meetings to discuss use of environmental variation in salmon management, led by Tech Committee staff.
- Potential workshop topics:
    - In depth methodologies on using environmental indicators, including:
        - How to choose which environmental covariates to incorporate into your model (and how to do it).
        - Model choice for incorporation of environmental data, including model diagnostics and selection.
        - Best practices for communicating environmental model results to managers.
    - Broader, bigger picture topics for improved salmon assessment and management
        - How to consider/incorporate Indigenous Knowledge into models and/or management, and how to get those conversations started with First Nations/Tribes.
        - Looking forward: how to take future environmental conditions into account when making current decisions, including prioritization of actions, such as mitigation measures, hatchery planning, and assessing risks to stocks.

H. Responses to post-workshop questionnaire

Following the workshop, we sent out a questionnaire to workshop participants with a variety of questions on how useful the workshop was, whether it met their expectations, and their ideas for future workshops or issues related to environmental indicators and the PSC. Here, we provide a brief summary of responses to this questionnaire. The individual responses to the questions are provided in the Appendix.

A total of 27 participants completed the Post-Workshop Questionnaire. Almost everyone found the workshop to be useful and that the half-day schedule was a suitable duration. Although a small number of individuals found the workshop content to be too basic, the vast majority considered it sufficiently, but not overly technical. Nearly everyone found the 20-minute presentations to be a good length and that they included a broad enough range of topics. Although the feedback on the workshop was almost entirely positive, most participants found that there was not enough time for questions or discussion.

Almost all participants of the workshop would like to see more events that consider environmental variability and change and their implications for salmon assessments and management in support of the PST process in the future. The topics that individuals would like to see covered at these events were diverse and overall supported a workshop that included a broad range of topics (Fig. 1). Most individuals would prefer it to be structured as either a seminar and discussion-based workshop or an interactive workshop. Finally, most participants supported holding the workshop in either fall or winter, with only a few who would like it held in spring of next year.

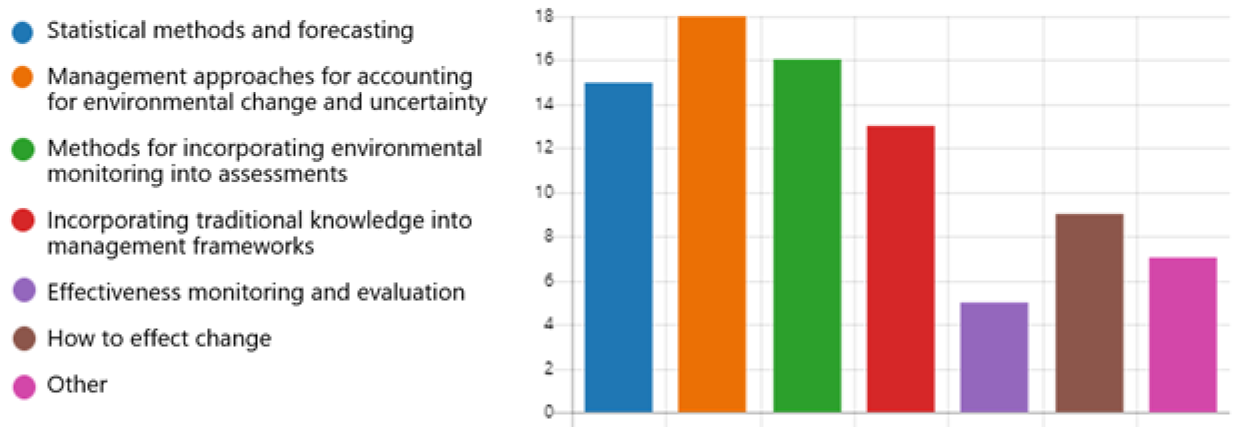

Figure 1. Topics that workshop participants would like to see covered in future events.

Long-answer response summaries

Question 1: What are the biggest barriers to the incorporation of environmental information into assessment and management of salmon in your geographic area under the PST?

The participants of the workshop identified a variety of barriers at different stages of the process of incorporating environmental information into assessment and management of salmon. Some of the barriers were specific to personnel, such as lack of statistical knowledge and technical skills as well as insufficient time for the additional workload these efforts would require. Other, more quantitative barriers were also highlighted, such as lack of basic stock assessment data and the inability of current models to incorporate uncertainty. The most commonly identified barrier was determining appropriate environmental indicators, which would allow for the improvement of forecasts. This is especially challenging due to rapidly changing environmental conditions which differ among regions as well as stocks. The fixed structure of in-season management also poses a barrier for some.

Question 2: What opportunities are there to incorporate environmental information into assessment and management of salmon under the PST?

Across participants, the most widely discussed opportunity for the incorporation of environmental information into assessment and management of salmon was the improvement of forecasting. It was noted that this information may also be useful for integrating uncertainty into assessments and allowing for precautionary management. Other participants addressed the need for incorporation of traditional knowledge and the value of involving First Nations and Tribes in the monitoring and restoration of salmon populations and habitats.

Question 3: What role should the PSC leadership (i.e., Commissioners, Panels, and Technical Committees) play in incorporation of environmental information into assessment and management (e.g., directing the…).

Many participants suggested that the PSC leadership should take more of a directive role, including clearly outlining the intended direction they aim to take for incorporating environmental information into assessment and management. Participants also suggested that the PSC leadership should focus on the development of environmental indicators and encourage their use in research, forecasting and assessments. These activities would include outlining standards for each species, making this information accessible to biologists, and providing guidance for how environmental indicators can be applied. The organization of future workshops similar to the one recently completed to facilitate information sharing and communication was favored by a number of participants as well. It was suggested that PSC leadership could provide support for individual entities to build knowledge, allowing localized experts to make decisions at smaller scales. In addition, examples of how the PSC leadership could directly incorporate environmental information into current assessment and management practices were given.

Question 4: How can the PST community best influence the institutions involved in Pacific salmon management and research to adapt and respond to environmental variability and change?

The need for formal acknowledgement by the PST community that changing environmental conditions are of concern for salmon populations was addressed by several participants. Examples of ways in which the PST community could influence institutions were suggested, including promoting workshops, funding and supporting projects, and collecting basic stock assessment data. A need for demonstrating the utility of incorporating environmental indicators within the agencies, Tribes, and First Nations that participate in the PST process was identified. The PST community could also provide information and data resources for environmental covariates that are useful for different regions and species.

Question 5: Please share any other thoughts you have.

Participants shared both feedback on the workshop itself as well as insightful thoughts and recommendations based on the presentations that were given.

I. Speaker profiles

Dr. Laurie Weitkamp has been a Research Fisheries Biologist at the Northwest Fisheries Science Center (NWFSC) since 1992. Her work at the NWFSC primarily consists of salmon conservation, salmon research, and salmon management. She has been involved in Endangered Species Act listings of Pacific salmon, from the scientific basis for listings to periodic status updates. Her research focuses on the ecology of salmon in estuarine and marine environments, specifically how physical conditions influence biological processes that are important for salmon survival, including the likely impacts of climate change. A starting point for this work is understanding where salmon are during all stages of ocean residence, including the poorly understood winter period. On the management side, Laurie serves on the CoTC of the PSC. She received her B.S., M.S., and Ph.D. degrees from the University of Washington.

Dr. Chris Harvey is a fishery biologist in the Ecosystem Sciences Program at the NOAA Fisheries Northwest Fisheries Science Center in Seattle, where he has been since 2002. His main research interest is the ecology of aquatic and marine food webs and how their dynamics interact with fisheries, climate variability, climate change, and other environmental drivers. Chris is also co-lead of the NOAA California Current Integrated Ecosystem Assessment team, which uses qualitative and quantitative tools to synthesize ecological, economic, and social data into tangible products that are useful for ecosystem-based management along the West Coast.

Dr. Nate Mantua leads the Salmon Ecology Team at NOAA's Southwest Fisheries Science Center in Santa Cruz, California. This interdisciplinary group of scientists works to understand links between habitat and anadromous fish that spawn in California's watersheds but migrate to the ocean for growth and maturation. Nate worked at the University of Washington in Seattle from 1995-2012 where he co-directed the Climate Impacts Group. He was an Associate Professor in the University of Washington School of Aquatic and Fishery Sciences from 2006-2012. His research interests include climate variability and predictability, climate impacts on natural resources, and the use of climate information in resource management.

Dr. Andrea Reid is a citizen of the Nisga'a Nation and a new Assistant Professor with the University of British Columbia's Institute for the Oceans and Fisheries. She is helping to launch and lead the Centre for Indigenous Fisheries, working to build a national and international hub for the study and protection of culturally significant fish and fisheries. Her research program adopts highly interdisciplinary and applied approaches to improving our understanding of the complex interrelationships between fish, people, and place. Reid's Ph.D. in Biology (Governor General's Gold Medal; Carleton University '20) centered on multiple stressor effects on Pacific salmon, using tools and insights from Western and Indigenous sciences in tandem. Reid is a cofounder of Riparia, a Canadian charity that connects diverse young women with science on the water to grow the next generation of water protectors. She is also a National Geographic Explorer and a Fellow of The Explorers Club.

Dr. Brian Burke has worked in fisheries since 1993 and joined the NWFSC in early 2002. His interests lie primarily in ecological modeling--from small-scale processes such as energetics and physiology of individuals to larger-scale processes such as animal movement, habitat quality, and population fluctuations. Brian received a B.S. in Natural Resource Management from Ohio

State University, an M.S. in Zoology from North Carolina State University, and a Ph.D. from the School of Aquatic and Fishery Sciences at the University of Washington. Brian currently leads the Ocean Ecology Team in the Fish Ecology Division at the Northwest Fisheries Science Center. With team members and various collaborators, he is focused on several studies, including habitat preferences and behavior of Pacific salmon during their early ocean residence and the influence of various ocean indicators on salmon survival.

Sue Grant, along with Bronwyn MacDonald, leads DFO's State of the Salmon Program. Sue's aquatic biology career in Canada has spanned Atlantic cod on the east coast, fish ecology in Northern Alberta, and in recent decades Pacific salmon on the west coast. The goal of the State of the Salmon Program is to track and understand Pacific Salmon trends. This program leads integrative processes and develops data visualization tools to achieve these goals. Through this work, climate change has emerged as a key threat to Pacific Salmon, which will rapidly require new innovative and integrative ways to prioritize management actions going forward.

Dr. Kathryn Sobocinski is an Assistant Professor in the Department of Environmental Sciences and the Marine and Coastal Science program at Western Washington University. She is an applied marine ecologist focusing on fishes, fish habitats, and impacts of human disturbance and climate change in coastal ecosystems. She uses statistical, ecological, and individual-based models in conjunction with field data to describe patterns and processes in these ecosystems. She works on several projects related to salmon marine survival and fish ecology more broadly within the Salish Sea and the Bering Sea. Dr. Sobocinski has B.A. from Connecticut College, M.S. from UW-School of Aquatic and Fishery Sciences, and a Ph.D. from the College of William & Mary, Virginia Institute of Marine Science. She completed postdoctoral work at Oregon State and NOAA-NWFSC.

Appendix. Individual responses to post-workshop questionnaire

Question 1: What are the biggest barriers to the incorporation of environmental information into assessment and management of salmon in your geographic area under the PST?

- Technical capacity and knowledge.
- Technical knowledge of statistical methods to appropriately analyze environmental data and use them for forecasts, staff time and availability to do so, and lack of technical understanding of policy- and decision-makers concerning the outcomes of respective data analyses.
- Insufficient time to do this work under the PST and lack of bilateral agreement.
- Additional workload.
- The PSC Chinook Model does not have the ability to incorporate uncertainty into it, environmental or otherwise. Our biggest barrier is time to recode the model and testing.

- The lack of basic stock assessment information that is accurate and precise, as without those components it is meaningless to try and incorporate environmental information.
- Basic stock assessment data. Seber, in his 1982 book on estimating animal abundance, recommended that for conducting careful research into population dynamics, abundance should be measured with an accuracy of 10% with 95% probability. This bar is rarely met. In addition to the lack of basic stock assessment data, salmon research lacks basic, experimentally-driven research. Correlating environmental information into stock research is all well and good, but ultimately it is observational-based research and does not provide the insight into the underlying mechanisms like experiments can. There remains only a few, and actually maybe just one (Little Port Walter) research hatcheries and even there, the work has been highly curtailed.
- Not enough interaction between agencies and areas to develop and implement consistent methods. There is not a lot of information out there on what datasets exist for environmental indicators.
- The fact that this is a (relatively) new big-picture criteria to be incorporated into the scheme of agencies' considerations.
- Determining appropriate information.
- Quantitative: figuring out what fits and/or works and how to identify when historical fits are breaking down. Qualitative: where to even begin regarding the inclusion of Indigenous knowledge.
- The interplay between environmental information and the FRAM Model results.
- Based on the information provided at the workshop, it seems that there are no broad indicators with widespread application. This means that existing environmental indicators have to be almost stock-specific, and even at that level can vary year-to-year.
- With Chum, we are still at the stage of getting a good handle on the abundance and are just starting to dip our toes into the environmental information. Our struggle right now is knowing what information is out there that does or may apply to Chum (i.e., how to get started).
- Consistent, relevant time series that can be used in forecasting.
- The lack of covariates that consistently help forecast abundance for effective management.
- Currently there are no quantifiable or approved methods for improving forecasts and resulting management of local stocks or PST coastwide stocks that I am aware of. The majority of literature I have read on this topic identifies changing environmental conditions but does not specifically address how those changes can be implemented in management. I thought that was the number one thing this workshop was lacking: a clear path to using this information in a practical management setting.

- Change management of stakeholders, political perspectives. Uncertainty around forecasts.
- Changing relationships and the need to make robust predictions in-season (i.e., the environmental indicators must also be available in-season).
- Rigid structure of pre-season forecast, harvest, and post-season assessment.
- The environment is changing rapidly and when it wasn't, we had a hard time predicting abundance. Having a lot of trust in using environmental information to apply to specific stocks is challenging, particularly after hearing how much more, and rapidly, things are changing.
- Fragmentation, inertia, and pace of environmental change.
- I think these questions are too narrow in scope. Conditions are dramatically changing, and urgent visionary action is required under climate change. Our management systems are too complex and will break given the huge environmental change occurring. This demands radical reorganization and directions. I think the focus on environmental indicators for fisheries management is way behind where we need to be going. I am seeing less need to improve forecasts and predictions for next year, and instead what do we need to do to realign management and science towards a very different future under climate change.
- Too complex with questionable outcomes.
- There are those who do not agree with the concept of anthropogenic climate forcing and appear resistant to including environmental indicators as it makes things "too complicated".

Question 2: What opportunities are there to incorporate environmental information into assessment and management of salmon under the PST?

- Forecasting is probably the most obvious, but also stock-recruitment work should consider this kind of information.
- Forecasting seems to be the most universal.
- Run-size forecasting, escapement estimation, return timing (implemented already).
- I won't speak to the DFO forecast, but for the PSC there is an opportunity to use environmental information in alternate models to help predict run size, timing, and diversion rate of both sockeye and pinks pre-season that could serve to corroborate the DFO forecasts and could also be used as in-season tools especially for pinks given the difficulties associated with delay etc.
- Perhaps with continued research into indicators, there may be application of existing or new indicators into assessment and forecasting. I'm hopeful.

- Forecasting is perhaps the easiest way to incorporate environmental information into assessments. But taking into account environmental changes and changes in productivity also cause changes to escapement goals and this is a much more important area to include environmental information.
- Environmental information and indicators can be used to help inform management to provide uncertainty into the assessments and management, giving managers a range of options when making decisions.
- I think everyone is starting to understand the importance of doing this, and there are lots of opportunities to do so with the various assessment models we have.
- Our fisheries are abundance based, so additional environmental information does not affect in-season management. This information would be more helpful in forecasting and understanding trends in production, for a post-season look on why returns were what they were and may also be helpful for framing future negotiations of the PST.
- By estimating marine survivals for many Chinook stocks coastwide, trends could be identified and incorporated into the Chinook model, including changing maturation rates which has the biggest influence on model outputs.
- Precautionary approach. Recent migration mortality research seems to be strongly relating river flow/temperature stress as well as stress from terminal harvest encounters to mortality, requiring careful consideration of management priorities to ensure there are spawners on the spawning grounds.
- Reduce emphasis on reductionist research and management approaches and focus instead on integrated consideration of uncertainty, precautionary management to improve resiliency and adaptation, including restructuring of fishing practices and patterns. Increase involvement of First Nations and Tribes in monitoring and restoration of fish and habitats, including application of their traditional sciences and knowledges.
- Due to the horrific outlook around climate change and the rapidly changing and unpredictable impacts to natural resources, it seems that incorporating environmental information and traditional knowledge to manage for recovery is a must. Simply put, not sure how long we can keep propping up pre-terminal fisheries in light of the need for recovery and climate change. Traditional knowledge would have us fishing way closer to terminal areas on mature and known stocks while assuring escapement (using ISUs).
- The willingness must be there.
- Given that there are a whole lot of individuals and groups working on these issues, there is an opportunity to discuss and compile best practices (i.e., what works and what doesn't work) for each species, so newer staff don't need to start from scratch.
- There are new programs such as the $50 million ocean monitoring funded by the National Science Foundation, IYOS, international, and interagency monitoring programs.
- Many.

- Not many, as only a handful of stocks have accurate and precise measures of full run reconstruction.
- We are losing the forest for the trees. Focusing on environmental indicators is not enough now.
- Good for reference but should not be used as a management tool.
- Assessments, but not going to get into that as there are lots that are already being used for Fraser River sockeye. However, management (i.e., because we do not "manage salmon") becomes a lot more interesting. Do we adjust in-season management decisions based on adverse migration conditions (and if yes, how) and how does that back out into marine approach waters? Does genomics information exist that we can use to inform marine fisheries decisions? What is even "allowed" under the current PST language? How do we (biologists) support future renegotiation of the PST Chapters from an environmental change perspective? At what point do the people in charge of finances say "Nope, not enough fish, we are pulling out of the PST."?

Question 3: What role should the PSC leadership (i.e., Commissioners, Panels, and Technical Committees) play in incorporation of environmental information into assessment and management (e.g., directing the…).

- As planned, organize additional workshops of this nature. Hopefully develop tools that are sufficiently generalized to be applicable with each Technical Committee.
- This workshop approach is the best first step in trying to determine and answer this.
- Organizing workshops, providing and disseminating information on how to best analyze environmental information for forecasts, educate policy staff and decision makers so that they are able to properly apply the results of analyses performed by technical staff.
- Define the big-picture strategy and direction. It helps if we are all pulling in the same direction. Also, more cross-pollination between Technical Committees and those working on incorporating environmental information (i.e., between species, between countries).
- Advisory and education. Decisions on if, and how best to incorporate environmental data into stock assessment and management is best left to the subject experts at the individual agencies.
- Any efforts in this regard should be directed from the Commissioner level or the various panels (e.g., the Chinook Interface Group). This kind of endeavour would be a multi-year approach and would also require very specific and clear direction.
- Commissioners can direct Panels and Technical Committees to focus efforts on incorporating this information. My impression is that we are willing to make the change if it is requested of us. We would rely heavily on agencies to provide information for assessment, and there is a significant amount of work to determine which indicators perform best, but I believe given the directive, we could make the changes (it would not be an overnight thing though).

- I think PSC leadership should focus on the development of indicators and standards for each species and ensure coordination among Technical Committees so there isn't a duplication of work. I am not as familiar with what environmental information is out there now or could potentially be tracked to know if there are large gaps that need filling.
- Using and communicating the use of the environmental indicators into the model results. Possibly using indicators to inform scenario planning and/or describing uncertainty in model results.
- The PSC can probably play a productive role in supporting the efforts of individual entities to build capacity and knowledge to incorporate such information. Workshops/seminars like this are a good way to do this.
- All of the above examples (i.e., development of indicators and standards for each species, coastwide environmental sampling initiatives). A synthesis or summary of information about what data are currently being collected, and where to find it. Build and maintain an accessible database containing environmental data that are relevant to all PST chapters. This is a big ask, but maybe something to consider for the future.
- Collaboration and discussion (like these workshops) that hopefully create agreement and a shared research agenda across institutions.
- It is essential that the PSC (and agency) leadership increase the research and development of environmental indicators into assessment and management. This workshop confirms that our environment continues to change at a rapid rate and in unpredictable ways, so doing whatever we can to conserve Pacific salmon is vital.
- Promoting coast-wide sampling networks and a holistic look at salmon and the total of their environments. Much light could be shed on the black box that is ocean survival.
- Reduce focus on fishery management and undertake efforts to integrate environmental considerations and overcome institutional conflicts and barriers. Undertake serious, substantive dialogue and create institutional structures to reconcile differences to effect change.
- Managing total mortality based on expected migration and environmental indications.
- Push for terminal area management to recover and continue to fish.
- First, evaluate which existing management systems are most risk-averse in the face of environmental change. Second, invest in more near-shore in-season (e.g., assessments for Chinook and coho salmon). Third, publish a mission statement to the administrations and political bodies of both countries to highlight the devastating effects of climate change on salmon and the need to reduce greenhouse gas emissions.
- The PSC needs to go way beyond these questions here in terms of leadership. Acknowledgement of global climate change as a key threat, and that we are already seeing serious consequences, needs to be addressed. All other factors driving salmon trends are enmeshed in global climate change and can't be disentangled from it. How can

we maintain economic opportunity going forward, particularly in southern latitudes, how will the US-Canada Treaty influence this going forward? Increasingly, the focus will be less on large commercial fisheries, and more on terminal ones, and how will we ensure that we have some salmon in the future? Not all salmon populations and species will survive climate changes, so how do we align, how do we look to habitat and hatcheries to retain cool water refugia in freshwater, etc.?

- An easy first step would be to incorporate known cause and effect relationships (e.g., el Niño).
- Include changes in productivity into reference points and escapement goals.
- We are on thin ice with this topic. Although I appreciate the eagerness to pull in environmental information into our stock assessments, forecasts, etc., for the vast majority of stocks we are not shoring up the first part of the equation which is gathering accurate and precise measures of full run reconstruction over the long haul. This is a cart before the horse exercise for most stocks along the coast.
- They shouldn’t.

Question 4: How can the PST community best influence the institutions involved in Pacific salmon management and research to adapt and respond to environmental variability and change?

- By strongly acknowledging climate change and the radical changes we are already seeing and starting to chart a bold vision for how the PST can help going forward. We have very complex management systems that will break under rapid climate change, so how do we start adjusting now?
- Acknowledge that environmental change is likely to continue to affect salmon population dynamics in the future, at not just the Technical Committee but also the Panel and Commissioner level, and in Treaty language. This seems to be a no-brainer, but at times it feels like there is some conflict between the scientific perspective (i.e., advocates for incorporating time-varying productivity into models) and bilateral management objectives (i.e., setting and managing to fixed escapement goals for some species, despite the challenges posed by shifts in productivity that all species are experiencing).
- The PST community can lead as an innovative and progressive bilateral, international organization that can spread the application of environmental indicators (and other salmon conservation initiatives) throughout the agencies, Tribes, and First Nations that participate in the PST process.
- Take a leadership role in advancing alternatives to address uncertainty and risk throughout salmon life cycles.
- Provide resources for environmental covariates that are useful for different regions and species.

- By establishing a timeseries of indicator data and continuing to work on understanding their interactions with each other and on the various salmon species.
- By demonstrating their potential utility.
- Support and provide a nexus for learning and coordination.
- Continue to support/encourage involvement in workshops like this. Presenting results and sharing the importance of it with the senior-level PST groups (e.g., the Southern Panel) would likely ensure their continued support as well.
- Continuation of these workshops with further group discussions on this topic as part of the process would be informative.
- Funding more basic stock assessment projects and bolstering existing projects.
- By emphasizing the basics of gathering accurate and precise measures of escapement, harvest, run by age, size and sex to allow estimates of parent year return, survival, and exploitation rate along with calendar year harvest rates.
- Southern Endowment Fund projects. Reaching out to collaborators to suggest areas of interest and value. This should likely be a two-way street though.
- The thing that strikes me the most about salmon stock assessments and forecasting is the lack of incorporating uncertainty into management reference points. If we are unable to directly estimate uncertainty can we use indicators to inform scenario planning so we can be prepared when the models are wrong.
- Harvest is the impact we have the most control over. Use this lever! Habitat is out of our control, hatcheries have limited use in conservation if they are unable to successfully contribute to escapement (high holding mortalities after stressful migrations, low marine survival).
- The managers are effective. The salmon abundance is dropping, and managers seem to be responding appropriately.
- Think big. Think ahead. I think my biggest concern is that we are all very good at reacting to the stuff thrown at us. But, because there's so much stuff being thrown at us, we seldom have the time to be proactive. And we need to make time to be proactive. Now.
- There are a mix of managers who recognize, appreciate, and follow the PST process and some who do not. As long as this exists, the PST community will not have the level of influence required to implement large-scale systemic changes.
- I doubt the PST can influence Canadian domestic salmon management other than what is outlined in the Treaty.
- They shouldn’t.

Question 5: Please share any other thoughts you have.

- Thank you for organizing the workshop. I really appreciated the learning opportunity.
- Well-run and clean workshop. It covered a wide variety of topics and I think sparked a lot of information exchange.
- I felt that this was an excellent virtual workshop. The speakers were fantastic (heavy hitters), the presentations were sharp, and you could tell that it was well coordinated. All the way around, it was an extremely useful and well run workshop. The only thing that would have made it better would have been if it was in person. But I would say that it was the best virtual workshop I've attended. Also, I loved the funny personal vignettes at the start of each presentation. Nice touch. Thank you for your hard work. It paid off.
- The workshop and speakers were excellent. My only suggestion would be to have a longer interactive roundtable discussion at the end; perhaps this was planned but Covid/Zoom prevented it.
- The meeting was great; the presentations were generally at a good level for sharing ideas. The panel discussion questions did not reflect the tone of many of the presentations and got too in the weeds. I think it is critical to step back and look at the big picture, as many of the presentations were indicating, and really figure out what is needed. I also think these large meetings are good for information presented, but too large for meaningful discussion. You might want a combination of smaller meetings with great thinkers and break-out groups and structure to foster meaningful discussion. I think the PSC needs to get bold, visionary, and lead.
- Lots of great info. It was a bit like being fire-hosed with data, and with little to no time for questions and discussion before moving on to the next presentation, it was hard to get a good grasp on any particular one.
- The workshop would have been better described as a half-day academic conference, rather than an actual workshop. A workshop is an event where the audience gets to participate, rather than just getting talked at.
- I thought the workshop was a good start to learning about the importance of incorporating environmental information into assessment and management. It felt a bit more "conferency" than I was expecting though, rather than an instructive workshop. In particular there was a lot to digest very quickly and there was not enough time for discussion. Though it was great to see examples of how this has been done already and better understand the importance and complexity of the process, I didn't feel that I walked away with an understanding of how to get started. I would love to see a more technical workshop, but even then, it doesn't have to get into the extreme details of modelling. As a start, some of the things I'd like to know are: how to choose which environmental covariates to incorporate into your model (is there a standard list of common ones that affect abundance/survival? Does it matter whether you're looking at everything on the same time step as your abundance/survival data?); what kinds of models you can use to incorporate environmental data (if you already have a S-R model, do you have to build one with a different structure?); how to handle/communicate the fact that the best models

may change annually because of changing ocean conditions; model diagnostics and selection - what is different from other types of models (e.g., it was mentioned a few times that AIC may not be the best choice - what is the alternative?). This could easily be a one-two day workshop. In addition, this added complexity could make management discussions more difficult. Best practices for communicating about this information would be helpful. I am also very interested to learn more about how to consider/incorporate Indigenous knowledge into models and/or management, and how to get those conversations started with First Nations.

- Application of Traditional Ecological Knowledge is an admirable goal. There is lots of talk regarding its potential role, but little demonstration of application. If it's to be included in future workshops, I'd prefer to see the application side of its role, rather than social commentary.

- Too many scientists and not enough stakeholders.

- Although I listen very closely to stakeholders and try and soak up their vast and many varied experiences, I implore staff to first dedicate the funds necessary to estimate the basics. For far too many important stocks along the coast we fail to accurately and precisely measure run reconstruction components, as basic as escapement. It's within our ability to measure freshwater production and adult returns; the in-between, which is a focus of this forum, may never be understood and even so, what would we be able to do with the information?

- Overall, this was a well-run workshop with a wide array of presenters on different aspects of environmental variability and change. Despite the large amount of information and scientific researchers presenting their work, I didn't hear directed messages on specific ways to affect salmon management with all this new information. That lack of practicality left me wanting for more (i.e., yes, the ocean is warming, so what?). How do we use this information to better inform forecasts, abundance estimates, and resulting coastwide management? How do we get away from inferring ocean distributions based on catches and fishery sampling and use alternate methods to better inform ocean distribution and timing? These are lingering questions in my mind and could be included in subsequent workshops. Appreciate the efforts on this very wide ranging, broad, important topic.

- The PSC is not going to cool down the oceans and rivers. The PSC needs to partner with similar organizations to fight against ruining the Earth’s ability to support salmon and ecological systems.

- Climate is changing rapidly. Stocks declining. Recovery. Do we continue to fish on mixed stocks (weak included), mixed species, and all age classes? It seems like we are trying to justify our preterminal “need” to fish. I do understand that there is much more to it and it is not as simple as turning off preterminal fisheries. I just hope, despite all of the climate issues that were presented, that oceans turn around and allow for recovery with continued preterminal fishing. If not, nature will shut it down for us.

- Broader, bigger-picture things such as how to take future environmental conditions into account when making future decisions (e.g., mitigation measures). What is appropriate for now compared to what is appropriate for the future (e.g., planning for hatcheries to take into account future conditions, which stocks are likely to need help or are "lost causes"). We can't do everything, so how do we prioritize?

- Read some of the literature around the Canadian East Coast cod collapse to better understand the insanity of fighting over allocation for declining population abundances, and the political complexities.

- Develop a framework that will facilitate deliberation and provide readily accessible information regarding environmental change and Pacific salmon.