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REVIEW

Sea lion and fur seal interactions with fisheries and aquaculture in South American waters: threats and management perspectives

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Keywords
bycatch, mortality, pinnipeds, South America, South American sea lion *Otaria flavescens*, South American fur seal *Arctocephalus australis*

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ABSTRACT

1. The main issue affecting the conservation of most pinniped species has been identified as interactions with fisheries and aquaculture. In South American waters in particular, this problem has not been well evaluated. Consequently, there is an urgent need for research and conservation measures to address the problem, particularly for species of conservation concern.
2. In this study, we reviewed published and unpublished research and observations from the last 25 years on operational and biological interactions between pinnipeds and fisheries and salmonid aquaculture activities in South American waters, and the conservation and management implications of these interactions in the near future.
3. Two species of pinnipeds are primarily involved in biological and operational interactions with fisheries and aquaculture in South America: the South American sea lion *Otaria flavescens* and the South American fur seal *Arctocephalus australis*. Although phocids are present in South American waters, there is no published research on conflicts between phocids and human activities.
4. Interactions between fisheries and pinnipeds have been reported by many countries. In South American waters, interactions mostly involve male and

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subadult male South American sea lions. However, despite the high frequency of interactions, the estimated economic losses to fisheries and aquaculture related to sea lion depredation are generally low.
5. Incidental capture and mortality of pinnipeds has been reported, especially in artisanal gillnet fisheries and in industrial purse seine and trawl fisheries. Mortality of sea lions in salmonid aquaculture has been reported, but the magnitude of the problem is unknown.
6. In South America, limited progress has been made to incorporate mitigation measures, such as time-area closures, acoustic deterrent devices, and modifications to fishing gear, into fisheries and aquaculture. This is likely to be due to our limited understanding of ecosystem complexity, the costs of modifying fishing gear or incorporating acoustic deterrent devices, and the scarcity of fishing controls. We suggest that strategies for effectively reducing conflicts between pinnipeds, fisheries, and aquaculture should involve all stakeholders in participative research to facilitate co-management.

Palabras clave
América del Sur, captura incidental, lobo fino sudamericano *Arctocephalus australis*, lobo marino común *Otaria flavescens*, mortalidad, pinnípedos

RESUMEN EN ESPAÑOL

1. Las interacciones con pesquerías y acuicultura han sido identificadas como uno de los principales problemas de conservación para la mayoría de los pinnípedos. En América del Sur, en particular, este problema ha recibido poca atención, por lo que urge una mayor investigación y el diseño de medidas de conservación, particularmente para especies con problemas de conservación.
2. Esta revisión analiza los trabajos realizados en los últimos 25 años sobre las interacciones biológicas y operacionales entre pinnípedos y pesquerías y salmonicultura en aguas de América del Sur, y discute sus implicancias para el manejo y la conservación futuros de estas especies.
3. Dos especies de pinnípedos presentan interacciones biológicas y operacionales con pesquerías y acuicultura; el lobo marino común *Otaria flavescens* y el lobo fino sudamericano *Arctocephalus australis*. Aunque especies de focas se encuentran comúnmente en el continente, no existen registros de conflictos con actividades humanas.
4. Se han registrado interacciones entre pinnípedos y pesquerías en la mayoría de los países. En aguas de América del sur, las interacciones involucran principalmente a machos adultos y subadultos del lobo marino común. Sin embargo, pese a la alta frecuencia de interacciones, las pérdidas económicas estimadas por efecto de depredación de lobos marinos en pesquerías y acuicultura son generalmente bajas.
5. Se ha reportado captura incidental y mortalidad de lobos marinos, especialmente en pesquerías artesanales de enmalle e industriales de cerco y arrastre. Se ha reportado mortalidad de lobos marinos en salmonicultura, pero se desconoce la magnitud del problema.
6. En América del Sur, la incorporación de medidas de mitigación, tales como cierres espacio-temporales de áreas, incorporación de sistemas acústicos o modificaciones a las artes de pesca ha tenido un lento desarrollo. Esto se debe principalmente a nuestro limitado conocimiento de la complejidad ecosistémica, los costos de modificación de artes de pesca o la incorporación de los sistemas acústicos disuasivos, y a escasos controles de la actividad pesquera. Sugerimos que futuras estrategias para reducir de manera efectiva los conflictos entre pinnípedos y pesquerías y acuicultura involucren a todos los actores relevantes en investigaciones participativas que faciliten el co-manejo.

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INTRODUCTION

Pinnipeds (including the seals, sea lions, and fur seals) are the most conspicuous marine mammals in South American waters due to their coastal distributions, gregarious breeding colonies, and frequent interactions with industrial fisheries, artisanal or small-scale fisheries, and aquaculture activities (Crespo et al. 2021). The most common pinniped species in South American waters are: South American sea lions (SASL) *Otaria flavescens* (=*byronia*), South American fur seals (SAFS) *Arctocephalus australis*, Juan Fernández fur seals *Arctocephalus philippii*, Galápagos fur seals *Arctocephalus galapagoensis* (Trillmich 2021), Galápagos sea lions *Zalophus wollebaeki* (Krüger et al. 2021), and elephant seals *Mirounga leonina* (Crespo 2009). However, only the SASL and the SAFS are known to be incidentally caught in fisheries. The SASL is the most conspicuous species in South America in terms of abundance and interactions with human activities, particularly with fisheries and aquaculture (Crespo et al. 2021). These interactions probably occur because the SASL is as a benthic forager that mostly exploits nearshore resources, whereas the SAFS is a pelagic forager with an offshore feeding strategy (Riverón et al. 2021). The pattern of SASL feeding in inshore habitats, together with the generalist and opportunistic feeding behaviour of the species (Muñoz et al. 2013) and its occupation of the shallow coastal zone, facilitates interactions with fisheries and aquaculture (Szteren et al. 2018).

Interactions between pinnipeds and fisheries and aquaculture are commonly reported in eastern and western South American waters (Crespo et al. 2021, Crespo & Oliveira 2021). As a result of these interactions, pinnipeds may be injured or killed, deliberately or incidentally, mainly in gillnets, bottom and pelagic trawls, and purse seines (Crespo et al. 2021, Crespo & Oliveira 2021). For most pinniped species, as well as marine mammals in general, incidental mortality (bycatch) has been identified as the main cause of anthropogenic mortality (Avila et al. 2018), and consequently, it is a research and management priority, particularly for species of conservation concern (Reeves et al. 2013).

Evaluations of the magnitude and causes of incidental mortality are timely given the recent provisions from the United States Department of Commerce on imports of fish and fish products related to the USA's Marine Mammal Protection Act (MMPA). These provisions have incentivised countries, which export fish products to the USA to improve both their standards and their records of monitoring and mitigation of marine mammal interactions (Williams et al. 2016). In countries with fisheries to which this legislation applies, and for which levels of reported interactions with marine mammals exceed US standards, this provision establishes a five-year exemption period to develop mitigation programmes comparable with those in the USA (Williams et al. 2016). An evaluation of interactions and incidental mortality of pinnipeds in South American waters is therefore critical considering that several South American countries export fish and fish products to the USA and must comply with the MMPA import provision for this to continue.

The objectives of this study are fourfold. The first objective is to review contributions published in the last 25 years on operational and biological interactions between pinnipeds and fisheries and aquaculture activities in South American waters. The second is to evaluate the techniques and mitigation methods implemented in South America for reducing interactions between pinnipeds and fisheries and salmon aquaculture. The third objective is to analyse the regulations made by each South American country to ensure the protection of pinnipeds, and identify measures that have been successful in reducing interactions and preventing bycatch. Finally, the fourth objective is to discuss the short-term implications of these findings for the conservation and management of pinnipeds in South American waters.

METHODS

We systematically reviewed scientific and technical articles published in peer-reviewed journals and 'grey' literature between 1997 and 2022 that discussed various issues relating to pinnipeds and fisheries and aquaculture interactions, focussing on those studies carried out in South America. Scientific reference searches were performed using Web of Science, SCOPUS and Google Scholar databases. The keywords used in our searches were combinations of different words, such as 1) bycatch, pinnipeds, South America, 2) fisheries, seals, sea lions, 3) salmon farming, salmonid aquaculture, Chile, 4) interactions, predation, otariids. Published information about interacting species was retrieved using common and scientific names of pinniped species as search query phrases. Keywords and query phrases were applied to the titles, abstracts, and keywords of original articles, reviews, and proceedings papers. Eighty articles were included in our review.

RESULTS AND DISCUSSION

Distribution and abundance of pinnipeds in South American waters

Six species of pinnipeds have been reported as resident along the coast of South America (Crespo 2009). The most

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common and widely distributed species is the SASL, which occurs almost continuously from southern Brazil to Cape Horn on the Atlantic coast and northward up the west coast of the continent to Zorritos, northern Peru, on the Pacific coast (Crespo et al. 2021; Fig. 1). The estimated population of this species is 450000 individuals (Crespo et al. 2021). The SAFS is also distributed along the western South Atlantic (southern Brazil, Uruguay, Argentina, and the Falkland/Malvinas Islands) and eastern South Pacific coasts (Crespo & Oliveira 2021; Fig. 1). The total estimated population of this species is 400000 individuals (Crespo & Oliveira 2021). The Juan Fernandez fur seal is endemic to the Chilean coast and is found exclusively in the Juan Fernández Archipelago and Desventuradas Islands (Fig. 1); the estimated population is 250000 individuals (Renato Borras, personal communication). Both Galápagos fur seals and Galápagos sea lions are endemic to the Galapagos archipelago. The populations of Galápagos fur seals and Galápagos sea lions are about 11000 and 17000 individuals, respectively (Krüger et al. 2021, Trillmich 2021). Individuals from two stocks of southern elephant seals can be found on the coast of South America: the South Georgia stock (including the Malvinas/Falkland population) and the Península Valdés stock (Lewis & Eder 2021; Fig. 1). The estimated population of both stocks combined is 450000 (Lewis & Eder 2021).

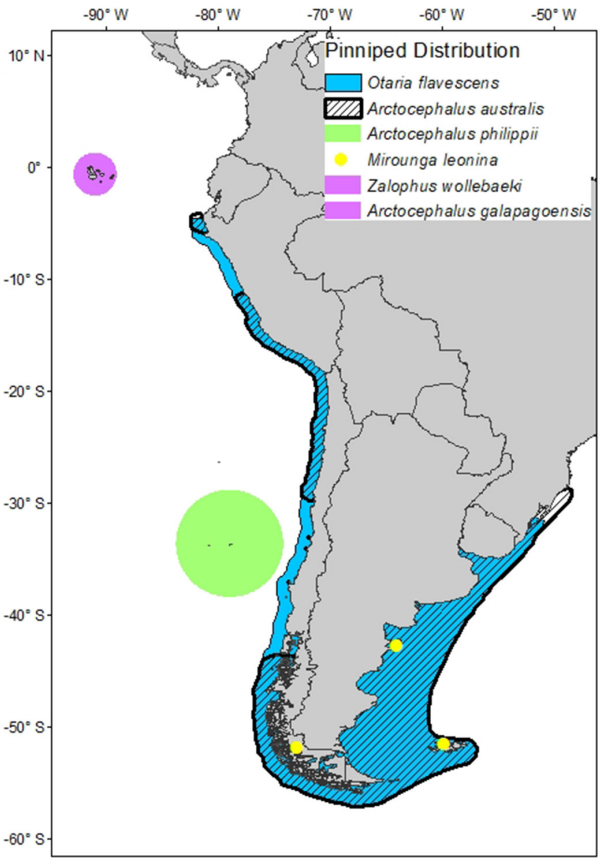

Fig. 1. Geographic distribution of the South American sea lion *Otaria flavescens*, South American fur seal *Arctocephalus australis*, Juan Fernández fur seal *Arctocephalus philippii*, Galápagos sea lion *Zalophus wollebaeki*, Galápagos fur seal *Arctocephalus galapagoensis*, and Southern elephant seal *Mirounga leonina* in the coastal waters of South America.

Interaction between fisheries and pinnipeds

Interactions between pinnipeds and fisheries can be classified as 1) operational (or direct) interactions, when pinnipeds are affected due to their entanglement or incidental capture or fisheries are affected because of interactions which cause catch losses due to depredation and/or damage to fishing gear (Wickens 1995); and 2) ecosystem (or biological) interactions, related to competition for the same resources. Both types of interaction have been studied in South American waters to different degrees (e.g. Crespo et al. 1997, Riet-Sapriza et al. 2013, Machado et al. 2015, 2016).

OPERATIONAL INTERACTIONS: DEPREDATION AND DAMAGE TO FISHING GEAR

DAMAGE CAUSED BY PINNIPEDS TO ARTISANAL FISHERIES

Artisanal fisheries are defined differently in different countries. Peru, Chile, and Argentina define artisanal fisheries as including vessels less than 15, 18, and 10 m long, respectively, whereas Uruguay and Brazil define artisanal fisheries as those with vessels with a maximum Gross Registered Tonnage of 10 and 20 thousand kg, respectively.

Artisanal fisheries in South American waters employ various types of fishing gear, such as gillnets, purse seines, and longlines. Gillnets are the most common gear used by fishers in all South American countries, and there has been a gradual and constant increase in the size of fishing nets used (Machado et al. 2016). Interactions between artisanal fisheries and pinnipeds have been reported for all South American countries that have been studied, with the exception of Argentina (from which very few artisanal boats operate), and mainly for fisheries that use gillnets (Fig. 2). Some studies have reported that most SASLs interacting with artisanal fisheries are subadult and adult males (Goetz et al. 2008, Sanguinetti et al. 2021).

The frequency of interactions with pinnipeds is similar for different gear types and is usually more than 50% of the observed hauls (e.g. 57% for the gillnet fishery of central Chile, Sepúlveda et al. 2018; 52% for the longline fishery of southern Chile, de la Torriente et al. 2009;

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56–83% in the gillnet fishery of Piriápolis Uruguay, Szteren & Lezama 2006; and 100% for gillnets of Peru, Arias Schreiber 1993). However, other studies have found a lower frequency of operational interactions (e.g. 24% for fixed bottom gillnets of Brazil, Machado et al. 2016). The differences between studies may be explained by interannual differences in resource availability (Sepúlveda et al. 2018). According to Kaschner and Pauly (2005), conflicts between pinnipeds and fisheries are aggravated when fish stocks decline. This suggests that when prey become scarce, a greater proportion of the pinniped population may aggregate around fishing vessels, which in turn could lead to an increase in the frequency of encounters with pinnipeds during fishing activities (Machado et al. 2016).

Despite the high frequency of interactions, the estimated economic loss related to depredation of fish stocks by pinnipeds seems to be low. For example, the estimated losses caused during the fisheries interactions ranged from less than 1% to 3% of the total catch from gillnets of southern Brazil (Machado et al. 2016, Oliveira et al. 2020), from 1.6% to 3.5% in the southern hake *Merluccius australis* longline fishery of southern Chile (de la Torriente et al. 2009) and from 1.4% to 16% in the artisanal gillnet fishery of Uruguay (De María et al. 2014). Sanguinetti et al. (2021) in Chile and Oliveira et al. (2020) in Brazil demonstrated that the actual economic losses caused by the SASL to local fisheries are small compared with the damage they are perceived to cause by fishers. Therefore, it is possible that the observed negative perception of SASLs is independent of any particular event, but rather relates to the continuous presence of SASLs in areas where fishing takes place (Sanguinetti et al. 2021).

DAMAGE CAUSED BY PINNIPEDS TO INDUSTRIAL FISHERIES

Industrial fisheries in South American water also employ various types of fishing gear, most commonly purse seines, longlines, and mid-water and bottom trawls (Lorenzo 2016). Most studies of pinniped interactions with industrial fisheries have been focussed on fisheries that use trawls or purse seines (Fig. 2).

The number of pinnipeds interacting with industrial fisheries varies depending on the type of gear. For instance, in the purse seine fishery for jack mackerel *Trachurus symmetricus* off central Chile, the mean number of SASLs observed per set was 21; the maximum was 50 individuals (Hückstädt & Antezana 2003). Larger SASL numbers were recorded off Peru, where up to 3000 individuals (mean ± standard deviation: 62 ±114) were counted interacting with purse seine gear between 2015 and 2019 (Rivadeneyra-Villafuerte & Román-Amancio 2022). Off northern Argentina, the maximum number of SASLs reported was two in the semi-industrial mid-water trawl fishery, and in

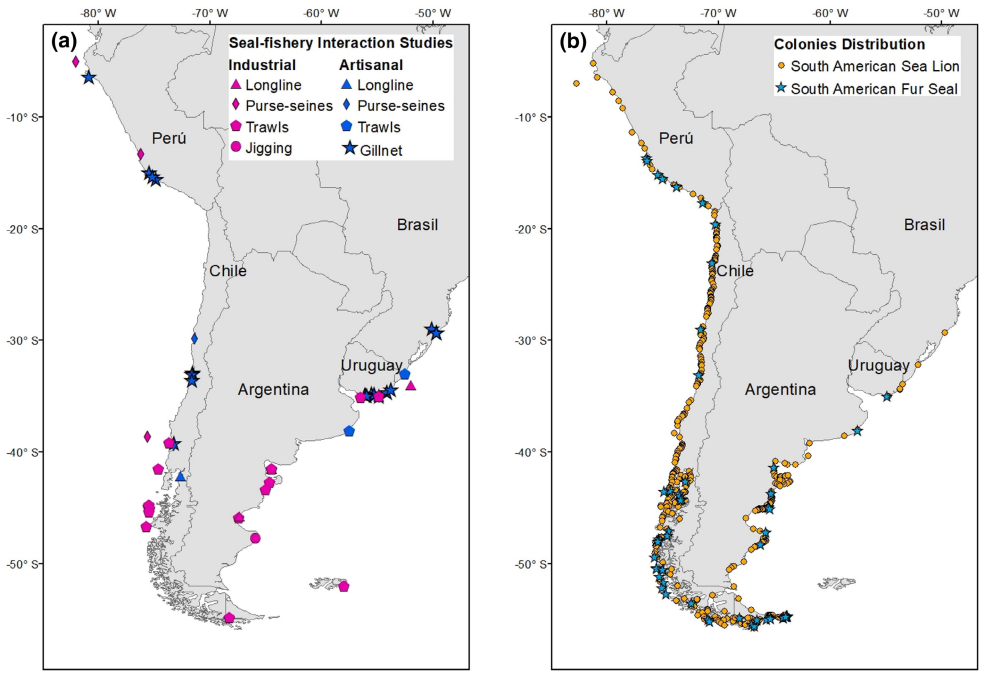

Fig. 2. a) Map showing studies of interactions between fisheries and South American sea lions *Otaria flavescens* and South American fur seals *Arctocephalus australis* conducted in South American waters. Studies are differentiated according to fishing gear used. b) The colonies of South American sea lions and South American fur seals are also shown.

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the bottom pair-trawl fishery the maximum number reported was three, with a mean of 0.7 (±1) SASLs (Seco Pon et al. 2013). Lower numbers of SASLs in trawl fisheries may be explained because, contrary to purse seines, fish caught in trawl nets are confined in a small space, which is a dangerous place for SASLs to forage (Northridge 2018).

Similar to artisanal fisheries, the consumption and estimated economic losses related to depredation of fish by pinnipeds in industrial fisheries seem to be low. Hückstädt and Antezana (2003) estimated that the amount of fish consumed by the SASL per set was as little as 0.4% of the catch. These estimates are consistent with those calculated by Wickens et al. (1992) for interactions between Cape fur seals *Arctocephalus pusillus* and several types of industrial fisheries off South Africa and by Trijoulet et al. (2018) for interactions between grey seals *Halichoerus grypus* and the demersal trawl fishery off Scotland. These results suggest that predation by pinnipeds is not a serious cause of economic loss to the fishing industry (Hückstädt & Antezana 2003).

OPERATIONAL INTERACTIONS: BYCATCH AND ENTANGLEMENT

Although there are many other causes of mortality in marine mammals, it has been established that the main sources of human-caused mortality are entanglement, entrapment, and hooking in commercial fishing gear (Reeves et al. 2013, Avila et al. 2018), collectively referred to as 'bycatch'. Bycatch has been mentioned as an acute threat for some pinnipeds of conservation concern, such as the Australian sea lion *Neophoca cinerea*, the Caspian seal *Pusa caspica* and the ringed seal *Pusa hispida* (Kovacs et al. 2012). In South American waters, three species in particular have been reported as incidentally caught in fisheries; the SASL, the SAFS and the Juan Fernández fur seal, with records of bycatch in both artisanal and industrial fisheries (Félix et al. 2021).

INCIDENTAL CAPTURE AND MORTALITY IN ARTISANAL FISHERIES

Among the different types of gear currently used by artisanal fishers, gillnets pose the main threat to pinnipeds due to the high probability of entanglement (Reeves et al. 2013). In South American artisanal gillnet fisheries, there are some records of SASL incidental captures off Peru (0.3 per fishing trip, Arias Schreiber 1993) and Chile (0.9 per fishing trip, Bartheld et al. 2008). However, for the SASL off Brazil, bycatch in artisanal gillnets is apparently uncommon (Ramos et al. 2020) and does not seem to be a significant cause of mortality (no incidental bycatch was recorded in 484 gillnet operations monitored between 1991 and 2012; Machado et al. 2016). The main threat to pinnipeds does not therefore seem to come from artisanal fisheries but from interactions with industrial fisheries and indirect fishery interactions (see below).

INCIDENTAL CAPTURE AND MORTALITY IN INDUSTRIAL FISHERIES

Off south-central Chile, Hückstädt and Antezana (2003) reported the capture of 18 SASLs (0.64 per set) and the deaths of two SASLs in industrial purse seine fisheries. More recently, the scientific observer programme of the Chilean Institute of Fisheries Development (IFOP) reported the capture of a high number of SASLs in industrial purse seine fisheries operating from northern Chile (4468 individuals in 3350 observed sets from 2017 to 2020; Vega et al. 2021). However, most SASLs that were caught managed to escape from the gear; thus, a low mortality rate was reported (0.2%; Vega et al. 2021). The low mortality of SASLs in these fisheries (those that interact during fishing operations) is explained because they readily jump over the cork line before the haul is ended, and escape (Fig. 3a; Punt et al. 2021).

In contrast to bycatch in purse seines, mortality of pinnipeds in trawl fisheries is much higher (Punt et al. 2021). This is because after entering the trawl net, pinnipeds have difficulty finding a way back out, so are either drowned or pushed back in the net and crushed by the weight of incoming fish (Reyes et al. 2013, Crespo et al. 2021; Fig. 3b). In the trawl fisheries off central Chile, Reyes et al. (2013) reported the incidental catch of 82 individuals (1.2 SASL per set) in the South Pacific common hake *Merluccius gayi* fishery, of which 12 were found dead. Additionally, the scientific observers of IFOP reported the incidental capture of 147 SASLs in the South Pacific common hake trawl fishery off central Chile in 2019, with a mortality rate of 82% (Bernal et al. 2020). For trawl fisheries operating from southern Chile, IFOP reported a capture of 100 SASLs and 62 SAFSs in 2019, with a mortality rate of 75% and 79%, respectively (Bernal et al. 2020).

For the Atlantic Ocean, based on observer counts and the recovery of dead animals retrieved by fishers, Crespo et al. (1997) and Dans et al. (2003) estimated that 176-602 SASLs die annually in bottom trawl fisheries in Patagonia Argentina, representing 1–2% of the local population. Likewise, based on data provided by fishers, the annual mortality of SASLs in trawl fisheries was estimated at 77 individuals annually off Uruguay, which represents approximately 0.8% of the local population (Franco-Trecu et al. 2019). Off Uruguay, an annual mortality of 25 SAFSs in trawl fisheries was estimated, which represents approximately 0.02% of the local population (Franco-Trecu et al. 2019). Finally, off southern Brazil, Machado et al. (2015) reported for the first time the mortality of

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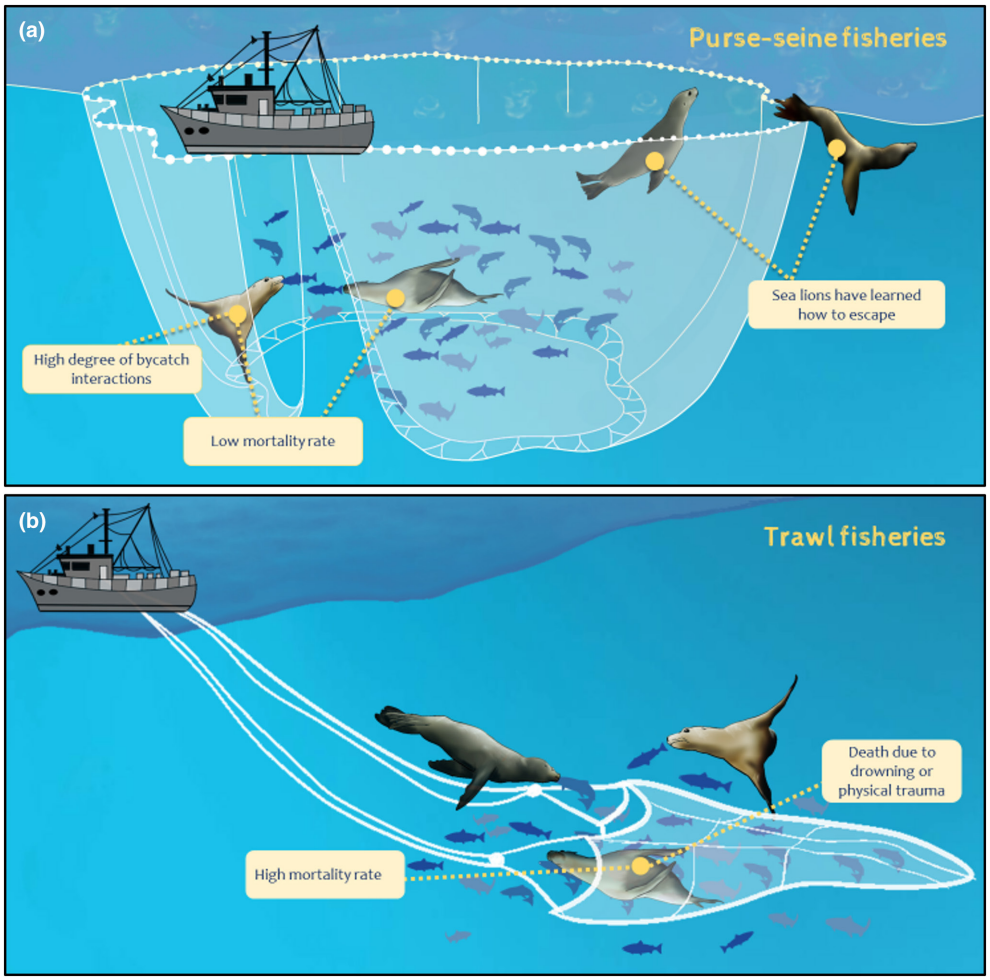

Fig. 3. Visual summary of interactions between South American sea lions *Otaria flavescens* and the a) purse seine and b) trawl fisheries. Illustration by Alicia I. Guerrero.

a young male SASL in the pair-trawl fishery at a depth of 15–20m.

ECOSYSTEM INTERACTIONS

Ecosystem (or biological) interactions between pinnipeds and fisheries are difficult to quantify, and cause-and-effect relationships are challenging to establish (Jusufovski et al. 2019). Nevertheless, biological interactions can indirectly induce changes to ecosystems that affect foraging habits, energy intake, and may cause nutritional stress among pinnipeds (Kovacs et al. 2012).

When analysing ecosystem interactions, much emphasis is usually placed on the competitive effects of pinnipeds on commercial fisheries, and not on the reverse (Jusufovski et al. 2019). South America is no exception, and most studies have been motivated by an increase in pinniped populations in areas with commercially important fish stocks. Due to their frequent interaction with fishing activities, SASLs have been posited as having a negative impact upon commercial fisheries, and of being responsible (at least partially) for the decline of fish stocks. However, there is no scientific evidence to support this, because spatial overlap, or the co-use of the same resources by a predator and a fishery does not necessarily mean that competition exists (Yodzis 2001).

Studies in South American waters have shown an overlap in prey species taken by the SASL and the target species of fisheries (Bustos et al. 2012, Jarma et al. 2019). However, a comparison between the size of prey consumed by SASLs and those taken by fisheries suggested a low general trophic overlap, because SASLs feed on smaller prey than is caught by fisheries (Romero et al. 2011). However, while differences in targeted prey sizes suggest that there is limited direct resource competition between SASLs and fisheries, the removal of smaller fish by SALs could reduce

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recruitment to the adult reproductive population of the fish stock, and also the removal of large fish by humans could result in reduced recruitment, resulting in indirect competition. Using ecosystem modelling, Sepúlveda et al. (2016) estimated trophic overlap between the SASL diet and purse seine and trawl fisheries of northern and southern Chile and found that between 50% (in the south) and 80% (in the north) of the prey consumed by the SASL was also caught by the fisheries. These authors reported that the biomass removed by SASLs was lower (by one order of magnitude) than the biomass removed by fishing activity. Moreover, it was found that a decrease or removal of the SASL population would not generate the expected increase in fish catches; instead, it would have negative effects on other components of the modelled trophic webs. The effect of the SASL population on Argentine hake *Merluccius hubbsi* in the Gulf of San Matías (Patagonia, Argentina) has also been evaluated using ecosystem modelling tools (Ocampo et al. 2016). It was found that even after four decades of increases in the biomass of SASLs, higher mortality of Argentine hake was not observed.

In conclusion, although fisheries and otariids target the same prey species in South American waters, the extent to which ecosystem interactions occur is not clear. Since some of the SASL populations are increasing, there is particular interest in understanding their impacts upon fisheries, but comparatively little is known about the impact of fisheries on SASLs. Further research is needed to broaden the information presented here, in order to increase understanding of the causes, effects, and trends of ecosystem interactions between pinnipeds and commercial fisheries.

INDIRECT OBSERVATIONS RELATED TO FISHERIES INTERACTIONS

In some South American countries, there is indirect evidence from the examination of beach-washed carcasses that numbers of fishery-related pinniped mortalities might be higher than those reported (Kovacs et al. 2012). In southern Brazil, Machado (2013) reported that 25% of 70 SASL carcasses collected between 1991 and 2011 had signs of trauma on their skulls, some of which may have resulted from interactions with fishers. In the same context, in Uruguay, 10% of 270 skulls (16 SASL and 11 SAFS) examined from scientific collections showed evidence of trauma that may have resulted from interactions with fishers (Sabrina Riverón, personal communication). Furthermore, post-mortem analyses of stranded SASLs conducted over multiple years by the Instituto del Mar del Perú found evidence of possible fisheries interactions (for instance skull and jaw fractures, internal haemorrhages caused by sharp objects, and the presence of remnants of fishing gear and a neurotoxic poison in stomachs; IMARPE 2013).

Pinnipeds and aquaculture interactions

SALMONID AQUACULTURE: AN INTRODUCTION

Farming of Atlantic salmon *Salmo salar*, coho salmon *Oncorhynchus kisutch*, and rainbow trout *Oncorhynchus mykiss* (Salmonidae, hereafter salmonids) has expanded rapidly in the last three decades in southern Chile (Quiñones et al. 2019). The aquaculture industry, both in size and in the number of farming facilities, is rapidly expanding further south to remote areas of Chilean Patagonia (Soto et al. 2022). The high density of fish stocked inside the salmonid pens (16–20 kg/m^3) constitutes a strong attractor for various predators, including the SASL (Sepúlveda & Oliva 2005, Vilata et al. 2010).

IMPACTS OF SALMONID AQUACULTURE ON SEA LIONS

Off southern Chile, interactions between the SASL and salmonid farming have been described and quantified (Sepúlveda & Oliva 2005, Vilata et al. 2010). Muñoz et al. (2013) found that farmed salmonids were some of the main dietary items consumed by SASLs. However, subsequent studies demonstrated that the consumption of salmonids by SASLs had decreased, and they were no longer important items in the diet (Sepúlveda et al. 2017, Gomez-Uchida et al. 2021). A potential explanation for this pattern is the significant decrease in salmonid production in the region in response to a large-scale outbreak of the infectious salmon anaemia (ISA) that occurred in 2010. In response to the viral outbreak, the salmonid aquaculture industry implemented improvements in management procedures and the density of floating salmonid pens greatly decreased (Niklitschek et al. 2013).

Besides its potential trophic impact on the SASL, the salmonid farming industry represents a threat to this predator due to incidental mortality by entanglement in anti-predator nets that are designed to protect salmonids from predation by pinnipeds (Fig. 4; Heredia et al. 2022). To our knowledge, the only study that has reported incidental capture by entanglement in anti-predator nets reported the capture and death of 10 individual SASLs in three salmonid farms during a three-month sampling period off southern Chile (Vilata 2009). This record suggests that entanglement of SASLs in predator nets may be frequent and could be a significant source of mortality affecting SASLs in southern Chile (Heredia et al. 2022).

IMPACTS OF SEA LIONS ON SALMONID AQUACULTURE

Pinnipeds negatively affect salmonid aquaculture worldwide, including in Scotland, the USA, Canada, Australia, New Zealand, Norway, and Chile (Heredia et al. 2022). Depredation of salmonids can impact fish production

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(Table 1; see also Heredia et al. 2022). In Chile in particular, one of the main problems is that SASLs bite salmonids through the nets (Sepúlveda & Oliva 2005), and rip nets and release salmonids with consequent ecological, economic, and social impacts (Heredia et al. 2022). This behaviour can also cause stress to the fish, which increases their susceptibility to disease and affects their survival and growth rates (Table 1, Fig. 4). These kinds of impacts are difficult to quantify, since it is not always possible to associate stress indicators or diseases with the presence of predators (Heredia et al. 2022).

Mitigation methods and their impacts on pinniped populations

The numerous impacts of predators on fisheries and aquaculture have led to the development of methods to avoid, minimise, or mitigate interactions (FAO 2021). The techniques for preventing or minimising bycatch and for avoiding interactions with fisheries and aquaculture that have been used or proposed for use against pinnipeds in fisheries and/or aquaculture can be categorised as follows: 1) time-area closures; 2) acoustic deterrent devices; 3) modifications to fishing gear; and 4) other strategies (FAO 2021, Heredia et al. 2022).

TIME-AREA CLOSURES

Mitigating bycatch using time-area closures focusses on reducing interactions between pinnipeds and fisheries in areas where they both occur, especially in critical habitats for the pinnipeds, such as breeding or foraging areas (FAO 2021). Spatial closures restrict fishing in a particular area (permanently or for a defined period), whereas temporal closures restrict fishing activity seasonally (FAO 2021). Time-area closures have been established by some countries in response to pinniped bycatch (e.g. in New Zealand, Chilvers 2008, and Australia, Goldsworthy et al. 2022). One of the best examples is the permanent spatial gillnet closure implemented in South Australia to prevent the bycatch of the Endangered Australian sea lion, which demonstrated a significant reduction in bycatch mortality (Goldsworthy et al. 2022).

Some countries in South America, such as Brazil and Chile, have created Marine Protected Areas to protect critical species. However, Machado et al. (2016) showed that SASLs usually interact with fishing boats beyond the limits of the Marine Protected Areas off southern Brazil. This suggests that the extension of Marine Protected Areas is critical to protect SASLs from fishing impacts (Chilvers 2008). In general, time-area closures to mitigate bycatch in fisheries off South America are not considered a viable management option, due to the lack of infrastructure and support for monitoring and enforcement (Berninsone et al. 2020).

ACOUSTIC DETERRENT DEVICES

Acoustic deterrent devices produce sounds to alert marine mammals to the presence of nets; acoustic harassment devices (AHDs), which produce louder sounds, aim to scare or otherwise harass animals away from fishing gear and pens (FAO 2021). The number of aquaculture facilities using AHDs has increased. However, their success at deterring predators from approaching marine farms is still questionable, with some studies evaluating them as partially effective (e.g. Quick et al. 2004) and others simply stating that they are ineffective (Kemper et al. 2003).

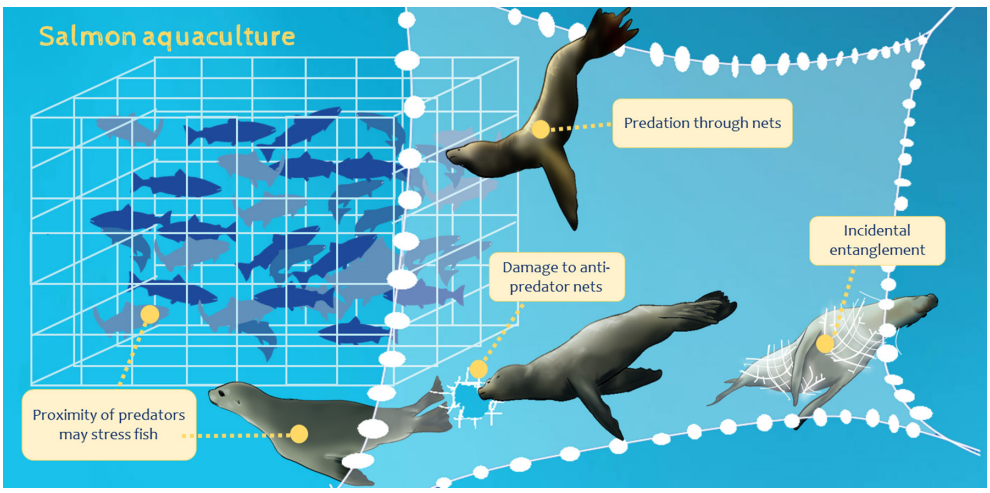

Fig. 4. Visual summary of interactions between the South American sea lion *Otaria flavescens* and salmonid aquaculture in Southern Chile. Illustration by Alicia I. Guerrero.

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Table 1. Types of interaction between the South American sea lion *Otaria flavescens* and the salmonid aquaculture industry in southern Chile, and their consequences

Type of interaction	Effect or consequence
Closeness of sea lions to salmonid farms	• Increased susceptibility of salmonids to disease • Stress-induced reduction in feeding by salmonids
Sea lions entering cages and biting salmonids through cages and anti-predator nets	• Salmonid mortality • Reduction or loss of salmonid commercial value • Increased requirement for divers to remove dead sea lions from cages • Damage to anti-predator nets • Stress-induced reduction in feeding by salmonids • Increased susceptibility of salmonids to disease
Damage to anti-predator nets or other facilities by sea lions	• Increased maintenance required to repair anti-predator nets • Salmonid escapes • Increased economic costs due to necessary repairs

Sepúlveda and Oliva (2005) stated that the use of AHDs was ineffective in the salmonid farms of southern Chile, and their use was consequently stopped by salmonid farmers. AHDs have been tested in some fisheries of Chile (Félix et al. 2021): SASLs quickly become habituated to the sounds emitted by the devices, and no longer show any adverse reaction to them. Off Argentina, the use of acoustic deterrent devices to reduce incidental captures of Franciscana dolphins *Pontoporia blainvillei* was effective to protect the dolphins, but was shown to be counterproductive for SASLs: the devices actually attracted SASLs to the gillnets (Bordino et al. 2002).

MODIFICATIONS TO FISHING GEAR

Fishing gear may be modified to reduce interactions with pinnipeds or to allow animals to self-release when they become hooked or entrapped (FAO 2021). There are many possible physical modifications, but seal excluder devices (SEDs) are the most commonly used to prevent pinniped bycatch (Hamilton & Baker 2015). SEDs consist of a grid that allows the target catch to pass through to the codend of a trawl net, but prevents access by pinnipeds. The grid is placed inside the net, before the codend, at an angle, so that pinnipeds approaching the grid are directed towards an escape opening (hole) through which they can exit the net (Hamilton & Baker 2015, FAO 2021). This technique has been tested on various species of pinnipeds, such as the grey seal (Königson et al. 2015), the New Zealand sea lion *Phocarctos hookeri* (Hamilton & Baker 2015) and the Australian sea lion (Lyle et al. 2016). These studies demonstrated that the risk of pinniped mortality is significantly reduced when SEDs are used, since most of the pinnipeds are observed to exit the net through the opening in apparently good condition (Hamilton & Baker 2015). However, the fate of escaped animals has not been adequately evaluated (FAO 2021).

In South America, SEDs have been voluntarily implemented in trawl fisheries off central Chile, and a significant subsequent decrease in SASL bycatch has been demonstrated (Queirolo et al. 2019). Fishers along the central coast of Chile find the use of SEDs appealing, not necessarily from a mammal conservation perspective, but because dead SASLs in trawl nets negatively affect their fishing operation. The Falkland Islands Fisheries Department implemented SEDs fitted inside a net extension between the trawl net and the codend and found that they were the most efficient method for reducing bycatch mortality. SEDs became mandatory in Falkland Islands fisheries in September 2017 and, since then, the number of SASL and SAFS mortalities has remained insignificant (Iriarte et al. 2020).

In the salmonid aquaculture industry, the most common damage control method is use of the anti-predator net (Heredia et al. 2022). This method is designed to prevent predators attacking from underneath cages and from jumping or scrambling over the cages (Thompson et al. 2021). However, a potential impact of this method is the death or injury of predators, including SASLs, due to entanglement. When salmonid aquaculture first began in Chile, most of the salmonid farms used anti-predator nets with a 50 cm knot-to-knot mesh size (Sepúlveda & Oliva 2005). However, that size resulted in bycatch of SASLs, and thus the industry agreed to use 25 cm knot-to-knot mesh size, reducing the probability of bycatch (Durán et al. 2011). However, official statistics of bycatch due to entanglement in anti-predator nets do not exist in Chile, and thus, the impact on the SASL population is unknown.

OTHER STRATEGIES

Three different models of fish traps were tested off Piriápolis, Uruguay (during 2014-2016), to reduce the damage and catch loss caused by interactions with SASLs during fishing and consequently mitigate the conflict. Models were collectively designed and were built using iron rods and polyvinyl chloride pipes lined with mesh. The traps included two entrances and a small bag containing bait, which was placed inside. These traps resulted in low fish catches, so two new models with four

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openings were also tested. Although SASLs were recorded in 28% of the fishing events monitored, no damage was ever recorded to the catches or the traps. These fish traps are a promising alternative to other types of fishing gear; however, additional studies are necessary to improve their performance (Diana Szteren, personal communication).

Shooting as a deterrence method to scare off pinnipeds has been tested in both artisanal fisheries (Sepúlveda et al. 2018) and salmonid aquaculture (Sepúlveda & Oliva 2005). However, in both studies this method was found to have no effect on the occurrence of interactions: predators either remained on site or returned to the fishing area shortly after the shooting ceased.

Another potential measure to reduce pinniped bycatch in the medium to long term is environmental education. Pont et al. (2016) and Sanguinetti et al. (2021) recommended the implementation of a comprehensive and long-term programme of environmental education in the fishing community, including both ecological aspects (e.g. the role of pinnipeds as top predators in the marine system and the possible negative impacts of their removal) and topics related to the sustainable use of the marine resources and their potential for wildlife tourism.

Management arrangements to reduce or mitigate interactions in South America

For the countries of South America, regulations that aim to ensure the protection of marine mammals, and measures that tend to reduce interactions and prevent bycatch, are varied (Table 2). In a study assessing the point of view of fishers about the fisheries-SASLs conflict Oliveira et al. (2020) found that fishers proposed economic compensation for the damage caused by predators to fishing communities. Governments may accept that fishers find it difficult to mitigate interactions with pinnipeds while fishing and therefore may provide temporary financial compensation to help fishers earn a living while developing ways to reduce the pinniped–fisheries interactions. However, these financial compensation schemes depend on an evaluation of the economic losses of each fishing boat and on the existence of governmental budgets to fund this proposal (Oliveira et al. 2020). Oliveira et al. (2020) also reported that most of the respondents suggested eradication of SASLs as the solution to fishery interactions (i.e. culling; Westerberg 2010). It is unclear, however, whether this measure would effectively reduce interactions, since there appears to be little correlation between the overall size of

Table 2. Management arrangements to reduce or mitigate interactions between fisheries and marine mammals in South American waters, by country

Country	Management arrangements	Legislation
Brazil	National legislation prohibits hunting, fishing and capture of marine mammals.	Portaria SUDEPE number N-11, 21 February 1986 (available at https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Portaria/1986/p_sudepe_11_n_1986_proibepescapequenoscetaceos_pinipedes_sirenios.pdf)
Uruguay	Law promotes conservation, research and sustainable development of hydro-biological resources and their ecosystems. Prohibition of hunting, harassment and any type of appropriation of marine mammals. Additional requirement that marine mammals caught in fishing operations must be released immediately.	Law 19.175 and its decree 115/018 (available at https://www.impo.com.uy/bases/decretos/115-2018) Decree 238/998 (available at https://www.impo.com.uy/bases/decretos/238-1998)
Argentina	No relevant management arrangements	No legislation
Chile	Marine mammals are protected species. Ban of killing and capturing South American sea lion (2021-2030). Discards and incidental catch checks, with established penalties and mechanisms for checks at sea. Measures and protocols for the reduction of incidental capture of pinnipeds in trawling fisheries. Protocol for the reduction of incidental capture and handling of marine mammals in purse seine fisheries in northern Chile.	Decree 225/1995 (available at https://www.bcn.cl/leychile/navegar?idNorma=20721&idParte=0&idVersion=) Decree 202100004 (available at http://www.sernapesca.cl/sites/default/files/d.ex_4-2021.pdf) Law 20625 (available at https://www.subpesca.cl/portal/615/articles-80306_documento.pdf) Resolution N° 1357-2022 (available at https://www.bcn.cl/leychile/navegar?idNorma=1178384&idParte=0) Resolution N° 2667-2021 (available at https://www.subpesca.cl/portal/615/articles-112315_documento.pdf)
Peru	Marine mammals are protected species.	Decree 034-2004-MINAGRI and DS 004-2014-MINAGRI (available at https://www.midagri.gob.pe/portal/download/pdf/marcolegal/normaslegales/decretossupremos/2014/ds04-2014-minagri.pdf)

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a pinniped population and the conflict it generates with fishers (Bowen & Lidgard 2013). Furthermore, killing sea lions is not an option for many of the countries in South America, since all marine mammals are protected under national laws (see below).

In Brazil and Peru, all marine mammal species are protected under national legislation that prohibits hunting, fishing or capture of these species. However, in these countries there are no specific regulatory measures in place to monitor, reduce, or mitigate interactions between pinnipeds and fisheries. In Argentina, there are no regulations regarding the bycatch of marine mammals. Although reports of bycatch have been made to the authorities over the last 30 years, no management measures have been undertaken. In Uruguay, hunting, harassment, and any other appropriation of marine mammals are prohibited (Decree 238/998; MGAP-DINARA). However, no concrete measures have been directed towards reducing interactions between pinnipeds and fisheries, with the exception of the above-mentioned assessment of fish traps. In Chile, all marine mammals have been protected by Decree N° 225 (Undersecretary of Fisheries and Aquaculture) since 1995. Furthermore, Law N° 20625 (Undersecretary of Fisheries and Aquaculture) includes the concept of incidental catch, as well as penalties and mechanisms for its control (Félix et al. 2021). Recently, under the auspices of the USA's MMPA Import Provision, a series of regulations were introduced in Chile to reduce interactions with marine mammals and prevent bycatch (Table 2). These regulations have been adopted by fishers who are developing compliance protocols (Luis Cocas, Undersecretary of Fisheries and Aquaculture).

In addition to legislative requirements, in Chile and Peru, a programme of research by fisheries observers has been implemented, to quantify discards and incidental catches and identify causes of bycatch. In Chile, from 2015 onward, fisheries observers have been tasked with registering bycatch of marine mammals in the country's main fisheries (Félix et al. 2021). In Peru, since 2017, the industrial purse seine industry has run an onboard observer programme, with the objective of monitoring and releasing non-target fauna incidentally caught during fishing operations (Peraltilla et al. 2022). Such initiatives may assist the industry if they seek sustainable seafood certifications (e.g. Marine Stewardship Council certification), or wish to comply with import provisions under the USA's MMPA. Additionally, beginning January 2020, compliance with the discard and incidental catch reduction plans and regulations in Chile has been evaluated by electronic monitoring systems using onboard cameras and is reported through electronic logbooks in all vessels of the industrial fleets (>18 m). Furthermore, artisanal boats longer than 15 m will be required to carry electronic monitoring systems by January 2024 (Félix et al. 2021).

CONCLUSIONS

Studies carried out in the last 25 years demonstrate that the SASL, and to a lesser degree the SAFS, continue to interact with human fishing and aquaculture activities in South America. However, while these species (and particularly the SASL) are commonly blamed for causing significant economic losses to the fishing and aquaculture industries, previous analyses suggest that actual losses are not as high as reported by local fishers (e.g. 0.8-3% of the total catch in Brazil, Oliveira et al. 2020; 2.5% of the catch in Chile, Sanguinetti et al. 2021). Beyond assessing the frequency or the magnitude of depredation by pinnipeds, it is important to compare the target catch in the presence and absence of SASLs. Assessments to date suggest there is no significant difference (e.g. in Uruguay, Bombau & Szteren 2017; in Chile, de la Torriente et al. 2009, Sanguinetti et al. 2021). This indicates that SASL is not a determining factor in the variation of artisanal fisheries catch. Negative attitudes from fishers may be ameliorated through environmental education that includes, among other issues, the critical role of these marine top predators in trophic webs and consequently the negative impacts of their removal (Pont et al. 2016, Sanguinetti et al. 2021).

Considering the multiple factors involved in the interactions between pinnipeds and fisheries, our limited understanding of ecosystem complexity, and the capacity of pinnipeds to modify ecosystem structure and dynamics, it is very difficult to justify a population reduction of these predators to manage the problem (de la Torriente et al. 2009, De María et al. 2014). On the contrary, it has been shown that a population cull would not result in higher fisheries yields (Yodzis 2001) and could cause ecological damage at both population and ecosystem levels (Sepúlveda et al. 2016). We suggest that strategies for effectively reducing conflicts between pinnipeds, fisheries, and aquaculture should involve all stakeholders in participative research to facilitate co-management (Pont et al. 2016, Oliveira et al. 2020). Therefore, it is recommended that a long-term education programme is established among the fishing community that teaches about the critical role of this marine top predator in the trophic web and consequently the negative impacts of their removal (Pont et al. 2016, Sanguinetti et al. 2021).

Limited progress and inconsistency exists among the different countries of South America regarding conservation priorities and actions to reduce marine mammal bycatch and to manage pinniped-related damage and predation. The causes of the limited progress in the adoption of mitigation measures in South America are multiple, including ecological aspects that are unknown or that cannot be overcome with current technology; the high cost of modifying nets or incorporating acoustic

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deterrent devices; and the scarcity of fishing controls, particularly in the large artisanal fleets (Reeves et al. 2013). The nations of South America are aware of this reality, due to the incidental mortality of marine mammals in their fisheries, which has not been quantified. This has begun to change in the last three years, partly due to the new import provisions established in the MMPA. Chile in particular stands out as the country making the greatest progress in marine mammal bycatch monitoring, as well as in the adoption of management measures and fishery control, and the incorporation of onboard cameras and scientific observers in its main fisheries. All these measures have been developed directly to prevent or reduce marine mammal bycatch. In this context, the MMPA legislation has been valuable in spurring on improved data collection and in promoting measures aimed at improving the standards of protection for marine mammals (Williams et al. 2016). However, this situation is not repeated in other countries. Despite the amount of information that the scientific community has collected in recent years, knowledge has not been translated into the incorporation of mitigation measures. Thus, it is recommended that countries in South America begin consultations with relevant stakeholders and use the information obtained as inputs when developing or updating their regulatory programmes (Félix et al. 2021). This is a relevant challenge for these countries and highlights the need to improve policy and management relating to marine mammal interactions with fisheries and aquaculture.

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