Resilient socio-ecological systems

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Research Need 3.
Resilient socio-ecological systems

1. Introduction

Understanding the changes in structure, functioning, and biodiversity of polar ecosystems in the Arctic and Antarctic poses some common challenges. Both Polar Regions are hard to access and difficult to study because of their remoteness and scant infrastructure. Long-term observational systems, necessary for better future predictions, are mainly operated within the more accessible geographical sites, sectors, and ecoregions, such as the Bering and Barents Sea in the Arctic and the West Antarctic Peninsula Region in Antarctica. Lack of baseline knowledge of broad scale variations of drivers and the dynamic responses of species and biological communities (i.e., spatial ecology) poses significant constraints on detecting and evaluating climate-induced ecosystem changes, or assessing the cumulative impacts of multiple drivers.

In the Arctic, the permanent residents are directly affected and need to adapt to the consequences of a changing climate. Although the majority of Arctic residents in northern Europe inhabit modern cities, they strongly rely on services provided by ecosystems and are culturally deeply rooted in their local environment. Studying climate change impacts in a socio-ecological context is therefore pivotal. Integrating science with local and traditional knowledge and observation systems, and including a diversity of perceptions and values to set priorities for monitoring socio-ecological changes, can provide a better understanding of the complex interlinkages between ecosystems and society at different levels.

Antarctica, although now exclusively dedicated to science and environmentally protected, has received major human impacts from sealing, whaling industries, and, to a lesser degree, from the fishing industry, all powered by industrialisation in the nineteenth and early twentieth century. Especially the impact of fishing on the highly specialised and unique Southern Ocean marine ecosystems and Antarctic food webs continues today, and continued monitoring is essential to assess ecological consequences. These impacts on the marine and coastal Antarctic ecosystems are regulated by the Convention for the Conservation of Antarctic Seals (CCAS), the International Whaling Commission (IWC), and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). In addition, coastal Antarctic ecosystems are under the jurisdiction of the Antarctic Treaty Consultative Meeting´s Committee for Environmental Protection (CEP).

Ultimately, past, and present human interferences shape ecosystem structure and functioning in both Polar Regions and need to be accounted for in past, present and future biodiversity assessments and analyses of spatial ecology to guide conservation measures.

The concept of socio-ecological systems (SES) conveys that human societies cannot be understood as separate from polar ecosystems, but are active agents of ecosystem change, which feeds back directly or indirectly to the people depending on these ecosystems. Global connectedness also increasingly influences polar systems and changes the local socio-ecological dynamics. Resilience, i.e. the ability of the systems to absorb and cope with these changes, the vulnerability of social groups or communities exposed to “surprising” changes, extreme events, and unexpected stressors (Pershing, et al. 2019), and their adaptive capacity to respond to such changes, are inherent to the SES concept. Rapidly changing climate and weather conditions and increasing regional and global impacts necessitate more than projections and predictions of trends in polar areas, and instead call for scenario models that can envision both plausible and desired futures. Ecosystem-based management of SES also needs to consider the multiple values, diverse knowledge systems and complex interactions between local and global interests as the Arctic is changing. In the Antarctic, the grade of accomplishment of existing conservation measures needs to be revised and updated in the face of climate change and increasing human pressure on marine and terrestrial ecosystems, and of the changed global geopolitics.

Photo: Ronald JW Visser

Figure 6. Resilience and vulnerability of socio-ecological systems (SES).

From an ecological perspective, the major differences between both Polar Regions relate to the long-lasting biogeographical isolation of Antarctica and its extremely cold climate. Whilst Antarctic terrestrial biotas are highly endemic and predominantly consist of a few dominant groups of lower plants and invertebrate fauna, a higher marine biodiversity is attributed to the genetic isolation of the Southern Ocean marine communities. Long-term isolation of both marine and terrestrial biotas in an extreme cold environment has fostered adaptive changes of molecular, structural and physiological capacities, leading to the evolution of highly specialised organisms that form large populations in the Antarctic (e.g. krill), but are also highly sensitive to the vagaries of environmental variability and change. With several important groups not well represented (e.g. fish) or entirely missing in freshwater bodies, Antarctic marine ecosystems and food webs are highly specialised to meet the environmental conditions and constraints caused by permanent or seasonal ice cover. Their response to climate change needs further investigation, from organismal to community and to ecosystem level, and with respect to connected ecosystem services. The large Antarctic krill swarms, and the seabirds, whales and seals depending on them, are good examples that show the response to change of sea ice dependent communities. Under pressure from climate change and the target of a major Antarctic fishery, krill accelerates carbon draw down to the deep ocean, sustains large populations of charismatic top-predators and, hence, provide provisional, regulatory, and cultural ecosystem services. These are massively at stake if climate warming continues unabated (Further reading: Bennett, et al. 2015; Rogers, et al. 2019).

On the contrary, the stronger connectivity between the Arctic and boreal regions combined with a much younger ecosystem means that there are generally fewer endemic species in the Arctic compared to the Antarctic. The connectivity to lower latitudes also enables poleward migrations and range shifts of temperate species and lowers physical barriers for dispersal of non-native species (NNS), including pathogens. The ecosystems in the Arctic have also been exposed to multiple waves of resource exploitation in the past that have impacted the communities. Extended ice and snow free periods alter light availability that lead to substantial shifts in productivity and phenology and alter ecosystem structure and food webs. For example, the loss of sea ice has been estimated to increase ocean productivity in some regions, and expansion of Atlantic water into the Arctic has driven range expansion of several temperate commercial fish stocks.

Photo: Ronald JW Visser

Photo: Ronald JW Visser

Research Need 3.2. Human footprint in the Arctic and Antarctic

A major difference between both Polar Regions is linked to the historical human colonisation and the accelerating societal development and urbanisation of the Arctic.

Humans have relied on living resources in the Arctic for thousands of years, and substantial impacts upon the ecosystem started at least 400 years ago when European whalers decimated populations of several Arctic marine mammals, which have never recovered. Commercial fisheries in the Arctic are substantial. They contribute about 10% to the global catch and are concentrated in the Bering Sea, Norwegian Sea, Barents Sea, and the West Greenland shelf. Examples of local overfishing of commercial stocks started in the 1970s, and extensive trawling has undoubtedly resulted in expansive changes, especially in benthic biodiversity. In recent decades, an increasing number of studies have documented how temperate flora and fauna are expanding north. Similarly, melting of sea ice provides access to new areas for fisheries. The Central Arctic Ocean Fisheries agreement has been promoted as an example of precautionary ecosystem-based management. It prevents the signatory Parties to engage in unregulated commercial fishing in the high seas of the Central Arctic Ocean for a specified duration of time. In addition, the increased fishing activity further north of the EEZ and the pressures of multiple human activities impacting the coastal socio-ecological systems have been studied only to a limited degree. The terrestrial ecosystems also lack general baseline data due to lack of monitoring in these areas.

Photo: Ronald JW Visser

In contrast, the remoteness and the absence of native human populations in Antarctica has until recently minimised direct human impact on the continent. However, human presence in form of the Antarctic fishing industry, tourism industry, and national scientific and logistic activities is increasing with potentially negative consequence for Antarctic ecosystems. For example, ship traffic has increased by 5-10 times since the 1960s, commercial visitor numbers having increased to ca. 60,000 tourists annually, and the continent now supports over 100 research stations, camps, and runways. These activities may increase local pollution, disturbance of wildlife and the risk of non-native species (NNS) introductions to marine and terrestrial environments. At present, the great majority of Antarctic human footprint, in the form of tourist visitor sites and research stations, is concentrated on ca. 6,000 km^2 of ice-free land near the coast, and in particular around the Antarctic Peninsula, as this affords ready access by ship. However, this same area supports much of Antarctica's terrestrial vegetation, as well as seabird colonies and seal haul out sites, which have in some cases been destroyed or displaced in locations where human activities have taken priority. Contrary, although krill *(Euphausia superba)* and the Antarctic toothfish *(Dissostichus mawsoni)* are the largest ongoing fishery in the Antarctic, their catch limits are strictly controlled by CCAMLR.

One of the greatest threats to Antarctic marine and terrestrial environments is in the introduction of NNS (McCarthy, et al. 2019; Hughes, et al. 2020). Within short reach from South America, the West Antarctic Peninsula (WAP) is receiving 99% of the Antarctic tourism and the major part of logistic support travel for the land stations operated here. In addition to trampling and littering the environment, humans visiting Antarctic coastal areas facilitate introduction of NNS. Most of the introduced organisms are still not able to survive under Antarctic environmental conditions. However, as terrestrial and ocean temperatures warm, migration of organisms and exchange of larvae and algal propagules between South America and the WAP becomes more likely. In the Arctic region 34 non-native marine species have been introduced since 1960 (Chan, et al. 2019), a low number compared to other regions in the world, but high compared to the Antarctic.

2. Societal Relevance

The research proposed here addresses knowledge gaps in the understanding of ecosystems and the services they provide, and illustrates their importance for human health, well-being, community identity and culture, quality of life, and subsistence economies. The polar ecosystems are an important element in the cultural heritage of Indigenous as well as non-Indigenous Arctic communities. Their well-being strongly relies on the ecosystem for subsistence hunting and for food and water security, especially in rural regions. The strong interlinkage between ecosystems and human communities creates specific demands with respect to ecosystem conservation and management that sets the baseline to support Arctic societies in finding their ways to cope with climate change and globalisation in the Polar Regions (Figure 6).

The term "One Health" (OH, see also KQ 3.2) describes a multidisciplinary approach to health risks in humans, animals, plants, and the environment. It considers traditional and local knowledge and uses the experience to identify and respond to health issues.

In order to understand how changes in the terrestrial and marine ecosystems in the Arctic and the Antarctic are influencing the socio-ecological system at local, regional and global scale, we need to understand the structure and functioning of the polar ecosystems, more clearly identify the hierarchy of drivers and stressors, and determine how they influence the ecosystems. In doing so we can better understand the relations between ecosystems on the one hand and human health and well-being on the other, and infer how ecosystem change impinges on the socio-ecological system.

With this knowledge, we can address societal challenges like:

- Protecting the fragile marine and terrestrial polar ecosystems by developing proper management tools.
- Assessing the main health risks for human and animal populations in the changing polar environment.
- Improving the quality of life in rural and urban Arctic communities and including its multidisciplinary integration into the OH concept to address changing polar socio-ecological systems.

3. Research Questions

Key Question 3.1. Understanding key issues of polar ecosystem structure, functioning, and change

Climate change and increasing human pressure at a global scale cause rapid and irreversible changes of ecosystem structure and functioning in both Polar Regions. Warming of the Arctic and Antarctic results in melting of their ice sheets, thawing of permafrost layers, loss of sea ice, and glacier retreat. This leads to shifts or loss of habitat for polar species and complex impacts on biogeochemical cycles, biodiversity, ecosystem structure, as well as productivity and carbon cycling (ecosystem function). In addition, pollutants from local and distant sources are taken up by organisms and incorporated into polar food webs, with the highest concentrations building up in the apex predators. Warming allows temperate species to move and expand their dispersal ranges toward the poles, where they compete with native polar biotas. Furthermore, human shipping and visiting activities on land increase the risk of introducing invasive non-native species (NNS) and disease vectors. Thus, polar ecosystems are exposed to a multitude of forcing factors, from general large-scale drivers that affect entire Polar Regions, to more specific processes acting at local scale, including changes in the physical environment, ocean acidification, changing coastal matter fluxes, reduced oxygen availability, extraction of living and non-living resources, and arrival of new pathogens that may threaten the wildlife, human beings and livestock. Combined, these drivers create a mosaic of multiple and mutually reinforcing anthropogenic stressors

Photo: Doris Abele

Figure 7. Layers of dying krill beaching on King-George Island, West Antarctica. The krill has been exposed to glacial melting and dead animals had ingested sediments from subglacial in the coastal environment erosion (Fuentes, et al. 2016). *Photo: Doris Abele.*

acting on the unique and highly vulnerable polar ecosystems. To improve our capability to quantify and predict changes in polar ecosystem structure and functioning in response to macro-scale and local drivers, and to allow timely adaptation to, and mitigation of disturbances, we must improve our capacities to analyse and quantify changes in polar ecosystems, and further our understanding of the combination of stressors that drive these changes. Goals should include:

- To develop standardised biological baselines for the biodiversity and ecosystem structure of polar ecosystems and develop suitable indicators and observing programmes to monitor health and rates of ecosystem change, and
- To obtain better understanding of major drivers across geographic regions/sectors and improved process understanding of the resulting changes in polar ecosystems and across different habitats, including the cumulative effects of multiple drivers.

Development of coordinated circumpolar observation systems combined with other initiatives such as the Distributed Biological Observatory[9] or the Synoptic Arctic Survey[10], including data on both environmental drivers and ecosystem responses, is essential to support this research. Ecosystem change research must include knowledge derived from biogeochemical and biological archives and take into account the evolutionary history and adaptive capacities of polar species to allow projections into the future, and facilitate the development of standardised indicators and methods for Arctic and Antarctic ecosystem analysis. Importantly, we also need to improve methods for ranking stressor impacts and determine their combined impact across different ecological subsystems (habitats). Further knowledge gaps exist with respect to the regional hotspots and essential habitats[11] targeted by the anticipated impact. Hence, indicators need to be tested at different hierarchical levels and for different levels of complexity: from individual performance traits and markers for stress sensitivity/resilience, to community composition and structure, including migrating and introduced organisms, and demographic/ evolutionary traits of key species. Definition of desired ecosystem states and the development of management tools for impact mitigation and conservation in the future requires further advances in our understanding of how societies interact and respond to ecosystem changes. Participatory approaches require the inclusion of local and traditional knowledge in terms of provision of datasets and of an alternative understanding of the causality chain.

[9] https://www.pmel.noaa.gov/dbo/

[10] https://synopticarcticsurvey.w.uib.no/

[11] Essential habitats: important feeding or fishing/hunting grounds or other habitats of specific importance.

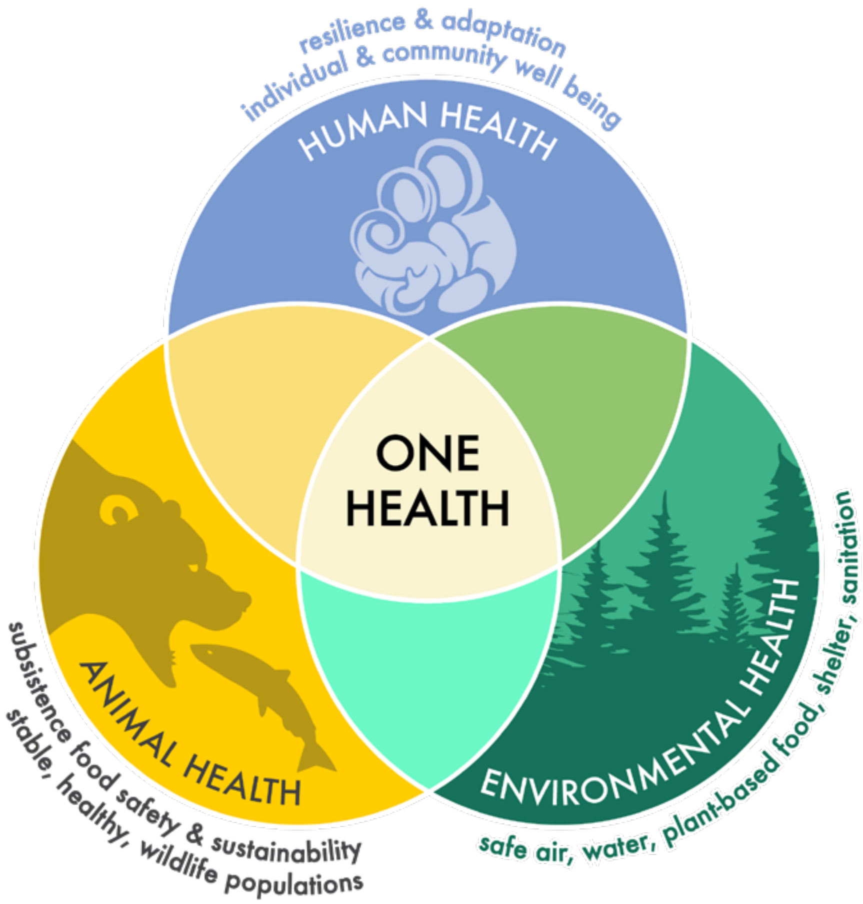

Figure 8. One-health concept based on Center of One Health Research (University of Alaska Fairbanks), which shows the different disciplines used to define it.

Key Question 3.2.
Designing a healthy socio-ecological system

Without a healthy ecosystem that maintains its intrinsic biodiversity, there is no human health (Figure 8). One Health (OH) is a concept that incorporates all atmospheric, terrestrial, and marine ecosystems, and all the life forms that inhabit them, including humans. It is the essence of traditional knowledge and since the beginning of evolutionary biology in the midst of 1800s, it has been a concept receiving acceptance particularly when faced with complex challenges such as climate warming, global migrations, infectious disease spread, and worldwide dispersal of contaminants by atmospheric cold condensation or oceanic transport. The dynamic processes, characterising ecosystems in constant change, demand efficient monitoring and surveillance across borders. Species facing climate change may go locally extinct and move poleward, or shift distribution range to higher elevations or into the deep ocean regions, and bring with them zoonotic infections that endanger other susceptible species and humans. Food and water security are at risk. With the increasing risk of cultural ruptures due to ecosystem changes, psychological stress and mental health problems are already affecting especially the Indigenous populations of the Arctic. The identity of Indigenous Peoples is strongly connected with well-being and good quality of life, turning culture into a proper tool to be used in health care to inspire mental wellness (RN 4). Increasing urbanisation, the importance of mass-media, especially social networks, the lack of wage-earning jobs, as well as intensified import of goods (including alcohol and drugs) exert additional pressures on local cultures, social structures and hierarchies adding to the stress for the inhabitants of human settlements and cities.

In the OH model the focus is on the link between healthy and productive ecosystems, biodiversity and human well-being and health, which is not so much used in all parts of the Arctic. The involvement of the local population in the monitoring, as an integrated part of ecosystems, is an essential element of the OH model. There is a growing need for education on different levels, from educational systems to the general public. Communication with decision makers as well as with the populations at large, including the business part of societies, is becoming increasingly important and necessary and should be emphasised in the approach, tasks, and deliverables of research consortia.

Photo: Anna Karin Landin

Key Question 3.3. Expanding observation of socio-ecological systems

A primary challenge in polar systems consists in obtaining sufficient spatial coverage of quality controlled environmental and ecological data and knowledge that allows for process analysis of the dynamic changes in socio-ecological systems. There is a particular need to create observation systems that can effectively track changes of relevance to the sustainable development goals for the Post 2020 Biodiversity framework, and for enhancing adaptive capacity and resilience, reducing vulnerability, and contributing to sustainable development with respect to the Paris Agreement.

This requires improved and consistent sampling strategies of sufficient spatial coverage and temporal resolution, both in physical and biological parameters, in support of polar ecosystem modelling. This is becoming more important, since Polar Regions as terminal areas for the deposition of many historical and emerging pollutants, lay the cornerstone for monitoring and for assessing the effectiveness of regulatory measures within and outside the Polar Regions. Integrated approaches for environmental measurements and the analysis of the polar biota, the community structure, and species interactions need to be further developed. Advanced technological and analytical solutions are required for automated observation and repeated surveys of environmental and biological parameters in ice-covered and inaccessible environments. More generally, bio-logging and omic-based technologies are relevant tools to identify key habitats and pollutant hotspots, evaluate impact of human activities (fisheries, shipping routes) on biodiversity, and set-up protected areas. Enhanced spatial coverage is also required in polar socio-ecological system research for future predictions of human well-being, living conditions, and Polar community health (e.g., scattered data from field stations provide insufficient basis for terrestrial observation).

In addition, generic information systems are required for improved data management and accessibility, including visualisation of data and statistical requests in space and time for prompt recognition of research gaps and trends (RN 6).

Integration of ecosystem change analysis with the economy, social sciences and humanities is still weak. An additional major challenge is, therefore, in understanding the connectivity between ecosystem and societal change, including feedback loops of human interventions on the dynamics of polar socio-ecological systems at multiple levels. In this context, the collection and storage of human data also pose additional questions of ethics and security.

Photo: Henning Lorenz

Key Question 3.4. Ecosystem-based management, governance and transformative solutions toward a sustainable future

The widespread and accelerating changes taking place in polar ecosystems, their biodiversity and ecosystem services, embody fundamental challenges that ecosystem-based management and governance need to prepare for. In the search for ecosystem-based approaches that can manage resources and ecosystems sustainably, a diverse set of tools have been developed that can potentially address the complex interactions between ecosystems and society.

There are significant advances in developing management tools that enable us to implement ecosystem-based management (cumulative impact assessments, spatial planning, zoning, protected areas, etc.). The challenge is that these tools lack baseline data and constant observations. Furthermore, as the demand for ecosystem goods and services is increasing as polar ecosystems become more accessible, ecosystems functioning may be adversely affected by expansion of human interventions and interaction with the natural environment.

Managing the underlying drivers that are influencing the complex dynamic systems, including the current mismatch between social systems and ecosystem dynamics on multiple scales, requires coordinated governance regimes at the highest possible levels that can effectively respond to changes, despite uncertainties, by using precautionary approaches and science diplomacy.

Science can provide some support through innovative solutions for understanding the future sustainable pathways by drawing on information from the past, and by using scenario methodologies to predict, explore and to co-create desired sustainable futures with stakeholders holding diverse values and knowledge. However, enhancing resilience and creating sustainable futures is also more fundamentally about governance and collaboration between science, governments, civil societies, and markets to address future challenges. Implementing ecosystem-based governance, irrespective of political and other borders, requires the current powerholders to value and support ecosystem-based governance, even if it creates debates and conflicts about the required trade-offs.

Photo: Diane Erceg

A key challenge in the coming decades will also be related to transforming to a currently unknown future state of ecosystems and socio-ecological systems in the Arctic and Antarctic. Scenario approaches can help to build capacities to prepare for alternative plausible futures either by use of qualitative, story-telling approaches or through predictive modelling. The key to transforming societies to embrace sustainable management pathways requires partnership between governments, civil society, and businesses. For the Arctic, a constructive way of working with Indigenous and local people through co-design and co-production of knowledge can help building transformative solutions that are perceived as positive, constructive, and socially and culturally acceptable. Transformative changes also demand a multi-level perspective, including capacity building and recognising these capacities as legitimate for Arctic communities to act as an active agent for changing their own future. Developing integrated, adaptive, informed, and inclusive approaches for responding to these future ecological and societal changes is a major challenge for the coming decades. The key question is therefore: how can we transform to create sustainable pathways for the future?

4. Resource Requirements

In order to investigate the changes of socio-ecological polar ecosystems and the implications of these, there is an urgent need for:

- Improving the baseline knowledge of biodiversity and ecosystem functioning in Polar Regions at all levels of complexity, from microbes to plants and animals, to homogenise data across time and space and achieve better connection between marine, terrestrial, biological and atmospheric ecosystem facets, and social sciences. This will strengthen participation of communities and interest groups and their involvement in study design of major research activities to secure existing long-term biological surveys and demographic studies as well, and
- Advances in modelling and molecular techniques need to link broad-scale effects of drivers in socio-ecological systems to predict consequences for society and the natural environment at multiple scales. This will advance interdisciplinary and collaborative analyses of marine and terrestrial systems. The outcome will create plausible future trajectories of socio-ecological systems that allow for effective adaptation and decision-making.

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