SUPPORTING INFORMATION

Case Study: Bowhead whale data

Bowhead whale distribution data previously collected, processed and utilised within other studies (Chambault et al., 2018; Yurkowski et al., 2018; Fortune et al., 2020a; Matthews et al., 2020; Halliday et al., 2022) were provided for the purpose of this case study. Briefly, between 2001 and 2016, 156 bowhead whales from the Eastern Canada-Western Greenland population were remotely tagged with satellite-linked Argos tags (Wildlife Computers Inc, Redmond, Washington, USA) in Disko Bay, West Greenland (n = 98 whales; see details in Chambault et al., 2018) and in Foxe Basin, Cumberland Sound, and Admiralty Inlet, Nunavut, Canada (n = 58; see details (including permitting information) in Yurkowski et al., 2018, Fortune et al., 2020a and Matthews et al., 2020). The telemetry point data from tagged bowhead whales were modelled to provide one point per tagged whale per day using two methods (see Halliday et al., 2022). Data from whales tagged in West Greenland were processed using a continuous time multivariate non-Gaussian state space model (see Albertsen et al., 2015 and Chambault et al., 2018), whereas data from whales tagged in Nunavut were processed using a hierarchical discrete-time correlated random walk state-space model (see Yurkowski et al., 2019). The modelled daily points (as per Halliday et al. (2022) were then utilised within the present study.

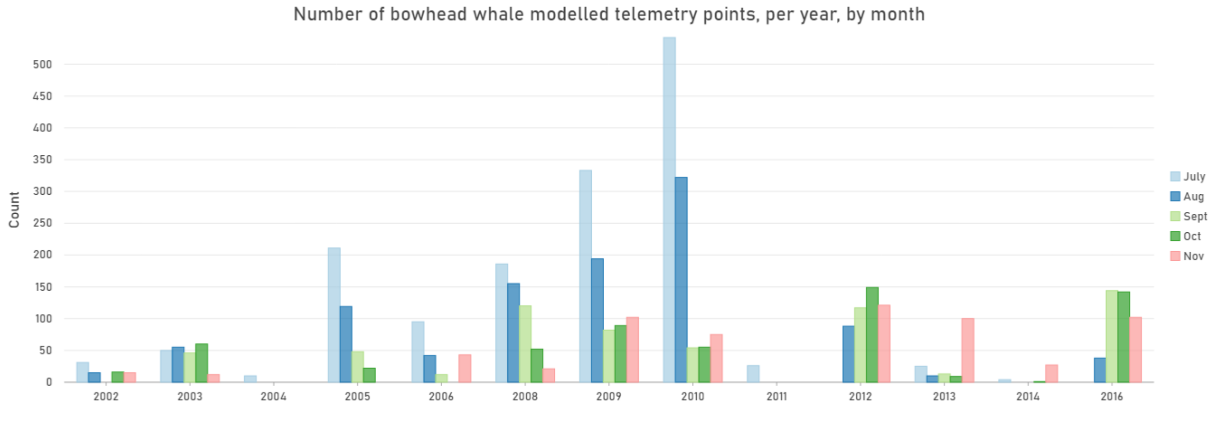

Figure S1. *The temporal coverage of modelled telemetry points (one per tagged whale per day) that formed the input bowhead whale case study dataset. Counts are separated per year, and per month.*

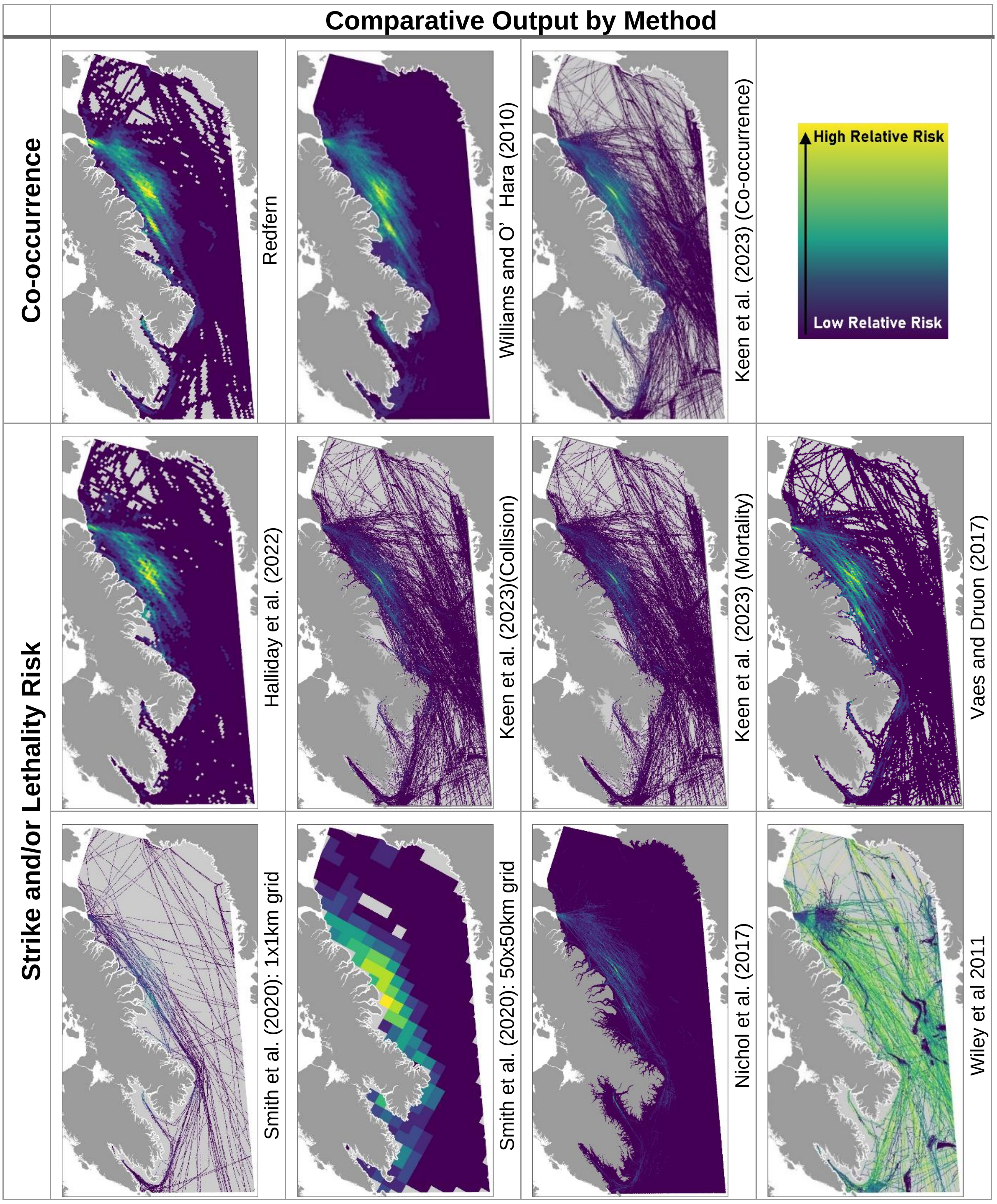

***Figure S2** Output maps of predicted vessel related-risk, mapped alongside one another to allow for comparison of the high (yellow) and low risk (navy) areas predicted.*

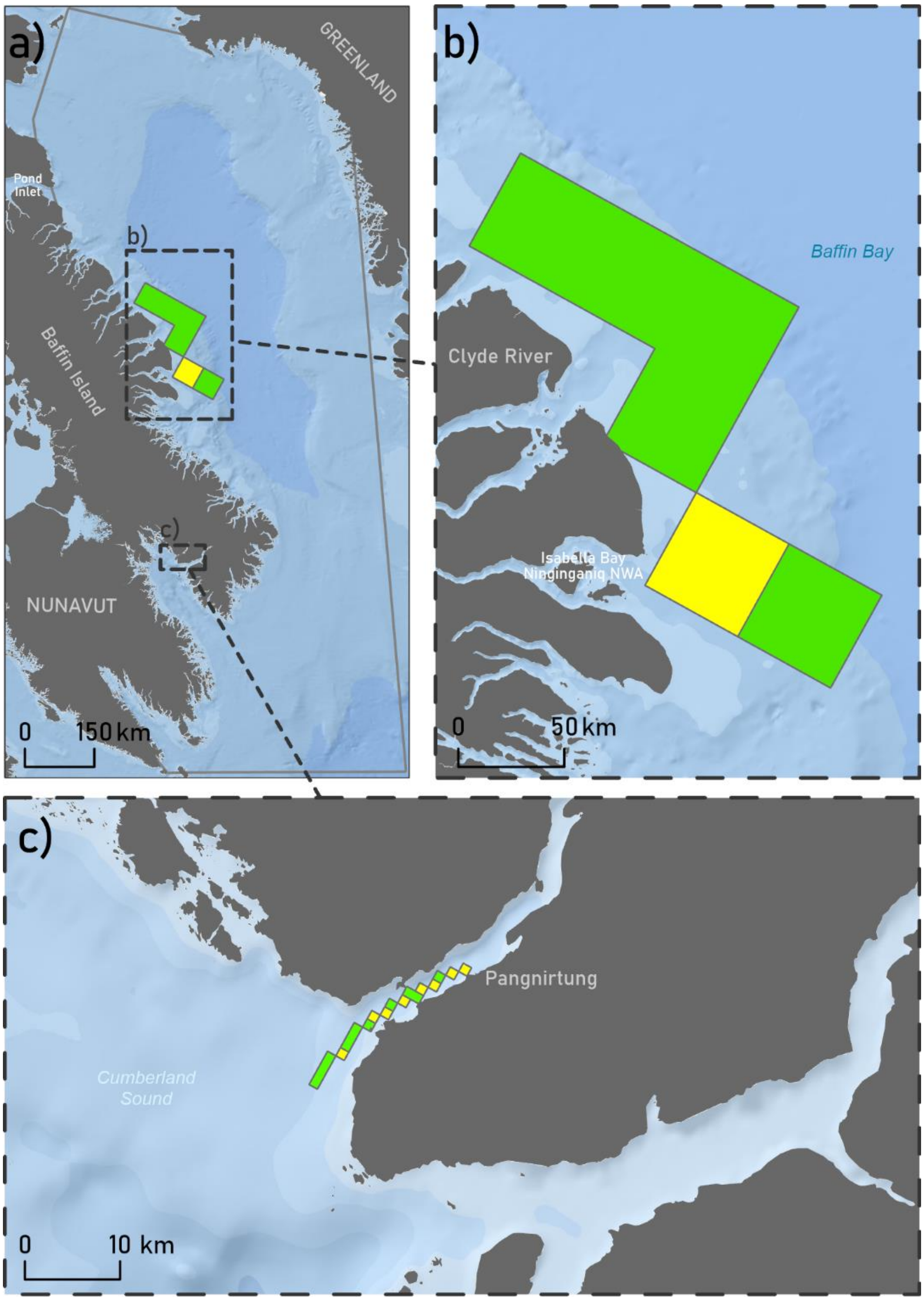

Figure S3 *a) Map to show the high-risk areas (top 2 (of 10) classes defined by Natural Breaks (Jenks)), predicted by Method B6: Smith et al. (2020), at different grid scales b) 50x50 km^2 and c) at 1x1 km^2. Lime green indicates the 9th risk class, and yellow the 10th (highest) risk class.*

Workflows

The following table provides a summary workflow for each replicated methodology within the main manuscript. The workflows are designed to support a reproduction of each analysis should you like to do this with your own data. These workflows should be followed in conjunction with the original method described in each respective publication. Please contact the respective authors of each method if you have any questions about that approach.

Approximate time taken for analysis (including data preparation) are shared to provide an indication of the time potentially required to replicate each method. However, these estimates should be interpreted with caution as time taken to replicate will vary largely with familiarity with each respective software, size of input datasets, size of study area, and computing power.

Table S1 *Summary workflow for each replicated method to map vessel risk*

Method	**Method A1: Co-occurrence (Redfern et al., 2020)**
Summary	Redfern et al. (2020) estimate risk of ship traffic to fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*) and blue whales off California, USA, using AIS data and predicted whale distributions to predict co-occurrence. An eight-year AIS dataset was used to summarise the cumulative distance travelled by ship traffic each year, and the average distance travelled per day, in a 10x10 km^2 grid. Only ships over 80m in length and travelling at a speed over ground of ≥2.5 knots were included in the analysis. Redfern et al. (2020) multiply the predicted number of whales per grid cell with the mean daily kilometres of ship traffic per grid cell to present a metric of vessel risk.
DOI	https://doi.org/10.3389/fmars.2019.00793
Software used to replicate method	ArcGIS Pro 2.9.2
Approximate time taken	~Days
Workflow	• Create a 10x10km^2 Fishnet Grid, and clip it to the study area (*Create Fishnet* and *Pairwise Clip*) • Subset and extract AIS data to only include ships >80m in length, and travelling at over 2.5 knots (*Export Features*) • Reconstruct the subset of AIS point data into track lines, with tracks being matched based on MMSI, specifying to split tracks if points are >1 hr apart in time (*Reconstruct Tracks*). • Clip tracks into short segments that each fall within the respective 10x10 km^2 grid cell, to allow for summary of traffic within each grid cell (*Intersect*) • Calculate the length, in km, of each track segment, and record this in a new field in the Attribute Table (*Calculate Geometry*) • Summarise all track segments within each 10x10 km^2 grid cell, also generating the total sum of all track lengths travelling through each grid cell, in km (*Spatial Join*) • Calculate the average km transited through each grid cell per day, by dividing the summed total by the total number of days represented within the AIS data (*Calculate Field*). • Convert the bowhead whale kernel density into a raster of 10x10 km^2 (*Raster to Point*) then *Spatial Join* to 10 x 10km grid, then (*Feature to Raster*) • Convert the summarised 10x10 km^2 grid of average daily vessel length transits to a raster (*Feature to Raster*)

	• Multiply the two raster layers together, to generate a measure of co-occurrence, as the number of whales multiplied by the km/day travelled by ships through that grid cell (*Times*)
Method	**Method A2: Co-occurrence (Williams and O'Hara, 2010)**
Summary	Williams and O'Hara (2010) identify areas of potential vessel risk to fin, humpback and killer whales (*Orcinus orca*) in the coastal waters off British Columbia (BC), Canada, by demonstrating areas of overlap between shipping activity and areas used by their species of interest. The authors use a one-year AIS dataset, including only ships >20m, or ships engaged in towing or pushing anything more than 20m (other than fishing gear) with a combined length of >45m. Yachts <30m and fishing vessels <24m and 150 tonnes were excluded. The approach only included moving ships, defined as 'showing movement between grid cells'. As the grid size used was 5x5 km^2, to replicate this for the present study we only include vessels travelling at speed over ground of >2.7 knots (i.e. >5 km/hr). The total number of uniquely identifiable vessels per grid cell per hour are used as an index of vessel intensity. Vessel intensity was then multiplied with a whale density estimate grid, using an 'Inverse Distance Weighting' function, which estimates individual grid cell values by averaging the values of neighbouring cells. This gave a metric of predicted co-occurrence per grid cell, to estimate vessel risk for each species.
DOI	https://doi.org/10.47536/jcrm.v11i1.624
Software used to replicate method	ArcGIS Pro 2.9.2
Approximate time taken	~Days

Workflow	• Subset and extract AIS data to only include ships >20m in length, only yachts >30m, only fishing vessels >24m and only fishing vessels >150 tonnes. Further subset the data to only to include vessels travelling >2.7 knots (the methodology requires there to be movement between each 5x5 km^2 grid cell (>5 km hr^{-1})) (*Export Features*)
	• Subset and then summarise the AIS data to only include one uniquely identifiable ship observation (MMSI) per hour per cell in a 5x5 km^2 grid.
	    ○ Convert points to tracks for each unique MMSI, with tracks specified to be split every 1 hr (*Reconstruct Tracks*)
	    ○ Clip the 1 hr tracks into short segments that each fall within the respective 5 x 5 km grid cell (*Intersect*)
	    ○ Dissolve the short track segment into a 5x5 km^2 grid (by Fishnet Grid ID and MMSI) (*Dissolve*)
	    ○ Summarise the number of unique MMSIs within each grid cell (*Summary Statistics*), then join this information to an empty 5x5 km^2 fishnet grid covering the study area (Baffin-Davis) (*Add Join*)
	• Use inverse distance weighting function to process the vessel density grid
	    ○ Convert the summarised 5x5 km^2 of number of unique MMSIs per grid cell, to point data, with one point representing number of unique MMSIs per grid cell (*Feature to Point*)
	    ○ Interpolate surrounding neighbour values of number of unique MMSIs per grid cell, by averaging values of neighbours in the surrounding area (*Inverse Distance Weighting*)
	• Process the bowhead whale data
	    ○ Convert the bowhead whale modelled sightings point data into a raster of grid cell size of 2x2 nm^2 (equivalent to 3.7x3.7 km^2) (as per Williams and O'Hara, 2010), summarising the number of sightings points within each grid cell (note, we use modelled daily point data of bowhead whale sightings, rather than predicted whale density surface, as used in Williams and O'Hara (2010)) (*Feature to Raster*)

	○ Convert the summarised 2x2 nm^2 grid of density of bowhead whale sightings, to point data, with one point representing number of modelled bowhead whale sightings per cell for each grid cell (*Feature to Point*) ○ Interpolate surrounding neighbour values of number of bowhead whale sightings per grid cell, by averaging values of neighbours in the surrounding area (*Inverse Distance Weighting*) • Multiply the two inverse distance weighting raster layers (vessel density, plus bowhead density) together, to generate a measure of co-occurrence, as the number of whales multiplied by the number of unique vessels through that grid cell (*Times*).

Method	**Method A3, B1 and B2: Co-occurrence, collision and mortality rate (Keen et al., 2023)**
Summary	***Method A3: Keen et al. (2023)*** Keen et al. (2023) use AIS data from all of 2019 within an area covering the central waters of the Gitga'at First Nation, in the lower Kitimat Fjord System of mainland BC, Canada, to predict vessel-whale co-occurrence for humpback and fin whales. They first develop a grid of predictions of the number of times a vessel and a whale occur in the same 1x1 km^2 cell (i.e. co-occurrence), using 1x1 km^2 grids of vessel traffic and whale density. This approach has R code available to aid replication, available as the 'shipstrike' package in R (Keen, 2023). ***Method B1 (Collision) and B2 (Mortality): Keen et al. 2023*** Keen et al. (2023) build upon their co-occurrence prediction grids described in Method A3, by incorporating avoidance rates (by both vessels, and/or whales), and data on whale dive depths distribution (gained from humpback whale telemetry data), to infer the time a whale might spend in the 'strike-zone' (i.e. 1 or 1.5 times the draught of the vessel). These methods are used to predict collision (Method B1) and mortality rate (Method B2) for only ships >180m long. For collision rate, the number of predicted strike zone events per grid cell were scaled according to an avoidance metric, which is based on vessel speed (Method B1). For mortality rate, this is further scaled by the probability that a strike at a certain speed would result in the death of a whale (using the probability of lethality curve described in Kelley et al., 2021). Keen et al. (2023) input fin and humpback dimension and movement parameters as part of the data input to inform strike-zone. To replicate the method and make it relevant to our case study species, we input the equivalent data parameters relevant for bowhead whales, which were gained from relevant literature (Finley, 2001; Simon et al., 2009; Lubetkin et al., 2012; Heide-Jørgensen et al., 2012, 2013; Fortune et al., 2020b; Hendricks et al., 2021).
DOI	https://doi.org/10.3354/esr01244
Relevant Links	• Supplementary Material https://www.int-res.com/articles/suppl/n051p031_supp.pdf • Github code to support ○ https://ericmkeen.github.io/shipstrike/#content ○ https://github.com/ericmkeen/shipstrike
Software used to replicate method	R
Approximate time taken	~ Month *Note: the high volume of AIS data to process (due to long study window (July – November) and relatively large spatial coverage)) meant processing time in R for some parts of the process was substantial (weeks) and computing power required was high. Lower volumes of input AIS data would likely result in quicker times to follow and replicate this methodology.*
Workflow	Please see https://doi.org/10.5281/zenodo.13769540 for adapted R code

Method	Method B3: Risk of lethal strike (Nichol et al., 2017)
Summary	Nichol et al. (2017) estimate the relative risk of ship strikes to humpback and fin whales off the west coast of Vancouver Island, BC, Canada. The authors use a 1-year AIS dataset, with data binned into ship speed categories (e.g., 5-10 knots), excluding vessel speeds <5 knot or >40 knots, and then grid this across a 1x1 km^2 grid to represent vessel density. To predict the relative probability of ship strike, Nichol et al. (2017) estimated the likelihood of whales and vessels occupying the same grid cell, and then advance this by also considering the risk that a strike would be lethal given the average speed of vessels travelling through each grid cell, using the probability of lethality curve described by Conn and Silber (2013). The probability of encounter within each grid cell, and the probability of lethality within each grid cell, are then multiplied together to gain the relative risk of lethal collision.
DOI	https://doi.org/10.3354/esr00813
Software used to replicate method	ArcGIS Pro 2.9.2
Approximate time taken	~1 week

Workflow	• Subset AIS data to only include following vessel types (*Export Features*);
	  ○ Cargo (container, bulk), tanker, passenger (cruise ships, ferries), tug, towing, fishing, pleasure vessels
	• Subset AIS data into the following categories based on ship speed (*Export Features*);
	  ○ 5-10 knots
	  ○ 10-15 knots
	  ○ 15-20 knots
	  ○ >20-40 knots
	• Group AIS data into mean average daily ship-hours (ship-h) in 1x1 km^2 grid (averaged over the whole year); Subset and then summarise the AIS data to only include one uniquely identifiable ship observation (MMSI) per hour per cell in a grid of 1x1 km^2 cells.
	  ○ Convert points to tracks for each unique MMSI (*Reconstruct Tracks*)
	  ○ Clip the tracks into short segments that each fall within the respective 1x1 km^2 grid cell (*Intersect*)
	  ○ Dissolve the short track segment 1x1 km^2 grid (by Fishnet Grid ID and MMSI) (*Dissolve*)
	  ○ Summarise the number of unique MMSIs within each 1x1 km^2 grid cell (*Summary Statistics*), then join this information to an empty 1x1 km^2 fishnet grid covering the study area (*Add Join*)
	  ○ Then standardise the layer by dividing the number of unique MMSIs per grid cell by the number of hours in the study period (*Calculate Field*)
	• For each density/speed vessel layer, multiply each grid cell value by the median speed relative to its vessel speed class (7.5, 12.5, 17.5 or 23). Then standardise each layer by dividing by the highest value within each respective layer (*Calculate Field*).
	• Calculating P(*Lethal*)
	  ○ The standardised speed for each respective speed class is then input into the Conn and Silber (2013) Probability of Lethality curve, which follows the standard logistic regression equation where -1.91 is the intercept estimate and 0.22 is the speed estimate from the coefficients in the PLETH curve:
	
	$$P_{lethal} = \frac{1}{1 + exp^{-(\beta_0 + \beta_1 speed)}}$$

	○ P(*Lethal*) = 1 / (1 + exp (- (– 1.91 + (0.22 * 'standardised speed for each vessel class')))) ○ In Python: 1/(1+math.exp(-(-1.91+(!standardised speed for each vessel class! * 0.22)))). (*Calculate Field*) ○ Add P(*Lethal*) for each speed class together to get a total P(Lethal) per grid cell (*Calculate Field*) ○ Convert the P(*Lethal*) 1x1 km^2 grids to a raster (*Feature to Raster*) Calculating P_{rel}(*Whale*) • Estimate bowhead density via kernel density as number of individuals per 25x25km^2 grid then split this into 1x1km^2 grid • Standardise the bowhead whale density values to determine the relative probability of observing a whale within each grid cell over the total study area (i.e. divide all grid cell values by the highest density value of whales per grid cell) (*Calculate Field*) • Convert the P_{rel}(*Whale*) 1x1km^{2}standardised grid to a raster (*Feature to Raster*) Calculating P_{rel}(*Vessel*) • Calculate Vi = the annual average of daily ships per hr (only including vessels over 5 knots) ○ Average of MMSIperhr (*Calculate Field*) • Standardise the vessel traffic intensity values to determine the relative probability of observing a ship within each grid cell over the total study area (i.e. divide all grid cell values by the highest density value of ships per hr per grid cell) (*Calculate Field*) • Convert the P_{rel}(*Vessel*) 1x1km^2 standardised grid to a raster (*Feature to Raster*) Calculating P_{rel}(*Encounter*) • Multiply the two raster layers together (P_{rel}(*Vessel*) x P_{rel}(*Whale*)), to generate a measure of relative probability of encounter (*Times*) • Standardise the relative probability of encounter values to determine the relative probability of encounter within each grid cell over the total study area (i.e. divide all grid cell values by the highest relative probability of encounter per grid cell) (*Calculate Field*) • Multiply the P_{rel}(*Encounter*) raster by the P(*Lethal*) raster, to get risk of lethal strike as function of ship speed (*Times*)

Method	**Method B4: Vessel Strike Risk, Vaes and Druon (2013)**
Summary	Vaes and Druon (2013) use AIS data from three months in 2009 to predict daily and monthly collision risk for fin whales in the western Mediterranean Sea. Here, collision risk is considered the number of potential collisions with whales for a given grid cell, per day. Their calculations build on work presented in Tregenza et al. (2000), and take into account the width of the vessel, whale length, whale density and habitat preferences, whale time at surface, and probability of lethality of strike at set speeds, using the probability of lethality equation presented in Vanderlaan and Taggart (2007). Daily traffic density (which is calculated as the length of vessel transect within a given cell per day) and mean speed are plotted into a 4.6x4.6 km^2 grid, using AIS data with only speeds >5 knots, and excluding 'impossible speeds'. From this, daily risk estimates are calculated, and then can be summed to calculate risk over a given period (e.g. monthly, or longer).
DOI	https://doi.org/10.2788/8520
Relevant Links	○ https://op.europa.eu/en/publication-detail/-/publication/7c09b782-e939-424e-ae63-ec61f8ac3963/language-en ○ https://data.europa.eu/doi/10.2788/8520
Software used to replicate method	ArcGIS Pro 2.9.2 Note, original authors completed analysis in MATLAB

Approximate time taken	Weeks

Workflow	• Create a 4.6x4.6km^2 Fishnet Grid, and clip it to the study area (*Create Fishnet* and *Pairwise Clip*)
	  ○ Subset and extract AIS data to only include ships travelling at ≥5 knots, and remove 'impossible' speeds (here, we use ≤40 knots as impossible speed) (*Export Features*)
	  ○ Check whether all vessels have width recorded (*Data Engineering*) (here, 66 MMSIs with null values (= 1167 rows)). For all rows with null values, populate the width row using the average width of all vessels (here, 21.8m) (*Export Features,* edit Width column *(Calculate Field),* then *Merge*))
	• Use *Convert Time Field* to convert the YMD_HMS format into two columns, one with only YMD and one with only MM.
	• Reconstruct the tracks for each vessel, starting a new track when points are received >1 hr apart (*Reconstruct Tracks*)
	• Intersect to 4.6x4.6 km^2 grid (*Intersect*)
	• Generate field with total km travelled per track (*Calculate Geometry*)
	• Generate a field with the PLETH for each track within each grid cell, using the Vanderlaan and Taggart (2007) Probability of Lethality (P(Lethality)) curve, which follows the standard logistic regression equation, where -4.89 is the intercept estimate and 0.41 is the speed estimate:
	$P_{lethal} = \frac{1}{1 + exp^{-(\beta_0+\beta_1 speed)}}$
	  • P(Lethality) = 1 / (1 + exp (- (– 4.89 + (0.41 * speed over ground))))
	  • In ArcGIS Pro Python = 1/(1+math.exp(-(-4.89+(0.41*!SOG!)))) (*Calculate Field*)
	• Subset the AIS data to generate an AIS dataset per day, per unique MMSI (use *ModelBuilder: Iterate Feature Selection, Group By* MMSI and Date fields, then *Copy Features,* naming each new layer by *%Value%)*
	• Calculate the average PLETH and total distance travelled, per grid cell per day, per vessel, within each grid cell (*Batch Spatial Join* and *Calculate Field*). Ensure each grid cell holds information related to the tracks for each vessel, per day (i.e. PLETH, vessel speed, vessel width, and total distance travelled).
	• Calculate the predicted number of collisions for each grid cell, per vessel, per day, using an adapted version of the overall ship strike formulation within Tregenza et al. (2000) (see Vaes and Druon (2013) for original equation) (*Batch Calculate Field*):
	
	*Ncoll = (W + 0.64L) * 0.001 * Dcell * Cs*
	
	  - *Ncoll* is the number of potential collisions with whales for a given grid cell per day (individuals/day),
	  - *W* is the damaging width of the vessel (m),
	  - *L* is the whale length (m), (here, we use the midpoint between males and female adult body length as presented in Lubetkin et al. (2012) (male = 14.8m, females = 16.2m, midpoint body length used = 15.5m)),
	  - *Dcell* is the length of vessel transect that is within a given cell per day (km/day),
	  - *Cs* is the coefficient of collision risk related to the vessel speed for a given cell and day (no dimension) (i.e. the PLETH)
	
	*Note, to be calculated in full, the Ncoll calculation also should take into account further whale distribution information; i.e. Pmax * Hab * T*
	  - *Pmax* is an estimate of the maximum whale density in the study area (individuals/km^2) (here, this is implemented in the last step when the initial Ncoll calculation is multiplied by the whale density raster)

	- *Hab* is the potential habitat coefficient for a given cell, which varies between 0 and 1 (we did not calculate or include *Hab* for the purpose of this study, to ensure bowhead whale input data was the same throughout the risk methods we were comparing) - *T* is the percentage of whale time at the surface (no dimension) (we did not calculate or include *T* for the purpose of this study, to ensure bowhead whale input data were the same throughout the risk methods we were comparing (i.e. only density input) • Sum the total daily predicted number of collisions per grid cell (*Ncoll*), to a 4.6x4.6 km^2 grid, to generate a metric of the total predicted collisions per cell over the study period (*Merge*) • Generate a raster of the predicted number of collisions (*Ncoll*) per grid cell (*Feature to Raster*) • Multiply the *Ncoll* raster with a 4.6x4.6km^2 raster of bowhead whale kernel density (*Times*)

Method	**Method B5: Strike Risk (Halliday et al., 2022)**
Summary	Halliday et al. (2022) predict monthly vessel strike risk for two populations of bowhead whales in the North American Arctic, using AIS data from 2012 to 2018. After exclusion of vessels travelling <1 knot and >40 knots, vessel data are grouped by vessel class, and converted into tracks, to calculate the number of times each individual vessel crossed a grid cell (in a 10x10 km^2 grid) per month, and the mean speed per vessel class per grid cell per month. A whale density layer was then multiplied with each vessel class density layer, to identify overlap. Overlap was then corrected by average speed per vessel class, per cell, using the probability of lethality equation presented by Vanderlaan and Taggart (2007).
DOI	https://doi.org/10.1016/j.biocon.2022.109820
Software used to replicate method	ArcGIS Pro 2.9.2
Approximate time taken	1 week
Workflow	• Create a 10 x 10 Fishnet Grid, and clip it to the study (*Create Fishnet* and *Pairwise Clip*) • Using only vessels travelling ≥1 knot and ≤40 knots, extract AIS and subset data into different monthly subsets for each vessel type, as follows (*Export Features* and *Batch Feature Class to Feature Class*): o bulk carriers, o container ships, o cruise ships, o ferries, o fishing vessels, o government vessels (including coast guard ships, ice breakers, and other research ships), o navy vessels, o pleasure craft (private yachts, sailboats, small boats, and other recreational boats), o tanker ships, o tugboats • Reconstruct each monthly subset of AIS point data into track lines, with tracks being matched based on MMSI, specifying to split tracks if points are >1 hr apart in time (*Batch Reconstruct Tracks*). • Clip tracks into short segments that each fall within the respective 10x10 km^2 grid cell, to allow for summary of traffic, by vessel type, within each grid cell (*Intersect*) • Calculate the number of unique tracks within each grid cell, and record this in a new field in the Attribute Table, to generate the summed number of times that individual vessel tracks in each vessel class crossed each

	grid cell in each month of each year (*Batch Calculate Field*) (add 1 to each row) • Calculate the average speed travelled, by vessel type and month, and the number of tracks within each grid cell (*Batch Spatial Join*) • Using the Spatial Join layers, calculate the average PLETH per grid cell, per vessel type, using the Vanderlaan and Taggart (2007) Probability of Lethality curve, which follows the standard logistic regression equation where -4.89 is the intercept estimate and 0.41 is the speed estimate from the coefficients in the PLETH curve: $$P_{lethal} = \frac{1}{1 + exp^{-(\beta_0+\beta_1 speed)}}$$ o PLETH = 1 / (1 + exp (- (– 4.89 + (0.41 * speed over ground)))) o In Python: 1/(1+math.exp(-(-4.89+(!SOG LAYER! * 0.41)))) (*Batch Calculate Field*) • Merge the monthly vessel type files into one vessel layer per month (*Merge*) • Convert the summarised 10x10 km^2 grids of vessel densities to a raster (*Feature to Raster*) • Process the bowhead whale data; o Generate kernel density maps, using bowhead whale modelled sightings data, for the months corresponding with AIS data (*Kernel Density*) o Convert the monthly bowhead whale modelled sightings kernel density data into 10x10 km^2 grid. Normalise each monthly dataset, so that the value the following raster is based on a value between 0 and 1 (i.e. divide all cells by the maximum value for each monthly dataset) (*Batch Raster to Point*, then *Batch Spatial Join* then *Calculate Field* separately for each monthly file), o Convert to into monthly rasters of grid cell size 10x10 km^2 based on the normalised density value (*Batch Feature to Raster*) • Multiply the corresponding monthly bowhead and vessel density raster layers together (*Times*) • Generate a raster that uses the average PLETH per grid cell as the 'value', then Times this raster by the bowhead x vessel overlap raster layer (*Batch Feature to Raster*)

Method	**Method B6: Relative Expected Fatality of a whale from ship strike (Smith et al., 2020)**
Summary	Smith et al. (2020) quantify the relative risk of ship strike for humpback whales in the Great Barrier Reef Marine Park using AIS data spanning 3 months over 3 years (collected July–September, in years 2013-2016) from only cargo, tanker and passenger vessels, >80m in length, using only data that showed vessel speeds >0.4 knots. Vessel point data were converted to tracks for each individual vessel, and then gridded to a 1x1 km^2 grid which summarised the distance travelled by vessels per grid cell, as a measure of vessel density. A 1x1 km^2 grid of whale density is multiplied with the vessel density grid, as well as the average vessel beam (width) per grid cell, and the average probability of lethal strike per grid cell based on the average vessel speed for each grid cell (using the Conn and Silber (2013) probability of lethality equation) to quantify the total relative risk per grid cell. Relative risk was also calculated at the scale of a 50x50 km^2 grid, to explore trends at a regional scale.
DOI	https://doi.org/10.3389/fmars.2020.00067
Relevant Links	
Software used to replicate method	ArcGIS Pro 2.9.2

Approximate time taken	~Days

Workflow	• Create a 1x1 km^2 Fishnet Grid, and clip it to the study area (*Create Fishnet* and *Pairwise Clip*)
	• Subset and extract AIS data within the study area to only include ships >80m in length, of type Tanker, Cargo or Passenger, and travelling at over 0.4 knots (*Export Features*)
	• Reconstruct the subset of AIS point data into track lines, with tracks being matched based on MMSI, specifying to split tracks if points are >1 hr apart in time, and calculating the min, max and mean speed over ground of each track, the min and max course over ground of each track, and ensuring the beam of each respective vessel track is recorded in the output attribute table (*Reconstruct Tracks*)
	• Clip tracks into short segments that each fall within the respective 1x1 km^2 grid cell, to allow for summary of traffic within each grid cell (*Intersect*)
	• Calculate the length, in km, of each track segment, and record this in a new field in the Attribute Table (*Calculate Geometry*)
	• Each clipped track segment will have within its attribute table the mean speed over ground. This can then be inputted into the Conn and Silber (2013) Probability of Lethality curve, which follows the standard logistic regression equation, where -1.905 is the intercept estimate and 0.217 is the speed estimate from the coefficients in the PLETH curve:
	$$P_{lethal} = \frac{1}{1 + exp^{-(\beta_0 + \beta_1 speed)}}$$
	    ○ PLETH = 1 / (1 + exp (- (– 1.905 + (0.217 * speed over ground))))
	    ○ In Python: 1/(1+math.exp(-(-1.905+(!SOG! * 0.217)))) (*Calculate Field*)
	• Summarise all track segments within each 1x1 km^2 grid cell, also generating the total sum of all track lengths travelling through each grid cell, in km, the average PLETH per grid cell, and the average width and draught per grid cell (*Spatial Join*)
	• Multiply the total sum of all track lengths per grid cell, by the average PLETH per grid cell, by the average vessel beam (width) per grid cell (*Calculate Field*)
	• Convert the summarised 1x1 km^2 grid of the previous calculation to a raster (*Feature to Raster*)
	• Multiply the two raster layers together (using the kernel density layer converted to a 1x1 km^2 (or 50x50 km^2) raster) as the input whale data layer), to generate a measure of co-occurrence, as the predicted kernel density of whales, multiplied by the km/day travelled by ships through that grid cell (*Times*)
	• *Repeat above steps with 50x50km^2 fishnet grid, to generate risk map for 50x50km^2 grid areas*

Method	**Method B7: Probability of lethality per grid cell (Wiley et al., 2011)**
Summary	Wiley et al. (2011) utilise a method to better understand potential lethal collisions within a study area which is particularly suitable for whale dense regions, in their case, the Stellwagen Bank National Marine Sanctuary (USA), which is seasonally dense with North Atlantic right, humpback and fin whales. The method utilises AIS data for vessels >295 tonnes collected in 2006 within a whale dense region, utilising the speed over ground recorded of vessel tracks within a 1x1 min grid (1.85x1.85 km^2), to predict each grid cells overall probability of lethality based on average speed vessels travel through each grid cell. Average speeds are input into the Pace and Silber (2005) probability of lethality (PLETH) curve, to generate

	PLETH per grid cell. This method therefore does not require whale density data, but instead is used for areas where densities are expected to be high throughout and/or areas that are recognised as being important to multiple whale species.
DOI	https://doi.org/10.1016/j.biocon.2011.05.007
Software used to replicate method	ArcGIS Pro 2.9.2
Approximate time taken	1 day
Workflow	• Create a 1.85x1.85 km^2 (1 min latitude x 1 min longitude) Fishnet Grid, and clip it to the study area (*Create Fishnet* and *Pairwise Clip*) • Subset and extract AIS data to only include ships ≥295 tonnes (*Export Features*) • Reconstruct the subset of AIS point data into track lines, with tracks being matched based on MMSI, specifying to split tracks if points are >1 hr apart in time, and splitting each track at 15 minutes (*Reconstruct Tracks*). • Clip tracks into short segments that each fall within the respective 1.85x1.85 km^2 grid cell, to allow for summary of traffic within each grid cell (*Intersect*). • Each clipped 15 min track segment will have within its attribute table the mean speed over ground. This can then be inputted into the Pace and Silber (2005) Probability of Lethality curve, which follows the standard logistic regression equation, where -3.594 is the intercept estimate and 0.341 is the speed estimate from the coefficients in the PLETH curve: $$P_{lethal} = \frac{1}{1 + exp^{-(\beta_0 + \beta_1 speed)}}$$ ◦ PLETH = 1 / (1 + exp (- (– 3.594 + (0.341 * speed over ground)))) ◦ In ArcGIS Pro Python: 1/(1+math.exp(-(-3.594+(!SOG! * 0.341)))) (*Calculate Field*) • Add a row in the attribute table where each row has a value of 1, so that this field can be used in the following step (where we calculate the total number of short track segments per grid cell) (*Calculate Field*) • Generate the total number of individual short tracks within each grid cell, and the sum total of all PLETH values for each grid cell (*Spatial Join*) • Divide the sum of all PLETH values per grid cell by the total number of short tracks per grid cell, to get the average PLETH per grid cell (*Calculate Field*)

References

Albertsen, C.M., Whoriskey, K., Yurkowski, D., Nielsen, A. and Flemming, J.M. 2015. Fast fitting of non-Gaussian state-space models to animal movement data via Template Model Builder. *Ecology*, 96: 2598-2604. https://doi.org/10.1890/14-2101.1

Chambault, P., Albertsen, C.M., Patterson, T.A., Hansen, R.G., Tervo, O., Laidre, K.L. and Heide-Jørgensen, M.P., 2018. Sea surface temperature predicts the movements of an Arctic cetacean: the bowhead whale. *Scientific reports*, *8*(1), p.9658. https://doi.org/10.1038/s41598-018-27966-1

Conn, P.B. and Silber, G.K., 2013. Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. *Ecosphere*, *4*(4), pp.1-16. https://doi.org/10.1890/ES13-00004.1

Finley, K.J., 2001. Natural history and conservation of the Greenland whale, or bowhead, in the Northwest Atlantic. *Arctic*, pp.55-76.

Fortune, S.M., Young, B.G. and Ferguson, S.H., 2020a. Age-and sex-specific movement, behaviour and habitat-use patterns of bowhead whales (Balaena mysticetus) in the Eastern Canadian Arctic. *Polar Biology*, *43*, pp.1725-1744. https://doi.org/10.1007/s00300-020-02739-7

Fortune, S.M., Ferguson, S.H., Trites, A.W., LeBlanc, B., LeMay, V., Hudson, J.M. and Baumgartner, M.F., 2020b. Seasonal diving and foraging behaviour of Eastern Canada-West Greenland bowhead whales. *Marine Ecology Progress Series*, 643, pp.197-217.

Halliday, W.D., Le Baron, N., Citta, J.J., Dawson, J., Doniol-Valcroze, T., Ferguson, M., Ferguson, S.H., Fortune, S., Harwood, L.A., Heide-Jørgensen, M.P. and Lea, E.V., 2022. Overlap between bowhead whales (Balaena mysticetus) and vessel traffic in the North American Arctic and implications for conservation and management. *Biological Conservation*, *276*, p.109820. https://doi.org/10.1016/j.biocon.2022.109820

Heide-Jørgensen, M.P., Garde, E., Nielsen, N.H., Andersen, O.N. and Hansen, S.H., 2012. A note on biological data from the hunt of bowhead whales in West Greenland 2009–2011. *J. Cetacean Res. Manage*., 12(3), pp.329-333.

Heide-Jørgensen, M.P., Laidre, K.L., Nielsen, N.H., Hansen, R.G. and Røstad, A., 2013. Winter and spring diving behavior of bowhead whales relative to prey. *Animal Biotelemetry*, 1(1), pp.1-14.

Hendricks, B., Keen, E.M., Shine, C., Wray, J.L., Alidina, H.M. and Picard, C.R., 2021. Acoustic tracking of fin whales: Habitat use and movement patterns within a Canadian Pacific fjord system. *The Journal of the Acoustical Society of America*, 149(6), pp.4264-4280.

Keen E (2023). shipstrike: Utilities for spatially- and temporally-explicit predictions of whale-ship collisions. R package version 2.2.0.

Keen, E.M., Mahony, É.O., Nichol, L.M., Wright, B.M., Shine, C., Hendricks, B., Meuter, H., Alidina, H.M. and Wray, J., 2023. Ship-strike forecast and mitigation for whales in Gitga'at First Nation territory. *Endangered Species Research*, *51*, pp.31-58. https://doi.org/10.3354/esr01244

Kelley, D.E., Vlasic, J.P. and Brillant, S.W., 2021. Assessing the lethality of ship strikes on whales using simple biophysical models. *Marine Mammal Science*, *37*(1), pp.251-267. https://doi.org/10.1111/mms.12745

Lubetkin, S.C., Zeh, J.E. and George, J.C., 2012. Statistical modeling of baleen and body length at age in bowhead whales (Balaena mysticetus). *Canadian Journal of Zoology*, 90(8), pp.915-931. https://doi.org/10.1139/z2012-057

Matthews, C.J., Breed, G.A., LeBlanc, B. and Ferguson, S.H., 2020. Killer whale presence drives bowhead whale selection for sea ice in Arctic seascapes of fear. *Proceedings of the National Academy of Sciences*, *117*(12), pp.6590-6598. https://doi.org/10.1073/pnas.1911761117

Nichol LM, Wright BM, Hara PO, Ford JK. Risk of lethal vessel strikes to humpback and fin whales off the west coast of Vancouver Island, Canada. *Endangered Species Research*. 2017 May 4;32:373-90. https://doi.org/10.3354/esr00813

Pace, R.M. III and Silber, G., 2005. Simple analysis of ship and large whale collisions: does speed kill? Poster paper. In: The 16th Biennial Conference on the Biology of Marine Mammals, Society for Marine Mammalogy, San Diego, CA, December 12–16. https://www.researchgate.net/publication/341001162_Pace_Silber_Vessel_Speed_and_Ship_Strikes_Poster_San_Diego_2005MMS

Redfern, J.V., Becker, E.A. and Moore, T.J., 2020. Effects of variability in ship traffic and whale distributions on the risk of ships striking whales. *Frontiers in Marine Science*, *6*, p.793. https://doi.org/10.3389/fmars.2019.00793

Simon, M., Johnson, M., Tyack, P. and Madsen, P.T., 2009. Behaviour and kinematics of continuous ram filtration in bowhead whales (Balaena mysticetus). *Proceedings of the Royal Society B*: Biological Sciences, 276(1674), pp.3819-3828.

Smith, J.N., Kelly, N., Childerhouse, S., Redfern, J.V., Moore, T.J. and Peel, D., 2020. Quantifying ship strike risk to breeding whales in a multiple-use marine park: the Great Barrier Reef. *Frontiers in Marine Science*, 7, p.67. https://doi.org/10.3389/fmars.2020.00067

Tregenza, N., Aguilar, N., Carrillo, M., Delgado, I., Díaz, F., Brito, A. and Martin, V., 2000. Potential impact of fast ferries on whale populations: a simple model with examples from the Canary Islands. *European Research on Cetaceans*, 14, pp.195-197.

Vaes, T. and Druon, J-N. 2013. *Mapping of potential risk of ship strike with fin whales in the Western Mediterranean Sea*, Publications Office: Joint Research Centre, Institute for the Protection and Security of the Citizen. https://data.europa.eu/doi/10.2788/8520 https://doi.org/10.2788/8520

Vanderlaan, A.S. and Taggart, C.T., 2007. Vessel collisions with whales: the probability of lethal injury based on vessel speed. *Marine Mammal Science*, 23(1), pp.144-156. https://doi.org/10.1111/j.1748-7692.2006.00098.x

Wiley, D.N., Thompson, M., Pace III, R.M. and Levenson, J., 2011. Modeling speed restrictions to mitigate lethal collisions between ships and whales in the Stellwagen Bank National Marine Sanctuary, USA. *Biological Conservation*, 144(9), pp.2377-2381. https://doi.org/10.1016/j.biocon.2011.05.007

Williams, R. and O'Hara, P., 2010. Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. J. Cetacean Res. Manage., 11(1), pp.1-8. https://journal.iwc.int/index.php/jcrm/article/view/624/349

Yurkowski, D.J., Auger-Méthé, M., Mallory, M.L., Wong, S.N., Gilchrist, G., Derocher, A.E., Richardson, E., Lunn, N.J., Hussey, N.E., Marcoux, M. and Togunov, R.R., 2019. Abundance and species diversity hotspots of tracked marine predators across the North American Arctic. *Diversity and Distributions*, *25*(3), pp.328-345. https://doi.org/10.1111/ddi.12860