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The Importance of Connected Ocean Monitoring Knowledge Systems and Communities

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Ocean monitoring will improve outcomes if ways of knowing and priorities from a range of interest groups are successfully integrated. Coastal Indigenous communities hold unique knowledge of the ocean gathered through many generations of inter-dependent living with marine ecosystems. Experiences and observations from living within that system have generated ongoing local and traditional ecological knowledge (LEK and TEK) and Indigenous knowledge (IK) upon which localized sustainable management strategies have been based. Consequently, a comprehensive approach to ocean monitoring should connect academic practices ("science") and local community and Indigenous practices, encompassing "TEK, LEK, and IK." This paper recommends research approaches and methods for connecting scientists, local communities, and IK holders and their respective knowledge systems, and priorities, to help improve marine ecosystem management. Case studies from Canada and New Zealand (NZ) highlight the emerging recognition of IK systems in natural resource management, policy and economic development. The in-depth case studies from Ocean Networks Canada (ONC) and the new Moana Project, NZ highlight real-world experiences connecting IK with scientific monitoring programs. Trial-tested recommendations for successful collaboration include practices for two-way knowledge sharing between scientists and communities, co-development of funding proposals, project plans and educational resources, mutually agreed installation of monitoring equipment, and ongoing sharing of data and research results. We recommend that future ocean monitoring research be conducted using cross-cultural and/or transdisciplinary approaches. Vast oceans and relatively limited monitoring data coupled with the urgency of a changing climate emphasize the need for all eyes possible providing new data and insights. Community members and ocean monitoring scientists in joint research teams are essential for increasing ocean information using diverse methods compared with previous scientific research. Research partnerships can also ensure impactful outcomes through improved understanding of community needs and priorities.

Keywords: Indigenous knowledge, ocean monitoring, Ocean Networks Canada, mātauranga Māori, Inuit Nunangat, Whakatōhea, traditional ecological knowledge, socio-ecological systems

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INTRODUCTION

For ocean monitoring to result in improved outcomes for human and ecological systems, both must be accounted for, together. This is particularly true in places where connections to ecosystem productivity remain direct, visible, and integrated socially, culturally and ecologically with coastal communities (Chaturvedi, 2016). However, a comprehensive approach to ocean monitoring that includes local and traditional ecological knowledge (LEK and TEK), and Indigenous knowledge (IK) (Lessard et al., 2002; Clark et al., 2010; Addison et al., 2018) requires costly investments in time and resources (Danovaro et al., 2016). Monitoring investment decisions are generally based on current knowledge, knowledge gaps, and interests across a wide range of both ecosystem services and interest groups (Patrício et al., 2016). These groups range from local to global and may include Indigenous communities. The scale at which ocean monitoring investment decisions are made therefore often varies. When funding and/or scientific inquiry leading to changes in ocean monitoring comes from regional or global interests, successful mechanisms for maintaining local and Indigenous relationships to the systems must be put in place to fully and equitably engage the local and Indigenous communities (Proctor et al., 2010).

Where Indigenous communities form part or all of the socio-ecological system in particular, the socio-ecological system conditions, and their vulnerabilities, are spatially and institutionally dependent (Berkes, 2009). Therefore, one-size-fits-all methods are unlikely to ensure localized ecosystem and cultural integrity (Berkes, 2009). In these cases, Indigenous communities play a very important role in understanding and sustaining the ecosystems to which they belong. Indigenous communities provide knowledge that helps create appropriate management strategies for a given locality (DeFries et al., 2005). However, given the rapidly changing climate, scientific, local, and Indigenous monitoring can complement each other and greatly assist co-management of marine species harvests, including seaweeds by locals and Indigenous communities (Moller et al., 2004) and arctic char fishing in the Canadian Arctic.

In this paper, we refer to monitoring practices rooted in the academic, scientific tradition as "science" and practices which have emerged through Indigenous communities' long histories of practice in managing local resources as "Indigenous knowledge (IK)." These have often been described as TEK, LEK, and other methods. Citizen science, where the non-academic community participates in data collection creating citizen-based observations which then need to be standardized and made compatible with other datasets, sits within the IK-Science spectrum (Busch et al., 2016). We recognize that these systems of knowledge are not mutually exclusive. Indeed, the focus of this paper is to explore how methods in these systems can complement each other in developing a more complete approach to ecosystem management and ecological knowledge.

Connecting IK and science enables Indigenous marine system participants to evaluate scientific predictions using their own forms of adaptive management; these can include "learning by doing" (Walters and Holling, 1990), creating a general community consensus (Berkes et al., 2000), and adaptive harvesting according to seasonal indicators based on oral traditions and community knowledge. Scientific and Indigenous monitoring methods complement each other because they can operate efficiently at different scales and with different foci, both of which are needed for improved decision-making and environmental and resource governance.

Science can provide a precise and quantitative evaluation of marine conditions and expectations, and address larger spatial scales, e.g., using remote sensing. Science-based observing provides a methodology for systematic coverage of larger study areas which include locations where no harvesting – or harvesting by interests outside of the socio-ecological system – occurs, or where Indigenous monitoring and information exchange intensity is likely to be lower and/or more diffuse. These methods can determine how and why a certain species or ecosystem is changing/fluctuating, but they can be expensive and can miss key ecosystem interactions that are already understood at local scales.

Monitoring based on IK fills in other gaps which science cannot. Indigenous methods are typically qualitative, and relatively inexpensive as the costs are shared with direct participation in the culture and use of the marine resources. Indigenous methods are rapid, can incorporate large sample sizes of harvested resources (as opposed to temporally or spatially limited scientific field samples), are based on centuries long time period observations, and enable the local participants to engage directly in the ecosystem's sustainability and protection (Moller et al., 2004). This is the case, for example, when the observations depend on specialized knowledge of the observer such as a hunter's knowledge of species migration or knowledge of safe alternative travel routes over ice. If this knowledge has been gained through experience or shared traditions, then subtle observations of changes to migration routes or reacting to varying weather patterns is best done by the holder of this knowledge and may not be easily captured through science.

Furthermore, Indigenous monitoring can generate reports of unusual events and occurrences instead of average patterns. For instance, Indigenous communities in the Arctic have observed increases in frequency of extreme and less predictable weather events, which is a sign of long-term ecosystem alteration (Krupnik and Jolly, 2002). The Local Environmental Observer (LEO) network is an example of documenting these observations through an on-line, map-based internet portal in which users can upload unusual climate-related environmental observations (Alaska Native Tribal Health Consortium [ANTHC], 2018). In a large geographical area where detailed data are needed, having a large number of knowledgeable observers, the "many eyes" approach (Dickinson et al., 2012), is an effective way of finding rare organisms, tracking changes in species presence or abundance, tracking boom and bust cycles, among other ecologically relevant discoveries.

Communities can provide a better understanding of underlying patterns and can test the tools that can reduce monitoring costs and improve outcomes in marine systems. These tools may include co-management and collaborative management generated specifically for the socio-ecological systems and institutional frameworks of the Indigenous communities and stakeholders, maintaining their vital roles in understanding marine ecosystem values and the risks they face in the next decade and beyond. However, it can be difficult for researchers and harvesters to work together, as resource dependent and Indigenous communities do not always trust scientists or their methods (Moller et al., 2009). Nonetheless, consistent scientific monitoring could improve predictions and signal if, for example, a population will be, or is, overharvested, or at risk from a forecasted environmental event, such as a marine heat wave, prompting resource users to adapt and change their methods and strategies to assure resource sustainability.

Changes in monitoring capabilities currently underway are dramatically lowering technical and information costs, through, e.g., requirements for ships to have working Automatic Identification Systems (AIS) and the rapid expansion and implementation of Unmanned Aerial Vehicles (UAV) across multiple scales (e.g., note the Commercial UAV Show has grown to include over 3000 attendees from over 60 countries in 5 years[1]), as well as real-time satellite imagery and response opportunities (Dunn et al., 2018). While these are increasing prospects for widespread ocean monitoring, including in remote areas, and focusing discussion on "the Essential Ocean Variables (EOVs)" for sustainability (Miloslavich et al., 2018a), these valuable efforts lack inclusion of TEK, LEK, IK and Indigenous communities, and will omit some types of observations dependent on specialized knowledge or "many eyes" as described above.

Coming changes in underlying benefits and costs of spatially and institutionally dependent ocean productivities will change how monitoring investments return benefits to communities. These changes must be anticipated in any integrated scientific and Indigenous framework that aims to include how knowledge from monitoring is to be acquired, taken up, acted upon, and used going forward. To accomplish this, Indigenous communities must be actively and comprehensively included in the research and governance processes as more than either contributors of TEK or IK, or recipients of, e.g., conservation mandates. Local and Indigenous communities must maintain at least joint decision-making power of the new knowledge produced. This is particularly important in regions where Indigenous territorial rights and governing autonomy are increasingly recognized, such as in the Canadian and NZ contexts. This paper investigates case studies in Indigenous communities of Canada and NZ to better understand how decisions regarding ocean monitoring are interlinked with the well-being of community members. We explore underlying patterns regarding the emerging power of IK systems, especially in influencing natural resource management, policy, and economic development in these particular contexts.

Success or failure of monitoring investments will depend on the extent to which they can facilitate improvements in the socio-ecological systems. An example of recent success is the Arctic Marine Pulses Model, which works to align "spatially focused and time-deep" IK with "spatially broad and time-shallow" conventional science through commonalities grounded in seasonal cycles rather than attempting to force a "one-to-one correspondence between biophysical event and subsistence activity" (Moore et al., 2018). Both scientists and Indigenous hunters provide inputs into the shared framework and both gain from the increased information because the research and IK co-exist on a common spatio-temporal scale that is "recognizably meaningful" to both groups (Moore et al., 2018).

This highlights the importance of considering how benefits and costs of increased monitoring of ocean conditions vary amongst different interest groups, and whether there are useful dimensions through which to fully or partially align them. As Indigenous communities redevelop their economic base and resource control, opportunities may emerge to co-invest which may also improve power relationships. In particular, we will emphasize expected issues regarding ocean monitoring of human behavior, and the joint determination, and feedback effects, of how we choose what and where to invest in monitoring across various scales, and the human behaviors and potential outcomes for well-being.

Our discussion focuses on resource use and governance systems for existing natural resource stocks, and for cases where resources may be enhanced by human interventions such as aquaculture. Systems may be susceptible to ecological and/or social changes occurring in space and time as well as across layers of knowledge and distributions of benefits from ecosystems' many services. Investments in knowing more, through monitoring, then become a response to these susceptibilities that target different spatial, temporal, informational and distributional scales accordingly. A comprehensive approach to the future of ocean resource use and monitoring presents improved opportunities for understanding changes in the ecosystem, whether induced by direct or indirect human actions. Ocean monitoring investments represent a policy intervention to be applied at large scale, technological monitoring systems, and also at multiple points in the process of change, beginning with the determination of baseline conditions and continuing through efforts to prevent, contain, control, mitigate, or adapt to negative consequences of change.

SETTING THE STAGE: LOCAL AND INDIGENOUS COMMUNITIES IN OCEAN MONITORING

Indigenous communities are widely engaged in ocean monitoring that affects their well-being. Before discussing cases from Canada and NZ in depth, we briefly consider an example that illustrates some of the complexities involved; in particular, we consider the role of body condition of a hunted resource as a focus for monitoring efforts. This example also illustrates how science and IK can cooperate in monitoring, subject to careful consideration of introduced biases or interconnected ecosystem impacts.

Each autumn Rakiura Māori travel across 35 islands surrounding Stewart Island, to harvest sooty shearwater (*Puffinus griseus*), also called *tītī* (Moller et al., 2004) at the southern end of NZ. These events are important for Rakiura Māori for the

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[1] www.terrapinn.com/exhibition/the-commercial-uav-show

earnings gained by selling *tītī*, and as part of their cultural identity and cultural well-being (Lyver et al., 1999; Kitson, 2004). Written records of harvest rates, weather, and hunt times are kept (Moller et al., 2004, 2009). *Tītī* gatherers have been able to monitor *tītī* well-being over the long-term using catch rates. By observing yearly fluctuations in catch rate, they concluded, for example, that body condition, harvest intensity and breeding habitat in Rakiura, NZ depended on outside factors that influenced the population during migration (Lyver, 2002). Rakiura Māori base their short-term catch on "touch, feel, and sight," as they determine *tītī* presence or absence by smell and sound (Newman and Moller, 2005). Body condition is used as a population health indicator, where fat represents health; i.e., the fatter the animal, the healthier the animal (Kofinas et al., 2004). However, high body condition can only be an indicator of population well-being if body condition is independent from population density. In fact, body condition depends on population density; hence, a high body condition can represent overharvesting or overgrazing, which could lead to a drastic decrease in population if nothing is done (Moller et al., 2004).

Human and ecological conditions are susceptible to change. The desire to establish global baselines and monitoring capabilities is increasing. Miloslavich et al. (2018a) use a Drivers-Pressures-State-Impact-Response (DPSIR) model to capture important global ocean trends and identify EOVs that should be monitored over time. This is part of a young but growing literature setting the stage for monitoring demands, and therefore investment priorities, over the coming decade (Pereira et al., 2013; Bax et al., 2018; Chiba et al., 2018; Crise et al., 2018; Miloslavich et al., 2018a,b; Moore and Reeves, 2018; Muller-Karger et al., 2018).

Bax et al. (2018) reference an older literature that stressed how sustained observing "requires a coordinated, collaborative and culturally appropriate process, incorporating Indigenous and local knowledge, with long-term resourcing that meets identified local, national, and regional needs." This framework resulted in the development of ocean monitoring focused on project-based needs rather than a more broadly strategic global initiative. This has resulted in limited applicability to broader audiences. A positive initial focus on capacity development may subsequently be devolving into a linear progression from large-scale scientific data being packaged and distributed as information to end-users instead of co-producers and collaborators.

A further concern relates to the ways in which research publication outlets may mask important lessons from project-based research. That is, there is some indication that the scientific literature may perpetuate conventional science at the expense of more collaborative and inclusive efforts. Miloslavich et al. (2018a), in developing their DPSIR model, drew on thousands of papers in the SCOPUS database, and 100+ biological ocean observing programs since the dawn of the 20th century, but mainly after the 1970s, to source their findings regarding EOVs. There is no mention, however, of Indigenous communities or traditional knowledge (TK) holders as continuous sources of TEK stretching back many generations. Drawing on SCOPUS to measure the scientifically relevant and societal impact of potential EOVs may exacerbate exclusions of IK and communities.

Of the remaining recent articles on emerging EOVs identified above, only Chiba et al. (2018) and Moore and Reeves (2018) make any mention of Indigenous communities. Chiba et al. (2018) simply identify 2020 AICHI Target 14, which aims to monitor and protect "ecosystems that [. . .] take into account the needs of Indigenous and Local communities" among other needs, as still lacking a marine relevant specific indicator.

This may initially appear to be a small-scale concern given the marginal status of many marine and coastal Indigenous stakeholders (Gutiérrez et al., 2011). However, there are approximately 370 million Indigenous people, from 5000 groups, in 90 countries around the world[2]. Globally, small scale fisheries employ about 90% of fishers worldwide and about 50% of fish consumed by humans (Le Cornu et al., 2018). Living ocean resources are at the same time becoming scarcer, which pushes fishers and harvesters to overharvest in order to meet growing demand (Auriemma et al., 2014). As a result, Costello et al. (2012) show in their study that 64% of small-scale fisheries are suffering from overfishing consequences, endangering food security for hundreds of millions of people. In Pacific Island countries, over ¼ of households engage directly in fishing activities and current fish consumption can be as high as 110 kg/person/year. Local fish shortages resulting in significant food insecurity are predicted to occur within the next two decades (James et al., 2018). Management strategies to avoid overfishing must be employed globally and still be able to adapt to independent local fishery and community needs.

In addition, aquaculture is increasingly being turned to as a way to increase marine resource bases and increase food security. This is, however, generating a new and complex set of concerns, including marine environmental pollution that requires monitoring and understanding (Pelletier et al., 2018).

Fisheries are also an important resource for economic transitions from non-market to market activities. In Greenland, for example, where 90% of the population is Indigenous Inuit, about 90% of its Gross Domestic Product (GDP) is generated from fishing[3]. Furthermore, a significant portion of the food supply comes from subsistence fishing and hunting (eds. Glomsrød et al., 2017). Revenues from small-scale Pacific Island fisheries, even when fragmented, poorly managed and greatly undervalued in GDP statistics (Zeller et al., 2006), are significant contributors to local communities, with the potential to reach billions of dollars in value if they enter global supply chains through a more market-driven focus (Dunn et al., 2018; Le Cornu et al., 2018).

The changing demands for ocean resources through potential overharvesting and increased breadth and marketization of ecosystem uses in fisheries and aquaculture argue for building strong connections with scientific, local and Indigenous monitoring; successful monitoring efforts will be context specific, will include connecting resource uses across scales and community interests, and will generate participant

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[2] www.culturalsurvival.org

[3] http://www.stat.gl/ (accessed March 10, 2019).

buy-in through a combination of actionable results and specific understanding.

It is essential that information from successful projects be integrated into the development of monitoring tools and EOVs at every scale, so that the "learning, designing, and managing" (Le Cornu et al., 2018) needed to improve local and Indigenous livelihoods, far from globalized trade and information routes, can evolve. The case studies presented here support this need by drawing together multiple project results from distinct Indigenous communities to re-assert the primacy of socio-ecological systems in the co-production of knowledge in the rapidly emerging technology-driven progress in ocean observing.

CASE STUDIES

NZ Case Study

NZ Cultural Context

The principles and history of the Treaty of Waitangi 1840 (the Treaty) are fundamental to understanding Māori-Crown relationships in NZ. Māori are the Indigenous peoples of NZ; there are over 100 Iwi (tribes) and over 800 Hapū (sub-tribes)[4]. From the late 1700s European settlers came to NZ, and desired a government. In 1840, >500 Māori leaders signed the Treaty of Waitangi with British Crown representatives, who went on to form the government. The Treaty was written in English and Te Reo Māori (the Māori language), with the Te Reo Māori version assuring Māori would retain rangatiratanga (sovereignty) over land, forests, fisheries and prized possessions, while the English version said that Māori would cede sovereignty. This caused rights and sovereignty disputes between parties. The Treaty principles are: partnership, participation, and protection. The Crown breached these principles numerous times, and created a history of mistrust. However, NZ is now in an era of grievance settlement. Treaty principles are recognized throughout government policy and legislation, including Treaty grievance settlement legislation (Hepi et al., 2018). These changes are encouraging Crown agents, including Crown funded researchers and research institutions, to over overcome the historical mistrust and build strong, positive relationships with Māori to ensure public confidence in their work (Māori Policy Unit., 2011).

Since 2005, the Vision Mātauranga (VM) policy has provided strategic direction on how Māori people, resources and mātauranga (knowledge) can help to create a healthier, more vibrant and sustainable NZ, through government-funded research (Ministry of Science Research and Technology, 2005). This includes investing in Māori-relevant research, developing Māori research capability, fostering connections between Māori, government, the science system, and industry; and supporting Māori community-led research and development strategies. Since 2015, VM has been integrated across the government science investments, which has motivated researchers to improve their engagement with Māori communities (Local Government New Zealand, 2007, 2011).

Cross-Cultural Research in NZ

The extensive interactions of Māori with the natural world have contributed to a comprehensive body of knowledge, often referred to as mātauranga Māori (Harmsworth and Awatere, 2013; Hikuroa, 2017; Jackson et al., 2017). Mātauranga Māori exists, is understood and is applied at various levels, i.e., by Māori across NZ, at Iwi, Hapū and whānau (family) levels. Mātauranga Māori also includes processes for gaining, managing, applying, and transferring knowledge (Robb et al., 2015). Smith (2012) defined kaupapa Māori research principles that help to focus what "good" research might be like for Māori. These principles include:

- Tino rangatiratanga (self-determination),
- Taonga tuku iho (cultural aspiration),
- Ako Māori (culturally preferred pedagogy),
- Kia piki ake i ngā raru o te kainga (socio-economic mediation),
- Whānau (extended family structure),
- Kaupapa (collective philosophy),
- Te Tiriti o Waitangi (The Treaty of Waitangi), and
- Ata (growing respectful relationships).[5]

Cross-cultural research allows a broader set of knowledge systems, principles, and non-Māori to participate in research, with kaupapa-Māori research remaining an important part of the bigger research picture. Cross-cultural research takes place across or between cultures, including research undertaken by non-Indigenous researchers into the lives of Indigenous people or by Indigenous people working from within western frameworks, with their own people (Gibbs, 2001). Hardy et al. (2015) consider cross-cultural research to be possibly one of the most difficult areas of research, with the cultural and institutional setting of the research, and the personalities involved, determining which methods are most appropriate.

In collaborative research, research participants and researchers are equal partners in the research process, and all parties benefit from the research (Gibbs, 2001). Transdisciplinary collaborations work across different knowledge systems and cultures, and include collaborative discussions between researchers, interest groups and community representatives (e.g., natural resource managers, policy-makers, local, and Indigenous communities) (Ogilvie et al., 2018). Hepi et al. (2018) provides a NZ marine example where cross-cultural research practices were used by Environmental Science Research (the research provider), Te Uri o Hau (the Iwi), and Integrated Kaipara Harbour Management Group (the management collective), jointly setting the research agenda, collecting, and analyzing the data. They commonly seek to establish priorities and then foster research that helps different parties move toward commonly sought outcomes, while creating new knowledge and understanding.

Hardy et al. (2015) draws on two case studies from the North Island, NZ (Tauranga Harbour and Horowhenua coastline) to provide real examples of cross-cultural research processes, principles, and methods. Success factors for

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[4] http://www.tkm.govt.nz/ (accessed November 15, 2018).

[5] For more on these principles visit http://www.rangahau.co.nz/research-idea/27/.

cross-cultural environmental research identified in the authors' experiences were:

- That the research itself is meaningful and beneficial to Indigenous people and local communities and goes beyond outputs and outcomes;
- To agree on a shared research vision/purpose, and research objectives, and genuine will to be collaborative are vital;
- Respect and space for different knowledge systems need to be practiced not just preached;
- Methodological pluralism must occur;
- "Knowledge integration" (except where appropriate) and "knowledge imperialism" need to be resisted;
- Building capacity on both sides is vital to understanding each other's perspectives and knowledge bases;
- Honesty and communication are what build trust and long-term relationships; and
- Shared space for understanding and sharing from different knowledge systems, i.e., science and Indigenous, should be built into the research design.

Importance of the Marine Environment to Māori

Rout et al. (2018) characterize seafood as the most important part of the Māori marine economy (**Figure 1**). Historically Māori were significant fishers and traders in seafood although the first fisheries legislation, the Oyster Fisheries Act 1866, excluded Māori, despite clear evidence that Māori had been major oyster traders. Fisheries legislation contained provisions supposedly protecting the fisheries guaranteed to Māori under the Treaty, but these protections were ineffective (Tau, 2006). Today Māori again hold significant rights in fisheries and aquaculture due to the Māori Fisheries Settlement process, which began in the 1990s, and Māori Aquaculture Settlement process, which began in the 2000s.

The seafood sector brings $4.18B to NZ annually. It is managed through recreational, customary, and commercial fisheries, and aquaculture. Māori own 1/3 of the NZ aquaculture industry, and >50% of the NZ commercial fishery. Māori represent a large part of the recreational fishery and are sole participants in the customary fishery. Moana New Zealand is the largest Māori-owned seafood company that arose through the Māori Fisheries Settlement. The Māori worldview is increasingly informing how Māori commercial fishing operates, with increasing effort on sustainability[6]. NZ has the 10th longest coastline of countries globally, and successful aquaculture operations for mussels, salmon and oysters under both Māori and non-Māori owned companies.

In addition to Māori seafood sector interests, and more importantly, is Māori ability to exercise cultural practices that reflect values, such as kaitiakitanga. Kaitiakitanga is a reciprocal responsibility of care between Māori and their affiliated place. The term "tiaki" includes notions of guardianship, care and wise management. Kaitiakitanga transcends across the spiritual, intellectual and physical planes, recognizing that physical damage to a resource also results in spiritual damage and an intellectual loss. Failure to recognize all elements of a resource results in a loss of mauri (life force). Upholding mauri is directly connected to the mana (prestige, authority) and rangatiratanga (sovereignty) of the local Māori people, and is therefore vital to positive Māori well-being (Tawharau o nga Hapū o Whakatohea Iwi Management Plan, 1993). Māori will be better able to exercise tīkanga and kaitiakitanga over their rohe moana (ocean territories) by sharing ocean mātauranga, participating in ocean monitoring, and also by responding to the information provided by the ocean monitoring through managing their marine ecosystem activities, e.g., fishing, aquaculture, boating.

The Moana Project

The Moana Project[7] aims to revolutionize ocean forecasting to underpin NZ's blue economy. The project spans multiple sectors and interests, and it includes representatives from Iwi, Māori academics, the ocean observing and modeling community, and seafood sector. While only in early stages, the project provides an example for coastal Indigenous communities with marine sector aspirations globally.

Using transdisciplinary methods from kaupapa-Māori research, social sciences and novel ocean observing and modeling technologies, an ocean-knowledge exchange platform will be developed that supports marine spatial planning and impact assessments to inform Iwi governance of multi-sector activities in their rohe moana (territorial sea). Embracing Internet of Things concepts, we are developing low-cost temperature sensors that can be deployed on all boats, at all times, by anyone. The data will feed back into our ocean modeling platforms, providing optimized ocean forecasts to the community more broadly, thereby completing the circle from data collection to informed decision making.

A case study with Bay of Plenty Iwi, Whakatōhea (**Figure 2**), demonstrates an exchange of oceanographic knowledge across Indigenous and science communities. Alongside their customary fisheries and cultural interests, i.e., kaitiakitanga, Whakatōhea has specific commercial interests in fisheries and aquaculture. Whakatōhea has four seafood entities: Whakatōhea Fisheries Asset Holding Company, Pākihi Trading Company Limited, Whakatōhea Mussels Ōpōtiki Ltd., and Eastern Seafarms Ltd. Whakatōhea has been researching offshore mussel farming since 2010, and has interests in a 3800 ha mussel farm with a further 5000 ha proposed through a Treaty settlement, which would create the largest offshore aquaculture area in the world. The Moana project will also support regional growth aspirations, such as creating 350+ aquaculture-related jobs by 2023.

Ocean Networks Canada Case Study: A Project on Changing Sea Ice

Ocean Networks Canada (ONC), a Canadian national not-for-profit society, operates and manages innovative cabled observatories on behalf of the University of Victoria. These observatories supply continuous power and Internet connectivity to various scientific instruments located in coastal, deep-ocean, and Arctic environments. ONC's cable arrays host

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[6] See www.moana.co.nz/ responsibility for Moana New Zealand's sustainability journey.

[7] www.moanaproject.org

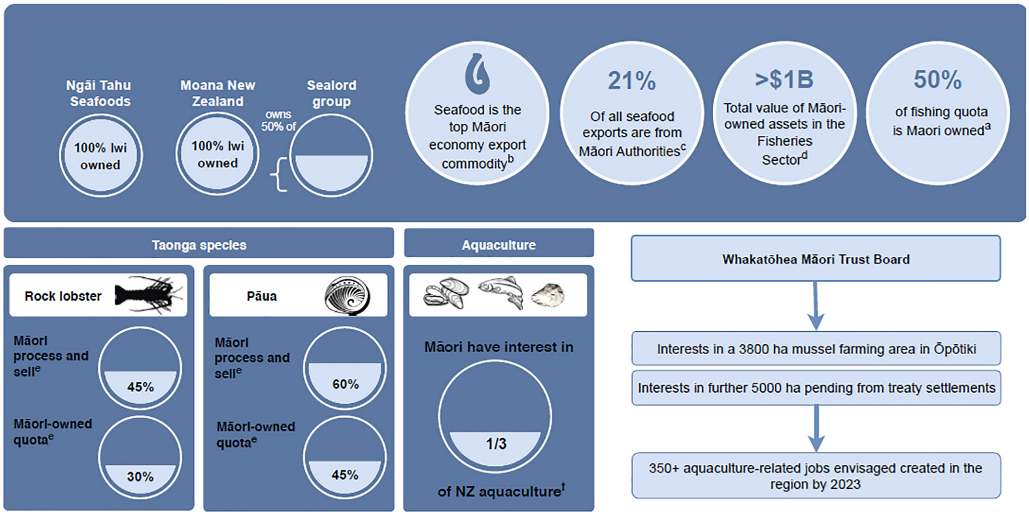

FIGURE 1 | The economic benefit of fisheries and aquaculture to Māori, including Whakatōhea Māori Trust Board. [a]Inns (2013). [b]NZ Government Business Growth Agenda. [c]Joseph (2017). [d]Nana et al. (2011). [e]McClurg (personal communication). [f]NZ Aquaculture (personal communication).

hundreds of sensors distributed in, on and above the seabed, along with mobile and land-based assets. In addition to fixed observatories, ONC is developing a national network of community-based monitoring programs with data collection performed by community members (**Figure 3**).

Ocean Networks Canada uses an approach where local residents in communities, academic scientists, and government staff collaborate in projects that benefit all parties. For any monitoring activity taking place in communities, ONC seeks involvement and feedback from local communities throughout the lifetime of the project, from conception to proposal, planning, and implementation. The community-based approach enhances instrument-based and remote sensing programs by directly incorporating IK.

Data from these efforts are complemented by IK; monitoring locations and programs are informed by priorities in coastal communities. Data are made freely available over the Internet, on local data displays, and disseminated directly in communities through meetings and face-to-face communication. The information is used by a wide variety of stakeholders, including community members, scientists, teachers, students, researchers, community leaders, government staff, and industry in Canada, and around the world.

Canadian Cultural Context

There are approximately 65,000 Inuit in Canada, the majority of whom live in four northern regions: the Inuvialuit Settlement Region (Northwest Territories), Nunavut Territory, Nunavik (Northern Québec), and Nunatsiavut (Northern Labrador). Collectively, these four regions make up Inuit Nunangat, the Inuit homeland in Canada. This vast area includes 53 communities and encompasses roughly 35% of Canada's landmass and 50% of its coastline (Inuit Tapiriit Kanatami [ITK], 2018). Compared with the current overall Canadian population of just over 37,000,000 (Statistics Canada, 2018), geographically speaking, the Inuit have a proportionately large responsibility and interest in the coastal environment.

The Inuit Tapiriit Kanatami (ITK) is the national representational organization for the Inuit. In 2018, the ITK published the "National Inuit Strategy on Research," a comprehensive document which outlines recommendations and practices which respect Inuit self-determination in Inuit Nunangat research (Inuit Tapiriit Kanatami [ITK], 2018). The Strategy is based on the premise that public policies, informed by the best available evidence derived from both Inuit knowledge and western science will support optimal decision-making for Inuit, and in turn will bring benefit to all Canadians.

Research in Inuit Nunangat by and large has excluded Inuit as equal participants, resulting in research that is resourced and conducted in a way that has limited Inuit participation. Rather than including Inuit expertise as a core source of knowledge, environmental research was (and in some cases, continues to be) conducted by researchers with little connection or respect for the deep experience of the residents and caretakers of Inuit Nunangat.

Within the broad goal of creating social and economic equity, and in the context of ongoing reconciliation with Indigenous peoples in Canada, the Strategy outlines five critical areas for action which will lead to an equitable and mutually beneficial relationship between all research participants in Inuit Nunangat: (1) Advance Inuit governance in research; (2) Enhance the ethical conduct of research; (3) Align funding with Inuit research priorities; (4) Ensure Inuit access, ownership, and control over data and information; and (5) Build capacity in Inuit Nunangat research.

Some areas of collaboration specific to environmental research and monitoring include ensuring that Inuit:

- Are partners in setting the research agenda,
- Actively participate in all aspects of the research, and

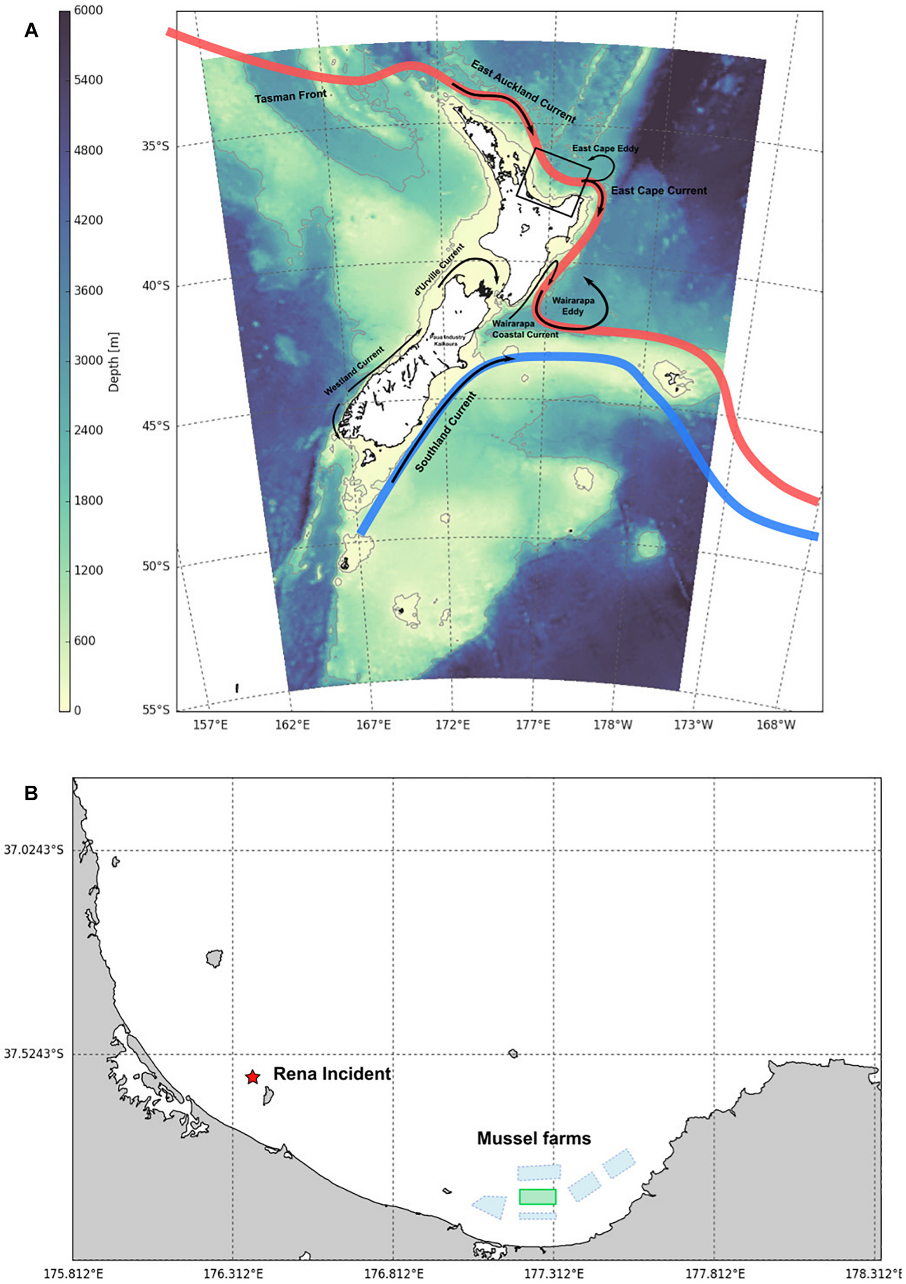

FIGURE 2 | Diagram showing the **(A)** NZ maritime region and the dominant circulation and **(B)** regional zoom in of the Bay of Plenty region showing WMTB existing and proposed mussel farms. Adapted from https://www.moanaproject.org/nz-seafood under a Creative Commons public license Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0).

- Determine how data and information about people, wildlife, and environment are collected, stored, used, and shared.

Case Study Overview

The subject of this case study is the project "Connecting Inuit Knowledge with sea-ice research to better understand changing conditions for sea-ice freeze-up and break-up." This joint initiative includes the communities of Kugluktuk, Cambridge Bay, Gjoa Haven, and Iqaluit, in the territory of Nunavut in Inuit Nunangat, together with ONC, the University of Victoria, Nunavut Arctic College, and groups within two federal government departments: Environment and Climate Change Canada [ECCC (CIS)], and Fisheries and Oceans Canada. Formally, the project has five objectives:

1. Work with knowledgeable hunters, Elders, youth, and other community members to identify changes in sea-ice

FIGURE 3 | A map of Ocean Networks Canada's community observatory and community engagement locations.

and the impact on community activities such as hunting, fishing, transportation, recreation, and other activities.

2. Provide opportunities for youth to engage in science in all communities.
3. Implement a community-based water and ice monitoring program with Canadian Rangers and Fisheries and Oceans Canada.
4. Develop sea-ice products for community use with the Canadian Ice Service (CIS).
5. Launch a new Instrument Technology course with Nunavut Arctic College.

The science goals of the project, centered on sea-ice, include an analysis of variables such as sea-ice thickness, growth, and decay as well as changes in dates of freeze-up and break-up in different regions. ECCC, a Canadian government department, is a partner in this initiative through the CIS and expects to gather local input that will allow them to tailor information, such as sea-ice charts and other sea-ice data products, to address community needs with support from Ocean Networks Canada in delivering those products. The project also aims to identify next steps for ocean and sea-ice monitoring programs, data needs, education, and training programs according to community priorities. The project is funded through a Canadian government granting program from Polar Knowledge Canada (POLAR) with support from ONC.

One of the main project elements is to have knowledgeable hunters and Elders identify specific changes in sea-ice formation and decay, and thickness and stability, that have an impact on residents or their activities. The information provided by these community members, along with data collected by the ONC community observatory in Cambridge Bay and remote sensing (satellite) of ice cover and concentration, will co-contribute to knowledge on local ice conditions.

Methodological Background

The formal integration of TK in ecological research dates back to the 1980s (e.g., Johannes, 1981; Berkes, 1999; Ford and Martinez, 2000), but few studies have discussed the key elements and techniques that use different knowledge systems (e.g., Huntington et al., 2002; Parrado-Rosselli, 2007; Brook et al., 2009). This project draws from methods in the social sciences such as interviews, workshops, local observations, and mapping exercises during the workshops and interviews. Briggs (1986) and Huntington (1998) have documented the use of interviews on ecological research. Huntington et al. (2002) also used workshops while mapping exercises have been documented in Naidoo and Hill (2006) and Murray et al. (2008).

Methods

Collaborative project planning, execution, and reporting

Collaboration between local residents, academic researchers, and government staff via regular conference calls, joint preparation, planning and project execution has been key to the success of this effort from the beginning of the project.

Establishing an oversight committee

Collaborative research is achieved through a project Oversight Committee (OC), established in each community. These committees have representatives from each main community organization: the Hunters and Trappers Organization, Hamlet, and the Kitikmeot Inuit Associations in Cambridge Bay, Kugluktuk, and Gjoa Haven. The OC guides research priorities and identifies community participants for workshops and interviews. The OC also keep their respective organizations informed on project activities. The OC ensures that TK is shared in the project by identifying Elders and knowledgeable hunters to participate in interviews, workshops, and field trip activities.

Workshops

Elders and local experts participated in workshops in November 2017, July 2018, and November 2018, to identify representative community sites to be monitored, and information to be collected. For example, in Kugluktuk, workshop participants identified two areas of interest for monitoring sea-ice conditions along the channel/bay: (i) Marker Island or Seven Mile Island, where ship traffic and sound could be monitored alongside water properties and ice thickness, and (ii) the mouth of the Coppermine River where they conduct their fishing activities, and fresh water mixes with saltwater. Sea-ice safety has been a common concern in all of these communities. During interviews in Cambridge Bay in November 2017, and in Kugluktuk, in November 2018, Elders identified an interest in measuring snow and ice thickness and growth along common travel routes and identified areas of concern where ice thickness can be unsafe for travel due to ocean currents and wind conditions.

Interviews

Face-to-face semi-directed interviews are being conducted with key community knowledge holders. The interviews are audio recorded and transcribed for analysis, and also allow the science team to build relationships in the community to understand the broader social and cultural context of the project. The interview questions have focused on the topics of snow and ice conditions, freeze-up and break-up dates, impacts of changes, information needs, and weather observations, among others.

Site visits

Multiple field trips were made from each community. TK was used to select the field sites to ensure that they represented local environmental variability in places relevant to the communities' subsistence activities and travel routes. Elder hunters, academic researchers and government staff traveled by snowmobile to these sites in order to document typical conditions and locations where significant changes in sea-ice conditions had been observed. The field teams took measurements and made observations using traditional methods and instrument technology on the travel routes. In other words, participants collaborated by doing, not only talking, to learn from each other in the practice of documenting sea-ice conditions. This information was then discussed with the Elders and workshop participants in Cambridge Bay and Kugluktuk after the trips and during a workshop in Gjoa Haven. It is also expected that this type of information will serve as a basis for funding applications for equipment purchases and deployment at monitoring stations.

The field trips also enabled the ONC team, government staff and community residents to share a common experience that set the stage for developing stronger relationships in subsequent site visits. Even simple pieces of information are critical to developing a common language and understanding; for example, it was learned that community members better understood ice thickness measurements in inches rather than metric units. The site visits were particularly relevant for scientists and government staff in terms of understanding the use of sea-ice for different activities and learning about the ice types that are considered safe. For example, residents feel that at three inches (7.5 cm), the ice is strong enough for a person to walk on and at five to six inches (12–15 cm), it is safe for travel by snowmobile. Elders consider the ice to be completely safe for any activity when it is one to one-and-a-half feet (30–45 cm) thick.

Co-development of education and training programs

The communities involved in this project, and many of the other communities with which ONC collaborates, are rich in TEK, LEK, and IK, and yet do not typically have a depth of resident scientific expertise. While the science and government teams have funding to visit communities and learn from Elders and knowledge holders in the community, youth and adults in the community who wish to further engage in science have limited opportunities to pursue training in their communities. In order to have true two-way partnerships, it is necessary to create local training opportunities. In this project, a full college-level course in Instrument Technology has been developed and integrated into the curriculum of the Environmental Technology Program at Nunavut Arctic College.

Furthermore, part-time Youth Science Ambassadors have been hired in each community to act as mentors for other youth with an interest in science. ONC's Ocean Sense program, facilitated by the Youth Science Ambassadors, enables students to gain a cross-cultural understanding of the ocean by incorporating ocean science and Inuit knowledge of the ocean into education resources and activities which are co-developed with community educators. The goal of these programs is to increase interest and create opportunities for Inuit and northern students, who are underrepresented in science, to be directly engaged in local research and the transfer of Inuit knowledge.

Data and information sharing

Conference calls with the Oversight Committee and annual (or more frequently as travel permits) public meetings are held in each community to update community members on the project progress and to seek broad input on project activities. All results from the project will be translated into local language and communicated in oral and written form to the communities. A key outcome will also be the joint development of data products specifically designed to meet community needs as determined from community feedback collected through the means described above.

Summary

Potential outcomes from this project for the communities include: enhanced community and personal safety, community resiliency, and the potential for economic opportunity, employment and training; a strengthened network for community monitoring; and data products which combine local information with scientific data. Conducting the project in true partnership has been enriching for all participants and is also essential to the scientific success and community relevance of the outcomes.

The original project timeline was from April 2017 to March 2019, although the project builds on engagement in one community, Cambridge Bay, ongoing since 2012. In response to high community interest, additional funding has been secured with support from ECCC to continue examining the need for community-oriented ice data products through to March 2021. Additional funding proposals for monitoring programs, training, and youth engagements are currently in progress.

FURTHER EXAMPLES

Theory and Practice of Resource Use and Governance Systems in Context

In addition to monitoring the physical and bio-geochemical properties of ocean change, monitoring human behavior is a common need. For example, fishing areas under strict regulations but with no property rights in open access zones are often overexploited. This occurs when short run incentives motivate fishers to intensively harvest the resource before any other fisher is able to do so (Gordon, 1954; Hardin, 1968). Similarly, unenforced property rights due to, e.g., lacking monitoring and enforcement resources, have resulted in overharvesting by third parties not entitled to the resources under international law; examples throughout Pacific Islands, particularly for tuna species, abound (Hanich et al., 2010; Rohe et al., 2017).

Significant progress has been made in cooperative monitoring and technology transfer between major fishing nations and local communities (Dunn et al., 2018). Satellite-based monitoring capabilities are rapidly evolving through AIS, and significant gains are being achieved through monitoring mechanisms such as Global Fishing Watch. This is part of a global effort to combat illegal, unreported and unregulated (IUU) fishing, which can impact all types of fisheries and can impose costly damages to marine ecosystems, global food security and local economies (FAO, 2010; Schatz, 2016). In curbing IUU, monitoring and enforcement simultaneously protect a broad range of socio-ecological conditions and provide a platform for further environmental condition monitoring instrumentation.

Ecosystem-based management approaches can mitigate overexploitation of natural resources in communities with few monitoring and enforcement resources. These include the establishment of various forms of marine protection, e.g., no-take zones, marine spatial planning, and Rights-Based Fisheries Management (RBFM). All share a goal of increasing ecosystem health and resilience (Hilborn et al., 2006) by using management techniques that promote sustainable resource use (Gelcich et al., 2006; Cancino et al., 2007; Uchida et al., 2012).

RBFM offers authorized fishers' exclusive access to harvesting marine resources while strictly excluding unauthorized fishers (Wilen et al., 2012). Individual Transferable Quotas (ITQs), fishing cooperatives, and Territorial Use Rights in Fisheries (TURFs) are the three different forms under which RBFM operates. ITQs and fishing cooperatives are both efficient management techniques, albeit with differing emphasis on decision-making and the role of the commercial fisheries within the greater ecosystem (Arnason, 2012; Deacon, 2012; Yagi et al., 2012). Implementing ITQs can have negative distributional impacts for communities that cooperative agreements may more easily resolve. As NZ's perpetual ITQs have shown, ITQs can create and exacerbate imbalances in terms of who stands to benefit from both ecosystem use and its long run conservation, by assigning strong but incomplete rights to only a subset of interest groups (Hersoug, 2018). Furthermore, ITQ systems cannot easily incorporate multiple species, even when the commercial fisheries dynamics are well understood (Cancino et al., 2007; Wilen et al., 2012).

Ecosystems that have multiple users, including Indigenous communities, who rely on overlapping components of a shifting and uncertain ecosystem, require system monitoring and regulation that acknowledges and acts to sustain a set of marine system productivities that extends beyond an individual species. At the same time it must be more cognizant of the socio-ecological conditions relying on those productivities. One option for this broader consideration is the use of TURFs (Auriemma et al., 2014), particularly community-managed ones. These offer greater flexibility on harvest and rights and may cover a wide variety of community and ecosystem issues. Defined boundaries and rights are given to specific community-sanctioned fishers as a function of their geographic location (Cancino et al., 2007; Wilen et al., 2012).

TURFs help overfished fisheries recover and steer the environment toward long-term sustainability. Inshore Japanese fisheries, for example, have operated under a wide range of TURF arrangements for centuries. The main drawback of TURFs occurs when there is considerable exchange in and out of the TURFs without accompanying negotiation mechanisms between governance regimes. This is in many ways analogous to challenges faced by local and Indigenous communities whose ecosystems are put at risk by activities from outside the system.

Large-Scale Data Collection, Integration, and Dissemination

Marine ecosystems are put under constant pressure due to global-scale anthropogenic activities such as high seas overexploitation, pollution, eutrophication, and introduced species (Halpern et al., 2008; Hoegh-Guldberg and Bruno, 2010; Burrows et al., 2011), and global effects, such as ocean acidification and climate change (Doney et al., 2012; AMAP, 2018). These stressors have a great altering effect on marine ecosystems functioning, decreasing the amount of goods and services that they can provide (Worm et al., 2006; Crain et al., 2008). Hence, monitoring marine ecosystems to understand these stressors' consequences on the marine ecosystem functioning is critically needed (Danovaro et al., 2008; Nõges et al., 2016; Zeppilli et al., 2016) to help identify sustainable and cost-effective solutions that governments and communities will be able to apply.

Examples of large-scale, integrated portals that have emerged in recent years include the Integrated Ocean Observing System, and the Marine Biodiversity Observation Network (MBON), a thematic network within the Group on Earth Observations Biodiversity Observation Network (GEO BON). These global organizations assemble disparate scientific observations so researchers and decision-makers better understand local and regional impacts, ecosystem feedback mechanisms, teleconnections, and ocean change.

GEO BON is a multinational and multi-organizational partnership initiated in 2008. Its activities operate through scientific working groups in conjunction with Biodiversity Observation Networks arranged by geography or theme, including MBON[8]. GEO BON's structure is continually evolving to facilitate and help inform assessment and decision making by various levels, from governments to individuals, by providing state of the global environment information (Tallis et al., 2012). The partnership cooperates with the UN Convention on Biological Diversity and the International Protocol on Biodiversity and Ecosystem Services, further integrating monitoring and governance efforts.

GEO BON is incorporating information on biophysical and social tendencies, on existing databases, resources and ecosystem services in governance and decision-making, to fill gaps in observation systems, and to create protocols for new ecosystem services or observations that are currently without guidelines. Its main focus remains, however, on the national scale. A tradeoff continues between access to more conventional, consistent and replicable data and information and more community-integrated data and information whose origins, needs and uses may be more specific and less transferable to other communities and scenarios.

In general, the globally scaled observation systems are not well-integrated into socio-ecological systems or local and Indigenous communities, particularly where poor connectivity hinders information transfer and/or systems are isolated from substantial trade. Feedback effects and the consequences of ecosystem degradation and biodiversity loss for human well-being at the appropriate scale are missed. To better understand monitoring needs, an ecosystem supply chain can be imagined. Any socio-ecological system depends on (1) supply as a function of the biophysical potential, (2) services that indicate the location and activities of the beneficiaries, and (3) benefits that locate societal preferences and human well-being. Trade-offs result from the biophysical and cultural limits of this socio-ecological system (Nelson et al., 2009). When the biophysical limits and feedbacks are understood and monitored clearly in the context of cultural limits and changing conditions requiring human responses, the systems become more adaptable and resilient.

Alternatives to national statistics can supplement these accounts. For example, field-based observations, including those from local and Indigenous communities, may offer a more differentiated spatial analysis of supply chains with wider services (Nelson et al., 2009). Remote sensing can inform assessment of ecosystem service changes and biodiversity conditions, from a local to global scale, over time (Hibbard et al., 2010). Remote sensing is too infrequently employed at a global scale to create a reliable and usable monitoring platform system, however, it remains a promising technique for monitoring water quality (Matthews et al., 2010). Furthermore, progress through new technologies, e.g., the Nested Environmental status Assessment Tool, is improving the ability to aggregate and disaggregate existing data at scales that bridge gaps between marine systems and the people who depend upon them (Borja et al., 2019).

Numerical simulations (models) can fill the gaps left by field-based observations. Models provide quantitative outputs regarding ecosystem services' conditions, changes, and distribution based on ecosystem understanding and dynamics (Tallis et al., 2012; Piroddi et al., 2015; Lynam et al., 2016). Models can also directly incorporate socio-ecological system decision-making and human feedback loops into information systems (Kaiser and Roumasset, 2014). This moves monitoring from an accounting process toward becoming a management tool. As monitoring efforts progress, models must not oversimplify the connections of local and Indigenous communities to resource stewardship.

Community-Focused Data Sharing Creates Actionable Information

Large, international data repositories as information-sharing tools can present challenges for communities. Here are some of the major challenges, and ideas and recommendations for alternatives. The challenges include: (1) internet connectivity in remote communities; (2) training and capacity building needs for data interpretation; (3) integrating scientific data and IK, and (4) multi-modal data-sharing.

Many coastal communities distant from main population centers or transportation routes do not have access to reliable, high-speed internet. For example, the Arctic communities of Kugluktuk, Cambridge Bay, and Gjoa Haven, featured in the Canadian case study, rely on satellite internet connectivity with limited bandwidth shared by the entire community. Although telephone/internet connectivity is rapidly changing (e.g., Kugluktuk and Cambridge Bay recent upgraded to 4G cellular networks, but Gjoa Haven does not yet have cellular service), it will be decades before all remote community members have high-speed internet.

Low-bandwidth versions of websites or locally hosted data repositories can enable community access. In addition, data formatting and content should match end-user needs, which may include mobile access and varying time scales, including the present and future. When data portals are accessible in communities, there is a further challenge in that the community members and decision-makers may not be familiar with the data presentation, units of measurement, instrumentation, and applications of the data.

Data availability is a start but providing support and training to the community to use the data is equally important. Data products must be designed with community members in mind, for example, by incorporating local place names and language alongside scientific units and interpreting data online in publicly accessible language and in public venues, e.g., at the local store or hunter's office.

Data products must further acknowledge that the information stream is multi-directional. As a goal of this paper is to inform co-management and policy through data from both scientific and IK-based research methods (including TEK and LEK), it is necessary to collect and present the data in a way that recognizes the contribution of these data sources. This poses a data compatibility challenge as data are of different types and formats. Effective study designs will plan to include both scientific and IK data from the outset. Northern Norway's BarentsWatch[9]

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[8] https://geobon.org/bons/thematic-bon/mbon (accessed May 29, 2019).

[9] https://www.barentswatch.no/en (accessed May 29, 2019).

is one such technology-driven community-based monitoring and data collection for marine conditions, fisheries governance, and other vital coastal information. More research is needed, however, on methods and practices for making effective use of scientific and IK for ecological monitoring and decision-making, particularly where communities are not as digitally connected as the northern Norwegian coast.

In Indigenous communities, information is often shared informally through phone calls, face-to-face conversations, and social media (Facebook). Community members and guests also use printed maps and observations in central locations in the community, i.e., a shop or community center. For scientists involved in community-engaged research, knowledge mobilization cannot rely solely on scientific publications or white papers. Communities must be involved in deciding how research and monitoring results are shared. Public meetings, local project contacts, and spokespeople are key components to understanding the formats and means that are familiar and meaningful to the community.

Monitoring Tools That Bridge Scales

The Salienseas project[10] aims at "co-production of marine climate services," in response to the above challenges, and those of transport between isolated coastal Arctic communities. The project is bringing together end-users of Arctic climate information, including TEK and IK holders and users in Greenland, with large private and public sector providers of climate monitoring services, to provide monitoring tools that bridge local, regional, and global scales.

Recent ocean acidification monitoring and assessment efforts by the Arctic Monitoring and Assessment Program (AMAP) aim to link monitoring and assessment with end-users. The 2018 Arctic Ocean Acidification AMAP Assessment started with the goal of establishing end-to-end modeling of the bio-geological processes, ecological and socio-economic risks, and threats from changing ocean pH levels in the circumpolar Arctic. The assessment's goals evolved over the years as the realities of truly integrated interdisciplinary research with cross-cultural interest groups became clear. Groups emphasized that context always matters and there is rarely, if ever, a simple formula for benefits transfer (Newbold et al., 2018) from one ecosystem, community, geo-physical system, or socio-ecological system, to another. Furthermore, knowledge production is non-linear, and should not be "top-down." The end result is six case studies on individual Arctic socio-ecological systems potentially at risk for ocean acidification impacts (AMAP, 2018). Taken together, the studies highlight how communities need to act even when the science is imperfect and incomplete, and therefore require multidimensional and inclusive processes to scientific investigation, IK, and how accumulated knowledge is used, distributed, and built into future decisions.

This means that large scale monitoring, using new *in situ* technologies and remote sensing (Turner et al., 2003; Blondeau-Patissier et al., 2004; Pettorelli et al., 2014), must be connected to community well-being to be meaningful community investments. Five *in situ* instruments used to monitor marine abiotic and biotic changes are discussed in this context: chemical sensors, seabed observatories, underwater autonomous and integrated monitoring, biosensors, and acoustic monitoring.

Chemical sensors monitor concentrations of heavy metals, organic pollutants and algal toxins (Danovaro et al., 2016). In many cases, pollutant sources and the communities affected by the pollution are separated by wide distances. How sensors directly identify health threats and indirectly identify pollution sources and assess mechanisms for stemming pollution streams should be considered.

Seabed observatories (video cameras on Remotely Operated Vehicles and autonomous underwater vehicles) represent powerful, non-destructive tools for studying benthic organisms' dynamics. Seabed research has historically focused on mineral resources rather than communities' ecosystem foundations. However, seabed observatories are increasing understanding of continental margin and deep-sea ecosystems' biodiversity and functioning and shifting the focus back to communities, especially if locals are directly involved in the deployment and monitoring (Solan et al., 2003; Stoner et al., 2008; Danovaro et al., 2016). One promising new underwater autonomous and integrated monitoring technology to follow is CLEAN SEA (Continuous Long-term Environmental and Asset iNtegrity monitoring at SEA) (Danovaro et al., 2016).

Nature, too, provides *in situ* monitoring tools. Bivalves are filter feeders that serve as good biosensors to evaluate localized water quality. Bivalves are high frequency non-invasive (HFNI) "valvometers" that can provide conventional monitoring in human-impacted areas, e.g., harbors, oil platforms and aquaculture (Andrade et al., 2016). LEK, TEK and community use of bivalves provide a good pivot point for aligning interests across science and IK.

Finally, monitoring the undersea acoustics and the impacts of noise pollution on marine organisms is increasing as the ocean soundscape becomes more crowded with, for example, vessel noise, air gun arrays from seismic exploration, and long range sonar for military uses. Understanding how marine organisms that produce sounds (mammals and invertebrates) for communication, reproduction, predation, etc., is needed to make decisions over local and distant sound emissions to balance local communities' needs with global, commercial drivers of sound emissions (Danovaro et al., 2016).

DISCUSSION

New technologies and capabilities for ocean monitoring will be useful and successful if there is uptake by interest groups. The challenges of large-scale monitoring, information collection and transfer outside the main pathways include: appropriate physical and human scales for monitoring; sharing information in timely and meaningful ways; combing science with TEK, LEK, and IK in beneficial ways; and how results are used.

As technology and information sharing rapidly transform, the access gap between communities may widen, and those

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[10] http://www.salienseas.com/ (accessed March 10, 2019).

distant from an increasingly globalized stream of data may be passive receptors of ocean monitoring decisions and ocean change itself, rather than co-creators of knowledge and regulation, governing, monitoring, and their outcomes.

Monitoring human behavior is as important as monitoring bio-geochemical changes. Improving livelihoods will be more effective if misaligned incentives are targeted directly rather than targeting ecosystem functions in uncertain, complex, socio-ecological systems. Local and Indigenous communities that depend on ocean resources and hold knowledge systems that differ from conventional science provide excellent understanding of this.

Two case studies in NZ and Canada provide an overview of how connections between communities and monitoring can evolve. The in-depth case studies highlight real-world examples of connecting Indigenous and wider community information with scientific data from monitoring programs. Recommendations for successful collaboration to improve societal outcomes are also given. The areas of collaboration include:

- Identifying scientific and community stakeholders and interested parties.
- Co-developing funding proposals and project plans.
- Sharing community and scientific information on local environmental concerns, important/sensitive locations, other related research projects, instrument deployments, educational needs and opportunities, and additional partners.
- Regular interactions through face-to-face meetings, workshops and personal communications.
- Jointly installing monitoring equipment: site surveys, permits, permissions, shore infrastructure development, above-water and underwater sensor deployment.
- Co-developing educational resources: collaborating with educators to create suitable materials for local needs appropriately including TEK, LEK, and IK.
- Jointly developing data products and services according to community needs.
- Ongoing engagement through sharing data and results, connecting to broader Indigenous and scientific environmental monitoring communities.
- Connecting environmental and bio-geochemical process monitoring with human behavior monitoring in the community context.

The authors' experiences in these projects have been rewarding. We hope these studies provide inspiration to others involved in ocean monitoring to embrace the benefits of connecting scientists, local communities and IK holders and their respective knowledge systems for improved marine ecosystem management.

Global change is undeniably occurring and we cannot manage this change without monitoring it. The scale of this monitoring continues to expand, and new technologies and information systems are driving pushes for standardization, global systems, user-friendly interfaces and international networks. The global scale presents challenges in transmitting the information between community use and governance scales that can and should be addressed with feedback mechanisms and communication with local communities.

AUTHOR CONTRIBUTIONS

BK, NH, KM, MR, KS, and DP scoped and structured the manuscript. BK, NH, AS, MH, and NTL contributed to the introduction, theory, literature review, and discussion. KM, MR, KS, and DP contributed to writing and reviewing the NZ case study. MH and LE-M contributed to writing the Canadian case study. MR contributed to **Figures 1**, **2**. SJ and CH provided the editorial support and preparatory discussions. BK, KM, NH, MH, and SJ reviewed the manuscript.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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