Marine Pollution Bulletin 186 (2023) 114439

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Assessing variability in marine traffic exposure between baleen whale species off the Galician Coast, Spain

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ARTICLE INFO

Keywords:
Minke whale
Blue whale
Fin whale
Vessel exposure
Iberian Peninsula
Automatic identification systems

ABSTRACT

Increases in marine traffic represent a growing issue for marine wildlife, posing threats through the impacts of ship strikes and noise pollution. Baleen whales are especially vulnerable to these impacts, yet regional and species-specific information on exposure to such threats is lacking. This study uses AIS and observational data to provide the first assessment of baleen whale exposure to vessel traffic on the NW coast of Spain. Overlap with vessel traffic was detected for all areas where whales were sighted, indicating that these species may be at risk of vessel exposure and its associated impacts. Level of exposure to vessel traffic experienced by whales was species-specific, with risk of exposure appearing highest for minke whales. Vessel exposure also displayed intra- and inter-annual variability and a significant influence of feeding behaviour highlighting the need for dynamic management tools to minimise interactions between baleen whales and marine traffic off the Galician Coast.

1. Introduction

As marine megafauna and top predators, whales have important roles in ecosystem engineering and food web stability (Bowen, 1997; Smith, 2007; Roman et al., 2014). Reductions in their populations may therefore cause changes to the structure and functioning of marine ecosystems (Worm et al., 2006; Ballance et al., 2007). However, marine environments are increasingly placed under pressures from both offshore and land-based activities, with humans now representing the largest driver of environmental change (Worm et al., 2006; Halpern et al., 2015). Human activities have already caused whale populations to suffer detrimental impacts, namely the large-scale commercial whaling which overharvested many populations to the brink of extinction during the 20th century (Clapham et al., 1999; Thomas et al., 2016). These populations are still recovering, with one quarter of whale species listed on the IUCN Red List classified as Critically Endangered, Endangered or Vulnerable, including the blue (*Balaenoptera musculus*), fin (*B. physalus*) and North Atlantic right whale (*Eubalaena glacialis*) (Cooke, 2018a, 2018b, 2020). Many species have the potential to return to historical abundances (Kareiva et al., 2007): gray whales (*Eschrichtius robustus*), for example, are thought to have returned to pre-whaling abundances within the Eastern Pacific (Alter et al., 2007). However, human exploitation of marine ecosystems for their goods and services through fisheries, commercial shipping, and the operation of polluting industries pose both lethal and sub-lethal threats to recovering populations (Clapham et al., 1999; Thomas et al., 2016). Vessel traffic in particular represents a growing threat due to the increases in seaborne trade to meet the demands of the growing global human population (Tournadre, 2014; Pirotta et al., 2019).

Vessel traffic is one of the largest threats currently facing whales through the impacts of noise pollution and ship strikes (Laist et al., 2001; Thomas et al., 2016). As marine mammals that rely on sound as their primary sensory modality, whales use acoustic cues for critical life functions including navigation, communication with conspecifics, and for prey and predator detection (Clark et al., 2009; Williams et al., 2013). Much research effort has therefore focussed on the impacts of noise pollution. While high amplitude sounds created by military sonar and seismic surveys have received considerable attention (Tyack et al., 2011; Goldbogen et al., 2013), commercial shipping represents the largest source of anthropogenic noise into the marine environment (Ellison et al., 2011; Williams et al., 2013). In addition, commercial shipping is the greatest contributor of anthropogenic noise of lower frequencies (20–200 Hz; Ross, 1976), overlapping with those utilised by baleen whales (Mysticetes), low-frequency specialists, making this group particularly vulnerable (Clark et al., 2009).

This additional noise input into the marine soundscape has raised

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https://doi.org/10.1016/j.marpolbul.2022.114439
Received 6 July 2022; Received in revised form 21 November 2022; Accepted 25 November 2022

concerns of inducing physiological responses such as chronic stress, acoustic masking of important biological cues as well as the displacement of animals from critical habitat (Clark et al., 2009; Pirotta et al., 2012; Rolland et al., 2012; Williams et al., 2014; Holt et al., 2021). For example, reductions in glucocorticoid levels, a hormone linked to physiological stress, were observed in right whales within the Bay of Fundy, Canada, in association with a reduction of vessel traffic (Rolland et al., 2012). Clark et al. (2009) also discussed the potential impacts of acoustic masking in whales, with fin whale songs much less evident in the Mediterranean Sea, an area with higher shipping activity, compared to those singing in the Gulf of California, highlighting spatial differences in the distribution of vessel traffic impacts across the globe.

The largest anthropogenic source of whale mortality is attributed to ship strikes, with collisions causing direct mortality through blunt force trauma and propeller cuts, and indirectly by reducing fitness through severe injury (Laist et al., 2001; Soldevilla et al., 2017). Baleen whales, as some of the largest species, have been highlighted as those most frequently involved in these collisions (Laist et al., 2001; Schoeman et al., 2020). High mortality of blue, fin and humpback whales (*Megaptera novaeangliae*) due to vessel collisions, for example, have been reported for populations along the West Coast of the US and in the Mediterranean Sea (Berman-Kowalewski et al., 2010; Rockwood et al., 2017). The frequency and severity of vessel collisions have been found to be influenced by many factors including whale surface active behaviour, speed and size of vessels, density of vessel traffic and the extent of overlap in the spatiotemporal distribution of whale species and vessel traffic (Vanderlaan and Taggart, 2007; Conn and Silber, 2013; Soldevilla et al., 2017). Whales engaged in feeding activities, for example, have been reported to be less alert to surrounding noise and activities, including vessel traffic (Laist et al., 2001). Few assessments however of vessel exposure report on the influence of more than one of the above factors.

As demand for seaborne trade continues and a greater number of ships and those of greater size may become present in the oceans, there is a growing importance in evaluating the exposure of whale species to vessel traffic (Halpern et al., 2015; Pirotta et al., 2019). While spatiotemporal overlap does not confirm animals will be impacted, it is a necessary precursor for impact to occur and to identify species and areas of risk. Assessments of many cetacean species have been undertaken but are spatially biased towards the Mediterranean Sea and the coasts of North America, and in most cases are based only on a single year of shipping traffic data with cetacean presence averaged over time (Erbe et al., 2014; Pennino et al., 2017; Rockwood et al., 2017, for exceptions see Redfern et al., 2013, 2019, 2020 and Abrahms et al., 2019). This does not account for temporal variability in both vessel traffic and whale presence, factors which are fundamental to the development of effective management strategies for the protection of species and to minimise wildlife-user conflict (Redfern et al., 2020).

While the negative impacts of ship strike and noise pollution associated with marine traffic are well established, species-specific exposure to these threats remain unevaluated in many regions (Laist et al., 2001; Thomas et al., 2016; Erbe et al., 2019). The continental shelf in Galician waters (North-Western Spain), an area highly exposed to human activities and a historically significant whaling area, has been identified as a region frequently utilised by endangered rorqual whales for foraging (Sanpera and Aguilar, 1992; Díaz López and Methion, 2019; Methion & Díaz López, 2019), with confirmed year-round presence of minke whales as well as a high seasonality of blue and fin whale presence (Díaz López and Methion, 2019). Some whales are known to migrate from the Azores however the specific migratory route of most individuals identified is unknown (Díaz López et al., 2022). Interactions between cetaceans and vessels have also been recorded in Galicia but research efforts have focussed on smaller cetaceans such as bottlenose dolphins (*Tursiops truncatus*) and their interactions with fisheries (Goetz et al., 2014; Díaz López and Methion, 2018; Díaz López et al., 2019; Giralt Paradell et al., 2021). Here, we aim to address this gap by developing the first analysis of marine traffic exposure for baleen whales off the Galician Coast. Specifically, vessel types and density within the study region were identified and their spatiotemporal overlap compared with the presence of three key species: the blue whale, fin whale, and minke whale (*Balaenoptera acutorotrata*). We used 4 years of data to explore differences in exposure to marine traffic between different whale species. Generalised linear mixed models (GLMMs) were used to analyse whether whale species, group size, behaviour, season, or year were related to vessel density in the areas where whales were sighted. The results of this study will therefore provide useful insight for the identification of conservation priorities and may inform marine management strategies within the study area that can be designed with temporal differences of exposure risk in mind.

2. Materials and methods

2.1. Study area

This study was undertaken along the North-Western coast of the Iberian Peninsula, specifically the Galician coast, encompassing the continental shelf and inshore waters from Muros (42.79° N, 9.25° W) to the Cíes Islands (42.36° N, 8.94° W) (Fig. 1). Galicia lies along the northern edge of the eastern boundary of the North Atlantic upwelling system, one of the major upwelling systems of the world (Wooster et al., 1976). Seasonal upwelling of cold and nutrient-rich North Atlantic Central Water situated at depths of 70–500 m results in this oceanic region being one of the most biologically productive in the world (Blanton et al., 1984; Figueiras et al., 2002; Spyrakos et al., 2011). The productivity of the Galician coast is reflected in its high biodiversity, with at least 300 fish species, 80 cephalopod species and 20 cetacean species recorded in the area (Guerra, 1992; Spyrakos et al., 2011). Whale presence has been noted in previous studies to peak at the end of summer and beginning of autumn due to higher concentrations of zooplankton produced by the seasonal upwelling events (Díaz López and Methion, 2019; Methion and Díaz López, 2019; Díaz López et al., 2021).

2.2. Data collection

Presence data for baleen whales was collected by the Bottlenose Dolphin Research Institute BDRI (www.thebdri.com) as part of their long-term studies on the ecology and behaviour of cetacean species within Galician waters. Boat-based surveys were conducted year-round onboard a 12 m research vessel during daylight hours at a constant speed of 6–8 knots. Surveys were conducted systematically along transect lines designed to cover the study area equally, adapted to the specific conditions of the study area and the meteorological conditions of each day (Díaz López and Methion, 2019). Spatial distribution of effort could vary according to weather conditions and time constraints throughout the study period, as surveys were conducted only when visibility was not reduced by rain or fog and when sea conditions were no greater than three on the Douglas Sea Force scale (Díaz López and Methion, 2018).

At least three experienced observers were stationed on the flying bridge of the vessel (4 m above sea level) at all times, scanning 360° of the sea surface for presence of whales with the naked eye or with 10 × 50 binoculars (Díaz López and Methion, 2019). Upon sighting a whale, the vessel slowly moved towards the individual or group to reduce disturbance during the approach (Díaz López and Methion, 2018). A sighting was defined as one or more whales of the same species observed within 1 nautical mile radius engaged in the same behavioural activity (Díaz López and Methion, 2019). Group size was estimated at the beginning of the observation and confirmed throughout the sighting. The species (identified by colour patterns, head shape, size and the shape of the dorsal fin), date, time, and geographical position (UTM longitude and UTM latitude: WGS 84 UTM Zone 29N) were recorded as an instantaneous point sample every 5 min. The behavioural state (feeding or not feeding) of the individual or group was determined at the

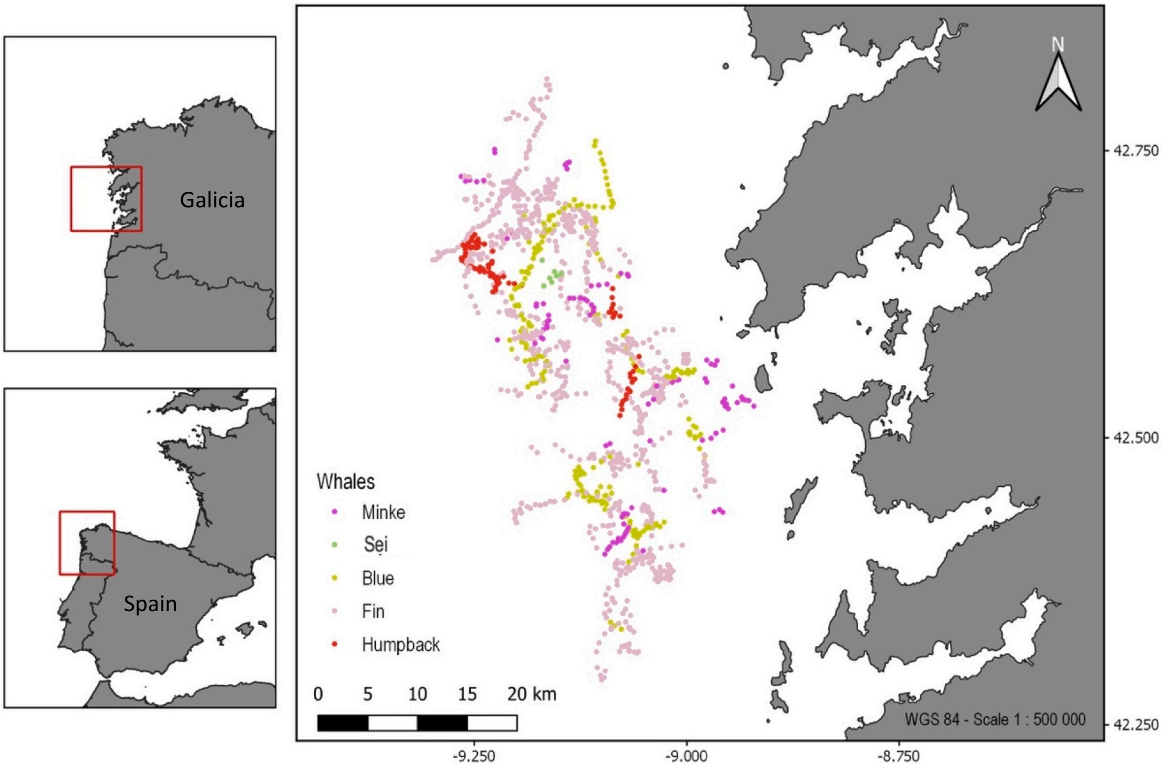

Fig. 1. Map of the study area (southern coast of Galicia, Spain) showing the distribution of the observed baleen whales between 2017 and 2020 (points indicate the position of instantaneous point samples recorded every 5 min of each sighting).

end of each five-minute sample. Whales were considered to be feeding when swimming in different directions in the same area (lunge feeding: mainly observed in blue and fin whales; characterised by high-speed, vertical lunges in which the animal opened its mouth and distended the gular region a few metres from the water surface, turning on itself and showing the ventral region at the surface; or deep feeding: characterised by sequences of regular dives followed by long and steep dives (tail-stock or flukes-up dives)) (Díaz López et al., 2021). Samples were collected until the individual/group was lost or weather became unfavourable and the sighting was ended.

Presence data from 2017 to 2020 were selected to temporally match available vessel density data (see below), giving a total of 1800 samples from 187 sightings of 5 species (blue, fin, minke, humpback and sei whale: *Balaenoptera borealis*) over a total of 19 months. Presence data for sei and humpback whales were excluded from the analysis due to the low frequency of sightings ($n = 2$ and $n = 4$, respectively) and similarly, a small number of samples collected during the winter months were also excluded (n = 4).

2.3. Vessel density

Automatic identification systems (AIS) are tracking systems used onboard ships and by coastal authorities, capable of providing information on vessel identification, location and speed (IMO, 2019). All passenger ships, ships ≥300 gross tonnage engaged in international voyages, and cargo ships ≥500 gross tonnage engaged in domestic voyages are required to be fitted with AIS under the SOLAS regulation V/19, and AIS transponders are carried voluntarily on many other vessel types (IMO, 2019). AIS is therefore an appropriate data source for vessel density and has been utilised in previous studies assessing variability in ship traffic and its impacts on cetaceans (Moore et al., 2018; Redfern et al., 2020; Smith et al., 2020; Silber et al., 2021).

In the present study vessel data were obtained from the European Marine Observation and Data Network (EMODnet, 2021; https://www.emodnet-humanactivities.eu/). Vessel density maps based on AIS data covering all EU waters and some neighbouring areas were available for the following vessel categories: fishing, service, dredging or underwater operations, sailing, pleasure craft, high speed craft, tug and towing, passenger, cargo, tanker, military and law enforcement, other, unknown, and all. Raster GIS files (GeoTIFF) of vessel density maps, available by month of year from 2017 to 2020, were downloaded and imported into a geographical information system (QGIS 3.16) and projected into the ETRS89/ETRS-LAEA coordinate reference system (CRS) (ESPG: 3035). Shipping density was shown in 1 × 1 km cells and expressed as hours per square kilometer per month.

To determine the spatiotemporal overlap between whale presence and vessel density, whale presence point samples were first imported into QGIS 3.16 as shapefiles, grouped by sightings per month of year of each species. Samples were then reprojected to the ESPG:3035 CRS to ensure all layers were in the same reference system for spatial analysis. Using the QGIS Python Point Sampling Tool Plugin, vessel density was extracted for each point sample, selecting the vessel density raster layer to probe values from that which corresponded with the month of year of the sighting. The extracted value therefore corresponded with the total number hours of vessel traffic within the 1 × 1 km grid cell in which the whale was sighted, in the month and year it was sighted in. While this value is not the real-time presence of boats during the sighting, this approach was taken to represent the general marine traffic activity within the areas that blue, fin and minke whales were sighted in.

Factors including the size, speed and noise produced by a vessel have been reported to influence whale presence (Campana et al., 2017; Blondin et al., 2020; Schoeman et al., 2020), but differences in these characteristics exist between vessel types, thus presenting different risks on exposure to whales. Due to the negligible contribution of many vessel types to marine traffic in the study area, only four vessel categories were used in further analysis: fishing boats, sailing boats, large vessels and all (representing the total number of hours of traffic from all vessel types combined). Vessel density values from 'dredging or underwater operations', 'cargo' and 'tanker' were aggregated to create the category of 'large' because of the risks to cetaceans associated specifically with larger vessels as reported in the literature (Laist et al., 2001; Thomas et al., 2016; Schoeman et al., 2020).

2.4. Statistical analysis

All statistical analyses were conducted in R version 4.0.4 (R Core Team, 2021). Differences in exposure of whales to vessel traffic were analysed using general linear mixed models (GLMMs) in the 'nlme' package (Pinheiro et al., 2021). Specifically, GLMMs were used to analyse whether whale species, group size, behaviour, season, or year were related to vessel density in the areas where whales were sighted. Vessel density of 'all' vessel types for point samples was fitted as the response variable. These data were slightly skewed and so were log transformed; this successfully produced a normal distribution. Four variables were initially considered to have potential effects on whale exposure to vessel traffic and so were fitted as fixed effects in the initial model: species of whale, group size, behaviour and season. Analysis was therefore restricted to point samples for which all of the above data were available (n = 1294). Season indicates upwelling and post-upwelling periods, with upwelling events occurring between May and August and post-upwelling occurring between September and November (Díaz López and Methion, 2019; Giralt Paradell et al., 2020). Overlap between vessel traffic and cetacean feeding grounds has been reported in previous studies so to explore the effect of feeding behaviour on exposure to vessel traffic, behaviour was defined as "feeding" or "not feeding" (Goetz et al., 2014; Cruz et al., 2016; Díaz López et al., 2019; Ricci et al., 2021). To explore species-specific differences in vessel density in the areas that they were sighted in, species and its interactions with group size, behaviour and season were also fitted as fixed effects in the initial model. Year was fitted as a fixed effect to directly investigate whether the risk of exposure differed between years. To control for nonindependence of consecutive point samples within a sighting of the same individual or group, each sighting was given an identifier with sighting identity then fitted as a random effect.

Collinearity between explanatory variables was assessed by examining correlations and variance inflation factors (VIFs) prior to model selection, following Zuur et al. (2009). All variables were included in the initial model because correlations between them were weak ($r < 0.4$) with small associated VIFs (<3). The model was then refined using backwards stepwise deletion. Explanatory variables were removed sequentially in order of increasing test statistic value if likelihood test ratios showed that they did not explain any significant variation. Each variable was assessed in turn until the minimal model was obtained and then reinstated into the model to confirm significant terms had not been inappropriately excluded and to determine the degree of non-significance. The final model included only significant variables and was validated by plotting the distribution of the residuals and the residuals against the fitted values, following Zuur et al. (2009). Estimates and standard error values for variables with multiple comparisons (species and year) were obtained in the 'multcomp' package (Hothorn et al., 2008).

2.5. Species-specific variability in vessel traffic exposure

To investigate variability in the type of vessel traffic (fishing, sailboats and/or large vessels) a species was exposed to and whether differences existed between years, species-specific two-way ANOVA tests were conducted. When a significant F value was identified, a Tukey's Honest Significant Difference test was run to find where the significant differences lay. Only the first sample of each sighting were selected to limit autocorrelation and pseudoreplication arising from consecutive samples (fin: n = 89; minke: n = 24). Analysis of minke whales were restricted to 2018–2020 due to the low representation of sightings of this species during 2017 (n = 4). Low sighting numbers of blue whales in 2018 and 2019 (n = 4 and n = 2, respectively) excluded this species from two-way ANOVA analysis, however a one-way ANOVA was conducted to investigate the variability in the type of vessel traffic this species was exposed to.

3. Results

3.1. Spatiotemporal overlap of whale presence and vessel traffic

Between 2017 and 2020, 132 sightings of blue, fin and minke whales were made along the study area (Table 1). The distribution of marine traffic varied both spatially and temporally within the study area, with coastal regions generally showing higher vessel densities than areas further offshore (see Fig. 2 for example).

All point samples (n = 1294) used in the analysis (representing the position of at least one individual every 5 min) were found in areas where the monthly density of marine traffic was greater than zero when considering all vessel types, confirming spatiotemporal overlap of whale presence and vessel traffic for minke, blue and fin whales within the study area in each year analysed (see Fig. 3 for example).

3.2. Factors influencing whale exposure to vessel traffic

Exposure to vessel traffic varied significantly between species (Table 2). For areas minke whales were sighted in, vessel density was significantly higher than for those where blue whales and fin whales were sighted (Table 1), with mean monthly vessel density for minke whale point samples 5.208 ± 0.333 h compared to 3.400 ± 0.087 and 3.286 ± 0.062 h for blue and fin whales respectively. The difference in vessel density between areas where fin whales and blue whales were sighted was found to be nonsignificant and no interactions between species and other variables were found to have a significant effect (Table 1). A significant relationship was, however, found between season and vessel traffic in areas where whales were sighted (Table 1). For each species, individuals were found in areas of higher vessel density in autumn than during summer. Feeding individuals were also sighted in areas of significantly higher vessel density than those not feeding (Table 1). Vessel density in the areas where whales were sighted also varied significantly with years (Table 1; Fig. 4). Specifically, whales were found in areas of significantly higher vessel density in 2017 compared to both 2019 and 2020, and in 2018 compared to 2019 (Table 3). All other pairwise comparisons between years were found to be nonsignificant (Table 3). Vessel density in the areas where whales were sighted did not vary significantly with group size (Table 3).

3.3. Variability in species exposure to different vessel types

3.3.1. Minke whales

No statistically significant interactive effect was detected between vessel type and year on vessel density in areas where minke whales were sighted (ANOVA, $F(4, 51) = 2.096$; $p = 0.095$). However, the effect of

Table 1
Number of sightings and individuals observed of each species during surveys between 2017 and 2020.

Species		Year				Total
		2017	2018	2019	2020	
Minke	Sightings	5	10	5	6	26
	Individuals[a]	7	12	5	7	31
Fin	Sightings	22	12	12	33	79
	Individuals[a]	36	22	15	136	209
Blue	Sightings	5	4	2	16	27
	Individuals[a]	5	4	2	24	35

[a] The total number of individuals observed of the same species is the sum of the number of whales observed on each day without taking into account that some individuals may have been sighted on multiple different days.

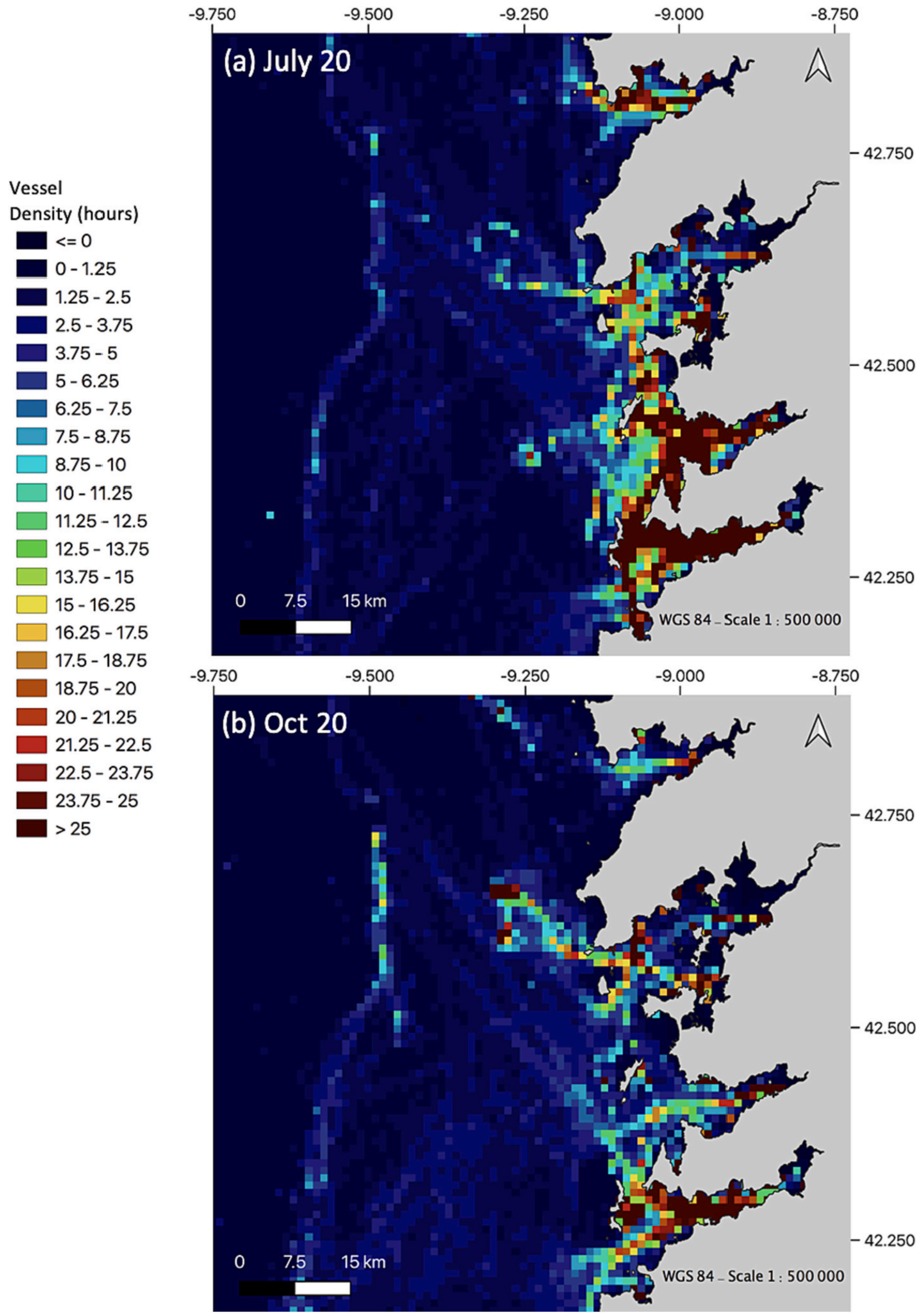

Fig. 2. Maps of vessel density within the study area during (a) summer and (b) autumn 2020. Vessel density of all vessel types of July and October 2020 were selected for illustrative purposes. Vessel density is shown in 1 × 1 km grid cells, expressed as hours per square kilometer per month.

vessel type on mean vessel density in areas where minke whales were sighted was found to be significant (ANOVA, $F(4, 51) = 17.328$, $p < 0.001$; Fig. 5). Specifically, fishing vessels contributed a significantly greater proportion to the total vessel density in areas where minke whales were sighted compared to large vessels ($p < 0.001$) and sailboats ($p < 0.001$; Fig. 5). The difference between mean vessel density of sailboats and large vessels was nonsignificant ($p = 0.996$). The effect of year on mean vessel density was found to be significant (ANOVA, $F(4, 51) = 3.754$, $p = 0.030$; Fig. 5); vessel density in areas where minke whales were sighted in was significantly different in 2018 compared to 2020 ($p = 0.029$).

3.3.2. *Fin whales*

A statistically significant interaction between vessel type and year on mean vessel density in the areas that fin whales were sighted in was found (ANOVA, $F(6, 255) = 2.962$; $p = 0.008$; Fig. 6). Specifically, fishing vessel density in areas where fin whales were sighted during 2017 was significantly higher than in 2019 ($p = 0.015$). This vessel type also contributed a significantly greater proportion to the total vessel density in areas fin whales were sighted compared to both large vessels ($p < 0.001$) and sailboats ($p < 0.001$) in all years analysed (Fig. 6). There was no evidence that vessel density of large vessels or sailboats in areas where fin whales were sighted differed significantly between years, or that this species experienced greater exposure to large vessels compared to sailboats in any one year, and vice versa.

3.3.3. *Blue whales*

A statistically significant difference was detected between the mean vessel density of difference vessel types in the areas where blue whales were sighted in (ANOVA, $F(2, 84) = 53.64$; $p < 0.001$; Fig. 7); fishing

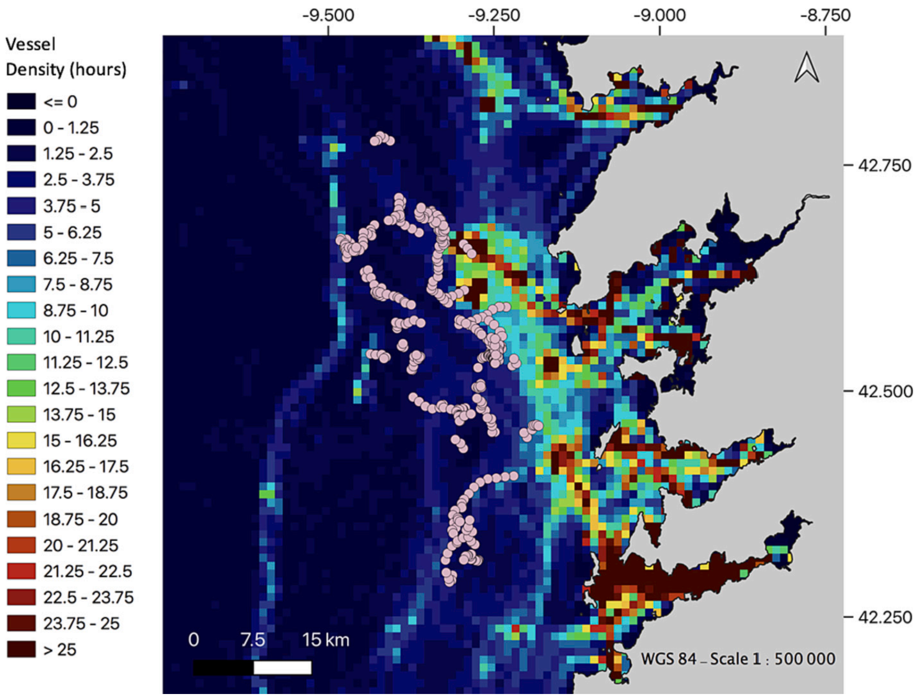

Fig. 3. Map of fin whale exposure to vessel traffic within the study region. Vessel density of all vessel types is shown for this species, the most frequently sighted in the area, during a high-risk month in the most recent year of available data (September 2020) to highlight spatiotemporal overlap of whale presence and vessel traffic. Pink circles indicate fin whale presence (instantaneous point samples) and vessel density is shown in 1 × 1 km grid cells, expressed as hours per square kilometer per month. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Percentage of samples of presence of each whale species in areas with a density of marine traffic over 5 h per month.

Species	>5 h/month
Minke whale	39.1 %
Fin whale	13.4 %
Blue whale	17.3 %

vessels contributed a significantly greater proportion to the total vessel density than large vessels ($p < 0.001$) and sailboats ($p < 0.001$).

4. Discussion

The potential impacts of vessel traffic to marine megafauna have been extensively noted, including the effects of noise pollution (Clark et al., 2009; Erbe et al., 2019), ship strike (Laist et al., 2001; Schoeman et al., 2020) and vessel presence itself (Williams et al., 2006).

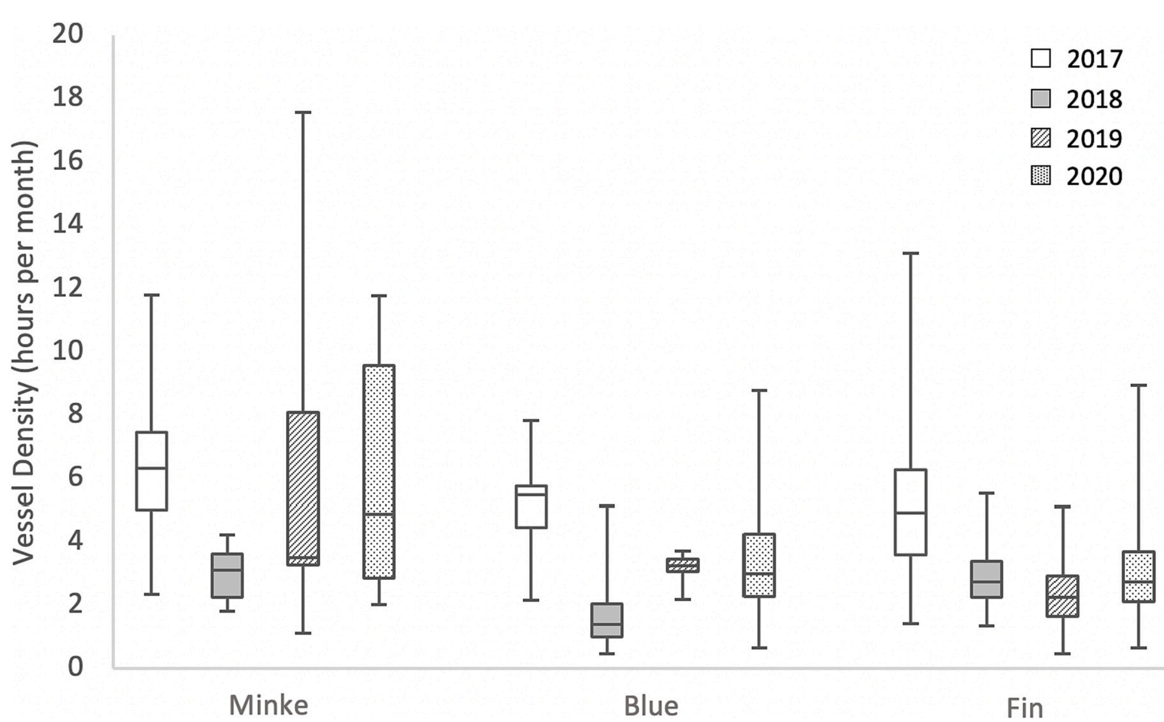

Fig. 4. The effect of year on species-specific exposure to vessel density. Box and whisker plots illustrate the median, interquartile range, lower and upper quartiles, and minimum and maximum values of vessel density in the areas where each species was sighted, each year from 2017 to 2020.

Table 3
The results of the minimal adequate general linear mixed model (GLMM) of the factors influencing whale exposure to vessel traffic. Analyses were restricted to sampling points for which complete data were available ($n = 1294$).

Random effect	Variance
Sighting identity	0.521
Residual	0.320

Fixed effects	Estimate ± SE	x^2/z-value*	P**
Intercept	2.074 ± 0.133	–	–
Species	–	11.172	**0.004**
Minke v blue	−0.485 ± 0.159	−3.059	**0.006**
Minke v fin	−0.399 ± 0.132	−3.019	**0.007**
Fin v blue	0.086 ± 0.122	0.702	0.759
Season (autumn v summer)	−0.601 ± 0.115	26.133	**<0.001**
Behaviour (feeding v not feeding)	−0.190 ± 0.096	4.011	**0.045**
Group size	–	1.516	0.218
Year	–	77.116	**<0.001**
2018–2017	−0.149 ± 0.144	−1.041	0.711
2019–2017	−0.602 ± 0.778	−7.740	**<0.001**
2020–2017	−0.434 ± 0.108	−4.003	**<0.001**
2019–2018	−0.452 ± 0.128	−3.540	**0.002**
2020–2018	−0.284 ± 0.153	−1.852	0.236
2020–2019	0.168 ± 0.121	1.395	0.485
Species: season	–	0.531	0.767
Species: behaviour	–	0.145	0.930
Species: group size	–	0.910	0.923

* Chi-squared values are given for the overall effects of species, season, behaviour and year. *Z*-values are given for the pairwise comparisons between species and across years.
** Significant values ($p < 0.05$) derived from likelihood ratio tests and Tukey's Honest Significance tests are highlighted in bold.

Distribution of these threats is spatially and temporally heterogenous across the globe, making assessments of exposure critical for the identification of high-risk regions and species to inform conservation priorities (Clapham et al., 1999; Thomas et al., 2016). Yet, information on regional and species-specific threat exposure is lacking. This is likely due to the inherent challenges associated with the collection of distribution data on animals which spend the majority of their lives underwater, often relying on opportunistic cetacean sightings (Silber et al., 2017). This study contributes to the growing literature on cetacean threat exposure by providing the first assessment of marine traffic exposure off the Galician coast to three baleen whale species.

Spatiotemporal overlap of whale presence and vessel traffic off the Galician coast confirms vessel traffic presents a real risk within the region, with blue, fin and minke whales all sighted in areas utilised by vessels on a monthly basis. The level of exposure to vessel traffic experienced by individuals in the study area displayed inter-annual variability and appears to be species-specific and significantly related to feeding behaviour and season.

Risk of exposure within the study region appears to be highest for minke whales, with this species sighted in areas with significantly higher monthly vessel density compared to both blue and fin whales. Sightings of this species during the study period included those in regions much closer to the coast than those of blue and fin whales, consistent with higher levels of vessel traffic within the study area. The use of inshore and coastal waters by minke whales has also been noted in previous studies (Northridge et al., 1995; Weir et al., 2007; Lee et al., 2017), indicating that the higher exposure of this species to vessel traffic in the study region may be the result of species-specific habitat preferences. This is also supported by the general preference of blue and fin whales for deep offshore waters (Azzellino et al., 2008; Panigada et al., 2008; Andriolo et al., 2010; Díaz López and Methion, 2019), in which vessel density in the study area is typically lower.

Previous studies have suggested human-caused disturbances such as vessel presence or noise may be perceived as a form of predation risk (Frid and Dill, 2002) and whales may therefore respond to vessel presence with avoidance and anti-predatory behaviours (Pirotta et al., 2015). Blue whales, for example, have been observed to alter diving behaviour in response to approaching large vessels (McKenna et al., 2015) and Campana et al. (2015, 2017) found significantly lower vessel traffic present in areas where cetaceans, including fin whales, were sighted in the Western Mediterranean Sea compared to areas where they were not sighted. Campana et al. (2015) discuss this may represent a negative response to traffic activity, where whales may avoid more highly trafficked regions with small or large scale displacements or increased dive activity. Other studies report a lack of response of cetaceans to approaching marine traffic, specifically fishing boats characterised by slow movements (Díaz López et al., 2008). Short-term behavioural changes have also been associated with vessel presence (Williams et al., 2006; Castellote et al., 2012; Pirotta et al., 2015; Dahlheim and Castellote, 2016). Williams et al. (2006) noted for example that killer whales (*Orcinus orca*) within the Johnstone Straight of British Columbia were more likely to change their behavioural state in the presence of a vessel. This disruption raises concerns about population-level impacts of long-term vessel presence within Galicia if consistent interruption of foraging and feeding activities leads to reduced feeding opportunities and ultimately lower energetic acquisition (Williams et al., 2006; Blair et al., 2016). Previous studies have however reported that cetaceans engaged in feeding activities are less alert to their surroundings, including vessel traffic (Laist et al., 2001), with Campana et al. (2015, 2017) discussing co-existence of whales and vessels may be driven by ecological requirements, i.e. where favourable feeding grounds overlap with higher traffic pressure, indicating there may be a trade-off depending on the extent of risk perceived of vessel presence by the whale.

It should be noted that an inherent limitation of studies based on observational presence data is that the differences observed between species may be because individuals were simply not sighted during dedicated surveys, as opposed to species-specific differences in the areas that they utilise. This is a particular challenge for determining presence/absence of cetacean species, which spend most of their lives under the water surface where they are not visible. Future studies should aim to use spatial distribution models with presence/absence data for each whale species associated with multiple environmental and anthropogenic variables (including marine traffic) to determine habitat suitability.

Foraging often involves greater surface-active behaviour in whales, a factor noted to increase the likelihood of physical interaction with vessels, and thus injury or mortality resulting from collision (Parks et al., 2012; Crum et al., 2019). Previous studies have also found that when engaged in activities critical for survival, such as feeding, cetaceans are more likely to remain in their behavioural state, allowing vessels to approach more closely before they respond (Schuler et al., 2019; Bubac et al., 2020). This indicates that not only are feeding whales at risk of

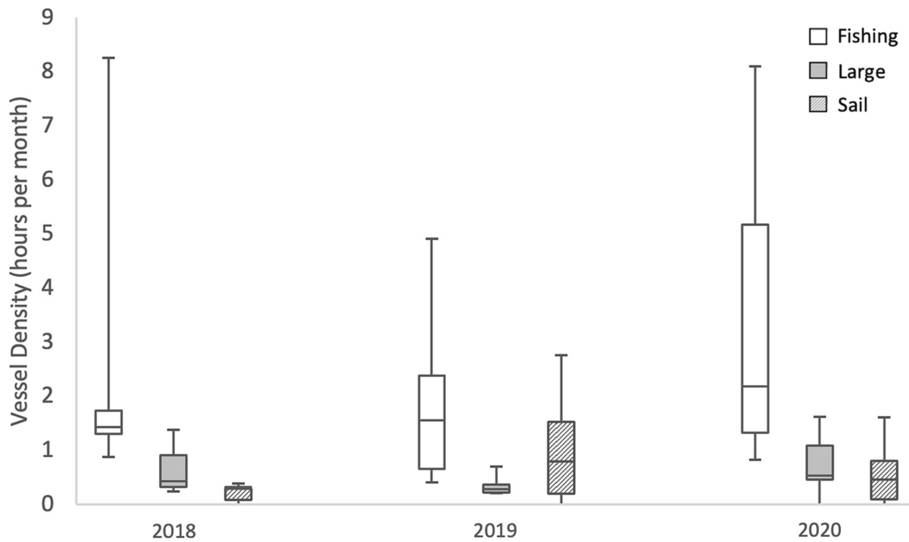

Fig. 5. Minke whale exposure to different vessel types. Box and whisker plots illustrate the median, interquartile range, lower and upper quartiles, and minimum and maximum values of vessel density of fishing vessels, large vessels and sailboats in the areas where minke whales were sighted each year between 2018 and 2020.

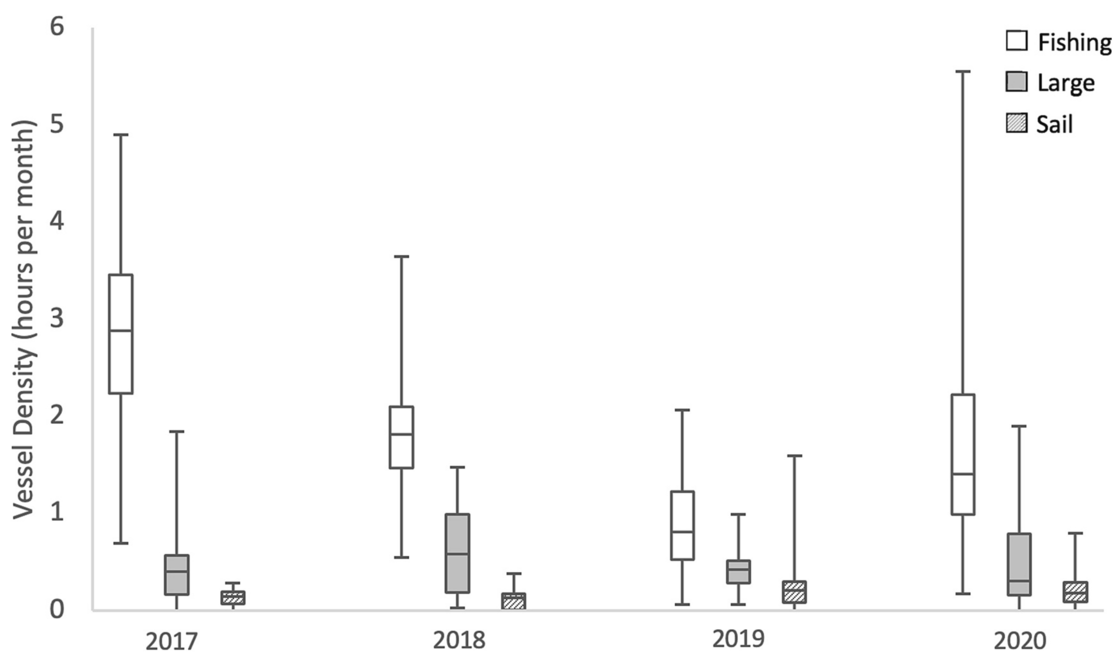

Fig. 6. Fin whale exposure to different vessel types. Box and whisker plots illustrate the median, interquartile range, lower and upper quartiles, and minimum and maximum values of vessel density of fishing vessels, large vessels and sailboats in the areas where fin whales were sighted each year from 2017 to 2020.

higher exposure to vessel traffic, but also at greater risk of collision. Baleen whales are often observed feeding at the surface in the study area (Díaz López et al., 2021). Surface feeding, a type of lunge feeding mainly observed in blue whales and fin whales (Díaz López et al., 2021), is a dynamic, unsteady, and unpredictable process, and so must be considered an important factor to consider as a potential risk for whales in the presence of vessels.

Seasonal changes in prey abundance are thought to drive blue and fin whale distribution specifically within Galician waters (Díaz López and Methion, 2019). Baleen whales are opportunistic predators that feed on diverse prey including euphausiids (Friedlaender et al., 2006, 2015) such as northern krill (*Meganyctiphanes norvegica*), which aggregate in dense patches in Galician waters following the phytoplankton bloom, with a time lag of several weeks (Bode et al., 2009; Visser et al., 2011). Characteristics of the upwelling regime and the temporal synchrony of whales with their prey therefore leads to whale presence peaking at the beginning of autumn within the study region (Díaz López and Methion, 2019; Díaz López et al., 2021). As biological productivity off the Iberian Peninsula peaks after seasonal upwelling events (Blanton et al., 1984), it is likely that fishing vessel presence also increases in autumn to temporally match increases in the abundance of target resources. This may explain why a significant effect of season on vessel exposure was detected: all whale species studied were sighted in areas with significantly higher monthly vessel traffic in autumn than during summer. The influence of season on exposure to vessel traffic was analysed only for summer and autumn due to low representation of sightings during other seasons, however the limited number of sightings during winter and spring appears to reflect the northward feeding migration pattern observed in rorqual whales from southerly grounds between July and October within the study region (Díaz López and Methion, 2019).

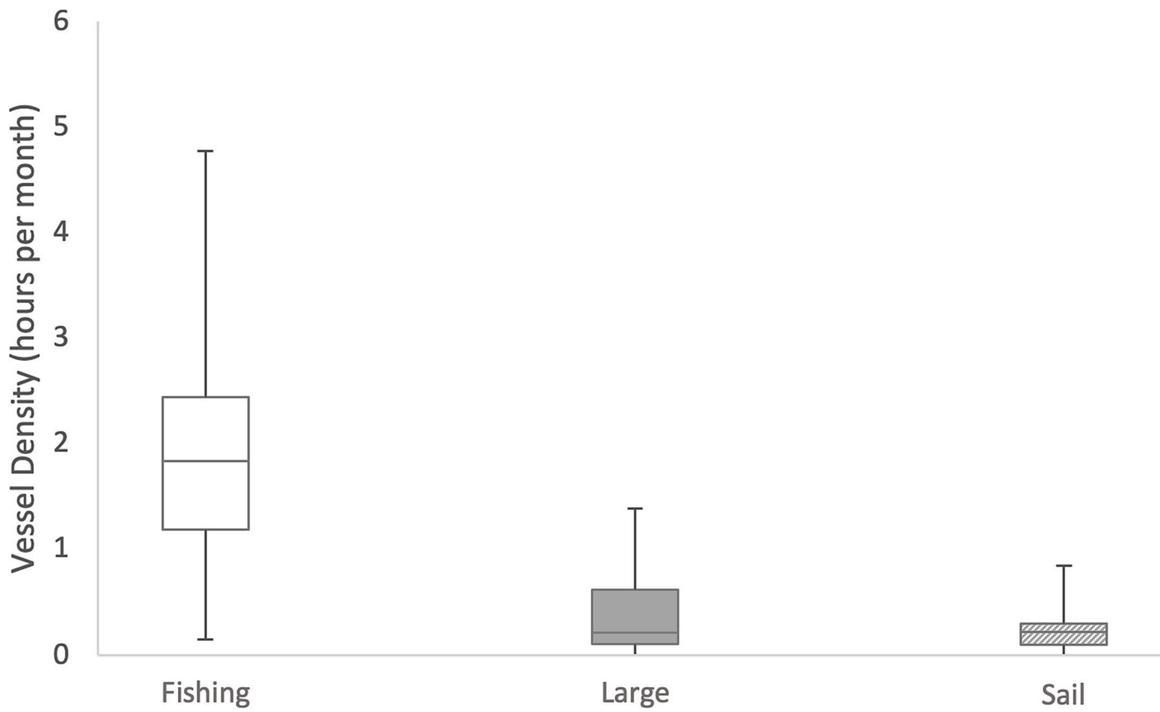

Fig. 7. Blue whale exposure to different vessel types. Box and whisker plots illustrate the median, interquartile range, lower and upper quartiles, and minimum and maximum values of vessel density of fishing vessels, large vessels and sailboats in the areas where blue whales were sighted between 2017 and 2020.

It should be noted that in this study it is not possible to know whether the spatial distribution of whales is due to a different distribution of prey, with minke whales displaying greater preference for crustaceans and plankton compared to blue whales and fin whales which feed on krill (Friedlaender et al., 2006, 2015; Skaug et al., 1997), or whether it could be conditioned by vessel avoidance, a factor future studies should aim to consider.

Seasonal differences in vessel exposure to baleen whales have been noted in other regions of the world. In the Mediterranean Sea, for example, risk of exposure is typically reported to be highest during summer months (Panigada et al., 2006; Campana et al., 2017; Pennino et al., 2017). This increased risk during summer can generally be attributed to increases in passenger boats during warmer months (Schuler et al., 2019), although the ecotourism industry appears to be less evident along the Galician coast (Díaz López and Methion, 2019). The importance of Galicia's fishing activity has, however, been commented on in previous studies (Cambiè et al., 2012; Surís-Regueiro and Santiago, 2014), indicating that the significant seasonal variation in minke, fin and blue whale exposure to vessel traffic is likely due to changes in fishing vessel operations to correspond with peaks in commercially targeted species' abundance and distribution. Fishing vessels were the most common vessel type found in the areas where whales were sighted: a trend that applied across all species, years and seasons analysed. As Galicia is one of the most important fishing regions within Europe with the largest Spanish fishing fleet (Galician Institute for Statistics, 2021), this finding was not unexpected but raises additional concerns of the anthropogenic threats posed to these species e.g., through fisheries bycatch (Surís-Regueiro and Santiago, 2014).

Frequent cetacean-fishery interactions have been reported within Galicia and other regions of the Iberian Peninsula (Goetz et al., 2014), including bycaught long-finned pilot whales (*Globicephala melas*), blue whales and fin whales (López et al., 2003; Aguilar and Borrell, 2022). Actual encounters between large cetacean species and fishing vessels may be low, with Goetz et al. (2014) reporting that baleen whales were sighted in <1 % of all cetacean sightings by 283 Galician fishermen. However, interactions are known to occur, for example a fin whale was recently observed with a fishing net caught around its head within Galician waters (Díaz López and Methion, 2019) and another fin whale observed with a fishing line around its body (Methion and Díaz López, 2019). Interactions between vessels and cetaceans also frequently go unreported (Neilson et al., 2012; Peel et al., 2018; Schoeman et al., 2020) and it would thus be pre-emptive at this stage to underestimate the potential impact of fishing vessels within the region.

Significant inter-annual variability in whale exposure to vessel traffic was detected, with whales sighted in 2019 and 2020 generally found in areas with lower vessel traffic compared to those sighted in 2017 and 2018. Variability in vessel exposure each year may be the result of avoidance behaviours, for example if whales actively avoided areas of higher traffic in more instances during one year compared to another. However, as discussed earlier, limited literature on avoidance behaviours of whales exists and the significant inter-annual variability in vessel traffic exposure to minke, blue and fin whales in this study is most fully explained by the variation in the abundance of fishing boats, the most common vessel type in the region.

Almost all vessel types have been reported as involved in ship strikes around the world (Laist et al., 2001), but as risk of collision is proportional to the size of the vessel and its speed, the involvement of larger vessels (>80 m) is more frequently observed (Gende et al., 2019; Schoeman et al., 2020). Injuries sustained by larger vessels are also thought to carry a greater risk of fatality because of higher force on impact (Laist et al., 2001; Moore et al., 2013). Sailing vessels have also been highlighted as a growing threat to cetaceans (Ritter, 2012). While significantly lower presence of larger vessels and sailboats was found in areas where whales were sighted compared to fishing vessels, encounters may still occur, presenting ship-strike risk within the study area to the three study species as well as additional noise in their soundscape (Clark et al., 2009; Erbe et al., 2019).

Intrinsic sensitivity to vessel noise will differ with each species' unique ecology, however larger vessels typically generate sound at frequencies below 1000 Hz (Ross, 1976), overlapping with those utilised and perceived by baleen whales (Clark et al., 2009). Minke, blue and fin whales may therefore be vulnerable to the impacts of acoustic masking off the Galician coast (Clark et al., 2009). Modelling noise pollution produced from vessel traffic in our study area was beyond the scope of our paper, however future studies should aim to characterise the acoustic environment of the study region as well as identify effective communication ranges of our three study species to investigate the extent to which their active space (the range over which the animals are able to communicate) is reduced in vessel presence (e.g. Merchant et al., 2014; Cholewiak et al., 2018).

4.1. Implications for conservation and management

Whales of the suborder Mysticeti are among some of the largest living animals in the world. These charismatic species, often deemed as ambassadors for marine conservation, hold important ecological roles in top-down regulation and the transference of nutrients and biomass (Bowen, 1997; Smith, 2007; Roman et al., 2014). Blue and fin whales are, however, classified as Endangered and Vulnerable respectively, in part owing to legacy effects of previous human persecution (Clapham et al., 1999; IUCN, 2008) and are now faced with the threat of several other anthropogenic pressures (Halpern et al., 2015; Albouy et al., 2020).

The present study contributes to the growing body of literature detailing exposure to anthropogenic pressures, confirming a considerable spatiotemporal overlap of vessel traffic, particularly of fishing vessels, with endangered baleen whale species off the southern coast of Galicia (Díaz López and Methion, 2019). This raises concerns not only of the exposure of minke, fin and blue whales within Galician waters to the impacts of ship strike and noise pollution (Laist et al., 2001; Clark et al., 2009; Cholewiak et al., 2018) but also to the risks associated with fisheries such as gear entanglement and bycatch (Van Der Hoop et al., 2014; Giralt Paradell et al., 2021). It should also be noted that due to the nature of this study, results indicate the minimum spatiotemporal overlap between whales and marine traffic, as vessel density values represent the minimum monthly vessel traffic within the areas that whales were sighted. This is because while many vessels are legally required to carry and transmit AIS, not all carry this requirement and thus not all traffic will be represented within our dataset (IMO, 2019). The potential threat of marine traffic off the Galician coast could therefore be much greater than presented.

There is a lack of information on ship collisions within the region, perhaps due do unreported interactions discussed earlier (Schoeman et al., 2020), however mortality due to fishery interactions have been recorded (López et al., 2003; Goetz et al., 2014; Aguilar and Borrell, 2022). The accumulation of single mortality events arising from human-induced disturbance can result in population-level impacts in long-lived, k-selected species such as baleen whales (Rockwood et al., 2017; Díaz López and Methion, 2019), making implementation of mitigation strategies a priority in regions where exposure to such disturbances has been noted.

The importance of the conservation of these species within Europe is recognised by their protection under Annex IV of the EU Habitats Directive (Council Directive 92/43/EEC). Special protection of minke, blue and fin whales (among other cetacean species) is given in Spanish waters under the Royal Decree 1727/2007, offering partial mitigation to the impacts of recreational vessels and whale-watching activities in Galician waters through the implementation of regulations such as reduced speed limits when approaching individuals, as well as exclusion zones which prohibit vessels from intentionally navigating within a 60 m radius of an observed cetacean. However, the protection measures in current Spanish legislation do not appear to help reduce the risk, as they do not focus on large vessels and fishing boats and appear to be static and non-specific. The results of the present study highlight that risk of vessel exposure to baleen whales off the Galician coast is dynamic, varying both temporally and between species, offering insight for management authorities to develop mitigation strategies which consider these differences, i.e., through the adoption of additional seasonal regulations when risk is greatest. Speed limits have been introduced in other highly trafficked regions of the world and proved effective at reducing ship-related mortality (Freedman et al., 2017; Joy et al., 2019), with several studies demonstrating that risk of mortality increases with vessel speed (Vanderlaan and Taggart, 2007; Conn and Silber, 2013). Introducing lower speed limits during summer months when coexistence of cetacean and vessel traffic is at its greatest should be considered.

5. Conclusions

Minke, blue and fin whales off the southern Galician coast may be at risk of vessel exposure and its associated impacts based on considerable spatial overlap between vessel traffic and whale distribution from AIS data and observations of whale presence over a four-year period. While these species are offered some protection within Spanish waters, avoidance behaviours of cetaceans and reductions in habitat quality due to vessel presence noted in other regions of the world (Nowacek et al., 2001; Williams et al., 2006, 2013; McKenna et al., 2015) indicates further protective legislation within Galicia may be required to ensure the continued utilisation of their waters as foraging ground for endangered whale species (Díaz López and Methion, 2019). The results of the present study provide useful insight for the identification of conservation priorities within the region, highlighting minke whales are exposed to a higher level of marine traffic, likely due to the spatial overlap between the distribution of this species with fishing activities. However, despite lower levels of exposure of fin and blue whales to marine traffic, this should not be mistaken as low risk, because as larger species they are more vulnerable to vessel collisions and sighted in areas utilised by large vessels in the study area. Our findings can therefore inform marine management strategies to be designed with the consideration of temporal and species-specific variation in vessel exposure and risk.

Assessments of exposure to anthropogenic threats will continue to play an important role in identifying species and areas of conservation concern, however, vulnerability of individuals to anthropogenic stressors is influenced not only by their spatiotemporal overlap but also the intrinsic sensitivity of a species e.g., to vessel noise. Future studies should therefore aim to characterise species-specific sensitivity to such threats. In doing so, a greater understanding of the impacts of human activities on populations can be gained, which is critical to minimise wildlife-user conflict and prevent local and regional extinctions.

CRediT authorship contribution statement

Rhian Bland: Conceptualization, Writing – Original Draft, Formal analysis, Review & Editing. Séverine Methion: Conceptualization, Investigation, Data curation, Writing – Review & Editing, Project administration, Funding acquisition. Stuart Sharp: Formal analysis, Review & Editing. Bruno Díaz López: Conceptualization, Investigation, Data curation, Methodology, Software, Formal analysis, Writing – Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data availability

Data will be made available on request.

Acknowledgements

This study would not have been possible without the cooperation of all BDRI members and volunteers who generously gave their time to help with field work. The boat-based surveys were carried out within the scientific project "BALAENATUR: seguimiento del rorcual azul dentro de la Red Natura 2000" with the support of the Fundación Biodiversidad of the Spanish Ministry for the ecological transition and the demographic challenge. The sampling campaigns were carried out with the administrative permit for the observation of cetaceans for scientific and educational purposes of the Spanish Government. Data collection complies with the current laws of the country in which it was performed (Spain).

Funding

Funding for this research came from the Bottlenose Dolphin Research Institute (BDRI). Boat based surveys during 2020 were supported by the project "BALAENATUR: seguimiento del rorcual azul dentro de la Red Natura 2000" with the support of the Fundación Biodiversidad of the Spanish Ministry for the ecological transition and the demographic challenge.

Code availability

R Script will be provided under request.

Ethics approval

Data collection complied with the current laws of Spain, the country in which it was performed.

Consent to participate

All authors gave final approval to participate.

Consent to publish

All authors gave final approval for publication.

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