Conservation Biology

Contributed Paper

Identifying key needs for the integration of social–ecological outcomes in arctic wildlife monitoring

Helen C. Wheeler,[1,2,3,4]* Dominique Berteaux,[1] Chris Furgal,[5] Kevin Cazelles,[6] Nigel G. Yoccoz,[3] and David Grémillet[2,7]

[1]Canada Research Chair on Northern Biodiversity and Centre for Northern Studies, Université du Québec à Rimouski, 300 Allée des Ursulines, Rimouski, QC, G5L 3A1, Canada
[2]Centre d'Ecologie Fonctionnelle et Evolutive, UMR 5175, Centre National de la Recherche Scientifique - Université de Montpellier - Université Paul-Valéry Montpellier - EPHE, 1919 route de Mende, Montpellier, 34090, France
[3]Department of Arctic and Marine Biology, UiT the Arctic University of Norway, Postboks 6050 Langnes, Tromsø, 9037, Norway
[4]School of Life Sciences, Anglia Ruskin University, East Road, Cambridge, CB1 1PT, U.K.
[5]Indigenous Environmental Studies and Sciences, Trent University, 1600 West Bank Drive, Peterborough, ON, K9L 0G2, Canada
[6]Department of Integrative Biology, University of Guelph, 50 Stone Rd E, Guelph, ON, N1G 2W1, Canada
[7]Department of Science and Technology - National Research Foundation Centre of Excellence, Percy FitzPatrick Institute, University of Cape Town, Rondebosch, South Africa

Abstract: *For effective monitoring in social–ecological systems to meet needs for biodiversity, science, and humans, desired outcomes must be clearly defined and routes from direct to derived outcomes understood. The Arctic is undergoing rapid climatic, ecological, social, and economic changes and requires effective wildlife monitoring to meet diverse stakeholder needs. To identify stakeholder priorities concerning desired outcomes of arctic wildlife monitoring, we conducted in-depth interviews with 29 arctic scientists, policy and decision makers, and representatives of indigenous organizations and nongovernmental organizations. Using qualitative content analysis, we identified and defined desired outcomes and documented links between outcomes. Using network analysis, we investigated the structure of perceived links between desired outcomes. We identified 18 desired outcomes from monitoring and classified them as either driven by monitoring information, monitoring process, or a combination of both. Highly cited outcomes were make decisions, conserve, detect change, disseminate, and secure food. These reflect key foci of arctic monitoring. Infrequently cited outcomes (e.g., govern) were emerging themes. Three modules comprised our outcome network. The modularity highlighted the low strength of perceived links between outcomes that were primarily information driven or more derived (e.g., detect change, make decisions, conserve, or secure food) and outcomes that were primarily process driven or more derived (e.g., cooperate, learn, educate). The outcomes expand monitoring community and disseminate created connections between these modules. Key desired outcomes are widely applicable to social–ecological systems within and outside the Arctic, particularly those with wildlife subsistence economies. Attributes and motivations associated with outcomes can guide development of integrated monitoring goals for biodiversity conservation and human needs. Our results demonstrated the disconnect between information- and process-driven goals and how expansion of the monitoring community and improved integration of monitoring stakeholders will help connect information- and process-derived outcomes for effective ecosystem stewardship.*

Keywords: adaptive management, climate change, network analysis, scientific monitoring, stakeholders, traditional knowledge

**Address correspondence to H. C. Wheeler, email hcwheele@ualberta.ca*
Article impact statement: *Desired monitoring outcomes are linked; stronger links between community participation and data use may expand social–ecological benefits.*
Paper submitted January 31, 2018; revised manuscript accepted November 22, 2018.

Conservation Biology, Volume 33, No. 4, 861–872

DOI: 10.1111/cobi.13257

Identificación de las Necesidades Clave para la Integración de Resultados Socio-Ecológicos en el Monitoreo de Fauna en el Ártico

Resumen: *Para que el monitoreo efectivo en los sistemas socio-ecológicos cumpla con las necesidades de la biodiversidad, la ciencia, y los humanos, se deben definir claramente los resultados deseados y se deben entender las rutas que se toman de los resultados directos hacia los resultados derivados. El Ártico está sufriendo rápidamente cambios climáticos, ecológicos, y económicos, y requiere de un monitoreo efectivo de fauna para cumplir con las necesidades de diversos accionistas. Realizamos entrevistas a profundidad con 29 científicos del Ártico, responsables de decisiones y políticas, y representativos de organizaciones indígenas y organizaciones no gubernamentales para identificar las prioridades de los accionistas con respecto a los resultados deseados del monitoreo de fauna ártica. Mediante un análisis cualitativo de contenido identificamos y definimos los resultados deseados y documentamos las conexiones entre los resultados. Con un análisis de redes investigamos la estructura de las conexiones percibidas y las clasificamos como causadas por el monitoreo de información, el monitoreo del proceso, o una combinación de ambos. Los resultados con un mayor número de menciones fueron tomar decisiones, conservar, detectar cambios, diseminar, y asegurar alimento. Estos reflejan los enfoques más importantes del monitoreo en el Ártico. Los resultados con poca frecuencia en las menciones (p. ej.: regular) correspondían a temas emergentes. Nuestra red de resultados estuvo compuesta por tres módulos. La modularidad resaltó la poca fuerza de las conexiones percibidas entre los resultados que fueron causados principalmente por la información o que estuvieron más derivados (p. ej.: detectar el cambio, tomar decisiones, conservar o asegurar alimento) y los resultados que fueron causados principalmente por el proceso o que estuvieron más derivados (p. ej.: cooperar, aprender, educar). Los resultados expanden la comunidad monitora y diseminan las conexiones creadas entre estos módulos. Los resultados clave deseados se pueden aplicar extensamente a los sistemas socio-ecológicos dentro y fuera del Ártico, particularmente aquellos con economías de sustento basadas en la fauna. Los atributos y motivaciones asociados con los resultados pueden guiar el desarrollo de los objetivos integrados de monitoreo para la conservación de la biodiversidad y las necesidades humanas. Nuestros resultados demostraron la desconexión entre los objetivos conducidos por la información y aquellos conducidos por el proceso y cómo la expansión de la comunidad monitora y una mejor integración de los accionistas monitores ayudarán a conectar los resultados derivados de la información y derivados del proceso para una administración efectiva del ecosistema.*

Palabras Clave: accionistas, análisis de redes, cambio climático, conocimiento tradicional, manejo adaptativo, monitoreo científico

摘要: *为了在社会生态系统中进行有效监测, 以满足生物多样性、科学和人类的需求, 应明确确定预期结果, 并理解直接结果向衍生结果的转化。北极正经历着气候、生态、社会和经济的快速变化, 需要有效的野生动物监测来满足不同利益相关者的需求。为确定利益相关者对北极野生动物监测预期结果最关注的问题, 我们深入采访了29 位北极科学家、决策者、原住民组织及非政府组织的代表。我们用定性内容分析找出并定义了预期结果, 记录了结果间的联系。利用网络分析, 我们还研究了预期结果间连接的结构。我们确定了18 项监测预期结果, 并将其分为监测信息驱动的、监测过程驱动的或二者兼而有之的。在这些结果中, 被常常提及的有决策、保护、监测变化、传播和保障食物安全, 它们反映出北极监测的重点。而那些不常被提到的结果是一些新兴话题 (如治理) 。我们的结果网络有三个模块组成, 网络的模块性表明, 主要由监测信息驱动或更多衍生的结果 (如监测变化、决策、保护或保障食物安全) 和主要由监测过程驱动或更多衍生的结果 (如合作、学习、教育) 之间被认为的连接强度较低。这些结果扩大了监测区域, 并传播了各模块间所创建的联系。关键的预期结果在北极内外的社会生态系统中广泛适用, 特别是那些依赖野生动物的经济体系, 而与预期结果有关的特性和动机可以指导生物多样性保护和人类需求的综合监测目标的制定。我们的结果显示, 信息驱动和过程驱动的目标之间存在脱节, 并说明了扩大监测区域、推动监测利益相关者一体化将如何为有效的生态系统管理建立起信息驱动及过程驱动结果间的连接。* **【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 适应性管理, 气候变化, 网络分析, 科学监测, 利益相关者, 传统知识

Introduction

Under rapidly changing climate and shifting human activities, effective long-term ecological monitoring can substantially inform adaptation to far-reaching environmental change (Tesar et al. 2016). Despite a well-recognized desire among scientists and decision makers for large-scale long-term ecological monitoring, difficulties in securing long-term funding often limit the ability to maintain monitoring programs (Lindenmayer & Likens 2010; Tulloch et al. 2013). Thus, it is essential to design programs that maximize effectiveness in reaching desired objectives (McDonald-Madden et al. 2010; Tulloch et al. 2013). Decisions about how, what, where, and when to monitor and who drives, conducts, analyses, and interprets monitoring information should be driven by a consideration of the desirable outcomes. To achieve effective social–ecological stewardship, clearly defined context relevant goals within these desired outcomes are needed. Identifying beneficiaries and their needs within each context is core to this endeavor.

Monitoring programs, particularly surveillance, have been criticized for lacking clear questions driving activities (Nichols & Williams 2006; Lindenmayer & Likens 2010). A call has been made for hypothesis-driven monitoring, which requires clear hypotheses and ecosystem conceptualizations to be used to determine what, where, and how to monitor (Yoccoz et al. 2001). Many recent ecosystem-based monitoring programs focus on determining causal relationships to increase ecological understanding, inform management decisions, and evaluate their efficacy (Ims & Yoccoz 2017).

As monitoring objectives broaden, how monitoring can meet the multiple objectives of different stakeholders needs to be examined. The diversity of actors involved in ecological monitoring is increasing, partially because of greater acceptance of participatory and citizen science approaches (Silvertown 2009; Chandler et al. 2017). The need to incorporate indigenous and local knowledge and information is also increasingly recognized (Diaz et al. 2015).

When evaluating effectiveness of monitoring in science-oriented arenas, the focuses on information-driven, scientific outcomes may undervalue the many potential benefits from monitoring across social–ecological systems, including meeting stakeholder needs. Higher-level frameworks are needed to maximize monitoring effectiveness for a wider set of biodiversity- and human-related goals and to incorporate the complexity of social–ecological systems (Ostrom 2009; Chapin et al. 2015). Benefits related to local capacity and environmental stewardship are important outcomes of monitoring (e.g., Fernandez-Gimenez et al. 2008; Şekercioğlu 2012; Kouril et al. 2015). These potential benefits are often considered separately from information needs, despite the importance of their integration.

Effective monitoring is essential in the Arctic, where warming exceeds twice the rate at lower latitudes (Overland et al. 2016). Changes in climate, snow, and ice have modified industrial, economic, and cultural activities and ecological systems (ACIA 2004; Meltofte et al. 2013). Thus, there is pressing need to translate monitoring activities into desirable outcomes for ecosystems and people. Initiatives to coordinate monitoring at pan-arctic scales have become increasingly common. These are composed of networks of regional and local monitoring efforts with diverse goals and approaches. The Circumpolar Biodiversity Monitoring program connects those involved in monitoring to set agendas and primarily involves monitoring undertaken by scientists, traditionally taking an ecosystem- or species-focused approach to select monitoring targets to represent different ecological roles or human needs (CAFF 2015).

In the Arctic, as elsewhere, monitoring approaches vary in motivations, degree, and characteristics of local participation and type of information produced (Brunet et al. 2014). Approaches range from theoretical (context-independent knowledge generation or evaluation of the influence of context) to applied science (knowledge built within the context in which it will be applied) (Brunet et al. 2014). Modes of local participation and partnership include externally driven projects with data collection and use by scientists not usually residing in the Arctic; externally driven projects with local data collectors (sometimes included within the definition of community-based monitoring); locally driven projects with external advice and external analysis of information (community-based or community-driven monitoring); and locally driven projects with local analysis (Danielsen et al. 2009; Kouril et al. 2015).

Scientific, indigenous, and local ecological knowledge all contribute to arctic monitoring. Indigenous knowledge has been characterized as local and context-specific, adaptive, and situated within people's lives, and this knowledge can be transmitted orally and through practice (Mistry & Berardi 2016). Local ecological knowledge reflects knowledge from people living in a given location (Brook & McLachlan 2008). Local participation can provide a mechanism for increased use of indigenous or local knowledge, although not all initiatives do so. Local participation in research in the Arctic from 1965 to 2010 has only increased slightly (Brunet et al. 2014). Accordingly, within many arctic monitoring organizations and elsewhere, there are aims to increase local participation and use of local and indigenous knowledge (Mustonen & Ford 2013; Johnson et al. 2015).

To identify the desirable outcomes of monitoring for biodiversity and people and the structure of interrelationships between desired outcomes, we analyzed perceptions of arctic stakeholders concerning pan-arctic monitoring of terrestrial vertebrates and seabirds. We sought to determine the desired outcomes of monitoring related to the process of and information from ecological monitoring and the structure of perceived causal links between different desired outcomes.

Desirable outcomes from monitoring may be direct results of monitoring (e.g., determining population size) or more abstracted and diffuse, such that pathways from monitoring activities to desirable outcomes may be indirect and difficult to define (Dickinson et al. 2012). We used network analysis to define structure, assess characteristics, and identify disconnects between linked sets of monitoring objectives. Developing greater understanding of the structure of links between desirable monitoring outcomes is key to achieving the more abstracted, ultimate outcomes.

Methods

Semistructured Interviews

We conducted one-on-one semistructured (Gubrium 2012) interviews with 29 arctic scientists, policy and decision makers, and representatives of indigenous organizations and nongovernmental organizations (NGOs) to determine desirable outcomes of monitoring. We selected participants from among attendees at international Arctic Council working group and expert network meetings and with subsequent snowball sampling (Teddlie & Yu 2007). We focused on people or organizations involved in the production or use of observations and recordings or associated with arctic wildlife use (e.g., hunting and harvesting) (Supporting Information). We aimed for a balance among those involved in policy and decision making and science and those representing indigenous organizations, although many participants performed more than one of these roles (Supporting Information). We purposively selected new potential participants from our pool of potential participants identified in our snowball technique to balance sampling across these groups. We chose our sample size to allow in-depth interviewing of each participant while ensuring a breadth of stakeholders. None of the participants had previously met the interviewer, although all shared interests in monitoring and the Arctic. The Trent University Research Ethics Board and Aboriginal Ethics Committee approved our study (file 24118). All participants gave written informed consent to their participation in accordance with the Tri-Council Policy Statement on Human Research Ethics and permission to be named both in general and for specific quotes.

Prior to the semistructured interviews we asked participants, “Is it important to monitor wildlife?” and provided a set of options for responses. All participants identified wildlife monitoring as having high importance. We asked this question to test the assumption that participants would forsee monitoring benefits. This question was neither part of the actual semistructured interview nor used for content analysis.

To identify desirable monitoring outcomes, we first followed up on our initial question by asking why participants thought it was important to monitor wildlife. We then asked participants to describe desirable outcomes from monitoring (defined as “any positive effects on people and society, the environment, or academia in- and outside the Arctic” and “the good things that can result from monitoring activities”). We stated that outcomes can relate to any stage of monitoring, including both the process of monitoring and the data derived from monitoring (Supporting Information). Although our interviews were semistructured, allowing us to prompt for further information or clarify the meaning of participant statements with nonleading questions, this normally involved repeating participants’ phrases back to them in questions to illicit clarification or explanation. We continued interviews until saturation was complete, as identified by review of interview material for new themes and theme richness and fullness (Mason 2010).

Interviews were audio recorded and transcribed, after which we identified themes among the outcomes of monitoring with content analysis (Vaismoradi et al. 2013). Our approach was primarily inductive in that we used interview material to generate themes. There was also a deductive component; we highlighted to participants our interest in the process of monitoring (how monitoring is done and interactions between people and monitoring activities) and the information-driven outcomes (deriving from data collected during monitoring). We categorized our themes according to these characteristics. These were desired outcomes that were driven by information, were derived from the process of monitoring, or were a combination of both. Once initial themes were established, they were rereviewed and amended to create clearly defined, nonoverlapping themes. We used a second review of the transcripts to code any further material to finalize themes and code any incidence where a participant identified a cause–effect relationship between themes (Supporting Information). Finally, we reviewed texts to extract key characteristics of responses for each theme. We used NVivo (Pro version 11, QSR International, Melbourne) for all coding and qualitative analysis. A second coder experienced in qualitative analysis randomly performed intercoder reliability checks on both code construction and application. Once themes were established and coded for each participant, we quantitatively tested post hoc for saturation of themes (Supporting Information).

Network Analysis of Stakeholder Perceptions of Relationships Between Outcomes of Monitoring

We extracted the number of participants mentioning each theme, and themes were represented by nodes in our network. We represented the frequency of directional cause–effect relationships stated between each theme as vectors connecting nodes. Vectors indicated the extent that participants considered different themes to be linked. We used the outward farness to the rest of the network to estimate the degree of abstraction from the direct act of monitoring for each desirable outcome (Batool & Niazi 2014; Supporting Information). Node outward farness measures the sum of minimum distances between any node and all other network nodes in a cause–effect direction. We used this measure to map a network of our themes based on abstraction from monitoring and perceived cause–effect connections.

We performed cluster analysis to identify highly connected groups of themes (referred to as “modules”). This allowed us to assess the degree to which different groups of themes were identified as being linked. According to Yang et al. (2016), we chose a walktrap algorithm for community detection (Pons & Latapy 2005), reflecting the high mixing parameter associated with modules in our network and low number of nodes (n = 18). We simplified the network to an undirected network and performed the analysis including weights associated with links between nodes. Because 2 additional community detection algorithms were appropriate for our data, we also applied these models to test whether results were affected by the algorithm used for community detection (Supporting Information). We focused on results from the walktrap algorithm, because this was the only algorithm that allowed hierarchical detection of communities, which allowed us to identify the relative support for splits between modules.

Given that our analysis suggested shared ownership of nodes between modules (as demonstrated by moderate modularity, a high mixing parameter, and some uncertainty in module assignment between algorithms), we also applied a community detection algorithm, which assigned links rather than nodes to modules (Ahn et al. 2010). This allowed quantification of the extent to which each node belonged to each edge community and whether there was shared ownership of nodes between modules, thus allowing nodes connecting different modules to be identified. All analyses were performed in R version 3.1.1 (R Development Core Team 2016) with packages linkcomm (Kalinka & Tomancak 2011) and igraph (Csardi & Nepusz 2006).

Results

We identified 18 core perceived desirable outcomes of wildlife monitoring (Table 1) (mean 10.7 [SE 0.6] desirable outcomes/participant). These were linked by 44 unique cause-and-effect links between desired outcomes (mean 4.8 [0.5] links /participant) (Fig. 1). Of our 18 desired outcomes, we identified 7 desired outcomes derived primarily from the information produced from monitoring (e.g., record status), 4 derived primarily from the process of monitoring (e.g., expand community), and 7 which had combined contributions from the information and monitoring process (e.g., make decisions). We highlight the key characteristics and motivations for each theme, as identified by stakeholders and indicative quotes in an extended version of Table 1 in Supporting Information.

The most direct outcomes of monitoring were 2 information-driven outcomes: record status and detect change (Fig. 1 & Table 1). The 4 process-driven outcomes of monitoring (expand community, cooperate, disseminate, educate) were also relatively direct. The most abstracted desired outcomes from the act of monitoring were those that combined monitoring information and process (Fig. 1 & Table 1). The 5 most commonly cited themes were make decisions (n = 28, 97% of participants), detect change (n = 26), conserve (n = 25), disseminate (n = 24) and secure food (n = 23) (Fig. 1). Govern (n = 5), identify system linkages (n = 7), and inform research and monitoring (n = 5) were themes identified by the fewest participants (17–24% of participants).

Community detection across nodes revealed 3 distinct modules within our desired outcomes of monitoring (Fig. 2a). The primary separation between modules divided one set of desired outcomes containing all process-driven outcomes and govern and learn from another set containing information-driven outcomes and the remaining combined (process- and information-driven) outcomes (referred to as the *process module* and *information module*, respectively, reflecting the composition of basal nodes in each module) (Fig. 2b). Within our information module information-driven outcomes linked with make decisions, conserve, secure food, support economic futures, and inform research and monitoring (Fig. 2a). There was the same division between process and information modules across all 3 community detection algorithms (Supporting Information). Although a secondary division was observed for all community detection algorithms, the identity of nodes separated by this division differed between detection methods (Supporting Information). For the walktrap algorithm, a secondary division within the information module separated 2 desired outcomes (identify system linkages and inform research and monitoring) (Fig. 2a, b); however, these outcomes were characterized by low connectivity (Fig. 2c). Detect change and make decisions were highly connected both within their own module and to other modules, and disseminating and expanding the monitoring community had strong links external to their module (Fig. 2c). Community detection analysis across links supported the separation of process and information modules but identified variation in the extent to which outcomes could be attributed to a single module across nodes. Although expand community and disseminate were primarily attributed to a process module analogous to that found in our community detection across nodes, there was also a clear contribution of these outcomes to the information module, which again comprised 2 submodules (Fig. 3).

Discussion

Dominant and Emerging Desired Impacts in Arctic Wildlife Monitoring

The 18 key desirable outcomes for arctic wildlife monitoring, defined by stakeholders (Table 1), ranged from direct to highly derived outcomes of monitoring. The 5 most common themes in our network (i.e., make decisions, conserve, detect change, disseminate, and secure food) highlight key foci of arctic monitoring. Conservation and food security are substantial concerns as the Arctic undergoes rapid social and ecological change (Loring

Table 1. Summary of desired outcomes of monitoring identified from semistructured interviews of stakeholders in pan-arctic wildlife monitoring (focused on seabirds and terrestrial vertebrates).[a]

Desirable outcome	*Description*
Data-driven activities	
record status	recording the state or baseline status of components of systems at a given point in time
detect change	identifying changes in components of systems over time or across space (e.g., identifying common or differing trends temporally or spatially)
identify drivers	identifying factors driving or causing temporal change in systems or system components or establishing the magnitude of effects of drivers on systems or system components; may include assessing the impacts of a single driver of interest
understand systems	building principles, rules, or understanding about systems, normally with some generality beyond a single location or single point in time
synthesise information	bringing together disparate information or data sets through data harmonization or combined approaches
project futures	forecast likely or potential states of systems in the future based on current or historical observations and analysis
identify system linkages	identify linkages within systems or between a subset of system components
Process-driven activities	
expand community	instigating changes in the composition of and recognition of people defining monitoring objectives, undertaking observation, or recording or analyzing monitoring data
disseminate	provide information or address questions regarding arctic change to people not directly producing that information, either directly to people or through media or other outlets
educate	education or informal training relating to monitoring activities to build skills and knowledge (SDG 4)[b]
cooperate	increase interactions between people involved in monitoring or outcomes from monitoring in different nations and different cultural and demographic groups resulting in trust building and reciprocally beneficial activities (SDG 17)[b]
Combined information-and process-driven activities	
make decisions	inform decision making, policy formation, and management, providing data, knowledge, or information to help make decisions regarding intervention or nonintervention in systems or broader agendas to reach some desired outcome; includes assessing effectiveness of decision making in reaching desired outcome
inform research and monitoring	provide data, knowledge, or information to help make decisions about what, where, or how or when to conduct monitoring or research
learn	enhance adoption of values or behaviors related to knowledge and skills, includes generating engagement or influencing attitudes toward issues relevant to change in the Arctic
govern	create effective accountable and inclusive institutions that provide justice (SDG 16)[b]
secure food	provide food security (access, availability, effective use, and stability of food to meet dietary needs and food preferences [Nilsson & Evergard 2015]) and sovereignty (culturally appropriate and healthy foods), includes opportunities to hunt and harvest local wildlife (SDG 2)[b]
conserve	protect, restore, or sustainably use ecosystems and their components; maintain biodiversity (SDG 14 and 15)[b]
support economic futures	ensure sustainable industry and economic activity (SDG 7, 8, 9, and 12)[b]

[a]*An extended version of this table is available in Supporting Information.*
[b]*Themes link to sustainable development goals (UN 2015) (e.g., SDG 1).*

& Gerlach 2015; Nilsson & Evengård 2015). The focus on conservation and food security highlights the dual aims of ecosystem resilience and human well-being for arctic stewardship (Chapin et al. 2015) and mirrors concerns in other regions (Sachs et al. 2010; Wittman et al. 2017). Past approaches to conservation, which consider the Arctic a wilderness and remove conservation activities from human needs, have been criticized, given >4 million people inhabit the Arctic (Nymand Larsen et al. 2010), and decision making driven from outside the Arctic was described by one participant as "paternalistic."

Detecting change and identifying drivers were perceived to have a major role in achieving more derived monitoring outcomes (Fig. 1). The most frequently described link was from detecting change to making decisions. Detecting change in single or suites of species informs decision making. Population management remains common in the Arctic and globally, for fisheries and

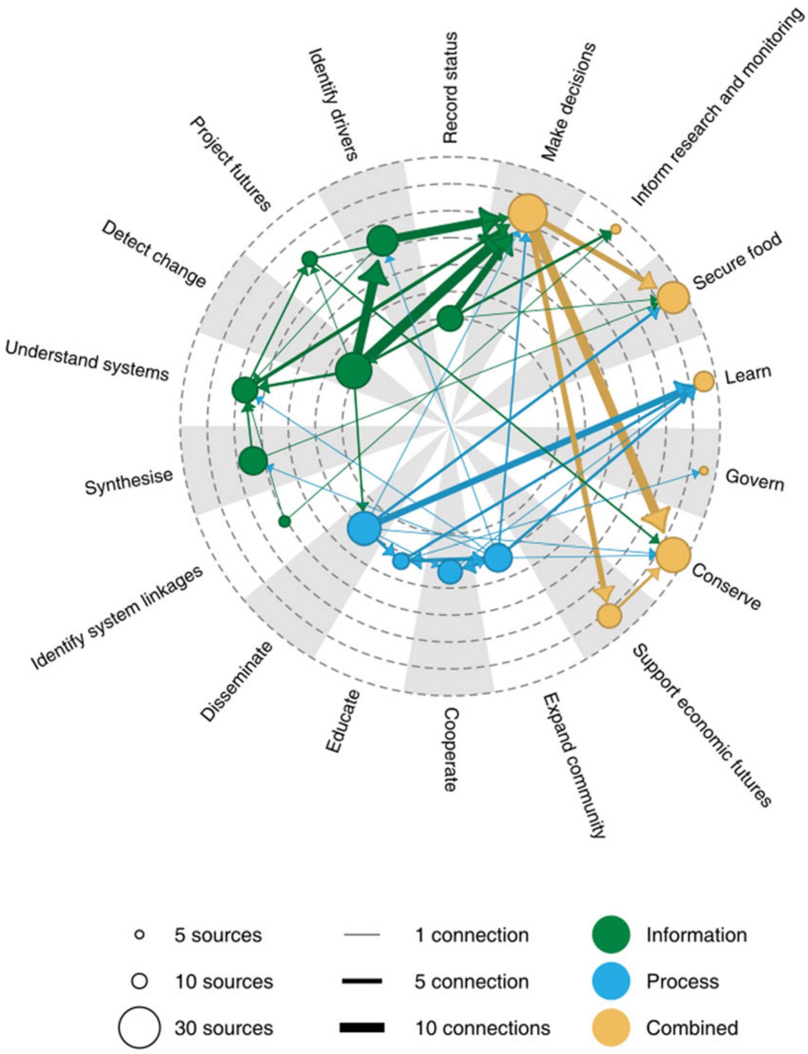

Figure 1. Network diagram of the desirable impacts of monitoring seabirds and terrestrial vertebrates as identified by 29 stakeholders in monitoring in the Arctic. Nodes represent primarily monitoring-information-driven themes, monitoring-process-driven themes, and themes that are a combination of information- and process-driven themes. Nodes representing themes are plotted radially according to their degree of abstraction from the act of monitoring, as measured by outward farness in a cause–effect direction. The most central nodes represent the most direct impacts from monitoring. Node size is proportional to the number of individuals identifying each theme (from 5 to 28). Arrows and their width represent the number of participants making cause–effect association between particular themes, and arrows are shaded according to the originating group of each link.

wildlife. Direct links between detecting change, ecosystem assessment and decision making also occur with sentinel species, such as seabirds (Wanless et al. 2007). Here, species are indicators of wider ecosystem change due to sensitivity to a number of ecosystem components. While this is most effective when drivers of change in the sentinel species are understood and consistent across space and time (Grémillet & Charmantier 2010), the decision-making action may be driven by population change alone.

Detecting change from ecosystems and social–ecological perspectives can also link to decision making, but links can be indirect, potentially involving social processes such as public awareness of change. There are clear parallels between the scientific move from a species-focus toward ecosystem-based and social–ecological system monitoring and indigenous conceptions of interlinked systems. Local communities may be well placed to identify novel and unexpected changes, given their long-term and often less spatially restricted association with ecological systems. The scientific concept of surveillance and implications of inefficiency, passivity, and a lack of goals (Nichols & Williams 2006) may not adhere to conceptions of monitoring by local people. One indigenous organizational representative pointed out that a characteristic of indigenous knowledge is being "hypothesis seeking." This highlights the important role of monitoring in defining multiple competing models of potential causes of change in ecological systems (Mäntyniemi et al. 2013). Detecting change through exploratory research is essential to defining scope and pertinent questions to inform decision making and thus guide hypothesis testing or confirmatory research (Tukey 1980). Exploratory research may also help examine alternative possible futures (Cook et al. 2014; Ims & Yoccoz 2017).

While detecting change may be possible over relatively large areas, particularly in collaboration with local people, identifying drivers requires a more intensive form of monitoring on a more limited number of ecosystems. Direct links between detecting change and decision making may allow relatively rapid response to change and allow a broader systems view and greater spatial coverage but limit the ability to test hypotheses, discriminate between

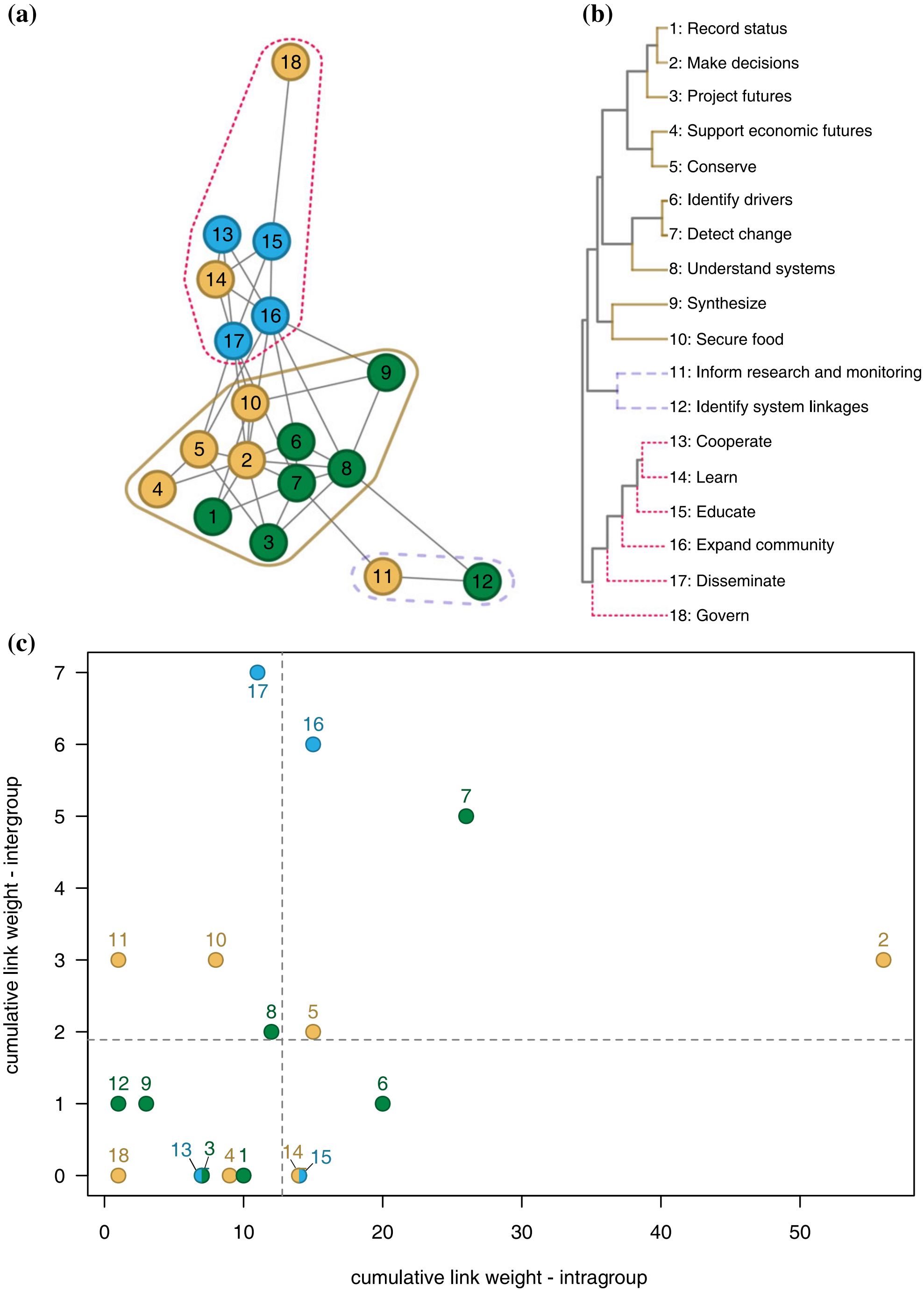

Figure 2. Summary of modules in the network of desirable impacts of monitoring of arctic seabirds and terrestrial vertebrates as identified by cluster analysis with a walktrap algorithm: (a) modules in the network (nodes 13–18, module containing mainly process-driven outcomes and combined outcomes [learn and govern]; nodes 1–12, module containing mainly information-driven outcomes and all other combined outcomes), (b) hierarchical separation of modules, (c) cumulative weights of intra- and intergroup connections for each node (dashed lines, mean intra- and inter-module link weight across nodes). Desired outcome nodes are shaded according to theme type: primarily monitoring-information-driven themes, primarily monitoring-process-driven themes, and themes that are a combination of information and process driven. The same shading is used to represent groupings in dendrogram branches. In the network, node placement is determined by degree of association with other nodes according to the number of relationships mentioned by participants according to Fruchterman-Reingold force-directed placement (Fruchterman & Reingold 1991). Nodes placed close to the interface between modules are those most connected to the alternative module.

drivers, and assess their relative magnitudes. Balancing an outward focus to encompass complex systems and representativeness across drivers and inward focus to accurately estimate magnitudes of driver impacts is a core challenge in monitoring.

Govern was one of the least identified desirable impacts in our network and had low connectivity. Governance challenges may increase in importance as the transformation of social–ecological systems accelerates. How and where monitoring is conducted may affect whether governance of changing human activities and management of conflicts over use of land and seas is fair and effective. In the Arctic, changes in sea ice and permafrost affect the relative accessibility of different areas to different stakeholders and affect traditional practices (Berkman & Young 2009; Stephenson et al. 2011). Because the Arctic is viewed as an opportunity for development, increasing conflicts are seen among energy extraction, predator conservation, and local practices such as reindeer (*Rangifer tarandus*) herding (Forbes et al. 2009; Tveraa et al. 2014). If decision making is evidence based, what is monitored, where monitoring occurs, and who is involved can influence the fairness of institutions. Absence of monitoring or focus on certain drivers may affect perception of causation and impacts, subsequent management interventions, and burden of responsibility. This issue was highlighted in multiple contexts related to species foci and traditional versus economic activities. In reference to perceptions of sustainability in fisheries management models and lack of inclusion of species within the broader ecosystem, a seabird scientist noted: "... it might be sustainable for the two or three species covered by the model, but there are not many seabirds in fishery management models."

Perception of Separate Decision Making and Learning Pathways

Our network analysis highlights a lack of connectivity between perceived objectives of monitoring associated with capacity building and development goals (such as cooperate, learn, educate, expand community, and disseminate contained in our process module) and objectives associated with production and use of information (such as record status, identify drivers, project futures, make decisions, conserve and secure food contained in our information module). This may reflect monitoring programmes focusing on either objectives leading to capacity building and development or information related objectives, but rarely both.

The apparent separation of the suite of capacity-building and development-related objectives and information-related objectives highlights potential gaps in current monitoring of social–ecological systems. For monitoring-related learning to be effective, it must draw from reliable evidence. Ensuring education and learning processes are strongly connected to monitoring information is key to maintaining the evidence to learning link, and may be a current gap, according to our analysis. Conversely, for communities to have meaningful influence in decision making, there also need to be mechanisms to link their learning to decision making and more derived outcomes (Buckland-Nicks 2015).

Linking Monitoring Process- and Information-Driven Outcomes

Expanding the monitoring community and dissemination could be key routes linking information and learning, due to the bridging role between process- and information-related outcomes (Figs. 2 & 3). Fragmentation of research communities, particularly according to knowledge systems or disciplines may limit the potential to bridge outcome types. Similar to other areas of research (e.g., arctic tourism, Stewart et al. 2017), actors in the monitoring have become increasingly connected over recent years, facilitated by key international funders and institutions. The identity of actors in this monitoring network and their associations are crucial. Greater meaningful participation of local people and inclusion of indigenous knowledge is needed in monitoring (Meltofte et al. 2013) to create benefits such as trust building and social learning (Fernandez-Gimenez et al. 2008). For effective linking of monitoring processes to information use and for scientists and people from outside communities to develop meaningful learning from local and indigenous knowledge, a depth of local engagement and involvement is required beyond extraction of information (Kay & Johnson 2017). Comanagement and coproduction of knowledge have been cited as important pathways to learning and adaptation to arctic change with an expanded community of local people, decision makers, and scientists (Armitage et al. 2011). The integration of decision makers in monitoring from an early stage may be key to greater uptake in decision making (Buckland-Nicks 2015). Such approaches must be applied cautiously and reflectively to ensure accountability, balance in the roles of different stakeholders, and that power imbalances and undesirable discourses do not undermine collaborative efforts (Hall & Sanders 2015).

In our network, learning and pathways to learning are not perceived to be linked strongly with decision making, conservation, and food security. To strengthen this link, frameworks linking beneficiaries of learning back to decision making are needed. In Canada land claims agreements mandate that indigenous representatives from various organizations be involved in decision making through wildlife management boards (Armitage et al. 2011), whereas in some other arctic countries this legislative link is absent. At an international level, local learning may be translated to policy as representatives from some indigenous organizations participate in Arctic

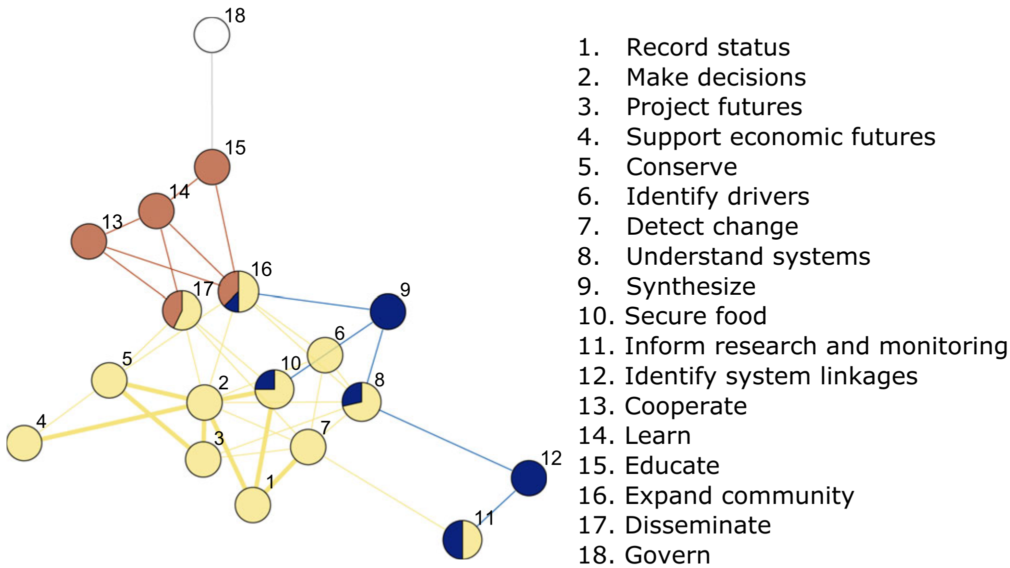

Figure 3. Network diagram showing communities of associated links between different desired outcomes for monitoring of arctic seabirds and terrestrial vertebrates. The contribution of edges from each community to each desired monitoring outcome (node) is shown as a pie segment in each node. Each edge community is shown in a different shade, and edge widths represent the number of individuals making each connection. The edge linking nodes 15 and 18 is not attributed to a community given its lack of connectivity with other edges. Accordingly, there is no edge community contribution to node 18 govern. The contribution of edge communities to each node pie represents the number of different edges from each community contributing to that node.

Council deliberation. The Arctic Council produces policy recommendations and arctic assessments at a pan-arctic scale. Although these are not legally binding, the Arctic Council is a major component of international arctic cooperation (Koivurova 2010). In addition to local people and organizations, other beneficiaries of learning from arctic monitoring were the global public. How to translate this public learning, concerning climate impacts on wildlife and people in the Arctic, into momentum for global action on policy to limit global warming, remains a major challenge.

Limitations

To assess pan-arctic monitoring needs, we focused on stakeholders involved in monitoring agendas at this scale; however, most also work at more local scales. This reflects that pan-arctic monitoring is comprised of a network of local and regional monitoring programmes. Institutions within the Arctic may affect the balance of different perspectives and their influence on stakeholder's perceived desirable monitoring outcomes. Institutions involved in arctic governance include states, NGOs, research institutes, and indigenous peoples' organizations (Bruun & Medby 2014). A number of supranational institutions work to promote discussion of arctic monitoring (e.g., Arctic Council, Arctic Monitoring, and Assessment Program and International Arctic Science Council). Funding agencies also influence monitoring design and practice. The discourses generated within these supranational institutions likely have an influence on perceived desirable monitoring objectives. This influence is undoubtedly a 2-way interaction; through these forums, stakeholders also influence monitoring discourses. Scientists and policy makers may have a longer history of participation or more influential status in these institutions and thus may have greater influence over discourse. Indigenous participation in environmental research has been dominated by participation from communities in North America, and this generates focus on certain compartmentalized research paradigms (climate change, wildlife management, and indigenous knowledge) that may be less relevant to indigenous peoples of Russia (Forbes & Stammler 2009). Although we worked to maximize representation across stakeholder groups and nations, these broader differences in representation will ultimately affect the discourses to which participants are exposed and their perceptions of desirable monitoring outcomes. We therefore acknowledge the dominance of a Western influence in our network of impacts and the potential for biases toward scientific discourses. Continued efforts to expand and diversify the monitoring community are likely to help counter these biases.

Aspirations for Future Monitoring

Consideration of a wider set of monitoring outcomes is important to both planning and evaluating the cost-effectiveness and utility of monitoring, which may otherwise be underestimated. Our network analysis revealed separation between the monitoring process-based pathway to learning and an information-driven pathway to decision making. Ensuring that learning both locally and at globally translates to effective decision making and stewardship should be a key goal. This can be facilitated by expanding participation, building local capacity, and improving governance structures in ways that target greater links to decision making and stewardship. Our network of monitoring impacts represents aspirations for arctic monitoring in social–ecological contexts, but can be applied to many social–ecological systems where the monitoring community involves community members. Undoubtedly, under existing constraints of limited long-term funding and high incentives for short-term achievements, these aspirations face major challenges (e.g., Wheeler et al. 2016). Creating funding opportunities and reward systems that encourage greater connectivity of information-based and process-based impacts would greatly advance opportunities to move toward these desired outcomes.

Acknowledgments

We are very grateful to interview participants (Supporting Information) for their insightful perspectives. We thank CAFF CBird expert group members for interesting discussions. Funding was provided by a Belmont Forum Small Cooperation Grant (TAMANI project) and supported by the National Sciences and Engineering Research Council of Canada, Agence Nationale de la Recherche, France, and The Research Council of Norway. We also thank the U.S. National Science Foundation, the Network of Centers of Excellence of Canada ArcticNet, and the French Polar Institute Paul-Emile Victor (ADACLIM programme No. 388) for support.

Supporting Information

Extended summary of desired outcomes of monitoring identified from semistructured interviews and indicative quotes (Appendix S1), summary of interview participants and interview guide (Appendix S2), and extended methods (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author. All code for analyses is available from https://github.com/KevCaz/monitoringOutcomes (https://doi.org/10.5281/zenodo.1652737).

Literature Cited

ACIA (Arctic Climate Impact Assessment). 2004. Impacts of a warming Arctic-Arctic Climate Impact Assessment. Cambridge University Press, Cambridge, United Kingdom.

Ahn Y-Y, Bagrow JP, Lehmann S. 2010. Link communities reveal multiscale complexity in networks. Nature **466:**761–764.

Armitage D, Berkes F, Dale A, Kocho-Schellenberg E, Patton E. 2011. Co-management and the co-production of knowledge: learning to adapt in Canada's Arctic. Global Environmental Change **21:**995–1004.

Batool K, Niazi MA. 2014. Towards a methodology for validation of centrality measures in complex networks. PLOS ONE **9** (e90283) https://doi.org/10.1371/journal.pone.0090283.

Berkman PA, Young OR. 2009. Governance and environmental change in the Arctic Ocean. Science **324:**339–340.

Brook RK, McLachlan SM. 2008. Trends and prospects for local knowledge in ecological and conservation research and monitoring. Biodiversity and Conservation **17:**3501–3512.

Brunet ND, Hickey GM, Humphries MM. 2014. The evolution of local participation and the mode of knowledge production in Arctic research. Ecology and Society **19:**69.

Bruun JM, Medby IA. 2014. Theorising the thaw: geopolitics in a changing Arctic. Geography Compass **8:**915–929.

Buckland-Nicks A. 2015. Keys to success: A case study approach to understanding community-based water monitoring uptake in governmental decision-making. Master's thesis, Dalhousie University, Halifax, Nova Scotia.

CAFF. 2015. Circumpolar seabird monitoring plan. CAFF monitoring report 17. Arctic Council, Tromsø, Norway.

Chandler M, See L, Copas K, Bonde AM, López BC, Danielsen F, Legind JK, Masinde S, Miller-Rushing AJ, Newman G. 2017. Contribution of citizen science towards international biodiversity monitoring. Biological Conservation **213:**280–294.

Chapin FS, Sommerkorn M, Robards MD, & Hillmer-Pegram K. 2015. Ecosystem stewardship: a resilience framework for arctic conservation. Global Environmental Change **34:**207–217.

Cook CN, Inayatullah S, Burgman MA, Sutherland WJ, Wintle BA. 2014. Strategic foresight: how planning for the unpredictable can improve environmental decision-making. Trends in Ecology & Evolution **29:**531–541.

Csardi G, Nepusz T. 2006. The igraph software package for complex network research. InterJournal, Complex Systems **1695:**1–9.

Danielsen F, et al. 2009. Local participation in natural resource monitoring: a characterization of approaches. Conservation Biology **23:**31–42.

Díaz S, et al. 2015. The IPBES Conceptual Framework—connecting nature and people. Current Opinion in Environmental Sustainability **14:**1–16.

Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T, Purcell K. 2012. The current state of citizen science as a tool for ecological research and public engagement. Frontiers in Ecology and the Environment **10:**291–297.

Fernandez-Gimenez M, Ballard H, Sturtevant V. 2008. Adaptive management and social learning in collaborative and community-based monitoring: a study of five community-based forestry organizations in the western USA. Ecology and Society **13:**2.

Forbes BC, Stammler F. 2009. Arctic climate change discourse: the contrasting politics of research agendas in the West and Russia. Polar Research **28:**28–42.

Forbes BC, Stammler F, Kumpula T, Meschtyb N, Pajunen A, Kaarlejärvi E. 2009. High resilience in the Yamal-Nenets social–ecological system, West Siberian Arctic, Russia. Proceedings of the National Academy of Sciences **106:**22041–22048.

Fruchterman TM, Reingold EM. 1991. Graph drawing by force-directed placement. Software: Practice and Experience **21:**1129–1164.

Grémillet D, Charmantier A. 2010. Shifts in phenotypic plasticity constrain the value of seabirds as ecological indicators of marine ecosystems. Ecological Applications **20:**1498–1503.

Gubrium JF. 2012. The SAGE handbook of interview research: The complexity of the craft. Sage, London, United Kingdom.

Hall EF, Sanders T. 2015. Accountability and the academy: producing knowledge about the human dimensions of climate change. Journal of the Royal Anthropological Institute **21:**438–461.

Ims RA, Yoccoz NG. 2017. Ecosystem-based monitoring in the age of rapid climate change and new technologies. Current Opinion in Environmental Sustainability **29:**170–176.

Johnson N, Alessa L, Behe C, Danielsen F, Gearheard S, Gofman-Wallingford V, Kliskey A, Krümmel E-M, Lynch A, Mustonen T. 2015. The contributions of community-based monitoring and traditional knowledge to Arctic observing networks: Reflections on the state of the field. Arctic **68:**28–40.

Kalinka AT, Tomancak P. 2011. linkcomm: an R package for the generation, visualization, and analysis of link communities in networks of arbitrary size and type. Bioinformatics **27:**2011–2012.

Kay AJ, Johnson CJ. 2017. Identifying effective and sustainable measures for community-based environmental monitoring. Environmental Management **60:**484–495.

Koivurova T. 2010. Limits and possibilities of the Arctic Council in a rapidly changing scene of Arctic governance. Polar Record **46:**146–156.

Kouril D, Furgal C, Whillans T. 2015. Trends and key elements in community-based monitoring: a systematic review of the literature with an emphasis on Arctic and Subarctic regions. Environmental Reviews **24:**151–163.

Lindenmayer DB, Likens GE. 2010. The science and application of ecological monitoring. Biological Conservation **143:**1317–1328.

Loring PA, Gerlach SC. 2015. Searching for progress on food security in the North American North: a research synthesis and meta-analysis of the peer-reviewed literature. Arctic **68:**380–392.

Mason M. 2010. Sample size and saturation in PhD studies using qualitative interviews. Qualitative Social Research **11:**3.

Mäntyniemi S, Haapasaari P, Kuikka S, Parmanne R, Lehtiniemi M, Kaitaranta J. 2013. Incorporating stakeholders' knowledge to stock assessment: Central Baltic herring. Canadian Journal of Fisheries and Aquatic Sciences **70:**591–599.

McDonald-Madden E, Baxter PWJ, Fuller RA, Martin TG, Game ET, Montambault J, Possingham HP. 2010. Monitoring does not always count. Trends in Ecology & Evolution **25:**547–550.

Meltofte H, Barry T, Berteaux D, Bültmann H, Christiansen JS, Cook JA, Dahlberg A, Daniëls FJ, Ehrich D, Fjeldså J. 2013. Synthesis: implications for conservation. Pages 21–65 in Meltofte H, editor. Arctic Biodiversity Assesment. Narayana Press, Odder, Denmark.

Mistry J, Berardi A. 2016. Bringing indigenous and scientific knowledge. Science **352:**1274–1275.

Mustonen T, Ford V. 2013. Indigenous peoples and biodiversity in the Arctic. Pages 18–19 in Meltofte H, editor. Arctic biodiversity assessment. Narayana Press, Odder, Denmark.

Nichols JD, Williams BK. 2006. Monitoring for conservation. Trends in Ecology & Evolution **21:**668–673.

Nilsson LM, Evengård B. 2015. Food security or food sovereignty: What is the main issue in the Arctic? Pages 213–223 in Evengård B, Nymand Larsen J, Paasche Ø, editors. The new Arctic. Springer, Berlin, Germany.

Nymand Larsen J, Fondahl G, Schweitzer P. 2010. Arctic social indicators: a follow-up to the Arctic Human Development Report. Nordic Council of Ministers.

Ostrom E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science **325:**419–422.

Overland J, Hanna EIH-B, Kim S-J, Walsh JE, Wang M, Bhatt US, Thoman RL. 2016. Surface air temperature. Arctic report card 2016. NOAA.

Pons P, Latapy M. 2005. Computing communities in large networks using random walks. Pages 284–293 in Yolum P, Güngör T, Gürgen F, Özturan C, editors. Proceedings of the 20th International Symposium on Computer and Information Sciences - ISCIS 2005. Springer, Berlin.

R Development Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Sachs J, et al. 2010. Monitoring the world's agriculture. Nature **466:**558.

Şekercioğlu ÇH. 2012. Promoting community-based bird monitoring in the tropics: conservation, research, environmental education, capacity-building, and local incomes. Biological Conservation **151:**69–73.

Silvertown J. 2009. A new dawn for citizen science. Trends in Ecology & Evolution **24:**467–471.

Stephenson SR, Smith LC, Agnew JA. 2011. Divergent long-term trajectories of human access to the Arctic. Nature Climate Change **1:**156–160.

Stewart EJ, Liggett D, Dawson J. 2017. The evolution of polar tourism scholarship: research themes, networks and agendas. Polar Geography **40:**59–84.

Teddlie C, Yu F. 2007. Mixed methods sample: a typology with methods. Journal of Mixed Methods Research **1:**77–100.

Tesar C, Dubois M-A, Shestakov A. 2016. Toward strategic, coherent, policy-relevant arctic science. Science **353:**1368–1370.

Tukey JW. 1980. We need both exploratory and confirmatory. The American Statistician **34:**23–25.

Tulloch AIT, Possingham HP, Joseph LN, Szabo J, Martin TG. 2013. Realising the full potential of citizen science monitoring programs. Biological Conservation **165:**128–138.

Tveraa T, Stien A, Brøseth H, Yoccoz NG. 2014. The role of predation and food limitation on claims for compensation, reindeer demography and population dynamics. Journal of Applied Ecology **51:**1264–1272.

UN. 2015. Transforming our world: the 2030 agenda for sustainable development. A/RES/70/1. UN, New York.

Vaismoradi M, Turunen H, Bondas T. 2013. Content analysis and thematic analysis: implications for conducting a qualitative descriptive study. Nursing & Health Sciences **15:**398–405.

Wanless S, Frederiksen M, Daunt F, Scott BE, Harris MP. 2007. Black-legged kittiwakes as indicators of environmental change in the North Sea: evidence from long-term studies. Progress in Oceanography **72:**30–38.

Wheeler HC, Berteaux D, Furgal C, Parlee B, Yoccoz NG, Grémillet D. 2016. Stakeholder perspectives on triage in wildlife monitoring in a rapidly changing Arctic. Frontiers in Ecology and Evolution **4:**128.

Wittman H, Chappell MJ, Abson DJ, Kerr RB, Blesh J, Hanspach J, Perfecto I, Fischer J. 2017. A social–ecological perspective on harmonizing food security and biodiversity conservation. Regional Environmental Change **17:**1291–1301.

Yang Z, Algesheimer R, Tessone CJ. 2016. A comparative analysis of community detection algorithms on artificial networks. Scientific Reports **6:**30750.

Yoccoz NG, Nichols JD, Boulinier T. 2001. Monitoring of biological diversity in space and time. Trends in Ecology & Evolution **16:**446–453.