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Lost and Found: Reassessing Ringed Seal Abundance in a Key Fjord System in Svalbard After a 20-Year Hiatus

Marc Rams i Ríos

Master’s thesis in Biology BIO-3950, May 2024

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Cover photo: VTOL DeltaQuad Pro #MAP - initiating an aerial survey in Tempelfjorden, Svalbard, May 2023. Photograph by Marc Rams.

Title page photo: Me setting up the VTOL DeltaQuad Pro #MAP for an aerial survey in Svalbard, May 2023. Photograph by Kit Kovacs.

Acknowledgements

Little did I know two years ago when I applied to a master's program at the northernmost university in the world that I would end up embarking on an incredible adventure in the Arctic Archipelago of Svalbard to conduct my thesis. It has been a long, tedious, and sometimes even painful journey, but one from which I have learned countless things, from flying drones over ice to writing science, as well as improving and learning to use tools like QGIS, R, and Python. That's why I can say nothing but thank you. Thanks to my supervisors Christian Lydersen, Kit Kovacs, and Rolf Anker Ims for offering their support, guiding me, and teaching me how to do science, something I had always dreamed of doing and now feel I am a bit closer to achieving.

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Abstract

Ringed seals (*Pusa hispida*) in Svalbard, Norway, are thought to be declining due to the impacts of climate change in the region, particularly due to a significant reduction in the extent of landfast sea ice that they rely on for breeding. The only available survey of ringed seals in Svalbard took place in 2002, so is now over twenty years old. Here, we address this data gap by conducting UAV aerial surveys throughout the Isfjorden fjord system on the island of Spitsbergen, Svalbard, during the moulting season in 2023. We also provide the first aerial-based assessment of size/age structure of the ringed seal population within Isfjorden using body length measured from the UAV images. From a total 7,042 images collected along 2,159 km of transects we covered an area of 132 km^2 of landfast sea ice. We show a decrease of 77% in landfast sea ice and concomitant decline in ringed seal abundance in Isfjorden of approximately 46% since 2002. We show that the declines in landfast sea ice and ringed seal abundance have led to an increase in the density of seals, from 1.86 seals/km^2 in 2002 to 2.41 seals/km^2 in 2023. Length-based estimates of age suggest that 65% of the contemporary population consists of immature individuals. Together, the results from this updated population survey underscore the urgent need for more frequent monitoring of ringed seals in Svalbard to better understand the drivers of population decline and highlights the broader implications of environmental changes on Arctic marine biodiversity. The innovative use of UAV technology in this study demonstrates its utility in wildlife research, offering a less invasive, cost-effective, and efficient method for collecting aerial images of ringed seals and their environment that enable a wide variety of studies that will be useful to inform management and climate change mitigation.

Keywords: ringed seal, *Pusa hispida*, UAV, abundance, density, maturity status, aerial survey, landfast sea ice, Svalbard

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1 Introduction

Climate change, primarily driven by human activities such as deforestation, exploitation of fossil fuels, and emission of greenhouse gases, is causing increases in air and water temperatures and acidification of ocean waters at a global scale (Calvin et al., 2023). From a wildlife perspective, animal species have two broad mechanisms by which they can ameliorate the impact of challenges arising from climate change, 1) they can successfully adapt to the changing conditions and thereby remain within their current ranges and habitats or 2) they must move to new areas that meet their requirements. Mobile species in equatorial or temperate environments can shift latitude (north or south) to track traditional habitat conditions when their range becomes inhospitable, but species that are unable to move will decline, potentially to extinction (Feeley et al., 2012; Robinson et al., 2009). Typically, species with long-life expectancies and low offspring production find it more difficult to adapt to environmental changes on short time scales, which limits their ability to cope with environmental change (Ricklefs & Wikelski, 2002).

Arctic endemic marine mammals are long-lived, highly specialized, ice-associated animals. Living primarily in the Arctic shelf areas, at the top of the world, they face geographical constraints that prevent further northward movement. Additionally, temperatures in this region have risen at rates 2-4 times those of other parts of the planet (Rantanen et al., 2022; Taylor et al., 2022), which have led to a rapid decline in their sea ice habitats (Meredith et al., 2019) This single change is having severe repercussions for endemic Arctic marine mammals (Kovacs et al., 2021). The reduced sea ice extent also has indirect impacts on Arctic marine mammals, including changing food webs, increased disease risks, increased competition from temperate species and increased human activity levels in previously ice-covered areas exacerbating the adverse effects of sea ice losses (Barratclough et al., 2023; Kovacs et al., 2011, 2012).

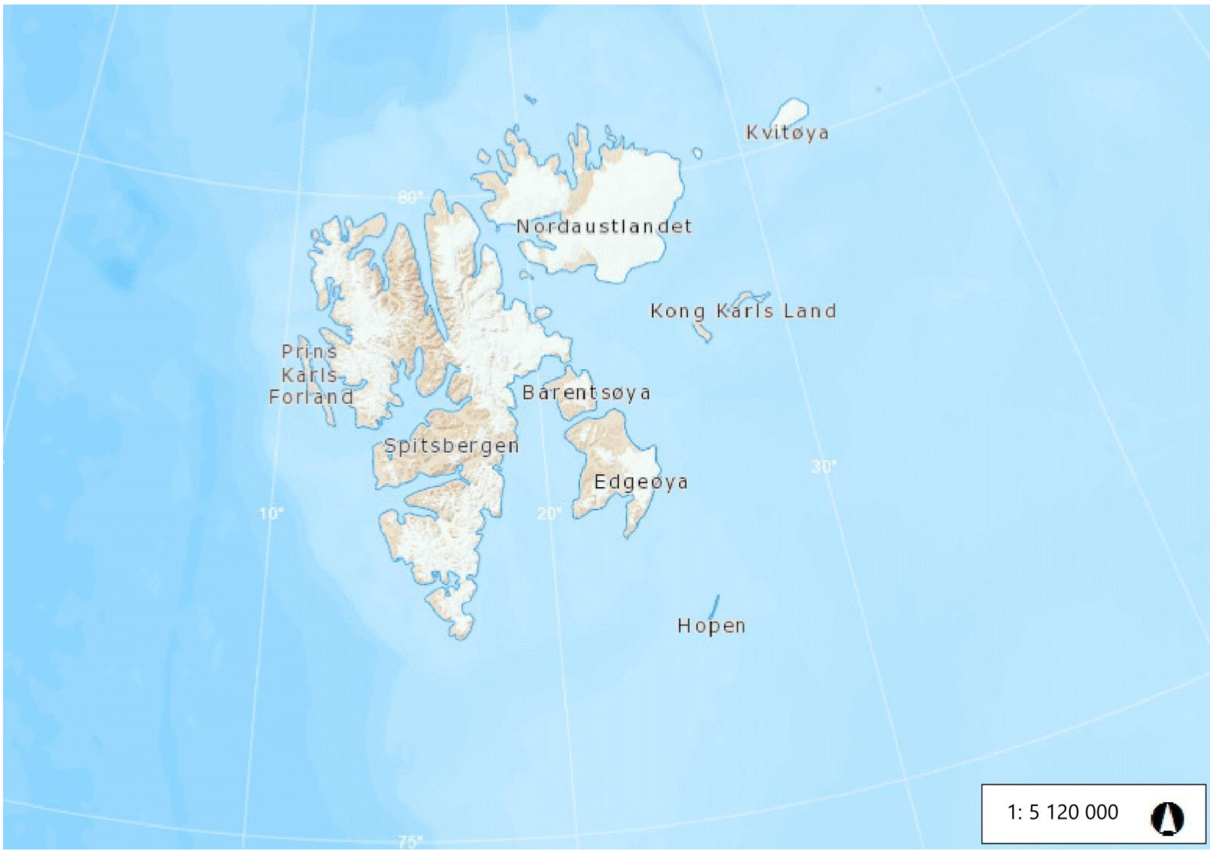

Figure 1 The Norwegian High Arctic Archipelago of Svalbard (Source: https://toposvalbard.npolar.no/).

The Norwegian High Arctic archipelago of Svalbard (Figure 1) is one of the Arctic regions that is experiencing the consequences of climate change most rapidly (Isaksen et al., 2022; Morris et al., 2020). The eastern part of the archipelago (Nordaustlandet) has been impacted somewhat less than the western part of the archipelago though it too is experiencing warmer temperatures and less ice (Przybylak et al., 2014; Urbański & Litwicka, 2022). On the west coast of Spitsbergen, the largest island in Svalbard, climatic conditions are changing at an unprecedented rate due to the influence of the West Spitsbergen Current (WSC), which transports warm, salty Atlantic Water to the region (Aagaard et al., 1987; Dahlke et al., 2020). The influx of this warm, saline water has not only moderated the climatic conditions of Svalbard but is also influencing species distributions and re-shaping ecosystems. In recent decades, the temperature and salinity of the Atlantic Water, as well as the volume of the flow into the fjords has increased (Marnela et al., 2020; Nilsen et al., 2019), leading to sea ice reductions and the retreat of tidewater glaciers (Geyman et al., 2022). One of the many consequences of this so-called «Atlantification» is the expansion of boreal species northwards, creating potential competition for the Arctic endemic species for both resources and habitat (Fossheim et al., 2015; Ingvaldsen et al., 2021). The loss of sea ice also has significant implications for many resident species (Descamps et al., 2017; Laidre et al., 2015), ranging from small plankton (Arrigo, 2017) to large marine vertebrates (Laidre & Regehr, 2017).

Ringed seals (*Pusa hispida*) are one of the Arctic endemic marine mammals that are likely to most sensitive to declining sea ice conditions because this small true seal species uses sea ice habitats for breeding, nursing, moulting, resting and feeding (Kovacs et al., 2011; Reeves, 2014). Recent ringed seal tracking studies have documented changes in at-sea movement patterns and foraging behaviour, in response to diminishing ice cover such as less area-restricted search, more time spent diving, less resting and less sympagic foraging (Hamilton et al., 2015, 2016, 2019; Lowther et al., 2017). Terrestrial haul-out, which had never been seen before, has also recently been reported for ringed seals in several areas in Svalbard (Lydersen et al., 2017). Some of these changes are likely related to a shifting distribution and population decline of polar cod (*Boreogadus saida*), the preferred prey of ringed seals in Svalbard (Bengtsson et al., 2020; Gonzalez-Pola et al., 2019; Labansen et al., 2007) which is also affected by sea ice losses, shifts in water temperatures, and changes in competition and predation (Hop & Gjøsæter, 2013; Huserbråten et al., 2019; Spotowitz et al., 2022).

A principal sensitivity to climate change for ringed seals is their dependence on snow lairs built over breathing holes in the sea that protect their pups from harsh environmental conditions and various predators (Smith & Stirling, 1975). Because the sea ice in Svalbard forms later (if at all) and melts earlier (van Pelt et al., 2019), in the last two decades, there is often not enough snow to construct lairs and the pups are born on the surface where they are extremely exposed to predator attacks and thermal stress (Lydersen & Gjertz, 1986). The main predators of ringed seals during the pupping season are polar bears (*Ursus maritimus*) and Arctic foxes (*Vulpes lagopus*) and if there is no snow for lair construction also large seabirds such as glaucous gulls (*Larus hyperboreus*) take these small pups (Lønø, 1970; Lydersen & Smith, 1989; Smith, 1976).

In addition to habitat loss and predation, ringed seals in Svalbard face other pressures, such as hunting, which is allowed in restricted areas during a restricted time of the year (https://www.inatur.no/jakt/5b10e7ca0b28260003316f47; Lydersen, 1998), despite being classified as “vulnerable” due to degradation of their habitat (Eldegard et al., 2021). The annual reported catch in the period from 2003 to 2023 varies between 15-78 animals (https://nammco.no/ringed-seal/#1475844711542-eedf1c7b-5dde). To evaluate the sustainability of this local sport hunt as well as for assessing the impacts that climate change may be having on the population, updated population estimates are essential. Only one survey has been conducted for ringed seals in Svalbard (Krafft et al., 2006) The prime time for assessing abundance of ringed seals is during the annual moulting season, which in Svalbard occurs during the last days of May and early June (Carlens et al., 2006). During this time, the highest fraction of the population is hauled out on the sea ice (Finley, 1979). The normal method is to use aerial photographic surveys and count seals hauled out on the ice. In addition, some behavioural information is needed with regard to how various external factors impact the haul-out behaviour, to make a correction factor for animals in the area that are not hauled out at the time the survey (Carlens et al., 2006; Krafft et al., 2006). Traditionally, such surveys are conducted with fixed-wing airplanes or helicopters, which can be costly and logistically challenging in remote areas. However, recent developments in uncrewed aerial systems (UAVs) have proven to be an efficient alternative to traditional survey methods for studying various marine mammal species because they are not only more cost-effective but also offer a safer and more flexible platform that adapts to the rapidly changing weather conditions of polar areas (Anderson & Gaston, 2013; Dickens et al., 2021; Goebel et al., 2015; Ramos et al., 2022).

The aim of the present study is to use UAVs to replicate selected areas covered in the 2002 survey to create an index of abundance for ringed seals in the Isfjorden fjord system in Svalbard (see figure 1) and compare the results of both assessments to explore local changes in abundance and density. In addition, we will also explore the possibility of measuring the length of ringed seals from photographs, which might allow us to classify animals into various age groups, given the relationship between age and length, and thus study whether there are any age structure differences among the different surveyed fjords and create a base-line for demographic studies.

2 Materials and methods

2.1 Data collection

UAV surveys were conducted from 15 May until 4 June 2023, in five fjords within the Isfjorden system on Spitsbergen (Figure 1): Borebukta, Ekmanfjorden, Dicksonfjorden, Billefjorden, and Tempelfjorden (Figure 2). These sites were the only areas that had landfast sea ice cover at the time the fieldwork took place. Surveys were performed during the afternoons, under conditions of wind speeds below 6 m/s and clear skies (with no precipitation), which are optimal as the majority of ringed seals in Svalbard tend to haul out during the moulting period (Carlens et al., 2006).

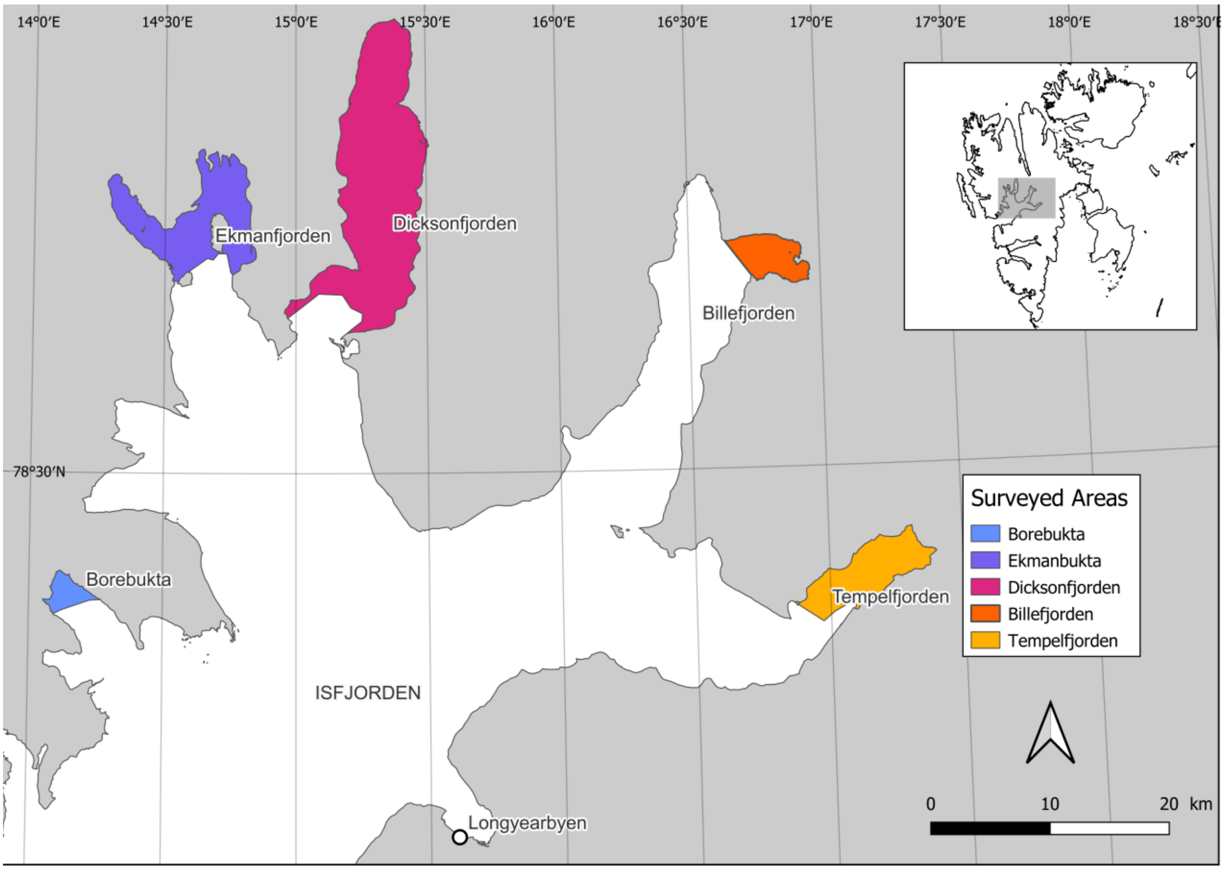

Figure 2 Spatial distribution of landfast sea ice coverage in the Isfjorden area during the UAV surveys conducted in 2023. The extent of landfast sea ice is indicated for Borebukta (May 15th), Ekmanfjorden (May 30th), Dicksonfjorden (June 2nd), Billefjorden (May 24th), and Tempelfjorden (May 19th).

A VTOL DeltaQuad Pro #MAP (DeltaQuad: https://www.deltaquad.com/vtol-drones/map/#specifications; Figure 3) UAV fitted with a Sony ILCE-6000 camera (SONY:

https://www.sony.co.uk/electronics/interchangeable-lens-cameras/ilce-6000-body-kit/specifications) was used as the primary survey vehicle. A Starlink internet antenna (Starlink: https://www.starlink.com/specifications), powered by a small generator, provided access to online mapping to update the route and re-plan the missions on the spot if necessary. The survey areas were reached using a Polarcirkel RIB boat, and launch sites were established either at the sea-ice edge or on shore close to the sea-ice area that was to be surveyed.

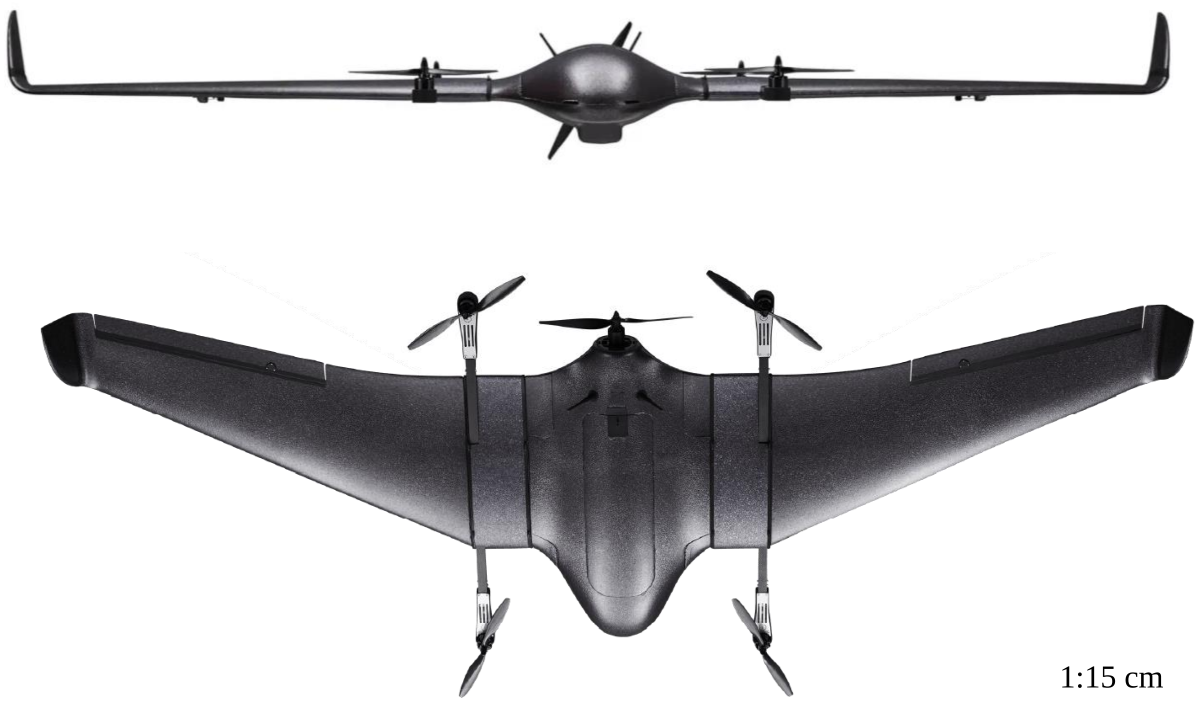

Figure 3 UAV used during the ringed seal surveys in 2023: VTOL DeltaQuad Pro #MAP front and top view.

Drones were flown at an altitude of 120 m, following a pre-defined grid pattern with minimal overlap between flight legs to avoid duplicate observations. Data were configured and uploaded to the UAV using QGroundControl software (https://docs.qgroundcontrol.com/). The DeltaQuad Mission Validator (https://validator.deltaquad.com/) verified transect viability relative to the battery status and defined safe take-off/landing locations considering environmental and terrain factors. If the transect was not viable because of terrain conditions, it was adjusted using the same QGroundControl software with a standard Windows laptop, ensuring the flight path was optimal and maintaining the predetermined altitude. Images were captured automatically at pre-defined waypoints triggered by the flight plan. The images were stored on an SD card and transferred to an external hard drive after each flight.

Flight time for each survey was determined primarily by the distance from the take-off point and limitations determined by the UAV and camera batteries. Collected images were organised by fjord and stored on an external hard drive, for subsequent manual inspection to count seals on the landfast sea ice surface.

2.2 Data processing and image analysis

Each aerial image was manually inspected for the presence of seals using Microsoft Photos software on a large screen to ensure complete image coverage. To facilitate accurate identification of the ringed seals, images were enlarged by 20% and, if necessary, segmented for analysis to avoid repeated counting of the same individuals. Finally, the images were sorted into two categories: those containing seals and those without seals and stored in separate folders for each fjord.

Flight logs were recorded in a native format (.ulg) by the UAV, which were incompatible with the chosen Geographic Information System (GIS) software used for subsequent spatial analyses (QGIS 3.28.10; *QGIS*, 2023). Consequently, a custom Python script, utilizing the ”pyulog” package (PX4 Autopilot, n.d.), was employed to convert the native flight logs into a .kml format, compatible with QGIS.

Within the QGIS environment, the converted flight paths were first separated by fjord. Subsequently, a new polygon vector layer encompassing the entire flight coverage area was created. All individual polygons within each fjord were then merged into a single entity, allowing for the calculation of the total area covered by the drone flights.

To measure the distances the UAV travelled for surveying each fjord, we employed Google Earth Pro software. This software permitted us to measure each survey's flight path, as represented by the .kml files, ensuring accurate calculation of the distances covered. The UAV flight paths, were then overlaid onto the previously mentioned fjord polygons. The intersections between the flight paths and the fjord polygons were computed to calculate the percentage of the total landfast sea ice surface surveyed within each fjord.

2.3 Landfast sea ice coverage

To compare the landfast sea ice extent in the fjords between the previous survey in 2002 and our study we use two sets of ice charts provided by the Ice Service of the Norwegian Meteorological Institute (MET Norway, http://cryo.met.no/en/latest-ice-charts). The first dataset contained the landfast sea ice extent during the time the 2002 survey was performed and was used to compare it with the landfast sea ice surface during our survey, the second dataset contained the landfast sea ice extent during our survey period. It was used both for comparing the landfast sea ice surface between the two survey periods and for assessing the proportion of total landfast sea ice area captured with the UAV imagery.

2.4 Abundance and density

Counts from aerial imagery were used to estimate the total number of seals on the landfast sea ice in each fjord. A fraction (q_i) of each fjord was surveyed through r_i aerial images. Seals visible (y_{ij}) in each image j (j = 1, ..., ri) were manually counted. The aggregate number of seals observed in each fjord, K_i ($K_i = \sum_{j=1}^{r_i} y_{ij}$), was then calculated. This sum was used to determine the total abundance of seals hauled out on the landfast sea ice, estimated as $\hat{Y}_i = K_i/q_i$. Given the extensive coverage (40%-75% as noted in Table 2) of the landfast sea ice in each fjord, and the even distribution of images across the ice, the images were considered a random sample. Therefore, the standard estimation method for sampling variance was applied, utilizing bootstrap methods without replacement.

$$\widehat{var}(\hat{Y}_i) = \left(\frac{r_i}{q_i} - r_i\right)\frac{\sigma_i}{q_i}$$

Where σ is the empirical variance in seal counts across the sampled images.

$$\sigma_i = \sum_{j=1}^{r_i} \frac{\left(y_{ij} - \bar{y}_i\right)^2}{r_i - 1}$$

To estimate the total abundance of seals in each fjord (including seals that were not hauled out on ice at the time of the survey), the number of observed seals on the ice was divided by an estimated proportion of seals that were hauled out at the time of the survey. This proportion was derived from Krafft et al. (2006) and is mainly dependant on time of day and wind speed. Our surveys were conducted under similar environmental conditions and times of day as those in the study by Krafft et al. (2006), thus we are confident in using the same correction factor in this study to estimate total abundance, noting there may be some degree of uncertainty. Finally, we calculate an arithmetic density of ringed seals for each area surveyed.

2.5 Body length

We measured the body lengths of the ringed seals on the images collected by the drone during the aerial surveys. Only seals that were positioned so that the full length of their bodies could be seen were measured. Out of the 344 observed seals, 261 individuals met these criteria. To scale the animal sizes from the aerial images information on flight altitude, camera sensor width, image size (in pixels), and focal length are used to calculate the ground sampling distance (GSD, see Ramos et al., 2022) which were then multiplied by the number of pixels measured to get the estimated length of the seal.

$$GSD = \left[\frac{sensor\ width\ (mm) \times flight\ altitude\ (m)}{focal\ length\ (mm) \times image\ width\ (px)}\right]$$

For our measurements, the camera focal length was 16 mm, the sensor width was 15.6 mm, and the image width was 4,000 pixels, which resulted in a pixel dimension of 0.0039 mm/pixel. These parameters were entered into MorphoMetriX (Torres & Bierlich, 2020), a photogrammetry graphical user interface that also allows correction for body curvature to measure the length in case the seals were not totally straight.

The body length of ringed seals is usually taken from the tip of the nose to the end of the tail (“Standard Length”) (Committee on Marine Mammals (1966–67), 1967). However, because of image resolution and shadowing we were unable to determine where the end of the tail was, so we measured each seal from the tip of the nose to the end of the rear flippers and corrected these measurements by calculating what proportion of the total body size the rear flippers represent in a selection of seals of various lengths that had been sampled empirically, we observed that the flippers represent an additional 9% of the total body length of the animal potentially introducing a bias towards slightly older animals. However, as long as subsequent assessments of aerial imagery maintain this measurement approach, these biases will be systematic, facilitating consistent tracking of relative age structure changes among the seal populations.

2.6 Maturity status

The measured lengths of the seals were used to group the animals into broad life history categories of mature and immature animals.
Using the inverse of the Von Bertalanffy growth function (Mackay & Moreau, 1990).

$$t = \frac{-1}{K} \times \ln\left(\frac{1 - L_t}{L_\infty}\right) + t_0$$

Where the standard length at age t is represented as L_t, L_∞ represents the asymptotic size, and K is a growth constant.
For ringed seals in Svalbard based on the values compiled from Krafft et al. (2004) this inverse Von Bertalanffy growth function will then be:

$$t = -1.639344 \times \ln\left(\frac{1 - L_t}{127.7}\right) + 0.42$$

Based on growth curves and knowledge of the age of sexual maturity of Svalbard ringed seals from Andersen et al. (2020) all seals older than 4 years were classified as sexually mature (4 ≤ years). By default, all measured seals with an estimated age below this threshold were classified as immature (0 to 4 years).

These two age groups were then used to investigate the ratio of mature and immature seals between the surveyed fjords. In this comparison we excluded Borebukta and Billefjorden from the analysis due to their small sample sizes. A Kruskal-Wallis test was used to determine if there were significant differences in the ratio of mature and immature between the fjords and we continued with a Dunn's test, a non-parametric pairwise analysis, to identify which fjords differed in their size distributions.

3 Results

3.1 Landfast sea ice extent

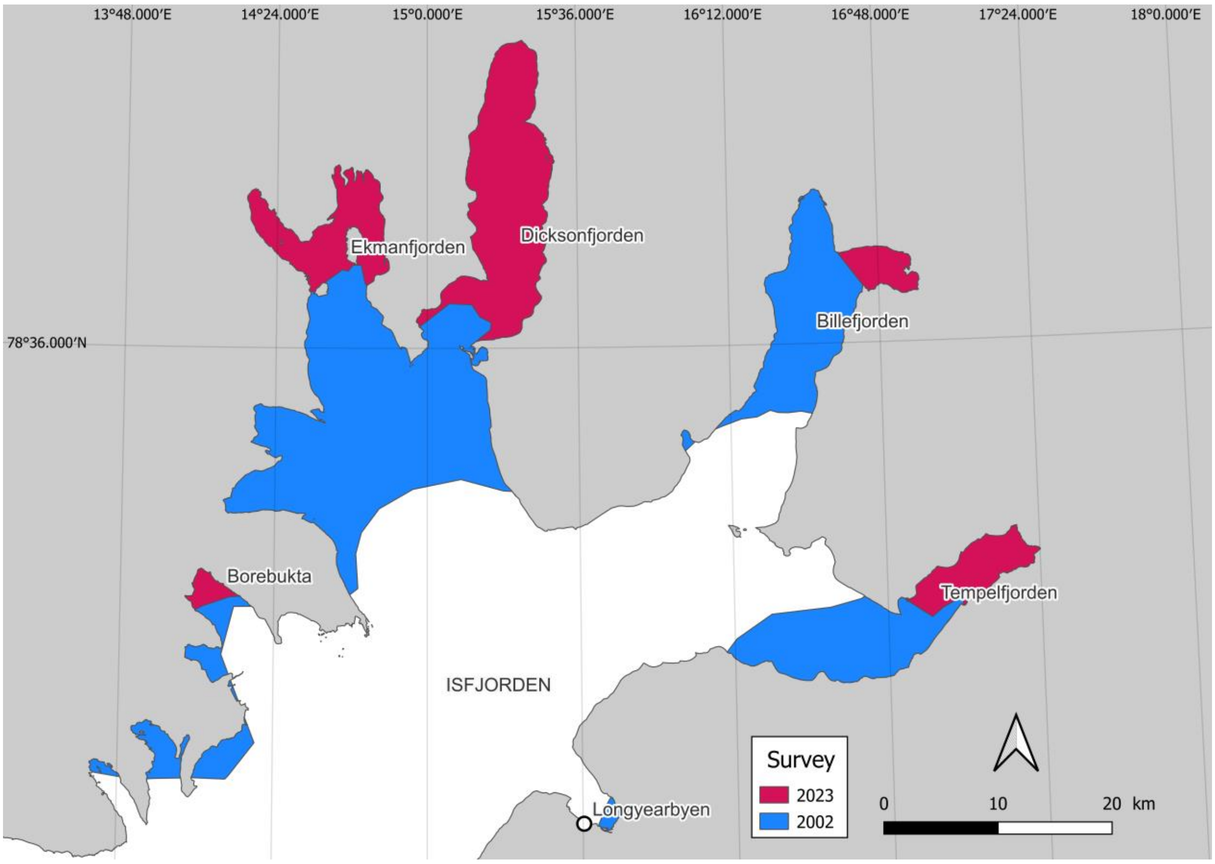

Figure 4 Extent of landfast sea ice coverage in Isfjorden, Svalbard in 2002 (blue) and 2023 (red) at the time each survey was performed.

In 2002, the landfast sea ice extent ranged from 22.3 km^2 in Borebukta to 679.6 km^2 in Ekmanfjorden (Figure 4; Table 1). In 2023, the landfast sea ice extent ranged from 7.7 km^2 in Borebukta to 147.4 km^2 in Dicksonfjorden. The total sea ice cover in these areas in 2023 was reduced by 77% compared to the coverage in 2002, with all areas experiencing marked reductions (Figure 4; Table 1).

Area	Landfast sea ice extent 2002 (km²)	Landfast sea ice extent 2023 (km²)	Difference 2002-2023 (%)
Borebukta	22.3	7.7	-65.52
Ekmanfjorden	679.6	60.7	-91.07
Dicksonfjorden	208.9	147.4	-29.44
Billefjorden	190.7	18.8	-90.17
Tempelfjorden	92.3	37.9	-58.98
ISFJORDEN	1,193.8	272.5	-77.17

Table 1 Changes in landfast sea ice extent in fjords in the Isfjorden complex, Svalbard (2002 vs. 2023)

3.2 UAV surveys

The study fjords were sampled with between 4 and 21 flights (see Figure 5), covering distances ranging from 116.62 kilometres to 1,145.47 kilometres photographing areas between 5.76 km² and 59.86 km² (Table 2). A total of 7,042 aerial images were taken during the surveys.

Figure 5 Maps showing the transect lines flown over the landfast sea ice in May-June 2023.

Area	Survey flights	Distance covered (km)	Surveyed area (km²)
Borebukta	4	116.62	5.76
Ekmanfjorden	11	362.37	29.27
Dicksonfjorden	21	1,145.47	59.86
Billefjorden	8	211.11	12.19
Tempelfjorden	7	323.51	24.92
ISFJORDEN	51	2,159.08	132

Table 2 Number of flights performed, distance surveyed and area photographed in the study fjords.

3.3 Trends in abundance and density

In the whole study area, the 2023 survey resulted in an estimate of 1,728 seals, compared with 3,206 estimated seals in the area in 2002. Thus, the current population represents a 46% decline in ringed seal numbers from 2002.

Comparisons between the numbers of ringed seals in the two time periods (2002 vs 2023) show a marked decline in the abundance of ringed (Krafft et al., 2006; Table 3; Figure 6) . Five of the six fjords in the study area had fewer ringed seals in 2023 (44-98% fewer than in 2002). Only one fjord, Dicksonfjorden, had more seals in 2023 compared to 2002 (3 x as many).

The average density of hauled-out seals in the fjords increased from 1.86 seals/km^2 in 2002 to 2.41 seals/km^2 in 2023. Densities of ringed seals were higher in the present survey for Borebukta, Ekmanfjorden and Dicksonfjorden but lower for Billefjorden and Tempelfjorden when compared to the 2002 survey (Table 3; Figure 6).

Area name	Area of land-fast sea ice surveyed with images (Km^2)		Fraction of total land-fast sea ice surveyed (%) (q)		No. Of images inspected (r)		No. Of seals counted on images (K)		Total land-fast sea ice coverage		Estimated nº of seals hauled out on the fast ice (Y)		Estimated density of hauled-out seals (Km^2)		Estimated total nº of seals in area* (N = Y/p)	
	2002	2023	2002	2023	2002	2023	2002	2023	2002	2023	2002	2023	2002	2023	2002	2023
Borebukta	34	5.8	73.5	74.9	221	366	39	14	46.3	7.7	53 (±6)	19 (±3)	1.15(±0.13)	2.47 (±0.36)	137 (±29)	49
Ekmanfjorden	316	29.3	46.5	48.24	1734	1856	262	145	679.6	60.7	563 (±37)	318 (±28)	0.83 (±0.05)	5.24 (±0.45)	1082 (±149)	610
Dicksonfjorden	155	59.9	74.2	40.6	691	2742	78	152	208.9	147.4	105 (±7)	374 (±26)	0.50 (±0.03)	2.54 (±0.18)	268 (±52)	954
Billefjorden	107	12.2	56.1	65.0	254	430	143	3	190.7	18.8	255 (±20)	5 (±2)	1.34 (±0.10)	0.27(±0.11)	577 (±99)	11
Tempelfjorden	49	24.9	53.1	65.8	559	1648	268	30	92.3	37.9	505 (±30)	46 (±5)	5.47 (±0.33)	1.22 (±0.15)	1142 (±187)	104

*Derived out from the proportion of seals estimated to be hauled-out during the 2002 survey.

Table 3 Estimated number of ringed seals hauled out, seal density and estimated total number of ringed seals in the surveyed fjords during UAV photogrammetry surveys conducted in the Isfjorden area in Svalbard, 15 May – 04 June, 2023. Data from aerial surveys in these fjords in June 2002 derived from Table 2 of Krafft et al. (2006), are provided for comparison.

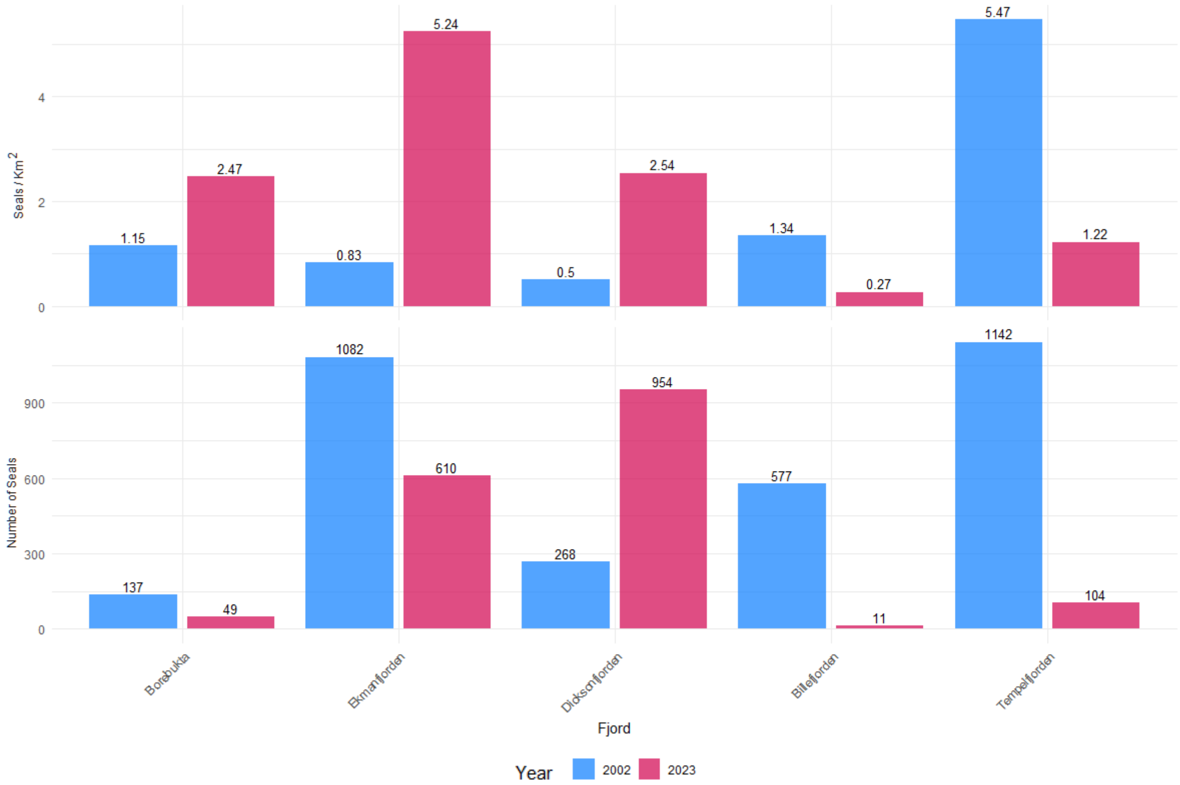

Figure 6 Comparative bar chart illustrating A) the density of hauled out seals and B) the estimated total number of seals within each fjord in the study area. Blue bars = 2002 and red bars = 2023.

3.4 Body length and maturity status

Seal length measurements ranged from a minimum of 66 cm to a maximum of 163 cm (Figure 7). The average length was 108 cm (S.D ± 16).

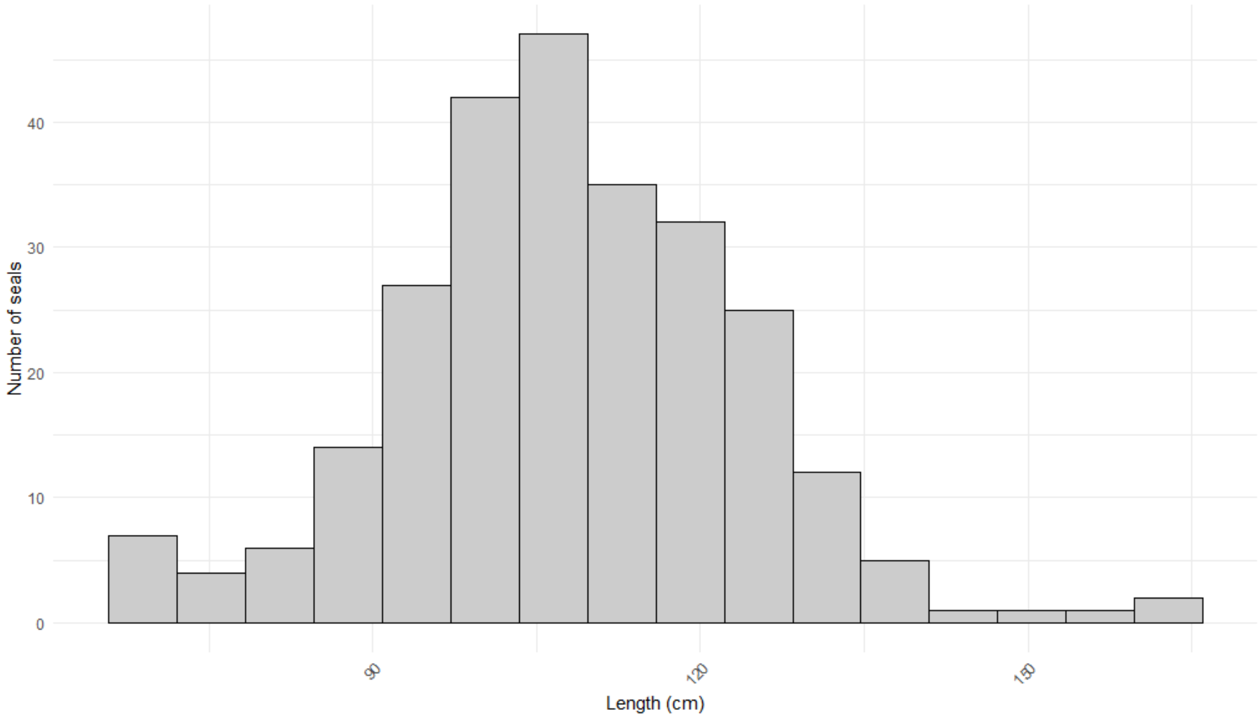

Figure 7 The histogram illustrates the distribution of lengths.

The total number of mature vs immature ringed seals in our measured sample was 90 mature and 171 immature (1:1.9). The age class varied somewhat between the fjords; Ekmanfjorden and Tempelfjorden had high proportions of immature seals, 2:4 and 1:6.3, respectively (Figure 8). While Dicksonfjorden had a ratio of mature vs immature of 1:1.3 which is higher and significantly different from both Ekmanfjorden and Tempelfjorden (Dunn's test, Table 4).

Comparison	Z	P.unadj	P.adj
Dicksonfjorden – Ekmanfjorden	2.4854	0.0129	0.0388
Dicksonfjorden – Tempelfjorden	3.0482	0.0023	0.0069
Ekmanfjorden – Tempelfjorden	1.6018	0.1091	0.3275

Table 4 Results of Dunn's test for comparison of age structures across different fjords. Includes Z-values, unadjusted p-values (P.unadj), and Bonferroni-adjusted p-values (P.adj) for each pairwise comparison.

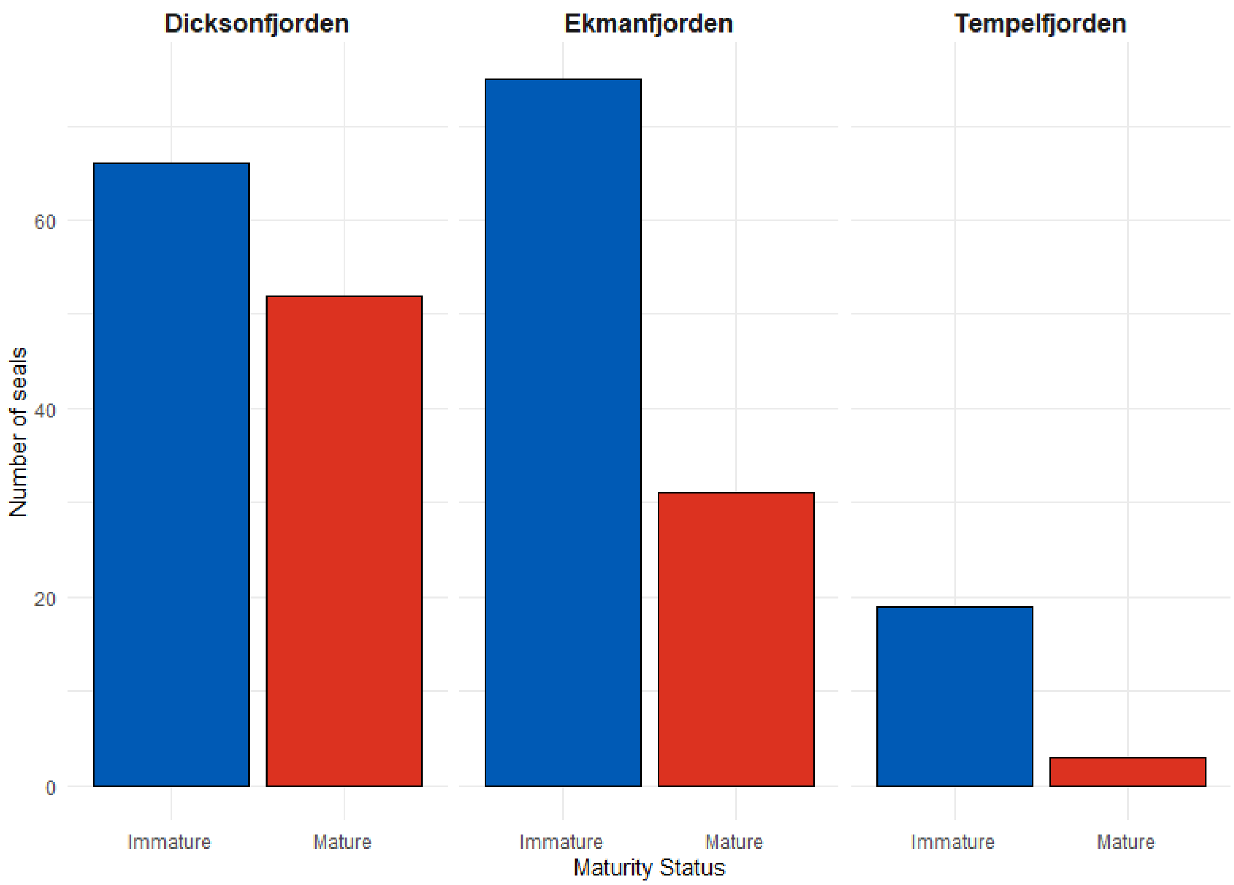

Figure 8 Comparative bar chart illustrating the maturity status distribution of ringed seals within three fjords: Dicksonfjorden, Ekmanfjorden, and Tempelfjorden. Based on length conversions - Immature (0-4 years), Mature (4 ≤ years).

4 Discussion

We present the first updated assessment of ringed seal abundance and distribution in a key fjord system in Svalbard in over two decades. We detected a sharp decline in ringed seal abundance which is concomitant with a large reduction in landfast ice cover. Despite the seal abundance declines, density of seals present on the ice has increased because of the rapidity of the ice declines. Using UAV collected imagery, we clearly demonstrate a feasible means of having at least a regional index to monitor ringed seal population status that can be done in a cost-effective way and at a frequency appropriate to monitor this rapidly changing marine system. Additionally, the high-resolution images collected using UAVs made it possible to make coarse assessments of the age structuring of ringed seals within surveyed areas.

Our drone-based aerial surveys enabled us to examine changes in seal abundance and density since 2002. We assumed that all seals visible in the images were accurately detected and identified. By conducting flights at an altitude of 120 meters, we minimized our impact on seal behaviour, and enhanced the reliability of our observations by minimizing disturbance risks (Palomino-González et al., 2021). This approach ensured that our data, which covered a substantial portion of the surface of the landfast sea ice during the moulting period, accurately reflects the current ringed seal population in our study area. The 2023 survey was conducted several weeks earlier in the year compared to the 2002 survey to mitigate the risk of no sea ice being present later in the spring season. Results from Carlens et al. (2006) suggest that this adjustment in timing should not influence the proportion of seals hauled out, provided the survey occurs between May 12th and June 25th.

All surveyed fjords have experienced considerable reduction in landfast sea ice cover between the two surveys, with the most substantial declines seen in Ekmanfjorden and Billefjorden, where ice cover has been reduced by circa 90%, suggesting a possible shift towards a future where landfast sea ice may no longer be a persistent feature even during winter in these parts of this fjord system (Lundesgaard et al., 2021; Pavlova et al., 2019). The variable sea ice loss between the various fjords is likely related to their geometry, location, sill depths (where these exist) and their degree of connectivity to Isfjorden (Carr et al., 2014; Muckenhuber et al., 2016; Skogseth et al., 2020) as in addition to temperature of the water and air that determine ice formation, it is tides and local winds that are the main driving forces influencing sea ice loss (Svendsen et al., 2002). Clearly, global warming and the Atlantification of Svalbard due to the West Spitsbergen current also play a major role in determining landfast sea ice extent on the fjords in the Isfjorden system (Nilsen et al., 2008). A major intrusion of warm Atlantic water into the fjords along the west coast of Spitsbergen in the winter of 2005/2006, had severe consequences for the sea ice formation (Cottier et al., 2005; Spielhagen et al., 2011) and the altered sea ice regime seen at the time has largely prevailed ever since.

The environmental change, including increased temperatures in the air and water and the drastic changes in Atlantic Water (volumes and temperatures) that have driven the ice changes in Svalbard fjords (Dahlke et al., 2020; Ingvaldsen et al., 2021; Isaksen et al., 2022; Kujawa et al., 2021; Pavlova et al., 2019; Urbański & Litwicka, 2022), have allowed the northward expansion of boreal species and increased the importance of the pelagic community compartment, while reducing the ice-associated ecosystem (Ingvaldsen et al., 2021). This shift has had detrimental effects on ice-associated species ranging from plankton to marine mammals (Hamilton et al., 2019; Vihtakari et al., 2018; Weydmann-Zwolicka et al., 2021).

Ringed seals are likely among the most likely species to be highly impacted by climate change because they rely heavily on stable landfast sea ice for successful breeding and use sea ice for haul-out during moulting in late spring, as well as for resting and feeding throughout the year throughout (S. H. Ferguson et al., 2017; Hamilton et al., 2015; Kelly, 2022). Ringed seals dig their lairs in snow drifts that form on top of the sea ice above cracks or breathing holes, often near pressure ridges because snow tends to accumulate around them (Smith et al., 1991; Smith & Stirling, 1975). Due to global warming, not only is the area of landfast sea ice shrinking, but the seasonal duration of the sea ice is shorter (forming later and melting earlier), and precipitation, even in winter, is occurring in the form of rain more often, reducing the potential for snow accumulation. Without sufficient snow for lair construction, ringed seals pups are exposed to the elements, and are more available to predators such as polar bears, arctic foxes, and glaucous gulls. In years with poor snow cover, pup mortality significantly increases, potentially affecting the abundance of the species (Bengtsson et al., 2021; Freitas et al., 2012; Gjertz & Lydersen, 1986; Lydersen & Smith, 1989; Pilfold et al., 2014; Smith, 1976). At the same time, the reduction of sea ice thickness leads to a higher risk of ice break up and lair collapses, increasing the risk of separation of mothers and pups (S. H. Ferguson et al., 2017; Kelly, 2022; Smith et al., 1981, 1991). Furthermore, prey availability for ringed seals has likely declined, because their favourite prey -polar cod- are declining in the Barents Region and the food web of west Spitsbergen has changed toward less Arctic prey as a consequence of the Atlantification (Gonzalez-Pola et al., 2019; Lowther et al., 2017).

Given the reliance of ringed seals on landfast sea ice, it is perhaps not surprising that we show a clear downward trend in overall abundance during the last two decades (Krafft et al., 2006). Nor is the increase in density particularly surprising given the dramatic declines in the amount of available landfast sea ice. But there is some fine-scale variation, that is likely caused by specific characteristics in the different fjords in the study area. For example, Dicksonfjorden actually had more seals in 2023 compared to 2002. This fjord does not have tidewater glaciers and is thus not an important breeding habitat. It had only 250 ringed seals during the 2002 survey, even though it is a very large fjord (Krafft et al., 2006). However. Dicksonfjorden is geographically situated such that it is protected from current and wave actions and thus has lost ice at a slower rate than more exposed fjords. This means that it has a more predictable ice situation in the moulting period and likely now acts as a geographic «sink» at the time ringed seals moult, drawing seals from other areas.

Billefjorden and Tempelfjorden used to be good breeding areas for ringed seals, with tidewater glaciers that produced bergy bits that froze into the fjord ice, around which snow accumulated to enable construction of birth lairs for the ringed seal females (Lydersen et al., 2014). A breeding habitat survey in Tempelfjorden in 1990 estimated that about 300 pups were born in this fjord annually (Lydersen & Ryg, 1991). In addition to mothers and pups, such stable breeding habitats would contain adult males, generally in the inner parts of the fjords where the females tend to build their lairs, plus juvenile animals out towards the ice edge (Krafft et al., 2007). During the aerial survey in 2002, Tempelfjorden contained over 1000 ringed seals (Krafft et al., 2006), as compared to around 100 in the 2023 survey. The change has been driven by reduced sea ice, but also the tidewater glaciers in this fjord (Tunabreen and Von Postbreen) have retracted to the point where the front are largely on land (Geyman et al., 2022), so good breeding habitats for ringed seals is dramatically reduced. Billefjorden is similar, with less sea ice and retracted glaciers.

Disturbances of seals, even during moulting, does cause them to go into the water. Such disturbances can be caused by predators, or by human activities such as hunting or snowmobile driving. Polar bears were present in several of the fjords during the survey, and hunting was ongoing in Eckman fjord. We do not have correction factors for these disturbance factors. However, we think that they had impacts only in very small areas.

Food availability probably has little impact in late spring because ng ringed seals feed little during the moult. They prefer to stay out of water as much as possible to be able to perfuse blood to the skin and hair to enhance the speed of the moulting process (Thometz et al., 2021).

Age structure has likely changed in the various areas with the relative changes in breeding and moulting habitats available across the Isfjorden system. Unfortunately, our measurements cannot be compared directly to previous studies due to differences in sampling methodology (Andersen et al., 2020). Previous studies have been based on measurements of hunted seals, which likely introduces a bias in the sample, as there were harvests during spring that avoided females accompanied by pups, resulting in an underrepresentation of pups in the samples and others that focused on stable ice in inner fjord areas, resulting in an underrepresentation of younger seals as they are typically found towards the outer parts of the fjords (Krafft et al., 2007). However, despite all of the various biases our results are similar to Andersen et al. (2020), with more immature than mature animals in all fjords. Andersen et al. (2020) found that 25% in their hunted sample from the Isfjorden area were animals that were 3 years or younger, which was a great proportion of young that in studies conducted in the early 2000s (Krafft et al., 2006) and early 1980s (Lydersen & Gjertz, 1987). This is somewhat surprising given the predicted low survival rates of pups during the last decades due to the poor breeding conditions described above. But clearly there is some pup survivorship, or disproportionate immigration of young animals from other areas in Svalbard (Freitas et al., 2008). In the present survey, Ekmanfjorden and Tempelfjorden had a higher proportion of immature compared to mature individuals than what was found in Dicksonfjorden. Social dynamics and age-related mobility probably both play roles in the age structures observed.

Converting image-based measurements into length estimates likely also has biases, but if these measurements are repeated in the future, with the same techniques, the current assessment should serve as a baseline for future comparisons.

In conclusion, this study has demonstrated a major reduction in seal abundance and a change in distribution over the last two decades. These results underline the urgent need for a more frequent survey regime to monitor trends in local abundance to track ecosystem change impacts and to assess the sustainability of hunting activities. The data obtained in this study can serve as a reference point for future research and conservation strategies, highlighting the important role that sea ice cover plays in seal population dynamics. Furthermore, having successfully conducted this study using new sampling techniques (UAVs) that are cost-effective, paves the way for larger-scale studies. Furthermore, estimating the size of animals and placing them in meaningful age groups, it might be possible to investigate survival and reproduction rates, and perhaps even estimate the rate of emigration and immigration between the different fjords.

The use of images taken with UAV could be improved through the adoption of automated image analysis techniques. By applying machine learning algorithms to this task, we can both reduce human bias and the cost of image analysis which can be in some cases more expensive as using onboard observers (M. C. Ferguson et al., 2018; Qian et al., 2023). Another interesting approach would be to use infrared images that make it easier to distinguish the different features of each image (Udevitz et al., 2008). Georeferencing each image would be another way to improve and expand the present study, by enabling us to pinpoint the exact location of each image and thus determine where in the fjord ringed seals haul out the most and if segregated by age or other factors changes with a changing environment. The use of aerial imagery could also be employed to not only measure the total length of the individuals but also to estimate the body volume and body condition (Allan et al., 2019; Glarou et al., 2023; Hirtle et al., 2022). Finally, another way to improve the present study would be to update ringed seal behavioural studies in case changing environmental conditions have altered haul-out probabilities, rather than applying correction factors from studies that were conducted decades ago. It is also important to recognize that the seals in Isfjorden may not represent an independent subpopulation; they are likely part of a larger population that has some degree of emigration and immigration (see Carlens et al. 2006). We currently lack data on these dynamics, which could significantly affect our understanding of overall population trends. To address this uncertainty, further genetic studies are recommended to better ascertain the connectivity and gene flow among fjords in the broader region.

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