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Persistent and emerging threats to Arctic biodiversity and ways to overcome them: a horizon scan

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Abstract

Arctic biodiversity is under threat from both climate-induced environmental change and anthropogenic activity. However, the rapid rate of change and the challenging conditions for studying Arctic environments mean that many research questions must be answered before we can strategically allocate resources for management. Addressing threats to biodiversity in the Arctic is further complicated by the region's complex geopolitics, as eight countries claim jurisdiction over the area, with multiple local considerations such as Indigenous sovereignty and resource rights. Here, we identify research priorities to serve as a starting point for addressing the most pressing threats to Arctic biodiversity. We began by collecting pressing research questions about Arctic biodiversity, thematizing them as either threats or actions, and then categorizing them further into 18 groups. Then, drawing on cross-disciplinary and global expertise of professionals in Arctic science, management, and policy, we considered the barriers to answering these questions and proposed potential solutions that could be implemented if barriers were overcome. Overall, our horizon scan provides an expert assessment of threats (e.g., species' responses to climate change) and actions (e.g., a lack of fundamental information regarding Arctic biodiversity) needing attention and is intended to guide future conservation action within the Arctic.

Key words: conservation, barriers, foresight, policy, management, climate change

1. Introduction

While often considered remote, the Arctic plays a large role in the functioning of many global environmental systems (Post et al. 2019; Timmermans and Marshall 2020). In particular, the Arctic is involved with the regulation of global climate (McGuire et al. 2006) with important implications for the ongoing climate crisis (Díaz et al. 2019). While the Arctic may hold less biodiversity than other biomes, this biome's biodiversity is unique in that it includes more than 21 000 known species of fungi, plants, and animals that are highly adapted to life in the cold and in some cases could not survive without it (see Fig. 1; Callaghan et al. 2004; Payer et al. 2013; Ruth et al. 2023). These adaptations come in many forms. For example, Arctic plants and microorganisms have traits that make them tolerant to freezing, and Arctic animals have developed various mechanisms such as fat storage that allow them to tolerate frigid temperatures (Callaghan et al. 2004; Guerrero and Rogers 2019). On a global scale, the Arctic is

Fig. 1. An example of the diversity of lichen and moss found throughout the Arctic. Photo by TAL taken in Resolute, Nunavut, August 2022.

home to 27% of the world's marine mammal species (Payer et al. 2013) and more than 20% of the world's lichenicolous fungi species (i.e., fungi that live on lichens; Dahlberg and Bültmann 2013; Payer et al. 2013). The Arctic also provides habitat for hundreds of species of birds that migrate to the Arctic from around the globe to breed and forage (Sullender 2019). There is even diversity within Arctic sea ice where numerous bacteria, viruses, algae, and sea ice infauna (e.g., ciliates, nematodes, turbellarians, crustaceans) reside (Bluhm et al. 2011; Patrohay et al. 2022).

Biodiversity is the variation that occurs throughout all life on Earth. For the context of our work, we defined biodiversity as having three forms, based on the definition of the Convention of Biological Diversity (CBD): genetic diversity (the genetic diversity within species), species diversity (the number of different species and their abundances), and ecosystem diversity (the diversity of habitats across space and time; CBD 2000). Biodiversity is essential for the proper functioning and productivity of ecosystems as it enables ecosystems to withstand change through building resilience (Tilman 1999; Cardinale et al. 2012). Biodiversity also supports the food security, livelihoods, well-being, and cultures of many people, in particular communities with longstanding residence in the Arctic, including Indigenous Peoples (e.g., the Inuit in Canada, Russia, Alaska, and Greenland, the Sámi in the Sápmi area of northern Europe, and many others; Mustonen and Ford 2013). Despite this importance, these ecosystem services are at risk due to environmental change (Nuttall 2007).

The fragmentary nature of information on Arctic biodiversity is especially concerning considering how quickly the Arctic is changing. Significant knowledge gaps exist in relation to Arctic biodiversity (CAFF 2013*a*) as its relative remoteness and harsh conditions create inherent challenges such as high costs for conducting research (Mallory et al. 2018). Additionally, the Arctic is warming as a result of climate change at a much faster rate than most of the globe (AMAP 2021; Rantanen et al. 2022). The last decade has also seen rapid development of extractive resource sectors (e.g., mining; Bartsch et al. 2021), commercial fishing (Fauchald et al. 2021), shipping and port development (Dawson et al. 2018), tourism (Runge et al. 2020), and military activity (Depledge and Kennedy-Pipe 2018). Given these issues and the importance of Arctic biodiversity to people and the planet, it is paramount to understand how threats will impact Arctic biodiversity. Doing so will not only help to understand and predict threats but also help identify effective mitigation and management strategies.

Identifying future threats can be accomplished through horizon scanning, a forward-looking process that often consolidates advice, in the form of research questions to be answered, from experts in a field (Sutherland and Woodroof 2009; Cuhls 2019). These scans provide insight on their focal topic to help guide future research and inform subsequent decision-making (Cuhls 2019; Wintle et al. 2020). We therefore conducted a horizon scan to address the following questions:

1. What are the most significant questions regarding persistent (i.e., non-novel) and emerging (i.e., new and (or) existing but being exacerbated) threats facing biodiversity

in the Arctic that, if addressed, would inform policy and management?
2. What barriers exist to obtaining answers to these questions, how can these barriers be overcome, and what actions could be taken if these barriers were overcome?

It was our expectation that this horizon scan would identify the greatest threats to Arctic biodiversity, reveal research priorities, provide insight into how these research priorities could be addressed, and inspire implementation of corresponding policies for threat management.

2. Methods

Following the methodology of Sutherland et al. (2011), we conducted a horizon scan to combine expert opinion and evidence to identify persistent and emerging threats related to Arctic biodiversity conservation. The process was structured in two key steps: an elicitation of expert knowledge through a "call for questions" from Arctic experts to identify persistent and emerging threats facing Arctic biodiversity, and an online workshop to identify the barriers to addressing those threats, ways to overcome them, and solutions that could be implemented if those barriers were overcome.

To begin, in October 2023, we used a search string of "Arctic AND biodiversity" in Web of Science Core Collection (Clarivate Plc, Philadelphia, PA) to identify appropriate publications and export a list of author information (including email addresses) to solicit a cross-disciplinary global network of Arctic experts (hereafter referred to as respondents). We also collected email addresses of organizations working throughout the Arctic (e.g., the Nunavut Research Institute, The Arctic Institute, etc.). We then created a "call for research questions" using an online form (Google Forms, Google LLC, Mountain View, CA; see "Form for Call for Questions" in supplementary information) that we sent to the 7150 email addresses collected. Respondents were asked to forward the request for questions to other Arctic experts (i.e., snowball sampling; Vogt and Johnson 2024). The call was also shared on many of the core authors' (TAL, JDRC, ALH, MLL, SKS, KMS, JP, SJC) personal social media accounts with sharing features enabled to reach larger networks. The call was also distributed by the Polar Continental Shelf Program to all the Arctic researchers they support. Emails and social media blasts were distributed between 4 and 25 October 2023 with initial notices for the call for questions being posted within the first week, and reminder notices being sent 2 weeks later.

As in Harper et al. (2021), no limitations were placed on the number of times the call for questions was shared to amplify the number of potential questions and participants. To this end, the total number of individuals who received the request is unknown. To help streamline information received, for the call for questions we specifically defined the Arctic as the area within the boundary outlined by the Conservation of Arctic Flora and Fauna (CAFF), the biodiversity Working Group of the Arctic Council (CAFF 2001; see "CAFF Boundary" in Supplementary information). The respondents submitted questions regarding persistent and emerging threats to Arctic biodiversity, along with information related to their experience, sector, role, and geographical location (see "Form for Call for Questions" in Supplementary information). The latter information was collected solely to analyze the demographics of the respondents, as submitted questions were anonymous. There was no limit to how many questions individuals were able to submit. Within the form, respondents were also informed to email us if they were interested in participating in the workshop.

The core author team screened all questions received (see "Arctic Biodiversity Call for Questions Responses" in Supplementary information for full list of questions). Questions were assigned to categories based on similar scope, leading to 18 categories, which fell under two distinct themes of threats or actions (see Tables 1 and 2). Categories within the threats theme arose from questions that related to stressors that themselves pose a direct threat to Arctic biodiversity. Categories within the actions theme on the other hand focused on the human dimensions of Arctic biodiversity conservation that if not addressed would result in indirect threats to this biome. This distinction was made because the drivers of biodiversity loss arise, directly or indirectly, from human behaviours, and solutions need to acknowledge human dimensions to be successful; in many cases, the "how" of conservation is as important as the "what" (Cooke et al. 2022).

Respondents who had informed us (by email as directed in the form) that they were interested in participating in our expert online workshop (hereafter referred to as the expert panel) were then contacted via email to confirm their availability. The expert panel was also provided the list of categories with their corresponding definitions and some sample questions to assess (for completeness, repetitiveness, and accuracy) and their feedback was incorporated into the category descriptions for the workshop. The workshop was held on 17 November 2023 from 0900 to 1130 EST and included 18 participants (hereafter referred to as the workshop participants). Discussion during the workshop covered barriers to answering questions related to each category, ways to overcome these barriers, and actions or outcomes that would result from overcoming these barriers (see Tables 1 and 2, and Fig. 2). During the workshop, two breakout rooms were randomly organized and each consisted of five members from the expert panel, a moderator, and a note-taker from the core author team, and two of the core author teams' main coauthors (JFP, CP, JRB, SJC). These workshop participants were located in Iceland (1), Sweden (1), Switzerland (1), the United States (1), Russia (2), the United Kingdom (3), and Canada (9).

The workshop was designed to facilitate open discussion and to collect thoughts and expert opinion regarding the various project objectives. The workshop participants were informed of the option to co-author the paper to promote effective engagement. Input was collected anonymously through the digital interactive whiteboard application Jamboard (Google LLC; see "Jamboard from Breakout Room 1" and "Jamboard from Breakout Room 2" in Supplementary information), to allow all workshop participants to anonymously and simultaneously contribute their ideas. For each category, workshop participants indicated whether they

Table 1. Summary of findings of each threat category in this horizon scan.

Category	4.1: Species' responses to climate change		
Category definition	How different Arctic species will respond to climate change (e.g., borealization, range expansion/contraction, trophic interactions). Includes behavioural, genetic, and evolutionary responses		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What is the adaptive capacity of Arctic (e.g., freshwater, marine, terrestrial) ecosystems to respond to climate change? • How is climate change affecting food webs and trophic interactions in Arctic ecosystems? • How will changing landscapes (due to climate change) impact species migration?	• Lack of fundamental information on species' historic ranges and population sizes • Lack of genetic data (i.e., reference genomes, population datasets) • Limited knowledge of physiological or reproductive capacities of marine taxa • Knowledge gaps on the speed, constraints, and genetic basis of adaptation • Difficult to estimate if and at what rate species may shift their ranges • Current biodiversity proxies may be insensitive to climate change effects in species-poor Arctic communities • Travel to the Arctic is expensive • Proposals that test novel hypotheses often prioritized	• Promote research on basic ecology, life histories etc. • Collaborate with long-term ecological research sites • Optimize information gathered, including bio-banking (collecting tissues for genetic sequencing) • Invest in genomic resources, demographic modelling (e.g., paleoarchelogical data), and monitoring technologies like remote sensing • Fund large open-access data archives (e.g., Arctic Animal Movement Archive) • Engage local communities and develop tools for monitoring	• Inform policy development of habitat conservation and mitigation measures • Give insight into potential invasive species of concern for monitoring/management • Intervention measures can be better planned, including the potential to rescue/restore populations in the future • Traditional knowledge can help fill fundamental information knowledge gaps, and improve monitoring with year-round, on the ground data
Category	4.2: Marine cryosphere and hydrological changes caused by climate change		
Category definition	How Arctic marine hydrology (e.g., sea ice) will change because of climate change in general and what the impacts of these changes will be (e.g., to weather patterns, biogeochemistry, species diversity, etc.)		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• How will Arctic wildlife respond to decreased ice cover? • What are the direct versus indirect effects of changing sea ice patterns on biodiversity? • What are the cascading ecosystem-level impacts of sea ice loss and thinning across the Arctic?	• Lack of information on how sea ice dependent communities function and vary • Need to scale up monitoring to a larger spatiotemporal scale to account for variation • Need for long-term monitoring data to identify long-term effects	• New technologies (eDNA) • More funding • Mandatory high-level tracking for ships combined with tracking of marine mammals	• Higher resolution monitoring
Category	4.3: Permafrost changes caused by climate change		
Category definition	How thawing permafrost as a result of climate change will impact Arctic biodiversity (e.g., habitat, greenhouse gases, ocean acidification)		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What novel microorganisms could be released through permafrost thawing? • How does permafrost loss impact ocean acidification, and near-shore carbon cycling/dynamics? • How will changes in permafrost impact landscape dynamics (namely slumping and drainage)?	• Access to certain areas • Detailed models predicting slumps • Heterogeneity in the sources and seasonality of permafrost loss • Understanding how migrating species are affected • Understanding how food supplies change in timing and type • Understanding the importance of biodiversity associated with permafrost communities • Understanding how aquifers are affected • Modelling ecosystem states and processes in mosaic land covers • A lack of in situ ground data	• Funding	• Studies can be driven by science questions rather than logistic access • Can build catchment-level models of permafrost to help assess freshwater biodiversity effects
Category	4.4: Natural resource extraction		
Category definition	How natural resource extraction (e.g., hydropower, mining, wind farms, oil, gas, forestry, fishing, hunting) will impact Arctic biodiversity		

Table 1. (*continued*).

Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• How can we quantify the damage to Arctic ecosystems from hydroelectric power generation, including water–land interactions? • What are the impacts of resource extraction, such as mining and drilling, on Arctic biodiversity? • How does unsustainable exploitation impact Arctic species (e.g., overfishing, overhunting)?	• Lack of in situ ground data and monitoring capacity • Societal interests • National variation in legislation • Gaps in legislation do not cover emerging threats • Restricted access to data • Impact assessments often are linked to large-scale changes not fine scale ones (i.e., contaminants, parasites)	• Ensure publicly available data • Improve monitoring capacity (include local and Indigenous knowledge) • International treaties • Independent monitoring • Increased collaboration with industry • Require impact assessments to address more subtle indicators	• Identify and prove that natural resource extraction is a threat to Arctic biodiversity • Earlier action instead of waiting for a population or ecosystem is in "free fall" • Common rigorous standards that would help protect the environment, Indigenous rights, and local rights Improved extraction methods
Category	4.5: Freshwater hydrological changes caused by climate change		
Category definition	How Arctic freshwater hydrology (e.g., runoff) will change because of climate change in general and what the impacts of these changes will be on Arctic biodiversity (e.g., to weather patterns, water availability, biogeochemistry, species diversity, etc.)		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• How will changes in the Arctic affect the availability of freshwater? • How is increased river runoff impacting Arctic shelf biogeochemistry, and what are the implications for the ecosystem? • How will changes to the amount, duration and physical properties of the snow cover affect animals living in the subnivium and their predators?	• Conflicts between societal needs and ecological needs • Difficult to evaluate issues at larger scales • Limited access, resources, and monitoring capacity • Geopolitical restrictions • Expensive • Lack of fundamental information	• Engage with local communities for data collection • Develop and integrate new technology • Improve collaboration throughout the Arctic • Invest in resources and training	• Deployment of remote sensors alongside locally engaged monitoring programs • Development of remote sensing applications • Implementation of high-resolution monitoring of ecosystem status and drivers of ecosystem stress • Collection of data to guide policy decisions
Category	4.6: Invasive species		
Category definition	The impacts on Arctic biodiversity and mitigation of the introduction and establishment of non-native species that outcompete native species		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to Overcome Barriers**
• Are endemic local organisms more resistant to extreme abiotic parameters related to climate change than invasive organisms? • What are the impacts of invasive/expanding species? • As shipping and traffic in the Arctic increases, what new invasive species might emerge in Arctic environments, and with what consequences?	• It is unknown which species will invade • The distribution of existing species is sparsely known • Knowledge on the competitive abilities of existing species is limited • Limited monitoring capacity • Evaluating compliance and enforcing rules is complicated by the vastness of species	• Improve fundamental information • Better tools for community-based sampling to document species • Increased funding • Increased political will • Emphasize research identifying what products and species are arriving from human vectors (e.g., ship, plane, truck) and natural vectors (e.g., wind, currents) • Establishment of collaborative and thematic programs	• Tighter control of vectors to limit the potential entry of invasive species • Better predictive modelling in relation to emergence and potential ecological impact • Better decision-making • If compliance and enforcement are better understood, biosecurity resources could be more efficiently employed • Modelling of transmission routes
Category	4.7: Emerging and persistent diseases		
Category definition	Anticipating and addressing emerging and persistent diseases and their impact on Arctic biodiversity		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What are the impacts of temperature related diseases in a warming climate? • How will sea ice loss and other climate change impacts affect the dynamics of disease exposure and transmission for marine mammals, and what are the implications for marine mammal health and population dynamics? • How can we better anticipate emerging wildlife diseases?	• Monitoring capacity • Monitoring of non-native species • Understanding which diseases are present, which are native, and which are new • Understanding how physiological stress and disease interact in the Arctic • Understanding what causes a lifestyle switch from commensal to a pathogen	• New technologies (eDNA, qPCR) • More research on stress and disease • Scaled up monitoring of disease with new technologies to identify vectors of disease transmission	• Better predictive monitoring • Ongoing long-term monitoring • Community-level capacity to track zoonoses • Better control of disease transmission vectors (i.e., ships) • One health approach

Table 1. (*continued*).

Category	4.8: Pollution		
Category definition	How various types of pollution will impact Arctic biodiversity (e.g., light, plastic, chemical, oil)		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What are the long-term effects of pollution, such as oil spills or plastic waste, on Arctic wildlife and ecosystems? • What are the impacts of light pollution in the Arctic on low-light adapted animals? • What are the long-range and local sources of pollution affecting the Arctic?	• Proving that compounds are actually toxic on ecologically relevant scales • Funding long-term monitoring projects • Differential behaviour of pollutants in the Arctic and ice-bound environments • Establishing a mechanistic link between a pollution event and an effect • Abilities and capacities of labs to measure emerging contaminants • Finding links between chemical pollution and disease susceptibility and fertility, as well as interaction with climate stressors • Insufficient monitoring to actively site pollution and identify causes in remote areas • Industrial willingness to engage	• Technologies that would allow for easier pollution measuring in communities and (or) smaller labs • New technology for autonomous monitoring in situ • Educate consumers so that their buying patterns influence industries • Specific source identification with communities to understand where to focus efforts • Better links with industry and better industrial will • Educate electorate so that politicians bring in better legislation • Go to the courts and sue	• Banning toxic substances • Local risk assessments that are done by the communities • Better controls at sources • Appropriate management policies • Better monitoring and more data yield better predictive models and decision-making potential
Category	4.9: Increasing development		
Category definition	How increasing development (e.g., cities, roads, tourism) throughout the Arctic will impact its biodiversity		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What impact will development have on Arctic biodiversity (from microbes to plants to animals and finally people)? • How are human infrastructure expansion (cities, roads, etc.) impacting wildlife population health including nutrition, disease transmission/susceptibility and reproduction? • What are the impacts of light pollution in the Arctic on low-light adapted animals?	• Understanding which species will be most impacted and which are most sensitive (sensitivity and threshold levels are largely unknown) • Lack of ecological and demographic data (where sensitive species are located, or what types of habitats they use) • Limited information on how development impacts connectivity, dispersal, or migration in the Arctic • Varied responses to development (impacting some species negatively, others positively) can have unknown interactions with cascading effects • Inadequate impact assessment of development projects (potentially more so for "green" infrastructure e.g., electronic data storage facilities) • Very little monitoring capacity • Change in government can shift values between economic development, Indigenous rights, nature conservation etc. • Unpredictable investment from government, industry, and civil sources • Conflicts of interest between conservation and wanting to develop and exploit resources	• Pre-development studies are needed to study the ecology of the area to understand what species might be affected, what the impacts could be, and monitor any changes • Fundamental research mapping the distribution of biodiversity in Arctic ecosystems to inform development planning to avoid developing on diversity hotspots • Integrate monitoring programs as part of development plans • Further investment in monitoring technologies, like autonomous sensors and remote sensing, and AI	• Sustainable development with minimal impacts and that align with biodiversity corridors could result • Better monitoring technology would make it easier and more economical to implement monitoring • The use of AI in monitoring could enable processing of massive volumes of data to build predictive models and inform decision-making
Category	4.10: Increasing vessel traffic		
Category definition	How increasing vessel traffic as a result of industry and tourism will impact Arctic biodiversity		

Table 1. (*concluded*).

Example questions	Barriers	Ways to overcome barriers	Actions that can be taken if able to overcome barriers
• What are the threats posed by the intensification of shipping along the Northern Sea Route? • What impacts do cruise ships have on Arctic biodiversity? • How does an increase in fishery vessel traffic impact Arctic ecosystems?	• Inability to track all vessel movement • Inadequate knowledge of vessel cargo • Geopolitical restrictions • Lack of consistent policies for vessel traffic • Lack of fundamental information	• Develop proactive laws and international agreements • Increase research on quantifying impacts of vessels on environment • Improve methods for conducting cargo surveys and vessel tracking	• Creation of shipping lanes that minimize impacts on communities and biodiversity • Development of protected areas and seasons • Improvement of vessel anti-fouling and cleaning measures • Development of emergency response planning at the community level • Inception of pan-Arctic vessel operating procedures
Category	4.11: Other anthropogenic threats		
Category definition	Other threats caused by human activity unrelated to pollution, vessel traffic, or development (e.g., military or technological testing, experience-based ecotourism) and how these threats will impact Arctic biodiversity		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What are the impacts of sonar testing? • What are the impacts of human disturbance from ecotourism (ex. Skiing)?	• Lack of monitoring and understanding of the impacts of tourism and increased military presence • Unpredictable new types of tourism • Wars and (or) preparations for them • Desires for sovereignty over the Arctic	• Engaging in risk mapping and understanding knowledge gaps • Stricter regulations • International treaties and agreements	• Regulations that support food security and international cultural trade • Eco-friendly tourism

Note: Example questions provided illustrate the types of questions that relate to the category. The columns containing barriers, ways to overcome barriers, and actions that can be taken if able to overcome barriers summarize the results of the discussion that took place regarding each category during the workshop. The categories are listed in order from most to least important as outlined in the ranking by our expert panel (see Fig. 3).

self-identified as experts on the topic (by way of using a digital green "sticky note"), based on whether they had published a peer-reviewed paper related to the category within the last 5 years. This method of self-identification was useful for assessing the robustness of expert input among categories. Once the workshop was completed, the barriers, ways to overcome them, and actions for each category were reviewed and summarized (see Tables 1 and 2, and Fig. 2).

Post-workshop, the expert panel was emailed and asked whether they were interested in co-authoring the paper. This broader group of experts (i.e., not just the workshop participants) was contacted to further substantiate workshop findings and to ensure we received input from experts with experience in a more diverse range of fields than those represented in the online workshop. The expert panel was also provided the workshop results and asked to rank the importance of each category on a scale from 1 to 1000 (Sutherland et al. 2022). Workshop participants were also asked to indicate the confidence level that each discussion captured all the barriers to the associated categories. However, there were too few responses, so confidence was instead confirmed by sharing results (by way of sending the draft publication) with the members of the expert panel who expressed interest in co-authoring the paper to confirm their agreement/disagreement with the study's findings.

3. Questions, participants, and ranking

We received 81 responses to our "call for questions" yielding 349 questions (see "Arctic Biodiversity Call for Questions Responses" in Supplementary information). Interestingly, while we asked for persistent and emerging threats to Arctic biodiversity, more than half (52.5%) of the questions we received actually related to actions that if not implemented and (or) dealt with would lead to threats. Also of interest, the category "Understanding fundamental information regarding Arctic biodiversity" received by far the most questions with 31.2% of questions relating to this category (see "Number of Questions Received per Category" in Supplementary information).

The primary affiliation for 74.1% of the respondents to our "call for questions" was academic, with the majority of respondents being researchers (90.1%; see "Primary Affiliations of Respondents to Call for Questions" and "Primary Roles of Respondents to Call for Questions" in Supplementary information). Most respondents were from North America; however, we also received replies from many other Arctic countries, including all eight with jurisdiction over the area (i.e., Canada, Kingdom of Denmark, Finland, Iceland, Norway, Sweden, the Russian Federation, and the United States of America; see "Number of Respondents to Call for Questions by Country" in Supplementary information). Over half

Table 2. Summary of findings for each action category in this horizon scan.

Category	5.1: Understanding fundamental information regarding Arctic biodiversity		
Category definition	Developing an understanding of the fundamental information we need to conserve Arctic biodiversity		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• How is biodiversity distributed across the Arctic, what are the drivers of this pattern and how does this relate to ecosystem function in the Arctic? • What aspect of diversity (i.e., intrapopulation, genetic variation) is most under threat in species poor Arctic ecosystems? • Which are the most vulnerable organisms we are going to lose first?	• Lack of in situ ground data • Taxonomic issues such as the absence of common species lists, especially plants and lichens • Lack of resources to collect fundamental data, (e.g., species loss and invasive species) and geographically balanced data	• Develop joint collaborative research projects and supportive research networks • Fund a portfolio of research that combines fundamental work with more applied, mission-oriented research to support many goals	• Recognition that fundamental science is often foundational to solving problems—just on a longer time frame
Category	5.2: Implementing and improving monitoring		
Category definition	Techniques, technologies, and programs that enable long-term monitoring of Arctic biodiversity		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What are the most efficient monitoring techniques we can use to monitor different levels of biodiversity? • How well does remote sensing data reflect biodiversity associations, e.g., how much useful information can we gain from a satellite? • How should we design monitoring programs to follow changes in Arctic biodiversity through time, and what role can new and emerging technologies such as environmental DNA play?	• Deciding when to transition from research observations to operational monitoring • Inadequate understanding of ecosystems, complicating the establishment of tailored monitoring programs • Poor understanding of interacting stressors • Lack of confidence in existing data • Poor understanding of where the knowledge gaps are • Expenses associated with data collection • Expenses associated with ground-truthing • Lack of people to dedicate to long-term monitoring • Lack of standardization	• Improve access to data • Establish transboundary monitoring of cumulative effects on migratory species • Make use of existing resources • Engage local communities in biodiversity observations • Foster a culture of data sharing and collaboration • Support the development of tools used to conceptualize and quantify cumulative effects • Develop simple protocols for long-term use	• Sharing existing data and knowledge and examine opportunities to create and integrate a national pan-arctic long-term data archive • Development of comprehensive datasets that can guide future research • Improved decision-making • The ability to measure the effects of policy and management decisions
Category	5.3: Supporting Indigenous governance		
Category definition	Consideration of resources, research, and knowledge of Indigenous communities and Rights Holders, and how to collaborate with Indigenous communities and Rights Holders on Arctic biodiversity management		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• How can we best apply Indigenous knowledge to protect and conserve biodiversity? • How can we speed up the creation of Indigenous Protected and Conserved Areas to protect Arctic biodiversity? • What is the best approach to co-constructing Arctic research with Indigenous communities?	• Exclusion of Indigenous Peoples in research groups • Time required to develop partnerships • Geopolitical restrictions • Lack of recognition of role Indigenous communities play in conservation	• Ask Indigenous communities how they would like to work with researchers • Include budget to work collaboratively with communities in funding applications • Build capacity for Indigenous communities/governments to engage in monitoring • Ensure monitoring serves local needs • Change in norms/perspectives around knowledge generation	• Implementation of better policies and practices that yield equitably distributed benefits • Development of co-produced research designs and monitoring plans
Category	5.4: Facilitating collaboration to protect Arctic biodiversity		
Category definition	How we can facilitate cooperation at the international, national, and local scales to protect Arctic biodiversity including the ecological knowledge of communities.		

Table 2. (*continued*).

Example questions	Barriers	Ways to overcome barriers	Actions that can be taken if able to overcome barriers
• How can local ecological knowledge of communities be integrated with scientific research to improve the conservation of Arctic biodiversity? • How can international cooperation and governance frameworks be improved to effectively address threats to Arctic biodiversity? • How can the international community support expertise gaps in Arctic science?	• Political unrest, conflicts, lack of resources needed to establish equitable research partnerships • Can require funding beforehand if projects are to be jointly developed • Unanticipated costs, like funding for translators • Besides mechanics of language barriers, need to find someone who can convey the proper meaning to reach a common understanding (e.g., words with multiple meanings/multiple words describing something, words with no direct translation) • Locals might perceive conservation as preventing them from being able to utilize the ecosystem services benefiting them • Lack of training on how to navigate forming partnerships	• Adjust funding cycles to include a pre-proposal application window to facilitate co-development of proposals • Plan collaboration costs into research budgets • Creation of an internationally pooled grant for globally shared issues • Consider the lessons learned from other disciplines (i.e., social science, anthropology) where there have already been discussions on working equitably with diverse groups of people • Make use of global networks that already exist (e.g., UK Science Innovation Network) • Work with local communities to find solutions that work for them, like ecotourism that promotes conservation but still allows locals to enjoy ecosystem services and bring in revenue	• More inclusive participation in research and conservation, with more diverse perspectives for setting research agendas and possible conservation solutions • Pooled grants would help bring together historically affected but excluded groups that have fewer funding opportunities with those that have more resources
Category	5.5: Facilitating improvements to management & policy		
Category definition	Regulations, decision-making, and implementation of policies that advance conservation goals for Arctic biodiversity (these are regulations not impacts)		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What policies, legislation, or regulations are missing that would ensure biodiversity protection is considered as a priority in land use planning, resource management, impact assessment, and industrial development processes? • How do we best define protected areas in Arctic environments, where richness and densities of species are often low? • How do we co-manage Arctic natural resources across local, regional and global scales?	• Diverse interests involved with transboundary and circum-Arctic issues complicate conservation actions • Political "interference" influences management action by moving focus to party needs and away from improving policies • Protected areas network development can be a slow process • Protected areas may not be responsive or adaptive enough to reflect on-the-ground changes in the functionality of sites	• Increased compliance regarding global treaties and frameworks • Address unique Arctic biodiversity and contexts in global processes • Centre the evidence by embracing evidence-based approaches instead of politics • Acknowledge the value in education and awareness	• Better regulations to incite favourable outcomes for conservation • More timely decision-making
Category	5.6: Design and implementation of conservation solutions		
Category definition	How we can design and implement innovative conservation solutions applied to Arctic biodiversity conservation problems		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• How can we manage population declines of Arctic species? • Can drone technology accurately capture changes in plant species composition across the landscape? • Can we identify hotspots of biodiversity (across taxa) in the Arctic, and how can these inform conservation priorities?	• Debates related to jurisdictional responsibilities • Uncertainty in the evidence base leading to decision paralysis	• Identify and agree upon national and international responsibilities • Leverage existing conventions, such as the Kunming–Montreal Global Biodiversity Framework (GBF) or the BBNJ implementation, to hold governments accountable • Address gaps in biodiversity groups • Replicate experiments, test, and study various interventions • Look for bright spots to figure out what works and then scale that up	• Removal of jurisdictional uncertainties and debates to facilitate partnerships

Table 2. (*concluded*).

Category	5.7: Identifying roles of stakeholders and Rights Holders		
Category definition	Determining the roles of individuals, institutions, and philanthropic organizations in Arctic biodiversity conservation.		
Example questions	**Barriers**	**Ways to overcome barriers**	**Actions that can be taken if able to overcome barriers**
• What roles can philanthropic organizations play in helping to protect and conserve Arctic biodiversity? • What are the roles of leading institutions and places of higher education? • How can individuals play a role in encouraging biodiversity conservation in the Arctic?	• Lack of effective communication and integration of different ways of knowing • Limited capacity of researchers to involve local communities and knowledge holders • Staff turnover in organizations that facilitate long-term monitoring • Maintenance of databases	• Develop forums to bring people in different sectors and roles together • Build funding and capacity for partnership and collaboration • Train students on how to work with northern communities (e.g., ArcticNet meetings) • Develop communication with Northern organizations and Indigenous Peoples • Expand mandates and policies to address biodiversity conservation in various stakeholder institutions to bring it into the mainstream	• Increased and more meaningful interactions, leading to impactful and efficient research • Identification of shared priorities for biodiversity conservation relevant to all stakeholders • Confidence that stakeholders are not working against each other and (or) duplicating efforts

Note: Example questions provided illustrate the types of questions that relate to the category. The columns containing barriers, ways to overcome barriers, and actions that can be taken if able to overcome barriers summarize the results of the discussion that took place regarding each category during the workshop. The categories are listed in order from most to least important as outlined in the ranking by our expert panel (see Fig. 3).

of these respondents (56.8%) had more than 21 years' experience working with Arctic biodiversity and most worked in either the terrestrial (40.7%) or marine (34.6%) domain (see "Years of Experience of Respondents to Call for Questions" and "Main Research Domains of Respondents to Call for Questions" in Supplementary information).

Ranking of categories by the expert panel post-workshop (see Fig. 3 and "rankings.R" in Supplementary information) indicated that the three most important categories (in order from most to least important) were Species' responses to climate change, Understanding fundamental information regarding Arctic biodiversity, and Marine cryosphere and hydrological changes caused by climate change. The least important categories (in order from least to most important) were Other anthropogenic threats, Identifying roles of stakeholders and Rights Holders, and Increasing vessel traffic.

4. Threat categories

The following subsections illustrate the context and key findings from the horizon scan for each of the threat categories as summarized in Table 1 and Fig. 2. The categories are listed in order from most to least important based on the ranking performed by the expert panel.

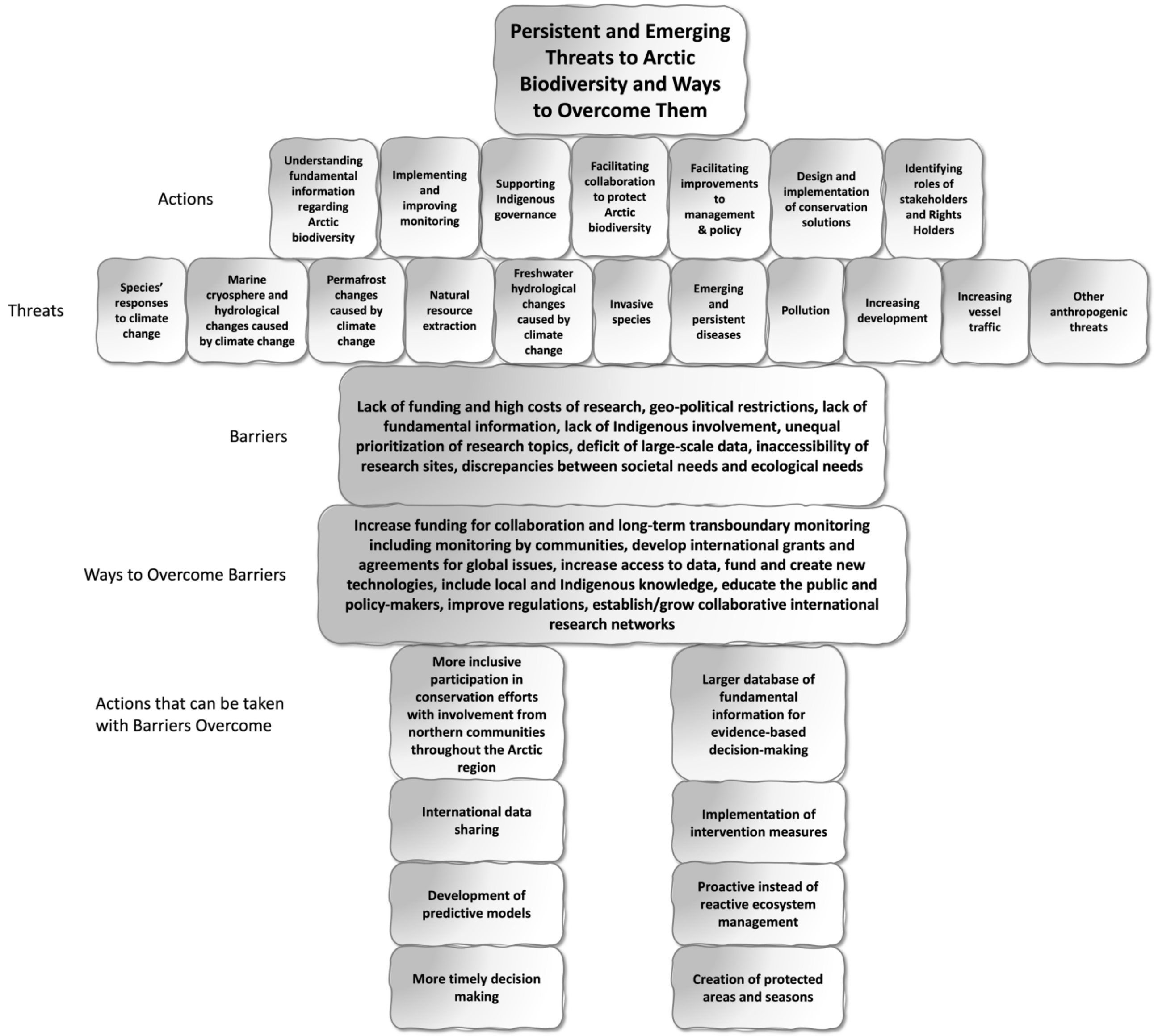
4.1. Species' responses to climate change

To understand how biological communities or ecosystems may change as a result of climate change, it is important to understand how individual species will respond, including behavioural, genetic, and evolutionary modifications (Baselga and Araújo 2009; Pucko et al. 2011). Numerous modifications in behaviour have already been documented for Arctic species, including shifts in the breeding range of migratory birds (Anderson et al. 2023) as well as more northerly range shifts for terrestrial species (Chen et al. 2011). Alterations in the timing of breeding, migration, or other timed life cycle events (i.e., changes in phenology) have also been seen (Cherry et al. 2013; Ward et al. 2016). Genetics will also play a large role in a species' response. Past climatic events have been shown to have measurable impacts on genetic diversity (Mellows et al. 2012; Stewart et al. 2016; Fedorov et al. 2020; Westbury et al. 2023), which is likely to be exacerbated with compounded threats like overexploitation or habitat loss further reducing populations (Kellner et al. 2024). Species facing declines in population size are also facing reduced genetic diversity and as a result have lower adaptive potential (McRae et al. 2012; Westbury et al. 2023). Furthermore, factors influencing the genetic basis of traits, like additive genetic variance (traits determined by multiple loci; Singh and Singh 2018) can have unpredictable effects on adaptive potential (van Heerwaarden and Sgrò 2014). A better understanding of these factors and processes could help quantify species' adaptive capacity, though there is also debate on whether highly specialized species (including Arctic species) will adapt quickly enough to changing conditions (Beever et al. 2016; Ainsworth and Drake 2020). A lack of both reference genetic data as well as historic ranges of species was therefore indicated by horizon scan participants as important barriers to answering questions within this category (see Table 1). Promoting this sort of research instead of novel research was suggested by participants as a good way to overcome these barriers so that appropriate intervention measures can be implemented (see Table 1).

4.2. Marine cryosphere and hydrological changes caused by climate change

Arctic sea ice has been in decline for several decades with over half of multiyear sea ice disappearing between 2002

Fig. 2. Summary of findings of this horizon scan. As some Indigenous Peoples use the Inukshuk to guide their way, we hope this image will guide and inspire readers in taking actions that protect Arctic biodiversity. Both actions and threats are listed from left to right in order of most to least important as outlined in the ranking summarized in Fig. 3.

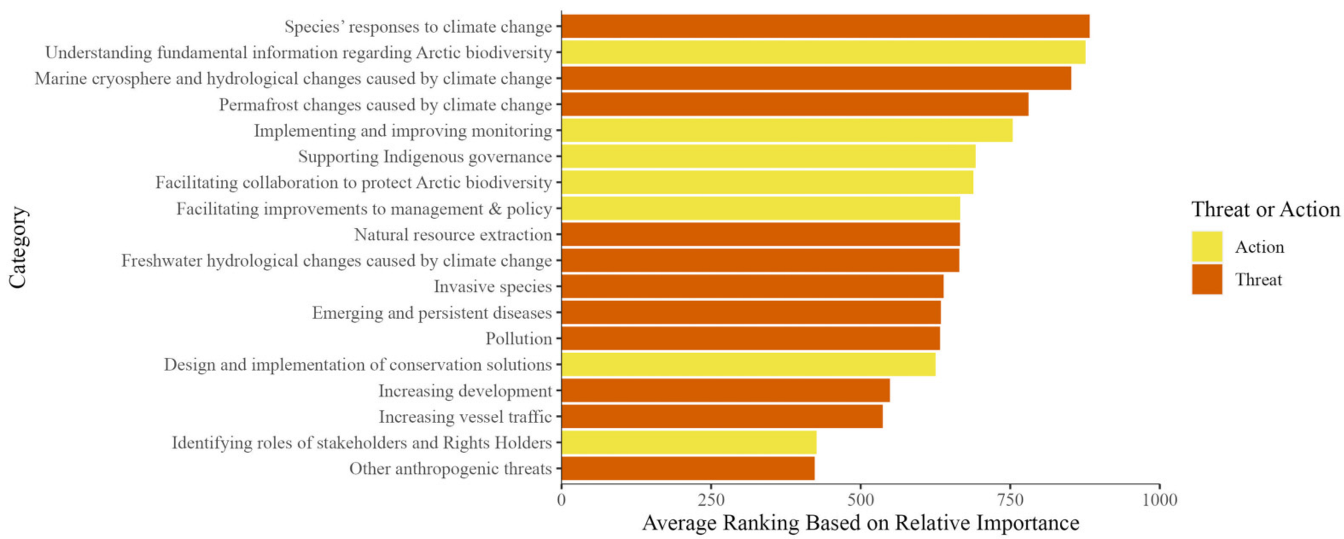


and 2017 (Kwok 2018; Li and Fedorov 2021). Climate models almost unanimously predict that sea ice coverage will continue to decline through the 21st Century in response to rising concentrations of atmospheric greenhouse gases (Zhang and Walsh 2006). This loss of sea ice coverage has a diverse set of impacts from changing the salinity content of the Arctic Ocean (Li and Fedorov 2021) to impacting marine mammals associated with sea ice (Kovacs et al. 2011; Eamer et al. 2013; Laidre et al. 2015). For example, freshening of the Arctic Ocean has a negative impact on primary producers because of the deepening of the nitracline (vertical flux of nitrate) and the creation of a subsurface chlorophyll maximum leading to lower primary productivity (Coupel et al. 2015). Furthermore, sea ice loss can impact ice-associated organisms by causing distribution shifts and compromising body condition, ultimately causing declines in reproductive effort or success and abundance (Kovacs et al. 2011; Eamer et al. 2013; Laidre et al. 2015). Horizon scan participants indicated that a lack of large-scale and long-term monitoring makes it difficult to answer research questions in this category (see Table 1). As such, participants suggested that mandatory monitoring through vessel traffic and the development and use of new technologies such as eDNA, be used to allow for the implementation of higher resolution monitoring (see Table 1).

4.3. Permafrost changes caused by climate change

Permafrost underlies 15%–25% of the Northern Hemisphere (Obu 2021; National Snow and Ice Data Center 2023). Its thickness can reach great depths, sometimes down to 1500 m (National Snow and Ice Data Center 2023). As

Fig. 3. The average importance of each category relative to all other categories as per the expert panel.



permafrost acts as a carbon sink, it represents a large global reservoir of carbon (Robinson et al. 2003; Hugelius et al. 2014). Thawing permafrost therefore releases carbon, which can have many impacts to biodiversity. For example, the release of carbon can change the composition of microbial communities (Ricketts et al. 2020) and alter food webs (Wauthy and Rautio 2020). Beyond incremental thawing, the rapid collapse of permafrost can lead to abrupt changes in ecosystems such as the introduction of contaminants and excess sediments (Vonk et al. 2015), with substantial consequences for local biodiversity (Thienpont et al. 2013). There is also concern that pathogens long frozen within permafrost will be released having catastrophic impacts to Arctic wildlife and inhabitants (Cohen 2023). However, horizon scan participants indicated that significant research gaps exist for our understanding of this phenomenon (see Table 1; Turetsky et al. 2019). Participants suggested that increased funding would allow for the development of models to help address research questions in this category (see Table 1).

4.4. Natural resource extraction

The Arctic remains of interest for natural resource extraction despite the difficulty in extracting resources from the harsh environment (Wilson and Stammler 2016). In 2007–2008, melting sea ice resulted in parts of the Northwest Passage becoming a more viable sea trading route; this is concerning given a U.S. Geological Survey estimated that roughly a quarter of the world's undiscovered oil and gas deposits were located in the Arctic (Harsem et al. 2011). Subsequently, a 2020 study found the primary economic activity in the circumpolar Arctic to be mineral and hydrocarbon extraction (Nekrich 2020). Poor management of natural resources to date has already led to population declines of Arctic organisms (Bunnefeld et al. 2011), and increased extraction can have drastic, deleterious impacts on Arctic animals, including threatened species (Johnson et al. 2005; Dabros et al. 2018). For example, oil extraction and potential spills associated with transport pose a threat to biodiversity as many marine species are sensitive to oil components, which can cause a variety of short- or long-term, harmful health impacts, including mortality (Hendriks et al. 2005; de Hoop et al. 2011). Mining activities have also had a negative impact on environmental health with side effects like effluents entering water systems deleteriously affecting the health of ecosystems (Smith et al. 2005). However, in other cases, the impacts of resource extraction on wildlife are less clear (Grajal-Puche et al. 2024). Given society's impacts on political decisions, societal interests were identified as a large barrier to answering research questions in this category by horizon scan participants (see Table 1). If industry was required to make all their data publicly available, participants suggested that standards could be implemented to allow natural resource extraction to take place in a way that limits its impact to the environment (see Table 1).

4.5. Freshwater hydrological changes caused by climate change

Freshwater biodiversity loss is a global issue resulting from pollution, habitat loss and degradation, invasive species, overexploitation, and changes to water flow (Dudgeon et al. 2006; Reid et al. 2019). Changes to freshwater hydrology via climate change will exacerbate these issues. Some of the impacts climate change is anticipated to have on freshwater hydrology in the Arctic include an increase of precipitation and severe weather events, drought, earlier snowmelt and later snowfall, and an increase in water temperatures (Wrona et al. 2004; CAFF 2013*b*). These impacts in turn are expected to alter hydrological and climate systems exacerbating the issue (Prowse et al. 2015). Changes to permafrost are also expected to greatly influence freshwater hydrology, though how is unclear (Walvoord and Kurylyk 2016). Some of these effects are already being observed (Smol and Douglas 2007; Hansen et al. 2014), which is especially concerning given that freshwater ecosystems are important in the Arctic, acting as a link

Fig. 4. Example of freshwater lakes in the region, which are home to Arctic char and threespine stickleback. In the background, you can see the edge of the Ice sheet. Photo by BM taken on a lake in Qassiarsuk, Greenland, September 2021.

between marine and terrestrial ecosystems, supporting high biodiversity that local communities depend on for their livelihoods (see Fig. 4; Wrona and Reist 2013). Given this connection, horizon scan participants recommended that an ideal way to mitigate the barriers of limited access to research sites and resources would be to work with local communities for data collection (see Table 1). With these data, remote sensing applications could then be developed (see Table 1).

4.6. Invasive species

Human presence in the Arctic can influence biodiversity in numerous ways, including the intentional and unintentional introduction of species. The intentional introduction of non-native species can be the result of farming/harvesting practices, as seen with the Arctic red king crab (*Paralithodes camtschaticus*) in Norway (Sundet and Hoel 2016), the pink salmon (*Oncorhynchus gorbusca*) in the European North Atlantic region (Lennox et al. 2023), and the Arctic fox (*Vulpes lagopus*) in the Aleutian Islands (West and Rudd 1983). These introduced species can cause management problems as well as wreak havoc on native biodiversity if they become invasive (West and Rudd 1983; Sundet and Hoel 2016). A species is considered invasive if it has been established in an area outside of its normal range and outcompetes native species in this new environment (Whitney and Gabler 2008). These species can also be unintentionally introduced by pathways such as container ships and shipment of infested wood (Hulme 2009; Humble 2010). Invasive species are a threat to biodiversity because they can outcompete native species for resources and put pressure on the stability of native populations (Whitney and Gabler 2008). Ongoing global change increases the likelihood of the arrival and establishment of these species in the Arctic (Cottier-Cook et al. 2024). The Arctic specifically is more susceptible to the establishment of invasive species given its relatively low biodiversity as compared to other biomes and because of increased development in the area (CAFF and PAME 2017). However, minimal invasions have occurred thus far, so there is an opportunity to prevent significant harm if immediate actions are taken (CAFF and PAME 2017). A significant barrier identified by horizon scan participants to implementing these actions is not knowing the current distributions of native Arctic species or how well they would be able to compete with invasives (see Table 1). It is therefore pertinent to conduct research to collect this fundamental information so that predictive models can be created (see Table 1).

4.7. Emerging and persistent diseases

As the Arctic warms due to climate change, the geographic and temporal ranges of several diseases are likely to expand into the Arctic (Parkinson et al. 2014). This potential for increased disease is concerning for both wildlife and for humans through zoonotic pathogens. An international circumpolar group of experts identified diseases such as *Brucella* spp., *Giardia* spp., and West Nile virus as potentially climate-sensitive zoonotic diseases of concern (Parkinson et al. 2014). Additionally, of special concern is avian influenza, which has the potential to drastically impact animal populations (Lee et al. 2020; Caliendo et al. 2022) and has recently been detected in breeding colonies of Arctic seabirds (Lee et al. 2020; McLaughlin et al. 2024), subsequently causing sporadic mortality in multiple bird and mammal species including a polar bear (*Ursus maritimus*; Caliendo et al. 2022; Alaska Division of Environmental Conservation 2024). One of the primary vectors of zoonotic diseases entering the Arctic is the northward movement of organisms such as birds that carry infected ticks or viruses (Revich et al. 2012). Diseases such as tick-borne encephalitis are experiencing an upward trend in the northern European Arctic with climate change as a contributing factor (Revich et al. 2012). While some of these diseases making their way to the Arctic do not directly impact humans (e.g., avian cholera, Henri et al. 2018; lungworms, Kafle et al. 2020), there are indirect impacts given the “One Health” concept in that animals, humans, and the environment are all dependent upon each other for their health (Ruscio et al. 2015). Therefore, horizon scan participants advocated that research must be focused on understanding and monitoring all types of disease to truly protect Arctic biodiversity (see Table 1). Most importantly, participants suggested that with the identification of the vectors of disease transmission, it may be possible to manage their spread and limit their impact (see Table 1).

4.8. Pollution

While pollution is a global threat, some associated risks particularly impact the Arctic, such as ice-bound pollutants. As polar ice continues to melt, an increasing number of pollutants will be released into surrounding environments, potentially negatively impacting biodiversity in associated ecosystems (Botterell et al. 2022). While there have been studies on the effects of pollution upon Arctic environments (Lifshits et al. 2021; Sonne et al. 2021; Svavarsson et al. 2021), little is known about how pollution release will specifically impact the environment or the specifics of the release processes, although release from Arctic environmental archives is underway (Ma et al. 2011). The impact of pollution making its way to the Arctic from the South is also an area of concern. For example, microplastics enter the Arctic from more Southern locations via oceanic and atmospheric currents and have the capacity to negatively influence animal reproduction, growth, metabolism, and behaviour (Anderson et al. 2016; Mishra et al. 2021). The lack of a clear understanding of pollution’s impacts to Arctic ecosystems was identified by horizon scan participants a key barrier to answering research questions within this category that can be mitigated with the development of new pollution monitoring technologies (see Table 1). With this information, participants suggested that it would be easier to regulate toxic substances as well as identify and manage point sources (see Table 1).

4.9. Increasing development

The negative impacts of human development and infrastructure (e.g., cities, roads, tourism) on biodiversity are well recognized globally (Coffin 2007; IPBES 2018). The impact that development has on Arctic biodiversity, however, is not as well understood. While the Arctic remains sparsely populated by humans and human infrastructure compared to other parts of the globe, development is increasing (Bartsch et al. 2021) and is being compounded with other stressors. For instance, Arctic species may be facing habitat loss/degradation from both human infrastructure and climate change (Wauchope et al. 2017; Pálsdóttir et al. 2022), and by development facilitating the spread of invasive species (Bock 2013). Additionally, some species use specific migration routes or have high fidelity to parts of their range (Cherry et al. 2013; Joly et al. 2021), which may be negatively impacted by human presence, development projects, or artificial infrastructure (Pálsdóttir et al. 2022). This is especially concerning for species already facing changing landscapes and reduced habitat from climate change such as polar bears and caribou (*Rangifer tarandus*) that show relatively high site fidelity to seasonal habitats and (or) migration routes (Cherry et al. 2013; Joly et al. 2021), as well as many seabirds that return to the same breeding and nesting sites each year (Léandri-Breton et al. 2021). Freshwater organisms are also impacted via the development of dams and other water diversion infrastructure, particularly downstream habitats (CAFF 2013*b*). Expansion of Arctic fisheries will not only lead to enhanced harvest of target species, but greater levels of bycatch of non-target fish, birds, and marine mammals (Anderson et al. 2018; Mallory et al. 2022*a*). Horizon scan participants identified inadequate understanding of the environmental impacts of development in the Arctic as well as conflicting interests as barriers to answering research questions in this category (see Table 1). Participants suggested that full research studies including a pre-development assessment and post-development long-term monitoring be included in the permit requirements for developers to overcome these barriers and limit the environmental impacts of development (see Table 1).

4.10. Increasing vessel traffic

The Arctic has historically been relatively inaccessible for most activities. Ice used to block vessel passage for most of the year; however, with the melting of sea ice, the Arctic is becoming more and more accessible for longer periods of time (see Fig. 5; Arctic Council 2009). This increased accessibility can be seen clearly when examining the distances travelled by vessels throughout the Arctic, which tripled from 1990 to 2015 (Dawson et al. 2018). Increasing vessel traffic has the potential to bring with it many complications (Qi et al. 2024). For example, shipping is a known vector for the spread of invasive species, which could consequently reduce Arctic biodiversity (CAFF 2013*b*; Stevenson et al. 2019). It is also anticipated that the pollution that accompanies vessels

Fig. 5. Passengers on an expedition tourism vessel moving through sea ice in the Northwest Passage, Nunavut. Photo by MLM, 2023.

(e.g., air, noise, greywater, waste, spills) will increase, which has a great potential to negatively impact the environment and aquatic life (Dunlop 2019; Stevenson et al. 2019). Vessel traffic also contributes to direct mortality via ship strikes (Halliday et al. 2022; Qi et al. 2024). To date, most attention has focused on impacts during the open water season, but there is growing investment in industrial icebreaking vessels that can operate year-round such as ice-rated LNG tankers that export gas via the Ob estuary in Russia, and nuclear-powered icebreakers that lead cargo convoys (Wilson et al. 2020). Year-round icebreaking operations potentially pose risks for ice-dependent species, such as ice-breeding pinnipeds, (Wilson et al. 2020) and have been shown to have detrimental physical impacts on seal breeding habitats such as causing mother–pup separations during lactation and direct mortality due to collisions (Wilson et al. 2017). Progress has been made in tracking shipping vessels (PAME 2024); however, horizon scan participants indicated that a key barrier to alleviating this threat is the inability to track all vessel movement, and laws should be implemented to make this information mandatory (see Table 1). As a result, participants suggested that knowledge of vessel movements would allow for the creation of shipping lanes that are both efficient and allow for minimal environmental impact (see Table 1).

4.11. Other anthropogenic threats

This category encompasses threats that do not fit within the other threat categories identified or could potentially relate to many of them. Arctic tourism, for example, has been increasing in the Arctic with both known and unknown impacts. The sheer number of tourists can directly impact biodiversity by damaging vegetation at tourist sites as well as by changing bird community composition when sensitive species are replaced with generalist species (Tolvanen and Kangas 2016). Given tensions between Arctic countries, war is another concern given not only its impacts to Arctic residents but also its catastrophic environmental impacts. The Arctic is also used for military or other technological testing, such as sonar (National Defence 2021), with some negative, but largely unknown, impacts on wildlife (Halliday et al. 2020). It is also anticipated that the cumulative impacts of all threats will be far more consequential than any threat alone; however, little research has been conducted in relation to these cumulative impacts (Schindler and Smol 2006; Smith et al. 2022). This general lack of understanding of the impacts of all these activities as well as the fact that they are constantly changing were identified by horizon scan participants as major barriers to answering research questions within this category (see Table 1). Participants suggested that the implementation of international treaties and agreements would be one way to help alleviate these barriers, so initiatives like eco-friendly tourism can be enforced (see Table 1).

5. Action categories

The following subsections illustrate the context and key findings from the horizon scan for each of the action categories as summarized in Table 2 and Fig. 2. The categories are listed in order from most to least important based on the ranking performed by the expert panel.

5.1. Understanding fundamental information regarding Arctic biodiversity

It is crucial to gain a better understanding of the Arctic biome to inform conservation practices. Fundamental information is obtained through experimental or theoretical work, as well as long-term monitoring (especially to capture fundamental temporal patterns; Gauthier et al. 2013) and is especially important to conservation biology (Courchamp et al. 2015). Robust information is necessary to address biodiversity crises and support evidence-based decisions that ultimately lead to better conservation practices (Buxton et al. 2021). Knowledge gaps and resource shortages related to

Fig. 6. Monitoring pollution in the Arctic since 1975 using eggs from seabirds. Photo by MLM taken at Prince Leopold Island, Nunavut, 2023.

Arctic biodiversity information, such as mapping biodiversity distributions across the Arctic, understanding the drivers of biodiversity patterns, and how this relates to ecosystem function in the Arctic, should be assessed to delineate specific information needs and encourage future research. While it is essential to avoid overstudying at the expense of taking action, fundamental information is still needed to be able to address the various identified threats. Better long-term biodiversity monitoring needs to be conducted in conjunction with environmental monitoring to be able to provide context to data (Gauthier et al. 2013). An overall lack of resources was identified by horizon scan participants as a main barrier to collecting these data, and the development of joint collaborative research projects would be an ideal way to alleviate this barrier (see Table 2). Ideally, these initiatives would lead to a common understanding that fundamental information is paramount for identifying and implementing effective conservation solutions (see Table 2).

5.2. Implementing and improving monitoring

Monitoring is a conservation tool used to track changes to an ecosystem over time (Lindenmayer and Likens 2009). The information gathered from monitoring programs is then used to inform conservation strategies suited to address a specific issue (Magurran et al. 2010) such as securing food, detecting change, educating, or supporting economic futures (Wheeler et al. 2018). Monitoring can be resource-intensive and requires baseline data to track the impacts of conservation actions effectively. Monitoring initiatives for the Arctic exist (e.g., Gill et al. 2011; Culp et al. 2012; Christensen et al. 2013; Jones et al. 2019; see Figs. 6 and 7), yet issues with data interoperability and sharing information complicate establishing effective monitoring plans. The need for better monitoring has increasingly been recognized (Barry et al. 2023;Provencher et al. 2023), and several international collaborative initiatives have attempted to identify and address the gaps (e.g., Aronsson et al. 2021; Christensen et al. 2021). How-

Fig. 7. These buoys and sondes (EXO2) are deployed for weeks at a time to measure high-frequency changes in oxygen, temperature, conductivity, algal biomass, and fluorescent-dissolved organic matter. The aim is to quantify lake metabolism. One of the constraints on such ecosystem monitoring is the need to replace the batteries and service the sensors every few months, making long-term deployments (e.g., over winter) difficult. Photo by BM taken on a lake in Qassiarsuk, Greenland, September 2021.

ever, realizing these improvements in monitoring has proven challenging with many conservation/research programs still falling short in terms of collecting enough or adequate information and being adaptive to the conservation goal (Legg and Nagy 2006; Hillebrand et al. 2018). This includes shortcomings like insufficient scales, lack of resource investment, and even issues with what data are being collected as recognized by horizon scan participants (see Table 2; Hillebrand et al. 2018). Therefore, participants suggested that the development of standard monitoring practices that obtain data that is accessible to all would allow for improved (and more transparent) decision-making and the development of a data archive (see Table 2).

5.3. Supporting Indigenous governance

Indigenous Peoples have been stewards of the land since time immemorial; however, the important role they play in global conservation is only recently being recognized (Nitah 2021). Land currently managed by Indigenous Peoples makes up only around 20% of global land, yet holds 80% of the world's biodiversity (Mearns and Norton 2010). Over a third of the world's intact forested landscapes are also found on Indigenous land (Fa et al. 2020). Indigenous governance, thus, is a key component of sustainable land management (CBD 2000; IPBES 2018; IPCC 2022). Supporting Indigenous governance is important globally; however, it is even more paramount in the Arctic where Indigenous Peoples comprise significant populations in many Arctic jurisdictions, composing the majority of some (Bogoyavlenskiy and Siggner 2004; Heleniak and Bogoyavlensky 2014; Young and Bjerregaard 2019). Embracing Indigenous leadership can enhance decision-making as Rights Holder groups have a close connection and knowledge of the local land and ecology. Indigenous involvement is essential to achieve biodiversity conservation goals, following the UN Declaration on the Rights of Indigenous Peoples framework (IPBES 2018; Nitah 2021; IPCC 2022). Various partnership networks exist, and should be further encouraged and supported, such as the Centre for Braiding Indigenous Knowledges and Science, that looks at how Indigenous knowledge and empirical science can come together to co-develop research projects, methodologies, and ethical guidelines, and produce knowledge/databases (UMass Amherst n.d.). There is also the Circumpolar Inuit Protocol from the Inuit Circumpolar Council that outlines best practices for equitable and ethical engagement with Inuit knowledge in research (Inuit Circumpolar Council 2022). Other

Arctic-specific Indigenous networks include the SIKU Indigenous knowledge network or the SmartICE platform, which is centred around providing tools to integrate Indigenous and local knowledge in data acquisition, monitoring, mapping, transfer, and preservation of knowledge (SIKU—The Indigenous Knowledge Social Network n.d.; SmartICE—Sea Ice Monitoring and Information Inc. n.d.). However, horizon scan participants highlighted that Indigenous Peoples are often not included in the research process presenting a major barrier (see Table 2). To alleviate this barrier, participants suggested that Indigenous communities be asked how they would like to work with researchers, and what their own research priorities are, prior to any research being conducted (see Table 2). Furthermore, it was suggested that research budgets for funding applications include the funds required to collaboratively work with these communities (see Table 2). Implementation of these practices will allow for better research, policies, and practices that yield equitably distributed benefits (see Table 2).

5.4. Facilitating collaboration to protect Arctic biodiversity

Many of the drivers of change facing the Arctic are global, and Arctic states cannot address them in isolation (Berkman and Vylegzhanin 2013; CAFF 2013*a*). The behaviour, health, and survival of many species are affected by countries outside the Arctic, either directly or indirectly (e.g., pollution diverting to the Arctic or migratory species that inhabit multiple countries; Burkow and Kallenborn 2000; Berkman and Vylegzhanin 2013; CAFF 2013*b*). Namely, climate change is one of the largest threats to the Arctic and is a prime issue that must be addressed globally (CAFF 2013*b*). Efficiently mitigating these threats requires the involvement of the international community (Berkman and Vylegzhanin 2013; CAFF 2013*a*), but conflicting legislation amongst nations becomes detrimental to biodiversity as it does not conform to the same boundaries (CAFF 1997). Likewise, environmental protection treaties may be drafted but not accepted/signed by all nations, reducing their effectiveness (Hensz and Soberón 2018). Conflicts involving Arctic nations also influence involvement and cooperation on joint Arctic programs (Dyck 2024). However, there are collaborative bodies that bring the Arctic nations together, such as the Arctic Council, and wide collaborative groups such as these can have great benefits, like maximizing scarce resources by sharing data, expertise, methodologies, and technologies (CAFF 2013*a*). Horizon scan participants indicated that a barrier to these collaborations can often be a communication issue due to challenges with language as well as a lack of funding causing the unequitable involvement of those who will be impacted by decision-making (see Table 2). Participants suggested that funding designated towards allowing different groups to come together would allow for more inclusive conservation practices (see Table 2).

5.5. Facilitating improvements to management and policy

The Arctic boundaries extend across eight Arctic states, each subject to its respective national and sub-national jurisdictions as governed by internal laws (Smieszek et al. 2021). Collaboration and governance in the Arctic are fostered and supported by the Arctic Council, and although the Arctic Council is a consensus-based high-level intergovernmental forum that does not implement or enforce its guidelines, assessments or recommendations, the Council successfully coordinates discussions amongst Arctic states and Indigenous Peoples and makes recommendations based on sound science for the benefit of the Arctic. Nonetheless, navigating decision-making in the Arctic proves challenging because of the array of opinions involved, a consequence of its shared nature (Cole et al. 2014). Border disputes remain among the eight Arctic countries (Schofield and Østhagen 2020) and multiscalar governance within and across boundaries impedes coordinated governance (Stephenson 2018; Linnebjerg et al. 2021). However, management and policy action are required to regulate and implement conservation action (Mills et al. 2013), so it is important to find ways to optimize management, in the form of regulations, policies, and decision-making, to advance conservation goals. These optimized management practices have been successful within the Arctic in the past through the implementation of effective policies such as the International Polar Bear Agreement (Prestrud and Stirling 1994), and coordination on marine mammal surveys (Boveng et al. 2017). Building on and continuing to find new solutions such as these will be paramount for Arctic biodiversity management. Horizon scan participants highlighted that this growth can be difficult however given the slow speed at which institutions react (see Table 2). Therefore, participants suggested that more timely decision-making would be possible if investments to support evidence-based policy-making was emphasized (see Table 2).

5.6. Design and implementation of conservation solutions

Conservation solutions aim to protect and preserve biodiversity and natural resources by addressing pressing environmental concerns with applied problem-solving conservation science (Gibbons et al. 2011). These solutions must be tested and an evidence base established so that the best interventions for threats to Arctic biodiversity can be implemented (i.e., so that the solutions can become actionable; Cooke et al. 2022). These solutions must also be robust and developed from numerous knowledge bases to ensure their effectiveness (Cooke et al. 2022). Such solutions might include designation of protected areas and other effective area-based conservation measures, restoration, and rehabilitation of habitat, or implementation of new technologies and legislations. Regardless of their form, however, any interventions must be implemented at the right time and scale and have the engagement of multidisciplinary actors to enact real change (Chapman et al. 2015). Innovative conservation solutions are needed to mitigate Arctic biodiversity loss, yet horizon scan participants emphasized that a lack of evidence and jurisdictional complexities cause difficulties in their design and execution (see Table 2). Participants suggested that identifying and agreeing upon national and international responsibilities and leveraging existing agreements would allow for these solutions to be implemented (see Table 2).

5.7. Identifying roles of stakeholders and Rights Holders

Stakeholders are individuals or groups that are affected by and (or) effect environmental management and policy decisions at different levels. Environmental decision-making in particular involves dialogue, communication, and collaboration with all stakeholders and Rights Holders. In rural societies, stakeholder participation facilitates decisions that lead to stronger environmental solutions (Berkes et al. 2007; Zikargae et al. 2022). Community inclusion and public engagement is especially important to foster trust, information sharing, encourage participation and action, and to ensure two-way communication (Cooke et al. 2013; Zikargae et al. 2022). There are an increasing number of examples where collaborative, community-scientist projects in the Arctic are producing strong, biodiversity-related knowledge with long-term support (e.g., Ostertag et al. 2018; Tomaselli et al. 2018; Mallory et al. 2022*b*). With respect to Arctic ecosystems, horizon scan participants indicated that identifying the roles that philanthropic organizations, leading institutions, places of higher education, and individuals play in helping to protect biodiversity can be difficult due to a lack of communication (see Table 2). Participants recommended that forums that bring people in different sectors and roles together to foster open communication be created and enhanced (see Table 2). With these roles identified, there can then be confidence that stakeholders and Rights Holders are not working against each other or duplicating efforts, both of which are essential given the limited resources available to study the Arctic (see Table 2).

6. Barriers

Arctic biodiversity faces many threats that do not have clear solutions (Prip 2016). In our workshop, participants identified several common barriers preventing more effective conservation efforts for protecting Arctic biodiversity from being implemented (see Tables 1 and 2, and Fig. 2). The most common barriers identified were issues surrounding funding for Arctic science. This is due to the costs of research in this region being disproportionately higher than in more southerly areas, even considering some of the special funds made available for this work (see Fig. 8; e.g., Mallory et al. 2018). Ibarguchi et al. (2018) argued that funding has not necessarily kept pace with the need to improve our understanding of the changing Arctic. This has led to inadequate resources to collect fundamental information, the inability to operate in the challenging Arctic environment, a restriction on the timespan over which research can be conducted, and limits to the relationships that can be formed with Indigenous Peoples (at a time when governments and Indigenous Peoples are actively seeking research engagement, e.g., ITK 2024). For example, a 2017 survey from 22 countries found that early career researchers value the knowledge of Indigenous Peoples but found that a lack of funding and a lack of networking opportunities were preventing more inclusive practices (Sjöberg et al. 2019). Furthermore, most funding applications require a proposal, but co-development of the proposal with local partners can require funding beforehand. This restricts inclusive conversations about Arctic conservation and considerations for Indigenous resources, research, knowledge, and ownership, and reduces opportunities for capacity-building and self-determination in research among Indigenous collaborators (e.g., Sadowsky et al. 2022). Increased funding between nations to allow international collaboration would also support initiatives such as open-access Arctic information leading to improved monitoring and access to fundamental information (Tulloch et al. 2015; CAFF 2017; Davidson et al. 2020).

Another common barrier identified by experts was that the Arctic is under the jurisdiction of numerous countries. International and jurisdictional boundaries as well as political unrest can prevent researchers from engaging in international research partnerships and restrict access to Arctic research infrastructure (Ruck et al. 2022). Additional barriers such as language and differences in attitudes towards Arctic conservation may also hinder conservation efforts. Furthermore, recent geo-political events have placed strain on international cooperation and have put a complete pause on important scientific communication and data sharing in some regards (Berkman et al. 2017; Koivurova and Shibata 2023; López-Blanco et al. 2024). We note, however, that the Arctic Council has modalities for the resumption of work at the working group level (Arctic Council 2023). International agreements such as the *Agreement on Enhancing International Arctic Scientific Cooperation* (2017) exist to reaffirm global efforts to cooperate scientifically in the Arctic (Berkman et al. 2017); however, these barriers are still prevalent.

An overall lack of fundamental information regarding Arctic ecosystems was another common barrier identified surrounding Arctic biodiversity conservation. The Arctic is a large, sparsely and patchily inhabited region, which remains one of the least explored regions on Earth (Gradinger et al. 2010; Virkkala et al. 2019). During our workshop, participants identified some of the largest knowledge gaps as being a lack of in situ data, a lack of confidence in existing data, poor understanding of how multiple stressors interact with one another, and a poor understanding of species behaviours in the Arctic region. Paleodata can help to fill in some missing information about the baseline history of the Arctic environment (Sun et al. 2013; Cohen 2018), a crucial aspect of predicting future environmental changes (Kaplan et al. 2003). However, logistical difficulties create challenges in understanding species and location-specific responses to threats leading to further gaps in fundamental information. Furthermore, the compounding effects of these various threat categories is complex and makes it difficult to tease out fundamental information specific to the Arctic. It is also difficult to influence policy-makers in implementing effective conservation without appropriate data to support recommendations, and data often cannot be collected without policy-maker support, creating wicked

Fig. 8. An extensive amount of research throughout the Arctic requires the use of helicopters to be able to access study sites. The costs associated with positioning the helicopters to the Arctic from the South as well as for caching the fuel these aircraft require for their use is astronomical. These high costs limit the amount of research that can take place. Photo by TAL taken in Resolute, Nunavut, July 2019.

problems (Mileski et al. 2018). However, inaction in the conservation of Arctic biodiversity due to not having the full picture is a management trap that must be overcome (DeFries and Nagendra 2017), given the current presence of threats outpacing the length of time it will take to collect data.

7. Ways to overcome barriers

Workshop participants also made numerous recommendations for overcoming these barriers such as increasing funding. Importantly, increasing funding to practices such as long-term data collection is key for establishing a baseline understanding of Arctic biodiversity that can be used to measure environmental change and other efforts; an area of research that currently lacks adequate support. Additionally, costs associated with collaboration, as well as working with northern communities (see Fig. 9), should be planned into budgets allowing for collaborative efforts to develop research projects and monitoring plans leading to better co-production between researchers and Arctic communities. Internationally pooled grants for globally shared issues were also suggested to remove barriers impeding international collaboration and to facilitate the inclusion of groups that are typically excluded and (or) have fewer resources.

The implementation of international agreements was also proposed as a method for overcoming barriers. Agreements suggested to include international treaties similar to the 1973 *Agreement on the Conservation of Polar Bears* (Lentfer 1974), global research networks like the Canada–Inuit Nunangat–United Kingdom Research Programme, global targets such as the Kunming–Montreal Global Biodiversity Framework (CBD 2022), and international organizations such as the International Arctic Science Committee. Strengthening existing agreements to conserve Arctic biodiversity such as the CAFF's Circumpolar Biodiversity Monitoring Program (CBMP; Barry et al. 2023) would also be key. Past international actions like the *Minamata Convention* (2013), a global legally binding agreement on mercury, have shown the impact that international cooperation can have (Platjouw et al. 2018). A large part of the scientific information that led to the *Minamata Convention* (2013) came from the Arctic Council's Arctic Monitoring and Assessment Programme working group (Platjouw et al. 2018), demonstrating the important role Arctic science can play in international conservation efforts. However, developing international action takes time, and scientists need a diverse set of tools to address issues that require fast solutions.

Additionally, workshop participants stated the need to improve access to data to make the information more accessible to the researchers and communities who need it. Increased international cooperation will improve this data sharing and monitoring programs (Prip 2016). Making data more accessible to those who need it is one of the goals of the CBMP. Barry et al. (2023) identified seven prerequisites to effective implementation of the CBMP as being effective coordination, sufficient and sustained funding, standards and protocols, co-production of knowledge, good data management, communication and outreach, and adequate resources to engage in international fora. Ensuring these prerequisites are met not only when utilizing the CBMP but for general cooperation in scientific endeavours would help to facilitate greater access to data as well as improved cooperation.

Fig. 9. An image of the community of Resolute, Nunavut in both the fall (top) and winter (bottom). Photo by TAL taken in Resolute, Nunavut, September 2019 and March 2018.

8. Actions that can be taken if able to overcome barriers

Actions that could be taken towards protecting Arctic biodiversity should the barriers be overcome were also discussed. The most common action identified was more inclusive participation in conservation efforts with involvement from northern communities throughout the Arctic region, an action that would be empowered with more funding and planned capacity for cooperation and inclusion (Doering et al. 2022; ITK 2024). Additionally, goals should go beyond inclusive participation to include self-determination for Indigenous communities. The *National Inuit Strategy on Research* (2018) lays out a plan for self-determination in research for Inuit communities and states that for self-determination to occur Inuit research objectives must no longer be marginalized and ignored by governments, researchers, and institutions, and that Inuit priorities should be made to be among the priorities of funding agencies (ITK 2024).

Another key action that could be taken with barriers removed is the global sharing of data using the FAIR and CARE principals (Carroll et al. 2021). Data sharing would allow scientists to harmonize data with one another by creating standards for data collection and storage (Barry et al. 2023) creating more comprehensive international datasets that are of greater use to the researchers and communities who need them. International data sharing has been suggested in the past as potentially beneficial if managed correctly and is most successful when participants are invested in maintaining datasets and ensuring their availability when needed (Gaiji et al. 2013; Chawinga and Zinn 2019). Currently, there are some mechanisms in place such as the Arctic Council and its affiliated working groups for international cooperation in the Arctic (Kankaanpää and Young 2012). This Council has had success identifying issues and presenting them to policymakers (Kankaanpää and Young 2012). Additional initiatives such as this that allow data sharing are essential for the implementation of effective conservation actions.

Collectively these actions would lead to an extension of the fundamental science available, potentially resulting in more informed international conservation decisions (Buxton et al. 2021). The availability of fundamental information would also enable the development of predictive models, allowing for the implementation of intervention measures, and overall enable proactive rather than reactive ecosystem management. However, having ample evidence for decision-making is just a first step as this information must also be translated into action towards conservation issues as a lack of information is not always the issue, but instead, it is often the mechanisms to actions that are lacking (Buxton et al. 2021). Therefore, with the barriers removed, the mobilization of this knowledge into action through mechanisms such as open science practices must also take place (Roche et al. 2022).

9. Persistent versus emerging threats

The Arctic Biodiversity Assessment (ABA; CAFF 2013*b*) was a multiyear scientific undertaking of over 250 contributors to assess the knowledge on the status and trends of Arctic biodiversity. This assessment included population size and distribution of Arctic species and, where available, presented projections of future change. The ABA discussed broad trends in habitat condition and extent, ecosystem function, and overall biodiversity, and identified important knowledge gaps and mechanisms driving change. This report and subsequent policy recommendations were delivered to the Arctic Council, with instructions for follow up in Arctic Council Ministerial Declarations. This horizon scan is markedly different to large-scale scientific reporting such as the ABA. Horizon scanning exercises can and should be conducted regularly to ensure expert opinion and up-to-date information is available for strategic decision-making and planning. As such, this horizon scan exercise for Arctic biodiversity provides a glimpse into the current status of this topic 11 years after the ABA.

All threats identified in this paper were also identified in the ABA. However, many of these threats have intensified since 2013 when the ABA was published. For example, shipping has increased in the Arctic (Dawson et al. 2018), more range shifts have been seen (Anderson et al. 2023), more sea ice has been lost (Kwok 2018), there has been an influx of disease (McLaughlin et al. 2024), and more development has taken place (Bartsch et al. 2021). Of note however is that while the categories in our actions theme were identified in the ABA, they were not identified as threats but as solutions. Yet when we sent out our call for questions for threats to Arctic biodiversity, these actions were all identified as threats. This shift in classification by experts from solutions to threats is likely due to the lack of implementation of these actions, as well as the inability to track their implementation, exacerbating the other direct threats to Arctic biodiversity mentioned. As such, we recommend that more rapid assessments by experts via regular horizon scanning for threats to Arctic biodiversity be conducted following this paper to allow for more timely and larger scale decision-making.

10. Limitations

While this study includes Arctic biodiversity experts from across continents, our workshop was limited by geographical time constraints, as international participation can be limited by different time zones and languages. Furthermore, while we attempted to reach participants from a broad range of affiliations and countries who had diverse roles in Arctic conservation, the majority of our participants were academic researchers from North America, which has the potential to bias our results. Also, a key limitation to our study was the lack of Indigenous participants. Additional, longer term approaches to Indigenous participation and other local traditional knowledge bases are essential, allowing for a more holistic view. In fact, we urge that this horizon scan be viewed as one that is limited by the experiences, perspectives, and biases of participants and should be complemented with additional scans focused on Indigenous knowledge and perspectives, and complementary fields of expertise. Doing so would require more time and resources than were available here.

11. Conclusion

The Arctic is an internationally shared and unique region and must be managed accordingly. Although many barriers are associated with this, the shared nature of the Arctic opens opportunities for collaboration, cross-boundary regulations, and knowledge sharing to optimize research investment. Ideas that came from this study should be seen as recommendations and used by a variety of disciplines (e.g., ecologists, policy-makers, protected area managers, government) to inform conservation decisions. Understanding and addressing the threats to Arctic biodiversity requires a holistic approach. The shared responsibility for the Arctic's future calls for sustained collaboration, informed decision-making, and adaptive management strategies. We reiterate here the biggest limitation in our review being a lack of Indigenous involvement and suggest additional efforts to capture Indigenous research priorities. Those efforts may be most effective at a local scale where Indigenous communities and governments can be involved in identifying research relevant to their contexts. Nonetheless, by identifying these persistent and emerging threats, recognizing common barriers, and proposing collaborative solutions, we hope this paper will contribute to the ongoing discourse on Arctic conservation and assist in moving it forward.

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References

Ainsworth, A., and Drake, D.R. 2020. Classifying Hawaiian plant species along a habitat generalist–specialist continuum: implications for species conservation under climate change. PLoS ONE, **15**: e0228573. doi:10.1371/journal.pone.0228573. PMID: 32032387.

Alaska Division of Environmental Conservation. 2024. Highly Pathogenic Avian Influenza (HPAI) Outbreaks and Biosecurity Toolkit from USDA APHIS[online]. Availablefrom https://dec.alaska.gov/eh/vet/announcements/avian-influenza-outbreaks/ [accessed 18 March 2024].

AMAP. 2021. Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway[online]. Availablefromhttps://www.amap.no/documents/doc/arctic-climate-change-update-2021-key-trends-and-impacts.-summary-for-policy-makers/3508 [accessed 10 March 2024].

Anderson, C.M., Fahrig, L., Rausch, J., Martin, J.-L., Daufresne, T., and Smith, P.A. 2023. Climate-related range shifts in Arctic-breeding shorebirds. Ecology and Evolution, **13**: e9797. doi:10.1002/ece3.9797. PMID: 36778838.

Anderson, C.M., Iverson, S.A., Black, A., Mallory, M.L., Hedd, A., Merkel, F., and Provencher, J.F. 2018. Modelling demographic impacts of a growing Arctic fishery on a seabird population in Canada and Greenland. Marine Environmental Research, **142**: 80–90. doi:10.1016/j.marenvres.2018.09.021. PMID: 30278994.

Anderson, J.C., Park, B.J., and Palace, V.P. 2016. Microplastics in aquatic environments: implications for Canadian ecosystems. Environmental Pollution, **218**: 269–280. doi:10.1016/j.envpol.2016.06.074. PMID: 27431693.

Arctic Council. 2009. Arctic Marine Shipping Assessment 2009 Report[online]. Availablefrom https://oaarchive.arctic-council.org/items/b01465f9-413d-4555-af59-07ddc7b7499a [accessed 19 November 2024].

Arctic Council. 2023. Three months into the Norwegian Chairship: a status update with SAO Chair Morten Høglund[online] Availablefrom https://arctic-council.org/news/three-months-into-the-norwegian-chairship-a-status-update-with-sao-chair-morten-hoglund/ [accessed 8 March 2024].

Aronsson, M., Heiðmarsson, S., Jóhannesdóttir, H., Barry, T., Braa, J., Burns, C.T., et al. 2021. State of the Arctic Terrestrial Biodiversity Report. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/b40d8974-9df6-4143-b669-346f35edd396/content [accessed 18 March 2024].

Barry, T., Christensen, T., Behe, C., Coon, C., Culp, J.M., Vongraven, D., et al. 2023. Development of a multi-scale monitoring programme: approaches for the Arctic and lessons learned from the Circumpolar

Biodiversity Monitoring Programme 2002–2022. Frontiers in Conservation Science, **4**: 1220521. doi:10.3389/fcosc.2023.1220521.

Bartsch, A., Pointner, G., Nitze, I., Efimova, A., Jakober, D., Ley, S., et al. 2021. Expanding infrastructure and growing anthropogenic impacts along Arctic coasts. Environmental Research Letters, **16**: 115013. doi:10.1088/1748-9326/ac3176.

Baselga, A., and Araújo, M.B. 2009. Individualistic vs community modelling of species distributions under climate change. Ecography, **32**: 55–65. doi:10.1111/j.1600-0587.2009.05856.x.

Beever, E.A., O'Leary, J., Mengelt, C., West, J.M., Julius, S., Green, N., et al. 2016. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conservation Letters, **9**: 131–137. doi:10.1111/conl.12190.

Berkes, F., Berkes, M., and Fast, H. 2007. Collaborative integrated management in Canada's North: the role of local and traditional knowledge and community-based monitoring. Coastal Management, **35**: 143–162. doi:10.1080/08920750600970487.

Berkman, P.A., and Vylegzhanin, A.N. (*Editors*). 2013. Environmental security in the Arctic Ocean. Springer, Dordrecht. doi:10.1007/978-94-007-4713-5.

Berkman, P.A., Kullerud, L., Pope, A., Vylegzhanin, A.N., and Young, O.R. 2017. The Arctic Science Agreement propels science diplomacy. Science, **358**: 596–598. doi:10.1126/science.aaq0890. PMID: 29097538.

Bluhm, B.A., Gebruk, A.V., Gradinger, R., Hopcroft, R.R., Huettmann, F., Kosobokova, K.N., et al. 2011. Arctic marine biodiversity: an update of species richness and examples of biodiversity change. Oceanography, **24**: 232–248. doi:10.5670/oceanog.2011.75.

Bock, N. 2013. Sustainable Development Considerations in the Arctic. *In* Environmental security in the Arctic Ocean. *Edited by* P.A. Berkman and A.N. Vylegzhanin. Springer, Dordrecht. pp. 37–57.

Bogoyavlenskiy, D., and Siggner, A. 2004. Arctic demography. *In* Arctic Human Development Report (AHDR). Stefansson Arctic Institute. pp. 27–41. Available from https://oaarchive.arctic-council.org/items/f6c63158-401c-4a14-a8d2-5bc9f10710bf [accessed 19 November 2024].

Botterell, Z.L.R., Bergmann, M., Hildebrandt, N., Krumpen, T., Steinke, M., Thompson, R.C., and Lindeque, P.K. 2022. Microplastic ingestion in zooplankton from the Fram Strait in the Arctic. Science of The Total Environment, **831**: 154886. doi:10.1016/j.scitotenv.2022.154886.

Boveng, P.L., Cameron, M.F., Conn, P.B., and Moreland, E.E. 2017. Abundance estimates of ice-associated seals: Bering Sea populations that inhabit the Chukchi Sea during the open-water period. Final Report. Bureau of Ocean Energy Management, Alaska Outer Continental Shelf Region, Anchorage, Alaska, USA[online]. Availablefrom https://espis.boem.gov/final%20reports/5578.PDF [accessed 19 November 2024].

Bunnefeld, N., Hoshino, E., and Milner-Gulland, E.J. 2011. Management strategy evaluation: a powerful tool for conservation? Trends in Ecology & Evolution, **26**: 441–447. doi:10.1016/j.tree.2011.05.003.

Burkow, I.C., and Kallenborn, R. 2000. Sources and transport of persistent pollutants to the Arctic. Toxicology Letters, **112-113**: 87–92. doi:10.1016/S0378-4274(99)00254-4.

Buxton, R.T., Bennett, J.R., Reid, A.J., Shulman, C., Cooke, S.J., Francis, C.M., et al. 2021. Key information needs to move from knowledge to action for biodiversity conservation in Canada. Biological Conservation, **256**: 108983. doi:10.1016/j.biocon.2021.108983.

CAFF and PAME. 2017. Arctic invasive alien species: strategy and action Plan. *In* Conservation of Arctic flora and fauna and protection of the Arctic marine environment, Akureyri, Iceland[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/c9cd06f5-fe87-4a9f-bf7b-137d892766c6/content [accessed 17 March 2024].

CAFF. 1997. Co-operative Strategy for the Conservation of Biological Diversity in the Arctic Region: Program for the Conservation of Arctic Flora and Fauna. Conservation of Arctic Flora and Fauna[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/d3148c85-434e-47e6-886e-9596e50bc78f/content [accessed 25 January 2024].

CAFF. 2001. Arctic Biodiversity Data Service—ABDS Catalog. Conservation of Arctic Flora and Fauna[online]. Available from https://geo.abds.is/geonetwork/srv/eng/catalog.search#/metadata/f0eb86a7-e408-4138-9432-dedb991f13d1 [accessed 9 April 2024].

CAFF. 2013a. Arctic Biodiversity Assessment: Report for Policy Makers. Conservation of Arctic Flora and Fauna, Akureyri, Iceland[online]. Available: https://oaarchive.arctic-council.org/server/api/core/bitstreams/564e2092-c358-4673-9e4a-fd40ee948252/content [accessed 19 November 2024].

CAFF. 2013b. Arctic Biodiversity Assessment: Status and Trends in Arctic Biodiversity. *In* Conservation of Arctic Flora and Fauna (CAFF). *Edited by* H. Meltofte, A.B. Josefson and D. Payer. Akureyri, Iceland.

CAFF. 2017. State of the Arctic Marine Biodiversity Report. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland[online] Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/e4f859d4-8396-4300-a4f0-878ab96f2ec3/content [accessed 19 November 2024].

Caliendo, V., Lewis, N.S., Pohlmann, A., Baillie, S.R., Banyard, A.C., Beer, M., et al. 2022. Transatlantic spread of highly pathogenic avian influenza H5N1 by wild birds from Europe to North America in 2021. Scientific Reports, **12**: 11729. doi:10.1038/s41598-022-13447-z.

Callaghan, T.V., Björn, L.O., Chernov, Y., Chapin, T., Christensen, T.R., Huntley, B., et al. 2004. Biodiversity, distributions and adaptations of Arctic species in the context of environmental change. AmbioAMBIO, **33**: 404–417. doi:10.1579/0044-7447-33.7.404.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., et al. 2012. Biodiversity loss and its impact on humanity. Nature, **486**: 59–67. doi:10.1038/nature11148. PMID: 22678280.

Carroll, S.R., Herczog, E., Hudson, M., Russell, K., and Stall, S. 2021. Operationalizing the CARE and FAIR Principles for Indigenous data futures. Scientific Data, **8**: 108. doi:10.1038/s41597-021-00892-0. PMID: 33863927.

CBD. 2000. Sustaining life on earth: how the convention on biological diversity promotes nature and human well-being. Secretariat of the Convention on Biological Diversity, Montreal [online]. Availablefrom https://www.cbd.int/doc/publications/cbd-sustain-en.pdf [accessed 19 November 2024].

CBD. 2022. COP15: Final text of Kunming–Montreal Global Biodiversity Framework. Secretariat of the Convention on Biological Diversity, Montreal[online]. Availablefrom https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222 [accessed 19 November 2024].

Chapman, J.M., Algera, D., Dick, M., Hawkins, E.E., Lawrence, M.J., Lennox, R.J., et al. 2015. Being relevant: practical guidance for early career researchers interested in solving conservation problems. Global Ecology and Conservation, **4**: 334–348. doi:10.1016/j.gecco.2015.07.013.

Chawinga, W.D., and Zinn, S. 2019. Global perspectives of research data sharing: a systematic literature review. Library & Information Science Research, **41**: 109–122. doi:10.1016/j.lisr.2019.04.004.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., and Thomas, C.D. 2011. Rapid range shifts of species associated with high levels of climate warming. Science, **333**: 1024–1026. doi:10.1126/science.1206432. PMID: 21852500.

Cherry, S.G., Derocher, A.E., Thiemann, G.W., and Lunn, N.J. 2013. Migration phenology and seasonal fidelity of an Arctic marine predator in relation to sea ice dynamics. Journal of Animal Ecology, **82**: 912–921. doi:10.1111/1365-2656.12050.

Christensen, T., Coon, C., Fletcher, S., Barry, T., and Lárusson, K.F. 2021. Circumpolar Biodiversity Monitoring Program Strategic Plan: 2021–2025. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland.

Christensen, T., Payne, J., Doyle, M., Ibarguchi, G., Taylor, M., Schmidt, N.M., et al. 2013. The Arctic Terrestrial Biodiversity Monitoring Plan. CAFF Monitoring Series Report Nr. 7. CAFF International Secretariat, Akureyri, Iceland[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/f21ba9f8-3f6b-4f44-a2ed-d946f96f5922/content[accessed 18 March 2024].

Coffin, A.W. 2007. From roadkill to road ecology: a review of the ecological effects of roads. Journal of Transport Geography, **15**: 396–406. doi:10.1016/j.jtrangeo.2006.11.006.

Cohen, A.S. 2018. The past is a key to the future: lessons paleoecological data can provide for management of the African Great Lakes. Journal of Great Lakes Research, **44**: 1142–1153. doi:10.1016/j.jglr.2017.10.001.

Cohen, J. 2023. Lurking in the deep freeze? Science, **381**: 1406–1407. doi:10.1126/science.adl0420. PMID: 37769079.

Cole, S., Izmalkov, S., and Sjöberg, E. 2014. Games in the Arctic: applying game theory insights to Arctic challenges. Polar Research, **33**: 23357. doi:10.3402/polar.v33.23357.

Cooke, S.J., Lapointe, N.W.R., Martins, E.G., Thiem, J.D., Raby, G.D., Taylor, M.K., et al. 2013. Failure to engage the public in issues related to inland fishes and fisheries: strategies for building public and political will to promote meaningful conservation. Journal of Fish Biology, **83**: 997–1018. doi:10.1111/jfb.12222.

Cooke, S.J., Michaels, S., Nyboer, E.A., Schiller, L., Littlechild, D.B.R., Hanna, D.E.L., et al. 2022. Reconceptualizing conservation. PLOS Sustainability and Transformation, **1**: e0000016. doi:10.1371/journal.pstr.0000016.

Cottier-Cook, E.J., Bentley-Abbot, J., Cottier, F.R., Minchin, D., Olenin, S., and Renaud, P.E. 2024. Horizon scanning of potential threats to high-Arctic biodiversity, human health and the economy from marine invasive alien species: a Svalbard case study. Global Change Biology, **30**: e17009. doi:10.1111/gcb.17009.

Coupel, P., Ruiz-Pino, D., Sicre, M.A., Chen, J.F., Lee, S.H., Schiffrine, N., et al. 2015. The impact of freshening on phytoplankton production in the Pacific Arctic Ocean. Progress in Oceanography, **131**: 113–125. doi:10.1016/j.pocean.2014.12.003.

Courchamp, F., Dunne, J.A., Le Maho, Y., May, R.M., Thébaud, C., and Hochberg, M.E. 2015. Fundamental ecology is fundamental. Trends in Ecology & Evolution, **30**: 9–16. doi:10.1016/j.tree.2014.11.005.

Cuhls, K.E. 2019. Horizon scanning in foresight—why horizon scanning is only a part of the game. Futures & Foresight Science, **2**(1): e23. doi:10.1002/ffo2.23.

Culp, J.M., Goedkoop, W., Lento, J., Christoffersen, K.S., Frenzel, S., Guðbergsson, G., et al. 2012. The Arctic Freshwater Biodiversity Monitoring Plan. CAFF Monitoring Series Report Nr. 7. CAFF International Secretariat, Akureyri, Iceland[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/8cf7b38a-b59d-46a8-8bda-ee3024891b84/content [accessed 18 March 2024].

Dabros, A., Pyper, M., and Castilla, G. 2018. Seismic lines in the boreal and arctic ecosystems of North America: environmental impacts, challenges, and opportunities. Environmental Reviews, **26**: 214–229. doi:10.1139/er-2017-0080.

Dahlberg, A., and Bültmann, H. 2013. Fungi. *In* Arctic biodiversity assessment: status and trends in Arctic biodiversity. *Edited by* H. Meltofte, A.B. Josefson and D. Payer. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland. pp. 355–371.

Davidson, S.C., Bohrer, G., Gurarie, E., LaPoint, S., Mahoney, P.J., Boelman, N.T., et al. 2020. Ecological insights from three decades of animal movement tracking across a changing Arctic. Science, **370**: 712–715. doi:10.1126/science.abb7080. PMID: 33154141.

Dawson, J., Pizzolato, L., Howell, S.E.L., Copland, L., and Johnston, M.E. 2018. Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. Arctic, **71**: 15–27. doi:10.14430/arctic4698.

de Hoop, L., Schipper, A.M., Leuven, R.S.E.W., Huijbregts, M.A.J., Olsen, G.H., Smit, M.G.D., and Hendriks, A.J. 2011. Sensitivity of polar and temperate marine organisms to oil components. Environmental Science & Technology, **45**: 9017–9023. doi:10.1021/es202296a.

DeFries, R., and Nagendra, H. 2017. Ecosystem management as a wicked problem. Science, **356**: 265–270. doi:10.1126/science.aal1950 10.1126/science.aal1950. PMID: 28428392.

Depledge, D., and Kennedy-Pipe, C. 2018. The changing world of the Arctic. Geography, **103**: 154–161. doi:10.1080/00167487.2018.12094052.

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A., et al. 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. Science, **366**: eaax3100. doi:10.1126/science.aax3100. PMID: 31831642.

Doering, N.N., Dudeck, S., Elverum, S., Fisher, C., Henriksen, J.E., Hermann, T.M., et al. 2022. Improving the relationships between Indigenous Rights Holders and researchers in the Arctic: an invitation for change in funding and collaboration. Environmental Research Letters, **17**: 065014. doi:10.1088/1748-9326/ac72b5.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., et al. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews, **81**: 163–182. doi:10.1017/S1464793105006950.

Dunlop, R.A. 2019. The effects of vessel noise on the communication network of humpback whales. Royal Society Open Science, **6**: 190967. doi:10.1098/rsos.190967.

Dyck, C. 2024. On thin ice: the Arctic Council's uncertain future. Marine Policy, **163**: 106060. doi:10.1016/j.marpol.2024.106060.

Eamer, J., Donaldson, G., Gaston, A., Kosobokova, K., Lárusson, K., Melnikov, I. et al., 2013. Life Linked to Ice. A guide to sea-ice-associated biodiversity in this time of rapid change Vol. Conservation of Arctic Flora and Fauna (CAFF). http://hdl.handle.net/11374/239. Iceland. pp. 116.

Fa, J.E., Watson, J.E., Leiper, I., Potapov, P., Evans, T.D., Burgess, N.D., et al. 2020. Importance of Indigenous Peoples' lands for the conservation of Intact Forest Landscapes. Frontiers in Ecology and the Environment, **18**: 135–140. doi:10.1002/fee.2148.

Fauchald, P., Arneberg, P., Debernard, J.B., Lind, S., Olsen, E., and Hausner, V.H. 2021. Poleward shifts in marine fisheries under Arctic warming. Environmental Research Letters, **16**: 074057. doi:10.1088/1748-9326/ac1010.

Fedorov, V.B., Trucchi, E., Goropashnaya, A.V., Waltari, E., Whidden, S.E., and Stenseth, N.Chr. 2020. Impact of past climate warming on genomic diversity and demographic history of collared lemmings across the Eurasian Arctic. Proceedings of the National Academy of Sciences, **117**: 3026–3033. doi:10.1073/pnas.1913596117.

Gaiji, S., Chavan, V., Ariño, A.H., Otegui, J., Hobern, D., Sood, R., and Robles, E. 2013. Content assessment of the primary biodiversity data published through GBIF network: status, challenges and potentials. Biodiversity Informatics, **8**. doi:10.17161/bi.v8i2.4124.

Gauthier, G., Bêty, J., Cadieux, M.-C., Legagneux, P., Doiron, M., Chevallier, C., et al. 2013. Long-term monitoring at multiple trophic levels suggests heterogeneity in responses to climate change in the Canadian Arctic tundra. Philosophical Transactions of the Royal Society B: Biological Sciences, **368**: 20120482. doi:10.1098/rstb.2012.0482.

Gibbons, D.W., Wilson, J.D., and Green, R.E. 2011. Using conservation science to solve conservation problems. Journal of Applied Ecology, **48**: 505–508. doi:10.1111/j.1365-2664.2011.01997.x.

Gill, M.J., Crane, K., Hindrum, R., Arneberg, P., Bysveen, I., Denisenko, N.V., et al. 2011. Arctic Marine Biodiversity Monitoring Plan (CBMP-MARINE PLAN). CAFF Monitoring Series Report No.3. CAFF International Secretariat, Akureyri, Iceland[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/0567a2b3-ca08-4bd5-830c-72d312f128c1/content [accessed 18 March 2024].

Gradinger, R., Bluhm, B.A., Hopcroft, R.R., Gebruk, A.V., Kosobokova, K., Sirenko, B., and Węsławski, J.M. 2010. Marine life in the Arctic. *In* Life in the world's oceans. 1st ed. *Edited by* A.D. McIntyre. Wiley. pp. 183–202. doi:10.1002/9781444325508.ch10.

Grajal-Puche, A., Driver, E.M., and Propper, C.R. 2024. Abandoned mines as a resource or liability for wildlife. Science of The Total Environment, **921**: 171017. doi:10.1016/j.scitotenv.2024.171017. PMID: 38369145.

Guerrero, A.I., and Rogers, T.L. 2019. From low to high latitudes: changes in fatty acid desaturation in mammalian fat tissue suggest a thermoregulatory role. BMC Evolutionary Biology, **19**: 155. doi:10.1186/s12862-019-1473-5.

Halliday, W.D., Le Baron, N., Citta, J.J., Dawson, J., Doniol-Valcroze, T., Ferguson, M., et al. 2022. Overlap between bowhead whales (*Balaena mysticetus*) and vessel traffic in the North American Arctic and implications for conservation and management. Biological Conservation, **276**: 109820. doi:10.1016/j.biocon.2022.109820.

Halliday, W.D., Pine, M.K., and Insley, S.J. 2020. Underwater noise and Arctic marine mammals: review and policy recommendations. Environmental Reviews, **28**(4): 438–448. doi:10.1139/er-2019-0033.

Hansen, B.B., Isaksen, K., Benestad, R.E., Kohler, J., Pedersen, Å.Ø., Loe, L.E., et al. 2014. Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic. Environmental Research Letters, **9**: 114021. doi:10.1088/1748-9326/9/11/114021.

Harper, M., Mejbel, H.S., Longert, D., Abell, R., Beard, T.D., Bennett, J.R., et al. 2021. Twenty-five essential research questions to inform the protection and restoration of freshwater biodiversity. Aquatic Conservation: Marine and Freshwater Ecosystems, **31**: 2632–2653. doi:10.1002/aqc.3634.

Harsem, Ø., Eide, A., and Heen, K. 2011. Factors influencing future oil and gas prospects in the Arctic. Energy Policy, **39**: 8037–8045. doi:10.1016/j.enpol.2011.09.058.

Heleniak, T., and Bogoyavlensky, D. 2014. Arctic populations and migration. *In* Arctic Human Development Report: Regional Processes and Global Linkages. *Edited by* J.N. Larsen and G. Fondahl. Norden. pp. 53–104. Available fromhttps://norden.diva-portal.org/smash/get/diva2:788965/FULLTEXT03.pdf [accessed 19 November 2024].

Hendriks, A.J., Traas, T.P., and Huijbregts, M.A.J. 2005. Critical body residues linked to octanol–water partitioning, organism composition, and LC50 QSARs: meta-analysis and model. Environmental Science & Technology, **39**: 3226–3236. doi:10.1021/es048442o.

Henri, D.A., Jean-Gagnon, F., and Gilchrist, H.G. 2018. Using Inuit traditional ecological knowledge for detecting and monitoring avian cholera among Common Eiders in the eastern Canadian Arctic. Ecology and Society, **23**. doi:10.5751/ES-09289-230122.

Hensz, C.M., and Soberón, J. 2018. Participation in the convention on migratory species: a biogeographic assessment. Ambio, **47**: 739–746. doi:10.1007/s13280-018-1024-0. PMID: 29478179.

Hillebrand, H., Blasius, B., Borer, E.T., Chase, J.M., Downing, J.A., Eriksson, B.K., et al. 2018. Biodiversity change is uncoupled from species richness trends: consequences for conservation and monitoring. Journal of Applied Ecology, **55**: 169–184. doi:10.1111/1365-2664.12959.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.L., et al. 2014. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences, **11**: 6573–6593. doi:10.5194/bg-11-6573-2014.

Hulme, P.E. 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. Journal of Applied Ecology, **46**: 10–18. doi:10.1111/j.1365-2664.2008.01600.x.

Humble, L. 2010. Pest risk analysis and invasion pathways—insects and wood packing revisited: what have we learned? New Zealand Journal of Forestry Science.

Ibarguchi, G., Rajdev, V., and Murray, M.S. 2018. Are current research funding structures sufficient to address rapid Arctic change in a meaningful way? Polar Research, **37**: 1540242. doi:10.1080/17518369.2018.1540242.

Inuit Circumpolar Council. 2022. Circumpolar Inuit Protocols for Equitable and Ethical Engagement. Report, Inuit Circumpolar Council. doi:10.25607/OBP-1874.

IPBES. 2018. Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental SciencePolicy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany[online]. Availablefrom https://api.research-repository.uwa.edu.au/ws/portalfiles/portal/35387924/2018_LDR_SPM_digital_layout_FINAL.pdf.

IPCC. 2022. Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. 1st ed. Cambridge University Press. doi:10.1017/9781009157988.

ITK. 2024. National Inuit Strategy on Research. Inuit Tapiriit Kanatami, Ottawa, Ontario, Canada[online]. Availablefrom https://www.itk.ca/projects/national-inuit-strategy-on-research/ [accessed 8 March 2024].

Johnson, C.J., Boyce, M.S., Case, R.L., Cluff, H.D., Gau, R.J., Gunn, A., and Mulders, R. 2005. Cumulative effects of human developments on arctic wildlife. Wildlife monographs, **160**(1): 1–36. doi:10.2193/0084-0173(2005)160%5b1:CEOHDO%5d2.0.CO;2.

Joly, K., Gurarie, E., Hansen, D.A., and Cameron, M.D. 2021. Seasonal patterns of spatial fidelity and temporal consistency in the distribution and movements of a migratory ungulate. Ecology and Evolution, **11**: 8183–8200. doi:10.1002/ece3.7650.

Jones, T., McLennan, D., Behe, C., Arvnes, M., Wesseberg, S., Sergienko, L., et al. 2019. Arctic Coastal Biodiversity Monitoring Plan. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland[online]. Availablefrom https://oaarchive.arctic-council.org/server/api/core/bitstreams/3b6ef816-3e42-4ccb-ad3b-d2e352fd1497/content [accessed 18 March 2024].

Kafle, P., Peller, P., Massolo, A., Hoberg, E., Leclerc, L.-M., Tomaselli, M., and Kutz, S. 2020. Range expansion of muskox lungworms track rapid arctic warming: implications for geographic colonization under climate forcing. Scientific Reports, **10**: 17323. doi:10.1038/s41598-020-74358-5.

Kankaanpää, P., and Young, O.R. 2012. The effectiveness of the Arctic Council. Polar Research, **31**: 17176. doi:10.3402/polar.v31i0.17176.

Kaplan, J.O., Bigelow, N.H., Prentice, I.C., Harrison, S.P., Bartlein, P.J., Christensen, T.R., et al. 2003. Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections. Journal of Geophysical Research: Atmospheres, **108**: D19:8171. doi:10.1029/2002JD002559.

Kellner, F.L., Le Moullec, M., Ellegaard, M.R., Rosvold, J., Peeters, B., Burnett, H.A., et al. 2024. A palaeogenomic investigation of overharvest implications in an endemic wild reindeer subspecies. Molecular Ecology, **33**: e17274. doi:10.1111/mec.17274.

Koivurova, T., and Shibata, A. 2023. After Russia's invasion of Ukraine in 2022: can we still cooperate with Russia in the Arctic? Polar Record, **59**: e12. doi:10.1017/S0032247423000049.

Kovacs, K.M., Lydersen, C., Overland, J.E., and Moore, S.E. 2011. Impacts of changing sea-ice conditions on Arctic marine mammals. Marine Biodiversity, **41**: 181–194. doi:10.1007/s12526-010-0061-0.

Kwok, R. 2018. Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). Environmental Research Letters, **13**: 105005. doi:10.1088/1748-9326/aae3ec.

Laidre, K.L., Stern, H., Kovacs, K.M., Lowry, L., Moore, S.E., Regehr, E.V., et al. 2015. Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. Conservation Biology, **29**: 724–737. doi:10.1111/cobi.12474.

Léandri-Breton, D., Tarroux, A., Elliott, K., Legagneux, P., Angelier, F., Blévin, P., et al. 2021. Long-term tracking of an Arctic-breeding seabird indicates high fidelity to pelagic wintering areas. Marine Ecology Progress Series, **676**: 205–218. doi:10.3354/meps13798.

Lee, M.M., Jaspers, V.L.B., Gabrielsen, G.W., Jenssen, B.M., Ciesielski, T.M., Mortensen, Å.-K., et al. 2020. Evidence of avian influenza virus in seabirds breeding on a Norwegian high-Arctic archipelago. BMC Veterinary Research, **16**: 48. doi:10.1186/s12917-020-2265-2.

Legg, C.J., and Nagy, L. 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management, **78**: 194–199. doi:10.1016/j.jenvman.2005.04.016.

Lennox, R.J., Berntsen, H.H., Garseth, Å.H., Hinch, S.G., Hindar, K., Ugedal, O., et al. 2023. Prospects for the future of pink salmon in three oceans: from the native Pacific to the novel Arctic and Atlantic. Fish and Fisheries, **24**: 759–776. doi:10.1111/faf.12760.

Lentfer, J. 1974. Agreement on conservation of Polar Bears. Polar Record, **17**: 327–330. doi:10.1017/S0032247400032071.

Li, H., and Fedorov, A.V. 2021. Persistent freshening of the Arctic Ocean and changes in the North Atlantic salinity caused by Arctic sea ice decline. Climate Dynamics, **57**: 2995–3013. doi:10.1007/s00382-021-05850-5.

Lifshits, S., Glyaznetsova, Y., Erofeevskaya, L., Chalaya, O., and Zueva, I. 2021. Effect of oil pollution on the ecological condition of soils and bottom sediments of the arctic region (Yakutia). Environmental Pollution, **288**: 117680. doi:10.1016/j.envpol.2021.117680.

Lindenmayer, D.B., and Likens, G.E. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends in Ecology & Evolution, **24**: 482–486. doi:10.1016/j.tree.2009.03.005.

Linnebjerg, J.F., Baak, J.E., Barry, T., Gavrilo, M.V., Mallory, M.L., Merkel, F.R., et al. 2021. Review of plastic pollution policies of Arctic countries in relation to seabirds. FACETS, **6**: 1–25. doi:10.1139/facets-2020-0052.

López-Blanco, E., Topp-Jørgensen, E., Christensen, T.R., Rasch, M., Skov, H., Arndal, M.F., et al. 2024. Towards an increasingly biased view on Arctic change. Nature Climate Change, **14**: 152–155. doi:10.1038/s41558-023-01903-1.

Ma, J., Hung, H., Tian, C., and Kallenborn, R. 2011. Revolatilization of persistent organic pollutants in the Arctic induced by climate change. Nature Climate Change, **1**(5): 255–260. doi:10.1038/nclimate1167.

Magurran, A.E., Baillie, S.R., Buckland, S.T., Dick, J.McP., Elston, D.A., Scott, E.M., et al. 2010. Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time. Trends in Ecology & Evolution, **25**: 574–582. doi:10.1016/j.tree.2010.06.016.

Mallory, M.L., Gilchrist, H.G., Janssen, M., Major, H.L., Merkel, F., Provencher, J.F., and Strom, H. 2018. Financial costs of conducting science in the Arctic: examples from seabird research. Arctic Science, **4**: 624–633. doi:10.1139/as-2017-0019.

Mallory, M.L., Robertson, G.J., Keegan, S., Pollet, I.L., Harris, L.N., Jivan, T., and Provencher, J.F. 2022a. Bycatch of loons assessed in coastal Arctic char fisheries in the Canadian Arctic. North American Journal of Fisheries Management, **42**(5): 1215–1225. doi:10.1002/nafm.10813.

Mallory, M.L., Toomasie, J., Emond, S., Lamarche, G., Roberts, L., Pirie-Dominix, L., and Provencher, J.F. 2022b. Community-scientist collaboration in the creation, management and research for two National Wildlife Areas in Arctic Canada. *In* Advances in Ecological Research, 66. pp. 37–61. doi:10.1016/bs.aecr.2022.04.002.

McGuire, A.D., Chapin, F.S., Walsh, J.E., and Wirth, C. 2006. Integrated regional changes in Arctic climate feedbacks: implications for the global climate system. Annual Review of Environment and Resources, **31**: 61–91. doi:10.1146/annurev.energy.31.020105.100253.

McLaughlin, A., Giacinti, J., Rahman, I., Wight, J., Hargan, K., Lang, A., et al. 2024. Spatiotemporal prevalence patterns of low and highly pathogenic avian influenza virus in murres in Canada from 2007–2022—a case study for wildlife viral monitoring. FACETS, **9**: 1–13, accepted. doi:10.1139/facets-2023-0185.

McRae, L., Böhm, M., Deinet, S., Gill, M., and Collen, B. 2012. The Arctic Species Trend Index: using vertebrate population trends to monitor the health of a rapidly changing ecosystem. Biodiversity, **13**: 144–156. doi:10.1080/14888386.2012.705085.

Mearns, R., and Norton, A. 2010. Equity and vulnerability in a warming world: introduction and overview. *In* Social dimensions of climate change: equity and vulnerability in a warming world. *Edited by* R. Mearns and A. Norton. pp. 1–44. The World Bank, Washington, D.C.[online] Availablefrom https://openknowledge.worldbank.org/server/api/core/bitstreams/57ef7f5d-df55-552f-91b8-843eb7b286a3/content [accessed 19 November 2024].

Mellows, A., Barnett, R., Dalén, L., Sandoval-Castellanos, E., Linderholm, A., McGovern, T.H., et al. 2012. The impact of past climate change on genetic variation and population connectivity in the Icelandic arctic fox. Proceedings of the Royal Society B: Biological Sciences, **279**: 4568–4573. doi:10.1098/rspb.2012.1796.

Mileski, J., Gharehgozli, A., Ghoram, L., and Swaney, R. 2018. Cooperation in developing a disaster prevention and response plan for Arctic shipping. Marine Policy, **92**: 131–137. doi:10.1016/j.marpol.2018.03.003.

Mills, M., Pressey, R.L., Ban, N.C., Foale, S., Aswani, S., and Knight, A.T. 2013. Understanding characteristics that define the feasibility of conservation actions in a common pool marine resource governance system. Conservation Letters, **6**: 418–429. doi:10.1111/conl.12025.

Mishra, A.K., Singh, J., and Mishra, P.P. 2021. Microplastics in polar regions: an early warning to the world's pristine ecosystem. Science of The Total Environment, **784**: 147149. doi:10.1016/j.scitotenv.2021.147149.

Mustonen, T., and Ford, V. 2013. Indigenous Peoples and biodiversity in the Arctic. *In* Arctic biodiversity assessment: status and trends in Arctic biodiversity. *Edited by* H. Meltofte, A.B. Josefson and D. Payer. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland. pp. 18–19.

National Defence, R.C.N. 2021. New sonar system tested aboard Harry DeWolf[online]. Availablefrom https://www.canada.ca/en/department-national-defence/maple-leaf/rcn/2021/12/new-sonar-system-tested-aboard-harry-dewolf.html [accessed 11 December 2023].

National Snow and Ice Data Center. 2023. Frozen ground & permafrost[online]. Availablefrom https://nsidc.org/learn/parts-cryosphere/frozen-ground-permafrost [accessed 13 December 2023].

Nekrich, A. 2020. Community-based resource management in the Arctic: transformation caused by the changing environment. IOP Conference Series: Earth and Environmental Science, **539**: 012178. doi:10.1088/1755-1315/539/1/012178.

Nitah, S. 2021. Indigenous Peoples proven to sustain biodiversity and address climate change: now it's time to recognize and support this leadership. One Earth, **4**: 907–909. doi:10.1016/j.oneear.2021.06.015.

Nuttall, M. 2007. An environment at risk: Arctic Indigenous peoples, local livelihoods and climate change. *In* Arctic Alpine Ecosystems and People in a changing environment. *Edited by* J.B. Ørbæk, R. Kallenborn, I. Tombre, E.N. Hegseth, S. Falk-Petersen and A.H. Hoel. Springer Berlin Heidelberg, Berlin, Heidelberg. pp. 19–35. doi:10.1007/978-3-540-48514-8_2.

Obu, J. 2021. How much of the Earth's surface is underlain by permafrost? Journal of Geophysical Research: Earth Surface, **126**: e2021JF006123. doi:10.1029/2021JF006123.

Ostertag, S.K., Loseto, L.L., Snow, K., Lam, J., Hynes, K., and Gillman, D.V. 2018. "That's how we know they're healthy": the inclusion of traditional ecological knowledge in beluga health monitoring in the Inuvialuit Settlement Region. Arctic Science, **4**: 1–29. doi:10.1139/as-2017-0050.

Pálsdóttir, A.E., Gill, J.A., Pálsson, S., Alves, J.A., Méndez, V., Þórisson, B., and Gunnarsson, T.G. 2022. Effects of overhead power-lines on the density of ground-nesting birds in open sub-arctic habitats. Ibis, **164**: 1257–1264. doi:10.1111/ibi.13089.

PAME. 2024. Arctic Ship Traffic Data—ASTD. PAME. Available from https://pame.is/index.php/projects/arctic-marine-shipping/astd [accessed 19 November 2024].

Parkinson, A.J., Evengard, B., Semenza, J.C., Ogden, N., Børresen, M.L., Berner, J., et al. 2014. Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. International Journal of Circumpolar Health, **73**: 25163. doi:10.3402/ijch.v73.25163.

Patrohay, E., Gradinger, R., Marquardt, M., and Bluhm, B.A. 2022. First trait-based characterization of Arctic ice meiofauna taxa. Polar Biology, **45**: 1673–1688. Springer. doi:10.1007/s00300-022-03099-0.

Payer, D.C., Josefson, A.B., and Fjeldså, J. 2013. Species diversity in the Arctic. *In* Arctic biodiversity assessment: status and trends in Arctic biodiversity. *Edited by* H. Meltofte, A.B. Josefson and D. Payer. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland [online]. pp. 67–77. Available from https://www.google.com/url?q=https://oaarchive.arctic-council.org/items/b32baf29-d9d7-4c9e-8598-877db37141da&sa=D&source=docs&ust=1709495265464127&usg=AOvVaw2Q4Uuyu-V_F-1Jyt9srwvu. [accessed 19 November 2024].

Platjouw, F.M., Steindal, E.H., and Borch, T. 2018. From Arctic science to international law: the road towards the Minamata Convention and the role of the Arctic Council. Arctic Review on Law and Politics, **9**: 226–243. doi:10.23865/arctic.v9.1234.

Post, E., Alley, R.B., Christensen, T.R., Macias-Fauria, M., Forbes, B.C., Gooseff, M.N., et al. 2019. The polar regions in a 2 °C warmer world. Science Advances, **5**: eaaw9883. doi:10.1126/sciadv.aaw9883.

Prestrud, P., and Stirling, I. 1994. The International Polar Bear Agreement and the current status of polar bear conservation. Aquatic Mammals, **20**: 113–124.

Prip, C. 2016. The Arctic Council and biodiversity—need for a stronger management framework? Nordic Environmental Law Journal, **2**: 37–53.

Provencher, J.F., Aliani, S., Bergmann, M., Bourdages, M., Buhl-Mortensen, L., Galgani, F., et al. 2023. Future monitoring of litter and microplastics in the Arctic—challenges, opportunities, and strategies. Arctic Science, **9**: 209–226. doi:10.1139/as-2022-0011.

Prowse, T., Bring, A., Mård, J., Carmack, E., Holland, M., Instanes, A., et al. 2015. Arctic freshwater synthesis: summary of key emerging issues. Journal of Geophysical Research: Biogeosciences, **120**: 1887–1893. doi:10.1002/2015JG003128.

Pucko, C., Beckage, B., Perkins, T., and Keeton, W.S. 2011. Species shifts in response to climate change: individual or shared responses? The Journal of the Torrey Botanical Society, **138**: 156–176. doi:10.3159/TORREY-D-10-00011.1.

Qi, X., Li, Z., Zhao, C., Zhang, Q., and Zhou, Y. 2024. Environmental impacts of Arctic shipping activities: a review. Ocean & Coastal Management, **247**: 106936. doi:10.1016/j.ocecoaman.2023.106936.

Rantanen, M., Karpechko, A.Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, **3**: 168. doi:10.1038/s43247-022-00498-3.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., et al. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews, **94**: 849–873. doi:10.1111/brv.12480.

Revich, B., Tokarevich, N., and Parkinson, A.J. 2012. Climate change and zoonotic infections in the Russian Arctic. International Journal of Circumpolar Health, **71**: 18792–18798. doi:10.3402/ijch.v71i0.18792.

Ricketts, M.P., Matamala, R., Jastrow, J.D., Antonopoulos, D.A., Koval, J., Ping, C.-L., et al. 2020. The effects of warming and soil chemistry on bacterial community structure in Arctic tundra soils. Soil Biology and Biochemistry, **148**: 107882. doi:10.1016/j.soilbio.2020.107882.

Robinson, S.D., Turetsky, M.R., Kettles, I.M., and Wieder, R.K. 2003. Permafrost and peatland carbon sink capacity with increasing latitude. *In* Proceedings of the 8th International Conference on Permafrost. LEIDEN, A A Balkema Publishers. pp. 965–970.

Roche, D.G., O'Dea, R.E., Kerr, K.A., Rytwinski, T., Schuster, R., Nguyen, V.M., et al. 2022. Closing the knowledge–action gap in conservation with open science. Conservation Biology, **36**: e13835. doi:10.1111/cobi.13835.

Ruck, K., Arndal, M., Biebow, N., Dahl, J., Flått, S., Granskog, M., et al. 2022. International access to research infrastructure in the Arctic. Polar Record, **58**. doi:10.1017/S0032247422000249.

Runge, C.A., Daigle, R.M., and Hausner, V.H. 2020. Quantifying tourism booms and the increasing footprint in the Arctic with social media data. PLoS ONE, **15**: e0227189. doi:10.1371/journal.pone.0227189.

Ruscio, B.A., Brubaker, M., Glasser, J., Hueston, W., and Hennessy, T.W. 2015. One Health—a strategy for resilience in a changing arctic. International Journal of Circumpolar Health, **74**: 27913. doi:10.3402/ijch.v74.27913.

Ruth, A, Svendsen, M.B.S., Nygaard, R., Christensen, E.A.F., Bushnell, P.G., and Steffensen, J.F. 2023. Physiological effects of temperature on Greenland halibut *Reinhardtius hippoglossoides* shows high vulnerability of Arctic stenotherms to global warming. Journal of Fish Biology, **103**: 675–683. doi:10.1111/jfb.15434.

Sadowsky, H., Brunet, N.D., Anaviapik, A., Kublu, A., Killiktee, C., and Henri, D.A. 2022. Inuit youth and environmental research: exploring engagement barriers, strategies, and impacts. FACETS, **7**: 45–70. doi:10.1139/facets-2021-0035.

Schindler, D.W., and Smol, J.P. 2006. Cumulative effects of climate warming and other human activities on freshwaters of Arctic and subarctic North America. AmbioAMBIO, **35**: 160–168. doi:10.1579/0044-7447(2006)35[160:ceocwa]2.0.co;2.

Schofield, C., and Østhagen, A. 2020. A divided Arctic: maritime boundary agreements and disputes in the Arctic Ocean. *In* Handbook on geopolitics and security in the Arctic: the high North between cooperation and confrontation. *Edited by* J. Weber. Springer International Publishing, Cham. pp. 171–191. doi:10.1007/978-3-030-45005-2_11.

SIKU—The Indigenous Knowledge Social Network. n.d.[online]. Availablefrom https://siku.org/ [accessed 16 March 2024].

Singh, V., and Singh, K. 2018. Additive genetic variance. *In* Encyclopedia of animal cognition and behavior. *Edited by* J. Vonk and T. Shackelford. Springer International Publishing, Cham. pp. 1–2. doi:10.1007/978-3-319-47829-6_5-1.

Sjöberg, Y., Gomach, S., Kwiatkowski, E., and Mansoz, M. 2019. Involvement of local Indigenous Peoples in Arctic research—expectations, needs and challenges perceived by early career researchers. Arctic Science, **5**: 27–53. doi:10.1139/as-2017-0045.

SmartICE—Sea Ice Monitoring and Information Inc. n.d.[online]. Availablefrom https://smartice.org/ [accessed 16 Marched 2024].

Smieszek, M., Young, O.R., Hoel, A.H., and Singh, K. 2021. The state and challenges of Arctic governance in an era of transformation. One Earth, **4**: 1665–1670. doi:10.1016/j.oneear.2021.11.014.

Smith, A.C., Virgl, J.A., Panayi, D., and Armstrong, A.R. 2005. Effects of a diamond mine on tundra-breeding birds. Arctic, **58**: 295–304.

Smith, R.A., Albonaimi, S.S., Hennin, H.L., Gilchrist, H.G., Fort, J., Parkinson, K.J.L., et al. 2022. Exposure to cumulative stressors affects the laying phenology and incubation behaviour of an Arctic-breeding marine bird. Science of The Total Environment, **807**: 150882. doi:10.1016/j.scitotenv.2021.150882.

Smol, J.P., and Douglas, M.S.V. 2007. Crossing the final ecological threshold in high Arctic ponds. Proceedings of the National Academy of Sciences, **104**: 12395–12397. doi:10.1073/pnas.0702777104.

Sonne, C., Dietz, R., Jenssen, B.M., Lam, S.S., and Letcher, R.J. 2021. Emerging contaminants and biological effects in Arctic wildlife. Trends in Ecology & Evolution, **36**: 421–429. doi:10.1016/j.tree.2021.01.007.

Stephenson, S.R. 2018. Confronting borders in the Arctic. Journal of Borderlands Studies, **33**: 183–190. doi:10.1080/08865655.2017.1302812.

Stevenson, T.C., Davies, J., Huntington, H.P., and Sheard, W. 2019. An examination of trans-Arctic vessel routing in the Central Arctic Ocean. Marine Policy, **100**: 83–89. doi:10.1016/j.marpol.2018.11.031.

Stewart, L., Alsos, I.G., Bay, C., Breen, A.L., Brochmann, C., Boulanger-Lapointe, N., et al. 2016. The regional species richness and genetic diversity of Arctic vegetation reflect both past glaciations and current climate. Global Ecology and Biogeography, **25**: 430–442. doi:10.1111/geb.12424.

Sullender, B.K. 2019. Migratory birds in the heart of the Arctic: a journey through the Arctic National Wildlife Refuge. Audubon Alaska, Anchorage, AK[online]. Availablefrom https://ak.audubon.org/sites/default/files/migratory_birds_in_heart_of_arctic_report.pdf [accessed 18 November 2023].

Sun, L.G., Emslie, S. D., Huang, T., Blais, J. M., Xie, Z.Q., Liu, X.D., et al. 2013. Vertebrate records in polar sediments: biological responses to past climate change and human activities. Earth-Science Reviews, **126**: 147–155. doi:10.1016/j.earscirev.2013.08.004.

Sundet, J.H., and Hoel, A.H. 2016. The Norwegian management of an introduced species: the Arctic red king crab fishery. Marine Policy, **72**: 278–284. doi:10.1016/j.marpol.2016.04.041.

Sutherland, W.J., and Woodroof, H.J. 2009. The need for environmental horizon scanning. Trends in Ecology & Evolution, **24**: 523–527. doi:10.1016/j.tree.2009.04.008.

Sutherland, W.J., Atkinson, P.W., Butchart, S.H.M., Capaja, M., Dicks, L.V., Fleishman, E., et al. 2022. A horizon scan of global biological conservation issues for 2022. Trends in Ecology & Evolution, **37**: 95–104. doi:10.1016/j.tree.2021.10.014.

Sutherland, W.J., Fleishman, E., Mascia, M.B., Pretty, J., and Rudd, M.A. 2011. Methods for collaboratively identifying research priorities and emerging issues in science and policy. Methods in Ecology and Evolution, **2**: 238–247. doi:10.1111/j.2041-210X.2010.00083.x.

Svavarsson, J., Guls, H.D., Sham, R.C., Leung, K.M.Y., and Halldórsson, H.P. 2021. Pollutants from shipping—new environmental challenges in the subarctic and the Arctic Ocean. Marine Pollution Bulletin, **164**: 112004. doi:10.1016/j.marpolbul.2021.112004.

Thienpont, J. R., Rühland, K. M., Pisaric, M. F. J., Kokelj, S. V., Kimpe, L. E., Blais, J. M., and Smol, J. P. 2013. Biological responses to permafrost thaw slumping in Canadian Arctic lakes. Freshwater Biology, **58**: 337–353. doi:10.1111/fwb.12061.

Tilman, D. 1999. The ecological consequences of changes in biodiversity: a search for general principles. Ecology, **80**: 1455–1474. doi:10.1890/0012-9658(1999)080[1455:TECOCI]2.0.CO;2.

Timmermans, M.-L., and Marshall, J. 2020. Understanding Arctic Ocean circulation: a review of ocean dynamics in a changing climate. Journal of Geophysical Research: Oceans, **125**: e2018JC014378. doi:10.1029/2018JC014378.

Tolvanen, A., and Kangas, K. 2016. Tourism, biodiversity and protected areas—review from northern Fennoscandia. Journal of Environmental Management, **169**: 58–66. doi:10.1016/j.jenvman.2015.12.011.

Tomaselli, M., Kutz, S., Gerlach, C., and Checkley, S. 2018. Local knowledge to enhance wildlife population health surveillance: conserving muskoxen and caribou in the Canadian Arctic. Biological Conservation, **217**: 337–348. doi:10.1016/j.biocon.2017.11.010.

Tulloch, V.J., Tulloch, A.I., Visconti, P., Halpern, B.S., Watson, J.E., Evans, M.C., et al. 2015. Why do we map threats? Linking threat mapping with actions to make better conservation decisions. Frontiers in Ecology and the Environment, **13**: 91–99. doi:10.1890/140022.

Turetsky, M.R., Abbott, B.W., Jones, M.C., Walter Anthony, K., Olefeldt, D., Schuur, E.A.G., et al. 2019. Permafrost collapse is accelerating carbon release. Nature, **569**: 32–34. doi:10.1038/d41586-019-01313-4.

UMass Amherst. n.d. Center for Braiding Indigenous Knowledges and Science[online]. Availablefrom https://www.umass.edu/gateway/research/indigenous-knowledges [accessed 6 December 2023].

van Heerwaarden, B., and Sgrò, C.M. 2014. Is adaptation to climate change really constrained in niche specialists?, Proceedings of the Royal Society B: Biological Sciences **281**: 20140396. doi:10.1098/rspb.2014.0396.

Virkkala, A.-M., Abdi, A.M., Luoto, M., and Metcalfe, D.B. 2019. Identifying multidisciplinary research gaps across Arctic terrestrial gradients.

Environmental Research Letters, **14**: 124061. doi:10.1088/1748-9326/ab4291.

Vogt, W.P., and Johnson, R.B. 2024. The SAGE dictionary of statistics & methodology: a nontechnical guide for the social sciences. 5th ed. SAGE Publications, Inc, Thousand Oaks. doi:10.4135/9781071909751.

Vonk, J.E., Tank, S.E., Bowden, W.B., Laurion, I., Vincent, W.F., Alekseychik, P., et al. 2015. Reviews and syntheses: effects of permafrost thaw on Arctic aquatic ecosystems. Biogeosciences, **12**: 7129–7167. doi:10.5194/bg-12-7129-2015.

Walvoord, M.A., and Kurylyk, B.L. 2016. Hydrologic impacts of thawing permafrost—a review. Vadose Zone Journal, **15**: 1. doi:10.2136/vzj2016.01.0010.

Ward, D.H., Helmericks, J., Hupp, J.W., McManus, L., Budde, M., Douglas, D.C., and Tape, K.D. 2016. Multi-decadal trends in spring arrival of avian migrants to the central Arctic coast of Alaska: effects of environmental and ecological factors. Journal of Avian Biology, **47**: 197–207. doi:10.1111/jav.00774.

Wauchope, H.S., Shaw, J.D., Varpe, Ø., Lappo, E.G., Boertmann, D., Lanctot, R.B., and Fuller, R.A. 2017. Rapid climate-driven loss of breeding habitat for Arctic migratory birds. Global Change Biology, **23**: 1085–1094. doi:10.1111/gcb.13404.

Wauthy, M., and Rautio, M. 2020. Permafrost thaw stimulates primary producers but has a moderate effect on primary consumers in subarctic ponds. Ecosphere, **11**: e03099. doi:10.1002/ecs2.3099.

West, E.W., and Rudd, R.L. 1983. Biological control of Aleutian Island Arctic fox: a preliminary strategy. International Journal for the Study of Animal Problems, **4**: 305–311.

Westbury, M.V., Brown, S.C., Lorenzen, J., O'Neill, S., Scott, M.B., McCuaig, J., et al. 2023. Impact of Holocene environmental change on the evolutionary ecology of an Arctic top predator. Science Advances, **9**: eadf3326. doi:10.1126/sciadv.adf3326.

Wheeler, H.C., Berteaux, D., Furgal, C., Cazelles, K., Yoccoz, N.G., and Grémillet, D. 2018. Identifying key needs for the integration of social–ecological outcomes in Arctic wildlife monitoring. Conservation Biology, **33**: 861–872. doi:10.1111/cobi.13257.

Whitney, K.D., and Gabler, C.A. 2008. Rapid evolution in introduced species, 'invasive traits' and recipient communities: challenges for predicting invasive potential. Diversity and Distributions, **14**: 569–580. doi:10.1111/j.1472-4642.2008.00473.x.

Wilson, E., and Stammler, F. 2016. Beyond extractivism and alternative cosmologies: Arctic communities and extractive industries in uncertain times. The Extractive Industries and Society, **3**: 1–8. doi:10.1016/j.exis.2015.12.001.

Wilson, S.C., Crawford, I., Trukhanova, I., Dmitrieva, L., and Goodman, S.J. 2020. Estimating risk to ice-breeding pinnipeds from shipping in Arctic and sub-Arctic seas. Marine Policy, **111**: 103694. doi:10.1016/j.marpol.2019.103694.

Wilson, S.C., Trukhanova, I., Dmitrieva, L., Dolgova, E., Crawford, I., Baimukanov, M., et al. 2017. Assessment of impacts and potential mitigation for icebreaking vessels transiting pupping areas of an ice-breeding seal. Biological Conservation, **214**: 213–222. doi:10.1016/j.biocon.2017.05.028.

Wintle, B.C., Kennicutt Ii, M.C., and Sutherland, W.J. 2020. Scanning horizons in research, policy and practice. *In* Conservation research, policy and practice. 1st ed. *Edited by* W.J. Sutherland, P.N.M. Brotherton, Z.G. Davies, N. Ockendon, N. Pettorelli and J.A. Vickery. Cambridge University Press. pp. 29–47. doi:10.1017/9781108638210.003.

Wrona, F.J., and Reist, J.D. 2013. Freshwater ecosystems. *In* Arctic biodiversity assessment: status and trends in Arctic biodiversity. *Edited by* H. Meltofte, A.B. Josefson and D. Payer. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland.

Wrona, F.J., Prowse, T.D., and Reist, J.D. 2004. Freshwater ecosystems (ACIA Chapter 8). Reykjavik, Iceland.

Young, T.K., and Bjerregaard, P. 2019. Towards estimating the Indigenous population in circumpolar regions. International Journal of Circumpolar Health, **78**: 1653749. doi:10.1080/22423982.2019.1653749.

Zhang, X., and Walsh, J.E. 2006. Toward a seasonally ice-covered Arctic Ocean: scenarios from the IPCC AR4 model simulations. Journal of Climate, **19**: 1730–1731,1734-1747. doi:10.1175/JCLI3767.1.

Zikargae, M.H., Woldearegay, A.G., and Skjerdal, T. 2022. Assessing the roles of stakeholders in community projects on environmental security and livelihood of impoverished rural society: a nongovernmental organization implementation strategy in focus. Heliyon, **8**: e10987. doi:10.1016/j.heliyon.2022.e10987.