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Operational interactions between sea lion species (Otariinae) and commercial fisheries

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ABSTRACT

Many marine mammal species, such as pinnipeds, have shown an increased frequency of interaction with fisheries. Thus, we aimed to investigate the operational interactions between commercial fishing and sea lion species of all five continents, between 1982 and 2018. We found 130 publications in which operational interactions between commercial fisheries and the species of sea lions were detected, in 12 countries. These interactions included bycatch, presence of the animals around boats, depredation, gear damage, entanglement in lost/discarded fishing gear, boat collisions, aggressions, gear-related injuries and harassment. Trawl and gillnet fisheries showed significantly increased association with bycatch, although purse seine fishing was reported as having the largest groups of pinnipeds in the interactions. Gillnet and line fisheries registered more events of depredation and gear damage. Other interactions, such as entanglement and aggressions, were also very common for all species. We suggest that the interactions should be monitored using the data of onboard observers from different fleets and fisheries. Bycatch limits, change in fishing practices, decreased fishing effort, and the establishment of effective MPAs may reduce impact on the fauna. Moreover, data on bycatch should be standardized to enable comparisons between fisheries and locations. The extent of commercial losses caused by pinnipeds should also be characterized to depict the real impact of operational interactions in fisheries economy. Lastly, the identification of interaction hotspots can enable efficient conflict management in the affected areas.

Keywords: Interactions; Sea Lions; Fisheries; Conflicts; Pinnipeds

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SIGNIFICANCE STATEMENT

This manuscript is original and it shows a review on operational interactions between commercial fisheries and sea lions worldwide, containing information on types and magnitude of interactions, as well as on the effect of mitigation of impacts in different countries and fisheries. Given that operational interactions with fisheries, such as bycatch, can be responsible for the population decline of several marine species, we consider this article is very relevant for conservation.

INTRODUCTION

Interactions between marine mammals and commercial fisheries have increased over time (DeMaster et al. 2001; Harwood 1983). One of the many factors that increase the frequency and intensity of interactions is a decline in fishery resources, which makes marine animals perceive fishing boats as an "easy" source of food (Kaschner and Pauly 2005). Since the ban on marine mammal culling imposed by many countries, some populations have been recovering from declines (Magera et al. 2013), although fish stocks and fishery catches have not followed this recovery (Myers and Worm 2003; Pauly and Zeller 2016). Additionally, fisheries have expanded to explore new areas and resources, (Swartz et al. 2010), possibly facilitating the occurrence of more interactions.

More specifically, interactions between marine mammals and commercial fisheries can be biological/trophic (indirect) or operational (direct) (Beverton 1985; Lavigne 2003). Biological interactions refer to the indirect effects of fisheries on marine animals, as in the case of competition for food resources, as they both often target the same prey (Kaschner and Pauly 2005; Plagányi and Buttenworth 2009). Operational interactions in fisheries usually occur when fishing grounds and the foraging area of marine mammals overlap and when the animals frequently come into physical contact with the fishing gear and boats. The operational interactions of fisheries have a negative effect on many populations of marine mammals. Bycatch, which is the non-intentional capture of individuals that will be later discarded dead or alive, may significantly reduce the abundance of top predators, thus altering the trophic structure and functioning of marine ecosystems (Dayton et al. 2002; Read 2008). More than 80% of marine mammal species have been captured as bycatch (Reeves et al. 2013), which makes the incidental capture of species one of the leading causes of population decline (Kovacs et al. 2012). This contact can also lead marine mammals to damage or capture and consume the fish caught by fishing gear (depredation), thus reducing the productivity and profitability of the fishery. Furthermore, the animals may be injured or killed due to entanglement in discarded/lost gear, boat collision and retaliation by fishermen (Alverson et al. 1994; Beverton 1985; Lavigne 2003; Read 2005).

Among marine mammals, pinnipeds (sea lions, fur seals, seals and walruses) belong to a group that exhibits increased levels of interactions with different fisheries (Perrin 1991; Wickens 1995). To assess direct operational interactions with fisheries, we chose this specific group of animals because some of them are endemic and endangered or near threatened and they interact with different fisheries worldwide (Wickens 1995).

This article is part of doctoral research conducted to analyse conflicts between South American sea lions (*Otaria flavescens*) and gillnet fisheries, and the conservation of these animals in Marine Protected Areas (Ramos, 2018).

This paper is a review of current knowledge on the occurrence and types of operational interactions between existing sea lion species and commercial fisheries. Furthermore, we aim to identify which fisheries interact most frequently with sea lions and detect any knowledge gaps.

METHODS

Species of sea lions

This group includes sea lions (subfamily Otariinae), represented by six extant species: the South American sea lion *Otaria flavescens* (Shaw 1800), the New Zealand sea lion *Phocarctos hookeri* (Peters 1866), the Australian sea lion *Neophoca cinerea* (Perón 1816), the California sea lion *Zalophus californianus* (Lesson 1828), the Galapagos sea lion *Zalophus wollebaeki* (Sivertsen 1953) and the Steller sea lion *Eumetopias jubatus* (Schreber 1776), with a wide distribution (Figure 1) and specific characteristics (Table 1).

Data collection for operational interactions

To describe the operational interactions between commercial fisheries and the species of sea lions, we performed a literature review of the research content of interest in the websites Science Direct, Scopus, LATINDEX, SciELO, REDALyC, Web of Science, Ingenta, the CAPES Portal of Journals and Research Gate. The keywords used for our investigation were a combination of the scientific name of each sea lion species plus each of the following keywords, separately: “interaction”, “conflict”, “bycatch”, “predation”, “depredation”, “capture”, “take”, “overlap”, “fisheries”,

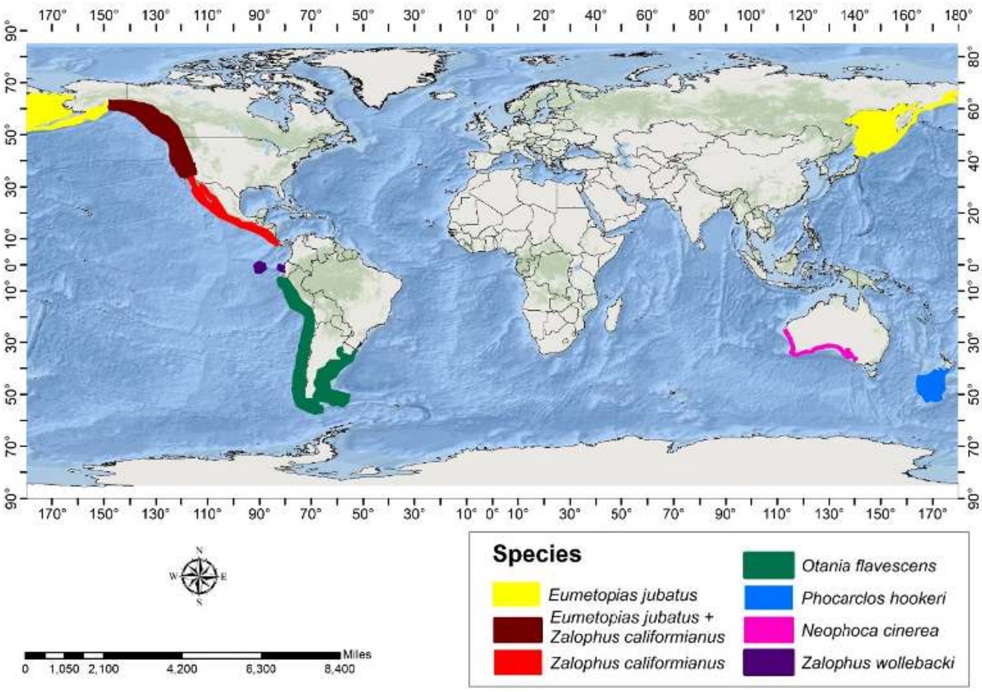

Figure 1. Map adapted from IUCN, showing the distribution of six species of sea lions in the world.

Table 1. Geographic range, population size, population trend and conservation status of sea lion species.

	O. flavescens	*P. hookeri*	*N. cinerea*	*Z. californianus*	*Z. wollebaeki*	*E. jubatus*
Geographic range	Northern Peru to Southern Brazil	New Zealand	Australia	Mexico to Canada; Alaska	Ecuador	Japan to California
Population size	≥ 445.000	Around 9.880	< 13.000	Around 387.646	* 9.200 to 10.600	Around 160.867
Population trend	Stable	Declining	Declining	Increasing	Declining	Increasing
Conservation status	Least concern	Endangered	Endangered	Least concern	Endangered	Near threatened

Legend: Aurioles-Gamboa and Hernández-Camacho (2015); Cárdenas-Alayza et al. (2016); Chilvers (2015); Geschke and Chilvers (2019); Gelatt and Sweeney (2016); Goldsworthy (2015); Loughlin et al. (1984); Maniscalco et al. (2004); Trillmich (2015); Vaz-Ferreira (1981); (*) Mature individuals.

"fishing", "fishery", "marine debris" and "entanglement". The keywords were chosen according to the most common types of interactions or terms found in research on marine mammal-fishery conflicts. Only studies published from 1982 to 2018, totalling 36 years, were chosen. Before 1982, studies were much scarcer and/or more difficult to access. After each search, the studies were filtered according to their title and abstracts. Data from academic theses, dissertations, monographs and abstracts presented at conferences and congresses were not used because we chose to focus on published articles and official reports. Moreover, studies regarding the interactions in farms that cultivate marine organisms were not included since they do not involve fishing. Studies in all languages were accepted.

The selected studies were divided according to the sea lion species, countries and the different types of fishery in order to compare the impacts of the operational interactions of the different fisheries. The fisheries were split into five categories: trawl, gillnet, purse seine, line fisheries and trap. The line fisheries category included all fisheries that use lines, baited hooks and visual attractions to capture marine organisms (longline, jigging, hook and line, troll and handline). Some data could not be classified into a particular fishery because they referred to entanglement in discarded/lost gear and other fishing-related marine debris mainly of unidentifiable origin. For the same reason, other types of interactions with fisheries (e.g. aggressions and boat collision) could not be related to a specific fishery, as they referred to stranding data. The majority of data were obtained by onboard observers and less frequently by interviews with fishermen and anecdotal reports. Some studies provided information for more than one type of fishery, but not separately. Thus, these data could not be presented separately by fishery.

RESULTS

Our search retrieved 130 studies on operational interactions for the six species of sea lion listed (Figure 2) and the five different types of fishery (Figure 3) identified in 12 countries (Figure 4). The species *Z. californianus* produced the most studies (n=44), followed by *O. flavescens, P. hookeri, E. jubatus, N. cinerea* and *Z. wollebaeki* (Figure 2).

Trawl and gillnet fisheries showed significantly increased association with bycatch occurrence and numbers (Figure 5; Tables 2 to 7). Depredation and gear damage events were more common in gillnet and line fisheries (Figure 5).

This study also showed that all species are impacted by other kinds of operational interactions, such as entanglement in lost/

discarded fishing gear, harassment, aggressions, gear-related injuries and boat collisions (Figure 6; Tables 2 to 7).

Otaria flavescens

From the 37 studies that depicted operational interactions with *O. flavescens*, 14 described interactions with gillnets, ten with line fisheries, seven with trawls, five with purse seines, two with traps and seven with other different types of interactions that occurred through unidentifiable gear (Table 2). The country with the highest number of studies was Chile (13), followed by Uruguay (9), Argentina (8), Brazil (5), Peru (1) and Colombia (1).

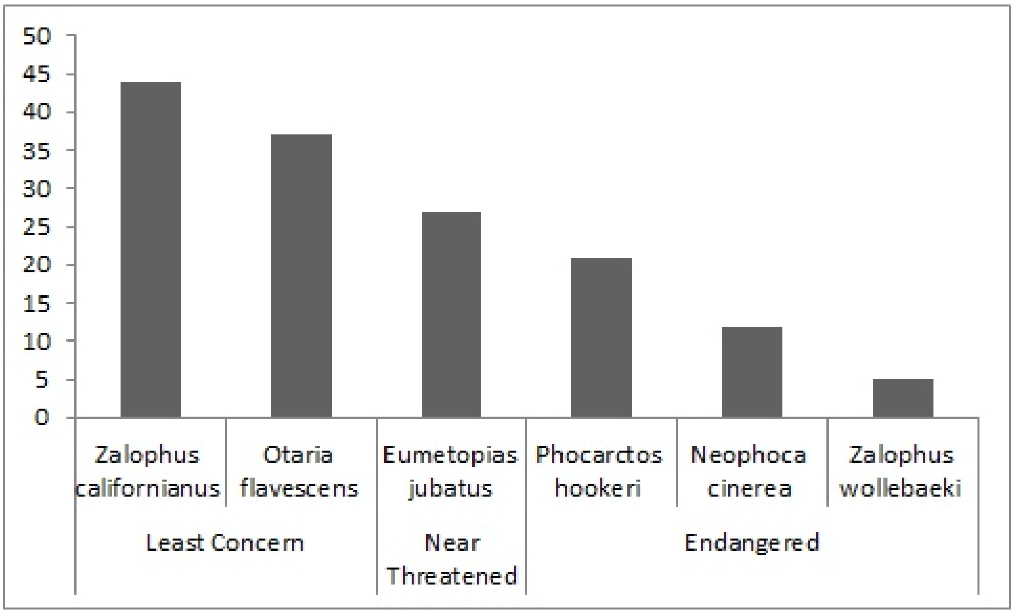

Figure 2. Number of studies on operational interactions with commercial fisheries by species of sea lions.

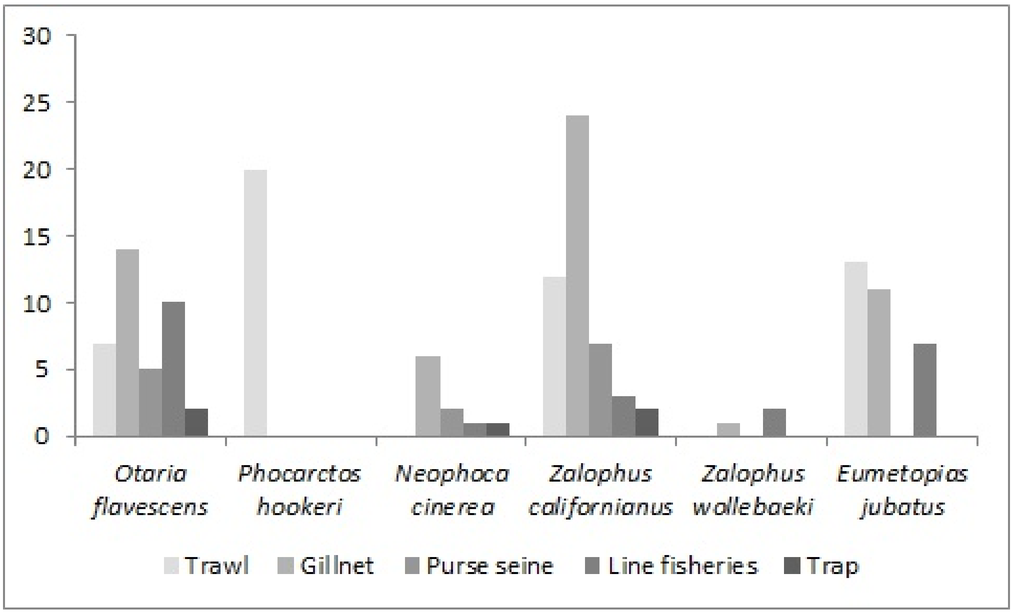

Figure 3. Number of studies on operational interactions with commercial fisheries by species of sea lions and fisheries.

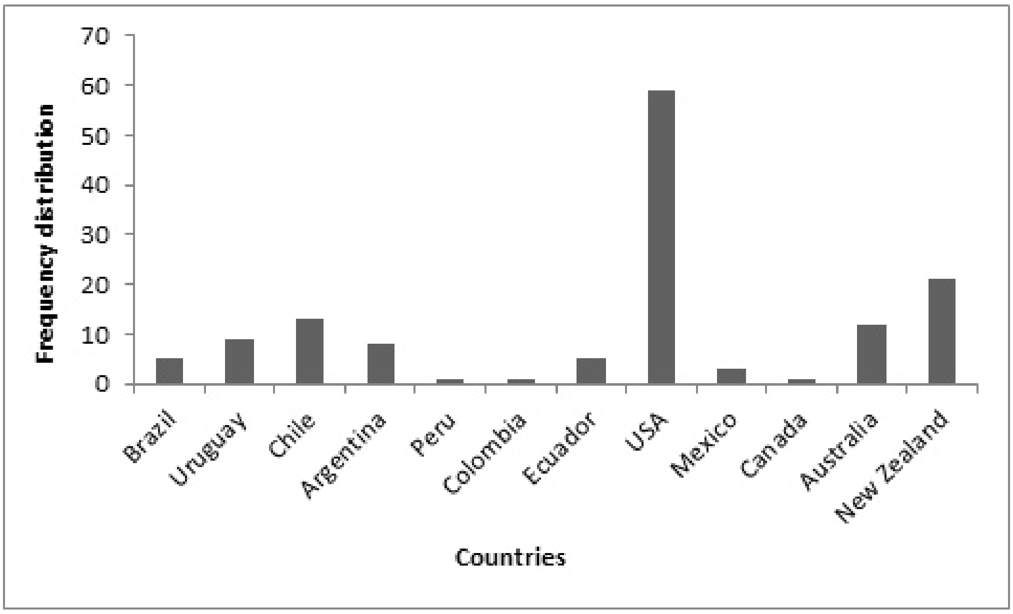

Figure 4. Number of studies on operational interactions with commercial fisheries and species of sea lions by country.

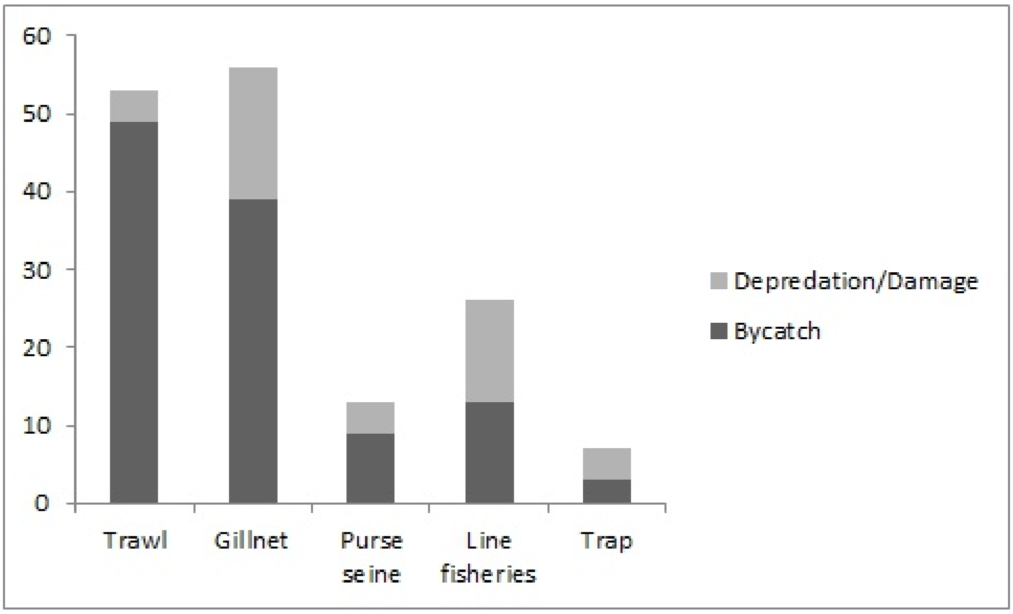

Figure 5. Frequency of bycatch and depredation/damage of sea lions by fishery.

Phocarctos hookeri

From the 21 studies that depicted the interactions with *P. hookeri*, 20 described interactions with trawl and one study with unidentifiable gear (Table 3).

Neophoca cinerea

From the 12 studies that depicted the interactions with *N. cinerea*, six described interactions with gillnets, two with purse seines, one with line fisheries, one with trap fishery and six with unidentifiable gear (Table 4).

Table 2. Information on operational interactions between South American sea lions and commercial fisheries. CPUE = capture per unit of effort and PPUE = predation per unit of effort". When there is no specific information, it means that the kind of interaction was not specified, although it occurred (e.g. presence around boats during fishing operations). "Yes" is given when the interaction occurred but was not quantified.

Local	Fishery	Annual bycatch estimated or observed	Depredation/Damage	Study period	References
	Trawl				
Argentina	Trawl	175 to 602	Non-registered	1992-94	Crespo et al. (1997); Dans et al. (2003)
Argentina	Trawl	11 observed	Non-registered	1990-98	Koen-Alonso et al. (2000)
Argentina	Trawl	Yes	Non-registered	2007-08	Seco Pon et al. (2013)
Argentina	Trawl	6 observed	Non-registered	2007-08	Seco Pon et al. (2013)
Brazil	Trawl	1 observed	Non-registered	2008	Machado et al. (2015)
Chile	Trawl	82 observed	Non-registered	2004	Reyes et al. (2013)
Uruguay	Trawl	Non-registered	Yes	2005-06	Segura et al. (2008)
	Gillnet				
Argentina	Gillnet	Non-registered	Yes	1980-90	Corcuera et al. (1994)
Argentina	Gillnet	Non-registered	Yes	1999-00	Bordino et al. (2002)
Brazil	Set and driftnet	Non-registered	Yes	1992-98; 2003-05; 2011-12	Machado et al. (2016)
Chile	Gillnet + longline	Non-registered	1.8-33.8% of CPUE	2004	Sepúlveda et al. (2007)
Chile	Gillnet	Non-registered	Yes	2014-16	Sepúlveda et al. (2018)
Peru	Driftnet	Yes	Non-registered	1991-98	Majluf et al. (2002)
Uruguay	Gillnet + longline	Non-registered	0.8-46.2% of CPUE	1997-98	Szteren and Páez (2002)
Uruguay	Gillnet		Yes	1997-98	Szteren (2006)
Uruguay	Gillnet	Non-registered	40-71.4% of fishing events	1997; 2001; 2002	Szteren and Lezama (2006a)
Uruguay	Gillnet	Non-registered	0-46.2% of PPUE	1997-98; 2002; 2002	Szteren and Lezama (2006b)

Uruguay	Gillnet	Yes	Non-registered	2004-06	Franco-Trecu et al. (2009)
Uruguay	Gillnet	Non-registered	1.4-16% of total catch	2010	De María et al. (2014)
Uruguay	Gillnet	Non-registered	Up to 0.9% of fishing events	2013-14	Bombau and Szteren (2017)
	Purse seine				
Argentina	Seine	Non-registered	Non-registered	2007-08	Seco Pon et al. (2012)
Chile	Seine	18 observed	Up to 0.4% of total catch of a set	1999	Hückstädt and Antezana (2003)
Chile	Seine	Non-registered	Non-registered	2002	Hückstädt and Krautz (2004)
Chile	Seine + jigging + longline + gillnet	Non-registered	Yes	2004	Goetz et al. (2008)
Chile	Seine	Non-registered	Non-registered	2010-11	González et al. (2015)
	Line fisheries				
Uruguay	Longline	Non-registered	Yes	1997-98	Szteren (2006)
Uruguay	Longline	Non-registered	0-72.7% of fishing events	1997; 2001; 2002	Szteren and Lezama (2006a)
Uruguay	Longline	Non-registered	1.73-14.6% of PPUE	1997-98; 2002; 2002	Szteren and Lezama (2006b)
Chile	Longline	Non-registered	Yes	2002-03	Moreno et al. (2003)
Chile	Longline	Non-registered	1.6% of total catch	2005-06	La Torriente et al. (2010)
Chile	Longline	≥3	Non-registered	1996-2007	Passadore et al. (2008; 2015)
	Trap				
Chile	Trap	Killed for bait	Non-registered	1976-86	Cardenas et al. (1987)
Chile	Trap	Non-registered	Yes		Oporto et al. (1991)
Argentina	Entanglement	Non-registered		Non-identified	Laist (1997)
Brazil	Aggression; gear-related injuries	Non-registered		1977-86	Rosas et al. (1994)
Brazil	Aggression; gear-related injuries	Non-registered		1997-98	Petry and Fonseca (2001)
Brazil	Aggression	Non-registered		1998-99	Przbylski and Monteiro-Filho (2001)
Colombia	Entanglement	Non-registered		1993	Mora-Pinto and Muñoz-Hincapié (1995)
Uruguay	Aggression	2 observed		1999	Hückstädt and Antezana (2003)
Uruguay	Entanglement	Non-registered		2007-13	Franco-Trecu et al. (2017)

Table 3. Information on operational interactions between New Zealand sea lions and industrial trawl fisheries. In “Annual bycatch”, average annual bycatch for the whole period is given in brackets.

Local	Fishery	Annual bycatch estimated or observed	Study period	References
	Trawl			
New Zealand	Trawl	17 to 141	1987-96	Baird (1996); Maunder et al. (2000)
New Zealand	Trawl	63	1998	Baird (1999)
New Zealand	Trawl	71	2000	Doonan (2000)
New Zealand	Trawl	12	1999	Baird (2001)
New Zealand	Trawl	66	2001	Doonan (2001)
New Zealand	Trawl	6	2001	Doonan (2001)
New Zealand	Trawl	34 to 173	1991-96	Manly et al. (2002)
New Zealand	Trawl	14 to 141	1988-2002	Breen et al. (2003)
New Zealand	Trawl	70	2000	Baird (2004)
New Zealand	Trawl	40	2003	Baird (2005b)
New Zealand	Trawl	74	2001-02	Baird (2005a); Baird and Doonan (2005)
New Zealand	Trawl	185.2	2004	Smith and Baird (2007)
New Zealand	Trawl	2 observed	2003	Smith and Baird (2007)
New Zealand	Trawl	1 observed	2004	Smith and Baird (2007)
New Zealand	Trawl	1 observed	2004	Smith and Baird (2007)
New Zealand	Trawl	14 to 123	1992-2007	Chilvers (2008)
New Zealand	Trawl	15 to 141	1995-2007	Thompson and Abraham (2009)
New Zealand	Trawl	1 to 14	2002-07	Thompson and Abraham (2009)
New Zealand	Trawl	12	2004-07	Thompson and Abraham (2009)
New Zealand	Trawl	5 to 10	2004-07	Thompson and Abraham (2009)
New Zealand	Trawl	14 to 123 (73.3)		Robertson and Chilvers (2011)
New Zealand	Trawl	14.4 to 163	1995-2006	Smith and Baird (2011)
New Zealand	Trawl	81	2009-11	Thompson et al. (2013)
New Zealand	Trawl	1 to 24	2007-11	Hamilton and Baker (2014)
New Zealand	Trawl	1 to 4	2006-11	Hamilton and Baker (2014)
New Zealand	Trawl	4 to 15	2006-11	Hamilton and Baker (2014)
New Zealand	Trawl	5 to 66	2006-11	Hamilton and Baker (2014)
New Zealand	Trawl	25 to 46	2006-11	Hamilton and Baker (2014)
New Zealand	Trawl	388 observed	1991-2013	Thompson et al. (2015)
Local	**Fishing gear/debris**	**Number of individuals**	**Study period**	**References**
New Zealand	Entanglement	Non-registered	Non-identified	Laist (1997)

Table 4. Information on operational interactions between Australian sea lions and commercial fisheries. "Yes" is given when the interaction occurred but was not quantified.

Local	Fishery	Annual bycatch estimated or observed	Depredation/Damage	Study period	References
	Gillnet				
Australia	Gillnet	1 observed	Non-registered	1994-99	McAuley and Simpfendorfer (2003)
Australia	Gillnet	Yes	Non-registered	1987-95	Shaughnessy et al. (2003)
Australia	Gillnet	Yes	Yes		NSSG and Stewardson (2007)
Australia	Gillnet	318 to 395	Non-registered	2006-09	Goldsworthy et al. (2010)
Australia	Gillnet	9.5 to 22.5	Non-registered	2006-07	Hamer et al. (2011)
Australia	Gillnet	193 to 227	Non-registered	2006-07	Hamer et al. (2013)
	Purse seine				
Australia	Purse seine	Yes	Non-registered	Non-identified	Shaughnessy et al. (2003)
Australia	Purse seine	Non-registered	Yes	Non-identified	NSSG and Stewardson (2007)
	Line fisheries				
Australia	Handline	Yes	Non-registered	Non-identified	NSSG and Stewardson (2007)
	Trap				
Australia	Trap	0 to 12	Yes	1999-2004	Campbell et al. (2008)
Local	**Fishing gear/debris**	**Number of individuals**		**Study period**	**References**
Australia	Entanglement	Non-registered		1987-92	Gales et al. (1994)
Australia	Entanglement	14 observed		1986-92	Jones (1995)
Australia	Entanglement	Non-registered		1980-96	Mawson and Coughran (1999)
Australia	Entanglement	Non-registered		1988-2002	Page et al. (2004)
Australia	Entanglement	Non-registered		Non-identified	NSSG and Stewardson (2007)
Australia	Entanglement	1 observed		Non-identified	Byard and Machado (2018)

Zalophus californianus

From the 43 studies that depicted the interactions with *Z. californianus*, 23 described interactions with gillnets, 12 with trawls, seven with purse seines, three with line fisheries, two with trap fishery and 18 with unidentifiable gear (Table 5). All the studies with *Z. californianus* were carried out in the United States, except three that were conducted in Mexico.

Table 5. Information on operational interactions between California sea lions and commercial fisheries. In "Annual bycatch", average annual bycatch for the whole period is given in brackets. "Yes" is given when the interaction occurred but was not quantified.

Local	Fishery	Annual bycatch estimated or observed	Depredation/Damage	Study period	References
	Trawl				
USA	Trawl	Non-registered	Non-registered	1980	Miller et al. (1983)
USA	Trawl	25	Non-registered	1994-98	Forney et al. (2000)
USA	Trawl	0 to 2 (1)	Non-registered	1994-98	Carretta et al. (2002)
USA	Trawl	1	Non-registered	1994; 1998-09	Perez (2003)
USA	Trawl	1 to 2 (1.6)	Non-registered	1997-2001	Carretta et al. (2005; 2006;2007a)
USA	Trawl	0.8	Non-registered	2000-04	Carretta et al. (2007b; 2009)
USA	Trawl	1.9	Non-registered	2001-04	Carretta et al. (2007b; 2009)
USA	Trawl	≥ 11	Non-registered	2002-08	Heery et al. (2010)
USA	Trawl	78 observed	Non-registered	2005-09	Carretta et al. (2015)
USA	Trawl	34	Non-registered	Non-identified	Ferrari et al. (2015)
	Gillnet				
Mexico	Set gillnet	Non-registered	30% of total catch; 40% of net damage	1999-2001	Maravilla-Chávez et al. (2006)
Mexico	Set gillnet	Yes	Non-registered	2006	Shester and Micheli (2011)
USA	Set and driftnet	1209	32.6% of total catch	1980	Miller et al. (1983)
USA	Gillnet + trammel nets	1 to 34 (15.2)	Non-registered	1980-89	Woodley and Lavigne (1991)

USA	Gillnet + trammel nets	15 to 43 (24.6)	Non-registered	1983-85	Woodley and Lavigne (1991)
USA	Driftnet	34 to 5130 (760.6)	Non-registered	1980-88; 1990-93	Barlow et al. (1994)
USA	Set gillnet	847 to 4288 (2537)	Non-registered	1980-88; 1990-93	Barlow et al. (1994)
USA	Driftnet	4 to 89 (63)	Non-registered	1992-94	Barlow et al. (1995)
USA	Set gillnet	109 to 3255 (1783)	Non-registered	1992-94	Barlow et al. (1995)
USA	Driftnet	49	Non-registered	1991-95	Barlow et al. (1997)
USA	Set gillnet	815	Non-registered	1991-95	Barlow et al. (1997)
USA	Driftnet	28 to 90 (50.5)	Non-registered	1990-95	Julian and Beeson (1998)
USA	Set gillnet	724 to 3418 (1616)	Non-registered	1990-95	Julian and Beeson (1998)
USA	Driftnet	26 to 201 (158)	Non-registered	1994-98	Forney et al. (2000)
USA	Set gillnet	724 to 1228 (1012)	Non-registered	1994-98	Forney et al. (2000)
USA	Driftnet	Yes	Non-registered	1996-97	Barlow and Cameron (2003)
USA	Driftnet	553	Non-registered	1996-2002	Carretta et al. (2004)
USA	Driftnet	15	Non-registered	2003	Carretta and Chivers (2004)
USA	Set gillnet	686	Non-registered	2003	Carretta and Chivers (2004)
USA	Driftnet	3 observed	Non-registered	2002-03	Carretta and Chivers (2004)
USA	Driftnet	81	Non-registered	1997-2001	Carretta et al. (2005; 2006; 2007a)
USA	Set gillnet	1267	Non-registered	1999-2001	Carretta et al. (2005; 2006; 2007a)
USA	Driftnet	64	Non-registered	2006	Carretta and Enriquez (2007)
USA	Driftnet	38	Non-registered	2000-04	Carretta et al. (2007b; 2009; 2011)

USA	Set gillnet	≥ 11.4	Non-registered	2000-04	Carretta et al. (2007b; 2009; 2011)
USA	Driftnet	13.5	Non-registered	2003-04	Carretta et al. (2007b; 2009; 2011)
USA	Driftnet	48	Non-registered	2007	Carretta and Enriquez (2009)
USA	Set gillnet	74	Non-registered	2007	Carretta and Enriquez (2009)
USA	Drifnet	95	Non-registered	2011	Carretta and Enriquez (2012)
USA	Set gillnet	74	Non-registered	2011	Carretta and Enriquez (2012)
USA	Driftnet	32	Non-registered	2012	Carretta et al. (2014)
USA	Set gillnet	326	Non-registered	2012	Carretta et al. (2014)
USA	Driftnet	42	Non-registered	2008-12	Carretta et al. (2015; 2016)
USA	Set gillnet	200	Non-registered	2010-12	Carretta et al. (2015; 2016)
	Purse seine				
USA	Purse seine	20	Non-registered	1980	Miller et al. (1983)
USA	Purse seine	1 observed	Yes	2004-07	Carretta and Enriquez (2009)
USA	Purse seine	Non-registered	Yes	2004-07	Carretta and Enriquez (2009)
USA	Purse seine	≥ 1	Non-registered	2004	Carretta et al. (2007b; 2009; 2011)
USA	Purse seine	≥ 2	Non-registered	2004-08	Carretta et al. (2015; 2016)
	Line fisheries				
USA	Troll	300	2% of total catch	1980	Miller et al. (1983)
USA	Hook-and-line	Non-registered	0.4% of total catch	1980	Miller et al. (1983)
USA	Troll	Non-registered	8.5-28.6% of total catch	1997-99	Weise and Harvey (2005)

USA	Hook-and-line	16 observed	Non-registered	2002-08	Heery et al. (2010)
	Trap				
USA	Trap	Non-registered	Yes	Non-identified	Beeson and Hanan (1996)
USA	Trap	1 observed	Yes	2017	El-Mallakh and Hartman (2018)
Local	**Fishing gear/debris**	**Number of individuals**		**Study period**	**References**
Mexico	Entanglement	19 observed		1992	Harcourt et al. (1994)
USA	Entanglement	36 observed		1998; 2000	Aurioles-Gamboa et al. (2003)
USA	Entanglement	Non-registered		1978-86	Stewart and Yochem (1987)
USA	Entanglement; aggression	Non-registered		1984-90	Gerber et al. (1993)
USA	Entanglement	Non-registered		Non-identified	Laist (1997)
USA	Entanglement	34 to 72		1991-95	Zavala-González and Mellink (1997)
USA	Entanglement; aggression; boat collision	Non-registered		Non-identified	Goldstein et al. (1999)
USA	Entanglement	820 observed		1976-88	Hanni and Pyle (2000)
USA	Entanglement	66		2000-04	Carretta et al. (2007b; 2009; 2011)
USA	Entanglement	106		2001-06	Dau et al. (2009)
USA	Entanglement	157 observed		2001-05	Moore et al. (2009)
USA	Entanglement; aggression	Non-registered		1983-2010	Keledjian and Mesnick (2013)
USA	Entanglement; aggression; boat collision	Non-registered		2007-11	Carretta et al. (2013)
USA	Entanglement	≥ 55		2008-12	Carretta et al. (2015; 2016)
USA	Entanglement; aggression; boat collision	444 observed		1991-2016	Warlick et al. (2018)

Zalophus wollebaeki

From the five studies that depicted the interactions with *Z. wollebaeki,* two described interactions with line fisheries, one with gillnet and three with unidentifiable gear (Table 6).

Eumetopias jubatus

From the 27 studies that depicted interactions with *E. jubatus*, 13 described interactions with trawls, 11 with gillnets, seven with line fisheries and nine with unidentifiable gear (Table 7).

Table 6. Information on operational interactions between Galapagos sea lions and commercial fisheries. "Yes" is given when the interaction occurred but was not quantified.

Local	Fishery	Annual bycatch estimated or observed	Depredation/ Damage	Study period	References
	Gillnet				
Ecuador		Non-registered	Yes	2012	Páez-Rosas and Guevara (2017)
	Line fisheries				
Ecuador	Longline	Non-registered	Yes	2012	Páez-Rosas and Guevara (2017)
Ecuador	Handline	2 observed	Non-registered	2012	Zimmerhackel et al. (2015)
Local	**Fishing gear/debris**	**Number of individuals**		**Study period**	**References**
Ecuador	Entanglement	Non-registered		Non-identified	Laist (1997)
Ecuador	Entanglement	251 observed		1995-2003	Alava and Salazar (2006)
Ecuador	Entanglement; aggression; boat collision; harassment	Non-registered		2008-12	Denkinger et al. (2015)

DISCUSSION

Z. californianus and *O. flavescens* are the species with the highest number of publications about operational interactions (Figure 2), although both are classified as "least concern". Regarding *O. flavescens*, this might be explained by the wide distribution of the species, covering several countries. Figure 4 shows that developed countries have more studies published, which is expected as they have more financial support for research.

Trawl and gillnet presented the highest frequency and number of incidental captures of sea lions (Figure 5), a phenomenon that is generally observed in other studies about marine mammals. According to Read et al. (2006), in the early 1990s, from 536,158 to 822,706 cetaceans and pinnipeds died annually because of incidental captures worldwide, and gillnets were mostly responsible for the interactions with cetaceans (84%) and pinnipeds (98%). Reeves et al. (2013) found that at least 75% of species of odontocetes, 64% of mysticetes and 66% of pinnipeds were caught by gillnets between 1990 and 2011,

Table 7. Information on operational interactions between Steller sea lions and commercial fisheries. In “Annual bycatch”,“W” = Steller sea lion’s west stock and “E” = Steller sea lion’s east stock. Average annual bycatch for the whole period is given in brackets. “Yes” is given when the interaction occurred but was not quantified.

Local	Fishery	Annual bycatch estimated or observed	Depredation/Damage	Study period	References
	Gillnet				
USA	Gillnet + trawl	724	Non-registered	1978-81	Loughlin et al. (1983)
USA	Driftnet	29 (W)	Non-registered	1991	Wynne et al. (1992)
USA	Driftnet	0 to 8 (2) (E)	Non-registered	1990-93	Barlow et al. (1994)
USA	Driftnet	2 obs. (W)	Non-registered	1990-92	Barlow et al. (1994)
USA	Driftnet	0 to 7 (2) (E)	Non-registered	1990-95	Julian and Beeson (1998)
USA	Gillnet	15 (E)	Non-registered	1991-95	Baraff and Loughlin (2000)
USA	Driftnet and set gillnet	5 (W)	Non-registered	1990-2003	Angliss et al. (2001)
USA	Driftnet	1.2 (E)	Non-registered	1990-2003	Angliss et al. (2001)
USA	Set gillnet		Yes	2002; 2005	Manly (2007)
USA	Gillnet + trawl	0 to 14 (E)	Non-registered	2002-08	Heery et al. (2010)
USA	Driftnet	14.5 (W)	Non-registered	1990-91	Allen and Angliss (2010; 2012)
USA	Driftnet	1.2 (E)	Non-registered	1990-98	Ferrero et al. (2000)

	Trawl				
USA	Trawl	216 to 1436 (W)	Yes	1982-84	Loughlin and Nelson (1986)
USA	Trawl	1 to 1530 (W)	Non-registered	1978-88	Woodley and Lavigne (1991)
USA	Trawl	0 to 472 (W)	Non-registered	1978-88	Perez and Loughlin (1991)
USA	Trawl	4 to 187 (W)	Non-registered	1978-88	Perez and Loughlin (1991)
USA	Trawl	8 to 247 (W)	Non-registered	1978-88	Perez and Loughlin (1991)
USA	Trawl	0 to 1462 (W)	Non-registered	1978-88	Perez and Loughlin (1991)
USA	Trawl	600 (W)	Non-registered	1966-88	Trites and Larkin (1992)
USA	Trawl	287 (W)	Non-registered	1966-88	Trites and Larkin (1992)
USA	Trawl	7.4 (W)	Non-registered	Non-identified	Ferrero et al. (2000)
USA	Trawl	1.2 (W)	Non-registered	Non-identified	Ferrero et al. (2000)
USA	Trawl	0.6 (E)	Non-registered	Non-identified	Ferrero et al. (2000)
USA	Trawl	7.6 (W)	Non-registered	Non-identified	Angliss et al. (2001)
USA	Trawl	0.4 (E)	Non-registered	1990-98	Angliss et al. (2001)
USA	Trawl	3 to 23 (13.5) (W)	Yes	1989-2001	Perez (2003)
USA	Trawl	3 to 23 (13.5) (W)	Non-registered	1989-2001	Perez (2003)

USA	Trawl	1 to 2 (1.2) (E)	Yes	1989-2001	Perez (2003)
USA	Trawl	8 (W)	Yes	1989	Perez (2003)
USA	Trawl	1.1 to 4.5 (2.4) (W)	Yes	1998-2003	Perez (2006)
USA	Trawl	1 to 6.4 (3) (W)	Yes	1998-2004	Perez (2006)
USA	Trawl	1.2 to 4.3 (2.7) (W)	Yes	1999; 2003	Perez (2006)
USA	Trawl	1 to 3.6 (2.8) (W)	Yes	1998-2002; 2004	Perez (2006)
USA	Trawl	4.7 (W)	Yes	2001	Perez (2006)
USA	Trawl	1.6 to 2.4 (2) (W)	Yes	1998; 2003	Perez (2006)
USA	Trawl	0 to 1.2 (0.1) (W)	Non-registered	2002-09	Allen and Angliss (2010; 2012)
USA	Trawl	0 to 11 (4.5) (W)	Non-registered	2002-09	Allen and Angliss (2010; 2012)
USA	Trawl	0 to 4.3 (0.6) (W)	Non-registered	2002-09	Allen and Angliss (2010; 2012)
USA	Trawl	0 to 9.5 (5) (W)	Non-registered	2002-09	Allen and Angliss (2010; 2012)
USA	Trawl	0 to 4.2 (0.6) (W)	Non-registered	2002-09	Allen and Angliss (2010; 2012)

USA	Trawl	0 to 1 (0.8) (W)	Non-registered	2000-04	Allen and Angliss (2012)
USA	Trawl	5.7 (E)	Non-registered	2005-09	Allen and Angliss (2014)
USA	Trawl	0 to 1 (0.2) (W)	Non-registered	2007-11	Allen and Angliss (2014)
USA	Trawl	3 to 11 (6) (W)	Non-registered	2007-11	Allen and Angliss (2014)
USA	Trawl	0 to 3 (1) (W)	Non-registered	2007-11	Allen and Angliss (2014)
USA	Trawl	3 to 10 (7.3) (W)	Non-registered	2007-11	Allen and Angliss (2014)
	Line fisheries				
USA	Longline	1 (W)	Non-registered	1990-98	Ferrero et al. (2000)
USA	Longline	0.8 (W)	Non-registered	1990-98	Angliss et al. (2001)
USA	Longline	0.2 (W)	Non-registered	1990-2003	Angliss et al. (2001)
USA	Longline	4 to 28 (16.5) (W)	Yes	1990; 1993; 1995; 2000	Perez (2003)
USA	Longline	3.7 (W)	Yes	2002	Perez (2006)
USA	Longline	0.7 (W)	Yes	2000-04	Perez (2006)
USA	Longline	1.3 (E)	Yes	2000-04	Perez (2006)

USA	Longline	0 to 6.2 (2) (W)	Non-registered	2002-06	Allen and Angliss (2010)
USA	Longline	0 to 3 (1) (W)	Non-registered	2007-09	Allen and Angliss (2012)
USA	Longline	0 to 1.6 (0.5) (W)	Non-registered	2007-11	Allen and Angliss (2014)
Local	**Fishing gear/debris**	**Number of individuals**		**Study period**	**References**
USA	Entanglement	6 observed		1985	Loughlin (1986)
USA	Entanglement	Non-registered		1980	Manville (1990)
USA	Entanglement	Non-registered		Non-identified	Laist (1997)
USA	Entanglement	27 observed		1976-88	Hanni and Pyle (2000)
USA	Entanglement	6 observed		2001-05	Moore et al. (2009)
USA/Canada	Entanglement; gear-related injuries	386 observed		Non-identified	Raum-Suryan et al. (2009)
USA	Entanglement; gear-related injuries; aggression; boat collision	≥ 1 (W)		2007-11	Allen and Angliss (2014)
USA	Entanglement; gear-related injuries; aggression; boat collision	≥ 34.6 (E)		2007-11	Allen and Angliss (2014)
USA	Entanglement; aggression; boat collision	176 observed		1991-2016	Warlick et al. (2018)
Canada	Entanglement (net)	1 observed		2012	Hipfner et al. (2018)

in addition to four species of sirenians and two species of sea otters.

Although aggressions seemed most common for *O. flavescens, Z. californianus* and *E. jubatus*, other species could be equally affected by this type of interaction. The higher number of aggressions reported could simply be a result of the greater number of publications for the three species.

Otaria flavescens

Considering all the species analysed, research conducted with sea lions in South America provided more data on the magnitude of the economic loss caused by sea lions (predation and gear damage). The commercial losses caused by the predation of sea lions in artisanal fishery in Uruguay (Szteren and Páez 2002) and Chile (Sepúlveda et al. 2007) demonstrated a wide variation and cannot be attributed exclusively to gillnet fishing since these studies evaluated line fishery together with gillnet fishing. In general, these losses were considered low (De María et al. 2014; Szteren and Páez 2002).

In southern Brazil, the bycatch of *O. flavescens* in gillnets is apparently an uncommon phenomenon, despite the occurrence of interactions and conflicts, especially in the winter (Machado et al. 2016). In Chile, Reyes et al. (2013) demonstrated that these interactions with trawl boats are alarming since they can remove many individuals from the population in a short period (82 individuals captured in 10 days) and, although only 14.6% of the sea lions were captured dead, those who survived were released with serious injuries and a high probability of subsequent death (Reyes et al., 2013). Machado et al. (2015) describe that the interactions between *O. flavescens* and the fisheries in southern Brazil may be contributing to the decline of the population in Uruguay, which showed an annual population reduction of 1.6% to 2.0% (Crespo et al. 2012; Páez 2005). The authors are also concerned about the lack of monitoring of the trawl fleet in southern Brazil, which prevents evaluations of the impact of this activity on the population.

Gillnet fishing in southern Brazil had the lowest interaction frequency for *O. flavescens* (interactions in 24% of the sets) but showed a high level of depredation, which occurred in 85.3% of the sets with interactions (Machado et al. 2016). This level of predation was greater than in Uruguay (predation on 51% of gillnet and longline sets; Szteren and Páez 2002), considering that unlike Brazil, Uruguay hosts breeding colonies where sea lions are much more abundant. Sepúlveda et al. (2007) reported interactions with *O. flavescens* in up to 71.4% of the fishing days and 14.5% of the gillnet, longline and handline fishing trips in Chile. Additionally, De María et al. (2014) recorded the occurrence of interactions between 40.5% and 63.4% of the gillnet sets in Uruguay.

It is possible that the fisheries monitored by Machado et al. (2016) suffered fewer loss impacts than the fisheries in Uruguay (De María et al. 2014; Szteren and Páez 2002) and Chile (Sepúlveda et al. 2007). However, Machado et al. (2016) monitored medium-scale vessels with greater autonomy of fishing than the ones observed by De María et al. (2014), Sepúlveda et al. (2007) and Szteren and Páez (2002), all of whom monitored artisanal fisheries with low fishing autonomy. In Peru, only one study described the interactions between fishing and pinnipeds (Majluf et al. 2008).

Regarding line fishing, only Passadore et al. (2008, 2015) recorded incidental captures in Chile. Nevertheless, La Torriente et al. (2010) reported that sea lions interacted with longlines in 58.3% of the fishing sets, with predation in 52% of these sets.

The species *O. flavescens* had the highest number of individuals that simultaneously interacted with fisheries. In general, about 10 individuals of *O. flavescens* were present in the interactions (De María et al. 2014; Machado et al. 2016; Sepúlveda et al. 2007; Szteren and Páez 2002), except in the case of purse seine fishing in Chile, with the presence of up to 290 sea lions (González et al. 2015; Hückstädt and Antezana 2003). Studies conducted in Brazil, Argentina, Uruguay and Colombia contained records of stranded dead animals with aggression marks, such as shots and strikes, and entangled in fishing gear (Table 2). There are old records of an intentional capture of the species as bait for trap fishing in Chile (Cardenas et al. 1987; Oporto et al. 1991). Adult females and subadult males of *O. flavescens* were the most commonly affected groups in interactions of Uruguayan fisheries (Szteren and Páez 2002).

Phocarctos hookeri

Females in reproductive age were the most common specimens accidentally captured in the squid trawl fishery in New Zealand (from 57% to 87.5% of the bycatch of *P. hookeri* (Baird and Doonan 2005; Smith and Baird 2007; 2011). Moreover, this fishery was responsible for high mortality rates of sea lions (Baird and Doonan 2005; Doonan 2001; Manly et al. 2002; Thompson and Abraham 2009; Thompson et al. 2015). According to Chilvers (2008) and the literature (Table 3), the bycatch of sea lions in this fishery did not significantly decrease after the introduction of sea lion excluder devices (SLED), and many that come out alive suffer severe internal injuries, compromising the post-release survival rate (Wilkinson et al. 2003). SLEDs are devices through which pinnipeds can be ejected and escape from trawl nets (Doonan 2001). Furthermore, the use of SLEDs prevented the direct count of injured and dead animals in the nets. In addition, the proportion of females captured has increased by up to 82% since 2004 (Chilvers 2008). For *P. hookeri*, quotas have been established every year for the squid trawl fishery in New Zealand since 1992. In this country, most of the fleet has onboard observers that halt fishing when the limits are reached (Chilvers 2008).

Neophoca cinerea

Purse seine fisheries did not quantify incidental captures and gillnet fisheries seemed to be the most dangerous in terms of number of sea lions captured (Figure 3; Table 4). This Australian endemic species is particularly vulnerable to extinction as its population breeds in the same rookeries where it was born (Gales et al. 1994). In Australia, few specimens of N. cinerea die per year due to trap fishing, but mortality reaches more than 80% for captured sea lions (Campbell et al. 2008). Marine Protected Areas (MPAs) do not always manage to protect a species from fishing impacts. In Australia and New Zealand, fishing exclusion zones in MPAs do not cover the entire foraging area of sea lions (Chilvers 2009; Hamer et al. 2011). However, when MPAs are well planned, they can significantly improve the survival probability of endangered species (Gormley et al. 2012). In Australia, the current levels of N. cinerea bycatch (Table 4) are apparently low but may still cause a population decline (Hamer et al. 2011). Entanglements were very common for this species.

Zalophus californianus

From the 43 studies that depicted interactions with *Z. californianus*, 23 described interactions with gillnets, 12 with trawls, seven with purse seines, three with line fisheries, two with trap fishery and 18 with unidentifiable gear (Table 5). All the studies with *Z. californianus* were carried out in the United States, except three that were conducted in Mexico.

Gillnet fisheries showed the highest incidental captures of California sea lions, especially in the case of set nets. Barlow and Cameron (2003) evaluated the effectiveness of acoustic deterrents (pingers) in drift gillnets in California, which may register 100% mortality among captured individuals of *Z. californianus.* Pingers are active sound emitters set on nets which alert individuals of the presence of the fishing gear aiming to avoid their capture (Dawson et al. 2013). The authors found that the rate of bycatch was lower in nets with pingers. However, even with the mandatory use of pingers in drift gillnets since 1997, the annual bycatch estimates for the period 1996-2007 were higher than in previous years (Carretta et al. 2004). In addition, after the initial reduction in the number of animals captured as bycatch, these animals can become habituated to the sound emitted by the pingers, leading to a reverse effect, especially in areas with a large number of boats (Barlow and Cameron 2003). Entanglements were very common for this species. Maravilla-Chávez et al. (2006) reported a reduction of depredation and gear damage just by reducing daily fishing trips and watching over the gillnets in the water.

Zalophus wollebaeki

Fisheries in Ecuador reported only two sea lions incidentally captured (handline) and the occurrence of depredation and damage in longline and gillnet fisheries, without details. Moreover, 251 individuals, mostly juveniles and adults, were found entangled by non-specified fishing gear and were affected by other kinds of operational interaction, like boat collision, aggression and harassment. Only gillnet and line fisheries interactions were recorded.

Eumetopias jubatus

Until the end of the 1980s, fisheries showed the greatest numbers of Steller sea lions bycatch, although this tendency could not be found in other fisheries besides trawl. Since then, incidental captures seem to have decreased significantly.

Depredation occurred in all kinds of fisheries for *E. jubatus*, although without details. No information about group size or economic loss was recorded. Information on the interactions for the west stock was more abundant than for the east stock. Entanglements and aggressions were also common for this species. The species is divided into two different stocks according to their distribution: the east stock of 144o latitude and the west stock of 144o latitude (Phillips et al. 2009), the latter of which has suffered a population decline of more than 80% (Atkinson et al. 2008).

Although the focus of this study is the effects of operational interactions on different sea lion species, some of the studies presented information on the need to conduct comparative research for the species analysed here, and additionally seek to make their conservation more effective. For example, the current and future effects of capture on reproductive females were addressed, as exemplified for *P. hookeri* (Baird and Doonan 2005; Smith and Baird 2007; 2011), as well as the most negatively affected species.

Additionally, Chilvers (2008) called into question the real effectiveness of SLEDs, which can be tested in relation to species-specific variables (prey size, fishing schedule, target species, etc.) or in relation to the functioning of devices (speed, size, intensity, etc.).

Despite the high number of studies on the effectiveness of Marine Protected Areas (MPAs) (Brandão et al. 2017; Giglio et al. 2019), these studies chiefly focus on general data about threats and risks. For the effective protection of the species presented here, MPAs must incorporate specific biological variables, such as dependence on foraging and/or reproduction sites, and the direction and intensity of the routes of vessels that use the most harmful gear, already identified in this study as trawl and gillnet. Besides, no-take zones can be beneficial not only for marine megafauna but also for the fishing sector, as these zones favour the spillover effect that enhances the sustainability of fisheries by exporting fish to surrounding areas (Forcada et al. 2009).

CONCLUSIONS

The identified operational interactions were bycatch, the presence of animals around boats during fishing operations, depredation, gear damage, entanglement in lost/discarded fishing gear, boat collisions, aggressions (shooting and striking), gear-related injuries, such as net marks and gear swallowing, and harassment. Trawl and gillnet fisheries captured more sea lions and more frequently than the other fisheries. Depredation and gear damage were more common for gillnet and line fisheries. Other interactions like entanglement and aggressions were also very common for all species.

Interactions in all fisheries should be equally assessed with the data of onboard observers and different strategies should be tested to avoid negative interactions and their consequences. These strategies can include bycatch limits (quotas), changes in fishing practices such as setting nets when pinnipeds are not active, reduced soaking time of gillnets and the avoidance of onboard discard in trawl operations, reduced fishing effort and the establishment of effective MPAs. The establishment of MPAs, especially in coastal waters, which is the area mainly inhabited by many species of pinnipeds, could significantly reduce the fishing effort and, therefore, reduce negative fishery-induced impacts on pinnipeds. MPAs, however, must not only protect rookeries and haul-out sites, but also foraging areas. Moreover, data on the magnitude of commercial losses caused by pinnipeds should be better investigated to show the real impact of this type of interaction on fisheries economy, which is commonly overestimated by fishermen. In addition, more efforts should be directed at identifying age and gender of the most affected pinnipeds. The data on bycatch and other variables should be standardized to enable comparisons of information between fisheries and sites. Finally, we suggest gathering data on the number of sea lions interacting with fisheries, so interaction hotspots can be identified for more efficient conflict management.

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DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

CONTRIBUTION STATEMENT

Conceived the presented idea: KLR.
Carried out the bibliographic review: KLR.
Carried out the data analysis: KLR, RM, AS.
Wrote the first draft of the manuscript: KLR.
Review and final write of the manuscript: KLR, RM, AS.
Supervision: AS.

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