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Humpback whale movements in a narrow and heavily-used shipping passage, Chile

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ABSTRACT

The Magellan Strait is a narrow passage connecting the Pacific and Atlantic oceans in South America. An average of 2023 ships per year transit this corridor with 80% representing the international fleet. The southwestern part of the Strait in Chile is an important summer feeding area for humpback whales. Considering the risk to whales of feeding among dense ship traffic, the movements of 25 satellite-tagged whales relative to vessel density were analyzed, to provide policy recommendations for protecting the species from vessel collisions. A total of 3694 filtered whale positions from 21 individuals were obtained along the southwest passage. The daily range covered by individual whales was 8.8 km, and <25 km on 90% of all days. Ship density in the same square kilometers where whales were encountered was 0.27 per week, slightly more often than once per month, however this encounter rate varied by 100-fold between individuals, depending on how often animals were in the central shipping lane. One of the tagged whales stopped transmitting and washed up dead suggesting a ship strike. In the last decade, four other humpback whales and three sei whales were killed by probable ship strikes, all near Isla Carlos III, the core of the humpback feeding area. A 10-knot speed restriction and onboard observers are recommended during the five months of maximum whale abundance, applying to all merchant vessels traveling through the Strait, between Cabo Holland and Isla Bonete north of Carlos III Island, for a distance of 28 nautical miles (52 km).

1. Introduction

The Magellan Strait of Chile is a vital shipping channel that simultaneously harbors marine habitats diverse in depth, coastal morphology, tides, and precipitation [1,2]. Upwelling in the narrow strait stimulates primary productivity and nourishes a food chain that includes 21 species of cetaceans [2,3]. One is the humpback whale (*Megaptera novaeangliae*), which uses the narrow, western section of the Strait as a summer feeding ground from November through April. The feeding distribution of humpback whales overlaps with the heavily-used shipping route, especially in the narrowest section of the Strait [3–5].

Southeastern Pacific humpbacks migrate annually along western South America between low-latitude breeding areas and high-latitude feeding areas. The primary feeding sites for the stock G population are along the west coast of the Antarctic Peninsula, south of the Antarctic Convergence [6], but cold coastal waters of South America and the fjords of Patagonia, including the Corcovado Gulf and Magellan Strait, are also important [4,7–9]. Through genetic tests and photo-identification, whales feeding in the Magellan Strait are known to breed between Peru and Nicaragua [4,9–13], and many individuals return each year to the Strait [4,10,14].

The humpback population in the Strait increased for the last decade [14], but the current population of 86–100 animals [5] is small enough that an even occasional ship strikes could have important consequences. Herein, we describe detailed movements of feeding whales throughout the Magellan Strait and its fjords by tracking satellite tags attached to individuals. We assess movements of individual whales relative to ship density in order to evaluate the potential of vessel collisions, and we report injuries and fatalities observed during the course of the research. Our goal is to provide policy recommendations for protection of whale

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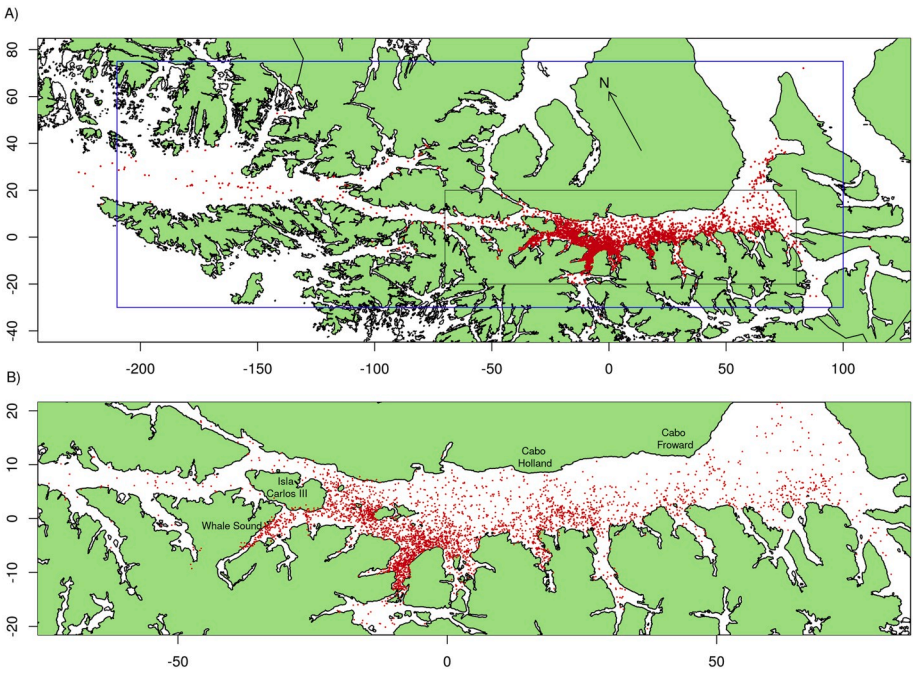

Fig. 1. Map of the Magellan Strait with all humpback whale satellite locations. The map is rotated 28.86° clockwise so that the axis of the channel is horizontal. Units are kilometers, describing a grid centered at latitude −53.79102, longitude −71.99234. A) Entire region with every whale observation. The blue rectangle is the study area, where all analyses were done. B) The study area around Carlos III Island, where most whales were observed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

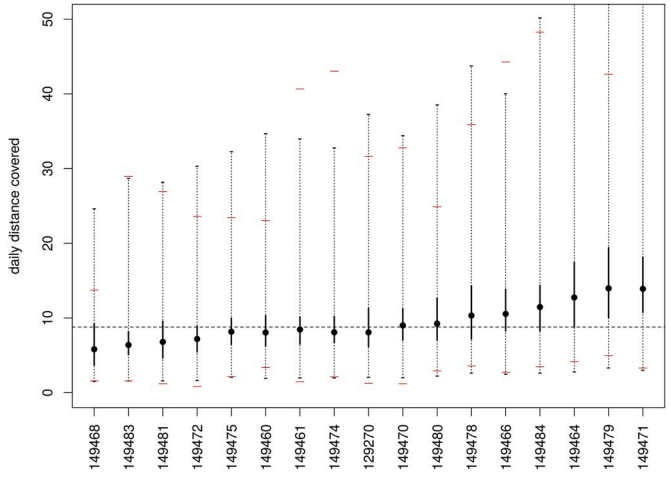

Fig. 2. Variation in daily distances covered by individual whales (km) as fitted by a log-normal distribution (see Methods). The estimated median daily distance covered is marked with a black circle, and the horizontal dashed line indicates the overall median of all whales (8.8 km). The heavy vertical lines show 95% credible intervals around the median for each whale, demonstrating statistically significant differences: the four least mobile whales moved significantly less (6–8 km daily) than the two most mobile (13–14 km daily). Dashed vertical lines are 95th percentiles of the fitted log-normal for each whale, and red marks are observed minima and maxima (for two whales, the maxima were >100 km and off the graph). Whales are sorted left to right from the least mobile to the most. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

species based on firm evidence.

2. Materials and methods

2.1. Study area and population assessment

Magellan Strait is a 570-km channel that connects the Pacific and the Atlantic Oceans and separates the southern part of South America from Tierra del Fuego and the Fueguian archipelago. The Francisco Coloane Coastal Marine Protected Area (CMPA) is located in the central section of this long channel, where the Tortuoso and English passages narrows to a width of ca. 2 km. We tagged whales in the Francisco Coloane CMPA around Whale Sound and the Charles Islands off Isla Carlos III (53°37′S, 72°21′W). This population has been systematically studied for consecutive feeding seasons from 1999 to 2018, and a total of 190 individuals have been identified and catalogued (Capella unpublished data) from photographs and unique markings [15]. About 85% of marked animals return from year to year [4,7,10,14]. The number of photo-identified individuals increased from 18 in 1999 to 102 in 2017 but then declined by 30 individuals from 2018 to 2020 [Capella unpublished data].

2.2. Tagging procedures

Humpback whales were tagged during three expeditions in 2009, 2011 and 2016. We used Wildlife Computers SPOT5 and SPOT6 satellite tags, model S193 and S303 (https://wildlifecomputers.com/spot-tag-product-sheet-spot-303/), deployed with a modified pneumatic line-thrower (model ARTS, Restech Inc., Bodø, Norway; https://restech.no/product/arts-whale-tagger/) coupled to a LK-carrier (developed by LKARTS, Bodø, Norway), widely used in satellite telemetry studies [16]. The use of the air-powered line thrower provides precision, avoiding the deployment of tags on undesirable or sensitive areas of the body. Air pressure ranged from 10 to 15 bars (10.2–15.3 kg/cm^2). Each factory transmitter consisted of a 2 cm diameter stainless steel tube case 17.5 cm in length coupled to a custom-made stainless-steel spear with a 3 cm triangular double-edged blade tip containing one to three pairs of 5 cm barbs placed at 90° to one other. Total tag weight (transmitter and spear) was 380 g. We tagged whales from 5 to 9 m long rigid-hulled inflatable boats at a distance of 2–4 m from the whale. The transmitters were attached to the whales about 10–25 cm below and ahead of the dorsal fin on right or left side. Our tag was designed to be attached for short periods of time, not penetrating to muscle and connective tissue [17]. A detailed description of tag configuration and tagging procedures is provided elsewhere [18,19].

Tags were chemically sterilized and wrapped in plastic in the laboratory. In the field, the tag and spear were sprayed with Neomycin Sulfate - Clostebol Acetate (Neobol®) before deployment. Long-term

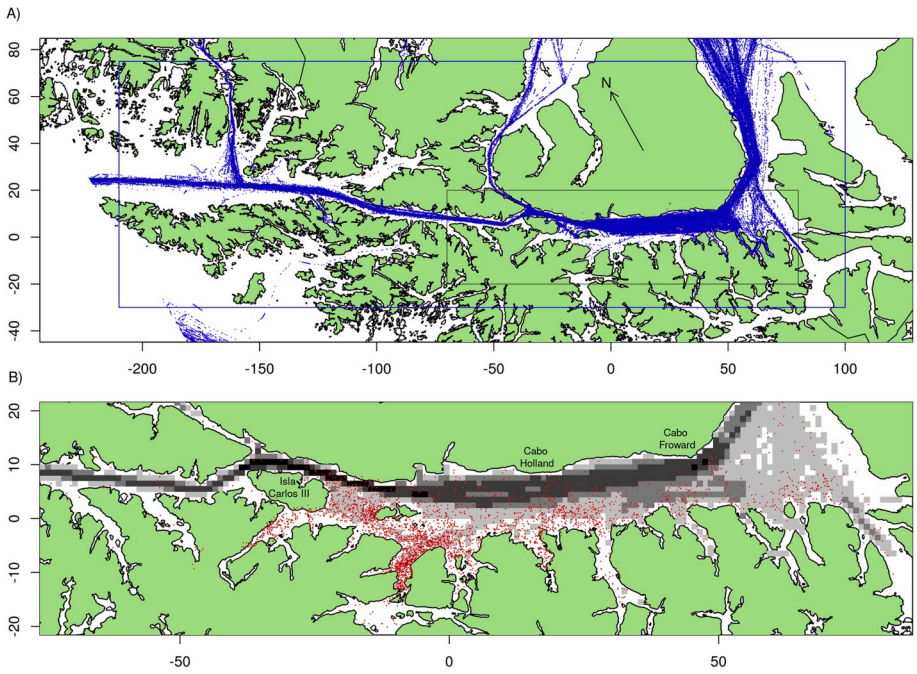

Fig. 3. Map of the Magellan Strait with ship locations, as Fig. 1 for whales. A) Entire region with every ship location marked. Density is so high near the center of the passage that fine variation is obscured. B) The core study area, with ship density per km^2 indicated by shading in order to show the variation across the channel (see Methods). Where water is white, km grid cells never had a ship, while black are cells averaged >1 ship daily. Three shades of gray show ship density >1 weekly, > 1 monthly, and >0, from darker to lighter. Whale locations are overlaid in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

assessment of percutaneous tagging in humpback whales in the study area showed complete wound healing within two years of tagging, with no impact behavior of individuals, including nursing, during and immediately after tagging [19]. The Animal Care and Use Committee of the Smithsonian Tropical Research Institute reviewed and approved the tagging procedures.

2.3. Argos satellite locations

The transmission and accuracy of Argos satellite locations is influenced by latitude, animal behavior (including movement speed or feeding activity), sea conditions, the number of satellites in the sky, and the number of transmissions during a satellite pass [20–22]. The Magellan Strait has high winds (mean 32 km per hr, reaching 122 km per hr) interacting with strong tidal currents [22], and whales are often feeding beneath the surface on their diet of krill, lobster krill and Fuegian sprat [23–27]. These limitations forced tradeoffs in the number and accuracy of positions we could collect. We utilized a wide range of Argos location-accuracy classes 3, 2, 1, 0, A, and B, which are those having errors of 0.15–5 km. This was necessary because the more accurate classes (1–3) require more transmissions [20,28], so excluding the other classes would have led to fewer locations. To conserve batteries, we set the tags to transmit a maximum of 300 times per day, or 75 per 6-h bin, with allowance for unused transmissions to carry over to the next day. For transmissions to reach the satellite when the animal has surfaced, fast and slow repetition rates (seconds) were set by the manufacturer to 41.5–47.5 s and 86.5–92.5 s, respectively [18].

We tagged 25 adult humpback whales, 5 in 2009, 2 in 2013 and 18 in 2016, but four failed to transmit. From the remaining 21 tagged whales, we collected 3767 Argos locations on 98 different days, including 43 locations on 11 days in March 2009, 149 locations on 23 days in May–June 2013, and 3575 locations on 64 days in March–May 2016. For limitations to accuracy and transmission described above and outside our control locations were concentrated between the hours of 1800 in the evening and 0600 in the morning, universal time (UTC) (97.4% of all positions). For this reason, we chose to define days as starting and ending at noon UTC, not the usually definition based on midnight. Local time is GMT-3, meaning our days began and ended at 9AM and that most whale locations were between 1500 and 0300 local time. Using this definition, nearly all locations within the same 'day' were within a span of 12 h, and nearly all locations on consecutive days were separated by > 18 h. This offered a convenient way to map and measure whale movements within a single day.

2.4. Screening for location error

To screen errors, we placed all whale positions on a map of the area [29] and found a few positions on land, some far from water. Argos' self-reported location quality was not a predictor of this. We thus decided to further screen positions to filter out errors that could have large impacts on descriptions of movements. This began with daily maps of each animal's positions, connected by lines indicating time sequence. We highlighted all positions on those maps that were >10 km from any other position the same day, and we identified every consecutive pair within a day >10 km apart or requiring movement at >10 km per hour (or kph). After some work, though, we amended the speed criterion, flagging only movement >10 kph if the time difference was >15 min. That was necessary because there were quite a number of positions just minutes apart, and a position error of only 200 m would then appear to require high speed swimming (also, small errors in time of the satellite reports would lead to erroneous speeds).

These criteria led to 180 flagged positions, and all were examined individually on the maps. The next criterion we used, which was easier to check visually than via computer calculations, was whether multiple points supported long or fast movements. Thus, if a whale suddenly appeared >10 km away, we checked what happened next. This led to 73 obvious errors: cases where a whale moved suddenly a long distance and then immediately back to where it was. The other 107 flagged positions included rather substantial movements but supported by multiple positions at both ends, so we accepted those as valid. Removing those 73 conspicuous errors reduced the sample size from 3767 whale positions to 3694.

2.5. Daily movements

For each whale within each day (as defined above), we calculated the greatest straight-line distance between any pair of locations. This estimates the linear range covered by the whale on that day. The

Table 1
Foraging time of 17 humpback whales relative to nearby ship density as estimated by the time budget model (see Methods). Whales are identified by their tag numbers, and for each the number of Argos positions collected is given. The column <1 ship y^{-1} gives the fraction of those positions in grid cells where fewer than one ship passed per year (i.e. within the same one-km grid cell); those are in fjords or close to the shore. Following is the fraction of locations where more than one ship passed weekly, always near the center of the Strait. Each fraction includes 95% credible intervals in parentheses. The final column is the mean number of ships passing weekly in all grid cells in which the whale was observed. Whales are sorted by the fraction with <1 ship y^{-1}, i.e. from those often near ships to those seldom near ships. The total in the last row is based on the fixed effect of the hierarchical model, which is the average of all the whales.

Whale	Positions	fraction <1 ship y^{-1}	fraction >1 ship wk^{-1}	Mean ships weekly
149478	143	0.194 (0.14, 0.26)	0.213 (0.17, 0.25)	0.697
149466	189	0.375 (0.32, 0.44)	0.122 (0.09, 0.15)	0.407
149479	126	0.403 (0.33, 0.49)	0.102 (0.07, 0.14)	0.335
149470	249	0.407 (0.35, 0.47)	0.019 (0.01, 0.03)	0.123
149464	152	0.465 (0.39, 0.55)	0.059 (0.03, 0.09)	0.205
149460	244	0.475 (0.41, 0.54)	0.084 (0.06, 0.11)	0.279
149480	190	0.475 (0.42, 0.54)	0.027 (0.01, 0.05)	0.129
149474	407	0.477 (0.43, 0.52)	0.076 (0.05, 0.10)	0.254
149471	253	0.482 (0.43, 0.54)	0.121 (0.10, 0.15)	0.456
149483	281	0.488 (0.44, 0.54)	0.054 (0.04, 0.08)	0.192
149475	318	0.509 (0.46, 0.56)	0.075 (0.05, 0.10)	0.251
149472	259	0.587 (0.53, 0.65)	0.077 (0.05, 0.10)	0.270
149461	323	0.588 (0.54, 0.63)	0.069 (0.05, 0.09)	0.235
149484	191	0.636 (0.57, 0.70)	0.087 (0.06, 0.11)	0.374
149468	78	0.691 (0.61, 0.79)	0.000 (0.00, 0.00)	0.007
149481	86	0.712 (0.63, 0.80)	0.000 (0.00, 0.00)	0.006
129270	143	0.817 (0.77, 0.88)	0.005 (0.00, 0.02)	0.031
Total	3632	0.406 (0.27, 0.64)	0.079 (0.04, 0.11)	0.266

distribution of daily ranges was fitted to a log-normal distribution, with whale as a random effect, using a Bayesian parameter-fitting method [30–32]. Before fitting the model, four whales were excluded because they had too few positions on too few days: the three whales tracked in 2009 each had <31 locations, and one whale in 2016 that had only 19 locations on three days. The 17 whales included in the model had at least 79 locations each over at least 15 days; one was tagged in 2013 and the rest in 2016. The model produced a hierarchical distribution, each whale's distribution nested within the total population distribution. The log-normal was selected because the daily ranges were conspicuously skewed, nearly all <10 km but occasionally >100 km, even after removing the obvious errors. The Bayesian parameter-fitting procedure produced credible intervals on the median daily movement of each whale. We judged differences between whales as statistically significant if their 95% credible intervals did not overlap.

To map daily positions of each whale, an ellipse was drawn around all daily locations. The ellipse was calculated by fitting a two-dimensional Gaussian surface around the positions, which amounts to fitting the probability of observations. The maximum of this surface equals the mean position of the whale on that day. The edge of the ellipse was defined as the position where the probability fell to 5% of the maximum. Details of the procedure are provided in Ren et al. [33]. These ellipses were used only on maps to illustrate daily positions, not for any other statistics.

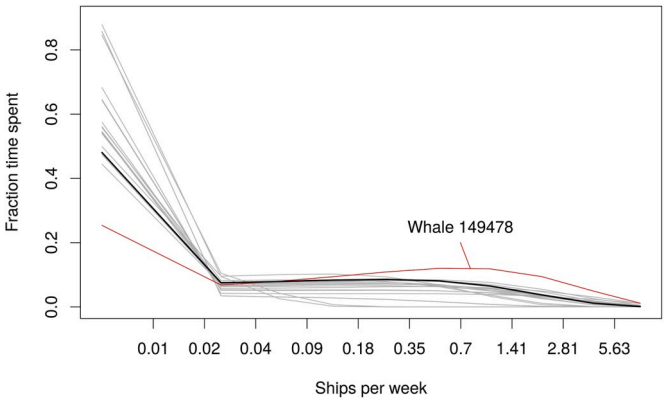

Fig. 4. Histogram describing proportion of time whales spent at varying ship densities, as fitted by a hierarchical Bayesian model (see Methods). The black curve is the average of all whales, or the fixed effect. The red is the whale killed by a ship. The light gray lines are the 16 other whales (all those with at least 75 locations). The whale that was killed was an outlier in how much time it spent in areas with high ship density. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.6. Ship density

Real-time commercial vessel track data from the global Automatic Identification System (AIS) network were obtained for ships traveling the Magellan Strait over 21 months, from November 2014, through July 2016, thus spanning most of whale tracking in March–May 2016. Initially, we had hoped this meant a complete track for each ship passing, but instead, the AIS reports only sporadic positions for each vessel. Our use of the vessel locations is thus limited to an overall estimate of the density of ships in different parts of the passage and to calculations of travel speed in some cases. To estimate ship density, a rectangular area of 310 by 105 km around the Magellan Strait was defined as the study area, and it was gridded into square kilometers (Fig. 1). In each square kilometer, the number of individual vessels was tallied on each day, and summed over all days (i.e. the number of unique vessel-date combinations). We regard this as an estimate of the number of ships that entered each square kilometer over the 21 months, and we refer to it as the number of ship visits per square kilometer. Because the vessel tracks are incomplete, we understand that it is an underestimate of the true number of ship visits, but we assume that it offers an unbiased estimate of relative ship density across the study area.

The number of ship visits per square kilometer was expressed on a weekly basis, dividing the total number of ship visits by 91 weeks, the length of the observation period. Since the total number of ships observed in the passage did not vary seasonally, we used the weekly average of ship visits in a given square kilometer cell from November 2014, to July 2016 as an estimate of the density of ships that a whale would encounter when it enters that cell.

We also used the 21 months of vessel tracks to create a profile of the speed of ships traversing the Strait. We started with every vessel record that included locations on both sides of the line defined by $x = 0$ in Fig. 1. From those, we extracted records where the two positions spanning the line were within 2.5 h and within 70 km, since these were most likely straight tracks within the Strait, and calculated the vessel speed (distance/time). We excluded intervals <0.5 h because they may exaggerate small errors in location. This led to 1455 speed records from 776 unique vessels; 52 of the vessels were included four or more times, and one (the Anoka) passed 108 times. Regardless of the duplicate records, it

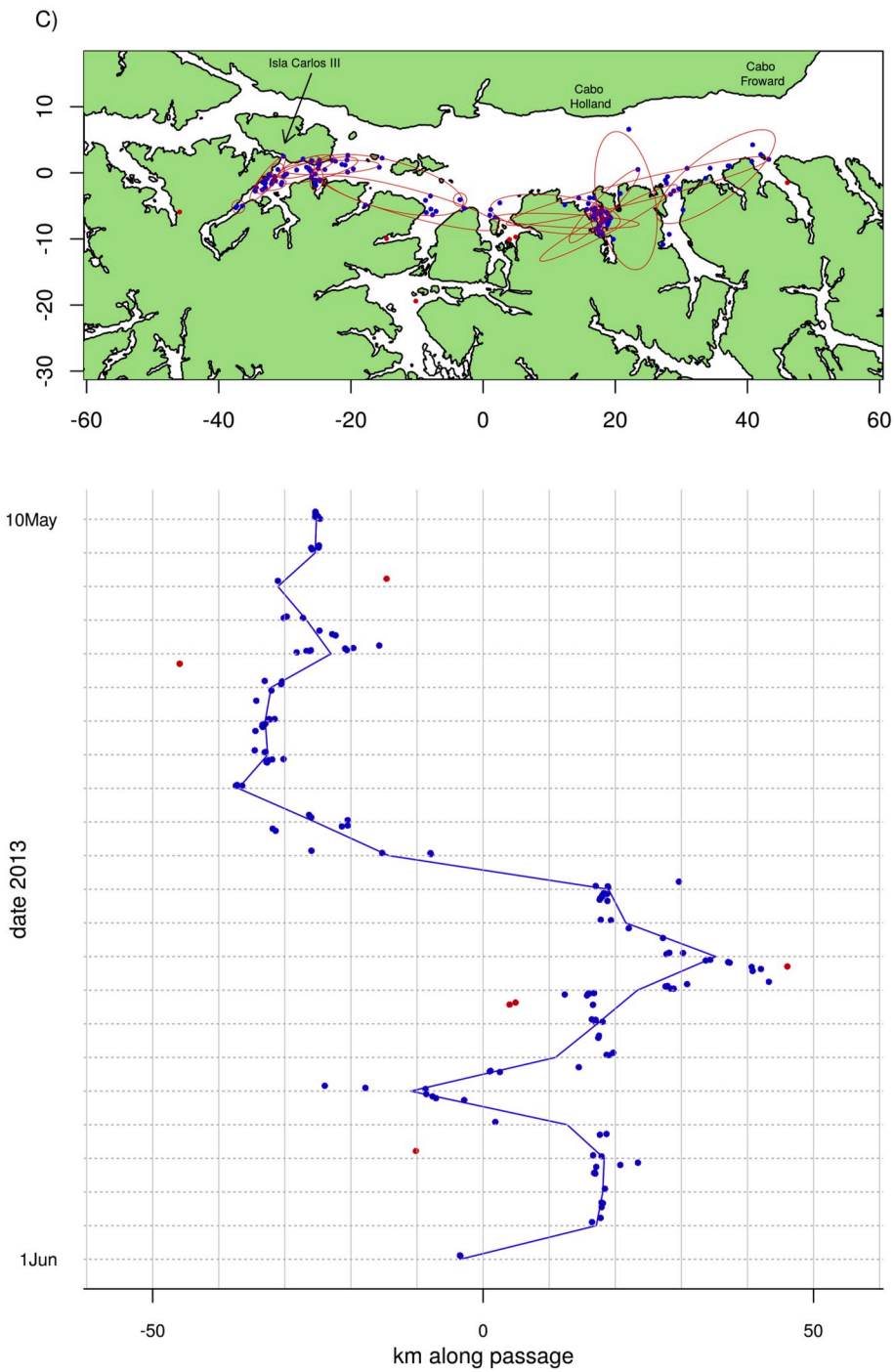

Fig. 5. Movements of the whale tagged 129270. The top portion is a map showing all observations, with positions shown by blue or red dots (the reds are those identified as errors). Ellipses are drawn around each set of daily observations (see Methods). The lower portion shows the whales position through time, but in only one dimension, the distance along the Strait (x-axis of the map). The horizontal dotted lines indicate days, and the blue (or red) points the exact x-position of the whale at an exact time; lines connect the mean daily positions, but are interrupted when a whale was missed on a day. The x-axis of the map is aligned with the x-axis of the graph, so that locations on the map can be linked to locations in time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

is a sample of the speeds at which ships traveled near the whales.

2.7. Risk of ship encounters

The estimated number of ship visits per square kilometer cell is an index of the risk of ship encounter for a whale in that cell. We calculated the mean risk for each whale by averaging ship density across all the cells in which it was observed. For example, if half a whale's locations were in grid cells where ship density averaged one per week and the other half had zero ships, the mean risk score is 0.5 ships per week.

To describe a complete risk profile for each whale, we estimated the distribution of risk scores of all its locations. This is a time profile: the fraction of time spent at a given risk. Risk distributions are often highly skewed, with most time spent at low risk accompanying occasional very high risk. To generate such a distribution, we modeled the unadjusted count of ship visits across grid cells – an integer – as a negative binomial distribution. The negative binomial can be highly skewed, in which case most counts are zero, but it can approach a non-skewed, Poisson distribution. The negative binomial was fitted to the entire set of whale locations in a hierarchical model, with whale as a random effect. To illustrate the risk profile, the fraction of time spent at different ship density was calculated from the two parameters of the negative binomial for each whale (mean m, clumping parameter k). For example, with $m = 24$ and $k = 0.184$, we expect 7.8% of locations to have >91 ships (equivalent to 1 ship weekly, since ship observations spanned 21 months = 91 weeks). The Bayesian parameter-fitting routine produced

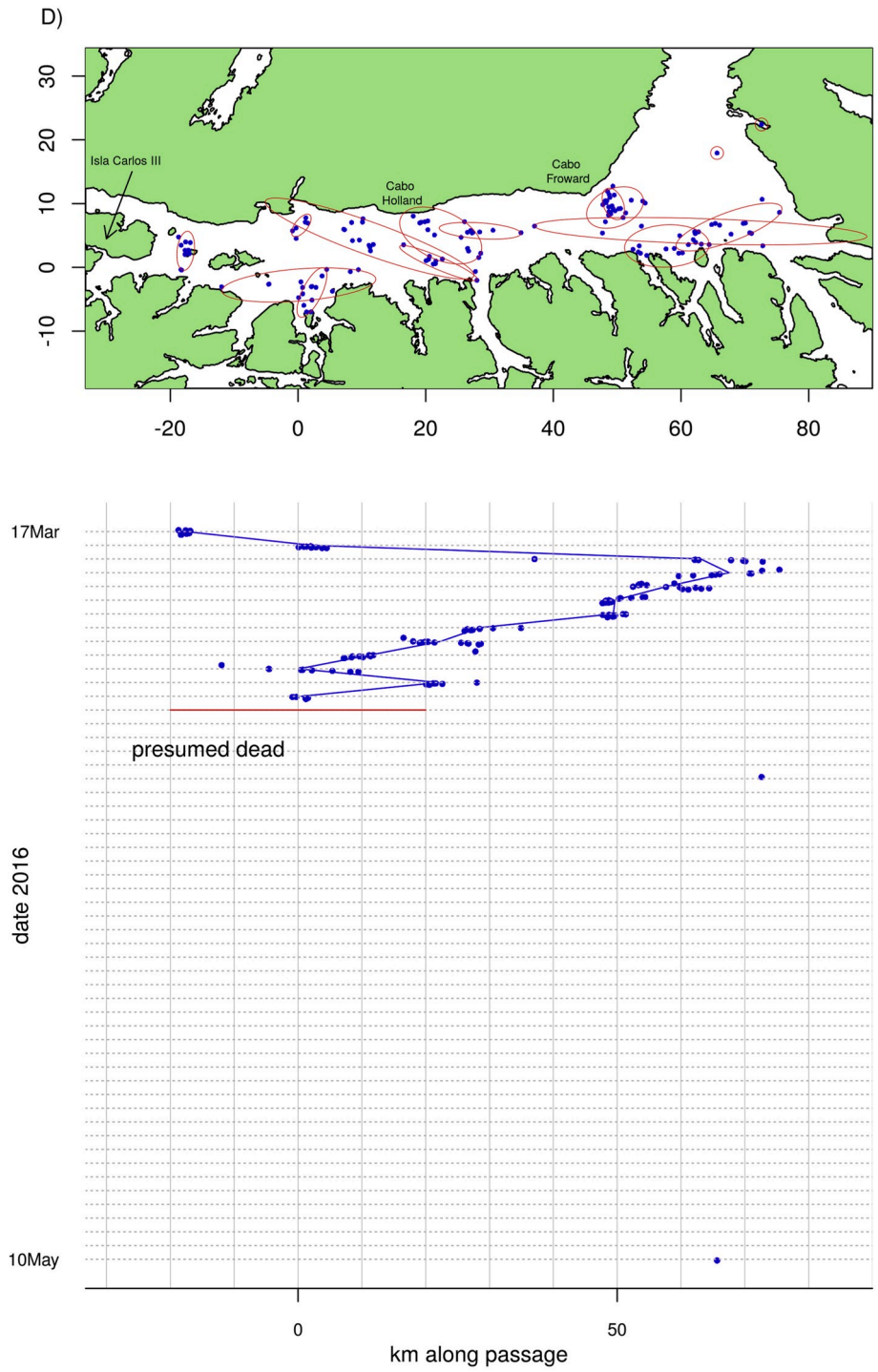

Fig. 6. Movement diagram for whale 149478, the one found dead with evidence of a ship strike. See Fig. 5 for details.

statistical inference via credible intervals of the estimated time budget for each whale.

3. Results

3.1. Whale positions

The 3694 filtered whale positions were concentrated along the southwestern side of the passage and up several inlets. They appeared less often in the center and the northeastern side of the Strait (Fig. 1).

3.2. Daily movements

The overall median daily range covered by a whale was 8.8 km, and whales moved <25 km on 90% of all days with at least four observations. The least mobile whale (tag 149468) ranged a median of 5.6 km per day, while the most mobile (tag 149471) ranged a median of 14.1 km; based on 95% credible intervals of the median, there was significant variation among whales (Fig. 2). There were movements >50 km on 8 of 432 days, and >110 km on two days. Those outliers demonstrate the usefulness of treating daily range size as a log-normal variate.

Table 2
Vessel speeds through the Magellan Strait, November 2014, through July 2016. Each entry is a count of the number of vessels traversing the Strait in a given category of speed and vessel type. For example, there were 303 occasions on which a cargo ship traversed at a speed between 10 and 15 knots. The fastest passage was a 51 kT cargo ship at 40 knots. The final column is the median gross kilotonnage of ships in each category.

Vessel type	<5	5–10	10–15	15–20	20–25	>25	Kilotons
Cargo	11	227	303	126	23	9	24.1
Tanker	3	82	96	50	20	3	53.8
Passenger	10	31	23	11	2	1	2.7
Other	37	216	138	28	5	0	0.1
Total	61	556	560	215	50	13	

3.3. Ship density encountered by whales

As expected, ships were greatly concentrated in the center of the Strait, where whales spent relatively little of their time (Fig. 3). Indeed, 55% of all whale sightings were in 1-km grid cells where no ships were observed. The mean density of ships in the same square kilometers where whales were present was 0.27 per week (Table 1), that is, whales encountered ships within the same kilometer slightly more often than once per month. This average comes about by spending a small amount of time where ships passed more than weekly with a large amount of time where few ships passed (Fig. 4). Whales varied substantially in their encounter rates, from 0.02 to 0.83 per week, and there was statistically significant variation among whales based on 95% credible intervals (Table 1).

3.4. Individual whale movements

Movements of whales throughout their tracking period are illustrated for four individual animals (Fig. 4). Whale 129270 had a low rate of ship encounters (Fig. 5), and whale 149478 had the highest (Fig. 6). Movement charts for the remaining tagged whales are shown in Supplementary Material.

3.4.1. Whale 129270

This was a female, tracked for just 23 days but observed every one of those days. Its median daily movement was 8.3 km, close to the average for all whales (Fig. 2). It concentrated its activity in two areas, around km = −30 and km = +20 (x-axis, Fig. 5). Since it was usually in inlets south of the main channel, it had a low encounter rate with ships, 0.03 per week (Table 1).

3.4.2. Whale 149478

This 10.5-year-old female had been with a calf in earlier years, 2012 and 2014, but was not in 2016. It was seen 13 consecutive days, the last sighting at km = 0 toward the north side of the passage on March 29, 2016 (Fig. 6). It moved steadily during those 13 days, and many of its locations were away from shore, close to the shipping lane. As a result, it had the highest encounter rate with ships, nearly one per week (Table 1). It was found dead on April 4, 2016 at Dawson Island, 76 km east of its last satellite record. It was probably dead when the Argos satellite stopped receiving it on 30 March.

3.5. Vessel speeds

Of 1455 records of vessels traversing the Strait near the whale feeding sites, 58% (838) were traveling faster than 10 knots (18.5 kph). Large cargos and tankers were faster, with 66% of records >10 knots (Table 2).

4. Discussion

4.1. Whale-vessel collision records

An average of 2023 ships per year (range 1586–2773) pass through the Magellan Strait according to 12-year record (2007–2018), of which 77.9% represent the international fleet [34]. The history of ship collisions with whales is difficult to record in general and even more so in an area as isolated as the Magellan Strait. Collisions may simply go unnoticed, due to the size of the ships (many 300 m in length) compared to whales (less than 15 m), and even if noticed ships may not report them. However, long-term monitoring by scientists in the area shows that these incidents have been occurring in recent years. Four of the whales identified in the area and returning regularly show signs of non-lethal impact of ships in the past: two with a partial mutilation of the tail and two with scars or wounds to the flanks, though it is not certain the injuries were caused in the Strait. There have been, though, five fatal incidents involving humpback whales and three involving sei whales near Carlos III Island in the past 10 years, all documented with the support of local fishermen, the Office of the Ministry of the Environment, and researchers (Table 3). This includes the incident we describe here, whale 149478, killed soon after March 30, 2016 then stranded on

Fig. 7. Tanker transiting at considerably speed the core feeding area near Carlos III Island and a nearby humpback whale.

Table 3
Summary of humpback (*Megaptera novaeangliae*) and sei (*Balaenoptera borealis*) whales fatalities reported in Magellan Strait between 1999 and 2020.

Date	Species	Site	Coordinates	Whale class	Source	Observations
11.02.01	Mn	Isla Carlos III	53°36′S, 72°19′W	Adult	Authors	Old bone remains
01.05.09	Mn	Whale Sound, Isla Santa Ines	53°44′S, 72°27′W	Adult	Authors	Stranded dead, semi decomposed
03.05.10	Mn	Isla Carlos III	53°35′S, 72°21′W	Juvenile	Fishermen	Stranded dead, semi decomposed
15.04.11	Mn	Near Cape Froward	53°53′S, 71°21′W	Calf	Fishermen	Floating dead
25.06.13	Bb	Jeronimo Channel	53°20′S, 72°26′W	Adult	Environment Ministry	Stranded dead, semi decomposed
01.07.15	Mn	Whale Sound, Isla Santa Ines	53°40′S, 72°28′W	Adult	Fishermen	Stranded dead, semi decomposed
25.04.16	Mn	Isla Dawson	53°56′S, 70°51′W	Adult	This study	Stranded dead, fresh, partial necropsy
14.11.17	Bb	Peterel Point, Brunswick Penn.	53°42′S, 71°58′W	Adult	Authors	Stranded dead, semi decomposed
7.03.20	Bb	Faro Punta de Palos, Bahía Chilota	53°17′S 70°27′W	Adult	Authors	Stranded dead, fresh, full necropsy

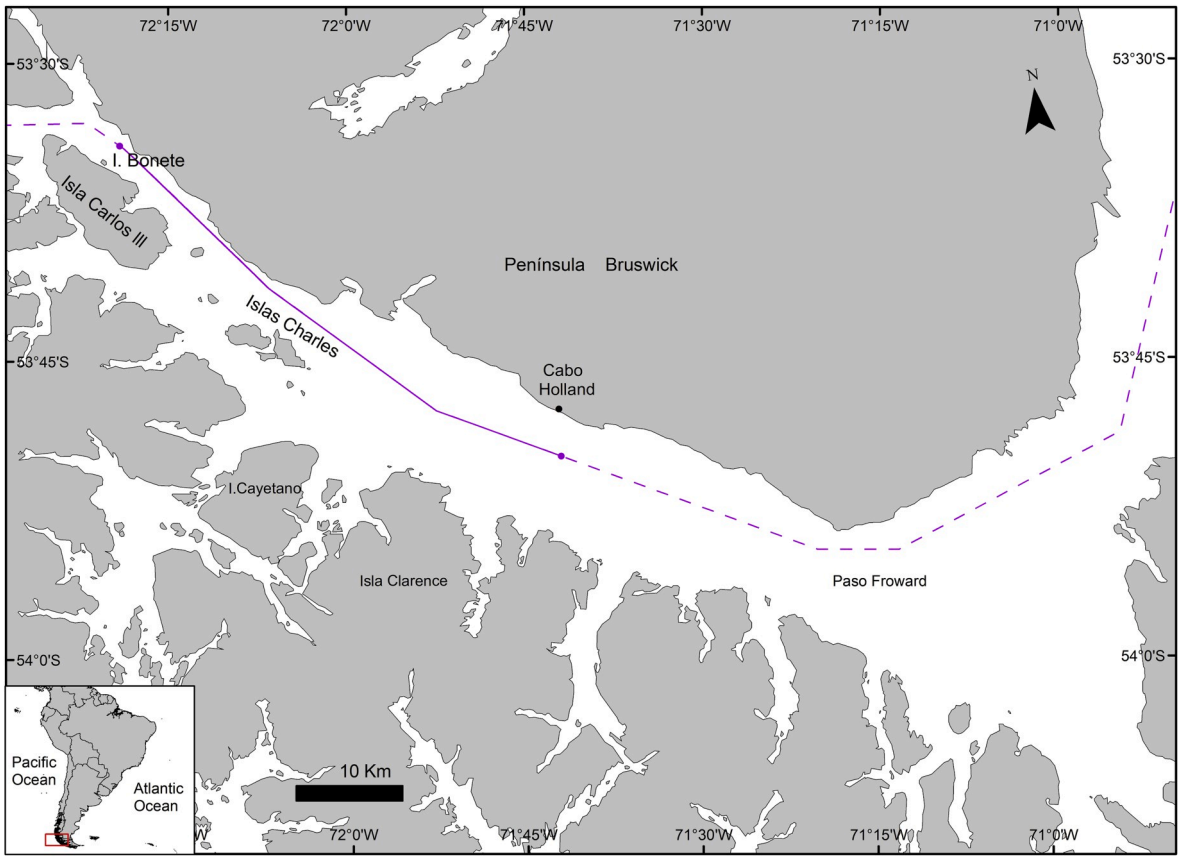

Fig. 8. Proposed navigation pathway for speed limit of vessels transiting the Magellan Strait. Black dashed line indicates current path as on international navigational charts (Admiralty chart No. 4266, Chile, Estrecho de Magallanes, Paso del Hambre to Paso Tortuoso, Edition 2005 revised 2016). Red dashed line indicates the section of the strait where speed should be reduced to 10 knots: between Isla Bonete in Paso Inglés north of Carlos III Island (coordinates 053° 49'.979 S - 071° 42'.273 W) and Cabo Holland (coordinates 053° 34'.368 S - 072° 20'.028 W), for a distance of 28 nautical miles (52 km). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Dawson Island in April, showing a broken and dislocated lower jaw. The sixth stranded recently showing multiple internal and external traumas. In these latest case (Table 3), there was certainty of the impact of a ship, while in the others no collision was documented but wounds are consistent with ship strikes, and entanglements are unlikely because no fishing nets were observed and there is little net-fishing in the area. We recognize the need for a reliable necropsy to produce an accurate inference on the causes of death, but this is nearly impossible in remote areas where transportation is limited [35,36].

At a weekly encounter rate of 0.27, and assuming whales spend 6 months per year in the Magellan Strait, the average humpback whale is within ~1 km of a vessel on seven occasions each year. Given a population of 93 whales [5], there would be 650 occasions in which whales and ships were nearby. Unfortunately, the information available to us is insufficient to be more precise about those encounters, since both whale and ship locations were spotty and subject to error (see Fig. 7). Gende et al. [3] argue on reasonable grounds that even one fatality every three years could reduce the population size, so 650 events where whales and ships were in the same kilometer of water suggests more than a negligible risk. In fact, in the study area five fatalities on humpbacks were detected in nine years (Table 3). The loss is even more significant when females die, and in the study area half the sightings were females 10–12.5% were mother-calf pairs [14]. Pairs might be the most susceptible to vessel strikes.

More directly, in a sample of just 21 whales with satellite tags, one female was struck and killed. The fact that the victim's encounter rate with ships was far higher than any of the other whales is significant. For 13 consecutive days, it was often near the center of the passage, and was likely killed 29–30 March, between Carlos III Island and Cabo Holland in the Magellan Strait. Its final transmissions were near the center of the Strait where the passing vessels are concentrated.

5. Conclusions and recommendations

A variety of results indicate that collisions with whales are more frequent and harmful when ships travel at higher speeds [37–41]. Such incidents can be lethal to both adults and young whales [42]. The [43] documented 1200 strikes annually, with many more strikes undetected or unreported. Recognizing this risk, the International Maritime Organization (IMO) together with the International Whaling Commission (IWC), the Government of Belgium and the International Fund for Animal Welfare (IFAW) published recommendations to seafarers in several languages about practices designed to reduce the risk of collisions with whales. There are currently several mechanisms approved by the IMO, for example, Traffic Separation Schemes, Areas to Be Avoided, Recommended Routes and vessel speed restrictions [44], and there are additional local measures, including Marine Protected Areas, Seasonal Dynamic Management Areas, and speed limits [45–47]. Conn & Silber [45] considered vessel speed restrictions "a powerful tool" for reducing mortality of large whales. "To date, there is no technological solution available and hence, for large commercial ships the only current mitigation measures shown to be effective involve routing ships or reducing speed"review in Ref. [36]. We report here that nearly two-thirds of the large vessels in the Magellan Strait exceed the recommended 10 knot speed limit.

The inland waters of the Magellan Strait are an important feeding

area for the humpback whale of the Southeast Pacific [4,7], and they also provide feeding areas for southern right whales (*Eubalaena australis*) [48] a critically endangered species [49]. Additionally, the sei whale (*Balaenoptera borealis*) frequents the Magellan Strait during the summer to feed, with increasing numbers of reports around Carlos III Island [50] and three records of dead whales.

The nation of Chile has passed laws aimed at the protection and conservation of cetaceans in its waters, including Decree 276 (2004) creating the Francisco Coloane Coastal Marine Protected Area in the Magellan Strait, Decree 230 (2008) declaring the Natural Monument to Cetaceans, Decree 179 (2008) prohibiting whale captures, and Law 20.293 (2008) modifying the Fishing Law to protect cetaceans. To comply with these laws, we recommend a vessel speed restriction within the Strait of Magellan to help reduce the risk of lethal collisions with cetaceans. Currently, there are no speed restrictions for transiting the entire Strait. To the extent that it is safe, ships should proceed at a speed not exceeding 10 knots from December 1 to April 30 of each year. This recommendation would apply to all merchant ships traveling in both directions along the Magellan Strait between Isla Bonete in Paso Inglés north of Carlos III Island (coordinates 053° 49'.979 S - 071° 42'.273 W) and Cabo Holland (coordinates 053° 34'.368 S - 072° 20'.028 W), for a distance of 28 nautical miles (52 km) (Fig. 8), 9.1% of the total length of the Magellan Strait. The proposed speed should be mandatory for all types of commercial vessels larger than 200 tons, and compliance should be assessed during the whale feeding season by local authorities. In addition, we recommend placing a mandatory observer onboard all commercial vessels, as has been suggested for other remote areas [51,52].

We believe a speed restriction is most reasonable, given that a shift in vessel routing around the Magellan Strait [53] is unlikely due to the cost to shipping. In addition, we suggest that large (over 30 m) and fast whale-watching vessels that have started tourist operations in the feeding area also be subject to these restrictions. Fostering the recovery of large whale populations post-whaling requires mechanisms that the risks posed by shipping to increasingly dense aggregations of animals.

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Declaration of competing interest

The authors declare no conflict of interest with authorities or AIS data provider.

CRediT authorship contribution statement

Héctor M. Guzman: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Juan J. Capella:** Methodology, Investigation, Writing - review & editing. **Carlos Valladares:** Supervision, Project administration, Funding acquisition. **Jorge Gibbons:** Resources, Supervision, Project administration. **Richard Condit:** Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

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