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PRACTICE AND POLICY

An ecologically sound and participatory monitoring network for pan-Arctic seabirds

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Abstract

In a warming Arctic, circumpolar long-term monitoring programs are key to advancing ecological knowledge and informing environmental policies. Calls for better involvement of Arctic peoples in all stages of the monitoring process are widespread, although such transformation of Arctic science is still in its infancy. Seabirds stand out as ecological sentinels of environmental changes, and priority has been given to implement the Circumpolar Seabird Monitoring Plan (CSMP). We assessed the representativeness of a pan-Arctic seabird monitoring network focused on the black-legged kittiwake (*Rissa tridactyla*) by comparing the distribution of environmental variables for all known versus monitored colonies.

Article impact statement: Community engagement can fill gaps in Arctic seabird monitoring and improve the ecological representativeness of the monitoring network.

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We found that with respect to its spatiotemporal coverage, this monitoring network does not fully embrace current and future environmental gradients. To improve the current scheme, we designed a method to identify colonies whose inclusion in the monitoring network will improve its ecological representativeness, limit logistical constraints, and improve involvement of Arctic peoples. We thereby highlight that inclusion of study sites in the Bering Sea, Siberia, western Russia, northern Norway, and southeastern Greenland could improve the current monitoring network and that their proximity to local populations might allow increased involvement of local communities. Our framework can be applied to improve existing monitoring networks in other ecoregions and sociological contexts.

KEYWORDS
black-legged kittiwakes, citizen science, environmental gradients, key monitoring sites, sentinel species

INTRODUCTION

Long-term and large-scale ecological monitoring is essential to the understanding of environmental processes and global change impacts on nature (Likens & Lindenmayer, 2018). A recent review showed how essential long-term monitoring studies are for advancing ecological knowledge and informing environmental policies (Hughes et al., 2017). These programs bear maximum relevance in regions subjected to major environmental changes (e.g., Bjorkman et al., 2020). This is the case in the Arctic, which is currently warming nearly 4 times faster than any other region (Rantanen et al., 2022). For Arctic biota and human populations facing rapid environmental changes (IPCC, 2021), circumpolar long-term monitoring programs are key to understanding socioecological consequences (Heino et al., 2020).

The Arctic Council, an international intergovernmental forum promoting cooperation in the Arctic, includes multiple environmental working groups, such as the Arctic Contaminants Action Program (ACAP), the Arctic Monitoring and Assessment Program (AMAP), the Conservation of Arctic Flora and Fauna (CAFF), and the Protection of the Arctic Marine Environment (PAME) (Barry et al., 2020). These greatly contribute to fostering the necessary international collaborations, which lead to sharing data and protocols, creating monitoring networks, and defining common road maps for future Arctic research (Christensen et al., 2020; Provencher et al., 2022). Moreover, there are numerous calls for a better involvement of Arctic peoples at all stages of the monitoring process, as recommended by the Circumpolar Biodiversity Monitoring Program (Hauser et al., 2021; Inuit Circumpolar Council Alaska., 2020; Logan et al., 2018). Yet, this transition of Arctic science is still in its infancy (Alexander et al., 2019).

Among monitored Arctic wildlife, seabirds stand out because they occur all around the Arctic and because they are culturally essential for Arctic peoples. Seabirds are key elements in cosmogony and founding narratives (e.g., Pearce, 1987) and are hunted, enhancing human resilience and food security (Wein et al., 1996; Young et al., 2014). Arctic birds are also ecological indicators of stressors, such as environmental contamination (Dietz et al., 2019; Furness & Camphuysen, 1997) and climate change effects (Amélineau et al., 2019; Grémillet & Descamps, 2023), and different stakeholder groups are justifiably concerned about their fate in rapidly changing ecosystems (Wheeler et al., 2016).

Among Arctic seabirds, the black-legged kittiwake (*Rissa tridactyla*) (hereafter kittiwake) is a vulnerable (BirdLife International, 2019) circumpolar species and one of the most intensively studied Arctic seabirds (16% of Arctic seabird publications [Web of Knowledge January 2022]) after the common eider (*Somateria mollissima*) (23%) and the thick-billed murre (*Uria lomvia*) (20%). The global kittiwake population has decreased 40% since 1975 (Descamps et al., 2017). This decline, caused by climate change, industrial fisheries, pollutants, predation, and further anthropogenic threats, is likely to continue (CAFF, 2020). As a consequence of this decline, the International Black-Legged Kittiwake Conservation Strategy and Action Plan of the Arctic Council (CAFF, 2020) stresses that priority should be given to implementing the Circumpolar Seabird Monitoring Plan (CSMP), which aims to maintain and enhance seabird populations through informed management decisions (Irons et al., 2015). The CSMP provides a list of key kittiwake breeding colonies that function as monitoring sites used to assess global change impacts on seabirds via regular assessments of various metrics, including population size, survival, reproduction rate, diet, foraging effort, and contaminant load (Irons et al., 2015). Despite its great conservation value, this plan does not assess how kittiwake monitoring sites are distributed across Arctic ecoregions and environmental gradients or whether the current monitoring network is suited to involving local communities or reflecting on the impacts of ongoing and future global changes on a pan-Arctic scale.

We used the pan-Arctic kittiwake monitoring network as a case study system to test the following hypotheses: the existing network of kittiwake monitoring sites is not ecologically representative because it does not embrace the full range of environmental conditions experienced by this species across the Arctic and this network prioritizes monitoring field sites according to logistical constraints and is therefore close to human settlements, potentially allowing meaningful Arctic peoples' participation. In this context, we designed an improved pan-Arctic kittiwake monitoring framework by identifying colonies for which monitoring will improve ecological representativeness of the network, limit logistic constraints, and increase the potential

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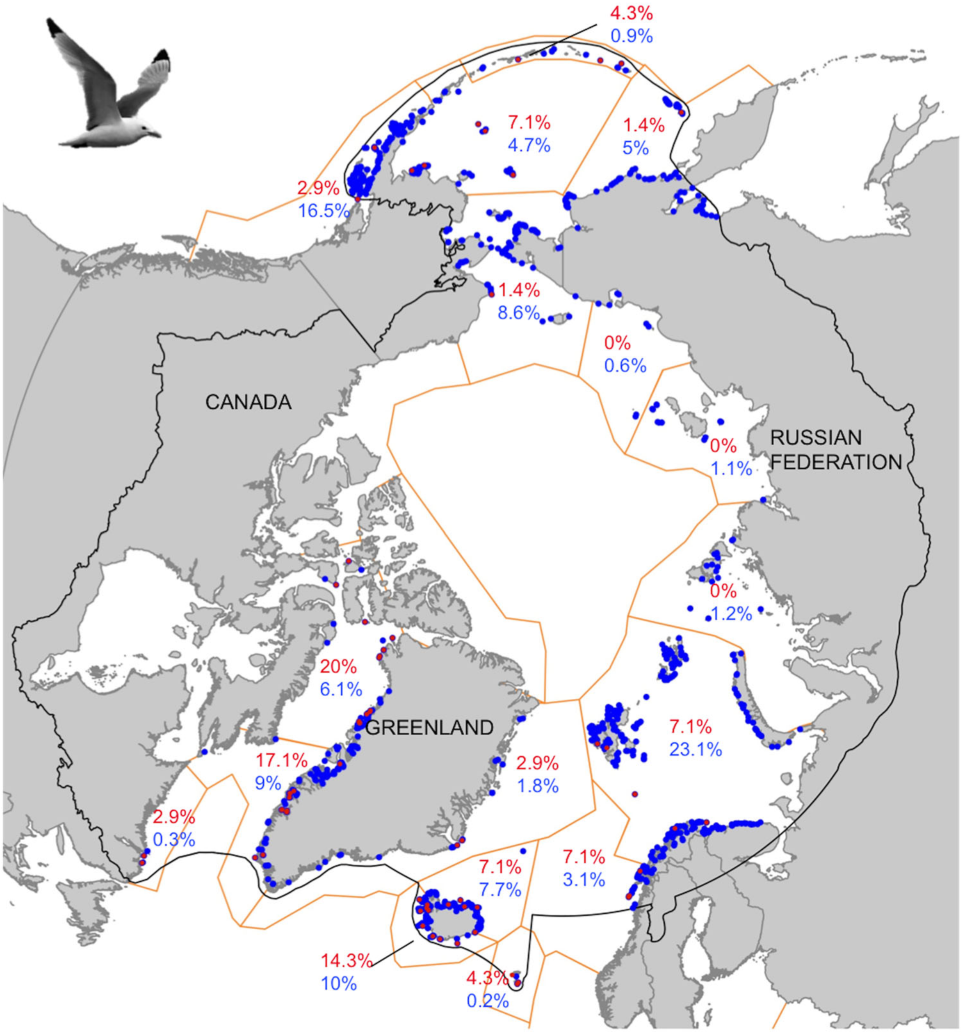

FIGURE 1 Locations of monitored (red dots) and known (blue dots) kittiwake colonies in the 22 Arctic ecoregions (orange lines) (black line, Arctic region boundary as defined by the Conservation of Arctic Fauna and Flora working group; red type, percentage of monitored colonies relative to the total number of monitored and known colonies; blue type, percentage of known colonies relative to the total number of monitored and known colonies; projection, North Pole Lambert Azimuthal Equal Area).

for involving Arctic peoples. We sought to provide a blueprint for similar improvements in other ecoregions and sociological contexts.

METHODS

Positions of all known Arctic kittiwake colonies were sourced from the International Black-legged Kittiwake Conservation Strategy and Action Plan (CAFF, 2020) and the Circumpolar Seabird Expert Group (Figure 1). The CSMP (Irons et al., 2015) advises the monitoring of 5 main variables (population trend, productivity, diet, survival, and phenology) at seabird colonies to assess status of seabird populations and detect potential changes due to environmental or anthropogenic processes. In practice, the degree of monitoring may vary strongly among colonies, from all of the 5 variables monitored every summer to one of the variables monitored every 20 years (Irons et al., 2015). We considered a seabird colony (SC) monitored when at least population trend or productivity had been monitored, and we calculated the degree of monitoring of each colony with the following index:

$$\text{Monitoring index} = \text{SC population trend} + \text{SC productivity} + \frac{(\text{SC diet} + \text{SC survival} + \text{C phenology})}{3}. \quad (1)$$

Once scaled, this index varied from 0 (unmonitored) to 1 (fully monitored) and was weighted to account for the importance of monitoring population trend and productivity, which are a prerequisite for the full implementation of the CSMP (Irons et al., 2015). Factors included in the index correspond to SC_m, which is 1/monitoring frequency of the monitored variables m, and the range of monitoring from 0 (variable unmonitored) to 1 (variable monitored every year).

The locations of the corresponding colonies were extracted from Appendix 2 of the CSMP. Colonies outside Arctic boundaries (as defined by the CAFF) were removed, and the locations of monitored colonies were cross-referenced among data sources to ensure that each monitored colony was also listed as a known colony.

We first compared the proportion of known and monitored colonies in the 22 Arctic monitored ecoregions (Irons et al., 2015) with a Fisher's exact test ($\alpha = 0.05$).

We then evaluated the ability of the circumpolar kittiwake monitoring network to embrace the entire range of environmental conditions experienced by the species in the Arctic. For this purpose, we compared the distribution of environmental variables (see Appendix S1 for sources) for all known versus monitored colonies. Suitable environmental variables were selected according to existing ecological knowledge. For instance, previous studies showed the importance of precipitation and air temperature to kittiwake breeding ecology (Alvestad, 2015; Sauve et al., 2022). We therefore calculated the average amount of precipitation and average, minimum, and maximum air temperature from 2000 to 2020 during the chick-rearing period (from June to August) at each colony location. Kittiwakes are central-place foragers during the breeding season. To consider the environmental conditions encountered at the core of Arctic kittiwake foraging ranges, we averaged the foraging range obtained from Christensen-Dalsgaard et al. (2018), Harris et al. (2020), and Osborne et al. (2020) during chick rearing. We therefore calculated average sea surface temperature, sea ice cover, wind speed, and chlorophyll-a concentration from 2000 to 2020 during summer within a 35-km radius around each colony. These variables are proxies for seabird prey availability (Kane et al., 2020) and affect kittiwake breeding productivity (Frederiksen et al., 2007) and foraging ecology (Elliott et al., 2014; Pratte et al., 2019). We also determined the ability of the monitoring network to consider industrial fisheries competition with seabirds. Using the Global Fishing Watch Automatic Identification System (AIS) database ($0.01 \times 0.01°$ spatial resolution) (Kroodsma et al., 2018), we calculated the average number of fishing hours per square kilometer within 35 km of each colony during chick rearing from 2012 to 2020.

Finally, to determine the reliability of the current monitoring network in describing future climate change impacts on kittiwake breeding ecology, we calculated for each colony the difference between the average values recorded (2000–2020) and predicted (2045–2055) under the International Panel on Climate Change (IPCC) RCP8.5 scenario for mean, maximum, and minimum air temperature, sea surface temperature, and sea ice cover during summer. Historical total cumulative CO_2 emissions are in close agreement with the ones predicted under this scenario, and RCP8.5 is the best match to midcentury conditions under current and stated policies (Schwalm et al., 2020). Future values for the corresponding variables were obtained by averaging outputs of 4 climatic models (HadGEM2-CC, MIROC-ESM, ACCESS 1-0, EC-EARTH) considered as performant in predicting future Arctic climate, particularly the cryosphere (Wang & Overland, 2015).

All environmental variables were interpolated on a 0.5° grid before extraction.

Distribution similarities of the abovementioned environmental variables between known and monitored colonies were measured using Bhattacharyya's coefficient, which assesses the distribution overlap and varies from 0 (no overlap) to 1 (complete overlap) (Bhattacharyya, 1943). For each variable, 2 histograms (one for values taken at monitored sites and one for values at known colonies) were plotted in n bins shared between the 2 distributions, and the coefficient was calculated as the sum of the square root of the products of relative counts for each bin. To limit overlap overestimation (n too low) or underestimation (n too high), we determined n following the Silverman's (1986) rule of thumb. The distribution of environmental variables at monitored colonies was weighted by the monitoring index (see above) to account for variation in the degree of monitoring. Further, for each environmental variable, we identified values overrepresented (bins of the histograms for which relative count was higher for monitored colonies than for known ones) and underrepresented (bins of the histograms for which relative count was lower for monitored colonies than for known ones) by the monitoring network.

To better understand constraints underlying the current monitoring network, we tested whether being monitored or not and degree of monitoring (described by the monitoring index, see above) were influenced by colony accessibility (referring here to proximity to communities). We built 2 generalized linear models into which we included sea ice concentration (see above for data source) within a 35-km radius around the colony, the minimum distance between the breeding site and the coastline, and the distance to the closest human settlement and the distance to the closest scientific base as fixed effects. The lists of Arctic human settlements (including both Indigenous and non-Indigenous communities) and scientific bases were provided by Arctic state members and are detailed in Appendices S2 and S3.

The first model investigated the likelihood for a colony to be monitored (1) or not (0) with a binomial error and logit link function, and the second aimed to explain the monitoring index (after log transformation) with a Gaussian error. All explanatory variables were scaled and were not correlated as tested using a Pearson pairwise correlation test and a variance inflation factor analysis (VIF < 2). The models were fitted in R with the lme4 package (Bates et al., 2015).

To identify colonies for which future monitoring will improve the ecological representativeness of the network, limit logistic cost, and enable the participation of local communities, as well as to underline the importance of specific monitored sites for the network, we use the following formula to calculate the suitability index for each colony:

$$\left[\left(\frac{\sum_{i=1}^{17}\text{SC Env}_i}{17}\right)^{1-\left\{\frac{\frac{(\text{SC Eco}+\text{SC DistM})}{2}}{\left(\frac{(\text{SC Eco}+\text{SC DistM})}{2}+0.5\right)}\right\}}\right]\times\left[\frac{(\text{SC DistSB}+\text{SC DistH})}{2}^{1-\left\{\frac{\frac{(\text{SC SI}+\text{SC DistC})}{2}}{\left(\frac{(\text{SC SI}+\text{SC DistC})}{2}+0.5\right)}\right\}}\right]. \quad (2)$$

The index was scaled from 0 (low) to 1 (high potential for the network) and was the product of 2 terms. The first one described the environmental representativeness of the site (considering environmental variables [SC Env], ecoregion sampling [Sc Eco]) and distance to the closest monitored colony (SC DistM), and the second represented the accessibility of the considered colony, including distance to the closest base station (SC DistBS), human settlement (SC DistH), sea-ice cover (SC SI), and distance to the coast (SC DistC), which can constraint the colony's accessibility when reached by boat. We adapted the seabird displacement vulnerability index equation built by Certain et al. (2015) to our own work, integrating for each term of our index a combination of primary factors (e.g., SC Env) and secondary ones (e.g., SC Eco and SC DistM), which weighted the influence of primary factors. Factors were scored on a 5-point scale from 0.2 to 1, as summarized in Appendix S4.

Finally, we ranked the colonies according to their index values, identified ecologically relevant and accessible sites, and discussed their future monitoring as part of an improvement strategy of the monitoring network.

RESULTS

There are 1305 known kittiwake colonies distributed across the Arctic (except for parts of northern Canada), among which 70 have been defined as monitored (Figure 1). The monitoring index for monitored colonies was on average 0.34 (SD 0.37), and in most cases, population trend, productivity, or both were the only variables recorded. The remaining variables (diet, survival, and phenology) were occasionally monitored but only in addition to population trend and productivity. Monitored colonies were on average monitored every 4.5 (SD 3.6) years, but monitoring frequency varied strongly among Arctic regions (e.g., Norwegian colonies were monitored more frequently than the Greenlandic colonies [Appendix 2 of the CSMP]).

There was very strong evidence that the proportions of known and monitored colonies differed among the 22 Arctic ecoregions (Fisher's exact test, $p = 0.0005$). Some areas, such as the Arctic part of Alaskan and Aleutian Islands, contained >15% of known colonies but <3% of the monitored sites, whereas western Greenland and Nunavut accounted for 6% of known colonies but nearly 20% of currently monitored colonies (Figure 1).

Adequacy of the kittiwake monitoring network with respect to environmental gradients

High Bhattacharyya's coefficients (all from 0.8 to 1) (Table 1), calculated for all considered environmental variables, reflected high overlap among environmental variable distributions around known and monitored colonies. The high values suggested a good coverage of overall environmental conditions experienced by pan-arctic kittiwakes throughout the current monitoring network.

Nevertheless, some environmental values were oversampled by the existing monitoring network, whereas others were strongly undersampled, sometimes at the same location (Figure 2; Appendices S5–S17). For example, large amounts of precipitation (>250 mm cumulated during the breeding season [Appendix S10]) experienced by kittiwakes in the Aleutian Islands were underrepresented, although encountered wind speeds are oversampled in the existing monitoring network (Appendix S12). Further, levels of chlorophyll-a above 3.7 mg·mm^3 experienced by kittiwakes breeding on the Aleutian Islands and in Iceland (Appendix S11) were underrepresented in the existing monitoring network. This was also the case for the lowest air temperatures and intermediate sea ice cover conditions (<2.7°C and sea ice cover from 47% to 65%, respectively [Appendices S6 & S9]) generally experienced in Franz Josef Land and Eastern Russia. Moreover, comparison of the difference between 2000–2020 and estimated 2045–2055 average air temperatures showed restricted sampling of kittiwake colonies in areas where global warming will be moderate (temperature increase from 0 to 1.3°C) (Appendix S16), such as the eastern Aleutian Islands, the Chukchi Sea in Franz Josef Land, and northern Norway. Areas where air and sea surface temperatures (Figure 2) were predicted to decrease strongly, as in southeastern Greenland, were also undersampled by the current monitoring network.

Maintaining and improving a pan-Arctic kittiwake monitoring network

As we hypothesized, our model predicted that monitoring likelihood increases when distance to an inhabited place decreases (−0.64 [SE 0.3], $p = 0.03$) (Appendix S18). There was no evidence that sea ice concentration around the colony, minimum distance of seabird colonies to the coastline, or distance to the

TABLE 1 Distribution similarities of environmental variables between known and monitored kittiwake colonies according to Bhattacharyya's coefficient calculation.

Environmental variable	Bhattacharyya's coefficient
Average amount of precipitation	0.86
Average air temperature	0.92
Maximum air temperature	0.84
Minimum air temperature	0.87
Average sea surface temperature	0.92
Average chlorophyll concentration	0.87
Average wind speed	0.91
Average sea ice concentration	0.87
Average number of fishing hours/km^2	0.83
Difference between 2000–2020 and 2045–2055 in average air temperature	0.85
Difference between 2000–2020 and 2045–2055 in maximum air temperature	0.85
Difference between 2000–2020 and 2045–2055 in minimum air temperature	0.81
Difference between 2000–2020 and 2045–2055 in average sea surface temperature	0.87
Difference between 2000–2020 and 2045–2055 in average sea ice cover	0.82

Note: Bhattacharyya's coefficient calculation measures the distribution overlap and varies from 0 to 1, where 1 indicates complete overlap and 0 indicates no overlap.

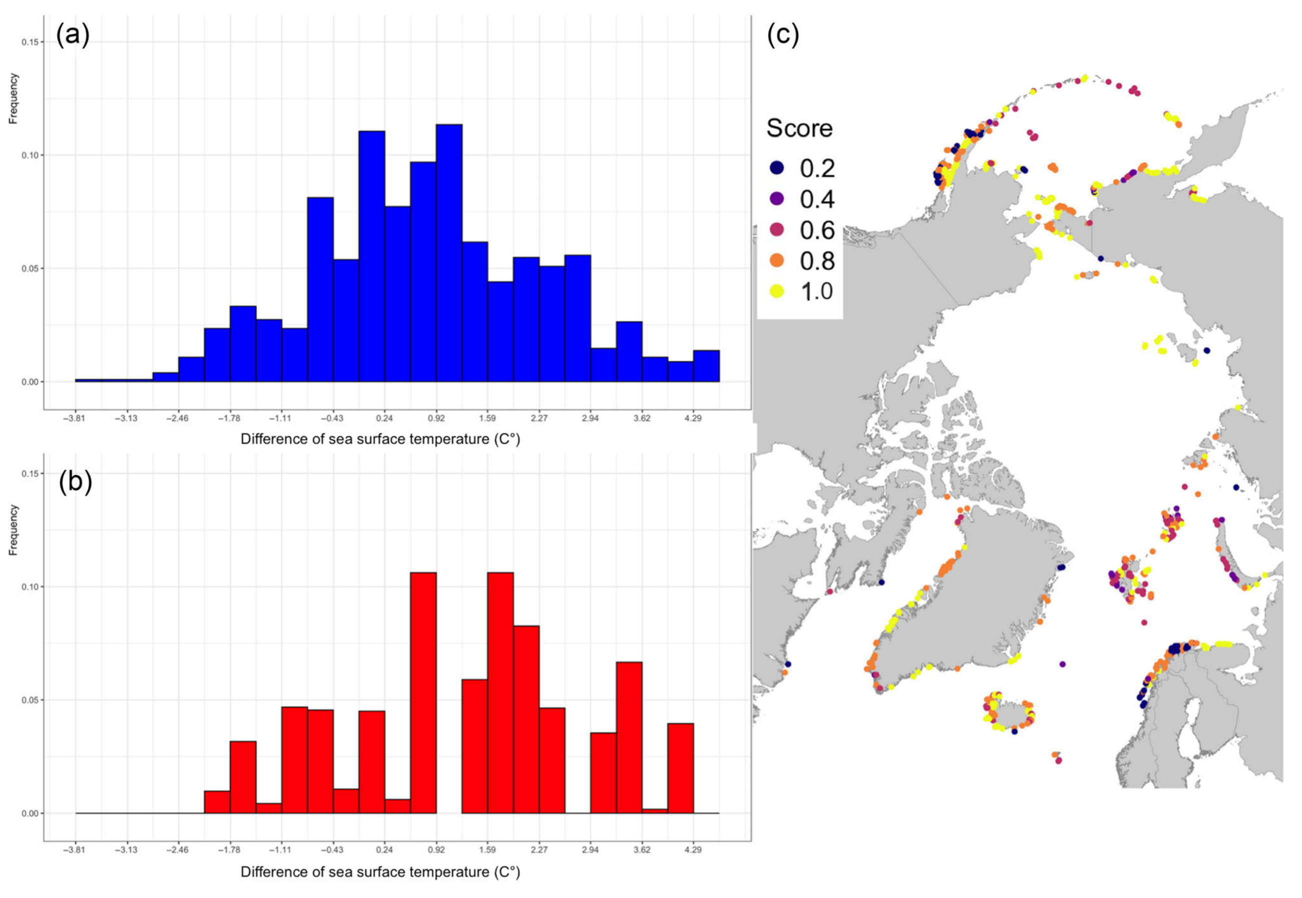

FIGURE 2 Distribution of the difference in average sea surface temperature (°C) between 2000–2020 and 2045–2055 at (a) known and (b) monitored colonies of Arctic black-legged kittiwake and (c) score of the variable at each colony (dark blue, strongly overrepresented; yellow, strongly underrepresented; projection, North Pole Lambert Azimuthal Equal Area). In panel (b), distribution of the variable at monitored colonies is weighted by the calculated monitoring index. Other variables are in Appendices S5–S17.

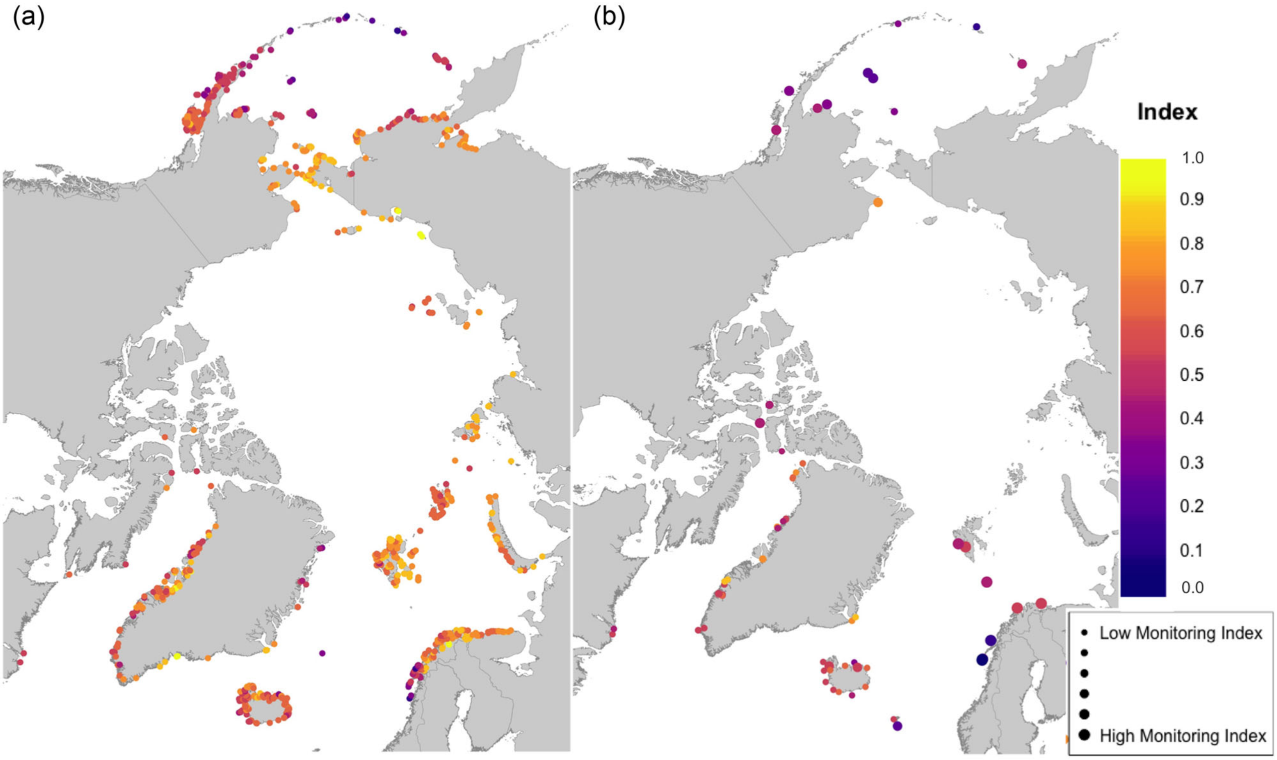

FIGURE 3 Suitability index values (0, low potential to improve the network; 1, high potential) for (a) unmonitored and (b) monitored colonies of Arctic black-legged kittiwake (the larger the point size, the higher the level of monitoring). The index includes environmental and accessibility factors that account for ecological representativeness and logistic aspects and that can be used to assess and improve monitoring in the network.

closest scientific base had an effect on kittiwake monitoring likelihood, suggesting that kittiwake colony proximity to research facilities was not the main criterion when selecting monitoring sites. Focusing on monitored colonies, we found no evidence that considered covariables had a significant effect when modeling the level of monitoring (see monitoring index above), suggesting that monitoring frequency of kittiwake colonies depended on other criteria beyond accessibility.

Monitored and unmonitored colonies were, on average, 36.9 km (SD 52.4) and 82.3 km (SD 154.3) from the closest settlement, respectively. Icelandic, Norwegian, and Greenlandic monitored colonies were usually close to inhabited places, unlike most of monitored colonies in the Aleutian Islands or in Canada (Appendix S19). On average, monitored and unmonitored colonies were far from research stations (397.8 km [SD 389.2] and 440.7 km [SD 396], respectively). Only 18% were closer than 100 km, highlighting the logistical constraints in maintaining kittiwake monitoring and the potential for local communities (Indigenous and non-Indigenous) to significantly enhance such research activities (Inuit Circumpolar Council, 2020).

Ranking unmonitored colonies according to the calculated suitability index, colonies in the Bering Sea, Siberia, western Russia, northern Norway, and southeastern Greenland showed the potential to improve the current monitoring network (Figure 3a). Overall, our environmental variables were undersampled by the current monitoring network at those locations, and their relative proximity to human settlements or scientific base stations makes them good candidates for future monitoring sites. Some of those colonies were <15 km from an inhabited place, potentially enabling better involvement of local communities and reduced logistical constraints. Although 3 black-legged kittiwake colonies were monitored in Svalbard, the presence of international scientific base stations and environmental conditions experienced there make the island a valuable site for future monitoring. Conversely, except in the southeast and at some colonies around Ummannaq, Greenlandic colonies had medium index values despite their proximity to human settlements, mainly because of their low scores related to distance with monitored colonies and ecoregion. Arctic Alaskan and Aleutian Islands had similar medium index values because of oversampled environmental conditions.

Ranking monitored colonies highlighted the importance of monitored sites in Greenland (Figure 3b) in the current network with respect to environmental representativeness and accessibility. On average, those colonies were monitored every 5 years, and population trend was the only monitored variable in most cases.

DISCUSSION

Our detailed spatiotemporal analyses showed that the current black-legged kittiwake monitoring framework is unevenly distributed across Arctic ecoregions and does not fully encompass current and estimated future environmental gradients. Notably, environmental conditions typical of areas such as the Bering Strait, the Russian Arctic, and northern Norway were undersampled by the existing network. However, the observed mismatch between environmental conditions at monitored versus unmonitored colonies was not as pronounced as expected. Through the computation of a comprehensive suitability index, we identified potential future monitoring sites. Adding these to the program would improve the current monitoring network because biologically relevant variables and logistic constraints would be considered. Crucially, such an addition might allow a stronger involvement of local communities through participatory science programs.

Maintaining or improving a large-scale monitoring network requires substantial resources and relies mostly on continuous funding. Ideally, all 5 variables (population trend, productivity, diet, survival, phenology) should be monitored every year at every colony of interest, but this is highly unrealistic due to constraints and costs associated with Arctic fieldwork (Mallory et al., 2018). The ability of the monitoring network to reveal impacts of environmental changes on seabirds relies on monitoring consistency; the same minimal set of biological variables should always be monitored to allow spatiotemporal comparisons. In agreement with the CSMP (Irons et al., 2015), we advise that population trend and productivity be monitoring priorities when adding a new colony to the network. Diet, survival, and phenology monitoring usually require more intensive fieldwork and could therefore be monitored to strengthen partially monitored sites when resources are available. Monitoring new sites every 3–5 years, which correspond to the kittiwake generation time (Cam et al., 2002), would be a first step to reduce monitoring costs that would still allow collection of baseline data and detection of variations in population trends. Annual monitoring is, however, a powerful tool for discovering impacts of extreme events, such as heat waves, storms, and disease outbreaks, and should therefore be conducted whenever possible.

A promising way to limit Arctic monitoring costs while increasing the number of sites monitored is the use of time-lapse cameras. Recording bird activities at colonies for months (and in some cases, for years), such cameras have been successfully used in the Arctic and the Antarctic (e.g., SeabirdWatch and the Penguin Watch, respectively) to monitor nest attendance (Huffeldt & Merkel, 2013), productivity (Merkel et al., 2016), chick survival, and phenology (Hinke et al., 2018). They require limited maintenance, and data can be easily collected, especially when sites of interest are close to human settlements. The vast amount of footage obtained can then be annotated as part of citizen science programs (e.g., Penguin Watch project, https://www.zooniverse.org/projects/penguintom79/penguin-watch/about/research) to train machine-learning algorithms and automated image analyses (Jones et al., 2018, 2020). Results obtained are comparable to those gathered through direct observations (Edney & Wood, 2020), raising hopes for more widespread use of this method in the future.

Our results were linked to a series of methodological choices and assumptions, which all need careful assessment. Some environmental variables were not available at all locations (e.g., difference in sea surface temperatures were missing for around 22% of known colonies), biasing our analyses toward areas for which environmental conditions were better sampled. Additionally, when calculating monitoring suitability scores, we assumed that each environmental variable had the same weight, even though some variables may be more directly linked to some monitored aspects than others. For example, summer temperature may be the main drivers of breeding phenology but may poorly explain interannual variations of adult survival because they could be mostly driven by winter conditions.

Some fine-scale environmental variables that may affect monitoring site choice were also lacking. For example, we did not take topography into account, although it could be an important constraint when deciding to monitor a site. Indeed, it could be easier to travel by boat or snowmobile than on land, even when straight-line distances from the closest human settlement suggest otherwise. Further, kittiwakes usually nest on cliffs, and the ability of researchers to reach them safely depends on local site topography and exposure. Safe (limited exposure to wind gust, low risk of polar bear [*Ursus maritimus*] encounter, etc.) and practical (e.g., ability to bring and store materials) conditions are also crucial to establish a campsite near a colony, potentially limiting where monitoring is possible. Additionally, some research sites may be far from human settlements to avoid potential urbanization and local anthropogenic impacts. Further, colonies with high numbers of breeding birds or that are close to other seabird colonies may be more attractive for monitoring than small or relatively more isolated colonies, but information was lacking to test this hypothesis. Additional aircraft surveys, such as those conducted in eastern and northern Greenland, will help address this problem (Boertmann et al., 2020). Further, the current monitoring network is the result of its gradual implementation across decades; some sites were originally chosen for specific research purposes, not necessarily with a vision for long-term monitoring. Monitored colonies were then progressively added to the scheme, potentially explaining why some areas are under or oversampled. In some areas, this process of filling the gaps could be significantly aided by local people recording new species distributions (Ksenofontov et al., 2019). Our study is a snapshot of the state of the monitoring network in 2015 and did not take into account potential additions or removals of monitored colonies from the overall network. Although including lower latitude colonies could have revealed the coverage of the species environmental niche, our focus was specifically on the Arctic monitoring network and constraints. The lack of centralized and homogeneous lists of monitored colonies beyond CAFF boundaries prevented us from expanding our analysis scope.

Finally, we acknowledge that spatial proximity to kittiwake colonies does not suffice to improve the participation of local Arctic peoples; achieving this will require funding, strong communication, partnership building, and training (e.g., Mallory et al., 2022). Further, the development of community-based monitoring programs must align with the needs and interests of Arctic peoples. Nonetheless, it is a first step in identifying where peoples are more likely to be involved while improving the existing monitoring network.

Despite these limitations, our results strongly suggest that Arctic peoples' involvement in kittiwake monitoring is possible due to their proximity and could be part of the monitoring network enhancement, in addition to adjusting the spatial distribution of monitoring sites to better embrace current and future ecological gradients. These findings echo strong calls from Indigenous Peoples around the world for more involvement (Ens et al., 2015; Inuit Tapiriit Kanatami, 2018) and consideration of their needs and interest in research activities (Huntington et al., 2019). However, 90% of circumpolar Arctic residents are not Indigenous Peoples (Arctic Council, https://arctic-council.org/explore/topics/arctic-peoples/), and enhanced participation of community residents in Arctic monitoring does not automatically support empowerment or self-determination of Indigenous Peoples with respect to research activities (Inuit Tapiriit Kanatami, 2018).

A transformation of Arctic science can take many forms. A first step, which can be implemented in the short term, is the development of participatory science programs (Couvet & Prevot, 2015), whereby members of the public (Indigenous or not) take part in data collection (e.g., the Seabird Youth Network, http://seabirdyouth.org/about-us/). This participation usually occurs on a voluntary basis and is in accordance with protocols designed by Western scientists who store, analyze, and publish the data (but see public repositories, e.g., GBIF, iNaturalist, eBIRD). Some recent examples of this approach involve seabird and pollution research in Baffin Bay (Huntington et al., 2019). The installation and maintenance of time lapse cameras (see above) and the annotation of gathered images by Arctic peoples in particular should be developed alongside the CSMP and represent a concrete action toward greater involvement of local communities. Following the guidelines provided by Chesser et al. (2020), scientists must ensure that such Citizen Science programs are inclusive (in particular of Indigenous Peoples), adaptive to Arctic people needs and wills, respectful of their cultural traditions and beliefs, and safe and beneficial for them (see Ward-Fear et al. [2019] for inclusion of citizen groups in coauthorship).

Further, research may be designed with local communities and Indigenous Peoples hired to collect data that can be later analyzed by scientists (Merkel, 2004). However, participation of Arctic peoples in data collection does not suffice to conduct locally driven and oriented research (Markussen, 2016); only 10% of marine citizen science conducted worldwide involves participants beyond data collection (Sandalh & Tøttrup, 2020). More advanced empowerment is achieved when Indigenous Peoples are coresearchers. This means that they are involved in all phases of the monitoring process, from design to implementation, to dissemination of knowledge to local communities and beyond (Alexander et al., 2019; Hamre et al., 2022; Wheeler et al., 2020). Indigenous knowledge is increasingly considered a key companion knowledge system in research (e.g., Mallory et al., 2003), protected area design (Mallory et al., 2006), environmental risk assessment (Kochanowicz et al., 2021), and freshwater ecology (Knopp et al., 2022) because it improves ecological understanding by providing information undetected by the conventional Western science framework.

Although the current pan-Arctic kittiwake monitoring network is unevenly distributed across Arctic ecoregions, it does a fair job of providing a circumpolar framework for population monitoring, given the massive logistical and financial constraints, which weigh heavily on Arctic research activities (Mallory et al., 2018). It is therefore of great value as an information source to motivate and improve ecological management and conservation on a pan-Arctic scale. As a major step forward, our study provides a conceptual and methodological framework for testing the environmental and societal adequacy of a wide range of environmental monitoring programs, which could be applied to others species or ecoregions. Conducting our analyses with other indicator species that are important for Arctic people (other birds, fish, plants, and marine and terrestrial mammals) and integrating all outputs in an overall index would allow determination of key monitoring sites that would provide a complete picture of how environmental change affects Arctic fauna and flora through an ecosystem-based approach that minimizes monitoring costs.

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REFERENCES

Alexander, S. M., Provencher, J. F., Henri, D. A., Taylor, J. J., Lloren, J. I., Nanayakkara, L., Johnson, J. T., & Steven, J. C. (2019). Bridging Indigenous and science-based knowledge in coastal and marine research, monitoring, and management in Canada. *Environmental Evidence*, *8*, 36.

Alvestad, R. J. (2015). *Effects of climate on chick growth in the black-legged kittiwake (Rissa tridactyla)*. Norwegian University of Science and Technology.

Amélineau, F., Grémillet, D., Harding, A. M. A., Walkusz, W., Choquet, R., & Fort, J. (2019). Arctic climate change and pollution impact little auk foraging and fitness across a decade. *Scientific Reports*, *9*(1), 1014.

Barry, T., Daviðsdóttir, B., Einarsson, N., & Young, O. R. (2020). The Arctic Council: An agent of change? *Global Environmental Change*, *63*, 102099.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48.

Bhattacharyya, A. (1943). On a measure of divergence between two statistical populations defined by their probability distributions. *Bulletin of the Calcutta Mathematical Society*, *35*, 99–109.

BirdLife International. (2019). Rissa tridactyla (amended version of 2018 assessment). The IUCN red list of threatened species 2019: E.T22694497A155617539. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22694497A155617539.en

Bjorkman, A. D., García Criado, M., Myers-Smith, I. H., Ravolainen, V., Jónsdóttir, I. S., Westergaard, K. B., Lawler, J. P., Aronsson, M., Bennet, B., Gardfjell, H., Heiðmarsson, S., Stewart, L., & Normand, S. (2020). Status and trends in Arctic vegetation: Evidence from experimental warming and long-term monitoring. *Ambio*, *49*(3), 678–692.

Boertmann, D., Merkel, F., & Gilg, O. (2020). Seabird breeding colonies in East and North Greenland. *Arctic*, *73*(1), 20–39.

Cam, E., Cafiou, B., Hines, J. E., & Monnat, J. (2002). Influence of behavioural tactics on recruitment and reproductive trajectory in the kittiwake. *Journal of Applied Statistics*, *29*(1-4), 163–185.

Certain, G., Jørgensen, L. L., Christel, I., Planque, B., & Bretagnolle, V. (2015). Mapping the vulnerability of animal community to pressure in marine systems: Disentangling pressure types and integrating their impact from the individual to the community level. *ICES Journal of Marine Science*, *72*(5), 1470–1482.

Chesser, S., Porter, M. M., & Tuckett, A. G. (2020). Cultivating citizen-science for all: Ethical considerations for research projects involving diverse and marginalized populations. *International Journal of Social Research Methodology*, *23*(5), 497–508.

Christensen, T., Barry, T., Taylor, J. J., Doyle, M., Aronsson, M., Braa, J., Burns, C., Coon, C., Coulson, S., Cuyler, C., Falk, K., Heiðmarsson, S., Kulmala, P., Lawler, J., MacNearney, D., Ravolainen, V., Smith, P. A., Soloviev, M., & Schmidt, N. M. (2020). Developing a circumpolar programme for the monitoring of Arctic terrestrial biodiversity. *Ambio*, *49*(3), 655–665.

Christensen-Dalsgaard, S., May, R., & Lorentsen, S. H. (2018). Taking a trip to the shelf: Behavioral decisions are mediated by the proximity to foraging habitats in the black-legged kittiwake. *Ecology and Evolution*, *8*, 866–878.

Conservation of Arctic Flora and Fauna (CAFF). (2020). International Black-legged Kittiwake Conservation Strategy and Action Plan. Circumpolar Seabird Expert Group. Conservation of Arctic Flora and Fauna, Akureyri, Iceland. ISBN 978-9935-431-85-1.

Couvet, D., & Prevot, A.-C. (2015). Citizen-science programs: Towards transformative biodiversity governance. *Environmental Development*, *13*, 39–45.

Descamps, S., Anker-Nilssen, T., Barrett, R. T., Irons, D. B., Merkel, F., Robertson, G. J., Yoccoz, N. G., Mallory, M. L., Montevecchi, W. A., Boertmann, D., Artukhin, Y., Christensen-Dalsgaard, S., Erikstad, K. E., Gilchrist, H. G., Labansen, A. L., Lorentsen, S. H., Mosbech, A., Olsen, B., Petersen, A., … Zelenskaya, L. (2017). Circumpolar dynamics of a marine top-predator track ocean warming rates. *Global Change Biology*, *23*(9), 3770–3780.

Dietz, R., Letcher, R. J., Desforges, J.-P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg, E., Basu, N., Barst, B. D., Bustnes, J. O., Bytingsvik, J., Ciesielski, T. M., Drevnick, P. E., Gabrielsen, G. W., Haarr, A., Hylland, K., Jenssen, B. M., Levin, M., McKinney, M. A., … Víkingsson, G. (2019). Current state of knowledge on biological effects from contaminants on arctic wildlife and fish. *Science of The Total Environment*, *696*, 133792.

Edney, A. J., & Wood, M. J. (2020). Applications of digital imaging and analysis in seabird monitoring and research. *Ibis*, *163*, 317–337.

Elliott, K. H., Chivers, L. S., Bessey, L., Gaston, A. J., Hatch, S. A., Kato, A., Osborne, O., Ropert-Coudert, Y., Speakman, J. R., & Hare, J. F. (2014). Windscapes shape seabird instantaneous energy costs but adult behavior buffers impact on offspring. *Movement Ecology*, *2*(1), 17.

Ens, E. J., Pert, P., Clarke, P. A., Budden, M., Clubb, L., Doran, B., Douras, C., Gaikwad, J., Gott, B., Leonard, S., Locke, J., Packer, J., Turpin, G., & Wason, S. (2015). Indigenous biocultural knowledge in ecosystem science and management: Review and insight from Australia. *Biological Conservation*, *181*, 133–149.

Frederiksen, M., Edwards, M., RA, M., & Wanless, S. (2007). Regional and annual variation in black-legged kittiwake breeding productivity is related to sea surface temperature. *Marine Ecology Progress Series*, *350*, 137–143.

Furness, R. W., & Camphuysen, K. (1997). Seabirds as monitors of the marine environment. *ICES Journal of Marine Science*, *54*(4), 726–737.

Grémillet, D., & Descamps, S. (2023). Ecological impacts of climate change on Arctic marine megafauna. *Trends in Ecology & Evolution*, *38*(8), 773–783.

Hamre, T., Danielsen, F., Poulsen, M. K., & Monsen, F. A. (2022). Standards-based data catalogue integrating scientific, community-based and citizen science data across the Arctic. *EGU General Assembly*, *2021*, EGU21-15783. https://doi.org/10.5194/egusphere-egu21-15783

Harris, S. M., Sneddon, L. U., Chastel, O., & Patrick, S. C. (2020). Personality predicts foraging site fidelity and trip repeatability in a marine predator. *Journal of Animal Ecology*, *89*, 68–79.

Hauser, D. D., Whiting, A. V., Mahoney, A. R., Goodwin, J., Harris, C., Schaeffer, R. J., & Zappa, C. J. (2021). Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. *Environmental Research Letters*, *16*(9), 095003.

Heino, J., Culp, J. M., Erkinaro, J., Goedkoop, W., Lento, J., Rühland, K. M., & Smol, J. P. (2020). Abruptly and irreversibly changing Arctic freshwaters urgently require standardized monitoring. *Journal of Applied Ecology*, *57*(7), 1192–1198.

Hinke, J. T., Barbosa, A., Emmerson, L. M., Hart, T., Juáres, M. A., Korczak-Abshire, M., Milinevsky, G., Santos, M., Trathan, P. N., Watters, G. M., & Southwell, C. (2018). Estimating nest-level phenology and reproductive success of colonial seabirds using time-lapse cameras. *Methods in Ecology and Evolution*, *9*, 1853–1863.

Huffeldt, N. P., & Merkel, F. R. (2013). Remote time-lapse photography as a monitoring tool for colonial breeding seabirds: A case study using Thick-billed Murres (*Uria lomvia*). *Waterbirds*, *36*(3), 330–341.

Hughes, B. B., Beas-Luna, R., Barner, A. K., Brewitt, K., Brumbaugh, D. R., Cerny-Chipman, E. B., Close, S. L., Coblentz, K. E., De Nesnera, K. L., Drobnitch, S. T., Figurski, J. D., Focht, B., Friedman, M., Freiwald, J., Heady, K. K., Heady, W. N., Hettinger, A., Johnson, A., Karr, K. A., … Carr, M. H. (2017). Long-term studies contribute disproportionately to ecology and policy. *Bioscience*, *67*(3), 271–278.

Huntington, H. P., Carey, M., Apok, C., Forbes, B. C., Fox, S., Holm, L. K., Ivanova, A., Jaypoody, J., Noongwook, G., & Stammler, F. (2019). Climate change in context: Putting people first in the Arctic. *Regional Environmental Change*, *19*(4), 1217–1223.

Intergovernmental Panel on Climate Change (IPPC). (2021). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3–32). Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

Inuit Circumpolar Council Alaska. (2020). Food sovereignty and self-governance: Inuit role in managing arctic marine resources. Author.

Inuit Circumpolar Council. (2020). Policy paper on the matter of "Local communities". https://iccalaska.org/wp-icc/wp-content/uploads/2020/10/FINAL-ICC-Policy-Paper-on-matter-of-local-communities.pdf

Inuit Tapiriit Kanatami. (2018). National Inuit strategy on research. Ottawa, Ontario, Canada.

Irons, D., Petersen, A., Anker-Nilssen, T., Artukhin, Y., Barrett, R., Boertmann, D., Gavrilo, M. V., Gilchrist, G., Hansen, E. S., Hario, M., Kuletz, K., Mallory, M., Merkel, F., Mosbech, A., Labansen, A. L., Olsen, B., Österblom, H., Reid, J., Robertson, G., … Strøm, H. (2015). Circumpolar Seabird Monitoring Plan. CAFF Monitoring Report No. 17. https://oaarchive.arctic-council.org/items/2cce8587-8e40-4144-8580-2b6d718d4fb4

Jones, F. M., Allen, C., Arteta, C., Arthur, J., Black, C., Emmerson, L. E., Freeman, R., Hines, G., Lintott, C. J., Macháčková, Z., Miller, G., Simpson, R., Soutwell, C., Torsey, H. R., Zisserman, A., & Hart, T. (2018). Time-lapse imagery and volunteer classifications from the Zooniverse Penguin Watch project. *Scientific Data*, *5*, 180124.

Jones, F. M., Arteta, C., Zisserman, A., Lempitsky, V., Lintott, C. J., & Hart, T. (2020). Processing citizen science-and machine-annotated time-lapse imagery for biologically meaningful metrics. *Scientific Data*, *7*, 102.

Kane, A., Pirotta, E., Wischnewski, S., Critchley, E. J., Bennison, A., & Jessopp, M. (2020). Spatio-temporal patterns of foraging behaviour in a wide-ranging seabird reveal the role of primary productivity in locating prey. *Marine Ecology Progress Series*, *646*, 175–188.

Knopp, J. A., Levenstein, B., Watson, A., Ivanova, I., & Lento, J. (2022). Systematic review of documented Indigenous Knowledge of freshwater biodiversity in the circumpolar Arctic. *Freshwater Biology*, *67*(1), 194–209.

Kochanowicz, Z., Dawson, J., Halliday, W. D., Sawada, M., Copland, L., Carter, N. A., Nicoll, A., Ferguson, S. H., Heide-Jørgensen, M. P., Marcoux, M., Watt, C., & Yurkowski, D. J. (2021). Using western science and Inuit knowledge to model ship-source noise exposure for cetaceans (marine mammals) in Tallurutiup Imanga (Lancaster Sound), Nunavut, Canada. *Marine Policy*, *130*, 104557.

Kroodsma, D. A., Mayorga, J., Hochberg, T., Miller, N. A., Boerder, K., Ferretti, F., Wilson, A., Bergman, B., White, T. D., Block, B. A., Woods, P., Sullivan, B., Costello, C., & Worm, B. (2018). Tracking the global footprint of fisheries. *Science*, *361*(6378), 904–908.

Ksenofontov, S., Backhaus, N., & Schaepman-Strub, G. (2019). "There are new species": Indigenous Knowledge of biodiversity change in Arctic Yakutia. *Polar Geography*, *42*(1), 34–57.

Likens, G., & Lindenmayer, D. (2018). *Effective ecological monitoring*. CSIRO Publishing. https://books.google.fr/books?id=QDBZDwAAQBAJ

Logan, S., Christensen, T., Barry, T., Price, C., & Lárussoon, K. (2018). *Circumpolar Biodiversity Monitoring Program Strategic Plan: 2018–2021*. Conservation of Arctic Fauna and Flora (CAFF) working group of the Arctic Council.

Mallory, M. L., Gilchrist, H. G., Janssen, M., Major, H. L., Merkel, F., Provencher, J. F., & Strøm, H. (2018). Financial costs of conducting science in the Arctic: Examples from seabird research. *Arctic Science*, *4*(4), 624–633.

Mallory, M. L., Fontaine, A. J., Akearok, J. A., & Johnston, V. H. (2006). Synergy of local ecological knowledge, community involvement and scientific study to develop marine wildlife areas in eastern Arctic Canada. *Polar Record*, *42*(3), 205–216.

Mallory, M. L., Gilchrist, H. G., Fontaine, A. J., & Akearok, J. A. (2003). Local ecological knowledge of Ivory gull declines in Arctic Canada. *Arctic*, *56*(3), 293–298.

Mallory, M. L., Toomasie, J., Emond, S., Lamarche, G., Roberts, L., Pirie-Dominix, L., & Provencher, J. F. (2022). Community-scientist collaboration in the creation, management and research for two National Wildlife Areas in Arctic Canada. In J. M. Holzer, J. Baird, & G. M. Hickey (Eds.), *Pluralism in ecosystem governance* (pp. 37–61). Academic Press.

Markussen, U. (2016). Towards an Arctic awakening: Neocolonalism, sustainable development, emancipatory research, collective action, and Arctic regional policymaking. In K. Latola & H. Savela (Eds.), *The Inter-connected Arctic, UArctic Congress 2016* (pp. 305–311). Springer.

Merkel, F. R. (2004). Evidence of population decline in common eiders breeding in Western Greenland. *Arctic*, *57*, 27–36.

Merkel, F. R., Johansen, K. L., & Kristensen, A. J. (2016). Use of time-lapse photography and digital images to estimate breeding success of a cliff-nesting seabird. *Journal of Field Ornithology*, *87*, 84–95.

Osborne, O. E., O'Hara, P. D., Whelan, S., Zandbergen, P., Hatch, S. A., & Elliott, K. H. (2020). Breeding seabirds increase foraging range in response to an extreme marine heatwave. *Marine Ecology Progress Series*, *646*, 161–173.

Pearce, S. M. (1987). Ivory, antler, feather and wood: Material culture and the cosmology of the Cumberland Sound Inult, Baffin Island, Canada. *Canadian Journal of Native Studies*, *7*(2), 307–321.

Pratte, I., Braune, B. M., Hobson, K. A., & Mallory, M. L. (2019). Variable sea-ice conditions influence trophic dynamics in an Arctic community of marine top predators. *Ecology and Evolution*, *9*(13), 7639–7651.

Provencher, J., Kögel, T., Lusher, A., Vorkamp, K., Gomiero, A., Peeken, I., Granberg, M., Hammer, S., Baak, J., Larsen, J. R., & Farmen, E. (2022). An ecosystem-scale litter and microplastic monitoring plan under the Arctic Monitoring and Assessment Programme (AMAP). *Arctic Science*, *8*, 1067–1081.

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth and Environment*, *3*, 168.

Sandalh, A., & Tøttrup, A. P. (2020). Marine citizen science: Recent developments and future recommendations. *Citizen Science: Theory and Practice*, *5*(1), 24.

Sauve, D., Charmantier, A., Hatch, S. A., & Friesen, V. L. (2022). Environmental conditions variably affect growth across the breeding season in a subarctic seabird. *Oecologia*, *198*, 307–318.

Schwalm, C. R., Glendon, S., & Duffy, P. B. (2020). RCP8.5 tracks cumulative CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(33), 19656–19657.

Silverman, B. W. (1986). *Density estimation for statistics and data analysis. Monographs on statistics and applied probability* (Vol. 26). Chapman and Hall.

Wang, M., & Overland, J. E. (2015). Projected future duration of the sea-ice-free season in the Alaskan Arctic. *Progress in Oceanography*, *136*, 50–59.

Ward-Fear, G., Pauly, G. B., Vendetti, J. E., & Shine, R. (2019). Authorship protocols must change to credit citizen scientists. *Trends in Ecology & Evolution*, *35*(3), 187–190.

Wein, E., Freeman, M., & Makus, J. (1996). Use of and preference for traditional foods among the Belcher Island Inuit. *Arctic*, *49*(3), 256–264.

Wheeler, H. C., Berteaux, D., Furgal, C., Parlee, B., Yoccoz, N. G., & Grémillet, D. (2016). Stakeholder perspectives on triage in wildlife monitoring in a rapidly changing Arctic. *Frontiers in Ecology and Evolution*, *4*, 128.

Wheeler, H. C., Danielsen, F., Fidel, M., Hausner, V., Horstkotte, T., Johnson, N., Lee, O., Mukherjee, N., Amos, A., Ashthorn, H., Ballari, Ø., Behe, C., Breton-Honeyman, K., Retter, G. B., Buschman, V., Jakobsen, P., Johnson, F., Lyberth, B., Parrott, J. A., … Vronski, N. (2020). The need for transformative changes in the use of Indigenous knowledge along with science for environmental decision-making in the Arctic. *People and Nature*, *2*, 544–556.

Young, R. C., Kitaysky, A. S., Carothers, C., & Dorresteijn, I. (2014). Seabirds as a subsistence and cultural resource in two remote Alaskan communities. *Ecology and Society*, *19*(4), 40.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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