Pinniped entanglement in oceanic plastic pollution: a global review

Emma M. Jepsen & P. J. Nico de Bruyn*

Mammal Research Institute, Department of Zoology and Entomology, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

Correspondence author: Nico de Bruyn - pjndebruyn@zoology.up.ac.za

Nico de Bruyn - ORCID: https://orcid.org/0000-0002-9114-9569

Highlights

- Review of 40-years of published pinniped entanglement records.
- Entanglement rates are biased to North America and Oceania despite plastic pollution and fishing hotspots off Asia.
- *Arctocephalus gazella* and *Zalophus californianus* are most frequently recorded to be entangled.
- Abandoned, lost and discarded fishing gear contribute almost all entanglement material.
- Knowledge of trends and drivers of pinniped entanglement in oceanic plastic pollution is poor.

Abstract

Oceanic plastic pollution is a growing worldwide environmental concern, endangering numerous marine species. Pinnipeds are particularly susceptible to entanglement, especially in abandoned, lost or discarded fishing gear and packaging straps. We searched three international databases to compile a comprehensive review of all reported pinniped entanglements over the last 40 years, with the aim to identify areas of concern and foci for mitigation. The majority of published records of entanglement emanate from North America and Oceania and are focused on a few populous species (notably, *Zalophus californianus* and *Arctocephalus gazella*). Reporting bias, skewed research effort, and incomplete understanding of plastic pollution and pinniped abundance overlap combine to cloud our understanding of the entanglement problem. Broader geographical effort in entanglement data collection, reporting of such data, and improved quantification of the proportions of populations, sexes and ages that are most susceptible, will aid our efforts to pinpoint priority mitigation measures.

Keywords

Pinniped, entanglement, oceanic plastic pollution, ghost-fishing, observer bias, ALDFG

Graphical abstract

Arctocephalus gazella juvenile entangled in a fishing net (presumably from ALDFG) at remote BouvetØya in the Southern Ocean. Photo credit: Nico de Bruyn

Introduction

The invention of Bakelite, the precursor to plastic, in 1907 by Leo H. Baekeland revolutionized many aspects of human lives, from initially insulating electrical cables to being part of most products today (Crespy *et al*. 2008). Its mass production commenced in earnest after World War II (Carpenter & Smith 1972). Plastic products remain favoured over natural materials, as they are comparatively affordable, do not rot, melt, become deformed, or scratch easily (Crespy *et al*. 2008). However, the intrinsic qualities that made it so popular have distinct disadvantages; most plastics are not biodegradable due to high molecular weights and structures that are too rigid for organismal digestion (Klemchuk 1990). Many plastics end up in landfills or oceans, can persist for decades, diminish environmental aesthetic value, and endanger biodiversity (Palmisano & Pettigrew 1992; Tudor & Williams 2003). Mounting public outcry over the state of plastic pollution, especially in our oceans, is frequently headlining international media (e.g. Parker

2018). Indeed, research findings underpin the public perception of this very real, global-scale environmental problem (e.g. Ryan *et al.* 2009; Law *et al.* 2018; Worm *et al.* 2018).

Plastics can be dangerous to marine organisms in a number of ways; through consumption, accumulation on the sea floor, facilitating invasions by non-native species, and entanglement of marine organisms (Derraik 2002). A wide diversity of marine taxa through multiple trophic levels, including zooplankton, fish, birds, cetaceans, pinnipeds and turtles have been shown to ingest a range of oceanic plastic from microplastics to plastic bags that resemble prey items (Gramentz 1988; Derraik 2002; Cole *et al.* 2011; Setälä *et al.* 2014). Ingestion can upset the animals' energy balance, affect behaviour, or even block the intestinal tract resulting in severe sub-lethal effects or even death (Kühn *et al.* 2015). Additionally, many plastics include polychlorinated biphenyls (PCBs) that can disrupt reproduction, increase animal susceptibility to diseases, alter hormone production and kill (Ryan *et al*. 1988; Lee *et al*. 2001; Derraik 2002). The accumulation of oceanic plastic on the sea floor can halt gas exchange and lead to hypoxia and anoxia in sediments, thereby altering ecosystem functioning (Goldberg 1994). The facilitation of invasive species to new environments is possible through organism transport on floating oceanic plastic (Carpenter & Smith 1972; McKinney 1998).

Entanglement in oceanic plastic pollution is a threat for at least 243 marine species; fewer species than for plastic ingestion, although entanglement is responsible for more known mortalities (Gall & Thompson 2015). Most of the plastics that cause entanglements appear to be monofilament lines, ropes and other fishing related gear that enter the water near coastal cities, via commercial fishery activities and in shipping corridors (Laist 1997). Before the middle of the 20th century, fishing gear was made from natural fibres such as hemp or cotton that disintegrate over time. However, the advent of synthetic material in its stead resulted in long-lasting plastics that withstand disintegration (Gregory 2009). Many such fishing material (especially ropes and nets) are abandoned, lost or purposefully discarded and continue to entangle through a phenomenon known as ghost-fishing (Kim *et al*. 2016). Although entanglement in active fishing gear is an important and widely studied problem (e.g. Wickens *et al.* 1992), our review is specifically focussed on the passive threat of entanglement in abandoned, lost or discarded fishing gear (ALDFG) and other oceanic plastic pollution (Gregory 2009). For the reader's convenience, we combine ALDFG and other plastics unrelated to fishing activities in the phrase 'oceanic plastic pollution' unless otherwise stated.

Notwithstanding the taxa, the consequences of being entangled are often the same: the animal may get caught on stationary objects by the material they are entangled in, they may become exhausted and drown, they may be entangled in such a way that they do not have full range of motion and may not be able to forage, or they may be physically cut by the material with the possibility of infections occurring in the wounds (Laist 1987). Most animals that become entangled are able to rapidly free themselves, but if unsuccessful their survival is usually compromised (Angliss & DeMaster 1998).

Despite the persistence of the entanglement problem, relatively few published works have attempted to draw together case studies to identify potential trends and identify mitigation potential. In one early major study on oceanic plastic entanglement, Laist (1997), outlined some important unresolved issues through compilation of an exhaustive list of all species known to be entangled, the effect that entanglement had on individuals and populations, and reviewing of management and mitigation procedures. Of the 115 extant marine mammal species (Kaschner *et al.* 2006), 54% are especially vulnerable to oceanic plastic pollution entanglement or ingestion (Gall & Thompson 2015), with particularly high rates among pinnipeds (Laist 1997). Gall & Thompson (2015), and Wilcox & Hardesty (2016) showed entanglement to be more detrimental to marine wildlife than plastic ingestion; marine mammals more so than sea turtles and sea birds. Stelfox *et al.* (2016) reviewed the effect that ghost-fishing has on marine megafauna, highlighting over 40 species that are affected (mostly marine mammals) and indicating geographical areas lacking information for this phenomenon, including the Indian, Southern, and Arctic oceans. Of the 33 extant pinniped species worldwide, the majority have been recorded with entanglements (Wehle & Coleman 1983).

'Otariids' (suborder Pinnipedia, family Otariidae - 'eared seals' including fur seals and sea lions, comprising 15 species) are more prone to entanglement than 'phocids' (Family Phocidae - 'true seals', comprising 18 species) (Laist 1997). Pinnipeds are generally associated with cold-water environments and most species are found in the North Atlantic, North Pacific, Arctic, and Southern oceans (Kovacs *et al.* 2012), coinciding with some regions where information on phenomena such as ghost-fishing is lacking (Stelfox *et al.* 2016). Otariids are distributed along the west coast of the Americas, Southern Africa and Australia as well as the sub-Antarctic, while phocids are more concentrated along both coasts of North America as well as the Antarctic, sub-Antarctic, limited areas of southern Australia and the west coast of South America (Davies 1958; Pompa *et al.* 2011; Kovacs *et al.* 2012). Pinnipeds, especially younger animals, tend to be attracted to oceanic plastic pollution due to their innate curiosity and playfulness, which purportedly makes them likelier candidates for entanglement (Pemberton *et al*. 1992). They poke their heads through holes and the material can get caught on their fur or appendages (Mattlin & Cawthorn 1986). As they grow, these artificial collars get tighter and more abrasive until they begin to cut the skin (Pemberton *et al*. 1992). It is a vicious cycle as once the animal has died and decomposed the plastic can then make a victim of another individual (Mattlin & Cawthorn 1986).

Yet, despite the overwhelming evidence that oceanic plastic pollution entanglements occur in many marine taxa and appear to be a widespread problem, a lack of spatial and temporal contextualization, knowledge of the proportions of populations affected, search effort and unsystematic reporting of the problem limit effective efforts for mitigation. Here we focus on one group of widespread marine vertebrate, the Pinnipedia; known to be entangled with ostensibly higher reporting rates than for other taxa, to critically assess the state of knowledge of entanglement in discarded oceanic plastic pollution.

Our review of pinniped entanglements worldwide specifically aims to:
(1) identify the spatial and temporal variation of publications (as a proxy for robust reporting) and search effort related to entangled pinnipeds,
(2) quantify the spatial and temporal trends in entanglements, sex and age demographics of entangled pinnipeds, the severity of the entanglements, and responsible material,

(3) identify where there are any reporting/knowledge gaps with regards to pinniped entanglements worldwide, and
(4) utilise these trends in pinniped entanglements (aims 1 & 2) to attempt to identify key driving factors, which may assist mitigation.

Materials and Methods

Literature search

Science Citation Index Expanded Web of Science, Elsevier's Scopus, and Google Scholar publication indexing databases were interrogated using broad search terms ("seals", "plastic pollution", "entanglement", "pinniped", "fishing nets", "ghost fishing", "abandoned, lost or discarded fishing gear (ALDFG)", "marine mammals" and "marine debris" with the Boolean operators AND/OR in various combinations). The search terms "entanglement AND seals", and "entanglement AND pinniped" returned the most relevant results. Replacement of '"entanglement" with "fishing nets", "plastic pollution" or "ALDFG" in combination with "seal" or "pinniped" returned very similar results to simply using "entanglement". From these search queries within the three chosen databases, 1818 results were obtained but ~96% were not relevant to the aims of this review . The majority were eliminated because the articles did not contain relevant data, were duplicates, or pertained to bycatch or interactions with active fishing gear. The latter aspects were excluded from this study, since our aims were not to investigate active fisheries-pinniped interactions, which are relatively widely studied, but rather the less-well understood passive threat of discarded oceanic plastic pollution for entanglement.

A total of 69 articles (~4%) contained pertinent information related to pinniped entanglement in oceanic plastic pollution. The following data was extracted from each paper: author(s), year of publication, journal, impact factor of the journal, location of the primary author, geographic location of the study, years when the study took place, total number of individual pinnipeds 'sampled' (entangled or not) in the study, the number of entangled individuals of each species, the species of the entangled pinnipeds, the age and sex distributions (pup, juvenile, subadult, adult; male, female) of the entangled pinnipeds, the categorized fate of the entangled individuals reported per paper (majority disentangled, majority not disentangled, majority dead), the type of oceanic plastic pollution involved, and the severity of the injury (loose, tight, severe, very severe). The classification of the severity of the injury was based on Croxall *et al*. (1990) where loose is a lack of constriction, tight is when the constricting material is snug but not breaking the skin, severe leads to lesions, and very severe when the material is cutting through the skin and underlying fat or muscle.

Identifying the presence or absence of observer or reporting bias was of interest. Quantification of such biases could only be attempted analytically in certain cases; such as with the number of entanglements per year (to determine whether the number of papers published per year had an effect) or the number of entanglements per species (if the number of entanglement studies conducted per species had an effect). Other potential sources of bias could merely be identified as being likely or not, with the aim that simply identifying these can aid the focus of future studies. Such biases included but were not limited to: likelihood of under-reporting/ non-reporting of entanglements when there is reasonable evidence for the presence of pinnipeds and oceanic plastic pollution in the same area (geographic bias); the possibility that certain human demographics may be less likely to report entanglement incidents (e.g. fishermen); or that entanglement records are reported in obscure publications not indexed by the searched databases. Further details are provided in the discussion.

Data analysis

Data was analysed in program R (RStudio Core Team 2016). All data was tested for normality using a Shapiro-Wilkes test, found not to be normally distributed and consequently subjected to appropriate non-parametric analyses, or normalized using log-transformations. Wilcoxon signed rank tests were used to investigate the relationship between the number of papers published and year, the spatial distribution of the primary author as well as of the study location, the number of articles published per journal and the relationship between the number of entangled pinnipeds and the year of publication. To test for possible bias between year and the number of publications or an interaction between the two on the number of entanglements recorded, a quasi-poisson distribution model was implemented. A Wilcoxon signed rank test was used to determine entanglement rates of different species, and to ensure there was no bias between the number of studies conducted on a species and the entanglements recorded for that species a quasi-poisson distribution model was run. Finally, Spearman's rank correlation tests and Welch two-sample t-tests were used to determine if sex or age class had an influence on entanglement rates, and both age class and fate of the pinnipeds were examined in decadal divisions to better determine trends over time.

Results

Spatial and temporal variation in publications and reported pinniped entanglements

Publications spanned the years 1980-2018 with an average length of 7.5 years of research per study. The number of article publications as a function of year was significant (Wilcoxon signed rank test, $p < 0.01$) but overall lacking a trend (Figure 1). The spatial distribution of study locations reported in articles was non-random (Wilcoxon signed rank test, $p < 0.01$, Figure 2) as was the location of the primary author (Wilcoxon signed rank test $p < 0.05$, Figure 3). The majority of articles focused on, and emanated from, North America followed by Oceania (Australia, New Zealand and associated islands) (Figure 2). The average impact factor of the journals publishing these papers was 1.685 (range: 0.44 – 5.099) although the bulk (67.3%) were published in journals with impact factors between 1.5 and 4.31 (Note: the data did not always come from a published journal, e.g. NOAA technical memorandum) (Figure 4). As expected, the number of articles per publication source was not random (Wilcoxon signed rank test, $p < 0.01$) with 17 of the 69 papers (24.6%) published in *Marine Pollution Bulletin*, and the majority of the remaining journals hosting just one relevant article (Figure 4).

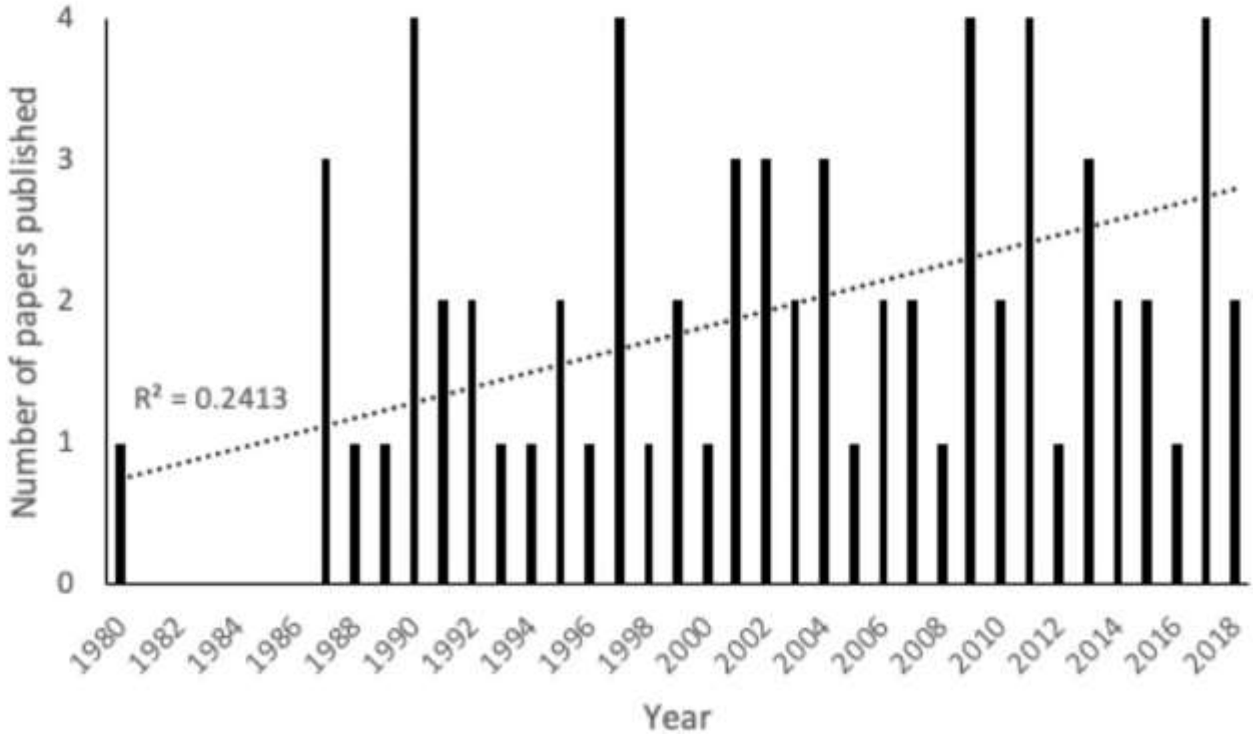


Figure 1: The number of papers published on pinniped entanglements per year.

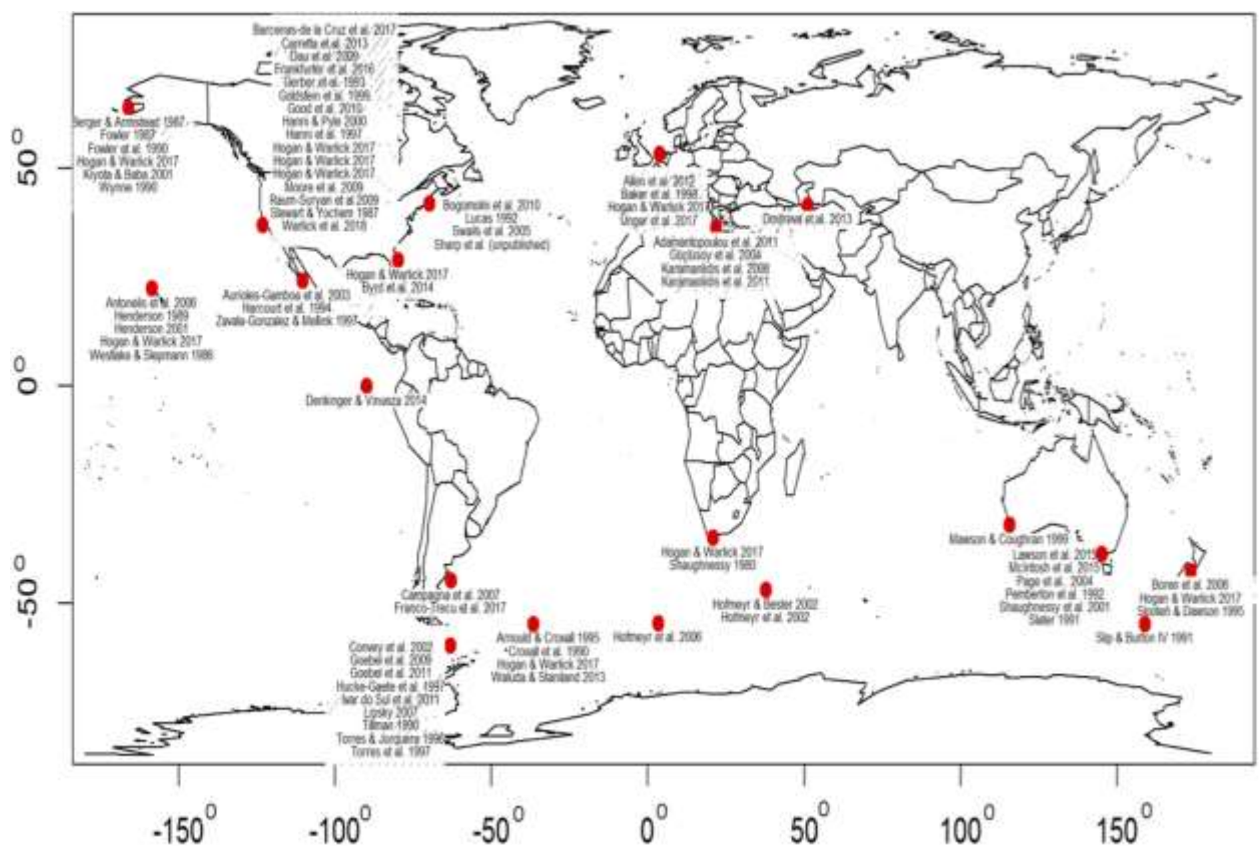


Figure 2: Global map depicting the study locations of all the papers included in this review from which data was sourced.

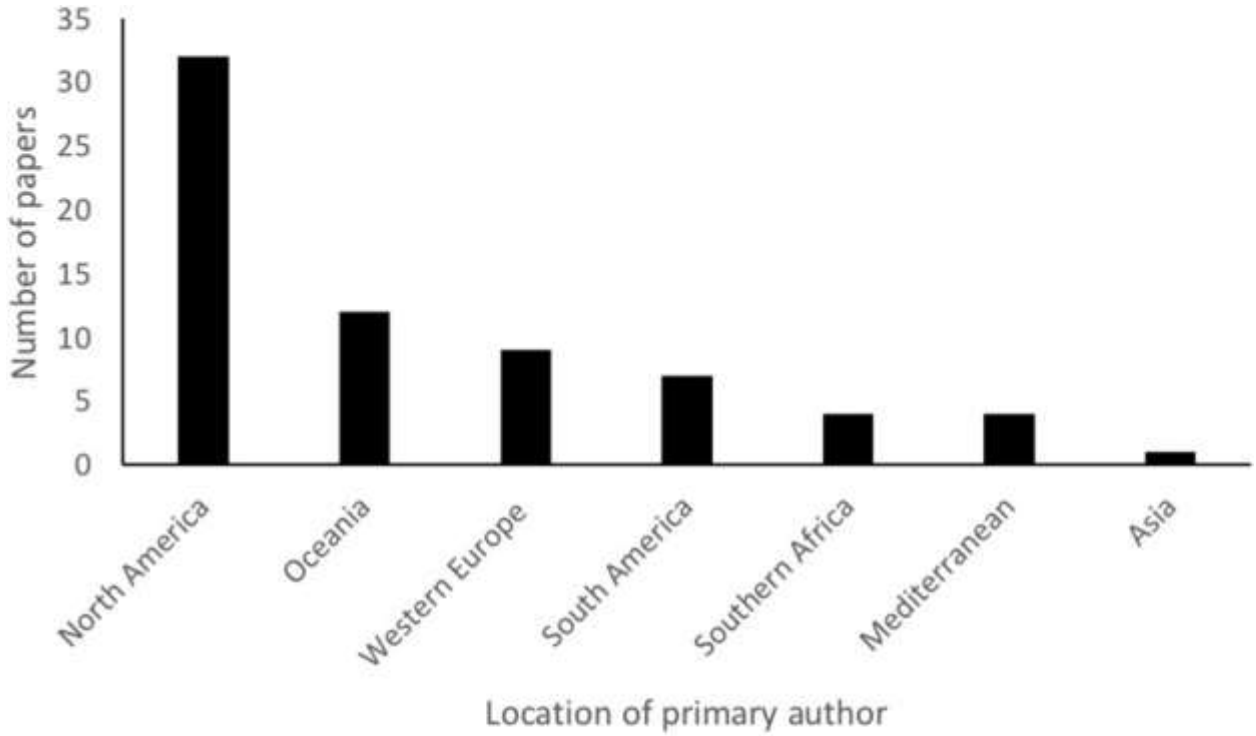


Figure 3: The location of the primary author of the papers sourced for this review. North America hosted the vast majority (n=32) and Asia the least (n=1).

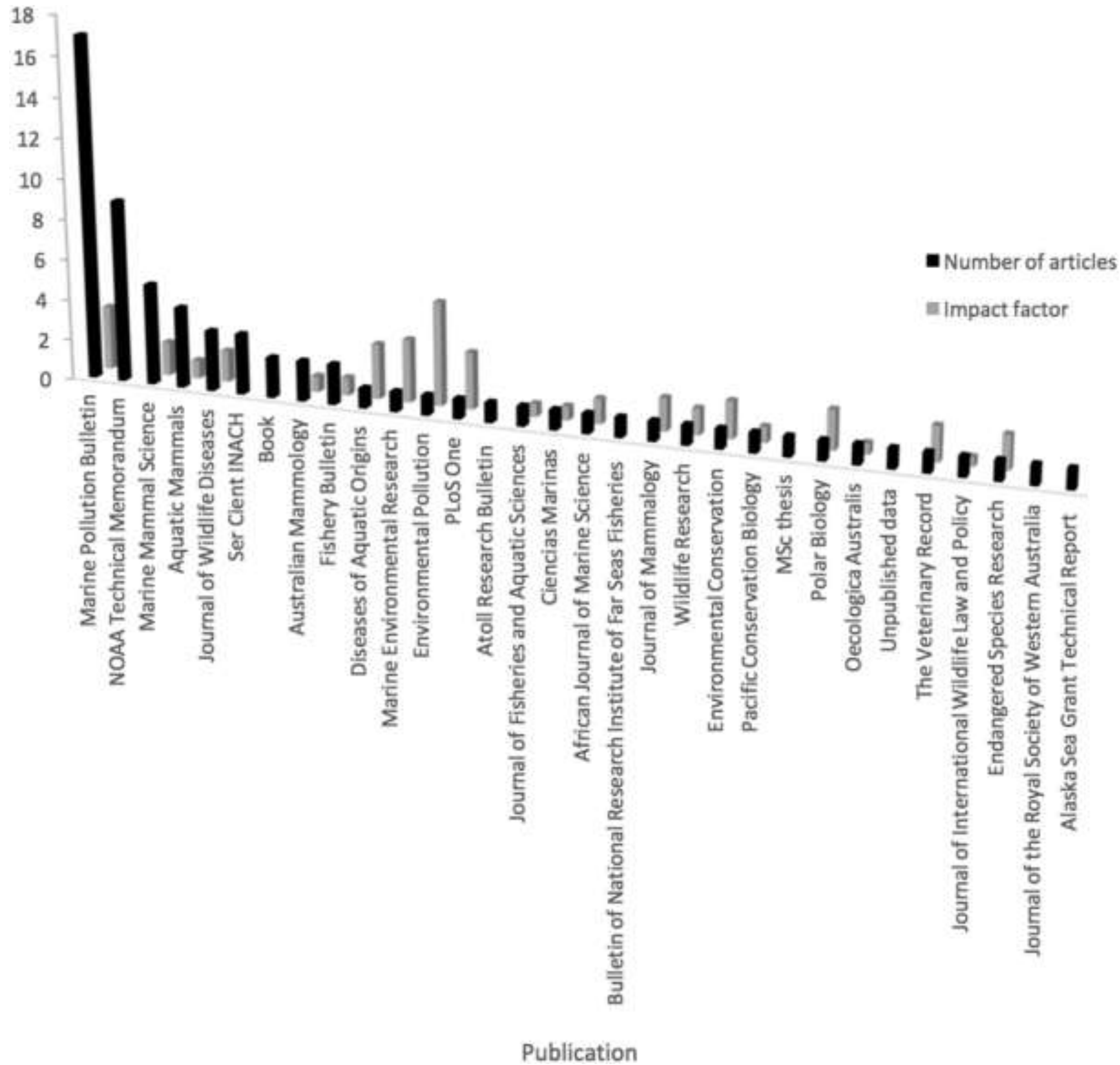


Figure 4: The number of articles per publication source (journals and other sources) as well as their respective impact factors.

A total of 27 (39.13%) papers focused solely on entangled pinnipeds while the remaining 42 (60.87%) included a broader focus and recorded all encountered pinnipeds, whether entangled or not. When excluding the studies where only entangled animals were reported (to avoid skewed results) and only focusing on studies that recorded all pinniped numbers, regardless of entanglement status, the percentage of entangled individuals was 0.37% (2518 of 676233 individuals). The relationship between the number of entangled pinnipeds and year was positive (Wilcoxon signed rank test, $p < 0.01$) (Figure 5a), however the relationship was significantly associated with the number of publications (quasi-poisson distribution model, $p < 0.05$, Figure 5b) and not to the year (quasi-poisson distribution model, $p > 0.05$, Figure 5a) or the interaction between the two (quasi-poisson distribution model, $p > 0.05$). The average number of entangled individuals per study was 120, and with the average study lasting 7.5 years that equates to 16 entanglements per year, or over one per month. Individuals from 22 of the 33 extant pinniped species were recorded with entanglements (67%). The distribution of entangled species was significantly skewed (Wilcoxon signed rank test, $p < 0.01$) with *Arctocephalus gazella* and *Zalophus californianus* being the most frequently recorded (Figure 6a). Moreover, these two species were also the most commonly studied species, so entanglements were more likely to be recorded whether or not it was the focus of the study. However, the number of studies performed on a certain species was not enough to explain the observed entanglement rates (quasi-poisson distribution model, $p > 0.05$).

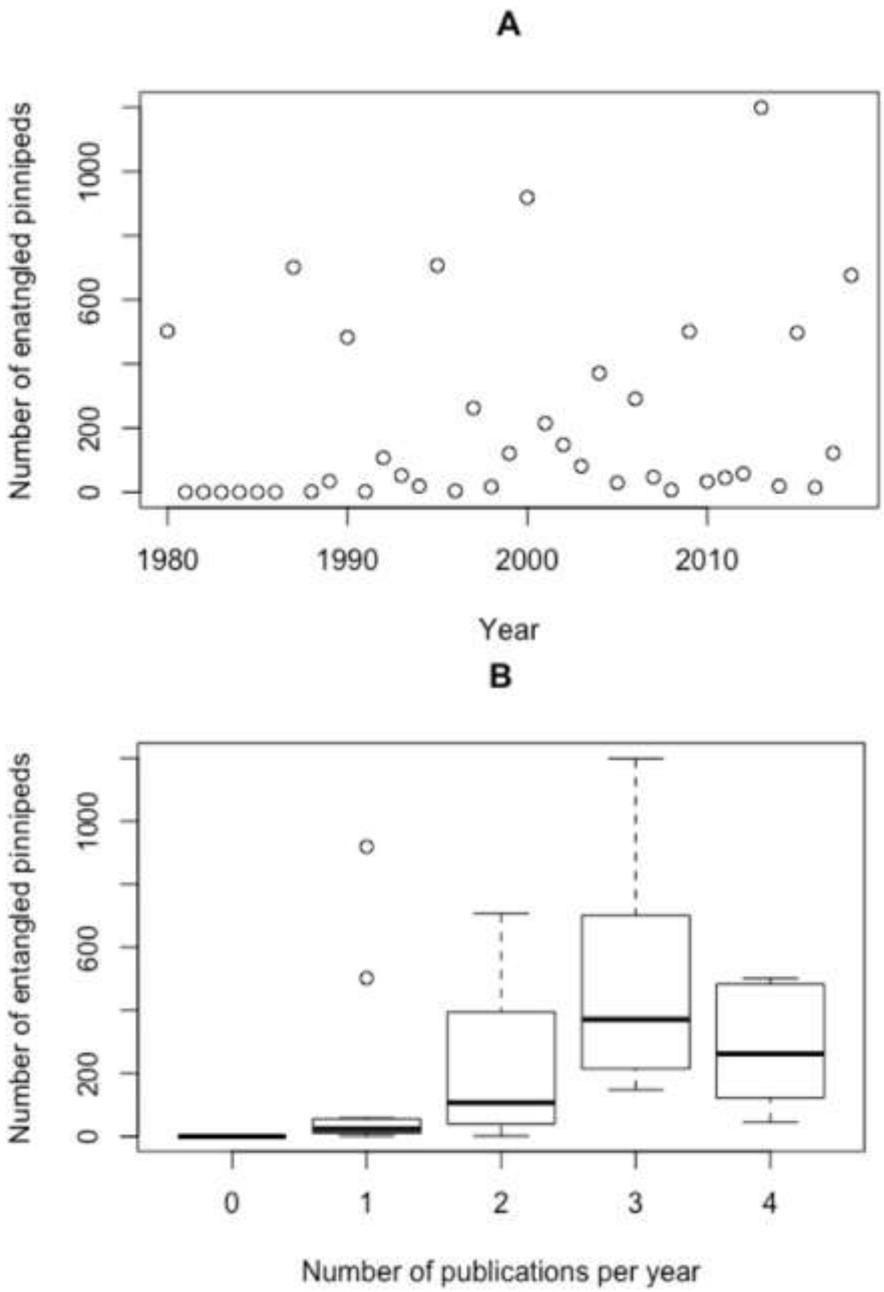


Figure 5: (A) Observer bias leading to the false impression that the year of the study has a significant effect on the number of entangled pinnipeds recorded, when in fact (B) the number of publications is the significant factors effecting the number of entangled pinnipeds recorded.

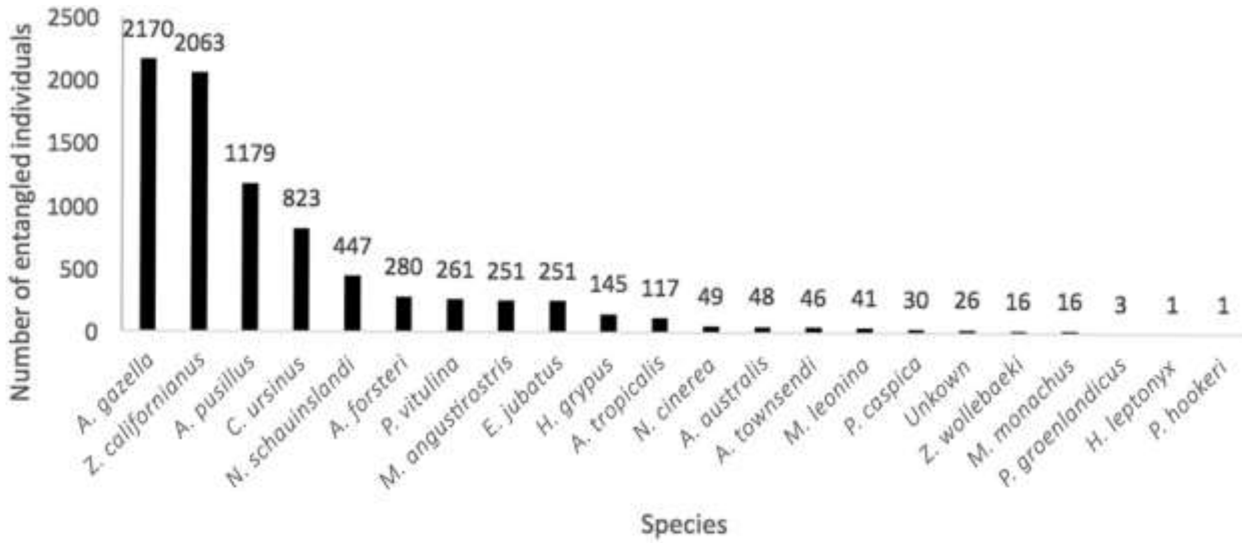


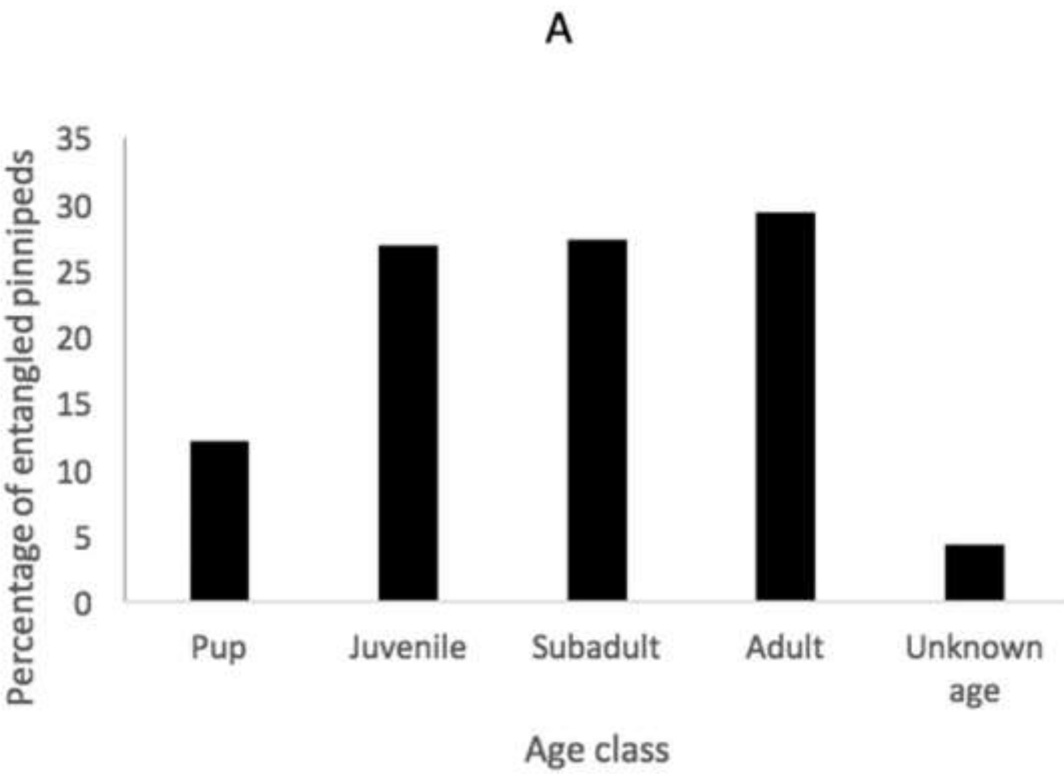
Figure 6: The number of recorded entangled individuals of each species.

Sex, and age demographics of entangled pinnipeds

Not all papers contained information on the sex, or age distribution of the entangled pinnipeds. Sex was only recorded in 42% of the studies and for those it was not significantly correlated with entanglement (Spearman's rank correlation, $p > 0.05$); roughly 45% were male, 31% female and 24% unknown. A total of 43.5% of the studies recorded age class but there was no significant difference in entanglement rates of juveniles, subadults, and adults (Spearman's rank correlation, $p > 0.05$) while pups were entangled significantly less often (Welch two sample t-test, $p < 0.05$) (Figure 7a). Figure 7b illustrates the number of entanglements per decade (1980-1989, 1990-1999, 2000-2009, 2010-2019), (Figure 7b). Otariids (n=7043) were more prone to entanglements than phocids (n=1195)(Spearman's rank correlation, $p < 0.01$).

Responsible material, severity of entanglements, and fate of the pinnipeds

All articles claimed ALDFG (including but not limited to monofilament lines, trawling nets, rope) and packaging strapping (often presumed to be from bait boxes) to be responsible for the vast majority of entanglements. Only 26% of the studies recorded the severity of the entanglements according to a benchmark (e.g. Croxall *et al.* 1990) (Figure 8). Injuries from loose entanglements were reported significantly less frequently (Welch two sample t-test, $p < 0.01$) than from other severity classifications (Welch two sample t-test, $p < 0.01$). The fate of entangled individuals was difficult to decipher from many articles due to missing information, however, when analysed according to the total known number of entangled individuals per study, the vast majority of pinnipeds appeared to be disentangled (70% freed, 28% left alone, and 2% found dead). Decadal divisions showed that in more recent times there appeared to be greater success in disentanglement of pinnipeds (Figure 9).



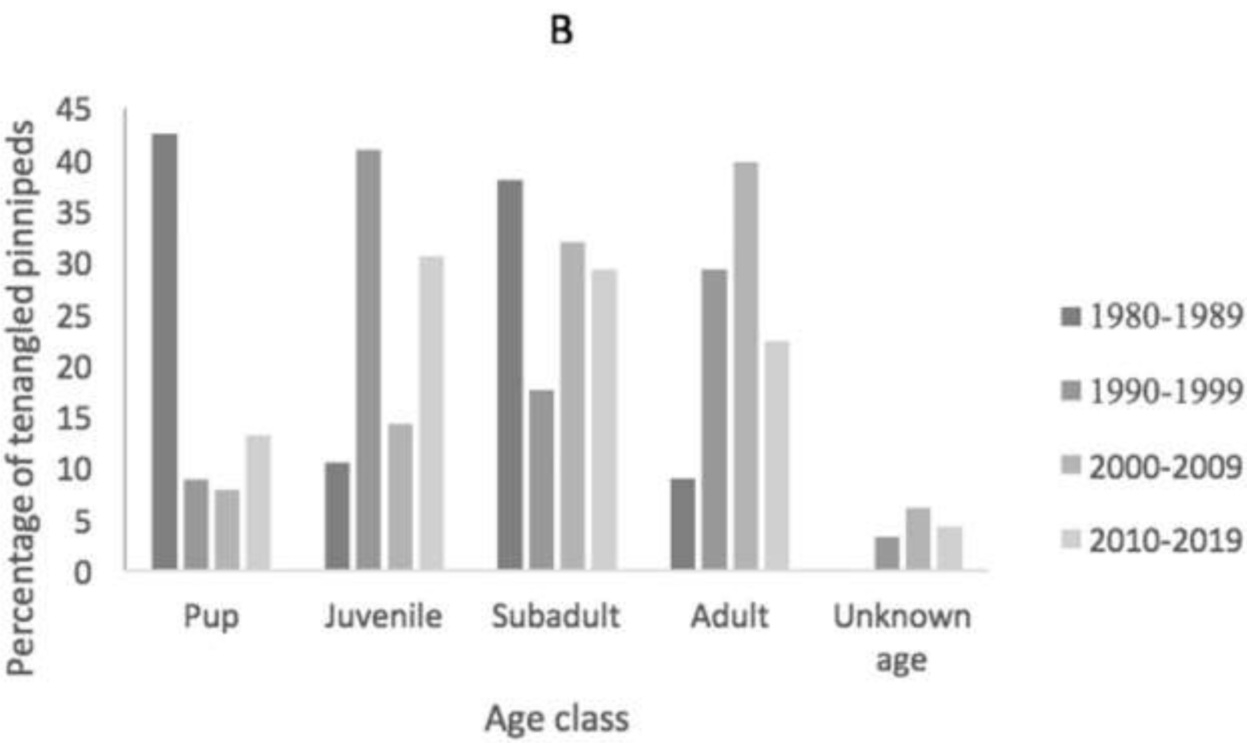


Figure 7: The age class distribution for all entangled individuals for (A) all years combined, and (B) by decade.

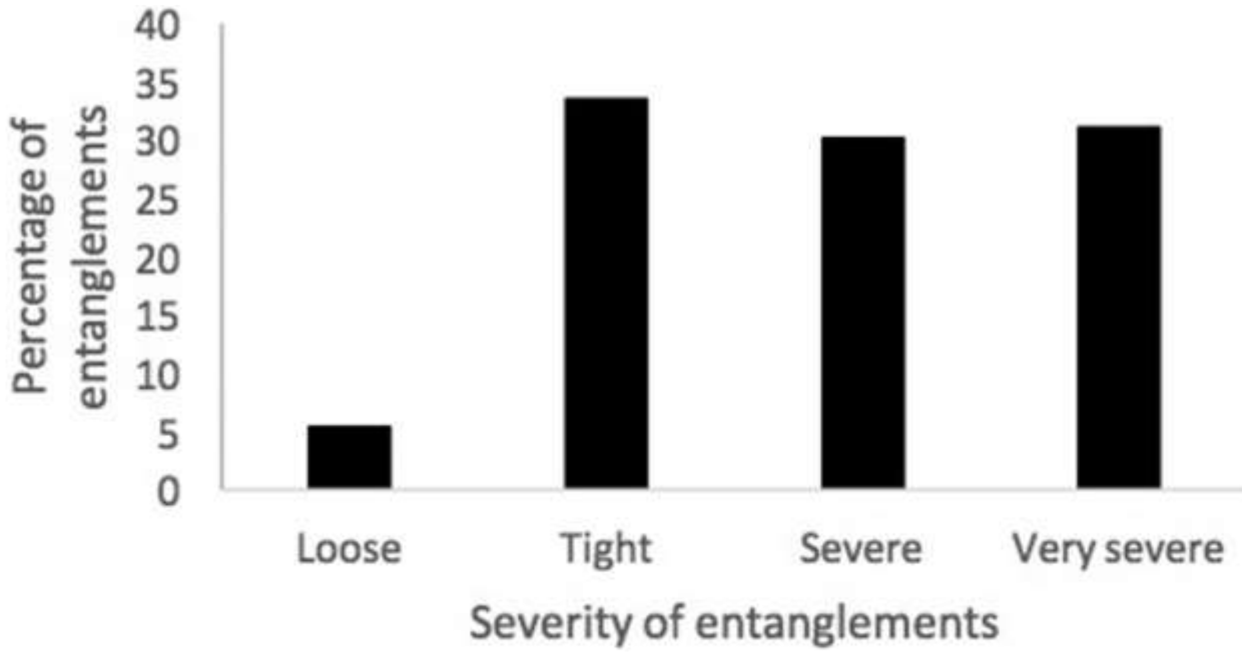


Figure 8: Proportional comparisons of the severity of entanglements classified according to Croxall et al. (1990).

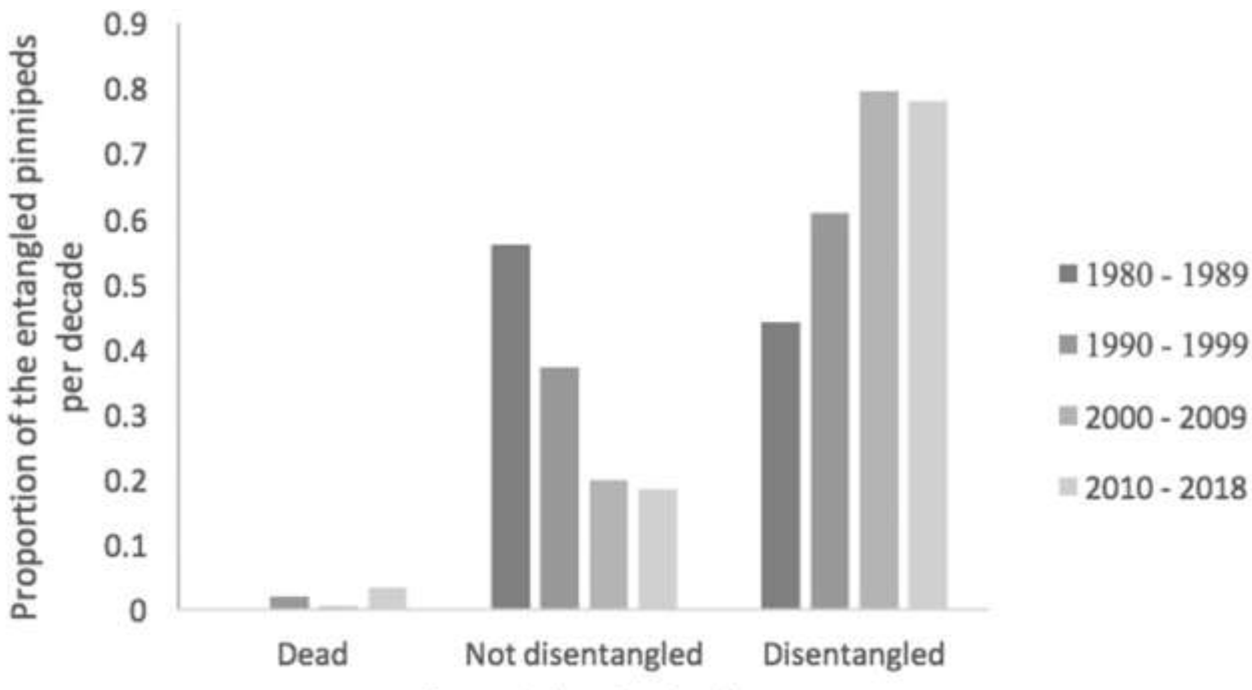


Figure 9: The fate of the majority of the individuals (as grouped by study) when divided into decadal divisions.

Discussion

Despite the global upturn in concern over plastics in the environment (e.g. Hartley *et al.* 2018) we show that temporal and spatial trends in pinniped entanglements are not well studied on a global scale. We show clear discrepancies in study effort and/or reporting around the world and with concern find that trends in known pinniped entanglements are best explained by observer/reporting effort rather than clear evidence of actual trends in entanglements of pinnipeds globally. While it is widely recognised that sampling methodology and reporting are lacking in detection and quantification of oceanic plastic pollution, there is broad consensus on the ubiquity of its presence in all the world's oceans (Law 2017). An estimated 10-20 million tons of plastic material end up in the oceans each year; the North Pacific is the most polluted, followed by the Indian, North Atlantic, Mediterranean, South Pacific, and South Atlantic oceans (Eriksen *et al.* 2014; Gourmelon 2015). All of these locations, with the exception of the Mediterranean, are sites where there are ocean gyres that have led to high concentrations of oceanic plastic pollution or "garbage patches" (Kershaw *et al.* 2011; Cózar *et al.* 2014). Additionally, worldwide fishing effort (source of ALDFG) has increased since the 1970's, and is globally distributed (Anticamara *et al.* 2010). The majority of the world's fishing effort occurs in tropical and subtropical regions with hotspots in Southeast Asia as well as on continental shelves (Watson *et al.* 2013). Many studies reviewed here (Figure 2) also coincide with continental shelf areas - where pinnipeds haul out and fishing intensity is high. Immediately evident in our results (Figure 2) is that global pinniped distribution (Kovacs *et al.* 2012) extends into many areas where few or no entanglements have been reported in published literature, despite the presence of fishing activities (Anticamara *et al.* 2010) and oceanic plastic pollution (Law 2017). Although fishing hotspots would obviously translate to hotspots in ALDFG, the worldwide distribution of fisheries combined with the action of currents and gyres, and the interconnectedness of ocean basins (Hays 2017) mean that ALDFG often mixes with other plastic pollution moving similarly around the world's oceans and ALDFG is thus categorised for our purposes within the term 'oceanic plastic pollution'.

Spatial and temporal variation in publications and entanglements

The overall lack of a temporal trend and the spatial disparity in publications related to pinniped entanglement in oceanic plastic pollution over time (Figure 1) has several potential explanations: (1) that most entanglements are not reported or published (e.g. publishing bias); (2) that reported entanglement trends are shrouded by observer bias (e.g. geographic spread of pinnipeds and research, entanglement data and research effort cannot be disentangled); (3) that there simply has not been an increase in entanglement of pinnipeds over time. These possibilities all require added research and aside from identifying, these patterns are currently difficult to explain, although we do elaborate on each of these options below.

(1) Our literature search was extensive within the largest scholarly publication repositories. However, other sources of information that were published in obscure or foreign language scholarly outlets, or in grey literature were not included. Sourcing relevant articles from these types of publications is not only practically complex, but the robustness of reported data can also

be variable and difficult to ascertain, especially if communicated in a foreign language. Chiefly however, the robustness of our bibliometric search methodology could not be maintained if we extended the search to these potential sources, simply because our own search effort could not be standardised in finding and including such literature. This may have added an additional source of bias to our results. Unpublished data from government monitoring agencies, non-governmental organizations (NGO's), rehabilitation centres, citizen science projects and other public sighting records would be an extremely valuable and potentially large data source. However, such data is either embargoed, in the process of being published, or in need of extensive analysis and thus fell outside the scope of what would be achievable in this review. That such data should be published is of course key, and is one of the aims of this review – creating awareness of this need. Published work found using our search criteria emanates mostly from more developed nations. Perhaps these nations have greater inclination to publish on the topic (e.g. awareness, or because there are greater numbers of scientists with more resources to do research and publish in general), or such published work is more visible (e.g. indexed global platforms being hosted by these developed nations), or because the problem of pinniped entanglement is greater in areas where scientists from developed nations work. To determine if there is a true bias towards pinniped entanglements occurring around developed nations, more studies need to be conducted in developing countries/regions, or such nations need to publish their data in appropriate outlets. These could be driven either by researchers, governments, NGOs or even citizen science projects. The disparity in scientific publishing between developed and developing nations is well known and proposing solutions to this broad issue is outside the scope of this review. Demand for products that contain plastic is not restricted to developed nations, nor are fisheries activities, which are an important source of oceanic plastic pollution (Bauman 2004; Gregory 2009; Gourmelon 2015; Jambeck *et al.* 2015). Indeed, ocean currents and circulation effectively blurs distinction between developed and developing nation maritime territory by dispersal of floating matter (including plastic) over the world's oceans (Hays 2017; Law 2017). Clearly then, with oceanic plastic pollution not being restricted to developing nation waters, either there are no pinnipeds to become entangled therein in some regions or entanglements are not reported. From our analyses (Figure 2, 3) and known pinniped distribution (e.g. Kovacs *et al.* 2012) it seems most likely that developing nations generally have lower reporting/publishing rates on this topic specifically (Todd *et al.* 2010). Asia is especially conspicuous in the absence of publications, which is concerning since for example China receives 56% of the world's plastic waste for reprocessing by small unregulated businesses (Gourmelon 2015). China also ranks highest globally in mismanagement of plastic waste, much of which makes its way into the oceans (Jambeck *et al.* 2015). Fishing activities as a source for ALDFG are also intense in Asian waters (Anticamara *et al.* 2010). Less accessible publications from Asia, perhaps due to a proclivity for Asian authors to publish in local or non-English journals may skew results (Meneghini & Packer 2007).

(2) Observer bias plays an important role in the confidence with which we can evaluate entanglement trends. Variation in pinniped distribution will obviously be a key driver in where interactions with plastics can occur. The overlap between the distribution of many pinniped species (of varying population sizes) and the most polluted (and heavily fished) waters globally is cause for concern given our limited understanding of the population proportions and dynamics

of pinniped entanglement. The distribution of study sites represented in our search results (Figure 2) would be linked to prevalence of entanglement. However, the strength of interaction between pinniped abundance, oceanic plastic pollution (including ALDFG) quantity, distribution, and entanglement rates is unclear. The majority of studies (Figure 2) focused attention on North American waters, Oceania (especially southern Australia), and the sub-Antarctic. All have large populations of both phocids and otariids, and additionally, several countries have territories in the sub-/Antarctic, allowing easier access to these Southern Ocean sites. These studies focussed on or near coastal shores and although pinnipeds feed in both coastal and pelagic waters, they haul out on land for breeding and parturition (Bartholomew 1970; Burton & Koch 1999) allowing easier access to large numbers of individuals for surveying. The rest of the world contributed few studies, sometimes due to a lack of pinnipeds, lack of reporting (as above) or other difficulties relating to the site including, for example, remoteness, funding, study permission, or lack of interest. Stelfox *et al.* (2016) found a lack of entanglement related information from the Arctic and Indian Oceans, corroborating our findings. Despite the potential reporting and observer biases mentioned, it appears that there is a collective interest (at a global scale) in the better understanding of entanglement and pinniped interactions. This is evidenced by most studies being published in the journal *Marine Pollution Bulletin* (impact factor of 3.146) (Figure 4), which is an outlet of good standing with international readership.

(3) The relationship between the number of entanglements per year and the number of papers published, might suggest that the rate of pinniped entanglement has not increased (Figure 5B). This could be due to better plastic waste management through recycling or stricter regulations, but we know this is not the case on a global scale (e.g. Kershaw *et al.* 2011; Cózar *et al.* 2014, Xanthos & Walker 2017). It is likely again that incomplete reporting and skewed study effort explain this finding, or that trends are variable at different spatio-temporal scales. For example, Henderson (2001) found no trend in the rates of pinniped entanglements over his 17-year study. Conversely, Stewart and Yochem (1987) and Hofmeyr *et al.* (2002), showed increasing proportions of entangled pinnipeds over the course of their respective long-term studies. *Zalophus californianus* and *Arctocephalus gazella*, the two most commonly entangled species, may be more susceptible to entanglement. However, they also have particularly large populations (*Zalophus californianus* > 300,000 - Szteren *et al.* 2006; and *Arctocephalus gazella* > 3 million - Reid & Forcada 2005) as compared to other pinnipeds such as *Monachus monachus* (500-600 individuals - Kiraç & Güçlüsoy, 2008), making them statistically more vulnerable to plastic encounters and entanglements, and are widely studied making entanglements more likely of being recorded.

Trends in entanglements for different pinniped species and in different regions are thus shrouded by skewed reporting and/or accessibility to reported encounters, variable global research effort, and uncertainty of the magnitude of oceanic plastic pollution, fisheries and pinniped abundance overlap.

Influence of individual pinniped entanglement on population trajectories

Information on the proportions of populations that are at risk of entanglement, or that actually become entangled is scant. Only for *Monachus monachus* is there evidence for significant demographic impact of entanglements on the population given that it is such a highly endangered pinniped species with a small global population (Karamanlidis *et al*. 2008).

While 11 species of pinnipeds have increasing population trends, four remain stable, seven are decreasing, and the population trajectories for 11 species are unknown (IUCN Red List, 2014-2016). Of the seven species that are facing population decline, individuals from six species have been recorded with entanglements; four are listed as endangered (*Neomonachus schauinslandi, Neophoca cinerea, Phocarctos hookeri,* and *Zalophus wollebaeki),* one as vulnerable (*Callorhinus ursinus*), and one as least concern (*Arctocephalus gazella*) (IUCN Red List, 2014-2015). The endangered species all have current population sizes below 15,000 individuals with the result that entanglements have the potential to heavily impact their populations. For example, the vulnerable (IUCN Red List, 2015) *C. ursinus*, is found in the North Pacific which is the most plastic polluted ocean (Eriksen *et al.* 2014).

Of the four species that have stable populations, two have entanglement reports (*Arctocephalus tropicalis* and *Mirounga leonina*). Both inhabit the Southern Ocean which is less plastic polluted than other oceans although fisheries sources for ALDFG are present (Eriksen *et al*. 2014), and both have populations over 400,000 individuals (IUCN Red List, 2014), meaning that entanglements are unlikely to impact the population dynamics.

Ten of the 11 species with positive population trends are reported as having been entangled. Eight of these are listed as least concern (*Arctocephalus australis, Arctocephalus forsteri, Arctocephalus pusillus, Arctocephalus townsendi, Halichoerus grypus, Mirounga angustirostris, Pagophilus groenlandicus,* and *Zalophus californianus*), one as near threatened (*Eumetopias jubatus*), and one as endangered (*Monachus monachus*) (IUCN Red List, 2014-2016). *Eumetopias jubatus* has a relatively large population (160,000) but inhabits areas with high oceanic plastic pollution occurrence. However, *Monachus monachus*, which has a population of only 500-600 individuals (IUCN Red List, 2015) as well as other species with small populations like *Neomonachus schauinslandi* with a population of 1200 individuals (IUCN Red List, 2014) are likely to suffer severe demographic consequences if, regularly, even a few individuals are entangled.

Three of the 11 species with unknown population trajectories have been recorded with entanglements. Two of these species are listed as least concern (*Hydrurga leptonyx* and *Phoca vitulina*), and one as endangered (*Pusa caspica*) (IUCN Red List, 2015). *Pusa caspica* has an estimated population size of 135,000 (IUCN Red List, 2015) but are geographically restricted to the Caspian Sea, and increased entanglement rates could negatively impact this species.

Notwithstanding the possible conservation effects for populations, entanglement of individual animals remains an animal welfare issue since entangled individuals are prone to unnatural suffering or death.

Sex and age demographics of entangled pinnipeds

IUCN Red List data indicates there to be around 23 million individual pinnipeds worldwide. If the estimate that 0.37% (2518 of 676233 individuals assessed for the presence/absence of entanglement) of pinnipeds that are entangled is expressed in absolute terms, the current global estimate of entangled individuals will be ~85,100. The majority of these are juveniles, subadults, and adults (Figure 7A), and are equally likely to be male or female. This lack of discrepancy between sexes is fortunate in that a biased entanglement propensity for specific sexes could exacerbate population risk. For example, pups of entangled females have higher mortality rates (Delong *et al*. 1988). The results for age-related risk in particular contradict several previous findings that juveniles face the highest risk of entanglement (Fowler *et al.* 1989; Pemberton *et al.* 1992; Arnould & Croxall 1995). This discrepancy may be an artefact of studies not always reporting the age categories (or categories not being consistent between studies) of entangled individuals. For example, Henderson (2001) classified juveniles and subadults within a single category. Pups have the lowest entanglement rates primarily because they remain ashore waiting to be fed, thus spending less time in the water (Charrier *et al.* 2001). Additionally, once pups enter the water they face several other high mortality risks (Doidge *et al.* 1984; Baker & Baker 1988) and so are more likely to die before the opportunity for entanglement arises. Otariids are significantly more likely to become entangled than phocids, which corroborates earlier findings (Laist 1997). These higher rates of entanglement could be due to the way otariids propel themselves in water, or their elongated fore flippers inhibiting them from freeing themselves from the responsible material. Phocids propel themselves with their hind flippers and keep their forelimbs close to their bodies while otariids use their fore flippers as propellers which could also cause them to be more easily entangled (Adam 2009). Additionally, phocids generally dive and forage much deeper in the water column than otariids (Costa 1993; Levenson & Schusterman 1999) and so may be less likely to encounter the floating oceanic plastic pollution.

Responsible material, severity of entanglements, and fate of the pinnipeds

Abandoned, lost or discarded fishing gear and fisheries associated material such as bait box packaging straps are responsible for almost all reported entanglements. It is not uncommon practice for ships to throw used ropes and nets overboard or to simply lose them (Sheavly & Register 2007). Packaging straps to bind boxes (mostly of bait for fishing vessels) are frequently removed from boxes without being cut, retaining their continuous loop design. Such packaging straps are serious culprits for neck-collar entanglements (Hofmeyr *et al.* 2002). The majority of reviewed studies did not record the severity of the entanglement. The significantly fewer number of 'loose' entanglements (Figure 8) recorded may result from many of the pinnipeds in this category escaping the entangling material by virtue of its 'looseness' before being observed. Instances of intervention to disentangle entangled pinnipeds were not more common than merely recording the entanglement (and presumably leaving the pinnipeds to their fate; Figure 9). This may be an artefact of reporting or the practicality of access to observed entangled pinnipeds, and/or inaction because pinnipeds can be dangerous. A higher proportion of pinnipeds are being disentangled in more recent decades possibly indicating that researchers have become more concerned for the fate of the individuals or that equipment and protocols improved to allow disentanglement of individuals.

The future?

With 67% (22 of 33; Figure 6) of extant pinniped species recorded as susceptible to entanglement, this phenomenon is taxonomically widespread. If the entanglement rates are extrapolated to unreported encounters or unstudied areas and populations, the global rate of pinniped entanglement is potentially higher than shown in this review. Unwillingness to report entanglements exacerbates the problem and may be a tendency amongst some groups who have higher probability of encountering entangled animals, such as fishermen, potentially because their own activities are often the source of entanglement. Further investigations are required to determine if the non-entangled species are actually evading entanglement, or if they are understudied. Some of the studies encompassed in this review included data that were interview-based, and the validity of such data is an important factor to continue to investigate, given potential biased reporting due to fear of recrimination.

Ultimately, removing the source of the entanglement is clearly a necessary part of finding a holistic solution to this global problem. Plastics have to be removed from the marine environment. Marine clean-up initiatives are integral given the longevity of plastics in the environment. Innovative techniques are constantly proposed to aid in clean-ups. For example, floating booms are designed to concentrate floating oceanic plastics, which can then be collected and eliminated (Sainte-Rose *et al*. 2016); or trawls dragged behind boats, and automated machines that tow trapping nets that then suction in all the oceanic plastic pollution floating in the waters are in use (Sigler 2014). However, many of these techniques are in early stages of development and can currently only target relatively small areas. Another frequently cited solution is to use biodegradable plastics which would disintegrate and ultimately be completely eliminated from the environment (Gross & Kalra 2002). Importantly, such plastics need to be completely degradable (Vaverková *et al.* 2012) and should not simply deteriorate into smaller pieces because microplastics are also a danger to the environment and biodiversity (Cole *et al.* 2011). In reality however, these materials are often more expensive to produce and market and thus are not at the forefront of plastic production (Amass *et al*. 1998). The drive for more durable and long-lasting engineered plastics also tends to decrease degradability (Philp *et al.* 2013). Currently, no commonly used plastics are biodegradable, and biodegradable plastics accounted for only 1% of total plastic production in 2015 (Geyer *et al.* 2017). By 2020 this number is expected to reach 2.5%, mainly in the production of food packaging, utensils, bags, and for agricultural uses (Van den Oever *et al.* 2017). For increased production of biodegradable plastics the cost-performance ratio has to be better than that of synthetic plastics and governments have to mandate for further research to be done in this field (Kolybaba *et al.* 2006). Some industries are responding faster than others (Kolybaba *et al.* 2006), however, few mega-corporations are currently incentivized to take responsibility for improving the environment (Smith & Ward 2007).

Perhaps foremost in mitigating pinniped entanglement is through intervention with fisheries activities and associated gear. Wilcox & Hardesty (2016) state three main ways to reduce the consequences of ALDFG: 1) Lower the ghost-fishing ability of the nets when they have been lost, such as through biodegradability or making them able to collapse when unattended; 2) increasing the chances of recovering lost gear, such as through mapping the losses or marking which can be economically and environmentally beneficial; 3) Make the nets harder to lose by adding markers or lights to them. Additionally, it has been proposed that using acoustics on fishing nets may help reduce entanglements and other interactions between fishing gear and marine mammals (Gearin *et al.* 1994; Jefferson & Curry 1996), however, this is more likely to be successful with active fishing/bycatch and not with ghost-fishing as these acoustic measures will not last long if not maintained. Simple materials such as cotton or jute ropes are not efficient for fishing activities as they degrade too rapidly in seawater (Cho 2011). Recently, a team from the Central Salt and Marine Chemicals Research Institute in India created biodegradable fishing ropes made from seaweed extracts (Herlekar 2015). These do not last as long as synthetic ropes but are said to not be hazardous to marine biota or the environment and have higher tensile strength than that of the synthetic ropes (Herlekar 2015). Kim *et al*. (2016) developed nylon fishing gear that degrades completely in salt water within a few years, faster in warmer water (Kim *et al*. 2016). Although an improvement, a few years of post-use persistence is still long enough to be able to entangle and maim or kill marine wildlife (Wilcox & Hardesty 2016). Fisheries management, especially on-board gear management is extremely important. Acts such as the Conservation Measure 63/XII for the Reduction in Use of Plastic Packaging Bands put forward by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), which restricts the use of packaging bands and if they are used mandates they be cut so they cannot entangle, are important steps toward reducing ALDFG and protecting pinnipeds as well as other marine fauna from entanglement. Reducing the number or fishing vessels, and therefore fishing effort, can both stop the overexploitation of marine life and lower the chances of ALDFG entering the water (Beddington *et al.* 2007). Additionally, management measures such as regulating mesh size in nets, and marking the fishing gear, both have the potential to lower entanglement rates (Flewwelling 1999). Drinkwin (2017) suggested strategies for the removal of ALDFG such as the use of acoustic sonar to scan seafloors, and boat-based, aerial, underwater, or dragging surveys for areas that have high concentrations of oceanic plastic pollution. To be able to locate and remove this ALDFG, its characteristics have to be understood, the likely high-density locations have to be found and then the material must be directly detected (McElwee *et al.* 2012). Groups such as the Global Ghost Gear Initiative (GGGI) work on different facets of this problem - from prevention of ALDFG entering the water to clean-up initiatives to remove it. Other mitigation measures include stricter monitoring of pinniped haul-out beaches and limiting or prohibiting fishing, and other facets of anthropogenic activity in such regional waters. These marine protected areas, or no-take zones (Halpern & Warner 2002) benefit many marine taxa, increase biodiversity, biomass and population sizes (Kelleher *et al.* 1995; Halpern 2003; Grantham *et al.* 2011). Some laws exist worldwide that prohibit dumping of wastes (both plastic and otherwise) in the ocean, but these are difficult to enforce (Leitzell 1972; Kite-Powell *et al.* 1998) and a re-evaluation of these measures is required. Clearly an ultimate solution to entanglements is elusive in that plastics continue to be produced *en masse* and existing products have a long post-production life in the environment. Our collective hope rests with adequate symptomatic mitigation.

We show that reporting bias, skewed research effort and limited understanding of the abundance overlap of ocean plastic pollution and pinniped populations combine to cloud our understanding of the interplay between such plastics and pinniped entanglement. Broader geographical effort in reporting of entanglements and improved quantification of the proportions of populations, sexes and ages that are entangled, will aid our efforts to pinpoint priority mitigation regions. Hurt or maimed animals, such as is often associated with entanglements, can enthuse emotive public action through awareness campaigns. Public participation through citizen science initiatives should be encouraged (e.g. Nelms et al. 2017), both in reporting and mitigation.

Author contributions

PJNdB conceptualised the idea, guided the methodology, co-wrote, edited and structured final versions of the manuscript. EMJ did the literature search, conducted analyses, wrote the first draft and created the figures.

References

Adam PJ (2009) Hind limb anatomy. In: Perrin WF, Würsig B, Thewissen JGM (eds) Encyclopedia of Marine Mammals (Second Edition) 562-565. Academic Press, Cambridge, USA.

Amass W, Amass A, Tighe B (1998) A review of biodegradable polymers: uses, current developments in the synthesis and characterization of biodegradable polyesters, blends of biodegradable polymers and recent advances in biodegradation studies. *Polymer International* 129: 89-144.

Angliss RP, DeMaster DP (1998) Differentiating serious and non-serious injury of marine mammals taken incidental to commercial fishing operations report of the serious injury workshop, 1-2 April 1997, Silver Spring, Maryland.

Anticamara JA, Watson R, Gelchu A, Pauly D (2011) Global fishing effort (1950–2010): trends, gaps, and implications. *Fisheries Research* 107: 131-136.

Antov P, Savov V, Neykov N (2017) Utilization of agricultural waste and wood industry residues in the production of natural fiber-reinforced composite materials. *International Journal – Wood, Design, and Technology* 6: 64-71.

Arnould JP, Croxall JP (1995) Trends in entanglement of Antarctic fur seals (*Arctocephalus gazella*) in man-made debris at South Georgia. *Marine Pollution Bulletin* 30: 707-712.

Baker JR, Baker R (1988) Effects of environment on grey seal (*Halichoerus grypus*) pup mortality. Studies on the Isle of May. *Journal of Zoology* 216: 529-537.

Bartholomew GA (1970) A model for the evolution of pinniped polygyny. *Evolution* 24: 546-559.

Bauman Z (2004) *Work, consumerism and the new poor*. McGraw-Hill Education, UK.

Beddington JR, Agnew DJ, Clark CW (2007) Current problems in the management of marine fisheries. *Science* 316: 1713-1716.

Burton RK, Koch PL (1999) Isotopic tracking of foraging and long-distance migration in northeastern Pacific pinnipeds. *Oecologia* 119: 578-585.

Carpenter EJ, Smith KL (1972) Plastics on the Sargasso Sea surface. *Science* 175: 1240-1241.

Charrier I, Mathevon N, Jouventin P (2001) Mother's voice recognition by seal pups. *Nature* 412: 873.

Cho DO (2011) Removing derelict fishing gear from the deep seabed of the East Sea. *Marine Policy* 35: 610-614.

Cole M, Lindeque P, Halsband C, Galloway TS (2011) Microplastics as contaminants in the marine environment: a review. *Marine Pollution Bulletin* 62: 2588-2597.

Costa DP (1993) The relationship between reproductive and foraging energetics and the evolution of the Pinnipedia. *Symposia of the Zoological Society of London* 66: 293-314.

Cózar A, Echevarría F, González-Gordillo JI, Irigoien X, Úbeda B, Hernández-León S, Palma ÁT, Navarro S, García-de-Lomas J, Ruiz A, Fernández-de-Puelles ML (2014) Plastic debris in the open ocean. *Proceedings of the National Academy of Sciences* 111: 10239-10244.

Crespy D, Bozonnet M, Meier M (2008) 100 Years of Bakelite, the Material of a 1000 Uses. *Angewandte Chemie International Edition* 47: 3322-3328.

Croxall JP, Rodwell S, Boyd IL (1990) Entanglement in man-made debris of Antarctic fur seals at Bird Island, South Georgia. *Marine Mammal Science* 6: 221-233.

Davies JL (1958) The Pinnipedia: an essay in zoogeography. *Geographical Review* 48: 474-493.

Derraik JG (2002) The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* 44: 842-852.

DeLong RL, Dawson P, Gearin PJ (1988) Incidence and impact of entanglement in netting debris on northern fur seal pups and adult females, St. Paul Island, Alaska. In: Kozloff P, Kajimura H (eds) Fur Seal Investigations 1985. U.S. Department of Commerce. NOAA-TM-NMFS-F/NWC-146:58-68.

Doidge DW, Croxall JP, Baker JR (1984) Density-dependent pup mortality in the Antarctic fur seal, *Arctocephalus gazella*, at South Georgia. *Journal of Zoology* 202: 449-460.

Drinkwin J (2017) Methods to locate derelict fishing gear in marine waters: A guidance document of the global ghost gear initiative catalyze and replicate solutions working group. *Global Ghost Gear Initiative* [online].

Eriksen M, Lebreton LC, Carson HS, Thiel M, Moore CJ, Borerro JC, Galgani F, Ryan PG, Reisser J (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS ONE* 9: p.e111913.

Flewwelling P (1999) *An introduction to monitoring, control and surveillance systems for capture fisheries*. [online] Fao.org. Available at: http://www.fao.org/3/v4250e/V4250E00.htm#toc [Accessed 11 Mar. 2019].

Fowler CW, Merrick R, Baker JD (1989) Studies of the population level effects of entanglement on northern fur seals. In *Proceedings of the Second International Conference on Marine Debris* 2: 453-474.

Gall SC, Thompson RC (2015) The impact of debris on marine life. *Marine Pollution Bulletin* 92: 170-179.

Gearin PJ, Goso ME, Laake JL, Cooke L, DeLong RL, Hughes KM (1994) Experimental testing of acoustic alarms (pingers) to reduce bycatch of harbour porpoise, *Phocoena phocoena*, in the state of Washington. *Journal of Cetacean Research and Management* 2: 1-9.

Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. *Science Advances* 3: p.e1700782

Gross RA, Kalra B (2002) Biodegradable polymers for the environment. *Science* 297: 803-807.

Goldberg ED (1994) Diamonds and plastics are forever? *Marine Pollution Bulletin* 28: 466.

Gourmelon G (2015) Global plastic production rises, recycling lags. *New Worldwatch Institute analysis explores trends in global plastic consumption and recycling.* Accessed at http://www.worldwatch.org.

Gramentz D (1988) Involvement of loggerhead turtle with the plastic, metal, and hydrocarbon pollution in the central Mediterranean. *Marine Pollution Bulletin* 19: 11-13.

Gregory MR (2009) Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364: 2013-2025.

Halpern BS, Warner RR (2002) Marine reserves have rapid and lasting effects. *Ecology Letters* 5: 361-366.

Halpern BS (2003) The impact of marine reserves: do reserves work and does reserve size matter? *Ecological Applications* 13: 117-137.

Hartley BL, Pahl S, Veiga J, Vlachogianni T, Vasconcelos L, Maes T, Doyle T, Metcalfe RDA, Öztürk AA, Di Berardo M, Thompson RC (2018) Exploring public views on marine litter in Europe: Perceived causes, consequences and pathways to change. *Marine Pollution Bulletin* 133: 945-955.

Hays GC (2017) Ocean currents and marine life. *Current Biology* 27: R470-R473.

Henderson JR (2001) A pre-and post-MARPOL Annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the Northwestern Hawaiian Islands, 1982–1998. *Marine Pollution Bulletin* 42: 584-589.

Herlekar I (2015) Biodegradable ropes from seaweed extracts. *Current Science* 108: 2140.

Hofmeyr G, De Maine M, Bester M, Kirkman S, Pistorius P, Makhado A (2002) Entanglement Of Pinnipeds At Marion Island, Southern Ocean: 1991-2001. *Australian Mammalogy* 24: 141-146.

Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, Narayan R, Law KL (2015) Plastic waste inputs from land into the ocean. *Science* 347: 768-771.

Jefferson TA, Curry BE (1996) Acoustic methods of reducing or eliminating marine mammal-fishery interactions: do they work? *Ocean and Coastal Management* 31: 41-70

Karamanlidis AA, Androukaki E, Adamantopoulou S, Chatzispyrou A, Johnson WM, Kotomatas S, Papadopoulos A, Paravas V, Paximadis G, Pires R, Tounta E (2008) Assessing accidental entanglement as a threat to the Mediterranean monk seal *Monachus monachus*. *Endangered Species Research* 5: 205-213.

Kaschner K, Watson R, Trites AW, Pauly D (2006) Mapping world-wide distributions of marine mammal species using a relative environmental suitability (RES) model. *Marine Ecology Progress Series* 316: 285-310.

Kelleher G, Bleakly C, Wells S (1995) A global representative system of marine protected areas. *The International Bank for Reconstruction* 2: 1-106.

Kershaw P, Katsuhiko S, Lee S, Woodring D (2011) Plastic debris in the ocean. *United Nations Environment Programme Year Book* 21-33.

Kim S, Kim P, Lim J, An H, Suuronen P (2016) Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. *Animal Conservation* 19: 309-319.

Kıraç CO, Güçlüsoy H (2008) Foça and Mediterranean monk seal; conservation and monitoring of the Mediterranean monk seals (*Monachus monachus*) in Foça special environment protection area. *Republic of Türkiye Ministry of Environment and Forest Environment Protection Agency for Special Areas* 1-50.

Kite-Powell HL, Hoagland P, Jin D (1998) Policy, law, and public opposition: the prospects for abyssal ocean waste disposal in the United States. *Journal of Marine Systems* 14: 377-396.

Klemchuk PP (1990) Degradable plastics: a critical review. *Polymer Degradation and Stability* 27: 183-202.

Kolybaba M, Tabil LG, Panigrahi S, Crerar WJ, Powell T, Wang B (2006) Biodegradable polymers: past, present, and future. In *ASABE/CSBE North Central Intersectional Meeting*. American Society of Agricultural and Biological Engineers.

Kovacs KM, Aguilar A, Aurioles D, Burkanov V, Campagna C, Gales N, Gelatt T, Goldsworthy SD, Goodman SJ, Hofmeyr GJ, Härkönen T (2012) Global threats to pinnipeds. *Marine Mammal Science*, 28: 414-436.

Kühn S, Rebolledo ELB, van Franeker JA (2015) Deleterious effects of litter on marine life. In *Marine Anthropogenic Litter* pp. 75-116, Springer Publishers, New York, USA.

Laist DW, (1987) Overview of the biological effects of lost and discarded plastic debris in the marine environment. *Marine Pollution Bulletin* 18: 319-326.

Laist DW (1997) Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: *Marine Debris* 99-139. Springer, New York, USA.

Law KL (2017) Plastics in the marine environment. *Annual Review of Marine Science* 9: 205-229.

Lee KT, Tanabe S, Koh CH (2001) Contamination of polychlorinated biphenyls (PCBs) in sediments from Kyeonggi Bay and nearby areas, Korea. *Marine Pollution Bulletin* 42: 273-279.

Leitzell TL (1972) The Ocean Dumping Convention-A Hopeful Beginning. *San Diego Law Review* 10: 502.

Levenson DH, Schusterman RJ (1999) Dark adaptation and visual sensitivity in shallow and deep-diving pinnipeds. *Marine Mammal Science* 15: 1303-1313.

Mattlin RH, Cawthorn MW (1986) Marine debris – an international problem. *New Zealand Environment* 51: 3-6.

McElwee K, Donohue MJ, Courtney CA, Morishige C, Rivera-Vicente A (2012) A strategy for detecting derelict fishing gear at sea. *Marine Pollution Bulletin* 65: 7-15.

McKinney ML (1998) On predicting biotic homogenization: species-area patterns in marine biota. *Global Ecology and Biogeography Letters* 7: 297-301.

Meneghini R, Packer AL (2007) Is there science beyond English?: Initiatives to increase the quality and visibility of non-English publications might help to break down language barriers in scientific communication. *EMBO Reports* 8: 112-116.

Nelms SE, Coombes C, Foster LC, Galloway TS, Godley BJ, Lindeque PK, Witt MJ (2017) Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data. *Science of the Total Environment* 579: 1399-1409.

Palmisano AC, Pettigrew CA (1992) Biodegradability of plastics. *Bioscience* 42: 680-685.

Parker L (2018) We made plastic. We depend on it. Now we're drowning in it. *National Geographic* 233: 40–91.

Pemberton D, Brothers NP, Kirkwood R (1992) Entanglement of Australian fur seals in man-made debris in Tasmanian waters. *Wildlife Research* 19: 151-159.

Philp JC, Ritchie RJ, Guy K (2013) Biobased plastics in a bioeconomy. *Trends in Biotechnology* 31: 65-67.

Pompa S, Ehrlich PR, Ceballos G (2011) Global distribution and conservation of marine mammals. *Proceedings of the National Academy of Sciences, USA* 108: 13600-13605.

Reid K, Forcada J (2005) Causes of offspring mortality in the Antarctic fur seal, *Arctocephalus gazella*: the interaction of density dependence and ecosystem variability. *Canadian Journal of Zoology* 83: 604-609.

RStudio Team (2016). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/.

Ryan PG, Connell AD, Gardner BD (1988) Plastic ingestion and PCBs in seabirds: is there a relationship? *Marine Pollution Bulletin* 19: 174-176.

Ryan PG, Moore CJ, van Franeker JA, Maloney CL (2009) Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society, B Biological Sciences* 364: 1999-2012.

Setälä O, Fleming-Lehtinen V, Lehtiniemi M (2014) Ingestion and transfer of microplastics in the planktonic food web. *Environmental Pollution* 185: 77-83.

Sheavly SB, Register KM (2007) Marine debris and plastics: environmental concerns, sources, impacts and solutions. *Journal of Polymers and the Environment* 15: 301-305.

Stelfox M, Hudgins J, Sweet M (2016) A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. *Marine Pollution Bulletin* 111: 6-17.

Stewart BS, Yochem PK (1987) Entanglement of pinnipeds in synthetic debris and fishing net and line fragments at San Nicolas and San Miguel Islands, California, 1978–1986. *Marine Pollution Bulletin* 18: 336-339.

Szteren D, Aurioles D, Gerber LR (2006) Population status and trends of the California sea lion (*Zalophus californianus californianus*) in the Gulf of California, Mexico. *Sea Lions of the World. Alaska Sea Grant College Program, Fairbanks* 369-384.

Todd PA, Ong X, Chou LM (2010) Impacts of pollution on marine life in Southeast Asia. *Biodiversity and Conservation* 19: 1063-1082.

Tudor DT, Williams AT (2003) Public perception and opinion of visible beach aesthetic pollution: the utilisation of photography. *Journal of Coastal Research* 19: 1104-1115.

Van den Oever M, Molenveld K, van der Zee M, Bos H (2017) *Bio-based and biodegradable plastics: facts and figures: focus on food packaging in the Netherlands* (No. 1722). Wageningen Food & Biobased Research.

Vaverková M, Toman F, Adamcová D, Kotovicová J (2012) Study of the biodegradability of degradable/biodegradable plastic material in a controlled composting environment. *Ecological Chemistry and Engineering S* 19: 347-358.

Watson RA, Cheung WW, Anticamara JA, Sumaila RU, Zeller D. Pauly D (2013) Global marine yield halved as fishing intensity redoubles. *Fish and Fisheries* 14: 493-503.

Wehle DHS, Coleman FC (1983) A naturalist at large - plastics at sea. *Natural History* 92: 20.

Wickens PA, Japp DW, Shelton PA, Kriel F, Goosen PC, Rose B, Augustyn CJ, Bross CAR, Penney AJ, Krohn RG (1992) Seals and fisheries in South Africa—competition and conflict. *South African Journal of Marine Science* 12: 773-789.

Wilcox C, Hardesty BD (2016) Biodegradable nets are not a panacea, but can contribute to addressing the ghost fishing problem. *Animal Conservation* 19: 322-323.

Worm B, Lotze HK, Jubinville I, Wilcox C, Jambeck J (2018) Plastic as a persistent marine pollutant. *Annual Review of Environment and Resources* 42: 1-26.

Xanthos D, Walker TR (2017) International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. *Marine Pollution Bulletin* 118: 17-26.

Supplementary material Appendix

List of all references surveyed in the review literature search.

Adamantopoulou S, Androukaki E, Dendrinos P, Kotomatas S, Paravas V, Psaradellis M, Tounta E, Karamanlidis AA (2011) Movements of Mediterranean Monk Seals (*Monachus monachus*) in the Eastern Mediterranean Sea. *Aquatic Mammals* 37: 256-261.

Allen R, Jarvis D, Sayer S, Mills C (2012) Entanglement of grey seals, *Halichoerus grypus*, at a haul out site in Cornwall, UK. *Marine Pollution Bulletin* 64: 2815-2819.

Antonelis GA, Baker JD, Johanos TC, Braun RC, Harting AL (2004) Hawaiian monk seal (*Monachus schauinslandi*): status and conservation issues. In: DiNardo G, Parrish F (eds) Atoll research bulletin: Northwestern Hawaiian Islands: third scientific symposium, November 2-4, 2004. National Museum of Natural History, Smithsonian Institution, Washington, D.C., U.S.A. February 2006.

Arnould JPY, Croxall JP (1995) Trend in entanglement of Antarctic Fur seals (*Arctocephalus gazella*) in man-made debris at South Georgia. *Marine Pollution Bulletin* 30: 707-712.

Aurioles-Gamboa D, García-Rodríguez F, Ramirez-Rodríguez M, Hernández-Camacho C (2003) Interaction between the California sea lion and the artisanal fishery in La Paz Bay, Gulf of California, Mexico. *Ciencias Marinas* 29: 357-370.

Baker JR, Jepson PD, Simpson VR, Kuiken T (1998) *Veterinary Record* 142: 595-601.

Barcenas-De La Cruz D (2018) Evidence of anthropogenic trauma in marine mammals stranded along the central California coast, 2003-2015. *Marine Mammal Science* 34: 330-346.

Berger JD, Armistead CE (1987) Discarded net material in Alaskan waters, 1982-84. U.S. Department of Commerce. NOAA-TM-NMFS-F/NWC-110.

Bogomolni AL, Pugliares KR, Sharp SM, Patchett K, Harry CT, LaRocque JM, Touhey KM, Moore M (2010) Mortality trends of stranded marine mammals on Cape Cod and southeastern Massachusetts, USA, 2000 to 2006. *Diseases of Aquatic Organisms* 88: 143-155.

Boren LJ, Morrissey M, Muller CG, Gemmell NJ (2006) Entanglement of New Zealand fur seals in man-made debris at Kaikoura, New Zealand. 2006. *Marine Pollution Bulletin* 52: 442-446.

Byrd BL, Hohn AA, Lovewell GN, Altman KM, Barco SG, Friedlaender A, Harms CA, McLellan WA, Moore KT, Rosel PE, Thayer VG (2014) Strandings as indicators of marine mammal biodiversity and human interactions off the coast of North Carolina. *NOAA Fishery Bulletin* 112: 1-23.

Campagna C, Falabella V, Lewis M (2007) Entanglement of southern elephant seals in squid fishing gear. *Marine Mammal Science* 23: 414-418.

Carretta JV, Wilkin SM, Muto MM, Wilkinson K (2013) Sources of human-related injury and mortality for U.S. Pacific west coast marine mammal stock assessments, 2007-2011. U.S. Department of Commerce. NOAA-TM-NMFS-SWFC-514.

Convey P, Barnes D, Morton A (2002) Debris accumulation on oceanic island shores on Scotia Arc, Antarctica. *Polar Biology* 25: 612-617.

Croxall JP, Rodwell S, Boyd IL (1990) Entanglement in man-made debris or Antarctic fur seals at Bird Island, South Georgia. *Marine Mammal Science* 6: 221-233.

Dau BK, Gilardi KVK, Gulland FM, Higgins A, Holcomb JB, St. Leger J, Ziccardi MH (2009) Fishing gear-related injury in California marine wildlife. *Journal of Wildlife Diseases* 45: 355-362.

Denkinger J, Quiroga D, Murillo JC (2014) Chapter 13: Assessing human-wildlife conflicts and benefits of Galápagos sea lions on San Cristobal island, Galápagos. In: Denkinger J, Vinueza L (eds) The Galapagos marine reserve: a dynamic social-ecological system. Springer publishers, New York, USA.

Dmitreva L, Kondakov AA, Oleynikov E, Kydtrmanov A, Karamendin K, Kasimbekov Y, Balmukanov M, Wilson S, and Goodman SJ (2013) Assessment of Caspian Seal by-catch in an illegal fishery using an interview-based approach. *PLoS ONE* 8: e67074.

Fowler CW (1987) Marine debris and Northern fur seals: a case study. *Marine Pollution Bulletin* 18: 326-335.

Fowler CW, Merrick R, Baker JD (1990) Studies of the population level effects of entanglement on northern fur seals. U.S. Department of Commerce. NOAA-TM-NMFS-SWFSC-154.

Franco-Trecu V, Drago M, Katz H, Machín E, Marín Y (2017) With the noose around the neck: marine debris entangling otariid species. *Environmental Pollution* 220: 985-989.

Frankfurter G, DeRango E, Johnson S (2016) Use of acoustic transmitter-equipped remote sedation to aid in tracking and capture of entangled California sea lions (*Zalophus californianus*). *Journal of Wildlife Diseases* 53: 730-733.

Gerber JA, Roletto J, Morgan LE, Smith DM, Gage LJ (1993) Findings in pinnipeds stranded along the central and northern California coast, 1984-1990. *Journal of Wildlife Diseases* 29: 423-433.

Goebel ME, Krause D, Freeman S, Burner R, Bonin C, Vasquez del Mercado R, Van Cise A, Gafney J (2009) Pinniped research at Cape Shirreff, Livingston Island, Antarctica, 2008/09. U.S. Department of Commerce. NOAA-TM-NMFS-SWFSC-445.

Goebel ME, Pussini N, Buchheit R, Pietrzak K, Krause DJ, Van Cise AM, Walsh JG (2011). Pinniped research at Cape Shirreff, Livingston Island, Antarctica. U.S. Department of Commerce. NOAA-TM-NMFS-SWFSC-524.

Goldstein T, Johnson SP, Phillips AV, Hanni KD, Fauquier DA, Gulland FMD (1999) Human-related injuries observed in live stranded pinnipeds along the central California coast 1986-1998. *Aquatic Mammals* 25: 43-51.

Good TP, June JA, Etnier MA, Broadhurst G (2010) Derelict fishing nets in Puget Sound and the Northwest Straits: patterns and threats to marine fauna. *Marine Pollution Bulletin* 60: 39-50.

Güçlüsoy H, Kiraç CO, Veryeri NO, Savas Y (2004) Status of the Mediterranean monk seal, *Monachus monachus* (Hermann, 1779) in the coastal waters of Turkey. *E.U. Journal of Fisheries and Aquatic Sciences* 21: 201-210.

Hanni KD, Long DJ, Jones RE, Pyle P, Morgan LE (1997) Sightings and strandings of Guadalupe fur seals in central and northern California, 1988-1995. *Journal of Mammalogy* 78: 684-690.

Hanni KD, Pyle P (2000) Entanglement of pinnipeds in synthetic materials at south-east Farallon Island, California, 1976-1998. *Marine Pollution Bulletin* 40: 1076-1081.

Harcourt R, Aurioles D, Sanchez J (1994) Entanglement of California sea lions at Los Islotes, Baja California Sur, México. *Marine Mammal Science* 10: 122-125.

Henderson JR (1990) Recent entanglements of Hawaiian monk seals in marine debris. U.S. Department of Commerce, NOAA-TM-NMFS-SWFSC-154.

Henderson JR (2001) Entanglements and marine debris accumulation in the Northwestern Hawaiian Islands, 1982-1998. *Marine Pollution Bulletin* 42: 584-589.

Hofmeyr G, De Maine M, Bester M, Kirkman S, Pistorius P, Makhado A (2002) Entanglement of pinnipeds at Marion Island, Southern Ocean: 1991-2001. *Australian Mammalogy* 24: 141-146.

Hofmeyr GJG, Bester MN (2002) Entanglement of pinnipeds at Marion Island. *South African Journal of Marine Science* 24: 383-386.

Hofmeyr GJG, Bester MN, Kirkman SP, Lydersen C, Kovacs KM (2006) Entanglement of Antarctic fur seals at Bouvetøya, Southern Ocean. *Marine Pollution Bulletin* 52: 1077-1080.

Hogan E, Warlick A (2017) Packing bands entangling pinnipeds around the world: global review and policy. *Journal of International Wildlife Law and Policy* 20: 96-104.

Hucke-Gaete R, Torres D, Vallejos V (1997) Entanglement of Antarctic fur seals, *Arctocephalus gazella,* in marine debris at Cape Shirreff and San Telmo Islets, Livingston Island, Antarctica: 1988-1997. *Ser. Cient. INACH* 47: 123-135.

Ivar do Sul JA, Barnes DKA, Costa MF, Convey P, Costa ES, Campos L (2011) Plastics in the Antarctic environment: are we looking only at the tip of the iceberg? *Oecologia Australis* 15: 150-170.

Karamanlidis AA, Androukaki E, Adamantopoulou S, Chatzispyrou A, Johnson WM, Kotomatas S, Papadopoulos A, Paravas V, Paximadis G, Pires R, Tounta E, Dendrinos P (2008) Assessing accidental entanglement as a threat to the Mediterranean monk seal *Monachus monachus*. *Endangered Species Research* 5: 205-213.

Karamanlidis AA, Kallianiotis A, Psaradellis M, Adamantopoulou S (2011) Stomach contents of a subadult Mediterranean monk seal (*Monachus monachus*) from the Aegean Sea. *Aquatic Mammals* 37: 280-283.

Kiyota M, Baba N (2001) Entanglement in marine debris among adult female northern fur seals at St. Paul Island, Alaska in 1991-1999*. Bulletin of National Research Institute of Far Seas Fisheries* 38: 13-20.

Lawson TJ, Wilcox C, Johns K, Dann P, Hardesty BD (2015) Characteristics of marine debris that entangle Australian fur seals (*Arctocephalus pusillus doriferus*) in southern Australia. *Marine Pollution Bulletin* 98: 354-357.

Lipsky JD (2007) AMLR 2006/2007 field season report: objectives, accomplishments and tentative conclusions. U.S. Department of Commerce, NOAA-TM-NMFS-SWFSC-409.

Lucas Z (1992) Monitoring persistent litter in the marine environment on Sable Island, Nova Scotia. *Marine Pollution Bulletin* 24: 192-199.

Mawson PR, Coughran DK (1999) Records of sick, injured and dead pinnipeds in Western Australia 1980-1996. *Journal of the Royal Society of Western Australia* 82: 121-128.

McIntosh RR, Kirkwood R, Sutherland DR, Dann PM (2015) Drivers and annual estimates of marine wildlife entanglement rates: a long-term study with Australian fur seals. *Marine Pollution Bulletin* 101: 716-725.

Moore E, Lyday S, Roletto J, Litle K, Parrish JK, Nevins H, Harvey J, Mortenson J, Greig D, Piazza M, Hermance A, Lee D, Adams D, Allen S, Kell S (2009) Entanglement of marine mammals and seabirds in central California and the north-west coast of the United States 2001-2005. *Marine Pollution Bulletin* 58: 1045-1051.

Page B, McKenzie J, McIntosh R, Baylis A, Morrissey A, Calvert N, Haase T, Berris M, Dowie D, Shaughnessy PD, Goldsworthy SD (2004) Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem. *Marine Pollution Bulletin* 49: 33-42.

Pemberton D, Brothers NP, Kirkwood R (1992) Entanglement of Australian fur seals in man-made debris in Tasmanian waters. *Wildlife Research* 19: 151-159.

Raum-Suryan KL, Jemison LA, Pitcher KW (2009) Entanglement of Stellar sea lions (*Eumetopias jubatus*) in marine debris: identifying causes and finding solutions. *Marine Pollution Bulletin* 58: 1487-1495.

Sharp SM, Johnson SP, Moore MJ, Harry CT, Hoppe JM, Moore KMT, Niemeyer ME, Patchett KM, Rose K, Zahniser D, Sharp WB. *Unpublished data*.

Shaughnessy PD (1980) Entanglement of cape fur seals with man-made objects. *Marine Pollution Bulletin* 11: 332-336.

Shaughnessy PD, Briggs SV, Constable R (2001) Observations on seals at Montague Island, New South Wales. *Australian Mammalogy* 23: 1-7.

Shaughnessy PD, Kirkwood R, Cawthorn M, Kemper C, Pemberton D (2003) Pinnipeds, cetaceans and fisheries in Australia: a review of operational interactions. *Marine mammals: fisheries, tourism and management issues.* CSIRO Publishing, Melbourne 136-152.

Slater J (1991) Leopard seal entanglement in Tasmania, Australia. *Marine Mammal Science* 7: 323.

Slip DJ, Burton IV HR (1991) Accumulation of fishing debris, plastic litter, and other artefacts, on Heard and Macquarie Islands in the Southern Ocean. *Environmental Conservation* 18: 249-254.

Slooten E, Dawson SM (1995) Conservation of marine mammals in New Zealand. *Pacific Conservation Biology* 2: 64-76.

Stewart BS, Yochem PK (1987) Entanglement of pinnipeds in synthetic debris and fishing net and line fragments at San Nicolas and San Miguel Islands, California, 1978-1986. *Marine Pollution Bulletin* 18: 336-339.

Sandmeyer Swails K (2005) Patterns of seal strandings and human interactions in Cape Cod, Massachusetts. MSc thesis, Duke University.

Tillman MF (1990) International efforts to control marine debris in the Antarctic. U.S. Department of Commerce, NOAA-TM-NMFS-SWFSC-154.

Torres D, Jorquera D (1996) Monitoring results of marine debris at Cape Shirreff, Livingston Island, South Shetland Islands, during the Antarctic season 1995/96. *Ser. Cient. INACH* 46: 121-132.

Torres D, Jorquera D, Vallejos V, Hucke-Gaete R, Zárate S (1997) Beach debris at Cape Shirreff, Livingston Island, during the Antarctic season 1996/97. *Ser. Cient. INACH* 47: 137-147.

Unger B, Herr H, Benke H, Böhmert M, Burkhardt-Holm P, Däne M, Hillmann M, Wolff-Schimdt K, Wohlsein P, Siebert U (2017) Marine debris in harbour porpoises and seals from German waters. *Marine Environmental Research* 130: 77-84.

Waluda CM, Staniland JL (2013) Entanglement of Antarctic fur seals at Bird Island, South Georgia. *Marine Pollution Bulletin* 74: 244-252.

Warlick AJ, Duffield DA, Lambourn DM, Jeffries SJ, Rice JM, Gaydos JK, Huggins JL, Calambokidis J, Lahner LL, Olson J, Agnese ED, Souze V, Elsby A, Norman SA (2018) Spatio-temporal characterization of pinniped strandings and human interaction cases in the Pacific Northwest, 1991-2016. *Aquatic Mammals* 44: 299-318.

Westlake RL, Slepmann PJ (1986) Hawaiian Monk seal and green turtle research on Lisianski Island, 1986. U.S. Department of Commerce. NOAA-TM-NMFS-SWFC-119.

Wynne K (1990) Marine mammal interactions with the salmon drift gillnet fishery on the Copper River delta, Alaska 1988-1989. *Alaska Sea Grant College Program Technical Report No. 90-05.*

Zavala-González A, Mellink E (1997) Entanglement of California sea lions, *Zalophus californianus californianus,* in fishing gear in the central-northern part of the Gulf of California, Mexico. *Fishery Bulletin* 95: 180-184.