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A spatially explicit cetacean bycatch risk assessment for Chilean fisheries

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INTRODUCTION

In many developing countries, fisheries bycatch of marine mammals is poorly monitored or regulated. This poses a particular challenge for countries with economically important fisheries that export to countries with stricter bycatch regulations, like the United States and the European Union (Johnson et al. 2017). Data gaps in fishing effort, bycatch rates, and the fate of animals post-capture, as well as in abundance and trends of affected populations are key obstacles that impede the ability to characterize the risk of fisheries bycatch, including loss or damage to fishing gear and constrain management action. With the new U.S. Marine Mammal Protection Act Rule (MMPA Rule) being imposed on many developing countries, international collaborations to address these data gaps is critical. One of the drivers for developing the open-source Bycatch Risk Assessment (ByRA) toolbox was to assist in addressing these gaps, reducing bycatch, and inform sustainable fisheries management (Hines et al. 2020; Verutes et al. 2020). Though there has been a lot of recent work by Chilean scientists to fill critical information gaps on distribution and abundance of many cetaceans, there is still a lack of data on the species and regions that are the most affected by fisheries bycatch. Additionally, this work assists in identifying a baseline of bycatch risk that can be used to assess the effectiveness of recent and future bycatch mitigation measures in Chile. In the same sense, although there are some reports of direct interactions between cetaceans and industrial and artisanal fisheries (Goodall et al. 1988, Reyes y Oporto 1994, Oporto y Brieva 1994, Pérez-Alvarez et al 2007, Bravo et al 2010, González-But and

Sepúlveda 2016), their impact on local populations has not been further evaluated (González-But and Sepúlveda 2016). Despite the ever-present need for more data, there is an equally strong need to make better use of existing data to develop bycatch risk assessments for marine mammals of conservation concern and use risk data to generate estimates of population-level impacts and inform management strategies (Stelzenmùller et al 2015). Risk assessments identify, analyze, and evaluate the likelihood or probability of an event, and the consequences of that event (Gibbs & Browman 2015).

For this project, funded in 2020 by Lenfest Oceans (https://www.lenfestocean.org/en/news-and-publications/fact-sheet/new-research-to-assess-marine-mammal-bycatch-risk-in-chile), we assembled a team of scientists from Chile and abroad to consult with Chilean government fisheries agencies and local scientists to manage and analyze existing data, and generate methods for gathering new data that characterize the spatial and seasonal distribution and abundance of fishing boats, gear, and marine mammals to assess marine mammal bycatch risk. We are currently completing our research that includes 15 fisheries and 14 marine mammal species with varying amounts of data. For this report, we show our results for two of the major artisanal fisheries in Chile, the swordfish gillnet fishery, and the northern anchovy purse seine. In Chile, artisanal vessels are under 18m in length. Gradually, artisanal catches have been increasing and starting to import their catch (van der Meer et al 2015).

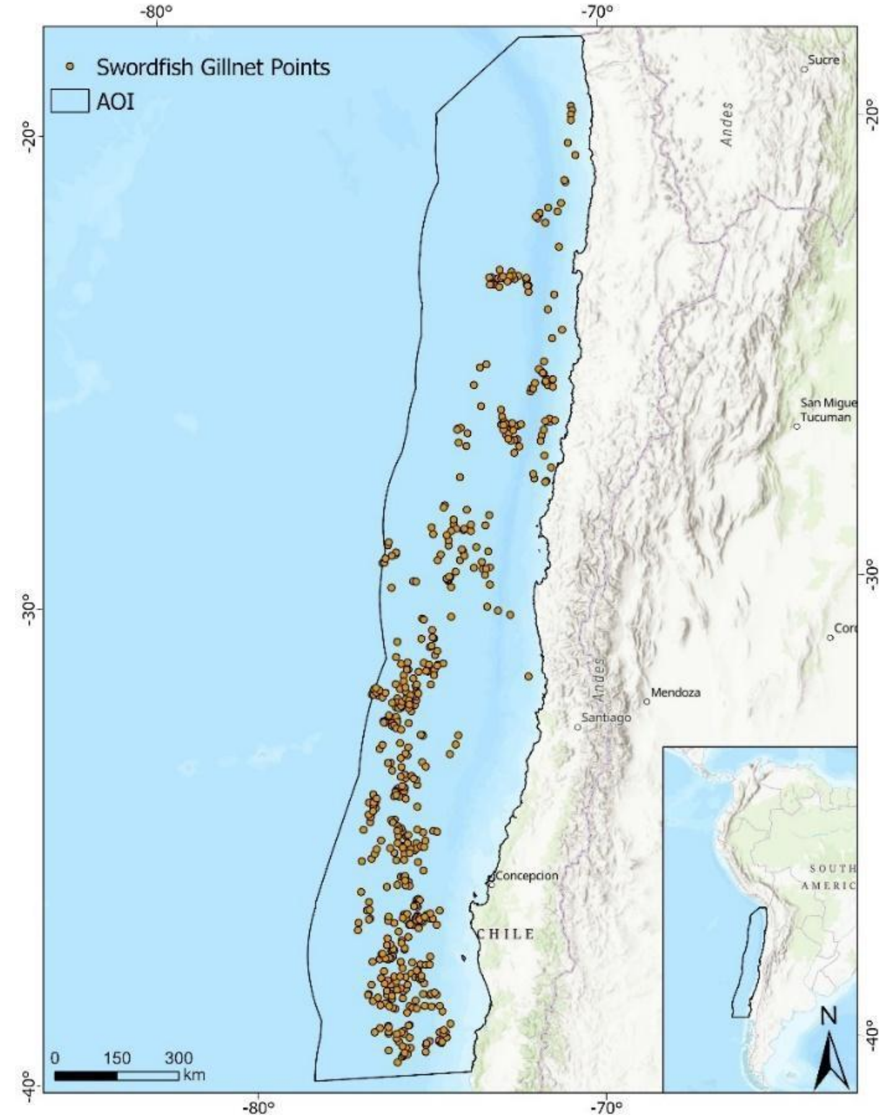
METHODS

Areas of Interest

Areas of interest were determined based on fishery tracking data and management boundaries. The data for both fisheries were provided by the Fisheries Development Institute (IFOP; Instituto de Fomento Pesquero) in Chile.

Artisanal Swordfish Gillnet Fishery

Data for the artisanal swordfish gillnet fishery, or the swordfish fishery, was provided by IFOP for the years 2015-2019. The swordfish fishery operates March through July and extends to the western boundary of Chile's Exclusive Economic Zone (EEZ), south to 40.8°S (Figure 1). In 2021, Chile enacted a law requiring the use of pingers in an effort to reduce incidental bycatch of marine mammals. A kernel density of the gillnet points was generated using a 3 km cell size and 10 km search radius based on expert consultation with IFOP scientists that consider fishery specific characteristics, like typical boat clustering and distance. The resulting kernel density estimation was reclassified to integer values 1-3 using quantile classification in ArcGIS Pro (v3.0.3) to meet the spatial exposure criterion in the Bycatch Risk Assessment Tool (ByRA).


Swordfish Gillnet Points
AOI
-80°
-70°
-20°
-30°
-40°
Sucre
Andes
San Miguel
Tucuman
Mendoza
Santiago
Concepcion
CHILE
SOUTH
AMERIC
N
0 150 300
km

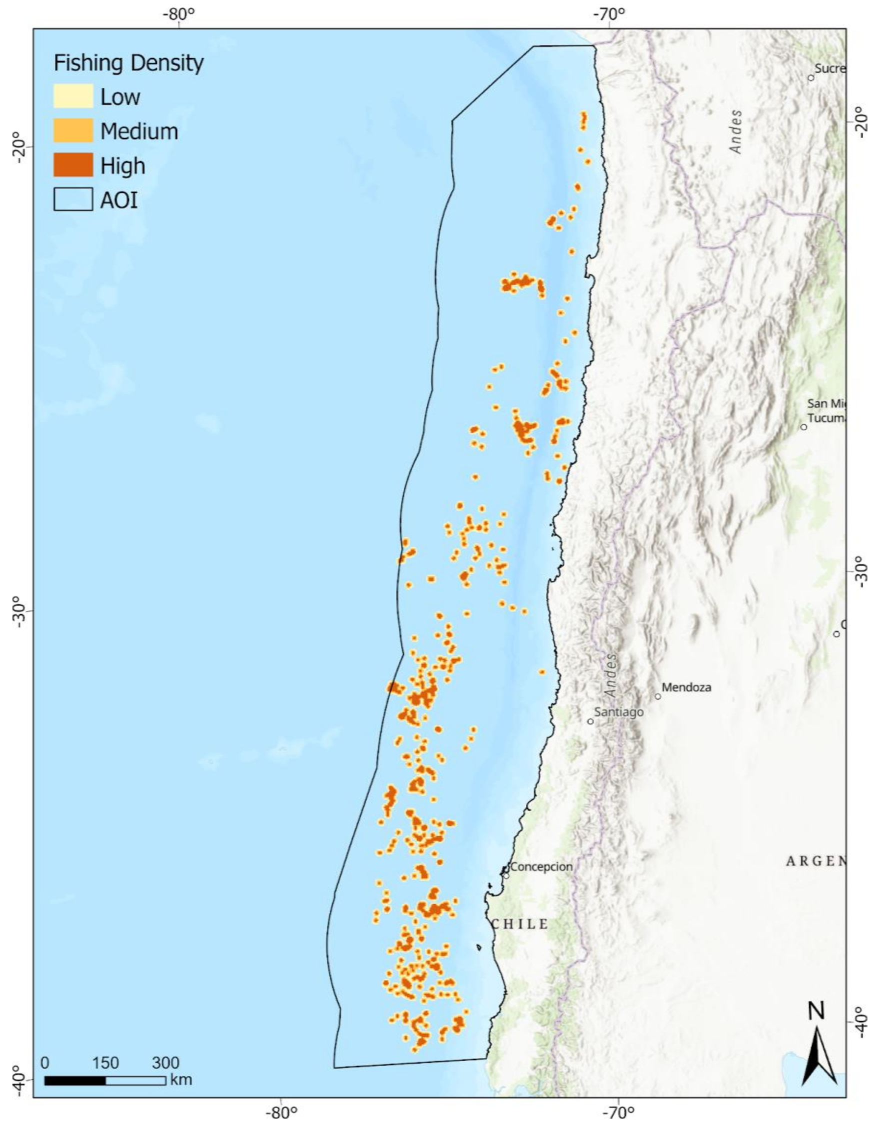
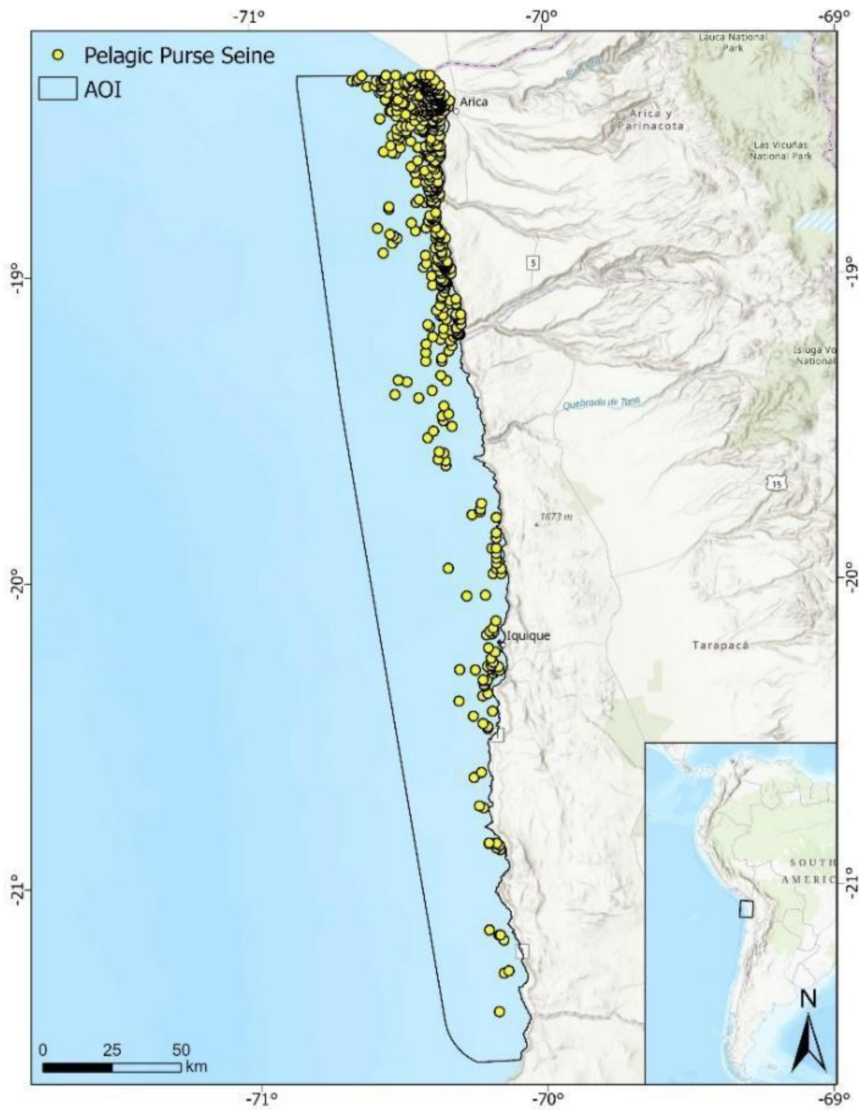


Figure 1. Artisanal swordfish gillnet fishery area of interest and net haul points [top]. Kernel density estimated swordfish fishery distribution reclassified with quantiles [bottom].

Northern Anchovy Purse Seine

The northern artisanal pelagic purse seine anchovy fishery, or the anchovy fishery, operates from the Chilean border with Peru to 21.5°S during all months except January and September (Figure 2). The data provided by IFOP included fishing haul locations that occurred between 2017 – 2020. The area of interest was generated in ArcGIS Pro (ESRI 2022. ArcGIS Pro 3.0.3, Redlands, CA: Environmental Systems Research Institute) using a convex hull of all fishing points buffered by 20 km to include all points and allow space when calculating the kernel density estimation of fishing points. The edges of the area of interest were aligned with the coastline and northern boundary of the EEZ. A kernel density of fishing points was generated using a 3 km cell size and 5 km search radius based on expert consultation with IFOP scientists that consider fishery specific characteristics (Figure 2).



Pelagic Purse Seine
AOI
Arica
Arica y Parinacota
Las Vicuñas National Park
Lauca National Park
Quebrada de Tana
1673 m
Iquique
Tarapacá
SOUTH AMERICA
N
0
25
50
km
-71°
-70°
-69°
-19°
-20°
-21°

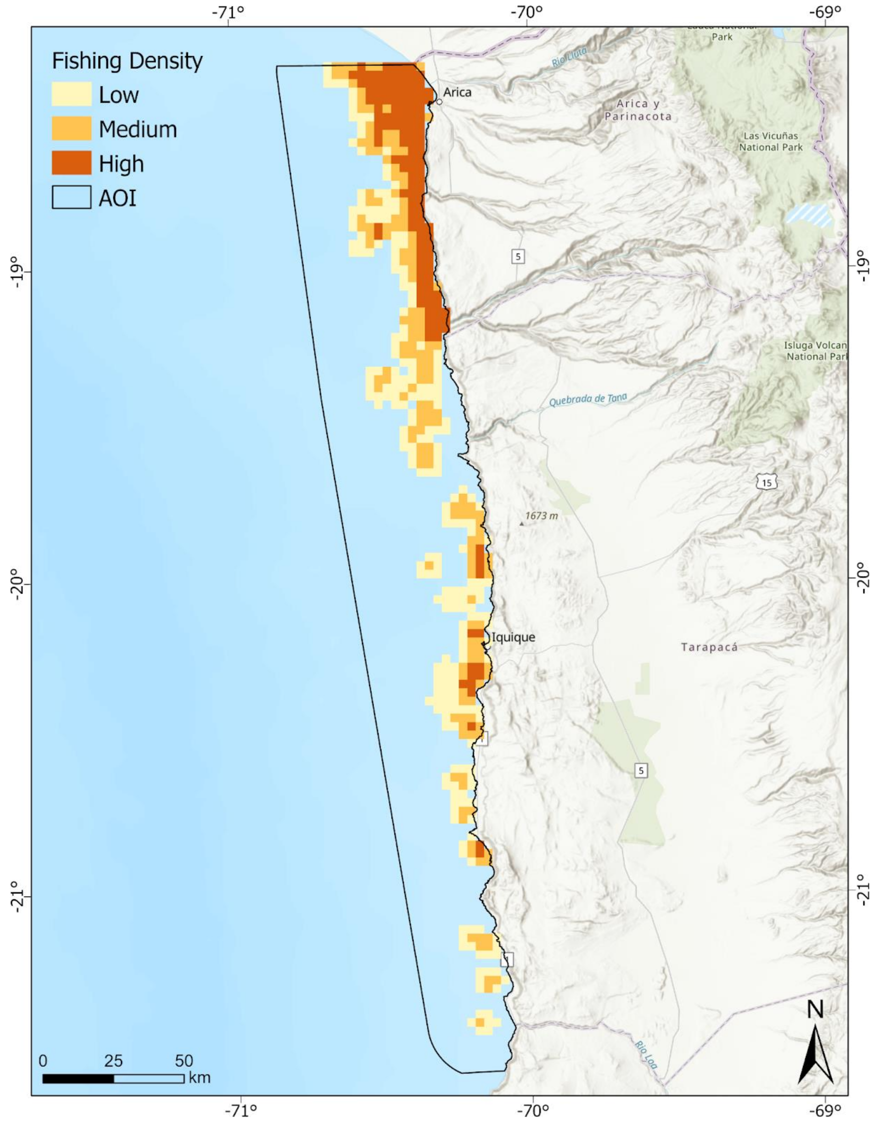


Figure 2. Artisanal pelagic purse seine anchovy fishery and net haul points [top]. Kernel density estimated anchovy fishery distribution reclassified with quantiles [bottom].

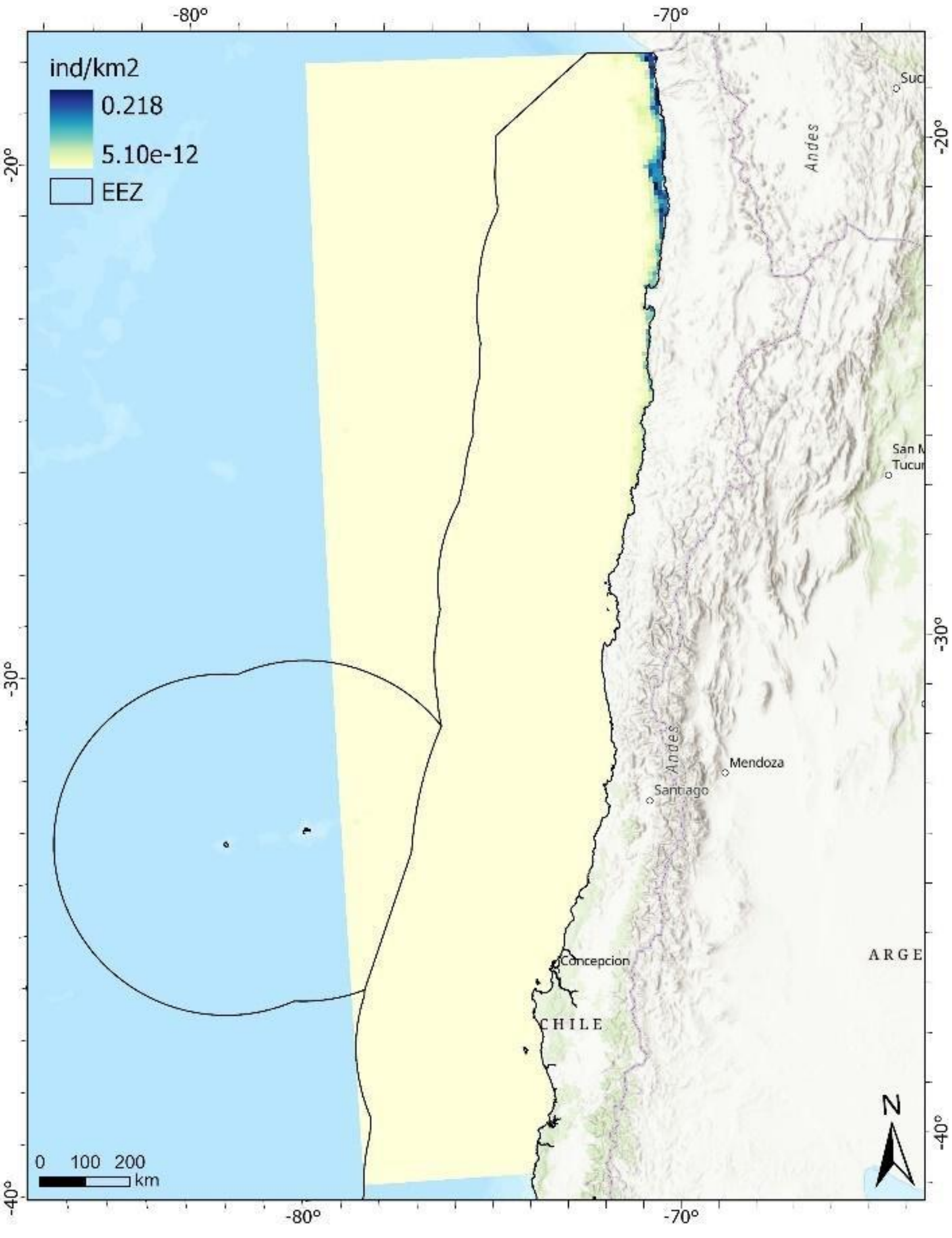
Marine mammal distributions

Bycatch risk for six cetaceans: five odontocetes and one mysticete, were analyzed across both fisheries. Burmeister's porpoise (*Phocoena spinipinnis*), dusky dolphin (*Lagenorhynchus obscurus*), common dolphin (*Delphinus spp.*), and bottlenose dolphin (*Tursiops spp.*) were analyzed with the anchovy fishery. The swordfish fishery was also assessed with Burmeister's porpoise, dusky dolphin, and common dolphin, in addition to pilot *(Globicephala spp.)* and fin whales (*Balaenoptera physalus*). The two pilot whale species (*Globicephala macrorhynchus* and *Globicephala melas*), were combined to species level as we could not confirm subspecies identification. Two primary data types and distribution estimation methods were used for species distribution modeling, including systematic versus opportunistic survey data and statistical models versus kernel density estimations, which could then be classified into higher and lower certainty data, respectively.

High certainty data

For the fin whale, common dolphin, and dusky dolphin distributions, Binomial N-Mixture Models (BNMM) from Bedriñana-Romano et al. 2022 were extrapolated to the larger swordfish fishery area of interest (Bedriñana-Romano et al. 2022). These predicted distributions were considered high certainty because they were generated using line transect survey data collected systematically between 2016 - 2021, which is a similar timeframe as the fishery distribution data (2015-2019). Each distribution was reclassified from individuals per square kilometer to high (3), medium (2), and low (1) likelihood of presence, using either quantiles or natural breaks (Jenks) in ArcGIS Pro (v3.0.3) to meet the requirements for ByRA's spatial exposure criteria inputs (Jenks 1967).

Dusky dolphins are mainly distributed in coastal waters on the continental shelf in the north where the anchovy fishery is also concentrated (Figure 3). The continuous predicted distribution raster was reclassified using natural breaks (Table 1). Common dolphins are less restricted to coastal waters, with the model exhibiting higher concentrations in nearshore and offshore waters in the north (Figure 4). The continuous distribution raster was reclassified using quantiles (Table 2). Fin whale distribution is higher in coastal areas with lower densities occurring in offshore waters. The continuous distribution raster was reclassified using natural breaks (Table 3) (Figure 5). Each reclassified distribution was clipped to the respective area of interest for each bycatch risk assessment.



ind/km2
0.218
5.10e-12
EEZ
-80°
-70°
-20°
-30°
-40°
Andes
Mendoza
Santiago
Concepcion
CHILE
ARGE
0 100 200
km
N

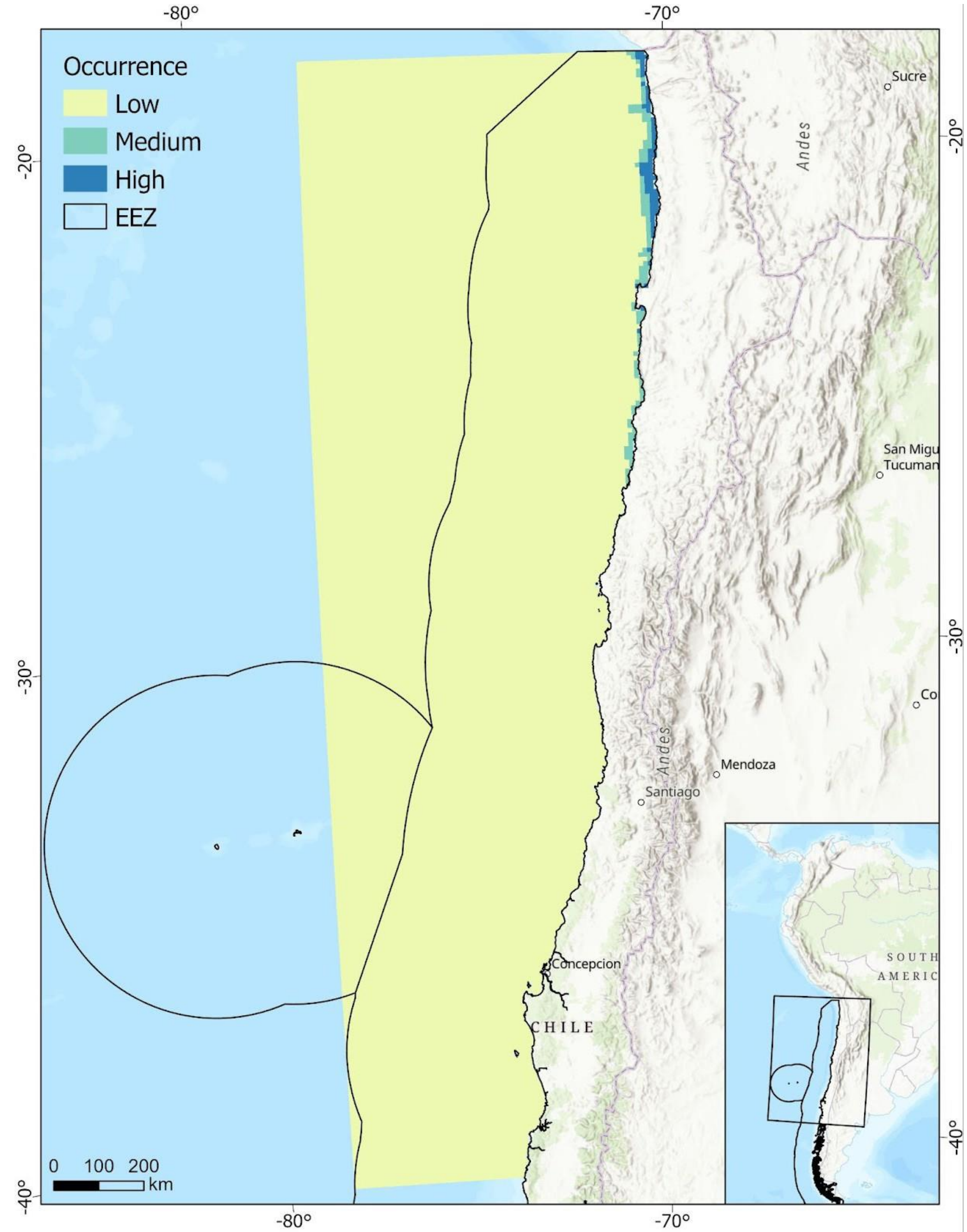
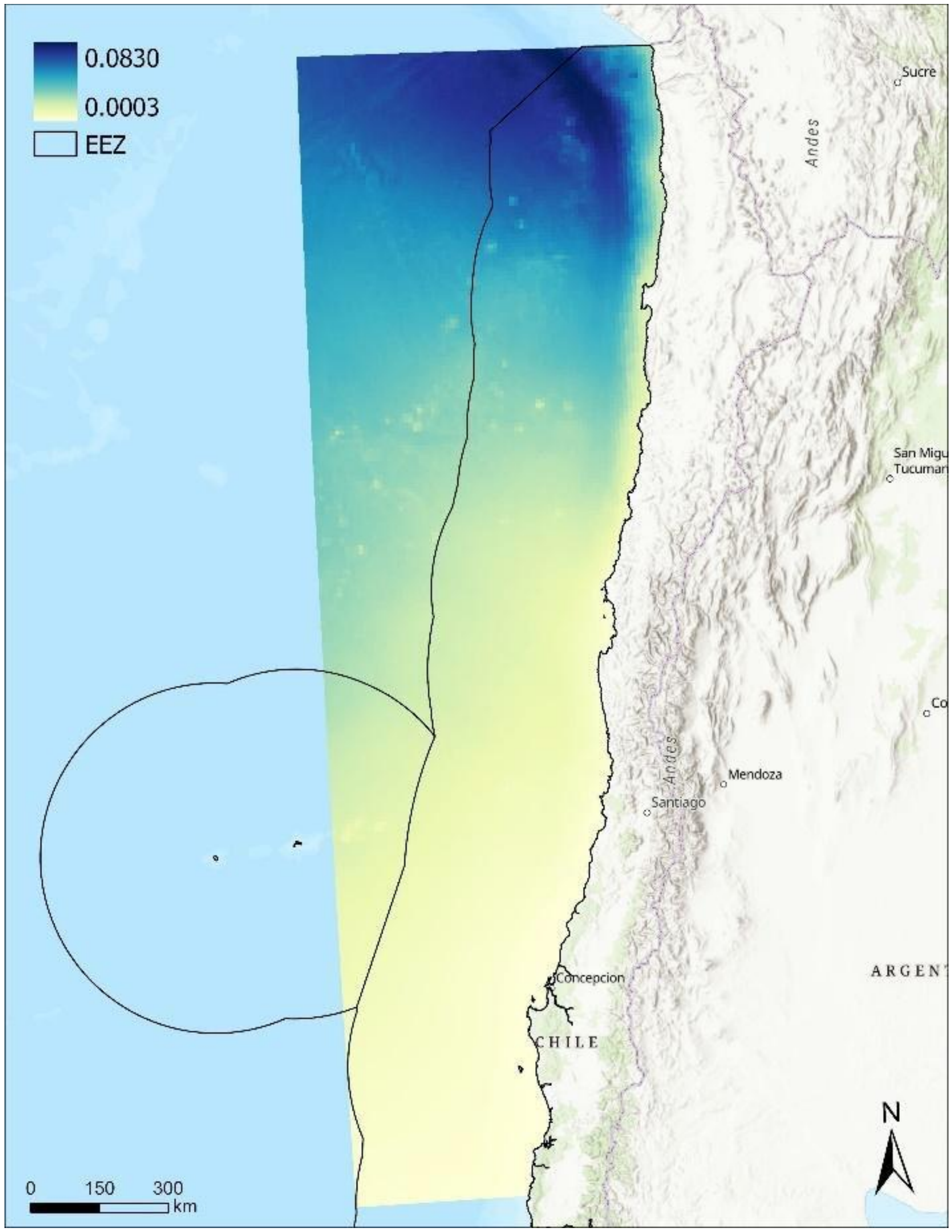


Figure 3. Binomial N-Mixture Model predicted dusky dolphin distribution (individuals per square kilometer) [top]. Natural breaks reclassified dusky dolphin distribution [bottom].

Table 1. Binomial N-Mixture Model predicted dusky dolphin distribution Jenks natural breaks reclassification values.

Start	End	Reclass value
0.000001	0.026511	1
0.026511	0.097493	2
0.097493	0.218077	3


0.0830
0.0003
EEZ
Sucre
Andes
San Migu
Tucuman
Co
Mendoza
Andes
Santiago
Concepcion
CHILE
ARGENT
N
0
150
300
km

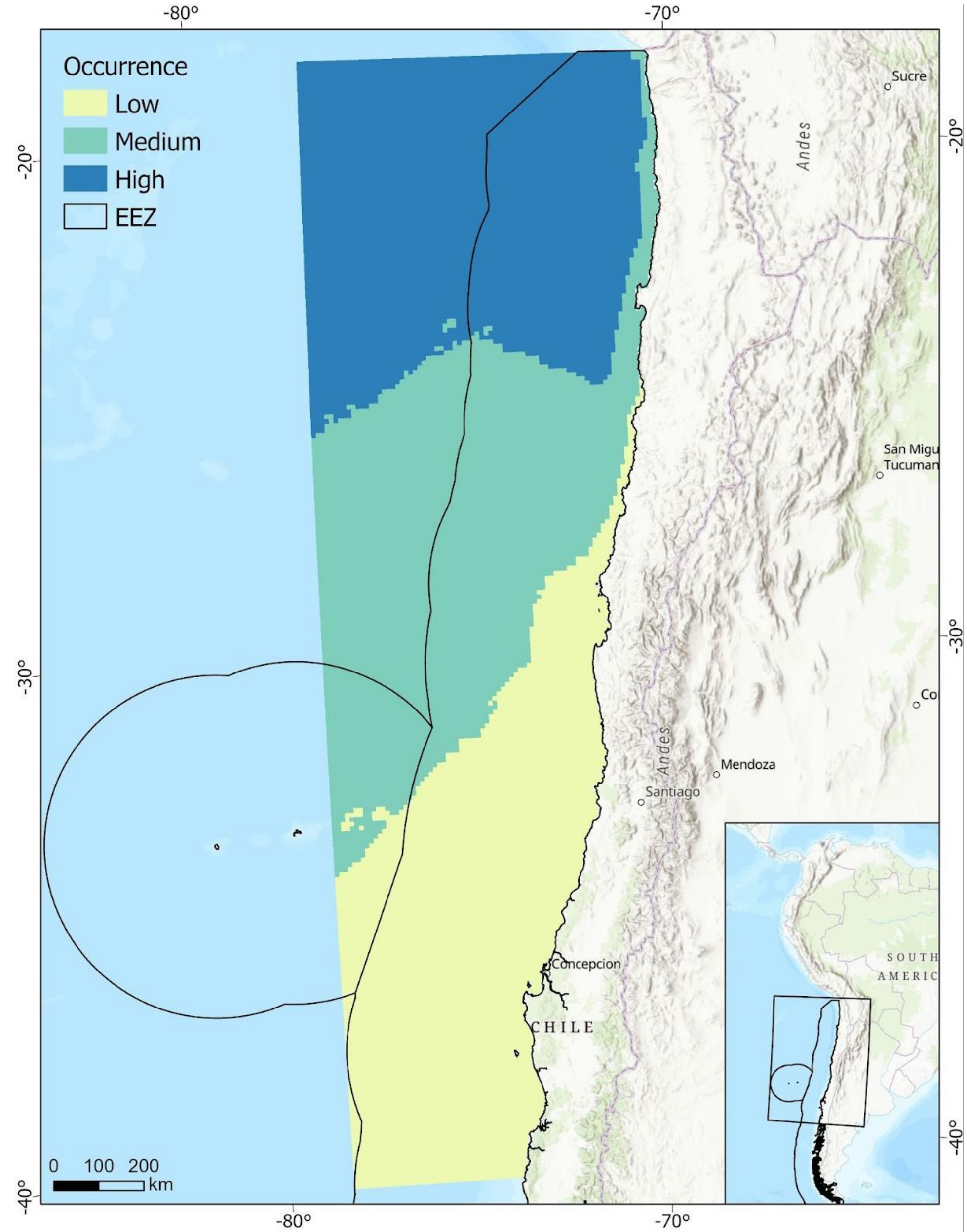


Figure 4. Binomial N-Mixture Model predicted common dolphin distribution (individuals per square kilometer) [top]. Quantiles reclassified common dolphin distribution (1 – low likelihood of presence; 2 – medium likelihood of presence; 3 – high likelihood of presence) [bottom].

Table 2. Binomial N-Mixture Model predicted common dolphin distribution quantile reclassification values.

Start	End	Reclass value
0.000285	0.012615	1
0.012615	0.035004	2
0.035004	0.083025	3


0.0439
0.0004
EEZ
Sucre
Andes
San Migu
Tucuman
Co
Andes
Mendoza
Santiago
Concepcion
CHILE
ARGENT
N
0
150
300
km

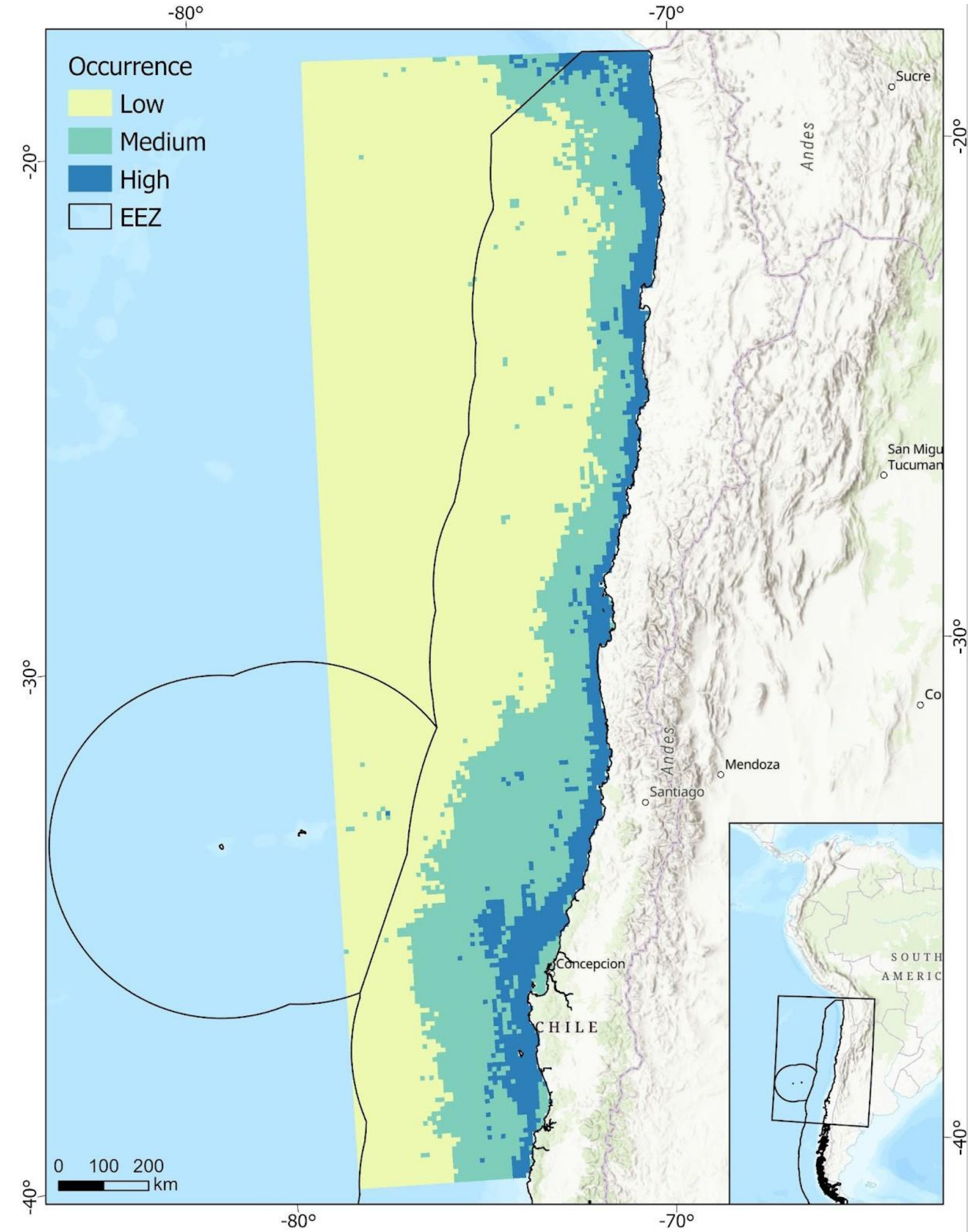


Figure 5. Binomial N-Mixture Model predicted fin whale distribution (individuals per square kilometer) [top]. Natural breaks reclassified fin whale distribution (1 – low likelihood of presence; 2 – medium likelihood of presence; 3 – high likelihood of presence) [bottom].

Table 3. Binomial N-Mixture Model predicted fin whale distribution quantile reclassification values.

Start	End	Reclass value
0.00035	0.002742	1
0.002742	0.006499	2
0.006499	0.043904	3

Low certainty data

When systematic survey data were not available, opportunistic data or buffer distances from the coast were used to generate distribution estimations of marine mammals of interest based on expert opinion of at-risk species for each fishery. All distribution methods were determined through literature review and consultation with Chilean and international marine mammal scientists.

Pilot whale

Opportunistic sightings of pilot whales were collated from IFOP, the Global Biodiversity Information Facility (GBIF), the Ocean Biodiversity Information System (OBIS), and the literature (Aguayo-Lobo et al. 1998, Buscaglia et al. 2020). Outliers and points on land that were associated with strandings were removed (n = 4). Points that were located on land but not associated with strandings were moved directly offshore, either in accordance with the distance from shore described in the sighting metadata or within 2 km from shore. This resulted in a total of 69 sightings that were observed between 1958 and 2019 in all months except January. Most sightings fall between latitude 18.8 deg S and 40.0 deg S.

The distribution estimation combines all sightings of long-finned, short-finned, and unspecified pilot whales (Figure 6). A kernel density estimation of the cleaned opportunistic sightings was created using a cell size of 3km and a search radius of 150km. The search radius was calculated using a spatial variant of Silverman's Rule of Thumb (Silverman 1986). This is the default method in ArcGIS Pro (v3.0.3). To meet ByRA spatial criteria requirements, the raw point density values were reclassified into classes 1-3 using quantiles, where 1 is low relative sighting density, 2 is medium, and 3 is high. Values of 0 were assigned to 'nodata'.

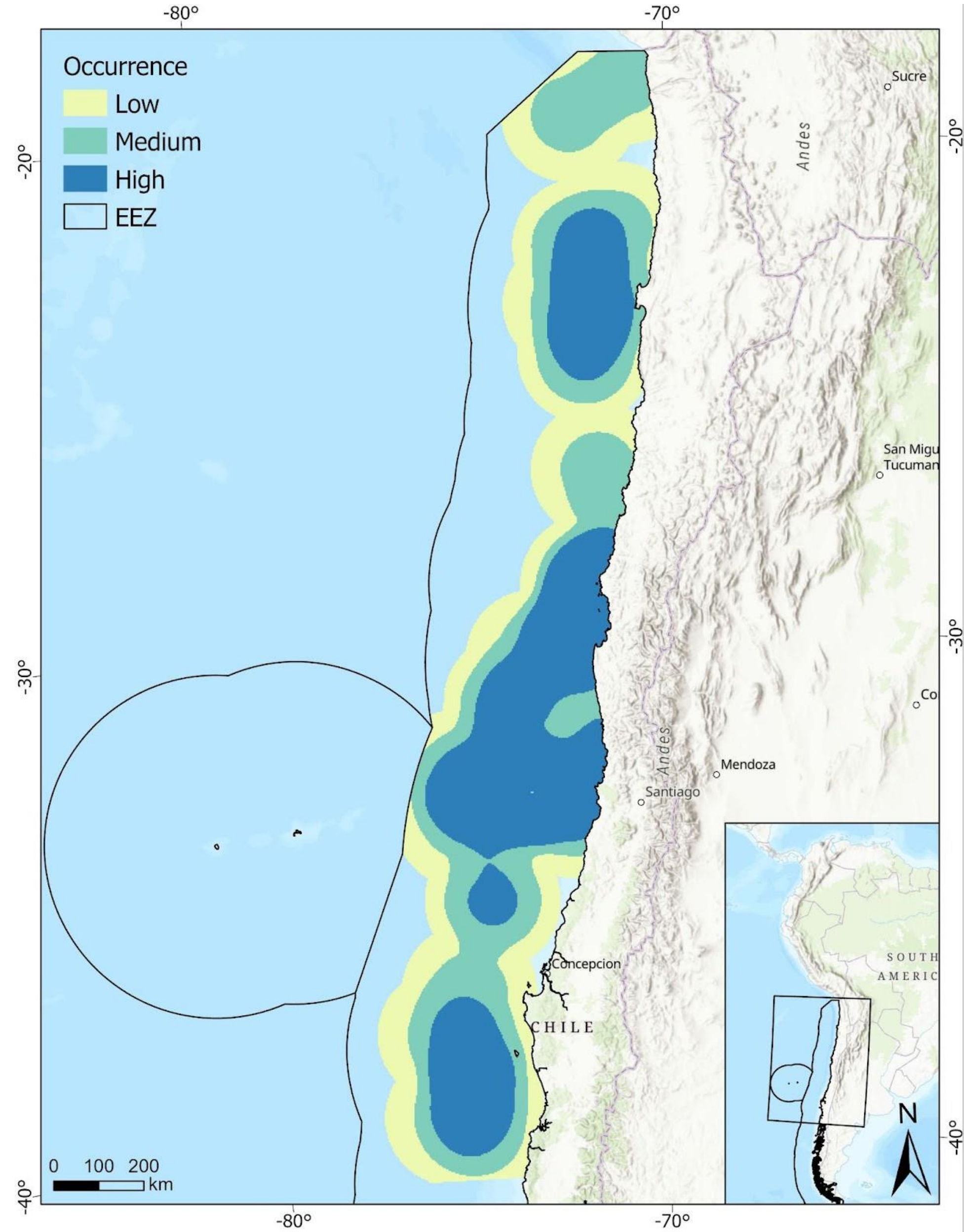


Figure 6. Quantile reclassified kernel density estimation of opportunistic pilot whale sightings.

Burmeister's porpoise

Since sightings data for this species were sparse, and literature suggests that the distribution is continuous along the coast of Chile, a coastal distribution was generated using multiple-ring buffers of 10, 20, and 50 kilometers from the shore (Felix et al. 2018 and project scientists). A rating of 3 was assigned to areas within 10km, designating high likelihood of presence, 2 for medium areas within 10-20 km, and 1 for lower likelihood of presence areas between 20-50 km. These buffer distances were determined through a literature review of articles that discuss Burmeister's porpoise distribution in the southeast Pacific. While Burmeister's distribution is generally described as coastal, they are frequently found within 20 km from shore with some detections out to 50 km from shore (Reyes and Oporto 1994, Reyes 2009, Clay et al. 2018).

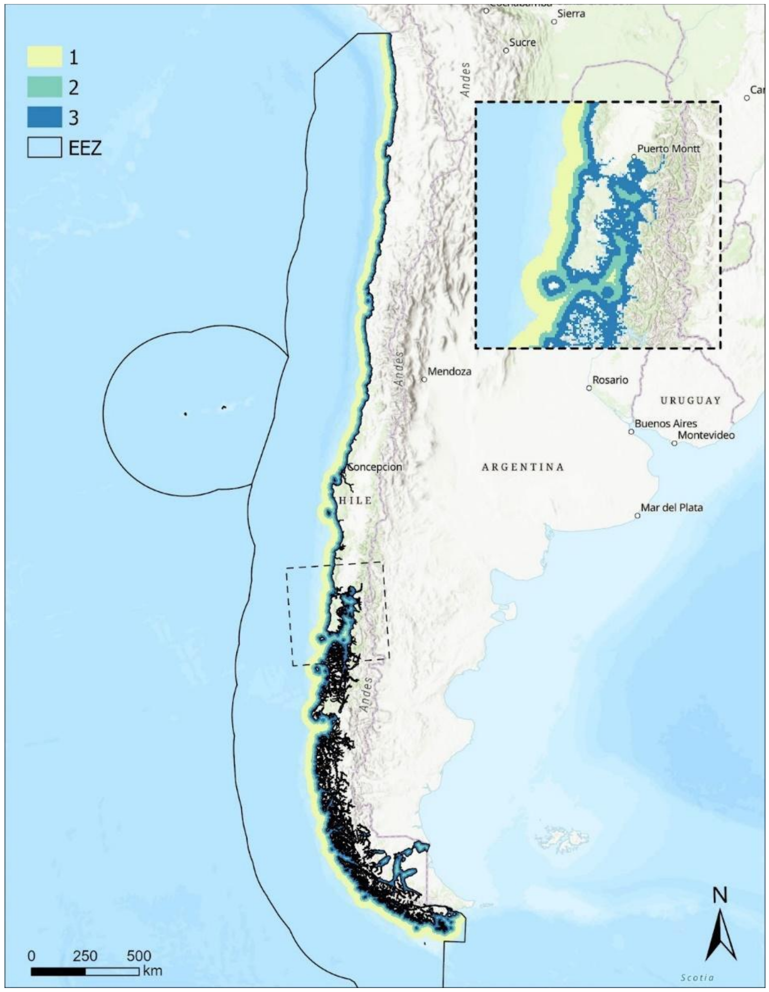


Figure 7. Coastal buffer distribution of opportunistic pilot whale sightings (1 – low likelihood of presence between 20-50 km; 2 – medium likelihood of presence between 10-20 km; 3 – high likelihood of presence between shore and 10 km). The inset map shows detailed distribution buffers around Isla Grande de Chiloé, southern Chile.

Bottlenose dolphin

Opportunistic sightings of bottlenose dolphins were collated from IFOP, GBIF, OBIS, and the literature (Sanino et al. 2005, Aguayo et al. 2006, Sanino and Waerebeek 2008, Olavarría et al. 2010, Viddi et al. 2010, Buscaglia et al. 2020). A kernel density estimation of these observations (n=65) was generated using a cell size of 5 km and search radius of 78 km, calculated using a spatial variant of Silverman's Rule of Thumb, in northern Chile (Silverman 1986). The kernel density was reclassified using a quantile classification method into the required three classes of low (1), medium (2), and high (3) likelihood of presence (Figure 8).

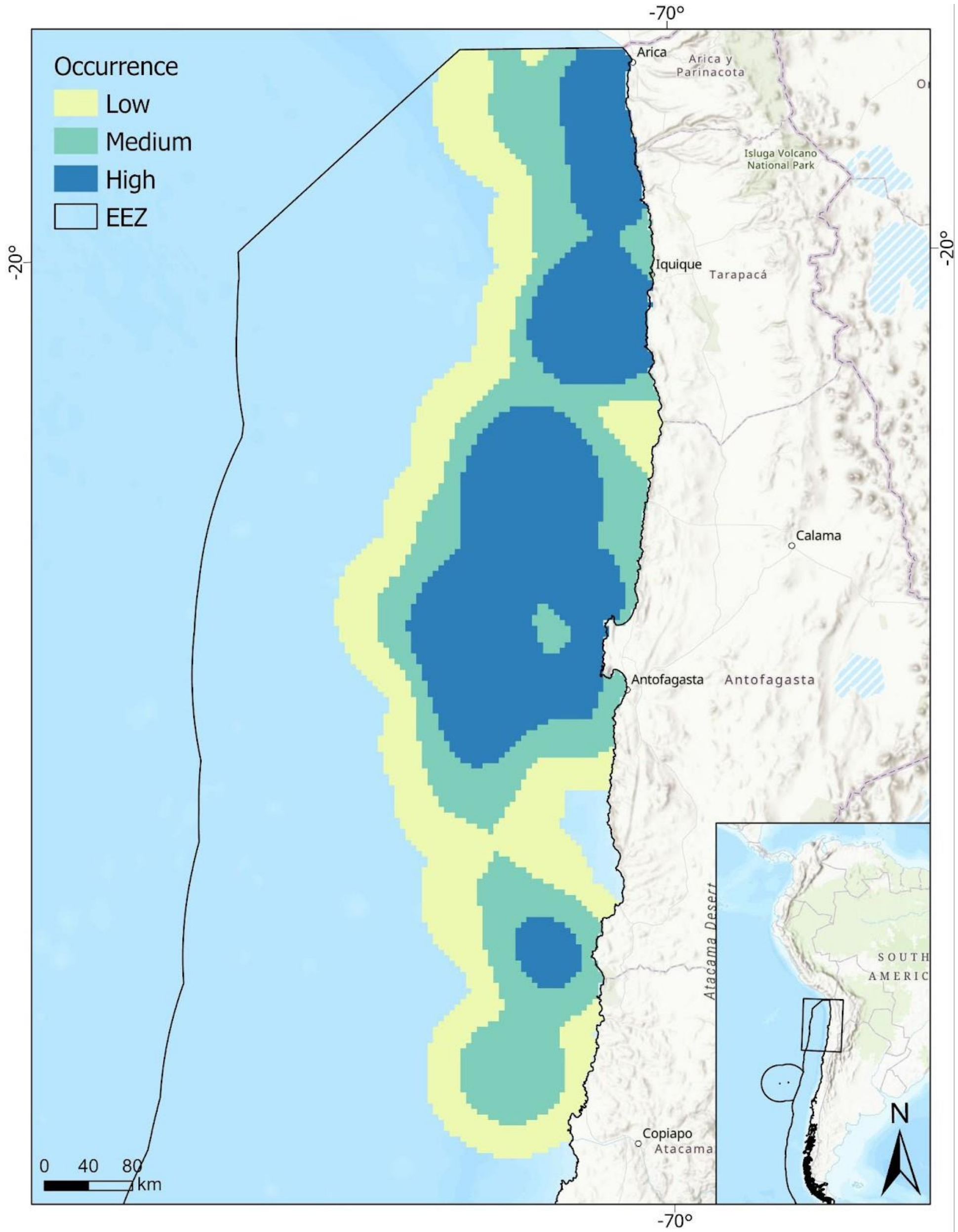


Figure 8. Reclassified kernel density estimation of opportunistic bottlenose dolphin sightings (1 – low likelihood of presence; 2 – medium likelihood of presence; 3 – high likelihood of presence).

Likelihood of interaction

A likelihood of interaction (LOI) layer was calculated for each cetacean and fishery pair as a simple summation of the fishing intensity and animal distribution layers. The resulting summed raster was reclassified as integers 1-3 (5-6 = 3; 4 = 2; 2-3 = 1) and used as the likelihood of interaction spatial exposure criteria in ByRA. This layer represents the overlap between species habitat and fishing density. Four likelihood of interaction layers were generated for the anchovy fishery (Figure 9) and five for the swordfish fishery, including: Burmeister's porpoise (Figure 10), common dolphin (Figure 11), dusky dolphin (Figure 12), fin whale (Figure 13), and pilot whale (Figure 14). The same 3km cell size was used for both fisheries.

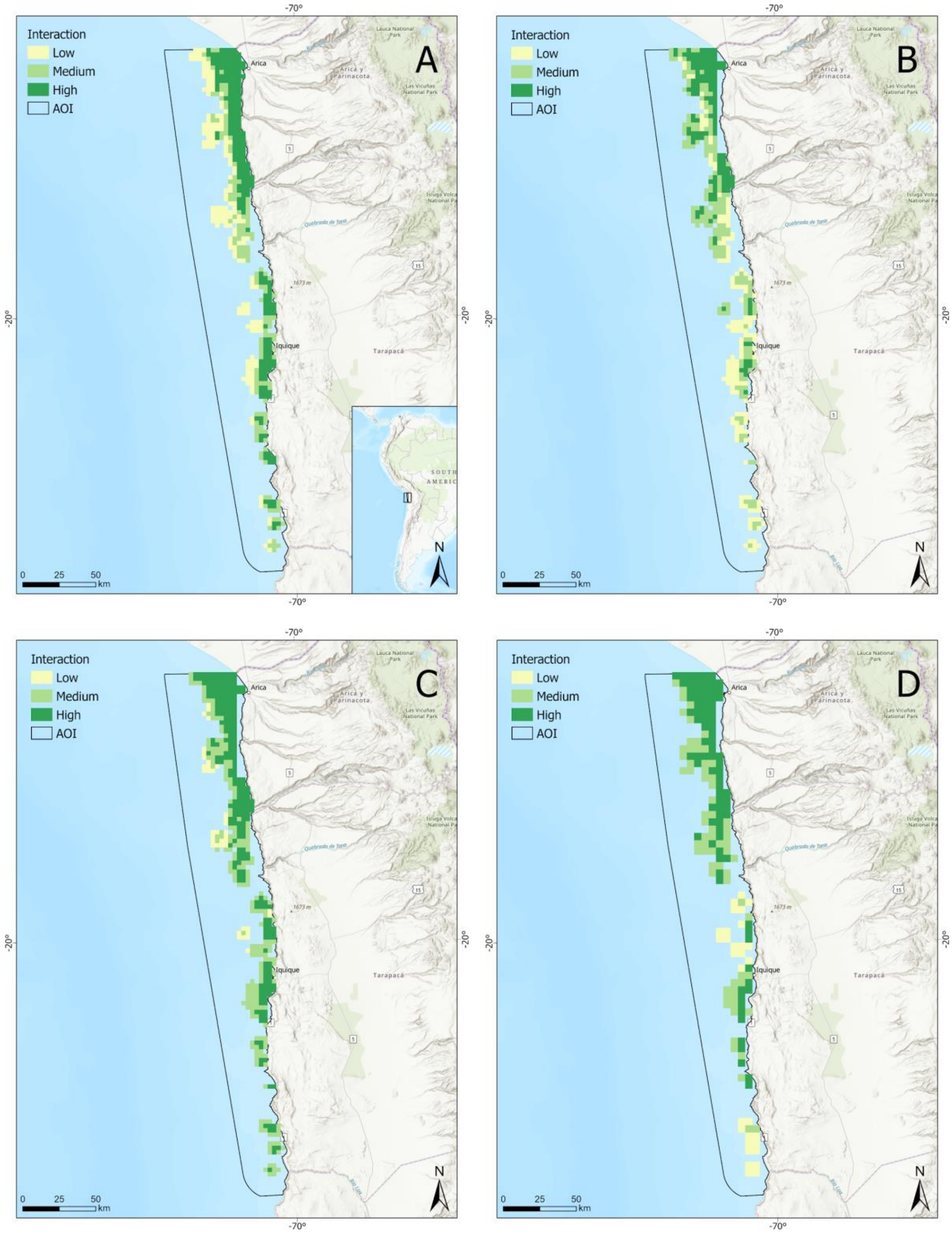


Figure 9. Likelihood of interaction layers for (A) Burmeister's porpoise, (B) common dolphin, (C) dusky dolphin, and (D) bottlenose dolphin with the northern anchovy fishery.

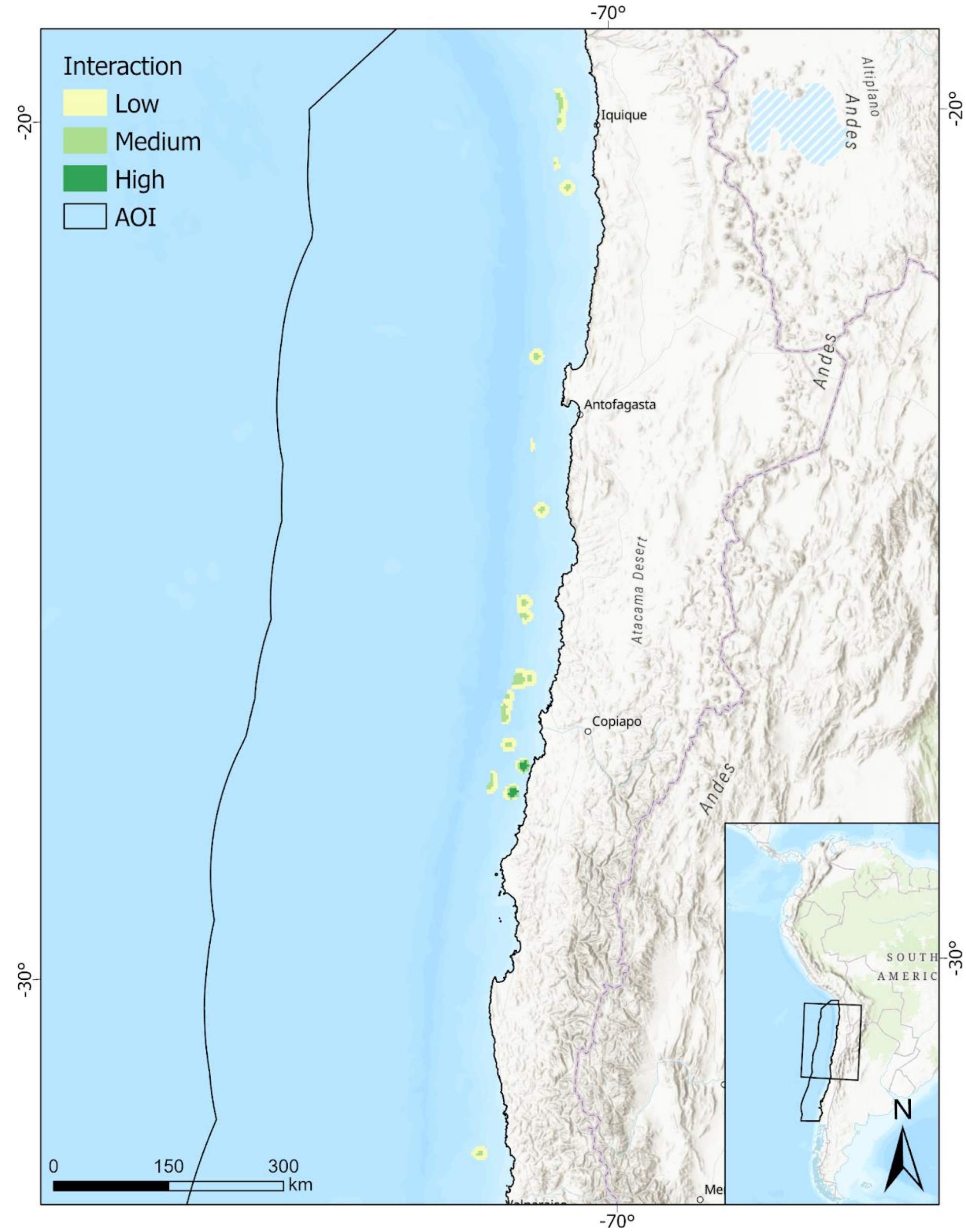


Figure 10. Likelihood of interaction between Burmeister's porpoise and the swordfish gillnet fishery.

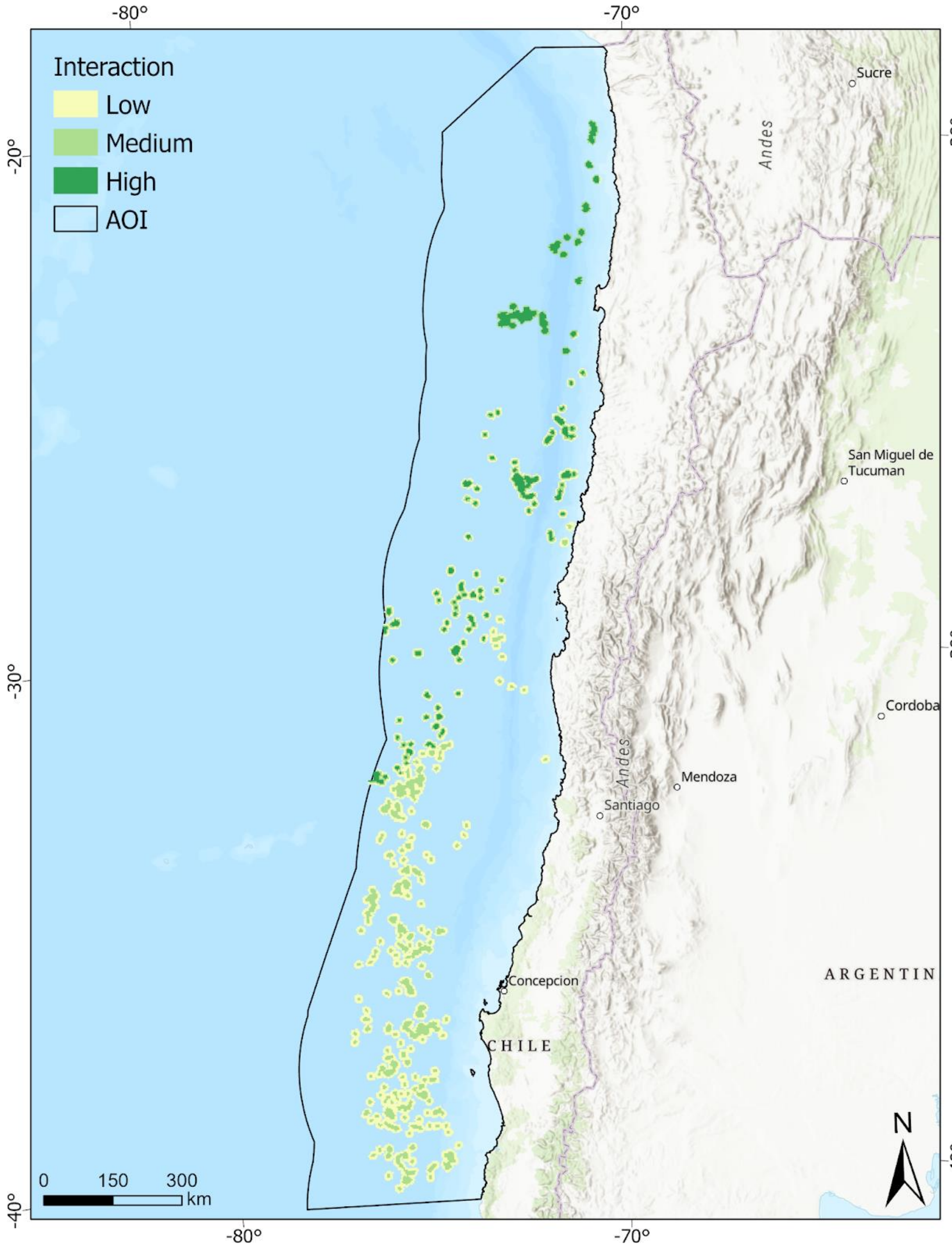


Figure 11. Likelihood of interaction between the common dolphin and the swordfish gillnet fishery.

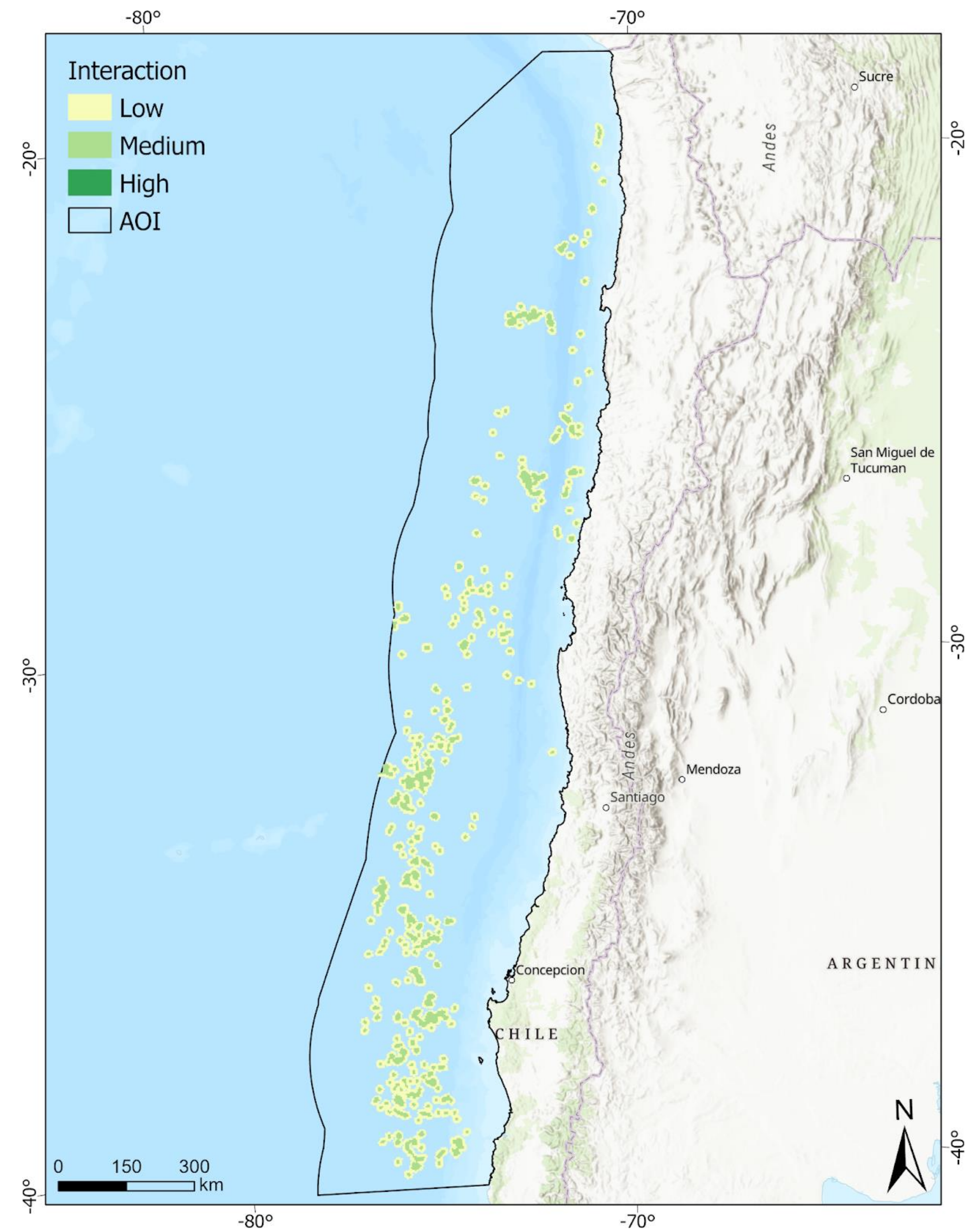


Figure 12. Likelihood of interaction between the dusky dolphin and the swordfish gillnet fishery.

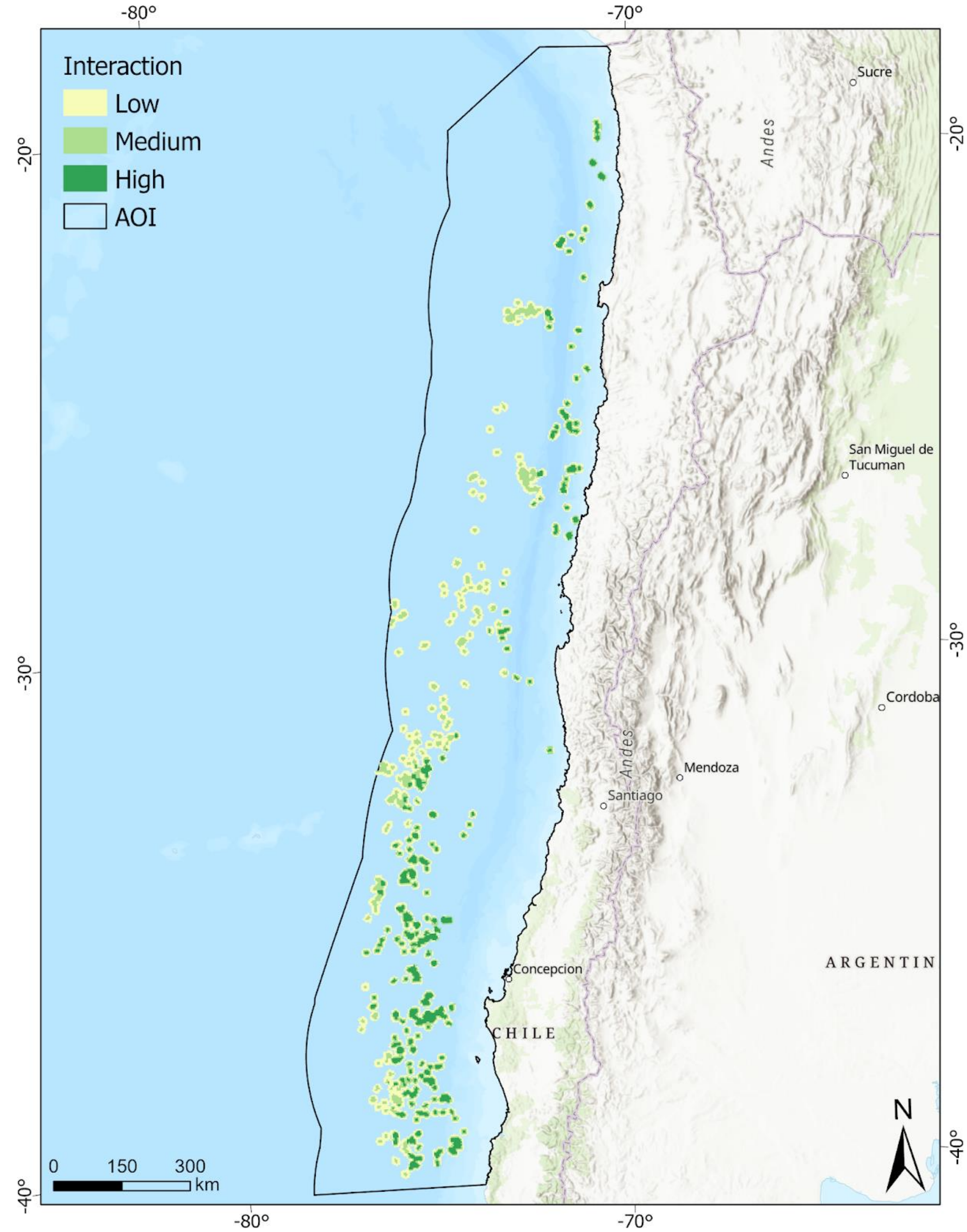


Figure 12. Likelihood of interaction between the fin whale and the swordfish gillnet fishery.

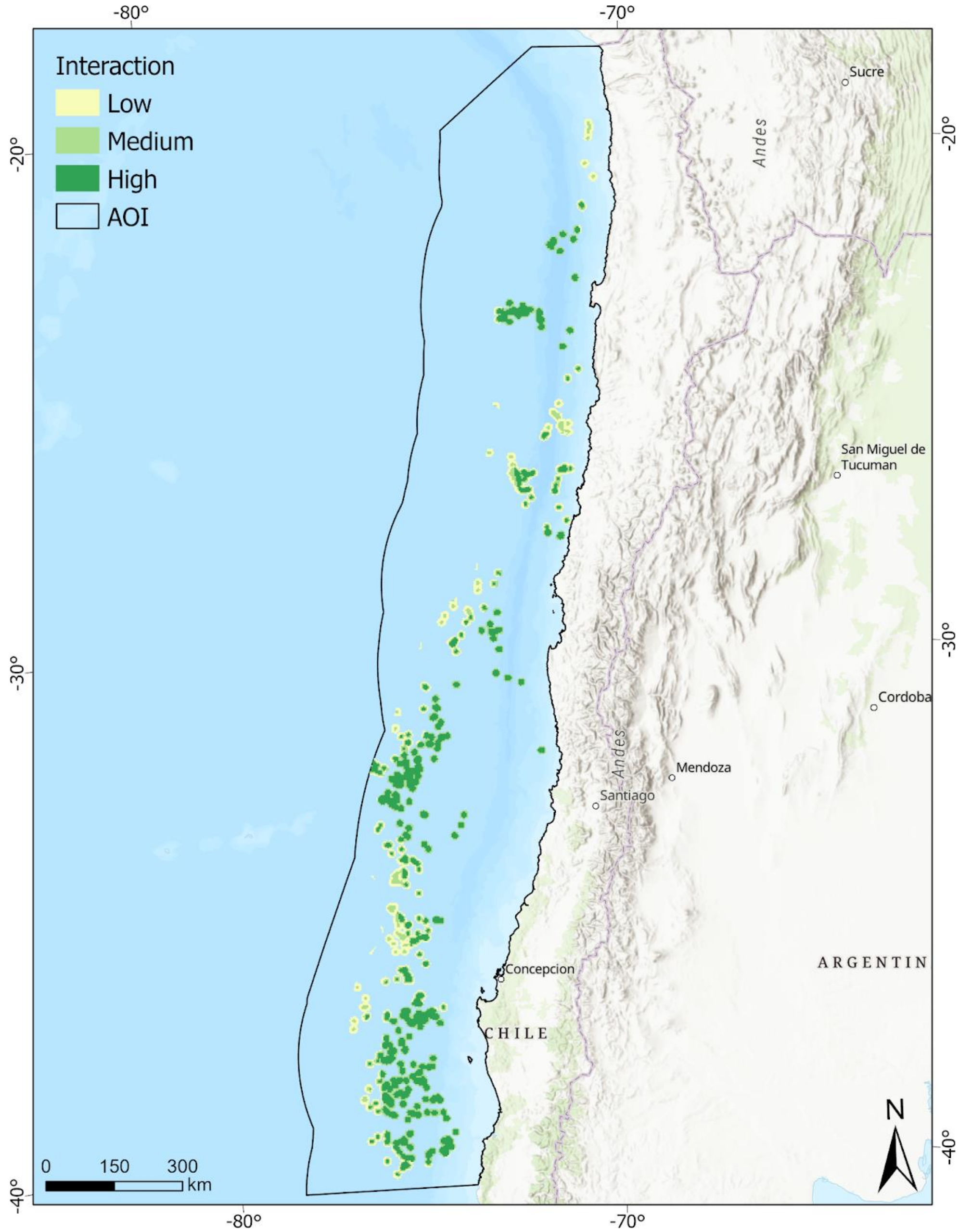


Figure 13. Likelihood of interaction between pilot whale and the swordfish gillnet fishery.

Non-spatial Exposure and Consequence Criteria

In addition to spatial exposure criteria model inputs described above, several non-spatial exposure and consequence criteria were incorporated into the model as constants that are species and fishery specific. Exposure criteria provides information on the degree to which a species experiences a stressor and the consequence criteria incorporates the species-specific response to the stressor (Samhouri and Levin 2012).

In this research, we considered four non-spatial exposure criteria for the anchovy fishery and three for the swordfish gillnet fishery, including: temporal overlap, catchability, current status of management, and soak time. All bycatch assessments included six non-spatial consequence criteria, when known, for the species being assessed, including: age of maturity, reproductive strategy, population connectivity, local species status, mortality, and life stages affected by gear. The definition and scoring guidelines for each criterion was based on Verutes et al. 2020 and Costanza et al. 2022 and can be found in Table 4 (Verutes et al. 2020, Costanza et al. 2021). Exposure and consequence spreadsheets for each species and fishery pair can be found in Appendix 1.

Table 4. Exposure (E) and Consequence (C) scoring criteria and definitions used in this research.

Criteria Name	Type	Definition	Scoring
Temporal Overlap	E	The duration of time that the species and gear overlap in space.	3) lethal, (2) sublethal, (1) negligible, (0) no score
Catchability	E	The likelihood of an animal being caught in the gear, given that they overlap.	(3) high, (2) medium, (1) low, (0) no score
Current Status of Management	E	The existence and status of management plans limiting gear use or otherwise mitigating bycatch.	(3) no strategy identified, (2) management strategy identified but not fully enforced (1) management strategy identified and well-implemented, (0) no score
Soak time*	E	The duration of time nets was set reported by the fishermen. Longer duration would mean greater risk.	(3) 8 or more hours, (2) 4-7 hours, (1) 0-4 hours
Age of Maturity	C	The age a species reaches reproductive maturity.	(3) > 4 years, (2) 2-4 years, (1) < 2 years, or (0) no score
Reproductive Strategy	C	The frequency of reproduction, and how much protection and care is given to offspring.	(3) long calving interval / high parental investment, (2) medium calving interval / high parental investment, (1) short calving interval / short to medium parental investment, (0) no score
Population Connectivity	C	The connectivity of the population of interest, within the area of study, to other populations.	(3) negligible movement/exchange between the focal regional population and other populations (a DPS or ESU), (2) occasional movement/exchange between the focal regional population and other populations, (1) regular movement/exchange between the focal regional population and other populations (not a DPS or ESU), or (0) no score
Local Species Status	C	The conservation status of the species of interest, within the country.	(3) endangered, (2) threatened or of concern, (1) low concern, or (0) no score
Mortality	C	The direct effect of gear on the rate of mortality for a species	(3) lethal, (2) sublethal, (1) negligible, (0) no score
Life Stages Affected by Gear	C	The life stages that interact with and are affected by a gear	(3) adults only, (2) mixed (1) juveniles only, (0) unknown

*Only considered in the artisanal anchovy fishery since soak time is known and distinguishes this fishery from the industrial fleet in a forthcoming analysis.

Bycatch Risk Assessment Model

Using the spatial and non-spatial exposure and consequence scores described above for each species and fishery pair, ByRA calculates the risk scores as the Euclidean distance from the least possible risk score to the intersection of the average exposure and consequence values (Figure 14). Risk is only calculated where the species occurs and varies spatially based on the fishery distribution and exposure and consequence scores. To classify risk as low, medium, and high for each species-fishery combination, the InVEST Natural Capital Habitat Risk Assessment (HRA) model uses a quantiles classification of the maximum possible risk score. In this research, we use a maximum criteria score of 3, which results in the maximum possible risk value being 2.83 using the risk formula in the figure below. Using a maximum pairwise risk score of 2.83, the HRA model classifies pixels with a risk 0-0.94 as low, 0.94-1.88 as medium, and 1.88-2.83 as high.

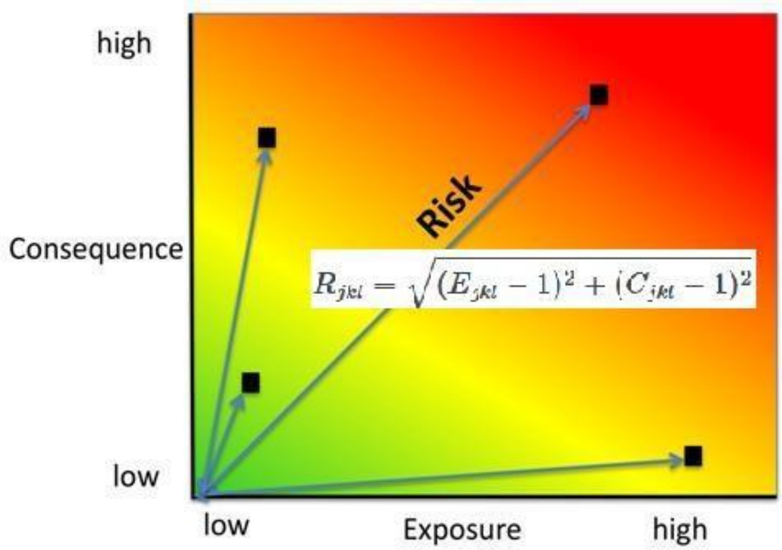


Figure 14. Risk (R) to each species (j) with each fishery (k) at each location (l) is calculated as the Euclidean distance from the origin of the exposure (E) and consequence (C) plot to the intersection of the exposure and consequence value for each species-fishery pair in each cell across the raster surface. This figure was adapted from the InVEST Natural Capital Habitat Risk Assessment User Guide.

RESULTS

Risk maps were generated for each fishery and marine mammal pair resulting in nine risk maps across both fisheries. ByRA also outputs a summary statistics table for each analysis to create risk plots for each fishery. Cetaceans evaluated with the northern anchovy fishery show similar spatial risk (Figure 15). When maximum exposure and consequence values were plotted, maximum exposure was equal across all species but the consequence of bycatch was highest for dusky dolphins with this fishery (Figure 16), but all species are considered medium risk according to the InVEST Natural Capital Habitat Risk Assessment classification scheme.

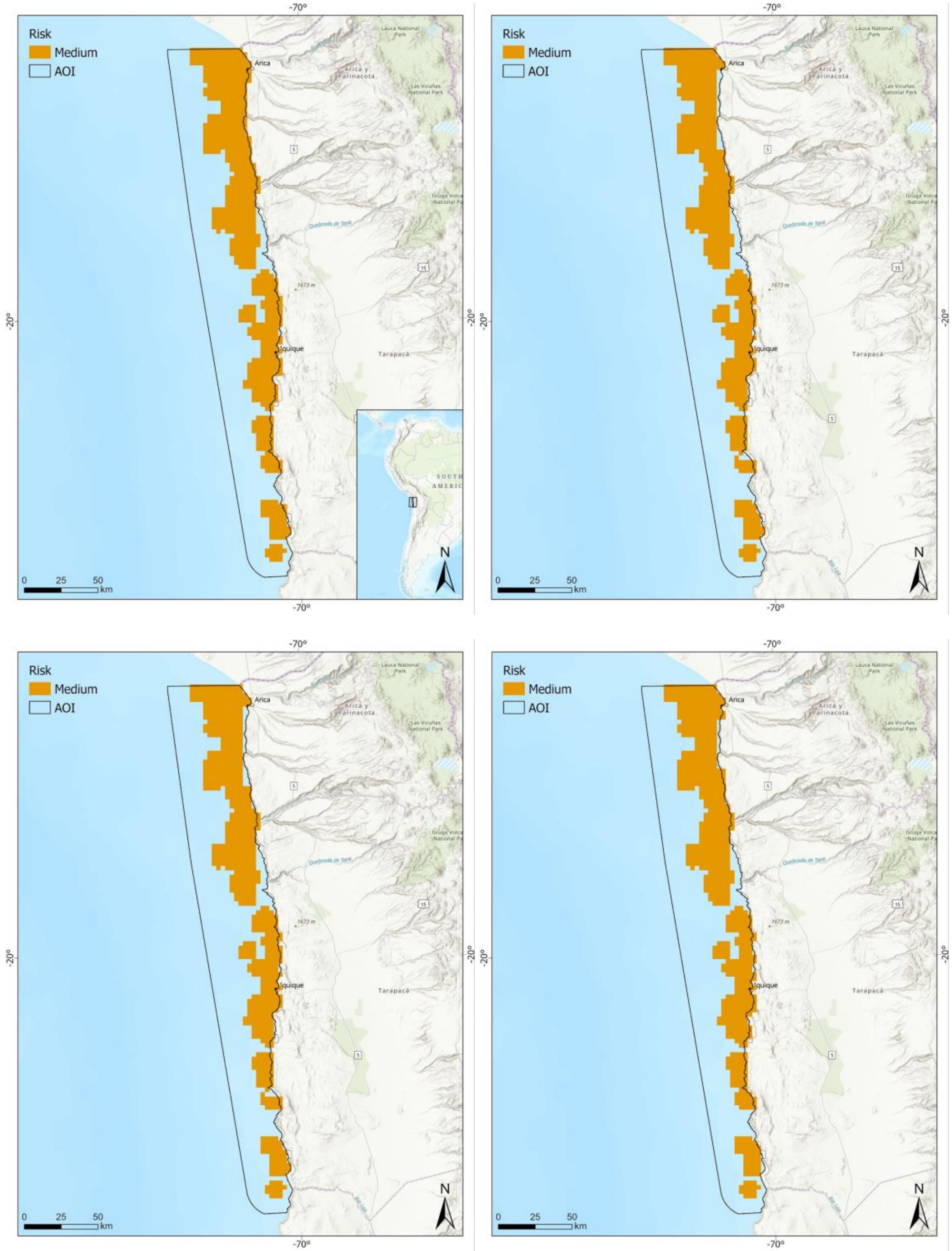


Figure 15. Bycatch risk assessment output maps for (A) Burmeister’s porpoises, (B)common dolphins, (C)dusky dolphins, and (D)bottlenose dolphins for the northern anchovy fishery.

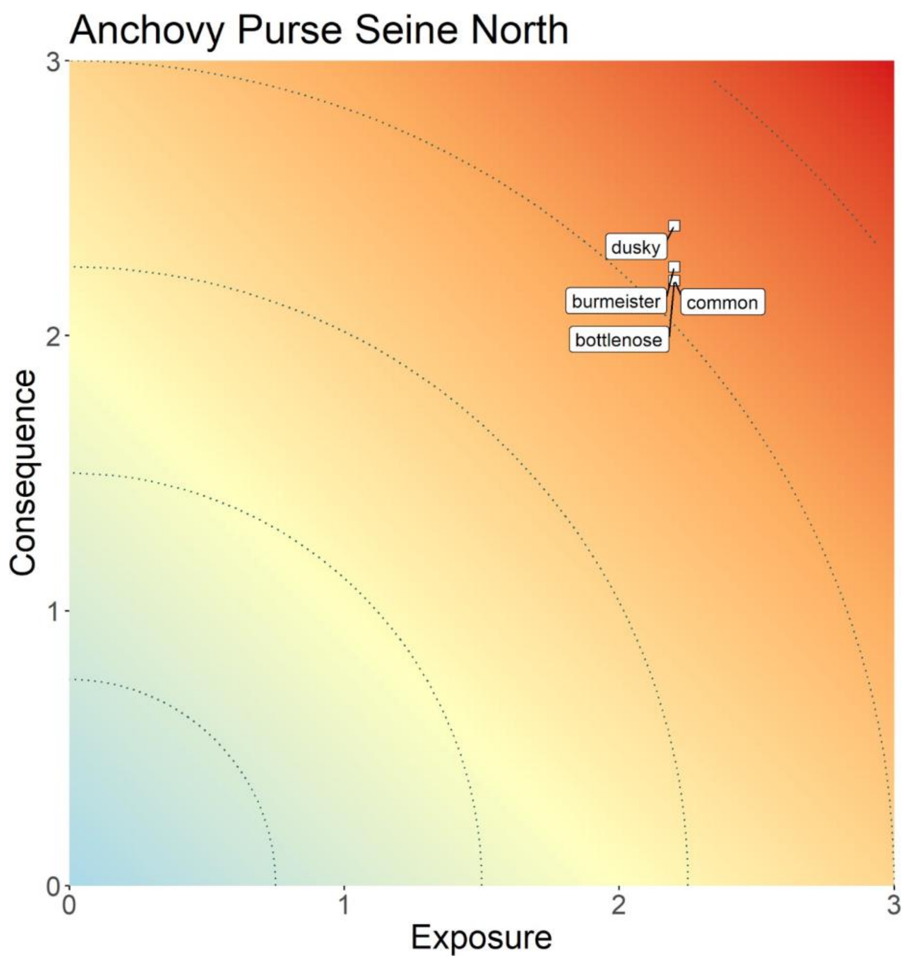


Figure 16. Maximum exposure and consequence scores for each species assessed within the northern artisanal anchovy purse seine fishery.

Bycatch risk to selected cetaceans in the swordfish gillnet fishery varied spatially due to the different extents of species distributions. Since Burmeister's porpoises are a highly coastal species, risk is concentrated close to shore in the northern portion of the area of interest (Figure 17). Common dolphins (Figure 18), dusky dolphins (Figure 19), fin whales (Figure 20), and pilot whales (Figure 21) have similar spatial risk extents. However, dusky dolphins and fin whales exhibit areas of high risk, unlike common and dusky dolphins. For the swordfish fishery, maximum exposure and consequence scores for each species suggests that the consequence of bycatch is highest for fin whales though exposure to the fishery is slightly lower than the odontocetes (Figure 22).

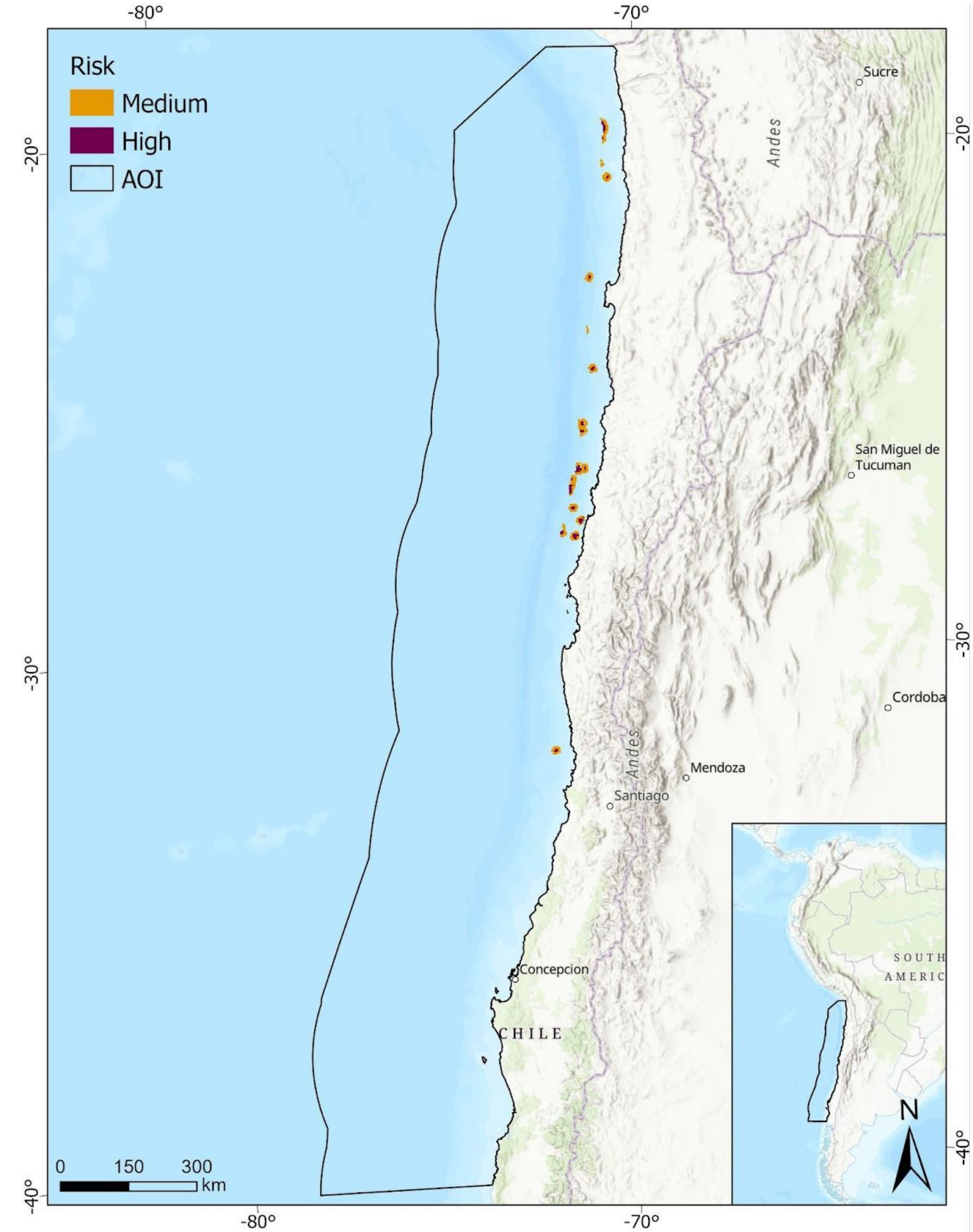


Figure 17. Bycatch risk assessment output map for Burmeister's porpoises in the swordfish fishery.

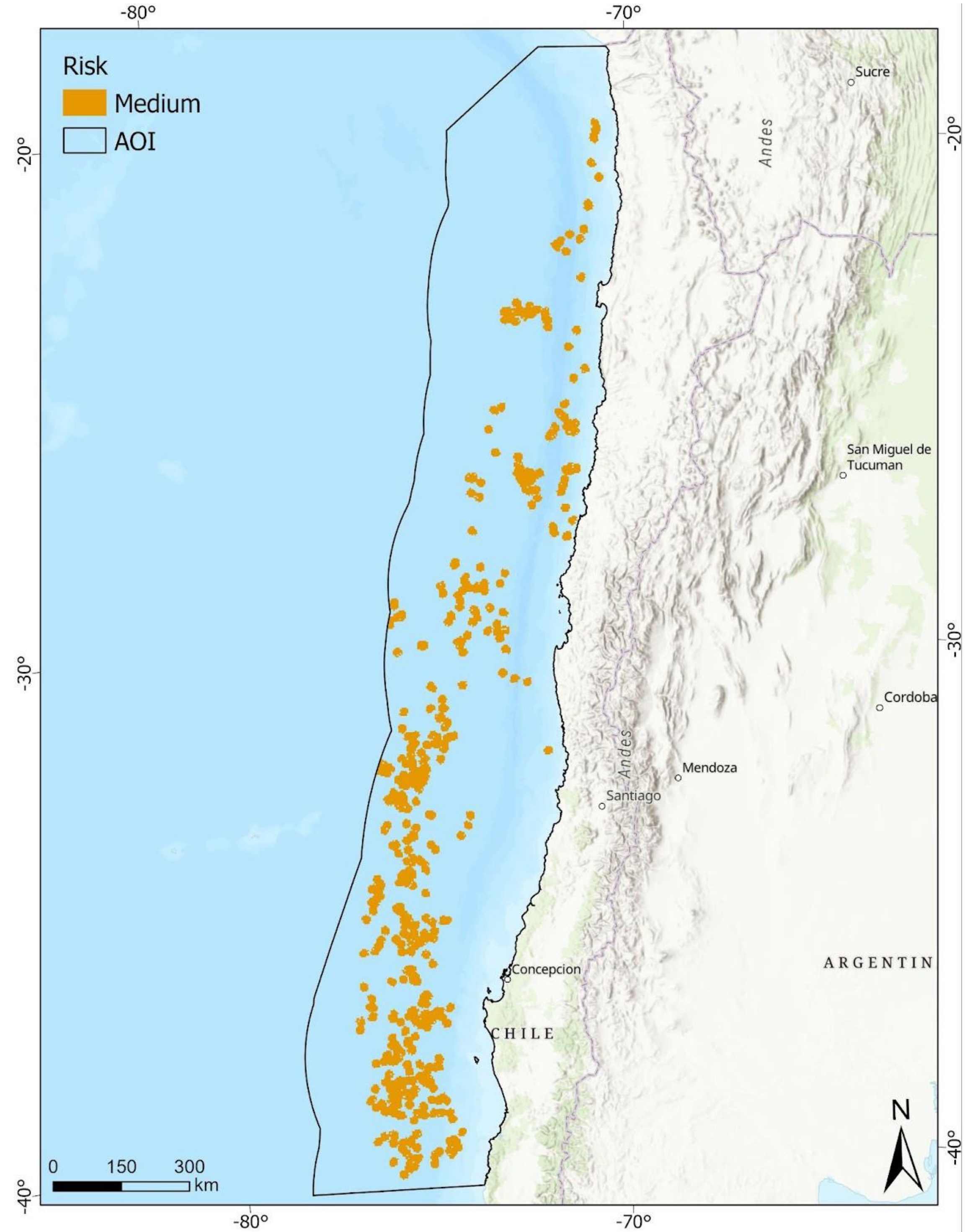


Figure 18. Bycatch risk assessment output map for common dolphins in the swordfish fishery.

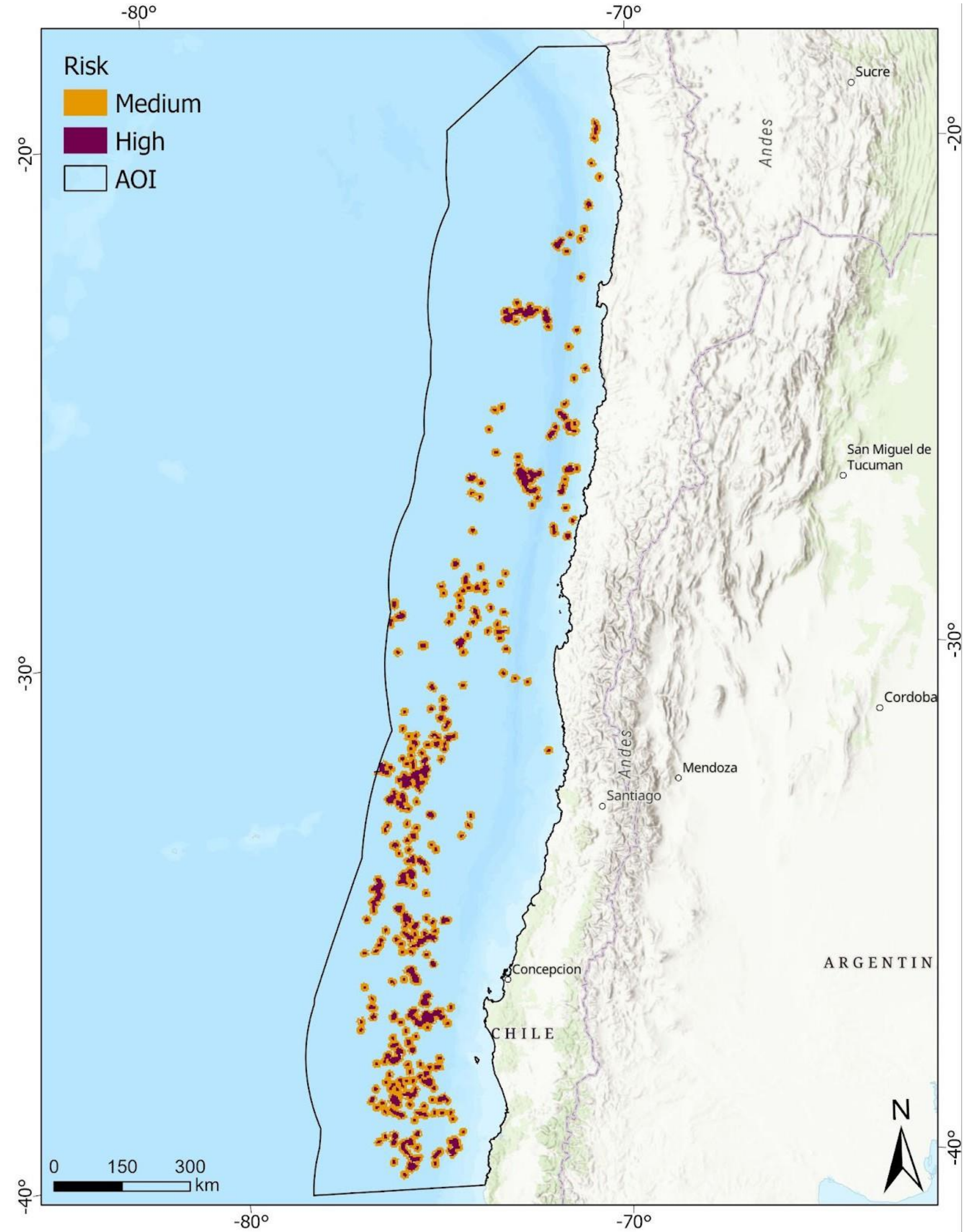


Figure 19. Bycatch risk assessment output map for dusky dolphins in the swordfish fishery.

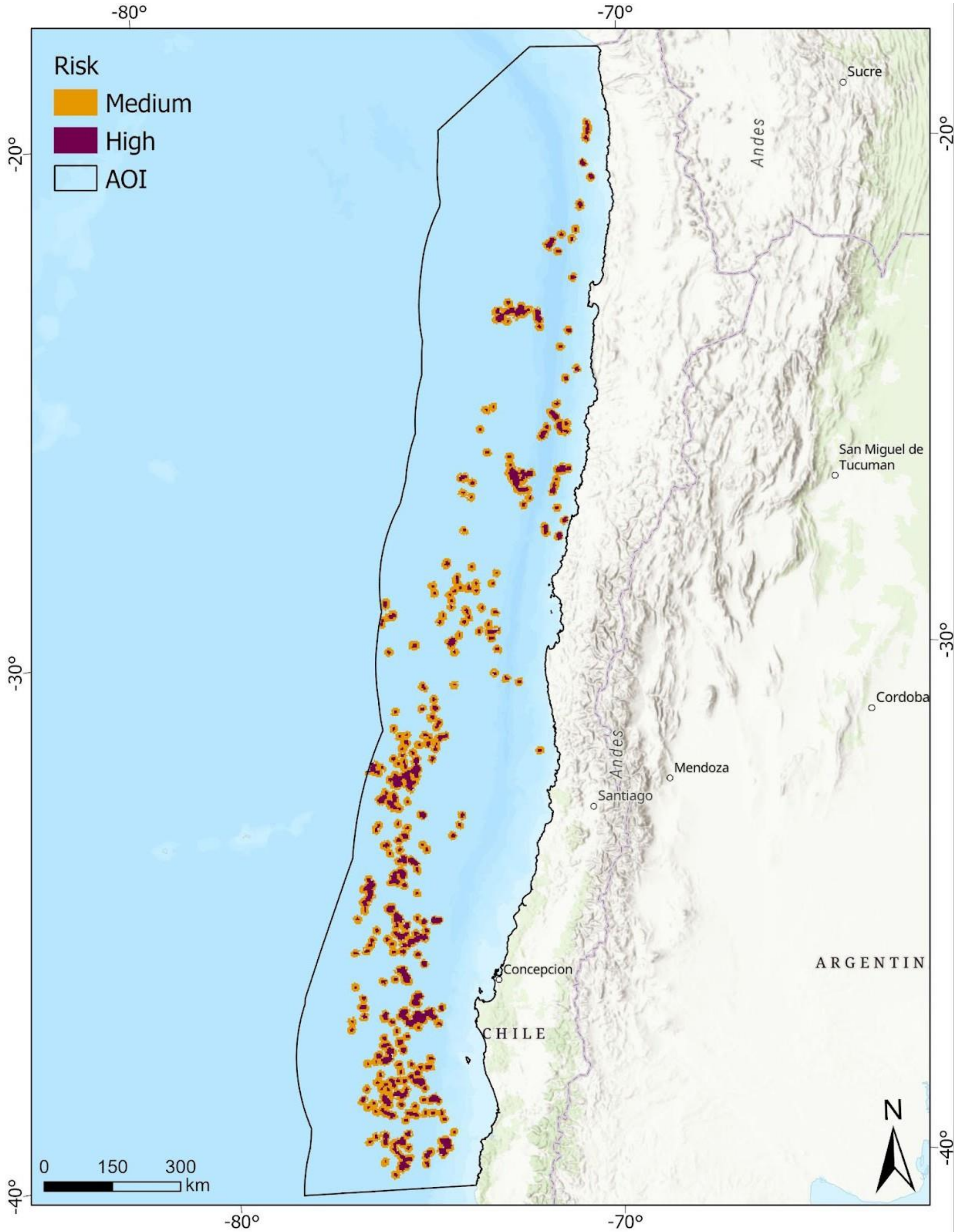


Figure 20. Bycatch risk assessment output map for fin whales in the swordfish fishery.

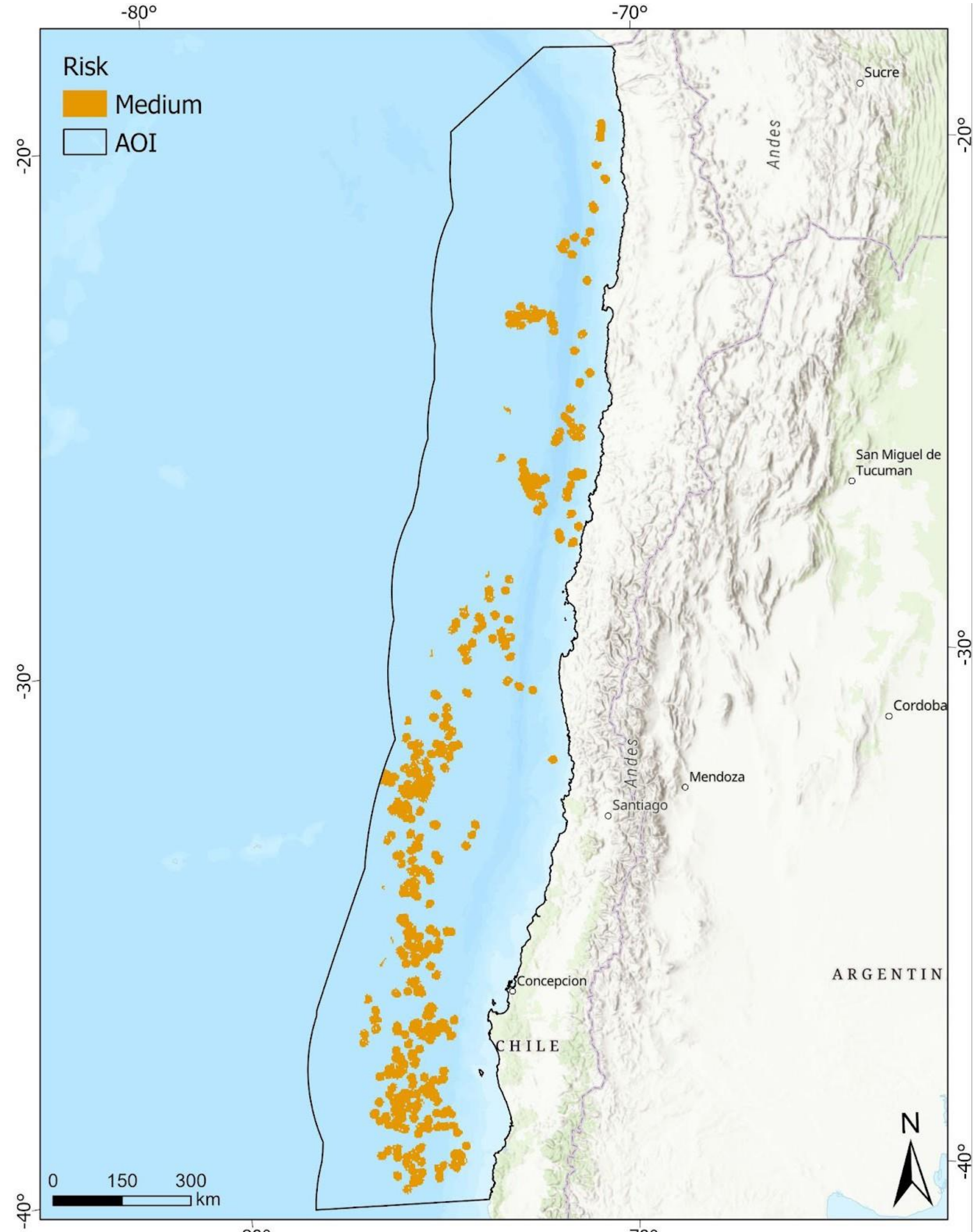


Figure 21. Bycatch risk assessment output maps for pilot whales in the swordfish fishery.

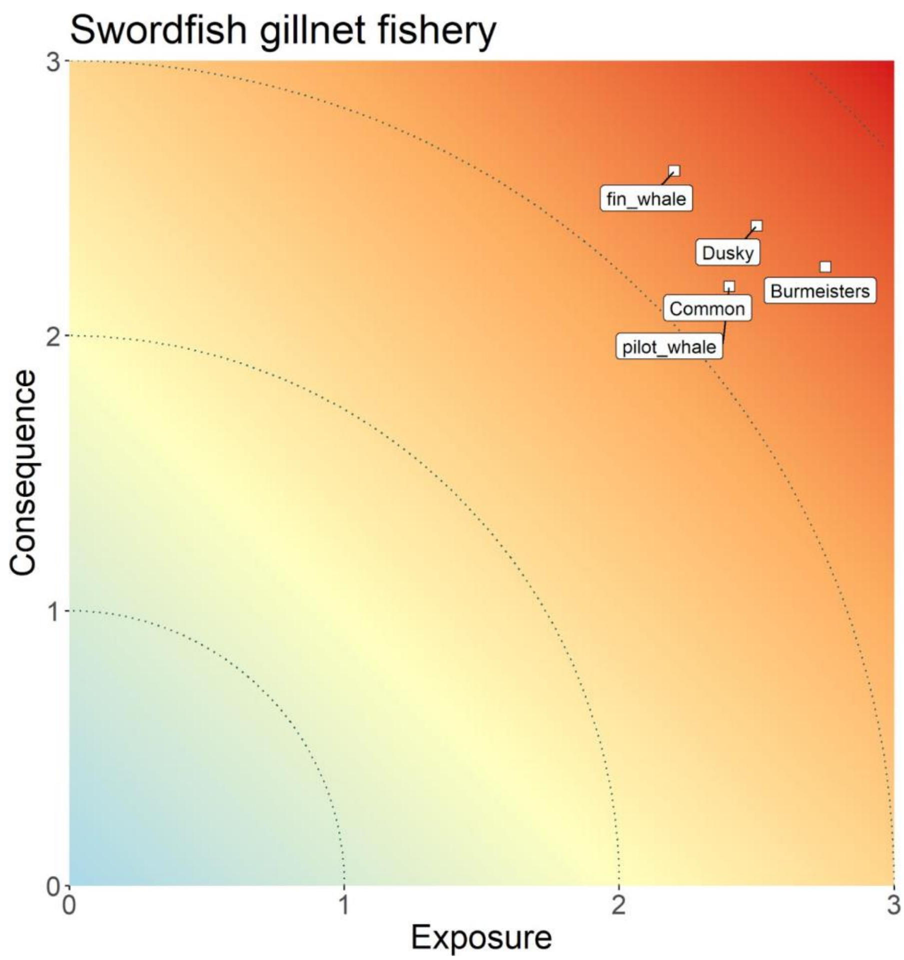


Figure 22. Maximum exposure and consequence scores for each species assessed within the artisanal swordfish gillnet fishery.

Discussion

While our results showed medium risk for most species in these fisheries, the higher levels of risk and consequence for Burmeister's porpoises, dusky dolphins and fin whales should signal caution and trigger mitigating actions. As our knowledge about the distribution and abundance about the Burmeister's porpoise in particular is low, this high level of risk can be interpreted as leading towards both precautionary management and targeted research. As we complete our project, we have begun to present our results to our Chilean partners. The ByRA results will provide Chilean fisheries agencies with information on areas and seasons of bycatch risk for ongoing monitoring, as well as the levels of risk for various fishing gear at those times and locations, which can support precautionary actions, policies, and inform carefully designed research and management. Once ByRA analysis has been integrated into the fisheries monitoring programs, agencies will be able to use the resulting information for fisheries management that reduces marine mammal bycatch and addresses NOAA's bycatch monitoring and reduction rule. These mapped results can be used in marine spatial planning as mitigation measures, for instance, to plan fishing gear restrictions and seasonal closures for marine mammal protection. ByRA map visualizations will be presented to communities of fisheries stakeholders, both industrial and artisanal, to illustrate bycatch risk in fishing areas. For local scientists, ByRA results will be used to pinpoint research planning and design robust trials for mitigation measures in higher risk areas – e.g. the effectiveness of attending nets vs. leaving them unattended, fishing gear modifications, trials of pingers on nets, and time/area closures. Scientists and managers can work together to apply ByRA results to adapting observer program designs and vessel monitoring systems as needed for bycatch management objectives. The output maps can be used to identify areas of concern that can be used to guide monitoring and bycatch mitigation management. By synthesizing and organizing bycatch risk assessment methods in an accessible framework, our project extends beyond Chile. At this writing, Byra projects and trainings have been conducted or are in progress in 12 countries worldwide.

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SUMMARY

The bycatch risk assessment toolkit (ByRA) is being used in Chile in a landmark collaboration between local and international marine mammal scientists and Chilean fisheries agency scientists and managers. As part of a larger project to assess the risk of marine mammal bycatch in Chilean fisheries, this report focuses on two of the major artisanal fisheries along the northern and central Chilean coast. The artisanal swordfish gillnet fishery, and the northern anchovy purse seine fishery. The species most at risk and at the highest consequence of bycatch to local populations were the dusky dolphin and Burmeister's porpoises in both fisheries, and the fin whale in the swordfish gillnet fishery. The ByRA results will provide Chilean fisheries agencies with information on areas and seasons of bycatch risk for ongoing monitoring, as well as the levels of risk for various fishing gear at those times and locations, which can support precautionary actions, policies, and inform carefully designed research and management.

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