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Mercury contamination and potential health risks to Arctic seabirds and shorebirds

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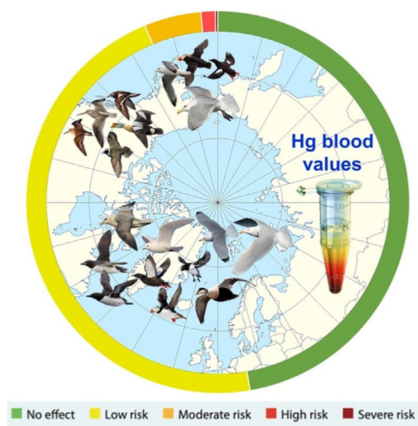
HIGHLIGHTS

- Hg exposure and potential health risk for 36 Arctic seabirds and shorebirds species
- Toxicity benchmarks established for blood and converted for eggs, liver, feathers
- 95 % of the species considered at lower risk, 2.5 % of seabirds at high risk
- Adult survival unaffected by Hg which impacts physiology and depresses reproduction
- Categorized low risk Hg levels may be harmful if co-occurring with other stressors.

GRAPHICAL ABSTRACT

Hg exposure and potential health risk for Arctic seabirds and shorebirds



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ABSTRACT

Since the last Arctic Monitoring and Assessment Programme (AMAP) effort to review biological effects of mercury (Hg) on Arctic biota in 2011 and 2018, there has been a considerable number of new Arctic bird studies. This review article provides contemporary Hg exposure and potential health risk for 36 Arctic seabird and shorebird species, representing a larger portion of the Arctic than during previous AMAP assessments now also including parts of the Russian Arctic. To assess risk to birds, we used Hg toxicity benchmarks established for blood and converted to egg, liver, and feather tissues. Several Arctic seabird populations showed Hg concentrations that exceeded toxicity benchmarks, with 50 % of individual birds exceeding the "no adverse health effect" level. In particular, 5 % of all studied birds were considered to be at moderate or higher risk to Hg toxicity. However, most seabirds (95 %) were generally at lower risk to Hg toxicity. The highest Hg contamination was observed in seabirds breeding in the western Atlantic and Pacific Oceans. Most Arctic shorebirds exhibited low Hg concentrations, with approximately 45 % of individuals categorized at no risk, 2.5 % at high risk category, and no individual at severe risk. Although the majority Arctic-breeding seabirds and shorebirds appeared at lower risk to Hg toxicity, recent studies have reported deleterious effects of Hg on some pituitary hormones, genotoxicity, and reproductive performance. Adult survival appeared unaffected by Hg exposure, although long-term banding studies incorporating Hg are still limited. Although Hg contamination across the Arctic is considered low for most bird species, Hg in combination with other stressors, including other contaminants, diseases, parasites, and climate change, may still cause adverse effects. Future investigations on the global impact of Hg on Arctic birds should be conducted within a multi-stressor framework. This information helps to address Article 22 (Effectiveness Evaluation) of the Minamata Convention on Mercury as a global pollutant.

1. Introduction

Among contaminants of concern, mercury (Hg) is a non-essential trace element from both natural (e.g., volcanic eruptions, forest fires, biomass burning) and anthropogenic sources (e.g., fossil fuel combustion, mining, waste disposal and chemical production). Due to long-range transport by atmospheric, oceanic, and riverine pathways (AMAP, 2021), the Arctic is considered a sink to atmospheric Hg deposition (Dastoor et al., 2022; Nerentorp et al., 2022; AMAP, 2021). Mercury contamination has increased globally from anthropogenic inputs and has become a major concern in the Arctic (AMAP, 2021).

The toxic form of Hg, methylmercury (MeHg), bioaccumulates in organisms, biomagnifies throughout trophic food webs, and can have numerous detrimental effects on Arctic wildlife (Scheuhammer et al., 2007; Ackerman et al., 2016). Avian reproduction is especially sensitive to MeHg toxicity, with even low levels of exposure potentially leading to adverse effects (Wiener et al., 2003; Heinz et al., 2009). Aquatic birds typically have the highest exposures to environmental Hg contamination (Ackerman et al., 2016), although terrestrial birds, like riparian songbirds, may also bioaccumulate MeHg to potentially harmful levels (Cristol et al., 2008; Ackerman et al., 2019; Cristol and Evers, 2020). Within the Arctic, aquatic birds are primarily exposed to elevated levels of MeHg in pelagic environments (Provencher et al., 2014a; Braune et al., 2015; Peck et al., 2016; Burnham et al., 2022; Albert et al., 2019, 2021), coastal shorelines, and wetland foraging habitats (Hargreaves et al., 2011; McCloskey et al., 2013; Perkins et al., 2016; Sun et al., 2019).

Among aquatic birds, seabirds are long-lived species often at the top of food web chains, both leading them to exhibit some of the highest Hg concentrations observed in wildlife, making them particularly sensitive to the harmful effects of MeHg exposure. Hence, seabirds are commonly and efficiently used as bio-indicators of the health of their environment (Elliott and Elliott, 2013). Originally centered on the Canadian Arctic (e.g., Braune et al., 2014a), the characterization of MeHg contamination in seabirds has been recently expanded to many other localities and species of the Arctic regions (e.g., Albert et al., 2021).

Recently Hg data have also become available for another group of aquatic birds - shorebirds (Perkins et al., 2016; Perkins, 2018; Pratte et al., 2020, Burnham et al., 2022). As long-lived species with widespread distributions across the Arctic during the breeding season, shorebirds may represent an ideal group for Arctic Hg exposure research. Shorebirds nest and forage within wetland habitats in the Arctic tundra and can occupy relatively high trophic levels. Because Hg research on terrestrial avian invertivores in the Arctic is limited (Scheuhammer et al., 2015), recent investigations of shorebird Hg concentrations fills an important knowledge gap (Perkins et al., 2016, Burnham et al., 2022).

The first objective of the present study was to provide contemporary (post-2000) information on Hg contamination and potential health risks for Arctic seabirds and shorebirds, updating the AMAP, 2011 Hg Assessment and the AMAP 2018 Effect Assessment (AMAP, 2011, AMAP, 2018, Dietz et al., 2013, 2019). Therefore, we provide the most up-to-date risk assessment of Hg exposure on Arctic seabirds and shorebirds, including more species, tissues (blood, feather, eggs, liver), regions, and larger sample sizes than done in previous assessments. This review was meant to be an update to the last AMAP effects assessment (AMAP, 2018; Dietz et al., 2019a), and, as such, does not constitute a complete synthesis of raw data extracted from the literature that has been previously published. In particular, Burnham et al. (2022) provides an additional resource, particularly for Hg concentrations in birds from Greenland during 2010–2012. We also address some of the knowledge gaps identified in previous AMAP (2011) assessments. Some of these gaps include geographical data gaps in the Russian Arctic, where new seabird data have become available, including a substantial amount from the ARCTOX project (https://arctox.cnrs.fr/en/work-area/, e.g., Albert et al., 2021). In addition, we include Hg data on shorebirds (Perkins, 2018, in collaboration with the Arctic Shorebird Demographics Network (ASDN); Lanctot et al., 2016) which have recently become available. This paper includes more Hg data, a greater number of species, and a wider coverage of the Arctic than was reported previously in the assessment of the risk of Hg to birds in western North America first carried out by Ackerman et al. (2016). The generation of such a knowledgebase is also important for Article 22 of the Minamata Convention, which calls for an effectiveness evaluation program, within which Hg levels in Arctic avian species are an important component (https://www.mercuryconvention.org/sites/default/files/documents/information_document/4_INF12_MonitoringGuidance.English.pdf).

The second objective of this study is to update the previous AMAP (2011) assessment by reviewing the effects of Hg contamination on Arctic seabirds and shorebirds. Establishing links between contaminant exposure and health is difficult (Rodríguez-Estival and Mateo, 2019). However, this information is extremely important for managing and conserving wildlife populations including those of globally declining seabirds and shorebirds (Colwell, 2010, Paleczny et al., 2015). Herein, we report on post-2011 studies, mostly on seabirds, that have examined the relationships between Hg exposure and behavioral and physiological mechanisms that may explain the links between Hg exposure and Arctic seabird and shorebird demography (reproduction and survival). Studies conducted on Arctic seabirds and shorebirds are viewed with respect to research conducted on Antarctic birds, which face ecological constraints comparable to those of Arctic birds. Studies based on long-term mark-capture-recapture monitoring, have made it possible to explore the effects of Hg exposure on demographic parameters. Hene, in recent years there have been some studies on the effects of Hg in both Arctic and Antarctic birds (e.g., Bårdsen et al., 2018; Amélineau et al., 2019; Carravieri et al., 2021). As this type of study is still rare in the Arctic, we believe it is relevant to place Arctic studies in the more general context of the effects of Hg in polar birds. This section is intended to be comprehensive, including potential mechanisms that have been little studied.

In this article we:

1) Provide Hg exposure and potential health risk assessments for 36 Arctic seabird and shorebird species, by using toxicity benchmarks established for blood and converting them into their toxicity equivalents for egg, liver, and feather tissues.
2) Discuss Hg exposure and potential health risks. To do so, we will review recent studies that have investigated relationships between Hg exposure, behavior, physiology, and fitness in Arctic seabirds and shorebirds.
3) Make suggestions for future research on the impact of Hg exposure in Arctic seabirds and shorebirds.

2. Methods

In birds, most of the total Hg (THg) consists of MeHg in many tissues including blood, feather and eggs (Bond and Diamond, 2009; Rimmer et al., 2005; Ackerman et al., 2013; Renedo et al., 2017). In the present study, Hg refers to THg and is reported as a proxy for MeHg, except for liver where a significant proportion of Hg is in its inorganic form (Eagles-Smith et al., 2009). Adult seabird blood, body feathers, eggs, and liver Hg data were collected in 24 species from several areas of the Arctic (see Supplementary Material, Tables S1-S3). Data presented here are based on published data (Ackerman et al., 2016; Tartu et al., 2013, 2016; Goutte et al., 2015; Blévin et al., 2018; Fleishman et al., 2019; Braune et al., 2015; Braune et al., 2014a, 2014b, 2016; Jæger et al., 2009; Helgason et al., 2008; Miljeteig et al., 2009; Hoydal and Dam 2005, 2009; Nielsen et al., 2014; Saunes, 2011) and, where possible, raw data as cited in the Supplementary Material, Tables S1-S3 (particularly from ARCTOX: https://arctox.cnrs.fr/en/work-area/).

For shorebirds (see Supplementary Material, Tables S4 and S5), a study of the period 2012 to 2013 led by Perkins (Perkins et al., 2016; Perkins, 2018), in collaboration with the Arctic Shorebird Demographics Network (ASDN; Lanctot et al., 2016) and several other partners, sampled 12 breeding species from five sites in Alaska located near Nome, Cape Krusenstern, Barrow, the Ikpikpuk River and the Colville River (Alaska), and three sites in Canada near the Mackenzie River Delta, Bylot Island and East Bay (Nunavut). An additional Canadian study site, Igloolik (Nunavut), was included with the previously sampled sites in 2013. The ASDN biologists collected blood and feather samples from adult shorebirds captured while conducting routine fieldwork during the breeding season.

We reviewed and assessed the potential for MeHg toxicity in Arctic seabirds and shorebirds using the available data (see Supplementary Material, Tables S1-S5). To assess risk, we used MeHg toxicity benchmarks previously established for bird blood (Ackerman et al., 2016) and converted these values into equivalent total Hg concentrations in other bird tissues that are also commonly sampled in the Arctic, such as eggs, liver, and body feathers.

Blood-equivalent Hg concentrations <0.2 μg/g (wet weight, ww) are below the lowest-observed effect levels, whereas birds are generally considered to be at low risk when blood Hg concentrations are 0.2–1.0 μg/g ww, moderate risk at 1.0–3.0 μg/g ww, high risk at 3.0–4.0 μg/g ww, and severe risk at >4.0 μg/g ww (Ackerman et al., 2016). We converted these toxicity benchmarks in bird blood into equivalent concentrations in eggs, based on a review paper that established a general bird maternal transfer equation of Hg from females to their eggs (Ackerman et al., 2020). Similarly, we converted blood to equivalent liver Hg concentrations using an inter-tissue correlation equation built for four species of seabirds and shorebirds (Eagles-Smith et al., 2008a, 2008b). Because many of the Arctic bird data for Hg contamination have been sampled using bird feathers (Albert et al., 2019), we also converted these toxicity benchmarks for bird blood into equivalent body feather Hg concentrations using an unpublished dataset ($n = 16$ species, $n = 2077$ measurements during 2015 to 2017; Equation: $\ln$ (Hg body feather μg/g dw) $= 0.64 \times \ln$ (Hg Blood μg/g ww) $+ 1.51$; Fort, unpublished). Unlike the other equations, inter-tissue correlations for feathers and internal tissues, such as blood or eggs, tend to be poor (Evers et al., 1998; Eagles-Smith et al., 2008a, 2008b; Ackerman et al., 2016). Feather molt represents a major excretion pathway in birds during which 60 % to 90 % of accumulated Hg is excreted (Honda et al., 1986; Braune, 1987; Braune and Gaskin, 1987; Lewis et al., 1993; Agusa et al., 2005). Mercury in feathers becomes stable once they have been fully grown to the adult stage (Appelquist et al., 1984), even though they are changed on a regular basis during annual or bi-annual molt. Since feathers have often grown months before they are collected, the existing temporal and spatial mismatch in Hg concentrations between feathers and other tissues is exacerbated. In addition, feather Hg concentrations can be difficult to interpret for several reasons: a) the complex timing and location of feather molt (Pyle, 2008; Pyle et al., 2018); b) differences among feather tracts (such as head vs. body feathers; Braune and Gaskin, 1987; Ackerman et al., 2016, Fort et al., 2016); c) the large scale movements of birds that expose migratory species to Hg over different regions (Fleishman et al., 2019); and d) the extreme variability in Hg concentrations in some species both within and among individual feathers from the same individual bird (Peterson et al., 2019).

Because of these complexities, feathers of adult birds are typically not recommended for Hg biomonitoring programs if detailed information about bird-species biology is lacking (Ackerman et al., 2016; Chételat et al., 2020) such as the species-specific precise feather molt timing or distribution over their annual cycle (Ackerman et al., 2012; Albert et al., 2019). Feathers can be a useful sampling tool to represent Hg contamination in specific cases, such as in remote oceanic locations where birds are difficult to sample. For example, nape feathers of red-legged kittiwakes (*Rissa brevirostris*) are thought to be grown at the end of the wintering period and were sampled from birds on their breeding grounds, where these kittiwakes can be more easily captured on their nests (Fleishman et al., 2019). This sampling strategy coupled with tracking dataloggers demonstrated that red-legged kittiwakes wintering at more southern latitudes within the North Pacific Ocean had higher Hg concentrations than birds wintering at more northern latitudes (Fleishman et al., 2019). Similarly, head feathers of little auks (*Alle alle*), which grow on the wintering grounds, were used to demonstrate that the bird's feathers were 3.5 times more contaminated when outside of their Arctic breeding locations, indicating that MeHg acquired at non-Arctic wintering areas in the northwest Atlantic Ocean can be transported to Arctic breeding areas by migratory birds and has the potential to affect reproductive success (Fort et al., 2014). Therefore, feathers were useful for demonstrating that non-Arctic regions that were used by the Arctic avian community for several months per year, during which birds travel thousands of kilometers between their Arctic breeding sites and non-Arctic non-breeding grounds (e.g., Egevang et al., 2010), are of high concern due to higher Hg contamination experienced during winter (Albert et al., 2021).

3. Results and discussion

3.1. Hg exposure and potential health risk for Arctic seabirds and shorebirds

3.1.1. Seabirds

Based on toxicity benchmarks, we found 50 % of individual seabirds ($n = 5000$) showed tissue Hg concentrations that were above the no risk level for adverse health effects (i.e., a blood-equivalent Hg concentration > 0.2 μg/g ww) and that 1 % of seabirds were either in the high or severe risk categories (Figs. 1.1, 1.2, and 1.3. Supplementary Material, Table S1, S2 and S3). In particular, northern fulmar (*Fulmarus glacialis*), ivory gull (*Pagophila eburnea*), glaucous-winged gull (*Larus glaucescens*), glaucous gull (*Larus hyperboreus*), lesser black-backed gull (*Larus fuscus*), black-legged kittiwake (*Rissa tridactyla*), red-legged kittiwake, Atlantic puffin (*Fratercula arctica*), thick-billed murre (Brünnich's guillemot, *Uria lomvia*), black guillemot (*Cepphus grylle*), pigeon guillemot (*Cepphus columba*), rhinoceros auklet (*Cerorhinca monocerata*), and double-crested cormorant (*Phalacrocorax auritus*) had at least 5 % of the individuals sampled with blood-equivalent Hg concentrations at levels considered to be at moderate, high, or severe risk to toxicity (Figs. 1.1, 1.2 and 1.3.; Supplementary Material, Table S1-S3). Mercury concentrations in seabirds tended to increase through time within the Arctic, but trends have flattened recently in several Arctic regions (Braune et al., 2001, 2006, 2016; Braune, 2007; Bond et al., 2015; but c.f. Fort et al., 2016 in East Greenland and Tartu et al., 2022 in Svalbard). As is common, seabird Hg concentrations differed widely among sites in the Arctic (Fig. 2) due to differences in bioaccumulation pathways and processes (Braune et al., 2002, 2014b). Braune et al. (2014a) found that thick-billed murres breeding at two High Arctic colonies (above 66°30′ N) tended to have higher Hg concentrations than murres breeding at three Low Arctic locations (below 66°30′ N). In contrast, seabirds wintering at more southern latitudes generally had higher Hg exposure (Fort et al., 2014; Fleishman et al., 2019). In general, seabirds tended to have higher Hg concentrations in the Canadian Arctic, western Canada, and western Greenland than in the European Arctic or Russian Arctic (Fig. 2; Provencher et al., 2014a; Albert et al., 2021).

3.1.2. Shorebirds

Blood Hg concentrations in individual shorebirds ranged from 0.01 to 3.52 μg/g ww, with an overall mean ± standard deviation of 0.30 ± 0.27 μg/g ww (Fig. 3.1., Supplementary Material Table S4). Among the shorebird species reviewed, the mean blood Hg concentration for long-billed dowitchers (*Limnodromus scolopaceus*; 0.74 ± 0.25 μg/g ww) was over 4.9 times greater than for American golden plovers (*Pluvialis dominica*; 0.15 ± 0.07 μg/g ww). For feathers of shorebird species, the mean Hg concentration was 1.14 ± 1.18 μg/g dw for all samples analyzed and ranged from 0.07 to 12.14 μg/g dw (Supplementary Material, Table S5). Feather Hg concentrations also differed by species, with the mean feather Hg concentration for pectoral sandpipers (*Calidris melanotos*; 2.58 ± 1.76 μg/g dw) over 4.3 times greater than for red phalaropes (*Phalaropus fulicarius*; 0.60 ± 0.44 μg/g dw). Most Arctic-breeding shorebirds had blood Hg concentrations which placed individuals in the no risk or low risk categories (Fig. 3.1) and below the level at which there can be adverse effects of Hg exposure, with approximately 45 % of individuals in the no risk category and 47 % in the low risk category (Fig. 3.1). We found no individuals in the severe risk category, and a low proportion of individuals with blood Hg concentrations in the moderate risk (4.5 %) and high risk (2.5 %) categories. The greatest proportion of individuals in the moderate risk and high-risk categories were sampled at the Barrow (Alaska) study site while the Cape Krusenstern, Ikpikpuk River, Mackenzie River Delta, and Bylot Island sites did not have any individual shorebirds with blood Hg concentrations in these moderate and high-risk categories. Long-billed dowitchers had the greatest proportion of individuals in the moderate risk (22 %) and high-risk categories (17 %). Pectoral sandpiper also had 17 % and 9 % of individuals within the moderate and high-risk categories, respectively. Individual American golden plover, Baird's sandpiper (*Calidris bairdii*), grey plover (*Pluvialis squatarola*), and black turnstone (*Arenaria melaocephala*) had blood Hg concentrations only in the no effect and low risk categories. Because no temporal trend data were available from shorebirds, no further information on highly Hg exposed species and regions with temporal trend information could be conducted.

3.2. Review of the consequences of Hg exposure in Arctic seabird and shorebirds

3.2.1. Demographic consequences

Impaired reproductive success is the most widely investigated and reported consequence of Hg exposure in wildlife (Evers et al., 2008, Scheuhammer et al., 2012, Whitney and Cristol, 2017). Chronic exposure to MeHg might also compromise survival rates and long-term reproductive output, potentially leading to population declines, although very few studies have investigated such demographic consequences (Tartu et al., 2013).

3.2.1.1. Reproductive performance. Exposure to MeHg can alter avian sexual and mating behaviors (Frederick and Jayasena, 2011 for waterbirds, Spickler et al., 2020 for a domesticated songbird model species, the zebra finch *Taeniopygia guttata*). For Arctic birds, no information is available. In contrast to legacy chlorinated Persistent Organic Pollutants (POPs; Blévin et al., 2014), Hg concentrations in Svalbard black-legged kittiwakes were

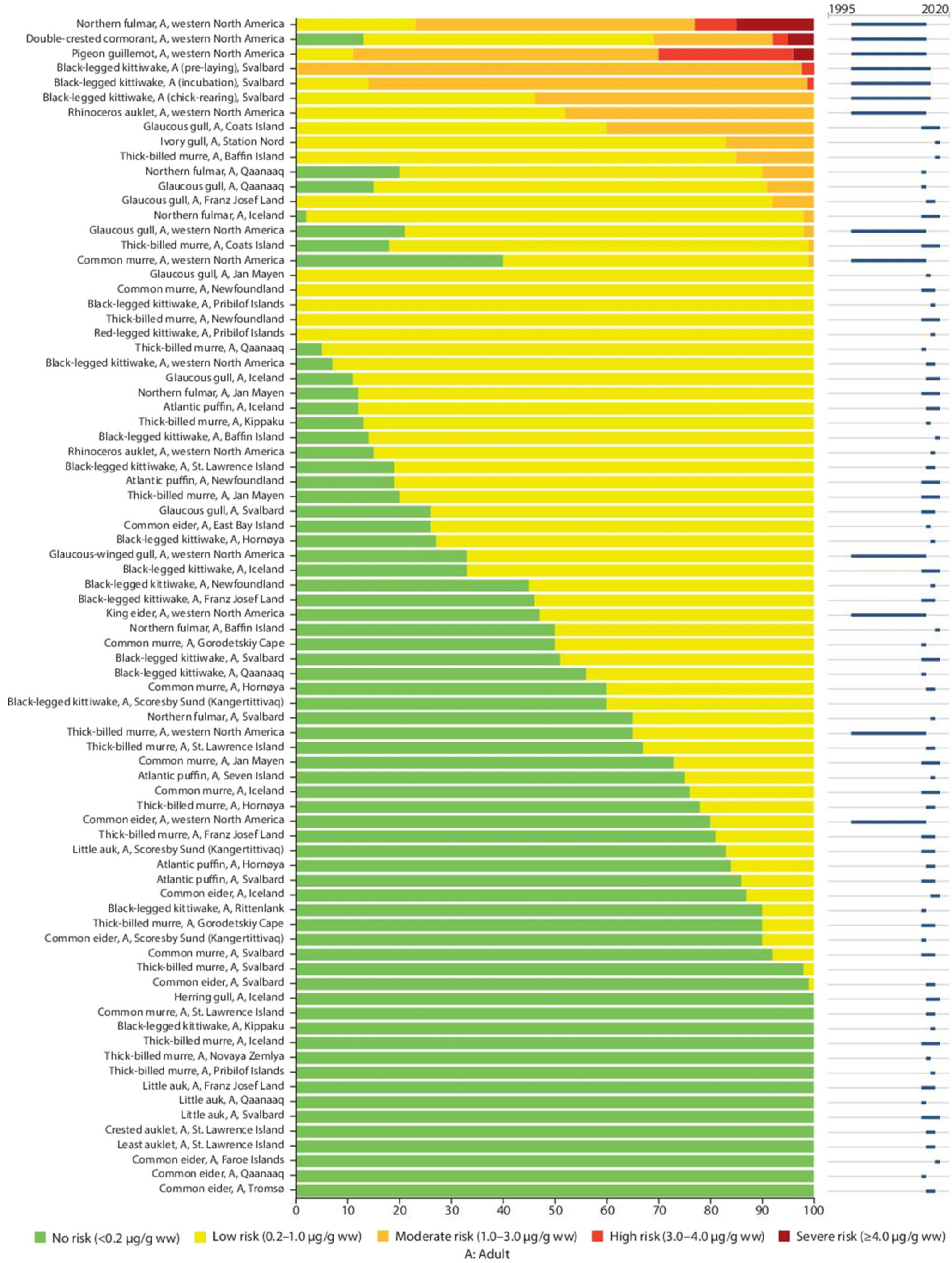

Fig. 1.1. Ranked overview (from highest to lowest risk) of the proportion of seabird blood per region from the Arctic, which are at risk for Hg-mediated health effects (categorized in five risk categories based upon blood Hg effect thresholds). Blue bars on the right side indicate the date range of the samples. Please see Supplementary Material Table S1 for detailed information upon which this summary graphic is based, including scientific names for all species.

not associated with carotenoid-based sexual ornamentations, carotenoid concentrations in plasma, nor to pairing success (Costantini et al. submitted). Further, the prevalence of abnormal sperm cells observed in Svalbard kittiwakes (Humann-Guilleminot et al., 2018) was unrelated to Hg blood concentrations (Blévin et al., unpublished data). Amélineau et al. (2019) reported that adult little auks with high Hg concentrations had reduced body condition. Skipping a breeding event is a common phenomenon in long-lived birds (Charlesworth, 1980). Investigations conducted in Svalbard have shown that foregoing breeding was associated with high Hg concentrations in pre-laying kittiwakes, whereas laying date and clutch size were not related to Hg concentrations (Tartu et al., 2013). Similarly, Hg levels were unrelated to clutch size and timing of breeding in common eiders (*Somateria mollissima*; Provencher et al., 2017) and Leach's storm petrel (*Hydrobates leucorhous*; Pollet et al., 2017). In another study of Svalbard kittiwakes, breeding success (probability to raise at least one chick) in males was negatively related to Hg concentration (Tartu et al., 2016). In a study of three shorebird species (ruddy turnstones, grey plover, and semipalmated plover *Charadrius semipalmatus)*, hatching success was not influenced by egg Hg concentrations (Hargreaves et al., 2010). In contrast, hatching success was negatively related to paternal Hg concentrations in feathers (Hargreaves et al., 2010).

Impaired reproductive performance may also originate from eggshell thinning (Olivero-Verbel et al., 2013), although evidence is lacking for seabirds (Peterson et al., 2020). Low hatching success may also be the

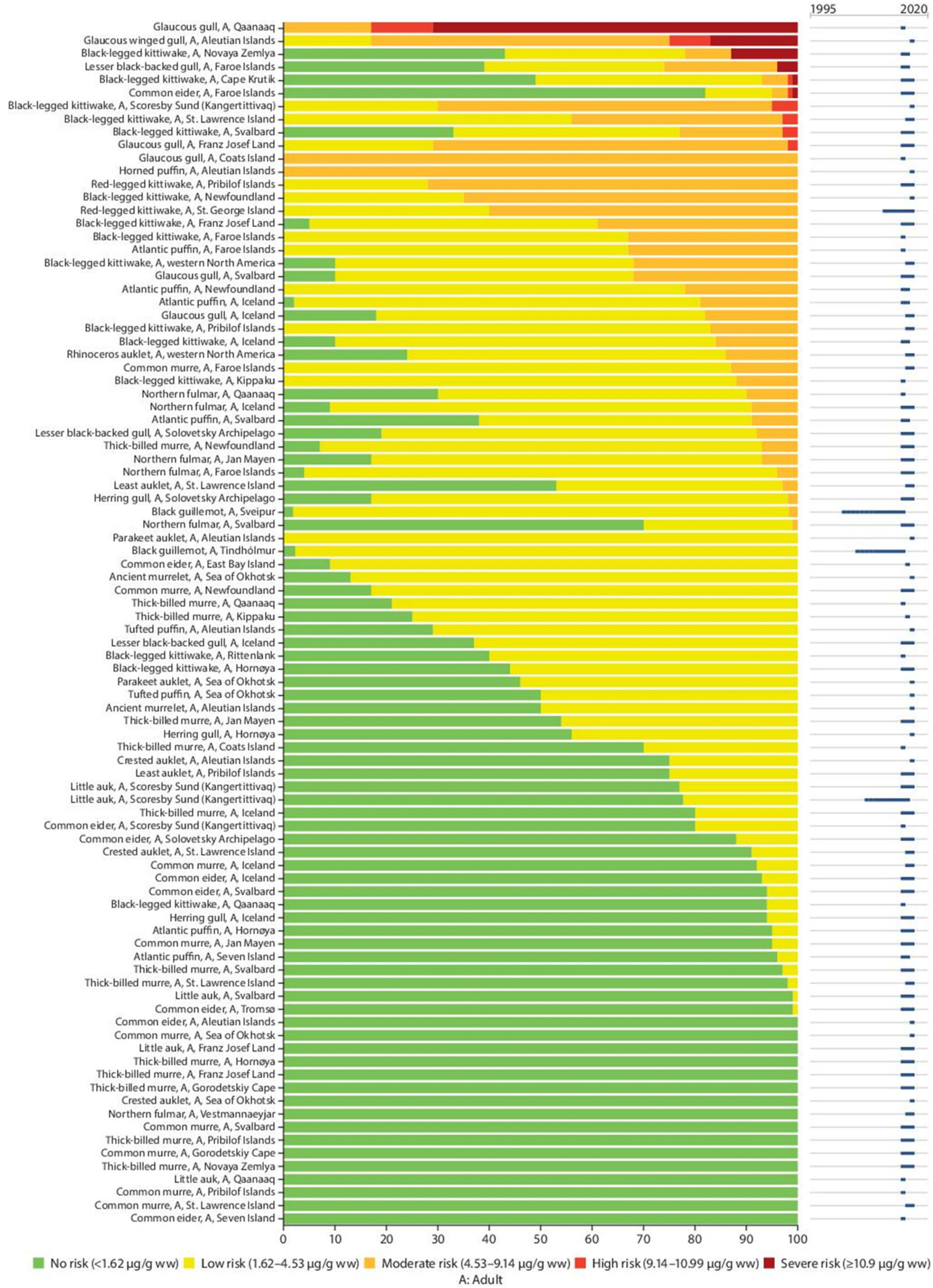

Fig. 1.2. Ranked overview (from highest to lowest risk) of the proportion of seabird feathers per region from the Arctic, that are at risk for Hg-mediated health effects (categorized in five risk categories based upon feather Hg effect thresholds). Blue bars on the right side indicate the date range of the samples. Please see Supplementary Material Table S2 for detailed information upon which this summary graphic is based, including scientific names for all species.

consequence of a reduced egg size. For example, female little auks with greater feather Hg concentrations laid smaller eggs in Greenland (Fort et al., 2014), whereas egg volume was not related to Hg in Leach's storm petrels (Pollet et al., 2017). The negative effect of Hg exposure on egg hatchability was experimentally demonstrated in thick-billed murres and Arctic terns (*Sterna paradisea*) by injecting birds with a range of environmentally relevant concentrations (0–6.4 μg/g ww) of MeHg chloride (MeHgCl). This study by Braune et al. (2012) showed the relative sensitivity of the developing embryos to MeHg in these two Arctic seabird species. Finally, in Greenland, chicks of little auks with the highest Hg concentrations hatched with a body mass reduced by approximately 30 % compared to those with the lowest concentrations, although no impact was further observed on their growth and fledging success (Kerric, pers. comm). Nevertheless, Amélineau et al. (2019) found that the long-term increase in Hg contamination of this same population of little auks was associated with a decreased chick growth rate during the last decade.

Previous studies therefore demonstrated that reproductive performances can be impaired by MeHg in a number of Arctic species. However, those effects were not observed in all study species and further meta-analysis approaches (i.e. Carravieri et al., 2022) are now required to fully

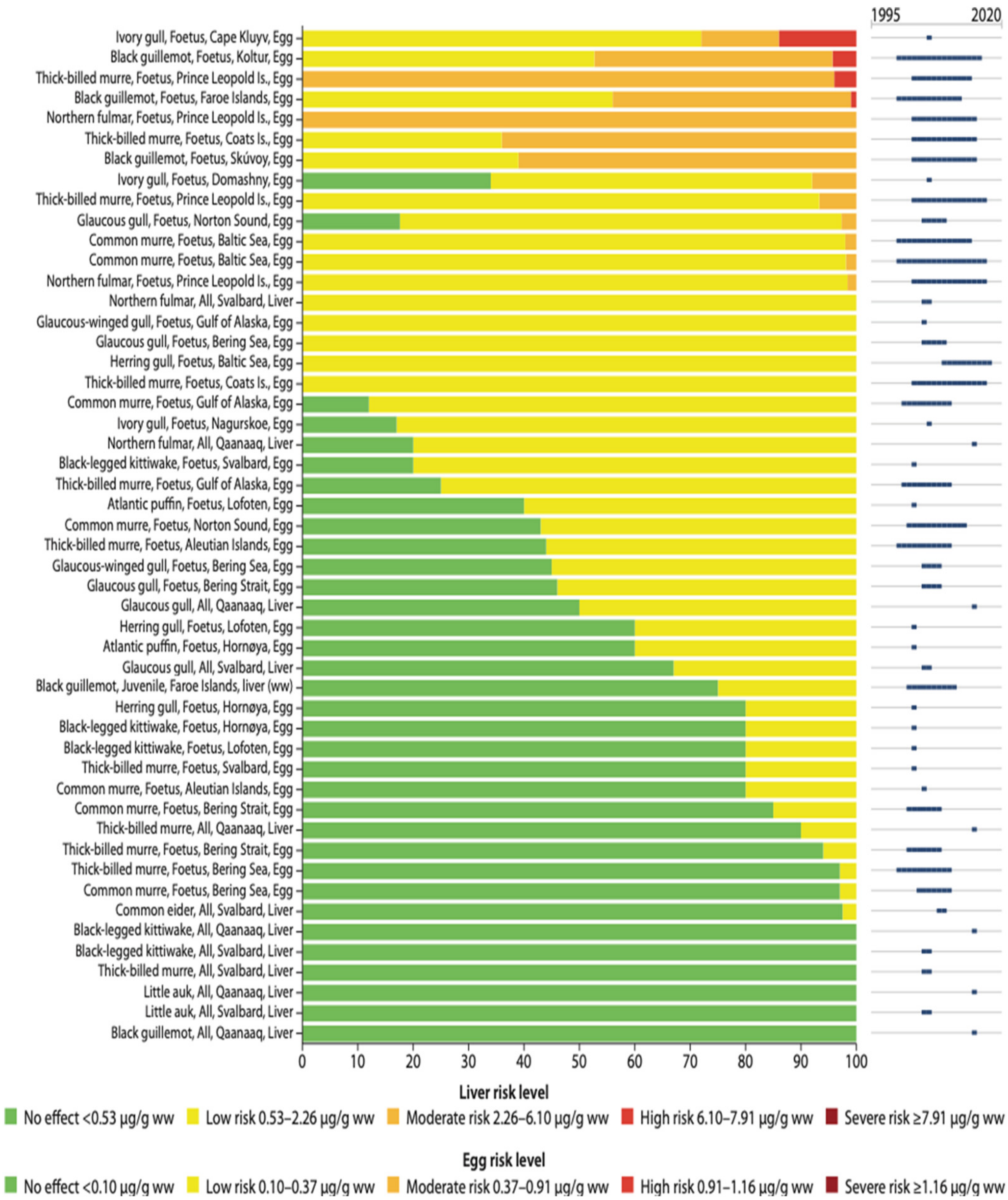

Fig. 1.3. Ranked overview (from highest to lowest risk) of the proportion of seabird livers and eggs per region from the Arctic, that are at risk for Hg-mediated health effects (categorized in five risk categories based upon liver and egg Hg effect thresholds). Blue bars on the right side indicate the date range of the samples. Please see Supplementary Material Table S3 for detailed information upon which this summary graphic is based, including scientific names for all species.

understand how Hg, alone or in interaction with other environmental stressors, is impacting the reproduction of Arctic seabirds. Additionally, most of those studies focused on breeding birds, thus excluding individuals which did not breed and potentially hiding some Hg effects on seabird body condition or breeding probability. Considering this part of the population is challenging but important when investigating effects of contaminants to avoid biased interpretations (Tartu et al., 2013).

3.2.1.2. Long-term demographic consequences. Our understanding of the ultimate consequences of Hg exposure on long-term fitness is still limited in free-living Arctic birds because of the paucity of long-term data sets that would be required to address this topic. Few long-term capture-mark-recapture studies on Antarctic (wandering albatross *Diomedea exulans*; Goutte et al., 2014a, Bustamante et al., 2016, grey-headed albatrosses *Thalassarche chrysostoma*, Mills et al., 2020; subantarctic and south polar skuas *Catharacta lonnbergi*, *C. maccormicki* Goutte et al., 2014b) and Arctic seabirds (Svalbard: glaucous gull and black-legged kittiwake Erikstad et al., 2013; Goutte et al., 2015; Greenland: little auk, Amélineau et al., 2019; Northern Norway: common eider Bårdsen et al., 2018) have estimated the impact of contaminants on long-term breeding probability, reproductive success, and/or adult survival. These studies, based on long-term ringing programs have mainly focused on legacy chlorinated POPs, but some of them have included blood and feather Hg concentrations in demographic models (Goutte et al., 2014a, 2014b, 2015; Bustamante et al., 2016; Pollet et al., 2017; Bårdsen et al., 2018; Amélineau et al., 2019). Regarding Arctic seabirds, a long-term study on Svalbard kittiwakes found reduced breeding probability with higher Hg concentrations, but the overall impact of Hg on demographic parameters was modest compared to that of some legacy chlorinated POPs (Goutte et al., 2015). Importantly, all these long-term studies (reviewed in Whitney and Cristol, 2017) revealed no effect of Hg on adult survival, a key parameter for seabird population dynamics, despite an order of magnitude range in blood Hg concentrations

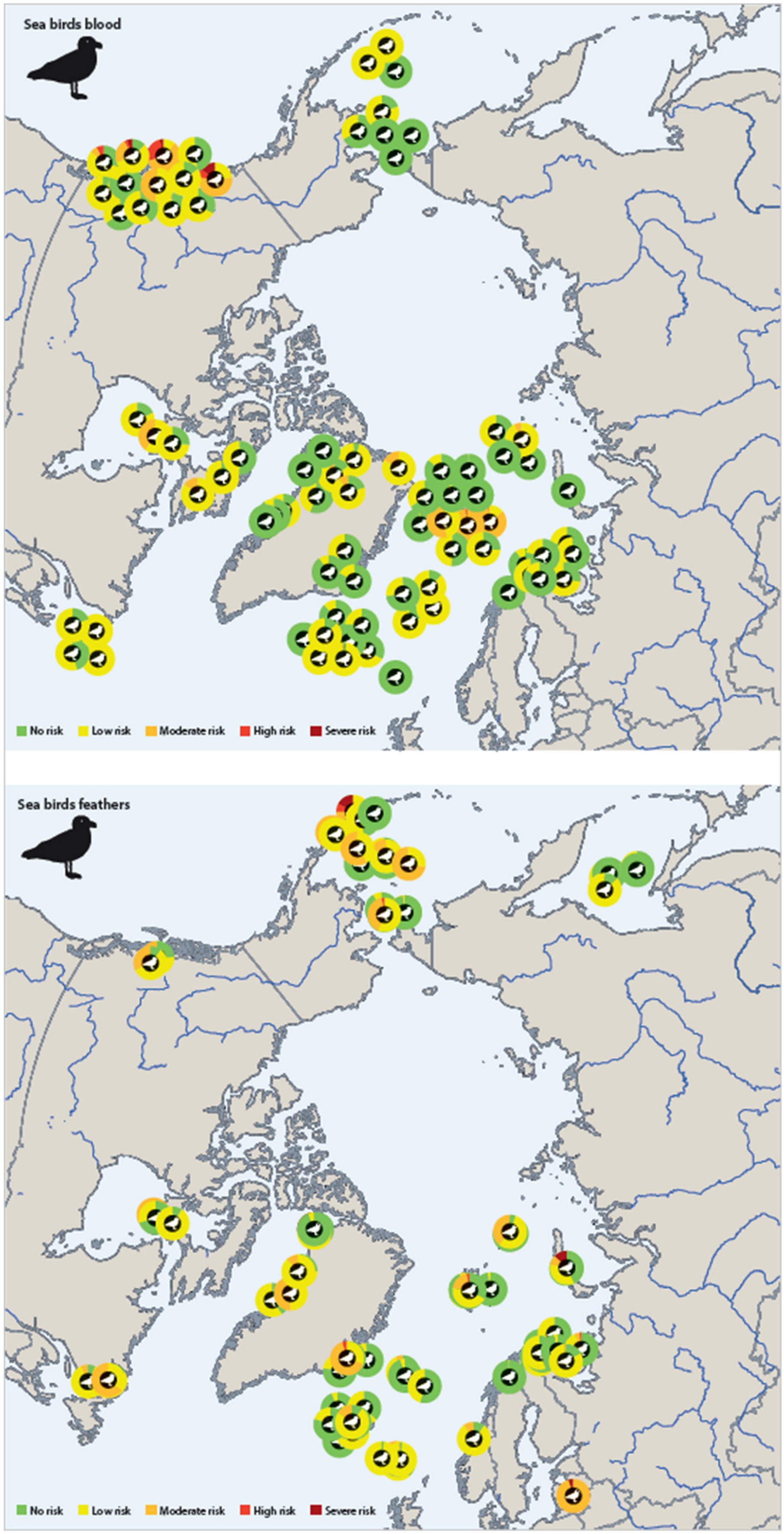

Fig. 2. Geographical overview of the proportion of adult seabirds that are at risk of Hg-mediated health effects based on data for blood (upper) and feathers (lower). Please see Supplementary Material Table S1 and S2, and Figs. 1.1 (blood) and 1.2 (feathers), for detailed information upon which this summary graphic is based.

across species (from 0.89 to 8.22 ± 0.24 μg/g dw). In summary, it appears that Hg exposure affects reproduction more than adult survival in Arctic birds. Further studies are nonetheless needed to confirm this pattern.

3.2.2. Behavioral and physiological mechanisms potentially involved in the demographic consequences of Hg exposure

3.2.2.1. Parental behavior. In birds, incubation-related behaviors are influenced by hormonal regulation. In some Antarctic seabirds, Tartu et al. (2015a) showed that Hg concentrations were associated with a lower commitment to incubate eggs. Nonetheless, relatively little is known about the effect of contaminants on incubation temperature for wild birds (Hartman et al., 2019; Taylor et al., 2018). By using loggers placed into artificial eggs, Blévin et al. (2018) investigated relationships between three groups of contaminants (organochlorine pesticides (OCs), poly − /per-fluoroalkyl substances (PFAS), and Hg) with incubation temperature and brood patch in Svalbard black-legged kittiwakes. This study revealed that, contrary to OCs, Hg concentrations in blood (2.00 ± 0.59 μg/g dw in males; 1.43 ± 0.38 μg/g dw in females) were not related to the minimum incubation temperature, nor the size of the brood patch. However, incubation does not solely imply the active warming of the eggs but also the active turning of eggs to facilitate albumen absorption by the embryo, reduce the likelihood of an embryo being mispositioned for hatching (Herring et al., 2010), and prevent the embryo from adhering to the inner shell membrane. Using egg-loggers, Blévin et al. (2020) found that, unlike polychlorinated biphenyls (PCBs) and PFAS, blood Hg concentrations were unrelated to egg-turning behavior in Svalbard black-legged kittiwakes, similar to studies on egg turning in seabirds at temperate latitudes (Taylor et al., 2018).

3.2.2.2. Endocrine system. To maximize fitness, individuals must make behavioral decisions on their reproduction depending on environmental conditions (e.g., whether to breed or not, when to breed, what level of parental investment). These behavioral decisions are mediated by hormones, including luteinizing hormone, a pituitary hormone involved in the onset of breeding (Dawson et al., 2001); stress hormones (corticosterone, Wingfield and Sapolsky, 2003); and prolactin, a pituitary hormone involved in the expression of parental care (Angelier and Chastel, 2009). Because Hg is a known endocrine disruptor (Tan et al., 2009), Hg may impair breeding decisions (Hartman et al., 2019) and could alter the ability of Arctic seabirds to adequately respond to ongoing environmental changes (Jenssen, 2006).

Research conducted on Svalbard black-legged kittiwakes has shown that Hg (0.91–3.08 μg/g dw) influences pituitary hormones. For example, high Hg concentrations in blood were related to a decreased secretion of luteinizing hormone (Tartu et al., 2013). Additionally, experimental challenges with exogenous GnRH (gonadotropin-releasing hormone) were conducted to test the ability of the pituitary to release luteinizing hormone in relation to Hg concentrations. These investigations suggested that Hg disrupted luteinizing hormone secretion by suppressing GnRH input to the pituitary and that elevated Hg concentrations were linked to years where birds did not reproduce (Tartu et al., 2013). A similar pattern was observed for Antarctic seabirds (Tartu et al., 2014). As for luteinizing hormone, Hg seems to impact another pituitary hormone, prolactin, which is known to play a key role in the expression of avian parental care (Angelier and Chastel, 2009). In black-legged kittiwakes from Svalbard as well as in several Antarctic seabirds, high Hg exposure appeared to be associated with lower plasma prolactin levels and poor incubation behavior (Tartu et al., 2015a, 2016, Smith et al. pers. comm). The effect of Hg on stress hormones secretion is less clear (see Herring et al., 2012 for temperate seabird nestlings and Provencher et al., 2016a for common eider ducks). In Svalbard kittiwakes, baseline and stress-induced corticosterone levels were unrelated to Hg concentrations (range: 0.82–2.96 μg/g dw). In this population, exacerbated baseline and stress-induced corticosterone levels appeared to be triggered by PCBs, possibly via a stimulation of adrenocorticotropic hormone (ACTH) receptors (Tartu et al., 2015b). Further research is thus required on a wider diversity of species to fully grasp the relationships between Hg contamination and endocrine system in Arctic seabirds.

3.2.2.3. Bioenergetics-energy expenditure and thyroids hormones. Individual variation in energy metabolism may influence fitness because of the trade-off in allocating energy toward self-maintenance (survival), activity, growth, and reproduction (Stearns, 1992). The minimal energetic cost of living in endotherms, the basal metabolic rate (BMR), is known to be influenced by thyroid hormones (THs) which can stimulate in vitro oxygen consumption of tissues in birds and mammals (Merryman and Buckles, 1998). A disruption of THs by environmental contaminants could act on energy expenditure, yet the effect of Hg on BMR is still poorly documented for wildlife (see Gerson et al., 2019 on a lab passerine model). Blévin et al. (2017) investigated the relationships between OCs, PFAS, and Hg with metabolic rate and circulating total THs (thyroxine (TT4) and triiodothyronine (TT3)) in adult black-legged kittiwakes from Svalbard. This study indicated that, contrary to some OCs and PFAS (Blévin et al., 2017; Melnes et al., 2017 for glaucous gull), metabolic rate and some thyroid hormones (T3) were not associated with Hg blood levels in Svalbard kittiwakes. Further investigation on the link between Hg exposure, THs, and energy expenditure (basal and field metabolic rate) could be helpful, especially for the most Hg-contaminated species.

3.2.2.4. Oxidative stress and telomeres. One potential important biochemical mechanism for Hg to influence wildlife is how it may affect oxidative stress, because of its possible detrimental effects on fitness traits (e.g., reproduction, susceptibility to disease, survival; Costantini, 2014; Sebastiano et al., 2016). Investigations on temperate and Antarctic seabirds have reported some associations between Hg and oxidative stress (Costantini et al., 2014; Gibson et al., 2014; Hoffman et al., 2011). For Arctic seabirds, Wayland et al. (2010) investigated glaucous gulls from the Canadian Arctic and found associations between some oxidative markers (thiols, lipid peroxidation) and Hg burdens. In Svalbard, there was no association between blood Hg concentrations (1.96–4.82 μg/g dw) and several oxidative status markers for kittiwakes (Chastel, unpublished data). Similarly, Fenstad et al. (2016a, 2016b) found no association between Hg exposure and total antioxidant capacity in Baltic and Svalbard common eiders. Oxidative stress can be considered as one of the mechanisms involved in telomere shortening. Telomeres are repeated sequences of non-coding DNA located at the terminal ends of chromosomes (Blackburn, 2005). Following their discovery and implications for maintaining chromosome stability, health, and ageing, there has been a growing interest for studies relating telomere dynamics to contaminant exposure (Angelier et al., 2018). Because they are associated with longevity and survival in vertebrates, telomeres represent a physiological marker that may be useful to estimate the toxicological consequences of contaminant exposure (Sebastiano et al., 2020). A recent study has reported that higher feather Hg concentration was associated with shorter te-lomeres in Cory's Shearwater Calonectris borealis (Bauch et al., 2022). However, to date only a few studies have explored telomere-contaminant relationships in Arctic free-living birds, mainly in relation to organic pollutants (Sletten et al., 2016; Blévin et al., 2016, 2017; Eckbo et al., 2019; Sebastiano et al., 2020). Regarding Hg, only one study has been conducted, and they found that absolute telomere length was positively but weakly associated with blood Hg concentrations in Svalbard kittiwakes (Angelier et al., 2018). Thus, there is a current data gap for our understanding of the relationship between Hg and telomeres.

3.2.2.5. Genotoxicity. Alterations in genetic material may have severe consequences on the survival of individuals and ultimately on the fate of populations. Since 2010, several studies have investigated the genotoxic effects of environmental exposure to pollutants in Arctic seabirds (e.g., Fenstad et al., 2014; Haarr et al., 2018). Fenstad et al. (2016b) assessed the impact of blood Hg concentrations on DNA double-strand break (DSB) frequency, in blood cells of a higher exposed Baltic (Hg: 0.43–1.71 nmol/gww), and

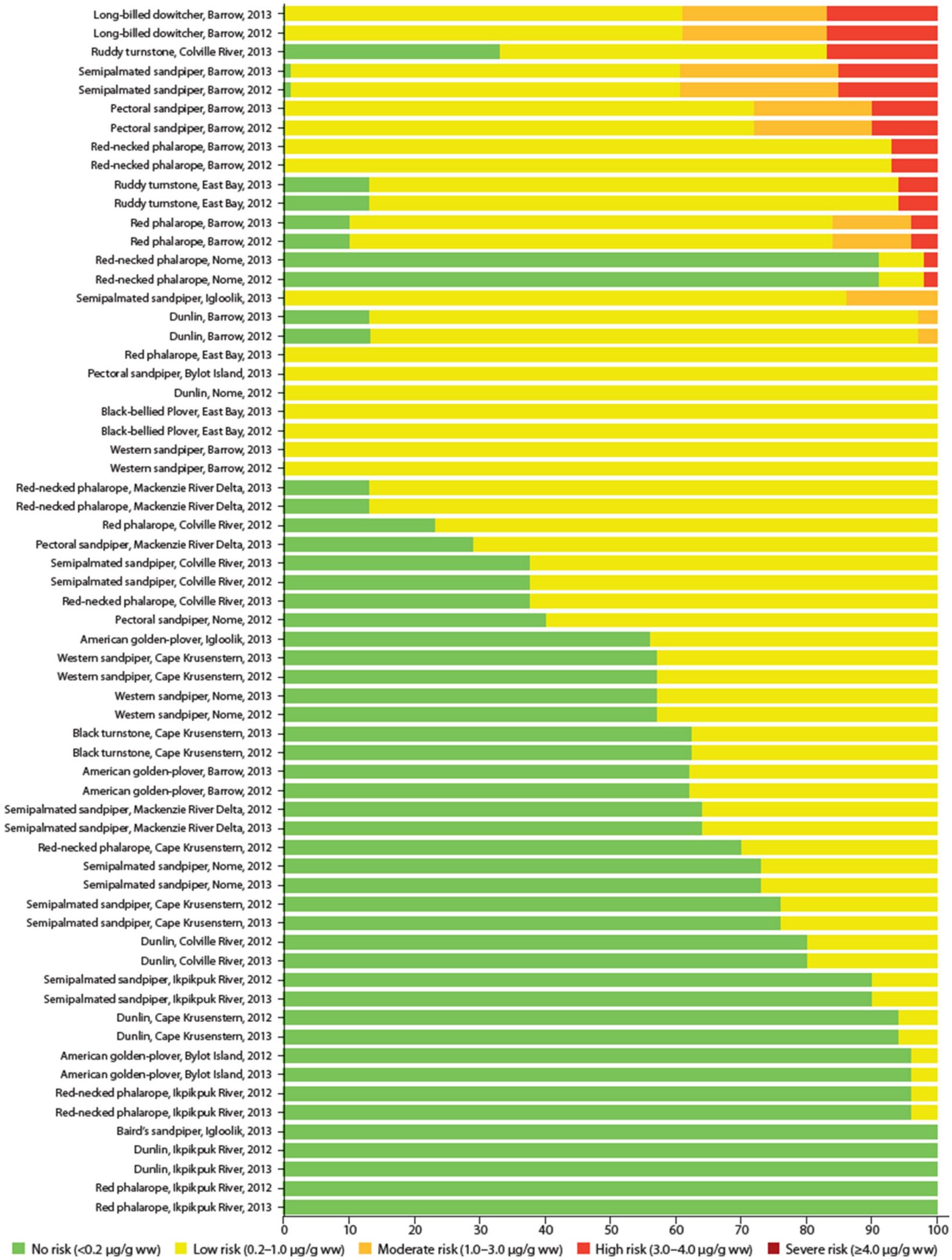

Fig. 3.1. Ranked overview (from highest to lowest risk) of the proportion of shorebirds blood, per region from the Arctic, that are at risk for Hg-mediated health effects (categorized in five risk categories based upon liver Hg effect thresholds). Please see Supplementary Material Table S4 for detailed information upon which this summary graphic is based, including scientific names for all species.

lower exposed Arctic population (Svalbard, Hg: 0.31–0.98 nmol/gww) of common eiders. Significant positive relationships between Hg and DNA DSB frequency were found in Baltic, but not in Svalbard eiders.

3.2.2.6. Neurology. To understand the effects of Hg exposure on developing thick-billed murre and arctic tern embryos, Braune et al. (2012) investigated the concentrations of receptors in the brain, a biomarker of MeHg effects in wildlife (Basu et al., 2006; Scheuhammer et al., 2015). However, no relationship was found between Hg concentration and density of specific neuroreceptors in brain tissue in either species. Despite strong evidence that Hg poses neurotoxic risks to a diverse range of taxa (including birds), there is limited information from the Arctic.

3.2.2.7. Immune system. Exposure to Hg can be associated with depressed avian immune responses (Fallacara et al., 2011; Lewis et al., 2013), and this may interfere with reproduction and survival in some contaminated individuals. Furthermore, such impairment of the immune system may pose an additional threat to Arctic birds because climate change could increase the emergence of new infectious diseases or a higher prevalence of parasites (Eagles-Smith et al., 2018; Lee et al., 2020). Provencher et al. (2016a) did not find an association between Hg blood levels and immunoglobulinY (IgY) in female eider ducks from the Canadian Arctic. Similarly, in an experimental study of Svalbard barnacle geese (*Branta leucopsis*), de Jong et al. (2017) found that exposure to Hg from a historic coal mine area had little impact on four innate immune parameters (haemolysis, haemagglutination, haptoglobin-like activity, and nitric oxide) in goslings. Though studies have failed to detect strong effects of Hg on immune response in Arctic birds, contaminants and parasites may negatively affect wildlife health and reproduction either additively or synergistically (Marcogliese and Pietrock, 2011). To date, only one study on common eiders from the Canadian Arctic indicated that Hg (breast muscle levels: 0.63 ± 0.24 μg/g dw [mean ± *SD*]) and gastrointestinal parasites potentially influence each other (Provencher et al., 2016b). Because of their connection with the immune system, changes in vitamins A, D, and E have been investigated as biomarkers of contaminant exposure and effects in Arctic wildlife (for POPs see Helgason et al., 2010; Braune et al., 2011; Verreault et al., 2013). Since 2010, few studies addressing the relationships between Hg and vitamins in Arctic seabirds have been conducted. In the ivory gull, a year-round and contaminated resident of the Arctic (Bond et al., 2015; Lucia et al., 2015), eggs from Svalbard and the Russian Arctic populations were sampled to investigate relationships between whole egg Hg content (0.06–0.30 μg/g ww), eggshell thinning, vitamin A, and vitamin E (Miljeteig et al., 2012). No association between Hg concentration, eggshell thinning and the two vitamins were found in this study. Additional research on Hg-vitamin relationships could be helpful for interpreting Hg effects on birds in the arctic, especially in the context of thiamine (vitamin B1) deficiency observed in the Baltic Sea (Sonne et al., 2012).

4. Discussion and suggestions for future research on the potential impact of Hg in arctic seabirds and shorebirds

Overall, the ability of the AMAP monitoring program to provide Hg concentrations in Arctic seabirds and shorebirds has greatly improved since 2011 with the addition of 24 Arctic seabird and 12 Arctic shorebird species, and include more tissues (e.g., blood, feathers, eggs, embryo, liver), regions (Alaska, Nunavut, Northwest Territories, Greenland, Svalbard, Scandinavia), and sample sizes than prior work. This manuscript also addresses some of the knowledge gaps identified in previous AMAP assessments. These prior data gaps include geographical data gaps in the Russian Arctic, where new seabird data have become available and allowed the risk analysis first carried out by Ackerman et al. (2016) of North American birds to be extended to other parts of the circumarctic region. Continuous efforts to further fill some still existing spatial gaps (especially in the Russian Arctic) is nonetheless needed. The knowledge on Hg exposure of Arctic shorebirds has considerably progressed but is still limited to North America and there is a need to collect additional data on Hg exposure in birds from the European Arctic and Russia which support considerable shorebird populations (Colwell, 2010). The present study is particularly timely given the recent entry into force of the Minamata Convention on Mercury (https://www.mercuryconvention.org/en), which makes special note of the Arctic's vulnerability to Hg. In particular, there is specific interest in monitoring Hg levels in birds in this region as part of the Minamata Convention's plans for effectiveness evaluation.

4.1. Incorporating Hg monitoring into long-term banding studies

Despite recent important advances in assessing Hg exposure in Arctic seabirds and shorebirds, our understanding of the ultimate consequences of Hg exposure in Arctic seabirds and shorebirds is still limited by the availability of long-term demographic studies. Seabirds and shorebirds are long-lived animals and, as such, their populations are especially sensitive to any decrease in adult survival (Sæther and Bakke, 2000). To date, long-term ringing (banding) studies investigating the demographic consequences of Hg and other contaminants in Arctic seabirds are limited to a handful of species and locations (Svalbard black-legged kittiwakes, Svalbard glaucous gulls, Greenland little auks, Northern Norway common eider; Erikstad et al., 2013; Goutte et al., 2015; Bårdsen et al., 2018; Amélineau et al., 2019; Sebastiano et al., 2020). For shorebirds, this type of long-term ringing study incorporating Hg measurements is not currently available, but it would be useful given the current, large-scale declines in many Arctic shorebird populations (e.g., Kubelka et al., 2018).Thus, investigating whether Hg contamination is linked to adult survival and reproduction, especially for at-risk species, may be particularly useful. These mark-recapture studies on individuals that have been marked and subjected to demographic monitoring over several years would help our understanding of the effects of Hg on bird demography.

4.2. Considering a multi-stressor perspective

Overall, our review indicates that most individual Arctic seabirds (93 %) and shorebirds (95 %) were considered at lower risk to potential Hg impairment (<1.0 μg/g ww in blood). For instance, according to Hg toxicity benchmarks observed for blood, most Svalbard kittiwakes and 100 % of Greenland little auks were considered at no or low risk, yet behavioral and physiological disruption together with impaired breeding performances have been reported in these species (Tartu et al., 2013, 2016; Goutte et al., 2015; Amélineau et al., 2019). Arctic birds are exposed to multiple stressors and the impacts of Hg probably act in concert with both natural and other anthropogenic stressors (e.g., other contaminants, diseases, parasites, climate-related environmental changes; see Provencher et al., 2016b). Thus, even Hg concentrations considered as posing low or moderate risks to birds, may cause adverse effects if they co-occur with other stressors (Goutte et al., 2014b; Fort et al., 2015; Tartu et al., 2016; Amélineau et al., 2019).

4.2.1. Interactions between Hg and other contaminants

The Arctic is a sink for a mixture of various pollutants (Dietz et al., 2019), thus future investigations could also incorporate other types of contaminants (e.g., legacy chlorinated and brominated POPs, PFAS, and other non-essential trace elements) known to interact with behavior, physiology, and fitness into demographic models to better assess the specific impacts of Hg. For instance, little is known about levels and effects of trace elements such as copper (Cu), iron (Fe), or selenium (Se) (but see Anderson et al., 2010; Hargreaves et al., 2010, 2011; Borgå et al., 2006; Fromant et al., 2016). These trace elements are essential for biological processes within a narrow range of concentrations, but can lead to deleterious effects outside the range, and are able to interact with other contaminant uptake, storage, and toxic effects (Walker et al., 2012). Specifically, Se may have a protecting role against Hg toxicity (Khan and Wang, 2009), yet only a few studies have quantified their co-exposure and interaction in seabirds (e.g., Carravieri et al., 2017, 2020; Carvalho et al., 2013; Cipro et al., 2014; Gonzalez-Solís et al., 2002; Provencher et al., 2014b). Demethylation of MeHg and subsequent sequestration of inorganic Hg with Se has often been suggested as a probable detoxification mechanism for vertebrates (Eagles-Smith et al., 2009; Renedo et al., 2021; Manceau et al., 2021). Ralston (2009) reported that the molar ratio of Hg:Se was critical to the expression of MeHg toxicity. Specifically, molar excesses of Se over Hg may be important in the potential to protect cells from Hg toxicity, such as by detoxifying Hg by forming tiemannite complexes (Dietz et al., 2013, 2019). However, the process is complex, and recent studies indicate that demethylation may require four Se rather than one per atom of Hg (Manceau et al., 2021). Incorporating Se measurements into Hg assays might allow refinement of our understanding of Hg toxicity and, more generally, allow for better assessment of the overall impact of Hg on wildlife (Goutte et al., 2014a; Carravieri et al., 2017).

4.2.2. Interplay between Hg and parasites

Hg and parasites are ubiquitous stressors that can affect animal physiology and derive from similar dietary sources (co-exposure). Parasites could modulate the kinetics of Hg in its organism (assimilation, distribution in tissues, accumulation) and effects on health (Bustnes et al., 2006). Understanding Hg concentrations in bird tissues and their parasites (Morrill et al., 2015) and the interaction of Hg with parasites could be useful for biomonitoring pollution, and to realistically quantify the health risks for Arctic birds (Provencher et al., 2016a, 2016b). Finally, quantifying the effects of Hg and parasites, alone or in combination, on markers representative of the health status of the organism (Carravieri et al., 2020) could test the hypothesis that parasites may act as a “contaminant sink” and thus relieve the host of some of its Hg contamination.

4.2.3. Possible carry-over effects

Most seabirds and shorebirds leave the Arctic after the breeding period and some are long distance migrants, spending the winter in sub-Arctic, temperate, tropical, or Antarctic areas (e.g., Egevang et al., 2010; Battley et al., 2012; Gilg et al., 2013). Environmental stressors and Hg uptake experienced outside of the breeding season can result in sub-lethal to lethal effects and can synergistically contribute to high bird mortality by impacting their body condition (Fort et al., 2015). Environmental stressors can also result in non-lethal effects that will be carried on to the next breeding season (carry-over effects; Norris, 2005) and which could impact fitness and population dynamics. Combining miniaturized tracking systems (e.g., geolocators to document migratory movements and wintering areas) with measurements of Hg levels in tissue archives (e.g., feathers molted during winter; Albert et al., 2021; Fleishman et al., 2019), environmental stressors, and detailed demographic surveys could provide relevant information on the global impact of Hg on Arctic birds. Moreover, recent advances in Hg isotope analyses and studies suggest that Hg isotopes may be used to differentiate between specific environmental Hg sources and processes (Tsui et al., 2020), which again may provide insight into the sources, source areas, and biogeochemical processes involved in Hg uptake and exposure in migrating birds.

4.2.4. Climate change and assessments of Hg risk for Arctic seabirds and shorebirds

The Arctic is warming two to three times faster than any other region on Earth (AMAP, 2021) with impacts on precipitation, snow cover, permafrost levels, and sea-ice thickness and extent. These changes are causing fundamental alterations in ecosystems that affect biogeochemical fluxes, bottom-up processes, ecosystems, and food webs, which may lead to modifications in Hg exposure in Arctic biota (Stern et al., 2012; Braune et al., 2014b; Mckinney et al., 2015; Tartu et al., 2022). Of particular concern is that global warming, which will lead to an earlier onset of thawing and a later start of freezing, will likely extend the period of Hg methylation (Stern et al., 2012) and thus may increase exposure of the toxic form of Hg, MeHg, to seabirds and shorebirds. The permafrost stores large amounts of Hg, nearly twice as much as other soils, the ocean, and the atmosphere combined, which may become mobilized and released during thawing and therefore may represent a significant source of Hg (Schuster et al., 2018). A recent study on Hg contamination of polar bears (*Ursus maritimus*) in the Barents Sea (northern coasts of Norway and Russia) showed that the increased Hg in polar bears during the last two decades was attributed to re-emissions of previously stored Hg from thawing sea-ice, glaciers, and permafrost, with this Hg then becoming bioavailable and biomagnifying in the Arctic marine food webs (Lippold et al., 2020). These results indicate that climate-induced re-emission of legacy Hg may already be happening in the Arctic.

Climate change in the Arctic may challenge physiological processes of individuals (water balance, thermoregulation, nutrition, immune, endocrine, and neurological systems) critical for coping with the external environment, causing Artic birds to become more sensitive to Hg contamination because they may be pushed to the limits of their physiological tolerance (Hooper et al., 2013). Alternatively, increased exposure to Hg could make birds more sensitive to stressors (heat waves, increased precipitation, diseases, changes in food web, and nesting habitats) induced by climate change (Hooper et al., 2013). In this multi-stressor context, the challenge will be to identify potential interactions between non-chemical and chemical stressors affecting key physiological processes in Arctic seabirds and shorebirds. Understanding Hg exposure and climate change interactions could facilitate the assessment of the potential health risks for Arctic birds.

CRediT authorship contribution statement

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Céline Albert	Seabird data contribution, Review & Editing
Frédéric Angelier	Seabird data contribution
Niladri Basu	Writing – Review & editing; Writing – original Draft; Resources; Investigation
Pierre Blévin	Seabird data contribution
Paco Bustamante	Seabird data contribution, Review & Editing
Jan Ove Bustnes	Seabird data contribution
Rune Dietz	Writing – original Draft, Resources; Investigation, Review & Editing
Igor Eulaers	Seabird data contribution, Writing – original Draft
Geir Gabrielsen	Seabird data contribution
Aurélie Goutte	Seabird data contribution
Robert J. Letcher	Writing – original Draft, Resources; Investigation, Review & Editing
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Flemming Ravn	Merkel Seabird data contribution
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Anders Mosbech	Seabird data contribution
Jens Søndergaard	Seabird data contribution
Sabrina Tartu	Seabird data contribution, Review & Editing
Simon Wilson	Resources, Investigation, Graphics
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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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