PERSPECTIVE

Kings of the North: Bridging Disciplines to Understand the Effects of Changing Climate on Chinook Salmon in the Arctic–Yukon–Kuskokwim Region

Megan L. Feddern | College of Fisheries and Ocean Sciences, University of Alaska Fairbanks, 17101 Point Lena Loop Road, Juneau, AK 99801. E-mail: mfeddern@alaska.edu

Erik R. Schoen | International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK

Rebecca Shaftel | Alaska Center for Conservation Science, University of Alaska Anchorage, Anchorage, AK

Curry J. Cunningham | College of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Juneau, AK

Craig Chythlook | International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK

Brendan M. Connors | Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, Canada

Alyssa D. Murdoch | Department of Biology and Canadian Centre for Evidence-Based Conservation, Carleton University, Ottawa, ON, Canada | Wildlife Conservation Society Canada, Whitehorse, YT, Canada

Vanessa R. vonBiela | U.S. Geological Survey, Alaska Science Center, Anchorage, AK

Brooke Woods | Woodwell Climate Research Center, Falmouth, MA

Understanding how species are responding to environmental change is a central challenge for stewards and managers of fish and wildlife who seek to maintain harvest opportunities for communities and Indigenous peoples. This is a particularly daunting but increasingly important task in remote, high-latitude regions where environmental conditions are changing rapidly and data collection is logistically difficult. The Arctic–Yukon–Kuskokwim (AYK) region encompasses the northern extent of the Chinook Salmon *Oncorhynchus tshawytscha* range where populations are experiencing rapid rates of environmental change across both freshwater and marine habitats due to global climate change. Climate–salmon interactions in the AYK region are a particularly pressing issue as many local communities have a deep reliance on a subsistence way of life. Here, we synthesize perspectives shared at a recent workshop on Chinook Salmon declines in the AYK region. The objectives were to discuss current understandings of climate–Chinook Salmon interactions, develop a set of outstanding questions, review available data and its limitations in addressing these questions, and describe the perspectives expressed by participants in this workshop from diverse backgrounds. We conclude by suggesting pathways forward to integrate different types of information and build relationships among communities, academic partners, and fishery management agencies.

INTRODUCTION

A new paradigm of Pacific salmon *Oncorhynchus* spp. population decline has emerged in one of the least expected places, at the northern extent of their range. Fish declines are often tied to habitat degradation from human infrastructure development at regional and local scales (e.g., dams or the reshaping of beaches, wetlands, and side channels for housing and agriculture), which have the potential to interact with climate change to produce unexpected effects on fish populations (Munsch et al. 2022). In the Arctic–Yukon–Kuskokwim (AYK) region, which includes the Yukon River (USA and Canada), Kuskokwim River, and Norton Sound drainages (Schindler et al. 2013), large-scale infrastructure is nearly absent. Yet despite the continued availability of relatively cool thermal habitats nearly year-round, many salmon populations in the AYK region have declined in abundance, and global climate change has emerged as a potential driver. Here, we summarize the outcomes from a 2022 workshop focused on understanding the causes of Chinook Salmon *Oncorhynchus tshawytscha* declines in AYK watersheds. The AYK region presents a notable example of rapid environmental change, remoteness, and data limitations, but these challenges are not unique, and we summarize pathways forward that are broadly applicable to other regions and species.

Origins

In April 2022, an international group of participants from Tribes and First Nations, government agencies, nonprofits, and universities in the United States and Canada gathered in Fairbanks, Alaska to discuss environmental processes impacting Chinook Salmon, commonly known as king salmon (Feddern et al. 2023; Supplemental Information). The

DOI: 10.1002/fsh.10923

initial goal of this workshop, entitled "Drivers and Diversity of Chinook Salmon, an Arctic–Yukon–Kuskokwim Region Focus," was for university scientists to discuss data quality with agency collaborators in preparation for an analysis quantifying environmental drivers of Chinook Salmon productivity in the AYK region. During the planning process it became clear that this gathering presented a unique opportunity to broaden the conversation and bring researchers, fishery managers, and local and traditional knowledge holders together across borders, regions, and backgrounds. Together, we discussed the current state of AYK Chinook Salmon populations, challenges facing both salmon and people, and available sources of information to address these challenges, and developed a set of questions to guide future collaborative research and actions to support Chinook Salmon conservation and recovery (Figure 1; Table 1).

The workshop was attended by 48 people, including 2 facilitators and 4 organizers, representing 10 departments at 3 universities, 10 Native communities and intertribal commissions, and 6 government agencies (Feddern et al. 2023; Supplemental Information). The goals outlined for the workshop were to (1) summarize the current understanding of Chinook Salmon–Climate interactions in the AYK region, (2) develop a set of questions related to Chinook Salmon and the environment, (3) identify data or information that could address these questions, and (4) initiate this manuscript. Conversations were structured both formally, in the form of presentations, and informally, in the form of open-ended brainstorming and break-out group conversations (Supplementary Information). The content and value of the manuscript was discussed at the workshop and all participants were invited to participate as coauthors. It was collectively decided that the synthesis of perspectives shared in this manuscript would not be attributed to individual participants or user groups. Participants were provided with an opportunity to provide feedback on an initial draft of this manuscript prepared by workshop organizers after the workshop and were encouraged to opt in as coauthors at multiple stages of the process, as they felt appropriate.

Positionality

In this Perspective, we synthesize the ideas that were presented and key themes that emerged at the 2022 workshop. The intellectual guidance of workshop participants, including elders, Indigenous leaders, scientists, students, and others who shared knowledge, experiences, and reflections at the workshop are the foundation of this publication. However, workshop participants only represented a portion of diverse identities and perspectives in the Yukon, Kuskokwim, and Norton Sound watersheds, and this paper does not fully encompass the knowledge and experiences of all people in the region. These ideas were a product of who was able to participate in the workshop, and we acknowledge the themes and conversations would have been different if others were present. During the production of this manuscript, we grappled with how to respectfully represent diverse and sometimes competing perspectives, attribute authorship, and solicit post-workshop participation for a publication that adheres to academic norms. The authors of this paper represent both Indigenous and non-Indigenous identities and are mostly academics, for whom writing and manuscript preparation falls within their compensated job description. This is broadly emblematic of inequity in decision making, utility, and the means and abilities to realize research products. We wish to recognize the vital intellectual contributions of all of the workshop participants; without their contributions, this synthesis would not have been possible.

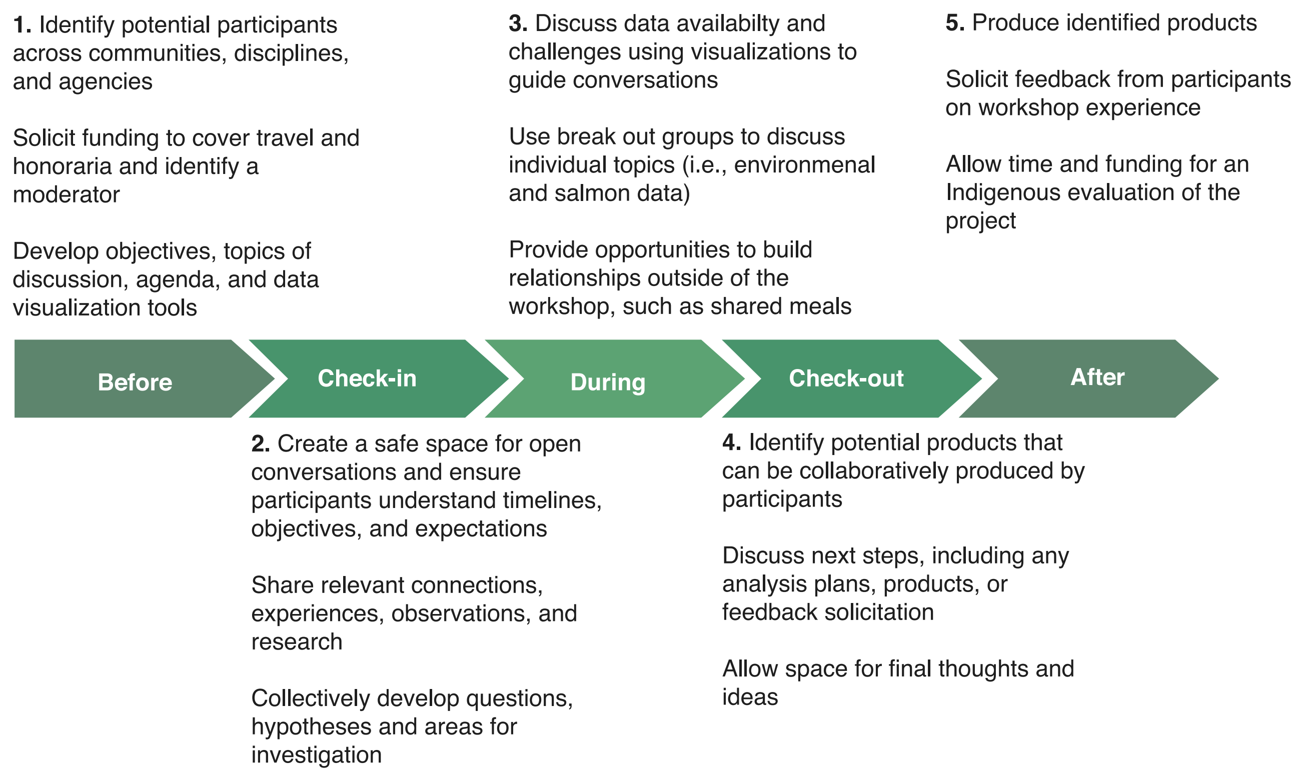


Figure 1. Workshop structure for planning collaborative meetings based on the 2022 Arctic–Yukon–Kuskokwim region Chinook workshop.

Table 1. Persisting questions of how environmental conditions could impact Chinook Salmon productivity in the Arctic–Yukon–Kuskokwim region. Questions were brainstormed by participants drawing on research, personal observations, and experiences. Questions were documented on a whiteboard, in notes taken by workshop organizers, and in a recording of the conversation that was used for reference in drafting this table. Feedback was solicited from participants after the workshop to identify missing ideas and provide clarification.

Perisisting questions
Do cold winters and low water, such as that observed in the Porcupine River where ice froze to gravel, lead to slower embryo development or mortality?
What is the importance of groundwater in temperature refugia (warmer refugia in winter, cool refugia in summer) and hydrologic regimes in these systems? How is it related to melting glaciers?
What is the effect of beaver dams blocking access to rearing and spawning habitat? Have increases in beaver abundance due to regulations restricting human caused mortality impacted salmon?
Has there been a change in frequency of hydro-dam blowouts due to changes in hydrology and flow? How might blowouts impact juvenile Chinook?
How do the number of high water events affect young of year and egg deposition?
How frequently are fry getting stranded from habitat and migration corridors by dewatering of channels or loss of connectivity to off-channel habitats? How does water level in fall to spring interact with flooding and highwater events to cause this?
How do wildfires impact Chinook Salmon productivity? How does silt and nutrients introduced by fire impact egg development and juvenile Chinook?
How is permafrost melt impacting water temperature, carbon content, water quality, sedimentation, and nutrients? How is change in permafrost (observed near Old Crow) impacting salmon productivity?
Are there size, body condition, or timing requirements for smolt outmigration? How might this impact survival and productivity?
Is freshwater predation an important consideration and how has it changed? Particularly with pike, burbot, sheefish and other whitefish, which used to be fished more intensively to feed dog teams before snowmobiles became widespread.
Does salinity impact smolt distribution, diet, and growth as they transition from river to nearshore marine waters?
How does piscivory and diet during outmigration and early marine residency impact Chinook Salmon? (i.e., consumption of pink salmon fry versus insects)
What is the role of habitat complexity in maintaining salmon productivity, such as side channels and spring creeks, which seem to be declining?
What is the role and mechanism of ice breakup timing impacting Chinook Salmon productivity?
What is the role of alternate life histories? (i.e., fry that stay an extra year in freshwater or are freshwater residents as observed in Teslin River)
How does the presence of predators, such as belugas, impact Chinook Salmon river entry?
Is environmental variation shared across salmon rearing areas or migration corridors eliciting common responses, or are tributary-specific environmental conditions more important for regulating salmon survival and productivity?
How does abundance of other Pacific salmon, particularly hatchery produced Chum Salmon, impact marine survival? Is this driven by predation, interference competition, or competition for common resources at certain life stages?
How do high flow events in fall and early winter impact nutrients and juvenile growth the next year?
How has marine predation on Chinook Salmon changed, particularly with regards to marine mammals, Salmon Sharks *Lamna ditropis*, and the "increasingly dangerous ocean" hypothesis?
How does spawning migration success relate to discharge levels during migration (in the mainstem Yukon specifically)?
How does adult migration stress (e.g., due to high water temperatures) affect survival and reproductive success?
How does the range of Chinook Salmon in the ocean overlap with major fisheries such as pollock? Is this changing? How might it impact bycatch?
Would reductions in bycatch improve salmon run abundance? What is the overall impact of bycatch on the number of adults that return spawn and overall productivity?

CLIMATE–CHINOOK SALMON INTERACTIONS IN THE AYK REGION

The workshop began with a discussion of how Chinook Salmon populations have changed throughout the AYK region, which included recent research and personal experiences. Here, we review the science that was presented and the perspectives that were shared.

Changes in High Latitude Salmon Systems: A Review

Chinook Salmon have supported subsistence ways of life and the wellbeing of Indigenous peoples in the AYK region, including 118 Alaskan Tribes and over 18 Canadian First Nations, since time immemorial. They also supported valuable commercial, recreational, and subsistence fisheries during much of the 20th century. A provision to maintain opportunities for a subsistence way of life on U.S. federal lands was established by the Alaska National Interest Lands Conservation Act of 1980 (16 U.S.C. Section 3101–3233) and is applicable to a large portion of the AYK region. In Canada, the Aboriginal Fisheries Strategy was implemented in 1992 and protects the right to fish for food, social, and ceremonial purposes. Declines in Chinook Salmon abundance and productivity during the 1990s and mid-2000s resulted in closures of Chinook Salmon commercial fisheries and limits to directed subsistence opportunities throughout most of the region that have continued in recent years (ADFG 2013; Schindler et al. 2013; JTC 2022), causing severe hardship for subsistence-dependent peoples and communities.

The AYK region has experienced rapid warming and altered seasonal precipitation patterns, and these changes are projected to accelerate. Warming in western and interior Alaska is nearly four times faster than the global average

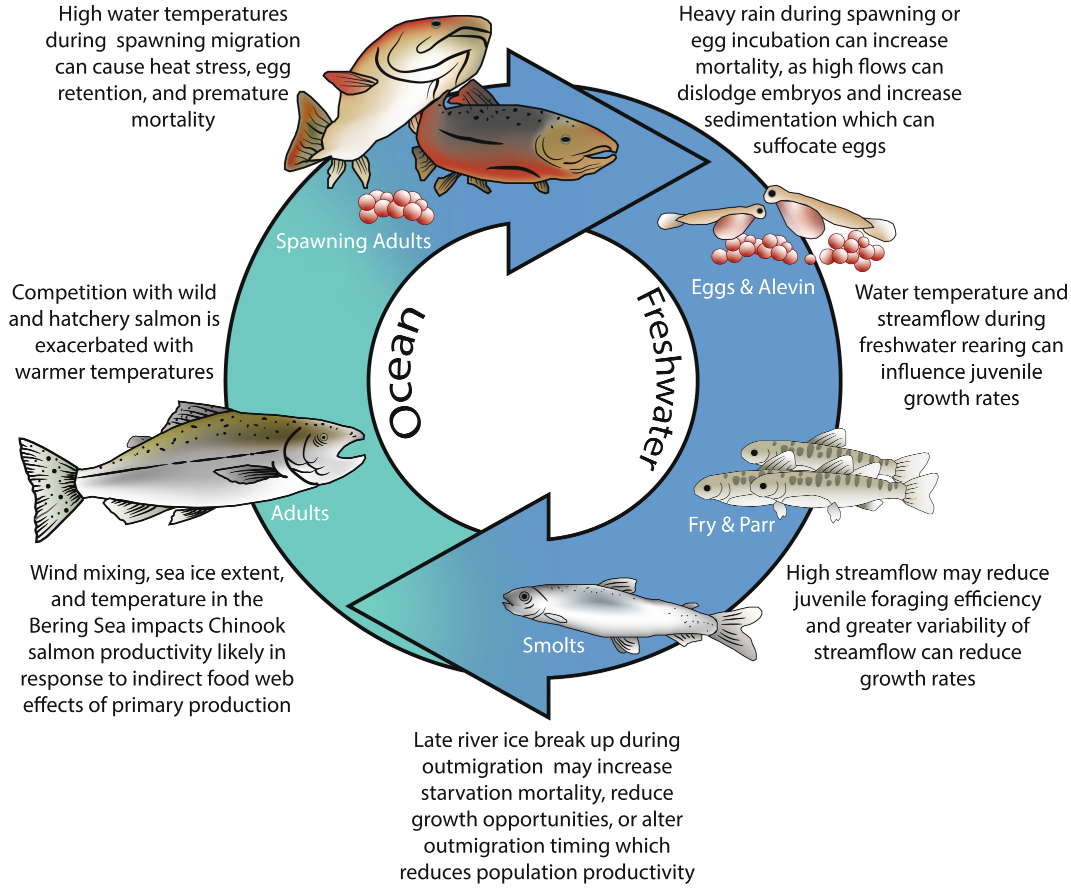


Figure 2. Interactions between environmental conditions and Chinook Salmon throughout the salmon lifecycle based on western science research.

and twice that of the continental USA (Stewart et al. 2022). Climate change can affect Chinook Salmon throughout their lifecycle (Figure 2; Crozier et al. 2021), and local and traditional knowledge holders and western scientists have drawn connections between rapid changes in rivers and the ocean, and declining Chinook Salmon returns in the AYK region. Three major climate events in the past decade have been particularly salient in recognizing that many AYK salmon habitats have experienced warming beyond their envelope of natural variation, which include the Pacific Marine Heatwave of 2014–2016, the Pacific Marine Heatwave of 2019, and an air temperature heatwave and drought in 2019. This warming is believed to have negatively impacted Chinook Salmon, which would represent a fundamental departure from previous decades of salmon ecology research that consistently found that warmer conditions improved salmon production in northern regions (Hare et al. 1999).

The Yukon River is a worst-case example of salmon declines in the AYK region. A transboundary system with salmon crossing through Alaska destined for Canada, the Yukon River involves multiple entities in the salmon management decision process. These decisions impact a diverse group of communities that rely on salmon for economic, cultural, traditional, and food security needs. In 2020, multiple species of salmon returned to the Yukon River at near record low abundances in both Canada and Alaska, followed by record low returns in both 2021 (JTC 2022) and 2022 (C. Cunningham, unpublished data). This resulted in complete subsistence salmon closures within Alaskan waters with only whitefish (Coregoninae) harvest opportunities in 2021 and 2022 for any user group, something that has never occurred in the Alaska Yukon Management Area. The Yukon River Panel establishes the international (USA and Canada) escapement goal for the number of Canadian-origin salmon that return to Canada to spawn. Despite salmon fishery closures, the escapement goal for Canada-bound Chinook Salmon has not been met for 5 of the past 10 years (2013–2022; JTC 2022). Both Chinook Salmon and Chum Salmon *O. keta* historically provided valuable subsistence opportunities and the simultaneous low returns of both species presents a multispecies food security and subsistence management crisis in the Yukon watershed (Siddon 2021). Concurrent poor Chinook Salmon and Chum Salmon returns have also been common in the Kuskokwim and Norton Sound areas of the AYK region; however, healthy run sizes of at least one salmon species on a given year has allowed for limited harvest opportunities. Kuskokwim Chinook Salmon runs have been below average since 2010, but large enough to meet most established escapement goals at the expense of subsistence harvest restrictions (KRITFC 2022).

For Yukon River Chinook Salmon, most of the year-to-year variability in adult returns since 2003 can be attributed to changes in fecundity, survival, and interception occurring sometime between the start of the spawning migration and the end of the first summer in the ocean (Howard and von Biela 2023). During the spawning migration, high river temperatures (>18°C) are associated with heat stress (von Biela et al. 2020), and premature mortality of adult Chinook

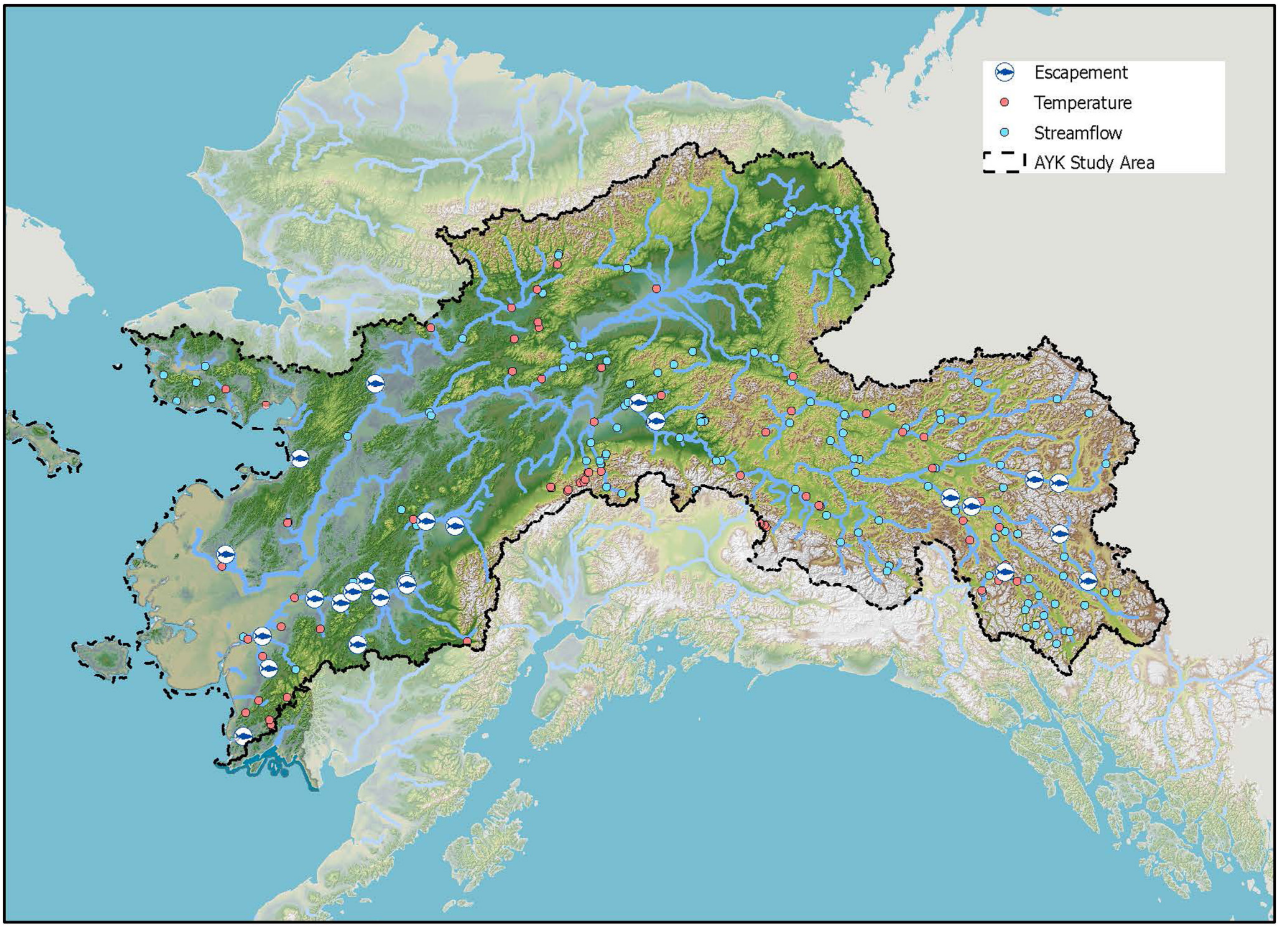


Figure 3. Locations of escapement, temperature, and streamflow monitoring sites across the Arctic–Yukon–Kuskokwim (AYK) region discussed during the workshop. Escapement sites shown meet data quality standards discussed and agreed upon by workshop participants (e.g., minimum of 10 years of data). Stream temperature monitoring sites are from the Alaska Online Aquatic Temperature Site (https://bit.ly/3N0MQSD) with additional sites provided by the U.S. Geological Survey, U.S. Fish and Wildlife Service, Alaska Department of Fish and Game, and Al von Finster as part of data discovery prior to the workshop. Streamflow monitoring sites are from the U.S. Geological Survey and Environment and Climate Change Canada databases. Eighty-nine stream temperature and 135 streamflow monitoring data sets are shown that have a minimum of 5 years of data. Of the 25 escapement monitoring sites with high-quality time series, 16 have co-located temperature sites and 5 have co-located streamflow measurements.

Salmon and Chum Salmon migrants was observed at multiple locations during the unprecedented heatwave in 2019 (von Biela et al. 2022). Heavy rains and floods during the spawning and egg incubation period can also reduce Chinook Salmon survival and population productivity (Jones et al. 2020), but this has not yet been documented in the AYK region where streamflow data are sparse (Figure 3). Higher summer streamflow during the juvenile rearing stage, and later spring breakup of river ice during the year of smolt outmigration have been associated with reduced productivity of some well-studied AYK Chinook Salmon populations (Neuswanger et al. 2015; Cunningham et al. 2018). Sea surface temperature and sea ice retreat during the first year in the ocean impact growth (Yasumiishi et al. 2020b), diet, and energy density (Garcia and Sewall 2021). The 2014–2016 marine heatwave in the Gulf of Alaska and Bering Sea was associated with ecosystem responses that persisted for multiple years (Suryan et al. 2021). These ecological responses included reductions in diet mass and lower piscivory during the early marine feeding period for Chinook Salmon (Garcia and Sewall 2021), changes in energy density of juvenile Chinook Salmon (Garcia and Sewall 2021), and egg retention in a Sockeye Salmon *O. nerka* population in the AYK region (Carey et al. 2021). Even among studies that do not span the marine heatwave years, juvenile Chinook Salmon appear to face summers that are too warm in the marine environment where summer growth was faster in cooler years (1974–2010 data in Yasumiishi et al. 2020b).

Changes in High Latitude Salmon Systems: Shared Perspectives

Workshop participants shared many perspectives on their experiences and relationships with salmon. While personal connections to Chinook Salmon and the AYK region varied, it was clear that members of fishing communities, agency staff, academics, and others all felt deep respect for salmon and a sense of purpose in identifying actions and research opportunities to help these fish persist and ensure subsistence opportunities for the communities connected to them. In particular, First Nations and Tribal members expressed profound grief at the loss of fish and the inability to share traditions with their family and communities at fish camps (see Loring and Gerlach 2010). Fish camps provide an opportunity to share knowledge and identity across generations through relationships with salmon, which is integral to the physical, social, economic, cultural, spiritual, psychological, and emotional wellbeing of AYK communities (Carothers et al. 2021). This human–salmon relationship is core to cultural and spiritual ways of life, which have been cultivated over at least 11,000 years and are now at risk due to salmon declines (Halffman et al. 2015).

Workshop participants shared their observations of changing hydrologic conditions throughout the AYK region. Participants noted altered streamflow throughout the region, which they attributed to changes in groundwater, upland permafrost, and glacial runoff. Participants reported low water levels in tributaries in the Porcupine River watershed in Canada, which caused ice to freeze to the gravel riverbed during winter, potentially jeopardizing eggs incubating in salmon redds. Similarly, observed changes in flow during the summer due to low water have caused mortality of resident fishes and prevented surviving juvenile salmon from accessing rearing habitat. Shortly after the workshop, one participant reported a die-off of thousands of fish, including juvenile salmon on the Fishing Branch River, a tributary of the Porcupine River, due to low winter flows. The water level of Kluane Lake near the town of Burwash Landing has also dropped over 2.5 m since 2016 due to changes in glacier runoff (McKnight et al. 2021), which has created challenges for nearby communities as docks no longer reach the lake.

Climate is not the only challenge AYK Chinook Salmon face; participants noted that Chinook Salmon populations are also influenced by changes in demographics and food webs, and are susceptible to bycatch and interception in other fisheries (Table 1). Long-term declines in the average body size and age of spawning Chinook Salmon (Ohlberger et al. 2018) and associated reduced fecundity of adult females (Ohlberger et al. 2020; Oke et al. 2020) could have contributed to recent population declines and were a source of concern for participants. Participants hypothesized climate change may also have affected salmon indirectly through documented changes in the food web, such as increased invertebrate prey production (Klobucar et al. 2018), reduced nutritional value of forage fish (von Biela et al. 2019), changes in prey resources (Yasumiishi et al. 2020a), and increased rates of consumption by predators such as Northern Pike *Esox lucius* (Schoen et al. 2022). Warming waters also contribute to greater rates of infection by pathogens and parasites, such as *Ichthyophonus*, due to increased rates of disease progression at higher temperatures (Kocan et al. 2009), and the impact of disease–climate interactions was identified by participants as a critical unknown.

Many participants expressed concerns about bycatch of AYK Chinook Salmon in the Bering Sea fishery for Walleye Pollock *Gadus chalcogrammus* and other commercial salmon fisheries, which are a known source of mortality for Chinook Salmon originating from the AYK region and elsewhere (Ianelli and Stram 2014). While extreme environmental events have become common in recent years, poor returns have impacted communities since 2003 and some participants felt bycatch in commercial fisheries have exacerbated the problem. They also noted that allowing bycatch prioritizes commercial interests over subsistence opportunities, which are protected by the Alaska National Interest Lands Conservation Act. Other participants noted that the exceptionally high total abundance of salmon in the ocean in recent years may be negatively impacting AYK Chinook Salmon through direct competition for resources. These negative effects on AYK salmon may be further exacerbated by increases in hatchery production across the North Pacific (Ruggerone et al. 2021). For example, some Chinook Salmon populations in the Yukon River have been less productive in years when Chum Salmon originating from hatcheries in Japan were more numerous (Cunningham et al. 2018).

CLIMATE IMPACTS ON AYK CHINOOK SALMON: CHALLENGES AND APPROACHES

Quantitative data collection for western science is often limited in remote locations due to cost, time, and logistic uncertainty. Many monitoring sites in the AYK region are located far from cities and road systems, making access limited and subject to changing conditions in weather and funding (Figure 3). For example, participants experienced flooding, wildfire, and transportation challenges that disrupted access to monitoring sites. Funding uncertainty also impeded successful monitoring programs, which often lack long-term funding streams and are subjected to annual budgetary cycles, resulting in data sets prone to temporal gaps. As a result, multiple data sets with different characteristics (i.e., location, sampling strategy, equipment) are often combined to create longer-term indices of abundance or environmental conditions (e.g., Jones et al. 2020; Connors et al. 2022). While different types of data and observations can be valuable and informative, differences in formats, measurements, or perceived reliability complicate use by western science.

Other challenges identified during the workshop were differences between the locations of environmental monitoring sites and the range of habitats used by the different life stages of Chinook Salmon (Figure 2). Projects monitoring streamflow and temperature often focus on mainstem rivers by necessity, given limited resources, accessibility, and relevance to community safety needs (i.e., flooding). However, the locations of interest with respect to salmon survival and growth may be at the tributary scale where spawning, incubation, rearing, and overwintering may occur (Figure 3). Heterogeneity in tributary conditions does occur (e.g., water temperature; von Biela et al. 2020) and can have important impacts on salmon at specific life stages. Tributary-scale data sets, and detailed understanding of how Chinook Salmon use diverse freshwater habitats, are necessary to identify the full suite of salmon–environment connections and the relative importance of each life history stage to population dynamics.

Climate Products and Satellite Data

A central goal of this meeting was to identify relevant sources of information to understand salmon population dynamics and the environmental processes, which may shape them (Figure 1). Streamflow and stream temperature monitoring sites are sparsely distributed across Alaska and northern Canada, typically active for short durations, and managed independently across agencies and communities (Figure 3). Empirical climate data are often asynchronous with biological data sets in either space or time, and gridded climate data products that are interpolated across the study area can provide alternatives for quantifying freshwater habitat conditions (Table 2). Options for developing time series of freshwater habitat conditions for salmon stocks in remote regions include using models to extend time series when streamflow or stream temperature monitoring stations are co-located with escapement monitoring, or developing geospatial models to predict freshwater conditions in unmonitored locations. At a

Table 2. Spatial and temporal domains and drawbacks of available climate products and satellite data to derive environmental time series data.

Product type	Project example	Variable	Temporal resolution and domain	Spatial resolution and domain	Drawbacks
Monitoring sites	U.S. Geological Survey Water Resources	Stream flow and temperature	Daily resolution, domain varies	89 streamflow and 20 temperature sites in Arctic–Yukon–Kuskokwim region	Sparsely distributed
Historical gridded data sets	Daily Surface Weather and Climatological Summaries (DAYMET)	Temperature and precipitation	Daily, 1980–present	1 km, North America	Data is statistically interpolated between monitoring sites. Requires good monitoring network to reduce uncertainty
Remotely sensed data	The Terra Moderate Resolution Imaging Spectroradiometer Land Surface Temperature/ Emissivity Daily Version 6.1	Land surface temperature	Daily and 8-day, 2002–present	5 km, global	Affected by cloud cover
Global climate models (GCMs)	Geophysical Fluid Dyamics Laboratory Climate Model 3	Many	Hourly, 1860–2100	200 km, global	Too spatially coarse for many research questions, model bias
Statistically downscaled GCM	Scenarios Network for Arctic and Alaska Planning statistical downscaling using delta method of five GCMs from the Coupled Model Intercomparison Project 5	Air temperature and precipitation	Monthly 2006–2100	2 km, Alaska and western Canada	Assumes stationary relationship between global and local processes, requires good monitoring network
Dynamically downscaled GCM	Weather Research and Forecasting Model dynamical downscaling of ERA-Interim Historical Reananlysis and two GCMs from The Coupled Model Intercomparison Project Phase 5	Many	Hourly, historic, and future projections, 1979–2100	20-km grid, Alaska and western Canada	Requires bias correction

minimum, there is a need to extend streamflow or stream temperature time series to match biological data sets of salmon abundance and production.

Workshop participants acknowledged several critical impediments to the use of available climate products for informing research. Different types of climate data sets available for Alaska include empirical data from monitoring sites, historical gridded data, remotely sensed data, and statistically or dynamically downscaled global climate models (Table 2). While these diverse tools have improved the spatial and temporal coverage of available data, it is challenging for salmon biologists to understand the benefits and drawbacks associated with different climate data products. In order to select appropriate data sets for modeling freshwater habitat conditions, considerations include the suite of available variables, the spatial domain and resolution (e.g., grid cell size), the temporal domain and resolution (e.g., daily, weekly, monthly), the availability of future projections, and accessibility (e.g., software compatibility, data set size; Table 2). Even when an appropriate climate product is identified, they are often infrequently updated, which makes alignment with empirical response data sets (e.g., streamflow and stream temperature) challenging. Successful incorporation of climate products within the research process will require coordination and collaboration among analysts across disciplines.

Community-Based Monitoring and Observations

Observations from local and traditional knowledge holders provide valuable information on changing environments in the AYK region. Participants from all backgrounds acknowledged the necessity of incorporating different ways of knowing. Participants noted that quantitative analyses, and the management systems that depend on them, are often not well equipped to incorporate findings from local and traditional knowledge systems. A key theme that emerged from group discussions was the need to further fund and better integrate local observers into research and management. Local observations can provide benefits, including contextualizing recent changes within the longer-term perspectives of local residents. These insights about recent anomalies in salmon or the environment can inform additional research on a tactical basis to address time-sensitive issues and needs relevant to communities.

Participants noted local observations were extremely valuable in documenting salmon die-offs in the Yukon River basin during the 2019 heatwave. Observations compiled from the Local Environmental Observer Network (https://www.leonetwork.org/) and other sources informed recent and ongoing investigations into the role of thermal stress in premature spawner mortality (von Biela et al. 2022). Similarly, an observation by a lower Yukon fisherman that belly fat content had declined in Chinook Salmon complemented studies of poor marine feeding conditions. These examples highlight how local observations play a critical role in identifying relevant changes in the ecosystem or biology of salmon, which can provide a basis for co-producing further research.

Participants discussed the value of community-based monitoring programs as a source of information and collaboration throughout the AYK region, but noted these programs often lack long-term and consistent funding. Many local organizations collect environmental and fisheries data through community-based monitoring programs in the AYK region (Table 3) and these programs often complement and expand upon agency-led monitoring efforts. Community-based monitoring strengthens the resilience of salmon fisheries by building the capacity of local communities to conduct scientific research; improving the communication between subsistence fishers, agency staff, and stakeholders; and increasing trust in

Table 3. Selected community-based monitoring programs focused on salmon and related environmental conditions in the Arctic–Yukon–Kuskokwim region. These programs are operated predominantly by local community members.

Organization	Monitoring data collected
Kuskokwim River Inter-Tribal Fish Commission with Bering Sea Fishermen's Association	Subsistence fisheries harvest, salmon spawning escapement, and smolt production
Orutsararmiut Traditional Native Council	Subsistence fisheries harvest
Native Village of Napaimute	Salmon spawning escapement
Vuntut Gwitchin First Nation	Predatory fish diet composition
Kluane First Nation	Water levels in Kluane Lake
Yukon Delta Fisheries Development Association	Salmon smolt abundance, density, diet, and energy density in Yukon River Delta
Norton Sound Economic Development Corporation	Salmon spawning escapement and acoustic tagging in Norton Sound region

agency data stewards (Inman et al. 2021). These projects provide valuable data on spawning abundance, body size, and harvest (Liller et al. 2019; Whitworth and Bechtol 2022) and serve as unique platforms for research on topics such as heat stress and environmental DNA applications. Some community-based monitoring programs, such as the Takotna River and Kwethluk River weirs were originally established by agencies, and are now fully operated by the Kuskokwim River Intertribal Fish Commission (KRITFC), and staffed mostly by residents of nearby villages, who bring valuable local knowledge and experience and receive technical training and jobs (Whitworth and Bechtol 2022). These interrelationships have become increasingly important as fishing opportunities have been limited to provide for stock conservation. Multiple community-based monitoring programs are also active in the Yukon River basin (e.g., Tanana Chiefs Conference and Yukon River Inter-Tribal Watershed Council) and Norton Sound (e.g., Norton Sound Economic Development Corporation), collecting data on stream temperatures, lake water levels, salmon spawning abundance, and the condition, diet, and energetics of smolts (Table 3).

Despite many examples of the value of incorporating local observations and community-based monitoring in the research process, several participants highlighted the need for improved coordination and communication with local communities, salmon harvesters, and Tribal and First Nations organizations. Participants expressed that engagement needs to occur throughout the research process, from planning to sharing and interpreting results. A frequent stumbling block has been the lack of regular conferences or meetings for these exchanges that bring together experts who live in many different places. Some participants shared that once coordination and communication are established, equity in research funding is a major barrier, because funding for local and traditional knowledge experts has been inadequate. This challenge is emblematic of a broader concern regarding inequity in decision making and inequity in opportunity to participate in research. Western scientists are more frequently able to participate at all phases of the research process as part of their paid employment. In contrast, community members are often expected to volunteer their time to participate, which results in community members being excluded. This highlights how inequity in the scientific and management process is often reinforced by distribution of funding, and the need for more concerted effort to ensure financial support for meaningful participation and engagement. With meaningful involvement from community members or their representatives, the objectives, design, and implementation of research will have greater overall success.

PATHWAYS FORWARD

Incorporating Different Sources of Information

Integrating multiple sources of information (Figure 4) is key to ensuring environmental and biological data sets are at spatial and temporal scales where ecological responses can be detected. Increased collaboration with climate scientists could help researchers use these data sets more fully (Figure 5). Community-based monitoring programs are another source of information that can improve spatiotemporal data coverage, but need reliable long-term funding. While discussion focused on available salmon and climate data to inform statistical analyses, participants also noted the persistent challenge of how to incorporate different types of knowledge and observations within analytical frameworks. The statistical methods proposed for this line of research focus on estimating associations between survival of AYK Chinook Salmon at multiple life stages and climatic or habitat conditions based on *in situ* observations or downscaled climate products. A major shortcoming of this statistical approach is an inherent inability to incorporate observations or other local and traditional knowledge. Documenting traditional knowledge regarding Chinook Salmon declines and environmental change across the AYK region would offer a more complete and improved understanding of the system and its local and regional dynamics than quantitative data alone. This has immense value for understanding all systems, but is exceptionally important when quantitative data are limited. Local observations and traditional knowledge can inform data collection or analysis efforts that are relevant to community needs. This line of research would require increased funding, support, and collaboration with qualitative researchers.

Visualization Tools

Visualization tools can aid collaborations by helping identify groups, resources, data, decisionmakers, and communities that should be incorporated into the research process (Figure 5). Participants across affiliations expressed that they faced barriers to using existing data, because they did not know who to reach out to and involve in collaborations, what monitoring programs exist, the spatial and temporal domain of the data, and data limitations (i.e., missing information, observations with poor quality). We developed a Web-based visualization tool prior to the meeting (https://

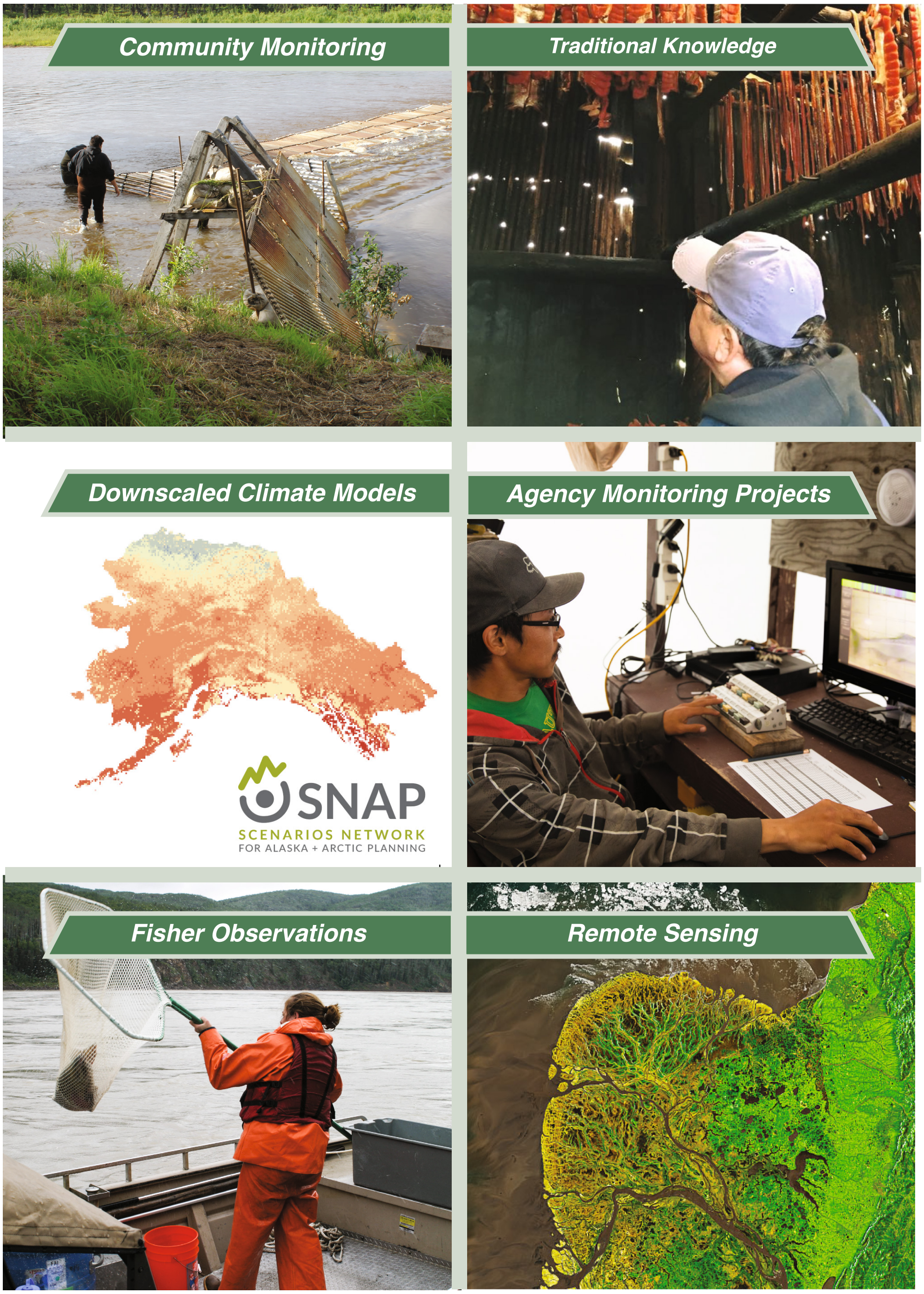
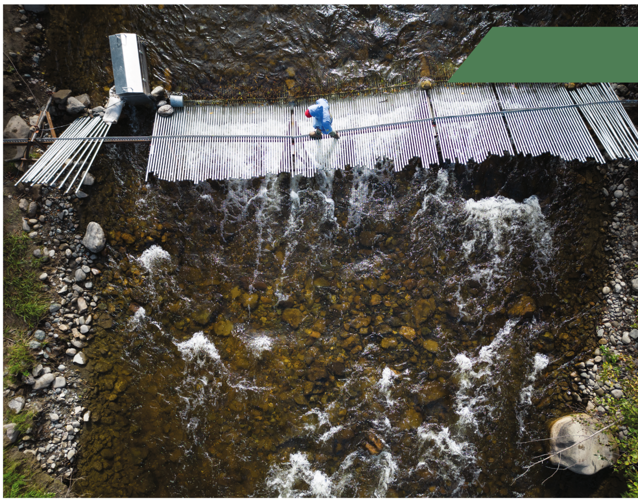


Figure 4. Complementary sources of information that address challenges of data sparseness, co-location, and scale include (1) community-based monitoring, (2) traditional knowledge, (3) downscaled climate model data, (4) agency monitoring programs, (5) fisher observations, and (6) remote sensing data. Photo credit (respective to numbers above): K. Whitworth, Kuskokwim River Intertribal Fish Commission; Tanana Chiefs Conference; Scenarios Network for Alaska and Arctic Planning (https://uaf-snap.org/); Lisa Hupp, U.S. Fish and Wildlife Service; Randy Brown, U.S. Geological Survey, Alaska Science Center; Joshua Stevens, National Aeronautics and Space Administration.

bit.ly/3N9TFS1) to help guide break out group discussions about what data and monitoring information exists. This tool fostered efficient conversations about data availability and allowed people to share expertise and caveats regarding different data sources. Ultimately participants were able to make decisions collectively about what data would be sufficient for future analyses focused on climate–salmon interactions in the AYK region, because everyone could easily query plots from the tool as questions arose. Visualization tools from other regions, such as the Pacific Salmon Foundation explorer (https://bit.ly/3ot4qnT) provide other examples of helpful depictions of data availability and trends.

Participants felt another visualization tool, designed specifically to build relationships and foster equity in decision making, would be a helpful product to engage regional communities and stimulate cross-border and cross-watershed

Pathways Forward

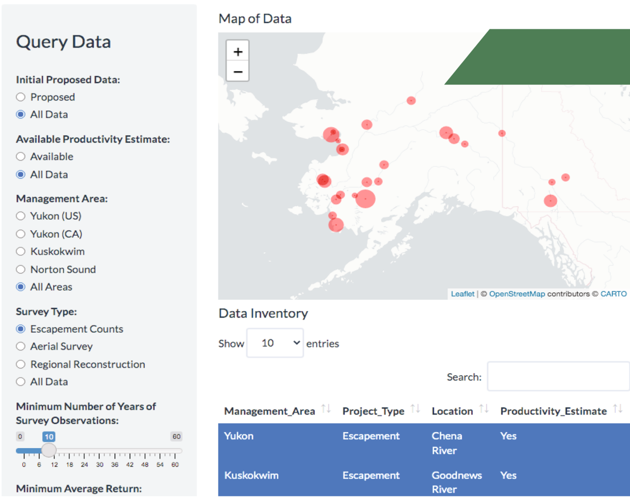


Integrating Information Sources

- Increase collaboration with climate scientists to improve access to data derived from climate models

- Improve access to sustainable and equitable funding streams for community based monitoring programs

- Develop processes to better integrate Traditional and local Knowledge into the research process



Visualization Tools

- Utilize data visualization tools to identify gaps, prioritize information, and guide conversation

- Design visualization tools that illustrate communities, agencies, programs, and projects involved with AYK Chinook salmon and their connection to decision makers

Co-production

- Partner with Indigenous and subsistence dependent communities early in the research process

- Provide equitable compensation to Knowledge holders and community members who participate in research

- Integrate a co-production framework into strategic planning

Figure 5. Pathways forward for understanding climate–species interactions in remote, rapidly changing regions. Photo credits (top to bottom): Elizabeth Macdonald; M. Feddern; P. Westley, University of Alaska Fairbanks.

collaborations. Identifying who to involve in collaborations and how groups are connected to decisionmakers across countries and regions is a challenge, particularly among nonagency-affiliated participants. The combined watersheds of the Yukon River, Kuskokwim River, and northwestern Alaska drainages cover approximately 450,000 square miles, an area larger than the U.S. states of California, Oregon, Washington, and Idaho combined. As a result, communities and researchers are often siloed by distance, and cultural and institutional boundaries. As one participant stated, "relationships are everything," and getting to know one another facilitates trust and true collaboration. Participants collectively agreed that tools that mapped the spectrum of collaborations, projects, and decision makers throughout the region would be useful. There is no one size fits all for productive collaborations, and the goal of this tool would be to aid communities and researchers in identifying who is leading projects in the region and how those groups are connected to decisionmakers. Towards these goals, the Yukon River Drainage Fisheries Association recently compiled a useful description of many of the organizations involved in Yukon River fisheries (Fitka 2022). Further efforts in this direction could guide community members and researchers in identifying helpful connections and ensuring different groups have equitable access to research and decision-making processes.

Co-Production of Knowledge

Co-production of knowledge (CPK) is defined as a process that brings together different knowledge systems such as Indigenous peoples' knowledge systems and western science to generate new knowledge and understandings (Yua et al. 2022). Importantly, these new understandings would likely not be achieved from only one knowledge system on its own (Yua et al. 2022). The CPK framework emphasizes equity, inclusivity, and utility of outcomes in research relationships at every step of the research process. For this project, additional perspectives were solicited during a listening session at the 2022 Alaska Forum on the Environment, but this occurred after the proposal was written for the analysis and the project was funded. This project would have benefited from broader participation earlier in the research planning phase. In addition, the workshop highlighted here was originally conceptualized as a meeting among academic and agency researchers. It became increasingly clear that this gathering would be more effective and impactful if it included perspectives, ideas, and viewpoints from local residents and Tribal members who are most directly connected with Chinook Salmon and environmental changes. Participants indicated that journal articles and scientific presentations alone are of limited value to communities and salmon user groups, and graphics communicating results of the analysis that could easily be shared on social media and with constituencies would be valuable. Moving forward from this workshop, ongoing collaboration and efforts towards the CPK framework can continue to support participants in building institutional, agency, and regional relationships by offering more opportunities for information analysis and allowing participants time to review project and workshop results, products, and outcomes. Project leads will continue to work with participants to solicit ideas for useful materials for community use. Inviting community members and traditional knowledge holders to the research planning process, equitably paying them for their contributions, and allowing time for their evaluation of research projects would strengthen the research process and improve efforts towards a CPK process (Figure 5).

CONCLUSION

Continued climate warming is transitioning our range-wide view of Pacific salmon ecology and management away from the "inverse production regime" (Hare et al. 1999), where warm conditions broadly favored Alaska's salmon populations and cool conditions favored West Coast salmon populations. Now, it is becoming increasingly clear that salmon respond to both regional and local climatic conditions throughout their range. Rapid environmental change in the AYK region highlights how decades of research on the biological and management outcomes for Pacific Salmon from the southern extent of their range are increasingly relevant to fisheries management and conservation in Alaska and Canada. Collaboration across regions, communities, agencies, and researchers can identify the most relevant knowledge to inform conservation strategies that will be most impactful to communities and have the highest likelihood of success.

Some collaborative and self-determined management structures already exist in the AYK region. In 1988, the Alaska Board of Fisheries established the Kuskokwim River Salmon Management Working Group with member seats representing elders, fish processors, agencies, and subsistence, recreational, and commercial fishers. In 2016, the KRITFC and U.S. Fish and Wildlife Service adopted a Memorandum of Understanding to integrate tribes and rural residents into federal fisheries management with the goal of cooperatively managing Chinook Salmon stocks. An objective of the KRITFC management plan is to meaningfully integrate local and traditional knowledge into in-season fisheries management decisions and to apply precautionary buffers to escapement goals and subsistence harvest targets to account for uncertainty, including the effects of climate and heat stress.

Increased collaboration across fisheries will also be useful, as AYK Chinook Salmon and Chum Salmon are caught as bycatch in pelagic trawl fisheries within the Eastern Bering Sea and other subsistence fisheries are also being impacted by climate change (Leppi et al. in press). Currently, the North Pacific Fishery Management Council limits bycatch to 45,000 or 60,000 total Chinook Salmon (across all populations) depending on the recent total return abundance across three index stocks, and implements spatial closures (Amendments 91 and 110 to NPFMC 2012). Implementing a bycatch cap for other Pacific salmon species, specifically Chum Salmon, adjusting bycatch limits following years of low salmon returns or poor environmental conditions, and applying these approaches to other fisheries that intercept AYK Chinook Salmon, may provide a proactive approach to reducing mortality and supporting subsistence fishing opportunities in the AYK region. Extending these collaborative approaches across watersheds, fisheries, countries, and latitudes can facilitate out of the box solutions required for this complex conservation issue, especially where it is not clear how standard habitat restoration techniques may address the underlying drivers of change.

Notably, the challenges faced in the AYK region, and pathways forward we propose (Figure 5), are broadly applicable to other investigations focused on climate–species interactions and implications for fisheries. For example, many salmon populations in British Columbia are also data limited and facing rapid and complex environmental change. The workshop highlighted here builds on past efforts (ADFG 2013; Schindler et al. 2013) towards collaborative discussions and building relationships. Finally, collaborations need purpose. All fishing communities, managers, and researchers share the purpose of supporting Pacific salmon systems inclusive of human communities that depend on them. The challenges of finding agreement on an equitable path to reach that goal necessitates strong relationships, mutual respect, and open communication among the people involved.

ACKNOWLEDGMENTS

We offer our gratitude to the 2022 workshop participants who shared their knowledge and experiences; without their vital intellectual contributions, this synthesis would not have been possible. We thank workshop facilitators Peter Westley and Julia McMahon, and workshop coordinator Tohru Saito for their time and commitment. The workshop was sponsored by the Salmon Science Network and the Alaska Sustainable Salmon Fund and hosted by the International Arctic Research Center at the University of Alaska Fairbanks. Thanks to Elizabeth MacDonald, Jeremy Brammer, Zach Liller, Katie Howard, Al von Finster, and James Savereide for providing additional feedback. We also thank three anonymous reviewers who saw value in this synthesis and provided thoughtful insight. Any use of trade names does not imply endorsement by the U.S. Government. There is no conflict of interest declared in this article.

ORCID

Megan L. Feddern https://orcid.org/0000-0002-5863-7229
Erik R. Schoen https://orcid.org/0000-0001-8301-6419
Rebecca Shaftel https://orcid.org/0000-0002-4789-4211
Curry J. Cunningham https://orcid.org/0000-0002-1234-1297
Craig Chythlook https://orcid.org/0000-0003-1551-0129
Alyssa D. Murdoch https://orcid.org/0000-0003-0582-6584
Vanessa R. von Biela https://orcid.org/0000-0002-7139-5981

REFERENCES

ADFG (Alaska Department of Fish and Game). 2013. Chinook Salmon stock assessment and research plan. Available: https://bit.ly/36Xez1d. (April 2023).

von Biela, V. R., M. Arimitsu, J. F. Piatt, B. Heflin, S. K. Schoen, J. L. C. Trowbridge, and M. Chelsea. 2019. Pacific Sand Lance energy density, length, and age, Prince William Sound, Alaska, 2012–2016. U.S. Geological Survey, Alaska Science Center, Anchorage.

von Biela, V. R., L. Bowen, S. D. McCormick, M. P. Carey, D. S. Donnelly, S. Waters, A. M. Regish, S. M. Laske, R. J. Brown, and S. Larson. 2020. Evidence of prevalent heat stress in Yukon River Chinook Salmon. Canadian Journal of Fisheries and Aquatic Sciences 77:1878–1892.

von Biela, V. R., C. J. Sergeant, M. P. Carey, Z. Liller, C. Russell, S. Quinn-Davidson, P. S. Rand, P. A. Westley, and C. E. Zimmerman. 2022. Premature mortality observations among Alaska's Pacific salmon during record heat and drought in 2019. Fisheries 47:157–168.

Carey, M. P., V. R. von Biela, A. Dunker, K. D. Keith, M. Schelske, C. Lean, and C. E. Zimmerman. 2021. Egg retention of high-latitude Sockeye Salmon (*Oncorhynchus nerka*) in the Pilgrim River, Alaska, during the Pacific marine heatwave of 2014–2016. Polar Biology 44:1643–1654.

Carothers, C., J. Black, S. J. Langdon, R. Donkersloot, D. Ringer, J. Coleman, E. R. Gavenus, W. Justin, M. Williams, F. Christiansen, J. Samuelson, C. Stevens, B. Woods, S. J. Clark, P. M. Clay, L. Mack, J. Raymond-Yakoubian, A. A. Sanders, B. L. Stevens, and A. Whiting. 2021. Indigenous peoples and salmon stewardship: a critical relationship. Ecology and Society [online serial] 26:article 16.

Connors, B. M., M. R. Siegle, J. Harding, S. Rossi, B. A. Staton, M. L. Jones, M. J. Bradford, R. Brown, B. Bechtol, B. Doherty, S. Cox, and B. J. G. Sutherland. 2022. Chinook Salmon diversity contributes to fishery stability and trade-offs with mixed-stock harvest. Ecological Applications [online serial] 32:e2709.

Crozier, L. G., B. J. Burke, B. E. Chasco, D. L. Widener, and R. W. Zabel. 2021. Climate change threatens Chinook Salmon throughout their life cycle. Communications Biology [online serial] 4:article 222.

Cunningham, C. J., P. A. H. Westley, and M. D. Adkison. 2018. Signals of large scale climate drivers, hatchery enhancement, and marine factors in Yukon River Chinook Salmon survival revealed with a Bayesian life history model. Global Change Biology 24:4399–4416.

Feddern, M. L., E. R. Schoen, R. Shaftel, and C. J. Cunningham. 2023. Drivers and diversity of Chinook Salmon: perspectives from the Arctic-Yukon-Kuskokwim Region. University of Alaska Fairbanks. Available: https://bit.ly/3mUB3us. (April 2023).

Fitka, S. 2022. Yukon River fisheries: who does what? Yukon River Drainage Fisheries Association (July 8). Available: https://bit.ly/43RF57v. (April 2023).

Garcia, S., and F. Sewall. 2021. Diet and energy density assessment of juvenile Chinook Salmon from the northeastern Bering Sea, 2004-2017. Alaska Department of Fish and Game, fishery data series No. 21-05. Available: https://bit.ly/3Akp24z. (April 2023).

Halffman, C. M., B. A. Potter, H. J. McKinney, B. P. Finney, A. T. Rodrigues, D. Y. Yang, and B. M. Kemp. 2015. Early human use of anadromous salmon in North America at 11,500 y ago. Proceedings of the National Academy of Sciences of the United States of America 112:12344–12348.

Hare, S. R., N. J. Mantua, and R. C. Francis. 1999. Inverse production regimes: Alaska and west coast Pacific salmon. Fisheries 24(1):6–14.

Howard, K., and V. R. von Biela. 2023. Adult spawners: a critical period for subarctic Chinook Salmon in a changing climate. Global Change Biology 29:1759–1773.

Ianelli, J. N., and D. L. Stram. 2014. Estimating impacts of the pollock fishery bycatch on western Alaska Chinook Salmon. ICES Journal of Marine Science 72:1159–1172.

Inman, S. C., J. Esquible, M. L. Jones, W. R. Bechtol, and B. Connors. 2021. Opportunities and impediments for use of local data in the management of salmon fisheries. Ecology and Society [online serial] 26:article 26.

Jones, L. A., E. R. Schoen, R. Shaftel, C. J. Cunningham, S. Mauger, D. J. Rinella, and A. St. Saviour. 2020. Watershed-scale climate influences productivity of Chinook Salmon populations across southcentral Alaska. Global Change Biology 26:4919–4936.

JTC (Joint Technical Committee of the Yukon River U.S./Canada Panel). 2022. Yukon River salmon 2020 season summary and 2021 season outlook. Alaska Department of Fish and Game, Division of Commercial Fisheries, regional information report, Anchorage.

Klobucar, S. L., J. W. Gaeta, and P. Budy. 2018. A changing menu in a changing climate: using experimental and long-term data to predict invertebrate prey biomass and availability in lakes of Arctic Alaska. Freshwater Biology 63:1352–1364.

Kocan, R., P. Hershberger, G. Sanders, and J. Winton. 2009. Effects of temperature on disease progression and swimming stamina in ichthyophonus-infected Rainbow Trout, *Oncorhynchus mykiss* (Walbaum). Journal of Fish Diseases 32:835–843.

KRITFC (Kuskokwim River Intertribal Fish Commission). 2022. Kuskokwim River salmon situation report. Available: https://bit.ly/41Fe9pE. (April 2023).

Leppi J. C., D. J. Rinella, M. S. Wipfli, A. K. Liljedahl, A. C. Seitz, and J. A. Falke. In press. Climate change risks to freshwater subsistence fisheries in Arctic Alaska: insights and uncertainty from Broad Whitefish Coregonus nasus. Fisheries. Available: https://doi.org/10.1002/fsh.10918. (May 2023).

Liller, Z. W., K. E. Froning, N. J. Smith, and J. Esquible. 2019. Age, sex, and length composition of Chinook Salmon harvested in the 2016 and 2017 lower Kuskokwim River subsistence fishery. Alaska Department of Fish and Game, fishery data series 19-18. Available: https://bit.ly/41MkShn. (April 2023).

Loring, P. A., and C. Gerlach. 2010. Food security and conservation of Yukon River salmon: are we asking too much of the Yukon River? Sustainability 2:2965–2987.

McKnight, E. A., H. Swanson, J. Brahney, and D. S. Hik. 2021. The physical and chemical limnology of Yukon's largest lake, Lhù'ààn Mân' (Kluane Lake), prior to the 2016 'A'ą̈y Chù' diversion. Arctic Science 7:655–678.

Munsch, S. H., C. M. Greene, N. J. Mantua, and W. H. Satterwaite. 2022. One hundred-seventy years of stressors erode salmon fishery

climate resilience in California's warming landscape. Global Change Biology 28:2183–2201.
Neuswanger, J. R., M. S. Wipfli, M. J. Evenson, N. F. Hughes, and A. E. Rosenberger. 2015. Low productivity of Chinook Salmon strongly correlates with high summer stream discharge in two Alaskan rivers in the Yukon drainage. Canadian Journal of Fisheries and Aquatic Sciences 72:1125–1137.
(NPDMC) North Pacific Fishery Management Council. 2012. Fishery management plan for groundfish of the Bering Sea and Aleutian Islands Management Area. Available: https://bit.ly/3KZguEZ. (April 2023).
Ohlberger, J., D. E. Schindler, R. J. Brown, J. M. Harding, M. D. Adkison, A. R. Munro, L. Horstmann, and J. Spaeder. 2020. The reproductive value of large females: consequences of shifts in demographic structure for population reproductive potential in Chinook Salmon. Canadian Journal of Fisheries and Aquatic Sciences 77:1292–1301.
Ohlberger, J., E. J. Ward, D. E. Schindler, and B. Lewis. 2018. Demographic changes in Chinook Salmon across the northeast Pacific Ocean. Fish and Fisheries 19:533–546.
Oke, K. B., C. J. Cunningham, P. A. H. Westley, M. L. Baskett, S. M. Carlson, J. Clark, A. P. Hendry, V. A. Karatayev, N. W. Kendall, J. Kibele, H. K. Kindsvater, K. M. Kobayashi, B. Lewis, S. Munch, J. D. Reynolds, G. K. Vick, and E. P. Palkovacs. 2020. Recent declines in salmon body size impact ecosystems and fisheries. Nature Communications [online serial] 11:4155.
Schindler, D., C. Krueger, P. Bisson, M. Bradford, B. Clark, J. Conitz, K. Howard, M. Jones, J. Murphy, K. Myers, M. Scheuerell, E. Volk, and J. Winton. 2013. Arctic-Yukon-Kuskokwim Chinook Salmon research action plan: evidence of decline of Chinook Salmon populations and recommendations for future research. Available: https://bit.ly/43QN8S3. (April 2023).
Schoen, E. R., K. W. Sellmer, M. S. Wipfli, J. A. López, R. Ivanoff, and B. E. Meyer. 2022. Piscine predation on juvenile salmon in sub-arctic Alaskan rivers: associations with season, habitat, predator size and streamflow. Ecology of Freshwater Fish 31:243–259.
Siddon, E. 2021. Ecosystem status report 2021: eastern Bering Sea, stock assessment and fishery evaluation report. North Pacific Fishery Management Council, Anchorage, Alaska.
Stewart, B. C., K. E. Kunkel, S. M. Champion, R. Frankson, L. E. Stevens, G. Wendler, J. Simonson, and M. Stuefer. 2022. Alaska state climate summary. National Oceanic and Atmospheric Administration, technical report NESDIS 150-AK, Silver Spring, Maryland.
Suryan, R. M., M. L. Arimitsu, H. A. Coletti, R. R. Hopcroft, M. R. Lindeberg, S. J. Barbeaux, S. D. Batten, W. J. Burt, M. A. Bishop, and J. L. Bodkin. 2021. Ecosystem response persists after a prolonged marine heatwave. Scientific Reports [online serial] 11:6235.
Whitworth, K. L., and W. R. Bechtol. 2022. 2021 Takotna River salmon run timing and abundance. Kuskokwim River Inter-Tribal Fish Commission, Bethel, Alaska.
Yasumiishi, E. M., K. Cieciel, A. G. Andrews, J. Murphy, and J. A. Dimond. 2020a. Climate-related changes in the biomass and distribution of small pelagic fishes in the eastern Bering Sea during late summer, 2002–2018. Deep Sea Research Part II: Topical Studies in Oceanography [online serial] 181–182:104907.
Yasumiishi, E. M., J. F. Edward, V. J. Maselko, K. Y. Aydin, K. A. Kearney, A. J. Hermann, G. T. Ruggerone, K. G. Howard, and W. W. Strasburger. 2020b. Differential north–south response of juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) marine growth to ecosystem change in the eastern Bering Sea, 1974–2010. ICES Journal of Marine Science 77:216–229.
Yua, E., J. Raymond-Yakoubian, R. A. Daniel, and C. Behe. 2022. A framework for co-production of knowledge in the context of Arctic research [Negeqlikacaarni kangingnaulriani ayuqenrilnguut piyaraitgun kangingnauryararkat]. Ecology and Society [online serial] 27:article 34.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.

Appendix S1. AFS