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Review

Narwhal, beluga and bowhead whale responses to marine vessel traffic: A systematic map

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ABSTRACT

The remote and harsh environment that endemic Arctic whales (bowhead, narwhal and beluga) reside in has so far limited their exposure to many human activities. However, Arctic industrialisation coupled with increasingly accessible ice-free waters means these species increasingly co-occur, and are exposed to, a number of potentially impactful activities, many of which are directly or indirectly associated with marine vessels. We conducted a systematic map, using five search databases, to ascertain the current level of understanding relating to how Arctic whales respond to marine vessels and vessel-associated activities. We identified a limited volume of literature (n = 169), and a disparity in volume between species, subpopulations, and vessel types. Several vessel types are increasingly present in the Arctic (e.g. cruise ships, fishing vessels), yet received limited consideration. Similarly, several endangered subpopulations have received little attention. Only with sufficient understanding of the associated impacts of vessels can we develop appropriate management and mitigation measures which can effectively conserve these unique, vulnerable and inherently valuable species.

1. Introduction

1.1. Arctic whales

Whilst many cetacean species utilise Arctic waters as temporary seasonal visitors, there are only three species that are considered endemic and are found year-round at high latitudes. The bowhead whale (*Balaena mysticetus*) is the only resident baleen whale, whilst narwhal (*Monodon monoceros*) and beluga (*Delphinapterus leucas*) are toothed whales. Hereafter these three species will interchangeably be referred to as 'Arctic whales'.

Globally, there are estimated to be 136,000 mature individual beluga (Lowry et al., 2017a), which can be divided into 21 recognised stocks; nineteen that are distributed across much of the circumpolar Arctic, and two that are resident in sub-Arctic waters (St. Lawrence Estuary (Quebec, Canada) and Cook Inlet (Alaska, USA) (Kovacs et al., 2021). Some beluga stocks are of particular conservation concern, such as the St. Lawrence Estuary stock, which is currently listed as 'Threatened' under Canada's Species at Risk Act (DFO, 2012) and 'Endangered' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (COSEWIC, 2014). Despite the application of protective measures designed to conserve this stock for almost a decade, the population has shown no sign of recovery, which has been attributed to the ongoing impact of anthropogenic activities within their habitat, along with contaminant exposure (Mosnier et al., 2015).

In contrast to the wider circumpolar distribution of the beluga, narwhal distribution is centred around the Atlantic Arctic (Tervo et al., 2023). The global population is estimated to be 123,000 mature narwhals, comprising of at least twelve stocks, each with differing or unknown population trajectories, some of which are of low abundance and declining (e.g. the East Greenland stock) (Lowry et al., 2017b; Hobbs et al., 2019). The small-scale habitat preferences of narwhal can result in separate summer stocks temporarily overlapping in their wintering areas (Heide-Jørgensen et al., 2015).

There are estimated to be 10,000 mature bowhead whale individuals globally (Cooke and Reeves, 2018a), which can be divided into four subpopulations, each with differing population trajectories. The two smallest subpopulations, the Okhotsk Sea and the East Greenland-Svalbard-Barents Sea, are both estimated to number <250 individuals, and are thus both classified by the International Union for Conservation of Nature (IUCN) as 'Endangered' (Cooke et al., 2018; Cooke and Reeves, 2018b). The already small Okhotsk Sea

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subpopulation is also predicted to be decreasing (Cooke et al., 2018). In contrast to these smaller endangered subpopulations, the Bering-Chukchi-Beaufort Sea subpopulation is increasing (Givens et al., 2016, 2017). All four subpopulations of bowheads are migratory to some degree, though the extent of this movement varies regionally (Reeves et al., 2014).

Since time immemorial, Arctic whales have formed an essential component of the survival, culture, identity and unique heritage for many Arctic communities (Friesen and Arnold, 1995; Sakakibara, 2013). They provide sustenance and food security, with country food central to economic, social and cultural identity (country food refers to the traditional diets of Indigenous peoples, i.e. all food harvested from the land and sea; Tyrrell, 2007). Since the 1600s, Arctic whales (particularly bowheads) were also exploited by commercial industrial scale whaling operations, driven primarily by a rising demand for whale oil in Europe (Avango et al., 2014). The volume of commercial operations had reduced substantially by the early 1900s, and has now ceased, though subsistence takes of Arctic whales still occur in several Arctic states (Canada, Greenland, Russia, and the United States) (Gambell, 1993; NAMMCO, 2023). Commercial whaling led to the severe depletion of whales in some regions, with some populations only recently showing signs of recovery, whilst others have shown little growth and several remain data deficient, and thus the true consequences of commercial whaling remain difficult to quantify (Mitchell and Reeves, 1982; Allen and Keay, 2006; Higdon and Ferguson, 2010).

1.2. Maritime activity and impacts in the Arctic

For many centuries, commercial and subsistence takes were the main direct anthropogenic threat faced by Arctic whales, however, an increasing global human footprint coupled with industrialisation and developing technology means Arctic whales are increasingly co-occurring or being exposed to a rising number of potentially impactful anthropogenic activities, including shipping, fishing and fossil fuel exploration and extraction (Reeves et al., 2012, 2014; Rolland et al., 2019). The remoteness and harshness of the Arctic environment has limited the volume of human activity and industrialisation in some locations, with sea ice and extreme temperatures the major restricting factors. Therefore, exposure for some subpopulations of Arctic whales has potentially remained rare and limited, especially in comparison to populations that occupy more human populous regions (Halpern et al., 2015).

Anthropogenic-induced climate change has led to increasing air and sea surface temperatures in the Arctic, resulting in prolonged ice-free summer seasons, coupled with a reduction in ice thickness and extent (Comiso and Hall, 2014; Nielsen-Englyst et al., 2023). In shipping terms, this means an increasingly navigable Arctic, and a longer duration where northern voyages are viable without the assistance and additional expense of an icebreaking vessel (Pizzolato et al., 2014; Melia et al., 2016; Dawson et al., 2018; Ng et al., 2018; Min et al., 2023). This increasing accessibility is already being capitalised on, with cruise ships and cargo vessels navigating through previously inaccessible or dangerous passages (e.g. in 2018, the *Venta Maersk* was the first commercial container ship to successfully navigate through the Arctic without an associated icebreaker). Arctic vessel traffic is predicted to increase, given the potential to utilise Arctic shipping routes as time-effective alternatives for travelling from Europe or North America to East Asia via the Panama or the Suez Canal, and vice versa (Schøyen and Bråthen, 2011; Melia et al., 2016). Although there are several uncertainties related to the scale and the rate of change in vessel activity, the volume of vessels that are transiting through the Arctic Polar Code area is increasing (PAME, 2020). This includes vessels transiting physically restrictive waters in both the Northwest Passage (Canadian Arctic) and the Northern Sea Route (Russian Arctic) while serving oil and gas exploration areas (Allen, 2014) and mining operations (Huntington et al., 2015). Other vessel-based industries, such as commercial fishing, and cruise and 'adventure' tourism, are also projected to continue to accelerate and capitalise upon increasing accessibility to formerly remote areas (Lasserre and Têtu, 2015; Huddart et al., 2020; PAME, 2020).

The Arctic Ocean functioned as an acoustic refuge from industrial noise until as recently as the 1970s (Diachok and Winokur, 1974), but several studies now speculate or provide evidence that the introduction of anthropogenic noise from commercial traffic is altering the soundscape of this region, and poses a significant threat to Arctic species (Reeves et al., 2012; Halliday et al., 2020; Duarte et al., 2021; Ladegaard et al., 2021). Globally, increased shipping is already estimated to have contributed to a 32-fold increase in low frequency noise along major shipping routes over the past 50 years (Malakoff, 2010). Sound is paramount to the survival of many marine species, including Arctic whales, as they use it to detect and navigate their environments, locate prey and communicate with one another (Huntington et al., 2015), thus the consequences of increasing vessel activity have the potential to be far reaching and detrimental to Arctic whale species. The contribution of chronic, low frequency noise emitted from maritime vessels is of particular concern due to the potential for masking (Dunlop, 2016; Erbe et al., 2016; Brewer et al., 2023). Other noise associated with vessels (e.g. icebreaking, seismic survey noise) may also impact Arctic whales (Richardson et al., 1986; Cosens and Dueck, 1993; Erbe and Farmer, 2000; McDonald et al., 2012; Blackwell et al., 2013, 2015; Reeves et al., 2012, 2014).

Vessels also pose several other direct and in-direct threats to marine mammals, one being the risk of collision (Reimer et al., 2016). There is evidence of the susceptibility of bowhead whales to ship strikes, given a percentage of whales taken in recent years by Alaskan subsistence hunters presented with scars or other wounds consistent with vessel strike (George et al., 1994, 2017, 2019; Reeves et al., 2012). Other vessel related stressors include risk of exposure to vessel-generated oil spills or maritime waste (including oily water, sewage discharge or ballast water) (Huntington et al., 2015). In the Arctic, spill events are of particular concern not only because of the acute and chronic toxicity to marine organisms and their habitats (Peterson, 2001), but also because oil is expected to degrade much more slowly at polar temperatures (Huntington et al., 2015). This is exacerbated in the Arctic due to the remoteness and weather conditions limiting the capacity and capability of any clean-up efforts. For Arctic species, ingestion of pollutants is a concern for the animals' health, and for those that consume polluted meat which may retain contaminants that are then bioaccumulated through the food chain (Hoekstra et al., 2002, 2003; Dehn et al., 2006). Other maritime debris, such as abandoned fishing gear or lost cargo, also has the potential to negatively affect Arctic whales, from ingestion of microplastics to entanglement and mortality events in ghost gear (Williams et al., 2011; Stelfox et al., 2016).

1.3. Understanding and mitigating for the effects of increasing Arctic activity

In order to mitigate and protect marine mammals from human activities, historically, cetacean conservation initiatives have typically resulted in semi- or permanent spatially-defined regions that delineate biologically important areas and may include (often voluntary) measures to mitigate potential impacts (such as vessel slowdowns, or areas to be avoided), under the implicit assumption that the target species would continue to aggregate within their known habitat distribution and utilise those areas within their range (such as migratory corridors, calving grounds, foraging sites) (Reimer et al., 2016). These measures may be implemented following various international obligations, such as the United Nations Convention on the Law of the Seas (UNCLOS) which obligates signatories to protect and preserve the marine environment (UNCLOS, 1982) and the International Convention for the Regulation of Whaling, which aims to provide for the protection and conservation of whale stocks (IWC, 1946). However, any increase in anthropogenic activities (including vessel traffic), could result in animals altering their habitat use (for example, changing migration patterns, less predictable regional residency, abandonment of previously important areas (Findley and Vidal, 2002; Rowntree et al., 2020)). Alterations in habitat use may be further exacerbated by climate related changes, particularly for Arctic whales (Laidre et al., 2008; Tsujii et al., 2021; van Weelden et al., 2021; Chambault et al., 2022). Thus, conventional protection measures, such as identification of areas to be avoided, may require additional complementary measures to provide sufficient protection for Arctic whale species (Reimer et al., 2016). Additionally, the human context should be considered when discussing proposed management measures, particularly in the Arctic given spatial restrictions may have impacts for accessibility and success rates of local subsistence hunters (Reeves et al., 2012; Huntington et al., 2015).

Considering the ongoing and forecasted increases in vessel activity in the Arctic, there is a need to proactively explore and better understand the conservation challenges that this poses for Arctic whales, including the identification of knowledge and data gaps that are still to be addressed. This knowledge is essential to make informed decisions regarding the management and mitigation of any vessel associated impacts. We therefore conducted a systematic map to summarise and quantify the current state of published knowledge relating to the responses of Arctic whales to marine vessels and their associated activities. The specific research questions this work addresses are:

1. What is the current state of knowledge of how Arctic whales respond to vessels and their associated activities?
2. How does the state of knowledge vary:
   a. Across species distribution range, including between subpopulations?
   b. With vessel type?

2. Methods

A short summary of the systematic mapping protocol is provided below. The development of the protocol, and the subsequent reporting were guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher et al., 2009; Page et al., 2021) and the RepOrting standards for Systematic Evidence Syntheses (ROSES) protocol (Haddaway et al., 2018) (Supplementary Material: Table S1).

2.1. Eligibility criteria

For a study to be included in the review database, it had to adhere to the following eligibility criteria;

- *Eligible subjects **(the population)**:* One or more of the selected endemic Arctic whale study species: bowhead whale, beluga whale or narwhal.
- *Eligible **interventions:*** One or more of the following: vessel(s) (motorised and non-motorised included), vessel-related equipment or activities (i.e. depth-sounder, seismic survey operation), and/or vessel-related infrastructure (i.e. activities related to port, harbour, dock, mooring infrastructure). Studies were not eligible if they only reported direct impact of subsistence or commercial whaling hunt practices (i.e. death). However, studies were eligible if they reported response of animals to the hunt vessels themselves. Similarly, studies were eligible that reported responses of the study species to fishing vessels, or to fishing activity (e.g. attraction to live fishing gear attached to the vessel). However, studies were not eligible that reported the responses of animals to fishing gear that was permanently or semi-permanently detached from the vessel (for example, entanglement in rope (e.g. Philo et al., 1992) or static fishing gear such as cod and crab pots (for example, Citta et al., 2014))).
- *Eligible **comparators:*** Studies were not required stricto sensu to have a control or comparator.
- *Eligible **outcomes:*** Studies were not required stricto sensu to have a specific outcome. All and any outcomes were included iteratively as they were identified within the literature and were then coded accordingly (example outcomes that were identified, but not predefined, include an acoustic or behavioural response to vessels).
- *Eligible types of study design:* Studies that involved primary research involving field-based experimental manipulations and observations were eligible for inclusion. Further, studies that modelled or predicted response to vessels, and studies that observed or predicted potential co-occurrence of the species of interest and vessels were also eligible for inclusion, though were coded to ensure differentiation could be made with primary research studies. There were no limits on the potential source of information (i.e. captive, harvested individuals, necropsy or stranding all eligible). Studies were eligible if they presented controlled exposure experiments of playbacks of vessels and vessel activity (e.g. recordings of a seismic survey vessel with firing air guns) but were not eligible if they only included a simulated version of the activity (e.g. simulated air gun noise) or a recording of the activity alone (e.g. just seismic air guns, without inclusion of vessel noise).
- *Eligible study location:* There were no limits for eligibility based on study location, despite some stocks of Arctic whales being located in sub-Arctic rather than high-Arctic waters (e.g. St Lawrence Estuary beluga whales).
- *Eligible languages:* All languages were eligible to be included. The search was conducted in English, but if any non-English studies appeared in the search results, then they would be translated using online translation tools, and then would be screened for eligibility for inclusion in the review database.
- *Eligible document types:* Eligible document types included peer review literature (i.e. research articles, short notes or communications), grey literature (i.e. reports, non-peer reviewed research), Master's or PhD theses, and conference or workshop related documents (e.g. conference proceedings, meeting abstracts, posters). Reviews were not eligible for inclusion if they only summarised previous literature and did not present any new information or findings.

2.2. Search and screening strategy

The basis of a search string was developed by a small research team specialising in vessel impacts to marine mammals (including the authors), with additional Arctic relevant search terms identified and added to the search string list (i.e. Indigenous language and terminology related to vessels and Arctic whales). Search strings were then adapted using database specific syntax, as appropriate. The following bibliographic databases were then searched, using search terms in English: Scopus, Web of Science, PubMed and ProQuest. Searches of grey literature were also conducted using Google Scholar. Searches were conducted on 01 and June 02, 2023. Search strings and number of publications found per database are provided within the Supplementary Material: Table S2.

Search results across all databases were combined into one database, which was then uploaded into the systematic review application 'Rayyan' (Ouzzani et al., 2016). There were 4589 documents collated in the initial search (Fig. 1). Prior to the search, the authors constructed a list of articles that were deemed key literature related to the research questions. To assess the comprehensiveness of the search and the quality of the search terms, we checked the search results to confirm all identified six 'key' articles were found within the initial literature search. Following this, the Duplicate Detection function in Rayyan was used, and detected 2781 duplicates, which were then screened manually. 1858 were confirmed to be duplicates and subsequently deleted, which resulted in a final total of 2731 documents for screening. Articles were initially screened by title and abstract only, which resulted in 2503

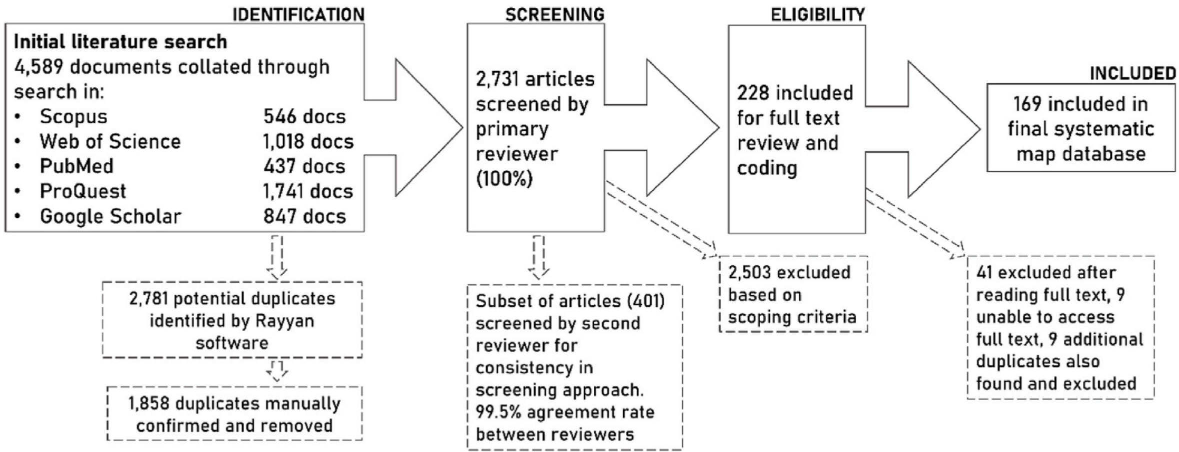


Fig. 1. Search and screening process for the systematic map, showing the volume of literature found and then included or excluded from the map at the screening and eligibility stage. PRISMA flow diagram adapted from Page et al. (2021).

being excluded based on the aforementioned eligibility criteria, and 228 were included for full text review. Uncertain articles were included at this stage, to allow for a decision at the full text stage. Of the 228 articles, the full text of nine documents could not be accessed or located, 41 articles were excluded after reading the full text, and nine articles were manually identified as duplicates. This resulted in 169 full text articles that were available to be coded.

Consistency in screening: One reviewer screened the abstracts of all 2731 documents. A second reviewer screened 15% of the document abstracts (401) to ensure consistency in the screening process. The two reviewers screened the documents blind (i.e. they were not aware of the other reviewers decision on each article), and then met to share document decisions, and discuss and resolve any conflicting decisions (0.5%, n = 2). There was an extremely high rate of agreement between the two reviewers (99.5%).

Critical appraisal: Critical appraisal of the identified documents was not undertaken as part of this systematic mapping process, as this was not necessary to achieve the aims of the map. Anecdotally, all research included in the final systematic map database appeared reliable without major deficiencies based on a very basic quality assessment during coding.

2.3. Review data extraction

One reviewer manually processed each of the 169 documents included in the review, transferring information and meta-data for each included document into a searchable review database. The database was populated with study specific information including study location(s) (latitude and longitude), study species (including subpopulation or stock (see Section 2.4.1)), vessel type, vessel activity, study methodology, study findings, and study metadata (e.g. first author institution, publication type, year of publication). Some studies included multiple sites and/or had a vast focus area; in this case an attempt was made to record the most representative study location (i.e. site of most data collection). Study location maps presented in the 'Results' therefore represent a best approximation of study location for some studies, though for many (n = 152) it was possible to record exact location. Where study locations spanned multiple subpopulations or stocks, a location was recorded for each respective subpopulation or stock. Study findings were recorded, alongside the outcome. Here, we noted whether each data record presented a prediction on potential risk (e.g. identifying possible spatial or temporal overlap (co-occurrence)) or predicted a response to vessels, versus provided observations of a recorded response(s) to vessels, to demonstrate whether the state of knowledge was based on observational evidence or on studies of a predictive nature.

A record was made of the specific vessel type of each study, and following coding of all studies, studies were also given broad vessel type categories as follows:

- *All vessels included*: e.g. passive acoustic monitoring studies recording overall vessel noise of an area, or studies looking at responses to multiple vessels in one area. This category also included studies that used Automatic Identification System (AIS) data as a proxy for vessel presence.
- *Goods*: cargo (including ice-strengthened cargo ships), container, carrier (including ore carriers)
- *Cruise Ship*
- *Fishing vessel*
- *Harbour, Port or Navigation:* harbour/port associated dredgers, harbour/port construction or maintenance associated vessels
- *Icebreaker*
- *Passenger*: ferries and passenger day trips (e.g. wildlife watching trips)
- *Human-powered (Kayak, paddleboard, row boat, windsurfer)*: all human-powered recreational activities
- *Motorboat*: subsistence hunt vessels, small (<20m) vessels with inboard or outboard engines, recreational engine-powered craft (e.g. speedboat)
- *Oil and Gas related*: drillships, oil/gas construction associated dredgers, seismic survey vessels, oil/gas platform servicing vessels, crew transfer vessels, oil tankers
- *Miscellaneous*: other vessel types that do not fall within any other category, e.g. sub-bottom profilers, hovercraft, sea plane, jet ski, vessels under sail, and vessel associated equipment (e.g. anchor)
- *Tug:* (including ice-strengthened tugs)

The categories were defined to complement the categories within the vessel data described in Section 2.4.2.

2.4. Study mapping and presentation (narrative synthesis)

To summarise the volume of research conducted on the topic of interest for each species, sub-population/stock and vessel type, we display volume of evidence and describe findings related to the key variables in tables and figures, including heat map tables and Sankey diagrams. In addition, studies are mapped using a geographical information system (GIS) to display geographic distribution of studies. Knowledge gaps that are under-represented in the evidence base are identified using the heat map tables and summary figures. All geoprocessing, mapping and subsequent analysis was conducted in ArcGIS Pro Version 2.9.2.

2.4.1. Subpopulation/stock distribution data

To explore how vessel related studies are distributed across the known range of each endemic Arctic cetacean species, we mapped the overall species range, along with the ranges of individual subpopulations/stocks. Narwhal stock distribution maps were digitised using the 'Create Features Tool' in ArcGIS Pro from the stock map presented within the 'Global Review of the Conservation Status of Monodontid Stocks' (Hobbs et al., 2019). Bowhead whale subpopulation distribution shapefiles were downloaded from the IUCN Red List of Threatened Species assessment listing (Cooke and Reeves, 2018a), and the most up-to-date beluga subpopulation map (as presented within Kovacs et al., 2021) was provided to the authors as a shapefile by the Norwegian Polar Institute.

Each respective data record within the review was categorised during coding into the relevant subpopulation or stock it pertained to. Where possible, this was based on the explicit identification of the subpopulation or stock studied within the text itself (100 documents). For the remaining 69 documents that did not report which subpopulation or stock the study referred to, this was categorised using the study location and the respective stock or subpopulation map. By categorising each data record into a respective stock or subpopulation, this allowed for comparison of volume of research between subpopulation/stocks for each species. Furthermore, the three species distribution maps were merged to present the entire potential range of endemic Artic whales, according to current data, which was then used to explore overlap with vessel traffic.

To illustrate the volume of research alongside the population size of each sub-population or stock, population size estimates were collated for narwhal and belugas from Hobbs et al. (2019), and for bowhead whales from the IUCN Red List of Threatened Species assessment listings (Cooke and Reeves, 2018a, 2018b) and accompanying references (Givens et al., 2017; Doniol-Valcroze et al., 2020).

2.4.2. Vessel data

To illustrate the distribution of vessel activity in the Arctic alongside the locations of vessel related studies on Arctic whales, we acquired Arctic Ship Traffic Data (ASTD) collected throughout 2019 from the Protection of the Arctic Marine Environment (PAME). The PAME vessel data does not cover all species subpopulation ranges and/or study locations (i.e. no coverage of St. Lawrence Estuary or the Okhotsk Sea), however the data is presented for illustrative purposes only; to provide an overview of representative vessel traffic experienced by the three endemic species whilst they occupy Arctic waters. Data from 2019 was used to represent a year of 'typical' vessel traffic, prior to the COVID-19 pandemic which led to a short-term global reduction in maritime activity (March et al., 2021).

The ASTD data contains Automatic Identification System (AIS) data from ships operating in the Arctic, and ship characteristic information (ship type). We received ASTD Level 3 data access from PAME, which meant ship types were pre-categorised into broad ASTD-defined categories (Chemical tankers, Gas tankers, Bulk carriers, General cargo ships, Container ships, Ro-Ro cargo ships, Refrigerated cargo ships, Offshore supply ships, Other service offshore vessels, Other activities, Fishing vessels, Crude oil tankers, Oil product tankers, Passenger ships and Cruise ships). For the purpose of summary data presentation, we collated the ASTD data into six categories as follows:

1. Cruise Ship
2. Oil and Gas Related (Gas tankers, Offshore supply ships, Other service offshore vessels, Crude oil tankers, Oil product tankers)
3. Passenger
4. Fishing
5. Goods (Chemical tankers, Bulk carriers, General cargo ships, Container ships, Ro-Ro cargo ships, Refrigerated cargo ships)
6. Miscellaneous

Monthly ASTD vessel data (point data) were merged into one annual ASTD data layer for the year of 2019, and then processed into a fishnet grid in order to represent vessel density per unit area. The grid was then clipped to the combined range of all three study species, to present vessel density within the range of the species of interest. For species-specific analysis, the ASTD fishnet grid was clipped to each species range, and for vessel-category specific analysis, ASTD fishnet grids were developed using data from only specific vessel types.

Vessel densities are presented alongside the review findings to illustrate how vessel-related studies overlap with vessel dense areas. However, it is important to note that the vessel data presented does not include data for vessel types that are not legally obligated to transmit AIS data (e.g. small craft), and as such, these vessel types will be underrepresented in the vessel density maps. The maps therefore represent a minimum estimate of vessel activity in Arctic waters for 2019.

3. Results

3.1. Systematic review summary

The search resulted in 2731 unique results, of which 169 fitted all eligibility criteria and were available to be included within the review database. Many of the documents reported on one or more species, on one or more vessel types, and reported on one or more responses being predicted or observed. Each of these records were added as separate data records to the review database. This resulted in 596 unique records from the 169 review documents.

The majority of the 169 documents were peer-review articles (n = 97), 37 were reports, 20 were meeting abstracts, posters, conference or workshop proceedings, ten were Master's or PhD theses, three were book chapters, and two were research without peer review (i.e. preprint) (Supplementary Material: Fig. S1). In some cases, it is expected that the same data or study were presented across multiple document types (e.g. as a Master's thesis and then as a peer-review publication, or as a one year report, and then a five-year report). We could not reliably account for this duplication in reporting, therefore this should be taken into consideration when interpreting the review results, as the presented data records from the review database may be inflated due to this duplication.

The publishing date of documents spanned 1953 to 2023, with the first report in 1953 documenting Western Hudson Bay beluga whales progressively becoming more responsive and 'frightened' of the approach of a motorboat over the course of a summer season (Doan and Douglas, 1953). After 1953, there was no literature published on this topic for almost 30 years, with the next document appearing in 1981. Since then, for most years at least one document has been published per year on this topic. Overall, the annual contribution to the literature on this topic remains relatively low (max = 12 documents per year), though the rate of publication of peer review literature does appear to have increased since the 1980s, particularly from 2011 onwards (Supplementary Material: Fig. S1).

Location Study locations spanned the five principal range states of the Arctic (Canada, United States of America (USA), Greenland, Russia and Norway), though there was great disparity in the volume of data records from each range state, with Canada (n = 404) and the USA (n = 199) being the location of substantially more data records than Russia (n = 61), Norway (n = 42) or Greenland (n = 40) (Supplementary Material: Fig. S2) (note, there are more records per range state (n = 759) than total records (n = 596), because records in some cases spanned multiple range states). Similarly, lead author institution location was also heavily skewed towards Canada (n = 91) and the USA (n = 62), with minimal contribution to the literature on this topic from institutions based in other countries (Denmark n = 2; France n = 2, Greenland n = 4; Norway n = 1; Russia n = 5, not specified = 2).

3.2. Species specific systematic map results

There was disparity in number of data records per species collated as part of this review, with 316 records on beluga whales (from 110 documents), 200 on bowheads (from 64 documents), and 80 on narwhals (from 24 documents) (Table 1). Information on beluga response to vessels was first published in 1953, on bowheads in 1981, and on narwhals in 1983 (Fig. 2). Data records presenting information on narwhals have been published sporadically in low numbers following this first publication 40 years ago, with some notable gaps in publishing (e.g. there are no narwhal records in the review data records between 1994 and 2011). In contrast, there has been more regular additions to the literature focusing on beluga responses to vessels, with almost annual additions since 1983 (Fig. 2). Data records reporting on bowhead whale responses to vessels remain at a low rate since 1981, with the exception of some years having a particularly high volume of records (notably 1982, 1985 and 2018), and again gaps in new data records over multiple years (e.g. no records between 1996 and 2003) (Fig. 2).

Response: Overall, almost half (49.7%) of the data records in this review presented empirical evidence of a recorded response or impact observed to Arctic whales by vessels and their associated activities, with a small proportion observing no response to vessels and their associated activities (4.4%; Table 1). A third of studies were predictive (33.0%), with 15.3% predicting response by Arctic whales to vessels and their associated activities, 11.7% predicting co-occurrence, 5.0% predicting no co-occurrence, and 5.9% presenting inconclusive results (Table 1). This proportion of observed versus predictive studies within the data records was similar across the three endemic Arctic species (Table 1).

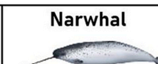
3.2.1. Beluga response to vessels and associated activity

The volume of data records across the 21 beluga stocks on response to vessels and their associated activities varied (range = 2–90, mean = 14.5, total = 305 stock-specific data records from 104 documents) (Fig. 3; Supplementary Material: Fig. S3). The five beluga stocks that each occupy a portion of the Okhotsk Sea all have only two or three data records in the review database per stock (from two to three documents), all have population trend recorded as 'Unknown' (Hobbs et al., 2019) (Fig. 3; Supplementary Material: Fig. S3). The two stocks with the highest volume of data records are both sub-Arctic stocks, St. Lawrence Estuary (62 data records, from 29 documents) and Cook Inlet (90 data records, from 30 documents), both have a declining population trajectory, with the latter stock also classed as 'Critically Endangered' by the IUCN Red List of Threatened Species (Fig. 3) (Lowry et al., 2019; Hobbs et al., 2019). The declining population trend of the two most heavily studied stocks may in part have encouraged a comparatively higher volume of research with regards vessel impacts, however the Cumberland Sound stock is also known to be declining and this stock has only two data records (from two documents), so stock population trend is perhaps not the only factor driving research effort. Another possibility is that both Cook Inlet and St. Lawrence Estuary stocks both occupy heavily trafficked estuaries, with proximity to ports and harbours, along with established vessel-based wildlife watching trips in both regions. Vessel traffic versus data record locations are discussed further in Section 4.3.

Within the 305 stock-specific beluga data records, 139 directly observed a response or impact to vessels and their associated activities, whereas 57 predicted a response or impact, 34 recorded no response or overlap (observed, or predicted), and fifteen records had inconclusive results (Fig. 3). Nine data records covered one or more fatal interactions with vessels and their activities, including fatal ship or motorboat collision (Mikaelian et al., 1999; Lair et al., 2014; Truchon et al., 2018), fatal interactions with fishing gear (Curren and Lien, 1998; Truchon et al., 2018), multiple deaths directly linked to a tanker oil spill (Andrianov et al., 2016) and deaths related to live-capture operations using a motorboat (Shpak and Glazov, 2014).

Within the review database, there are also 11 data records with regards belugas that describe data collected either in a captive setting, or in an area out with the expected habitat range. More specifically, there are three data records (from one document) of a solitary beluga in Long Island Sound and its interactions with various vessel types, including following a pleasure boat for more than 50 km (Overstrom et al., 1991). This is out of stock range, and so is not included in the stock distribution figures (Fig. 3 or Supplementary Material: Fig. S3). Additionally, there are eight data records (from five documents) from captive belugas, again information pertaining to captive studies are not included in Fig. 3 or Supplementary Material: Fig. S3. The captive studies mainly focused on playback experiments of recordings of large ships (e.g. container ship, icebreaker), to explore hearing thresholds (Mooney et al., 2020), effects

Table 1
Number of documents and unique data records that present information on an observed or predicted response (or inconclusive result) of Arctic whales to vessels and/or vessel activities. Note, many documents presented multiple data records. Cetacean illustrations by Uko Gorter.

		Beluga 		Bowhead whale 		Narwhal 		Total Data Records
		Documents	*Data Records*	*Documents*	*Data Records*	*Documents*	*Data Records*	
Predicted	*No response*	3	3 (0.9%)	1	1 (0.5%)	0	0 (0.0%)	**6 (1.0%)**
Observed	*No response*	7	11 (3.5%)	9	13 (6.5%)	1	1 (1.3%)	**26 (4.4%)**
Observed	*No detection*	1	1 (0.3%)	0	0 (0.0%)	0	0 (0.0%)	**1 (0.2%)**
Predicted	*No co-occurrence*	4	19 (6.0%)	4	7 (3.5%)	1	6 (7.5%)	**30 (5.0%)**
Predicted	*Co-occurrence*	6	31 (9.8%)	6	26 (13.0%)	2	13 (16.3%)	**70 (11.7%)**
Observed	*Co-occurrence*	11	29 (9.2%)	5	9 (4.5%)	2	3 (3.8%)	**41 (6.9%)**
Predicted	*Response or impact*	35	62 (19.6%)	14	18 (9.0%)	7	11 (13.8%)	**91 (15.3%)**
Observed	*Response or impact*	52	144 (45.6%)	33	114 (57.0%)	14	39 (48.8%)	**296 (49.7%)**
	Findings inconclusive	12	16 (5.1%)	7	12 (6.0%)	1	7 (8.8%)	**35 (5.9%)**
	Total	**110**	**316**	**64**	**200**	**24**	**80**	**596**

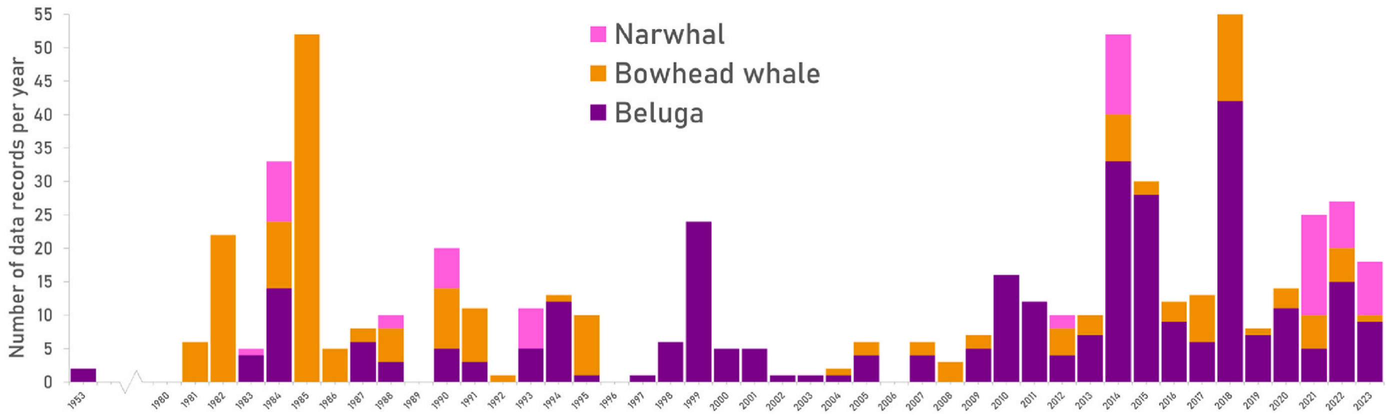


Fig. 2. The annual number of data records published focusing on endemic Arctic whale responses to vessels and/or vessel related activity, coloured by species.

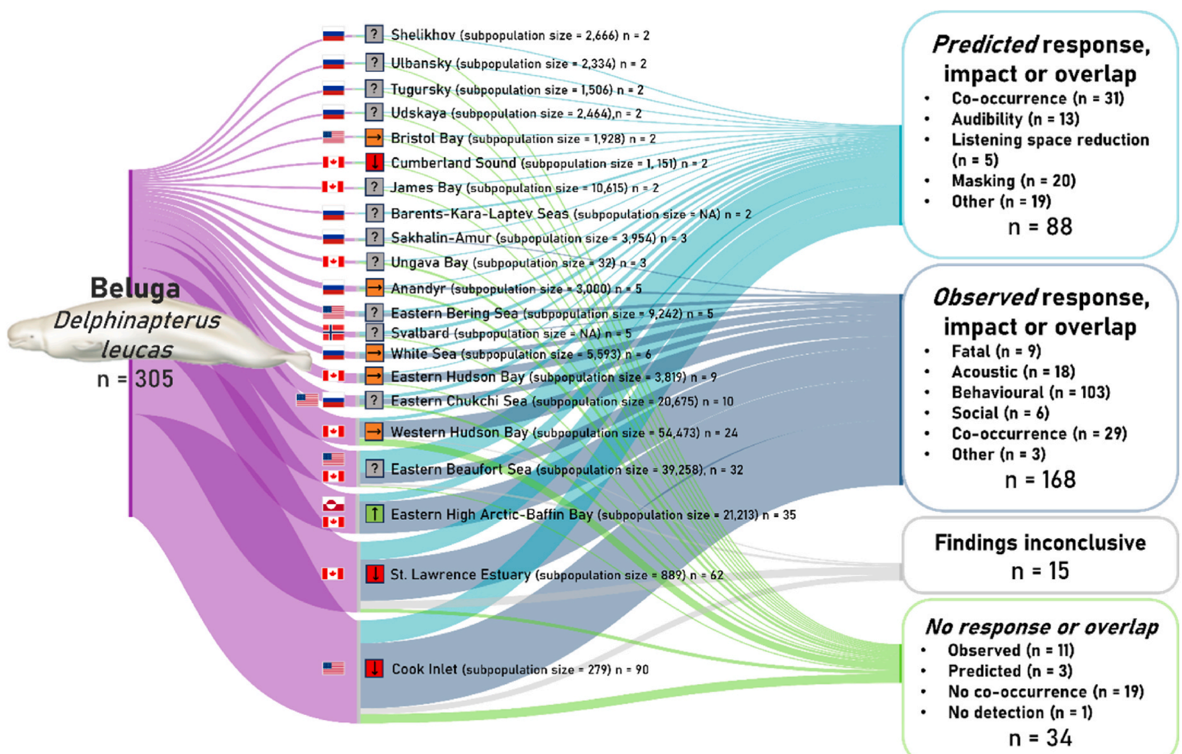


Fig. 3. Volume of data records per beluga stock that focus on response to vessels and/or vessel activities. Width of flow demonstrates the volume of data records for each response type. Stock metadata are provided for illustrative purposes: stock location (state or country flags), population trend (as directional arrows or question marks (i.e. unknown) within coloured squares), and abundance (from Hobbs et al., 2019). Beluga illustration by Uko Gorter.

of noise (i.e. potential for masking (Erbe, 1997), and evidence of physiological response by exploring change in cardiac activity (Lyamin et al., 2016)).

3.2.2. Bowhead whale response to vessels and associated activity

From the 64 documents identified that included information on bowhead whales, the review recorded a total of 200 data records referring to bowhead responses to vessels and their associated activities. There was a disparity in the number of data records per subpopulation, with both endangered subpopulations (Okhotsk Sea and East Greenland-Svalbard-Barents Sea) each only having four and seven data records respectively (from three and five documents), in comparison to 173 data records for the Bering-Chukchi-Beaufort Sea subpopulation (from 56 documents) (Fig. 4; Supplementary Material: Fig. S4). Of the four data records for the Okhotsk Sea population, two were expansive studies mapping Arctic-wide ship traffic or ship routes to predict potential for overlap and conflict across subpopulation ranges (Reeves et al., 2014; Hauser et al., 2018), whilst the other two records provided anecdotal accounts of negative interactions: ‘a *tourist boat hit a bowhead whale several times while pursuing the animal; at the same time, another whale, which was frightened, became entangled in the anchor line of a second boat*’ (Shpak & Paramonov, 2018). Similarly, studies of the East Greenland-Svalbard-Barents Sea were also based on largely predictive Arctic-wide studies, or passive acoustic monitoring to demonstrate spatial and temporal overlap (e.g. bowhead calls recorded simultaneously with vessel noise during passive acoustic monitoring (Moore et al., 2012; Ahonen et al., 2017), and prediction of overlap with shipping traffic or sea routes (Reeves et al., 2014; Hauser et al., 2018)).

A large proportion (122 of 200) of the data records for bowhead whales pertained to oil and gas related vessels (i.e. seismic surveys,

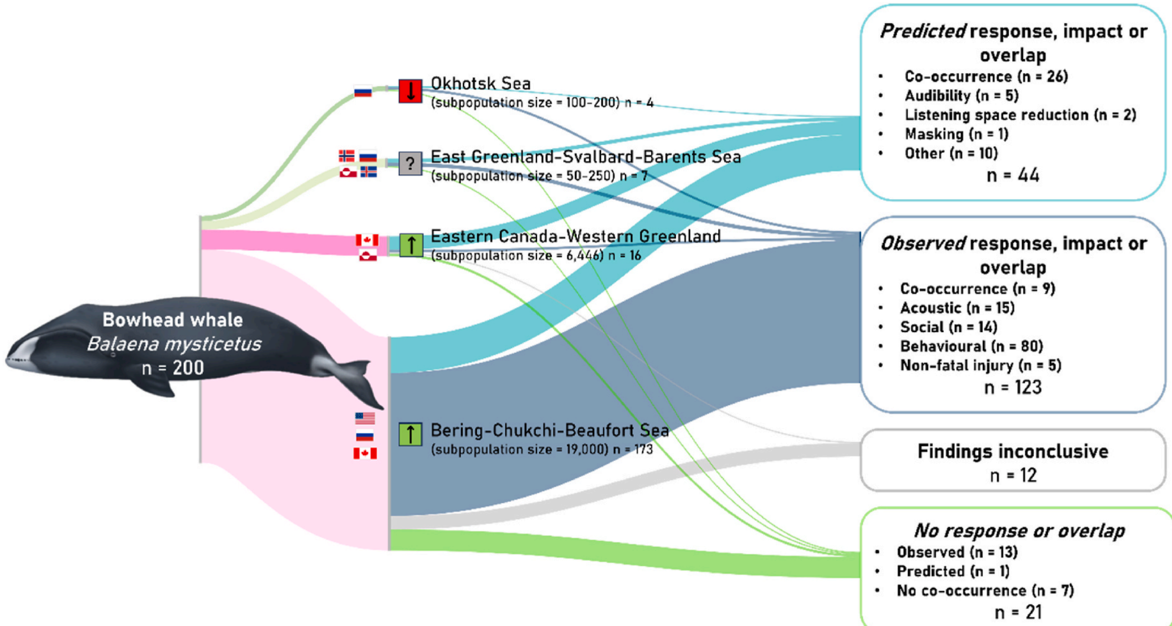


Fig. 4. Volume of data records per bowhead whale subpopulation that focus on response to vessels and/or vessel activities. Width of flow demonstrates the volume of data records for each response type. Subpopulation metadata are provided for illustrative purposes: subpopulation location (state or country flags), population trend (as directional arrows or question marks (i.e. unknown) within coloured squares), and abundance (from Givens et al., 2017; Cooke and Reeves, 2018a, 2018b; Doniol-Valcroze et al., 2020). Bowhead illustration by Uko Gorter.

drillships, crew transfer vessels, oil tankers). All but seven of the 122 data records on this topic were focused on the Bering-Chukchi-Beaufort Sea subpopulation. Much of research effort related to this topic and region is likely driven by oil and gas interest and developments in the eastern Beaufort Sea which have been ongoing since the late 1970s. 87 of the 122 oil and gas related data records reported a negative response to vessels and activities of this type, including behavioural changes, change in social activity (e.g. Richardson et al., 1985a; Ljungblad et al., 1988), spatial displacement (Fraker et al., 1982; Ljungblad et al., 1988), and change in sound production rate (e.g. Blackwell et al., 2013; Thode et al., 2020).

Within the 200 bowhead whale data records, 114 directly observed a response or impact to vessels and their associated activities, whereas 18 predicted a response or impact, 21 recorded no response or overlap (observed, or predicted), and twelve records had inconclusive results (Fig. 4; Supplementary Material: Fig. S4). There were no data records that reported fatal bowhead whale interactions with vessels and their activities, though there were multiple records of scarring related injuries likely the result of non-fatal vessel strikes (George et al., 1994, 2017, 2019). Behavioural changes were reported in 80 data records within 25 documents, including responses to vessels engaged in seismic surveying (Robertson et al., 2013; Richardson et al., 1986), and changing orientation, blow interval and surface duration during an approach from a 12.5-m motorboat (Richardson et al., 1984).

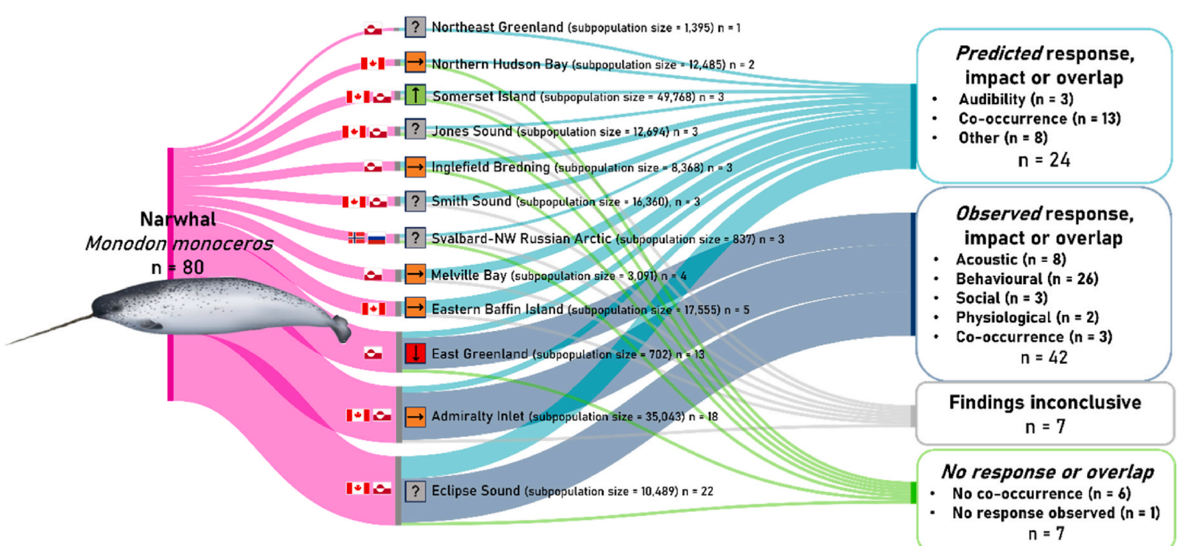


Fig. 5. Volume of data records per narwhal stock that focus on response to vessels and/or vessel activities. Width of flow demonstrates the volume of data records for each response type. Stock metadata are provided for illustrative purposes: stock location (state or country flags), population trend (as directional arrows or question marks (i.e. unknown) within coloured squares), and abundance (from Hobbs et al., 2019). Narwhal illustration by Uko Gorter.

3.2.3. Narwhal response to vessels and associated activity

There were 80 data records with regards to narwhal response to vessels and their associated activity, from 24 documents spanning 1983 to 2023. The volume of data records per stock was low (range = 1–22, from 1 to 14 documents per stock), with only three of the twelve stocks having more than five data records in the review database (with those data records from 5 to 14 documents) (Fig. 5; Supplementary Material: Fig. S5). Nine of the twelve stocks had no observational reports of responses to any vessel type or their associated activities, and instead there were only records for these stocks that predicted overlap of vessel traffic or shipping routes within their range (Reeves et al., 2014; Hauser et al., 2018), predicted audibility (Sweeney et al., 2022), or contained inconclusive findings.

The majority of the data records for narwhals focused on goods vessels (carriers, containers, cargo, n = 42) with the other records relating to icebreakers (n = 21) and oil and gas related vessels (n = 14). All data records on icebreakers reported empirical observations of a response to presence of a transiting and/or icebreaking vessel, including change in sound production rate (Finley et al., 1990), behavioural change such as change in activity, orientation, speed or displacement (LGL & Greeneridge, 1984; Miller and Davis, 1984; Cosens and Dueck, 1988), and change in distance to nearest neighbour (Finley et al., 1990). All 14 oil and gas related records involved seismic survey vessels, with ten of the data records reporting observations of response to the vessels and their activity (firing airguns), including cessation of foraging within 7–8 km of firing ships (Tervo et al., 2021), spatial displacement (Heide-Jørgensen et al., 2021) and change in dive response (Williams et al., 2022). The other four data records predicted narwhals to be at risk from such vessels (e.g. spatial/temporal overlap (Moore et al., 2012; Scharffenberg et al., 2021)).

3.3. Vessel systematic review results

3.3.1. Summary: study locations vs vessel dense regions

To illustrate how the data records of Arctic whale responses to vessels and their associated activities overlap with vessel density, we overlaid the review database records with PAME ASTD vessel traffic data (see Section 2.4.2) from 2019 (Fig. 6). The vessel data covers almost all of the combined ranges of the three study species, with the exception of the St. Lawrence Estuary (relevant to beluga range) and the Okhotsk Sea (relevant to beluga and bowhead whale range) for which there was no PAME vessel data coverage. Within the combined range of Arctic

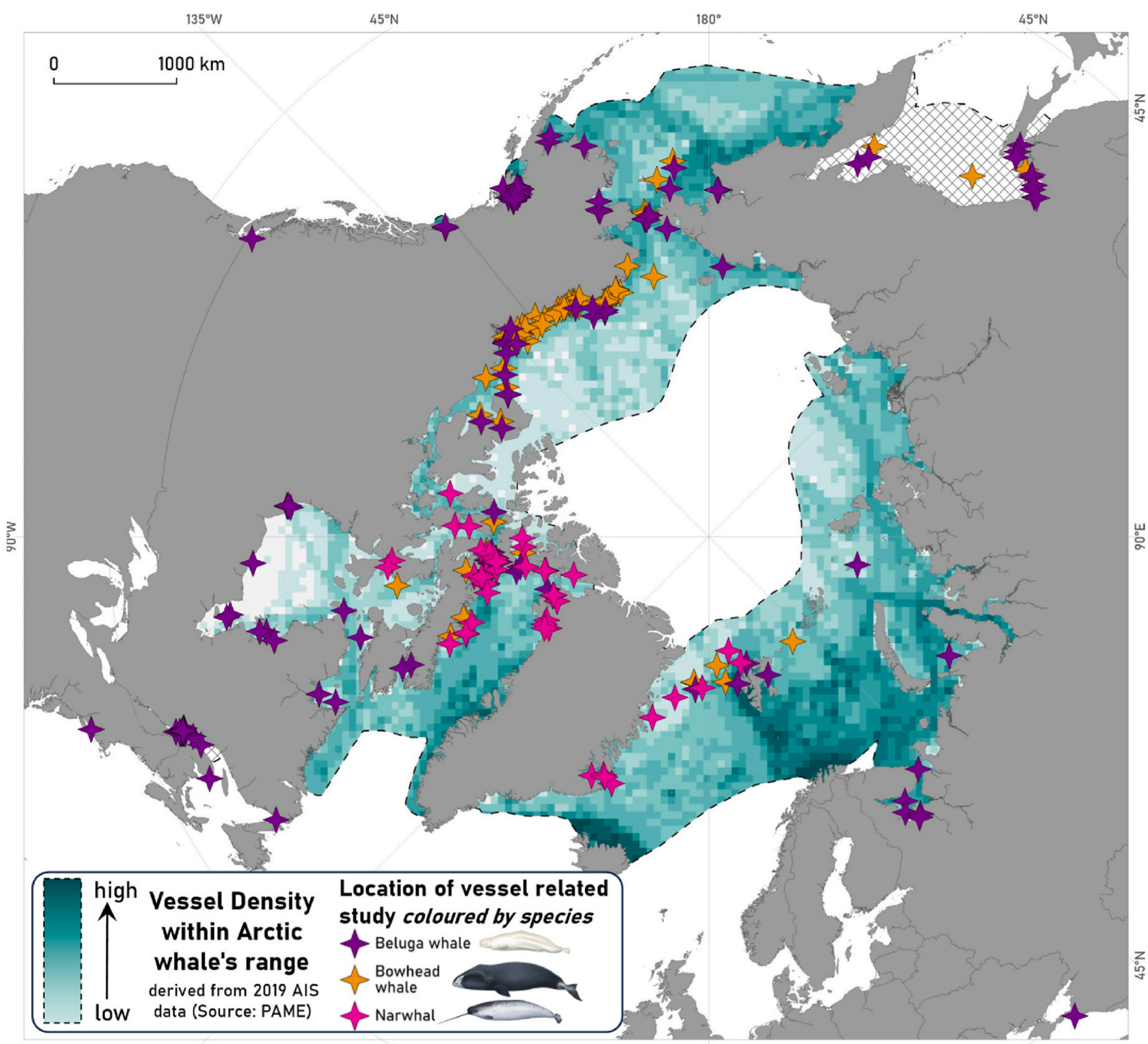


Fig. 6. Location of data records that present information on response to vessels and/or vessel activities. Data record locations are coloured based on species of study and are presented over a fishnet density grid of 2019 vessel density (data source: Protection of the Arctic Marine Environment), which has been clipped to the combined range of Arctic whales. Cross hatched areas indicate no vessel data were available within this area of Arctic whales range. Cetacean illustrations by Uko Gorter.

whales, vessel traffic in 2019 was comparatively higher within the Norwegian Sea, the Barents Sea, the Kara Sea (particularly the Gulf of Ob), the Iceland Sea, Davis Strait, Eclipse Sound, the Bering Sea (particularly coastal Russian areas), Cook Inlet and Bristol Bay. In contrast, the locations of data records identified within this review were mostly focused in Cook Inlet, Mackenzie Bay (Beaufort Sea), Lancaster Sound and the St. Lawrence Estuary (Fig. 6).

Belugas: For belugas, the most heavily trafficked regions within their range are the Kara Sea, waters surrounding Svalbard, Davis Strait, Cook Inlet and the Bering Sea (particularly coastal Russian areas), however beluga vessel research is most common within Cook Inlet, Lancaster Sound and St. Lawrence Estuary (Supplementary Material: Fig. S6a). There was no vessel data for the St. Lawrence Estuary to demonstrate the volume of vessel traffic there in comparison to the volume of studies (n = 62 data records on the St. Lawrence Estuary stock), however we know from other studies and vessel data resources that this an area that experiences a high volume of vessel activity (Pelot and Plummer, 2010; Veinot et al., 2023). This may have driven the high proportion of studies of this subpopulation.

Bowhead whale: The most heavily trafficked regions within the bowhead whales' range are the Norwegian Sea, the Barents Sea, the Iceland Sea and Davis Strait. However, bowhead vessel research effort appears to be highly concentrated within coastal areas of the Beaufort Sea, particularly Mackenzie Bay (Supplementary Material: Fig. S6b). There was no vessel data for the Okhotsk Sea to demonstrate the volume of vessel traffic there in comparison to the volume of studies (n = 4), however, other studies indicate a medium to high volume of vessel activity in the Okhotsk Sea which may pose a risk to whales (Silber et al., 2021). In this review, there were only four studies for the entire Okhotsk Sea subpopulation, and so more research effort for this region is recommended to better understand the impacts of vessel for this declining subpopulation.

Narwhal: Davis Strait, Pond Inlet and Eclipse Sound were the most heavily trafficked regions within the narwhals' overall range (Supplementary Material: Fig. S6c). Notably, narwhal data records were heavily concentrated within the heavily trafficked regions of Pond Inlet and Eclipse Sound, though there were no data records from the heavily trafficked portion of Davis Strait (Supplementary Material: Fig. S6c).

3.3.2. Vessel specific responses

585 of the 596 total data records specified the type(s) of vessel involved in the study. Of the eleven data records that did not identify the vessel type, six reported non-fatal injuries or scarring which were attributed to or confirmed as a result of a vessel strikes (beluga; Burek-Huntington et al., 2015; McGuire et al., 2020; bowhead whale; George et al., 1994, 2017, 2019), three data records reported fatal interactions with vessels (all beluga; Burek-Huntington et al., 2015; Truchon et al., 2018; McGuire et al., 2021), whilst two data records

Table 2

Heat map table to show number of data records per vessel type that present information on an observed or predicted response (or inconclusive result) of Arctic whales to vessels and/or vessel activities.

		Vessel Type												
		All vessels included	Goods (carriers, containers, cargo)	Cruise Ship	Fishing vessel	Harbour, Port or Navigation	Icebreaker	Kayak, paddleboard, row boat, windsurfer	Motorboat	Oil and Gas related	Miscellaneous	Passenger	Tug	Grand Total
Beluga	Observed response or impact	12	17	0	6	11	18	6	43	3	6	15	0	*137*
	Predicted response or impact	18	38	3	1	15	7	5	15	6	3	8	2	*121*
	No response or overlap observed or predicted	5	16	0	0	1	0	0	5	1	1	4	0	*33*
	Findings inconclusive	4	2	1	0	0	2	0	4	1	0	3	0	*17*
	Total	**39**	**73**	**4**	**7**	**27**	**27**	**11**	**67**	**11**	**10**	**30**	**2**	**308**
Bowhead whale	Observed response or impact	4	0	0	2	4	1	0	11	87	1	0	1	*111*
	Predicted response or impact	11	10	3	2	0	2	0	5	18	0	0	0	*51*
	No response or overlap observed or predicted	5	2	0	2	1	0	1	0	9	1	0	0	*21*
	Findings inconclusive	2	0	0	0	2	0	0	0	8	0	2	0	*14*
	Total	**22**	**12**	**3**	**6**	**7**	**3**	**1**	**16**	**122**	**2**	**2**	**1**	**197**
Narwhal	Observed response or impact	0	8	0	0	0	21	0	0	10	0	0	0	*39*
	Predicted response or impact	3	20	0	0	0	0	0	0	4	0	0	0	*27*
	No response or overlap observed or predicted	0	7	0	0	0	0	0	0	0	0	0	0	*7*
	Findings inconclusive	0	7	0	0	0	0	0	0	0	0	0	0	*7*
	Total	**3**	**42**	**0**	**0**	**0**	**21**	**0**	**0**	**14**	**0**	**0**	**0**	**80**
	Grand Total	**64**	**127**	**7**	**13**	**34**	**51**	**12**	**83**	**147**	**12**	**28**	**3**	**585**

quantified volume of butyltin compounds within liver samples (the source of butyltin is antifoulant used for small watercraft) (beluga; St-Louis et al., 2000). All eleven data records provide evidence of impact of vessels, without being able to confirm vessel type responsible. The results presented in the following section now only consider data records where vessel type is specified (n = 585).

There is great variation in the volume of data records per vessel type category (range = 3–147; Table 2). The vessel type most commonly studied (when specified) were oil and gas related vessels (n = 147), followed by goods vessels (carriers, containers, cargo; n = 127) (Fig. 7; Table 2). The most commonly studied vessel type varied between species; goods (carriers, containers, cargo) for beluga and narwhal (n = 73, n = 42, respectively), whereas oil and gas related vessels were by far the most commonly studied vessel type for bowhead whales (n = 122) (Table 2).

Of the recorded responses to vessels, oil and gas related vessels (n = 100), motorboats (n = 54) and icebreakers (n = 40) were the most commonly reported vessel types to elicit responses (Table 2). Attraction to vessels, i.e. closer interactions than expected by chance, were reported only for beluga whales, with attraction, close approaches and/or close interactions with kayaks (Ausen et al., 2022), motorboats (Chmelnitsky, 2010) and commercial wildlife watching passenger trips (Blane and Jackson, 1994) all documented.

The vessel data and associated data records from the systematic review were separated according to vessel categories (as defined by PAME) (Figs. 7 and 8), to explore and illustrate whether studies on specific vessel types corresponded with areas that have high levels of activity for that vessel type (Fig. 8).

Cruise ships: Activity was most concentrated around Svalbard, the Barents and Kara Seas, and in Glacier Bay (Alaska), with seven data records documenting responses to cruise ships located in Yakutat Bay, and the Amundsen Gulf and Beaufort Sea. There were four data records focusing on beluga whale responses to cruise ships, three relating to bowhead whales and zero for narwhals (Fig. 8a; Table 2). One study deployed acoustic recorders to explore cruise ship occurrence and potential impacts on beluga whale presence, however no analysis or findings were reported in the document (i.e. 'findings inconclusive) (O'Corry-Crowe et al., 2009). The other two documents that focused on cruise ships and beluga and bowhead whales were both focused on the Amundsen Gulf and Beaufort Sea, and predicted spatial overlap of this vessel type with both bowheads and belugas, along with a predicted listening space reduction due to cruise vessel noise (Halliday et al., 2018; Pine et al., 2018). There were no records of direct observations of response or impacts of cruise ships to any of the three species.

Oil and gas related vessels: Activity was most concentrated in Cook Inlet, around Svalbard, in the Barents and Kara Seas, and in all Russian coastal areas of the Chukchi and Bering Seas. However, despite oil and gas related vessels being the most commonly reported vessel type within this review, studies involving these vessels were extremely limited within the regions identified as having higher levels of activity. Instead, studies involving oil and gas vessels were most concentrated along the Alaskan and Canadian coastline of the Beaufort Sea (Fig. 8b). These records mainly focus on bowhead whales, and represent research effort conducted to assess the impacts of oil and gas exploration vessels (i.e. seismic surveys), drillships, and drilling associated vessels. Whilst the Beaufort Sea appears to have less oil and gas related vessel activity in 2019 according to the PAME ASTD data, it is possible that some oil and gas vessels (e.g. seismic survey vessels) fell into the 'Miscellaneous' PAME category and so are not represented in Fig. 8b. The majority of data records relating to oil and gas vessels involved bowhead whales (n = 122), with far less records for beluga and narwhals (n = 11, n = 14 respectively) (Table 2).

Passenger: Passenger vessel activity (ferries, tour boats; including wildlife watching day trips) appear to congregate along defined routes,

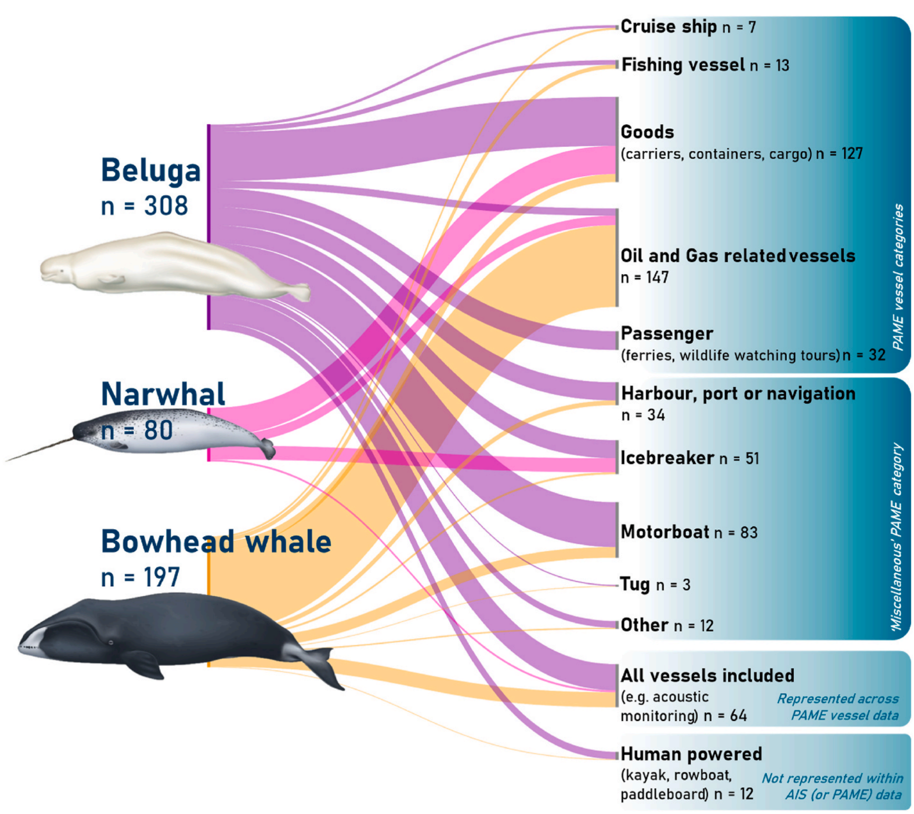


Fig. 7. Volume of data records per Arctic whale species that present information on response to vessels and/or vessel activities. Width of flow demonstrates the volume of data records for each vessel type. Vessel types are categorised into Protection of the Arctic Marine Environment (PAME) vessel data categories. Cetacean illustrations by Uko Gorter.

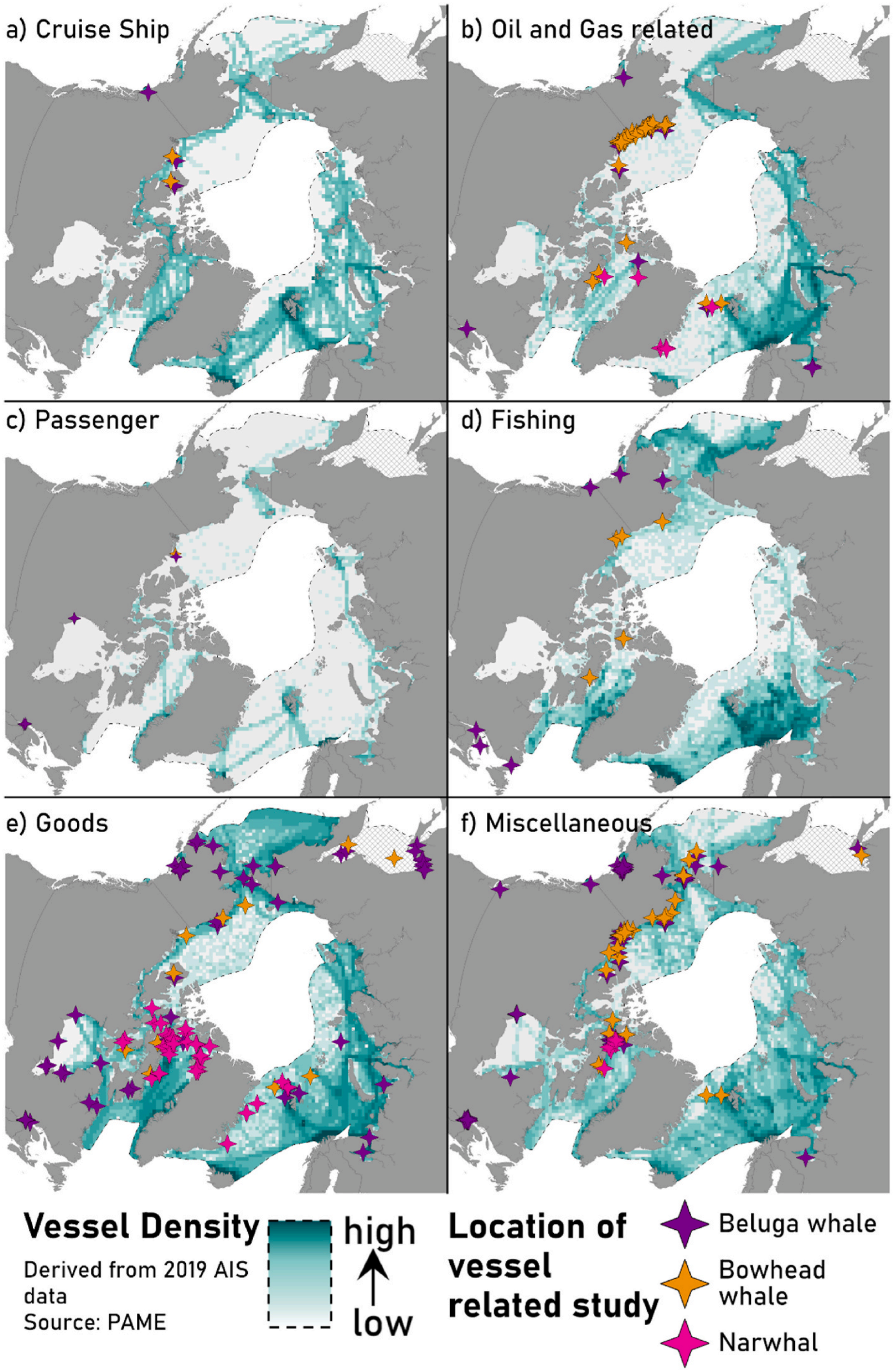


Fig. 8. Location of data records that present information on response to specific vessel categories and/or vessel activities. Panels represent data record locations and vessel density data only for that defined category (a) cruise ship, b) oil and gas related vessels, c) passenger vessels, d) fishing vessels, e) goods vessels, f) miscellaneous vessels). Data record locations are coloured based on species of study and are presented over fishnet density grids of 2019 vessel density for that specific vessel type (data source: Protection of the Arctic Marine Environment), which has been clipped to the combined range of Arctic whales. Cross hatched areas indicate no vessel data were available within this range area.

whilst also showing particularly high densities in some coastal regions, including northern Norway, Svalbard, northern Iceland, western Greenland, the Anzhu Islands and Cook Inlet (Fig. 8c). The locations of the 32 data records for passenger vessels do not overlap with any of the high activity areas for this type of vessel according to PAME data, and instead occur in the Inuvialuit Settlement Region in the western Canadian Arctic (bowhead and beluga; Halliday et al., 2018), in Churchill (Manitoba) (beluga; Malcolm and Penner, 2011; Ausen, 2022; Ausen et al., 2022; Westdal et al., 2023), and in the St. Lawrence Estuary (no vessel data). Studies on the St. Lawrence Estuary beluga stock account for 21 of the 32 records focusing on passenger vessels. Thirteen of these data records documented a response to wildlife watching vessels, including avoidance behaviour, increased speed, prolonged inter-breath intervals and evidence of Lombard vocal response (Blane and Jackson, 1994; Scheifele et al., 2005). Six data records from the St. Lawrence Estuary belugas also observed a response to ferry noise (administered via controlled exposure experiments), documenting change in call rates, call duration and frequency range when exposed to ferry noise (Lesage et al., 1999). Only two of the 32 data records for passenger vessel focus on species other than beluga, providing predictions of risk and spatial overlap for Bering-Chukchi-Beaufort Sea bowhead whales (Halliday et al., 2018).

Fishing Vessels: The activity of fishing vessels appears to be reasonably well distributed across the range of Arctic whales, particularly around the USA, Greenland, Iceland, Norway, and Russia. Despite this spatial overlap, there are limited records of responses to fishing vessels and their associated activities, with only seven data records for belugas, six for bowhead whales and zero for narwhals (Fig. 8d; Table 2). Of the thirteen records identified, two reported fatal interactions with fishing vessels (both belugas; Curren and Lien, 1998; Truchon et al., 2018), two reported non-fatal injuries after interaction with fishing gear attached to the vessel itself (both belugas; Curren and Lien, 1998; Lucey et al., 2015), and the remainder reported behavioural responses to fishing vessels, including change in activity (bowhead whale; Richardson et al., 1985a), spatial displacement (beluga; Huntington et al., 1999) and attraction to the vessel itself (beluga; Overstrom et al., 1991).

Goods (Carriers, Containers, Cargo): There is widespread goods vessel activity across the entirety of all three species ranges, with lower volumes in the northern Beaufort Sea and in southern Hudson Bay. Goods vessels were the most commonly studied vessel type for both belugas and narwhals, and the second most studied vessel type in the review overall (n = 127). Studies are evenly distributed across the species ranges, but there were limited studies in Davis Strait and the Barents, Kara and Bering Seas, despite these waters all being highly trafficked by goods vessels (Fig. 8e). Only 26 of the 127 records presented empirical evidence of response of Arctic whales to goods vessels, with 25 data records reporting an acoustic or behavioural response (e.g. alarm calls, rapid movement; Finley et al., 1984) and one data record reporting no observed effect (Sweeney, 2021) (Table 2).

Miscellaneous Vessel Type: The 'Miscellaneous' category within this review provide data records for multiple vessel types, including tugs, motorboats, icebreakers and seaplanes, and is overlaid with 'Miscellaneous' vessel types as recorded within PAME data (Fig. 8f). The majority of these studies were located within Canadian Arctic and Alaskan waters, however, given the breadth of this category, it is not necessarily useful to make inferences about the location of these studies versus the vessel activity data, but they are displayed for illustrative purposes.

Miscellaneous (Tugs): There were only three data records on responses to tugs within the review database, with one documenting a behavioural response to a transiting ice strengthened tug by a group of bowhead whales (Fraker et al., 1982), and another demonstrating spatial and temporal overlap with beluga whales in Cook Inlet (Carlson et al., 2015).

Miscellaneous (Motorboats): There were 83 data records on motorboats, a category which included rigid-hulled inflatable boats (RHIBs) and Zodiacs, subsistence vessels, pleasure craft (e.g. speedboats), with 67 data records on belugas, sixteen on bowhead whales and no studies on narwhals. 43 of the 67 beluga records, and eleven of the sixteen bowhead whale records reported direct evidence of a response to motorboat, including change in sound production rate (Lesage et al., 1999), change in swim speed (Stewart, 2010), change in interbreath interval (Richardson et al., 1984), change in group composition (Richardson et al., 1985b), injury (Shpak & Paramonov, 2018) and death (Mikaelian et al., 1999; Lair et al., 2014).

Miscellaneous (Icebreakers): Of the 51 data records for icebreakers, 27 were related to belugas, three related to bowhead whales and 21 related to narwhal. The majority (n = 40) were demonstrating acoustic (e.g. Finley et al., 1990), behavioural (e.g. Cosens and Dueck, 1988; Richardson et al., 1995) or social response (e.g. LGL & Greeneridge, 1984).

Human powered recreational activity: Kayak, paddleboard, rowboat, windsurfer: There is no data to demonstrate areas of high or low activity from human powered recreational activity for the Arctic, though it is reasonable to assume that this type of activity occurs more frequently in coastal waters (due to safety and likelihood of suitable weather and sea state conditions), and likely occurs more frequently near to areas of human coastal habitation. In the review, there were twelve data records on this vessel type; eleven for beluga, one for bowhead whale and no records for narwhals (Table 2; Supplementary Material: Fig. S7). Responses to these vessel types were mixed, with no response observed from bowhead whales to an approaching aluminium rowing boat (Hobbs and Goebel, 1982), but conversely, there were behavioural response observed by belugas, including attraction to kayaks (Ausen et al., 2022), change in activity around kayaks (Malcolm and Penner, 2011), and spatial displacement when in the presence of paddleboards (Ausen et al., 2022).

4. Discussion

This systematic map highlights that there are limited published studies reporting the response(s) of Arctic whales to vessels, and that the published knowledge is uneven between the various stocks and subpopulations designated for each species, and for the various vessel types that are encountered in Arctic waters. The inherently costly (Mallory et al., 2018) and physically challenging nature of studying Arctic species and observing their responses to highly mobile and variable stressors (here, vessels) has likely been responsible for the limited volume of direct evidence demonstrating the responses of Arctic whales to vessels and their activities. Many documents can only predict impact or co-occurrence, to highlight the risks faced by these unique species.

The significant gaps in scientific knowledge relating to the consequences of vessel presence and their activities to Arctic whales is concerning, given that many of these subpopulations and stocks are still recovering from the effects of industrial whaling (e.g. Mitchell and Reeves, 1982; Allen and Keay, 2006), and all Arctic cetaceans are increasingly being exposed to numerous anthropogenic activities that pose direct and in-direct threats, including entanglement in fishing gear (George et al., 2019) and unsustainable levels of subsistence hunting of some stocks (e.g. Mitchell and Reeves, 1982; Heide-Jørgensen et al., 2020; NAMMCO, 2023). To date there has been little effort to quantify or assess the extent to which many activities and their associated impacts co-occur within the Arctic, or to consider what the interacting and cumulative effects of co-occurring multiple stressors might be (Andersen et al., 2017). While this systematic map did not consider whether vessel-related impacts were documented in isolation or cumulatively, there is widespread recognition that vessels pose multiple pathways to impact for Arctic whales and therefore this should be an area for further exploration.

Furthermore, the potential impacts of vessels, including their cumulative effects, are further exacerbated and affected by the overall wide-ranging impacts of climate change (e.g. Williams et al., 2021). All three Arctic whale species are expected to undergo distributional shifts northwards towards colder habitats as oceans continue to warm (Chambault et al., 2022), with similar predictions for a northward expansion of vessel activity as reduction of sea-ice allows, including exploration of the long hypothesised Transpolar Sea Route (Bennett et al., 2020). The implications of any changes in Arctic whale distribution on their associated exposure and vulnerability to vessel traffic are currently unknown but may be disproportionately felt by stocks and subpopulations that were, until recently, isolated from exposure due to remoteness.

Ecologically the Arctic is also under a state of flux, with the changing Arctic environment allowing for previously non-resident Arctic species to extend their ranges northwards, potentially resulting in increasing range overlaps with endemic Arctic species (van Weelden et al., 2021). This new overlap may increase the potential for disease transmission of diseases, which in turn could result in unusual mortality events given the naivety of immune systems of endemic Arctic species (Barratclough et al., 2023). Similarly, due to declining sea ice, killer whales (*Orcinus orca*) are also increasingly utilising Arctic waters, with some Arctic regions not previously utilised by killer whales now reporting exponential increases in sightings (Ferguson et al., 2010). For endemic Arctic cetaceans, this is alarming given killer whales are known predators of all three species, with their presence causing significant changes to the behaviour and distribution of Arctic whales (Ferguson et al., 2010; Breed et al., 2017; Matthews et al., 2020). Given the dynamic and changing nature of the multitude of direct and indirect pressures being imposed on endemic Arctic whales, including the aforementioned impacts of changing Arctic ecology, consideration of how these negative effects may interact with the possible negative impacts associated with increasing vessel traffic is essential.

4.1. Interpretation of the review

There is a substantially larger volume of literature citing study locations from within Canadian or American waters, compared to other Arctic states. Further, lead author institutions are also most often based within Canada or the USA than other Arctic states. This may be, in part, due to the search being conducted only in English language. We did not exclude any non-English documents based on language alone, but it is possible that more results from other Arctic states would have been found had additional searches been conducted in other languages (e.g. Norwegian or Russian). This was beyond the scope of this review, but a similar systematic mapping process in other languages would be beneficial. Furthermore, Indigenous knowledge and ways of knowing in relation to how Arctic whales respond to vessels are less likely to be documented within scientific literature, or recorded within the databases we searched as part of this systematic mapping process. Even so, Indigenous knowledge contributed to at least 23 records (14 documents) within this review, though we expect the full extent of Indigenous knowledge available to have not been captured within this review. This knowledge is a hugely valuable resource that can contribute towards our collective understanding and evidence base, which can then support policy advice, decision making and management decisions (Alexander et al., 2019), and so incorporation of Indigenous knowledge should be highly encouraged. Further, given that many stocks and subpopulations are data deficient, Indigenous knowledge may be the only resource available to inform protective measures for these animals. Therefore, it would be advisable that future work should involve and be informed from the outset by local communities that are intrinsically linked to these species.

Whilst the overall number of documents (169) and data records (596) included in this review may initially appear a reasonable volume for just three species, we expect review results may be slightly inflated due to the same data being presented in different formats (and therefore in some cases appearing on multiple occasions in our review database). Despite potential inflation, this work shows there are still an extremely limited number of studies and associated knowledge for the majority of subpopulations, stocks and vessel types, and that the annual publication rate is still low despite some subpopulations being critically endangered. While recent trends show more consistent effort, there has been a particular focus on beluga and on specific stocks (see Tables 1 and 2, and Figs. 3–5 and 7 for a more detailed view of knowledge gaps and research focus).

4.2. Recommendations

4.2.1. We recommend greater scientific focus on understudied species, subpopulations and stocks

This review identified variation in the volume of research between species, as well as variation in research volume between the various subpopulations or stocks. For each Arctic whale species, the majority of their respective subpopulations or stocks had received limited research attention with regards their response(s) to maritime traffic, and thus many subpopulations and stocks warrant further attention. We demonstrate that despite the endangered or unknown population status of some stocks, and often small or declining population size, they have still received little consideration in the literature, other than the identification of vessels as a potential threat due to spatial or temporal co-occurrence (e.g Reeves et al., 2014; Hauser et al., 2018). A similar non-uniformity in research between beluga stocks was identified in a recent complementary systematic review, which explored the volume of literature on threats that may be limiting stock recovery (Norman et al., 2022). Furthermore, a previous bibliometric analysis of research effort across all marine mammal species highlighted a higher proportion of research attention being dedicated to less endangered species (Jarić et al., 2015).

By considering the intensity of Arctic vessel traffic within the areas utilised by each of the different subpopulations and stocks, we can gain an appreciation for the potential variation in exposure levels to vessel traffic and to different vessel types. This can aid in interpretation of response. For example, Harasyn et al. (2022) suggest that in contrast to other stocks that are hunted more regularly, belugas in the Churchill River estuary may be less avoidant of boats as they are not often hunted in that area. As well, repeated or frequent exposure to (non-hunt related) vessels may lead to some populations becoming more tolerant of vessel presence or specific activities, whilst populations with limited exposure may demonstrate clearer evoked responses to unfamiliar stimuli, though reduced responsiveness, potentially due to tolerance or habituation, should not be interpreted as lack of vulnerability to that stressor (Bejder et al., 2009; Harris et al., 2018). As identified within this review, we currently have an extremely limited understanding of the heterogeneity in responsiveness to vessels between Arctic whale stocks and subpopulations. However, to effectively identify and then mitigate against potential impacts of vessels it is essential to identify any potential subtleties in responsiveness or response behaviour between stocks, which may in part be influenced by their relative exposure history, amongst other factors (e.g. Heide-Jørgensen et al., 2015; Harris et al., 2018). Using data from more well studied stocks (or indeed, other species (e.g. Allen, 2014)) as proxies for response for other stocks or species has limitations and may not be appropriate for many cases. We would therefore recommend increased efforts towards collection of data on the less understood subpopulations and stocks, in order to provide decision makers with stock-specific evidence and knowledge that can then inform the most appropriate vessel-related management approaches for that locale.

4.2.2. We recommend further studies of vessel types that have increasing presence in the Arctic

This review also identified considerable variation in the volume of research focusing on response to specific vessel types, with more research on oil and gas related vessels and goods ships than any other vessel type. In contrast, some vessel types have been given very limited consideration (e.g. cruise ship (n = 7), fishing vessel (n = 13), tugs (n = 3), human powered recreational activity (n = 12); Fig. 7), and in some cases there were no records of any studies documenting a response to specific vessel types for all three Arctic whale species (e.g. cruise ship). These vessel types are increasing (Dawson et al., 2018), some at great pace and with further expansion likely (e.g. Tai et al., 2019), and it is therefore all the more urgent to develop a more substantial understanding of the effects that increasing exposure may have on Arctic species that may have insofar received limited exposure to these different types of vessel. In parallel to studies that quantify and characterise the temporal and spatial patterns and changes in Arctic vessel traffic (e.g. Dawson et al., 2018), we recommend research on response to these vessels be explored, particularly for those lesser studied vessel types identified by this review. Such studies can then serve to inform the most appropriate vessel specific management solutions to reduce and mitigate their associated impacts (e.g. Halliday et al., 2018; McWhinnie et al., 2018).

4.2.3. We recommend further research on underrepresented vessel-related stressors

Whilst it was beyond the scope of this review to quantify the specific vessel related stressors addressed within each data record, there was a noticeable focus towards effects of vessel noise pollution within the reviewed documents, whilst many other vessel associated stressors received limited attention. For example, there were only a few records focusing on the effects of hydrocarbon spills (bowhead whale; Jayko et al., 1990; beluga; Andrianov et al., 2016), vessel related pollutants (butyltin; St-Louis et al., 2000), ship strike (e.g. George et al., 2017), introduction of invasive species, inhalation of emissions, or cumulative effects of vessels to Arctic whales. The minimal literature on such topics contrasts with the research requirements being called for by some international bodies. For example, in their 'strategic plan to mitigate ship strikes', the International Whaling Commission identified the Western Arctic (territory of USA and Russia) as a potential high-risk area for bowhead whales that should be monitored (IWC, 2022).

We therefore recommend a more holistic approach to vessel related stressor studies, that builds upon and integrates outputs from vessel noise-related studies with other forms of stressor(s) and moves towards an understanding of the cumulative impacts of vessel traffic.

4.2.4. We recommend more focus on gaining empirical evidence rather than reliance on predictive studies

As aforementioned, this review has identified that there are numerous stocks, subpopulations, vessel types and vessel related stressors that have a limited evidence base with regards observed response to vessels and their associated activities, and instead the evidence is more often based upon predictive studies. Whilst we acknowledge the challenges associated with collecting direct observations, particularly in polar regions, we recommend a move towards studies that provide empirical evidence of the effects of vessels and their activities in order to properly quantify and address the potential impacts of vessels on Arctic whales. This evidence base will be critical to develop appropriate conservation measures to mitigate impacts of vessels to Arctic whales and would aid designation of spatially-delineated areas of conservation importance to these species. For example, knowledge of the vulnerability to disturbance to threats is outlined as evidence required towards the designation of an area as an Important Marine Mammal Area (IMMA), and so building the evidence base for these species is critical (Corrigan et al., 2014).

Furthermore, collecting such data for polar whales has often not involved, or benefited from the inclusion of, or collaboration with, Indigenous communities (Breton-Honeyman et al., 2016). Working with local communities and knowledge holders will likely be the most successful and valuable way to establish a thorough and robust evidence base for all stocks and subpopulations. Therefore, we would also highlight both the importance of co-developing studies with Indigenous communities, and of placing greater importance on utilising local knowledge and ways of knowing within research and monitoring plans.

4.2.5. We recommend a proactive and adaptive approach to vessel-related management measures for Arctic whales, that are relevant to each species, stock or subpopulation

Ice coverage has previously provided the Arctic with a natural buffering system for marine resource governance, as ice has seasonally restricted access to many public goods and common pool resources (Fernandez et al., 2016). Now that ice regimes are changing, conservation and management in the Arctic, as in many other places, can be contentious because it involves "messy problems", shaped by ecological and social forces (Meek et al., 2011). In addition, mobile and stationary Arctic resources often straddle various political and geographic boundaries at regional and international scales (Fernandez et al., 2016). With regards Arctic whales, this is critical given their trans-boundary nature, and thus makes it important that communication and strategic planning are pursued on bilateral, multilateral and international basis (Reeves et al., 2012). Currently, each Arctic country and Indigenous community may have sovereign legally binding statutes separately in their own jurisdictions.

The Polar Code, developed by the United Nations International Maritime Organisation (IMO) aimed to bridge all Arctic jurisdictions and provides a mandatory code of conduct which aims to harmonize and upgrade vessel operating standards within international Arctic waters (Reeves et al., 2014). However, it is remains to be seen whether the current Arctic governance structure is sufficient to handle the demands of increasing maritime activities, whilst achieving environmental protection (including conservation of Arctic whale species).

We strongly recommend a timely and proactive approach to the development of area- and species-appropriate management measures, which can mitigate against the effects of increasing maritime activity, whilst being adaptive to the changing use of the Arctic by both vessels and the whales (for example, areas to be avoided, vessel slowdown zones, whale watching time and distance regulations). The findings of this systematic map indicate that despite the limited evidence base for many subpopulations and stocks, there is evidence for all three Arctic whale species that vessels can have deleterious impacts, and therefore proactive efforts should be made to mitigate against the effects of any further increases in marine traffic.

5. Concluding remarks

In 2014, Reeves et al. (2014) described Arctic ship traffic data as '*woefully inadequate for environmental assessment purposes*'. Whilst there have been substantial advances in vessel data capture since 2014, we identify here that published knowledge of how Arctic whales are impacted by vessels continues to be substantially lacking, especially considering the ongoing and forecasted increases in Arctic vessel activity in conjunction with the other pressures these species are increasingly facing. These endemic species occupy some of the most remote and pristine waters and, aside from whaling, until recently have received limited exposure to many anthropogenic threats. From the limited data records identified within this review, there is clear evidence that Arctic whales respond to vessels and their associated activities. Therefore, prior to proceeding with plans to further exploit Arctic resources, trade routes or tourism opportunities, it is imperative that knowledge gaps related to the consequences of increasing vessel traffic on Arctic whales are addressed, allowing the development of proactive and appropriate management measures that will aim to mitigate any impacts that current and future maritime activities might have on these valuable species and the unique environment they inhabit.

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CRediT authorship contribution statement

Emily L. Hague: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lauren H. McWhinnie:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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