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Opportunistic sightings from fisheries surveys inform habitat suitability for northern bottlenose whales *Hyperoodon ampullatus* and sperm whales *Physeter macrocephalus* in Baffin Bay and Davis Strait, Canadian Arctic

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ABSTRACT: Knowledge of spatial habitat patterns is critical for understanding the ecology of cetaceans and informing conservation efforts. However, this can be difficult to obtain for species that live in deep, offshore Arctic waters where they are not easily observed. We investigated habitat suitability for 2 cetacean species, northern bottlenose whale *Hyperoodon ampullatus* and sperm whale *Physeter macrocephalus*, in Baffin Bay and Davis Strait, eastern Canadian Arctic. Presence locations were obtained from a unique marine mammal sightings data set where observations were opportunistically recorded during annual government-led fisheries surveys (1999–2017). Environmental variable data were used as predictors in presence-only habitat suitability modelling in Maxent software. A total of 12 sperm whales were observed at 9 unique locations, and 282 northern bottlenose whales were observed at 66 unique locations. The best habitat suitability model for sperm whale (area under the curve [AUC] = 0.72) and for northern bottlenose whale (AUC = 0.88) indicated higher suitability for both species in the central portion of the study area; higher suitability for sperm whales was also present in the southern part of the study area. A future projections scenario using environmental data from 2021 forecasted an increase in suitability in northern regions for both species. Post-model comparisons identified significant relationships between survey effort and habitat suitability, and squid biomass and habitat suitability for both species, although the variance explained by these models was low. We discuss the importance of monitoring cetacean range expansion of temperate whales in the Arctic and how this could lead to shifts in ecosystem dynamics and increased conflict with commercial fisheries.

KEY WORDS: Presence · Sperm whale · Northern bottlenose whale · Squid biomass · Survey effort

1. INTRODUCTION

Identifying spatial patterns for species is one of the foundational approaches in ecology (Legendre & Fortin 1989) as it aids in understanding biological processes of entire populations (McIntire & Fajardo 2009). It is also a critical parameter for the application of appropriate conservation and management measures especially for vulnerable species (O'Hara et al. 2019). However, we are limited in our understanding

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of spatial patterns for species that are difficult to observe and/or are transient within a particular environment. Cetaceans are highly mobile animals with the ability to travel large distances to take advantage of resources in different habitats, leading to highly variable spatial–temporal patterns. From changes in seasonal prey availability to larger shifts in climate conditions, habitats may become more or less suitable for cetaceans, leading to shifts in their distributions (Kerosky et al. 2012). Determining the suitability of habitats for cetaceans is therefore an important tool for understanding their ecology now and into the future.

The Canadian Arctic is home to several cetaceans, including endemic species such as beluga *Delphinapterus leucas*, narwhal *Monodon monoceros*, and bowhead whales *Balaena mysticetus*, as well as transients such as minke *Balaenoptera acutorostrata* and fin whales *Balaenoptera physalus*, among others. The high variability of the Arctic marine environment results in spatial and temporal variation in cetacean distribution patterns (Fortune et al. 2020). Climate change is causing fluctuations in sea temperature and ice conditions (Comiso 2003, Stroeve et al. 2007), making new habitats available for subpolar cetaceans to exploit (van Weelden et al. 2021). These environmental changes have ecological implications; for example, the decline in sea ice has coincided with an increased presence of killer whales *Orcinus orca* in the Canadian Arctic (Higdon et al. 2012), which in turn impacts the behaviour of other endemic species (Breed et al. 2017). It is therefore crucial to monitor the presence and behaviour of all cetaceans in Arctic waters.

Reliable data are central to examining spatial patterns. However, it can be difficult to obtain basic data in remote areas, such as the offshore Arctic, leaving these areas comparatively data poor. Marine mammal presence and behavioural observations can be recorded relatively inexpensively from vessel-based surveys (Richardson et al. 2012). Since annual vessel-based surveys are often performed by fisheries management agencies to monitor commercial species, they provide an ideal platform for direct observation of cetaceans. Opportunistic sightings, such as these, have been useful in providing insights on spatial and temporal trends for a variety of whale species (Richardson et al. 2012, Olson et al. 2018, Chou et al. 2022).

We present previously unpublished observations of cetaceans in the eastern Canadian Arctic recorded during annual fisheries surveys aboard the RV 'Pâmiut' between 1999 and 2017. We summarized patterns in spatial–temporal occurrence for 2 focal species, sperm whale *Physeter macrocephalus*, a subpolar species that has been recorded visiting northern latitudes (Christensen et al. 1992, Posdaljian et al. 2022), and northern bottlenose whale *Hyperoodon ampullatus*, a seasonal resident with the Davis Strait–Baffin Bay–Labrador Sea subpopulation (COSEWIC 2011) whose population is classified as data-deficient. We used the sightings data together with environmental predictors to produce habitat suitability models under current and future scenarios. We expected that suitability would be highest for both species in deep, sloped areas driven by seasonal foraging behaviour corresponding to prey distribution (Christensen et al. 1992, Hooker & Baird 1999, Bjørke 2001). The aim was to contribute to a growing body of knowledge of these species in the eastern Canadian Arctic and aid in conservation and management efforts.

2. METHODS

2.1. Study location

This study took place in the eastern Canadian Arctic across Baffin Bay and Davis Strait (Fig. 1). This marine environment is characterized by a wide variation in bathymetric features including depth and slope, and in physical oceanographic characteristics such as sea surface temperature (SST). Baffin Bay and Davis Strait are also the location of commercial fishing activity, targeting Greenland halibut *Reinhardtius hippoglossoides* and shrimp (*Pandalus borealis* and *P. montagui*).

2.2. Trawl survey and cetacean observations

Fisheries and Oceans Canada (DFO) has conducted depth-stratified random bottom trawl surveys in the eastern Canadian Arctic (Northwest Atlantic Fisheries Organization [NAFO] Divisions 0A and 0B; Fig. 1) since 1999. These surveys occurred between August and November, and trawling operated on a 24 h basis (i.e. day and night). Between 1999 and 2017, marine mammal species were opportunistically observed by several different members of the science staff and ship crew during the survey. For each marine mammal observation, the date, species name, and number of whales observed were recorded. Trawl data from years with marine mammal observations, including information on survey location, duration, and number of trawls, was also compiled (Table 1). Vessel latitude

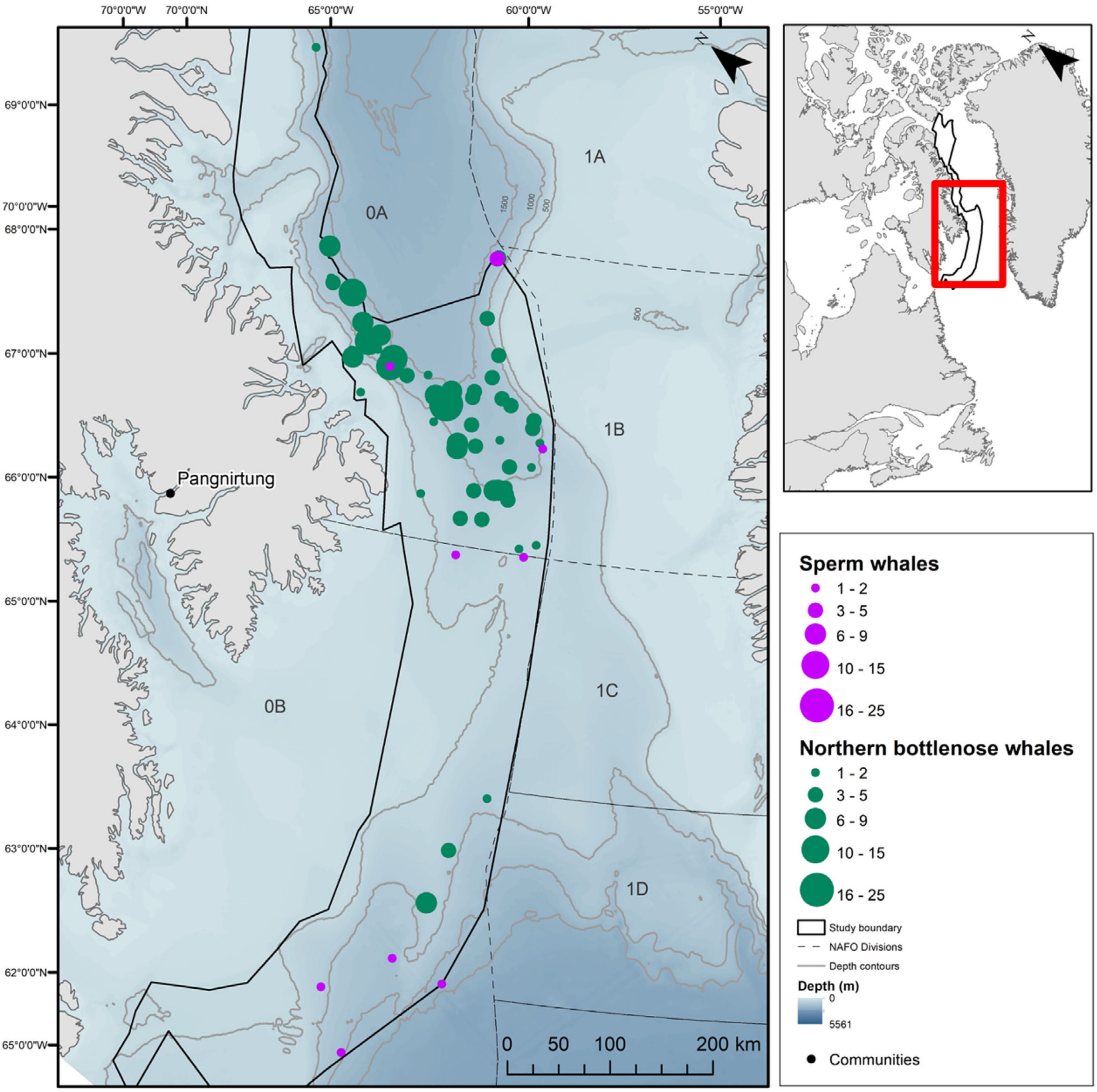

Fig. 1. Locations and counts of sperm whale and northern bottlenose whale sightings as recorded by opportunistic observations aboard RV 'Pâmiut' between 2004 and 2017. The black outline represents the boundary of the study area as delineated by the outer edges of the trawl survey tracks, and the dashed lines and labels indicate the divisions of the Northwest Atlantic Fisheries Organization (NAFO; available from www.nafo.int). The location of Baffin Bay is considered across NAFO areas 0A, 1A, and 1B, while Davis Strait is considered across areas 0B, 1C, and 1D. Country outlines available from Natural Earth (https://www.naturalearthdata.com), community data available from Natural Resources Canada (https://natural-resources.canada.ca/maps-tools-and-publications/21448), and bathymetry data available from General Bathymetric Chart of the Oceans (http://gebco.net). The contour lines delineate depths at 500 m intervals

and longitude at the time of the observation were recorded as a proxy for the location of the observed whales. A confidence level was assigned by the observer to each observation to convey the level of certainty of the species identification. In 2017, a dedicated marine mammal technician joined the survey, which allowed for the collection of additional data on cetacean behaviour. Due to non-standard observation methods, no true absence data were recorded, and information about observation effort was only available for 2017. The occurrence records were cleaned and filtered for the focal cetacean species and for those

Table 1. Date, location, and trawl set details for Fisheries and Oceans Canada bottom trawl surveys in Baffin Bay and Davis Strait (Northwest Atlantic Fisheries Organization Divisions 0A and 0B) between 1999 and 2017. Survey details only reported for years with marine mammal observations that contributed to the habitat suitability modelling (i.e. 1999 trawl information was removed)

Year	Management area(s)	Dates	Survey days	Number of trawl sets	Depth range of trawl sets (m)	Latitude range (°N)
2004	0A	Oct. 14–21	10	58	400–1500	66–72
2006	0A	Aug. 26–Sept. 5	11	89	100–800	66–72
2006	0A	Oct. 27–Nov.7	12	61	400–1500	66–71
2008	0A	Oct. 8–Nov. 4	26	161	400–1500	66–72
2010	0A	Oct. 17–Nov. 8	23	144	400–1500	66–76
2011	0B	Sept. 23–29, Oct. 9–15	13	96	100–1500	61–66
2012	0A	Sept. 29–Oct. 27	28	201	100–1500	66–76
2013	0B	Sept. 22–29, Oct. 10–14	11	88	100–1500	61–66
2014	0A and 0B	Sept. 22–Oct. 19	27	141	400–1500	61–73
2017	0A	Oct 26–Nov 8	13	78	510–1447	66–70

Table 2. Marine mammal observations (date, species, and count) for focal species recorded during Fisheries and Oceans Canada trawl surveys in Baffin Bay and Davis Strait. Observations where species were unidentifiable were not included. Only information for observations that contributed to the habitat suitability modelling are included in the table

Year	Month	Species	Total observed
2004	10	Northern bottlenose whale	23
2006	11	Northern bottlenose whale	8
2008	10	Northern bottlenose whale	44
2010	10	Northern bottlenose whale	8
2010	11	Northern bottlenose whale	16
2010	11	Sperm whale	4
2011	9	Northern bottlenose whale	3
2011	9	Sperm whale	2
2012	9	Northern bottlenose whale	4
2012	10	Northern bottlenose whale	39
2013	10	Northern bottlenose whale	4
2014	9	Northern bottlenose whale	7
2014	10	Northern bottlenose whale	56
2014	10	Sperm whale	6
2017	10	Northern bottlenose whale	72
2017	11	Northern bottlenose whale	5

where the species identification confidence level was recorded as 'certain' or 'best' (Table 2; for non-focal species records, see Table S1 in the Supplement at www.int-res.com/articles/suppl/m723p057_supp.pdf). Data were imported into ArcMap Desktop (version 10.8.2, ESRI 2022) for initial visualization.

2.3. Environmental variables

Habitat suitability was modelled based on the relationship between cetacean occurrences and environmental predictors (Dwyer et al. 2020) (Table 3). Our assumption was that the focal species would be using northern habitats to feed, and therefore environmental predictor variables that represent suitable foraging habitat were chosen. SST and chlorophyll *a* (chl *a*) data were downloaded through the PolarWatch Data Catalog (polarwatch.noaa.gov) at 0.01° and 0.04° spatial resolution, respectively, for all years with cetacean observations (i.e. 2004–2017; observations in 1999 [n = 3 whales observed] fell outside of the time frame of data availability for the environmental predictors and were not used in further analyses). SST data were downloaded at a monthly time scale for the months with observations. Chl *a* data were also downloaded at a monthly time scale; however, data were absent or spatially limited within the study area during the months of October and November, while there was good coverage in September. Due to the assumption that the prey of our deep-diving focal species will likely utilize nutrients as they sink to the bottom, a process that takes months to occur, we used data from the month of September as a proxy for productivity in October and November. SST and chl *a* data were also downloaded for September 2021 and used in a future projection analysis. Bathymetric data were downloaded from the General Bathymetric Chart of the Oceans (gebco.net) at 200 m spatial resolution.

2.4. Data formatting

All data were imported into ArcMap Desktop (version 10.8.2, ESRI 2022) and reprojected to the WGS 1984 Stereographic North Pole projection using the 'Project' or 'Project Raster' tools. The latitude and lon-

Table 3. Source information and manipulation details for environmental variables (bathymetry, slope, sea surface temperature [SST], and chlorophyll *a*), squid biomass, and spatial effort data included in habitat suitability or post hoc analysis. GEBCO: General Bathymetric Chart of the Oceans; IBCAO: International Bathymetric Chart of the Arctic Ocean; SST: sea surface temperature; MUR: Multi-scale Ultra-high Resolution; JPL: Jet Propulsion Laboratory; DFO: Fisheries and Oceans Canada

Variable	Source	Resolution	Manipulation for analysis	Analysis
Bathymetry (m)	GEBCO–IBCAO grid	200 m	Formatted to 4 km grid	Habitat suitability
Slope	ArcGIS derived	–	Derived from bathymetry data, formatted to 4 km grid	Habitat suitability
SST (°C)	PolarWatch Catalog (SST from MUR – NASA JPL)	0.01°, monthly (data extracted for year/month with whale observations)	Reprojected, mean and SD layers computed, formatted to 4 km grid	Habitat suitability
Chlorophyll *a* ($mg\ m^{-3}$)	PolarWatch Catalog (Aqua MODIS, NASA)	0.04°, monthly (data extracted for September of year with whale observation)	Reprojected, mean and SD layers computed	Habitat suitability
Squid biomass	DFO	$kg\ m^{-2}$	Transformed to $kg\ km^{-2}$, formatted to 4 km grid	Post-model comparison
Spatial survey (total length of tracklines for all surveys per grid cell)	DFO	–	Trawl locations connected and transformed into polylines, formatted to a 4 km effort grid cell with total length of unique lines summed for each cell	Post-model comparison

gitude of the cetacean observations were recalculated for the new projection with the 'Calculate Geometry' tool. The slope variable was created from the bathymetric layer with the 'Slope' tool. The mean and standard deviation (SD) of the SST and chl *a* layers were computed using the 'Cell Statistics' tool. All raster layers were transformed into a 4 by 4 km grid based on the variable with the lowest spatial resolution (i.e. chl *a* data). The study boundary was defined by the total footprint of the trawl surveys conducted in Divisions 0A and 0B during years with cetacean observations (Fig. S1). The locations (latitude and longitude) of each trawl set were joined in sequential order for each year using the 'Points to Line' tool. The R package 'concavemen' (Gombin et al. 2017, R Core Team 2022) was used to create the study boundary by connecting the outermost locations of the survey tracks into a polygon. The concavity and length threshold values were set to 2. The boundary was expanded by 4 km using the 'Buffer' tool to include 9 cetacean observations that occurred just outside of the boundary.

To test the influences of spatial bias, which have been found to impact habitat suitability results in presence-only species distribution modelling (Fiedler et al. 2018), a bias file was created to restrict the area available for selection of background points by the model. Sunrise and sunset information were obtained through the 'suncalc' package (Thieurmel & Elmarhraoui 2022) for each of the trawl locations, and those locations where trawling occurred in the daytime (i.e. between sunrise and sunset) were selected. A buffer of 5 km was applied to the daytime points to represent the spatial area available for observing whales, and the polygons were transformed into a raster file with the 'Polygon to Raster' tool.

All raster layers were clipped to the study boundary with the 'Extract by Mask' tool (Fig. S1). Finally, the raster layers were converted to ascii format with the 'Raster to ASCII' tool.

2.5. Habitat suitability analysis

Environmental rasters, cetacean occurrence data, and the bias file were imported into Maxent software (version 3.4.4, Phillips et al. 2006) for habitat suitability modelling. Maxent was created to work with presence-only data (Phillips et al. 2006, Phillips & Dudík 2008) and has been used to produce reliable distribution estimates for studies with limited occurrence records (Hernandez et al. 2006, Pearson et al. 2006, Shcheglovitova & Anderson 2013, Morales et al. 2017); presence-only data and limited occurrence records were both key factors in our study. Following the Maxent work-flow, cetacean occurrence data were reduced such that only spatially unique locations across years were included in the model (i.e. n = 9 sperm whale locations, n = 66 northern bottlenose whale locations). Further, only the mean and SD layers for SST and chl *a* data were included in the analysis, a similar approach to Maxent-based modelling as used by others (e.g. Merow et al. 2013, Gomez et al. 2017). The model components were tuned across multiple runs to avoid overfitting and to ensure the best model runs compared to those produced by the default parameters (Morales et al. 2017). The feature class combinations of linear (l), quadratic (q), product (p), and hinge (h) were tested (options chosen with guidance from Merow et al. 2013 and Low et al. 2021). Values from 0.5 to 5 were tested for the regularization multiplier to provide a spread of options around the default value (i.e. 1) (values chosen with guidance from Merow et al. 2013, Radosavljevic & Anderson 2014, Morales et al. 2017, Phillips et al. 2017). Background points from 100 to 1000, informed by the sample size and the total pixels available from environmental layers, were tested. Tuning was performed with the 'ENMevaluate' function in the 'ENMeval' package (Kass et al. 2021) in R. Akaike's information criterion corrected for small sample sizes (AICc) was used to evaluate the runs.

After tuning, Maxent models were performed for each species with (1) presence-only and random background points, and (2) presence-only and background points derived within the bias file. The replicated run type was set to 'bootstrap', the random test percentage was 25, and the number of replicates was equal to the number of observations for sperm whale runs and set to 10 for northern bottlenose whale runs. The output format was set to logistic, and the model iterations were increased to 1000 to allow for model convergence. Maxent model runs were evaluated with the area under the curve (AUC) measure. The mean AUC value for runs with and without a bias file were compared for each species at each background point level, with a 2-sample *t*-test run in the 'ggpubr' package (Kassambara 2023). Upon review of the *t*-test results, the final model was chosen for each species. The contribution of each variable to the final model was evaluated through a jackknife test.

A 'future projection' model was run as an example of forecasted habitat suitability ('Projections' in Maxent software). These runs were performed for both species with the same model settings as the best runs, and considered the same data for cetacean observations, depth, and slope as the previous runs, but the SST and chl *a* input layers were data from September 2021.

2.6. Post-model comparisons

A post-model comparison was made with the output of the best habitat suitability models and a proxy for spatial survey effort to further understand any spatial bias in habitat suitability. The total length of the survey tracklines across years used in the modelling (i.e. 2004–2017) was used as the proxy for spatial survey effort. The tracklines were mapped onto a 4 km grid and, using the 'Intercept', 'Dissolve', and 'Spatial Join' functions in ArcMap, the total length of tracklines was calculated per grid cell (Fig. S1). Values of 0 for spatial survey effort and habitat suitability were removed to avoid bias, as no standardized absences were recorded for whale observations. The relationship between habitat suitability and survey effort was tested with a beta regression given the data range (i.e. 0–1) of the dependent variable (i.e. habitat suitability); the model was run with the 'betareg' function in the 'betareg' R package (Cribari-Neto & Zeileis 2010). The distribution of the residuals was reviewed with q–q plots.

A second comparison was made with squid biomass to further understand the relationship between habitat suitability with a unique, unpublished prey data set. Data for squid caught during the same trawl surveys that recorded cetacean observations were made available from DFO. Standardized squid biomass (kg km^{-2}) was mapped onto a 4 km grid based on the start latitude and longitude for each set that caught squid (Fig. S2). If multiple biomass values were assigned to the same grid cell, the average was calculated. Biomass values were log transformed, and, similar to above, values of 0 for squid biomass and habitat suitability were removed due to a lack of standardized absences recorded for whale observations or squid biomass. As above, the relationship between habitat suitability and squid biomass was tested with a beta regression, and the residuals were reviewed with q–q plots.

3. RESULTS

Across the study area, 12 sperm whales were observed at 9 unique locations, and 282 northern bottlenose whales were observed at 66 unique locations. Both sperm whales and northern bottlenose whales were primarily observed in the southern region of the study area (70–62° N latitude) (Fig. 1). In 2017, northern bottlenose whales ($n = 64$) were observed travelling, milling (surfacing in various directions), or foraging across multiple sites (Fig. S3) (no behavioural data were recorded for sperm whales in 2017). The environmental variables used in the habitat suitability model, i.e. depth, slope, SST (mean and SD), and chl *a* (mean and SD), varied across the study area (Fig. S4).

The tuning parameters associated with the lowest AICc value for each species were: feature class l and regularization multiplier 1.5 for sperm whales, and feature class h and regularization multiplier 2.5 for northern bottlenose whales. The results of the *t*-tests indicated that the model runs which incorporated the bias file were not statistically different from the model runs without the bias file, considering both species and all levels of background points (Table S2); the non-bias file runs were used going forward.

The AUC for the best fit habitat suitability model was 0.72 for sperm whales and 0.88 for northern bottlenose whales. SST (mean) had the highest percent contribution (47%) for the best sperm whale model while chl *a* (mean) had the highest percent contribution (43%) for the best northern bottlenose whale model (Fig. 2), with varying relationships between the predicted habitat suitability and the individual environmental variables (Fig. 3). The best model indicated higher suitability for both species in the central portion of the study area north of the sill that separates Baffin Bay and Davis Strait (Fig. 4). Habitat suitability was also higher in southern areas of the study site for sperm whales, with more moderate suitability in deep-water channels that connect to the inshore. Habitat suitability was low outside of the central area for northern bottlenose whales.

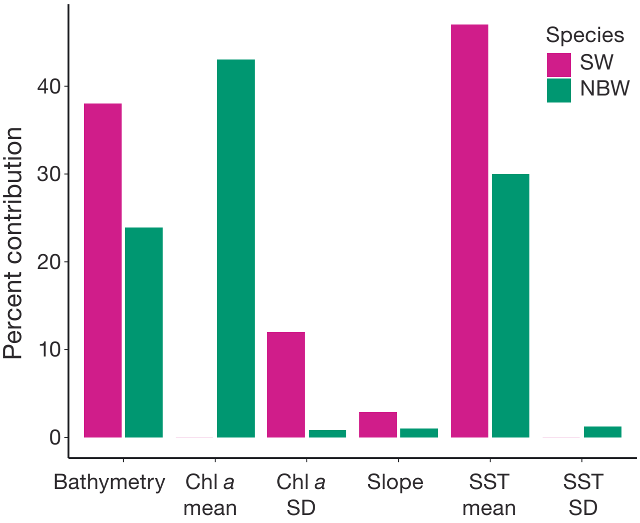

Fig. 2. Percent contribution of environmental predictor variables, bathymetry, chlorophyll *a* mean and SD (chl *a* mean, chl *a* SD), slope, and sea surface temperature mean and SD (SST mean, SST SD) to the best fit habitat suitability model for sperm whales (SW) and northern bottlenose whales (NBW) in Baffin Bay and Davis Strait. Habitat suitability models were created with Maxent software

The future projection scenario resulted in slightly higher suitability across the study site for sperm whales, including an increase in suitability in the northern part of the study site when compared to the best model output (Fig. 4). For northern bottlenose whales, the future projection scenario indicated an increase in habitat suitability in the northern area of the study region. (Fig. 4).

The total amount of tracklines combined for all survey years ranged from 0.001 km to ~25 km per grid cell within the study boundary (Fig. S1). There was a significant negative relationship between the spatial survey effort proxy and habitat suitability for sperm whales (coefficient = -6.195×10^{-6}, $p < 0.0001$, pseudo $R^2 = 0.29 \times 10^{-2}$; Fig. 5) compared with a significant positive relationship between the spatial survey effort proxy and habitat suitability for northern bottlenose whale (coefficient = 6.795×10^{-5}, $p < 0.0001$, pseudo $R^2 = 0.051$; Fig. 5). The amount of squid biomass ranged from 0.01 to 51.8 kg km^{-2} across the 4 km study boundary grid (Fig. S2). There was a significant negative linear relationship between log squid biomass and habitat suitability for sperm whales (coefficient = -0.034, $p < 0.001$, pseudo $R^2 = 0.021$) compared with a positive linear relationship between log squid biomass and habitat suitability for northern bottlenose whales (coefficient = 0.176, $p < 0.0001$, pseudo $R^2 = 0.089$; Fig. 5).

4. DISCUSSION

Opportunistic sightings have made an important contribution towards understanding the ecology of elusive whale species (Torreblanca et al. 2019) for the benefit of conservation (Pirotta & Harcourt 2021) and management (Luque et al. 2006). A recent summary of sperm whale observations recorded between 1970 and 2014 in Baffin Bay and Davis Strait revealed high numbers of whales sighted near Greenland but a lack of observations in Canadian waters (Posdaljian et al. 2022). Summaries of northern bottlenose whale sightings made between 1867 and 2010 have emphasized a higher number of whales sighted at lower latitudes, with only some recorded in the southern Davis Strait/Northern Labrador Sea and Baffin Bay (Reeves et al. 1993, COSEWIC 2011).

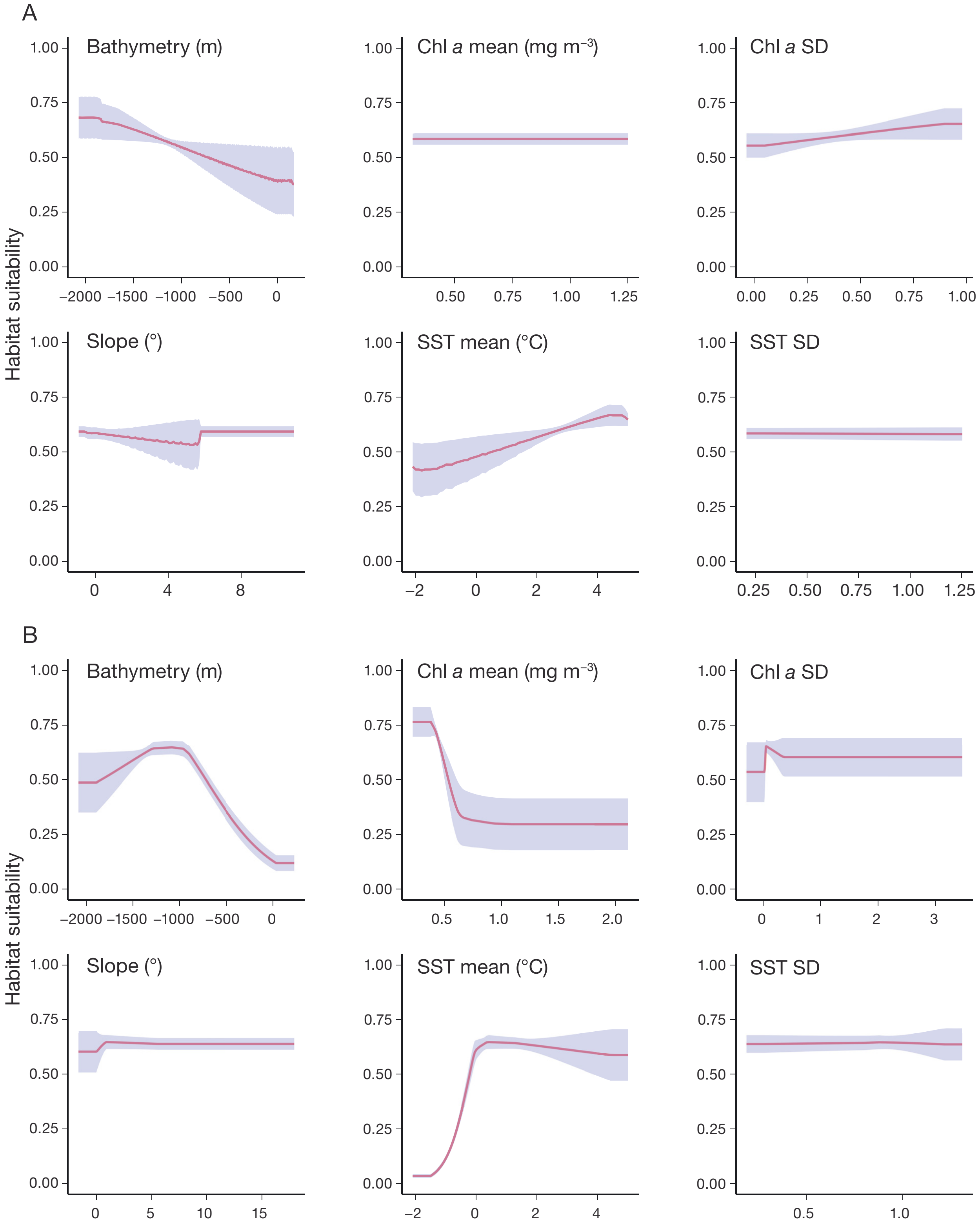

Fig. 3. Response curves depicting the relationship between predicted habitat suitability and environmental variables bathymetry (bathy), chlorophyll *a* mean and SD (chl *a* mean, chl *a* SD), slope, and sea surface temperature mean and SD (SST mean, SST SD) for the best models for (A) sperm whales and (B) northern bottlenose whales. The plots show the mean response from all model replicates (red line) ±1 SD (shading)

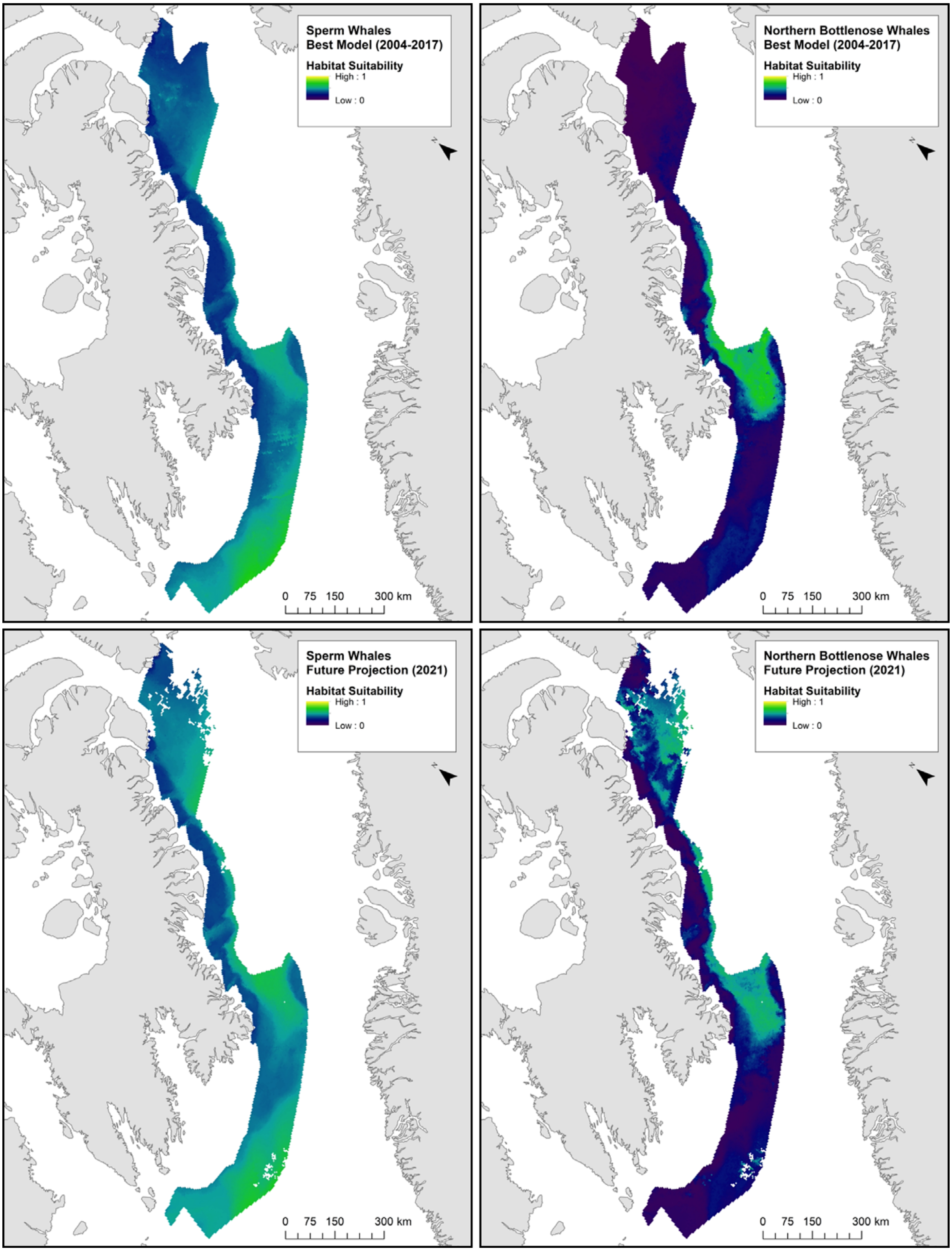

Fig. 4. Best model run of the Maxent habitat suitability model for sperm whales and northern bottlenose whales across the study area. Models were derived from whale observations between 2004 and 2017, and environmental predictor data corresponding to the dates of the whale observations. Future habitat suitability projection for sperm whales and northern bottlenose whales were modelled in Maxent with environmental data from 2021

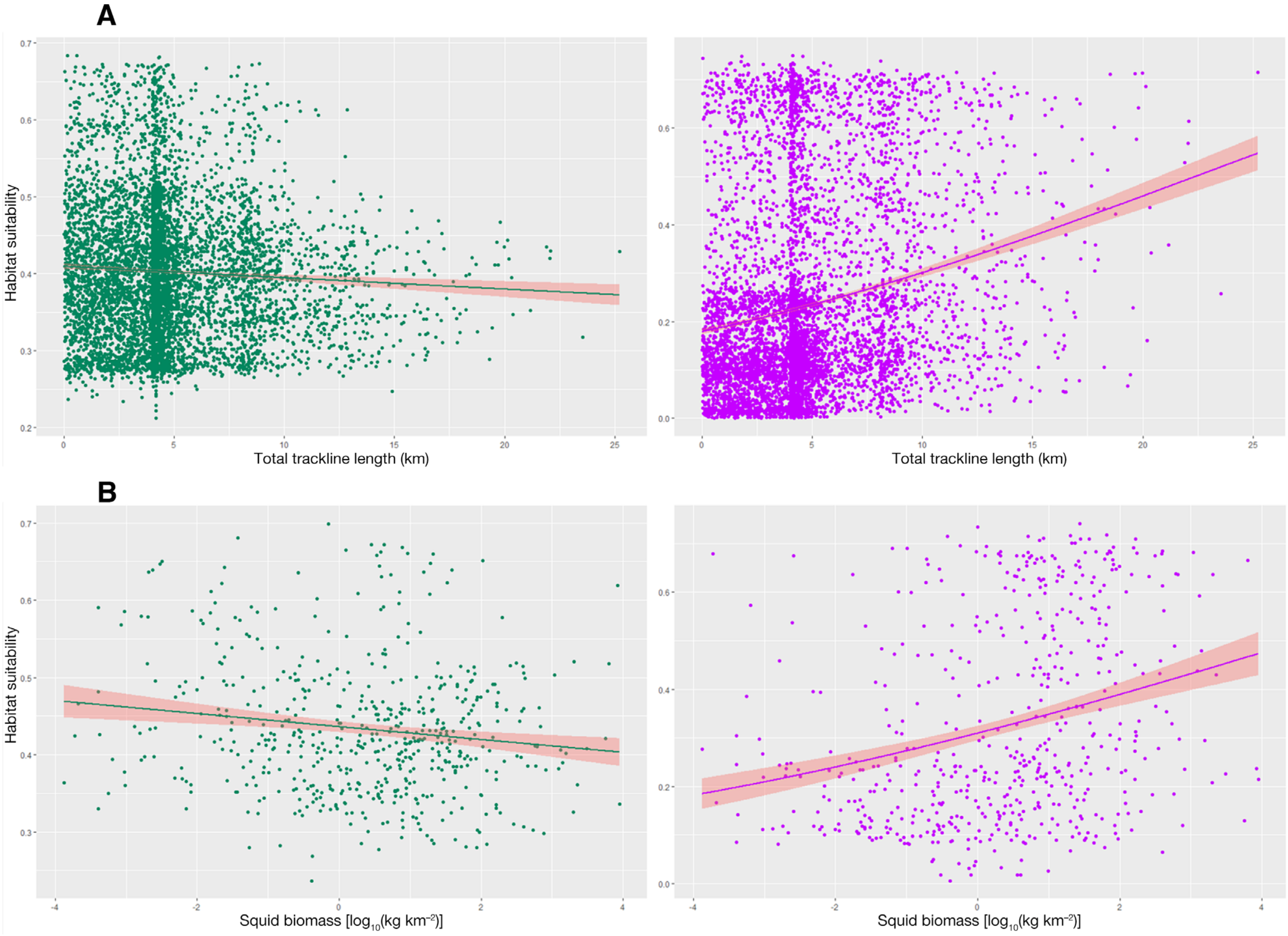

Fig. 5. Post-model comparison of the best habitat suitability model for sperm whales (green) and for northern bottlenose whales (purple) with (A) total trackline length as a proxy for spatial survey effort and (B) squid biomass. The trackline length was derived from straight-line paths drawn between trawl locations for each year of a survey with cetacean observations. The total length of the lines was summed per 4 km grid cell. Squid were sampled at specific locations during the bottom trawl surveys (2004–2017) and reformatted to match the 4 km grid of the habitat suitability model. The solid lines represent the relationship between the variables derived from the beta regression models and red shading represents 95 % confidence intervals

The observational data presented in this study fills spatial gaps in presence locations for both species, increasing our understanding of their whereabouts in Canadian Arctic waters. There should be a continued monitoring effort for these species in high-latitude environments, and such efforts could extend beyond opportunistic sightings. For example, systematic line-transect (aerial or at-sea) surveys have been used to study spatial–temporal patterns of other cetaceans in other areas of Canada (Lawson & Gosselin 2009, Doniol-Valcroze et al. 2020, Wright et al. 2021), and dedicated aerial cetacean surveys have been successful for recording observations of sperm whales and northern bottlenose whales in West Greenland (Hansen et al. 2018).

Our modelling results showed suitable habitat for sperm whale in Baffin Bay and Davis Strait. The results for habitat suitability in Davis Strait agreed with past modelling efforts by others for sperm whales in the same area (Mannocci et al. 2017). These habitat suitability results together with recently published global density estimates (~0.012 density km^{-2} in Baffin Bay; Whitehead & Shin 2022) and a recently reported high-latitude sighting in Eclipse Sound (Lefort et al. 2022) signal that there could be more sperm whales in Baffin Bay and Davis Strait than previously thought. Additionally, genetic analysis of sperm whale biopsy samples from Baffin Bay and Davis Strait obtained during the 2017 survey indicated that only males were present (DFO unpubl. data; sex data were not available for the other survey years, i.e. 2004–2014). This sex information is important for further characterizing the use of Baffin Bay and Davis Strait by sperm whales, and is consistent with patterns of sex segregation at high latitudes for this species discussed by others (e.g. Whitehead 2003). The best fit model for sperm whales estimated SST (mean) to be the largest contributor to habitat suitability, followed by bathymetry. These results agreed with others who suggested SST as a good predictor of habitat suitability (Correia et al. 2021), as it relates to the limits of the whales' thermal tolerance (Peters et al. 2022). Conversely, some reported that slope had a higher contribution to sperm whale habitat suitability models (Chavez-Rosales et al. 2019), along with variables representing deep-water layers and fine-scale features such as frontal zones, seamounts, and fractal areas (Skov et al. 2008, Mannocci et al. 2017, Virgili et al. 2022). It is likely that sperm whales are associated with depth, slope, and deep-water features due to foraging strategy. Our best model indicated that bathymetry was the second highest contributor to habitat suitability; however, detailed physical oceanographic data at the scale needed to improve habitat suitability models are lacking for Baffin Bay and Davis Strait. Lastly, our model showed that deep-water channels adjacent to Baffin Island had moderate suitability, and we suggest they could be used as a route to reach inshore waters, where they have been observed in recent years (Lefort et al. 2022) or be attractive as a physical mechanism for concentrating prey.

Our data showed many northern bottlenose whale observations in the study area. In contrast to sperm whales, we suspect that northern bottlenose whales observed in this study are a mix of both sexes and ages, based on (1) the social structure and patterns observed in the southern Scotian Shelf population (Whitehead & Hooker 2012), (2) the delineation of a separate subpopulation of northern bottlenose whales in this region (i.e. the Davis Strait–Baffin Bay–Labrador Sea subpopulation; COSEWIC 2011), and (3) observations of young northern bottlenose whales with adults in the study area (Johnson et al. 2021). More data are needed to fully understand the spatial–temporal behaviour and habitat use patterns of the subpopulation of northern bottlenose whales in Baffin Bay and Davis Strait. The outcome of our habitat suitability model suggested that the mid-latitudinal section of the study area (~67° latitude) at south Baffin Bay had the highest habitat suitability for northern bottlenose whales. These findings contrast past modelling efforts for northern bottlenose whales which suggested that northern Davis Strait, adjacent to the southern boundary of our study area, was highly suitable habitat (Gomez et al. 2017). We suggest that this contrast could be evidence for differing habitat preferences for the Davis Strait–Baffin Bay–Labrador Sea subpopulation compared with the southern subpopulation, and advise additional surveying, genetic sampling, and tracking of individuals from both populations to further investigate this hypothesis. The best fit model for northern bottlenose whales found that chl *a* (mean) had the highest contribution to the model outcome, followed by SST (mean) and bathymetry. As habitat suitability appeared to be higher in areas of low chlorophyll, we suggest that chlorophyll may not be a good indicator of foraging locations as hypothesized. While our results agreed with some studies which found that SST and depth contributed to the best model for northern bottlenose whales (Gomez et al. 2017, Storrie et al. 2018), slope was identified as a top contributor by others (Storrie et al. 2018). Slope did not have a high contribution to our model output as hypothesized, possibly because this area has less-steep slopes than the canyon habitats with which more southern populations have been associated (Reeves et al. 1993, COSEWIC 2011).

We presumed that sperm and northern bottlenose whales would be primarily foraging while in our study site. Their primary prey are deep-sea squid, which are distributed widely across Baffin Bay and Davis Strait (Gardiner & Dick 2010). While nomadic male sperm whales do feed on squid at high latitudes, they also consume a variety of fish species (Evans 1997, Teloni et al. 2008), suggesting that impacts of prey distribution in Baffin Bay and Davis Strait on their spatial–temporal behaviour may be more complex. This diversity in their diet could be a further explanation for the negative relationship seen between habitat suitability and squid biomass for sperm whales. Conversely, northern bottlenose whales have a restricted niche due to a preference for the genus *Gonatus* (Whitehead 2003), and therefore may be more impacted by any future spatial–temporal fluctuations in prey distribution compared to species with a wider foraging niche. A reliance on *Gonatus* spp. could also be an explanatory factor for the positive relationship reported between habitat suitability and squid biomass for northern bottlenose whales. The behavioural data collected in 2017 indicated fewer northern bottlenose whales observed foraging in the study area compared with other observed behaviours (Fig. S3). Given the limited behavioural data together with the understanding that the distributions of cephalopods are generally expected to expand in Arctic waters (Golikov et al. 2013), we emphasize that future research efforts should focus on increasing behavioural observations and/or employing methods such as tagging aimed at describing and understanding the degree of foraging for sperm whales and northern bottlenose whales in this Arctic habitat.

While we emphasize the value of the observational data presented in our study, especially in the face of limited Arctic data for these species, there were some limitations to our study:

(1) Data collection and sample size. There was a lack of true absence data and sightings effort information (apart from 2017 observations), which limited the statistical analysis methods available for habitat modelling. While we addressed sightings effort by testing the relationship between habitat suitability and a proxy for spatial survey effort, by standardizing the methodology and data collection during the survey, including the systematic collection of absence data and measures of observation effort, the habitat suitability model could be improved. Combining systematic and opportunistic data collection methods (Muir et al. 2015) could also improve habitat analyses. Further, we recognize that there were a limited number of presence points available for the sperm whale modelling, and while we are confident in the ability of Maxent to produce viable suitability models for small sample sizes, we suggest an increase in data collection to improve confidence in future habitat models.

(2) Spatial and other biases. As stated earlier, presence-only data are inherently accompanied by spatial bias due to the lack of true absence points. We accounted for this bias in our analysis by tuning all model runs, selecting the number of background points relative to the number of observations (i.e. a reduction compared to a standard 10000 background points in other studies; Phillips & Dudík 2008), and restricting the study site to the footprint of the survey. We also performed model runs with a bias file that restricted the selection of background points to only those spatial areas with daytime trawling, and compared the results to our original model runs. The results of our bias-file vs. non-bias file runs were not statistically different, which increased our confidence in the final habitat suitability model; however, there may still be spatial bias that we were unable address due to the nature of the data, as was seen in the post-model comparison with areas of higher effort corresponding to areas of higher habitat suitability for northern bottlenose whales. Further, unaccounted-for bias is likely present in the results due to detection bias and occupancy bias (Yackulic et al. 2013, Fiedler et al. 2018). We emphasize that further research is needed to improve the predicted habitat suitability of these species in Arctic waters; until then, managers should act within the precautionary approach for conservation and management actions regarding these species in this environment.

(3) Addressing uncertainty. Uncertainty in predictions is attributed to many factors, for example the number of observations, the type of environmental inputs, and the model type (Kaky et al. 2020). However, standardized methods for evaluating uncertainty in species distribution modelling are not well established (Leroy 2022). We have been transparent in the limitations of our study related to the data and biases (see above), both of which are associated with prediction uncertainty. Additionally, using ensemble techniques has been identified as a method to address uncertainty in species distribution model algorithms (Abrahms et al. 2019, Kaky et al. 2020, Peters et al. 2022), but these methods are outside of the scope of this study and require a more robust data set than the one presented in this study.

(4) Selection of environmental predictor variables. Virgili et al. (2022) indicated that surface variables may not be ideal predictors for depth-associated species modelling. However, there is a lack of reliable sub-surface data within our study area. Oceanographic data collection, especially for deep-water variables, could be improved in this area with the use of animal-borne sensors on cetaceans themselves (Laidre & Heide-Jørgensen 2007). As well, while Storrie et al. (2018) found that sea ice was a significant predictor for sperm and northern bottlenose whale habitat suitability modelling, we did not include it as a variable, since our observation dates were limited to ice-free times. As sea-ice dynamics, including concentration and timing of breakup/formation, are changing in Baffin Bay (Laidre et al. 2015, Ballinger et al. 2022), we recommend increasing survey effort across the year and including ice as a variable in future analyses, as it may relate to the timing of sperm and northern bottlenose whale presence (as suggested by Posdaljian et al. 2022).

(5) Vessel attraction. There may have been a bias in our analysis due to whales being attracted to the vessel during gear hauling, particularly curious males. To account for this, we reported the relationship between habitat suitability and our proxy for spatial survey effort. We found a positive relationship for northern bottlenose whales, which agreed with the observations of others of northern bottlenose whales interacting with vessels (Johnson et al. 2021); however, we found a negative relationship for sperm whales, which may have been related to the small

sample size in our study. Remote measures such as acoustic monitoring or telemetry could be used to improve presence data in the area in the absence of active fishing.

While our models indicated suitable habitat for sperm and northern bottlenose whales in Baffin Bay and Davis Strait, we highlight that there are activities that could impact the quality of that habitat for these species. There has been an expansion in marine vessel traffic in Baffin Bay in recent years (Dawson et al. 2018) that could contribute to increased ship strikes and increased underwater noise, which can impair and alter the behaviour of whales (Miller et al. 2015, Halliday et al. 2022). Further, there has been an increase in fishing activity in Nunavut, including in offshore Baffin Bay (Government of Nunavut 2016), which will likely lead to an increase in interactions with the fishing industry. Increased depredation and discards could impact the whales' feeding ecology and increase the risk of entanglement (Feyrer et al. 2021, Johnson et al. 2021). Interactions between sperm and northern bottlenose whales and fishing vessels have already been observed in Baffin Bay (Johnson et al. 2021) and in other parts of the Northwest Atlantic (Oyarbide et al. 2023). As a result of our study, having an increased understanding of the habitat suitability for these species in Baffin Bay and Davis Strait could be helpful in identifying areas where, for example, depredation mitigation is required.

In conclusion, our study has contributed new information to help inform our understanding of the spatial–temporal presence of and habitat suitability for sperm and northern bottlenose whales in Baffin Bay and Davis Strait. Research is still needed to describe fine-scale behaviours of these species in Canadian Arctic waters, some of which has been accomplished by recent studies using satellite telemetry (Lefort et al. 2022) and acoustic monitoring methodologies (Posdaljian et al. 2022). Collaborating with local Inuit communities to record visual or acoustic presence of the whales would also provide information on their Arctic presence. While sperm whales are not considered at risk in Canada, the Davis Strait–Baffin Bay–Labrador Sea population of northern bottlenose whale has been classified as a species of 'special concern' by the Committee on the Status of Endangered Wildlife in Canada due to uncertain population size, reduced numbers as a result of historic whaling, and population threats (COSEWIC 2011). As such, this population is under consideration for listing under Schedule 1 of the Species at Risk Act. By aiming to understand spatial distributions of northern bottlenose whales in Baffin Bay and Davis Strait, our research helps to advance northern bottlenose whale ecology, a core part of the listing process. Further, the areas of suitable habitat identified from this work together with the collection of additional data to address spatial biases, contributes towards advancing their conservation status through further identification and eventual protection of key habitat.

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