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Estimating risk to ice-breeding pinnipeds from shipping in Arctic and sub-Arctic seas

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ABSTRACT

Industrial shipping activity in some Arctic and sub-Arctic seas is increasing during the winter and spring seasons of heavy ice cover. Here, following from a previous study of icebreaker impact on seals in the Caspian Sea, the extent of overlap between shipping and breeding habitat of ice-associated pinnipeds in other seas is investigated. Significant industrial shipping activity in potential pinniped breeding areas during the spring pupping period 2017 was recorded in the Baltic Gulfs of Finland and Bothnia (grey and ringed seals), the White Sea and Newfoundland Belle Isle Strait (harp seal), the Ob Estuary in the Kara Sea (ringed seal), The Pechora Sea (walrus) and Sakhalin Island area in the Okhotsk sea (ringed, bearded, ribbon and spotted seals). Most areas lack sufficient pup density distribution data to apply quantitative evaluations, but for the Caspian and White Seas it was possible to estimate a measure of vessel disturbance in terms of the potential number of collisions with pups in the path of a single vessel of a given beam width, giving a result of 9.6% of Caspian seal pups and 1.9% of White Sea harp seal pups in the 2006 and 2009 seasons respectively. This study highlights the need to consider policy and regulatory frameworks for vessels transiting pinniped ice breeding areas in advance of further growth in vessel traffic during winter and spring. Stakeholders operating shipping through pinniped breeding habitat in sea ice could play a role in generating the data necessary for such impact assessments and evidence-based mitigation measures.

1. Introduction

Shipping activity and industrial development in Arctic and sub-Arctic seas has been growing in recent years, exposing their ecosystems to new forms of anthropogenic pressure and disturbance [1–3]. The potential for ice-breaking vessel traffic to cause detrimental impacts on ice-breeding seals was first raised as a concern for the Canadian Arctic [4–6], where there are extensive populations of ringed (*Pusa hispida*) and bearded seals (*Erignathus barbatus*) and walrus (*Odobenus rosmarus*) [7–11]. More recently, the impact of industrial shipping has been raised in the White Sea concerning breeding harp seals (*Phoca groenlandica*) [12] and in the Baltic Gulfs of Bothnia and Finland [13,14] – historically home to breeding ringed and grey (*Halichoerus grypus*) seals. These sea areas have become major shipping routes for large cargo ships and crude oil carriers [15], which break up the fast ice cover, creating artificial drift ice conditions [16].

However, the actual impact of vessel traffic on seals breeding on the ice had not been directly quantified until a recent study in the north-eastern Caspian Sea [17]. Here the impacts included vessel collisions with individual mothers or pups, displacement of mothers and pups from their natal site, separation of pups from their mothers and nursery habitat breakage. This study highlighted the need to evaluate the potential for similar impacts in other areas where the routes and activities of industrial vessels (oil and liquefied gas tankers, cargo ships, ice-breakers and tugs) overlap with sea-ice areas used by pinnipeds in Arctic and sub-Arctic areas for birthing and pup-rearing (jointly referred to as ‘pupping’).

Policy and regulatory guidelines for vessel impacts on marine

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mammals in the Arctic have lagged behind the recent growth in shipping. In order to develop international policies and conservation measures to protect ice-breeding pinnipeds from shipping [18–20], it is first necessary to identify the present and potential scale of the problem with respect to different sea areas and species. While several risk assessment studies in relation to shipping have been conducted for Arctic marine mammals, these have focused on cetaceans [21] or the open water season [3], but the specific impacts and vulnerabilities for ice-breeding pinnipeds during their pupping seasons have yet to be considered in detail.

The objectives of the present study are therefore (a) to identify sea ice areas, species and periods where there is likely to be an existing problem of vessel-pinniped overlap and (b) to estimate the numbers and types of vessels transiting particular sea-ice areas, their size and typical speeds, and – in two areas with adequate pup density distribution data – associated implications for collision risk.

2. Methods

2.1. Pinniped species

We consider potential shipping overlap with breeding areas on sea ice for the walrus and seven ice-breeding phocid seal species: bearded seal, Baltic grey seal, harp seal, ringed seal, hooded seal (*Cystophora cristata*), ribbon seal (*Histriophoca fasciata*) and spotted seal (*Phoca largha*). GPS locations or spatial polygons defining the approximate areas of sea-ice breeding for each of these species were collated from a systematic literature survey using genus names and the terms 'breeding' and 'pupping' in Google Scholar. Additionally, pre-2000 publications in the Seal Conservation Society archive and Proceedings of the Marine Mammals of the Holarctic conference series from 2008 were also reviewed. Data including pupping locations, periods, and pup densities, were collated in an Excel database. Where GPS locations were not given in the original source, they were determined as closely as possible from the published maps and place names. Spatial data were plotted in Google Earth for visual reference.

2.2. Locations and types of vessels transiting ice-covered sea areas, spring 2017

The vessel activity surveys were partitioned into 17 sea areas: Beaufort Sea, Canadian High Arctic, Baffin Bay (including Hudson Bay), Newfoundland and Labrador (including the Gulf of St Lawrence), Greenland, Baltic (including Gulfs of Bothnia, Finland E of 27° and Riga), Norwegian, Barents, White, Pechora, Kara, Laptev, East Siberian, Chukchi, Bering Strait, Bering and Okhotsk Seas. The Greenland, Norwegian, Baltic, Kara, Chukchi, Bering and Okhotsk seas were further subdivided, yielding a total of 29 areas (Fig. 1). The Caspian Sea was not included in the spring 2017 survey because the Caspian seal pupping season extends from late January to the end of February. However, data from earlier years [17] were available.

To evaluate vessel traffic in ice-covered sea areas during the 2017 spring pupping season, Automatic Information System (AIS) vessel data were recorded from www.marinetraffic.com. 'Snapshots' of vessels estimated to be in ice-covered areas were recorded once in each sea area at intervals of 1–2 weeks, from February 27, 2017 to the end of May

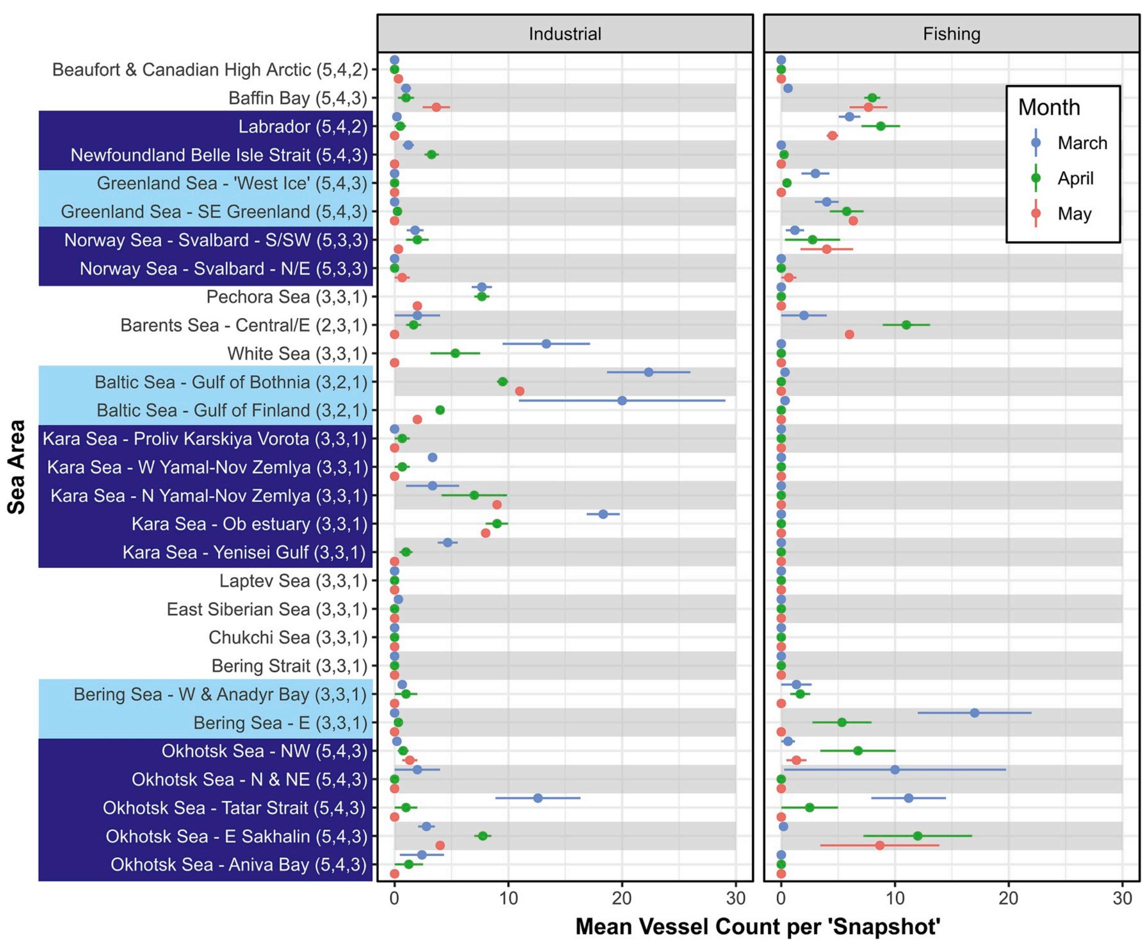

Fig. 1. Mean vessel count per snapshot by month (March, April, May 2017) derived from Marine Traffic data, in different sea areas. Points indicate mean counts, and whiskers standard errors. Values in parentheses for y axis labels give the number of snapshot surveys in March, April, and May respectively.

2017. Sea-ice concentration images for each sea region were obtained immediately before each snapshot survey from the National Snow and Ice Data Center (https://nsidc.org/data/seaice_index/). For each snapshot, the available AIS data was recorded for each vessel which was estimated visually from the updated NSIDC map to be within the ice area or at the ice edge.

Although the primary focus was on industrial vessels (cargo, tanker, industrial support and Search and Rescue), data were recorded for all vessels moving at >1kn in ice-covered areas. Vessel types recorded were categorised – where the AIS data were available, into *cargo*, *tanker*, *industrial support* (which included tugs, icebreakers and supply ships), *SAR* (Search and Rescue), *passenger, pilot* and *fishing* vessels. The vessel *length*, *beam width*, *draught* and *speed* (kn) were recorded for each vessel where the data were available. In addition, comprehensive AIS data on vessel location and speed in the White Sea for the peak pupping season March 13–25 were purchased from www.marinetraffic.com.

The weekly snapshot surveys were divided into one-month periods, for March, April and May. Vessel frequencies were expressed as the mean number of vessels per snapshot by month, together with associated standard error. Vessels in port, moored or moving ≤1kn were omitted from the frequency estimation. Median values for vessel length, beam width, draught and speed (>1kn) in each sea area were used in estimations of potential impact on breeding seals in each sea area.

Vessel GPS locations were visualised in QGIS [22] using a heatmap tool showing frequencies of vessel recordings as a green-to-red gradient with the green colour reflecting the 1st quartile (low frequencies) of the data and the red colour - the 4th quartile (high frequencies). A map of the maximum sea ice extent for 2017 was added as recorded for March 07, 2017.

2.3. Metrics for potential vessel-seal collision exposure in the Caspian and White Seas

To assess potential vessel impacts on ice-breeding pinnipeds, and to inform mitigation measures and vessel routing, appropriate risk metrics are needed [17]. Where spatial data on seal pup density distributions on sea ice (e.g. from aerial surveys) are available, 'path cost analysis' approaches can be employed to provide an index of the potential impact of actual, or proposed, vessel routings. These use information on the length and width of vessel tracks through different areas of a species' spatial density distribution to estimate numbers of individuals potentially exposed to the influence of a vessel or collisions [23]. Lawson and Lesage [23] proposed a simple estimator of vessel collision risk for cetaceans in open water, under an assumption of random vessel-animal encounters in proportion to spatial population density with no avoidance action by vessels or animals, which we extend here for breeding seals on ice. This should be regarded only as an indicative relative risk metric, since in practice seal distributions and vessel routing may not be random with respect to ice conditions. Here this potential collision risk metric is used as an indicator of potential overall disturbance to breeding seals on ice, including displacement and separation of mothers and pups and nursery habitat breakage as well the potential for actual vessel/pup collisions.

2.3.1. Exposure of pups on ice surface to collision risk in the Caspian and White Seas

For the Caspian and White Seas, seal pup density distribution data were available from previous aerial surveys [24–26]. Following Lawson and Lesage [23], for a single vessel transit breaking a new channel, the *Collision Area* (CA) can be estimated as:

$$\mathrm{CA} = (\mathrm{W} + 0.64\mathrm{L}) \times \mathrm{D}/1000\ \mathrm{km}^2$$

where W = vessel beam width (m), L = length of animal or structure (m) and D = distance travelled by a vessel within seal breeding population area (km).

The estimated potential number of collisions (PNC), as a measure of potential exposure to collision risk, during a single vessel transit would therefore be a function of the *Collision Area* and the *seal population density*.

$$\mathrm{PNC} = \mathrm{CA} \times \mathrm{T} \times \mathrm{P}$$

where T - % time animal is on ice or near surface, P – *seal population density* per km^2. The % time at or near the surface is taken to be 100% for lanugal seal pups.

Spatial seal pup density contours (pups per km^2) were generated for Caspian seals [24,25] and harp seals in the White Sea [26] using published survey data for the 2006 and 2009 peak seasons respectively, and then combined with vessel routing information to estimate PNC values, under the assumption of a single vessel transit while breaking a new channel at peak season. For the Caspian Sea, routing was based on a GPS track for an actual vessel transit in February 2006 [17], while for the White Sea a vessel route, taken to be typical of ships each year crossing between Archangelsk from the northern coastline of the White Sea, was established from AIS ship locations in spring 2017. Path lengths of track segments passing through different pup density contour regions were calculated in QGIS, with a PNC value estimated for each density segment, and then summed to yield to a total PNC for the complete tracks. The median vessel width from AIS surveys was used for W, and Caspian and harp seal pup lengths were assumed to be approximately 0.8 m and 0.9 m respectively [27,28].

2.4. Assessing potential shipping traffic risk profiles to seals from vessel properties

The above indicator of vessel disturbance applies to mothers and pups on the ice surface. However, if seals are in the water, collision underwater with the vessel bow, hull or propeller may occur due to the drawing forces of the vessel. Vessel dimensions influence the drawing forces according to the following relationship [29]:

$$\mathrm{DV} = \mathrm{L} \times 2\mathrm{W} \times 2\mathrm{Dr}\ \mathrm{m}^3$$

Where DV = the danger volume of water surrounding the vessel, L = vessel length, W = beam width and Dr is the vessel draught [29]. The intensity of impact varies linearly with vessel speed ranging upwards from 5kn, with force being exerted on an animal drawing it towards the stern, when submerged at 1–2 times the ship draught, increasing the probability of propeller strikes [29]. Using the AIS data, median vessel dimensions were calculated for vessels operating in each sea area, and then median DV values for each area were calculated as above. Similarly, median vessel speeds were also calculated for each sea area from the AIS data. Vessel risk profiles for seals in the water were then visualised by plotting median DV versus median speed for each area.

3. Results

3.1. Pinniped breeding areas and vessel activity

A summary of literature search results for pinniped species breeding in each ice-covered sea area is given in Table 1. Bearded and ringed seal breeding was reported for the greatest number of areas (82% and 100% respectively), with breeding grey, hooded, ribbon and spotted seals occurring in the fewest areas (12%–18%).

From the snapshot surveys March–May 2017, no or very limited vessel activity was recorded in the Beaufort Sea, Canadian High Arctic, Laptev, East Siberian and Chukchi Seas and Bering Strait (Figs. 1 and 2; Supplementary Table S2). Moderate to frequent industrial shipping traffic occurred in only a few pinniped breeding areas, with the principle areas and species potentially impacted being the White Sea (harp seals), Pechora Sea (walrus), Ob estuary (ringed seals), Gulfs of Bothnia and Finland in the Baltic Sea (ringed and grey seals), the coastal shelf of east

Table 1
Occurrence of pinniped species breeding in each sea area, derived from literature sources (see Supplementary Table S1). Shading – breeding present, no shading – breeding absent.

	Pinniped species breeding on sea ice							
Sea area	Bearded seal	Grey seal	Harp seal	Hooded seal	Ribbon seal	Ringed seal	Spotted seal	Walrus
Baffin Bay	■			■		■		■
Baltic Sea		■				■		
Barents Sea	■	■	■			■		■
Beaufort Sea	■					■		
Bering Sea	■				■	■	■	■
Bering Strait	■					■		■
Canadian High Arctic	■					■		■
Chukchi Sea	■				■	■	■	■
East Siberian Sea	■					■		■
Greenland Sea	■		■	■		■		■
Kara Sea	■					■		■
Laptev Sea	■					■		■
Newfoundland & Labrador			■	■		■		
Norwegian Sea	■					■		■
Okhotsk Sea	■				■	■	■	
Pechora Sea	■					■		■
White Sea			■			■		

and west Sakhalin in the Okhotsk Sea (ringed, ribbon, spotted and bearded seals) and the small area of the Belle Isle Strait in NW Newfoundland (harp seals). There was very little sea ice in spring 2017 in potential seal breeding areas in the Baltic Gulf of Riga and in the Gulf of St Lawrence; shipping in these areas was therefore not considered further here. In most areas mean snapshot values were in the range of tens of vessels or fewer, with a maximum of 22.3 for the Baltic Gulf of Bothnia in March (Fig. 1). The highest vessel counts for individual snapshots were 38 for the Baltic Gulf of Finland (E of 27°) in March, 12 in Northern Yamal (Kara Sea) during April and 11 in the Baltic Gulf of Bothnia in May (Supplementary Table S2). Fewer vessels in ice areas were counted in May due to diminishing ice extent. Fishing vessel activity is considered further in Supplementary file S3.

3.2. *Properties of vessels operating in seal breeding areas*

The predominant vessel types were cargo ships and industrial support vessels (including tugs, ice-breakers and supply ships) (Fig. 3). Tankers were less frequent except in the Ob estuary, while cargo ships were not recorded in the Pechora or Caspian seas. SAR vessels predominated in the Belle Isle Strait and were also recorded in E. Sakhalin (Fig. 3).

Vessel dimensions and speed were only available for some of the vessels recorded in snapshots and these data are given in Table 2. From the available data, median vessel length (L) ranged from 66 m in the Caspian to 150 m in the Ob Estuary, median beam width from 11 m in the Tatar Strait to 26 m in the Ob Estuary and median draught from 3 m in the very shallow NE Caspian to 8 m in the Ob estuary (Table 2). Median vessel speeds ranged from 5.3kn in the Caspian Sea and Belle Isle Strait (Newfoundland) to 10.5 and 11.2kn in the Baltic Gulfs of Bothnia and Finland (Table 2). No data were available for the size or speed of vessels which might impact walruses in the Pechora Sea.

3.3. *Potential exposure of pups to collision risk in the Caspian and White Sea*

Pup densities and vessel routes for the Caspian and White Seas are shown in Fig. 4. In both cases, the vessel routing passed through areas of high seal pup density (>30 pups per km^2). The single transit PNC estimates (Table 3) yielded 2,526 for Caspian seal pups, relative to an estimated pup production of 26,378 in 2006 [30], or 9.6% of the total pups; and 2,123 for harp seal pups in the White Sea, relative to pup production of approximately 109–156,000 in 2009 [26,31], or ~1.4–1.9% of the total pups.

3.4. *Shipping traffic risk profiles based on vessel properties*

The median danger distance for seals to the side of the vessel (SoV) varied between 6 and 9 m in most of the areas, but was greatest, at up to 13 m, in the Ob estuary (Table 2). The median areas of danger for seals in the water surrounding vessels ranged from approximately 1500 m^2 in the Tatar Strait to 7800 m^2 in the Ob estuary, and the danger volumes varied from approximately 12,700 m^3 in the Caspian (with ships' draughts of only 3 m in the very shallow water) to 124,800 m^3 in the Ob estuary (Table 2, Fig. 5). Since the median vessel speed in all areas was >5kn (Table 2), seals in the water in *all* of the areas considered would be prone to come under the drawing forces of the vessel, with the highest speeds – and therefore the greatest intensity of the suction effect – being in the Ob estuary, White Sea and Baltic Gulfs of Bothnia and Finland (Fig. 5).

4. Discussion

4.1. *Industrial vessels' overlap with seal breeding ice*

Recently there has been increasing awareness of the potential effects of shipping on Arctic marine mammals, but little attention paid to the specific impact of shipping on seals breeding on ice through which vessels are transiting. Huntington [1] and Laidre et al. [32] have highlighted the need to monitor how increasing industrial activity in the Arctic, in combination with reduction in sea ice due to climate change, is impacting marine mammal populations. In other risk assessment studies Reeves et al. [21] considered the distribution of endemic Arctic cetacean species in open waters in relation to oil and gas production areas and shipping densities on Arctic routes, while Hauser et al. [3] attributed vulnerability scores (spatial exposure to sea routes and sensitivity variables based on species traits) to species subpopulations in the Arctic, also during the ice-free season. The present study is the first to consider specifically the locations where Arctic and sub-Arctic shipping may be overlapping with seals and walruses during the spring season for

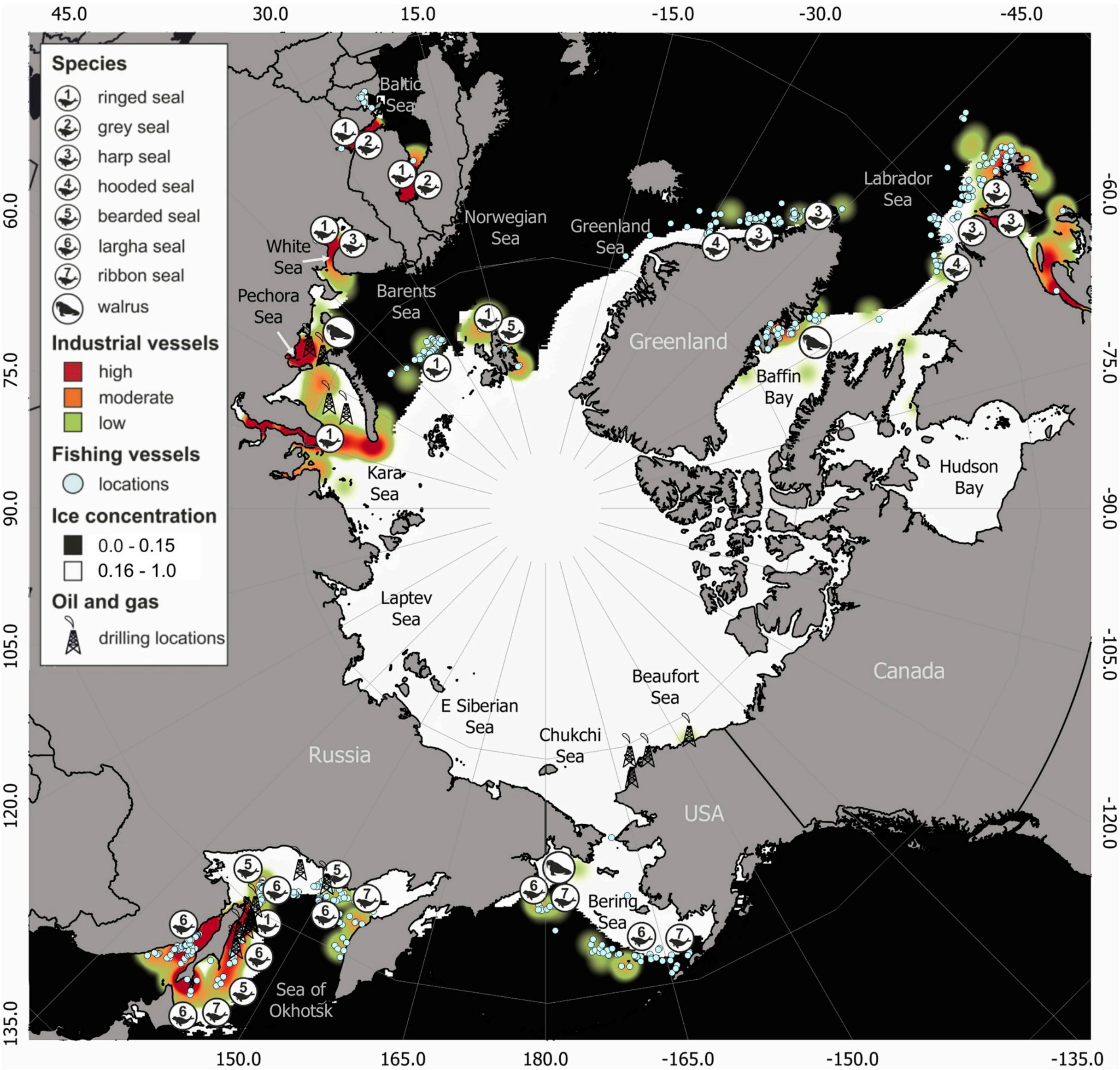

Fig. 2. Spatial distribution of vessel activity in ice-covered sea and pinniped breeding areas, Spring 2017.

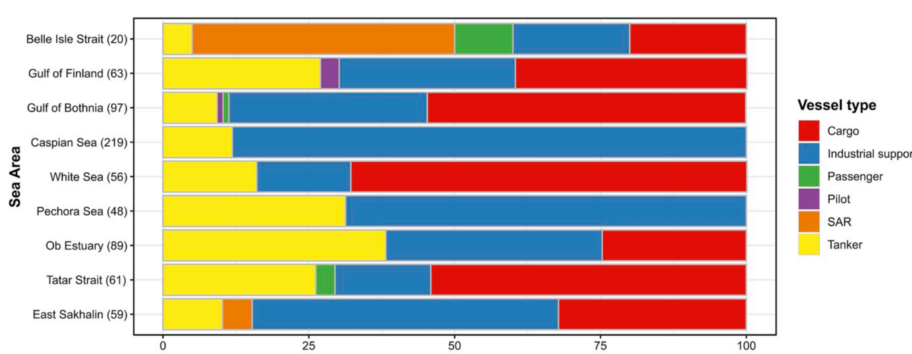

Fig. 3. Percentage vessel types in nine ice-covered sea areas with breeding pinnipeds (total no. vessels for which vessel type available in brackets). Industrial support class includes tugs, icebreakers and supply vessels.

pupping and calving on sea ice.

The areas where industrial traffic overlapping with pinniped ice-breeding areas was recorded (Fig. 1) were all in the vicinity of major cargo shipping ports (Gulf of St Lawrence, White Sea, Baltic Gulfs of Bothnia and Finland, Tatar Strait) or oil and gas exploration or production areas (Caspian Sea, Pechora Sea, Ob Estuary and East Sakhalin). The species and areas that the survey indicated were most likely to have current potential impacts from industrial vessels were harp seals (White

Table 2
Vessel data recorded in seal ice-breeding areas (spring 2017) and estimated danger zones for seals in surrounding water (SoV – side of vessel).

Sea area	Sample size (N)	Median speed (vessels moving at > 1kn)	Median length (L) (m)	Median beam width (W) (m)	Median draught (m)	Estimated Danger distance from SoV (m)	Danger water area surrounding vessel (L × 2W) m^2	Danger zone DEPTH 2Dr (m)	Danger water volume surrounding vessel (L × 2W × 2Dr) m^3
Belle Isle Strait	15	5.3	88	18	7	9	3168	14	44,352
Gulf of Bothnia	72	10.6	99	15.5	7	9	3069	14	42,966
Gulf of Finland	142	11.0	115	18	6	9	4140	12	49,680
Caspian Sea	138 (2013)	5.3 (2013)	66 (2013)	16 (2006)	3 (2006)	8 (2006)	2112	6	12,672
White Sea	42	9.2 (n = 237)	98	16	6	8	3136	12	37,632
Ob estuary	35	8.0	150	26	8	13	7800	16	124,800
Tatar Strait	57	6.2	68	11	5	6	1496	10	14,960
Sakhalin (E)	64	5.7	92	17	6	9	3128	12	37,536

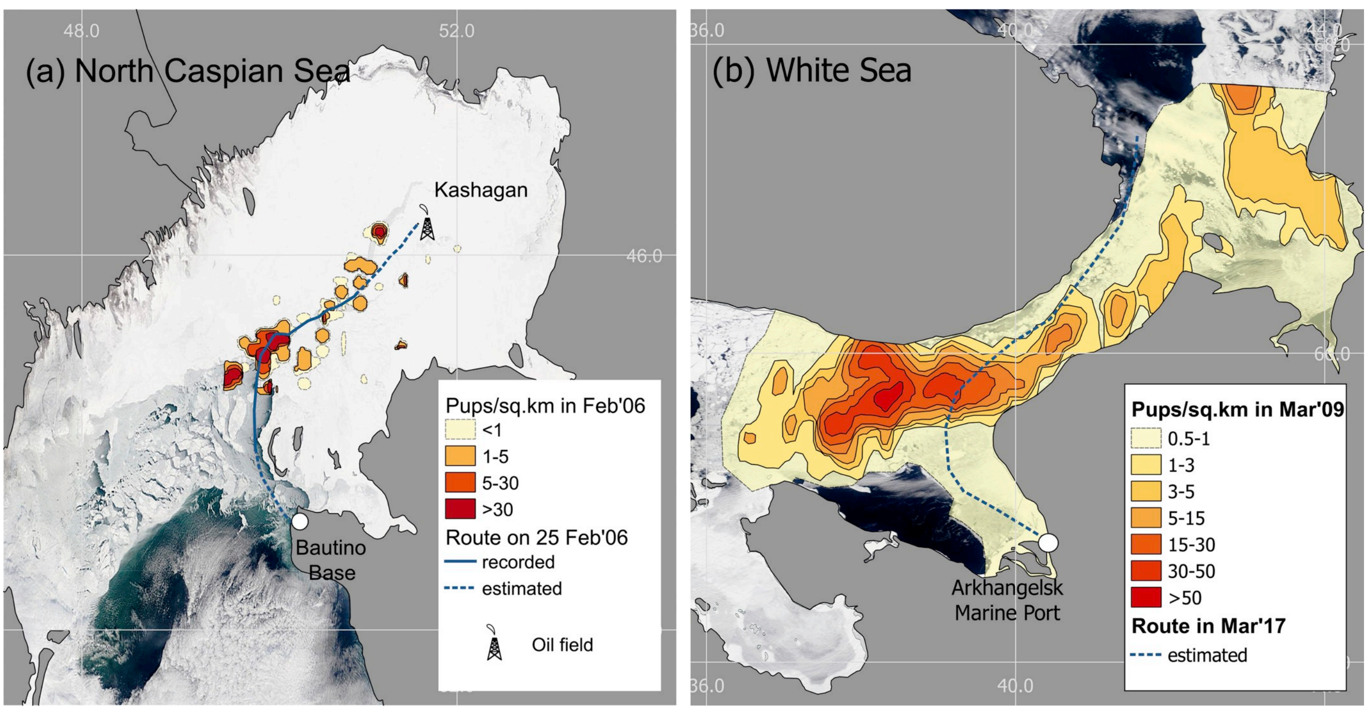

Fig. 4. Pup density distributions and vessel transit routes in (a) the northeast Caspian Sea and (b) the White Sea.

Sea and parts of the Gulf of St Lawrence), ringed seals (Baltic, Ob Estuary, East Sakhalin), grey seals (Baltic), spotted seals (Tatar Strait and East Sakhalin), walrus (Pechora Sea), and bearded and ribbon seals (East Sakhalin).

These areas of shipping overlap with pinnipeds breeding on ice identified in this study are very different from those found by Hauser et al. [3] to have greatest vulnerability for walruses, bearded seals and ringed seals during the open water season. In the latter study, the Laptev Sea area (on the Northern Sea Route) was found to have the greatest vulnerability, followed by the Bering Strait (emphasised also by Huntington et al. [2]), Chukchi and Beaufort Seas and parts of the Canadian High Arctic. By contrast, all of these areas were vessel-free in ice-covered areas during our spring 2017 seal pupping season survey. Conversely, in the ice-covered areas of the White and Pechora Seas, we found significant vessel overlap from our spring 2017 survey with breeding ringed and harp seals in the White Sea and walrus and bearded seals in the Pechora Sea, whereas Hauser et al. [3] estimated walrus and ringed and bearded seals to have insignificant vulnerability in the open water season (and did not consider harp seals) in these sea areas. Similarly, for the Kara Sea we identified a potential risk to breeding ringed and bearded seals in spring 2017 from large ships in the vicinity of the Ob estuary, but this area was considered in the Hauser et al. study of open water periods to have low vulnerability for these seal species [3]. These key contrasts between assessments of open water and ice-breeding seasons emphasise the critical importance of evaluating breeding season vulnerability to shipping impacts separately from the open-water season.

For ice-breeding seals, the spring pupping season is the most important sensitive and critical part of the annual cycle. The additional mortality, and indirect impacts on stress and energy expenditure for individuals which can arise from vessel impacts, as documented for Caspian seals [17], have potential to translate into consequences for population dynamics [33], but presently the demographic effects of shipping disturbance are almost entirely unknown.

Table 3
Estimates of potential exposure to collision risk (PNC) with seal pups in the path of ships transiting seal breeding ice.

Approx. pup density/km^2	Vessel track segment distance (km)	PNC for one transit	Estimate total no. pups born in assessment year
Caspian seal – Northeast Caspian 2006			
0.5	8.98	7.41	26,378; CV 7.04*
3.0	19.46	96.40	
12.5	48.14	993.67	
40.0	21.63	1,428.62	
TOTAL PNC ESTIMATE 2,526			
Harp seal – White Sea 2009			
0.75	220.3	273.9	109,187 ± 28,260**
4	9.03	59.9	156,690 ± 24,511***
7.5	11.34	141.0	
12.5	6.51	134.9	
22.5	20.03	747.2	
40	11.55	765.7	
TOTAL PNC ESTIMATE 2,123			

* [30] ** [31] *** [26].

4.2. Current and projected levels of industrial shipping in Arctic through sea ice in pinniped breeding areas

In spring 2017 the overall level of industrial shipping in ice-covered seas recorded by our survey was relatively low, although mean snapshot ship counts were in the 10s in some areas overlapping with pinniped breeding areas. These were primarily in the Baltic Gulfs of Bothnia and Finland, the Okhotsk Sea around Sakhalin Island and along the Northern Sea Route (NSR) encompassing the White, Pechora, Barents and Kara Seas.

Until recently industrial shipping levels along the Northern Sea Route (NSR) were greatest between July and November, with almost no vessel traffic penetrating the sea ice between December and May [34]. However, since 2013 vessel traffic along the NSR between December and May, encompassing the pinniped birthing period, has increased to around 20 vessels per day [34] and was slightly higher during March–May in 2017 than in 2016 [35].

Year-round traffic from the gas fields in the Yamal Peninsula has been made possible by the introduction of nuclear-powered icebreaking vessels, such as the *50 Let Pobedy* (measuring 160 m × 30 m) [36], which was recorded twice in the Ob estuary during our spring 2017 survey. Three more multi-purpose, nuclear-powered icebreaking vessels (Project 2220, LK-60, 173 m × 34 m) are now being built for deployment in the Yamal gas field and are capable of tackling ice up to 3 m thick [36]. A series of 15 double-action (normal bow and ice-breaking stern) ice-breaking tankers are being constructed to carry Liquid Nitrogen Gas (LNG) westwards along the NSR from Yamal year-round, including during the ice season January to May. These tankers measure 299 m × 50 m and can travel at 5 kn in 1.5m-thick ice. The first of these, the *Christophe de Margerie*, was deployed at Yamal in 2017 [37], and was recorded travelling westwards from Yamal during our spring 2017 survey. These powerful icebreaking ships are designed to transport their cargo according to a scheduled timeline irrespective of ice conditions [38].

The increasing numbers, size and power of icebreaking ships on the NSR will make the introduction of regulations to protect breeding pinnipeds increasingly difficult unless appropriate mitigation measures, appropriate to the species and ice habitat, are incorporated into shipping schedules at this relatively early stage in the development of the oil and gas fields. Such regulations should involve identification of seal or walrus birthing ice areas and require circumventing or moving slowly through these ice fields. One positive aspect of the double-action ships and tankers from the perspective of mitigation is that they are equipped with azimuth thrusters, which increase their ability to manoeuvre [39], and thus potentially enable these vessels to navigate around sensitive areas. Further evaluation of the volume, spatial distribution and vessel properties of shipping traffic is required to fully understand exposure of pinniped populations in these areas on an ongoing basis.

4.3. Estimates of potential exposure to collision risk in the Caspian and White Seas

We used the potential number of vessel/seal pup collisions (PNC) as a measure of collision exposure risk from vessel transits. We estimated that approximately 9.6% of Caspian seal pups and up to 1.9% of harp seal pups in the White Sea could be exposed to collision risk from a single vessel transit. This highlights that even very low traffic volumes have potential to cause significant impacts, depending on vessel routing

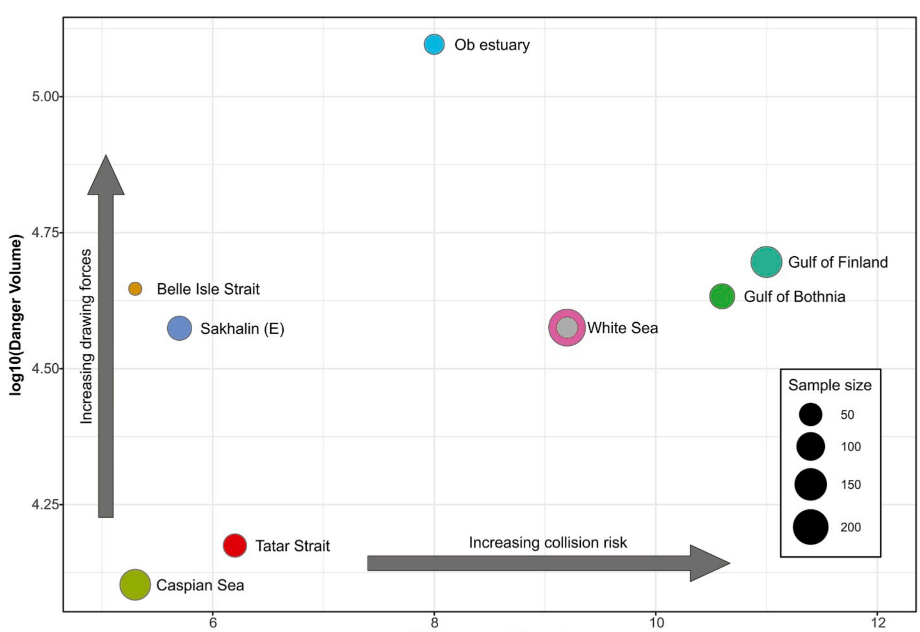

Fig. 5. Plot of Median vessel speed (knots) versus log 10 Danger volume (m^3), based on median vessel dimensions for different sea areas. White Sea, inner circle n = 42 – Median danger volume; outer circle n = 237, Median speed.

relative to seal distributions. However, using the potential collision risk (PNC) approach to extrapolate impacts from a sample vessel track - assuming breaking of a new channel at peak pupping season - to a whole pupping season is problematic because (a) vessels breaking new channels are most likely to occur early in the season, before the number of pups reaches a peak, (b) once a channel is broken, subsequent vessels may re-use some or all of the channels, thereby reducing further collision risk, and (c) seal and ice distributions are dynamic within a season, meaning seal densities encountered by vessels may change over time. Nevertheless, where seal density data is concurrent with vessel routing, it can be applied as a metric for comparative purposes to evaluate the relative risk profile of vessel tracks through seal breeding areas, either retrospectively, or for planning vessel navigation as part of a pre-emptive mitigation strategy [17], which may be of value to vessel operators and regulators. There is potential to develop more sophisticated spatial models [40], which in this context could incorporate data on how ice conditions influence seal distributions, and vessel behaviour.

4.4. Development of risk profiles based on vessel properties

Where detailed spatial data on seal distributions relative to vessel tracks are not available, we suggest that a potential risk profile for vessels can be evaluated based on vessel dimensions, which influence the volume of water around the vessel subject to drawing forces, and vessel speeds which affect collision risk. The fleet in the Ob estuary was dominated by large vessels, making it the area with highest risk associated with drawing forces. The commonest breeding pinniped species in the Ob estuary area is the ringed seal (Fig. 2), in which species adult breeding activity is entirely in the water beneath the ice, and therefore probably the most vulnerable of all pinniped species to underwater disturbance and collision by vessels. Median vessel speeds were highest in the White Sea and Baltic, being considerably greater than the 4-knot threshold identified for increased collision risk in the Caspian [17]. Therefore, speed reductions while traversing seal breeding ice could be one mitigation approach considered for these areas. Nevertheless, impacts are possible in all areas irrespective of properties, depending on the operating procedures, navigation constraints, and nature of vessel-seal interactions.

4.5. Role of behavioural traits in modulating sensitivity to vessel disturbance

In their study of vessel impact on Caspian seals pupping on ice, Wilson et al. [17] provided evidence that behavioural traits including flight distance, the pup being left unattended, mother chaperoning the pup and the pup following response [41] were likely to influence vulnerability to vessel impacts. Considering other species, short flight distances, leaving pup unattended, low levels of maternal chaperoning of pups or poor pup following responses can increase the collision risk. However, assessments of the responses of mothers and pups of other ice-breeding pinnipeds to vessels have not yet been carried out, although some useful data have been obtained on ice seals in the vicinity of oil and gas activity in the Beaufort and Chukchi Seas in the late spring and summer months. The 'alert', 'dive' and altered 'track or speed' of seals and walruses in response to approach of a research ship were found to average >300 m to ≥ 200 m for ringed, spotted and bearded seals, but >550 m to ≥ 300 m for walrus [42]. Other studies have found that ringed seals on the ice surface appear not to be deterred by oil and gas activity [43], and in some circumstances, seals may actively approach drilling units [44].

5. Conclusions and recommendations

Studies in the Caspian Sea have demonstrated the potential for detrimental impacts on ice-breeding pinnipeds where ice-breaking vessels are transiting pupping areas, and the need for effective mitigation measures to protect breeding seals and their habitat [17]. In order to develop evidence-based policy for regulators and to aid vessel operators to develop mitigation measures, the first step is to evaluate overlap between ice-breaking vessel traffic and the ranges of the species of interest, identifying potentially vulnerable areas, time periods and species. The present study is the first to focus specifically on ice-breeding pinnipeds, and shows there are multiple areas in Arctic and sub-Arctic seas where vessel traffic overlaps with areas used by pinnipeds for breeding during the spring pupping period. Many of these areas differ from those identified as being vulnerable to vessel disturbance in the open water season. This highlights a critical need for risk assessments specifically targeted to ice-breeding pinnipeds during their pupping seasons, as existing studies may not adequately capture the relevant impacts. Since vessel traffic is growing rapidly with commissioning of new large industrial vessels capable of year-round operations, assessments of vessel activity overlaps need to be continued with larger datasets on an ongoing basis across the Arctic and sub-Arctic seas, with a particular focus on the areas identified here.

Different species may vary in the vulnerability to vessel related impacts depending on behavioural responses to vessels, and pup ontogeny [41,45,46], and there is growing recognition of the importance of incorporating trait data into risk assessments [3]. For most Arctic pinnipeds, detailed data on behaviour relative to vessel impacts is lacking, so there is an urgent need for behavioural studies. Priority areas may include the White Sea and East Sakhalin (Okhotsk Sea) since these areas have frequent vessel traffic and offer opportunities for observations on multiple species. Further methodological development is required for some species such as ringed seals, since their use of under-snow lairs precludes direct observation in most cases, although aircraft, drone or vessel-mounted infrared sensors may allow breeding animals to be detected [47]. In combination, enhanced data on seal distributions, vessel activity, and species traits will allow policy and mitigation measures appropriate to individual species, habitats, and vessel operating constraints to be developed.

At present codes of conduct with legally-binding regulation for vessels transiting pupping areas of ice pinnipeds are absent or insufficient. Given that traffic volumes are still relatively low, now is the time to develop regulatory frameworks, rather than following further growth, where stakeholders may have invested in infrastructure and operating procedures that might conflict with recommended best practice. Developing protection for pinniped breeding areas requires recognition and awareness of the issue by all stakeholders, and participation and mutual cooperation by extractive industry companies, shipping companies and vessel crews, port authorities, international animal conservation and welfare organisations such as WWF and IFAW, and international bodies such as IMO and UNCLOS. Ultimately regulatory frameworks need to be overseen by national governments, in conjunction with the United Nations International Maritime Organisation through the Polar Code [48].

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2019.103694.

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