A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs

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Olive Ridley Project
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Michael John Sweet
University of Derby
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Review

A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs

Martin Stelfox [a,b,*], Jillian Hudgins [b], Michael Sweet [a]

[a] Environment Sustainability Research Centre, College of Life and Natural Sciences, University of Derby, UK
[b] Olive Ridley Project, 8 Thornton Avenue, Plymouth, UK

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ABSTRACT

This review focuses on the effect that ghost gear entanglement has on marine megafauna, namely mammals, reptiles and elasmobranchs. A total of 76 publications and other sources of grey literature were assessed, and these highlighted that over 5400 individuals from 40 different species were recorded as entangled in, or associated with, ghost gear. Interestingly, there appeared to be a deficit of research in the Indian, Southern, and Arctic Oceans; and so, we recommend that future studies focus efforts on these areas. Furthermore, studies assessing the effects of ghost gear on elasmobranchs, manatees, and dugongs should also be prioritised, as these groups were underrepresented in the current literature. The development of regional databases, capable of recording entanglement incidences following a minimum global set of criteria, would be a logical next step in order to analyse the effect that ghost gear has on megafauna populations worldwide.

Contents

1. Introduction

Though fishing gear has been lost since fishing began, historically such gear was made from natural materials that would have

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* Corresponding author at: Environment Sustainability Research Centre, College of Life and Natural Sciences, University of Derby, UK.

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decomposed quickly and created a relatively small threat to marine wildlife. However, in recent years advances in technology and improvements in gear designs have forced fishers to switch to gear made from synthetic materials, namely plastics (e.g., Macfadyen et al., 2009). Synthetic fishing materials such as nylon, polyethylene, and polypropylene are impervious to natural biodegradation and can remain unchanged in the marine environment for decades. This promotes a phenomenon called 'ghost fishing', whereby lost or discarded gear continue to catch an abundance of wildlife from a range of taxa. The actual amount of abandoned, lost, or otherwise discarded fishing gear (often shortened to ALDFG) is extremely difficult to quantify. However, it has been estimated that each year, upwards of 640,000 tons of gear is lost globally, meaning that ALDFG accounts for over 10% of the total marine debris floating in our oceans (Macfadyen et al., 2009). Given that survey effort for ALDFG is often poor or sporadic in many areas around the world, this 10% is therefore likely to be a gross underestimate of the true amount.

As early as the 1980s, the Food and Agriculture Organisation (FAO) recognised ALDFG as a global problem. ALDFG also fits under the mandate of the International Maritime Organisation (IMO), which heads the International Convention for the Prevention of Pollution from Ships (MARPOL Annex V). Furthermore, the issue has been raised at numerous United Nation general assemblies (Macfadyen et al., 2009). Although ALDFG is clearly a global concern affecting many species, it is important to pay particular attention to those species that are sensitive to anthropogenic stress (i.e., those with low fecundity or increased age at sexual maturity).

This review focusses on how entanglement in ALDFG impacts marine megafauna, such as mammals, reptiles and elasmobranchs. Numbers were pulled from all traceable literature dating back to the last comprehensive review conducted by Laist (1997). We also aimed to identify the different gear types that contribute to ghost fishing and give recommendations on how to manage and mitigate the issue.

1.1. Supply and demand - A brief look at global fishing pressure

Fishing pressure has increased dramatically worldwide since the 1970s (Anticamara et al., 2011). It is thought that a growing global human population, combined with higher incomes and an insatiable appetite for seafood around the world, were likely factors contributing to this observable increase (Swartz et al., 2010). To date, 28.8% of global fish stocks are thought to be over-exploited with a further 61.3% fully fished out with no room for further expansion of catch (FAO, 2014). Advances in technology have created powerful mechanised fishing vessels that are capable of fishing on a global scale and at increasing depths. An estimated 4.72 million fishing vessels were legally operating in 2012, of which 57% were engine powered (FAO, 2014). Although these figures are staggering, they do not take into account illegal, unreported, and unregulated (IUU) fishing, or those countries that failed to submit data to the FAO database. Therefore, the actual fishing pressure in the world's oceans is likely to be significantly higher.

Due to increasing demand, higher competition, and reduced fish stocks, fishers around the world, both small local artisan fishers and commercial operations, have had to change their fishing techniques and increase their effort by switching to increasingly more durable and longer lasting materials as a response (Carr and Harris, 1997). For example, artisan fishers in many states of India were first introduced to nylon monofilament nets as late as 1990 and by the early 2000s monofilament nets had almost completely replaced multifilament nylon nets in small and large scale gill net fisheries. Fishers in other parts of South East Asia are now increasingly favouring thinner nets, referred to as 'superfine nets'. Unfortunately, the thinness of the twine means that the nets break easily and, unlike stronger multifilament nets, become difficult to repair once damaged (Rao, 2010). Similarly, by the late 1980s traditional fishers in parts of Queensland, Australia started to favour fishing with pots made from multifilament polyethylene trawl mesh over the less durable pots constructed of wire mesh and steel that would corrode quickly (Campbell & Sumpton, 2009). This change in gear design was most likely driven by the cost of the new nets and pots, as they are cheaper to purchase and, they are easy to replace if, or when, they are damaged.

1.2. When does fishing gear become ALDFG?

Fishing gear becomes ALDFG when the fisher loses all operational control of the equipment (Smolowitz, 1978). A switch from the natural or biodegradable material that was traditionally used for centuries to synthetic fishing gear (as described above) has led to a rise in the amount of ALDFG accumulating in the world's oceans. The causes of ALDFG include: snagging on the bottom, storms or bad weather, operational damages, improper gear use, gear conflicts, high cost relating to proper disposal, lack of disposal facilities, lack of space on fishing craft, and logistical difficulties retrieving gear. For a summary of the multitude of reasons why fishing gear may be lost we refer you to Macfadyen et al. (2009).

1.3. What factors affect ghost fishing rates?

Ghost fishing is defined as the ability of fishing gear to continue to fish after all control of that gear is lost (Smolowitz, 1978). This definition however, does not give specifics on how to identify mortality rates associated with ghost fishing. Matsuoka et al. (2005) suggested that the presence of lost fishing gear and the entry of organisms into that gear, for example, was not substantial enough evidence to prove that the gear was 'ghost fishing'. Additionally, the identification of any dead animals must be conducted to species level in order to give reliable mortality rates of ghost fishing. The survival rate of animals that have escaped entanglement must also be considered; a problem that is more difficult to quantify. Using a terrestrial example of entanglement and mortality, a study by Votier et al. (2011) argued that colonial seabirds released from entangling plastic would not survive without human intervention. They suggested that individuals that had escaped or were released from the gear would likely succumb to death as a direct result of the entanglement and should, therefore, also be considered in the mortality estimate.

Mortality due to ghost fishing is therefore very difficult to quantify. Early studies suggested that the rate of ghost fishing may be influenced by numerous factors including: the abundance of fauna in any given area, the environmental conditions that the gear is exposed to at any given time (such as currents or storms), and the habitat type (Kaiser et al., 1996). Unsurprisingly, there was a general consensus in the literature that static ghost nets show a general decline in catch rates over time (e.g., Humborstad et al., 2003; MacMullen et al., 2003; Revill and Dunlin, 2003; Tschernij and Larsson, 2003). For example, in-water observations of lost gill nets in the relatively sheltered waters of the Baltic Sea suggested that catch efficiency rapidly deteriorates and then stabilises at around 20% of the original level after three months. After 27 months, the level of ghost fishing efficiency is reduced further to approximately 5–6% of the original level (Tschernij and Larsson, 2003). However, the catch efficiency of set nets will depend on the net structure and this can be affected by the presence or absence of obstacles such as wrecks or rocky bottoms versus smooth sandy bottoms or deep water. A net has a greater chance of being snagged in situ on an obstacle, such as a rocky bottom or coral reef, which may tear the mesh creating larger holes for larger animals to become entangled. Conversely, if a net is set and lost on a shallow sandy bottom, it will continue to ghost fish until the weight of the catch reduces the vertical height of the net and it ends up as a pile on the sea floor with little to no fishing ability (Baeta et al., 2009). Since the structure of fishing gear is an important factor when determining ghost fishing efficiency, it was suggested that traps and pots may be more prone to ghost fishing simply because they are made of longer-lasting, more rigid materials that maintain their optimal configuration over time (Adey et al., 2008). For

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example, early studies on the escape rate of Dungeness crabs (*Metacarcinus magister*) from pots in the Columbia River estuary estimated mortality rates of legal sized crabs to be 52% (Breen, 1987); however, similar studies of baited creels on Norwegian lobsters (*Nephrops norvegicus*) showed a much lower ghost fishing efficiency. This was attributed to a gear design that allowed other non-target species to escape and the unique ability of Norwegian lobsters to survive long periods after it is caught (Adey et al., 2008). Although such types of ALDFG pose little direct threat to marine megafauna, simply due to the size of the animals, the associated lines that connect the traps and pots to the surface could be a considerable entangling threat to these groups. Furthermore, the traps may also act as a potential food source increasing the likelihood of megafauna coming into contact with the traps, fragments of them, and/or the associated fishing lines. This highlights an indirect effect that some types of ALDFG may have on certain species or taxa. For example, lobster fishers on the Atlantic side of the Florida Keys recorded dolphins and turtles breaking gear as they foraged for lobsters caught inside the traps (Butler and Matthews, 2015); however, no data has been published highlighting if any indirect entanglements occurred due to this opportunistic feeding behavior.

Considerable literature exists on the rate of ghost fishing for static ALDFG; however, little information is available for transient ALDFG that follow winds and geostrophic currents. Fragments of nets or drifting fish aggregating devices (dFADs) are extremely difficult to track or find, making prolonged studies very challenging. Most information available on this cryptic gear is from anecdotal records since the costs and logistics involved in a wide scale study are prohibitive. It is tempting to assume that the rate of ghost fishing for this type of ALDFG may follow the same influencing factors as for static gear, but no conclusions can be drawn until more research is focussed on this type of gear.

Ghost fishing rates are likely also biased towards survey effort (i.e., the more time put into the survey, the more animals that are likely to be found entangled). For example, eight survey cruises at 11 breeding colonies of Californian sea lions (*Zalophus californianus*) between 1991 and 1995, recorded entanglement rates between 0 and 2.24% (Zavala-gonzalez and Mellink, 1997). A similar survey of grey seals (*Halichoerus grypus*) in the UK reported entanglement rates of 3.1–4.9% (Sayer, 2015); however, survey effort was much greater in the latter study, with surveys averaging 226 days out of 365 between 2004 and 2013. Similarly, early data collected for entangled Olive Ridley turtles (*Lepidochelys olivacea*) in the Maldives reported only 25 incidences of entanglements over eight years between 1999 and 2007 (Anderson et al., 2009); though, with an increase in recording efforts, this number rose to 163 in just two years (2013–2015) (Stelfox and Hudgins, 2015).

The above illustrates the importance of incorporating a unit of effort metric when describing the effect of ghost gear on any specific organism. Furthermore, the difficulty in getting to certain locations coupled with local weather conditions can make observing entangled animals and empty nets difficult (Boren et al., 2006). Therefore, it is very important to note and understand that any estimated entanglement rates in the literature represent only instantaneous measures of entanglement or mortality since not all entangled animals can be observed at any given time (Matthews and Glazer, 2010; Henderson, 1984).

1.4. The cyclical nature of ghost fishing and the role of bio-fouling

ALDFG that remains in water for long enough will eventually accumulate sessile organisms in a process referred to as 'bio-fouling'. The time it takes to accumulate such bio-fouling greatly depends on environmental factors such as temperature, location, etc. (Bixler and Bhushan, 2012). It was suggested that bio-fouling could be one reason why ghost fishing efficiency decreases with time (as described above), as the net becomes more visible to animals (Revill and Dunlin, 2003). Visibility of nets likely has a major effect on ghost fishing efficiency. Monofilament nets have higher catch rates than multifilament nets and it is thought that the higher visibility of the multifilament nets is the main reason for this difference (Ayaz et al., 2006). On the other hand, floating ALDFG with significant bio-fouling may attract small animals looking for food and shelter, which in turn would attract larger predators (such as turtles, cetaceans, sharks, etc.). This could give rise to a continuous cycle of ghost fishing initially brought on by biofilm buildup (Carr, 1987).

Bio-fouling can also assist researchers in aging the ALDFG. For example, analyses of size classes of common bivalve species on nets showed that shell length of *Anomia* sp. can be used to age ALDFG in the Bay of Biscay (Pawson, 2003). The amount of bio-fouling on any given net, along with the species found (which varies depending on geographic location), could, therefore, be used as a tool to calculate approximate drifting times of ALDFG, with the goal of determining its approximate origin. This could help address one of the issues highlighted above: the lack of detailed studies on transient ALDFGs. Care should, however, be taken during replication studies, since the environment and surrounding temperatures would likely dictate the growth rates of different bivalve species and these factors would need to be replicated in the laboratory for accuracy.

Depth plays a critical role on the rate of biofilm buildup since nets at deeper depths (beyond the epipelagic zone) are not exposed to as many macro-fouling organisms and the rate of buildup is subsequently reduced (Lehaitre et al., 2008). Also, there is a marked reduction in light penetration and effects from weather are minimized at these depths. These factors may contribute to the net remaining relatively physically unchanged for long periods of time at deeper depths. Humborstad et al. (2003) suggested that ghost fishing in deeper water could be a more serious problem since the only factor that appears to affect deep water ALDFG's ability to ghost fish is the amount of catch, which weighs the net down, reducing its vertical height until it reaches the sea floor.

Multifilament nets, especially trawl nets, are made from thick synthetic materials that are buoyant in seawater. Attached floats give this type of ALDFG even more positive buoyancy. Over time, biofilm accumulation combined with the weight of catch causes the net to lose vertical profile and it sinks slowly (Macfadyen et al., 2009). It has been suggested that bio-fouling and catch may be flushed from the net during stormy weather (Ayaz et al., 2006). Coupled with the loss of ghost catch from predation, the nets could become buoyant again, rising back to the surface to continue the ghost fishing cycle (Fig. 1).

2. Materials and methods

We have carried out an extensive literature review with the aim of highlighting the threat of entanglement in ALDFG to marine megafauna. Furthermore, we tried to identify what type(s) of gear poses the greatest threat to these animal groups.

Electronic keyword searches were performed using Google Scholar and Science Direct to identify literature. Key words used were: *entanglement*, *ghost fishing*, *ghost gear*, *derelict fishing gear*, *marine debris*, *and ALDFG*. These were paired with *snake*, *crocodile*, *turtle*, *shark*, *ray*, *manta*, *seal*, *sea lion*, *whale*, *dolphin*, *manatee*, *dugong*, *pinniped*, *cetacean*, *elasmobranch*, *marine mammal*, *reptile, and megafauna*. In addition, all cited references from each paper we reviewed were extensively searched for keywords described above. Contact by email was made to the secretariat of the Global Ghost Gear Initiative (GGGI)[*] and its working group members to identify additional sources of literature, particularly unpublished grey literature.

Laist (1997) compiled a comprehensive list of animal interactions with marine debris, which also included entanglements in fishing gear. Since this publication, new literature on the effects of marine debris has been published, with some focusing specifically on ghost fishing

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[*] *The Global Ghost Gear Initiative (GGGI) formed by World Animal Protection is a cross-sectoral alliance committed to driving solutions to the problem of lost and abandoned fishing gear worldwide.*

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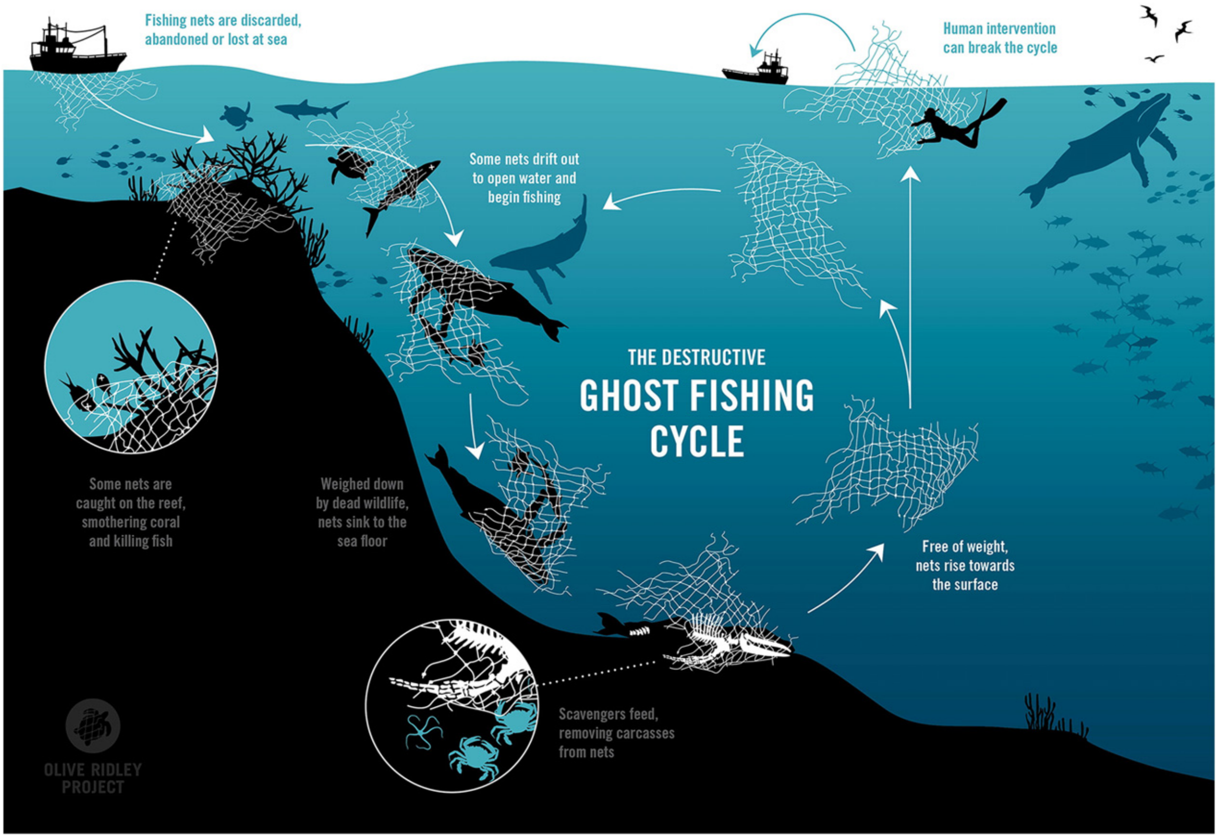

Fig. 1. Ghost fishing cycle (Courtesy of the Olive Ridley Project, created by Susie Gibson).

and others aimed more towards scarring that could not be attributed to ALDFG or interactions with fisheries (e.g., Knowlton et al., 2012; Bradford et al., 2009; Neilson et al., 2009; Robbins and Mattila, 2001, etc.). From this point on, we will only discuss literature published between 1997 and 2015 and direct the reader to Laist's 1997 review for data before this date.

We screened the literature to focus on megafauna entanglement in ALDFG only. Most reports grouped general marine debris, such as plastic wrapping, clothing, cement bags, tires, metal rings, etc., with ALDFG. Combining these two entanglement hazards makes assessing ghost fishing entanglement rates and the effects they have on particular species or populations almost impossible to interpret. Furthermore, conclusions on the impact of ALDFG to various species are difficult to evaluate if the entangling material cannot be identified. To address this problem, we decided to implement a strict criterion during the selection of literature. We separated the number of animals entangled in ALDFG, or entanglements that could not be identified as being from active or derelict fishing gear, from those animals entangled in general marine debris and those that were entangled during active fishing activity. If a clear separation was not possible then the number of animals entangled was not included in this review; this was to ensure that general marine debris entanglement or bycatch were not included in our interpretation.

3. Results

3.1. The effects of ghost fishing on marine mammals, reptiles and elasmobranchs

In total, 76 papers were identified and 40 different species were recorded entangled in ALDFG (27 marine mammals species, seven reptile species, and six elasmobranchs species). Marine mammals accounted for 70% of all entanglements reported in this review. Humpback whales (*Megaptera novaeangliae*) were the most recorded species with 670 entangled individuals, closely followed by the North Atlantic right whale (*Eubalaena glacialis*) ($n = 648$). Many observations of cetaceans were only of the tail (peduncle), which is left with scarring once the gear is eventually shed (e.g., Jensen et al., 2009; Neilson et al., 2009; Johnson et al., 2005; Robbins and Mattila, 2004; Wells et al., 1998). Humpback whales and North Atlantic right whales received considerable attention in the literature, in both instances accounting for 12% (total 24% for both species) of all entangled animals identified in this review (Table 1). In some studies approximately half (48–57%) of the humpbacks assessed showed signs of some form of prior entanglement (Robbins and Mattila, 2004). Similarly when 626 photos of North Atlantic right whales from the East coast of USA and Canada were assessed, 83% showed evidence of entanglement (Knowlton et al., 2012).

The highest number of entangled individuals for all pinnipeds on record was for the Antarctic fur sea (*Arctocephalus gazelle*) ($n = 492$) followed by the Californian sea lion (*Zalophus californianus*) ($n = 443$). The manatee (*Trichechus manatus latirostris*) was the fifth most recorded marine mammal entangled in ghost gear despite only one published study being available ($n = 375$) (Adimey et al., 2014) (Table 1).

Reptiles accounted for 27% of all animals entangled. With the exception of one saltwater crocodile (*Crocodylus porosus*) entangled in Australia, all reptiles recorded were sea turtles. The Olive Ridley turtle (*Lepidochelys olivacea*) accounted for the majority of identified sea turtles (68%, $n = 303$) (Table 2).

Only 2% of all entangled animals were elasmobranchs; however; the leafscale gulper shark (*Centrophorous squamosus*) and the Greenland shark (*Somniosus microcephalus*) were recorded by weight not by count (6.2 tons and 1 ton, respectively) and were, therefore, not included in the analyses of entangled individuals in this review (Table 3).

Since Laist's review in 1997, a total of 12 new species have been reported entangled in ALDFG in published or grey literature (Tables 1, 2, and 3). Unfortunately, Laist did not quantify the number of individual animals entangled in ALDFG in his review; therefore, we cannot analyse

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Table 1
Number of marine mammals recorded entangled in ghost gear since Laist (1997). (UR) Unknown Rope, (NL) Net Line combination, (ML) Monofilament Line, (RPT) Rope attached to Pots and Traps, (N) Nets.

Species			Ghost gear type					
(nt = Total # of individual species entangled)	Ocean basin	n	UR	NL	ML	RPT	N	Source
Grey seal (*Halichoerus grypus*) (nt = 262)	Atlantic	58						Allen et al., 2012
		204			8		76	Sayer et al., 2015
Guadalupe fur seal (*Arctocephalus townsendi*) (nt = 3)	Pacific	3						Moore et al., 2009
Antartic fur seal (*Arctocephalus gazelle*) (nt = 492)	Atlantic	441			261		180	Waluda and Staniland, 2013
		51					51	Hofmeyr et al., 2006
Northern fur seal (*Calorhinus ursinus*) (nt = 49)	Pacific	20					20	Kiyota and Baba, 2001
		27			5		22	Zavadil et al., 2007
		2			1		1	Moore et al., 2009
Hawaiian monk seal (*Monachus schauinslandi*) (nt = 120)	Pacific	120		16	48		56	Henderson, 2001
		R						Boland and Donohue, 2003
		R						Donohue and Foley, 2007
New Zealand fur seal (*Arctocephalus forsteri*) (nt = 161)	Pacific	107	6		3		96	Boren et al., 2006
		54	9		3	12	26	Page et al., 2004
Californian sea lion (*Zalophus californianus*) (nt = 443)	Pacific	106						Dau et al., 2009
		178			21		58	Hanni and Pyle, 2000
		157			68			Moore et al., 2009
		2					2	Good et al., 2007
Northern elephant seal (*Mirounga angustirostris*) (nt = 26)	Pacific	16						Dau et al., 2009
		10			8		1	Hanni and Pyle, 2000
Steller sea lion (*Eumetopias jubatus*) (nt = 24)	Pacific	18			1		1	Hanni and Pyle, 2000
		6	3		1		2	Raum-Suryan et al., 2009
Australian fur seal (*Arctocephalus pusillus dorifus*) (nt = 7)	Indian	R						Lawson et al., 2015
	Pacific	7						Shaughnessy et al., 2001
Australian sea lion (*Neophoca cinerea*) (nt = 30)	Indian	30	5		2		23	Page et al., 2004
Harbour seal (*Phoca vitulina*) (nt = 23)	Pacific	11						Moore et al., 2009
		4						Dau et al., 2009
		8					8	Good et al., 2007
Arctocephalus spp. (nt = 13)	Indian	13	5				8	Hofmeyr and Bester, 2002
Pinniped review	Southern	R						Ivar do Sul et al., 2011
	All	R						Gall and Thompson, 2015
Total number of pinnipeds		**1653**	**28**	**16**	**430**	**12**	**631**	
Bottlenose dolphin (*Tursiops truncatus*) (nt = 153)	Atlantic	10	1				9	McFee and Hopkins-Murphy, 2002
		25	10		2	6	5	McFee et al., 2006
		10						Stolen et al., 2013
		107		4	75	25	3	Adimey et al., 2014
		1			1			Wells et al., 1998
		R						Barco et al., 2010
Western grey whale (*Eschrichtius robustus*) (nt = 30)	Pacific	30						Bradford et al., 2009
Minke whale (*Balaenoptera acutarostrata*) (nt = 172)	Atlantic	5						Cassoff et al., 2011
		3						Nelson et al., 2007
		15						Glass et al., 2009
		12						Henry et al., 2014
		27						Cole et al., 2006
		4						Henry et al., 2012
		101						Van Der Hoop et al., 2013
		5						Cassoff et al., 2011
Bryde's whale (*Balaenoptera brydei*) (nt = 4)[a]	Atlantic	2						Van Der Hoop et al., 2012
		1						Cole et al., 2006
		1						Cassoff et al., 2011
North Atlantic right whale (*Eubalaena glacialis*) (nt = 648)	Atlantic	4						Nelson et al., 2007
		4						Henry et al., 2014
		8						Glass et al., 2009
		29						Cole et al., 2006
		2						Henry et al., 2012
		13				10	3	Johnson et al., 2005
		31						Knowlton and Kraus, 2001
		519						Knowlton et al., 2012
		31						Van Der Hoop et al., 2012
		7						Cassoff et al., 2011
Humpback whale (*Megaptera novaeangliae*) (nt = 670)	Atlantic	13						Nelson et al., 2007
		7						Henry et al., 2012
		34						Glass et al., 2009
		74						Cole et al., 2006
		1						Henry et al., 2014
		20			1	7	11	Johnson et al., 2005
		43						Robbins and Mattila, 2001
		49						Robbins and Mattila, 2004
		156						Robbins, 2009
		116						Van Der Hoop et al., 2012
		62	5		26	31		Lyman, 2012
	Pacific	1				1		Moore et al., 2009
		94						Neilson et al., 2009
Fin whale (*Balaenoptera physalus*) (nt = 46)	Atlantic	3						Henry et al., 2014

(continued on next page)

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Table 1 (*continued*)

Species			Ghost gear type					
(nt = Total # of individual species entangled)	Ocean basin	n	UR	NL	ML	RPT	N	Source
		26						Van Der Hoop et al., 2012
		9						Cole et al., 2006
		8						Glass et al., 2009
Blue whale (*Balaenoptera musculus*) (nt = 1)	Atlantic	1						Cole et al., 2006
Sei whale (*Balaenoptera borealis*) (nt = 8)[a]	Atlantic	1						Henry et al., 2012
		1						Glass et al., 2009
		5						Van Der Hoop et al., 2012
	Pacific	1						Lyman, 2012
Sperm whale (*Physeter macrocephalus*) (nt = 12)	Pacific	2						Lyman, 2012
		1					1	Moore et al., 2009
		9						Van Der Hoop et al., 2012
Southern right whale (*Eubalaena australis*) (nt = 13)	Indian	13						Kemper et al., 2008
Finless porpoise(*Neophocaena phocaenoides*) (nt = 1)[a]	Pacific	1			1			Hong et al., 2013
Harbour porpoise (*Phocoena phocoena*) (nt = 1)	Pacific	1					1	Good et al., 2007
Unknown species (nt = 46)	Atlantic	33						Van Der Hoop et al., 2012
		2						Nelson et al., 2007
		5						Glass et al., 2009
		6						Cole et al., 2006
Cetacean review	All	R						Baulch and Perry, 2014
		R						Clapham et al., 1999
		R						Simmonds, 2012
		R						Butterworth et al., 2012
Total number of cetaceans		**1805**	**16**	**4**	**106**	**80**	**33**	
Manatee (*Trichechus manatus latirostris*) (nt = 375)	Atlantic	375		2	286	83	4	Adimey et al., 2014
	Indian	R						Wilcox et al., 2014
Dugong (*Dugong dugon*) (nt = 1)[a]	Indian	1					1	Gunn et al., 2010
Total number of *Sirenia*		**376**	**0**	**2**	**286**	**83**	**5**	
Total number of marine mammals		**3834**	**44**	**22**	**822**	**175**	**669**	

R literature review.

[a] Species not reported in Laist, 1997 review.

changes over time in entanglement rate for particular species. Secondly, our review set a strict criterion to ensure general marine debris was not included in our results while Laist focussed on marine debris as a whole, making direct comparisons between this review and Laist's difficult.

3.2. Gear type

Just over half the ALDFG could not be identified to type because the animal either shed the gear before being found or the incident was recorded from photographs of scarring. 55% (n = 1324) of identified ALDFG were ghost fishing nets and 35% (n = 833) were monofilament lines (ML) externally entangling the animal. Ropes from traps and pots (RTP), unknown rope (UR), and a combination of net and line (NL) collectively accounted for only 10% of entangling gear. However, ML and RTP were the most observed gear types entangling cetaceans (n = 106 and n = 80, respectively) (Fig. 2). Of the 12 reptile publications that could identify gear type, only two reported monofilament line and the rest reported ghost nets as the primary entangling material. Ghost nets are highlighted in this review as being one of the major types of ALDFG affecting pinnipeds (56% of of all recorded pinnipeds were entangled in nets) and sea turtles.

3.3. Bias in results

A distinct geographical bias was noticed in the literature reviewed. Together, the Atlantic (n = 35) and Pacific Oceans (n = 18) dominated the research efforts, totaling 79% of all studies (excluding review papers), with the Indian (n = 11), Southern (n = 2), and Arctic Ocean (n = 0) having considerably fewer published studies. This variation may be due to logistical difficulties combined with a lack of resources in these areas (Fig. 3).

There appeared to be no correlation between the number of publications for a species and the recorded number of entangled individuals (Fig. 4). For example, entangled humpback and North Atlantic right whales appeared in the most publications and also had the highest number of recorded entangled individuals compared to all other species. However manatees, leafscale gulper sharks, and Greenland sharks appeared in very few published reports (one for each species) but an equally high number of entangled individuals were recorded. Spatial distribution between species could lead to a bias in the number of animals found in any given area (i.e., if more animals of a particular species reside in a particular habitat then it would make sense to assume that that species has a higher chance of entanglement over a species rarely found in the same area). If we take this to be true, then the total number of entangled animals may be influenced by survey effort in that region; however, further work needs to be conducted to confirm or deny this hypothesis. It is also unlikely that all entanglement cases were recorded. An unknown number of entangled individuals never make it back to shore or are never observed and are, therefore, less likely to be recorded (Fowler, 1987).

4. Discussion

4.1. Cetaceans and ghost fishing

The analysis of recent literature (from 1997 onwards) highlighted that all animal groups considered in this review are vulnerable to ghost fishing to some degree. The group most commonly recorded as entangled in the literature was cetaceans. However, this may be the result of observer bias, as positive identification of an animal's interaction with ALDFG can only be made when the animal is observed at the surface or stranded on shore. Many observations of cetaceans were only of the tail (peduncle), which is left with scarring once the gear is eventually shed. However, for cetaceans, this means that another source of data (video and photographs) can be used to collect information on previous entanglements. One particular species that is of particular concern is the North Atlantic right whale because of its small population. The International Union for Conservation of Nature (IUCN) Red List of

Table 2
Number of reptiles entangled in ghost gear since Laist (1997). (UR) Unknown Rope,(NL) Net Line combination, (ML) Monofilament Line, (RPT) Rope attached to Pots and Traps, (N) Nets.

Species			Ghost gear type					
(nt = Total # of individual species entangled)	Ocean basin	n	UR	NL	ML	RPT	N	Source
Loggerhead turtle (*Caretta caretta*) (nt = 77)	Atlantic	3			3			Barreiros and Raykov, 2014
		10						López-Jurado et al., 2003
		64						Casale et al., 2010
Olive Ridley (*Lepidochelys olivacea*) (nt = 303)	Indian	163					163	Stelfox and Hudgins, 2015
		53					53	Wilcox et al., 2013
		25					25	Anderson et al., 2009
		44					44	Jensen et al., 2013
	Atlantic	18					18	Santos et al., 2012
Green turtle (*Chelonia mydas*) (nt = 16)	Indian	2					2	Stelfox and Hudgins, 2015
		14					14	Wilcox et al., 2013
Hawksbill turtle (*Eretmochelys imbricata*) (nt = 43)	Indian	6					6	Stelfox and Hudgins, 2015
		2					2	White, 2006
		35					35	Wilcox et al., 2013
Leatherback turtle (*Dermochelys coriacea*) (nt = 3)	Indian	1					1	Stelfox and Hudgins, 2015
		2			1		1	Moore et al., 2009
Flatback turtle (*Natator depressor*) (nt = 3)[a]	Indian	3					3	Wilcox et al., 2013
Saltwater crocodile (*Crocodylus porosus*) (nt = 1)[a]	Indian	1					1	Gunn et al., 2010
Unknown species and literature review (nt = 1041)	Indian	137					137	Wilcox et al., 2014
		17					17	Chanrachkij and Loog-on, 2004
	Atlantic	862						Adimey et al., 2014
		23					23	Orós et al., 2005
	Indian	2					2	White, 2006
	All	R						Nelms et al., 2015
Total number of reptiles		**1487**	**0**	**0**	**4**	**0**	**547**	

R literature review.

[a] Species not included in Laist, 1997 review.

Threatened Species classes the North Atlantic right whale as Endangered (IUCN, 2013) with an estimated population of only 526 individuals (Pettis and Hamilton, 2014). Entanglement in fishing gear is, therefore, a primary threat to this small population.

Johnson et al. (2005) concluded that fixed gear such as lobster pots and set gill nets were the main source of entanglement for whales, a result that is supported by this review. The ropes and lines routinely associated with this gear can easily entangle passing whales; however, we still do not know exactly how much of this gear, once lost or abandoned, interacts with passing whales. As discussed previously, it is difficult to attribute with certainty the source of scarring on a cetacean to ALDFG or active fishing gear (e.g., García-Godos et al., 2013; Robbins, 2009).

Juvenile cetaceans appear to be the most at risk of mortality due to entanglement in comparison to adults (e.g., Knowlton et al., 2012; Lyman, 2012; Cassoff et al., 2011; Zavadil et al., 2007). Analyses of peduncle scars on adult humpback whales in Alaska and the Gulf of Maine suggest that the majority of individuals were entangled at some stage in their life (Neilson et al., 2009; Robbins and Mattila, 2004). However, when comparing the number of individuals that display scarring to the number of reported entanglements, which is low, it is tempting to speculate that larger animals are capable of either shedding gear or a large number of entanglement cases in these regions have gone unrecorded.

4.2. Pinnipeds and ghost fishing

Pinniped-ALDFG interactions have been widely studied (e.g., Sayer, 2015; Allen et al., 2012; Page et al., 2004; Hanni and Pyle, 2000, etc.). Most entanglements occur around the neck or the body of the animal, which reduces their foraging capabilities, eventually leading to strangulation and starvation (Fowler, 1987). Entanglement likely increases drag as the animal moves through the water, further tiring them. Juvenile animals are more often observed entangled in marine debris (e.g., Waluda and Staniland, 2013; Henderson, 2001), which may be a reflection of the curious and playful behavior of younger individuals (Laist, 1997; Fowler, 1987). Recent observations of juvenile grey seals interacting with fragments of monofilament and multifilament fishing net on shore may support this hypothesis (Allen et al., 2012). Female pinnipeds usually give birth to one pup annually and maternal care may last anywhere between four days to three years (Boness and Bowen, 1996). Supplying milk to pups is labor intensive; if females are entangled in ALDFG it may severely affect their haul out capability and ability to care for pups.

The reviewed studies that focused on pinnipeds and ALDFG highlighted three vulnerable species: the Antarctic fur seal, the Californian sea lion, and the grey seal. Grey seals in the British Isles account for around 39% of the world's population and recent research has suggested that the grey seals living on the coast of Wales and SW England are a genetically distinct sub-population of around 5000 individuals (Allen et al., 2012). These facts together raise the concern of the consequence of ALDFG to this sub-population, in particular.

Although we can attempt to quantify the effects of entanglements on certain populations of pinnipeds, estimating mortality due to ghost fishing directly remains difficult because most publications for this group recorded all marine debris items, including plastic packaging, rubber bands, plastic sheet, cloth, six pack holders, etc. together with ALDFG (e.g. Waluda and Staniland, 2013; Zavadil et al., 2007).

4.3. Manatee and dugong and ghost fishing

Only three publications documented the effect of ghost fishing or ALDFG on manatees and dugongs, but one study did record a large number of entangled manatees (n = 375) (Adimey et al., 2014).

As with most species in this review, it is difficult to make any conclusions about the effect of ALDFG on manatee populations due to the lack of research directed to this species. Manatees occupy both freshwater and coastal marine environments and sport fishers encroach on both environments, increasing the chance of this species' interaction with derelict gear. Globally there has been an increase in sport fishing and results from Adimey et al. (2014) showed that monofilament lines and hooks are the main debris that manatees interact with, either through ingestion or entanglement. However, there is not yet enough evidence to suggest that hook and line is the only significant type of ALDFG posing a risk to this species.

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Table 3
Number of elasmobranchs entangled in ghost gear and multiple species reviews since Laist (1997). (UR) Unknown Rope, (NL) Net Line combination, (ML) Monofilament Line, (RPT) Rope attached to Pots and Traps, (N) Nets.

Species (nt = Total # of individual species entangled)	Ocean Basin	n	Ghost gear type UR	NL	ML	RPT	N	Source
Leafscale gulper shark (*Centrophorous squamosus*) (nt = 6.2 t)[a]	Atlantic	6.2 ton[b]					6.2 ton	Large et al., 2009
Greenland shark (*Somniosus microcephalus*) (nt = 1 t)[a]	Atlantic	1 ton[b]					1 ton	Large et al., 2009
Nurse shark (*Ginglymostoma cirratum*) (nt = 2)[a]	Atlantic	2					2	López-Jurado et al., 2003
Small tooth sawfish (*Pristis pectinata*) (nt = 12)[a]	Atlantic	12	1		7	3	1	Seitz and Poulakis, 2006
Spiny dogfish shark (*Squalus acanthias*) (nt = 103)[a]	Pacific	103					103	Good et al., 2010
Six gill shark (*Hexanchus griseus*) (nt = 1)[a]	Pacific	1					1	Good et al., 2010
Carcharhinus spp. (nt = 1)	Indian	1					1	White, 2006
Total number of elasmobranchs		**119**	**1**	**0**	**7**	**3**	**108**	
Review all species	All	R						Katsanevakis, 2008
Review all species	All	R						Gregory, 2009
Review all species	All	R						Macfadyen et al., 2009
Review all species	All	R						Shaughnessy et al., 2003
Review all species	All	R						Uhlmann and Broadhurst, 2015

[a] Species not included in Laist, 1997 review.
[b] Number of entangled individuals recorded by weight in tons (t) not by count. This data was excluded from all graphs.

4.4. Marine turtles and ghost fishing

The group with the second highest entanglement rate in this review was reptiles, in particular, marine turtles. Marine turtle-ALDFG interactions are of particular concern because ALDFG presents a significant problem in three key turtle habitats: nesting beaches, reefs, and the open ocean. ALDFG on nesting beaches may act as obstacles for both nesting females and hatchlings. Hatchlings may become entangled preventing them from ever making it into the sea (Ramos et al., 2015; Carr, 1987). Furthermore, wind and sand movements may bury ALDFG over time resulting in nesting females digging into net material (M. Stelfox, pers. obs.). Monofilament fishing nets, in particular, pose a significant risk to sea turtles on coral reefs as monofilament nets are very thin and they are likely undetectable to the turtles (M. Stelfox, pers. obs. in Maldives and Pakistan). ALDFG floating in the open ocean are also of particular concern, as sea turtles spend their first three to five years floating with oceanic currents and many species migrate long distances across the open ocean between breeding and foraging grounds. It is likely that during this time they come into contact with marine debris that follows the same currents (Carr, 1987). Floating algal mats on the sea surface act as an ideal substrate for sedentary animals, such as hydrozoa, bryozoan, and barnacles, to attach and start growing. ALDFG behaves in the same way as these algal mats. Animals, such as turtles, are often attracted to these floating mats and/or ALDFG in search of shelter and food (Carr, 1987). Of the seven species of sea turtle that exist globally, two species are known to spend more of their adult years in oceanic waters: the Olive Ridley (*Lepidochelys olivacea*) and the leatherback (*Dermochelys coriacea*). Other species are opportunistic feeders during their juvenile life stage but switch to benthic feeding in neritic zones as they move into adulthood (Carr, 1987). Therefore, leatherbacks and Olive Ridley turtles probably have a higher chance of encountering floating ALDFG, as they inhabit the open ocean for more of their life cycle compared to other turtle species.

One of the few studies that addressed turtle entanglement in ALDFG was a spatial risk analyses conducted by Wilcox et al. (2013). The authors combined oceanic drift and beach clean data with known distributions of turtle species in Australia in order to determine entanglement locations and level of risk. Results highlighted that entanglements occurred in areas with both high ghost net density and high turtle density. Stranding records where turtles were observed dead or alive offered a good opportunity to conduct further research and validate Wilcox et al.'s model predictions. Two further studies (Santos et al., 2012; Casale et al., 2010) in Brazil found that the majority of entangled Olive Ridley turtles were sub-adults or adults. Nelms et al. (2015) suggested that this could be because juveniles have a greater chance of escaping the ALDFG as they are smaller or that nets were impacting breeding or migrating areas and not impacting juvenile habitats. Conversely, recent data on entangled Olive Ridley turtles in the Maldives found that the majority of entangled turtles were juveniles; however, the reason for this remains unclear and needs to be explored in greater detail (Stelfox and Hudgins, 2015). This review clearly highlights the dangers of ghost nets in comparison to other ALDFG for marine turtles.

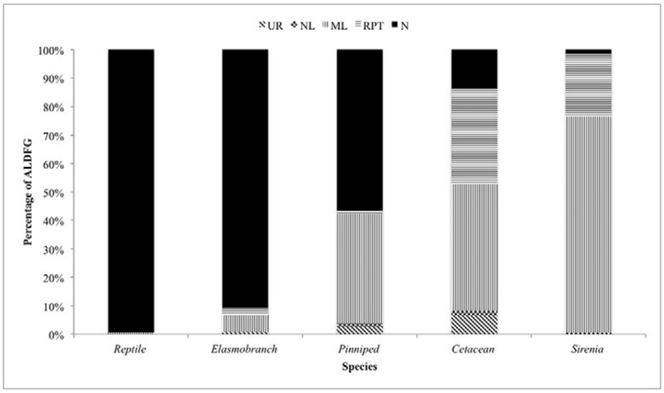

Fig. 2. Percentage of gear type entangling reptiles, pinnipeds, cetaceans, sirenia and elasmobranchs. (UR) Unknown Rope, (NL) Net Line combination, (ML) Monofilament Line, (RPT) Rope attached to Pots and Traps, (N) Nets.

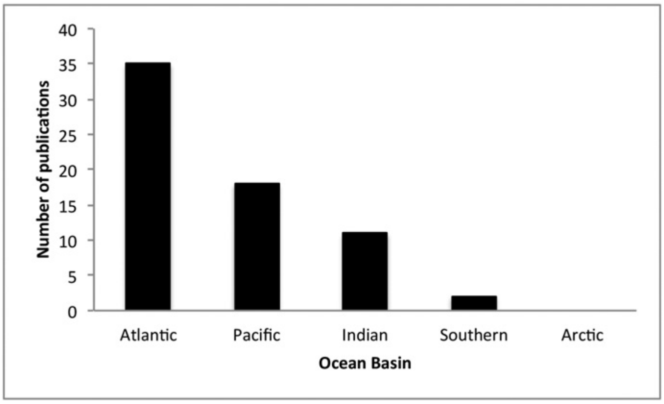

Fig. 3. Number of publications per ocean basin.

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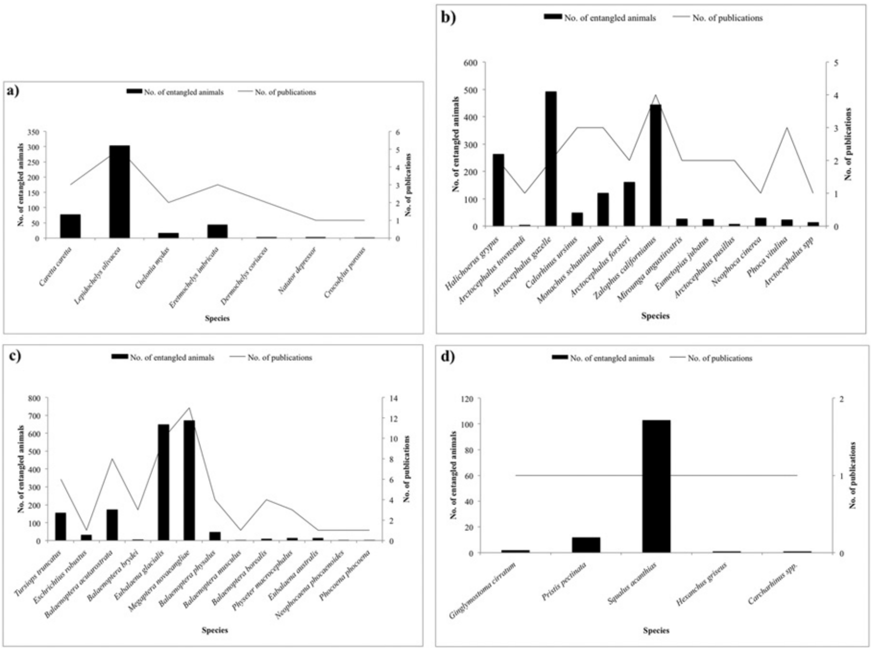

Fig. 4. Number of entangled animals a) reptile, b) pinniped, c) cetacean, and d) elasmobranch plotted against the number of publications for each species, excluding manatees and dugongs.

4.5. Elasmobranchs and ghost fishing

This group of organisms appears to be either less vulnerable to entanglement or, more likely, fewer studies have assessed the level of impact of ghost fishing on these organisms. Although only a few studies have been conducted and published, relatively high numbers of entangled sharks and rays were noted in these publications. Certain species may be more vulnerable to ALDFG than others. For example, the unique elongated, toothed rostrum of the small tooth sawfish (*Pristis pectinata*) may put this species at higher risk of entanglement in ghost nets. Although not directly fitting into the remit of this review, bycatch of sawfish is said to be the probable cause of declining populations of this species, which has resulted in the sawfish being assigned Critical Endangered status by the IUCN (IUCN, 2013).

The direct effect of ALDFG on shark populations remains unknown due to the lack of data. However, the limited number of studies that have been conducted on shark species suggests that ALDFG could be a significant cause of mortality. Top predators, such as sharks, are known to be attracted to floating mats of algae or debris as these mats are home to many of their prey, who in turn are in search of shelter and food. Indeed the fishing industry actually exploits this phenomenon, with purse seine and pole and line fisheries using artificial floating devices known as Fish Aggregating Devices (or FADs) to attract their catch. FADs usually consist of a floating frame with a marker on the surface and long aggregators (nets) hanging underneath. While attracting their target species, such as tuna, many other non-targeted species are also caught. Studies have shown that silky sharks (*Carcharhinus falciformis*) and oceanic white tip sharks (*Carcharhinus longimanus*) together make up around 90% of the bycatch from this type of fishing (Gilman, 2011). One of the dangers of FADs is that once they are lost they continue to fish at full potential. The Indian Ocean Tuna Commission (IOTC) are aware of this problem and that it can undermine the efficiency of conservation and management measures that they have put in place. However, retrieval of FADs in the Indian Ocean is not yet regulated. Ghost fishing of silky sharks has impacted abundance and catch rate, and the true effect that the purse seiners have had, and continue to have, on this species is severely underrepresented (IOTC, 2013).

4.6. Management and mitigation

Numerous tactics have been implemented to address the issue of ghost gear and it has been suggested that the problem can be approached in two ways: by using preventative or curative measures (Brown and Macfadyen, 2007). Arguments can be made for and against the various methods and it is evident that gear retrieval is the main curative tool practiced globally (e.g., Large et al., 2009; Brown and Macfadyen, 2007; Guillory, 2001). In deep water, ghost gear can be recovered by using “creepers”; machinery that is towed behind fishing boats. The Norwegian creeper is one such example. It is a three metre long bar with three dredges attached by a hinge. It is used to scrape the seabed and snag any abandoned nets (Large et al., 2009). Other creeper designs exist but they tend to apply the same principles of snagging. This method is only effective when a certain level of prior knowledge is available. This includes where the proposed gear lies, the amount of gear, the bottom topography, and the presence of any sensitive habitats. Bad weather can prevent retrieval attempts altogether. Furthermore, a study by Cefas (2006) noted that no full gill nets were ever recorded when this practice was undertaken. This begs the question whether creepers are actually capable of retrieving full nets or if the creeper simply rips through the entire net only retrieving pieces at a time. To the authors' knowledge, no reliable in-water observations exist to confirm or contradict this theory. Gear retrieval on shallow reefs and wrecks requires a different method of retrieval. Often divers are used in such instances, as done by various NGOs such as Ghost Fishing, Olive Ridley Project, North West Straits, Project Aware, etc. Limitations do, however, exist here as well including dive limits, depth, bottom time, human safety (chance of entanglement), and weather conditions.

Regardless of the method of removal, it has been suggested that detailed cost-benefit analyses should be conducted with regard to measuring the effectiveness of different methods of dealing with ALDFG. This would assist in identifying what methods are most effective, which could help navigate managerial decisions (Gilardi et al., 2010). In addition to the removal of ALDFG, the importance of education of fishers must also be mentioned. For instance, a fisher incentive program to

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deposit old or damaged nets at designated collection points was first met with resistance in South Korea; but, after educational workshops, the program quickly became a success with Incheon City collecting 18,000 tons of derelict gear in only four years (Cho, 2005). However, it was also highlighted that this program may have stopped if no further financial support was given for fishers to dispose of nets correctly. Similarly, in northern Australia a combination of building trust, providing resources, and building capacity for rangers by actively listening and giving feedback to indigenous communities, resulted in the recovery of 5532 ghost nets. Of these, 45% were identified back to their original source fishery (Gunn et al., 2010), which allowed for preventative measures to be put into place.

Identifying where fishing gear was initially lost is a particularly important challenge facing the study and management of ALDFG. Finding ghost gear in vast oceans can be difficult but research has shown that various sensors, such as video, thermal imaging, and radar used in manned or unmanned aircraft can be effective tools to locate ALDFG (Pichel et al., 2012). Alternatively, Mace (2012) suggested that using sensors to detect eddies and convergence zones in the open ocean may be a more effective way to find ALDFG conglomerations. However, sensors can be expensive and their deployment subject to weather conditions. Furthermore, it is recognised that sensors cannot perform all necessary steps from detection to removal (e.g., Pichel et al., 2012; Mace, 2012). Datasets obtained from Lagrangian drifters have helped to identify marine debris accumulation hotspots over time (Maximenko et al., 2012); however, although this is a useful tool for retrieval operations, it does not help to identify where the ALDFG initially came from. Drifters also have a very limited battery life and are rarely deployed from coastal regions (Martinez et al., 2009). The same study noted that geostrophic currents and Ekman drift have the ability to influence ALDFG drift patterns. For example, two tagged Dungeness crab traps deployed from the state of Oregon were eventually recovered at two separate locations in the NW Hawaiian islands four years later (Ebbesmeyer et al., 2012). Ocean Surface Current Simulator (OSCURS) models, combined with estimated loss dates acquired from interviews of the crab pot owners, allowed for potential drifting paths to be created. This is a good example of how numerical data can be used to identify drift patterns. In addition, it highlights the importance of gear marking in making precise identification of ALDFG back to its relevant fisheries. More research into detachment from buoy rate, vertical profile, and rates of fouling are needed to understand the effect that these may have on drifting patterns (McElwee and Morishige, 2010). Furthermore, the drifting patterns of floating ALDFG may be subject to winds, currents, and weather and the exact effects that these have on drifting ALDFG is still unknown (McElwee and Morishige, 2010). Tagging ALDFG may help confirm the accuracy of predictive models.

5. Conclusions

Though much literature exists on entanglement of many animal species in marine debris, linking ALDFG specifically to these entanglements (versus active fishing gear or general marine debris) is a relatively new field of study with very few published papers focussed on this topic. There is a strong need for more research into the effects of ghost fishing at the population level and more focussed research that explores preventative solutions. We suggest that additional research be directed to the Indian, Southern, and Arctic Oceans, where gaps in data currently exist. Animal groups that are currently underrepresented in the dataset include manatees, dugongs, sharks, and rays. Better identification of entangled animals to species level is also required.

Carefully separating ALDFG from general marine debris during data analyses could help accurately quantify the problem. Most studies on pinnipeds and cetaceans estimated entanglement rates by combining general marine debris with ALDFG or by looking at scarring in photos. Though some general marine debris may have come from the fishing industry, this highlights the importance of marking all fishing equipment to confirm its source. We suggest that ALDFG be treated separately from general marine debris, as fisheries need a different managerial approach when compared to debris originating from passing tourist or cruise boats. Due to its nature, accurate studies on the effects of ALDFG on marine mammals are logistically difficult since observations rely on the animal bringing the entangling material back to land, the animal being sighted entangled at sea, or analyzing scars on the animal's body to identify entanglements. Moreover, it is not always possible to make the distinction between interaction with ALDFG and interaction with active fishing gear, especially in large animals, such as cetaceans. In instances where fishing gear can be distinguished as the cause of entanglement, comparisons should be made to existing data from fishing interactions to roughly determine the number of animals interacting with ALDFG versus those interacting with active fishing operations. Education of fishers and observers is an important first step to increase this type of data recording.

During research for this review it became clear that entanglement records for all species are scattered and sparse. Many institutes, biologists, diving groups, NGOs, and local governments have information on ghost fishing incidences, but these incidences are rarely published and the issue is likely underrepresented in published literature. Many institutions are working independently to collect this information; however, regional databases for each major ocean basin and records of entanglements for each major animal group in those regions would provide consistent data and greatly improve knowledge on ALDFG interactions. Data collection in the future should follow a minimum set of global criteria, which would help direct future studies and allow for comparisons to be made in order to identify hotspot areas for ALDFG production and marine life interactions. It would also help direct effort and focus funding to particular sites.

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