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Food for Thought

Leveraging transboundary science to support Northeast Pacific fisheries and protected species management

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Abstract

Climate change is impacting marine ecosystems in increasingly rapid and unpredictable ways. The spatial extent of these impacts on marine fisheries and endangered and threatened species often spans regional and international boundaries. The transboundary nature of changing ocean conditions can challenge detection and anticipation of changes, and delay coordinated actions at the scales required to mitigate and respond. Here, we identify challenges and opportunities for transboundary science in the Northeast Pacific Ocean. Specifically, we aim to support the management of fisheries and protected species in response to a changing climate, while highlighting successful efforts. Challenges include (1) limited coordination of monitoring surveys; (2) institutional, cultural, and technological barriers to the sharing of data and analytical tools; (3) incomplete understanding of relationships among oceanographic conditions, trophic interactions, population dynamics, and species' distributions; (4) limited availability of high-resolution Earth system model projections that can be linked to ecosystem and fishery responses; and (5) differing prioritization of ecosystem information and limited communication among nations. Three opportunities to overcome these challenges include (1) coordinated monitoring and sharing of data at a transboundary scale to detect and understand marine ecosystem responses to climate change; (2) common assessment frameworks and modeling approaches to improve understanding and projections of ecological responses to climate change; and (3) increased communication of ecosystem information to support management needs across jurisdictions, enhance the use of existing science products, and strengthen pathways for science to inform management of marine resources. We focus on examples of these opportunities drawn from our collective experience as government scientists working on Northeast Pacific Ocean ecosystems.

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We suggest that by strategically focusing on these opportunities, transboundary science worldwide can improve predictions of ecosystem responses to climate change and better support regional and international management of shared resources.

Keywords data sharing, ecosystem models, fisheries, protected resources, science communication, transboundary

Introduction

Marine ecosystems are experiencing unprecedented climate-related change in ocean conditions with consequences for the distribution, productivity, and abundance of marine species and the fisheries that depend on them (Pinsky et al. 2013, Free et al. 2019, Plagányi 2019). These impacts are far-reaching and transboundary. The Northeast Pacific Ocean, spanning from south of the Baja Peninsula to the Chukchi Sea (Drenkard et al. 2024), is experiencing long-term warming and extreme temperatures, changes in seasonal phenology, reduced sea ice, ocean acidification, hypoxia, and other physical changes that have direct implications for multiple marine ecosystems, fisheries, and protected species along the west coast of North America and beyond (King et al. 2011, Hu et al. 2024). Examples of climate-related impacts on fisheries and protected species include large-scale mortalities (e.g. Murauskas et al. 2021), toxicity from harmful algal blooms, large recruitment events (Free et al. 2023), shifts in fish distribution (e.g. Jacobsen et al. 2022, Liu et al. 2025), changes in spawn timing (Rogers et al. 2025), changes in fish size (Oke et al. 2020), increased interactions of marine mammals with fishing gear (Santora et al. 2020), and fishery closures resulting from one or more of the preceding impacts (Richerson and Holland 2017, Ritzman et al. 2018, Barbeaux et al. 2020). As these climate-related changes to marine ecosystems continue in the near and long term, monitoring, research, modeling, and overall adaptive capacity must continue to evolve to support sustainable management of living marine resources.

Transboundary science—scientific collaboration that supports resources spanning international borders—can offer a robust, integrative approach to understanding the dynamics of marine ecosystems in a changing climate. These resources can include shared stocks (i.e. transboundary stocks that span multiple exclusive economic zones (EEZs), straddling stocks that visit the high seas from one or more EEZs, and highly migratory stocks) and populations of protected species that span international borders (FAO 1995, Munro et al. 2004). Transboundary science can help reconcile mismatches between political jurisdictions and ecological realities, a persistent challenge to sustainable resource management (Crowder et al. 2006, Song et al. 2017). Successful examples include shared risk frameworks in North Atlantic salmon management (Hickey et al. 2021), International Council for the Exploration of the Sea science to support management of Atlantic salmon (*Salmo salar*) (ICES 2025), cooperative science between European coastal states on North Atlantic mackerel (*Scomber scombrus*) (Østhagen et al. 2020), and joint US–Canada stock assessments of Pacific hake (*Merluccius productus*) (Helser and Alade 2012). Institutional progress hinges on both harmonizing existing monitoring and modeling efforts across borders and embedding transboundary thinking into future programs. Transboundary collaboration and coordination among science agencies and institutions create opportunities to learn, track, and predict by increasing the spatial domain and conditions over which inference is based.

Despite successes, key challenges persist in detecting, understanding, and projecting responses of transboundary oceans and ecosystems to climate change for informing management of fisheries and protected species. Although templates exist for providing science advice to support managing shared fish stocks and protected species (e.g. the Pacific Hake/Whiting Agreement, Pacific Salmon Commission, International Pacific Halibut Commission, Inter-American Tropical Tuna Commission), these templates can be rigid and difficult to adapt to environmental change (but see Link et al. 2011). The administrative and legal requirements for negotiating and maintaining agreements mean they are only developed for the most economically valuable species. Consequences of limited transboundary science for resource management can range from (1) delayed responses to distribution shifts (Pinsky et al. 2018, Palacios-Abrantes et al. 2022), (2) increased uncertainty in harvest specifications because population dynamics of shared stocks are misrepresented or ignored altogether (Kapur et al. 2024), (3) limited capacity to quickly understand and adapt to the magnitude and persistence of ecosystem perturbations (Free et al. 2023), and (4) reduced mechanistic understanding and ability to predict ecosystem changes based on restricted visibility of the bioclimatic niche and limited scientific capacity in expertise and relevant tools (Capotondi et al. 2024). As conditions in marine ecosystems are pushed beyond their historical ranges, the potential for surprising ecological responses to novel climates looms large for economically valuable species as well as other species of conservation, cultural, recreational, and ecological importance (Litzow et al. 2020a, Doak et al. 2008, Anderson et al. 2017). Continuing to advance our scientific tools and management responses may help us predict and adapt to future perturbations and directional trends in the environment (Muhling et al. 2020, Asch et al. 2022).

Here, we review challenges and opportunities in the Northeast Pacific Ocean related to transboundary science to support the management of fisheries and protected species in response to climate change. The authors are government scientists who are current or past members of a joint Canada–USA Climate and Fisheries Northeast Pacific Working Group. The challenges and opportunities highlighted in this paper have arisen from numerous knowledge exchanges, workshops, and discussions. We discuss case studies of successful transboundary science, identify challenges and consequences for decision-making, and generalize the opportunities that exist to overcome challenges more consistently (Fig. 1). We outline strategies for addressing the identified challenges to transboundary climate and fisheries science, centered on three overarching topics: data collection and use, ecosystem relationships and dynamics, and communication. While our review primarily draws from experiences in the Northeast Pacific Ocean, our insights provide a prospectus for advancing the capacity of transboundary science to support the management of fisheries and protected species worldwide in response to a rapidly changing climate. Similar to the lessons learned about multilateral coordination during health emergencies (e.g. COVID; Jit et al.

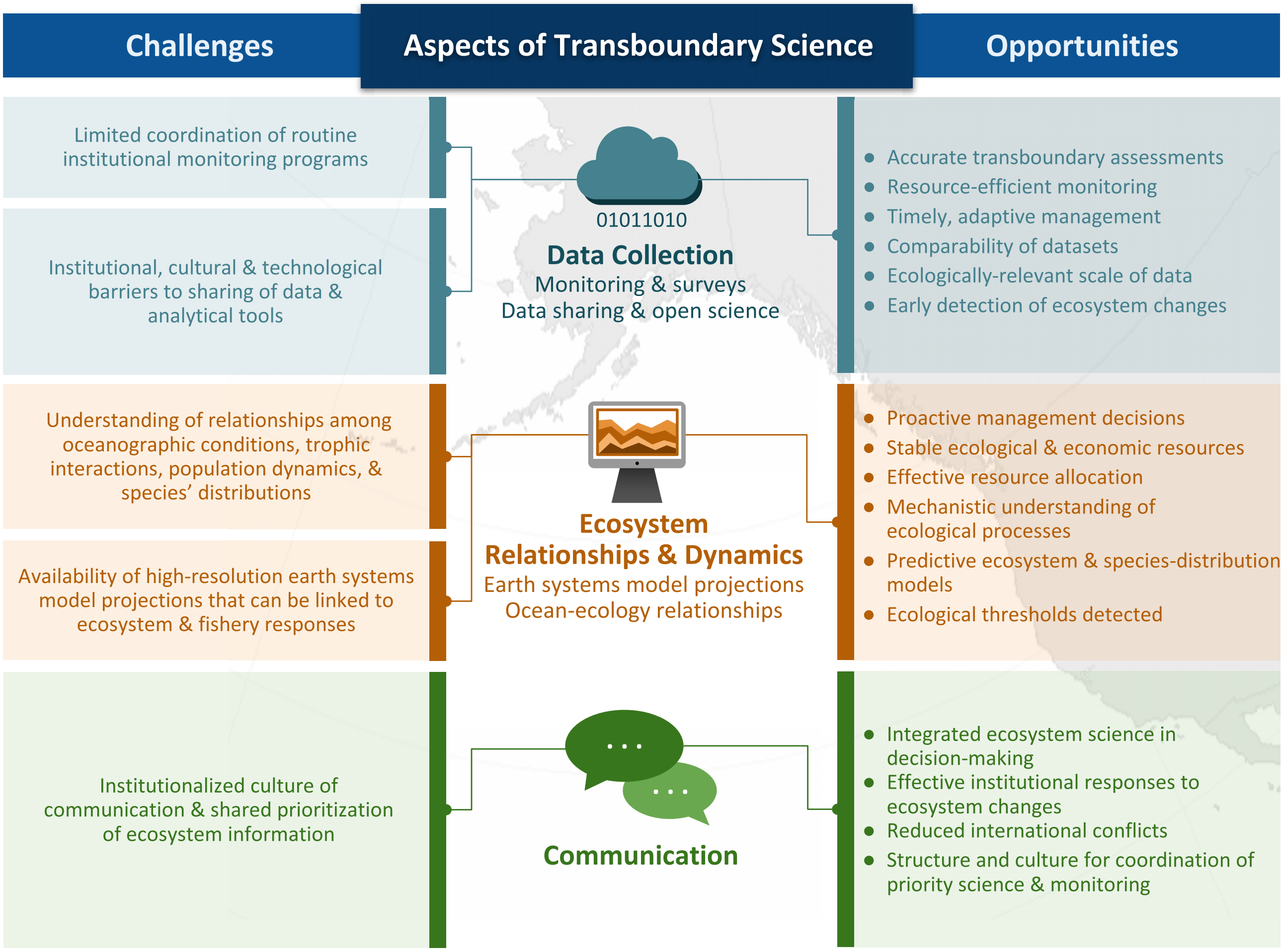

Figure 1 A summary of opportunities and challenges identified to advance transboundary science to support the management of fisheries and protected species in a changing environment (credit: Su Kim, NOAA Fisheries).

2021), there is a pressing need for agencies and organizations at regional, national, and international scales to work together to effectively manage and conserve species in the marine environment.

Challenges and opportunities

Data collection and use

Key message: Coordinated monitoring and sharing of data at a transboundary scale is required to detect and understand marine ecosystem responses to climate change.

Monitoring and surveys

Challenge: Long-term fishery and ecosystem monitoring programs are an essential source of information for developing science-based advice to management. However, most monitoring is conducted within regional or national boundaries even though fish stocks, and the physical and ecological processes that influence them, cross these borders. Limited coordination of institutional monitoring programs reduces the ability to combine data across jurisdictional boundaries to address climate-induced changes in distribution and understand the full range of responses of fish and fisheries to environmental change, and to support more flexible, adaptive, and effective decision-making when faced with novel conditions (Maureaud et al. 2021).

Most long-term programs established to monitor fish and oceanography align with individual jurisdictions with differing data collection protocols and are not based on ecological boundaries (Maureaud et al. 2021). For example, USA and Canadian federal government agencies run three bottom trawl survey programs (some programs including multiple surveys) in their respective regions of the Northeast Pacific continental shelf and slope. Although gear types and trawl protocols are similar, the surveys have not been calibrated against each other to assess differences in gear efficiency and size selectivity, they run at different times of the year, and protocols for collecting biological sample data (e.g. otoliths and fish lengths) differ across surveys (Maureaud et al. 2024, Ward et al. 2025). Furthermore, collected data are hosted regionally and modelers may not be familiar with the intricacies of accessing and joining data from neighboring regions (Ward et al. 2025). Unlike fisheries surveys, globally standardized efforts such as the Argo ocean float program offer an example of harmonized protocols and open data sharing at scale (Wong et al. 2020 and Box 2).

When transboundary monitoring programs are undertaken in the Northeast Pacific Ocean, they have usually been tied to international treaties for specific fish stocks or of short duration. Existing examples of Canada–USA monitoring programs that sample species across their entire ranges are largely linked to Canada–USA treaties and do not attempt to sample a broad range of taxa. For example, Pacific halibut (*Hippoglossus stenolepis*), Pacific hake (*Merluccius productus*), and Pacific salmon species (*Oncorhynchus* spp.) are surveyed by coordinated and distribution-wide monitoring programs as well as fishery-dependent data (de Blois 2020, Ualesi et al. 2023), but these are driven by formal agreements between nations, respectively: the Convention Between Canada and the United States of America for the Preservation of the Halibut Fishery of the Northern Pacific Ocean and Bering Sea (Canada–United States 1953), the Agreement Between the Government of the United States of America and the Government of Canada on Pacific Hake/Whiting (Canada–United States 2003), and the Treaty between the Government of Canada and the Government of the United States of America Concerning Pacific Salmon (Canada–United States 1985). The surveys and data-collection programs are successful in supporting the science and management of the target species, yet they have limited widespread utility beyond those species. The species-specific focus does not support transboundary science of other species of management and conservation importance, and does not inform broader ecosystem dynamics that could respond to novel climate conditions in unique ways. Other coordinated transboundary surveys are of limited duration due to short-term funding. For example, the International Year of the Salmon (https://yearofthesalmon.org/2022expedition/) coordinated sampling of Pacific salmon species in the Northeast Pacific Ocean high seas, but only operated in 2019, 2021, and 2022. This snapshot approach limits the ability of these surveys to provide insights into ecosystem change over time. A greater understanding of how salmon populations are responding to changing ocean conditions would advance early warning and predictive capabilities for management applications.

Opportunity: Coordination of monitoring and reporting efforts offers an opportunity to increase the value of existing regional datasets and produce monitoring reports that are critical for a transboundary perspective.

For biological surveys, such as the groundfish trawl surveys described earlier, performing calibration tows between surveys—side-by-side sampling used to measure differences in catch efficiency between survey methods or gears—could strengthen comparisons across neighboring transboundary regions, increasing the value of both historical and future data without compromising time series integrity. Thus far, modelers have attempted to calibrate survey data by proximity (Maureaud et al. 2021, O'Leary et al. 2021, Ward et al. 2024, Davidson et al. 2026). This method relies on the assumption that samples close in space and time are ecologically comparable and thus assumes one can estimate a catchability offset between surveys based on observed differences in nearby samples. However, spatial correlation provides an imperfect metric with which to calibrate, and the approach can introduce considerable estimation uncertainty. We expect calibration tows in neighboring regions would improve coastwide species distribution modeling and abundance estimation as well as "fill in" gaps in regional survey data. Simulation studies and within-region calibration experiments can help guide design and cost–benefit tradeoffs (ICES 2023).

In addition to calibrating existing surveys, there is an opportunity to coordinate the collection of auxiliary ecosystem information—data such as water properties, fish condition, diet—on surveys. These protocols currently differ among regions across the Northeast Pacific. For example, diet data are routinely collected on Alaska groundfish surveys and Canada's Integrated Pelagic Ecosystem surveys, among others. Applying similar protocols across both nations would support coastwide analyses of trophic dynamics in the context of variable environmental conditions (Barbeaux et al. 2020). Similarly, in Canada and along the USA West Coast, dissolved oxygen data are routinely collected from the bottom trawl and Integrated Pelagic Ecosystem surveys. More regular collection of these data in Alaska using standardized instrumentation would allow us to monitor this variable that is crucially important to many commercially important species and likely to cause changes to fish distribution and abundance coastwide (Essington et al. 2022, Thompson et al. 2023, Indivero et al. 2025).

Coordinating the types and formatting of standardized monitoring reports provides an opportunity to facilitate cross-region comparisons and detect shared responses to climate events. The annual groundfish data synopsis report produced in Canada is an example of such a format that could be adopted by neighboring regions (Anderson et al. 2019, 2020). This data report visualizes nearly all available survey data—along with fishery-dependent data—on two pages per species. Trends in survey indices and the distributions of ages and lengths, for example, are presented visually in a standardized format. This standardization enables rapid uptake of information across species, and potentially regions. In British Columbia, it has provided an early warning signal of a rapid increase in Bocaccio rockfish (*Sebastes paucispinis*) (Starr and Haigh 2022, Free et al. 2023) and a shared pattern of rapid decline in Pacific spiny dogfish (*Squalus suckleyi*) (Davidson et al. 2026). Adopting a similar standardized format in the neighboring USA West Coast and Alaska regions could facilitate comparison of trends across regions and accelerate early detection of ecosystem changes at broad spatial scales. The development of a Pacific joint Canada–USA assessment is another example of embracing open and reproducible science as a basis for greater collaboration and improved assessment practices (Box 1).

Data sharing and open science

Challenge: The sharing of tools and data is a crucial pillar in advancing scientific research, promoting collaboration, and fostering innovation in all branches of science (Molloy 2011). Despite these obvious benefits, numerous barriers have persisted within the scientific community, hindering the widespread adoption of best practices around "open science" and limiting the collective progress of the scientific community.

Box 1. Pacific hake assessment: open reproducible science

Pacific hake (*Merluccius productus*) is a commercially valuable fish species of importance to the USA, Canada, and USA Tribes, with an average annual catch of 325 000 t from 2015–2024, and a total economic impact of > 4000 jobs in the USA. Both nations depend on hake as a valuable shared resource, but limits need to be set to maintain a long-term sustainable harvest. As a result, in 2003 the USA and Canada signed the Pacific Hake/Whiting Agreement (Canada–United States 2003) to jointly monitor, assess, and manage the transboundary hake stock. Conducting the joint stock assessment has presented challenges, and open reproducible science has been a solution to several of them. First, sharing data, coding, and writing responsibilities across the US–Canada border proved difficult. As a solution, since 2016, GitHub has been used to efficiently share code and write the transboundary assessment document (Johnson et al. 2025). Second, the tight timeline between obtaining data in early January and submitting the draft stock assessment in late January was hard to manage while ensuring a high quality and accurate assessment. To solve this, the assessment document (Johnson et al. 2025) is built using R Markdown (Xie et al. 2019) such that it is fully reproducible and all figures, tables, and model outputs in the text are automatically derived from the raw data and assessment model results. When reviewers requested model changes, all outputs could be regenerated faithfully and automatically, and the nearly 300-page assessment document could be rebuilt, saving considerable time and avoiding transcription errors from manually inserting numbers, while meeting the submission deadline. The 2025 assessment included a hake-specific ecosystem summary, using data from both the USA and Canada, as a first step toward operationalizing climate-informed management that can be updated and expanded upon every year.

Barriers to data sharing in science are numerous and complex but include issues around funding limitations, intellectual property, data ownership and sovereignty, cultural norms, and technological or logistical limitations (van Panhuis et al. 2014); many of these barriers are amplified in an international transboundary science context (Matthews et al. 2020). Scientific journals have provided a means to disseminate scientific information for centuries; however, as publication models have shifted, there may be increasing asymmetry in which organizations or individuals have access to paywalled publications or funds for page costs (National Academies of Sciences, Engineering, and Medicine 2018, Bahlai et al. 2019). Furthermore, developers of new technologies, data, or software have expressed concerns about conflicts between open science and intellectual property, balancing benefits to themselves with benefits to society (Scheliga and Friesike 2014). Data ownership complications arise not only in large-scale research projects involving numerous scientists, but also when derived data products become valuable scientific output themselves (e.g. meta-analyses). Traditional metrics of scientific success (number of publications, impact factors) can incentivize individuals to restrict access to datasets, increasing barriers to open data or open science practices (Fecher et al. 2015). Several technological limitations have prevented widespread sharing of data and tools. For instance, until recently, access to online repositories for archiving data has not been widespread (Tenopir et al. 2011, Gomes et al. 2022). Finally, there are logistical challenges in collaborating across geopolitical borders. These may include both political constraints on collaboration and logistical restrictions (e.g. time zone or language differences) that can make collaboration difficult (Matthews et al. 2020).

Opportunity: Overcoming cultural and technological barriers to open science adoption has the potential to significantly enhance transboundary scientific research and collaboration and thereby foster a faster, more flexible decision-making process.

Cultural hurdles could be addressed by fostering a more inclusive, cooperative community that values and promotes openness (Bahlai et al. 2019, Lowndes et al. 2019), thereby accelerating the pace of discovery and innovation. This includes respecting the principles of data and information ownership, control, access, and possession, to support First Nations' and Indigenous Peoples' data sovereignty (https://fnigc.ca/). A more inclusive community supports broader participation across disciplines, institutions, and career stages (Murphy et al. 2020) to address issues of transboundary fisheries science under climate change. Opportunities to change the scientific culture around open data and open science include changing the incentive and reward structure from an individual-based model (e.g. focused on individual researchers' citation metrics) to incentives more centered on teams (e.g. team-based grants, tools, reports) (Maureaud et al. 2025). Encouraging the use of preprints or institutional repositories to disseminate results—including negative results—will aid in communicating results rapidly to a broader audience. Placing value on data sharing and reproducibility can incentivize research groups to adopt and gain trust in open science best practices (Stieglitz et al. 2020). Adoption of an open science culture creates space for diverse perspectives, learning styles, and lived experience to shape collaborative solutions (Murphy et al. 2020).

Overcoming technological barriers to open science adoption would allow more scientists to effectively use cutting-edge tools and platforms, democratizing access to advanced technology. Many scientific fields, including ecology and fisheries, have relied on open source programming languages (e.g. R, Python, Julia) and packages built with them; the adoption of open version control systems such as Git and popular platforms for hosting such systems such as GitHub (Box 1) have enabled a larger number of scientists to find and access these tools and become involved in tool development. Open-source model development and analytical platforms such as MOM6 for oceanographic modeling (Adcroft et al. 2019), Stock Synthesis (Methot and Wetzel 2013), and sdmTMB (Anderson et al. 2025) are accelerating harmonized workflows, and efficiencies in resources, but require shared conventions in input formatting, diagnostics, and model structure. By enabling more researchers to contribute to tool or method development, we can harness the collective intelligence of the scientific community, enhancing both the quality and impact of scientific research (Molloy 2011).

Despite the existence of these technologies, there are continued barriers to access, because their adoption often requires time or resources for learning new methods. Increasing the accessibility of these emerging technologies has been a major focus of training programs in the USA, such as OpenScapes (Lowndes et al. 2017, Robinson and Lowndes 2022, 2024) and the Open Science at NOAA Fisheries initiative (https://www.fisheries.noaa.gov/science-data/open-science-noaa-fisheries), and in Canada through the Technical Expertise in Stock Assessment (TESA) program (e.g. Edwards et al. 2018). Training employees in the use of open science tools requires funding. Since the availability of funding may vary across individuals or groups, large-scale funding mechanisms at the highest levels of government or organizations are likely to provide the greatest access to individuals. Internationally, similar challenges may arise if researchers from one group have institutional support for open science training while others do not. International organizations (e.g. International Council for the Exploration of the Sea [ICES] and North Pacific Marine Science Organization [PICES]) play an important role in these instances by endorsing and offering training with an emphasis on international collaboration.

Overcoming technical barriers is not limited only to tools and methods—it also applies to data accessibility. National agencies are increasingly making their monitoring data open (Canada Office of the Chief Science Advisor of Canada 2020, United States National Oceanic and Atmospheric Administration 2020). However, the formats of these regional or national databases are unique and joining the data sources, as required for transboundary modeling, requires considerable effort and regional knowledge. Regional experts are essential to the successful application and use of transboundary modeling, through the integration of valuable knowledge and the building of trust in the final products. Efforts to standardize and combine biological survey databases can alleviate these technical barriers (Maureaud et al. 2021, 2024, Ward et al. 2025) and facilitate large-scale transboundary analyses (Ward et al. 2024, Davidson et al. 2026, Indivero et al. 2025). Glider deployments highlight the value of standardization: some protocols are interoperable with IOOS data systems, while others are not (Testor et al. 2019). The global Argo float array is an example of successfully overcoming institutional and cultural barriers (Box 2).

Ecosystem relationships and dynamics

Key message: Common assessment frameworks and modeling approaches can improve understanding of environment–biology relationships and their responses to changing oceans.

Box 2. Argo observational array: international collaboration democratizing ocean data

The global Argo float array illustrates how with coordination, openness, and trust, collaborative science can transcend national boundaries to advance not only transboundary, but global, climate, and ocean science. With nearly four thousand autonomous floats collecting ocean temperature and salinity data worldwide, Argo has democratized access to ocean data. However, achieving this global reach presented substantial logistical challenges, especially coordinating independently funded national programs to ensure uniform float coverage. The solution has been sustained international communication—first, strategic documents, such as the original Argo Science Team (1998) report (most recently updated in Roemmich et al. 2019), which offered a unified vision; second, annual Argo Steering Team meetings and regional coordination efforts, which ensured balanced global coverage. A second major hurdle lay in public data accessibility and utility. To inform global-scale climate models and fuel oceanographic discovery, data needed to be not only open, but consistently high-quality (Wong et al. 2020). Argo's solution centered again on openness: annual data team meetings standardized practices, while public-facing data protocols and open-source tools on GitHub established a culture of accountability and speed (Argo data management 2025). The result is a system where thousands of researchers, in resource-limited countries as well as in those with large oceanographic budgets, can model ecosystem shifts and track climate trends (Johnson et al. 2022).

Earth system model projections

Challenge: Hindcasts, forecasts, and projections of physical and biogeochemical variables obtained from global and regional Earth system models are essential for assessing the impacts of climate on the management of fisheries and protected species (Drenkard et al. 2021), and yet they are scarce. Using ocean models to understand and predict ecological responses to varying climate scenarios often requires downscaling global climate models to resolve appropriate ecological scales. For example, water masses advected from west to east across the North Pacific bifurcate at the eastern boundary, with one branch turning poleward to become the Alaska Current while the other branch turns equatorward and becomes the California Current, transporting heat, nutrients, and other ecologically important components into the respective ecosystems (Cummins and Freeland 2007). These advective/transboundary processes are not well captured by existing modeling grids, and are also often poorly represented by the relatively coarse resolution global models that provide boundary conditions for regional models (Drenkard et al. 2021).

High computational costs and tradeoffs between modeling domain and resolution have resulted in a limited availability of physical projections that are both transboundary and high-resolution. Importantly, even high-resolution models exhibit considerable uncertainty in future projections, stemming from natural internal variability, model uncertainty, and scenario uncertainty. On regional scales, these uncertainties can manifest in the magnitude of trends (e.g. rate of projected warming) or even the sign of trends (e.g. increasing vs. decreasing biomass) (Pozo Buil et al. 2021, Eddy et al. 2025). Thus, exploring the range of potential futures necessitates running ensembles of projections with multiple Earth system models and scenarios, amplifying the computational cost of high-resolution transboundary simulations.

Adding biological components to these models increases their complexity further, with (sometimes) limited data for validation (Fulton et al. 2003, deYoung et al. 2004). And yet, "end to end" (physics to fisheries) models are necessary for linking climate changes to ecosystem and fishery responses (e.g. Fulton et al. 2011). High-resolution downscaling has traditionally been done on limited spatial domains (e.g. the Bering Sea, Gulf of Alaska, British Columbia continental margin, and California Current System in the Northeast Pacific Ocean) (Hermann et al. 2016, Cheng et al. 2021), which are not equipped to address transboundary processes operating across these regions. Smaller regional domains for downscaling have advantages including lower computational cost, stronger constraint of the regional domain by ocean boundary conditions, a limited set of ecosystem components and processes that must be represented, and comparative ease of evaluating models against region-specific observations and knowledge. Larger domain models can accommodate more spatial processes, but interactions among the ocean physical environment, biogeochemistry, and ecosystem/food web dynamics are more complex over larger spatial scales, and we often lack guiding principles on these interactions. Downscaled regional models that span jurisdictional boundaries should leverage transboundary coordination to use shared datasets (e.g. high-quality hydrographic datasets), incorporate regional understanding of key processes, and ensure consistent model outputs.

Opportunity: Increased accessibility and affordability of high-powered computing, dissemination of modeling skills and crowdsourcing model development have brought the needed modeling products closer to realization. The application of ocean models to transboundary ecological questions can be enhanced with high-resolution transboundary forecasts and projections, improved data access and processing, and standard indices for comparison of transboundary ocean conditions. The ability of downscaled global Earth system models to address climate-ecological topics involves overcoming the mismatch between transboundary behavior of marine species and existing model grids. In their overlapping areas, inter-model comparison may be used to address biases particular to each model and point to directions for future model improvements (Lotze et al. 2019, Blanchard et al. 2024). The extended domain of the downscaled models across national and jurisdictional boundaries presents opportunities for transboundary coordination so that the model better matches the scale of physical processes and the behavior of marine species, and the outputs can be more fully utilized. Additionally, coordination is required to ensure that the ocean model output is ready for uptake by ecological modelers from all relevant jurisdictions, in terms of both data access (e.g. through GitHub or Thematic Real-time Environmental Distributed Data Services [THREDDS] servers) and data processing (e.g. as raw model output, or more commonly used derived outputs such as 2D fields for a specified region). Shared domains and inter-model evaluation offer an entry point for aligning physical and ecological insights across national programs. NOAA's Changing Ecosystems and Fisheries Initiative is a successful example of how these models are being developed and applied, in support of basin-scale questions related to environmental variability (Box 3).

Box 3. NOAA's changing ecosystems and fisheries initiative (CEFI): coastwide ocean modeling

Under CEFI, coastwide ocean model grids are being developed that cover most USA and Canadian coasts, including a Northeast Pacific domain that spans from south of the Baja Peninsula to the Chukchi Sea (Drenkard et al. 2024). The model employs version 6 of the Modular Ocean Model (MOM6) coupled with the Carbon Ocean And Lower Trophics (COBALT) biogeochemical model to represent nutrients, carbon chemistry, phytoplankton, and zooplankton. A historical simulation covering recent decades has been produced, and under development are seasonal (1–12 month) and decadal (1–10 year) forecasts as well as long-term projections forced by multiple Earth system models under multiple shared socioeconomic pathways. Model outputs are available for visualization and download, access via THREDDS, and on the cloud (https://psl.noaa.gov/cefi_portal). The broad spatiotemporal coverage presents opportunities for transboundary research, routine decision support, and multinational efforts in model validation with regional datasets. On the other hand, there are tradeoffs to the large domain, including computational expense that can limit the spatial resolution (currently ∼10 km) and limited ability to regionally tailor the model configuration (e.g. one biogeochemical model needs to realistically represent plankton dynamics in the Bering Sea, Gulf of Alaska, and California Current).

Ocean–ecology relationships

Challenge: Fisheries managers and fishing communities benefit from reliable short- and long-term predictions of fish population dynamics. These predictions are best facilitated by a mechanistic understanding of relationships between ocean conditions, trophic interactions, fish population dynamics, and shifts in population distribution. Our ability to understand and predict ecological responses to ocean change remains limited, especially under novel conditions outside natural variability or when predicting how trophic interactions will influence a focal species' abundance and distribution (Litzow et al. 2020b, Brodie et al. 2022, Smith et al. 2022, Fredston et al. 2023, Free et al. 2023). Unexpected responses to short- or long-term changes in physical conditions can lead to "ecological surprises" (Doak et al. 2008) or "black swan events" (Anderson et al. 2017), posing challenges and opportunities for fisheries and the recovery of protected species (Hilborn 1987, Starr and Haigh 2022, Free et al. 2023).

Most process-based ecological studies (i.e. field or laboratory studies on ecological mechanisms) and ecosystem models are constrained by jurisdictional boundaries, despite the broad ranges of the species they aim to represent (Parker et al. 2024). Experimental work on mechanistic relationships, and the development of ecosystem and population dynamics models are most effective and comprehensive if such work includes the full extent of a species' range and resulting breadth of environmental and ecological interactions. However, this is rarely the case. Overall, the development of regionally specific modeling approaches and resulting regional climatic and biological indices, inhibits the comparison and integration of results across jurisdictions.

Opportunity: Increased transboundary coordination of process research, data synthesis, and ecological modeling, at the scale of relevant ecosystem dynamics and species' distributions, is invaluable to developing an understanding of mechanistic relationships upon which to predict ecological responses to changing ocean conditions. Prioritizing physiological research on environmental thresholds, trophodynamics, and other ecological relationships that can be extrapolated across political boundaries would enhance our understanding and predictions of habitat suitability and species' productivity across multiple regions. Creating shared databases across jurisdictions would support these research endeavors at scales matching those of the species and ecosystem drivers in question. Finally, creating ecosystem models that can either bridge jurisdictional boundaries or be comparable across regions (e.g. modeling framework, functional group definitions) can incorporate these empirical data into analyses under varying environmental and policy scenarios.

Process-based studies can parse environmental responses directly, so these relationships can be incorporated into other models and predict spatial and temporal shifts in range and habitat suitability. For example, laboratory-derived temperature effects on spawning habitat were combined with field-collected data and climate projections to predict a shift northward in Alaskan spawning habitat availability for commercially important Pacific cod (*Gadus macrocephalus*) under future climate scenarios (Laurel and Rogers 2020, Bigman et al. 2025). This mechanistic relationship was then applied across the range of habitats occupied by Pacific cod in the Northeast Pacific, including Canadian and USA West Coast waters, to put into context the historical (∼past 3–4 decades) decline in Pacific cod at the southern end of its range

(Laurel et al. 2023). If the appropriate environmental range is considered and local adaptation is limited, a relatively small number of studies might be sufficient to identify optimal ranges of temperature, oxygen, and other environmental variables for mortality, growth, and reproduction for the entire range of a species (Ward et al. 2024, Indivero et al. 2025). Transboundary coordination of research and prioritization of focal species would advance the pace of our collective understanding of these mechanistic relationships and their application across jurisdictional boundaries.

Transboundary data synthesis (as described in the section "Data collection and use") provides a broader understanding of the mechanistic responses of marine species to changes across large environmental gradients. Synthesizing the vast quantities of data generated by surveys and fisheries monitoring programs across jurisdictions can be statistically powerful to address ecological questions at these larger scales. For example, examining coastwide trends in fish distribution relative to environmental gradients and ecological communities can inform habitat suitability and potential shifts in community dynamics (Pinsky et al. 2013, Ward et al. 2024, 2025, Davidson et al. 2026). Studying phenology across several oceanographic and lower trophic variables on a coastwide scale would provide insights into mechanistic relationships influencing changes in productivity across a range of conditions at the base of the food web. A synthesis of multi-regional time-series would develop our understanding of the synchrony and/or coherence of life-history cycles and whether they are spatially consistent across the Northeast Pacific Ocean (e.g. Fisher et al. 2020). Diet data, paired with monitoring population dynamics and quantifying predator–prey species interdependencies, can advance our understanding of trophodynamics including direct and indirect responses to changing environmental conditions (King et al. 2018).

Box 4. Northeast Pacific salmon research

Pacific salmon (*Oncorhynchus* spp.) stand out among shared species for their biological and jurisdictional complexity, along with numerous protected species designations. Salmon populations are defined by their natal spawning streams, where they often support freshwater subsistence, cultural, commercial, and recreational fisheries, as well as non-economic benefits (e.g. Myrvold et al. 2019, McDowell Group 2022). Salmon migrate across borders of countries and indigenous territories in both freshwater and marine habitats, leading to international disputes that can be exacerbated by migration barriers (e.g. dams), mixed-stock fisheries, and competitive interactions with hatchery-origin fish. International management challenges arise most frequently during marine life stages because migration routes are poorly resolved, with multiple populations occupying the same regions, making it difficult to determine which populations are impacted by fisheries or other anthropogenic activities. To address this challenge, five nations participate in the North Pacific Anadromous Fish Commission, which successfully halted high-seas fishing for Pacific salmon (Dereynier 1998). In addition, bilateral agreements between the USA and Canada regulate many nearshore, mixed-stock fisheries via the Pacific Salmon Treaty (Canada-United States 1985) and negotiate freshwater migration passage issues (e.g. via the Columbia River Treaty, Canada-United States 1964). In part to inform these negotiations, the Pacific Salmon Commission coordinates a massive fish-tagging and reporting system with open databases—Regional Mark Processing Center (https://www.rmpc.org/) and Marine Data Portal (https://soggy2.zoology.ubc.ca/geonetwork/srv/eng/catalog.search#/metadata/00bc242d-9145-464b-bb92-c1d0eb1f469a)—which helps in estimating harvest rates and improves mechanistic understanding of the factors that influence fish abundance. More recently, genetic stock identification techniques, often relying on genetic baselines developed collaboratively, have allowed the origin of ocean-caught fish to be identified (e.g. DeFilippo et al. 2020). This information has been used to identify causes of decline (https://www.fisheries.noaa.gov/feature-story/whats-behind-chinook-and-chum-salmon-declines-alaska), including restricting fisheries (https://www.fisheries.noaa.gov/action/amendment-110-fmp-groundfish-bering-sea-and-aleutian-islands-management-area) that affect populations threatened with extinction.

Salmon are particularly vulnerable to climate change resulting from their dependence on both freshwater and marine ecosystems (Hare et al. 2016, McClure et al. 2023) and temperature-mediated threats from bycatch (Sabal et al. 2023). Transboundary assessments have demonstrated strong latitudinal clines in population sensitivity to warming and competition in the ocean (Fig. 2, Connors et al. 2020), potentially leading to new management opportunities (Connors et al. 2025). Shared geospatial, hydrological, and water quality data platforms, such as Terradapt (https://www.cascadiapartnerforum.org/terradapt), and resources describing the functional relationships between physical conditions and salmon responses, such as Stressor Response Library (https://connect.fisheries.noaa.gov/salmon_stressor_response_library/) and Chinook Technical Committee Data (https://psc1.shinyapps.io/ctc-shiny-app/_w_efbbad27/) are improving range-wide conservation planning and treaty-based management.

Transboundary approaches to stock assessments and ecological models for species and ecological processes allow the inclusion of the full niche breadth, range edges, and spatial structure. Transboundary stock assessment models help to better detect abrupt changes, overcome assessment model misspecification, capture distribution shifts, and better support management responses under changing environmental conditions (Palacios-Abrantes et al. 2020, Box 1). In the absence of transboundary stock assessment, increasing the comparability of region-specific stock assessments across jurisdictions through common methodology and timing of production can allow inter-regional comparison, ease the inclusion of extra-jurisdictional data in alternative sensitivity models to understand how the assessment responds to data from the full population range, and facilitate learning from surprises in nearby regions (Box 4). Ecosystem models and model ensembles can better address hypotheses for fisheries and protected species at appropriate ecological scales through either transboundary models (e.g. the Salish Sea Model, Khangaonkar et al. 2018) or through comparable regional models (e.g. the

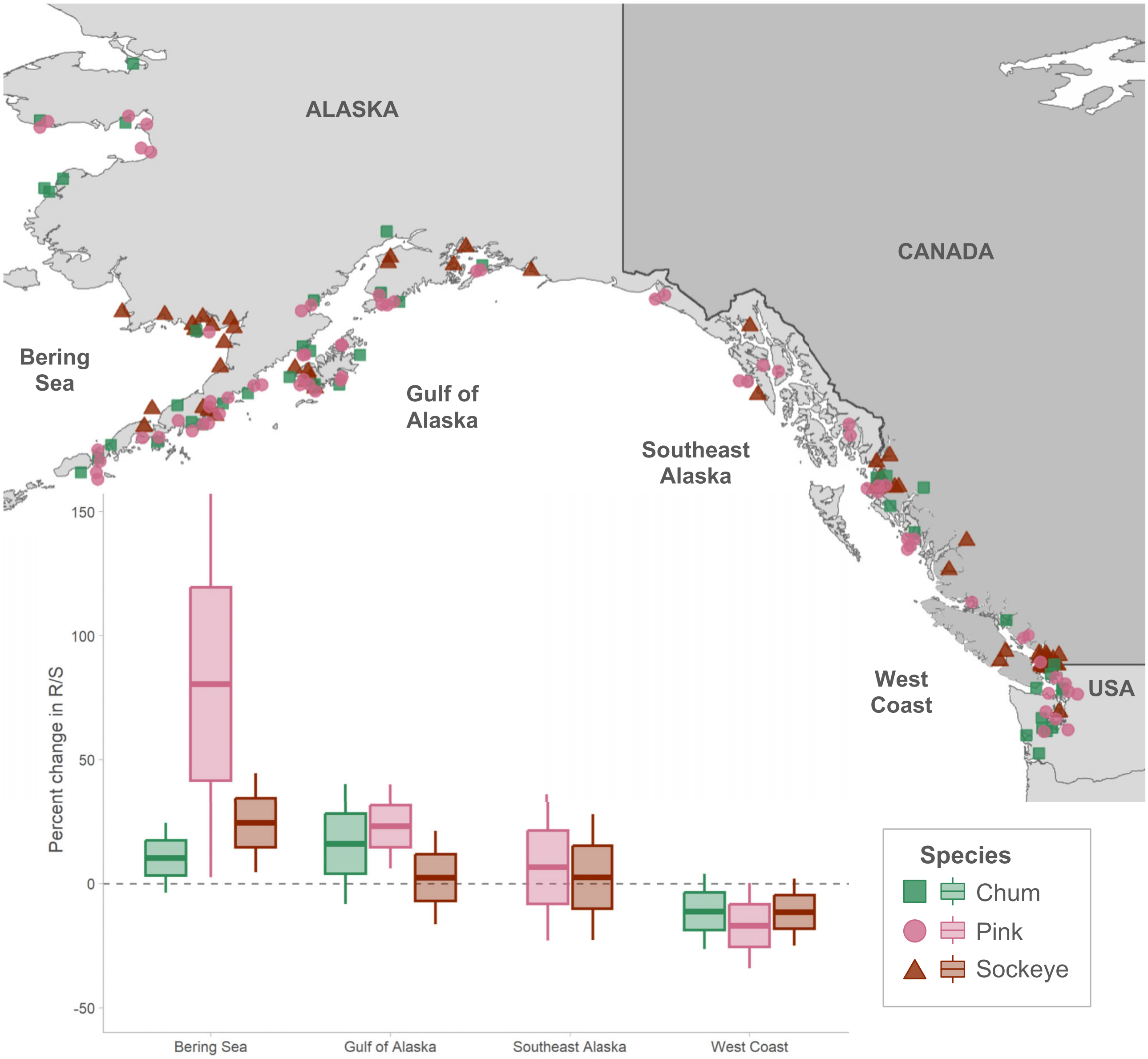

Figure 2 Predicted effects of ocean warming on Pacific salmon survival vary by species and in space. Boxplots show predicted effects (percentage change in adults produced per spawner) of a one standard deviation unit increase in sea surface temperature during the first few months of marine life for each of three Pacific salmon species by ocean region. Ocean entry locations for each population considered in the analyses are overlaid on the map along with international and stage/provincial borders. Updated from analyses described in Connors et al. (2020) and Mueter et al. (2002) by Hannah Hunter, Fisheries and Oceans Canada, and Su Kim, NOAA Fisheries.

Fisheries and marine ecosystem model intercomparison project, https://fishmip.org/tools.html). Encouraging the transboundary exchange of statistical tools and expertise across borders can increase the pace of research and provide efficiencies in modeling.

Communication and integration in management

Key message: Increased frequency and effectiveness of communication of ecosystem information to support management needs across jurisdictions can enhance the use of existing science products and strengthen on-ramps to integrate science in the management of fisheries and protected resources.

Challenge: Effective communication and integration of ecosystem information in management systems is required to maintain sustainable fisheries and protect resources in a changing environment. However, limited transboundary information exchange and regional differences in tools and methods to synthesize ecosystem information constrain the ability to integrate ecosystem information at broad scales (e.g. large marine ecosystem or coastwide) within a management context. Regional differences in the production and communication of ecosystem-related products and processes (including timing, management applications, and focal audiences) have limited the cross-region comparability of information in support of fisheries management. Management systems across jurisdictions in the Northeast Pacific can differ in priorities and policies, decision timelines, and perspectives of stakeholder communities. In some cases, the different management systems necessitate these divergences, such as the timing of groundfish assessments and harvest specification occurring throughout the year in British Columbia, Canada, and the USA West Coast, versus at a single annual meeting in Alaska, USA. The integration of ecosystem information in management can also vary across the Northeast Pacific. For example, depending on species, environmental information may be integrated directly into single species stock assessment models (Pepin et al. 2020, Wetzel et al. 2025), qualitatively summarized in risk tables (Dorn and Zador 2020), or included in species-specific ecosystem and socioeconomic profiles (Shotwell et al. 2022). These differences can lead to inconsistencies in the application of reporting metrics and analyses, or lead to parallel development efforts across neighboring regions.

Opportunity: Advancing the communication and alignment of science, synthesis tools, and analytical methods across borders can better support ecosystem-based management of fisheries and protected species. In the Northeast Pacific, ecosystem considerations are included in fisheries and protected species management and conservation through a diversity of products and processes across the Alaska, British Columbia, and USA West Coast regions, such as single species assessments (Marshall et al. 2019, Kulka et al. 2022, Karp and Vieser 2024), full ecosystem reports (Boldt et al. 2024, Ferriss 2024, Leising et al. 2025), and risk tables (Dorn and Zador 2020). Increased transboundary information exchange and collaboration would enhance the ability of existing regional products and processes to match the relevant ecosystem scales of interest. New synthesis tools are emerging to match evolving management requirements, but broader alignment is still needed. Transboundary alignment of ecosystem indicators would enhance the ability to compare and learn from ecosystem trends in neighboring regions. Without harmonized indicators or outputs, regions miss the opportunity to detect coastwide changes or share effective response strategies.

Transboundary science will be most effective for fisheries and protected resources management when there is strong institutional support that results in successful integration and communication to relevant research and decision-making bodies. Existing international science bodies provide successful templates for promoting transboundary exchange of science and synthesis tools, and developing shared priorities across regions, including the North Pacific Marine Science Organization (PICES), the International Council for the Exploration of the Sea (ICES), and the North Pacific Anadromous Fish Commission (NPAFC) (Box 5). National institutions can create a supportive culture and framework to further develop these collaborative efforts, and to further integrate the outcomes into regional management processes (e.g. Diack et al. 2024). Continued information exchange between regions (e.g. seminars, meetings of bilateral groups, and participation in existing annual meetings) can help familiarize stakeholders with regionally specific management systems, existing ecosystem-related indicators, products, and communication pipelines, and science and management priorities. Regular transboundary exchange of regional ecosystem information and inclusion of expanded ecosystem information in regional synthesis reports and discussions can provide a coastwide or oceanic ecosystem context for existing reporting that occurs at regional scales. Ongoing communication and exchange of knowledge can provide opportunities to build upon successes in neighboring regions, supporting more efficient adoption of advanced technologies, effective partnerships between agencies and the fishing industry, and incorporating local and traditional knowledge into the fisheries management process (Hamelin et al. 2024, Wing and Woodward 2024, Caldeira et al. 2025).

Updating regional ecosystem information and indicators more frequently (e.g. as available for satellite-based data or seasonal surveys), coupled with increased accessibility of results, would allow for better uptake of ecosystem information in neighboring regions with different decision timelines for management of fisheries and protected resources. Neighboring regions do not necessarily have updated ecosystem information available on similar annual timeframes. This asynchrony creates challenges for incorporating coastwide ecosystem information into decisions for stocks assessed and managed on separate schedules in each jurisdiction, but also for stocks managed with explicit transboundary agreements (e.g. Pacific hake and Pacific salmon stocks). Creating a common suite of ecosystem indicators, analytical tools, and visualizations among regions would advance our ability to efficiently communicate coastwide trends and comparisons. Common indicators benefit from readily accessible data, sharing, and co-development of analytical tools (e.g. Edwards et al. 2024, Anderson et al. 2025, Ward et al. 2025), and standardized models (e.g. the MOM6 oceanographic model; Adcroft et al. 2019) or data collection methods as discussed above. Hunsicker et al. (2022a) and Box 5 describe the strength of applying a common analytical framework to regional data to identify and compare ecological thresholds across North Pacific marine ecosystems, supporting timely detection and tracking of ecosystem trends and states. Regionally unique indicators and ecosystem monitoring approaches are important to address local management priorities, and they support a diverse portfolio of ecosystem information. A shared understanding of why certain aspects of the ecosystem are being monitored and reported within a jurisdiction can be informative to other countries and can help clarify science and management priorities within that jurisdiction. Combining unique indicators with a suite of more broadly applicable metrics would enhance our ability to detect and interpret coastwide ecosystem trends and more rapidly support management responses.

While regional management priorities may differ, coastwide or large marine ecosystem priorities could be developed in parallel to focus shared indicator development, information exchange, and support broader ecosystem-level planning. Shared stocks with USA–Canada international treaties (e.g. Pacific hake, Pacific halibut, Pacific salmon) have made strides in incorporating coastwide, climate-related information in stock assessments and can serve as examples of cross-region alignment in communication of ecosystem information. For example, the US–Canada Pacific halibut stock assessment has considered including the Pacific Decadal Oscillation index in the stock assessment (affecting average recruitment, Stewart and Hicks 2022) and management strategy evaluation (movement and recruit spatial distribution). As of 2025, the US–Canada Pacific hake stock assessment now includes an ecosystem-informed risk assessment (Johnson et al. 2025). A more systemic practice of institutional collaboration and communication will be required to support the majority of fish and protected species stocks that are not specifically managed by treaties.

Box 5. PICES working group as a forum for transboundary communication

Many countries use ecosystem indicators to monitor and report changing ecosystem conditions, with applications for fisheries and protected species management. Identifying environmental changes at larger, transboundary scales is challenging due to variation in the indicators evaluated and the use of different analytical tools to identify environmental trends. The PICES Working Group (WG) 36: Common Ecosystem Reference Points brought representatives from six North Pacific countries together, from 2016 to 2022 to address these challenges. The WG summarized available time series across the region, synthesized and shared analytical methods, identified methods for determining thresholds for ecosystem indicators, and discussed common tools to combine and compare ecosystem indicators and reference points across jurisdictions. Key outcomes of the WG included working across jurisdictions to: (1) summarize and identify driver-response relationships and thresholds to select potential ecosystem reference points; (2) identify ecosystem indicators most sensitive to biophysical changes in the environment (potential early warnings); and (3) develop conceptual models applied across countries to examine ecosystem reference points in the context of climate forcing, fishing, and ecosystem responses (Hunsicker et al. 2022a). The immediate benefits of the WG included knowledge exchange and workshops to advance the synthesis and methods for analysis of time series describing North Pacific ecosystems. The WG also published several reports and manuscripts, and has provided momentum to continue the application of these concepts to ecosystem indicators in the context of climate and fisheries management (Litzow et al. 2020b, Hunsicker et al. 2022a, Boldt et al. 2021, Ward et al. 2022, 2022b).

Conclusions

Transboundary science has never been more important to support management of fisheries and protected resources, as marine ecological systems respond to increased ecosystem variability, extreme events, and novel conditions. Successful templates exist in the form of species-specific international agreements, temporally limited joint research and survey events, and international working groups. Building on these successes relies in part on institutionalizing collaboration across government agencies within participating countries. Coordination of surveys, monitoring, and sharing of data and analytical tools at a transboundary scale is required to detect and understand marine ecosystem responses to climate change. Common assessment frameworks and modeling approaches can improve understanding of ecological relationships and projections of responses to climate change. Increased exchange of ecosystem information to support management needs across jurisdictions can enhance the use of existing science products and strengthen on-ramps for transboundary science to inform management of fisheries and protected resources.

Government institutions play a unique role in supporting and benefiting from increased transboundary collaboration, and in adapting socio-ecological systems to rapid climate-driven change in the world's oceans. Governments can institutionalize transboundary collaboration by embedding this culture in the structure of marine research, monitoring, prediction, and reporting. In return, the institutional ability to adjust the scale of monitoring and prediction from local to transboundary levels to match the relevant ecological scale increases the ability to meet management objectives under changing systems (Ingeman et al. 2019). Agencies can become more economically efficient through collaborative approaches to shared ecological challenges (Neeson et al. 2015). Monitoring transboundary phenomena can be achieved by connecting independent fish and ecosystem surveys across jurisdictional boundaries through increased data accessibility, alignment of survey methods and timing, and alignment of data collection protocols (Maureaud et al. 2021). Ongoing intergovernmental communication and data sharing can prepare management systems for changes in distribution (Pinsky et al. 2018). The joint Canada–USA Climate and Fisheries Northeast Pacific Working Group, in which we participate, has identified and fostered numerous specific instances of international cooperation and communication, but expansion and institutionalization of such groups is necessary to continue this work.

Local institutional capacity and focus is still required to meet current science and management needs, ideally in alignment with transboundary collaboration. For example, oceanographic and ecosystem models with high fidelity to smaller regions can facilitate inter-regional comparisons through comparable data, assumptions, and modeling platforms. Scientific products, such as stock assessment or ecosystem model outputs, must be summarized and communicated in the appropriate context for uptake by local scientists, managers, and stakeholders. Aligning the timing and format of summaries across regions can aid in the information uptake by other institutions. Institutional science primarily aims to support local resource management and conservation priorities, which may differ across jurisdictional boundaries. Neighboring regions can better adapt to changing marine ecosystems and shifting management priorities by drawing on shared knowledge and institutional expertise.

Opportunities for advancing transboundary science inevitably require answers to questions of prioritization, values, and support that are beyond the scope of this paper. Questions will have to be addressed around prioritization of species and ecosystem dynamics as the focus of data collection and modeling, equitable funding of joint surveys, and the application of science in management frameworks. Binding transboundary management agreements are one tool to support this level of collaborative science and to ensure a framework for equitable discussions and support (Miller and Munro 2004, Koubrak and VanderZwaag 2020). However, creating separate international agreements for each shared stock would be onerous for science and management agencies to support and would be subject to change as species' distributions shift in response to changing environmental conditions. A focus on institutional culture (e.g. open science) and practices (e.g. survey design with transboundary applications) at the national level would provide a baseline of best practices that could be resilient to our evolving transboundary science needs.

Consequences of not advancing transboundary collaboration in marine science may include depleted fish stocks and protected resources, with the resulting societal costs or lost fishing opportunities because of suboptimal harvest strategies caused by regionalization of shared stocks (Kapur et al. 2024). International resource-use conflicts can emerge from climate-driven changes in fish distribution across regions that do not have the science and management structure in place to support adaptive policies (Pinsky et al. 2018, Østhagen et al. 2020). For example, Connors et al. (2025) warns that shared Pacific salmon stocks could be mismanaged without a complete understanding of the carrying capacity of their boundary-spanning habitat and the impacts of supplementing the population with regional hatcheries. In the face of changing marine environments, transboundary science can help mediate the known and unknown impacts of changes to our fisheries and protected resources by supporting a more informed and adaptive management system.

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Author contributions

All authors contributed to conceptualization and writing of the original draft manuscript. B.E.F., B.M.C., L.G.C., and S.C.A. coordinated integration of contributions. All authors reviewed and edited the final manuscript.

Conflict of interest

The authors declare no conflicts of interest.

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Data availability

No new data were generated or analysed in support of this research.

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