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Avaliação do risco de colisão entre embarcações e baleias-jubarte (*Megaptera novaeangliae*) na costa brasileira.

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Assessment of collision risk between vessels and humpback whales (*Megaptera novaeangliae*) off the Brazilian coast.

Dissertação apresentada ao Programa de Pós-Graduação em Biodiversidade e Conservação da Natureza da Universidade Federal de Juiz de Fora como requisito parcial à obtenção do título de Mestre em Biodiversidade e Conservação da Natureza. Área de concentração: Processos Ecológicos e Conservação da Natureza.

Orientador: Dr. Alexandre Novaes Zerbini
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“Toda a nossa ciência, comparada a realidade, é primitiva e inocente; e, portanto, é o que temos de mais valioso. ” Albert Einsten

RESUMO

O crescente uso humano no ambiente marinho nas últimas décadas, enfatiza a necessidade de investigar as pressões antrópicas para melhorar a conservação da megafauna marinha. As colisões com navios tornaram-se uma das maiores ameaças para os cetáceos e uma importante fonte de mortalidade para as grandes baleias atualmente. Esforços para entender os efeitos dessa problemática têm se concentrado principalmente nas espécies do Hemisfério Norte. No Atlântico Sul, o impacto potencial do tráfego marítimo permanece ainda pouco conhecido. Aqui usamos o monitoramento por satélite de 30 baleias-jubarte (*Megaptera novaeangliae*) e dados AIS de tráfego marítimo para estimar o risco de colisão na costa central do Brasil, entre 2016 e 2019. Um modelo de espaço-estado foi usado para contabilizar o erro de observação e para regularizar os dados de telemetria. O tempo de residência e a proporção de tempo gasto na superfície pelas baleias (ou seja, a camada acima de 10 m da coluna d'água) combinado com a densidade de embarcações de cada frota, foram usados como proxies para estimar a probabilidade relativa de embarcações encontrarem baleias disponíveis para uma colisão em uma grade de células de ~8x8 km. Também identificamos áreas onde encontros potenciais provavelmente infligiriam ferimentos letais em baleias-jubarte com base no comprimento e velocidade da embarcação. A frota de carga foi a mais densamente distribuída e, juntamente com a frota de petroleiros, representa uma grande preocupação para as baleias-jubarte no Brasil. Um maior risco de colisão foi registrado ao longo da plataforma continental, no Banco dos Abrolhos – principal área reprodutiva dessa população – e no litoral dos estados do Rio de Janeiro e Espírito Santo, área de intenso tráfego marítimo com portos movimentados. Ao incorporar informações abrangentes sobre baleias-jubarte e tráfego de embarcações, este estudo destaca a importância de avaliações de risco espacialmente explícitas para a conservação das baleias-jubarte no Brasil.

Palavras-chave: Rastreamento por satélite. Movimento. Telemetria. Oceano Atlântico Sul Ocidental. Tráfego marítimo. Conservação.

ABSTRACT

The increase in the human use of the marine environment in the last several decades emphasizes the need for investigations on anthropogenic pressures to improve the conservation of marine megafauna. Ship strikes have become one of the greatest threats to cetaceans and an important source of mortality to whales in the present day. Efforts to understand the effects of this threat have been mostly focused on Northern Hemisphere species. In the South Atlantic, the potential impact of marine traffic remains poorly known. Here we used humpback whale (*Megaptera novaeangliae*; n=30) satellite monitoring and maritime traffic AIS data to estimate the collision risk at the central coast of Brazil between 2016 and 2019. A state-space model was used to account for observation errors and to regularize telemetry data. Residence time and proportion of time spent at the surface (i.e. the upper 10m layer of the water column) by whales, combined with fleet-specific vessel density, were used as proxies to estimate the relative probability of vessels encountering whales available to a collision in grid cells of ~8x8 km. We also identified areas where potential encounters were likely to inflict lethal injuries on humpback whales based on vessel length and speed. The cargo fleet was the most densely distributed and along with the tanker fleet, represented a great concern to humpback whales in Brazil. A higher risk of collision risk was recorded along the continental shelf, on the Abrolhos Bank – the main breeding ground for this population – and off the coasts of Rio de Janeiro and Espírito Santo states, an intense shipping traffic area with busy ports. By incorporating comprehensive whale- and vessel-related information, this study highlights the importance of spatially explicit risk assessments to conserve humpback whales in Brazil.

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Keywords: Satellite tracking. Movement. Telemetry. Western South Atlantic Ocean. Marine traffic. Conservation.

Figures list

SUMÁRIO

1 INTRODUCTION

The increase in marine anthropogenic activities during the last decades is a concern for biodiversity conservation worldwide (O'HARA; FRAZIER; HALPERN, 2021; SELIG *et al.*, 2014; SORDELLO *et al.*, 2020). In response to globalization, maritime trade routes and transport infrastructures are in constant expansion, emphasizing the need for research on the pressures derived from these activities and the required conservation measures (ABDULLA; LINDEN, 2008). The major negative ecosystem impacts of an increase in marine traffic include: underwater noise, chemical pollution, spread of invasive species, and ship strikes (LEAPER; MARTIN; RYAN, 2014; WALKER *et al.*, 2019). The latter is considered one of the greatest threats to many marine vertebrate species in the present day time. For example, the West Indian manatees (*Trichechus manatus latirostris*), are an endangered species whose collisions with watercrafts are responsible for 20−25% of reported mortalities off the coast of Florida (BASSETT *et al.*, 2020). In Western Australia, a study that investigated the causes of trauma and mortality in Little Penguins (*Eudyptula minor*), revealed that most likely, the primary causes of these injuries and deaths were due to collisions with watercrafts (CANNELL *et al.*, 2016). It is clear then that ship strikes are a significant source of mortality and injury for most whale species (ROCKWOOD; CALAMBOKIDIS; JAHNCKE, 2018), and can even lead to potential population-level consequences (CLAPHAM; YOUNG; BROWNELL, 1999; JENSEN; SILBER, 2003). In the North Atlantic, ship strikes appear to have hindered the right whale (*Eubalaena glacialis*) population from recovering after the end of commercial whaling (KRAUS *et al.*, 2005) and currently, ship strikes remain a critical issue for this population (KOUBRACK; VANDERZWAAG; WORM, 2021). For North Pacific blue whales (*Balaenoptera musculus*), while ship strikes have not directly harmed population growth, current levels of ship strikes are likely above the legal limits. Moreover, the increasing impact on the population is evident as vessel traffic increases and ship strikes become more common (MONNAHAN; BRANCH; PUNT, 2015).

Whilst definitely increasing in the last few years, reported whale-vessel collision rates are undoubtedly underestimated (VAN WAEREBEEK; LEAPER, 2008). Most incidents are not accounted for because they remain unnoticed or are not reported because of the fear of legal repercussions. Furthermore, whale carcasses are seldom recovered or washed ashore, and when they do, advanced decomposition has set in and might prevent a proper determination of cause of death (VAN DER HOOP *et al.*, 2013). Additionally, in most countries appropriate necropsy response teams are inexistent or insufficiently prepared to detect evidence of ship strikes on carcasses (VAN WAEREBEEK *et al.*, 2007). Particularly, in Brazil north to south, there are several beach monitoring projects that analyze cetacean carcasses and identify signs of ship strikes (*i.e.* MAYORGA *et al.*, 2020; VIANNA *et al.*, 2016). A study examining the skeletal tissues of humpback whale carcasses off the central coast of Brazil demonstrated the potential to identify signs of ship strikes also through lesions on the bones (GROCH *et al.*, 2012). In this regard, and in order to collect global data on ship strikes, a strategy was adopted by the Ship Strike Working Group of the International Whaling Commission which consisted in the development of a standardized global database of collisions (CATES *et al.*, 2017).

Mapping anthropogenic pressures has been an essential tool for managers and policy makers to make strategic decisions and monitor progress toward the management and use of marine space (AUGÉ *et al.,* 2018). Investigating important areas for large whales is necessary in order to map possible impacts; nonetheless, it is especially challenging because these species are highly mobile, with many carrying out large migrations (BOYD *et al.,* 2017; PENDLETON *et al.,* 2020). Consequently, the data gaps are a frequent issue in cetacean assessments, where more than 35% of species are classified as Data Deficient, which can lead policy makers into a false impression of 'no concern' (PARSONS et al., 2015). In this sense, tracking technologies have taken hold to known species distribution and marine traffic routes, becoming an important tool to identify risk areas (ASCHETTINO *et al.,* 2020; PANIGADA *et al.,* 2017).

Whale-vessel encounters are more prevalent in areas where both co-occur in high densities (HAM *et al.*, 2021). Many studies of strike risk assessments are based solely on overlapping distributions to identify areas of relatively high risk(GARCÍA-CEGARRA; PACHECO, 2019; GUZMAN *et al.*, 2012; ROSENBAUM *et al.*, 2014). However, the probability of a collision is affected by multiple aspects related to both vessels and whales (SCHOEMAN; PATTERSON-ABROLAT; PLÖN, 2020). Because ship dimensions, navigation strategies and routes vary by vessel type, it is crucial that risk assessments treat fleets separately for more directed and effective management purposes (PENNINO *et al.*, 2017). Vessel factors such speed and size determine the severity of a ship strike, where large ships travelling at high speeds are more likely to inflict lethal injuries (VANDERLAAN; TAGGART, 2007). As a consequence of the law of reflection from a plane surface, lower frequencies emitted by ships with hulls large enough to cause lethal injuries to whales are significantly attenuated near the surface, what is known as Lloyd's Mirror effect (GERSTEIN; BLUE; FORYSTHE, 2005). The ability's whales to hear low-frequency sounds from a ship, especially frequencies generated by the rotations of a propeller, is at its worst when the animals are near the surface, what makes them vulnerable (GERSTEIN; BLUE; FORYSTHE, 2005). In this way, collision risk also depends on whale behavior, with the time spend at or near the surface as an important factor to determine the susceptibility to a strike (IZADI *et al.*, 2018). Advanced tracking technology allows us to assess fine-scale movement using dive information for more comprehensive risk evaluations (KEEN *et al.*, 2019). Nonetheless, implementing such a range of whale- and fleet-specific information simultaneously is still incipient in collision risk studies (SCHOEMAN; PATTERSON-ABROLAT; PLÖN, 2020).

Most studies on the causes and consequences of ship strikes on whale species have been concentrated in the Northern Hemisphere's whale populations (CRUM *et al.*, 2019; PANIGADA *et al.*, 2006; REDFERN; BECKER; MOORE, 2020), while in the Southern Hemisphere, large areas remain poorly covered (VAN WAEREBEEK *et al.*, 2007). Brazil holds one of the longest coastlines in South America and its economy is majorly dependent on activities that involve the marine environment, such as hydrocarbon exploration, exportation, fishing, and tourism(FRANZ *et al.*, 2021; LOPES *et al.*, 2015; SEABRA *et al.*, 2015). Reports show that cargo movements in Brazilian ports increased by almost 40% between 2010 and 2020(ANTAQ, 2021), and 3D seismic activities increased by more than 290% in 2020 compared to 2019, with nearly half (42.5%) of the drilled wells located in the marine environment (ANP, 2021). The main oil exploration basins off of Brazil are located in the southeastern regions, where intensely busied ports and high vessel traffic are adjacent to major wintering ground for humpback whales (*Megaptera novaeangliae*) in the Southwestern Atlantic Ocean (*i.e.,* the Abrolhos Bank region) (*i.e.,* the Abrolhos Bank region) (ANP, 2021; MARTINS *et al.*, 2001; SOARES *et al.*, 2020; ZACHARIAS; FORNARO, 2020).

Humpback whales are among the most frequently reported species to be struck by vessels worldwide (JENSEN; SILBER, 2003). In Brazil, there have been numerous reports of stranded humpback whale carcasses with evidence of ship strikes and there have also been registers of vessel collisions.(BORTOLOTTO *et al.*, 2016a; ZAPPES *et al.*, 2013a). Evidence of ship strikes has also been documented for other species, such as the South Atlantic right whale (*Eubalaena glacialis*, Greig et al., 2001) and more recently, the Bryde's whale (*Balaenoptera brydei*, ATHAYDE et al., 2022). The western South Atlantic humpback whale population, referred to as "Breeding Stock A" by the International Whaling Commission (INTERNATIONAL WHALING COMMISSION, 2005) migrates from feeding grounds near South Georgia, the South Sandwich Islands, and adjacent waters to the wintering grounds in Brazilian tropical waters during the austral winter (ANDRIOLO *et al.*, 2010; BARACHO-NETO *et al.*, 2012; BEDRIÑANA-ROMANO *et al.*, 2021; ZERBINI *et al.*, 2006). Recent studies show that this population is increasing and re-occupying previous breeding areas on the coast of Brazil since it has been protected from whaling (BORTOLOTTO *et al.*, 2016b; ZERBINI *et al.*, 2019). Population increase along with an expansion of vessel traffic has probably resulted in higher likelihood of strike events and, although humpback whales are known to be vulnerable to ship strikes off the Brazilian coast (BEZAMAT; WEDEKIN; SIMÕES-LOPES, 2014), the factors affecting the risk of collision remain poorly understood.

2.1 HYPOTHESIS

With this study, we expect to develop a proxy for the intensity of space usage (both vertically and horizontally) by whales and identify areas where marine traffic is more intense. As a result of this research, we expect that the probability of a humpback whale suffering a strike by a vessel is higher in areas of common use when compared to the entire study area. It is expected that the vessel type, as well as its characteristics of size and navigation speed, will be important to estimate the probability and lethality of the risk index.

2.3 OBJECTIVES

1. Characterize the spatial traffic patterns of large vessels in the study area;

2. Identify areas where humpback whales might be more susceptible to ship strikes, using horizontal and vertical movement information;

3. Estimate how risk assessments vary when considering different fleet data;

4. Assess the relative risk of a vessel inflicting a lethal injury on a whale during a collision.

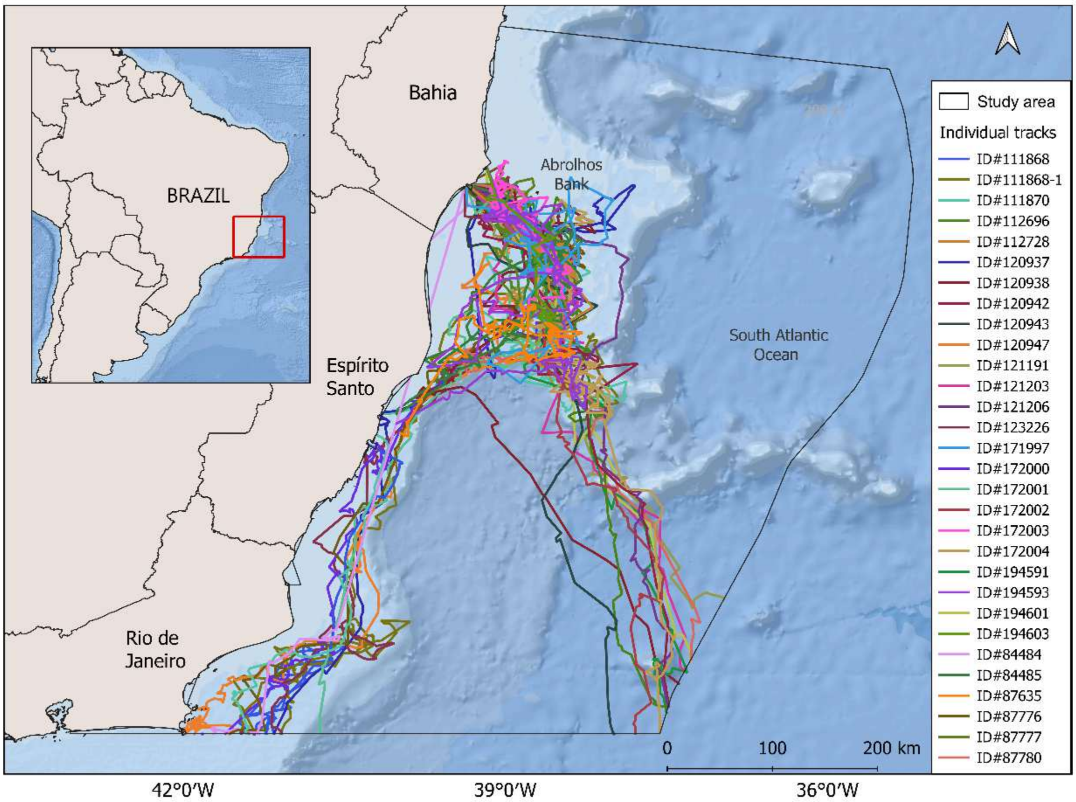
2 METHODS

2.1 STUDY AREA AND SATELLITE TAGGING

Movement data from 30 humpback whale individuals was obtained from tagging efforts conducted off the southeastern and northeastern Brazilian coasts during October–November from 2016 to 2019 (n = 2, 23, 1, 4 in 2016, 2017, 2018 and 2019, respectively). The study area was defined based on information on the distribution and movements of humpback whales off the Brazilian coast (ANDRIOLO *et al.*, 2010; BORTOLOTTO *et al.*, 2016b; ZERBINI *et al.*, 2006), extending from the states of Bahia (38°52’S, 16°21’W) down to Rio de Janeiro (43°11’S, 23°00’W) and including the Brazilian Economic Exclusive Zone (EEZ), which extends 200 nautical miles from the coast (Figure 1).

Transdermal satellite transmitters (Type C as defined by Andrews et al. 2019) in the SPLASH 10 configuration (Wildlife Computers Inc., Redmond, WA, USA) were deployed in the dorsal surface of humpback whales with a pneumatic delivery system(HEIDE-JØRGENSEN *et al.*, 2001) in coastal waters of Espírito Santo (2016) and Bahia (2017, 2018, 2019) States. Tagging efforts were undertaken during relatively good weather conditions (Beaufort sea state ≤ 4) from rigid hull inflatable boats ranging from 5.5 to 6.7 m in length. The SPLASH tag depth sensor was configured to record a dive each time the animal reached a depth below 10 m.

Figure 1 - Map of the study area, showing the trajectories of 30 humpback whale individuals tagged between 2016 and 2019. The black polygon indicates the boundaries of the study area that range from the south of the state of Bahia to the south of Rio de Janeiro, delimited by the Brazilian Exclusive Economic Zone (EEZ), that is, 200 nautical miles from the coastline.



2.2 MODELING WHALE DATA

Telemetry data from the 30 individual whales used in this study was censored prior to analysis to remove locations outside of the study area. The data was then filtered to remove extreme positions using the R package *argosfilter v 0.63* (FREITAS *et al.*, 2008). A continuous-time correlated-random-walk model (CTCRW) was used to account for observational error and estimate locations at regular time-steps (JOHNSON *et al.*, 2008). The model estimates two state variables, velocity, and true locations from error-prone observed locations, and two parameters, β controlling directional persistence and σ controlling the overall variability in velocity. Standard deviations for modeling location errors were derived from Argos error ellipse and calculated as indicated by Mcclintock *et al.* (2015). The model was fit within a Bayesian framework, therefore, to obtain locations at regular intervals, NAs were imputed every hour within each whale's track. In addition to providing hourly locations for each whale, 50 track realizations were obtained for each whale by randomly sampling from the posterior distributions.

2.3 VESSEL TRAFFIC DATA

To characterize marine traffic in the study area, daily vessel tracking was obtained from Marine Traffic (http://www.marinetraffic.com). This platform provides longitudinal data about ship movements around the world from Automatic Identification System (AIS) since 2009. AIS is an onboard communication and safety system that transmits vessel identification, position, course, speed, and other data at regular intervals. The system was implemented by the International Maritime Organization in 2004, and is required for all ships of 300 gross tonnage and upwards engaged on international voyages, and cargo ships of 500 gross tonnage and upwards not engaged on international voyages, and passenger ships irrespective of size (ROBARDS *et al.*, 2016).

The vessel data within the study area used was obtained in the years 2012 and 2019 and included the Maritime Mobile Service Identity, vessel type, hour, date, speed, course, heading and dimensions (length and width) for each geographic position obtained from Marine Traffic. Positions with speed ≤ 3 knots were considered non-travelling and removed along with locations on land and stationary AIS beacons.. For this purpose, a visual inspection (using georeferenced plots) was carried out at 0, 1, 2, and 3 knots, and it was found that vessels are only moving through space at speeds registering from 3 knots. In addition, speed positions greater than 30 knots were considered unrealistic outliers and therefore discarded (WANG *et al.*, 2020).Vessels were classified according to sector of activity into 8 fleet types: cargo, tanker, tug, military, passenger ship, fishing, dredger and sailing. .

All analyses described in the next segment were conducted using a 0.072 × 0.072º (~8x8 km) grid, and were carried out separately for 2012 and 2019. Vessel density (VD) was calculated for each fleet type as the sum of the daily number of unique vessels crossing each grid-cell i in a month, divided by the total number of days for that month (BEDRIÑANA-ROMANO *et al.*, 2021). This procedure was conducted for the humpback whales' breeding period (August-November, see **APPENDIX A:** Figure A1-A9) and then averaged into a single layer for each fleet type.

2.4 DEFINING A WHALE POTENTIAL SUSCEPTIBILITY TO COLLISION

In our risk analysis, we defined the susceptibility of a whale to a strike event, by the amount of time spent in an area (t) and the proportion of that time it spends near the surface defined as the upper 10 m layer of the water column (*s*). *t* was estimated with a continuous-time discrete-space Markov chain model fitted to each track realization j from all whales using the R package ctmcmove (HANKS, 2018). The average residence time for each track realization j for each grid cell i (t_{ji}) was computed as the average of all estimated *t* values within i.

s was computed for each track realization j as the median of each set of dive + post-dive surface time within each grid cell i (s_{ji}). To accurately associate the surface events with locations, trajectories of each track realization (consisting of regular points at 60-minute intervals) were re-discretized into a 5-minute interval using the AdehabitatLT (CALENGE, 2006) R package. Spatially explicit estimates of t and s were generated individually for each output track realization j from the CTCRW model. So, the relative probability of a whale being available to a collision (RPWS) was calculated using the following formula:

$$RPWS_{ji} = \frac{Rt_{ji}Rs_{ji}}{\sum_{ji=1}^{n}(Rt_{ji}Rs_{ji})}$$

where, $Rt_{ji} = \frac{t_{ji}}{\sum_{ji=1}^{n}(t_{ji})}$ corresponds to the spatially explicit estimate residence time within each grid-cell i relative to all other grid cells n to each track realization j, and $Rs_{ji} = \frac{s_{ji}}{\sum_{ji=1}^{n}(s_{ji})}$ corresponds to the spatially explicit estimate proportion of time spent at the surface within each grid-cell i relative to all other grid cells n to each track realization j. An overall RPWS layer was generated by averaging the results for all track realizations and then averaging these across the 30 individuals into a single layer.

2.5 ESTIMATING RELATIVE PROBABILITIES OF VESSELS ENCOUNTERS WHALES

Encounter probabilities were estimated through the combination of VD and RPWS. For that, we computed the relative probability of observing a vessel within each grid cell i (Rvd_i) as:

$$Rvd_{i} = \frac{VD_{i}}{\sum_{i=1}^{n}(VD_{i})}$$

Spatially explicit estimates of Rvd_i were generated independently for each fleet type and for each output track realization j from the CTCRW model, as done for RPWS. Thus, the relative probability of a vessel encountering a whale susceptible to a collision (RPVWS) was given as:

$$RPVWS_{ji} = \frac{RPWS_{ji}\,Rvd_i}{\sum_{ji=1}^{n}(RPWS_{ji}Rvd_i)}$$

An overall RPVWS layer was generated by averaging the results for all track realizations and then averaging these across the 30 individuals into a single layer. Because RPVWS represents relative probabilities between the set of grid cells independently for each fleet type, to compare the eight fleet types with each other, and between the two years (2012 and 2019), it was possible to measure the area of each grid cells with a RPVWS > 0 for each fleet type and each year. All analyses were performed in the software R version 4.1.3 (R CORE TEAM, 2022) using *sf* (PEBESMA, 2018) and *raster* (HIJMANS, 2022) packages and maps were created in QGIS version 3.12.0 (QGIS DEVELOPMENT TEAM, 2022).

2.6 RELATIVE RISK OF A LETHAL COLLISION

For this assessment, we considered only vessels longer than 80 m in length, because most lethal and serious injuries to whales are caused by larger vessels (LAIST *et al.*, 2001). We used navigation speed of the vessels as a proxy, with an approach adapted from Nichol et al. (2017):

$$vs_i = \frac{\sum_{ci}^{n}(Md_{ci}VD_{ci})}{\sum_{ci=1}^{n}(VD_{ci})}$$

where Md_{ci} was the median speed of each of the 4 vessel speed classes (4-9, 10-15, 16-22, 23-30 knots, respectively), and VD_{ci} was the vessel density per cell i for each speed class c. Using vs_i as 4 vessel speed classes averaged into a single layer and a simple logistic regression model (CONN; SILBER, 2013), we calculated the probability of a whale suffering a lethal injury during an encounter (PL) (see **APPENDIX A:** Figure A10): To assess the overall risk of a lethal collision for humpback whales off the study area, the speed of the vessels was used as a proxy (NICHOL *et al.*, 2017), and as mentioned above, only vessels longer than 80m were considered (LAIST *et al.*, 2001). In this sense, each vessel position was classified according to the speed into 4 classes (4-9, 10-15, 16-22, 23-30 knots) and the relative risk of a lethal collision (RRLC) was computed for all fleet types together. Following Nichol et al. (2017), the spatially explicit vessel speed estimate (vs) for each class *c* within each grid cell *i* was computed as:

$$vs_{ci} = \frac{\sum_{ci}^{n} (Md_{ci} VD_{ci})}{\sum_{ci=1}^{n} (VD_{ci})}$$

where Md_{ci} was the median speed of each of the 4 vessel speed classes, and VD_{ci} was the vessel density per cell *i* for each speed class *c*. An overall *vs* layer was generated by averaging all vs_c layers. The probability of a whale suffering a lethal injury during an encounter (*PL*) was computed based on the simple logistic regression proposed by Conn & Silber (2013), using the overall *vs* layer, as follows:

$$PL_i = \frac{1}{1+exp^{-(-1.91+0.22vs_i)}}$$

Then, we estimated the relative risk of a lethal collision (RRLC) between a vessel and a whale as follows:

$$RRLC_{ji} = \frac{RPVWA_{ji} PL_i}{\sum_{ji=1}^{n} (RPVWA_{ji} Rs_i)}$$

An overall RRLC layer was generated by averaging the results for all track realizations and then averaging these across the 30 individuals into a single layer. Because RRLC represents relative probabilities between the set of grid cells independently for each year, to compare 2012 with 2019, we measured the area of each grid cell with RRLC > 0 for each year.

3 RESULTS

A total of 555,539 whale locations predicted from the CTCRW model were used to provide risk estimates. Individual tracks ranged from 121 to 917 locations (mean = 405.8, sd = 200.9, median = 369). The average travel distance per whale in the study area was 2,387 km (sd = 1,210 km, max = 5,403km, min = 706 km), and a total of

21,925 sets of dive + post-dive surface time was recorded, varying from 72 to 2,200 per whale (mean = 756, sd = 491.8, median = 614).

A total of 1,851 vessels crossed the study area in 2012 and 2,314 in 2019, as obtained from the AIS data (Table 1). Cargo ships were the most prevalent fleet (2012 = 1,324, 2019 = 1,502), followed by tanker (2012 = 315, 2019 = 500) and tug (2012 = 109, 2019 = 93) (Table 1). The tanker fleet held the largest ship length in 2012, but in 2019 the cargo fleet was the largest on average (Table 1). Passenger ships (2012 = 14.8 knots, 2019 = 13.2 knots) had the highest average speed navigation in both years, while sailing vessels (6.9 knots) were the slowest in 2012 and dredgers (7.0 knots) in 2019 (Table 1). The cargo (VD 2012 = 0-7.4, VD 2019 = 0-7.2), tug (VD 2012 = 0-2.6, VD 2019 = 0-4.3) and tanker (VD 2012 = 0-0.6, VD 2019 = 0-2.5) fleets occurred in highest densities in the study area, especially in 2019, while the sailing (VD 2012 = 0-0.2, VD 2019 = 0-0.27) and fishing (VD 2012 = 0-0.02, VD 2019 = 0-0.6) fleets had lowest densities in both the years (Figures 2 and 3).

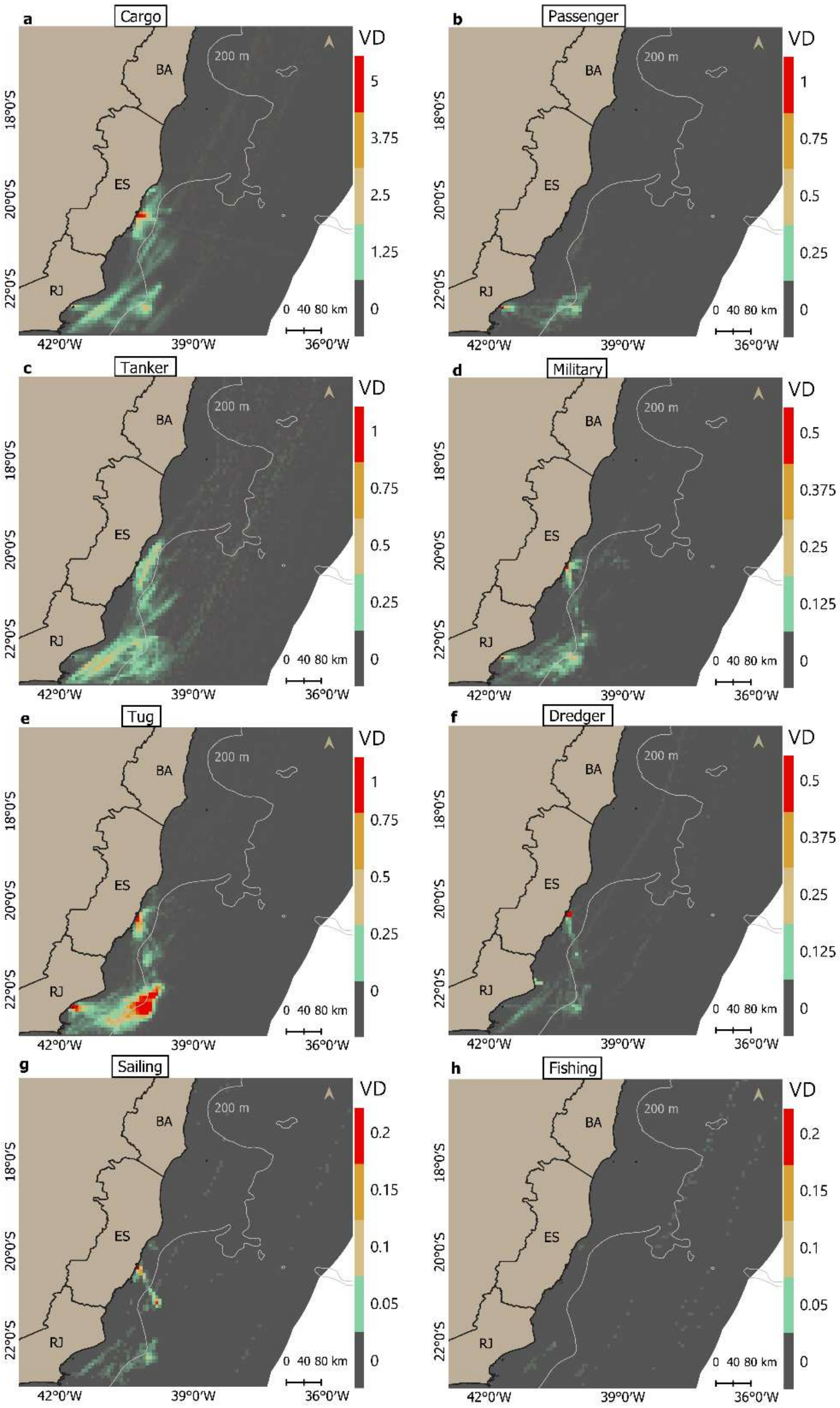
RPWS values were higher along the continental shelf, with humpback whales especially susceptible to collisions near the Abrolhos Bank region (Figure 4 and 5). The total area of relative probabilities of vessels encountering whales (i.e., $RPVWS_i > 0$) varied among the eight fleets evaluated, with the cargo (2012 = 78057.3 km2, 2019 = 89002.6 km2) and tanker (2012 = 88861.6 km2, 2019 = 90666.7 km2) fleets showing higher values (Table 1). Moreover, for 75% (n = 6) of the fleets analyzed the area of risk increased from 2012 to 2019, except for the dredge fleet which showed the opposite trend and for cargo which remained equal (Figures 6 and 7, Table 1). The total area with a relative risk of a whale suffering a lethal injury during an encounter (RRLC), obtained with basis on the vessel speed, increased from 48,407 km2 in 2012 to 91,424 km2 in 2019 (Figure 8).

Table 1. Number of vessels (n) and summary statistics (mean ± SD) for the navigation speed (knots), and vessel length (meters) for each fleet recorded between August-November of 2012 and 2019 in the study area. Total risk area (sum of cells with RPVWS>0) in km^2 was ALSO measured for each vessel fleet.

Vessel type	2012					2019				
	n	Speed mean (sd)	Length mean (sd)	VD range	RPVWS area (km^2)	n	Speed mean (sd)	Length mean (sd)	VD range	RPVWS area (km^2)
Cargo	1324	9.5 (4)	142.5 (78.1)	0-7.4	78057.3	1502	12.6 (2.4)	213.1 (47.5)	0-7.2	89002.61
Dredger	19	8.7 (2.8)	116.2 (26.9)	0-2.1	18727.1	4	7 (1.8)	86.1 (12.6)	0-0.9	5433.246
Fishing	13	9.8 (1.8)	69.7 (28.9)	0-0.01	2257.1	83	8.6 (3.2)	48.3 (27.8)	0-0.6	53856.08
Military	33	7.3 (3.2)	82.6 (22.0)	0-0.6	20749.4	26	7.9 (2.5)	71.9 (41.1)	0-0.2	32202.85
Passenger	22	14.8 (4.9)	57.7 (39.6)	0-1.03	15564.6	29	13.2 (3.8)	133.9 (84.6	0-0.5	41100.47
Sailing	16	6.9 (2.6)	75.6 (17.4)	0-0.2	9496.1	77	7.4 (3.9)	20.4 (9.4)	0-0.3	43379.36
Tanker	315	10.2 (3.5)	205.0 (63.4)	0-0.6	58861.6	500	12.1 (2.4)	198.9 (50.0)	0-2.5	90666.77
Tug	109	7.1 (2.7)	74.1 (14.8)	0-2.6	30436.1	93	8.7 (2.4)	41.3 (20.6)	0-4.3	52242.35
Total	1851	9 (3.9)	129.9 (75.8)	-	-	2314	11.9 (2.8)	148.5 (70.7)	-	-

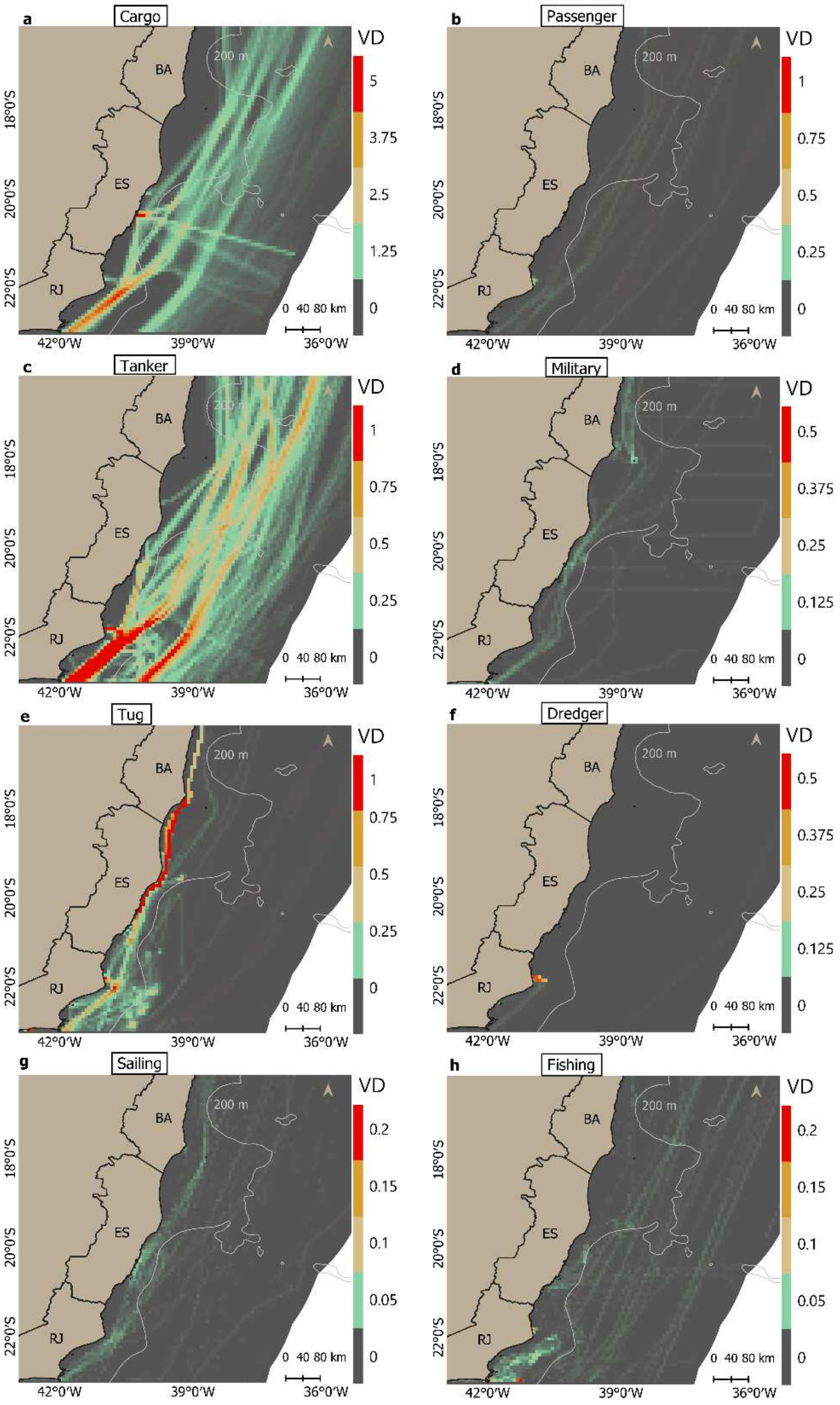
Source: Elaborated by the author (2023).

Figure 2 - Vessel density (VD), defined as the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, for each vessel fleet category in the study area between August and November of 2012. Color scales are not necessarily equivalent, to improve visualization of data for each fleet.



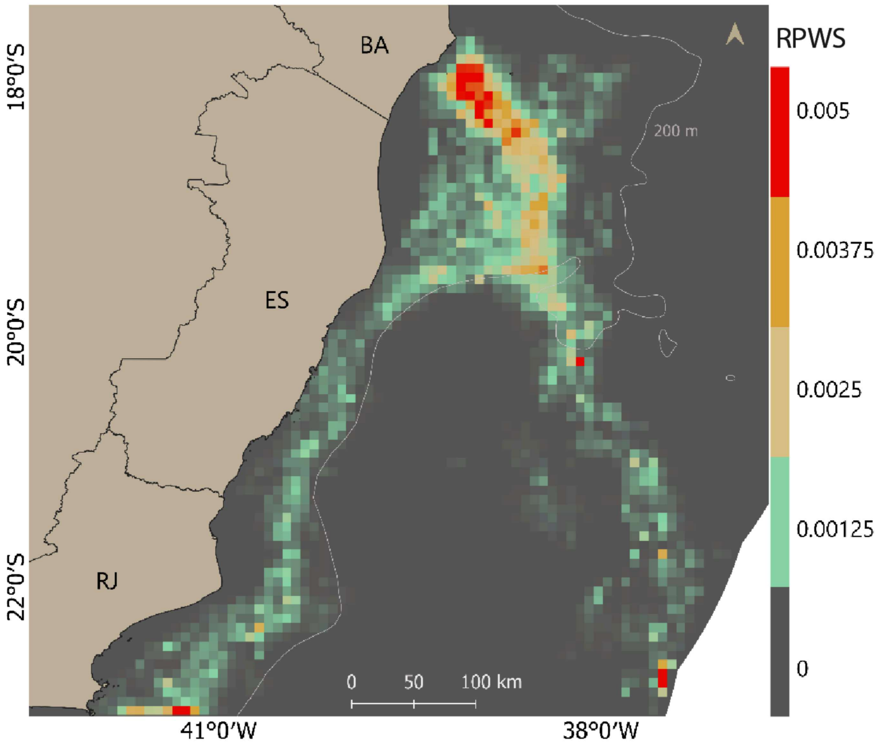
Source: Elaborated by the author (2023).

Figure 3 - Vessel density (VD), defined as the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, for each vessel fleet category in the study area between August and November of 2019. Color scales are not necessarily equivalent, to improve the visualization of data for each fleet.



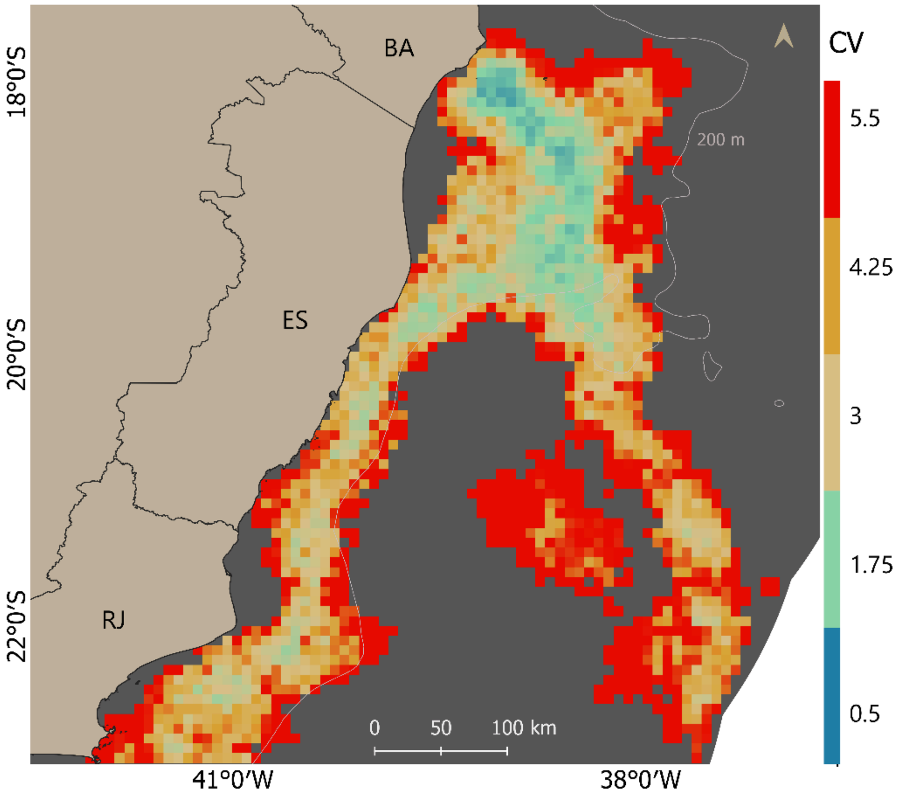
Source: Elaborated by the author (2023).

Figure 4. Relative probability of a humpback whale susceptible to collision (RPWS) in 0.072 x 0.072º (~8x8 km) grid cells in the study area, estimated individually and averaged among all 30 humpback whale individuals.



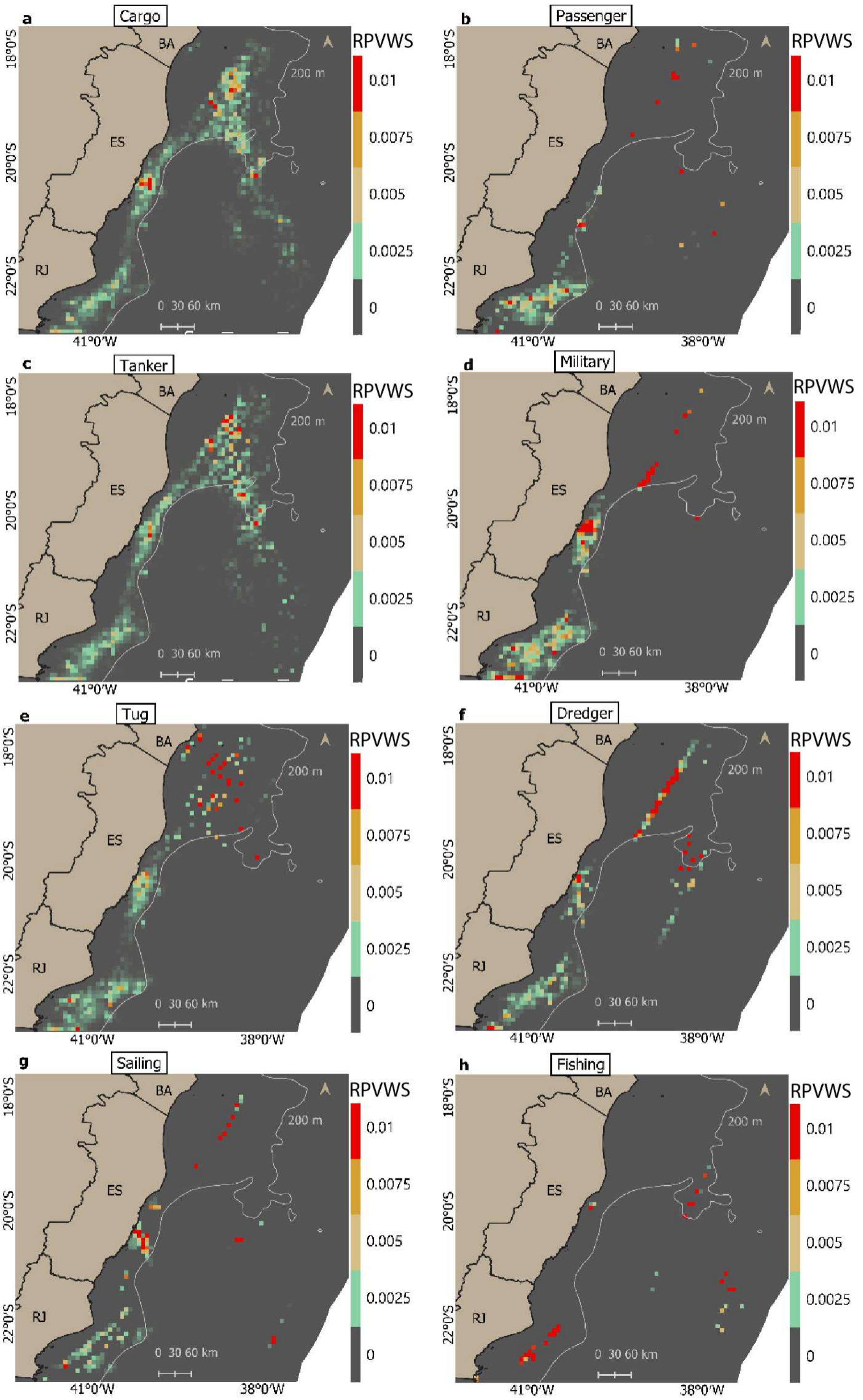
Source: Elaborated by the author (2023).

Figure 5 - Coefficient of Variation (CV) regarding RPWS average of 30 humpback whale individuals in 0.072 x 0.072º (~8x8 km) grid cells in the study area. RPWS is the relative probability of a humpback whale susceptible to collision.



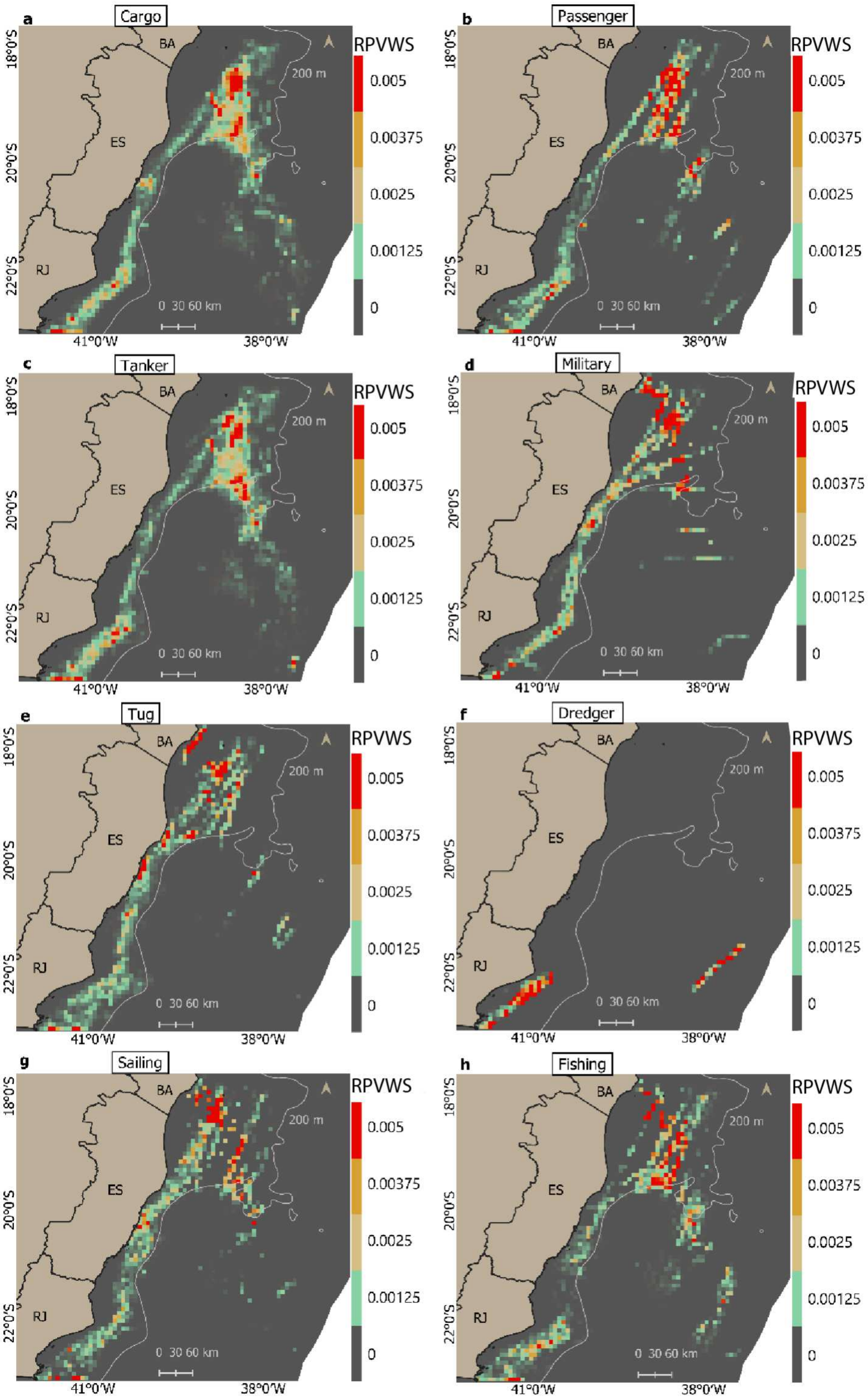
Source: Elaborated by the author (2023).

Figure 6 - Relative probability of a vessel encountering a humpback whale susceptible to collision (RPVWS) in 0.072 x 0.072º (~8x8 km) grid cells in the study area, depicted for the eight vessel fleet categories in 2012. RPVWS was estimated individually and averaged among all 30 humpback whale individuals.



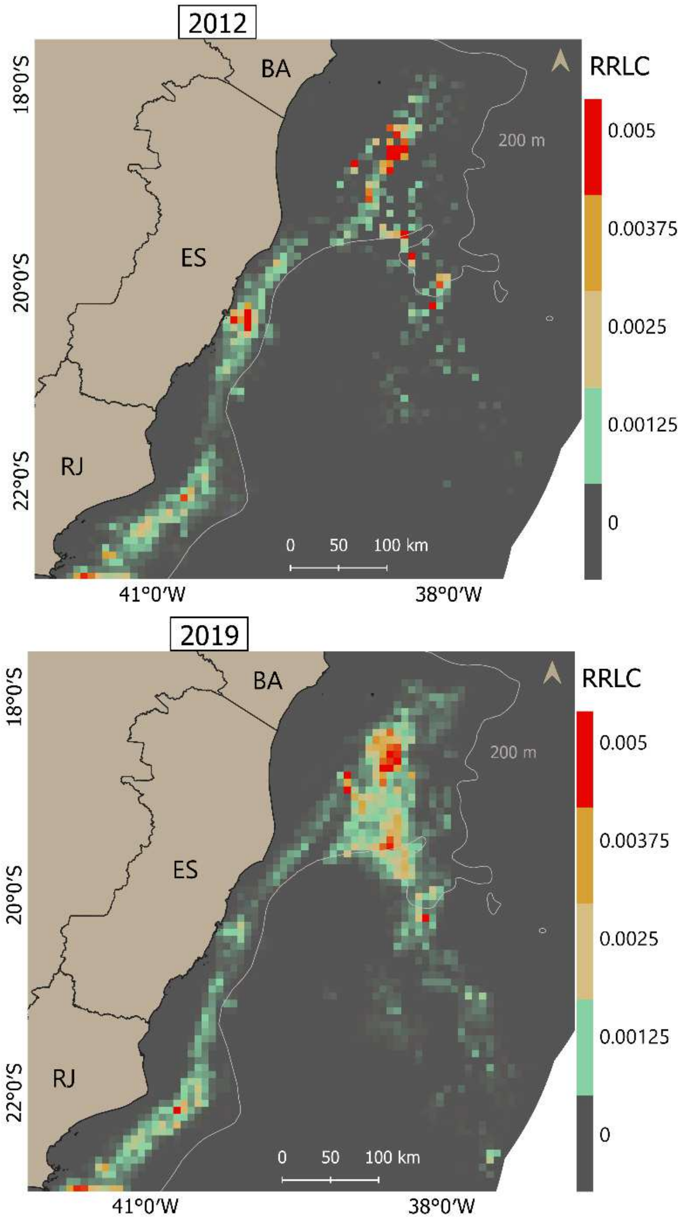
Source: Elaborated by the author (2023).

Figure 7 - Relative probability of a vessel encountering a humpback whale susceptible to collision (RPVWS) in 0.072 x 0.072º (~8x8 km) grid cells in the study area, depicted for the eight vessel fleet categories in 2019. RPVWS was estimated individually and averaged among all 30 humpback whale individuals.



Source: Elaborated by the author (2023).

Figure 8 - Relative risk of a lethal collision between a vessel and a humpback whale (RRLC) in 0.072 x 0.072º (~8x8 km) grid cells in the study area, depicted for vessels >80 m in length. RPVWS was estimated individually and averaged among all 30 humpback whale individuals.



Source: Elaborated by the author (2023).

4 DISCUSSION

In this study, we provide a spatially explicit risk assessment about the potential negative interactions between multiple vessel fleets and humpback whales at their main breeding ground in the Southwestern Atlantic Ocean. Baleen whale movement patterns derived from satellite telemetry data in conjunction with AIS data has been previously used to identify high risk areas for several species, including humpback, bowhead and blue whales and even odontocetes like belugas (ASCHETTINO *et al.*, 2020; BEDRIÑANA-ROMANO *et al.*, 2021; HALLIDAY *et al.*, 2020). Here we expand the approach used in these previous studies by incorporating the proportion of time that humpback whales spend near the surface as a variable to estimate the probability of a strike event. This variable is the key to assessing collision risk more accurately because a strike is only viable if the whale is susceptible or near the surface, within reach of the vessel's propeller or hull (VAN WAEREBEEK *et al.*, 2007). Nevertheless, this parameter is still poorly explored in collision risk assessments for larger whales (SCHOEMAN; PATTERSON-ABROLAT; PLÖN, 2020).

Individual-level diving information as used here is valuable to predict where whales are most susceptible to a vessel encounter because patterns of vertical habitat use can vary depending on: species, sex, age or type of activity performed (CHALCOBSKY; CRESPO; COSCARELLA, 2020; DOMBROSKI; PARKS; NOWACEK, 2021; FÉLIX, 2004; VERSIANI; AZEVEDO, 2020). In Western Australia, lactating humpback whales, and their calves, spend considerable time resting (on average 35% of time), stationary, at relatively shallow depths, within the reach of ship hulls (BEJDER *et al.*, 2019). Medium to larger container ships have a 15-m depth average draft but the strike zone could be closer to 30-m because a moving ship may double its range below water (CALAMBOKIDIS *et al.*, 2019). In our study, the criteria for defining humpback whale susceptibility was then established at the upper 10 m layer of the water column, which is entirely within the danger zone to a ship strike. With this said, and probably underestimated, our risk assessment provides conservative and robust results for future management measures in the humpback whales' breeding area in Brazil.

RPWS estimates showed that humpback whales were more susceptible to ship strikes within the Abrolhos Bank. The region is considered the most important wintering and calving ground for the species in the Southwest Atlantic Ocean and concentrates large aggregations of individuals (ANDRIOLO *et al.*, 2010; PAVANATO *et al.*, 2018). Slower movements and large periods at the surface are typical behaviors expected in breeding and calving areas, yielding the highest exposure to collisions (CRUM *et al.*, 2019; IZADI *et al.*, 2018). The higher susceptibility of whales to ship strikes near the Abrolhos Bank observed here concur with previous studies, which based their assessment of risk on density estimates from sighting data (BEZAMAT; WEDEKIN; SIMÕES-LOPES, 2014; DIENSTMANN, 2015). Nonetheless, our study also demonstrates the high susceptibility of whales to ship strikes when the animals are using habitats along the continental shelf. Most accidents with large whales recorded around the world occur on or near the shelf and involve mainly calves, juveniles, and females (LAIST *et al.*, 2001). This demonstrates the utility of tracking in relation to other methods used to assess whale distribution in order to allow for a greater reach in conservation risk assessments.

Our findings also highlight variability of large vessel traffic shaping the ship strike risk for humpback whales off the central Brazilian coast through spatially-explicit estimates. By considering vessel speed as a proxy of lethal collision risk, our results clearly demonstrate the increasing potential negative impact of ship collisions on a population level. Assessing critical factors that rule occurrence and severity of a ship strike and mapping potential risk areas is relevant to building efficient management strategies that will ensure the observed recovery of the western South Atlantic humpback whale population (ASCHETTINO *et al.*, 2020; CRUM *et al.*, 2019; NICHOL *et al.*, 2017; PANIGADA *et al.*, 2017; ZERBINI *et al.*, 2019).

Indeed, we recorded high RPVWS values along the continental shelf for different vessel fleets, with the highest VD values along the coasts of Espírito Santo (ES) and Rio de Janeiro (RJ). When leaving the Abrolhos Bank, part of the individuals travel along the southeastern coast of Brazil up to about 20ºS latitude, where the migration towards the feeding areas starts (ZERBINI *et al.*, 2006). This region hosts some of the largest Brazilian cities with intensely busy ports, which explains the high VD and RPVWS values recorded, especially for the most frequent fleets such as cargo ships, tankers and tugs. Nonetheless, although high VD values occur in these areas, spatial distribution varied substantially between fleets. Cargo ships and tankers showed a more homogeneous distribution, which matched humpback whale habitat use within most of the study area, and therefore had the larger RPVWS areas. Other vessel categories, such as dredgers and tugs, showed rather more localized risk areas. Cargo and tanker fleets are considered the most concerning for the whales, given that their typically greater sizes and higher cruise speeds are responsible for most of the lethal collisions (LAIST *et al.*, 2001). Cargo ships comprised more than 60% of vessels documented in both years investigated here, with up to 5 times a higher number of vessels crossing a single cell when compared to other fleets. Therefore, this fleet should be considered with the highest concern regarding vessel-derived negative interactions with humpback whales off the coast of Brazil. Lethal or severe injure to whales are often caused by vessel with 80 m in length or longer (LAIST *et al.*, 2001). According to Vanderlaan & Taggart (2007) chances of a lethal injury increase from approximately 20% at 8.6 knots to approximately 80% at 15 knots. This premise becomes an issue when we consider the growing demand in international trade, that involves increasingly faster and larger ships, which pose a greater risk to whales (PIROTTA *et al.*, 2019). Our findings showed that RRLC area extension was larger in 2019 than in 2012, suggesting that safe corridors for humpback whales in Brazilian waters might be decreasing due to increased vessel traffic. One fact that could differentiate the data between both years could also be related to the increase in the number of ships using the AIS system; however, in this case it seems unlikely, once most of the vessels evaluated here are large and use AIS mandatorily since 2008 (ROBARDS *et al.*, 2016). The differences in the RPVWS area extensions between the years studied indicates that there is an increased risk to whales across all of the analyzed fleets, except for the dredgers.

The increasing number of sail and fishing vessels and of their use of the observed space in this study is possibly underestimated because these fleets encompass many small vessels that do not meet the mandatory requirements of the AIS system. Collisions with smaller vessels pose substantially lower risk of injuries to whales, but conversely the accidents may damage vessels and endanger human lives (RITTER, 2012). Indeed, collisions between humpback whales and smaller vessels have been increasingly reported worldwide, including off the coast of Brazil (FRASER *et al.*, 2020; RITTER, 2012) and reinforce the need to develop management measures to address this problem. Moreover, although our findings suggest that vessel routes have not changed substantially within seven years, the increase in vessel density and distribution from 2012 to 2019 is expected, given the worldwide expansion of trade routes and maritime transport infrastructure (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT, 2020). Global projections combining models based on socio economic indicators and a temporal validation set with economic development scenarios showed that the rise in marine traffic could increase by 240–1,209% by 2050 (SARDAIN; SARDAIN; LEUNG, 2019). In the face of expected increase in marine traffic in the next decades, continuous monitoring is essential to implement management practices that guarantee a safe coexistence between humans and wildlife at sea.

In our study, RPWS areas were similar to RRLC and RPVWS areas, demonstrating that spatial risk is highly driven by the whales' spatial use of the habitat. Different to studies conducted in feeding areas, where correlations between whales use/densities and environmental covariates are expected to occur (BEDRIÑANA-ROMANO *et al.*, 2021; NICHOL *et al.*, 2017), in breeding grounds social interactions might be more important in shaping whale distribution (CERCHIO *et al.*, 2016; ERSTS; ROSENBAUM, 2003). Environmental characteristics such as shallow depths and warmer waters are common in humpback whales breeding grounds, but predicted distribution based on behavior information seems to better explain the movement patterns inside these areas (DERVILLE *et al.*, 2020; DULAU *et al.*, 2017; STEVICK *et al.*, 2011). As mentioned before, RPWS results showed that important areas to humpback whales are similar to those from other studies that used other survey methods. However, with respect to collision risk, our approach allowed us to predict areas where whales are possibly at greater risk to be struck by a ship. This is because our analysis considers the proportion of the amount of time whales spend near the surface calculated from dive data archived in the satellite tags. Telemetry results may not provide results representative of the behavior of a population when sample sizes are small (CITTA *et al.*, 2016). In this study, we used a relatively large sample within a somewhat small area. Our results provide guidance on risk areas for humpback whales in Brazil, and therefore are important for the development of marine spatial planning efforts to protect habitats for this species.

Brazil is one of the world's leading producers and exporters of grain and the largest in the export of soybeans with 76 million tons shipped each year (FULLER *et al.*, 2003). Moreover, the country's southeast region is bordered by coastlines that are densely populated, where industrial and agricultural activities, along with tourism and fisheries are of significant economic importance (FAO, 2011; SILVA *et al.*, 2018). As demonstrated in this study, areas of intense shipping traffic have increased in the last few years. Recent studies show that reductions in vessel speed and small shifts in shipping routes may be effective for addressing stakeholder needs and reducing the risk of ship strikes (CONN; SILBER, 2013; LEAPER, 2019). Technical measures to detect whales both onboard and off-board can also be an alternative to avoid or reduce collisions (SÈBE; KONTOVAS; PENDLETON, 2019). This may involve for example, alert systems that to generate real-time updated maps for ships (e.g., Strike-alert, MADON *et al.*, 2017), dedicated observe (WEINRICH; PEKARCIK; TACKABERRY, 2010) or acoustic detection systems (SILBER *et al.*, 2009). Considering that humpback whales use Brazilian waters more substantially during the austral winter, restrictions limited to this period and risk areas shown in our study could be effective. As the Abrolhos Bank region might be considered the spot of higher relative and absolute probabilities of negative interactions between humpback whales and vessels, mitigate actions should focus mainly on this area. Nonetheless, the Brazilian coast is an important habitat to many baleen whale populations and therefore more species-specific risk assessments are needed (DI TULLIO *et al.*, 2016; LODI *et al.*, 2015; ZAPPES *et al.*, 2013b). For example, right whales are highly vulnerable to collisions and inhabit mainly shallow waters in southern Brazil to breed and raise calves (JENSEN; SILBER, 2003; RENAULT-BRAGA; GROCH; SIMÕES-LOPES, 2022).

In practice, the initiative to implement and monitor mitigation strategies to prevent or reduce collisions between vessels and whales can and should involve various actors and organizations. The International Maritime Organization (IMO) is the main entity responsible for issues related to maritime safety and the protection of the marine environment at the international level, therefore it is up to them to develop mandatory standards and guidelines for the prevention of collisions between ships and whales (https://www.imo.org). In Brazil case, the governmental agencies that regulating maritime traffic (Agência Nacional de Transportes Aquaviários – ANTAQ, https://www.gov.br/antaq/pt-br) and control environmental protection (Ministério do Meio Ambiente e Mudança do Clima – MMA, https://www.gov.br/mma/pt-br) also can be responsible to implement and manage mitigation strategies, as well as establish policies and regulations necessary to garantee whales' safe. The Marinha do Brasil (MB), specifically the a Diretoria de Portos e Costas e os Comandos do Distrito Naval (https://www.marinha.mil.br/dpc/node/3505), which represent the MB for the environment issues, also play an important role in managing these strategies. Roling such as active participation in research and monitoring programs, promote education and awareness on the subject, and, most importantly, to enforce compliance with established regulations and measures. In addition to monitoring whale populations, non-governmental organizations (NGOs) dedicated to marine conservation, can propose mitigation measures to be discussed and also raise social awareness. Lastly, the naval industry can contribute by adopting technologies and practices that reduce the risk of collisions, as well as collaborating with the authorities and organizations involved.

5 CONCLUSION

The results highlighted here cleave for a series of future studies that can deepen the understanding of collisions between vessels and whales in the South Atlantic Ocean. Our ship strike risk analysis based on whale tracking and diving information provided an effective approach for identifying regions of conservation concern for humpback whales. However, more comprehensive assessments such as: spatial analysis on a larger scale and including other species; investigations of the influence of oceanographic factors on the spatial distribution of whales and vessels; methodology using different data collection methods for whales beyond tracking, such as counting data; investigations of the evasion behavior of whales, if it occurs; and monitoring whale populations to assess the long-term impacts of collisions, are needed.

Like several large whale populations, the South Atlantic humpback whale has been recovering after decades of whaling and is expected to reach its pre-exploitation abundance within the next decade (ZERBINI *et al.*, 2019). Without proper management, the number of collisions between humpback whales and vessels will tend to increase in the next few years and could slow the recovery of this population. According to the Ship Strike Strategic Plan by IWC (INTERNATIONAL WHALING COMMISSION, 2022), the Southwest Atlantic is a high risk ship strike area for humpback whales and practical options based on risk analysis must be considered. Our ship strike risk analysis based on whale tracking and diving information provided an effective approach for identifying regions of conservation concern. The results presented here showed that the Abrolhos Bank is the area with highest probabilities of whales interacting with vessels in Brazil, and is also where there is an increased risk of a whale suffering a lethal injury during a collision. Among the vessel fleets discussed, cargo ships and tankers proved to be a key part of building possible solutions of this conflict, especially in the areas outside Abrolhos Bank, such as the coasts of states of Rio de Janeiro and Espírito Santo. The information presented here, could be used by Governmental and International organizations to design strategies such as: to set future conservation goals, delimit safe corridors for humpback whales or even delimit speed restriction zones for trafficking vessels.

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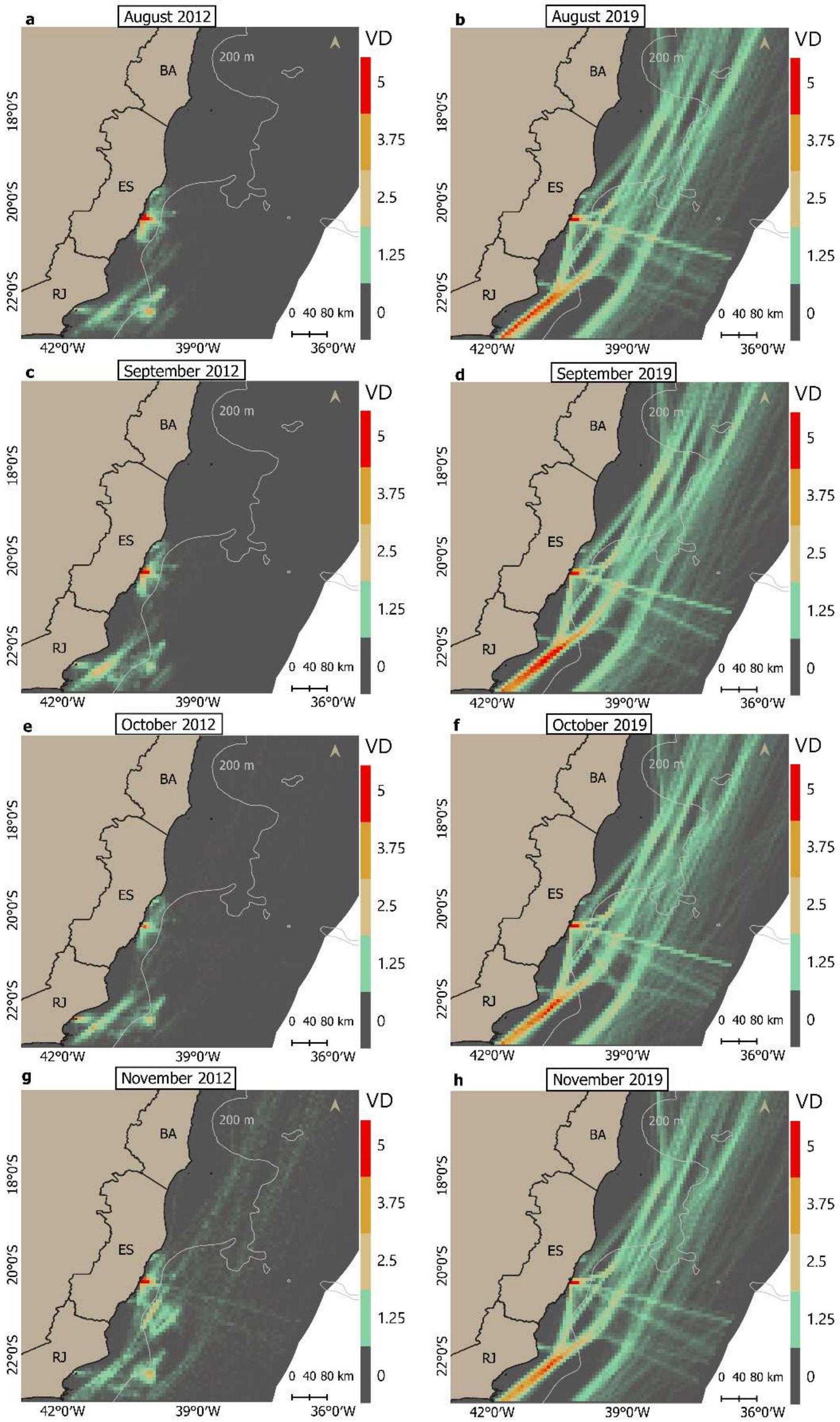
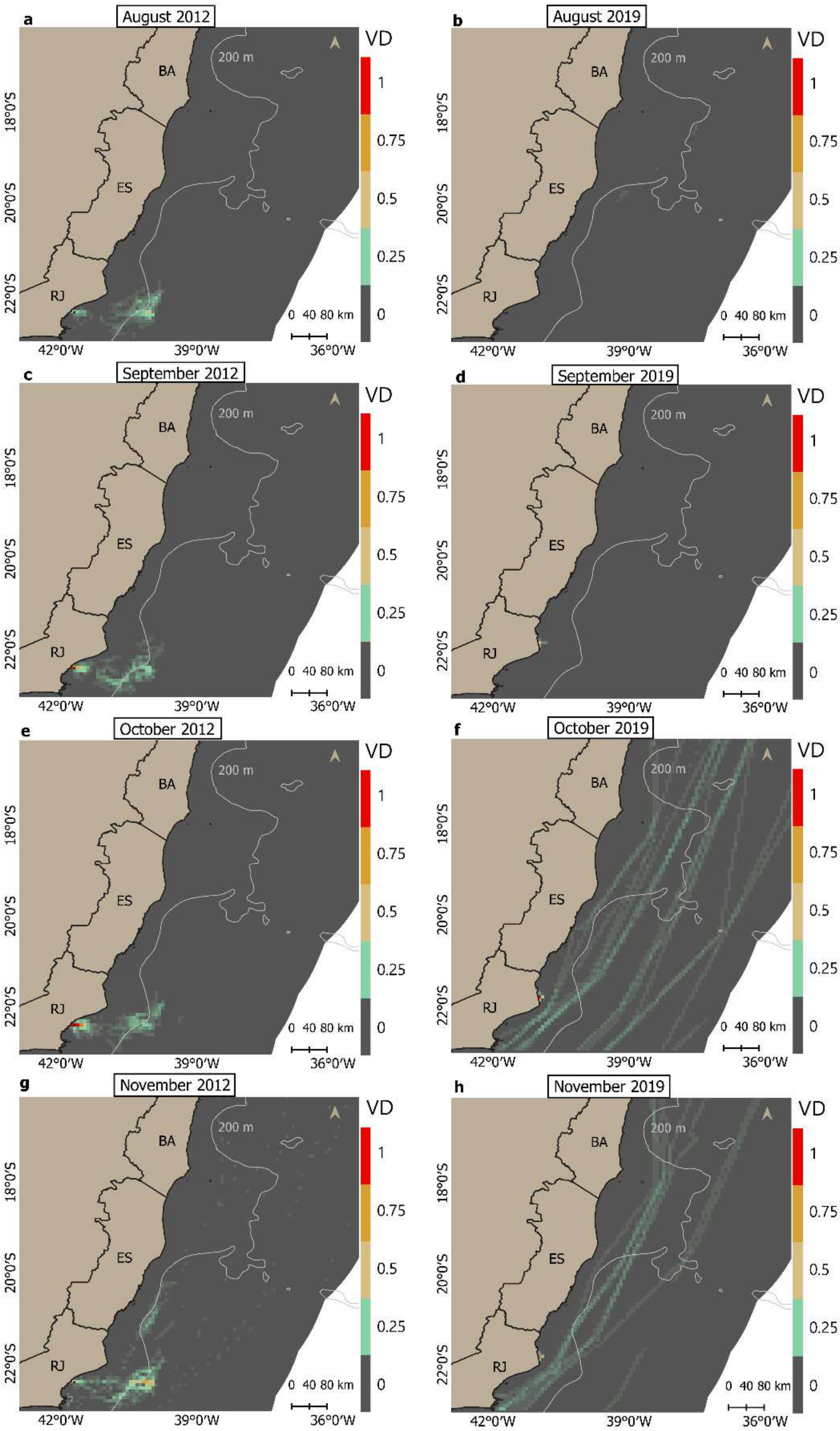
APÊNDICE A - Additional maps referring to data analysis steps

Figure A1. Monthly vessel density (VD) for cargo fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



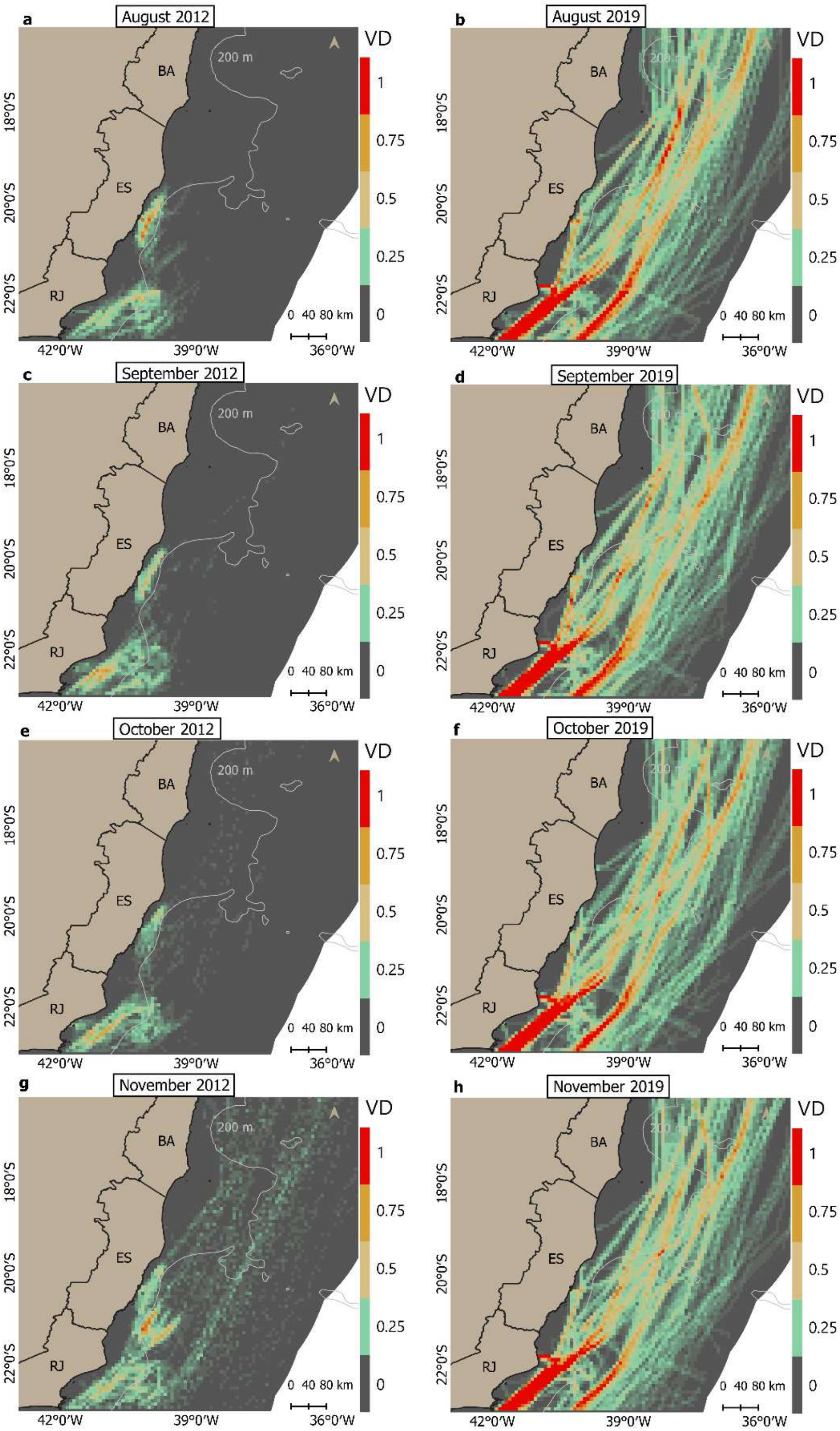
Source: Elaborated by the author (2023).

Figure A2. Monthly vessel density (VD) for passenger fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



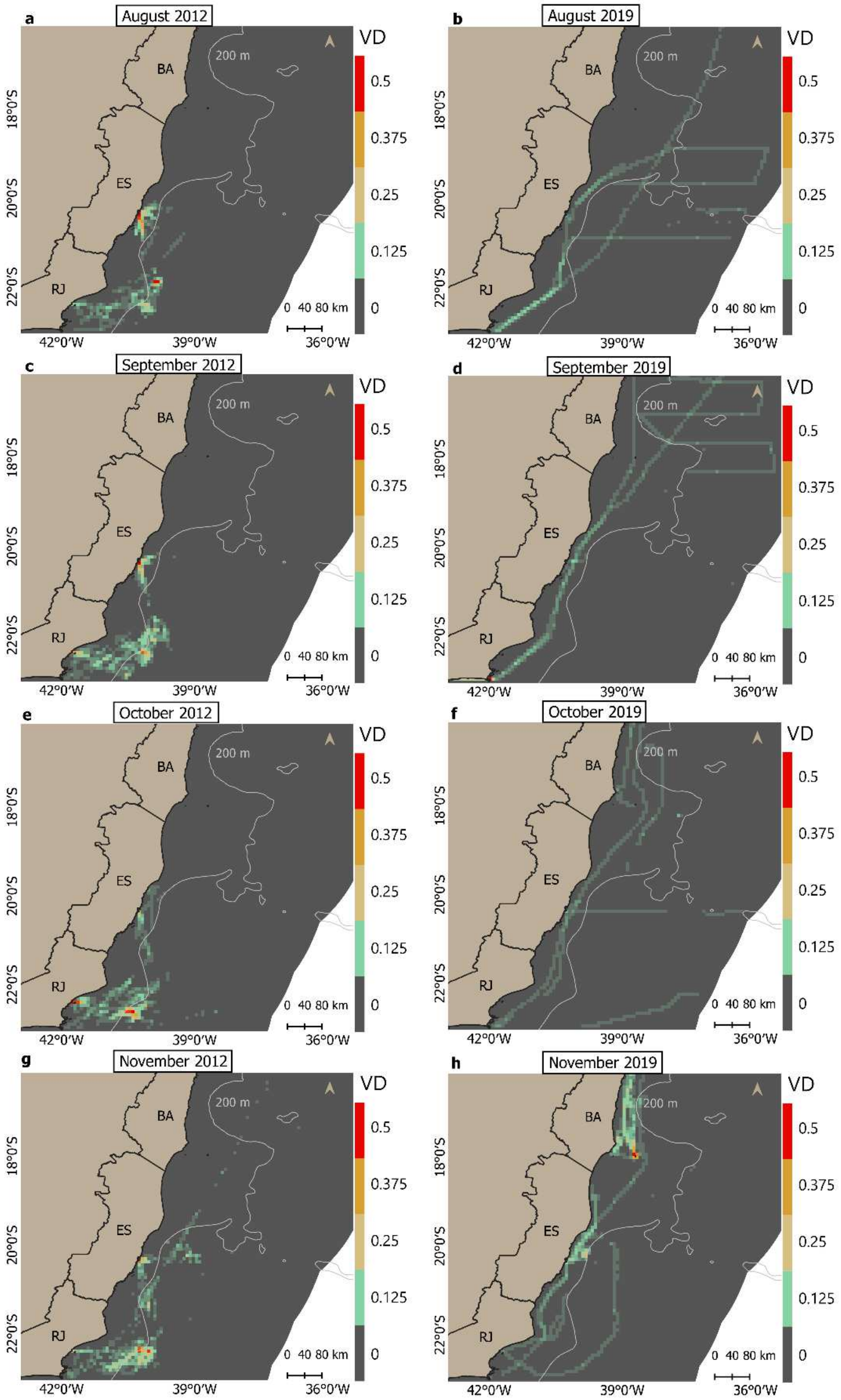
Source: Elaborated by the author (2023).

Figure A3. Monthly vessel density (VD) for tanker fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



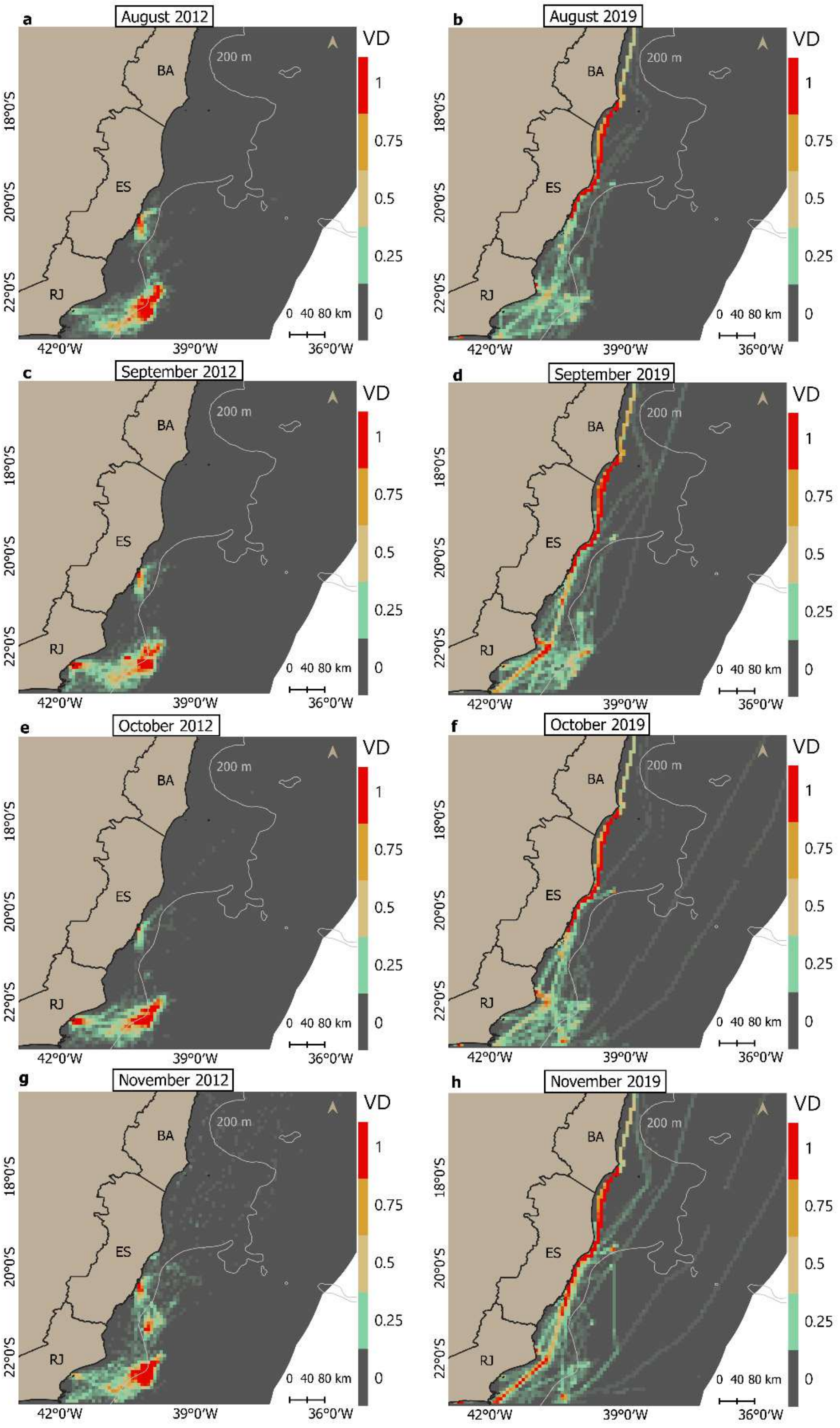
Source: Elaborated by the author (2023).

Figure A4. Monthly vessel density (VD) for military fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



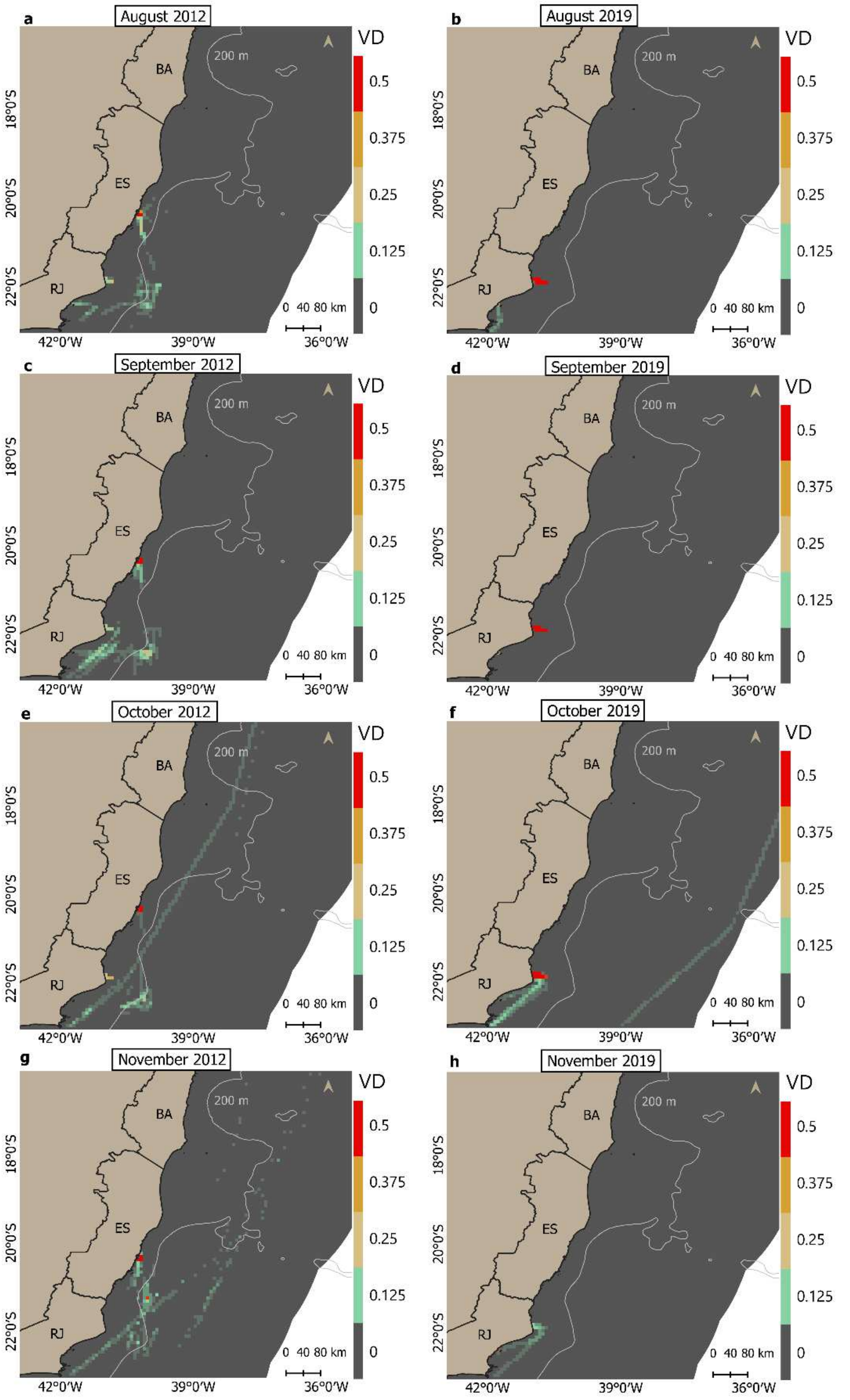
Source: Elaborated by the author (2023).

Figure A5. Monthly vessel density (VD) for tug fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



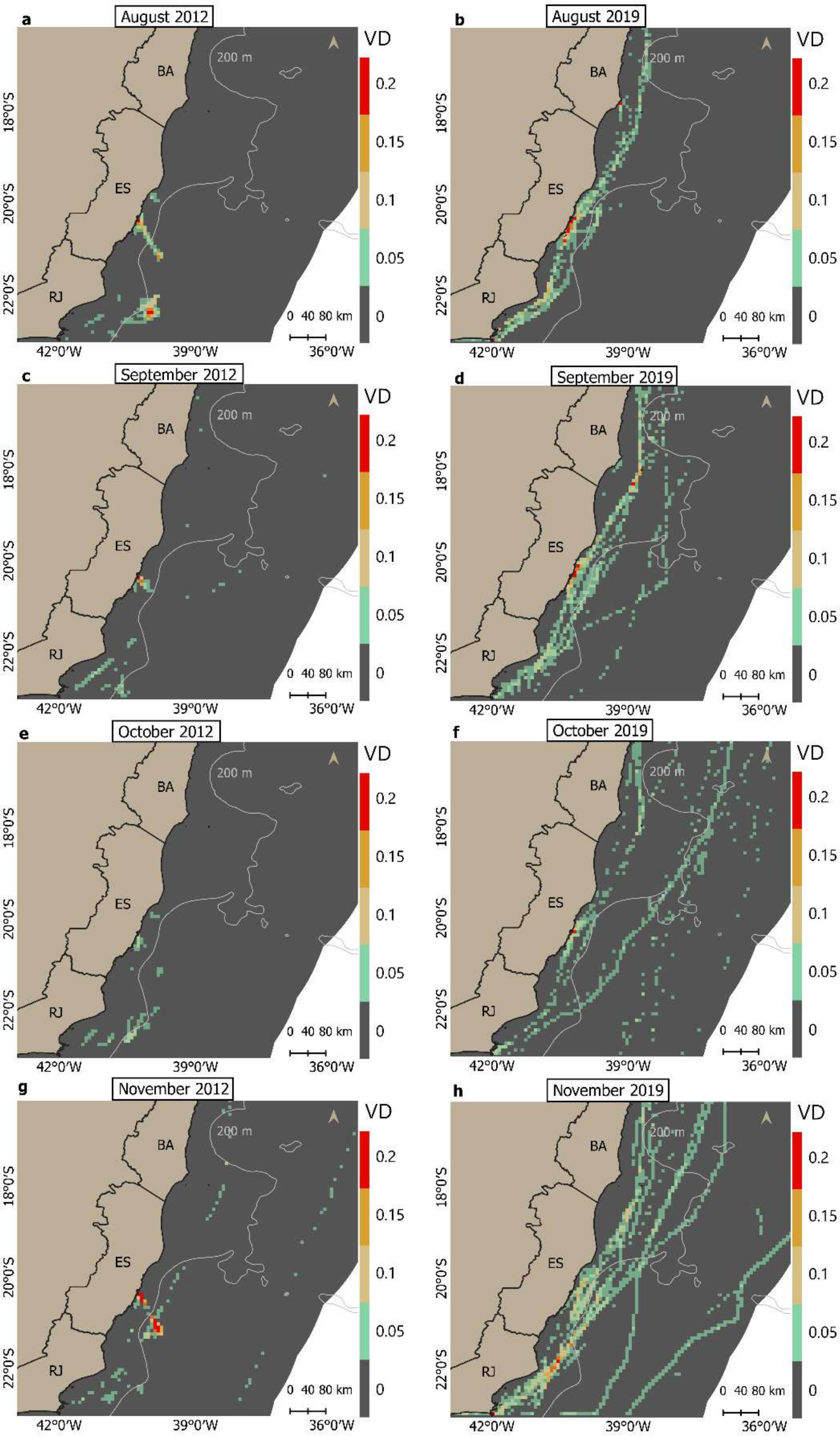
Source: Elaborated by the author (2023).

Figure A6. Monthly vessel density (VD) for dredger fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



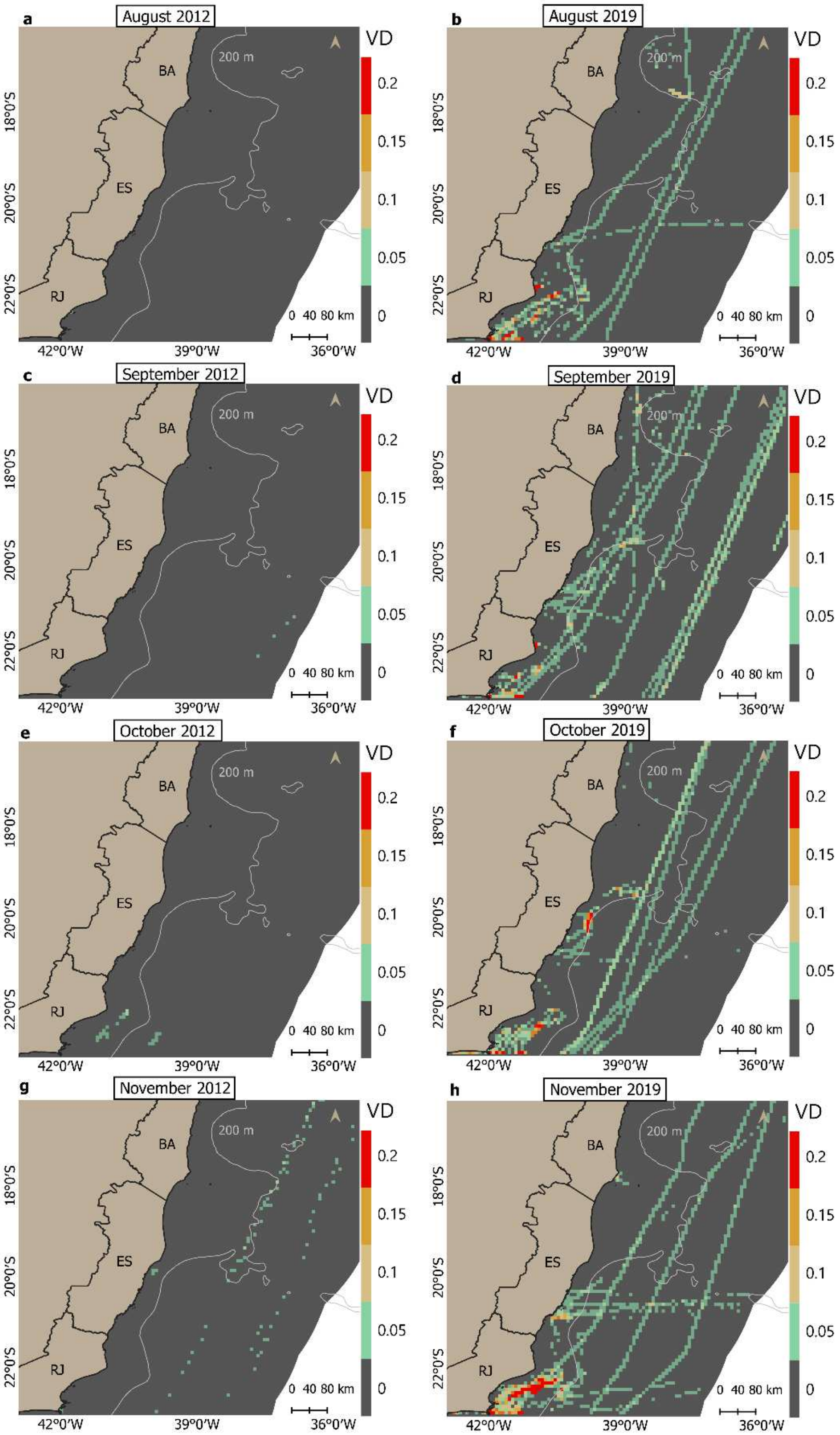
Source: Elaborated by the author (2023).

Figure A7. Monthly vessel density (VD) for sailing fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



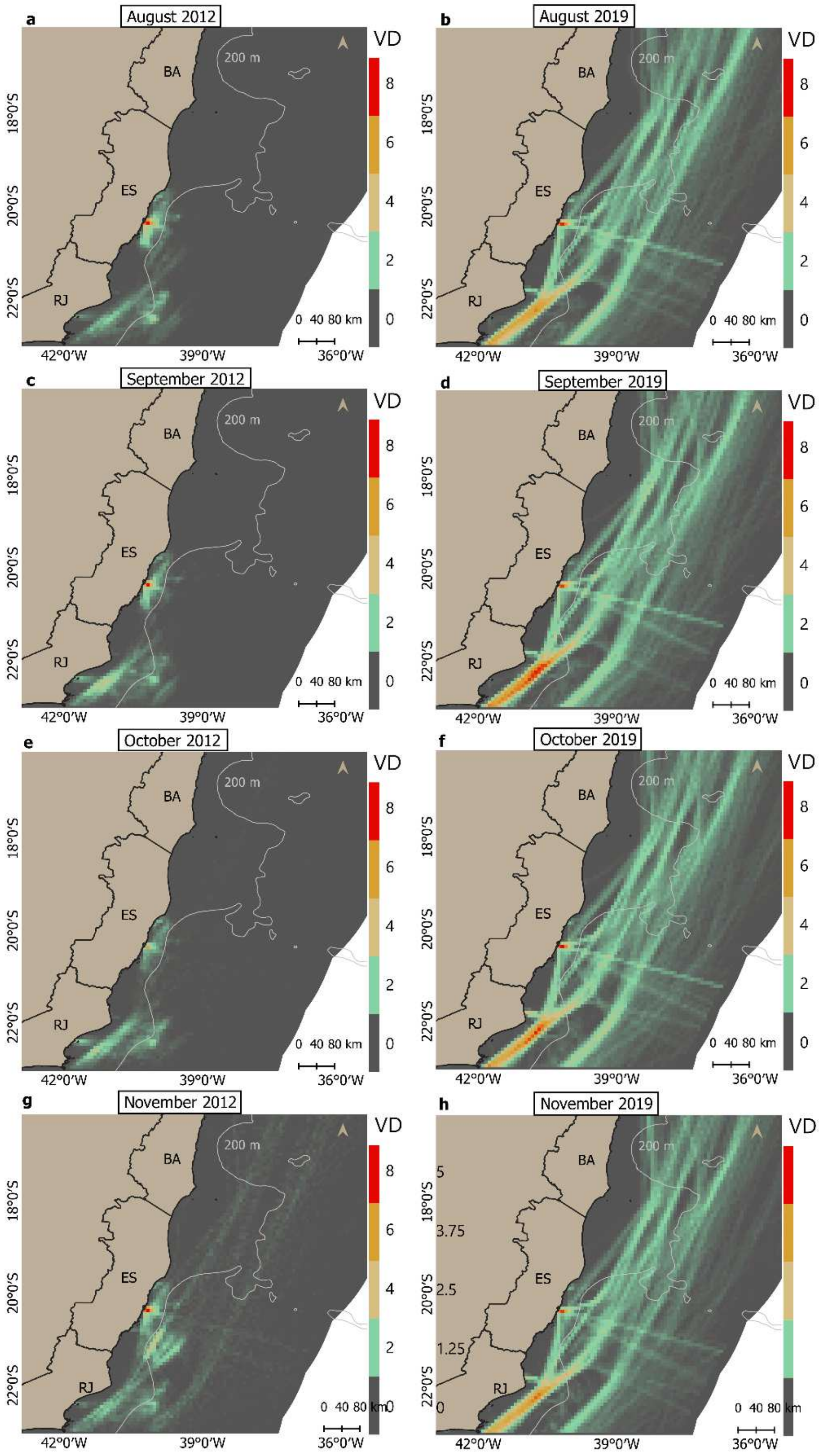
Source: Elaborated by the author (2023).

Figure A8. Monthly vessel density (VD) for fishing fleet. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



Source: Elaborated by the author (2023).

Figure A9. Monthly vessel density (VD) for vessels >80 m in length. VD is the average number of vessels crossing grid cells of 0.072 × 0.072º (~8x8 km) daily, depicted to each month between August-November 2012 and 2019.



a August 2012

b August 2019

c September 2012

d September 2019

e October 2012

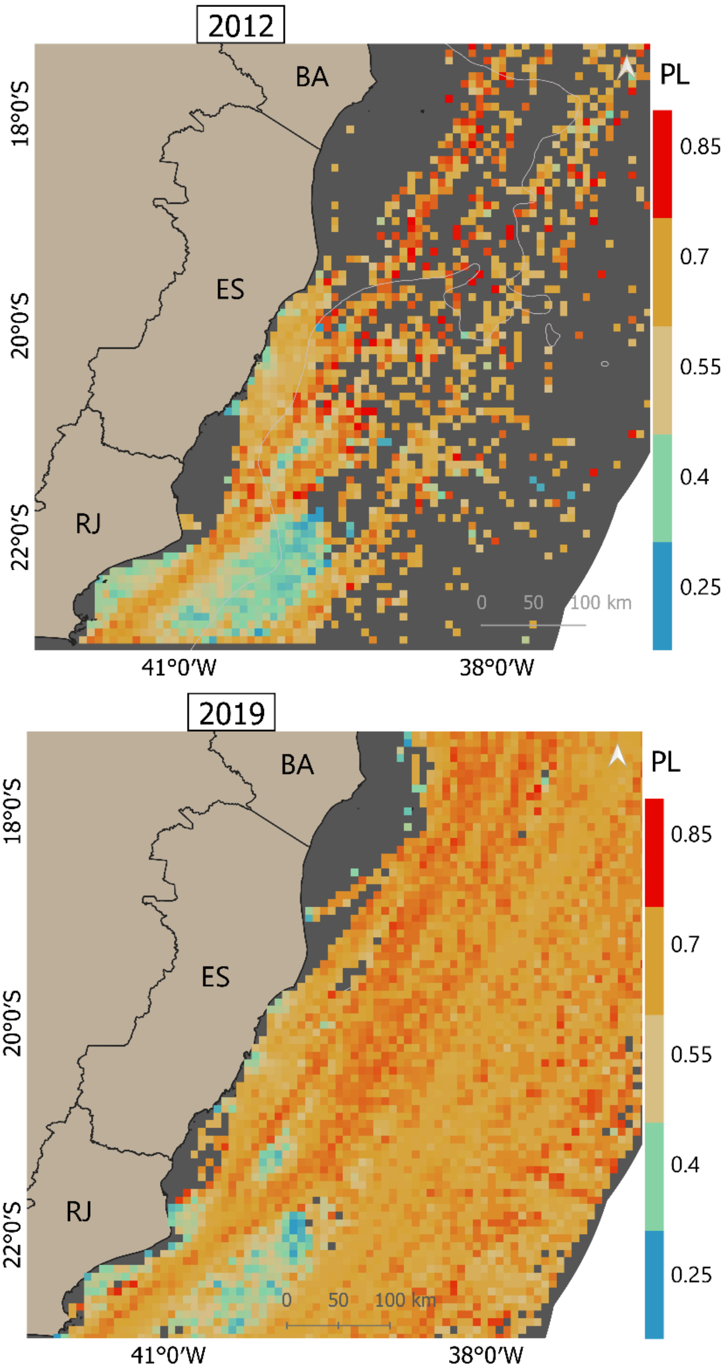
f October 2019

g November 2012

h November 2019

Source: Elaborated by the author (2023).

Figure A10. Probability of a whale suffering a lethal injury during an encounter (PL) in 0.072 x 0.072º (~8x8 km) grid cells in the study area for 2012 and 2019. This information is depicted for vessels >80 m in length.



Source: Elaborated by the author (2023).