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High rate of ship strike to large whales off Chile: Historical data and proposed actions to reduce risk

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ABSTRACT

Ship strikes are a worldwide threat to large whales as a major cause of mortality and injury. In the Southeast Pacific, this has been poorly studied. In the last decade, an increase in ship strikes has been observed off Chile. This study assesses ship strike mortality in large whales off Chile using data on fatal strandings from the past 52 years, (1972–2023) and vessel traffic patterns. In 63 out of 226 strandings (28 %), ship strike was the direct or probable cause of mortality, i.e. the primary cause of non-natural death in whales. Fin whales (*B. physalus*) suffered highest total ship strikes (n = 23; 37 %), followed by humpback (*M. novaeangliae*) (n = 13; 21 %), blue

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whales (*B. musculus*) (n = 7; 11 %), sei (*B. borealis*) and sperm whales (*P. macrocephalus*) (n = 6; 10 %). Ship strikes were highest in the Regions of Valparaiso, Coquimbo, Atacama and Antofagasta (Central-Northern Chile), Los Lagos, Aysen and Magallanes (Southern Chile). Since 2013, when necropsies began to be systematically performed, an average of 5 individuals/year have been killed by ships, mostly between January and May. We review all ship strike studies globally and compare rates in Chile with those elsewhere. Based on data between 2013 and 2023, Chile is the country with the highest ship strike mortality globally; considering the entire time series since 1972, Chile ranks number six worldwide. We identify major knowledge gaps and recommend policy measures, including establishing High-Risk Areas and the implementation of shipping lanes modifications and vessel speed restrictions.

R E S U M E N

Las colisiones con buques son una amenaza mundial para las grandes ballenas como causa principal de mortalidad y lesiones. En el Pacífico Suroriental, este fenómeno ha sido poco estudiado. En la última década, se ha observado un aumento de colisiones con embarcaciones frente a las costas de Chile. Este estudio evalúa la mortalidad por colisión con embarcaciones en grandes cetáceos frente a Chile utilizando datos sobre varamientos mortales de los últimos 52 años (1972-2023) y patrones de tráfico de embarcaciones. En 63 de 226 varamientos (28 %), la colisión con embarcaciones fue la causa directa o probable de mortalidad, es decir, la causa principal de muerte no natural en ballenas. Los rorcuales comunes (*B. physalus*) sufrieron el mayor número total de colisiones con buques (n = 23; 37 %), seguidos de las ballenas jorobadas (*M. novaeangliae*) (n = 13; 21 %), las ballenas azules (*B. musculus*) (n = 7; 11 %), las ballenas sei (*B. borealis*) y los cachalotes (*P. macrocephalus*) (n = 6; 10 %). Las mayores colisiones con embarcaciones se produjeron en las regiones de Valparaíso, Coquimbo, Atacama y Antofagasta (centro-norte de Chile), Los Lagos, Aysén y Magallanes (sur de Chile). Desde 2013, cuando se empezaron a realizar necropsias de forma sistemática, un promedio de 5 individuos/año han muerto por buques, principalmente entre enero y mayo. Revisamos todos los estudios sobre colisiones con buques a nivel mundial y comparamos las tasas de Chile con las de otros países. Sobre la base de los datos entre 2013 y 2023, Chile es el país con la mayor mortalidad por colisión con buques a nivel mundial; considerando toda la serie temporal desde 1972, Chile ocupa el sexto lugar a nivel mundial. Identificamos las principales lagunas de conocimiento y recomendamos medidas políticas, incluyendo el establecimiento de Zonas de Alto Riesgo y la implementación de modificaciones en las rutas marítimas y restricciones de velocidad de los buques.

1. Introduction

Ship strikes are a major cause of injury and mortality to large whales worldwide [1,2]. In a review of the International Whaling Commission (IWC) ship strike database, 605 confirmed cases of cetaceans killed by ship strikes were reported worldwide between 1820 and 2019 [3]. Additionally, 328 cases were considered probable or possible cases of large whales killed by ships. The South Pacific was identified as the third area with most events (n = 61), after the North Atlantic (n = 299) and the North Pacific (n = 139). However, most of the reports in the South Pacific were from Australia and New Zealand, with little data from South America. In a global review of ship strike risk, Nisi et al. [4] identified Chile as a high-risk area that has been poorly studied and these authors called for additional research to fill this knowledge gap.

High mortality of large whales has been observed due to ship strikes in Brazil, Uruguay and Argentina, in the last decades [3,4]. In Chile, there has been an increase in the mortality of fin whales due to ship strikes in recent years [5,6]. In Colombia, Ecuador and Peru, 20 cases of mortality for ship strike were described for sperm whales, blue and more frequently humpback whales in the last 100 years [4,7]. The Southeast Pacific (specifically, the Fishing and Agricultural Organization fishing area 87; www.fao.org/fishery), has been highlighted as one of the three areas where “possible” ship strike reports exceeded “confirmed” ship strike reports, indicating data deficiency in this region [3]. The Eastern Tropical Pacific has also been recently identified as a region where ship strikes are underreported [7]. In addition, it is now well-known that only a small fraction of large whale carcasses reaches the coast and therefore the number of stranded whales does not adequately reflect real mortality rates [8,9]. Moreover, when strikes occur, these are not reported because the large size of ships means that they are often not seen by the crew, and/or may occur in poor weather or at night. This means that ship strike mortality in large whales may be underreported by two thirds [5–9].

The coast of Chile hosts critical habitat for several large whale species, including migratory corridors, nursing areas and feeding grounds [10–20]. There are feeding habitats for fin whales (*Balaenoptera physalus*) off Central-Northern Chile [10–12]; blue whales (*Balaenoptera musculus*) in Northern Chilean Patagonia [13–16], and humpback whales (*Megaptera novaeangliae*) off Southern Chilean Patagonia [17–19]. In recent years, in Chile increased reports of whales being killed or injured by ship collisions have appeared in the press, as well as in the scientific literature [20–22]. Also, ship traffic has been found to overlap with critical whale habitats at several sites along the coast [23–26], but these studies are restricted to delimited areas. In this study, we compile data between 1972 and 2023 on stranded whales along the entire Chilean coast, to assess the magnitude of the ship strike problem in Chile, characterize the spatial distribution of ship strike risk, and make recommendations to reduce this risk.

2. Methods

2.1. Stranding database compilation

Stranding data of large whales from January 1972 to September 2023 were compiled from several sources to build a national database (partially presented in Alvarado-Ryback et al., 2020) [20]. Strandings were compiled from: 1) the Chilean National Fisheries and Aquaculture Service (SERNAPESCA; www.sernapesca.cl/) stranding database, which is informed by official reports made by local Non-governmental organization (such as Panthalassa, Center for Marine Fauna Research and Whale Watching (CIFAMAC), Centro de Conservación Cetacea (CCC), Centro Ballena Azul (CBA), Whale sound, and Museo del Rio Seco), universities (e.g. Universidad de Chile, Pontificia Universidad Católica de Chile, Universidad Austral de Chile, Universidad de Concepción, Universidad Santo Tomás, Universidad Andres Bello, Universidad San Sebastián) and the general public reporting to these institutions. 2) Literature searches conducted in English and Spanish, from three main electronic databases: Web of Science, PubMed, and the Scientific Library

Online (SciELO); using multiple keywords: "stranded" OR "stranding" AND "large whales" "Mysticeti" "Physeteridae" OR "sperm whales" and "Chile" OR "Pacific" OR "South America" and all the scientific names of the large whales present in Chilen waters. 3) Gray literature including proceedings from conferences, Chilean newspapers, magazines, local reports, and social media (e.g., Facebook). Information was extracted and put into a database with details on every specific event including the cetacean species, the number of individuals involved in the event, date, geographical coordinates of the reported location, and suspected or probable cause of mortality (see below).

Only animals that were dead when they stranded or died after stranding were considered in the analysis; animals that stranded alive and were then successfully returned to the sea were not considered. From here on in the text, strandings refer only to these dead stranded animals. The cause of mortality was defined as any injury, disease or disorder that initiated the physiological derangement leading to the stranding and mortality of the animal, based on standard definitions in veterinary forensic pathology [27]. The cause of mortality was determined for each case based on a review of the history, necropsy reports and photographs taken during necropsies and/or history and pathological findings reported in the gray literature or published studies. Most of the necropsies were performed by the authors of the present study (n = 19) and some by trained veterinarians and biologists from SERNAPESCA and/or the Association of Chilean Wildlife Veterinarians (n = 9) (AMEVEFAS; www.amevefas.cl/). Necropsy completeness ranged from external examination with minimal dissection to complete dissection of the abdominal and thoracic cavities. Brains were not examined. Complete necropsies were performed on carcasses with a decomposition state of 1–3 (n = 14). For animals with a decomposition state of 4–5 (n = 3), only partial necropsies or morphometric analyses were conducted, and skeletal system pathologies were described. Causes of mortality were classified as "probable" when necropsy findings supported a particular cause of mortality, and "suspected" when the necropsy findings provided some evidence for an injury or disease that could have led to mortality, but the amount of information was not enough to support a more definitive claim. The following categories of probable or suspected causes of mortality were allocated to each case: "ship strike" "predation" or "entanglement". The criteria for ship strike mortality included history via eyewitness reports of collision with a vessel and/or retrieval of carcasses from ship compartments, and the presence of significant signs of blunt trauma such as laceration, abrasions, hemorrhage, and bone fractures as specified for large whales injured by vessels [1]. The criteria for predation included history of predator attack and signs of sharp and bite trauma such as rake marks, lacerated tongue, blubber and skeletal muscles. The criteria for entanglement included presence of fishing gear in the carcass associated with linear, sharp patterns of skin and blubber lacerations and hemorrhage [1]. When the cause of mortality could not be determined, cases was classified as "unknown".

2.2. Stranding data analysis

For the analyses below, we consider ship strikes as all possible plus suspected cases combined. The causes of mortality were examined for each large cetacean species and reported as total individuals, and as a percentage of total strandings to determine the contribution of ship strikes to non-natural mortality in large cetaceans. Additionally, the species most affected by ship strikes was determined by considering ship strikes in that species as a percentage of total strikes across all species. For each individual species, we examined the causes of mortality as a percentage of total strandings.

Total ship strikes per year were examined as a time series. In 2013, there was an increase in training and national technical capacity allowing systematic necropsies to be carried out. Therefore, a minimum estimate of strike mortality based on stranding data, uncorrected for effort and abbreviated as minimum strike mortality (ind./yr), was calculated for data before and after 2013, as well as the entire study period. Monthly totals of ship strikes were also examined as a total count (not an average per month over all years) in order to examine any possible seasonal differences. To quantify the significance of differences between seasons (December-February = summer; March to May = autumn; June to August = winter; September to November = spring), we used a Kruskal-Wallis test using the stats (v4.1.1) package with the 'aov' function in R [28]. Given that the data did not follow a normal distribution and the assumption of homogeneity of variances was not met, this test is suitable for comparing the four seasons. Minimum ship strike mortality were examined per administrative region in Chile (as a percentage of total stranded animals in the region) to determine any regional differences in ship strikes.

To compare minimum strike mortality rate in Chile with the situation worldwide, it was compared as a percentage of total strandings for Chile, with the same metric calculated from available reports in the literature from other parts of the United States, Canada, Canary Islands, Mediterranean Sea, Italy, France, South Africa, Turi Sia, Siri Lanka, New Caledonia and Nicaragua (1–12; Cited Literature Appendix A). Also, the minimum strike mortality for Chile (as ind./yr), pre- and post-2013, was compared with the same metric calculated or reported in the available literature as far back as 1820. These data were obtained from original stranding investigations, with at least 5 years of data, where information on the cause and/or possible cause of mortality in large whales was available (Appendix A). It is important to make clear that there is no data on monitoring or reporting effort for strandings or ship strikes, so it was not possible to correct ship strike data for reporting effort. This means that distinguishing between trends driven by changes in reporting effort and changes in actual ship strikes was not possible. Additionally, we did not normalize according to population trends for whale species because there are no national level abundance and population trend estimates for any whale species in Chile.

To better identify ship strike hotspots spatially, a heatmap (visualization of a point density interpolation using Kernel Density Estimation) was created using all ship strike geolocations with a 100 m pixel resolution and a radius (h) of 50.4 km with QGIS v.3.36.3 [29]. We used this radius because a study conducted in Brazil estimated that a whale carcass in advanced decomposition (code IV, up to seven days since death date) can drift over 50.4 km from the site of death to the stranding site [30,31]. In the absence of any similar study in Chilean waters, we considered this value a realistic first estimation.

2.3. Marine traffic data analysis

To characterize vessel traffic patterns off the coast of Chile, daily vessel tracking information (time-stamped Global Positioning System, GPS, locations for individual vessels) was obtained from the Chilean National Fisheries and Aquaculture Service (SERNAPESCA). Details about this database have been summarized elsewhere [23]. We used a 7 × 7 km grid to calculate vessel density (VD) for each grid-cell. Vessel data are provided daily, with data gaps occurring for some days. Therefore, VD was calculated by summing the daily number of unique vessels crossing each grid-cell in a month divided by the total number of days with available data (range: 25–31 days). This procedure was conducted for the austral summer, autumn, winter, and spring months from March of 2019 to December of 2020 and then averaged into a single layer. The analysis was conducted for three main activities: aquaculture, artisanal fisheries, and industrial fisheries. To also consider large transport vessels, we conducted the same analysis for the cargo fleet using Automatic Identification System (AIS) shipping data, which tracks information about a vessel according to its unique Maritime Mobile Service Identity number (www.imo.org). Maps of this vessel traffic data are provided in Appendix B.

To reconcile VD data with the heatmap on the spatial distribution of ship strikes described above, we resampled the latter to match the grid resolution of the former (7 × 7 km). This resampled raster of ship strikes was multiplied by the VD raster for each fleet to generate a vessel-stranding co-occurrence index. This index does not directly measure collision risk but rather identifies areas of interest where vessel density and cetacean strandings overlap. Although it is a simplified approach, it highlights priority areas for future research and management.

3. Results

3.1. Causes of mortality

A total of 226 strandings of large whales were recorded between January 1972 and September 2023 (Fig. 1), of these, 141 cases (62 %) had an unknown cause of mortality and in 63 cases (28 %) were associated with ship strikes (probable and suspected). Most of these cases were where ship strike was determined as the probable cause of mortality given the blunt trauma suffered by the animal (55 cases). Five cases (7 %) were caused by entanglement (probable and suspected); and seven cases caused by predation (probable and suspected) (3 %). The main cause of non-natural mortality is identified from stranded animals.

3.2. Species affected by ship strike

In terms of the total number of ship strike events, the species most affected by ship strikes were fin whales with 23 cases (37 % of total ship strikes across all species), followed by humpback whales 13 cases (21 % of total ship strikes), and sei and blue whales, seven cases for both species (11 %). However, if we examine the minimum ship strike mortality per species, i.e. as a percentage of total strandings for a given species, 67 % of the strandings of Bryde's whales (n = 4) were caused by ship strike, followed by fin whales (55 %; n = 23), blue whales (44 %; n = 7), humpback whales (30 %; n = 13), sei whales (15 %; n = 6), right whales and sperm whales (11 %; n = 1 and n = 6, respectively); and minke whales (10 %; n = 2) (Fig. 1).

For fin whales, most ship strikes occurred in the regions Antofagasta (n = 5) and Coquimbo (n = 5), Valparaiso (n = 4), Bío-Bío (n = 3), and Tarapacá (n = 2); for humpback whales the regions of Magallanes (n = 7), Atacama (n = 2), Antofagasta (n = 1) and Los Lagos (n = 1); and for blue whales in the regions of Los Lagos (n = 4), Arica y Parinacota, Tarapacá and Aysen (n = 1) (Fig. 2).

3.3. Temporal and regional trends

Over the entire study period, the minimum strike mortality increased from 0.3 ind./yr (1972–2012) to a rate of 5 ind./yr between 2013 and 2023 (Fig. 3a). 79 % (n = 50) of stranded whales with ship strike injuries were found during that time, possibly because of the increase in necropsy effort. 2021 was the year with the highest number of ships strikes (n = 9). Fifty-five percent (n = 34) of ship strikes occurred between January and May, i.e., the austral summer and autumn, with April having the highest occurrence (15 %; n = 9) (Fig. 3b). Summer followed by autumn had the highest number of strikes; we found significant differences between summer and winter (p = 3.7e-05), between summer and spring (p = 4.2e-05), and between autumn and spring (p = 0.00063). The administrative regions with the most ship strike events were Magallanes (Southern Chilean Patagonia), with 21 % (n = 13 events), Los Lagos (Northern Chilean Patagonia) 18 % (n = 11), Antofagasta (Northern Chile) with 13 % (n = 8), and Valparaiso and Coquimbo (Northern-Central Chile) with 8 % each (n = 5 each) (Fig. 2).

3.4. Marine traffic

Each fleet displayed vastly different distributions along the coast of Chile (Appendix B). The aquaculture fleet yielded high vessel-stranding co-occurrence, strongly concentrated in Southern Chile, south of 41°S (Fig. 4a), which coincides with hotspots of ships strikes in Chilean Patagonia (Fig. 4e); High vessel-stranding co-occurrence associated with the artisanal fishery fleet was strongly centered in Central-Southern Chile, particularly in the Bío-Bío Region (Fig. 4b) due to high artisan vessel density in this area (Appendix B), high ship strikes are also seen in this area (Fig. 4e). Vessel-stranding co-occurrence due to the industrial fishing fleet was highest off Central-Northern Chile (Fig. 4c), where this fleet is concentrated (Appendix B), which coincides with hotspots of ship strikes off Central and Northern Chile (Fig. 4e); this area has high presence of fin whales during the austral summer. The cargo fleet vessel-stranding co-occurrence was clearly centered around the main Chilean ports (Fig. 4d), which is also where ship strike hot spots are located (Fig. 4e).

4. Discussion

4.1. The global and national situation of ship strikes

Over 51 years of data from the coast of Chile, at least 28 % (n = 63 cases) of stranded whale mortalities were probably or suspected to have been caused by ship strikes. This is well above the highest rate reported in other regions (14.3 %; Table 1). Of the 63 total ship strikes, 50 (= 79 %) occurred since 2013 when we see a sharp rise in the time series with ship strikes occurring annually from then on. Based on the data since 2013, Chile has the highest minimum strike mortality in the world (Appendix A); and if we consider the entire time series since 1972, Chile

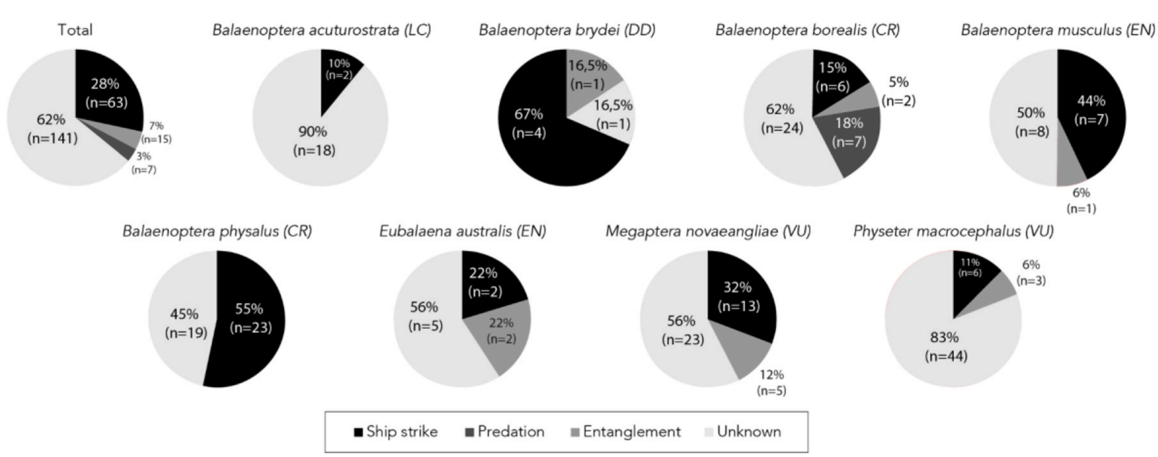

Fig. 1. Causes (probable + suspected) of mortality of stranded animals between 1972 and 2023 per species, expressed as total individuals and as a percentage of total strandings for that species. We include the conservation categories of each species of large whales for Chile according to the Chilean Ministry of the Environment; CR = Critically Endangered, DD = Data Deficient, EN = Endangered, LC = Least Concern, VU = Vulnerable (https://clasificacionespecies.mma.gob.cl/).

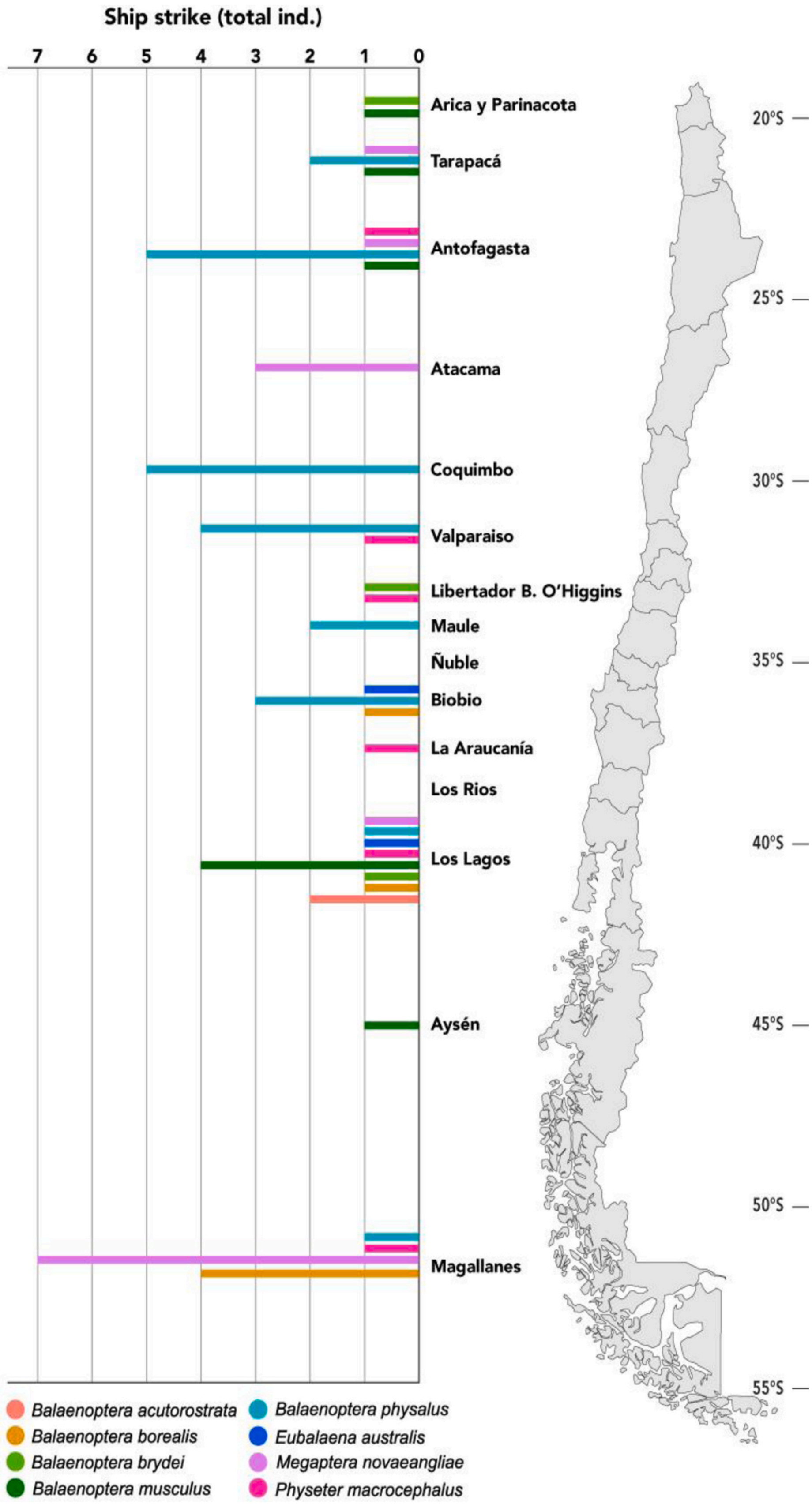

Fig. 2. Total confirmed whale mortalities by ship strike (total individuals) per administrative region in Chile, in geographical order from north to south, per species, for all data between 1972 and 2023.

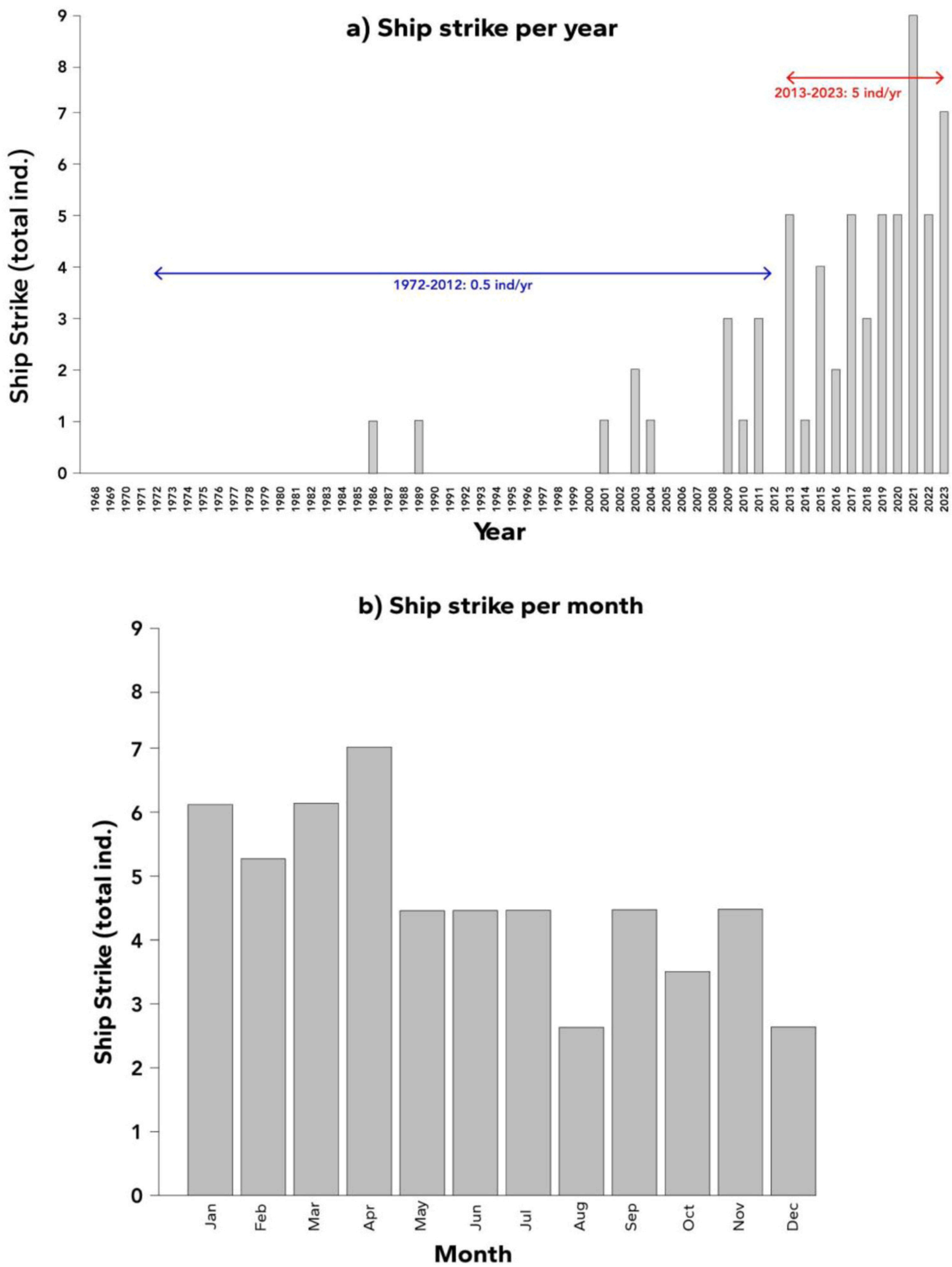

Fig. 3. a) Time series of minimum strike mortality per year between 1972 and 2023, with the rate of individuals killed per year over two periods of time, pre- and post-2013; b) minimum strike mortality per month for all years together (1972–2023). Note: 2013 is when systematic necropsies started to be performed in Chile.

ranks number six worldwide (Appendix A).

These findings fill an important knowledge gap on ship strikes in the southern hemisphere highlighted in previous studies [3,4]. Compared to South Africa, Italy, France, the United States and the Mediterranean (Table 1), Chile has the highest number of ships strikes as a percentage of total strandings, with 31 % considering data post-2013 and 28 % considering data from the entire time series since 1972. Comparing minimum ship strike mortality (ind./yr) with other studies around the world going back as far as 1820 (Appendix A), and considering the entire time series since 1972, Chile (1.22 ind./yr) ranks sixth after the Northwest Atlantic Coast, United States and Canada (4.38 ind./yr), the Atlantic United States (2.23 ind./yr), the Canary Islands (2.13 ind./yr) North America, and is below the worldwide rate (2.39 ind./yr). However, if we only consider data since 2013 and compare with studies for the same time period, Chile ranks number one (5 ind./yr), followed by the United States West Coast and Sri Lanka (3.5 ind./yr) (Appendix A).

Minimum ship strike mortality presented here are almost certainly underestimated, given that only since 2007 stranding events have been systematically recorded in Chile, and no systematic necropsies were performed before 2013. Therefore, many internal injuries such as fractures or hematoma may not have been detected in the carcasses of stranded animals prior to 2013 [20,32]. Also, globally we know that ship strikes are likely to be underreported given that carcasses can sink or float out to sea and do not always present as dead animals stranded on beaches [8]. Ship strikes may also be underestimated due to advanced stages of decomposition of carcasses, poor access to areas where animals are stranded for carrying out necropsies, and poor data collection [27]. For North Atlantic right whales (*Eubalaena glacialis*), a large percentage of cryptic mortality is thought to be associated with entanglement and ship strikes [33]. Lastly, it is also important to bear in mind that animals that die by ship strike may have been more vulnerable to ship strike due to infectious disease, entanglement, predation or low prey availability,

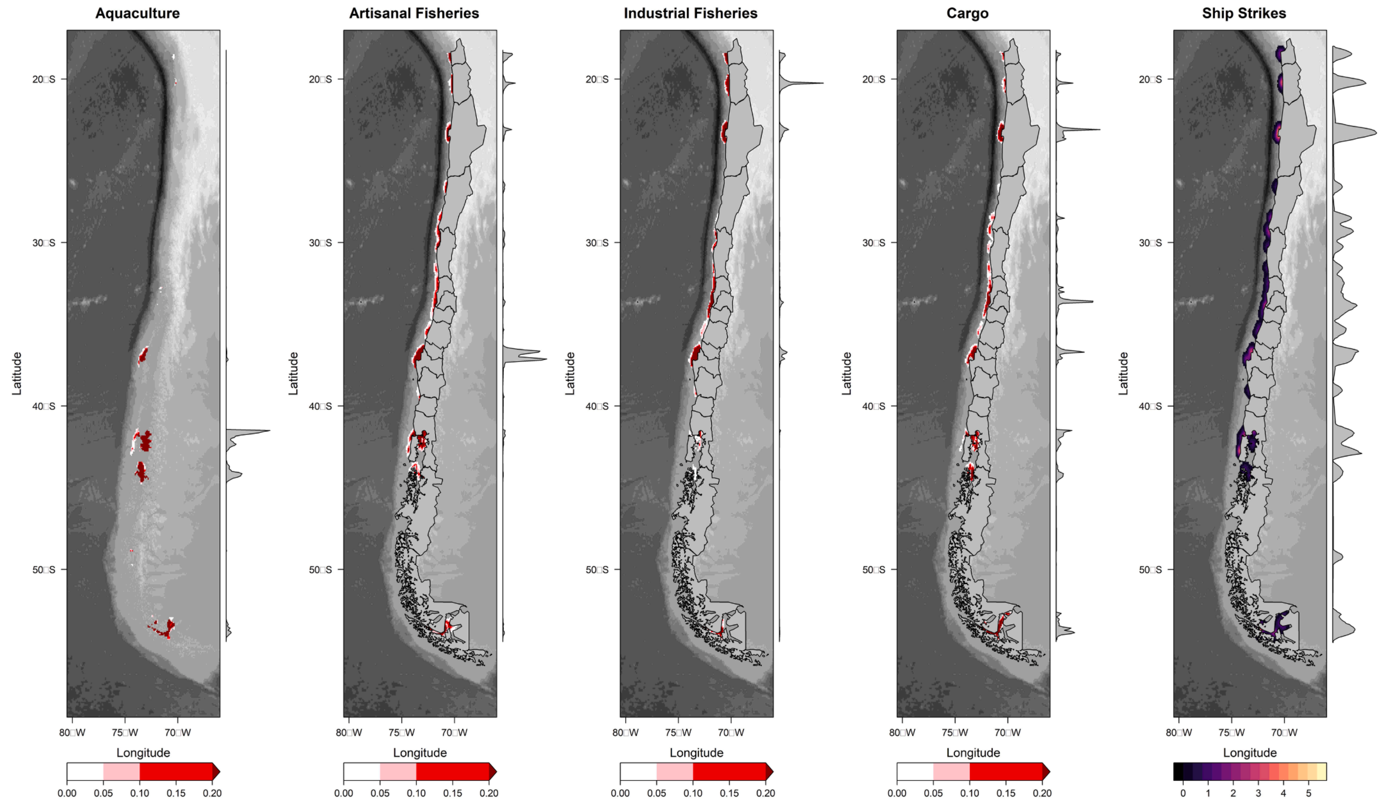

Fig. 4. Spatial vessel-stranding co-occurrence calculated as a function of vessel density (average number of unique vessels per 7 ×7 km grid cell) and the number of strandings along the coast of Chile per industry type a) Aquaculture; b) Artisanal fishing; c) Industrial fishing, and d) Cargo. The final plot e) shows the heatmap with the interpolated spatial distribution of standings known or suspected to be the result of ship strikes (SS; ship strike/50.4 km radius). Plots in the y axes represent the mean value of each variable by latitude better illustrating the magnitude of risk hot spots. Administrative Regions of Chile in geographic order from north to south: Arica y Parinacota; Tarapacá; Antofagasta; Atacama; Coquimbo; Valparaiso; Libertador G. Bernardo OHiggins; Maule; Ñuble; Bío-Bío; La Araucanía; Los Rios; Los Lagos; Aysén del G. Carlos Ibañez del Campo; Magallanes.

Table 1
Comparison of large whale strandings by minimum ship strike mortality as a percentage of total strandings for regions of the world based on available literature, including data from this study between 1972 and 2023 and 2013–2023. Note: 2013 is when systematic necropsies started to be performed in Chile.

Minimum Ship strike rate (% of total strandings)	Study period (years)	Study duration (years)	Strandings events (ind.)	Ships strikes events (ind.)	Species	Species with most confirmed ship strikes	Location	References
28 %	1972–2023	51	226	63	All large cetaceans	*Balaenoptera physalus*	Chile	This study
31 %	2013–2023	10	145	50	All large cetaceans	*Balaenoptera physalus*	Chile	This study
20 %	1963–1998	35	55	11	All large cetaceans	*Eubalaena australis*	South Africa	Laist et al. 2001
16 %	1972–2001	29	287	46	Fin whales	*Balaenoptera physalus*	Mediterranean sea	Panigada et al. 2006
14 %	1975–1996	21	31	3	All large cetaceans	*Balaenoptera physalus*	Atlantic United States	Laist et al. 2001
13 %	1972–1998	26	127	16	All large cetaceans	*Balaenoptera physalus*	France	Laist et al. 2001
12 %	Unspecified	11	113	13	All large cetaceans	*Balaenoptera physalus*	Italy	Laist et al. 2001

which can increase the probability of being hit by a ship, since these variables can decrease their physiological capabilities, both for diving and swimming performance [34]. Therefore, other stressors are likely to interact with ship strike occurrence.

The relative trend in rising ship strikes might be explained by several, non-mutually exclusive reasons: (1) increase in reporting effort, particularly over the past decade due to research initiatives, use of social media, and interest by the press and the general public; (2) increase the number, frequency, size, speed and expansion of marine traffic along the coast over the past decade; and (3) potential population increase of large whales off the coast of Chile, as commercial whaling ceased in the 1980's. While this study does not correct for reporting effort, population trends, or traffic density changes over time, we hypothesize that the increase in ship strikes may in fact be caused by a combination of all three effects. Similar conclusions have been discussed by authors in other parts of the world, such as Australia and France where the increase in animal abundance, the increase in reporting, the increase in traffic, and increase in speed and size of vessels have all generated an increase in the ship strike reports of different species of large whales [2,34]. Although a whale can be hit by a ship of any length, lethal injuries are more likely to be caused by vessels greater than 80 m [32]. Vessel speed also must be examined, since most serious injuries and/or death have been found to be caused at speeds of at speeds of 10 kt and greater [35, 36] and 14 kt and greater 14 kt or greater [32]. Future research efforts should include obtaining data on spatiotemporal changes in vessel traffic over time, whale population levels, and reporting effort.

The principal areas where ship strikes occurred overlap with areas of high densities of marine traffic and high densities of large whales (large port areas). The association between ship strikes and areas of high marine traffic density has also been reported in other places. Eight ship-strike risk hotspots have been identified for blue, fin, humpback, and sperm whales, primarily concentrated in coastal areas of key regions, such as the west coast of North America, the northern Indian Ocean, the Mediterranean, the east coast of South America, and Southern Africa [4]. Species-specific risk areas have been identified for fin whales in the Northwest Mediterranean Sea [33,34,37], for humpback whales off Alaska [38], and for blue whales off California [39]. All these studies agree that collisions with ships are now one of the major threats to large whales worldwide [32–34,37,38]. Given that an increase in marine traffic is expected to continue in the future, there is an urgent need to implement a variety of mitigation measures to minimize the probability of ship strikes in high-risk areas, such as proper planning of new and existing shipping lanes, reductions in vessel speed, and the implementation of traffic separation schemes [39,40,41] (see the Policy Recommendations section below).

4.2. Species affected by ship strikes in Chile

Ship strikes most affected fin whales (n = 23; 37 % of total ship strikes), followed by humpback, sei and blue whales. Ship strikes also accounted for more than half (55 %) of total strandings in fin whales. These results coincide with other studies that found that fin whales were the most hit species [3,4,32,37,40–43], specifically 14 % of ship strikes in the United States are to fin whales; 20 % in Italy, 22 % in France [33, 43–45], and 16 % in the Mediterranean Sea [32] (Table 1). Since differences in ship strikes among species have been associated with differences in species abundance [43], higher ship strikes in fin whales may be linked to the higher abundance of this species, as suggested by recent estimates for the Humboldt Current System (for Central and Northern Chile only) [23]. However, reporting effort is expected to be disproportionally higher in Central and Northern Chile when compared to the remote convoluted coastline of the fjords and channels in Chilean Patagonia. The data would indicate that the increase of collisions between boats and whales would be related to the increase of whale populations, such as humpback, Sei, and blue whales.The fin whale is an exception, possibly because it has an oceanic distribution compared to the other species.

Other potential explanations for the differences among species could be related to carcass buoyancy characteristics that influence whether certain species strand on beaches, float or sink and skew reporting for certain species [46]. Specifically, right and sperm whales are usually expected to float, whereas fin and blue whales more often sink [42]; this means that the numbers reported here for fin and blue whales may be further underestimated. Also, it is unclear whether there are behavioral differences that may explain high strike rates in some species versus others, including their capacity of avoiding strikes. For example: (1) limited capacity to maneuver and avoid ship strike has been seen in blue whales off the coast of California [47], which might contribute to the high number of ships strikes in blue whales (2) Balaenopterids are shallow divers (20 m) especially at night, which makes them vulnerable to collisions during nighttime and twilight, as seen in fin whales [48–50], which may contribute to the high number of ships strike found in fin whales. (3) Acoustic shadows may arise at the front of boats, meaning that on an oncoming vessel is not easily detected by a whale [51], which may increase the risk of ship strike in all species.

4.3. Regional and seasonal differences

Regional differences in ship strikes may be explained in part, by regional variation in the abundance of whales, since areas of high whale abundance associated with feeding areas can increase the probability of ship strikes, which has been documented for fin, blue, humpback, right, and sperm whales in other areas of the world, [33,34,39,43,52–54]. We found that ship strikes were highest in regions where known feeding grounds are found for fin (Central and Northern Regions of Valparaiso, Coquimbo, Atacama and Antofagasta; [10–12,55], humpback (Southern Regions of Los Lagos and Magallanes; [17,18,56] and blue whales (Southern Regions of Los Lagos and Aysen; [13–15,22,57]. In other parts of the world, high ship strikes have also been reported in feeding grounds for blue whales and humpback whales off Sri Lanka, California and New York [58–60].

However, regional differences in ship strikes within Chile are also clearly linked to spatial differences in traffic density and the location of large port areas (Fig. 4). The Region of Magallanes hosts the port of Punta Arenas, and the Region of Los Lagos contains the port of Puerto Montt and the dense traffic area of the inner sea of Chiloe. In Central-Southern Chile the Region of Bío-Bío contains the large port area of Talcahuano. In Central Chile, the Region of Valparaiso contains the ports of San Antonio and Valparaiso; in Northern Chile the Region of Coquimbo contains the port of Coquimbo, the Region of Antofagasta contains the ports of Antofagasta and Mejillones. All the above-mentioned regions are good starting points for identifying High Risk Areas (see Policy Recommendations below).

It is important to highlight that different industries are responsible for traffic in different regions and must be engaged in policy decisions. Traffic in the regions of Southern Chile (Magallanes and Los Lagos) is strongly contributed to by the aquaculture industry. Traffic hotspots in both Northern and Central Chile have important contributions from the industrial and artisan fishing fleets. Cargo ship traffic is present along the entire Chilean coast but likely serves different industries, for example providing transport for the aquaculture industry in Southern Chile and the mining industries in Northern Chile. In the SERNAPESCA traffic database, no data was available on vessel size, however this variable should be taken into consideration in future spatial analyses. For example, although the artisan fleet is high density, it is made up of vessels no greater than 18 m in length as dictated by Chilean law; whereas industrial fishing vessels are above 18 m in length and the largest one operating in Chile is 100 m length; and cargo vessels can be 100–300 m in length. The increase in vessel size (especially over 80 m) is more likely to cause serious or fatal injury [32,41].

Ship strikes were predominantly reported in summer and autumn, which coincides with what is known about the seasonal residence of large whales on their feeding grounds off the coast of Chile [10–19]. Summer and late summer are when prey biomass (krill and small pelagic fish) increases for whales, as found for blue whales in Northern Patagonia [14,15]. Policy measures should be tailored to these regional and seasonal differences in ship strikes.

4.4. Knowledge gaps and future research

To better understand how ship strikes affect whale populations off Chile, we need more robust data on the abundance and distribution (spatio-temporal trends), movements and migratory routes, feeding sites and distribution of prey resources, and dive behavior (including diel and seasonal changes). For example, a study of fin whales off the coast of California found that strike risk was higher at night due to diel differences in dive behavior [48]. Diel and seasonal differences in behavior that could affect ship strike risk should be assessed in Chile too. Future research efforts should focus on understanding spatio-temporal changes in marine traffic and ship strike risk; gaining more knowledge on marine traffic, with data such as ship route, type, size, max speed, especially large cargo vessels (over 80 m); performing timely systematic necropsies on dead animals to determine causes of mortality (to reduce the high "unknown" cause of mortality category); and quantifying and understanding changes in reporting effort.

It is essential to conduct studies to assess whether the sites where ship strikes with whales occur are related to the areas where these animals eventually strand on the coast. This approach would allow for a better understanding of the spatial dynamics of these events. A relevant example is the work of Peltier et al. [61], where dead cetaceans were tagged to observe the time and fate of carcasses driven by currents. Similarly, release trials and modeling of the movement of large cetacean carcasses, or objects of similar weight, with ocean currents are necessary to gain a deeper understanding of the stranding process. Future studies should also include the collection of high-resolution digital tag and satellite tag data, as well as systematic sighting data, coupled with oceanographic data to model whale space use, refine calculations of spatial overlap between ships and whales, and calculate ship strike risk indices for the Chilean coast (e.g. as per [4]).

4.5. Policy recommendations

Our findings here suggest that Chile has one of the highest rates worldwide of fatal ship strikes to large whales and we recommend that policy steps be urgently taken to tackle this issue. It is important to mention that for Chile, policy measures have already been proposed to reduce ship strikes in certain areas [4,62]. These include vessel speed restrictions proposed along 28 nautical miles (52 km) within inland waters of the Francisco Coloane Marine Coastal Protected Area, in the central part of the Magellan Strait. This proposal was based on classifying this area as a High-Risk Area, as defined by the IWC, based on the following attributes: high levels of marine traffic, high abundance of whales and high prevalence of feeding and resting behaviors. Given that marine spatial planning and management of human activities is challenging and complex, where different interests are at play, ship strike reduction decisions should not only be carried out by government authorities, but must be a joint effort that includes scientists, non-governmental organizations, shipping companies, and coastal communities. An interesting case of this has been seen in Mejillones Bay in Northern Chile, which is the only case of obligatory re-routing measures implemented in Chile in 2022 so far.

We recommend the following urgent policy actions to reduce ships strike mortality in Chile:

- The Regions of Antofagasta, Coquimbo, Valparaiso, Bío-Bío, Los Lagos, and Magallanes should be designated as the first Critical High-Risk Areas for ship strikes, as defined by the IWC. There, local governments should define specific mitigation actions in dialog with local stakeholders. Actions should include vessel speed restrictions, where possible vessel re-routing, and avoiding new traffic routes in areas of critical habitat.
- Preliminary voluntary agreements can provide a valuable basis for future bills for nationwide regulation of marine traffic.
- Future legislation should include compulsory (not voluntary) regulations regarding shipping lanes and vessel speed restrictions and how these should be implemented in High-Risk Areas.
- The current marine mammal stranding unit from SERNAPESCA should be strengthened and properly funded. Cooperation agreements should be established between SERNAPESCA and research institutions, locally and nationwide, to aid stranding response, define standardized fieldwork protocols, assist with analyses and training, among others.
- New port installations should be carefully planned to avoid overlap with critical habitats for whales.

To explore specific maritime regulations, a national ship strike task force should be established, made up of research centers, public agencies, citizen science initiatives, the Navy, shipping companies, among others. This should be coordinated by the General Directorate of the Maritime Territory and Merchant Marine of Chile (DIRECTEMAR). Additionally, the following complementary steps would help to reduce ship strike mortality in Chile:

- Active visual observers should be present on large vessels within 10 miles of congested ports in High-Risk Areas. However, this will only be useful during daylight hours.
- Vessel transit should be prioritized during daylight hours.
- The use of real-time passive acoustic monitoring technologies to alert ships to the presence of whales in High-Risk areas should be considered as a complement to other measures. It is essential that these systems be fully validated and peer-reviewed to ensure optimal performance. These technologies will only be useful for detecting individuals/species with high rates of sound production.
- Active monitoring of cetacean strandings in all types of Marine Protected Areas, and stipulated in management plans of Marine Protected Areas where cetaceans are target species for conservation.
- Improve and routinely update public database with the latitude and longitude of stranding events for future spatial analysis (including GIS tools).
- Improve the Chilean National Fisheries and Aquaculture Service marine traffic database by incorporating information on all traffic fleets/types and associated metadata (e.g., length, gross tonnage).

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Author statement

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The conception and design of the study, or acquisition of data, or analysis and interpretation of data.
Drafting the article or revising it critically for important intellectual content.
Final approval of the version to be submitted.

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Author contributions

FT contributed to Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, writing of original draft, and reviewing and editing. SJB contributed to Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Visualization, writing of original draft, and reviewing and editing. MAR contributed to Data curation; Formal analysis; Methodology; Visualization; and Reviewing and editing. LBR contributed to Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing of original draft, and Reviewing and editing. AMCG, RHG, CO, MSepúlveda, BGV, WS, AA, JC, MJPA, FV, BC, JG, JA, HG, JG, RS, MSeguel, MFM contributed to contributed to Data curation; Investigation; Validation; Reviewing and editing. MSeguel also contributed to Formal analysis and Methodology.

Appendix A. . Comparison of minimum ship strike mortality with published studies from the literature that include data from 1820 and since 2013. Note: 2013 is when systematic necropsies started to be performed in Chile. Rows with gray shading indicate this study

Minimum Ship strike rate (ind./yr)	Study period (years)	Study duration (years)	Strandings events (ind.)	Ships strikes events (ind.)	Species	Species with most confirmed ship strikes	Location	References
Since 1820:								
4.38	1970–2009	39	1762	171	Blue whale, brydés whale, fin whale, humpback whale, minke whale, north atlantic right whale, sei whales, sperm whale	*Balaenoptera physalus*	Northwest Atlantic United States and Canada	Van Der Hoop et al., 2014
2.39	1820–2019	199		475	Blue, fin, sei, humpback, bryde, right, sperm minke and pygmy right whale	*Balaenoptera physalus*	Worldwide	Winkler et al., 2020
2.23	1975–1996	26	407	58	Fin, sei, humpback, right and minke whale	*Balaenoptera physalus*	Atlantic United States	Laist et al., 2001
2.13	1999–2008	8		17	Sperm whale	*Physeter macrocephalus*	Canary Islands	Fais et al., 2016
1.59	1972–2001	29	287	46	Fin whale	*Balaenoptera physalus*	Mediterranean sea	Panigada et al., 2006
1.22	1972–2023	51	226	62	Blue, fin, sei, humpback, minke, bryde, right, sperm and pygmy right whale	*Balaenoptera physalus*	Chile	This study, 1972–2021
1.18	Unspecified	11	113	13	Fin, minke and sperm whale	*Balaenoptera physalus*	Italy	Laist et al., 2001
0.86	1985–1992	7	20	6	Humpback whale	*Megaptera novaeangliae*	United States	Wiley et al., 1995
0.76	2000–2017	17	16	13	Sperm whale	*Physeter macrocephalus*	Canary Islands	Arregui et al., 2019
0.73	1980–2006	26	130	19	Blue, fin, gray, humpback, minke and sperm whale	*Eschrichtius robustus*	Washington State	Douglas et al., 2008
0.62	1972–1998	26	127	16	Fin whale	*Balaenoptera physalus*	France	Laist et al., 2001
0.55	1970–1999	29	45	16	Northern right whale	*Eubalaena glacialis*	Western North Atlantic Ocean	Knowlton y Kraus 2001
0.32	1988–2007	19	21	6	Blue whale	*Balaenoptera musculus*	California US	Berman-Kowalewski et al., 2010
0.31	1963–1998	35	55	11	Southern right whale	*Eubalaena australis*	South Africa	Laist et al., 2001; Best et al., 2001
0.26	1977–1985	19	25	5	Northern right whale	*Eubalaena glacialis*	United States and Canada	Kraus 1990

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(*continued*)

Minimum Ship strike rate (ind./yr)	Study period (years)	Study duration (years)	Strandings events (ind.)	Ships strikes events (ind.)	Species	Species with most confirmed ship strikes	Location	References
0.14	1975–1996	21	31	3	Sei, bryde, minke and sperm whale	*Physeter macrocephalus*	Gulf of Mexico coast	Laist et al., 2001
0.03	1937–2009	72	36	2	Sperm whale	*Physeter macrocephalus*	Tunisia	Karaa et al., 2012
0.02	1877–2005	94	23	2	Blue, sei, humpback, minke and sperm whale	*Balaenoptera acutorostrata*	New Caledonia	Borsa 2006
0.35	1905–2018	113		40	Blue, Omuras, humpback, bryde and sperm whale	*Megaptera novaeangliae*	Eastern Tropical Pacific	Ransome et al., 2021
Since 2013:								
5.0	2013–2023	10	156	50	Blue, fin, sei, humpback, minke, bryde, right, sperm and pygmy right whale	*Balaenoptera physalus*	Chile	This study, since 2013 *
3.5	2010–2014	4		14	Unspecified	*Balaenoptera musculus*	Sri Lanka	Nanayakkara and Herath 2017
3.5	2014	10		35	Blue, fin and humpback whale	*Balaenoptera physalus*	US West Coast	Rockwood et al., 2017
0.29	2014–2020	7	4	2	Humpback whale and bryde whale	*Megaptera novaeangliae* and *Balaenoptera edenii*	Nicaragua	Weerdt et al., 2021

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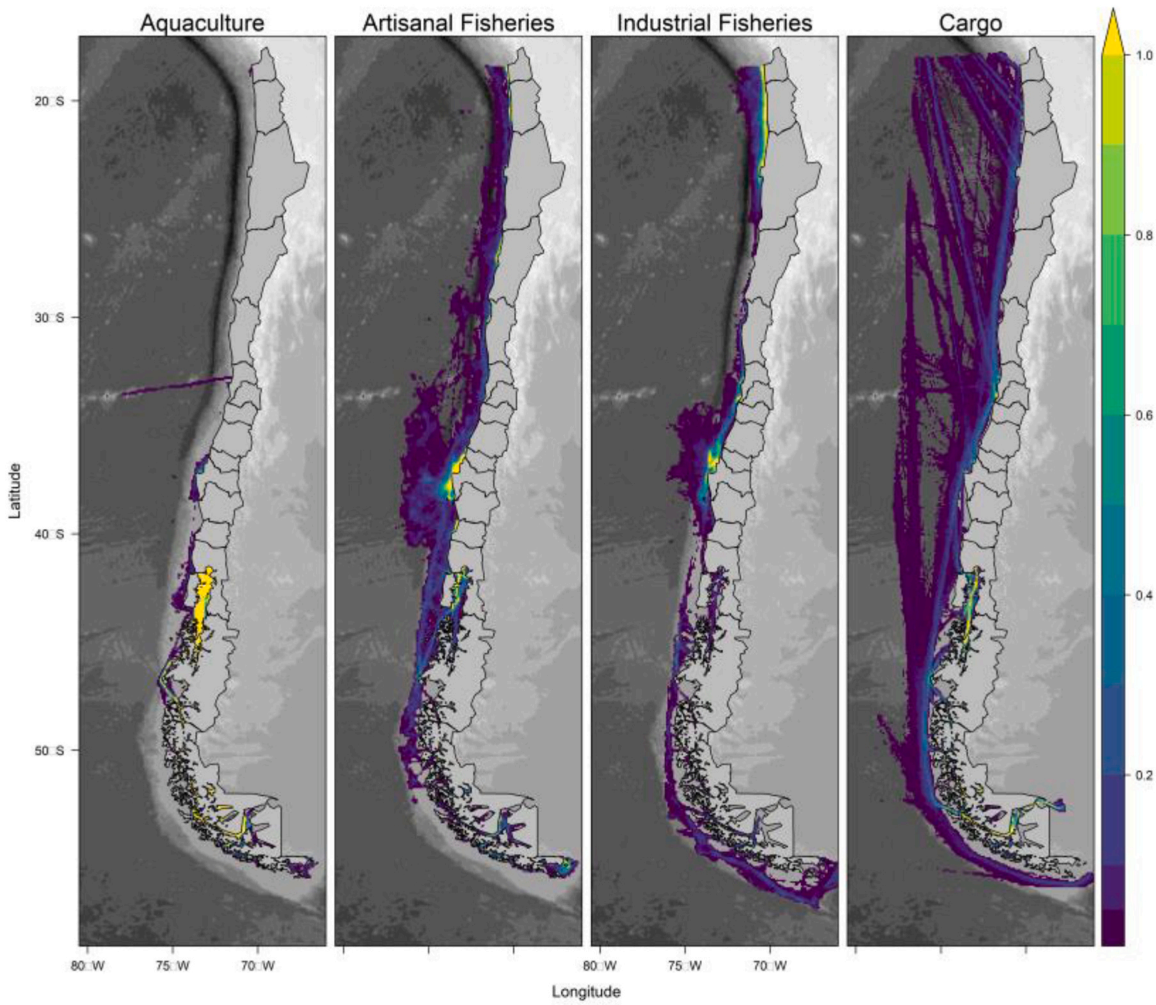
Appendix B. . Marine traffic patterns based on the Chilean National Fisheries and Aquaculture Service (SERNAPESCA; www.sernapesca.cl/) vessel database and AIS data (www.imo.org), processed as per [22,23]. Color bar shows scale of vessel density as vessel / km^2



Data availability

The authors do not have permission to share data.

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