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REVIEW

A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action

Emily M. Duncan[1,2,3,*], Zara L. R. Botterell[1,*], Annette C. Broderick[1], Tamara S. Galloway[2], Penelope K. Lindeque[3], Ana Nuno[1], Brendan J. Godley[1,**]

[1]Marine Turtle Research Group, Centre for Ecology and Conservation, University of Exeter, Penryn TR10 9FE, UK
[2]Biosciences, College of Life and Environmental Sciences, Geoffrey Pope Building, University of Exeter, Stocker Road, Exeter EX4 4QD, UK
[3]Marine Ecology and Biodiversity, Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, UK

ABSTRACT: Entanglement in anthropogenic debris poses a threat to marine wildlife. Although this is recognised as a cause of marine turtle mortality, there remain quantitative knowledge gaps on entanglement rates and population implications. We provide a global summary of this issue in this taxon using a mixed methods approach, including a literature review and expert opinions from conservation scientists and practitioners worldwide. The literature review yielded 23 reports of marine turtle entanglement in anthropogenic debris, which included records for 6 species, in all ocean basins. Our experts reported the occurrence of marine turtles found entangled across all species, life stages and ocean basins, with suggestions of particular vulnerability in pelagic juvenile life stages. Numbers of stranded turtles encountered by our 106 respondents were in the thousands per year, with 5.5% of turtles encountered entangled; 90.6% of these dead. Of our experts questioned, 84% consider that this issue could be causing population level effects in some areas. Lost or discarded fishing materials, known as 'ghost gear', contributed to the majority of reported entanglements with debris from land-based sources in the distinct minority. Surveyed experts rated entanglement a greater threat to marine turtles than oil pollution, climate change and direct exploitation but less of a threat than plastic ingestion and fisheries bycatch. The challenges, research needs and priority actions facing marine turtle entanglement are discussed as pathways to begin to resolve and further understand the issue. Collaboration among stakeholder groups such as strandings networks, the fisheries sector and the scientific community will facilitate the development of mitigating actions.

KEY WORDS: Conservation · Entanglement · Ghost fishing · Marine debris · Plastic pollution · Sea turtle · Strandings

INTRODUCTION

Marine plastic pollution

Anthropogenic materials, the majority of them plastic, are accumulating on the surface of the oceans, in the water column and on the seabed (Thompson et al. 2004). The durability of plastic means that it may persist for centuries (Barnes et al. 2009). It is estimated that 4.8 to 12.7 million tonnes of plastic waste could be entering the marine environment annually (Jambeck et al. 2015). Over 700 marine species have been demonstrated to interact with marine plastic pollution (Gall & Thompson 2015), which presents a risk to ani-

*These authors contributed equally to this work
**Corresponding author: b.j.godley@exeter.ac.uk

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mals through ingestion, entanglement, degradation of key habitats and wider ecosystem effects (Nelms et al. 2016). Megafauna such as marine turtles with complex life histories and highly mobile behaviour are particularly vulnerable to its impacts (Schuyler et al. 2014).

Entanglement in marine litter

Entanglement in plastic debris is recognised as a major risk for many marine species (Laist 1987, Vegter et al. 2014). This has become sufficiently high profile that the European Union's Marine Strategy Framework Directive (MSFD) Technical Subgroup on Marine Litter has announced that it will develop a dedicated monitoring protocol for its next report (MSFD GES Technical Subgroup on Marine Litter 2011). Entanglement has the potential to cause a range of fatal and non-fatal impacts such as serious wounds leading to maiming, amputation, increased drag, restricted movement or choking (Votier et al. 2011, Barreiros & Raykov 2014, Lawson et al. 2015).

Types of marine debris causing entanglement

The debris causing this entanglement falls into 2 broad categories. Firstly, hundreds of tons of fishing gear are lost, abandoned or discarded annually, forming 'ghost gear' which passively drifts over large distances, sometimes indiscriminately 'fishing' marine organisms (Macfadyen et al. 2009, Wilcox et al. 2013). This gear is commonly made of non-biodegradable synthetic material that will persist in the marine environment, potentially become biofouled by marine organisms and act as a fish aggregating device (FAD), attracting both grazers and predators such as marine turtles (Filmalter et al. 2013, Wilcox et al. 2013). It is important to distinguish here between 'entanglement' and 'bycatch'. Bycatch can be defined as unselective catch of either unused or unmanaged species during fishing, with a particular focus on 'active' gear, whereas ghost gear can be defined as equipment of which the fisher has lost operational control (Smolowitz 1978, Davies et al. 2009). Therefore, here we consider animals caught in passive ghost fishing gear as entangled, not bycaught. Secondly, there have also been reports of entanglement in litter from land-based sources (Chatto 1995, Bentivegna 1995, Santos et al. 2015). In this review we do not include bycaught turtles — only those that have become entangled in passive anthropogenic debris such as ghost gear or land-based debris.

Current knowledge gaps regarding turtle entanglement

Despite turtle entanglement being recognised as one of the major sources of turtle mortality in northern Australia and the Mediterranean, there is a quantitative knowledge gap with respect to the entanglement rates and possible implications in terms of global populations (Casale et al. 2010, Wilcox et al. 2013, Camedda et al. 2014, Gilman et al. 2016). A recent literature review by Nelms et al. (2016) returned only 9 peer-reviewed publications on marine debris entanglement and turtles (Bentivegna 1995, Chatto 1995, López-Jurado et al. 2003, Casale et al. 2010, Santos et al. 2012, Jensen et al. 2013, Wilcox et al. 2013, 2015, Barreiros & Raykov 2014). Of these, 7 were focused on ghost fishing gear, highlighting the distinct lack of knowledge of entanglement in debris from land-based sources. Even fewer of these studies focused on the potential variable susceptibility among life stages or species, with only one paper, Santos et al. (2012), reporting that the majority of entangled olive ridley turtles *Lepidochelys olivacea* on the Brazilian islands of Fernando de Noronha and Atol das Rocas were sub-adults and adults.

Research rationale in terms of marine turtles and pollution

In terms of global research priorities for sea turtle conservation and management, understanding the impact of pollution is considered of high importance (Hamann et al. 2010, Rees et al. 2016). To evaluate this effectively, the impact of anthropogenic debris, specifically, must be considered at a species and population level. Additionally, it is important to understand the variation in entanglement rates among species and life stages to better evaluate vulnerability and the frequency of interactions with different debris types (Nelms et al. 2016). Once these have been established, opportunities for delivering effective education and awareness can be given or other mitigation planned (Vegter et al. 2014).

Here, we define marine turtle entanglement as 'the process under which a marine turtle becomes entwined or trapped within anthropogenic materials.' We sought to include discarded fishing gear (ghost fishing) as well as land-based sources. The aim of this study was to (1) review existing, and obtain new, reports of the occurrence and global spatial distribution of marine turtle entanglement; (2) gain insights into patterns of species, life stage and debris type involved across entanglement cases; and (3) glean an insight into the change in prevalence of marine debris entanglement over time. To address these, a mixed methods approach was employed, involving a literature review and an elicitation of expert opinions. Given the difficulty of acquiring robust standardised data, this review is intended to highlight the value of mixed methods as a first step to understand complex conservation issues, and to provide suggestive yet relevant indications as to the scale of the threat of entanglement to marine turtles.

MATERIALS AND METHODS

Literature review

In January 2016 and again in June 2017 (during the manuscript review process), all relevant literature was reviewed that may have contained records of marine turtle entanglement. ISI Web of Knowledge, Google Scholar and the Marine Turtle Newsletter (www.seaturtle.org) were searched for the terms 'entanglement', 'entrapment', 'ensnare' or 'ghost fishing' and 'turtle'. The first 200 results were viewed, with results very rarely fulfilling the criteria after the first 20; spurious hits were ignored and all relevant references were recorded and investigated.

Elicitation of expert opinions

During the period 1–30 April 2016, an online questionnaire survey was conducted to investigate 3 main topics of interest: (1) the occurrence and global spatial distribution of sea turtle entanglement; (2) species, life stage and debris type involved; and (3) the change in entanglement prevalence over time. A total of 20 questions requiring both open and closed responses from a range of experts were used to obtain insight into the scale of marine turtle entanglement. We clearly explained to the respondents the definition of 'marine turtle entanglement' specific to this study. Grid-like responses and Likert scales, offering potential answers from a range of ordinal options, were used to aid in achieving a quantitative assessment of the issues (Elaine & Seaman 2007) (see Box S1 in the Supplement at www.int-res.com/articles/suppl/n034p431_supp.pdf).

Potential participants for this questionnaire were identified from lead authorship of papers compiled in the recent review on the effects of marine plastic debris on turtles from Nelms et al. (2016), and our review due to their involvement in research into marine debris. From reviewing the few published reports, it was apparent that governmental stranding networks, sea turtle rescue and rehabilitation centres and conservation projects may also hold many unpublished records of entanglement occurrence. A comprehensive list of such organisations from seaturtle.org (www.seaturtle.org/groups/; accessed 24 March 2016) was used to find more expert contacts to participate in the questionnaire. Additionally, considering the aim of attaining an appropriate number of respondents while avoiding potential sampling biases due to researchers' personal networks and perceptions about the issue (Newing 2011), we employed respondent-driven sampling; this purposive sampling approach involves requesting those directly contacted to recruit additional participants among colleagues, peers and other organisations that may have knowledge of additional records of marine turtle entanglement.

From this first questionnaire, an initial report was produced and sent to the expert respondents (n = 106) to share the results and thoughts that arose from the first questionnaire. This included 8 initial figures produced from the data given by respondents in the original questionnaire to aid feedback of our results (these were draft versions of Figs. 2, 3 & 4). Following this, during the period 24 May to 30 June 2016, a follow-up questionnaire survey was conducted with the expert participants of the first questionnaire survey who were then invited to comment and answer 10 open and closed questions (see Box S2 in the Supplement). This aimed to further understand the challenges, future requirements (both research and priority actions) and perceptions of the likelihood of population level effects of marine turtle entanglement. In this second questionnaire, respondents were asked to comment on our initial results and to provide suggestions on future knowledge gains and actions. Their answers were categorised using an inductive approach; summary themes were identified through the process of directly examining the data (Elo & Kyngäs 2008), instead of having predefined categories.

RESULTS

Literature review

Our literature search yielded 23 reports regarding entanglement in multiple species of marine turtles, the majority of which were peer-reviewed publications (n = 17) with additional grey literature reports (n = 6). Species included loggerhead *Caretta caretta* (n = 7), green *Chelonia mydas* (n = 7), leatherback *Dermochelys coriacea* (n = 5), hawksbill *Eretmochelys imbricata* (n = 5), olive ridley *Lepidochelys olivacea* (n = 9) and flatback *Natator depressus* (n = 2). There were no records for Kemp's ridley *Lepidochelys kempii* (Table 1). Of these publications, 18 reported entanglement due to ghost fishing or fisheries materials and 7 recorded entanglement in land-based plastic debris; 7 publications reported the size range and life stage of the entangled turtles. These publications highlighted a range of impacts of entanglement, such as serious wounds leading to maiming, amputation or death, increased drag, restricted movement or choking that were further illustrated by photographs from collaborating experts (Fig. 1).

Elicitation of expert opinions

Survey response rates and demographics

From an estimated pool of ca. 500 potential contacts, the 'Marine Turtle Entanglement Questionnaire' was received and completed by a total of 106 expert respondents from 43 countries. However, due to the anonymous nature of the survey and the potential augmentation from the use of respondent-driven sampling, it is not possible to determine how many of those initially contacted took part in the survey. All ocean basins were covered; the respondents' main oceanic region of work was given as: Atlantic (34.8%; n = 39), Pacific (18.9%; n = 20), Caribbean (25.5%; n = 27), Mediterranean (9.4%; n = 10) and Indian (9.4%; n = 10). Respondents experienced a wide

Fig. 1. Impacts of marine turtle entanglement: (a) live leatherback turtle entangled in fishing ropes which increases drag, Grenada 2014 (photo: Kate Charles, Ocean Spirits); (b) drowned green turtle entangled in ghost nets in Uruguay (photo: Karumbe); (c) live hawksbill turtle entangled in fishing material constricting shell growth, Kaeyama Island, Japan 2001 (photo: Sea Turtle Association of Japan); (d) live hawksbill turtle with anthropogenic debris wrapped around front left flipper constricting usage of limb which could lead to amputation and infection, Kaeyama Island, Japan 2015 (photo: Sea Turtle Association of Japan). All photos used with express permission

Table 1. Summary of all studies on entanglement of marine turtles in plastic debris. CCL: curved carapace length (cm); na: not available

Ocean basin/ Species	Study area	Reference	Year of study	N	CCL range	Pelagic juvenile	Neritic juvenile	Adult	Debris type
Loggerhead turtle *Caretta caretta*									
Atlantic Ocean	Northeastern (Boa Vista, Cape Verde Islands)	López-Jurado et al. (2003)	2001	10	62.0–89.0	X	✓	✓	Fishing
	Northeastern (Terceira Island, Azores)	Barreiros & Raykov (2014)	2004 –2008	3	37.3–64.1	X	✓	✓	Fishing/land-based
	Northeastern (Gran Canaria, Spain)	Orós et al. (2016)	1998–2014	945	Unknown	✓	✓	✓	Fishing/land-based
Mediterranean Sea	Tyrrhenian sea (Island of Panarea, Sicily)	Bentivegna (1995)	1994	1	48.5	X	✓	X	Land-based
	Central Mediterranean (Italy)	Casale et al. (2010)	1980–2008	226	3.8–97.0	✓	✓	✓	Fishing/land-based
	South Tyrrhenian sea	Blasi & Mattei (2017)	2009–2013	5	Unknown	na	na	na	Fishing/land-based
Global		Balazs (1985)	1967–1984	5	Unknown	✓	✓	✓	Fishing
Green turtle *Chelonia mydas*									
Indian Ocean	North (Maldives)	Stelfox & Hudgins (2015)	2013–2015	2	Unknown	na	na	na	Fishing
	Northeastern (Darwin, Australia)	Chatto (1995)	1994	1	35	X	✓	X	Fishing
	Northeastern (Australia)	Wilcox et al. (2013)	2005–2009	14	Unknown	na	na	na	Fishing
Global		Balazs (1985)	1967–1984	24	Unknown	✓	✓	✓	Fishing (21), land-based (3)
Pacific Ocean	Central (Hawaii)	Francke et al. (2014)	2013–2014	51	Unknown	✓	✓	✓	Fishing
		Chaloupka et al. (2008)	1982–2003	43	20.0–100.0	✓	✓	✓	Fishing
Caribbean Sea	Southeastern (Venezuela)	Barrios-Garrido et al. (2013)	2013	1	Unknown	na	na	na	Fishing
Leatherback turtle *Dermochelys coriacea*									
Indian Ocean	North (Maldives)	Stelfox & Hudgins (2015)	2013–2015	1	Unknown	na	na	na	Fishing
Pacific Ocean	Northeastern (USA)	Moore et al. (2009)	2001–2005	1	Unknown	na	na	na	Fishing
Atlantic Ocean	Northwestern (USA)	Hunt et al. (2016)	2007–2013	8	Unknown	na	na	na	Fishing
	Northwestern (USA)	Innis et al. (2010)	2007–2008	7	Unknown	na	na	na	Fishing
Global		Balazs (1985)	1967–1984	5	Unknown	X	X	✓	Fishing
Hawksbill turtle *Eretmochelys imbricata*									
Indian Ocean	North (Maldives)	Stelfox & Hudgins (2015)	2013–2015	6	Unknown	X	✓	X	Fishing
	Northeastern (Darwin, Australia)	Chatto (1995)	1994	1	32.5	X	✓	X	Fishing
	Northeastern (Australia)	Wilcox et al. (2013)	2005–2009	35	Unknown	na	na	na	Fishing
	Northeastern (Northern Territory, Australia)	White (2006)	2004	2	Unknown	X	✓	X	Fishing
Global		Balazs (1985)	1967–1984	9	Unknown	✓	✓	✓	Fishing (8), land-based (1)
Olive ridley turtle *Lepidochelys olivacea*									
Indian Ocean	North (Maldives)	Anderson et al. (2009)	1998–2007	25	10.0–61.0	✓	✓	X	Fishing (22), land-based (3)
	North (Maldives)	Stelfox & Hudgins (2015)	2013–2015	163	Unknown	✓	✓	✓	Fishing
	Northeastern (McCluer Island, Australia)	Jensen et al. (2013)	Unknown	44	Unknown	na	na	na	Fishing
	Northeastern (Australia)	Wilcox et al. (2013)	2005–2009	53	Unknown	na	na	na	Fishing
	Northeastern (Darwin, Australia)	Chatto (1995)	1994	2	64	X	X	✓	Fishing
	Northwestern (Seychelles)	Remie & Mortimer (2007)	2007	1	Unknown	X	✓	X	Unspecified
Atlantic Ocean	Southwestern (Brazil)	Santos et al. (2012)	1996–2011	18	2.01–80.0	X	✓	✓	Fishing
Global		Balazs (1985)	1967–1984	7	Unknown	✓	✓	✓	Fishing
Pacific Ocean	Central (Hawaii)	Francke et al. (2014)	2013–2014	1	Unknown	na	na	na	Fishing
Flatback turtle *Natator depressus*									
Indian Ocean	Northeastern (Darwin, Australia)	Chatto (1995)	1994	1	25.5	X	✓	X	Land-based
	Northeastern (Australia)	Wilcox et al. (2013)	2005–2009	3	Unknown	na	na	na	Fishing
Multiple									
Indian Ocean	Northeastern (Australia)	Wilcox et al. (2015)	2005–2012	336	Unknown	na	na	na	Fishing
Pacific Ocean	Southwestern (Australia)	Meager & Limpus (2012)	2011	5	Unknown	na	na	na	Fishing

range in the number of annual stranding cases in their respective study sites (annual maxima given in the survey; mean ± SE = 239.9 ± 71.7, range = 0 to 4100, n = 97) but in total, through addition of the respondents' answers, they are responsible for attending an estimated 23 000 stranded turtles yr^{-1}. Respondents also generally had many years of experience dealing with and reporting marine turtle strandings (range = 2 to 42 yr, mean ± SE = 15.6 ± 1.1, n = 98), confirming them as having relevant experience to answer the survey. The second follow-up questionnaire sent to all respondents (n = 106) received 63 responses with respondents from 31 countries.

Rates of entanglement

A majority of respondents (84.3%; n = 101) had encountered cases in which turtles were entangled in anthropogenic debris. When broken down by species, the proportion of stranded turtles that were entangled did not differ significantly (Kruskal-Wallis: χ^2 = 4.59, df = 6, p = 0.59) (Fig. 2a). There was a low percentage incidence for all species, with the grand median rate of 5.5%, although there was considerable inter- and intraspecific variation, with incidences in different responses ranging from 0 to 95.5%. In terms of the proportion of marine turtles alive when found entangled, there were significant interspecific differences (Kruskal-Wallis: χ^2 = 19.62, df = 6, p = 0.003). The proportion found alive (grand median = 9.4%) was significantly higher in green (25.5%) and loggerhead (15.5%) turtles than in all other species (5.5%) (Fig. 2b).

Entanglement rates also differed amongst life stages for each species. Whilst respondents indicated that all life stages of each species had been affected by entanglement, the results suggested adults were most impacted in leatherback and olive ridley turtles, whereas for the remaining species respondents indicated a higher rate of entanglement in juveniles (pelagic and neritic; Fig. 3).

When considering this issue over time (over the last 10 yr), a similar proportion of respondents (35.8% of 106) thought the prevalence of entanglement had increased or remained the same, while the remainder thought it had decreased (8.5%) or were unsure (19.8%). Among those respondents that noted an increase, some (n = 4) suggested that this may be caused by an increase in reporting and awareness, while others (n = 9) indicated the development of coastal fishing activities might be a factor. When asked to consider a shorter time period (the last 5 yr), the majority of respondents believed that the prevalence of entanglement they had experienced had remained stable (51.9%), whilst the others thought it had increased (29.2%), decreased (3.8%) or were not sure (15.1%).

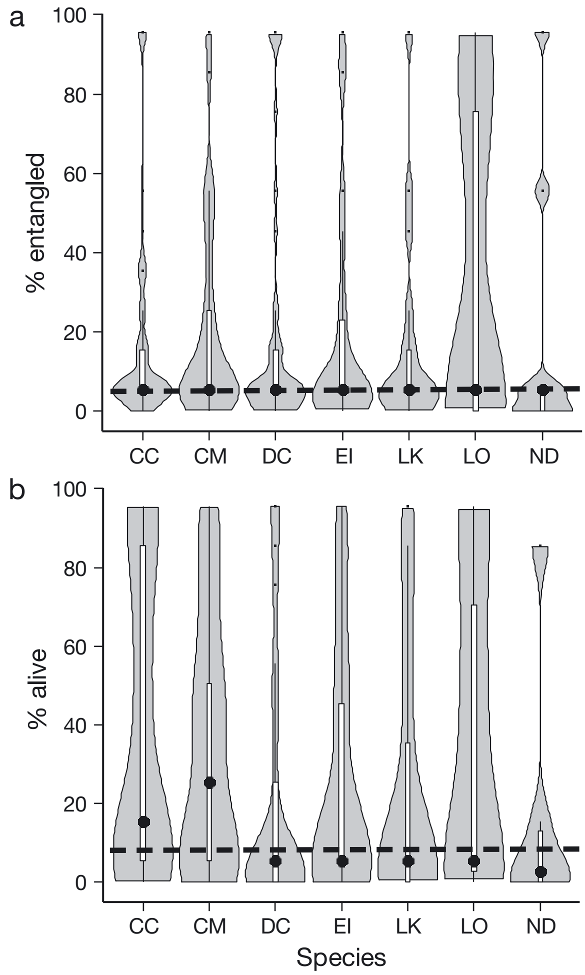

Fig. 2. Inter-species comparison of the proportion of: (a) stranded individuals found entangled and (b) individuals found alive when discovered entangled. Violin plots show the kernel density of data at different values. Median (black dot) with interquartile range boxplot (black/white) and grand median (black dashed line). Turtle species abbreviations: CC: loggerhead *Caretta caretta*; CM: green *Chelonia mydas*; DC: leatherback *Dermochelys coriacea*; EI: hawksbill *Eretmochelys imbricata*; LK: Kemp's ridley *Lepidochelys kempii*; LO: olive ridley *Lepidochelys olivacea*; ND: flatback turtle *Natator depressus*

Entanglement materials

The majority of entanglements recorded were with lost/discarded fishing gear (Fig. 4). A clear distinction was made between 'active' and 'lost/discarded'

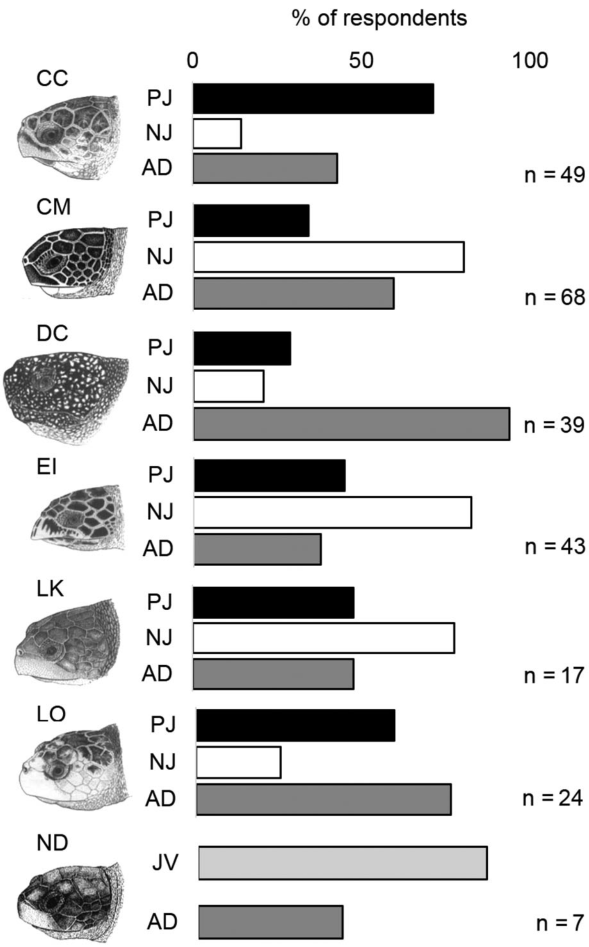

Fig. 3. Inter-specific comparison of the breakdown of entangled sea turtle species by life stage. Black: pelagic juveniles (PJ); white: neritic juveniles (NJ); light grey: juveniles (JV); dark grey: adults (AD); see Fig. 2 for species abbreviations. Flatback turtles were only categorised into juvenile or adult classes with advice from species experts. Sea turtle skull figures used with permission of WIDECAST; original artwork by Tom McFarland

fishing gear to try and separate incidents due to bycatch and subsequent stranding from those caused by ghost fishing. The number of responses on the occurrence of ghost fishing (GF) through discarded fishing debris (rope, net and line) was generally slightly higher than for bycatch (BC) through active gear.

A smaller percentage of respondents specified cases of turtle entanglement in land-based sources, from polythene sheeting (n = 71), woven sacks (n = 72) and non-fishing rope/twine (n = 68). But in only a few incidences were these said to be common occurrences (polythene sheeting [n = 3], woven sacks [n = 4], non-fishing rope/twine [n = 7]). Respondents were asked to comment on the occurrence of 'other'

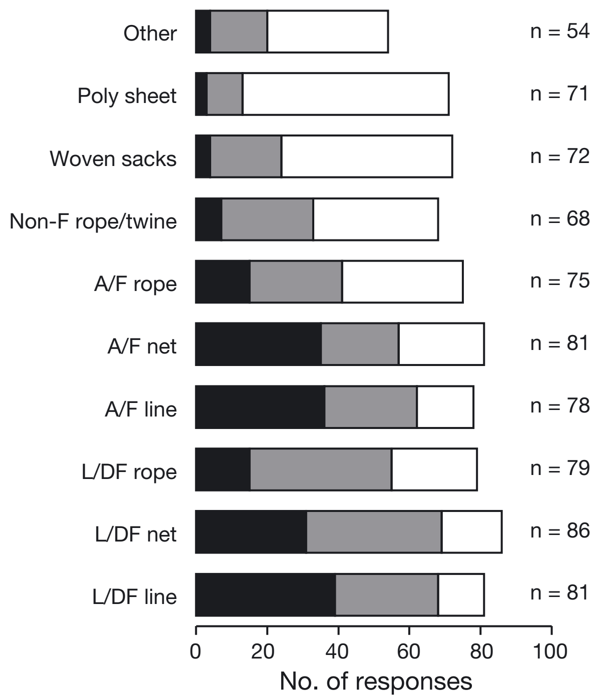

Fig. 4. Entangling materials. L/DF: lost/discarded fishing; A/F: active fishing; Non-F: non fishing; Poly sheet: polyethylene sheeting. Black: common (10% or more of cases); grey: sometimes (less than 10% of cases); white: never. Not all participants categorised each material; total number of responses for each material shown on the right of the graph

entangling materials (n = 54) and to provide examples (n = 20) that caused turtle entanglement. This included debris from land-based sources (plastic-balloon string, canned drink '6-pack' rings, kite string, plastic chairs, plastic packaging straps, wooden crates and weather balloons) and debris from other maritime activities (boating mooring line, anchor line and discarded seismic cable).

Scale of issue

In order to obtain further insights into the potential scale of this issue, respondents to the second survey were asked whether they thought entanglement in anthropogenic debris is causing population-level effect in marine turtles. Of the 63 respondents, 84.1% thought that this was probable, very likely or definite (see Fig. S1 in the Supplement). There was no significant difference in scaled responses by ocean basin (Kruskal-Wallis: $\chi^2 = 1.82$, df = 4, p = 0.77). In order to assess the relative importance of different threats according to experts, we also sought the experts' opinions on how they thought entanglement in anthropogenic debris compared to other threats to marine turtles (i.e. 'plastic ingestion', 'oil pollution', 'fisheries bycatch', 'direct exploitation' and 'climate change'). Although between 6.35 and 25.4% were unsure, there was a strong opinion that plastic ingestion and fisheries bycatch were greater threats, and that oil pollution, climate change and direct exploitation were less severe threats than entanglement (Fig. 5).

Challenges, priority actions and research needs

Respondents to the second survey converged on a limited number of themes when considering the challenges, research needs and priority actions within marine turtle entanglement. The challenges to addressing the issue (115 suggestions) could be grouped into 5 major categories: law and enforcement (23.5%; n = 27); sources and spatial extent of entanglement materials (24.3%; n = 28); education and innovation (24.3%; n = 28); understanding the full extent of the threat (18.3%; n = 21); and human response to entangled turtles (9.6%; n = 11) (Table 2). Seven major research areas were suggested by respondents (91 suggestions): more specific reporting and monitoring or a common database (23.1%; n = 21); mapping the threat/spatio-temporal hotspots (31.9%; n = 29); identifying entanglement materials and sea turtle interactions (24.2%; n = 22); understanding post-release mortality and physical effects (3.3%; n = 3); socio-economic impacts (4.4%; n = 4); innovation of new replacement materials (6.6%; n = 6); and demographic risk assessments (6.6%; n = 6) (Table 3). Priority actions (n = 121 suggestions) that respondents believe would help reduce turtle entanglement were grouped into 5 major areas: education/stakeholder engagement (31.4%; n = 38); fisheries management and monitoring (26.4%; n = 32); research (5%; n = 6); law and enforcement (20.7%; n = 25); and development of alternative materials and methods (16.5%; n = 20) (Table 4).

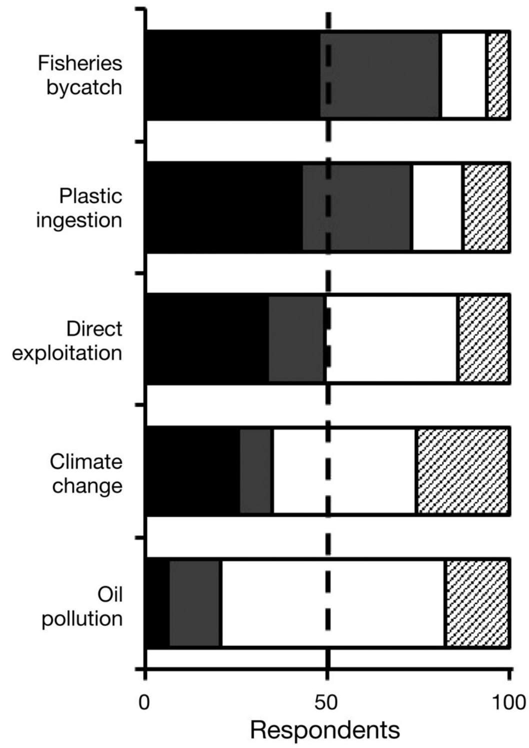

Fig. 5. Responses to comparison of other threats faced by marine turtles compared to entanglement (n = 63). Black: greater than entanglement; grey: similar threat; white: less than entanglement; striped: unsure

DISCUSSION

Global distribution

Our review and elicitation of expert opinions demonstrate that marine turtle entanglement is an issue operating at a global scale, occurring in all species, throughout their geographic range. We sought to answer key knowledge gaps surrounding the issue of turtle entanglement in marine debris as previously highlighted by Vegter et al. (2014) and Nelms et al. (2016). Difficulties in investigating these knowledge gaps are in part due to a lack of robust data. This highlights the importance of using mixed methods to access expert opinion to gain an insight into this global threat. The growing use of expert knowledge in conservation is driven by the need to identify and characterise issues under limited resource availability, and the urgency of conservation decisions (Martin et al. 2012).

Acknowledging the incomplete coverage of our estimates, given the mean estimated number of strandings and mortality rates, in the order of 1000 turtles die annually as a result of entanglement in the areas monitored by our respondents. These levels are likely a profound underestimation of the scale of this issue as the coverage of these actors is far from comprehensive. Second, it is well known that not all dead turtles strand (Epperly et al. 1996, Sasso & Epperly 2007), especially small and pelagic animals, and there can also be decay of entangled animals. Additionally, some of our respondents commented that detection of stranded animals may be further confounded due to take of stranded animals for human consumption.

Table 2. Summary of major challenges regarding marine turtle entanglement as listed by respondents

Challenge category	% of suggestions (n = 115)	Challenges described	Direct quotes from respondents
Law and enforcement	23.5	Management of both industrial and small-scale artisanal fisheries	'Under-resourced fisheries management of small-scale fisheries'
		The issue of discarded fishing gear at sea	'Trawlers should file a report anytime they lose netting'
		Ineffectiveness of Marine Protected Areas	'Shifting climate may render Marine Protected Areas as ineffective'
Source of entanglement materials and extent	24.3	Estimating the amount and durability of entangling material entering the sea	'Entangling material tends to be durable, so even if management scheme is put into place, have to deal with historic material already in the ocean'
		Retrieving lost fishing gear	'In my region, lost/discarded fishing lines are a big issue'
		Lack of accountability	'Inability to determine source of entanglement debris (no accountability)'
Education and innovation	24.3	Fisherman education and awareness	'Engagement/education/enticement to bring artisanal fishers in developing countries to a want to reduce turtle mortality' 'Figuring out how to reach out to boaters/fishermen with making them want to support sea turtle friendly habits'
		Developing a discipline to avoid abandonment of fishing gear	'Addressing amateur/recreational fishers is really hard. In my opinion, most of the discarded fishing lines are left by this group'
		Sourcing alternative materials	'Creation of degradable nylon'
Understanding the full extent of the threat	18.3	Lack of stranding networks' ability to measure the impact of the extent of the threats in multiple areas	'It is hard to estimate the total amount of entangled turtles, since these animals are highly migratory and tend to be scattered over wide areas. Additionally turtles that become entangled may quickly die and be predated. Scavengers, predators, wind and currents may prevent carcasses from coming ashore' 'Most entanglement records rely on land-based sampling and stranding do not represent total deaths at sea' 'It is hard to distinguish marine debris from active and ghost fishing gears'
		Difficulty in determining if entanglement occurred pre- or post-mortem	'Difficulty in determining if entanglement occurred pre- or post-mortem (for some entanglement types, such as discarded nets/line)'
		Survivorship of turtle found entangled alive	'Limited post-release monitoring of live entangled turtles'
Response to entangled turtles	9.6	Detangle permits	'Very few people are trained and permitted to disentangle them'
		Discovery times need to be quick	'Discovering entangled turtles quickly' 'Entangled turtle can be challenging to disentangle especially if they are not anchored and instead are free swimming'
		Ineffectiveness of reporting systems	'Having a good system in place that stranding will be reported (people that see an entangled turtle have to be able to notify the correct organization)'
		Lack of rehabilitation resources for entanglement incidents	'Lack of rehabilitation resources for turtles hurt in incidents of entanglement'

Table 3. Summary of research needs regarding marine turtle entanglement as listed by respondents

Research need category	% of suggestions (n = 91)	Research needs described	Direct quotes from respondents
More specific reporting and monitoring/common database	23.1	Creation of a common database	'A common database, long lasting surveys and a programme on a national base for monitoring of the state of debris in the sea'
		An increase in specificity of reporting of entanglement cases	'Better monitoring/reporting of entanglement cases by species, life stage, region'
			'Establish a protocol for sea turtle strandings networks for identify entanglements and report these'
		Collaboration of resource users in the marine environment	'More collaboration with resource users in the marine environment in respect to reporting cases of entanglement'
			'Getting information from fishermen when turtles get entangled. Support to Fisheries Division who can provide accurate information on net damage from reports by fishermen. Only a small percentage of stranded turtles will wash up ... carcasses may become destroyed prior to reaching those coasts'
Mapping the threat/spatio-temporal hotspots	31.9	Using stakeholder knowledge	'Surveys to fishermen (industrial, artisanal and sport) to understand where and when they discard nets or lines and in water monitoring programs in coastal areas with high pressure of artisanal and sport fishing'
		Identifying and mapping the entanglement rates due to different gear types and materials	'Understanding where the event occurs, such as targeting if the problem is more from floating debris versus debris in water column'
		Modelling/mapping patterns of debris distribution, patterns of marine turtle migrations and the characterization of fisheries distributions	'Understanding overlap between sea turtle habitats (e.g. nesting and feeding grounds) with areas of high debris concentration (e.g. convergence zones)'
			'Spatio-temporal scales. Hotspots'
Entanglement materials and sea turtle interactions	24.2	Studying sea turtle and debris behaviour and their interactions	'Behavioural (foraging or sheltering) traits in different turtle species or populations that may them more vulnerable to entanglement'
			'Investigate the behavioural characteristics of the turtles that lead to their entrapment in fishing gear with a view to improving mitigation actions'
Post-release mortality and survival/physical effects	3.3	Understanding true post-release mortality and morbidity	'The effects of flipper amputations on survival'
Socio-economic impact	4.4	Special focus on the fisher community	'What are the opportunities and barriers to intervention?'
Innovation of new replacement materials & methods	6.6	Innovation of biodegradable alternatives to commonly used plastic materials	'Alternative materials for fishing and other things/activities'
Demographic risk assessments	6.6	Development of demographic risk assessments for threatened populations of turtles	'Develop the appropriate population demographic models for marine turtles to allow for assessment/identification of those mortality factor that are not detrimental to maintaining robust non threatened population of turtle'

Table 4. Summary of priority actions regarding marine turtle entanglement as listed by respondents

Priority actions category	% of suggestions (n = 121)	Priority actions described	Direct quotes from respondents
Education/stakeholder engagement	31.4	Fisher involvement/education	'Develop questionnaire for fishermen for their recommendations on how it would be possible to reduce turtle entanglement'
			'Partnership with local fishermen to locate and remove abandoned or lost fishing gear (ghost gear). Financial incentives to return discarded gears to shore'
		Community/public awareness campaigns on marine litter	'Organizing campaigns with scuba divers to clean sea bottom from the man debris and ghost nets/discarded fishing lines'
			'Implement an environmental stewardship certificate system among ocean users and create a global open access database of entanglements to facilitate research efforts'
Fisheries management and monitoring	26.4	The development of traceable gear	'Developing/using traceable gear in combination with introducing a fining policy'
		Stricter regulations	'Increased collaborations with commercial fisherman and recreational fisherman to better understand their needs and the needs of the turtles....and how these can be combined'
Research/knowledge	5	The implementation of the research needs stated in Table 3	'We cannot say before understanding the main reasons, main sources and main habitats or localities in which entanglement occurs'
Law and enforcement on entanglement material	20.7	Banning at-sea disposal of entangling materials	'Enforcement of laws banning at-sea disposal of entangling material'
		Better waste management and increased recycling efforts	'Reduction of manmade debris, better waste management, more biodegradable products'
Development of alternative materials/methods	16.5	Development of alternative materials/methods	'Development of less environmentally persistent materials to be used in nets, fishing line, etc.'
		Shifting gear type/increasing the use of biodegradable materials	'Different strategies to different fishing gear; from the coastal sport fishermen to high seas industrial fishermen'
			'Introduce biodegradable chord into selected net fisheries with high loss to ghost nets'

Species differences

Although there was no interspecific difference in the incidence of entanglement, most peer-reviewed publications featured olive ridley turtles, with some experts reporting high incidences of entanglement for this species. Stelfox et al. (2016) noted that olive ridley turtles accounted for the majority of sea turtles identified as entangled (68%; n = 303), and this could be for the following reasons. Firstly, this species, which often exhibits mass nesting in the hundreds of thousands of individuals, is highly numerous, and at particularly high densities in some areas, leading to entanglement hotspots (Jensen et al. 2006, Koch et al. 2006, Wallace et al. 2010a). Secondly, the olive ridley forages along major oceanic fronts which are known to aggregate marine debris (Polovina et al. 2004, McMahon et al. 2007). Finally, their generalist feeding behaviour potentially attracts them to feed opportunistically on biofouled marine debris such as ghost gear (Stelfox et al. 2016).

Life stages

Entanglement was reported to occur in all life stages (pelagic juveniles, neritic juveniles and adults) across all species (the exception being flatback turtles which have no pelagic juveniles; Hamann et al. 2011). Perhaps of greatest concern is the signal of high entanglement incidence in the pelagic juvenile stage: despite the general inaccessibility of sampling this life stage, they are still appearing as stranded entangled. The currents that transport hatchlings to oceanic convergence zones are also now recognised as concentrating floating anthropogenic debris, creating the capacity for an ecological trap for these young turtles, whether it be through ingestion or entanglement (Nelms et al. 2016, Ryan et al. 2016). Many respondents considered that entanglement could be having a population level effect; a distinct possibility if this there is a large impact on this cryptic life stage and on pelagic foraging adults (Mazaris et al. 2005).

Entangling materials

Respondent data highlighted that the majority of entanglements were the result of fishery-based material and other maritime activities. The issue of ghost fishing featured highly, with numerous responses reporting entanglement within lost/discarded gear. This gear is often lost, abandoned or discarded when it becomes derelict, attracting scavengers and acting as FADs (Gilman 2011). Subsequently, species such as marine turtles become entangled within the gear, perhaps encouraged by this process of 'self-baiting' (Matsuoka et al. 2005).

Change in fishing practice

The issue of ghost fishing appears to have worsened since the 1950s, as the world's fishing industries have replaced their gear, which was originally made of natural fibres such as cotton, jute and hemp, with synthetic plastic materials such as nylon, polyethylene and polypropylene. Manufactured to be resistant to degradation in water means that once lost, it can remain in the marine environment for decades (Good et al. 2010). Furthermore, there has also been a shift in the type of synthetic nets being selected; for example, fishers in part of Southeast Asia now increasingly favour superfine nets. Although this can help increase catches, the twine thinness means that they break easily and are difficult to repair once damaged (Stelfox et al. 2016). The incidences of entanglement caused by this form of pollution in our expert surveys indicates that this source of mortality for marine turtles mirrors that in marine mammals and sea birds, which has increased substantially over the last century (Tasker et al. 2000, Good et al. 2010, McIntosh et al. 2015).

Differentiation from bycatch

It is quite plausible that ghost fishing may be working synergistically alongside bycatch, but because of its more cryptic nature this means that understanding its role in marine turtle mortality is much more difficult. Bycatch is better understood. For example, the analysis of catch rates in the Mediterranean allowed for the estimation of 132 000 captures and 44 000 incidental deaths per year (Casale 2011). Likewise, cumulative analysis of catch rates in US fisheries estimated a total of 71 000 annual deaths prior to the establishment of bycatch mitigation methods. Since these measures were implemented, mortality estimates are ~94% lower (4600 deaths yr^{-1}) (Finkbeiner et al. 2011). This highlights the importance of informed estimates to monitor the success of mitigation methods. In addition to bycatch mortality estimates, spatial and temporal patterns of bycatch incidences can be identified. Using onboard observer data, Gardner et al. (2008) found seasonal changes in catch distributions of loggerhead and leatherback turtles in the North Atlantic, with patterns of spatial clustering from July to October. Analysed on a global scale, Wallace et al. (2010b) were able to highlight region–gear combinations requiring urgent action such as gillnets, longlines and trawls in the Mediterranean Sea and eastern Pacific Ocean. Generating such estimates of catch rates and spatial/temporal patterns for entanglement are not yet possible due to the lack of quantitative information.

Land-based plastic entanglements

The domination of fisheries-based materials in the results does not mean that land-based plastics are not a source of entanglement. The increased input of plastic debris from terrestrial run-off means that these interactions are only likely to increase (Jambeck et al. 2015). Our literature search and 'other' materials stated by respondents contained a variety of items causing entanglement that could be decreased by reduction of use, replacement with more degradable alternatives and better waste management and recycling. The prevalence of these materials in the marine environment will very much depend on future waste governance, especially in those countries that generate the most plastic waste (Jambeck et al. 2015). A future technological solution which is currently being investigated or adopted in high plastic-generating countries such as Thailand and India is the pyrolysis of plastics. This process produces fuel from waste plastic, a better alternative to landfill and a partial replacement of depleting fossil fuels (Wong et al. 2015).

Caveats

It is important to recognise the biases associated with using stranding animals for data collection. Within and between stranding sites there are differences in turtle foraging ecology, life stages and proximity to human habitation (Bolten 2003, Rees et al. 2010), and therefore they are exposed to different levels and types of potential entangling materials. Individual turtles therefore may not represent a homogeneous group in terms of entanglement occurrence within that population (Casale et al. 2016). Additionally, recovered carcasses represent an unknown fraction of at-sea mortalities, with physical oceanography (e.g. currents) and biological factors (e.g. decomposition) affecting the probability and location of carcass strandings (Hart et al. 2006). However, examining reports of stranded animals represents a vital opportunity for research and can provide insights into the impacts of anthropogenic threats which would otherwise go undetected (Chaloupka et al. 2008, Casale et al. 2010). In addition, stranding information aids with the assessment of harder-to-access life stages, yielding key information on the risk to specific resident populations and contributing to building a worldwide perspective for conservation issues (Chaloupka et al. 2008, Casale et al. 2016). Indeed, this was the aim of our study: using stranding data from expert respondents to gain an initial indication of the estimated magnitude of this threat.

Surveying experts can be a powerful tool for obtaining insights on particular topics not widely known by others (Martin et al. 2012). Expert knowledge and opinions may be the result of training, research, skills and personal experience (Burgman et al. 2011a). In this study, we sought the opinions of conservation scientists and practitioners with experience in marine turtle entanglement and strandings. Due to the purposive sampling nature of our approach, we aimed to identify people with relevant experiences instead of focusing on obtaining a random selection of representatives; this is a widely used practice when undertaking social surveys that focus on particular subgroups or specialists (Newing 2011). Nevertheless, expert knowledge and opinions are also known to be subject to biases, including overconfidence, accessibility and motivation (see e.g. Burgman et al. 2011b and Martin et al. 2012). In the absence of empirical data to validate our findings, this remains as simply suggestive but nevertheless relevant information in terms of identifying a potentially important conservation issue and providing relative indications of the scale of entanglement as a threat to sea turtles.

Future actions and recommendations

Ghost fishing

Issue and policy. Presently, a large knowledge gap exists regarding effects of ghost fishing. While there has been some progress in documenting the frequency of loss from passive gear such as gillnets, little is known about loss from active gears; effective methodology to estimate the persistence of types of gear such as trawl nets has yet to be developed (Gilman et al. 2013). While it would be optimal to switch all gear to more biodegradable materials, synthetic materials will continue to be used within fisheries for the foreseeable future. This is an issue that has been highlighted in policy by the Food and Agriculture Organization (FAO), who recommend the identification, quantification and reduction of mortality caused by ghost fishing by implementing this into fisheries management plans, increasing scientific information and developing mitigation strategies; but this appears still to be in its infancy (Gilman et al. 2013). This is also reflected in mandates within the International Maritime Organisation (IMO) and International Convention for Prevention of Pollution from Ships (MARPOL Annex V) (Stelfox et al. 2016).

Need for a global database and spatial hotspot identification. Undoubtedly a common global metadatabase recording the spatial distribution and abundance of possible entangling ghost gear as well as incidences of marine turtle entanglement incorporating a unit of effort metric would assist in quantifying the mortality due to ghost gear that is needed to inform policy (Nelms et al. 2016). A recent global review (dominated by the Atlantic and Pacific oceans) on marine megafauna by Stelfox et al. (2016) reported a total of 5400 individuals of 40 species that had been associated with ghost gear between 1997 and 2015. They suggested this was a great underestimate due to lack of capacity to record incidence. Such data could feed into one of the major research priorities emphasised by respondents; modelling spatio-temporal hotspots of entanglement. An innovative study by Wilcox et al. (2013) used beach clean data and models of ocean drift to map the spatial degree of threat posed by ghost nets for marine turtles in northern Australia and map areas of high risk. With the input of more specific marine location data on ghost gear and the advocacy of the use of ever improving modelling, this could provide a powerful tool in the future.

Education and stakeholder engagement

Local initiative to reduce debris causing entanglement. On a more local and regional scale, many initiatives are being brought into place to encourage a reduction in the amount of ghost gear/plastic debris entering the ocean and combat discarding at sea by working closely with community education and engagement; another highlighted topic by our respondents. There are numerous examples: the sea turtle conservation program in Bonaire has started a 'Fishing Line Project' (www.bonaireturtles.org/wpp/what-we-do/fishing-line-project) working with volunteers to train them on how to remove discarded line and nets from coral reefs, and the Zoological Society of London's 'Net-works' (www.net-works.com) initiative has established a supply chain for discarded fishing nets from artisanal fishing communities in the Philippines to a carpet manufacturing company. With further replication of such community-based projects and stakeholder engagement, especially with artisanal fisheries awareness, the potential exists to start targeting hotspots of marine vertebrate entanglement directly.

Stranding networks training. Another set of stakeholders which will be important to engage are stranding networks. Responses to entangled turtles can often be slow, and respondents commented that many are not trained in the correct protocols to safely remove entangling materials. If stranding networks were fully trained in a standardised protocol for removal, the techniques could then be passed on through educational training programmes to the fishing community, quickening the response to such incidences. This is already beginning to happen for bycatch cases; Sicilian fisherman now actively volunteer to take part in the rescue of turtles in difficulty and are trained in contacting the competent authorities for the transfer of turtles to the nearest recovery centres. This level of involvement by workers in the fishery sector was stressed and encouraged through both effective education activity and specific targeted study campaigns (Russo et al. 2014).

Future research avenues into marine turtle entanglement

Respondents raised the issue of post-release mortality and the importance of behavioural research into the interactions between marine turtles and potential entangling materials present in the marine environment. The prominence of this has been emphasised within other taxa; for example, post-release mortality can result from long-term chronic effects of injuries in pinnipeds even after the entanglement has been removed (McIntosh et al. 2015). Furthermore, it has been argued that some colonial seabirds released from entangling plastic would not survive without human intervention (Votier et al. 2011).

To validate the success of release protocols after entanglement incidents (as mentioned above), techniques could be employed from other areas of marine turtle research. Satellite telemetry has already been used in a multitude of ways to provide information on conservation issues facing marine turtles; a number of studies have used this technique to consider post-release mortality after bycatch fisheries interactions (reviewed in Jeffers & Godley 2016). Deploying tagged turtles that have been involved in entanglements could aid in the understanding of survival after these events as well as simultaneously providing information on the location of sea turtles, feeding into information on entanglement hotspots to target mitigation actions. The benefits of utilising such techniques have been illustrated in other endangered species facing entanglement, such as studying mortality of silky sharks *Carcharhinus falciformis* in the Indian Ocean; estimates derived from satellite tracking showed that mortality due to entanglement was 5 to 10 times that of known bycatch mortality and provided evidence for a call advising immediate management intervention (Filmalter et al. 2013).

Other research methods and ideas could be modified from the study of plastic debris ingestion by sea turtles. Studies are currently underway to understand the selective mechanisms that lead to ingestion of plastic pieces (Schuyler et al. 2014, Nelms et al. 2016). For instance, a study by Santos et al. (2016) used Thayer's law of countershading to assess differences in the conspicuousness of plastic debris to infer the likelihood that visual foragers (sea turtles) would detect and possibly ingest the plastic fragments. Similar studies could be conducted to comprehend the underlying behavioural and physiological mechanisms that influence turtles to approach potential entangling materials when encountering them within the marine environment.

Similarly, comprehending how important the level of biofouling on this synthetic debris is in contributing to the likelihood of entanglement will be important. Total fish catches by monofilament gillnets in Turkey was lower, as a result of accumulating detritus and biofouling increasing the visibility of the nets in the water column (Ayaz et al. 2006). Furthermore, the level of biofouling could indicate the age of ghost gear entangling marine turtles. Retrieved lost/discarded fishing gears are usually found fouled by macro-benthic organisms, so if a relationship between soak time and biofouling level could be established, these organisms could provide a valid methodology to age the gear and enable better estimates of 'catches' made by the respective net (Saldanha et al. 2003).

Finally, it will be important to undertake demographic studies, calculating rates of entanglement, especially for specific populations that are known to be particularly vulnerable to a combination of other anthropogenic threats. For species such as pinnipeds, which are less elusive (hauling out on land) than marine turtles, the literature describes different methods. For example, a proportion derived from a count of entangled individuals from a sub-sample or an estimate of the total population (Raum-Suryan et al. 2009, McIntosh et al. 2015), or more recently, the use of mixed-effects models to obtain a prediction of the total number of seals entangled per year, by examining changes in entanglement rates over time and the potential drivers of these detected trends (McIntosh et al. 2015). However, this can only be achieved if reporting and recording such incidences in marine turtles improves in efficacy and standardisation.

CONCLUSIONS

Further research may show that the issue is more one of animal welfare than of substantive conservation concern to many marine turtle populations. It is clear, however, that entanglement with anthropogenic plastic materials such as discarded fishing gear and land-based sources is an under-reported and under-researched threat to marine turtles. Collaboration among stakeholder groups such as strandings networks, fisheries and the scientific community will aid in providing mitigating actions by targeting the issue of ghost fishing, engaging in education and producing urgently needed research to fill knowledge gaps.

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