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

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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 NGOs. 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 information driven or primarily information driven (e.g., detect change, make decisions, conserve or secure food) and process driven and derived outcomes (e.g., cooperate, learn, educate). The outcomes expand monitoring community and disseminate created connections between these modules. We identified key desired outcomes from monitoring that 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 future development of integrated monitoring goals for biodiversity conservation and human needs. Our results demonstrate the disconnect between information and process driven goals and how expanding the monitoring community and better

integrating monitoring stakeholders will help connect information derived and process derived outcomes for effective ecosystem stewardship.

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 programmes (Lindenmayer & Likens 2010; Tulloch et al. 2013). Thus, it is essential to design programmes that maximise 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 endeavour.

Monitoring programmes, particularly surveillance, have been criticised for lacking clear questions driving activities (Nichols & Williams 2006; Lindenmayer & Likens 2010). A call for hypothesis-driven monitoring has been made, where clear hypotheses and ecosystem conceptualisations are used to determine what, where, and how to monitor (Yoccoz et al. 2001). Many recent ecosystem-based monitoring programmes focus on determining causal relationships to increase ecological understanding, inform management decisions and evaluate their efficacy (Ims & Yoccoz, 2018).

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 recognised (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 and including meeting stakeholder needs. Higher-level frameworks are needed to maximise 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 (Fernandez-Gimenez et al. 2008; Latta & Faaborg 2009; 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 has 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 comprise networks of regional and local monitoring efforts, with diverse goals and approaches. The Circumpolar Biodiversity Monitoring programme (CMBP) 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 characterised as local and context-specific, adaptive and situated within people's lives, this knowledge can be transmitted orally and through practise (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 increase slightly (Brunet et al. 2014). Accordingly, within many arctic monitoring organisations 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 both biodiversity and people, and the structure of inter-relationships between desired outcomes, we analysed 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

Semi-structured interviews

We conducted one-on-one semi-structured (Gubrium 2012) interviews with 29 arctic scientists, policy and decision makers and representatives of Indigenous organisations and NGOs to determine desirable outcomes of monitoring. We selected participants from attendees at international, Arctic Council working group and expert network meetings and subsequent snowball sampling (Teddlie & Yu 2007). We focused on people or organisations: 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 between those involved in policy and decision-making, science and 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.

Prior to the semi-structured 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 semi-structured 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 and defined these as: 'any positive effects on people and society, the environment or academia both in and outside the Arctic', and put more simply '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 semi-structured, allowing us to prompt for further information or clarify the meaning of participant statements with non-leading questions, this normally involved repeating participant's 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 categorised our themes according to these characteristics: desired outcomes that were driven by information, were derived from the process of monitoring, or were a combination of the two. 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 finalise 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, Australia) 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, these 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.

Next, we performed cluster analysis to identify highly connected groups of themes (herein refered 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. As two 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 focus here on results from the walktrap algorithm, reflecting this was the only algorithm that allowed hierarchical detection of communities, enabling 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 applied a further community detection algorithm, which assigned links rather than nodes to modules (Ahn et al. 2010). This allows quantification of the extent to which each node belongs to each edge community, allowing shared ownership of nodes between modules and allowing nodes connecting different modules to be identified. All analyses were performed in R version 3.1.1

(R Development Core Team 2016) using packages linkcomm (Kalinka & Tomancak 2011) and igraph (Csardi & Nepusz 2006). The study was carried out under the approval of Trent University Research Ethics Board and Aboriginal Ethics Committee, file #24118. All participants gave written informed consent to their participation in accordance with the Declaration of Helsinki and permission to be named both in general and for specific quotes.

Results

We identified 18 core perceived desirable outcomes of wildlife monitoring (each defined in Table 1, mean ± SE desirable outcomes per participant: 10.7±0.6). These were linked by 44 unique cause-effect links between desired outcomes (Fig. 1, mean links per participant: 4.8±0.5). Of our 18 desired outcomes, we identified seven desired outcomes derived primarily from the information produced from monitoring (e.g. record status), four derived primarily from the process of monitoring (e.g. expand community) and seven 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 (Supporting Information).

The most direct outcomes of monitoring were two information driven outcomes: record status and detect change (Fig. 1, Table 1). In addition, the four 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 five most commonly cited themes were make decisions (n=28, 97% of participants), detect change (n=26) and conserve (n=25) followed by 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, these outcomes were still identified by 17-24% of participants.

Community detection across nodes revealed three district modules within our desired outcomes of monitoring (Fig. 2a). At the highest order of separation, was one set of desired outcomes containing all process-driven outcomes and govern and learn, and another set, which contained information-driven outcomes and the remaining combined (process and information-driven) outcomes (referred to herein 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 link 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 three 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 second division within the information-module separated two desired outcomes (identify system linkages and inform research and monitoring, Fig. 2a, b), however these outcomes were characterised by low connectivity (Fig. 2c). Detect change and make decisions were highly connected both within their own module and to other modules, while 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. While 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 two 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 five 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 & 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). Historical conservation only approaches, which view the Arctic as a wilderness and remove conservation activities from human needs, have been criticised, given >4 million people inhabit the Arctic (Larsen, Fondahl & Schweitzer 2010) and decision making driven from outside the Arctic was described by one interview 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 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 if 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

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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 organisational 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 the defining scope, pertinent questions and decisions to inform and foci of hypothesis testing or confirmatory research (Tukey 1980) and may help examine possible futures (Cook et al. 2014; Ims & Yoccoz 2018).

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 ability to test hypotheses, discriminate between 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 often 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). As the Arctic is viewed as an opportunity for development, increasing conflicts are seen between energy extraction, predator conservation and local practises 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 multiple contexts related to both 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, one seabird scientist noted: “I mean, 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 focussing 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 (Fig. 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). Co-management and co-production 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 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 link strongly back to 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 organisations are involved in decision-making through wildlife management boards (Armitage et al. 2011), while 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 organisations participate in Arctic 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 organisations, 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, our analysis 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' organisations (Bruun & Medby 2014). A number of supranational institutions work to promote discussion of arctic monitoring (e.g. the Arctic Council, the 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 two-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 they may have greater influence over discourse. Forbes and Stammler (2009) highlight that Indigenous participation in environmental research has been dominated by participation from communities in North America and that this generates focus on certain compartmentalised research paradigms (climate change, wildlife management and Indigenous knowledge) which may be less relevant to Indigenous peoples of Russia. While we worked to maximise representation across stakeholder groups and nations, these broader differences in representation will ultimately affect the discourses to which our 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 towards scientific discourses. Continued efforts to expand and diversify the monitoring community is likely to be mechanism to counter these biases.

Conclusions

We highlight a spectrum of desired outcomes from wildlife monitoring in the Arctic, and perceived interlinkages within a network of outcomes (Table 1, Fig. 1). 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. Expanding participation, local capacity-building, and improving governance structures to help strengthen links from local and wider learning to decision-making and stewardship, may improve integration between process and information related pathways. 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 is expanding to involve 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 towards these desired outcomes.

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Table 1. Summary of desired outcomes of monitoring identified from semi-structured interviews of stakeholders in pan arctic wildlife monitoring (focus on seabirds and terrestrial vertebrates).

Desirable outcome	Brief 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 and/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. can also 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 datasets 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 and/or recording or analysing 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)*
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)*
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 non-intervention 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 behaviours related to knowledge and skills, includes 'generating engagement' or 'influencing attitudes' towards issues relevant to arctic change.
govern	create effective accountable and inclusive institutions that provide justice (SDG 16)*
secure food	provide food security (access, availability, effective utilisation and stability of food to meet dietary needs and food preferences (nilsson et al 2015) and sovereignty (culturally appropriate and healthy foods), includes opportunities to hunt and harvest local wildlife (SDG 2)*
conserve	protect, restore or sustainably use ecosystems and their components. maintain biodiversity (SDG 14 and 15)*
support economic futures	ensure sustainable industry and economic activity (SDG 7, 8, 9 and 12)*

*Where themes link to sustainable development goals (UN 2015) these are provided in the definition in brackets (e.g. SDG 1).

Figure 1

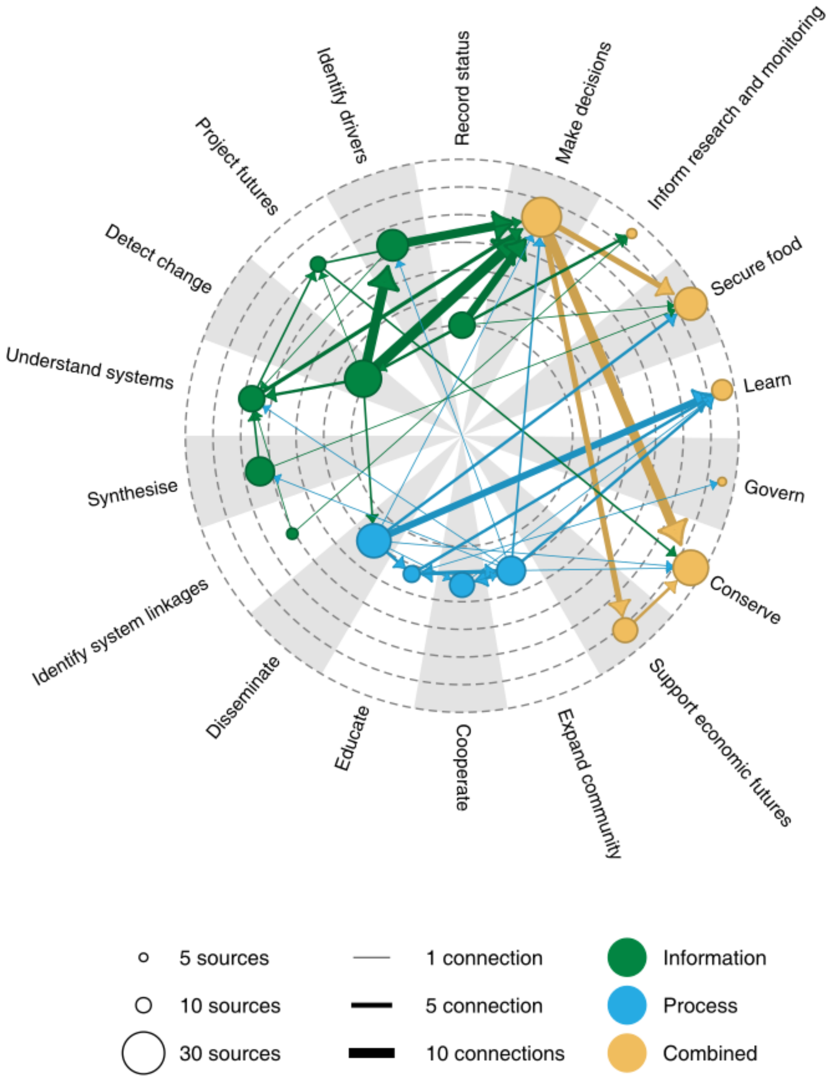

Figure 1. Network diagram of the desirable impacts of monitoring as identified by 29 stakeholders in arctic monitoring. Nodes represent primarily monitoring information-driven themes (“Information”), primarily monitoring process-driven themes (“Process”) and themes that are a combination of information- and process-driven themes (“Combined”). 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, with most central nodes representing more direct impacts from monitoring. Node size represents the number of individuals identifying each theme (between 5 and

28). Arrows and their width represent the number of participants making cause-effect association between particular themes, arrows are coloured according to the originating group of each link.

Figure 2

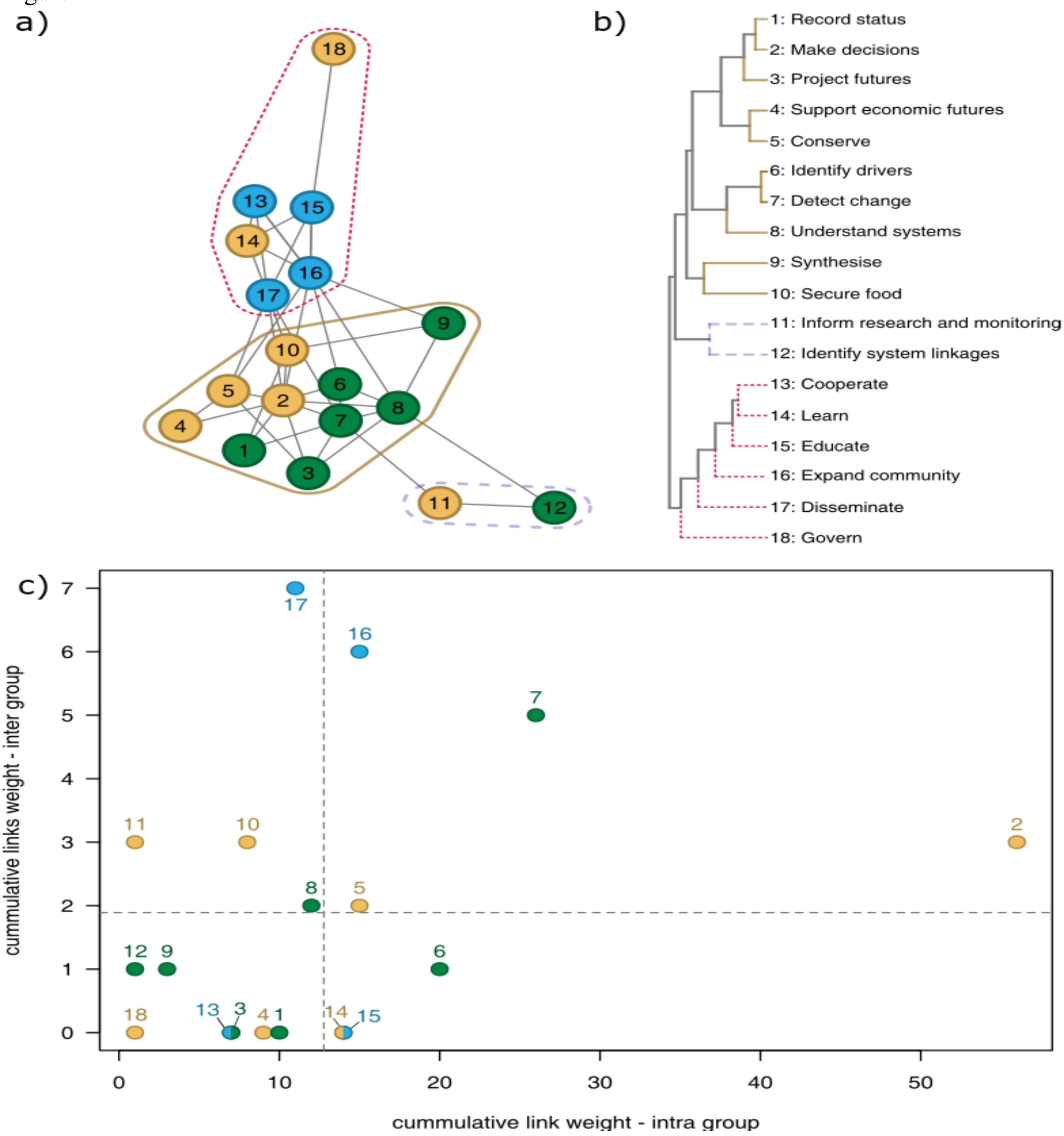

Figure 2. Summary of the distinct theme modules within the network of desirable impacts of monitoring as identified by cluster analysis with a walktrap algorithm: (a) modules with the network, b) a dendrogram showing hierarchical separation of modules, c) cumulative weights of intra- and inter-group connections for each node. The "process-module" containing mainly process-driven

outcomes and combined outcomes ("Learn" and "Govern") is contained in the top left cloud in the network diagram (nodes 13-18). The "information-module" containing mainly information-driven outcomes and all other combined outcomes comprises two sub-modules in the two right clouds (nodes 1-12). Desired outcome nodes are coloured according to their theme type; primarily monitoring information-driven themes ("Information"), primarily monitoring process-driven themes ("Process") and themes that are a combination of information- and process-driven ("Combined"). The same colour-coding 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 the nodes most connected to the alternative module. In c, dashed lines represent mean intra and inter-module link weight across nodes.

Figure 3

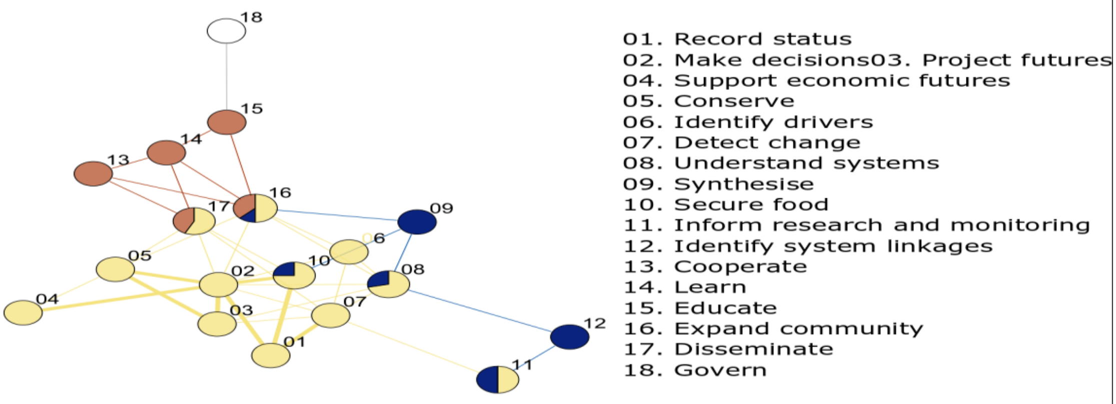

Figure 3. Network diagram showing edge communities and contribution of edges from each community to node themes. Each edge community is shown in a different colour and edge widths

represent the number of individuals making each connection. The edge linking nodes 15 and 18 is not attributed to a community given it's 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.