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Developing socio-ecological indicators for changing Northern Coastal environments

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Abstract

Monitoring tools and indicators that incorporate ecological and socio-economic aspects of ecosystems can lead to improved management outcomes and resource use benefits. Local and Indigenous communities in Northern coastal environments, including Nunatsiavut (northern Labrador, Canada), strongly rely on marine resources for food security, social, economic, and cultural integrity. Integrating Indigenous Knowledge and Western science through ethical and principled collaboration with local stakeholders and rights holders is a prerequisite for improving outcomes that support the priorities of local communities. Here, we identify a framework for developing socio-ecological indicators for northern coastal systems using case studies from our research program in Nunatsiavut. We highlight the importance and challenges of integrating science and local knowledge for ocean monitoring and management, and share our experiences to guide future efforts. Our 5-year collaborative research program identifies indicators of status and function of coastal ecosystems, moving beyond historical Western science practices by incorporating local and regional socio-cultural knowledge and needs. We propose that monitoring programs should include practical and accessible indicators that support Inuit priorities (e.g., ice thickness, fish size, and fish flesh color) that local communities and resource users can sustainably monitor and link to local priorities.

Key words: marine indicators, northern ecosystems, local knowledge, socio-ecological indicators, Inuit, Nunatsiavut

Introduction

Worldwide, multiple anthropogenic and climate-related drivers propel ongoing shifts in marine ecosystems and resources, raising concerns about the future of the global ocean and associated societal well-being (Halpern et al. 2008; Butchart et al. 2010). Especially at higher latitudes, rapid changes in climate and environmental conditions in recent decades (ACIA 2004; Prowse et al. 2009*a*) concurrently affect the ecological, social, institutional, and economic components of ecosystems (Prowse et al. 2009*b*). For example, reductions in the extent, thickness, and duration of sea-ice cover alter the socio-ecology of coastal and ocean systems. Reduction of sea-ice has ramifications for ice-dependent organisms (e.g., Arrigo et al. 2008; Kovacs et al. 2011; Grémillet et al. 2015), and jeopardizes safe and reliable access to local resources and food security (McCarney et al. 2018) with implications for mental health in local Inuit communities (Cunsolo Willox et al. 2013). Simultaneously, these changes will mean new opportunities for shipping that will potentially create new economic opportunities, but may also increase marine traffic in northern oceans, introducing additional environmental risks, management challenges, and impacts for local communities (Prowse et al. 2009*b*; Bishop et al. 2022). Indeed, ship traffic in the Canadian Arctic has nearly tripled over the last decade (Dawson et al. 2020). Ocean warming has also facilitated the introduction of invasive species and new pathogens to cold oceans, and increased the connectivity of populations and hybridization of species in polar and subpolar environments (Post et al. 2013; Kaiser and Kourantidou 2021).

How communities and industries will adapt and thrive under these changing conditions may depend on the extent to which they can monitor changes and govern for adaptation at appropriate temporal and spatial scales. Decision-making requires clear and effective metrics that describe the current and predicted state of ecosystems as well as how that state will affect societal objectives and needs, underpinning the need for quantitative monitoring of marine and associated ecosystems (Crain et al. 2008). Monitoring the structure and functioning of ecosystems in combination with socio-economic activities supports solutions for more sustainable management and use of resources (Kaiser et al. 2019). Ocean monitoring that results in improved outcomes for human and ecological systems must consider socio-ecological inter-linkages (Kaiser et al. 2019).

Effective monitoring requires identification of variables amenable to assessment, measurement, and quantification over time, which also reflect the status of a system given likely environmental changes. These variables, called indicators, encompass a wide range of purposes, functions, and applications which ultimately fall within the science policy tool kit (Lehtonen 2015). In general, ecological indicators are easily interpreted surrogates that help identify trends by isolating key aspects of natural systems (National Research Council 2000; Niemi and McDonald 2004). Collectively, monitoring measures of biodiversity and habitats, along with physical and biogeochemical ocean features, can assist scientists, managers, and policy makers in understanding, predicting, and preparing for the ecosystem changes typically associated with resource exploitation, coastal development, and climate change (García Molinos et al. 2016; Miloslavich et al. 2018). Among indicator frameworks, essential ocean variables, essential biodiversity variables, and essential climate variables have emerged to harmonize natural science efforts across broad spatial scales and include measures of physical oceanography, biogeochemistry, biodiversity, and ecosystem responses to a changing ocean based on quantitative data that can be used to support governance and management at regional to national to global scales (Pereira et al. 2013; Miloslavich et al. 2018; Muller-Karger et al. 2018).

Local-scale context can and should strongly complement the comprehensive focus of indicators developed with broad-scale reporting priorities. For instance, ecological context at high latitudes includes understanding food web dynamics and the effects of seasonal and broader (e.g., climate-induced and anthropological) changes often define the first step required to identify key variables for interpreting and tracking coastal ocean health. Although often time-intensive, costly, and necessitating sustained access to scientific resources, food web approaches provide opportunities to identify key indicators that can contribute to effective monitoring, even in resource-limited applications. Considering local social and economic dimensions, especially human relationships with the ocean, provides a means for researchers and managers to support the needs and priorities of communities more effectively (Kourantidou et al. 2020). Importantly, monitoring and management strategies aiming to improve socio-ecological outcomes must account for and monitor human behavior and well-being in combination with ecological components. This need is particularly important in regions with strong and integrated social, cultural economic, and ecological connections (Chaturvedi 2016; Kaiser et al. 2019). Indeed, in the Canadian Arctic, which is home to many Indigenous Peoples, the development of indicators must consider the close relationships between people and the land, including the integration of Indigenous knowledge systems and recognition of Indigenous rights.

Here, we share process and learning based on a case study from Nunatsiavut (meaning "our beautiful land"), a self-governing Inuit region in northern Labrador, Canada. We first highlight the importance and challenges in integrating Western science and Indigenous knowledge for ocean monitoring and management when developing place-based indicators for northern coastal systems. Second, we propose a framework for developing socio-ecological indicators for northern coastal systems. Third, we share our experiences as outcomes and challenges to guide similar efforts.

Integrating science and Inuit knowledge for ocean monitoring and management

This paper focuses on Nunatsiavut, one of four Inuit homelands that collectively comprise Inuit Nunangat, the homelands of Inuit in Canada. In Inuit Nunangat (which includes Nunavut, Nunavik, Nunatsiavut, and the Inuvialuit Settlement Region; Fig. 1), subsistence and commercial fisheries are important staples of Inuit wellbeing, contributing to social, cultural, and economic benefits for many communities (Snook et al. 2019, 2022; Kourantidou et al. 2022). Life in many Inuit communities is inextricably linked to marine harvests and has remained so for hundreds of years. The Inuit Tapiriit Kanatami National Inuit Strategy on Research (NISR) (2018) sets out clear guidelines for any visiting researchers who wish to conduct work in Inuit Nunangat; namely that all projects must uphold Inuit self-determination in research. This means that Inuit must be involved in all stages of the research program, from design, through implementation, interpretation, and communicating results. This ensures that Inuit priorities are the focus of research, that ethical guidelines are respected, and that Inuit knowledge guides the process (NISR 2018). To follow this guidance, researchers entering Inuit Nunangat must work with Inuit partners to integrate Inuit and Western sciences, priorities, and knowledge systems.

In this paper, we use the term "Inuit knowledge systems" to refer to the knowledge system encompassing the epistemology, ontology, and perspectives of Labrador Inuit, which helped to guide our research program. Across Inuit Nunangat, Inuit communities hold a deep connection to the marine environment, which provides food security, cultural continuity, and a sense of identity (Cadman et al. 2023). Inuit hold unique knowledge gathered through multi-generational

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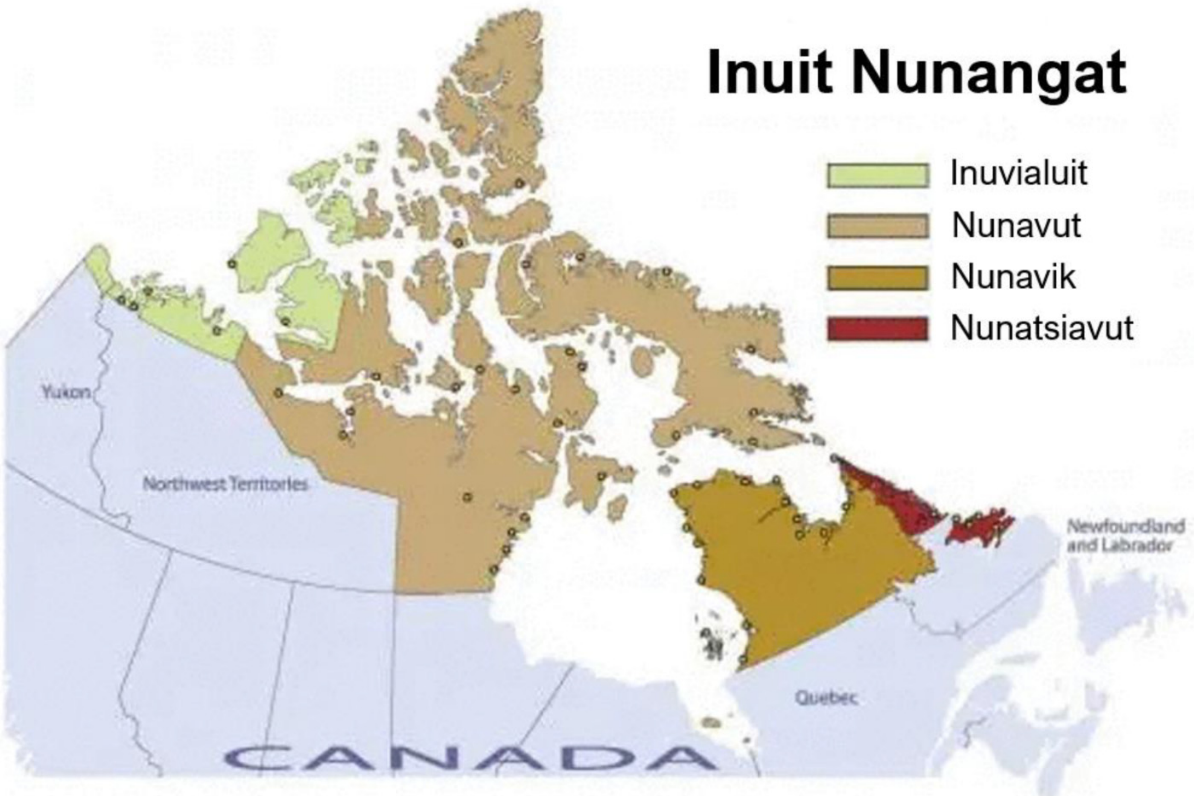
Fig. 1. Locations of Inuit Nunangat, the four Inuit regions of Canada. Nunatsiavut, where most of the research discussed in this work was conducted, is highlighted in red. Base map source: Inuit Tapiriit Kanatami (itk.ca).



experience living on and with the coastal ocean, including interdependence with marine ecosystems (Kaiser et al. 2019). Inuit knowledge systems are place-based, meaning that they are generated through a relationship with specific lands and waters, and they are holistic, encompassing all the ways that information is learned and shared (Tester and Irniq 2008; Todd 2014; Ferrazzi et al. 2019).

Many researchers have noted that co-producing indicators engaging Western and Indigenous partners can be a useful way to integrate knowledge systems (Parlee et al. 2005; Peacock et al. 2012; Kournatidou et al. 2020). Numerous studies emphasize the importance of Inuit knowledge in increasing understanding of climate variability and shifts, health of stocks, resource use, community vulnerability, and other important factors (Huntington 2000; Moller et al. 2004, 2009; Laidler 2006; Denny and Fanning 2013; Mistry and Berardi 2016). Inuit communities possess deep intergenerational knowledge about their traditional territories, and understand how to recognize change, adapt to new circumstances, and steward healthy ecosystems that provide fundamental resources and support livelihoods and economies (Alexander et al. 2019; Henri et al. 2020; Steeves 2021; Bowles et al. 2022). Given this long-term relation to and knowledge of their lands, Indigenous-led identification of indicators should be supported to meet global sustainability goals (Moore and Hauser 2019).

Additionally, scientific and Indigenous-based monitoring methods often complement each other by operating efficiently at different scales and with different foci (Kaiser et al. 2019). For example, Western science can provide a quantitative evaluation of marine conditions at large spatial scales of hundreds to many thousands of square kilometers (e.g., using remote sensing), including locations that community-engaged monitoring excludes (e.g., regions not used for traveling or harvesting). These methods provide ecological knowledge of ecosystems and can elucidate how and why changes occur at larger spatial and temporal scales. However, Western scientific methods often prove expensive, time consuming, and may not be focused on key ecosystem processes and interactions operating at local scales or over relevant time periods. This is particularly so within nearshore coastal environments not well characterized by vessel- or satellite-based monitoring. Local, Indigenous knowledge-based monitoring methods can often mitigate these shortcomings, and are well suited for identifying ongoing changes. This is possible because these methods are typically responsive, local residents know the area, and this form of monitoring is relatively inexpensive compared to mobilizing research teams to access remote locations, and thus sustainable (Kaiser et al. 2019). For example, monitoring conducted by local communities can incorporate larger sample sizes of harvested resources and centuries-long observational time periods compared to temporally (and sometimes spatially) limited scientific field samples that often span periods of just days or weeks (Moller et al. 2004). In many cases, the knowledge gained through experience and shared traditions enables the recognition of subtle changes as they occur and affect harvesting and other traditional activities, as well as reports of unusual events not captured by Western scientific methods (Kaiser et al. 2019).

Challenges in developing indicators for northern coastal systems

The development of indicators to inform management and sustainable use of resources in northern coastal systems poses significant challenges, especially in the Arctic. These challenges link to high resource dependence, and are exacerbated by geographic remoteness, limited availability of datasets, and strong economic, social, and cultural pressures (Kourantidou et al. 2020, 2021*a*). For example, the lack of methods for tracking changes in locally harvested marine resources threatens food security as well as the social, economic, and cultural integrity of local communities (Kourantidou et al. 2022).

The unique relationships and interdependencies between fisheries and Inuit have meant that Western science-based fisheries indicators that do not integrate regional needs and local knowledge cannot adequately support the needs and wellbeing of Inuit (Kourantidou et al. 2020, 2022). Despite the importance of including Inuit in the development of indicators, several barriers prevent active participation of Indigenous communities in consultation and regulatory processes in Canada. These barriers include documents written using technical jargon, language barriers, and limited time, funding, or resources available to Indigenous Peoples to participate and respond to decision-making processes, discussions, or hearings (Mason 2015; Giles et al. 2016; Supreme Court of Canada 2017; Kaiser et al. 2019).

Importantly, many Indigenous scholars emphasize Indigenous knowledge as a system of knowledge, more than just data points to remove out of context and place into Western management frameworks (Latulippe and Klenk 2020; Whyte 2018). Indigenous knowledge systems themselves represent frameworks for governance, inclusive of unique methodologies and based on each Peoples' own conceptualizations of institutions of law, education, and economy (McGregor 2018). Some critics point out that defining indicators generally reduces an integrated and embedded form of knowledge by removing it from its context and failing to capture the cultural values and experiences associated with it (Wilson et al. 2019; Liboiron 2021). Therefore, the debate continues regarding the extent to which integration of Indigenous knowledge and Western science can avoid subsuming the integrity of Indigenous knowledge.

These issues continue to challenge the integration of Inuit knowledge and Western science. To date, these factors have limited Inuit participation in research and monitoring activities conducted mostly by researchers with little connection to or recognition of the deep experience of Indigenous residents and caretakers of Inuit Nunangat (Inuit Tapiriit Kanatami 2018; Kaiser et al. 2019). As a result, Indigenous groups are often burdened by a colonial management system that is biased toward Western science (Kourantidou et al. 2020). This persistent scientific approach amplifies existing harms to Indigenous Peoples and communities, creating "feelings of being over-researched yet, ironically, made invisible", because of a "historical exploitation and mistreatment of people and materials" (Tuck 2009*a*). Shifts in research practices are occurring, for example, through increased uptake of participatory action research (PAR; Tuck 2009*b*; Liboiron 2021), knowledge co-production (Reid et al. 2020; Zurba and Papadopoulos 2021; Zurba et al. 2021), and partnership-driven work (UN General Assembly 2007).

Case study: developing socio-ecological indicators for Nunatsiavut

Here we showcase a project to advance understanding of indicator development through a collaboration between natural and social scientists and Inuit government, stakeholders, and rights holders. The Ocean Frontier Institute (OFI) research program on Ecosystem Indicators began in 2018, and was a 5-year program aimed to identify indicators of ocean status and function from microbes to humans that could be applied to and serve local and regional socio-cultural needs. The approach was designed to bridge research, policy, and practice, facilitate a learning process for those involved in and impacted by the research, and was predicated on previous work (for example, Nutley et al. 2003). To achieve these goals, the program explicitly sought to integrate stakeholder and rightsholder priorities and needs as part of the participatory process, and set a goal of building accessible and meaningful monitoring tools that local communities could use.

This project took place in Nunatsiavut. In 2016, driven by recognition of the importance of proactive involvement of local and Indigenous communities in research planning and environmental monitoring, a group of researchers within the OFI began discussions with the Nunatsiavut Government to write a proposal to develop ecosystem indicators of value to coastal communities in Nunatsiavut. Specifically, the group proposed to develop food web models and socio-ecological indicators drawing from marine resource use and at coastal locations identified as high priority by the communities in Nunatsiavut. The work was intended to support the Nunatsiavut Government's Imappivut ("our ocean") marine plan.

In synthesizing the OFI Ecosystem Indicators initiative, we present a framework (Fig. 2) for identifying socio-ecological indicators for a changing ocean built on both Western scientific approaches, and informed through collaboration with the Nunatsiavut Government and Inuit community members who shared their knowledge while supporting ice- and boat-based marine research activities. Here, we present case examples from the project that illustrate the process of identifying socio-ecological indicators aimed at improving understanding and management of marine resources in northern coastal environments. We conclude by identifying the challenges and further steps needed to integrate science and traditional and/or local knowledge effectively into policy by taking into account the needs of local rights holders and stakeholders.

The first phase (Phase 1, Fig. 2) of the framework identified key resources and activities (e.g., marine species and harvesting) that sustain local economic health and that Inuit

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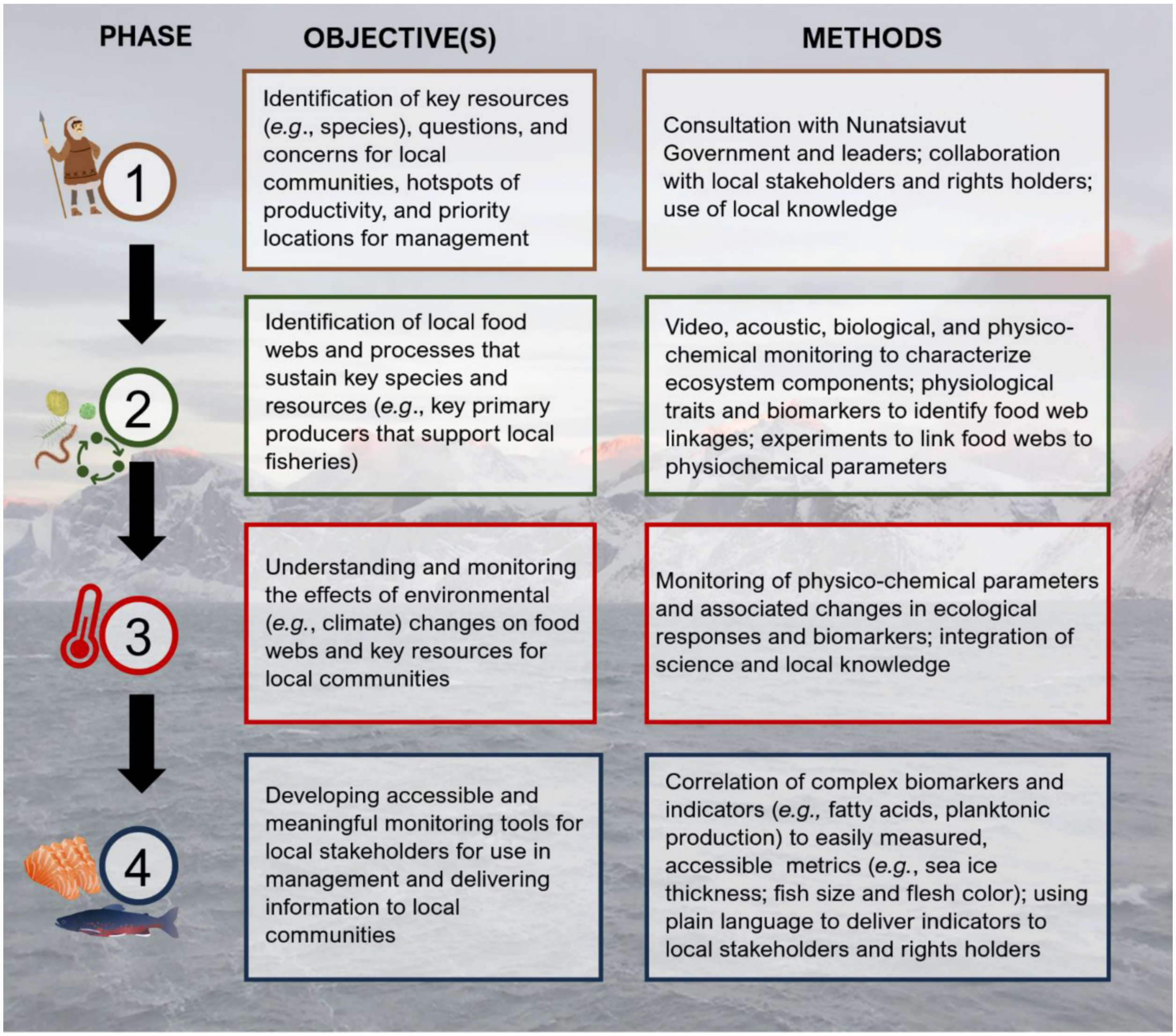
Fig. 2. Summary of the four main phases used in this framework to integrate local and scientific knowledge into the creation of accessible monitoring tools for northern coastal ecosystems, highlighting the objective(s) and methods of each phase. Icons were provided by Integration and Application Network, University of Maryland (ian.umces.edu/media-library) under a Creative Commons CC BY-4.0 license.



communities consider important for traditional livelihoods in coastal Labrador. The second phase (Phase 2, Fig. 2) evaluated the energy and nutrient sources upon which key species depend, and the associated food web that includes identifying the key primary producers and consumers that support fisheries critical for coastal Labrador communities. The third phase (Phase 3, Fig. 2) emphasized understanding how environmental changes can affect northern food webs and, in turn, the availability and quality of resources for local communities and their economy. Finally, the fourth phase (Phase 4, Fig. 2) identified accessible monitoring indicators and tools that local stakeholders and rights holders could use in managing resources in changing northern coastal environments. Delivery of those indicators will take place in 2025.

Collaborative research

Our project aimed to re-shape Western science environmental research practices to be useful to and respectful of Nunatsiavut communities. Throughout the phases completed so far, project leaders and scientists consulted and collaborated with the Nunatsiavut Government and with local rights holders and stakeholders (e.g., fishers, local governing, and fisheries management bodies), including working with local Inuit to design and execute field research and interpretation of results. This project brought together collaborators from diverse disciplines at two Atlantic Canadian universities, federal and regional government agencies, Indigenous representatives, and management authorities to enable discussions on key social and ecological challenges relating to commercial and subsistence harvesting. It also led to a follow-on project

(Sustainable Nunatsiavut Futures) fully co-developed with Indigenous communities.

Identifying key resources for local ecological, social, and economic health

At the onset of the project, in 2018, five university faculty and early-career scientists consulted with Nunatsiavut leaders in Nain and met with about ten local rights holders whose livelihoods rely on marine resources. On the recommendation of Nunatsiavut government leaders in Nain, we timed the meeting to avoid hunting seasons and align with a linked fisheries meeting of the Torngat Secretariat that attracted fishers from the broader region. With convening help from the Nunatsiavut Government and the Torngat Secretariat, who offered a broad invitation to participants of the Torngat Secretariat meeting, the team met with a group of ~10 participants who showed up for the discussion. We deliberately did not press them to identify themselves or their community, though some indicated the areas where they worked. We brought large maps and markers and, using a whiteboarding approach and open discussion, invited them to identify marine species and socio-ecological issues related to the marine environment representing their respective interests and concerns. The team received input on locations of high priority such as sites with relatively high productivity, accessibility, or concern due to issues such as historical disturbance (e.g., oil spill). This input helped to define the focal species, study locations, and potential ecological indicators on which the project would focus.

During this visit, the academic team met with the Nunatsiavut Government to learn about Imappivut, the Nunatsiavut Government plan to manage and protect Labrador Inuit interests in the coastal and marine areas of Labrador (https://imappivut.com/). This discussion addresses research goals and approaches appropriate to the region, and how the Ecological Indicators research initiative could support the development of Imappivut.

Characterizing the food webs that sustain key resource species for local communities and understanding the effects of environmental changes

During the spring, summer, and fall of 2019, the broader OFI team built on those established connections with the local Nain community to initiate fieldwork and experiments. Researchers stayed at the Nunatsiavut Research Centre, working with the staff and local individuals with expert knowledge of the areas we were working in to visit these priority areas and identify specific sampling locations, and protocols, and collect some preliminary samples to guide subsequent sampling practices. Local Nain residents subsequently took researchers to sampling sites on their boats and snow machines (depending on season), and they offered input on fishing sites, deployment of scientific instruments, and timing of sampling. Such work focused on the diverse ecosystem components of Nunatsiavut, working on societally relevant ecosystem components from microbes to fishes and fisheries, and environmental aspects spanning ocean temperature to nutrient stocks, ice thickness, and coastal circulation.

Through field work, surveys, and experiments that focused on western science tools but with local involvement and guidance, researchers aimed to characterize the food webs that sustain key species and resources across northern coastal environments in Nunatsiavut. Part of our goal was to use western science tools to develop locally accessible and informative methods that would not require regular access to specialized scientific equipment or tools. Scientific sampling, experiments, and the integration of multiple methods and techniques (see Table 1) helped in developing new insights on changing coastal food webs in relation to variation in riverine input, nutrient availability, coastal habitat, and ice conditions. This information allowed scientists to identify metrics that reflect changes in food webs, biogeochemistry, coastal ecosystem services (e.g., fish production), biodiversity, and resource abundance most relevant to local stakeholders and rights holders in the context of climate and other drivers of change.

All fish tagging followed Canadian Council on Animal Care Guidelines and was approved by the Memorial University Animal Care Committee under the protocol No. 19-01-RG.

Developing accessible monitoring indicators and tools for Nunatsiavut

During this ongoing final phase, scientists will return to Nain to collaborate and consult with local stakeholders and rights holders to determine linkages between those complex variables and biomarkers identified through phases 2 and 3 and identify simple, accessible monitoring tools that local practitioners can use, with the intent of delivering these tools back to local communities. Delays related to the COVID-19 pandemic have slowed efforts to complete some of the projects within the research program prior to communicating findings directly to the community; however, we recognize this step as critical to the engagement process and indeed an obligation to those who offered their knowledge during the planning phase. The last few pieces of the project will be completed over the next 6 months. We plan to present our findings in the five Nunatsiavut communities during spring of 2025. These engagement efforts will also showcase findings from the follow-on project, Sustainable Nunatsiavut Futures, and provide an opportunity for us to seek feedback and insights from Inuit community members.

Outcomes and challenges

Identification of key resources for local ecological, social, and economic health

The 2018 workshop with key members of the Nunatsiavut Department of Lands and Natural Resources and local communities, stakeholders, and rights holders in Nain was crucial in establishing communication with the leading local fish harvester, two local charter services and tour operators (and hunter/fishers), and three representatives of the Nunatsiavut Government's Department of Lands and Natural Resources, and to hear their advice, concerns, and priori-

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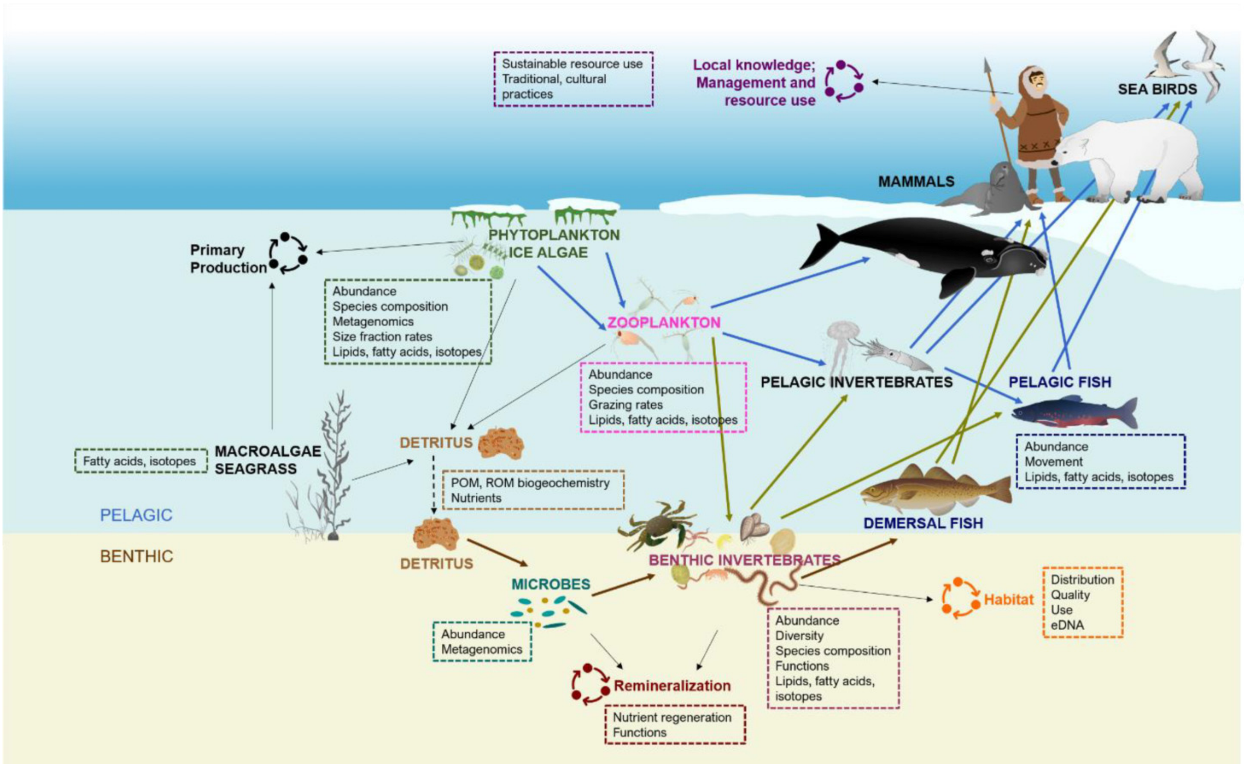
Table 1. Summary of the main Ocean Frontier Institute projects used as case studies to develop socio-ecological indicators, highlighting projects' objectives, methodologies, and researchers involved.

Project	Methods	Reference
Identifying energy and nutrient sources that sustain the local food web across different habitats.	Fatty acid and stable isotope composition of organisms from different trophic levels.	Campanyà-Llovet et al. (in preparation)
Fisheries management and governance in Inuit communities of Nunatsiavut and associated food security and equity dimensions.	Interviews, focus groups, workshops in Nain and Makkovik, bioeconomic modelling, governance analysis.	Kourantidou et al. (2020, 2021*a*, 2021*b*, 2022, 2024)
Assessing the forms, rates and sources of nitrogen and carbon supporting under-ice bacteria, phytoplankton, and zooplankton populations in the coastal environment including areas influenced by rivers.	Community composition, carbon and nitrogen uptake and regeneration rates by ice algae and three plankton populations (bacteria, phytoplankton, and zooplankton), the stable isotopic composition of each of these populations and contribution to the particulate carbon and nitrogen pools.	McBride et al. (in preparation)
Investigating benthic nutrient cycling and carbon mineralization rates in contrasting benthic communities, in response to different food sources (e.g., ice algae and phytoplankton) in an effort to understand the potential ecological impacts of declining sea ice cover and shifts in primary productivity.	Estimation of fluxes of oxygen and inorganic nutrients during short-term (24 h) ex situ incubations of sediment cores enriched with different food sources; characterization of macro-infaunal communities (taxonomic and functional diversity).	Clinton et al. (in preparation); Clinton et al. (2024)
Assessing spatial and temporal variation in diversity of benthic invertebrates and demersal fishes in relation to habitat and biogeophysical variables.	Baited camera deployments across different habitats for evaluation of invertebrate and fish diversity.	King et al. (in press); Campanyà-Llovet et al. (in preparation)
Resolving fine-scale population structure in IKaluk/Arctic charr (*Salvelinus alpinus*) and assessing climate change responses of charr and vulnerable populations.	Sequenced microsatellites and single nucleotide polymorphism (SNP) array on IKaluk/Arctic charr populations; integration of genomics and environmental modelling.	Layton et al. (2020, 2021)
Quantifying ogâtsuk/Greenland cod/rock cod (*Gadus macrocephalus ogac*) movement over a sub-Arctic latitudinal gradient.	Using acoustic telemetry to investigate ogâtsuk/Greenland cod/rock cod movement in coastal habitats along Newfoundland and Labrador.	King et al. (in preparation)
Linking IKaluk/Arctic char habitat use in the marine environment to prey fields.	Used acoustic telemetry, genomic methods, and long-term fisheries and diet data in coastal areas of northern Labrador.	Cote et al. (2021*a*)
Predicting climate change effects on the distribution of Atlantic cod (*Gadus morhua*), ogâtsuk/Greenland cod/rock cod, and Arctic cod (*Boreogadus saida*).	Combined climate projections and physiological models to predict distributions.	Cote et al. (2021*b*)
Characterizing physical oceanography of coastal ecosystems during the ice season informing controls on coastal ice dynamics and related ecosystem processes.	Measuring depth profiles of salinity, temperature, chlorophyll, colored dissolved organic matter, turbidity, and dissolved oxygen along transects from river to mouth of fjord systems.	Oliver et al. (unpublished data)
Investigating the factors that control salt-induced flocculation and thus potential sedimentation of dissolved organic matter and iron in northern coastal systems.	Experimental investigations of the changes in particulate carbon, particulate nitrogen, chlorophyll a, and stable isotopic composition of particulate carbon, dissolved organic carbon, dissolved organic nitrogen, dissolved iron, concentration and proportions when organic carbon rich river water meets coastal systems.	Khoo et al. (2022)
Assessing size fractionated biogeochemical constituents across adjacent coastal systems to inform approaches for integrating small catchment studies into regional models.	Quantification of particulate carbon, particulate nitrogen, chlorophyll a, and stable isotopic composition of particulate carbon, dissolved organic carbon, dissolved organic nitrogen, dissolved iron, specific UV absorbance of organic matter, spectral slope of organic matter.	Khoo et al. (2023)

ties. Consultation with local people through the workshop was important to developing relationships and trust with knowledgeable community members (e.g., field experts and local government researchers), establishing common goals, and facilitating future collaboration. Indeed, for many of the researchers involved in the project, this initiative was their first opportunity to work with northern communities and therefore also represented a learning process that would help in the co-development of future initiatives.

During the meeting, concerns were expressed with respect to the health of fish stocks, fluctuations in fish biomass associated with environmental changes, as well as market and

Fig. 3. Conceptual diagram summarizing the food web in coastal Northern ecosystems, including organisms and processes. Dotted boxes contain the main variables that scientists assessed during the project to characterize the structure and connectivity of the food web that sustains key resources. Icons were provided by Integration and Application Network, University of Maryland (ian.umces.edu/media-library) under a Creative Commons CC BY-4.0 license.



management components related to commercial and subsistence fisheries (e.g., mesh size, catch per unit effort, local processing capacity, prices, and landings). In addition, broader institutional and governance concerns surfaced in relation to quota allocation policies, access to fisheries, self-governance, and resource management dynamics along with opportunities and challenges to local economic development.

Among other key species of interest discussed (e.g., snow crab, northern shrimp, and Greenland halibut), consultations identified iKaluk/Arctic charr (*Salvelinus alpinus*) as an important component of the commercial and subsistence fisheries in Labrador (Andrews and Lear 1956; Snook et al. 2018), with the Fraser River outflow as a key fishing location for this species. For ogâtsuk/Greenland cod/rock cod, another important subsistence fishery, community members identified Two-Mile Bay and Metre Bay as key locations. Local fishers raised particular concerns about the status of charr populations and their poorly understood ecology. A primary concern for community members was better understanding the underlying causes of variation in charr flesh color in time and space that many residents had observed in the past, and which affected consumer preferences and market price (Anderson 2001), even though quality and flavor may remain the same. We hypothesized that diet might play a major factor in flesh color. Community members also repeatedly noted issues related to decreasing ice cover, and the effect of reduced ice cover on transportation, access to marine and terrestrial resources, and shifts in those resources.

These discussions raised numerous questions of interest not only to local fishermen and rights holders, but also to OFI scientists regarding species and their food webs, as well as the changing physical and socio-ecological environment. Combining Inuit knowledge and experience with the technical skills and experience of OFI scientists helped to ensure the bidirectional transfer of knowledge to the benefit and interest of both parties.

The intersection between iKaluk/Arctic charr health and the health of charr fisheries was particularly salient in conversations with fishers and local residents. Work by Kourantidou et al. (2024) to characterize the sustainability of co-existing subsistence and commercial Arctic charr harvests highlights how scientific uncertainties and potential char mis-management puts economic and cultural benefits at risk (Kourantidou et al. 2024).

Characterization of food webs that sustain key resource species for coastal communities

To assess marine food webs within the coastal waters surrounding Nain, our research team used a variety of approaches and techniques (see Table 1) that spanned from the base of the food web through humans as top consumers. Our research therefore focused on the important variables for different trophic levels (Fig. 3), from primary producers (photosynthesizers) through primary consumers (zooplankton) to the upper trophic levels that are important for local communities and commercial and subsistence fisheries (e.g., iKaluk/Arctic charr and ogâtsuk/Greenland cod/rock cod). This approach included assessing some of the important low trophic level functional processes that sustain ecosystems (e.g., nutrient regeneration). Some research components also assessed the influence of habitat type on local biodiversity and processes. On the advice of Inuit partners, we looked to ecological and biophysical functions that are well-known by Inuit and are already embedded in their lives and cultural practices, such as fisheries production and habitat use by fishes.

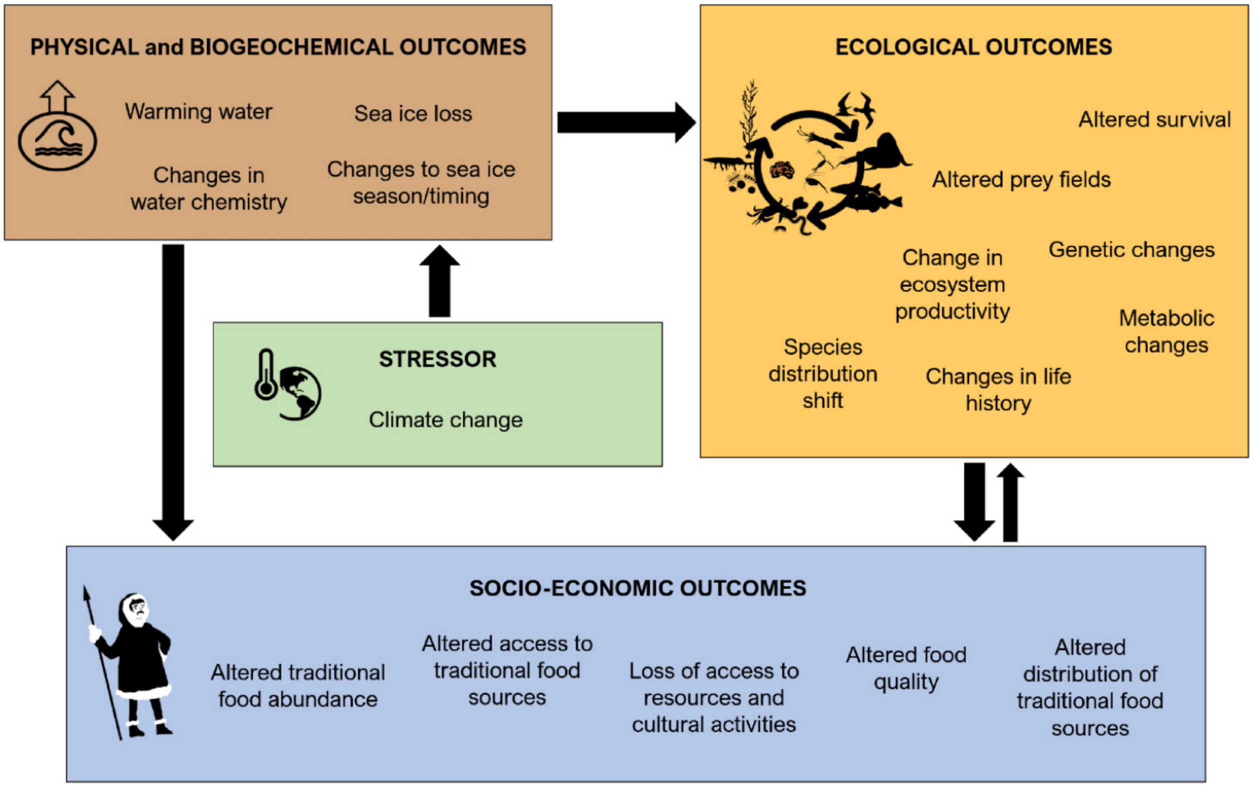
Sea ice has always been important for Labrador Inuit, providing a highway for travel and important habitat for species like natsik/Ringed seal, iKaluk/Arctic charr, and even tuttu/caribou. Knowing how to travel on the ice is essential for safety and requires that Inuit have an intimate understanding of navigation and of the quality of ice throughout the seasons. As a result, Labrador Inuit who fish and hunt on the ice and land are always monitoring the sea ice conditions. Because they already possess expertise and practice observation, monitoring sea ice extent, thickness, and color offers a relatively simple and accessible way to monitor ecosystem changes. Climate change-related decreases in sea ice extent and thickness, and altered timing of sea ice formation and break-up, will also directly impact the relative contributions of different primary producers, likely resulting in a reduction in ice algae and an increase in phytoplankton (Arrigo et al. 2008). These changes may, in turn, alter Arctic and sub-Arctic food webs. For example, some Arctic copepods use the ice algae bloom as a cue for reproduction, which allows their offspring to utilize the subsequent pelagic phytoplankton bloom that occurs after ice break-up (Leu et al. 2011). Recent evidence also suggests that changes in temperature and available food sources are leading to shifts in zooplankton size and species distribution via the borealization of sub-Arctic zones (Møller and Nielsen 2020). Therefore, any change in the onset, duration, or magnitude of the ice algae bloom may impact the growth and survival of other key northern species that contribute to the health and productivity of the food web.

Ice algae blooms are unique to polar and subpolar ecosystems, and are critical for establishing the ecological characteristics of these systems. Although phytoplankton and ice algae are both primary producers that play key roles in carbon and nutrient cycling, they serve separate ecosystem functions (Arrigo and van Dijken 2015; Baer et al. 2017; McBride et al. in preparation). A shift to pelagic blooms would not necessarily lead to a decrease in functional capacity, but would likely facilitate a shift in speciation reflective of lower latitudes which could have downstream effects on how the ecosystem functions (Arrigo et al. 2008). Sea ice reduces the light available for primary production, in regions with snow cover (Hill et al. 2022). Ice algae have adapted to these environments, allowing them to grow and accumulate biomass when the light levels beneath the ice remain limiting. During the annual sea ice melt and break-up, this accumulation of ice algae leads to an acute input of biomass to the pelagic and subsequently benthic systems. At the seafloor, ice algae provide a higher quality food source for benthic invertebrate communities compared to phytoplankton because they contain relatively high concentrations of polyunsaturated fatty acids (Falk-Petersen et al. 1998; McMahon et al. 2006), which many organisms require but cannot synthesize themselves. Additionally, the quantity and composition of algae and other organic matter reaching the seafloor may affect both the direction and magnitude of benthic nutrient fluxes, which regenerate inorganic nutrients essential to fuel primary production in surface waters (Clinton et al. unpublished data). The composition of the invertebrate communities inhabiting the seafloor also mediates these processes (Clinton et al. unpublished data). Therefore, monitoring changes in ice thickness, duration, extent and timing can provide valuable predictive insight into the ways and magnitude to which ecosystem functions shift as the northern climate continues to warm.

Community members, who carry a deep familiarity with ice and snow conditions based on Inuit Knowledge, can assess factors influencing light availability, such as ice thickness, snow cover, snow depth, the presence of melt ponds, rattles (polynas), and the timing and rate of sea ice formation and break-up. Characterizing the key taxa that form the prey of important local fish species and processes that define the structure and functioning of northern coastal food webs (e.g., determinants of productivity, preferred prey, characteristics that define preferred habitat) enables identification of indicators of change in ecosystems that may affect important local resources. These measurements are not only important in understanding the role of sea ice in marine food webs, but also provide important observations that relate to the state and stability of the ice as a mechanism for safely accessing marine and coastal resources.

Monitoring flesh color of iKaluk/Arctic charr offers another pathway to track ecosystem change, in that color reflects dietary changes potentially associated with food web alterations. iKaluk/Arctic charr flesh color ranges from whites and pale yellows to oranges and pinks/reds in relation to concentrations of the red-colored carotenoid, astaxanthin, responsible for their characteristic pink-flesh color. Astaxanthin occurs naturally in aquatic environments, synthesized by microorganisms or converted from other carotenoid precursors (e.g., β-carotene and zeaxanthin) in planktonic crustaceans. Salmonids such as iKaluk/Arctic charr, lack the capacity to synthesize or convert astaxanthin but instead bioaccumulate this pigment through the trophic web (Stachowiak and Szulc 2021). The most common prey items that sustain iKaluk/Arctic charr populations comprise benthic (sand lance—*Ammodytes* spp., sculpins—*Triglops* spp., and *Myoxocephalus* spp.) and pelagic (capelin—*Mallotus villosus*, hyperiid amphipods, *Parathemisto* spp.) food web components, with varying proportions of dietary items according to individual size, location, and time (Dempson et al. 2002). This diet flexibility denotes a predator adaptable to trophic structure variation resulting from species displacement or varying abundances with environmental change. Therefore, a diet dominated by astaxanthin-rich hyperiid amphipods for a particular individual, location, and/or time will lead to a pinker flesh

Fig. 4. Effects of climate change on local communities in Nunatsiavut through various and inter-connected physical and ecological outcomes. Icons were provided by Integration and Application Network, University of Maryland (ian.umces.edu/media-library) under a Creative Commons CC BY-4.0 license.



color, which will provide some hints on food web structure as well as influence charr's commercial value.

Recognition of the effects of environmental changes on local resources and processes

A key step in identifying indicators for ocean monitoring requires understanding effects of environmental change (e.g., climate change) on coastal Labrador food webs and processes. In turn, availability and quality of resources important for local communities and economies depend on related processes (Fig. 4).

The Labrador Sea sits at the center of a subpolar gyre and plays a critical role in global ocean circulation; it has a disproportionate role in global transport and storage of anthropogenic carbon-dioxide (Sabine et al. 2004). This location also offsets overall declines in oxygen level in regional and global oceans (Rhein et al. 2017) and in defining the key properties of North Atlantic Ocean water (Li et al. 2021). Climate change-related shifts in transport of Pacific water through the Arctic (Zhang et al. 2021), and freshwater released from glacial melting in Greenland (Garcia-Quintana et al. 2019) link to changes in deep-water convection in the Labrador Sea, with dramatic implications at both regional and global scales. While direct observations of deep ocean circulation, specifically the Atlantic Meridional Overturning Circulation (AMOC), have yet to reveal a clear trend (Li et al. 2021), most modeling groups (e.g., Jackson and Wood 2018) predict a decline in the strength of circulation with significant impacts both regionally and at the basin scale. Ditlevsen and Ditlevsen (2023) applied a statistical and data-driven approach to the North Atlantic suggesting that a collapse of the AMOC is likely by the middle of the century. Some work suggests that the cooling trend identified in the North Atlantic (Keil et al. 2020) indicates that AMOC weakening has already begun; if true this decline would lead to cooling in the subpolar gyre. These potential changes in the central Labrador Sea also have significant implications for the coastal ocean, affecting water characteristics, nutrient supply and primary production, annual sea-ice formation and transport, as well as movement of icebergs through the region. Recent model forecasts suggest that annual sea-ice extent could decrease by as much as 70% in the coming decades (Han et al. 2019). Several studies report recent changes in nutrient supply both in the open ocean in the Labrador Sea and the adjacent Labrador Shelf (Hátún et al. 2017; Tesdal et al. 2022), with, on one hand, reduced nutrients associated with increased stratification related to climate change and, on the other hand, offsetting of any reduction by increased winter convection/resupply.Overall implications for biological productivity remain uncertain. Further changes in atmospheric forcing and water transport at the boundaries, key drivers of this system, will almost certainly amplify shifts already seen in recent decades. Our research identified some of the most relevant potential effects of environmental changes on local food webs and key resources in coastal Labrador.

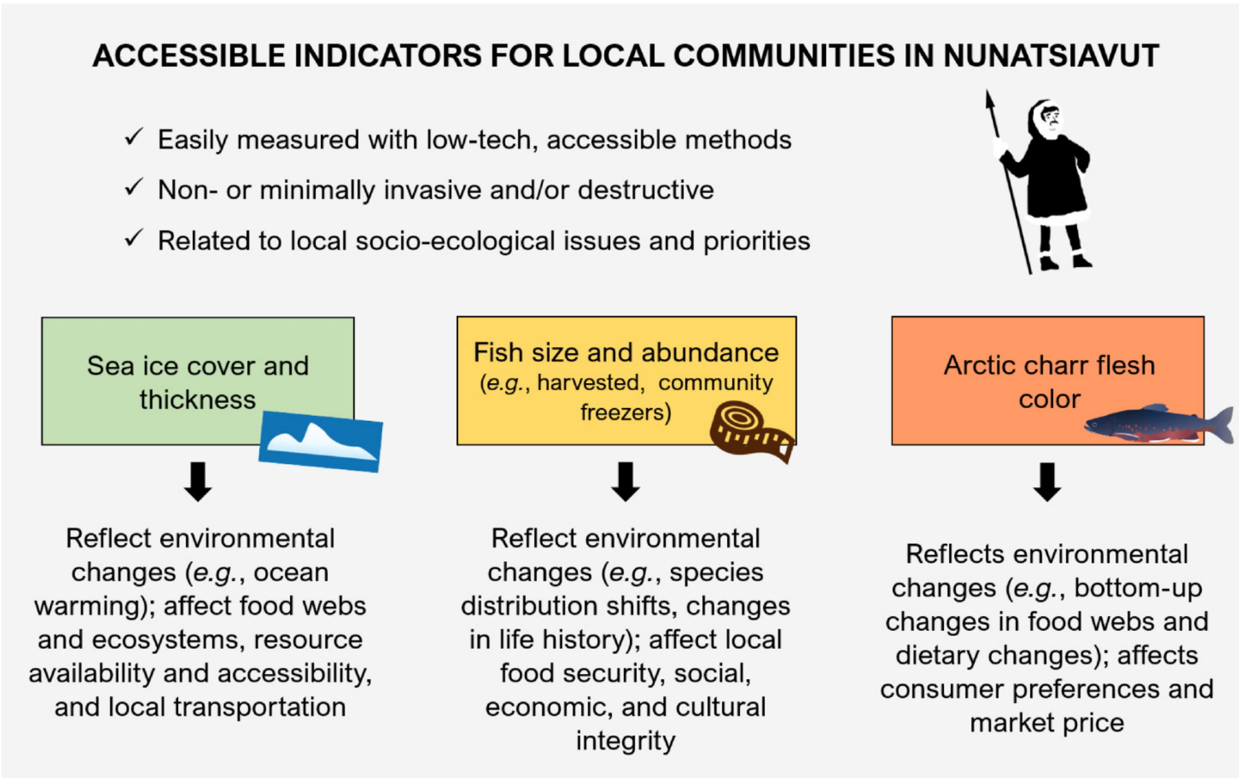
For example, Layton et al. (2020, 2021) found that climate change across a pronounced environmental gradient in Labrador will likely have negative effects on iKaluk/Arctic charr, a mainstay of subsistence, commercial, and communal fisheries, as well as cultural keystone species for generations of Inuit (Reist et al. 2006; Knopp 2010; Denniston et al. 2021). IKaluk/Arctic charr populations throughout Nunatsiavut exist as multiple migratory ecotypes, including freshwater resident and anadromous forms, with the larger anadromous populations prevalent in Northern Labrador. In general, iKaluk/Arctic charr appear to be structured at the scale of individual rivers, most with unique and genetically identifiable populations (Layton et al. 2020). Evidence suggests that iKaluk/Arctic charr have adapted to environmental differences in climate across the region, with over 10% of genomic variation in constituent populations explained by temperature (Layton et al. 2021). Regional changes in climate could consequently result in significant maladaptation in some populations, potentially causing charr population decline and a loss of genetic diversity and important life history variation.

Long-term data sets from the north coast of Nunatsiavut support these predictions on iKaluk/Arctic charr. Cooling waters and regime shifts in the early 1990s were linked to altered marine distributions and a shift in iKaluk/Arctic char diets from predominantly fish to invertebrates, causing a reduction in fish size and overall population abundance (Cote et al. 2021*a*; Layton et al. 2021). These changes, in turn, directly affected Inuit harvesters who reported typically smaller and less plentiful iKaluk/Arctic charr that had shifted into more exposed oceanic habitats that were less accessible and more dangerous to harvesters because of changing ice conditions and timing of ice formation. These deviations are expected to directly impact Inuit who rely on the iKaluk/Arctic charr fishery for their livelihood, including financial security, food security, and cultural continuity (Usher 2002; Knopp 2010; Denniston et al. 2021; Kourantidou et al. 2021*b*). This decline will also likely lead harvesters to pursue other species to make up for reduced catches. Layton et al. (2021) suggest that by 2050, warming climate will threaten the persistence of the larger and more valuable anadromous life history form of iKaluk/Arctic charr in southern parts of Labrador. Taken together, these results suggest sensitivity of this species in Labrador to climate forcing, placing southern anadromous populations at risk over the coming decades as the southern range limit for populations using this life history strategy shifts northward. Even in rivers where anadromous populations of charr persist, dietary shifts could negatively impact perceived quality of iKaluk/Arctic charr flesh. Consumption of carotenoid-laden invertebrates—taxa that dominate the diet of more northern populations—support the preferred redder flesh. In contrast, residents of Nain report fish with paler, less desirable flesh in years when capelin in coastal areas dominate charr diets, influencing its commercial value. Should temperate forage fish such as capelin become more available to iKaluk/Arctic charr with climate change, the resulting shifts in diet may have negative consequences for commercial fishery and, possibly, preferences in subsistence fishing activity. Thus, changes in the abundance, distribution, and quality of iKaluk/Arctic charr could strongly impact Inuit food security, well-being, and heritage (Knopp 2010; Kourantidou et al. 2021*b*, 2022).

Similarly, climate change could affect ogâtsuk/Greenland cod/rock cod, another important species harvested year-round throughout coastal Nunatsiavut for subsistence purposes (Dombrowski et al. 2013). Even though climate-driven distributional shifts have not been documented for ogâtsuk/Greenland cod/rock cod, a recent analysis estimated that habitat suitability for egg and juvenile life history stages of the species will likely shift poleward in line with continued ocean warming projections in the Northwest Atlantic (Cote et al. 2021*b*). Given that survival of early life history stages contributes to adult population stability (Houde 2008), potential mismatches in the spatial or temporal habitat requirements of these early life stages may have negative consequences on adult population productivity. Additionally, while relatively few studies have described ogâtsuk/Greenland cod/rock cod ecophysiology, gadids in general respond behaviorally to changes in ocean temperature. In the northern Pacific Ocean, populations of Pacific cod (*Gadus macrocephalus*) have shifted northward into the North Bering Sea during warming periods (Stevenson and Lauth 2019), whereas recent marine heatwave events reduced spawning habitat suitability and recruitment in the Gulf of Alaska (Laurel and Rogers 2020). In the Northwest Atlantic Ocean, Atlantic cod distributions have shifted northward during warming periods and southward after periods of cooling (Rose et al. 1994, 2000). Accordingly, if ocean warming continues as projected, ogâtsuk/Greenland cod/rock cod distributions will likely shift poleward. These changes could impact Inuit communities that may have to contend with potential changes in ogâtsuk/Greenland cod/rock cod distributions and abundance.

In addition to potential changes at higher trophic levels (e.g., range shifts, altered anadromy, etc.) reductions in sea ice may affect the base of marine food webs. As noted earlier, the lengthening of ice-free periods associated with climate change may decrease the relative contribution of ice algae to Arctic and sub-Arctic food webs, in favor of phytoplankton (Arrigo et al. 2008; Leu et al. 2011). Such changes in primary producer communities and associated marine detritus directly affect lower trophic levels, as well as ecosystem processes (e.g., nutrient cycling). For example, sediment cores experimentally enriched with either ice algae or phytoplankton exhibited differences in both the direction and magnitude of nutrient fluxes, with responses mediated by the composition of sedimentary infaunal communities (Clinton et al. unpublished data). Improved understanding of benthic community composition (e.g., polychaete- versus mollusc-dominated) may therefore explain how sea ice change may alter nutrient regeneration and how this loss, in turn, could affect the entire food web. Moreover, because ice algae offer a higher quality food source for benthic invertebrate communities by providing relatively high concentrations of essential polyunsaturated fatty acids (McMahon et al. 2006; Sun et al. 2009), reduced ice algae export to the seafloor may negatively affect benthic communities and the higher trophic levels they sustain, including species that support Inuit communities. For example, Leu et al. (2011) found that the

Fig. 5. Examples of accessible monitoring indicators for changing coastal environments that could be used by local communities in Nunatsiavut. Icons were provided by Integration and Application Network, University of Maryland (ian.umces.edu/media-library) under a Creative Commons CC BY-4.0 license. We note that Labrador Inuit are beneficiaries of the Labrador Inuit Land Claims Agreement (2005) and are recognized as holding treaty rights through the Agreement. In this paper we generally use the word "rightsholder" to refer to Labrador Inuit participants and project partners. However, for clarity we also occasionally refer to specific Labrador Inuit stakeholder groups, such as commercial fishers.



Arctic copepod *Calanus glacialis* times reproduction with the ice algae bloom, rather than pelagic phytoplankton. Mismatches resulting from altered timing of ice freeze-up and thaw could therefore have consequences for many higher trophic level species.

Development and delivery of accessible monitoring indicators and tools for/to Nunatsiavut

During the last phase of the framework, the team proposed accessible indicators of ocean change (Fig. 5) based on the information gained on the food webs that sustain key resources in coastal northern Labrador and the potential effects of environmental changes on resources and processes. For example, because the timing, extent, and thickness of sea ice influences these northern food webs, monitoring sea ice can help identify changes in resources (e.g., ice algae, phytoplankton abundance) and processes (ecosystem productivity) before they translate to higher trophic level species on which communities rely. Sea ice cover and thickness also affect the accessibility of marine resources to local communities because harvesting areas are often only accessible by traveling on sea ice.

IKaluk/Arctic charr was identified as a key resource for the subsistence, economy, and cultural heritage of Labrador Inuit. Because charr's flesh color changes based on their diet, and also affects the quality and market desirability of the fish, monitoring changes in flesh color can help identify changes in the local food web in a timely manner. For instance, based on local knowledge, paler flesh color can indicate a switch from invertebrate-dominated to fish-dominated diet, typical of years with increased abundance of temperate forage fish such as capelin in coastal Labrador, whose population can be monitored on spawning beaches (e.g., ecapelin website). Such changes not only affect the quality of a key resource for local communities, but also indicate a change in the local food webs possibly related to climate change and to the migration of temperate species northward.

Monitoring harvested fish abundance, size, and distribution can also offer insight on environmental changes while also indicating risks and challenges to food security of community members (Kourantidou et al. 2021*a*, 2021*b*). For example, in an environment undergoing some of the most rapid climate change on our planet, our findings that ogâtsuk/Greenland cod/rock cod occupy a broad geographic range in coastal habitats along Newfoundland and Labrador (King et al. In press), suggests a relatively broad temperature tolerance and that temperature-driven changes may not as severely impact this species as compared to iKaluk/Arctic charr. Our findings on sensitivity to temperature change in some populations of charr (Layton et al. 2021) suggest significant change may soon occur, and that planners/managers may wish to prepare for such change. By the same token, reduction in the abundance and size of fish caught or placed in the community shared freezers could reflect changes in growth conditions or survival in the marine environment, while also affecting the social norms in using the community shared freezers. Other examples of broad category indicators, drawing from focus groups with community members, interviews and consultations with local rights holders, rights holding organizations, and local stakeholders, and which are combined with already existing frameworks that build on Indigenous knowledge systems, focus on fish harvest, consumption, and availability (Moller et al. 2004; Jollands and Harmsworth 2007; Fedirchuk et al. 2008; Ford 2009; Wesche and Chan 2010; CBD 2013; Nilsson et al. 2013; IRC 2019; Lysenko and Schott 2019). For example, for food security monitoring purposes these indicators could include, among others: compilations of annual harvest and consumption of subsistence and commercial marine biomass per household, per capita annual consumption of combined subsistence and commercial marine biomass as a percentage of per capita total protein intake. Health-related indicators could include estimated contributions of the consumption of combined subsistence and commercial marine biomass to reductions in adverse health outcomes related to nutritional deficiencies or imbalances (e.g., obesity, diabetes, hypertension, heart disease, cancer, and others). Food security indicators could include estimated contributions to improved food security resulting from social norms or formal government programs comprising food sharing or other forms of nutritional support (e.g., the use of community freezers).

The final phase of the project focuses on collaborating with local communities to enhance and share tools that can support their ongoing efforts to monitor and understand their changing environment. This work aims to complement the deep knowledge and practices that Inuit have long utilized to observe and respond to changes in sea ice, as well as initiatives already in place by the Nunatsiavut Government. It remains important for southern researchers and scientists to work closely with each Nunatsiavut community to identify which types of tools, information/data collection methods, and communication methods are preferable and most likely to succeed in each community. The types of information needed by community members can differ between communities depending on several factors, including specific geographical and environmental conditions (e.g., sea ice dynamics, river dynamics, marine features, travel routes), hunting and other harvesting preferences and practices (e.g., which species are most commonly harvested, at which times of year, and through what methods), and the preferences of community members (e.g., in some places community members might prefer to use app-based tools, while in others they may prefer in-person monitoring or communication methods). Holding open community events that include cultural components (e.g., a meal, local music, products from local crafters, etc) can be successful at identifying what research questions are relevant to community members particularly if that is done in innovative ways (e.g., via games, using visualizations such as maps, or demonstrations). Methods for targeting specific locations to monitor, and when and how to access them safely, can use smaller meetings with key individuals in communities who are interested in collaborating on monitoring efforts (e.g., conservation officers, key individuals with respected knowledge in community). This is often a valuable approach in Nunatsiavut, particularly if it is done with open communication with and guidance from the Nunatsiavut Government and the relevant Inuit Community Government. However, it is important to consider a range of tools that may work for different groups of community members (e.g., youth, elders, key harvesters). Communities in Nunatsiavut are increasingly expressing support for communication to take place through interactive methods rather than formal and rigid presentations (e.g., on-the-land workshops have shown promise in facilitating effective and meaningful communication between southern researchers and communities in recent years; e.g., Anthony et al. 2023). Further, it will be key for southern researchers to identify community preferences and needs for communication, including how often community members want southern researchers to visit communities, how long they should stay each time they visit, and methods of communication in between visits. This synthesis will form part of that communication effort as we return to the community to relay our findings in plain language.

Conclusions and future steps

During several years of research characterizing coastal food webs and socio-ecological dynamics in northern Labrador, our research team integrated different techniques and food web components to inform a more holistic and complementary understanding of the ecosystem and elucidate relationships between trophic levels. In recognition of the need to uphold Inuit self-determination in developing tools and research in the region, the initial consultation with local communities and subsequent integration of local knowledge and resources prior to and during research created opportunities to design scientifically-relevant questions of value to communities living in and depending upon these ecosystems.

This joint effort of the local and scientific communities allowed us to propose accessible socio-ecological indicators to monitor a changing ocean in coastal Labrador. Local stakeholders and rights holders can continue monitoring indicators such as ice cover and thickness, water temperature, charr flesh color, and harvested fish size, abundance, and location, now expanding their interpretation of findings based on the new ecological relationships identified by this project. Not only can these indicators influence the outcomes of management efforts, they can also make monitoring data and, optimistically, policies more relevant, valuable, and acceptable to local communities. By including community members as active participants in developing indicators based on their own priorities, values, and perceived challenges, the prospects of successful conservation initiatives improve dramatically.

This work also provided an opportunity to evaluate the utility of different scientific techniques and approaches for the purpose of monitoring indicators. For example, Arctic charr flesh color can be a useful indicator of food web structure because observing and making note of changes to flesh is already practiced by Labrador Inuit, and therefore, can be easily folded into monitoring programs. On the other hand, some other approaches, though valuable for improving scientific understanding of ecosystems, might not be suitable for community-based monitoring. For instance, benthic communities are likely an impractical indicator for community monitoring as they exhibit considerable small-scale variability in composition, ecological roles, and responses to changing environmental conditions, and require special tools and training to be assessed. However, this project has identified ecological relationships between ice algae, benthic communities, and nutrient regeneration at the seafloor, suggesting that interpretation of community-collected sea ice data could be expanded to provide insight into low trophic level functional processes. Similarly, monitoring algae community composition and nutrient partitioning poses logistical challenges and is not always well reflected by sampling chlorophyll a, nutrient availability, and ice characteristics. Again, the potential for primary productivity can be better represented through Inuit expertise in sea ice conditions to monitor light availability, sea ice extent and thickness, and other limiting factors in remote Arctic and sub-Arctic ecosystems. Additional ongoing research in this project that we have not reported yet will eventually build upon the results presented here. For example, analysis of baited camera deployments could represent a valid option for community-based monitoring focusing on assessing variability in megafaunal assemblages including abundances, diversity, habitat associations, species distributions, and community composition over time (King et al. In press). Baited cameras present many advantages including being non-destructive and non-extractive, as well as cost-effective and relatively accessible.

The climate conditions and logistical hurdles of conducting research in remote, northern locations create significant challenges for this type of work. Much of the field sampling was conducted in winter and early spring by drilling holes through sea ice; as such, the increasingly short freeze-up period in Northern Labrador provides a narrow sampling window. In addition, limited daylight hours during winter, the difficulty in transporting and deploying specialized scientific equipment, and the harsh and unpredictable weather conditions reduce sampling opportunities. For this particular study, the COVID-19 pandemic and related travel restrictions further limited opportunities to meet and engage with community members, and forced a shift in the sampling approach and in-person engagement that created missed opportunities to carry out natural and social science research in the field. These challenges underscore the importance of partnering with Inuit knowledge holders familiar with working on the land, water, and ice that made this research possible, and greatly enhanced the quality of research output, as well as promoted research and monitoring capacity within Nunatsiavut, thus mitigating many of the spatial and temporal barriers faced by southern scientists. Community scientists and residents effectively enabled this research in Northern Labrador by providing geographic context and guidance, the opportunity to conduct on-ice field work safely, a research facility to process and store samples, as well as participating in data interpretation. This support was extended to individual scientists from the team during sporadic research visits to conduct specific field work for short periods of time.

Moving forward, greater involvement of Inuit in research projects—which can be accomplished by adjusting Western science to make space for existing Inuit expertise, by scientists adjusting their research methods based in input from Inuit, and by providing training to undertake specific sampling—will focus on temporal and spatial sampling of environmental monitoring data on the most relevant times, places and scales, ensure research is addressing questions of concern to communities as well as advancing scientific knowledge, enrich our mutual understanding of ecosystems and resources, and encouraging the uptake of research findings beyond the scientific literature. Although effective engagement of Indigenous communities requires additional time and effort, initial investments can quickly yield significant dividends through more impactful research outcomes. For example, as a direct result of this project, a new project entitled Sustainable Nunatsiavut Futures was co-developed and now funds an ongoing project co-led by the Nunatsiavut Government and grounded in multiple communities along the Labrador coast. Established and recurring relationships also avoid the problem of consultation fatigue, where different scientists descend in sequence, often asking the same sorts of questions of community members and effectively restarting the process. In short, effective Indigenous engagement relies heavily on relationships, and sustaining those relationships with the common goal to sustain ecosystem health to the betterment of humanity.

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Competing interests

The authors declare there are no competing interests.

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