BYCATCH RISK ASSESSMENT FOR SOUTH AMERICAN SEA LIONS USING A GIS-BASED TOOLBOX

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1. Introduction

Bycatch and mortality of individuals entangled, hooked, or entrapped in fishing gears are among the main threats to marine mammals worldwide (Avila et al. 2018, Moore et al. 2021, Wade et al. 2021), affecting more than 110 species and killing an estimated 650,000 annually (Read et al. 2006, Brownell Jr. et al. 2019). Several species of marine mammals have experienced severe declines in abundance due to fisheries bycatch (Avila et al. 201, Wade et al. 2021), including the critically endangered North Atlantic right whale (*Eubalaena glacialis*) (Knowlton et al. 2012, Cooke 2020), the critically endangered vaquita (*Phocoena sinus*) (Taylor et al. 2017, Braulik et al. 2023), the endangered New Zealand sea lion (*Phocarctos hookeri*) (Chilvers 2008, Chilvers & Meyer 2018), and the baiji or Yangtze River dolphin (*Lipotes vexillifer*), which ultimately became extinct (Turvey et al. 2007, Brownell Jr. et al. 2019).

To address this problem, a range of mitigation strategies has been implemented worldwide, including acoustic deterrent devices (pingers), gear modifications, time–area fishing closures, and changes in fishing practices (Hamilton & Baker 2019, Sepúlveda et al. 2023). Pingers can reduce cetacean bycatch but may in some cases lose effectiveness through habituation or attract other predators (Bordino et al. 2002, Hamilton & Baker 2019). Gear modifications (e.g. weak links, net illumination) can lower entanglement risk but may reduce fishing efficiency and are not applicable to all fisheries (Knowlton et al. 2016, Hamilton & Baker 2019). Time–area closures can provide strong protection but may involve higher socioeconomic costs relative of other measures, and low compliance, while changes in fishing practices are relatively low-cost but highly fishery-specific and difficult to enforce (Hamilton & Baker 2019, Sepúlveda et al. 2023). Limited implementation and compliance, together with logistical and operational challenges in enforcement and evaluation, have resulted in little global progress in reducing marine mammal bycatch and associated mortality (Sonne et al. 2024, Hordern et al. 2025). These limitations are further compounded by by persistent data gaps on species distribution and abundance, fishing effort, and bycatch rates (e.g. from fisheries observers or, minimally, from entanglement and stranding response), which also hinder effective management and enforcement (Hines et al. 2020, Félix et al. 2021, Wade et al. 2021, Temple et al. 2024).

Chile hosts a remarkably high diversity of marine mammals, with 53 species (42 cetaceans, 10 pinnipeds, and one mustelid), representing ~40% of the world's marine mammal species (Iriarte et al. 2023). This extraordinary diversity results from the country's extensive latitudinal range and the influence of the Humboldt Current Ecosystem (HCE), whose productive upwelling extends from the Galápagos Archipelago in the north to mid-latitudes around 42°S in the southeastern Pacific Ocean (Thiel et al. 2007, García-Reyes et al. 2023). This productive current also supports one of the world's largest commercial catches for a country, with combined landings of approximately ~2.6 million tons in 2024, of which almost 1.2 million tons (46%) came from industrial fleets (> 18 m maximum length and vessels above 50 gross tons), and ~1.4 million tons (54%) from small-scale artisanal fleets (maximum length of 18 m and 50 gross tons) (Sernapesca 2024), accounting for about 3% of global fish landings (FAO 2024). The main industrial fisheries operating in Chile target demersal and pelagic species, using bottom and mid-water trawls, traps, gillnets, and purse-seine nets. In 2024, the industrial fleet operated 96 vessels and landings were overwhelmingly dominated by pelagic purse-seine fisheries (anchovy (*Engraulis ringens*), chub mackerel (*Scomber japonicus*) and jack mackerel (*Trachurus murphyi*)), which accounted for ~95% of the industrial catch (Sernapesca 2024). Artisanal fisheries use primarily gillnets, longlines, trawls, and purse seines (Castilla 2010, Félix et al. 2021). These fisheries are dominated by a large, multi-gear fleet operating along most of the Chilean coast, with 13,082 vessels registered in 2024 (Sernapesca 2024). Although the artisanal sector targets a broad range of resources, landings are partially concentrated in small pelagics: anchovy, jack mackerel and common sardine (*Strangomera bentincki*) combined accounted for ~43% of artisanal landings in 2024 (Sernapesca 2024).

An intensification of fishing effort in recent decades, along with the recovery of some marine mammal species from direct exploitation through hunting, has increased the likelihood of bycatch interactions (Félix et al. 2021, Moore et al. 2021, Wade et al. 2021). Pinnipeds (seals, sea lions, and walrus) display some of the highest levels of interaction with fisheries as they prey upon the same resources and their foraging areas are closer to the coast, overlaping with fishing activities (Kovacs et al. 2012, Sepúlveda et al. 2023). Pinnipeds may be affected through entanglement or incidental capture, while fisheries can simultaneously experience catch losses and increased operational costs due to depredation and damage to fishing gear (Wickens 1995, Read et al. 2005). In most cases, incidental capture has been reported to result in the mortality of individuals entangled in the fishing gears (Félix et al. 2021, Sepúlveda et al. 2023). The South American sea lion (SASL; *Otaria byronia*) is the species of pinniped with the highest level of conflicts with fishing activities throughout their range in Chile (Sepúlveda et al. 2023). This species displays generalist and opportunistic foraging strategies, with a diverse diet that varies with the availability of resources in their environment (Muñoz et al. 2013, Crespo et al. 2021). In Chile, a large share of the prey species in the SASL's diet are of commercial importance (e.g. Guerrero et al. 2020, Sarmiento et al. 2020), increasing opportunities for conflict with artisanal and industrial fisheries (e.g. Hückstädt & Antezana 2003, Sepúlveda et al. 2007, 2018, Goetz et al. 2008, Reyes et al. 2013, González et al. 2015).

As a consequence of these interactions, bycatch and mortality of SASL in several fisheries has been reported along the Chilean coast, including mortality in artisanal and industrial purse-seine (Hückstädt & Antezana 2003, Punt et al. 2021, Vega et al. 2024), trawl (Reyes et al. 2013, Punt et al. 2021, Bernal et al. 2025, Queirolo et al. 2025), and gillnet (Pavés et al. 2025) fleets. Quantitative assessments of bycatch of these species are currently limited, primarily due to insufficient observer coverage across various Chilean fisheries, mainly in artisanal fisheries. Notably, artisanal gillnet fisheries are not being monitored in Chile, while existing scientific observer programs in both artisanal and industrial purse seine fleets typically report coverage rates below 5% (Punt et al. 2021, Vega et al. 2024). However, monitoring intensity is fishery-specific and includes notable high-coverage exceptions, such as the industrial swordfish surface longline fishery (with 100% observer coverage reported for some seasons; IATTC 2019) and several trawl fisheries where coverage has been reported to reach ~80% (Bernal et al. 2025). The more typically low observer effort in other fisheries, particularly in purse-seine fisheries that account for most of the industrial catch, hinders the ability to identify specific fisheries or potential areas where there may be high risk of interactions and mortality for SASL. Enhanced spatial and fishery-specific bycatch data are essential for informing effective conservation strategies for the SASL in Chile. Moreover, such data are crucial for complying with the regulatory requirements of the United States Marine Mammal Protection Act (MMPA), specifically the Fish and Fish Product Import Provisions (NOAA 2016). These provisions require exporting countries to implement measures for monitoring and mitigating both intentional and incidental marine mammal mortality and serious injury that are comparable in effectiveness to similar measures for U.S. fisheries under the MMPA (Sepúlveda et al. 2023). Because Chile is among the top seafood-exporting countries to the United States, the MMPA Fish and Fish Product Import Provisions may have substantial socio-economic implications for the country, particularly given the uneven development of monitoring and marine-mammal bycatch mitigation across fisheries (Félix et al. 2021).

To address existing gaps in data and information for bycatch management, Hines et al. (2020) developed the Bycatch Risk Assessment (ByRA) toolbox, a method for conducting spatial and temporal evaluations of bycatch risk using datasets of varying quality. ByRA facilitates the identification of priority areas for research and potential immediate management actions, while allowing the characterization and evaluation of the uncertainty of input data. Risk assessments systematically analyze both the likelihood of an event occurring and its potential consequences (Van Duijne et al. 2008, Gibbs & Browman 2015). When applied within a geographic information system (GIS) framework, risk assessments prove especially valuable by integrating data of variable quality to identify geographic areas where management interventions can be most effective (Verutes et al. 2020, Frantz et al. 2024). These assessments are crucial for characterizing bycatch risk, prioritizing monitoring efforts across different sites, gear types, and timeframes, and informing the design of future data collection strategies (Briscoe et al. 2016, Pitcher et al. 2017).

The ByRA toolbox was used to create a spatially explicit geodatabase for nine different fisheries that interact with SASL in Chile. The objectives were: (1) to spatially identify areas of greatest SASL bycatch risk, and (2) to compare the risk of SASL bycatch among different fisheries and fishing gears. These results will be used to design and implement national mitigation measures to reduce conflicts with fisheries while ensuring effective management as well as the conservation of the SASL in Chile.

2. METHODS

2.1 *South American sea lion distribution*

The SASL is distributed continuously along the Chilean coast (18°–56°S), with an estimated population of approximately 128,000 individuals (Oliva et al. 2020). For this study, the distribution and abundance of this species was divided into reproductive (January-February) and non-reproductive periods (March-December), using the most recent seasonal colony census data available for each region: between 2011-2019 from the Arica to Aysén regions (18-49°S; Oliva et al. 2020) and 2001 for the Magallanes region (49-56°S; Venegas et al. 2002) (Figure 1, Table S1). These surveys included demographic-level data on the abundance of pups, juveniles, females, subadult males, and adult males. Based on the estimated abundance of SASL at each colony, sites were classified as: very low (1-100 individuals), low (101-500 individuals), medium (501-1500 individuals), high (1501-5000 individuals) and very high (>5000 individuals), according to the criteria described in Oliva et al. (2019) and confirmed by Chilean pinniped specialists.

Within each abundance class (from very low to very high), multiple distance buffers were applied to all colonies, indicating the maximum recorded distance from shore that each demographic group (juveniles, females, subadult males and adult males) could travel from a colony. Juveniles generally travel within 20 km from a colony (Hückstädt et al. 2014), females within 40 km (Rodríguez et al. 2013), subadult males within 100 km (Rodríguez et al. 2013, Sepúlveda et al. 2015), and adult males within 300 km (Campagna et al. 2001, Hückstädt & Krautz 2004). The corresponding proportion of the population that could occur within each buffer distance was then attributed to the corresponding buffer. Within the first 20 km from the colony, 100% of the population may be present, so the potential presence value is 100. Beyond this distance, juveniles are no longer considered, reducing the potential presence to 90 (90% of the population). For each subsequent distance buffer, the proportion of the demographic group that does not range beyond that distance is subtracted (Table 1). For example, females are excluded beyond 40 km (Rodríguez et al. 2013), subadult males beyond 100 km (Rodríguez et al. 2013), and only adult males remain up to 300 km (Campagna et al. 2001). The 300 km buffer was not included in the reproductive period estimates because adult males are generally on land during this period while holding territories in reproductive colonies (Sepúlveda et al. 2011).

Table 1. Buffer distances from colonies with the percent of the population that could occur within them and corresponding demographic groups.

Buffer Distance (Km)	**Potential Presence Value (% of the population)**	**Demographic Group**
0-20	100	Adult males, subadult males, females, juveniles
20-40	90	Adult males, subadult males, females
40-100	50	Adult males, subadult males
100-300	10	Adult males*

* Adult males were excluded for the reproductive period distribution estimation

The resulting buffers of potential presence for each age/sex class were combined in a weighted sum to account for the higher number of animals likely to be present near to high abundance haul-out sites versus low abundance sites, using the software ArcGIS Pro 3.3 (ESRI 2024). To meet ByRA spatial criteria requirements, the weighted sum was classified as integer values 1-3 with the quantile method, assigning an equal number of pixels to each class. Values of 1 indicated low distribution probability, 2 medium, and 3 high. This approach resulted in two seasonal distribution maps (reproductive and non-reproductive), representing the maximum potential spatial extent accessible to SASL based on haul-out abundance and the at-sea ranging capacity of different demographic groups. These maps describe relative spatial patterns of potential presence rather than absolute occurrence probabilities.

2.2 ***Fisheries selection and data sources***

Based on previous studies documenting interactions and bycatch of SASL along the Chilean coast (see Table 1), nine fisheries with documented interactions were selected for this assessment, as reported in the scientific literature and confirmed by fisheries scientists at the Instituto de Fomento Pesquero (IFOP; Fisheries Development Institute): five using purse-seine gear and four using trawl gear. According to the Chilean General Law on Fishery and Aquaculture (Law No. 18.892), three of the purse-seine fisheries are classified as artisanal, whereas the remaining two purse-seine and all four trawl fisheries are classified as industrial (Table 2). The northern and central pelagic artisanal fisheries are the largest in terms of both the number of vessels operating in 2019 and total recorded landings.

For each fishery, information on the fishing dataset of the vessels was collected between December 2015 and January 2019. Data were obtained by on-board scientific observers from the IFOP as part of the discard and bycatch monitoring programs. A total of 23,278 geographic positions of fishing sets were recorded from the observers' data across the entire period and for all nine fisheries. These data were organized in an online management system using a standard coordinate and projection reference (UTM, WGS84).

Fishery boundaries were delineated in ArcGIS Pro by generating a 20 km buffered minimum convex hull around the fishing positions. The resulting polygons were then adjusted to accurately represent the operational area of each fishery. Fishing set data were filtered to exclude locations on land and, using the date of each set, were assigned to one of two seasons (reproductive and non-reproductive) to match the sea lion seasonal cycle. A kernel density analysis was performed using parameters defined through expert judgment from IFOP, according to the specific characteristics of each fishery. Search radii ranged from 5 to 15 km, based on the typical clustering of vessels, the spatial scale of the study, and the approximate distribution and density of fishing activity. The resulting kernel density maps represent the spatial distribution of fishing density and were later used as input data for the bycatch risk assessment analysis.

2.3 *Bycatch risk assessment*

The Bycatch Risk Assessment (ByRA) model (Hines et al. 2020, Verutes et al. 2020) was used to assess bycatch risk for SASL for each of the nine selected fisheries. ByRA is a spatially explicit and flexible analysis tool derived from the Habitat Risk Assessment (HRA) framework of the Natural Capital Project InVEST toolbox (naturalcapitalproject.stanford.edu/software/invest; Natural

Capital Project 2025) which estimates bycatch risk based on the spatial and temporal overlap between species occurrence and fishing activities. Within this framework, risk is calculated as a function of exposure and consequence (Samhouri & Levin 2012, Arkema et al. 2014). Exposure criteria represent the degree to which a population experiences a given fishery-related stressor in space and time, reflecting the extent and intensity of spatial overlap between species distribution and fishing activity. Consequence criteria describe species-specific sensitivity and resilience to fisheries impacts, reflecting how a population is expected to respond to an interaction with the stressor. In terms of sensitivity, consequence is defined by an expert assessment of how a population will respond to an impact (e.g., likelihood of mortality in specific gear type of the species and life stages affected by gear). In terms of resilience, consequence is defined based on a scientific assessment of the population dynamics and life history of a species (including the age of maturity, reproductive strategy, population connectivity and the local conservation status of the species) (Arkema et al. 2014, Verutes et al. 2000).

The ByRA framework relies on spatial data layers representing the best data available for the distribution of the species and the fisheries activity. For this analysis, geographic information system layers were generated to represented the spatial overlap between fishing activity and SASL seasonal distribution, as this spatial intersection constitutes a central component of the ByRA analysis. Exposure and consequence criteria were scored using ordinal rankings (low, medium, high, or null when not applicable) and incorporated into the model (see Verutes et al. 2020). Bycatch risk is therefore quantified as the combined effect of exposure and consequence, such that higher risk values result from greater spatial and temporal overlap, higher species sensitivity and/or lower resilience, or a combination of these factors. The criteria definitions and scoring framework used in previous ByRA applications were adopted, in which the maximum risk score for a single stressor is 2.83, as suggested by the Natural Capital Project (2025). Resulting risk values were interpreted as a relative, continuous gradient from lower to higher risk, following previous applications of the ByRA approach (Costanza et al. 2021, Frantz et al. 2024). In addition to spatial risk maps, ByRA outputs included exposure-consequence plots for the reproductive and non-reproductive periods, which summarize the relative position of each fishery within exposure-consequence space (Verutes et al. 2020).

Table 2. Summary of nine fisheries selected to evaluate the bycatch risk for the South American sea lion (*Otaria byronia*). For each fishery, the gear type, area of operation, number of vessels active in 2019, main target species, and total landings for 2019 are provided. Previous studies reporting interactions and/or bycatch are also included. Number of vessels and landing data are sourced from SERNAPESCA (2024).

Fishery	**Gear type**	**Area of operation**	**N° of vessels**	**Main resources extracted**	**Landings (t)**	**Interaction/bycatch evidence**
Pelagic artisanal north	Purse-seine	18° – 24°S	88	Anchovy (*Engraulis ringens*) Chub mackerel (*Scomber japonicus*) Jack Mackerel (*Trachurus murphyi*)	209,354 3,848 10,156	Sepúlveda et al. (2007), Vega et al. (2024).
Pelagic industrial north	Purse-seine	18° – 24°S	13	Anchovy (*Engraulis ringens*) Chub mackerel (*Scomber japonicus*) Jack Mackerel (*Trachurus murphyi*)	353,435 55,202 14,490	González et al. (2015), Punt et al. (2021), Vega et al. (2024).
Pelagic artisanal central	Purse-seine	33° – 40°S	406	Anchovy (*Engraulis ringens*) Common sardine (*Strangomera bentincki*)	150,080 253,760	Vega et al. (2024).

Pelagic industrial central	Purse-seine	33° – 44°S	27	Jack Mackerel (*Trachurus murphyi*) Jibia	402,199 40,629	Hückstädt & Antezana (2003), Vega et al. (2024).
Pelagic artisanal south	Purse-seine	40° – 44°S	423	Falkland sprat (*Sprattus fuegensis*) Chilean hake (*Merluccius gayi gayi*)	11,261 3,935	Vega et al. (2024).
Chilean hake Industrial < 1000 hp*	Trawl	33° – 34°S	4	Chilean hake (*Merluccius gayi gayi*)	3,625	Bernal et al. (2025), Apablaza et al. (2025).
Chilean hake industrial > 1000 hp*	Trawl	35° – 40°S	4	Chub mackerel (*Scomber japonicus*) Chilean hake (*Merluccius gayi gayi*)	27,117 14,375	Reyes et al. (2013), Bernal et al. (2025)
Bottom ice industrial fleet	Trawl	41° – 47°S	3	Patagonian grenadier (*Macruronus magellanicus*) Southern hake (*Merluccius australis*)	4,415 6,268	Punt et al. (2021), Bernal et al. (2025).

Bottom factory industrial fleet	Trawl	43° – 57°S	3	Patagonian grenadier (*Macruronus magellanicus*)	6,300	Punt et al. (2021), Bernal et al. (2025).
				Southern hake (*Merluccius australis*)	6,407	

*hp (horsepower, engine power). Vessels with >1000 hp are large industrial vessels with higher engine power and greater fishing capacity, whereas vessels with <1000 hp are smaller/lower-powered industrial vessels.

2.4 *Uncertainty standard*

To account for variation in data quality and availability, uncertainty metrics and importance weights were added for each data source and category bin in the exposure–consequence table (Constanza et al. 2021). The tri-color matrix designed by Verutes et al. (2020) was used to characterize the uncertainty associated with the sources informing the ByRA framework, including: (1) SASL haul-out presence and abundance data (Section 2.1), (2) SASL maximum recorded distance by age-class (Section 2.1; Table 1), (3) fishing occurrence data (Section 2.2), and (4) bycatch information (Table 2) (Hines et al. 2020). These datasets inform the risk calculations through the exposure–consequence table. The final color assigned to each data type was determined based on the quality of the available input data. Uncertainty is visualized with a stoplight framework of green, yellow, and red, indicating low to high uncertainty. Output risk maps are presented with a stoplight icon to highlight data limitations (Verutes et al. 2020).

3. RESULTS

3.1 *SASL distribution*

The distribution of SASL along the Chilean coast, with known haul-out sites, for the reproductive (January–February) and non-reproductive (March-December) periods is shown in Figure 1. The distribution range of the SASL is much larger during the non-reproductive period due to an increase in the number of colonies during this time and the wider dispersal of males once the reproductive period ceases. By contrast, during the reproductive period the distribution contracts and is concentrated around reproductive colonies, where adult males defend territories.

3.2 *Bycatch risk*

The spatial risk of bycatch for each fishery in reproductive and non-reproductive periods is shown in Figures 2 and 3, respectively. Among purse-seine fisheries, both risk magnitude and spatial extent differed considerably. The Pelagic industrial north fleet exhibited the highest bycatch risk among pelagic fleets, with two distinct hotspots: one in oceanic waters off northern Chile and another along the coast between 20° and 25°S (Figure 2). The Pelagic artisanal north and Pelagic industrial central fleets showed lower risk magnitudes but broader spatial coverage. In contrast, the Pelagic artisanal central and Pelagic artisanal south fleets presented the lowest bycatch risk, both in magnitude and extent (Figure 2). Four of five purse-seine fisheries were assigned a yellow stoplight, indicating moderate uncertainty in data quality and interpretation. The exception was the Pelagic industrial central fishery with a green–yellow stoplight, reflecting relatively low uncertainty in data.

In trawl fisheries, three of the four fleets exhibited comparatively higher bycatch risk. Risk magnitude was relatively homogeneous for Chilean hake Industrial >1000 hp and the Bottom ice fleet, while the Chilean hake Industrial <1000 hp fleet showed a more localized peak in the central region (Figure 3). The fleets with the widest risk extent were Chilean hake Industrial >1000 hp, Bottom ice, and Bottom factory, although the latter showed lower overall magnitude compared to the other trawls. All trawl fisheries received green–yellow stoplights, reflecting low uncertainty in data.

For most fisheries, the spatial extent of risk was larger during the non-reproductive season compared to the reproductive season. This was particularly marked in purse-seine fisheries, where risk contracted sharply during the reproductive season (Figure 2). In trawl fisheries, spatial extent was similar across both periods, especially for Chilean hake Industrial >1000 hp and the Bottom ice fleet (Figure 3). By contrast, risk magnitude was similar between periods, except in Pelagic artisanal south, Chilean hake Industrial <1000 hp, and the bottom ice fleet, within which all three showed higher risk during the non-reproductive season.

Bycatch risk was concentrated nearshore for most fisheries. Exceptions were the Pelagic industrial north and Pelagic industrial central during the non-reproductive season, and the Chilean hake Industrial <1000 hp fleet during both seasons, which showed more offshore-distributed bycatch risk.

3.3 *Exposure/consequence plots and gear*

The ByRA outputs showing exposure/consequence plots of bycatch risk by fishery for the reproductive and non-reproductive periods of the SASL are shown in Figure 4. During the reproductive period, differences in exposure levels among fisheries were more marked than in the non-reproductive period. In the reproductive period, the Chilean hake Industrial >1000 hp fishery, followed by the bottom ice fleet fishery, contributed the highest percentages of bycatch risk (Figure 4). In the non-reproductive period, bycatch risk was more evenly distributed across fisheries, with consistently higher risk values compared to the reproductive season. In this period, the highest risk values were associated with the Chilean hake Industrial <1000 hp and Chilean hake Industrial >1000 hp fisheries, followed by the Bottom factory fleet (Figure 4). These seasonal differences reflect changes in exposure associated with seasonal shifts in SASL distribution.

4. DISCUSSION

Results show clear temporal and fleet-specific differences in SASL distribution and bycatch risk along the Chilean coast. Overall, risk was highest in trawl fleets and the pelagic industrial north purse-seine fleet, with a broader spatial extent during the non-reproductive period.

Although SASL interactions with major Chilean fisheries have been documented previously (e.g. Vega et al. 2024, Bernal et al. 2025), no other study has synthesized these data to comparatively assess risk for a same species across fleets at a national scale. By identifying the fisheries, areas, and seasons associated with the highest risk, these findings provide guidance to prioritize targeted, cost-effective mitigation and monitoring where conservation benefits are expected to be greatest, while minimizing unnecessary burdens on low-risk fisheries. This is especially relevant in Chile, where conservation resources and enforcement capacity are limited across a vast coastline.

The ByRA approach provides essential insights into the bycatch risk of SASL across the nine analyzed fisheries. Results indicate that trawl fisheries pose the highest bycatch risk to SASL, particularly the Chilean hake industrial trawls (both <1000 hp and >1000 hp) during the non-reproductive period, and the bottom ice fleet during the reproductive period. The higher risk associated with trawl fisheries is consistent with the higher mortality documented for this gear type in Chile and elsewhere, because when interactions occur, trawls are more likely to result in fatal outcomes (Punt et al. 2021, Romero et al. 2025). In Chile, Reyes et al. (2013) reported an observed bycatch rate of 6.3 SASL per working day (equivalent to 1.2 sea lions per trawl) in the hake trawl fishery in 2004. Additionally, data collected by scientific observers from IFOP documented the bycatch of 146 SASL in the hake trawl fishery off central Chile in 2019, with an observed mortality rate of 82%, despite lower bycatch rates (<0.3 SASL per haul) (Bernal et al. 2020). Similar high mortality in trawls has also been reported in Argentine Patagonia and for other pinnipeds (e.g. Chilvers 2008, Hamer & Goldsworthy 2006, Romero et al. 2025).

The relatively high bycatch risk to SASL in industrial trawls occurs because pinnipeds, once entangled, are dragged to the seafloor (90–250 m depth), where trawls operate, and are unable to escape. Under these conditions, individuals typically die either from prolonged submergence (45 minutes to three hours) or from compressive trauma caused by tons of catch accumulating in the codend (Reyes et al. 2013, Crespo et al. 2021, Sepúlveda et al. 2023), resulting in high post-capture mortality (Punt et al. 2021). The bycatch risk for SASL in trawl fisheries relative to other fisheries may also be driven by their predominant operation in coastal areas (Molinet et al. 2024), where risk is consistently higher than in offshore zones. This pattern can be explained by several factors. In addition, the distance individuals can travel from haul-out sites varies by age and sex class: while some animals can move farther offshore, juveniles and lactating females usually remain within 20 km of colonies (Campagna et al. 2001, Hückstädt & Krautz 2004, Rodríguez et al. 2013, Hückstädt et al. 2014, Sepúlveda et al. 2015). Juveniles appear to be the most vulnerable group, as they forage closer to shore and are more prone to entanglement due to their limited foraging experience and lower ability to avoid gear (Bjørge et al. 2002, Hückstädt & Antezana 2003, Jounela et al. 2019). Compared to other age classes, juveniles' coastal foraging behavior results in higher spatial overlap with fishing operations in nearshore areas, where animal density is also higher (Romero et al. 2025). Several studies confirm this spatial pattern, reporting that bycatch increases as fishing activity occurs closer to SASL colonies (Riet-Sapriza et al. 2013, González et al. 2015, Sepúlveda et al. 2018). This likely reflects a strategy in which sea lions exploit prey near colonies to minimize travel costs while maximizing energy intake (Costa 1993, Pérez-Venegas et al. 2025). Similarly, fishers too prefer nearshore grounds because of lower operational costs (e.g. fuel and travel time), which further increases the probability of interaction (Daw 2008, Tidd et al. 2015).

Given the consistently high risk in trawl fisheries and the mechanisms driving high post-capture mortality, management efforts should prioritize mitigation in these fleets, especially the southern hake trawl fisheries. In 2021, the Chilean government made significant progress in implementing bycatch mitigation measures in industrial trawl and purse-seine fisheries, including the introduction of exclusion devices such as the Sea Lion Exclusion Device (SLED), which consists of a barrier or grid installed at the entrance to the codend to allow marine mammals to escape through a window located at the opening while retaining target species (SUBPESCA Res. Ex. N° 3120/2021). The deployment of SLEDs in the small-scale (<1000 hp) Chilean hake industrial trawl fishery in central Chile has resulted in a marked reduction in incidental mortality of SASLs, while maintaining operational efficiency and without compromising target species catch rates (Queirolo et al. 2025). Notably, when SASL entered the trawl net, they were able to exit safely through the SLED escape hatch during hauling operations (Queirolo et al. 2025). Similar outcomes have been reported in other countries where SLEDs have been implemented, supporting the efficacy of such devices in reducing marine mammal bycatch in demersal trawl fisheries (e.g. Hamilton & Baker 2019, Iriarte & Winter 2025). Based on these findings, starting in 2022, SLEDs are mandatory across all trawl fisheries (Rex. Ex. No. 3120/2021). Importantly, the risk maps show that interaction risk is broader—and in several fleets higher—during the non-reproductive period; therefore, SLED deployment and compliance checks should be prioritized from March to December in nearshore trawl grounds where overlap with SASL distribution is greatest.

Although bycatch in purse-seine fisheries is widely reported globally (Northridge 2018), the relative risk to SASL in these fisheries was lower in ByRA results as compared to trawls. Data from the IFOP scientific observer program indicate a high number of SASL captures in Chilean industrial purse-seine fleets (e.g. 4,468 individuals in 3,350 observed sets from 2017 to 2020; Vega et al. 2021). However, most of the sea lions escaped before entrapment by leaping over the cork line prior to net closure (Punt et al. 2021, Sepúlveda et al. 2023). This behavior is consistent with the low mortality rate recorded for purse seines (0.2%; Vega et al. 2021), which in turn accounts for the reduced overall bycatch risk of this gear type.

Among purse-seine fisheries, ByRA identified the industrial northern fleet as the pelagic fishery posing the highest bycatch risk to SASLs in both reproductive and non-reproductive periods. As in trawl fisheries, the elevated risk appears to be strongly associated with the fleet's predominant operations in coastal areas, where overlap with SASL distribution is greatest. Consistent with this pattern, Frantz et al. (2024) reported that cumulative risk is highest within the first 5 NM (9.3 km), where both fishing effort and SASL density are concentrated, highlighting this zone as a priority area for mitigation. In line with this, SUBPESCA issued regulation N° 2667/2021, primarily aimed at reducing small cetacean mortality but also including measures relevant to SASL. These include protocols for releasing animals by the use of protective barriers to minimize harm to both sea lions and crew in case of on-board interactions. However, these mitigation measures are currently restricted to the industrial sector and have not yet been implemented in artisanal fisheries, where interactions may also be frequent, especially considering that operations are even more concentrated in nearshore areas.

As expected, for almost all the fisheries analyzed, the risk of bycatch is higher during the non- reproductive period of the SASL. This pattern aligns with previous studies for this species, both for Chile (de la Torriente et al. 2010; Sepúlveda et al. 2007, 2018) and other countries (De María et al. 2014, Machado et al. 2016), showing that interactions between SASL and fisheries and the consequent bycatch of animals are significantly reduced or absent during the reproductive period. Temporal variation can be explained at least partly by the reproductive cycle of pinnipeds. This is because individuals, particularly males, remain near rookeries to defend territories or harems during the reproductive season and typically do not forage (Sepúlveda et al. 2011, Romero et al. 2025). During the austral fall, winter, and spring (March to December), males disperse to intensively forage and recover energy reserves lost during the reproductive season, leading to an expansion of their foraging range, which in turn could increase overlap with fishing activities (Sepúlveda et al. 2018) and increase their risk of bycatch. This seasonal shift in foraging behavior likely contributes to the observed increase in bycatch risk outside the reproductive period.

The quality and resolution of data varied among the assessed fisheries. Most of the pelagic fisheries were categorized as "yellow" under the data quality classification scheme, indicating a medium level of confidence in the available information. This classification primarily reflects some deficiencies in spatial and operational data, including poorly defined fishing effort distribution and/or limited observer coverages. For example, the pelagic industrial north fishery shows a high estimated bycatch risk based on model outputs; however, they are flagged with yellow stoplight indicators due to insufficient or low-quality supporting data. Despite this, independent records (e.g. IFOP reports from fisheries observers, Punt et al. 2021, Vega et al. 2024) have documented bycatch events involving the focal species in these fisheries, suggesting that the predicted relative risk may indeed correspond to actual risk. Conversely, the three pelagic artisanal fisheries (north, central and south) were associated with a low modeled bycatch risk, but it also received a yellow data quality classification. Such data limitations constrain the reliability of risk estimates and introduce a high degree of uncertainty. Consequently, the bycatch risk associated with these fisheries may be either underestimated or overestimated. Overall, the presence of yellow classifications in the data quality indicator does not necessarily invalidate the risk assessments, but it does necessitate a cautious interpretation of the results, and emphasizes the importance of targeted data improvement efforts in these fisheries. In addition, the lack of systematically recorded and georeferenced bycatch events for SASL across most fleets prevents a formal spatial validation of predicted risk against observed bycatch locations. Improving the public availability of spatially explicit information on vessel operations would enhance transparency and substantially strengthen risk assessment and management prioritization, particularly in data-poor fisheries.

To appropriately contextualize the scope of these findings, interpretation of ByRA outputs should consider three key limitations. First, results depend on the availability and quality of input data: many applications necessarily use qualitative information or data borrowed from other geographic locations, and data-quality indicators are therefore reported with the results. When more complete distribution data exist (e.g. formal surveys or comprehensive interview programs), ByRA can incorporate quantitative species distribution models to improve exposure characterization (Hines et al. 2020, Costanza et al. 2021, Frantz et al. 2024). Second, ByRA quantifies risk only from fishery stressors that directly overlap the species' distribution in space and time, and does not capture indirect pressures or risks outside overlap areas. Third, due to limited information on stressor interactions, ByRA assumes additive effects; this parsimonious assumption may underrepresent risk by omitting synergisms or overrepresent the role of individual stressors by not capturing more complex responses (see http://releases.naturalcapitalproject.org/invest-userguide/latest/en/habitat_risk_assessment.html).

Results highlight the importance of prioritizing mitigation in those Chilean fisheries identified as having the highest bycatch risk for SASL. Although estimated mortality levels may currently fall below the thresholds of biological concern (Punt et al. 2021), these estimates provide only a partial view given the limited spatial and temporal coverage of documented interactions, as well ans the unceartinty associated with the ByRA results. Furthermore, unexpected events such as intense El Niño Southern Oscillation (ENSO) episodes (Sielfeld & Guzmán 2002) or epizootics, such as the recent avian influenza outbreak that caused severe mortality in the SASL population in Chile (Ulloa et al. 2023, Plaza et al. 2024), could compound existing pressures and rapidly shift the conservation status of SASL. In this context, sustained monitoring combined with precautionary and adaptive management measures is essential to reduce uncertainty and safeguard the long-term persistence of SASL populations in Chilean waters.

According to these ByRA results, future management actions should prioritize spatially explicit and fleet-specific mitigation strategies, with particular attention to areas and seasons where interaction risk is elevated. Measures such as the mandatory implementation of mitigation tools (e.g. SLEDs) and spatiotemporal fishing restrictions should be reinforced where conservation benefits are expected to be greatest. To strengthen the effectiveness and credibility of bycatch management in Chile, particularly under increasing international scrutiny such as the U.S. Marine Mammal Protection Act (MMPA) import rule, it is essential to establish a long-term, standardized monitoring program. This should include increased observer coverage, technological tools for remote monitoring (such as electronic monitoring systems; Gilman et al. 2019), and capacity-building where data gaps remain significant, particularly in artisanal fisheries. Ultimately, advancing toward sustainable coexistence between fishing activity and marine mammal conservation will require adaptive, science-informed, and participatory management frameworks (Gilman et al. 2022). Overall, these findings provide a science-based foundation to guide targeted and efficient bycatch mitigation in Chilean fisheries.

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7. References

Apablaza, P., Queirolo, D., Sepúlveda, M., & Ahumada, M. (2025). Interaction between South American sea lions (*Otaria byronia*) and trawling fisheries recorded through video cameras. Marine Mammal Science, e13224.

Arkema, K. K., Verutes, G., Bernhardt, J. R., Clarke, C., Rosado, S., Canto, M., ... & De Zegher, J. (2014). Assessing habitat risk from human activities to inform coastal and marine spatial planning: a demonstration in Belize. Environmental Research Letters, 9(11), 114016.

Avila, I. C., Kaschner, K., & Dormann, C. F. (2018). Current global risks to marine mammals: taking stock of the threats. Biological Conservation, 221, 44-58.

Bernal, C., Román, C., Escobar, V., San Martín, M., Vargas, C., Adasme, L., López, J., Azócar, J., Saavedra, J & Bravo, C. (2020). Informe final. Sección I. Convenio de desempeño 2019, Programa de investigación y monitoreo del descarte y captura de pesca incidental en pesquerías demersales, año 2019. Subsecretaría de Economía y EMT. 283 p.

Bernal, C., Escobar, V., Román, C., San Martín, C., Adasme, C., Azócar, J., Vargas, C., Saavedra-Nievas, J., López, J., & Bravo, C. (2025). Informe final. Sección I. Convenio de desempeño 2024, Programa de investigación y monitoreo del descarte y captura de pesca incidental en pesquerías demersales, año 2024–2025. Subsecretaría de Economía y EMT. 166 p.

Bjørge, A., ØIen, N., Hartvedt, S., Bøthun, G., & Bekkby, T. (2002). Dispersal and bycatch mortality in gray, *Halichoerus grypus*, and harbor, *Phoca vitulina*, seals tagged at the Norwegian coast. Marine Mammal Science, 18(4), 963-976.

Bordino, P., Kraus, S., Albareda, D., Fazio, A., Palmerio, A., Mendez, M., & Botta, S. (2002). Reducing incidental mortality of Franciscana dolphin Pontoporia blainvillei with acoustic warning devices attached to fishing nets. Marine Mammal Science, 18(4), 833-842.

Braulik, G. T., Taylor, B. L., Minton, G., Notarbartolo di Sciara, G., Collins, T., Rojas-Bracho, L., ... & Reeves, R. R. (2023). Red-list status and extinction risk of the world's whales, dolphins, and porpoises. Conservation biology, 37(5), e14090.

Briscoe, D. K., Maxwell, S. M., Kudela, R., Crowder, L. B., & Croll, D. (2016). Are we missing important areas in pelagic marine conservation? Redefining conservation hotspots in the ocean. Endangered Species Research, 29(3), 229-237.

Brownell Jr, R. L., Reeves, R. R., Read, A. J., Smith, B. D., Thomas, P. O., Ralls, K., ... & Wang, J. Y. (2019). Bycatch in gillnet fisheries threatens critically endangered small cetaceans and other aquatic megafauna. Endangered Species Research, 40, 285-296.

Campagna, C., Werner, R., Karesh, W., Marín, M. R., Koontz, F., Cook, R., & Koontz, C. (2001). Movements and location at sea of South American sea lions (*Otaria flavescens*). Journal of Zoology, 255(2), 205-220.

Castilla, J. C. (2010). Fisheries in Chile: small pelagics, management, rights, and sea zoning. Bulletin of Marine Science, 86(2), 221-234.

Chilvers, B. L. (2008). New Zealand sea lions *Phocarctos hookeri* and squid trawl fisheries: bycatch problems and management options. Endangered Species Research, 5(2-3), 193-204.

Chilvers, B. L., & Meyer, S. (2018). Conservation needs for the endangered New Zealand sea lion, *Phocarctos hookeri*. Aquatic Conservation: Marine and Freshwater Ecosystems, 27(4), 846–855.

Cooke, J. G. (2020). *Eubalaena glacialis*. The IUCN Red List of Threatened Species 2020: e.T41712A162001243.

Costanza, A. B., Guidino, C., Mangel, J. C., Alfaro-Shigueto, J., Verutes, G., Caillat, M., Samanta, A. & Hines, E. (2021). Participatory risk assessment of humpback whale (*Megaptera *novaeangliae*) and leatherback turtle (*Dermochelys coriacea*) bycatch in northern Peru. Frontiers in Marine Science, 8, 776965.

Costa, D. P. (1993). The relationship between reproductive and foraging energetics and the evolution of pinniped lactation strategies. Symposia of the Zoological Society of London, 66, 293–314.

Crespo, E., Oliveira, L. & Sepúlveda, M. (2021). South American sea lion *Otaria flavescens* (Shaw, 1800). In: Heckel, G & Y. Schramm (Eds.): Ecology and Conservation of Pinnipeds in Latin America, pp. 93-118. Springer-Nature, Switzerland.

Daw, T. M. (2008). Spatial distribution of effort by artisanal fishers: Exploring economic factors affecting the lobster fisheries of the Corn Islands, Nicaragua. Fisheries Research, 90(1–3), 17–25.

De María, M., Barboza, F. R., & Szteren, D. (2014). Predation of South American sea lions (*Otaria flavescens*) on artisanal fisheries in the Rio de la Plata estuary. Fisheries Research, 149, 69-73.

De la Torriente, A., Quiñones, R. A., Miranda-Urbina, D. A., & Echevarría, F. (2010). South American sea lion and spiny dogfish predation on artisanal catches of southern hake in fjords of Chilean Patagonia. ICES Journal of Marine Science, 67(2), 294-303.

FAO. (2024). The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Rome: FAO.

Félix, F, Mangel, J.C., Alfaro-Shigueto, J., Cocas, L.A., Guerra, J., Pérez-Alvarez, M.J. & Sepúlveda, M. (2021). Challenges and opportunities for the conservation of marine mammals in the Southeast Pacific with the entry into force of the US Marine Mammal Protection Act. Regional Studies in Marine Science 48, 102036.

Frantz, B. H., Sepúlveda, M., García-Reyes, M., Vega, R., Palacios, D. M., Bedriñana-Romano, L., Hückstädt, L., Santos-Carvallo, M., David, J.D & Hines, E. (2024). Combining potential and realized distribution modeling of telemetry data for a bycatch risk assessment. Ecology and Evolution, 14(6), e11541.

García-Reyes, M., Sydeman, W., Koval, G., Palacios, D., Bedriñana-Romano, L., Sepúlveda, M & Hines, E. (2023). Changes in the Sea Surface Temperature "footprint" in Eastern Boundary Upwelling Systems. Frontiers of Marine Science 10, 1158472.

Gibbs, M. T., & Browman, H. I. (2015). Risk assessment and risk management: a primer for marine scientists. ICES Journal of Marine Science, 72(3), 992-996.

Gilman, E., Legorburu, G., Fedoruk, A., Heberer, C., Zimring, M., & Barkai, A. (2019). Increasing the functionalities and accuracy of fisheries electronic monitoring systems. Aquatic Conservation: Marine and Freshwater Ecosystems, 29(6), 901-926.

Gilman, E., Hall, M., Booth, H., Gupta, T., Chaloupka, M., Fennell, H., ... & Milner-Gulland, E. J. (2022). A decision support tool for integrated fisheries bycatch management. Reviews in Fish Biology and Fisheries, 32(2), 441-472.

Goetz, S., Wolff, M., Stotz, W., & Villegas, M. J. (2008). Interactions between the South American sea lion (*Otaria flavescens*) and the artisanal fishery off Coquimbo, northern Chile. ICES Journal of Marine Science, 65(9), 1739-1746.

González, A., Vega, R., & Yáñez, E. (2015). Operational interactions between the South American sea lion *Otaria flavescens* and purse seine fishing activities in northern Chile. Revista de Biología Marina y Oceanografía, 50(3), 479-489.

Guerrero, A.I, Pavez, G., Santos-Carvallo, M., Rogers, T.L. & Sepúlveda, M. (2020). Foraging behaviour of the South American sea lion (*Otaria byronia*) in two disparate ecosystems and evidence of farmed salmon consumption through blubber fatty acids analysis. Scientific Reports 10:5725.

Hamilton, S., & Baker, G. B. (2019). Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. Reviews in Fish Biology and Fisheries, 29(2), 223-247.

Hamer, D.J. & Goldsworthy, S.D. (2006). Seal–fishery operational interactions: Identifying the environmental and operational aspects of a trawl fishery that contribute to by-catch and mortality of Australian fur seals (*Arctocephalus pusillus doriferus*). Biological Conservation, 130(4), 517-529.

Hernández, J., et al. (2023). Programa de Seguimiento de las Principales Pesquerías Pelágicas de la zona norte de Chile, año 2022. Instituto de Fomento Pesquero, Boletín de Difusión.

Hines, E., Ponnampalam, L. S., Junchompoo, C., Peter, C., Vu, L., Huynh, T., ... & Verutes, G. M. (2020). Getting to the bottom of bycatch: a GIS-based toolbox to assess the risk of marine mammal bycatch. Endangered Species Research, 42, 37-57.

Hordern, E., White, T.B., Berthinussen, A., Smith, R.K., Sutherland, W.J., & Christie, A.P. (2025). Prioritizing future evidence needs for marine and freshwater mammal conservation action. Animal Conservation, 28(4), 542-552.

Hückstädt, L. A., & Antezana, T. (2003). Behaviour of the southern sea lion (*Otaria flavescens*) and consumption of the catch during purse-seining for jack mackerel (*Trachurus symmetricus*) off central Chile. ICES Journal of Marine Science, 60(5), 1003-1011.

Hückstädt, L. A., & Krautz, M. C. (2004). Interaction between southern sea lions *Otaria flavescens* and jack mackerel *Trachurus symmetricus* commercial fishery off central Chile: a geostatistical approach. Marine Ecology Progress Series, 282, 285-294.

Hückstädt, L. A., Quiñones, R. A., Sepúlveda, M., & Costa, D. P. (2014). Movement and diving patterns of juvenile male South American sea lions off the coast of central Chile. Marine Mammal Science, 30(3).

Iriarte, V., Winter, A. 2025. Disentangling pinniped incidental mortality in a bottom-trawl fishery with seal exclusion devices. Front. Mar. Sci. Sec. Marine Megafauna. Volume 12 – 2025.

Iriarte, A., Olavarría, C., Canto Hernández, J., Espinoza-Miranda, C., & Gelcich, S. (2023). Los mamíferos marinos de Chile. Ediciones Flora & Fauna de Chile.

Inter-American Tropical Tuna Commission (IATTC). 2019. *SAC-10-INF-C(b): National reports for 2018 – Chile.*Scientific Advisory Committee (SAC), 10th Meeting, IATTC.

Jounela P, Sipila¨ T, Koskela J, Tiilikainen R, Auttila M, Niemi M, et al (2019) Incidental bycatch mortality and fishing restrictions: impacts on juvenile survival in the Endangered Saimaa ringed seal *Pusa hispida saimensis*. Endang Species Res 38, 91–99.

Knowlton, A. R., Hamilton, P. K., Marx, M. K., Pettis, H. M., & Kraus, S. D. (2012). Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. Marine Ecology Progress Series, 466, 293-302.

Knowlton, A. R., Robbins, J., Landry, S., McKenna, H. A., Kraus, S. D., & Werner, T. B. (2016). Effects of fishing rope strength on the severity of large whale entanglements. Conservation Biology, 30(2), 318-328.

Kovacs, K. M., Aguilar, A., Aurioles, D., Burkanov, V., Campagna, C., Gales, N., ... & Trillmich, F. (2012). Global threats to pinnipeds. Marine Mammal Science, 28(2).

Machado, R., Ott, P. H., Moreno, I. B., Danilewicz, D., Tavares, M., Crespo, E. A., ... & Rosa De Oliveira, L. (2016). Operational interactions between South American sea lions and gillnet fishing in southern Brazil. Aquatic Conservation: Marine and Freshwater Ecosystems, 26(1), 108-120.

Molinet, C., & Niklitschek, E. J. (2024). Fisheries and marine conservation in Chilean Patagonia. In Conservation in Chilean Patagonia: Assessing the State of Knowledge, Opportunities, and Challenges (pp. 285-302). Cham: Springer International Publishing.

Moore, J.E., Heinemann, D., Francis, T.B., Hammond, P.S., Long, K.J., Punt, A.E., Reeves, R.R., Sepúlveda, M., Már Sigurosson, G., Siple, M.C., Vikingsson, G., Wade, P.R., Williams, R. & Zerbini, A.N. (2021). Estimating bycatch mortality for marine mammal stock assessment: concepts and best practices. Frontiers in Marine Science 8, 752356.

Muñoz, L., Pavez, G., Quiñones, R., Oliva, D., Santos-Carvallo, M. & Sepúlveda, M. (2013). Latitudinal variation in the diet of the South American sea lion revealed by stable isotopes. Revista de Biologia Marina y Oceanografía 48(3), 613-622.

Natural Capital Project, 2025. InVEST 3.17.0. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences. https://doi.org/10.60793/natcap-invest-3.17.0

NOAA. (2016). Fish and Fish Product Import Provisions of the Marine Mammal Protection Act. Federal Register / Vol. 81, No. 157/Monday, August 15, 2016/Rules and Regulations. P. 54389-54419. https://www.federalregister.gov/d/2016-19158

Northridge, S. (2018). Fisheries interactions. In Encyclopedia of marine mammals (pp. 375-383). Academic Press.

Oliva, D., Durán, L.R., Sepúlveda M., Cárcamo D., Pizarro M., Anguita C., Santos M., Canto A., Herrera P., Muñoz, L., Orellana, M. & Vásquez, P. (2020). Estimación poblacional de lobos marinos e impacto de la captura incidental. Pre-informe Final Proyecto FIP 2018-54, 190 pp + Anexos.

Pavés, H., Sepúlveda M., Goyeneche, F., Espinoza, M. & Oliva, D. (2025). Operational interaction and bycatch of seabirds and marine mammals with the artisanal gillnet fishery in southern Chile. Ocean and Coastal Management 262: 107554.

Perez-Venegas, D.J., Montalva, F., Molina-Burgos, B.E., Chiang, G., Harrod, C., Pavés, H., Sepúlveda, M. & Seguel, M. (2025). Foraging for offspring future: prenatal and postnatal maternal influence shape immunity and survival to parasitism in a top marine predator pups. Ecological and Evolutionary Physiology 97(6): 1-15

Plaza, P. I., Gamarra-Toledo, V., Euguí, J. R., Rosciano, N., & Lambertucci, S. A. (2024). Pacific and Atlantic sea lion mortality caused by highly pathogenic Avian Influenza A (H5N1) in South America. Travel medicine and infectious disease, 59, 102712.

Punt, A.E, Sepúlveda, M., Siple, M., Moore, J.E., Francis, T.B., Hammond, P.S., Heinemann, D., Long, K.J., Oliva, D., Reeves, R.R., Már Sigurosson, G., Vikingsson, G., Wade, P.R., Williams, R. & Zerbini, A.N. (2021). Assessing pinniped bycatch mortality with uncertainty in abundance and post-release mortality: a case study from Chile. Fisheries Research 235: 105816.

Queirolo, D., Ahumada, M., San Martín, M. A., Román, C., Apablaza, P., & Bernal, C. (2025). Testing and implementation of an exclusion device for mitigating the incidental capture of sea lions in the Chilean small-scale trawl hake fishery. Fisheries Research, 281, 1–9.

Read, A. J., Reynolds, J. E., Perrin, W. F., Reeves, R. R., Montgomery, S., & Ragen, T. J. (2005). Bycatch and depredation. Marine mammal research: conservation beyond crisis, 5-17.

Read, A. J., Drinker, P., & Northridge, S. (2006). Bycatch of marine mammals in US and global fisheries. Conservation biology, 20(1), 163-169.

Reyes, P., Hucke-Gaete, R., & Torres-Florez, J. P. (2013). First observations of operational interactions between bottom-trawling fisheries and South American sea lion, *Otaria flavescens* in south-central Chile. Journal of the Marine Biological Association of the United Kingdom, 93(2), 489-494.

Riet-Sapriza, F. G., Costa, D. P., Franco-Trecu, V., Marín, Y., Chocca, J., Gonzalez, B., ... & Hückstadt, L. A. (2013). Foraging behavior of lactating South American sea lions (*Otaria flavescens*) and spatial–temporal resource overlap with the Uruguayan fisheries. Deep Sea Research Part II: Topical Studies in Oceanography, 88, 106-119.

Rodríguez, D. H., Dassis, M., de Leon, A. P., Barreiro, C., Farenga, M., Bastida, R. O., & Davis, R. W. (2013). Foraging strategies of southern sea lion females in the La Plata River Estuary (Argentina–Uruguay). Deep Sea Research Part II: Topical Studies in Oceanography, 88, 120-130.

Romero, M. A., Flórez, L., Reinaldo, M. O., Machado, R., Coller, M., & Crespo, E. A. (2025). Bycatch in the balance: the trawl fisheries impact on South American sea lions in San Matias Gulf, with comments on other species. Marine Mammal Science, 41(2), e13181.

Samhouri, J. F., & Levin, P. S. (2012). Linking land-and sea-based activities to risk in coastal ecosystems. Biological Conservation, 145(1), 118-129.

Sarmiento-Hevia, R., Sepúlveda, M., Pavez, G., Valdés, J., Canto, A., Orellana, M. & Oliva, D. (2020). Diet composition of an opportunistic predator from an upwelling area in the Southerneast Pacific. Austral Ecology 45(8), 1145-1155.

Sepúlveda, M., Pérez, MJ., Sielfeld, W., Oliva, D., Durán, LR., Rodríguez, L., Araos, V. & Buscaglia, M. (2007). Operational interaction between South American sea lions *Otaria flavescens* and artisanal (small scale) fishing in Chile: results from interview surveys and on-board observations. Fisheries Research 83, 332-340.

Sepúlveda, M., Oliva, D., Urra, A., Pérez, M.J., Moraga, R., Schrader, D., Inostroza, P., Melo, A., Díaz, H. & Sielfeld, W. (2011). Abundance and status of South American sea lions (*Otaria flavescens*) off Central Chilean coast. Revista Chilena de Historia Natural 84(1), 97-106.

Sepúlveda, M., Newsome, S.D., Pavez, G., Oliva, D., Costa, D.P. & Hückstädt, L.A. (2015). Using satellite tracking and isotopic information to characterize the impact of South American sea lions on salmonid aquaculture in southern Chile. PLoS ONE 10(8), e0134926.

Sepúlveda M., Martínez, T., Oliva, D., Couve, P., Pavez, G., Navarro, C., Stehlik, M., Durán, L.R. & Luna, G. (2018). Spatial and temporal variation in the interaction of South American sea lions and the artisan gillnet fishery in Chile. Fisheries Research 208, 147-152.

Sepúlveda, M., Szteren, D., Alfaro-Shigueto, J., Crespo, E.A., Durán, L.R., Guerrero, A., Mangel, J.C., Oliva, D & Oliveira, L.R. (2023). Sea lion and fur seal interactions with fisheries and aquaculture in South American waters: threats and management perspectives. Mammal Review 53: 116-131.

Sernapesca. (2024). Anuario Estadístico de Pesca y Acuicultura 2024. Servicio Nacional de Pesca y Acuicultura, Valparaíso, Chile.

Sielfeld, W. & Guzmán, A. (2002). Effect of El Niño 1997/98 on a population of the Southern Sea Lion (*Otaria flavescens* Shaw) from Punta Patache/Punta Negra (Iquique, Chile). Investigaciones Marinas 30: 157-160.

Sonne, C., Lam, S. S., Foong, S. Y., Mahari, W. A. W., Ma, N. L., & Bank, M. S. (2024). A global meta-analysis of gillnet bycatch of toothed whales: Mitigation measures and research gaps. iScience, 27(12).

Taylor, B. L., Rojas-Bracho, L., Moore, J., Jaramillo-Legorreta, A., Ver Hoef, J. M., Cardenas-Hinojosa, G., ... & Hammond, P. S. (2017). Extinction is imminent for Mexico's endemic porpoise unless fishery bycatch is eliminated. Conservation Letters, 10(5), 588-595.

Temple, A. J., Langner, U. & Berumen, M. L. (2024). Management and research efforts are failing dolphins, porpoises, and other toothed whales. Scientific Reports, 14(1), 7077.

Thiel, M., Macaya, E. C., Acuña, E., Arntz, W. E., Bastias, H., Brokordt, K., et al. (2007). The Humboldt Current System of northern and central Chile: oceanographic processes, ecological interactions and socioeconomic feedback. Ocean. Mar. Biol. Annu. Rev. 45, 195–344.

Tidd, A. N., Vermard, Y., Marchal, P., Pinnegar, J., Blanchard, J. L., & Milner-Gulland, E. J. (2015). Fishing for space: Fine-scale multi-sector maritime activities influence fisher location choice. PLoS ONE, 10(1), e0116335.

Turvey, S. T., Pitman, R. L., Taylor, B. L., Barlow, J., Akamatsu, T., Barrett, L. A., ... & Wang, D. (2007). First human-caused extinction of a cetacean species?. Biology letters, 3(5), 537-540.

Ulloa, M., Fernández, A., Ariyama, N., Colom-Rivero, A., Rivera, C., Nuñez, P., ... & Sierra, E. (2023). Mass mortality event in South American sea lions (*Otaria flavescens*) correlated to highly pathogenic avian influenza (HPAI) H5N1 outbreak in Chile. Veterinary Quarterly, 43(1), 1-10.

Van Duijne, F. H., van Aken, D., & Schouten, E. G. (2008). Considerations in developing complete and quantified methods for risk assessment. Safety Science, 46(2), 245-254.

Vega, R., Ossa, L., Suárez, B., Jiménez, M.F, Henríquez, S., González, A., Ojeda, R., Oro, D., Simeone, A., Anguita, C., Hüne, M., Cari, I., Zarate, P., Clavijo, L. & Devia, D. (2021). Programa de investigación y monitoreo del descarte y captura de pesca incidental en pesquerías pelágicas, 2020-2021. Subsecretaría de Economía y EMT. 453 p.

Vega, R., Ossa, L., Suárez, B., Jiménez, M.F, Henríquez, S., González, A., Ojeda, R., Barraza, A., Saavedra, J.C., Simeone, A. & Hüne, M. (2024). Programa de investigación y monitoreo del descarte y captura de pesca incidental en pesquerías pelágicas, 2023-2024. Subsecretaría de Economía y EMT. 495 p.

Venegas, C., Gibbons, J., Aguayo, A., Sielfeld, W., Acevedo, J., Amado, N., ... & Valenzuela, C. (2002). Distribución y abundancia de lobos marinos (Pinnipedia: Otariidae) en la Región de Magallanes, Chile. In Anales del Instituto de la Patagonia (Vol. 30, pp. 67-82).

Verutes, G. M., Johnson, A. F., Caillat, M., Ponnampalam, L. S., Peter, C., Vu, L., ... & Hines, E. M. (2020). Using GIS and stakeholder involvement to innovate marine mammal bycatch risk assessment in data-limited fisheries. PLoS One, 15(8), e0237835.

Wade, P.R., Long, K.J., Francis, T.B., Punt, A.E., Hammond, P.S., Heinemann, D., Moore, J.E., Reeves, R.R., Sepúlveda, M., Sullaway, G., Már Sigurosson, G., Siple, M.C., Vikingsson, G., Williams, R. & Zerbini, A.N. (2021). Best practices for assessing and managing bycatch of marine mammals. Frontiers in Marine Science 8, 757330.

Wickens, P. A. (1995). A review of operational interactions between pinnipeds and fisheries. FAO Fisheries Technical Paper No. 346.

Abstract

Bycatch of marine mammals in fisheries is a critical conservation issue worldwide, and Chile is no exception. Pinnipeds such as the South American sea lion (*Otaria byronia*, SASL) frequently encounter fishing gear along the Chilean coast. Despite widespread evidence of these interactions, few studies have spatially assessed SASL bycatch risk across multiple fisheries for this species. This study applies the Bycatch Risk Assessment (ByRA) toolbox, a GIS-based model, to evaluate and compare the risk of SASL bycatch across nine Chilean purse-seine and trawl gear fisheries based on data from on-board scientific observer logs from 2015 to 2019. Our findings identify trawl fisheries, particularly those targeting southern hake (*Merluccius australis*), as posing the highest bycatch risk, especially during the non- reproductive season when SASL exhibit broader spatial distribution. Purse-seine fisheries presented lower risk overall, with the industrial northern fleet showing the highest relative risk. Spatial patterns revealed that risk is concentrated in nearshore areas, where the overlap between the distribution of SASL and fishing activity is the greatest. These results provide a robust, spatially explicit foundation for prioritizing mitigation measures, including the mandatory use of exclusion devices and seasonal restrictions. Our approach underscores the potential mitigation provided by evidence-based management of marine mammal bycatch in Chile and contributes information toward the assessment of compliance with domestic and international regulations.

Keywords: Chilean fisheries, trawl, purse-seine, sea lions, risk interaction modeling, ByRA toolbox

Figure captions

Figure 1. Distribution of South American sea lions for the reproductive (left panel) and non-reproductive (right panel) periods based on buffer distances described for each age/sex class. The coloured bands represent decreasing relative occurrence with increasing distance from colonies. Values of 1, 2, and 3 indicate low, medium and high distribution probability, respectively. Yellow dots indicate the geographic positions of the haul-outs, according to Oliva et al. (2020).

Figure 2. Final estimated bycatch risk for South American sea lions for the reproductive (top panels) and non-reproductive (bottom panels) periods for purse-seine fisheries. Polygons indicate the area of interest (AOI) based on spatial operation of each fishery. Data uncertainty is depicted with a stoplight as described in Constanza et al. (2021).

Figure 3. Final estimated bycatch risk for South American sea lions for the reproductive (top panels) and non-reproductive (bottom panels) periods for trawl fisheries. Polygons indicate the area of interest (AOI) based on spatial operation of each fishery. Data uncertainty is depicted with a stoplight as described in Constanza et al. (2021).

Figure 4. Exposure-consequence diagrams for each fishery during the reproductive (left panel) and non-reproductive (right panel) periods of the South American sea lions. Fisheries are classified as: (A): Pelagic artisanal north; (B): Pelagic industrial north; (C): Pelagic artisanal central; (D) Pelagic industrial central; (E): Pelagic artisanal south; (F): Chilean hake

Industrial <1000 hp; (G): Chilean hake Industrial >1000 hp; (H): Bottom ice fleet; and (I): Bottom factory fleets. The darkest red bands in the upper-right corner of the exposure–consequence plots indicate which fisheries were the strongest drivers of bycatch risk.

Figure 1

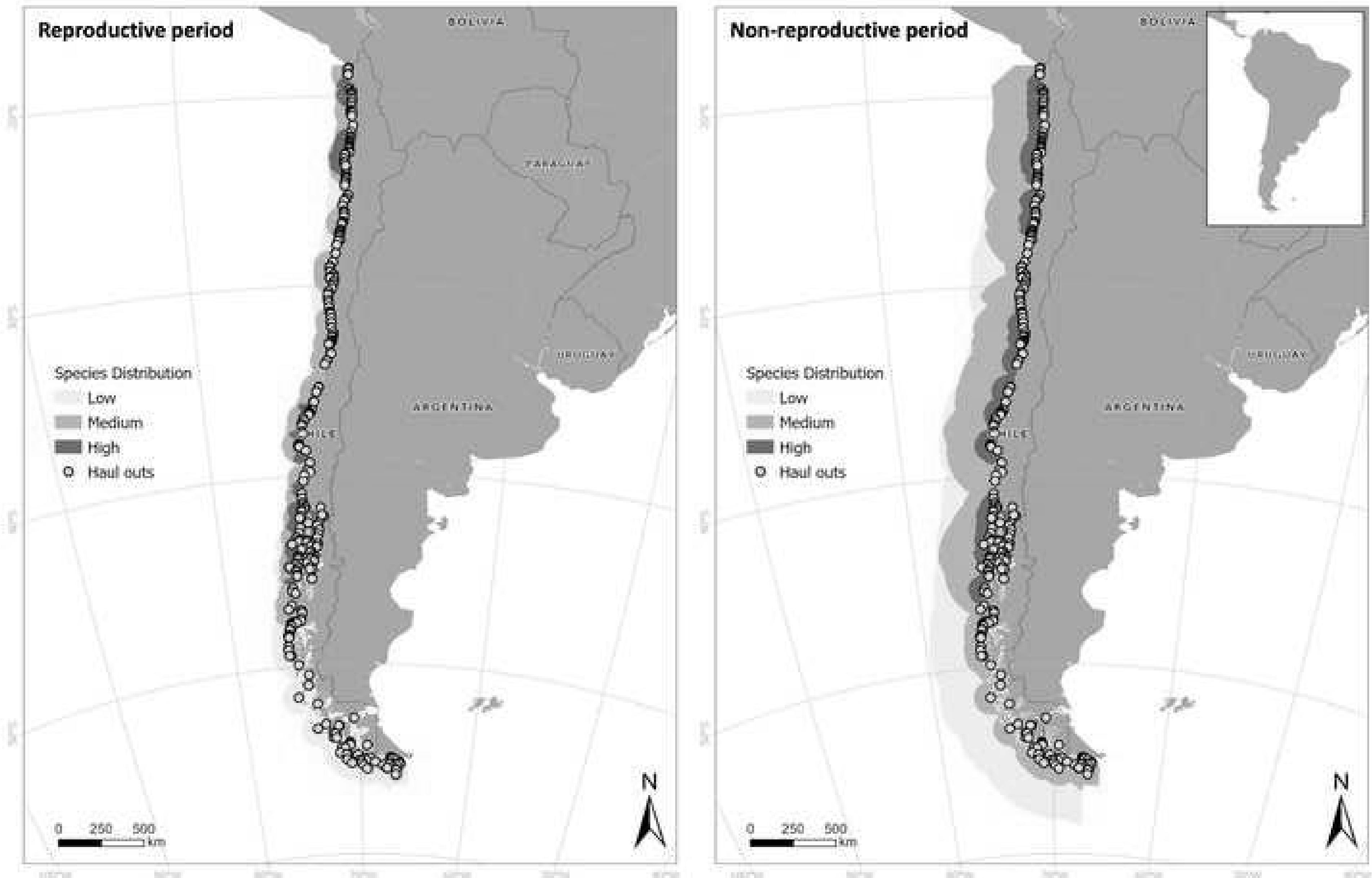
Reproductive period
Non-reproductive period
BOLIVIA
ARGENTINA
Species Distribution
Low
Medium
High
Haul outs
0 250 500 km
N

Figure 2

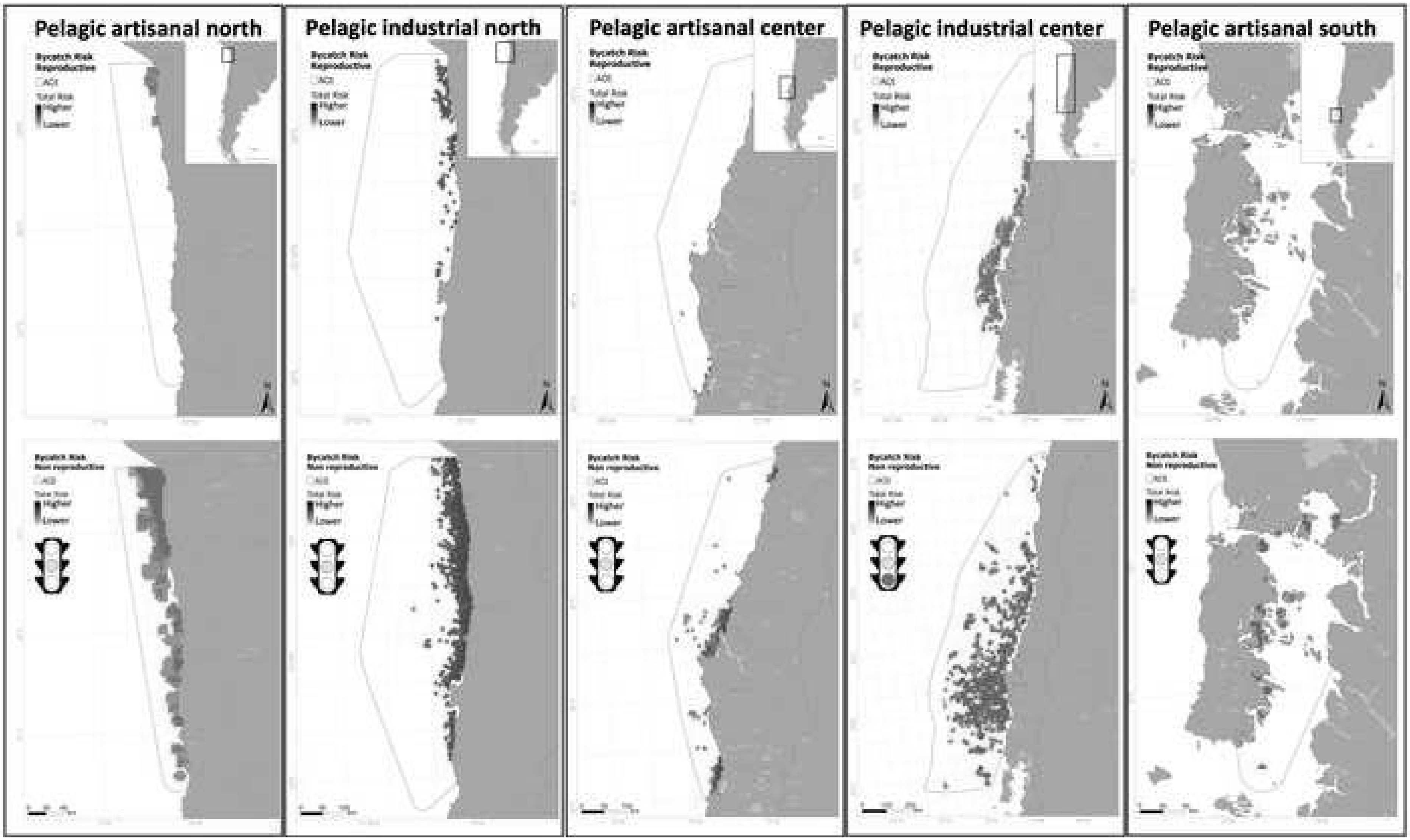
Pelagic artisanal north
Pelagic industrial north
Pelagic artisanal center
Pelagic industrial center
Pelagic artisanal south
Bycatch Risk
Reproductive
AOI
Total Risk
Higher
Lower
Bycatch Risk
Non reproductive

Figure 3

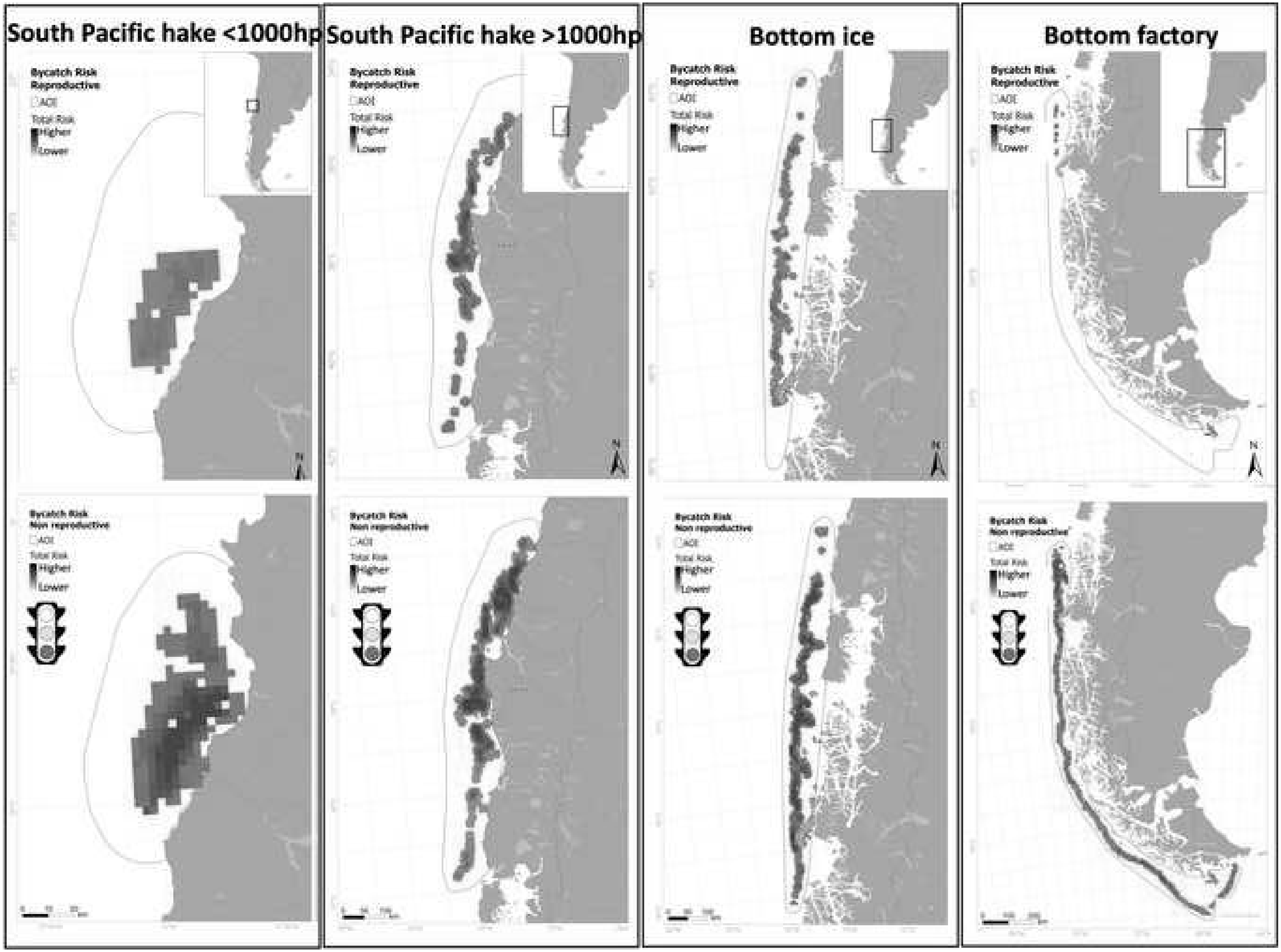
South Pacific hake <1000hp
South Pacific hake >1000hp
Bottom ice
Bottom factory
Bycatch Risk
Reproductive
AOI
Total Risk
Higher
Lower
Bycatch Risk
Non reproductive
AOI
Total Risk
Higher
Lower
N

Figure 4