REVIEW
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BEARDED SEALS IN THE ATLANTIC ARCTIC: REVIEW OF POST 2010 KNOWLEDGE AVAILABLE FOR INFORMING STOCK ASSESSMENTS

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ABSTRACT

The last extensive (pan-Arctic) review on knowledge available on the bearded seal (*Erignathus barbatus)* was conducted by Cameron et al. in 2010. As bearded seals are hunted off Svalbard and Greenland but no stock assessments are available, NAMMCO requested a status review, and if possible, an assessment of the species in its area. This literature review attempts to summarise the knowledge that has become available post 2010, with a focus on the Atlantic Arctic. A large amount of information has become available on the behaviour of the bearded seal, with hearing, vocalisation, haul-out behaviour and movement patterns (through satelitte tagging), and their phenology, being well studied. A database of baseline blood parameters is slowly being built but is still limited. New data on distribution has emerged from PAM studies and non-targeted surveys. Abundance estimates are missing for Svalbard, but partial estimates have become available for the North Water Polynya in 2009 and 2014. Additionally, observations of bearded seals from aerial line-transect surveys are available for several areas of Greenland but have not been analysed. More information has become available on the impact of anthropogenic stressors, such as climate change and other related environmental changes, although demographic impacts of changes are missing. Catch data exists for both Svalbard and Greenland, but for the latter the data needs to be thoroughly validated. In summary, information on stock structure as well as local and global abundance estimates, which are both important to assess the sustainability of current catches, are still missing. However other lines of evidence can inform the delineation of management areas and the results of a pan-arctic genetic study should become available shortly. There is survey data available from Greenland that could be used to generate local abundance estimates, the analysis of which should be prioritised.

Key words: Bearded seal, Erignathus barbatus, Atlantic Arctic, post-2010 knowledge, literature review

INTRODUCTION

Species description

The bearded seal (*Erignathus barbatus,* Erxleben 1777) is a Northern phocid with a patchy, circumpolar distribution and is found throughout most of the Arctic and subarctic regions (Cameron et al., 2010; Kovacs, 2016, 2018). They are pagophilic and are thought to prefer coastal areas with shallow water and access to drifting ice, either from glacier or broken annual sea ice. *E. barbatus* is divided into two subspecies, *E. b. nauticus* (Pallas 1811) in the Pacific and *E. b. barbatus* (Erxleben 1777) in the Atlantic (see Figure 1). There are, however, no physical boundaries separating the two subspecies and no conspicuous gaps separating their geographic distribution and distinguishing between the two based on appearance is difficult (Davis et al., 2008). While the range extent of the bearded seal is very broad, global abundance estimates are missing, and local abundance estimates are few and far between, especially for the Atlantic subspecies. The bearded seal is amongst the largest phocids in the Atlantic, with some individuals weighing more than 400 kg (Cameron et al., 2010). Distinguishing between males and females is difficult, although there is a slight sexual dimorphism, with females usually slightly larger than males (Kovacs, 2018; Quakenbush, Cita, & Crawford, 2011). It is generally a solitary species found at low densities throughout its range. While opportunistic and able to forage in both pelagic and benthic environments, the bearded seal feeds primarily on benthic prey in shallow waters (Kienle & Berta, 2016; Kienle, Hermann-Sorensen, Costa, Reichmuth, & Mehta, 2018). Their prey includes molluscs, crustaceans and fish, and their well-developed vibrissae are thought to be an adaptation to the benthic habitat their prey inhabits (Kienle & Berta, 2016; Kienle et al., 2018).

The breeding season for bearded seals varies geographically, likely in accordance with local conditions, but peaks between the end of March and May. Pups are born on drifting ice floes (Kovacs, Lydersen, & Gertz, 1996) and can swim within hours of birth (Lydersen, Hammill & Kovacs, 1994), and both diving duration and depth develops quickly in the first few weeks of life (Hamilton et al., 2019;

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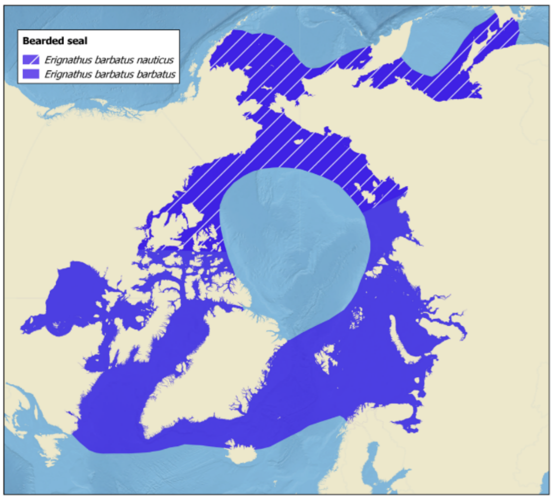

Figure 1. Distribution of *E. b. barbatus* and *E. b. nauticus* (NAMMCO website, Bearded Seal Species Page)

Watanabe et al., 2009). Mating season commences towards the end of the lactation period before the weaning is over, and the males' vocal activity peaks during this period. It involves very characteristic underwater vocalisations by sexually mature males, which differ throughout the range of bearded seals (Parisi et al., 2017). Trill is the primary call type used in the mating season, it is a repeated, long duration call which contains features that partly function to reduce acoustic masking both by competitors and the environment. Some males turn to hold the same territory from year to year (resident males) while others, usually thought to be the less successful males, are more migratory and do not necessarily hold a territory (transient males; Kovacs, 2018).

Laidre et al. (2015) reviewed the status of Arctic marine mammal populations and noted that estimates of trends in bearded seal populations were lacking across the Arctic. The bearded seal was listed as Least Concern in 2016 on the IUCN Red List of Species (Kovacs, 2016) due to its presumed large population size, broad circumpolar distribution and variable feeding habits. They had the same status on the Norwegian and Greenlandic Red Lists (Artsdatabanken, 2015; Boertman & Bay 2018), while the Committee on the Status of Endangered Wildlife in Canada listed bearded seals as Data Deficient (COSEWIC, 2007). However, the United States classified the Okhotsk and Beringia distinct population segments (DPSs) of the Pacific sector as threatened under the Endangered Species Act, and consequently as depleted under the Marine Mammal Protection Act (Federal Register 2012, https://www.fisheries.noaa.gov/species/bearded-seal). The species has recently been reassessed in Norway from Least Concern to Near Threatened due to declining habitat quality, particularly loss in sea ice habitat (Eldegard et al., 2021).

Scope and method

As the bearded seal is hunted in both Greenland and Svalbard and no stock assessments are currently available for the *E. b. barbatus* species, the NAMMCO Council requested the following "The Scientific Committee to convene a bearded seal working group in 2022 with the aim of conducting a thorough review of the existing data and

Bearded seal on ice. © Christian Lydersen, Norwegian Polar Institute

to go ahead with the assessment of stocks for which it was possible. If the data required by a full assessment of (some of) the stocks were not available, the WGs and the SC should identify, and prioritise, which specific data essential to their assessments are still needed" (Request R-2.7.1, NAMMCO, 2019). This review has been compiled to collate the knowledge developed on bearded seals in recent years to help inform the review of the NAMMCO Scientific Committee working group. The geographical scope of the review is therefore limited to the to the NAMMCO context (i.e. the Atlantic Arctic) and to the literature relevant for an assessment in that area.

The last extensive review of knowledge available on the bearded seal was conducted by the National Oceanic and Atmospheric Administration (NOAA) and covered work conducted up to 2010 (Cameron et al., 2010). This review therefore focuses on relevant scientific publications and grey literature that have become available since 2010.

The search for relevant information was conducted in the following ways:

- Searching ISI Web of Science using "bearded seal" and "bearded seals" as topics, with the time span set to 2010–2021.
- Performing similar searches on Google Scholar and PubMed.
- Distributing a Microsoft Excel file with the collected literature assigned to the categories to selected experts to enquire whether all relevant information had been captured. The selected experts included main authors or co-authors on multiple relevant papers, as well as members of the NAMMCO Scientific Committee and the Marine Mammal Expert Group of the Conservation of Arctic Flora and Fauna (CAFF) with specific knowledge of bearded seals.

This process resulted well over 200 publications and reports for review. In some cases, the contacted experts also provided information on publications in development and data collected but not yet analysed or published. This latter body of information was included where pertinent.

To organise the available literature and information for the review, nine initial sorting categories were defined: 1) General Biology; 2) Distribution and Movement; 3) Stock Structure; 4) Abundance Estimates; 5) Life History Traits; 6) Utilisation; 7) Threats; 8) Non-Empirical Research;

9) Outside Scope. Each article or report was categorised according to its content and could therefore be assigned to more than one of the defined topics. 'Non-Empirical Research' (NE) encompassed literature that summarised existing knowledge without presenting new conclusions and/or did not involve new observational or experimental work. This literature has not been included in the review. The category of 'Outside Scope' (OS) included literature that did not fall into any of the aforementioned categories and/or is not focused on the geographical area defined for the scope of this review. A publication initially categorised as 'OS' for geographical reasons might, however, have been included in the review if research on that particular topic was lacking in the defined focal area.

The review is organised into different sections surrounding different topics relevant for stock assessments. Each section includes an introduction to the topic, detailing the most important knowledge from literature up to 2010 followed by a review of literature that has been published since 2010 as well as discussing knowledge gaps where relevant. The literature is reviewed progressing from west to east.

GENERAL CHARACTERISTICS

This section will review the literature published since 2010 on the topics of morphology, physiology, behaviour, and life history. While it might not seem directly relevant to a stock assessment, this literature can still inform our understanding of the species and in turn increase the quality of the stock assessment. Thus, new knowledge on topics such as growth rates of whiskers (relevant to diet determination via stable isotopes), spectral reflectance of the pelt (relevant to potentially improved surveying methods of the species), hearing and sound perception (relevant to defining stocks and assessing the impact of noise pollution) and vocalisation and movement (also relevant for defining stocks) will be detailed in the following section.

Morphology and physiology

Kienle and Berta (2016) investigated the role of morphometrics in the feeding strategy of bearded seals. Aligning with previous studies, they concluded that bearded seals utilise suction feeding. Their work added that cranial characteristics are different in bearded seals in comparison to other species, including "a wide middle of the skull, a change in pterygoid hamuli position and a wide palate". They also noted that, similar to another pinniped known to utilise suction feeding, the walrus (*Odobenus rosmarus*), the canines of the bearded seal have been significantly reduced to rounded nubs with no cusps. The teeth are worn down to the gums when bearded seals are around 10 years old. Some feeding other than by suction has however been suggested to also occur (C. Lydersen, personal communication, March 22, 2022).

Not only are the cranial features of the bearded seal significantly different compared to other phocids, but it also has unique musculoskeletal adaptations, such as a bifurcated tongue. The styloglossus, a small muscle that aids in elevating and retracting the tongue, was found to be more developed in bearded seals compared to other phocids, which suggests that this creates traction for the tongue when suction feeding (Kienle & Berta, 2016). Taking morphometrics and musculoskeletal adaptations into consideration, the authors confirm the current belief that bearded seals are primarily suction feeders. Kienle et al. (2018) provide further evidence for this in a later study of captive bearded seals, demonstrating a strong correlation between skull and dental morphology and suction feeding in bearded seals. The authors also note that bearded seals have the highest average variability for suction feeding kinematics and attribute this to an ability to modify their feeding behaviour and kinematic performance in response to different feeding contexts (Kienle et al., 2018).

Whisker growth rates (after initial loss of whiskers in captive bearded seals) were investigated by McHuron, Williams, Costa, & Reichmuth (2020). Knowledge of whisker growth is of particular importance when whiskers are used to answer certain ecological and physiological questions. The authors found that whiskers grew rapidly following initial loss (0.08 ± 0.03 cm d^{-1} in the first 100 days after loss) whereafter it slowed to a linear pace (0.04 ± 0.01 cm d^{-1}) until the whiskers were shed. Among pinnipeds, such a rapid growth rate had only previously been observed in monk seals (*Neomonachus schauinslandi*).

The flexural stiffness (EI) of whiskers was investigated and compared to whiskers of other phocid species by Summarell et al. (2015). The authors found that EI was lower in beaded whiskers (present in all phocids except monk and bearded seals) compared to smooth whiskers (present in bearded seals). This is likely an adaption to increase sensitivity in mechanoreceptors detecting changes in the wake of prey. Summarell et al. (2015) note that the increased EI value observed in bearded seals compared to other pinnipeds might be an adaptation to their whiskers being used while foraging on benthos.

Vitamin A storage in the livers of 14 bearded seals was investigated by Senoo et al. (2012). They found 4.7 µmol total retinol gram^{-1} liver, which is relatively low when compared to the 33.5 µmol total retinol gram^{-1} liver found in another top predator, the polar bear (*Ursus maritimus*), but it is high compared to most mammals outside of the Arctic (Senoo et al., 2012). Despite these high levels of vitamin A, no signs of hypervitaminosis was found. The authors suggest that high levels of vitamin A, stored in specialised fat-storing cells, may contribute to Arctic top predators being able to thrive in the extreme conditions they inhabit by being able to supply vitamin A during periods with low dietary intake, as well as acting as a detoxifier when large amounts of dietary free retinol have been ingested.

Thometz, Hermann-Sørensen, Russell, Rosen, & Thoresen (2021) studied the effect moulting strategy has on metabolic rates, in particular resting metabolic rates (RMR). They used individuals of three pinniped species (bearded seal (n=1), spotted seal (*Phoca largha,* n=4,), and ringed seal (*Pusa hispida,* n=3) trained to participate in research to measure RMR over a full year. They observed clear and consistent annual patterns in RMR that related to the distinct moulting strategies of each species. For species that moulted over relatively short intervals—spotted (33 ± 4 days) and ringed (28 ± 6 days) seals—metabolic demands increased markedly in association with moult. In contrast, the bearded seal exhibited a prolonged moulting strategy (119 ± 2 days), which appeared to limit the overall cost of moulting as indicated by a relatively stable annual RMR. (Thometz et al., 2021). This strategy could also be a leftover trade from ancestral terrestrial carnivores that also shed fur over long periods. Using the same seals and one more bearded seal, Rosen, Thometz, & Reichmuth (2021) documented longitudinal changes in food intake, body mass and standard length in an attempt to understand the relationship between food intake and physical growth. The consistency of energy intake patterns, despite seals being maintained in semi-artificial conditions in different local climates, supported the hypothesis that seasonal oscillations are guided by underlying hormonal changes linked to key life history events and mediated by the physical environment. The patterns described highlighted times of the year when Arctic seals may be more sensitive to environmental perturbations and in particular reduced food supply.

Behaviour

Several researchers have published literature on the behaviour of bearded seals since 2010. Perception of sound (Charrier, Mathevon, & Aubin, 2013), hearing (Sills, Reichmuth, Southall, Whiting & Goodwin, 2020; Sills, Ruscher, Nichols, Southall, & Reichmuth, 2020), vocalisation (Madan, Latha, Ashokan, Raguraman, & Thirunavukkarasu, 2020; Parisi et al., 2017; Terhune, 2019), haul-out behaviour and movement patterns (Hamilton, Kovacs, & Lydersen, 2018, 2019; Rosing-Asvid, Dietz, Teilmann, Olsen, & Andersen, 2012; Rosing-Asvid, Riget, Mikkelsen, & Dietz, 2015) have been particularly well-studied and are detailed in the following section.

Hearing and vocalisation

Charrier et al. (2013) provided the first evidence of bearded seals being able to perceive geographic variation in the vocalisation of conspecifics. By exposing individuals in Greenland to synthetic trills from both local males and males from another area (Nunavut, Canada), they were able to observe differences in behavioural responses in the Greenlandic males. Males would clearly decrease vocal activity in response to playback of local males' vocalisations, while they would not significantly change vocal production after being exposed to trills from Nunavut males. The authors also noted an increased likelihood of males surfacing to attempt to locate local vocalising individuals compared to foreign individuals. They concluded that bearded seals could perceive geographic variation in vocalisation and hypothesised that local males were perceived as a greater threat than foreign males. This could point to a high level of competition between the Greenlandic males but can also shed light on population structure (see section 3.5 - Vocalisation data). Charrier and colleagues did, however, note that little is known about morphological differences between Nunavut and Greenlandic males, and that there is limited knowledge about whether individuals could assess the quality of another male based on vocalisations. Therefore, it could not be ruled out that the difference in response to local and foreign males was partly due to differences in the quality of males in the two locations.

The auditory range of two captive bearded seals was investigated by Sills, Reichmuth et al. (2020). While vocalization patterns of bearded seals have been described throughout a large part of their range, the auditory range had not previously been studied. Sills, Reichmuth et al. (2020) reported peak sensitivity near 50 dB re 1 μPa ([1] Sound pressure level referenced to 1 μPa in water) as well as a broad frequency range of best hearing from approximately 0.3 kHz to 45 kHz and a full range of hearing of at least 0.1 kHz to 60 kHz. Furthermore, the captive seals performed relatively well in a test that was designed to measure whether they could detect target signals embedded within background noise. The authors found critical ratios ranging from 12 dB to 30 dB between 0.1 kHz and 25.6 kHz. Bearded seals in this study have a similar range to other Northern phocids and the authors therefore suggest that it is reasonable to consider all Northern phocids as one functional hearing group when assessing the impacts of noise pollution on seals in the Arctic.

Sills, Ruscher et al. (2020) investigated the response (both in terms of hearing capabilities and behavioural changes) of bearded seals to loud noise exposure. By exposing a captive bearded seals to noise similar to noise from a seismic air gun, the authors were able to evaluate the following temporary threshold shifts (TTS). They found significant shifts in transient hearing thresholds at 400 Hz (the frequency with highest sensation levels) after the seal was exposed to 4 to 10 consecutive pulses (cumulative sound exposure level of 191–195 dB re 1 μPa s; 167–171 dB re 1 μPa s with frequency weighting for phocid carnivores in water). No changes in the auditory sensitivity were found at 100 Hz. Slight behavioural responses were noted. The authors suggest that TTS-onset levels of 170 dB 1 μPa^2 sound exposure level is likely appropriate for bearded seals in water.

Parisi et al. (2017) studied the complexity of underwater vocalisations of bearded seals in Kongsfjorden, Svalbard, with the help of passive acoustic monitoring (PAM). The authors managed to classify nine different call types, which is in agreement with studies on *E. b. barbatus* in other parts of its range – but adds five new call types compared to a previous study in Svalbard (Van Parijs, Kovacs, & Lydersen, 2001). However, contrary to what has been found in other areas, but in line with previous findings in Svalbard (Parisi et al., 2017; Risch et al., 2007; Van Parijs et al., 2001), the authors noted that they did not record any ascending vocalisation types.

The vocal range of bearded seals in Svalbard was studied by Madan et al. (2020), revealing that vocalisations occur between 0.35 kHz and 1.2 kHz, in the lower end of the hearing range. They compared this to anthropogenic noise (primarily at under 0.7 kHz), wind (0.5 kHz to 2 kHz), melting ice (1 kHz to 3 kHz) and walrus (0.2 kHz to 4 kHz, majority below 0.4 kHz) to generate a more complete understanding of the soundscape of Svalbard.

Terhune (2019) investigated the putative correlation between the complexity of phocid seal vocalisations and their phylogenetic relationship. Terhune compared vocalisation type with phylogeny and life-history traits and scored the vocal complexity of 13 different seal species based on waveform types, repertoire sizes, repetition and rhythm patterns, and frequency and duration measures. The bearded seal was scored as part of a middle-complexity group along with leopard seals (*Hydrurga leptonyx*), Ross seals (*Ommatophoca rossii*), and ribbon seals (*Histriophoca fasciata*), highlighting that vocal complexity is uncorrelated to phylogenetic relationship. The author hypothesised that the chances of detecting conspecific calls when other males are also vocalising or other masking noises are present increased in correlation with vocal complexity (Terhune, 2019).

Outside of the focus area, Agafonov and Chernetsky (2018) analysed bearded seal acoustic signals recorded in 1984–2017 in different parts of the White Sea, assessing territorial and temporal variability. They concluded that the underwater acoustic signalling system of bearded seals generally appeared spatio-temporally quite stable and even conservative.

Haul-out and movement patterns

Documenting the behavioural ontogeny of 13 bearded seal pups in Svalbard, Hamilton et al. (2019) found that individuals explore their surrounding area shortly after weaning, with a maximum in home range sizes in pups between 31 to 60 days of age. Pups generally stayed in shallow, coastal habitats with intermediate sea ice concentrations. Time spent hauled out decreased post weaning and only occurred sporadically after 75 days of age. Diving depth stabilised at around 50 days of age. At around 175 days of age, the diving patterns of the pups were similar to those of adult bearded seals.

In Baffin Bay, Rosing-Asvid et al. (2015), using satellite-linked data-loggers, observed that bearded seals hauled-out approximately 70–80% of the day in July during moulting. Lomac-MacNair et al. (2018) present haul-out observational data from the first study of marine mammals in Petermann Fjord, Northwest Greenland. They found that the average bathymetric depth and icecoverage where bearded seals occurred were 598 ± 259 m and 50% ± 21% ice cover respectively.

Three adult bearded seals were tagged with satellite-linked data-loggers in southern Greenland in 2009 (1) and 2010 (2) (Rosing-Asvid et al., 2012). The seals showed a high degree of site fidelity, staying within an average distance of 12.7 km from the tagging site. The individual tagged in 2009 did, however, undergo a summer 371 km northward trip and returned to the tagging side again after a few weeks (Figure 2).

The average and maximal recorded distance from the shore were 2 and 55 km respectively and the seals on average frequented regions with depth of 82 m. The deepest and longest dives were 500–600 m and 20–25 min respectively, the deepest and longest dives ever recorded at that time, and until now, for bearded seals.

Hamilton et al. (2018) studied the diving patterns of seven adult bearded seals in Svalbard (four females and three males). Dives were generally shallow (24 ± 7 m) and for short durations (6.6 ± 1.5 min), and the seals spent 74% ± 3% of their time diving. Benthic dives accounted for between 51–95% of dives. They were, remarkably, only hauled out for 5% ± 1% of the time. Hamilton et al. (2018) showed that the individuals exhibited high degrees of specialization in their habitat use and diving behaviour, differing markedly with respect to proportions of benthic vs pelagic dives (range: 51–95% benthic dives), distance to glacier fronts (range: 3–22km) and in the time spent at the bottom of dives (range: 43–77%). The authors hypothesised that having specialised strategies within a generalist population may help bearded seal adapt in a rapidly changing Arctic ecosystem.

Outside the focus area, London et al. (2022) also used data from satellite-linked bio-loggers deployed between 2005 and 2020 to investigate the seasonal timing and environmental factors affecting haul-out behaviour of bearded seals. They found evidence for strong diurnal and within-season patterns in haul-out behaviour, as well as strong weather effects (particularly wind and temperature). In general, seals were more likely to haul out on ice

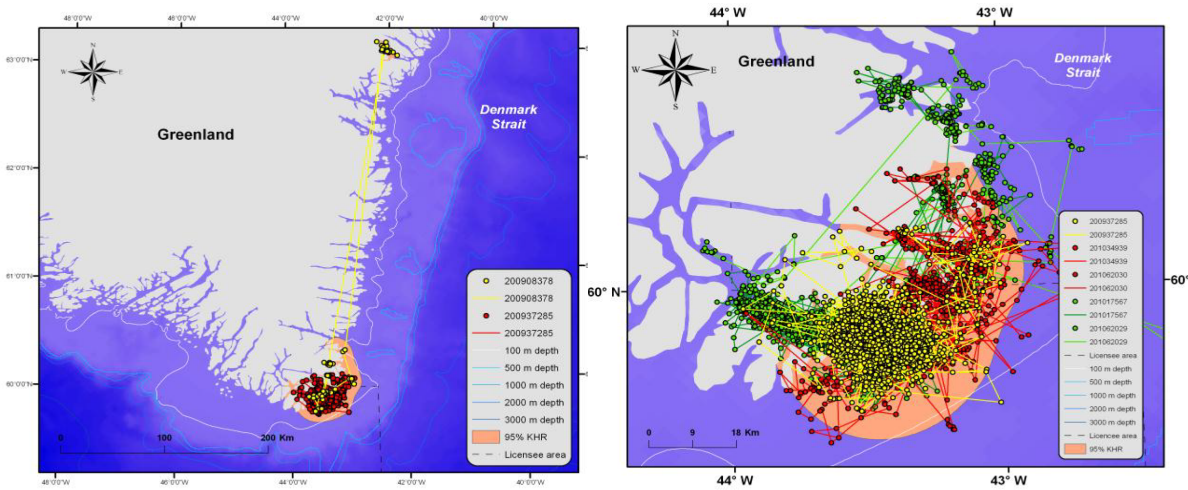

Figure 2. Positions (right) near Cape Farewell of one bearded seal tagged in September 2009 and two in September 2010, and long-distance movement northward from the seal tagged in 2009 (left). Contact with the three seals lasted over 11 months, up to 399 days (Rosing-Asvid et al., 2012).

in the middle of the day and when wind speeds were low and temperatures higher. Haul-out probability increased through March and April, peaking in May and early June before declining again. The timing and frequency of haul-out events also varied based on age-sex class. This data is very helpful, as accurate haul-out data is crucial to produce correction factors, which are needed to calculate abundance estimates.

Life history

In this review, life history traits primarily refer to: age and size at sexual maturity, juvenile sex ratio, body condition and mortality rates. While recent data is missing for most of the *E. b. barbatus* range, historic data and data from parts of the *E. b. nauticus* range can provide expected ranges for the Atlantic sub-species. Indeed, some Pacific sub-populations (especially the Alaskan sub-population) are well-monitored in terms of life history traits compared to the Atlantic counterparts.

In work published prior to 2010, female bearded seals in Svalbard were observed to reach sexual maturity at age 5 and males at age 6 at the latest (Andersen, Hjelset, Gjertz, Lydersen, & Gulliksen, 1999). The same study observed average weights of 245 kg and 247.3 kg for sexually mature females and males examined in the period May to September, respectively. Sex ratio in Alaska has been reported to be 1:1 at birth (Johnson, Fiscus, Ostenson, & Barbour, 1966), while sex ratios in older age groups are skewed towards females, likely due to either sampling issues (bearded seal females are more likely to float when shot and therefore more likely to be retrieved) or higher mortality amongst males (Burns & Frost, 1979; Johnson et al., 1966; Quakenbush et al., 2011; Smith, 1981).

Similar to other parameters discussed in this review, several factors such as the solitary nature and patchy circumpolar distribution of bearded seals complicate assessing long-term trends in life history traits. One method to assess factors such as sexual status and stress is to analyse the concentration of progesterone and cortisol in the successive annual depots of keratin in the claws. Karpovich et al. (2020) evaluated this method for bearded seals and ringed seals, concluding that it is possible to trace past pregnancy six to 12 years back in time in ringed seals by measuring the concentration of progesterone. It was not possible to conduct the same test for bearded seals, as the females in their sample were either pregnant or post-partum, precluding a comparison between pregnant and non-pregnant individuals (Karpovich, Horstmann, & Polasek, 2020). Crain, Karpovich, Quakenbush, & Polasek (2021) used claws to compare reproduction, stress and diet of female bearded and ringed seals in the Bering and Chukchi seas, Alaska, in two different periods.

In another study, the birth mass and pup growth of bearded seals in Svalbard was followed in the period from 1993 to 2007 (Kovacs, Kraft, & Lydersen, 2020). This study provides valuable information regarding the response of bearded seals to climate change by measuring growth in pups before and after the Svalbard sea ice collapse in 2006. Birth mass of pups born in the high ice concentration period (between 1993 and 2005) was 37.9 ± 2.5 kg while the birth mass of pups born in the low ice period (between 2005 and 2007) was 36.3 ± 3.3 kg ($t = 0.96$, $p = 0.28$). The measured daily growth rate in the high ice period was 3.2 ± 0.6 kg day^{-1} while it was 2.8 ± 0.7 kg day^{-1} in the low ice period ($p = 0.21$). Birth size and growth rate did not differ significantly between sexes. Seventeen of 153 (11%) pups reached more than 100 kg during the nursing period in the high ice period, while the same number was 1 out of 52 (2%) in the low ice period.

Quakenbush et al. (2011) assessed life history events of the *E. b. nauticus* subspecies in Alaska*,* with the use of samples collected from the Alaska native subsistence hunt. While this might not be within the geographical scope of the review, it provides indicators for the *E. b. barbatus* subspecies. The authors used these samples to determine diet, measure contaminants and antibodies (which in turn describes past pathogen loads), growth rates, blubber thickness, age distributions, sex ratios as well as age at maturity and pregnancy rates. They found great variation in prey choice, with 213 different prey taxa identified across 943 stomach samples, including invertebrates (with crustaceans and molluscs as most common), and fish (with sculpin (Cottidae), cod (Gadidae) and flatfish (Pleuronectidae) as dominant taxa). Concentrations of mercury and cadmium was amongst the highest of the seal species in the study. They did not detect any antibodies of phocine or canine distemper virus, although *Brucella* and phocine herpes virus antibodies were detected – implying that *Brucella* and phocine herpesvirus infections have historically occurred. They found that the average length of seals older than 10 years was shorter in the 2000s compared to the 1970s (208.6 cm, 95% CI: 203.2–214.0; 218.6 cm, 95% CI: 215.5–221.7 respectively). Blubber thickness was greater than the average between 2004 and 2014, although only significantly so in 2008 and 2010 (95% confidence interval does not overlap zero). Age distribution was found to vary between the periods investigated, although the main driver of this difference likely owed to the proportion of pups in the sample. The sex ratio of adults was generally biased towards females, with the size of the bias varying between regions. The sex ratio of pups was even, while subadult sex ratios varied both depending on region and decade ($p<0.01$). The age at sexual maturity did not differ significantly between the different time periods (Δ AIC = 2.26). The average combined age at sexual maturity for females was 3.97 years, while it was not measured for males. This study also provides a good example of how life history traits can be assessed in collaboration with hunters.

Seasonal patterns in vocalisation

Since 2010 several studies, which have investigated the presence/absence of bearded seals in the focus area using PAM, provide valuable information regarding seasonality in distribution patterns and mating behaviour (Boye, Simon, Laidre, Rigét, & Stafford, 2020; de Vincenzi et al., 2019; De Vreese et al., 2018; Frouin-Mouy, Kowarski, Martin, & Bröker, 2017; Llobet et al., 2021; Marcoux, Ferguson, Roy, Bedard, & Simard, 2017; Mattmüller, Thomisch, van Ozeeland, Laidre, & Simon, 2022; Moore et al., 2012).

Boye et al. (2020) investigated bearded seal vocalisation at seven different locations across southern Baffin Bay and Davis Strait in Greenland in the years 2006–2007 and

2011–2013. They found that sea ice concentration did not significantly impact the number of detections, however the timing of sea ice formation did. They report detections from November to June, with a peak in vocal activity during the mating season. Detections mostly occurred during early mornings (04:00 local time), and least during late afternoon (16:00 local time). Similar results have been observed in Svalbard in terms of correlation with sea ice formation and call times during the day, although the daily pattern was not observed during mating season, when light is continuous throughout the day (de Vincenzi et al., 2019). Recorders in two sites detected a large number of calls from January to March before the mating season began, likely linked to males claiming and holding territories. Other sites located at greater bathymetric depth recorded little bearded seal vocalisation during the same period, likely due to those sites being less desirable. Boye et al. (2020) did not detect any calls from July-November in either of their sites. This implies that the area being important during the winter and breeding season, but less so in the period immediately thereafter.

Frouin-Mouy et al. (2017) deployed two recorders off northwest Greenland from September 2013 to September 2014. They noted a peak in detections of bearded seal vocalisation from early May to mid-June at both sites and, similar to Marcoux et al. (2017), found a significant positive correlation between sea ice concentration and number of bearded seal calls ($p < 0.001$).

Mattmüller et al. (2022) investigated the seasonal patterns of bearded seal presence at two different sites near Tasiilaq in Southeast Greenland between 2014 and 2018, one monitored from August 2014 to August 2015, the other from September 2016 to September 2018. Bearded seals showed a strong seasonality, with a yearly peak in acoustic activity in May. Interestingly, the authors found an important relation between sea ice coverage and vocal activity from January to June; 73% of days, in which bearded seal calls were detected, had an overall sea ice coverage of more than 45% and some even up to 100%, while bearded seal vocalisations were only detected on 6% of days with lower than 15% sea ice coverage. Moore et al. (2012) placed a recorder in the Fram Strait (78.8°N, 5°W) in September 2008 which recorded until September 2009. They noted a peak in vocalisation in June, with noticeable vocalisation in May and July. They did not record any bearded seal vocalisations outside of this period.

De Vreese et al. (2018) investigated vocalisations in northeast Greenland with the use of two recorders and vocalisations in the Barents Sea, east of Svalbard with 1 recorder from fall 2013 to fall 2014. They detected the first vocalisations of bearded seals on the 2nd of April in the Barents Sea, at the beginning of April on G1 and in the 2nd week of February on G2. They noted that detections peaked during May and June and that calling ceased abruptly in July at all three locations.

De Vincenzi et al. (2019) collected data via two passive acoustic recorders in the inner and outer Kongsfjorden, Svalbard from August 2014 through July 2015. They found that calling commenced on the 12th of February and ceased on the 22nd of June. Similar to results from Canada, Greenland, and other locations in Svalbard, vocalisation increased with the formation of sea ice (Boye et al., 2020; Frouin-Mouy et al., 2017; Marcoux et al., 2017). They noted that vocalisations in the inner fjord end once sea ice is no longer present (June), whereafter an increased amount of vocalisation occurs in the outer fjords. They suggest that this could be due to seals following the retreating sea ice from the inner to the outer parts of the fjord.

Llobet et al. (2021) analysed year-round PAM data from Svalbard to investigate seasonal variation in the acoustic presence of male bearded seals and the phenology of different call types (long, step and sweep trills). This was done at three sites representing a variety of habitats with varied ice conditions: (1) Kongsfjorden, which has experienced an increased influx of Atlantic water and species ("Atlantification") over the past 15 years, (2) Rijpfjorden, which is a more typical Arctic ford, and (3) an open water drift-ice location north of Svalbard (Atwain). Bearded seals were vocally present at all three study sites, their calling behaviour was species-typical, and they vocalised for a longer period than previously reported in Svalbard. There were marked differences in the period over which calls were detected as well as in the intensity (rate) of calling among the different sites/habitat types. Trill rates at a newly studied drift-ice site (Atwain) were considerably higher than anticipated, while a reduction in trill rates had occurred in Kongsfjorden, suggesting a reduction in the number of bearded seals in this area subjected to Atlantification.

Diet

Only few dietary studies have been conducted since the 2010 review and only one in the focus area. Cameron et al. (2010) concluded that bearded seals fed primarily on benthic organisms (both invertebrates and fishes) but could switch to schooling pelagic fishes when advantageous. Bearded seals were considered to be foraging generalists, because they had a diverse diet with a large variety of prey items throughout their circumpolar range. Besides geographical and long-term temporal variations, likely due to variation in prey assemblages, variation in diet relating to age and season was also observed.

Hindell, Lydersen, Hop, & Kovacs (2012) investigated the diet of pregnant female bearded seals from Svalbard during three spring breeding periods with markedly contrasting ice conditions, using stable isotopes measured in whiskers of the newborn pups. The δ(15)N values in the whiskers of individual spanned almost two full trophic levels, with benthic gastropods and decapods as the most common prey. A large intraspecific variation was detected, with many of the seals found to be dietary specialists. This finding was supported by Hamilton et al. (2018) who showed that the dive behaviour of five seals tracked over several months in the same area was quite specialized among the different seals. Hindell et al. (2012) also suggested that the seals fed further offshore in years with greater ice cover, as indicated by the greatest proportion of pelagic fish and lesser benthic invertebrate content in those years. They moved into the fjords when ice-cover was minimal, consuming more benthic invertebrates and less pelagic fish. Juveniles are thought to dive deeper and feed on higher trophic levels than adults (Hamilton et al.

2019; Hamilton, Kovacs, & Lydersen, 2019; Senoo et al., 2012).

Disease, parasites and predators

Cameron et al. (2010) stated that relatively little was known about diseases in bearded seals and that the natural causes of mortality in bearded seals, other than predation (by polar bears, Ursus maritimus, walruses, killer whales, Orcinus orca, and Greenland shark, Somniosus microcephalus) were also largely unknown. A more recent study showed that polar bear predation on ringed seals was much greater than that on bearded seals in Svalbard waters (Iversen et al., 2013). Since 2010, and although health indicators are an invaluable tool to assess the health of individuals and populations, only very few health-related studies have been conducted in the focus area, thus studies from outside will also be mentioned below.

The first isolation of *Brucella pinnipedialis* was reported by Foster et al. (2018) from a bearded seal stranded in Scotland in 2012. They also reported on the detection of *Brucella* antibodies in free-ranging bearded seals from the Chukchi Sea (1990−2011; 19%) and Svalbard (1995−2007; 8%), whereas no antibodies were detected in bearded seals from the Bering Sea or Bering Strait or from captive bearded seals.

Tryland, Lydersen, Kovacs, Rafter, & Thoresen (2021) presented haematology and serum chemistry values for four captive bearded seals initially caught as pups in Svalbard and sampled over a 16-month period in 2006–2008. Serum chemistry analyses were also conducted on blood samples from 74 wild bearded seals from Svalbard sampled in 1995 and 2005–2007. The study provided reference values for bearded seals; it also indicated that the captivity had not markedly affected the physiological parameters of the animals.

Minzyuk, Kavtsevich, & Svetochev (2015) investigated the blood cell composition of bearded seals from the White Sea. Their study provides a preliminary comparative analysis of the haematological parameters of wild (n=5) and captive (n=3) bearded seals. The results suggest that the bearded seal blood system has specific morphological and functional features regarding immunity defence, although further studies are needed to evaluate the degree of difference between bearded and other phocids.

In another study from the White Sea (Erokhina & Kavtsevich, 2019), blood plasma samples from 10 bearded seals from three age groups collected in July 2014–15 were analysed for 27 metabolic indicators including proteins, lipids, carbohydrates, and mineral substances. The authors concluded that the biochemical indices of the metabolism of bearded seals corresponded to the values characteristic of other pinniped species, and the age-related changes were similar to those found in other mammals and also observed by Goertz, Reichmuth, Thometz, Ziel, & Boveng (2019).

A recent study on seals from Alaskan waters brings some initial references for haematology, serum chemistries and parasitology, as well as other species-level indicators of health that can be used to assess the condition of individual ice-seals, including bearded seals (Goertz et al., 2019). The study combines diagnostic information gathered between 2000 and 2017 from free-ranging seals, seals in short-term rehabilitation, and seals living in long-term human care to evaluate and compare key health parameters.

Although still limited, the data presented in the cited studies provide initial baseline of blood parameters for use in assessing the condition of individual seals, as well as informing monitoring and management efforts for wild seal populations. This set of initial baseline blood parameters is crucial in the context of emerging conservation concerns for the Arctic environments related to climate change, such as sea ice loss, increasing risks of contamination and introduction of pathogenic vectors.

Bearded seals typically do not crowd together and rarely share small ice floes with more than a few other seals, which theoretically reduces the risk of disease transmission (Cameron et al.,2010). However, since the 2010 review, two inter-species Unusual Mortality Events (UMEs), that have also affected bearded seals, have occurred in the Bering and Chukchi seas in Alaska (in 2011–2016 and 2018–2021); the latter one not declared closed at the end of 2021(https://www.fisheries.noaa.gov/alaska/marine-life-distress/diseased-ice-seals-and-unusual-mortality-events). Seals of all age-classes have been affected, and the disease-causing agent is currently unknown. Specifically, although tissues from infected seals were tested for a wide array infectious viral or bacterial agent(s), harmful algae toxins and industrial pollutants, no known (or new) agents have been identified that could explain the observed symptoms.

MOVEMENT AND STOCK STRUCTURE

Although there are likely distinct stocks or populations of bearded seals, little is currently known regarding their delineation and no stocks have therefore been defined for the species yet. Little research on stock structure has been conducted in the years since 2010. There is, however, older research and research in related fields that could aid in understanding and delineating stock structure in the future, and several lines of evidence can usefully contribute to delineating demographically independent populations (Martien et al., 2019).

While bearded seals are able to migrate over long distances, as seen in the Bering and Chukchi Seas where they migrate to follow the advance and retreat of sea ice, this might be less common in the Atlantic focus area of this review, where individuals are generally thought to be more sedentary (Hamilton et al., 2018; Rosing-Asvid et al., 2012). Seals tagged in coastal waters near Cape Farewell and in Melville Bay were indeed very stationary (Rosing-Asvid et al., 2012, 2015). However, high concentrations of bearded seals are known to follow the ice edge in Baffin Bay and Davis Strait, coming into Greenland waters during winter and retreating with the ice toward the Canadian coast during summer. This migration pattern has so far not been described by means of telemetry.

Movement from satellite tracking

Since 2010, there has been a significant increase in the availability of satellite tracking data, which is important to understand habitat use and movement of bearded seals. Several studies presenting tracking research in Greenland (Rosing-Asvid et al., 2012, 2015) and Svalbard (Hamilton, Kovacs, & Lydersen, 2019; Hamilton et al., 2018, 2019, 2021) have been published. Studies in Svalbard have focused on both juvenile (Hamilton et al., 2019) and adult bearded seals (Hamilton et al., 2018, 2021; Hamilton, Kovacs, & Lydersen 2019). Hamilton et al. (2018, 2019) and Rosing-Asvid et al. (2012) were reviewed in section 2.2 - Behaviour (4) and Hamilton, Kovacs, & Lydersen (2019) will be reviewed in section 4.1 - Distribution below.

During the Eastern Baffin Bay Environmental Studies Program 2011–2014, a small concentration of bearded seals was encountered in the inner part of Melville Bay, and two (a male and a female) were captured and tagged with satellite linked data-loggers. These were the first bearded seals tagged in the Baffin Bay area. Contact with the seals was kept for 358 and 312 days. Both seals showed a very high degree of site fidelity to the area where they were tagged (Boertmann & Mosbech, 2017; Rosing-Asvid et al., 2015), both seals stayed within the 100 m contour for most of the year, but the female would stray more often than the male. Seasonal migration would have been expected, as studies from other areas indicate that bearded seals only maintain breathing holes in relatively thin ice and normally avoid heavy ice-conditions such as those of the inner part of Melville Bay. Two hunters from the closest settlements (Kullorsuaq) who participated in the tagging reported, however, that they had seen bearded seals maintaining breathing holes in up to 1 m thick ice in the tagging area.

The movements of three male bearded seal tagged in South Greenland and a male and a female tagged in Melville Bay all show a high degree of site fidelity (Rosing-Asvid et al., 2012, 2015). However, seasonal changes in catches in Greenland and Canada could indicate that there also are bearded seals that migrate with the expansion of sea ice from the Canadian side of Baffin Bay and Davis Strait reaching Greenland waters in mid-winter, coming closest to the Greenland coast during maximum ice extent around April-May; with most of these seals and their newly weaned pups following the sea ice back towards Canada as it shrinks (A. Rosing-Asvid, personal communication, December 2, 2022). Canadian catches in Baffin Bay and Davis Strait drop as the sea ice forms during winter, and the winter ice in these areas becomes the heaviest. Increasing catches on the Greenland side during late winter / spring could indicate that many bearded seals follow the ice edge as it spreads toward Greenland; catches drop again in Greenland in early summer when the ice edge retreats towards Canada, where catches of bearded seals increase again (A. Rosing-Asvid, personal communication, December 2, 2022). However, ice affects hunters too, and this should also be taken into consideration in analysing the catch statistics.

Satellite tracking studies are limited off Greenland, because the seals are difficult to catch in open offshore waters, and a tag glued on in April-May will only last a month or two, because the seals start to moult in June. Bearded seals are found in pack ice in the summertime in Canadian waters, and Rosing-Asvid (personal communication, March 16, 2022) suggest that tagging animals there, if done right after the moult (early August), could generate up to 10 months of tracks, probably including animals coming into Greenland waters and back to Canada again.

As mentioned, Hamilton et al. (2018) analysed tracking data from seven adult bearded seals equipped with Argos transmitters in Svalbard in 2011 and 2012. They found relatively small 50% home ranges (10–32 km^2) in primarily shallow, coastal areas with low sea ice concentrations. However, three of the seven seals did regularly travel approximately 40 km, moving from feeding areas to haul out sites and one individual completed a long travelling bout of 306 km between the northernmost and southernmost locations. The 95% home ranges for six of the seven seals were between 67 and 218 km^2 while the 95% home range for the individual which undertook the longest migration was 807 km^2.

In a wider study based on satellite tracking and aiming at identifying the local richness of 13 marine mammal species around Svalbard, the Northern Barents Sea, Fram Strait and along the northeast coast of Greenland, Hamilton et al. (2021) identified hotspots for bearded seals during the period 2005-2013. A total of 20 seals had been tagged, including both pups and adults. The study defines both individual hotspots, which identify areas used by the majority of the tagged animals, and location hotspots, which identify areas heavily used, sometimes by only a small portion of the tagged animals. Bearded seals were located in shallow areas along the western and northern coasts of Svalbard. Both individual and location hotspots were located in north-western Svalbard (Figure 3).

Analysis of hunting patterns

As mentioned in section 2.2 - Behaviour, the three bearded seals satellite-tagged by Rosing-Asvid et al. (2012) equipped with satellite tags in South Greenland in 2009–2010 showed a high degree of site fidelity throughout the year, which can potentially inform stock structure. Based on this study and hunting patterns along West Greenland and East Baffin Island, Boye et al. (2020) concluded that at least a proportion of the bearded seals in the area follow the advancing/retreating sea ice in West Greenland. Bearded seals in Greenland are hunted throughout the year in coastal areas, but the hunting in Nunavut is limited to April and May, while the hunt on the east side of Baffin Island increases during the period July to October (Boye et al., 2020). Hunting occurs at the times when bearded seals are available in the respective regions. The tracking data and potential migration patterns derived from hunting statistics and observations indicate that the same stock may potentially be hunted across a large range by different coastal communities at different times, as seen in other species such as the narwhal (*Monodon monoceros*).

Genetic analyses

Davis, Stirling, Strobeck, & Coltman (2008) is the only publication to date that investigates the population genetics of bearded seals and will therefore be briefly summarised here. The genetic analysis suggested dividing the samples from six areas (Gulf of Anadyr, Saint Lawrence Island, Beaufort Sea, Labrador Sea, Qaanaaq and Svalbard) into two main genetic clusters, corresponding to the Atlantic and Pacific subspecies, respectively. No additional genetic structure was found among the Pacific localities, but most Atlantic localities exhibited significant levels of pairwise genetic differentiation, suggesting the existence of finer scale genetic structure. In addition, it was found that separation distances of just 500–1000 km are potentially sufficient for population structure to develop, provided seals occupy areas where ice-formation restricts movement (Davis et al., 2008). Both Davis et al. (2008) and studies based on morphometrics agree that the division into two subspecies should be upheld (Manning, 1974). It is relevant to note that, although the two subspecies are widely used and accepted, exact geographical and morphological boundaries are still to be set.

Distinct population segments

While not strictly the same as stock structure, Cameron et al. (2010) defined Distinct Population Segments (DPS) for bearded seals. The concept of DPS was developed to help differentiate and offer protection to potentially threatened segments of a subspecies. To be able to divide a subspecies into different DPS, three factors were considered by the NOAA Fisheries and U.S. Fish and Wildlife Service during the bearded seal review in 2010:

Discreteness of the population segment in relation to the remainder of the species to which it belongs,

- The significance of the population segment to the species to which it belongs, and
- The population segment's conservation status in relation to the Act's standards for listing (i.e., is the population segment, when treated as if it were a species, endangered or threatened?).

After considering these factors, Cameron et al. (2010) concluded that the *E. b. nauticus* subspecies could be differentiated into two different DPS – one in the Sea of Okhotsk and the other in the rest of its range but kept the *E. b. barbatus* subspecies as one segment only.

Vocalisation data

As also mentioned in the section 2.2 – Behaviour, Charrier et al. (2013) observed the response of bearded seals in Baffin Bay, Greenland to synthetic trills of individuals from Nunavut, Canada, and noted that individuals responded more strongly to local individuals than to individuals from Nunavut. This signals both regional differences in vocalisations and the ability of seals to perceive these regional differences and adjust their behaviour accordingly. The authors concluded that this suggested very little migration and interbreeding between the two sub-populations.

DISTRIBUTION AND ABUNDANCE

Bearded seals are pagophilic with a distribution closely correlated with the extent of sea ice and are dependent on sea ice for crucial life history events such as reproduction and moulting (Kovacs, Lydersen, Overland, & Moore, 2011; Laidre et al., 2012; MacIntyre, Stafford, Conn, Laidre, & Boveng, 2015; Stempniewicz et al., 2017). Bearded seals are thought to prefer sea ice with access to open water such as drifting ice floes, edges of fast ice or areas with larger leads, and they do not generally maintain breathing holes in thick sea ice (Quakenbush, Crawford, Nelson, & Olnes, 2019).

Bearded seals are primarily benthic feeders and thus are typically found in areas where seasonal sea ice gives them access to relatively shallow waters with a rich benthic community. However, this varies across their range and they are able to feed on pelagic organisms as well (Cameron et al., 2010; Kovacs, 2018).

Distribution

Since 2010, several PAM studies have investigated the presence/absence of bearded seals in the focus area (Boye et al., 2020; de Vincenzi et al., 2019; De Vreese et al., 2018; Frouin-Mouy et al., 2017; Marcoux et al., 2017; Mattmüller et al., 2022; Moore et al., 2012). The PAM technology was particularly useful in remote logistically challenging areas, allowing assessment of the year-round biodiversity and community composition (e.g., Mattmüller et al., 2022). Several of these studies also provided valuable information regarding phenology and mating seasons and were detailed under section 2.4 – Seasonal pattern in vocalisation.

As previously mentioned, a small concentration of bearded seals was encountered in the inner part of Melville Bay (Rosing-Asvid et al., 2015) and passive acoustic monitoring in southern Baffin Bay (Boye et al., 2020) also showed that bearded seals were present in late winter and spring when ice covered the areas. These observations ran counter to the belief that all bearded seals avoid heavy ice conditions during winter (Boertmann & Mosbech 2017).

During a ship-based survey of seabird breeding colonies and harbour seals habitats between Nanortalik and Tasiilaq (Southwest and Southeast Greenland respectively) Boertmann and Rosing-Asvid (2014 observed that, although bearded seals are thought to move into fjords during summer, some individuals were present in July along Southeast Greenland, all in some stage of moult. Mattmüller et al. (2022) investigated the seasonal pattern of acoustic marine mammal presence relative to sea ice concentration (SIC) off Tasiilaq in Southeast Greenland for three years. Their results showed that bearded seals exhibit a strong seasonality linked to the seasonal SIC. They were acoustically dominant during winter and spring while other species dominated during the sea ice-free summer and autumn, but that some individuals remained year-round in the area. From both studies, Mattmüller et al. (2022) suggested that the Tasiilaq area may be of ecological importance for bearded seals year-round, serving both as moulting and breeding ground.

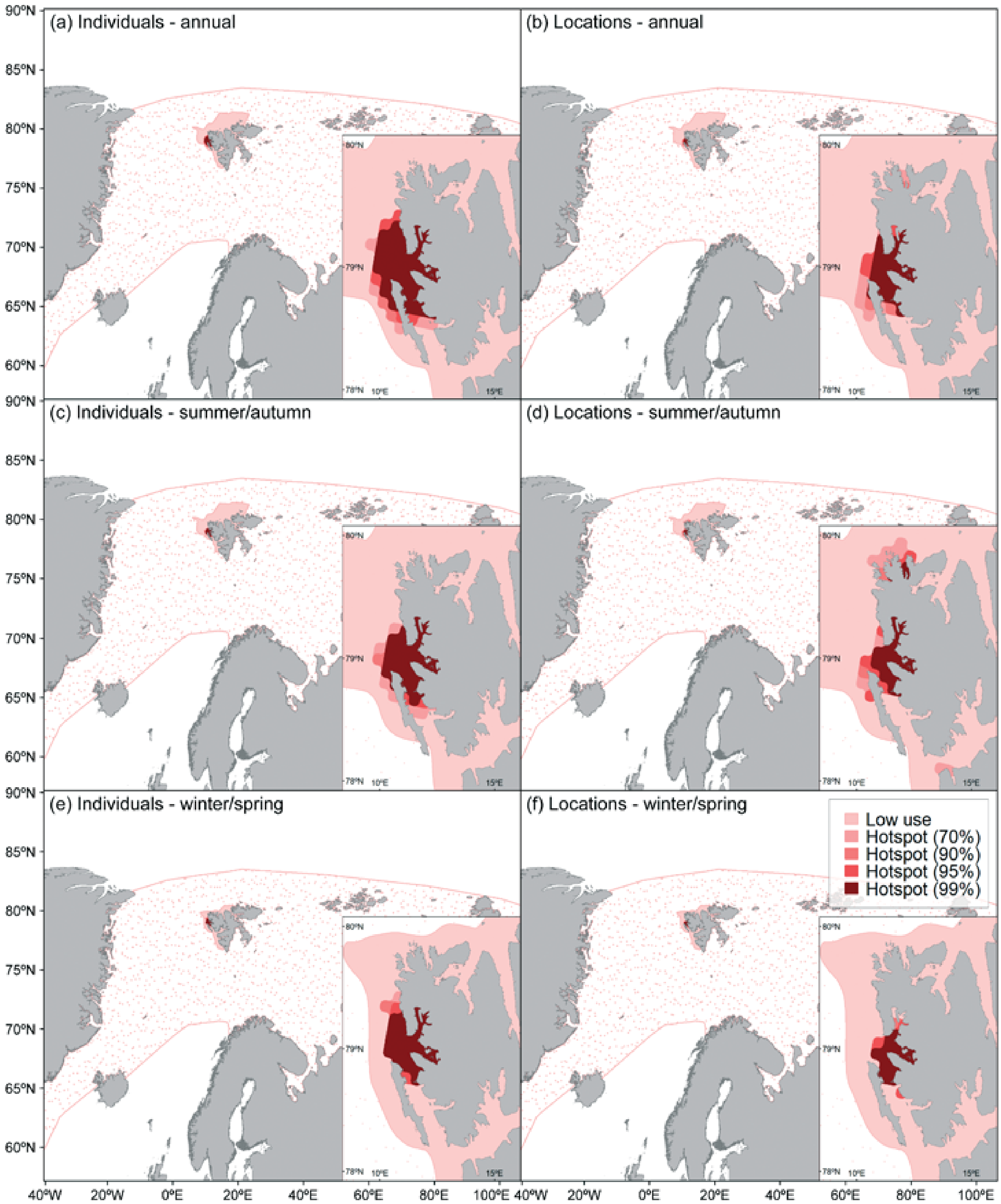

Figure 3. Getis–Ord Gi* (a,c,e) individual hotspots and (b,d,f) location hotspots for 20 bearded seals tagged in Svalbard over (a, b) the entire year, (c, d) during the summer/autumn and (e, f) during the winter/spring. Inset maps show hotspots in north-western Svalbard (Hamilton et al., 2021).

Since 2010, maps of aerial survey observations of bearded seals (and abundance estimates, see section 4.2 – Abundance) in 2009, 2010 and 2014 have been published for the North Water Polynya (NOW), off Northwest Greenland (Heide-Jørgensen et al., 2013; Heide-Jørgensen, Sinding, Nielsen, Rosing-Asvid, & Hansen, 2016). Contrary to previous reports of bearded seals along ice edges in the western part of the NOW (Finley & Renaud, 1980), Heide-Jørgensen and colleagues primarily detected individuals on ice floes or along ice edges over shallow water in the eastern part of the NOW (Heide-Jørgensen et al., 2013). Scherdin, Olsen, Heide-Jørgensen, & Hansen (2020) generated aerial survey observation maps of bearded seals from later surveys for the NOW (2018), Baffin Bay/ West Greenland (WG 2006 and 2012), and the North-East Water Polynya (NEW, 2017 winter and summer). The average bathymetric depth where animals have been observed was relatively high (between 287.50 ± 115.73 m and 400.50 ± 201.60 m in cell grids with observations), and the mean sea ice concentration in grids with observations was quite variable between 41.6% ± 26.2% and 91.8% ± 2.8% (Table 1). A survey was also conducted in West Greenland in 2022, but the distribution maps are not yet available.

A citizen science project in Svalbard was focussed on describing the distribution of various seal species, including bearded seals (Bengtsson, Hamilton, Lydersen, Andersen, & Kovacs, 2021). This study presents data from 2005–2018 and the results are based on records of 1,503 bearded seal observations made by members of the public, the Norwegian Coast Guard, various scientific cruises and others. The authors noted that bearded seals were frequently observed in North-Western Spitsbergen and that the mean latitude of observations had increased by 0.03° per year over the period. Bearded seals were most commonly observed in shallow areas close to the coast in the north-west corner of Svalbard. Areas with a bathymetric depth of under 100 m encompassed 80% of all observations.

Hamilton, Kovacs, & Lydersen (2019) investigated the potential spatial overlap between ringed and bearded seals in Svalbard, both species occurring principally in shallow areas near tidal glacier fronts. The authors concluded that the species-specific behaviour limited the overlap. Bearded seals had larger home ranges, spent more time diving, and used different depths for foraging than ringed seals. Also bearded seals dove into Transformed Atlantic Water in the winter, whereas ringed seals occupied Arctic water masses. As the two species foraged in different areas, Hamilton, Kovacs, & Lydersen (2019) concluded that interspecific competition was likely currently low, but that potential changes in abundance, distribution and diet might change the level of spatial overlap and competition.

Abundance

Bearded seals typically occur at low densities in remote areas across a large range. Surveying the species is therefore an expensive and logistically difficult challenge and, as a result, abundance and trends are currently unknown for most populations of the *E. b. barbatus* subspecies.

No aerial surveys of bearded seals have been conducted in Svalbard and none have directly targeted the species in Greenland either, which means that no island-wide abundance estimates are available for either Greenland or Svalbard. Only a few large-scale abundance estimates have been generated in the past. Cleator (1996) provided a minimum abundance estimate of 190,000 bearded seals for Canadian waters, although this was based on a multitude of different indices, such as the ratio between barded seals and ringed seals, and uncorrected densities generated from aerial surveys that were then extrapolated to cover larger areas.

Table 1: Some characteristics of the surveys and observations of bearded seal surveys mentioned above (Heide-Jørgensen et al., 2013, 2016; Scherdin et al., 2020). Bathymetric depth and sea ice concentration describe the mean values of cell grids in which an observation was made

	NOW2009	NOW2010	NOW2014	NOW2018	WG2006	WG2012	NEW2017 (winter)	NEW2017 (summer)
Effort [km]	5,483	5,398	1,431	2,844	4,549	3,515	3,789	2,188
Size [km^2]	54,839	51,223	16,135	18,037	44,298	41,876	8,930	30,826
Observations	22	104	22	7	100	124	8	14
Individual animals (n)	23	109	24	16	118	163	8	14
Density (n/effort)	0.004	0.020	0.017	0.006	0.026	0.046	0.002	0.006
Sea ice concentration (%)	44.0 (±15.5)	69.5 (±10.6)	57.5 (±9.9)	91.8 (±2.8)	41.6 (±26.2)	60.0 (±16.3)	86.4 (±25.2)	4.9 (±6.3)
Bathymetric depth [m]	-308.24 (±160.76)	-334.94 (±223.78)	-400.50 (±201.60)	-357.42 (±271.37)	-287.50 (±115.73)	-314.12 (±192.50)	-119.32 (±67.74)	234.79 (±59.95)

While large-scale abundance estimates of bearded seals are unavailable for Greenland, several local surveys have been conducted since 2010 (Table 1), and abundance estimates have been published for the NOW (Heide-Jørgensen et al., 2013, 2016). Based on aerial multi-species surveys conducted in May 2009 and 2010 in the NOW, Heide-Jørgensen et al. (2013) estimated the number of bearded seals on ice to be 2,448 (CV=0.19; 95% CI: 1,687–3,553, corrected for perception bias). The fully corrected abundance estimate of bearded seals in 2010 was 6,016 (CV=0.31; 95% CI 3,322–10,893), however this used an availability correction for the proportion of time spent hauled out on the ice developed for ringed seals (40.7%; CV=0.24; Born, Teilmann, & Riget, 2002).

A survey of the eastern part of the NOW in April 2014 resulted in a fully corrected abundance estimate of 6,005 bearded seals (95% CI: 4,070–8,858), applying an availability correction factor for the proportion of time the seals spent hauled out, estimated from two bearded seals instrumented in South Greenland (Heide-Jørgensen et al., 2016).

Further aerial line-transect surveys have been conducted in multiple years off Greenland, in the NOW (2018, covering the eastern part), Melville Bay (2012, 2014, August-September summer surveys), West Greenland (2006, 2012, 2022, all March-April winter surveys), East Greenland (2017 summer survey) and the NEW (2017 winter and summer surveys). While the target species of these surveys was not the bearded seal and survey designs were not optimised for that species and potentially missed key areas, they do provide valuable data on distribution and densities of local populations and abundance estimates should be generated for the surveys that had enough observations of bearded seals.

Scherdin et al. (2020) calculated bearded seal densities for survey areas in NEW and West Greenland (Baffin Bay). These preliminary data are presented in Table 2 for comparison with the NOW 2009–2010 and 2014 surveys, which have generated abundance estimates.

While not strictly in the focus area of this review, abundance estimates of bearded seals based on aerial surveys in Western Hudson Bay, Canada, have also been published since 2010 (Chambellant, Lunn, & Ferguson, 2012), but relate to years prior to 2010. The surveys were conducted in the following years: 1995, 1996, 1997, 1999, 2000, 2007 and 2008. Abundance estimates ranged from 278 (95% CI: 99–783) in 1997 to 1,494 in 1995 (95% CI: 862–2,589).

It should be noted that bearded seals are mainly spotted when hauled out in these aerial surveys, as they are more visible and more easily identifiable than when in water. Corrections are required to adjust for seals that are not spotted by observers, either available but missed (perception bias) or unavailable in/under water (availability bias). Correction for availability factors can be obtained from detailed dive data loggers. Such correction factors should be species specific and ideally identified for the location and time of the year and day when the survey is conducted, as the proportion of bearded seals hauled out depends on the season and ice condition, with a strong diurnal patterns in haul-out behaviour, as well as strong weather effects (particularly wind and temperature) (e.g., Hamilton et al., 2018; London et al., 2022; Rosing-Asvid et al., 2015).

New methods for generating abundance estimates

The spectral reflectance of bearded seal pelts was measured with the aim of assessing the viability of remote sensing surveys (Leblanc, Francis, Soffer, Kalacska, & de Gea, 2016). Remote sensing with automated detection is a potentially promising method, as it would likely be less costly than traditional visual surveys. Conn et al. (2014) developed and tested a hierarchical model for pagophilic seals to be used in similar automated detection systems. They noted that double sampling is important at this stage in the development of the methodology and, in their example, used digital photography as another sampler. Digital cameras were used to provide observations, estimate detectability, and to examine species identification errors. The authors conclude that this is a viable method to measure large-scale trends in abundance and distribution, but that it requires considerable hardware, software and modelling skills (Conn et al., 2014).

ver Hoef, Cameron, Boveng, London, & Moreland (2014) developed a spatial hierarchical model for abundance estimation of pagophilic seals in the Bering Sea. As previously mentioned, some of the challenges of surveying bearded seals include their large range, dynamic distribution and habitat and relatively low availability of visible seals to observers. The model is based on multiple daily abundance estimates that are then combined to create a more accurate total abundance estimate. The model was corrected for incomplete availability via a generalised mixed model and a hierarchical spatially-autocorrelated regression model was developed to predict abundance on each day. The authors concluded that the daily abundance estimates were imprecise as predicted, but that a combined abundance estimate combining these daily abundance estimates was largely consistent with previous abundance estimates of seals in the area.

ENVIRONMENTAL AND ANTHROPOGENIC STRESSORS

Climate change

Bearded seals are pagophilic and endemic to the Arctic, relying on the availability of suitable sea ice over relatively shallow waters for giving birth, nursing pups, moulting, resting, and accessing foraging areas. It is therefore expected that, as other ice-dependent pinnipeds, they will be negatively impacted by climate change. These effects may be direct e.g. through sea ice reduction (both extent and duration) and deterioration of their haul-out habitat as well as spatial separation of sea ice from their benthic feeding habitat, but can also be indirect through changes in biological community composition and quality, with negative effects on benthic productivity levels, and the increased use of the Arctic for marine operations and explorations (e.g., Cameron et al., 2010; Kovacs et al., 2011, 2012; Kovacs, 2016; Laidre et al., 2015; Lomac-MacNair et al., 2018; MacKenzie et al., 2022). The ice-dependent Arctic endemic marine mammals will be more affected by changes in their local marine ecosystem than migratory non-resident species, which can shift to new areas. Species such as bearded seals will be the most vulnerable as they can potentially be forced into suboptimal habitat where access to preferred prey is diminished (Kovacs et al., 2011; MacKenzie et al., 2022).

A satellite tracking study in Alaska (Breed et al., 2018) showed that the seasonal migratory behaviour of juvenile bearded seals results from tracking the sea ice edge as it seasonally expands and recedes over the continental shelves. Such association with the ice edge suggested that bearded seal habitat will shift as the climate warms.

Since 2010, several studies have examined the behaviour of bearded seals in relation to ice and their response to declining sea ice. When sea ice is not available, bearded seals in certain areas might haul-out on land but are dependent on sea ice for successful reproduction and generally show a very strong affiliation with either drift ice (especially near edges) or near-shore floe ice (Cameron et al., 2018; Hamilton et al., 2018; Hamilton, Kovacs, & Lydersen, 2019; Kovacs, 2018; MacIntyre et al., 2015; Olnes et al., 2020). In Svalbard, when annual ice failed to form in west coast fjords in 2006-2007, bearded seals shifted their pupping substrate to glacier ice (Kovacs et al., 2020; Lydersen et al., 2014), but this alternate habitat is not likely to be a long-term solution in this region given that tide-water glaciers are melting and retracting onto shore (Kovacs et al., 2021). However, from a study of marine mammal hotspots across the circumpolar Arctic, Hamilton et al. (2022) remarked that the habitat use of bearded seals might be more directly linked to bathymetric features than to sea-ice concentration for some regions and times of the year, as was also suggested by Olnes et al. (2020).

In their marine mammal update of the State of the Marine Biodiversity Report, Kovacs et al. (2021) concluded that the risk of health-related problems with reduced sea ice was a serious concern for Arctic endemic seals, including bearded seals. They are unlikely to have immunity to many viruses, bacteria or parasites that have not been part of their evolutionary history, but which are likely to become more prevalent in a warmer Arctic. Similarly, Goertz et al. (2019) concluded that, given the apparent low historical exposure to disease, and therefore presumed low resistance, recent extra-limital sightings of Arctic seals, and a projected increase in contacts between individuals and populations caused by reduced availability of sea ice, it was likely that the risk of epizootic events will continue to increase for these species.

Reduction in the geographic and seasonal extent of sea ice will likely result in higher energy expenditure, poorer body condition and reduced recruitment for ice-breeding seals, including bearded seals (e.g., Kovacs et al., 2011). However, demographic impacts of climate change on this species will be difficult to detect because of the lack of baseline data on abundance and trends in population sizes (Laidre et al., 2015).

Another consequence of sea ice loss and warmer waters in the Arctic might be the expansion of harmful algal blooms (HAB) into higher latitudes and therefore a higher exposure to algal toxins for marine mammals (Lefebvre et al., 2016). In Alaskan waters, the presence of the algal toxins domoic acid (DA) and saxitoxin (SXT) in 13 marine mammal species, including bearded seals, was studied by Lefebvre et al. (2016). Both DA and STX affect the central nervous system of vertebrates, with signs of DA poisoning including ataxia, head weaving, seizures, coma, and death (Gulland et al., 2002). Bearded seal samples were taken from harvested animals from Barrow, Chukchi and Bering Sea. A quarter of 55 tested bearded seals were positive for DA and 14 % of 44 tested bearded seals were positive for STX.

MacKenzie et al. (2022) found in their recent studies of the trophic niches of 10 marine mammals in the European Arctic, that the bearded seal together with the narwhal and polar bear were the three species having the smallest isotopic niches. The three were all High Arctic resident species and likely to be particularly vulnerable to changes in Arctic ecosystem.

Hamilton et al. (2018) concluded that bearded seals in Svalbard confronted with climate and associated changes, might benefit somewhat as a species from the high variability between individuals in movement patterns and foraging strategies. This specialization at the individual level indeed resulted in a generalist strategy at the species level. Whether the individual variability documented in Svalbard was common for bearded seals in other Arctic regions remained a question and warrants further investigation. A project was established by the CAFF marine mammal expert group in 2016 with the aim of stimulating the compilation of available data on bearded seals, relevant to the assessment of potential impacts of climate change throughout their range. Seven key areas for research were identified, including as the first three priorities, the bearded seal's circumpolar population structure, abundance, and habitat use studies. The 2021 Progress Report to CAFF points out that the project has been successful in drawing attention from Arctic Council nations to bearded seal research, but that progress had been somewhat slower than expected due to financial constraints and the lack of focussed monitoring programmes for bearded seals. All the identified key areas in need of research/monitoring effort had been addressed in at least one Arctic region, though significant gaps remained. The regional gaps in all key targets made the circumpolar integration of data across themes a challenge.

Pollution

Pollution in this section will refer to the introduction of harmful materials into the habitat of bearded seals, including oil spills and contaminants.

Quantifying the direct and indirect impact of oil spills, offshore extractions and transportation of oil and gas on bearded seal populations is complicated. Obtaining data on individual seals exposed to oil is difficult and therefore the knowledge of direct impact is limited (Helm et al., 2015). Helm et al. (2015) list damages to liver, kidney, intestine, digestive and urogenital systems, mucus membranes and eyes as likely consequences of direct contact with oil. Indirect consequences of oil spills likely include habitat degradation due to both short- and long-term negative impacts on prey populations, cumulative impacts on both the individual and ecosystem level, and other effects (Helm et al., 2015).

The potential impacts of pollutants such as polychlorinated biphenyls (PCBs), organochlorine pesticides (OC) and heavy metals such as mercury (Hg) are relatively well documented on various marine mammal species in the Arctic. However, only limited research has been conducted on the potential impacts these pollutants have on bearded seals specifically. While not specific to bearded seals, research from other pinniped species have linked PCBs and dichloro-diphenyltrichlorethanes (DDT) to endocrine disruptions, reproductive failure and other critical issues (Cameron et al., 2010).

Mercury has been found to impact behaviour, decrease fitness, and impair reproduction in several marine mammals. Marine mammals are primarily exposed to mercury via their diet, with exposure generally increasing with trophic level, as some forms of mercury can bioaccumulate in a food web. As described in section 1.1 – Species description, bearded seals generally feed on relatively low trophic levels and should therefore be less exposed to mercury compared to other well studied marine mammals in the Arctic, such as ringed seals or polar bears.

Although outside of the geographical scope of this review, mercury and selenium concentrations in Alaskan bearded seals were determined by Correa and colleagues (Correa, Castellini, Quakenbush, & O'Hara, 2015). They determined Hg concentration values for liver, kidney cortex, kidney medulla, skeletal muscle and heart left ventricle. They found the highest mean concentrations of total mercury in the liver (3.057 µg/g) while the lowest mean concentration was found in the heart left ventricle (0.017 µg/g).

In their update of a strategic environmental impact assessment of activities related to oil exploration and exploitation, Boertmann and Mosbech (2017) discussed the sensitivity of whales and seals to oil spills, particularly if they have to surface in oil slicks, and to inhaling oil vapours. They note that bearded seals, as other species, can be particularly vulnerable during an oil spill in winter when the availability of open water is limited by the sea ice. There also noted that since bearded seals are known to feed on seabed fauna, they may be exposed to oil through bioaccumulation.

Pathogens

The first isolation of *Brucella pinnipedialis* in bearded seals was made by Foster et al. (2018) in an individual that had stranded on the north-eastern coast of Scotland in early 2012. *Brucella* infections in marine mammals have been reported since 1994, although *B. pinnipedialis* had not been detected in bearded seals in the albeit limited research prior to this detection. The authors also isolated *B. pinnipedialis* antibodies in historic samples collected in Svalbard (1995–2008, 8%), as well as in 19% of samples collected in the Chukchi Sea (1990–2011). No *B. pinnipedialis* antibodies were detected in samples from the Bering Sea, the Bering Strait or from captive seals in Tromsø, Norway. The *B. pinnipedialis* type detected in these samples belonged to the ST24 lineage, which had previously been detected in harbour seals and grey seals. While *Brucella ceti,* a *Brucella* species found in cetaceans, has led to various severe pathologies in cetaceans, the effect *B. pinnipedialis* has on its pinniped hosts is somewhat unclear but thought to be less severe (Foster et al., 2018).

As discussed in section 1.1 – Species description, bearded seals are largely solitary and prefer dynamic pack ice over fast ice. This solitary behaviour coupled with their habitat of choice is likely to limit the threat of diseases transmitting easily within a subpopulation

Shipping noise and offshore activities

The soundscape of the Arctic is changing rapidly. Sea ice has declined dramatically over the last decades and will continue to do so. New shipping routes have become available, thereby introducing additional sources of anthropogenic noise in the Arctic. The Arctic has historically had lower ambient sound levels compared to non-Arctic marine habitats, primarily due to sea ice coverage (Haver

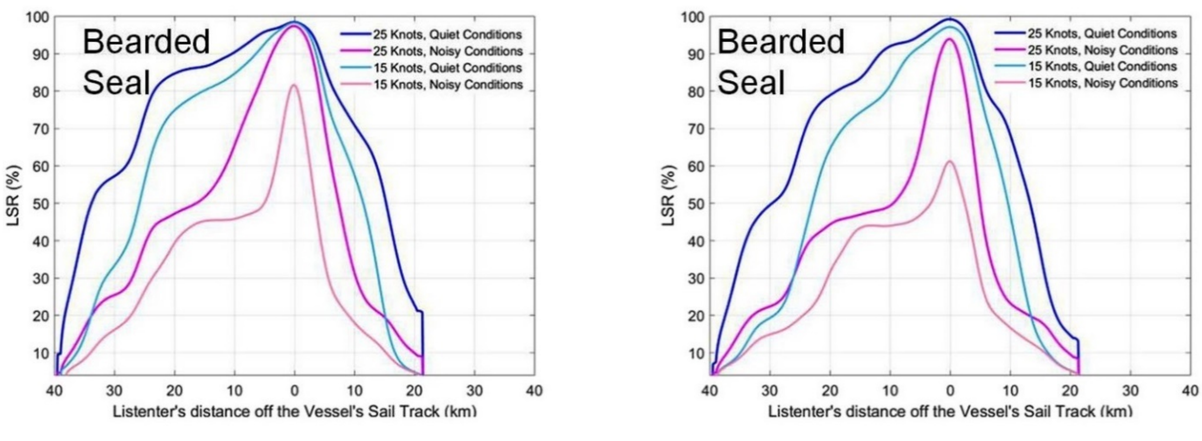

Figure 4. Modelled LSR (%) from a container (left) and cruise ship (right) at 15 and 25 knots under both quiet and noisy noise conditions (Pine et al., 2018)

et al., 2018; Roth, Hildebrand, Wiggins, & Ross, 2012). Increasing open water because of reduced sea ice formation is expected to result in higher levels of anthropogenic noise (Ladegaard et al., 2021). Bearded seal males rely on underwater vocalisation to attract mates as well as to hold territories. The reliance on vocalisations for crucial life history events such as courting means that the species could potentially be vulnerable to noise pollution. Recent studies pertaining to the effect noise pollution has on bearded seals will be reviewed in the following section.

Fournet and colleagues provided the first study on the effects increasing ambient noise has on the call amplitudes of bearded seal males (Fournet, Silvestri, Clark, Klinck, & Rice, 2021). The study suggested that bearded seals can increase call amplitudes to compensate for elevated ambient noise up to a certain threshold, suggested to be approximately 100 – 105 dB. Call amplitudes did not increase past this threshold. As presented in section 2.2, conspecific calls at the 100 – 900 Hz range need to be at least 12 dB higher than background noise for bearded seals seals to detect them (Sills, Ruscher et al., 2020). The predicted signal excess (defined as the excess of signal level relative to that required for a detection probability of 50%) that Fournet et al. (2021) calculated when ambient noise was at 111 dB (maximum observed in their study) was 17 dB lower than when ambient noise was at 83 dB (minimum observed), which is lower than the threshold described in the study by Sills, Ruscher et al. (2020). This suggests that detection of bearded seal calls by conspecifics will be reduced if ambient noise is increased. As ambient noise levels are likely to increase from anthropogenic noise resulting from increasing industrialisation in the Arctic, the described acoustic masking might have a direct impact on the fitness of bearded seal stocks.

Pine, Hannay, Insley, Halliday, & Juanes (2018) assessed the impact that slowing vessel speeds (from 25 to 15 knots) would have on the listening space reduction (*LSR*, defined as the percentage decrease in listening space) of several marine mammal species, including the bearded seal. They found that reducing vessel speed had a greater impact on bearded seal LSRs under noisy ambient conditions than under quiet ambient conditions. Under quiet ambient conditions, a reduction in vessel speed from 25 to 15 knots resulted in a smaller LSR by just 1–2%, while under noisy ambient conditions it resulted in a smaller LSR by 16–33%. Both LSRs vary between vessel type, as different vessel types produce varying amplitude and frequency of noise (Figure 4) (Pine et al., 2018).

The NAMMCO Scientific Committee (NAMMCO, 2015) drew the attention of the NAMMCO Council to the potentially severe consequences of industrial activities in the Arctic. The Committee noted that these activities will also likely have impacts on the hunting of these species and could affect the advice that it gives. Particular concerns were raised about a Canadian mining project currently under development in the Canadian Arctic, the Mary River Project operated by Baffinland Iron Mines Corp, with prospective year-round shipping through the heavy pack ice in Baffin Bay. It could have severe consequences for the large numbers of marine mammals of six species using the area in summer and winter, including bearded seals (e.g., Kovacs, 2016; Kovacs et al., 2021; Laidre et al., 2015; NAMMCO, 2015). These may include effects on the populations themselves but also on hunting activities and harvest sustainability. Other industrial activities that were considered as important disturbance factors for marine mammals were seismic explorations in Canada, and in West and East Greenland.

Lomac-MacNair, Andrade, & Esteves (2019, 2021) studied the behavioral responses from four pinniped species, including bearded seals, to an icebreaker vessel in northwest Greenland. The authors found a negative correlation between seal-to-vessel distance and seal flight activity, and did not observe any flush responses (i.e., flushing into the water from the floating ice on which seals were resting) at distances above 602 m for bearded seals. Bearded seals did have the smallest mean flush response distance to the icebreaker of the 4 studied seal species (410.1 m, SD = 177.64). Importantly, the study was carried out during the summer, and thus outside the breeding season for bearded seals: impacts on breeding seals and pups may differ. These findings are relevant to assess potential impacts of increasing vessel activity in the Arctic and to assist in the development of effective monitoring and mitigation strategies. The authors also noted that, as Arctic activities expand, the need for cumulative effects assessments will be imperative for the future protection of Arctic marine mammals.

Boertmann and Mosbech (2017) noted that another threat from climate change and increase ship traffic is the risk of introducing alien and invasive species by ship fouling and ballast water. Greenland waters have so far largely been spared but increasing water temperatures will increase the threat. They also point out that the construction of subsea wells and pipelines can destroy parts of important habitats on the seafloor. They mentioned that important habitats in this respect are feeding grounds for bearded seals, walrus and king eider *Somateria spectabilis*, which all feed on benthic mussels and other invertebrates.

Activities in the Arctic are rapidly increasing to support industrial growth and new shipping routes. This is expected to lead to increased interactions with marine mammals (e.g., Wilson, Crawford, Trukhanova, Dmitrieva & Goodman, 2020), although potential behavioural reactions of marine mammals to industry-related activities are still poorly addressed.

Hunting

Bearded seals are hunted across most of their distribution range, but assessments of the sustainability of catches are lacking for all areas except Alaska. Bearded seals are hunted for subsistence year-round in Greenland and the Eastern part of the Canadian Arctic, and outside of their breeding season within a restricted area in Svalbard. Skins are used for clothing, kayak coverings and more, while the meat is consumed by humans and used as food for sled dogs.

In Eastern Canadian waters, bearded seals are hunted off the coasts of Nunavut, Quebec, Labrador and Newfoundland. Cameron et al. (2010) estimated the expected total annual take by Native hunters in the Canadian Eastern

High Arctic as 5,000 to 6,000 bearded seals. Canadian catches were, and possibly are, therefore higher than the Greenlandic catches and likely at least partly from shared stocks. While detailed catch data for the Canadian Arctic are available for the period 1995-2001 (Priest and Usher, 2004), it is essential that recent catch data be available for assessments of the conservation status of bearded seals in the Baffin Bay-Davis Strait region.

In Greenland, the reported number of catches (NAMMCO, n.d.) has declined in recent years, from a yearly average of 1,685 (SD = 424) seals in 2000–2009 to a yearly average of 1,242 (SD = 125) seals in 2010–2019. Errors in the catch statistics have however been pointed out, with likely an over reporting of 10–20% in the earlier period (A. Rosing-Asvid, personal communication, March 16, 2022), and validation should be carried out before an assessment is conducted.

Catch data are not available prior to 2003 for Svalbard. The average of annual reported catches in 2011–2020 is 22 (SD = 8) seals, slightly more than the average in 2003–2010 of 18.5 (SD = 9) (NAMMCO, n.d.).

Bearded seals do occasionally occur in Iceland where take by local hunters is permitted. However, only one catch of a bearded seal in Iceland has been reported to NAMMCO between 2010 and 2020. The highest number of yearly catches ever reported occurred in 2004, with four bearded seals taken (NAMMCO, n.d.).

Struck and lost rates vary depending on the hunting method, the age of the seal taken, the hunter's experience and the weather conditions at the time of the hunt. Ice cover in hunting locations can dramatically affect the availability of seals and the success of hunters in retrieving seals that have been shot (Cameron et al., 2010). Cameron et al. (2010) suggested that struck and lost rates in the Alaskan hunt were between 25–70% and applied a correction factor of 50% to the catch statistics. In West and East Greenland, the struck and lost rate reported by hunters was 0–1% in 2018 and 2019. Although it is difficult to rely on such limited reporting, this figure appears comparatively very low, although bearded seals in Greenland are generally easier to approach at close range than other seal species, and likely therefore comparatively lower rates of struck and lost (A. Rosing-Asvid, personal communication, March 16, 2022). There is no reporting of struck and loss for Svalbard.

The current catch levels are thought to be sustainable on a species level as bearded seals have a very wide distribution that stretches to areas where humans are not present (Kovacs, 2016). However, depletion of local stocks remains a risk and requires assessment.

By-catch

The Greenland by-catch database to NAMMCO, initiated in 2018, includes seven and five bearded seals reported by-caught in 2018 and 2019 respectively, with no data yet reported for later years (NAMMCO, n.d.).

The Icelandic by-catch database, initiated in 2002, reports by-catch of bearded seals in some years, with a total of 13 bearded seals reported by-caught in the period 2002–2020, only in lump-sucker gillnets in cases where the fishery is specified (i.e., from 2011 onwards).There is no report of by-catch incident of bearded seals in Faroese waters and for the Faroese fisheries in foreign waters for the period 2000–2020.

By-catch of bearded seals have not been reported in Svalbard waters (K. Kovacs, personal communication, August 2, 2021) nor in the Norwegian by-catch database for the period 2006–2020. In the recent past in the shallow water around Svalbard, a prime distribution area for bearded seals, only shrimp trawlers operated in the fjords, and they have seal exclusion devices. By-catch may, however, become an issue in the future given the spread of fisheries northward. By-catches of bearded seals may occur when bearded seals roam into the coastal waters of Northern Norway (Finnmark), where densities of gillnets are high, but none have been reported in the records of the Norwegian Marine Research Institute (A. Bjørge, personal communication, August 2, 2021).

In summary, there are few reports of bearded seals being by-caught and there is little or no gillnet fisheries in the prime distribution area of bearded seals. Hence, we consider bycatch to be of little concern to bearded seals.

CONCLUSION AND SUGGESTIONS

The current removal levels of bearded seals are thought to be sustainable as the species has a very wide distribution that stretches to areas where they are little affected by human activities. Bearded seals, however, are also impacted by climate and associated changes, in particular the loss of sea ice, both in direct (e.g., loss of haul out substrate and habitat) and indirect ways (e.g., increased disturbances, decreased availability of prey, health related issues). However, demographic impacts of climate change on this species will be difficult to detect because of the lack of baseline data on abundance and trends in population sizes. The species was classified as threatened by the United States in 2012 and recently in 2021 as Near Threatened by Norway because of declining habitat quality.

In 2016, the IUCN recommended that bearded seals be monitored over the coming decades and reassessed as soon as more data became available (Kovacs, 2016). An assessment of the North Atlantic stock(s) is still lacking and has been requested by the Council of NAMMCO (NAMMCO, 2019, 2020). Indeed, this review was conducted to help decide whether sufficient information was available to perform stock assessments and evaluate the conservation risk from anthropogenic stressors, including direct and indirect removals, and if not, to highlight and prioritise required research efforts.

Critical information essential to management includes stock structure and regional abundance and trends. Although research on bearded seals has remained a secondary focus in the Atlantic Arctic since 2010, new information and data have emerged either as the result of focussed research or as a by-product of research targeting other species (i.e., abundance surveys). The project initiated by the CAFF in 2016 (Kovacs et al., 2021) also drew attention to bearded seal research and stimulated the analysis of available but not yet synthesized data on bearded seals, although progress has been slower than expected.

Key data on stock structure is still missing for bearded seals. It is crucial to know how bearded seals are distributed between Canada and Greenland during different seasons and how many distinct and shared populations they comprise. However, some data on stock structure and delineation should become available shortly from a circumpolar genetic analysis of bearded seals due in spring 2023 (M. Tange Olsen, personal communication, November 16, 2022). Other lines of evidence that have recently emerged from behavioural (tracking, vocalisation and dietary) studies will also inform the delineation of management areas if not of stocks.

Key data on region-wide abundance is still missing for bearded seals. This will likely not become available in the foreseeable future, but remote-sensing surveys, such as those initiated in Alaska (Leblanc et al., 2016), might aid in getting such information in the future. Partial abundance data are now available from surveys carried out since 2010 for multiple years for the North Water Polynya (NOW), Melville Bay, Baffin Bay/West Greenland, and the North-East Water Polynya (NEW). Progress in obtaining these two types of information might allow for a first assessment of bearded seals for these areas. Some data on local abundance in other areas of Greenland should become available shortly.

Catch data are available for Greenland and have recently become available for Svalbard. Some information on bycatch risk is also available for different areas. A Potential Biological Removal (PBR) approach shed some light on the sustainability of present removals (both direct and indirect). A PBR approach was used in Alaska by Nelson, Quakenbush, Taras, & Ice seal Commitee (2019), where removal levels were available for 41 of 55 hunting communities in their research area. They extrapolated the per capita removal estimates to the hunting communities where data were lacking and concluded that subsistence-hunting was sustainable. A similar exercise might be possible for other areas when minimum abundance estimates become available.

Although data on bearded seals are still limited, the NAMMCO Scientific Committee (SC) at its 23rd meeting in 2016 noted that substantial information had become available, and that the organisation of a status meeting was warranted (NAMMCO,2016). The SC specified the following Terms of Reference for the bearded seal working group:

1. Assess the global distribution and possible population delineations
2. Evaluate available information on biology including reproduction and feeding habits
3. Assess the exploitation and other anthropogenic effects including climate changes on bearded seals
4. Suggest populations and areas in the North Atlantic where sufficient data are available for assessing the effects of exploitation and reductions in habitats

Given that a considerable amount of new information has become available since 2016, a status review seems warranted and timely to attempt to define management areas and proceed with the review and possible assessment of the status of the populations in these areas, and to identify and prioritise which kind of data is needed to further assessments. The value and pertinence of such a review will be greatly enhanced if, ahead of the review, some ongoing analyses are finalised and some existing data analysed and/or and made available, including:

1. Greenland has a significant amount of abundance data not yet analysed that comes from non-bearded seal-focussed surveys (for NOW in 2018 and 2022, Melville Bay 2012 and 2014, Baffin Bay/West Greenland in 2006, 2012 and 2022, NEW in 2017 – though only few sightings). The analysis of these data should be prioritized and completed after correction factors have been calculated.
2. Correction factors to adjust for seals not hauled out should be calculated from tracking data for the different areas and likely time of the day/year when the surveys have been conducted.
3. Recent abundance estimates for Eastern Canada are needed.
4. The circumpolar population structure study conducted at the University of Copenhagen should be finalised and the results made available to the working group.
5. For a more accurate evaluation of the sustainability of catch levels and other stressors and of the conservation status of different population segments in Greenland, validated catches need to be available at a smaller scale than West Greenland, East Greenland, and Svalbard. This will allow exploring the relative impact of different anthropogenic stressors for different stock structure/management area hypotheses. This should not be a problem, as in Greenland, hunting statistics are reported by communities/villages. Recent (post 2001) validated catch statistics for Canadian waters need to be available.

As bearded seals have a large geographic distribution and are relatively flexible in habitat requirements, they might be less vulnerable to climate change than some of the other ice-associated pinnipeds. But they will, however, be impacted by climate and associated changes, both directly and indirectly. The decrease in sea ice habitat suitable for moulting, and the spatial separation of sea ice from benthic feeding habitat are considered as severe threats and may be the most significant in some areas.

Monitoring programs have been recommended repeatedly for this little-studied species, but there is currently no comprehensive monitoring program in any of the Arctic countries. It is therefore essential that the information which has become available since 2010 across the Arctic be thoroughly reviewed in order to design and implement a focussed monitoring programmes across the area. Integrating the data and results at a circumpolar level will help to fill in the gaps in knowledge from some areas, resulting from the logistical challenges inherent to bearded seal research.

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