Environmental Pollution 232 (2018) 467–476

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Incidence of marine debris in cetaceans stranded and bycaught in Ireland: Recent findings and a review of historical knowledge☆

Amy L. Lusher [a, *, 1], Gema Hernandez-Milian [b, 1], Simon Berrow [a, c], Emer Rogan [b], Ian O'Connor [a]

[a] Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology, Dublin Road, Galway, Ireland
[b] Aquaculture & Fisheries Development Centre (AFDC), School of Biological, Earth & Environmental Sciences (BEES), University College Cork, Distillery Fields, North Mall, Cork, Ireland
[c] Irish Whale and Dolphin Group, Merchants Quay, Kilrush, Co. Clare, Ireland

A R T I C L E I N F O

Article history:
Received 14 June 2017
Received in revised form
19 September 2017
Accepted 20 September 2017
Available online 5 October 2017

Keywords:
Plastic
Microplastic
Fisheries interaction
Marine mammals
Odontocetes
Pinnipeds

A B S T R A C T

Interactions between marine mammals and plastic debris have been the focus of studies for many years. Examples of interactions include entanglement in discarded fishing items or the presence of ingested debris in digestive tracts. Plastics, including microplastics, are a form of marine debris globally distributed in coastal areas, oceanic waters and deep seas. Cetaceans which strand along the coast present a unique opportunity to study interactions between animals with macro- and microplastics. A combination of novel techniques and a review of historical data was used to complete an extensive study of cetaceans interacting with marine debris within Irish waters. Of the 25 species of marine mammals reported in Irish waters, at least 19 species were reported stranded between 1990 and 2015 (n = 2934). Two hundred and forty-one of the stranded cetaceans presented signs of possible entanglement or interactions with fisheries. Of this number, 52.7% were positively identified as bycatch or as entangled in fisheries items, 26.6% were classified as mutilated and 20.7% could not be related to fisheries but showed signs of entanglement. In addition, 274 cetaceans were recorded as by-catch during observer programmes targeting albacore tuna. Post-mortem examinations were carried out on a total of 528 stranded and bycaught individuals and 45 (8.5%) had marine debris in their digestive tracts: 21 contained macrodebris, 21 contained microdebris and three had both macro- and microdebris. Forty percent of the ingested debris were fisheries related items. All 21 individuals investigated with the novel method for microplastics contained microplastics, composed of fibres (83.6%) and fragments (16.4%). Deep diving species presented more incidences of macrodebris ingestion but it was not possible to investigate this relationship to ecological habitat. More research on the plastic implications to higher trophic level organisms is required to understand the effects of these pollutants.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Marine debris, specifically plastic, is recognised as a major threat to habitats and biota globally (Kühn et al., 2015). Sources, pathways and consequences of litter into the aquatic environment are varied (UNEP, 2016). Marine organisms can be affected by marine plastics: over 250 species, including, fish, seabirds, mammals and invertebrates, are known to be impacted through entanglement and ingestion often with fatal consequences (Kühn et al., 2015). There are also sub-lethal effects including compromised feeding and disrupted digestion, and other alterations in physiological processes (see review in Lusher, 2015). In addition, it is thought that the toxicological effects of chemicals leaching into body tissues could be amplified through the transfer from prey to predator (see review in Rochman, 2015). Seabirds, fish, marine turtles and mammals have all been reported to ingest large items of plastics, which are collectively known as macroplastics (e.g. Baulch and Perry, 2014; Nelms et al., 2015; van Franeker and Law, 2015). In recent years, studies have begun to report the ingestion of smaller, microplastics <5 mm, by a range of marine organisms (see Lusher,

☆ This paper has been recommended for acceptance by Eddy Y. Zeng.
* Corresponding author. Current address: Norwegian Institute of Water Research (NIVA), Gaustadalléen 21, 0349 Oslo, Norway.
E-mail address: amy.lusher@niva.no (A.L. Lusher).
[1] ALL and GHM contributed equally to this manuscript.

https://doi.org/10.1016/j.envpol.2017.09.070
0269-7491/© 2017 Elsevier Ltd. All rights reserved.

2015). Globally, the visible evidence of interactions between marine mammals and large items of debris are well documented, both in the media and in peer-reviewed publications. A recent review found 56% of all cetacean species interact with marine debris with 69% of ingested debris classified as plastic or plastic-derived items (Baulch and Perry, 2014). Although the 2014 report presented worldwide data, data from many European countries including the Republic of Ireland were omitted.

Marine mammals are found in a range of diverse habitats, including offshore oceanic waters, deep seas and coastal and estuarine environments. Coastal populations of cetaceans might encounter localised plastics, such as those originating from urban areas, while migratory species could encounter accumulation areas of plastics in the ocean (UNEP, 2016). Observation of some interactions (e.g. entanglement in ghost nets) can be difficult to assess as marine mammals spend a large majority of their time underwater. Therefore, interactions with marine debris are generally observed during adverse events, such that visible entanglement can be seen, or ingestion may cause individuals to die and revealed during post-mortem analysis. Usually, macrodebris interactions are easily identifiable such as ingested items visible in the digestive tract; however, the absence of macrodebris does not imply that microdebris is also absent.

The incidence of microplastic ingestion by marine mammals is much more poorly understood. Recent studies have identified microplastics in the digestive tracts of harbour seals, *Phoca vitulina* (Bravo-Rebolledo et al., 2013), common dolphin, *Delphinus delphis* (Curran et al., 2014), True's beaked whales, *Mesoplodon mirus* (Lusher et al., 2015) and a single humpback whale, *Megaptera novaeangliae* (Besseling et al., 2015). Collecting viable dietary data from cetaceans' digestive tracts is easy to do however it is notoriously challenging to investigate the presence of microplastics. Acquiring animals for analysis is reliant on individuals either stranding or becoming bycaught; it is estimated that between 8 and 30% of dead cetaceans strand (e.g. Carretta et al., 2016; Peltier et al., 2012; Wells et al., 2015) and sampling can be difficult because of their fast decomposition rate. Alternatively, it has been suggested that micro- and macro-plastic interaction with cetaceans could be studied through biopsy sampling of live animals (e.g. Fossi et al., 2012). These authors suggested that phthalate concentrations from the blubber of stranded fin whales, *Balaenoptera physalus,* could act as tracers of marine pollution and mammals could therefore act as sentinel species. However, phthalates are notoriously difficult to measure, have low levels of desorption and are ubiquitous in the marine environment, and alternative methods to identify plastic items may be more appropriate.

Microplastic uptake by marine mammals are largely unknown but may occur through several mechanisms depending on their mode of feeding, such as filter feeding, inhalation at the water-air interface and secondary ingestion through trophic transfer from prey (see Lusher et al., 2015). Amounts and types of plastic found within the digestive tracts of marine mammals may be correlated to their feeding strategies. For example, the incidence of microplastics in fur seal, *Arctocephalus* sp., scats may be a result secondary ingestion from prey species (Eriksson and Burton, 2003) and recently it was estimated that a single striped dolphin, *Stenella coeruleoalba,* could be exposed to ~463 million microplastics based on its diet of mesopelagic fish (Lusher et al., 2016). Additionally, baleen whales may ingest microplastics through water filtration (Besseling et al., 2015). It is possible that microdebris may have adverse effects (e.g. sub-lethal effects, toxicological effects) on individuals but more research needs to be carried out.

Twenty-five cetacean species have been reported in the Irish Exclusive Economic Zone and the wider Irish Designated Area (Wall et al., 2013; IWDG *unpublished data*). Stranded animals provide a source of data to study the ecology of these top predators considering the large numbers of stranding events per year (McGovern et al., 2016). Standard methodologies, such as digestive tracts examination, stable isotope and fatty acid analysis, are used to assess diets and to provide information about their feeding behaviour (e.g. Hernandez-Milian et al., 2015a, b; Ryan et al., 2014). Methodology from dietary studies have been adapted to sample for microplastics in cetacean digestive tracts (Lusher et al., 2015). Here we combine information obtained through stomach content analysis and previously published data collected from historical records of cetaceans stranded and bycaught in the waters around Ireland to investigate the interactions between marine mammals and marine debris.

2. Material and methods

2.1. Definitions of terms used

Throughout this document, we refer to several terms such as ingestion, entanglement, and by-catch. Ingestion is considered when marine debris have been found in the digestive tracts of individuals. Entanglement is the interaction of an individual with an external barrier which impedes movement and can lead to death. For example, the entanglement of an organism in marine debris such as abandoned, lost or otherwise discarded fishing gear. Bycatch is the capturing of an animal during routine fishing operations when the captured animal is not the primary target. It was not always possible to differentiate between whether a stranded cetacean was entangled in marine debris or bycaught in active fishing gear, as the physical and visual evidence of both interactions can appear the same. As such, we present and discuss entanglement and bycaught concurrently.

It is important to state that post-mortem examinations in Ireland are not always carried out by specialists, e.g. vets and trained researchers; in such cases, general internal signs of bycatch are not reported. Distinguishing between cetaceans which had been by caught and released by fishermen but were not mutilated or those captured by fisheries related debris (e.g. ghost nets) can be complicated. For example, fishers may use a rope to free dead animals which are by caught in their nets. In this study, we considered three categories of entanglement where two were linked to fisheries (bycatch and mutilation), while with the third it was not possible to confirm if animals died due to entanglement or bycatch:

I. by-catch, individuals landed by fishers, or presenting typical signs of incidental fisheries interactions during post-mortem examinations, such as froth in the respiratory system, net marks related to recent fisheries interaction and broken beaks,
II. mutilated, individuals with mutilations on their bodies, for example, fluke, flippers and/or head were clearly cut off; this is usually linked to fisheries interactions where fishers release the dead animals from their fishing gear,
III. possible entanglement, when ropes or nets were found around stranded animals, but could not clearly be linked to fisheries, for example, a single rope on a tail stock.

Marine debris tend to concentrate in specific areas, such as upwelling zones, gyres or coastal waters. This is significant as cetaceans occupy different habitats and have different feeding strategies (suction, filtering, predatory and grazers) which could expose them to marine debris. In this study, cetaceans were classified into three ecological groups depending on their main habitat or the habitat that they usually feed: i) coastal, ii) pelagic or iii) deep divers. For example, coastal species feed mainly on demersal coastal species, pelagic cetaceans feed mainly in the water column, deep divers feed mainly on mesopelagic prey.

2.2. Historical review of marine debris interactions with stranded and bycaught cetaceans

This study compiles information on cetaceans stranded in the Republic of Ireland and Northern Ireland between 1990 and 2015, as well as some animals by caught in this geographic area. Data presented in peer-reviewed publications and reports in grey literature were gathered from electronic sources using Web of Science, Irish Naturalists' Journal, Google Scholar and Google. Additional data held by the Irish Whale and Dolphin Group (IWDG) and University College Cork (UCC) was also compiled. Keywords used in searches for debris included: marine debris, marine litter, plastic, and polystyrene. Keywords to identify species included: dolphin, whale, cetacean and porpoise. Data were assessed for any indication of entanglement or ingestion of marine debris. Also, incidences of cetacean mortality related to by-catch were noted. This study contains data from digestive tracts of cetaceans which were incidentally by caught during observer programmes examining the ecological effects of the drift net fishery targeting albacore tuna, *Thunnus alalunga,* which were operating in the waters to the South West of Ireland in 1996 and 1998.

2.3. Post mortem and laboratory analysis

Post-mortem examinations of marine mammals stranded and bycaught in Irish waters were carried out following standard protocols (Kuiken and Garcia-Hartmann, 1993), either *in situ* or in the laboratory. Animals were measured and sexed, and examined for external and internal anomalies. Pathologies were only reported when the individuals were considered with decomposition state 0 (recent stranding) to 3 (decayed). Nutritional state of animals is usually difficult to identify however, it was reported in cases where animals were obviously emaciated. In some instances, unusually thin blubber thickness was considered an indication of emaciation. Digestive tracts, from oesophagus to anus, were examined following the protocol for dietary studies by Hernandez-Milian (2014) conducted at UCC. In short, the location of marine debris was reported in three main compartments of the digestive tract: oesophagus, stomach (including forestomach, fundic stomach, pyloric chamber, and duodenal ampulla), and intestines. Intestines were divided into 20 sections of equal length and each analysed separately. During the period 2013–2015, the protocol was adapted to identify microplastics following the methods by Lusher et al., (2015) at developed at Galway-Mayo Institute of Technology and University College Cork. The number, size, colour and shape of micro and macro plastics identified per individual were recorded. This was conducted on a limited number of individuals under contamination controlled conditions (following Lusher et al., 2014). Instruments and equipment were cleaned and checked under a microscope for contamination with airborne fibres before use. All gut sections were covered prior to analysis to reduce exposure to air. To check for sufficient contamination control, EU guidelines suggest that background levels of microplastics in control samples should be less than 10% of the overall microplastic average throughout all samples (Galgani et al., 2013). Statistical analysis was not possible due to the unbalanced data. All results are presented as frequency occurrences (%). In addition to animals from 2013 to 2015, there was one harbour porpoise (HP 5/11, supplementary material, Table S1) which was included in the microplastics study because the digestive tract was stored frozen.

3. Results

A total of 2934 stranded cetaceans were recorded from 1990 to 2015. Of these individuals, 2593 (88.4%) were positively identified to species level. 19 species of cetaceans were identified, including four species of baleen whales, six species of deep diving whales, and nine species of delphinids (Table 1). Additionally, a total of 274 incidental captures from at least nine species were recorded during the observer programmes (see Rogan and Mackey, 2007). Common dolphin and striped dolphin were the most by caught cetaceans within the bycaught observer programme in 1998 and 1996 (66% and 29% respectively).

3.1. By-catch and entanglement in marine debris

Two hundred and forty-one individuals out of 2,934, from at least 11 species of cetaceans, were considered to have had interactions with fisheries (Table 2). Only 6% of these cetaceans were baleen whales, while the remaining animals were delphinids and a single unidentified cetacean species. Fisheries by catch or entanglement were positively linked to 127 individuals (52.7%). Another 64 (26.5%) individuals were found mutilated. Furthermore, 50 (20.8%) individuals were identified as entanglement but they could not be attributed directly to fisheries.

3.2. Ingestion of marine debris

Post mortem examination was carried out on 410 individuals (14.0% of the total stranded) during the study period. An additional 118 digestive tracts from the observer bycatch programme (43.1% of the total bycaught) were analysed. From the total of 528 digestive tracts examined, marine debris was identified in 45 (8.5%) individuals from 11 species. Of these 21 digestive tracts were also analysed for the presence of microplastics following Lusher et al. (2015), and microplastics were additionally reported in one historical publication. It was found that 21 (4.0% of the total) digestive tracts contained only macrodebris; 21 (4.0%) contained only microdebris, and three (0.6%) digestive tracts contained both macro and microdebris. The classification of marine debris was split into two categories, plastics (which occurred in 92.3% of individuals) and other items, which included a single metal fish hook and paint fragments (7.6%). Macrodebris with a fisheries origin occurred in eight (34.8%) stomachs; four individuals (17.4%) presented other types of macrodebris and causes of death were related to interactions with fisheries.

3.2.1. Macrodebris and macroplastics

Macrodebris was found throughout entire digestive tracts. Most of the animals presented macrodebris in their stomachs ($n = 17$, 73.9%), with a lower incidence in the oesophagus ($n = 4$, 17.4%) and intestines ($n = 6$, 26.1%). Plastic fragments and/or plastic bags were found in individuals from the three ecological groups. Plastic items ranged from as large as 600 mm to sizes $\leq$10 mm Some items may have originated from land based disposal whilst other items were more likely from fishing activities (e.g. pieces of nets) (Supplementary material, Table S1). There was no evidence that macrodebris led to stomach lesions; for example, a Risso's dolphin, *Grampus griseus,* which contained a fishing hook did not present with any damage to the stomach lining.

Two baleen whales which contained marine debris had plastic items in their digestive tracts. A fin whale, *Balaenoptera physalus*, had blue nylon rope in its baleen plates and within its digestive tract (Fig. 1a) and a humpback whale had a large piece of clear plastic in its stomach. Plastic bags were the most frequently recorded plastic item found within the digestive tracts of deep diving whales. A shotgun cartridge was identified in the main stomach of a True's beaked whale stranded in 2013. Other items identified in beaked whales included an ice cream wrapper and fragmented plastics. No ropes or lines were found (Supplementary

Table 1
Records of stranded cetacean on Irish coasts. When it was not possible to differentiate between common and striped dolphin individuals were pulled as Delphinids. NID: non-identified; Habitat: ecological habitat; N: 1990–2015: number of strandings from 1990 to 2015; DT: number of digestive tracts analysed from 1990 to 2015 for marine debris, including micro and macroplastics; MD: is the number of digestive tracts containing macro debris, MP: number of digestive tracts containing microplastic. B: number of individuals containing both micro and macroplastics. Numbers in brackets in column are the individuals from by catch programmes. *this value includes 2 individuals that had microplastics but were not analysed using the microplastics method.

Species	Habitat	N:1990–2015	DT	MD	MP	B
NID Mysticeti	Pelagic	45	0	–	–	–
NID Balaenopteridae	Pelagic	2	0	–	–	–
Balaenoptera acutorostrata	Pelagic	90	2	–	–	–
Balaenoptera borealis	Pelagic	1	0	–	–	–
Balaenoptera physalus	Pelagic	24	2	1	–	–
Megaptera novaeangliae	Pelagic	5	1	1	–	–
Physeter macrocephalus	Deep diver	57	2	–	–	–
Kogia breviceps	Deep diver	9	4	–	–	–
NID Cetacean	NA	50	0	–	–	–
NID Odontoceti	NA	17	0	–	–	–
NID beaked whale	Deep diver	10	0	–	–	–
Hyperoodon ampullatus	Deep diver	16	2	–	–	–
Mesoplodon bidens	Deep diver	11	1	1	–	–
Mesoplodon mirus	Deep diver	5	4	2	–	1
Ziphius cavirostris	Deep diver	38	6	1	1	–
NID Delphinidae	Pelagic	176	0	–	–	–
Delphinus delphis	Pelagic	755	147 (+72)	3	10*	1
Stenella coeruleoalba	Pelagic	219	42 (+42)	2	2	1
Delphinids	Pelagic	17	0	–	–	–
Delphinidae/Phocoenidae	Coastal	41	0	–	–	–
Phocoena phocoena	Coastal	608	125	6	5	–
Globicephala melas	Pelagic	338	8	–	–	–
Grampus griseus	Pelagic	68	8 (+1)	2	–	–
Lagenorhynchus acutus	Pelagic	152	37 (+1)	–	–	–
Lagenorhynchus albirostris	Pelagic	25	3	–	–	–
Orcinus orca	Pelagic	5	3	1	1	–
Tursiops truncatus	Coastal	150	15 (+2)	1	2	–
Total		**2934**	**410 (+118)**	**21**	**21**	**3**

Table 2
Stranded cetaceans considered to be interacting with fisheries. When it was not possible to differentiate between common and striped dolphin, these individuals were pooled as Delphinids. Bycatch: identified as by caught cetaceans, Mutilations: cetaceans presenting mutilations of flippers and/or head, Entanglement: cetaceans with evidence of entanglement or bycatch but not possible to differentiate.

Species	Bycatch	Mutilations	Entanglement	Total
Mysticeti	0	2	0	2
Balaenoptera acutorostrata	6	1	2	9
Balaenoptera physalus	0	0	1	1
Megaptera novaeangliae	2	0	0	2
Physeter macrocephalus	0	1	1	2
Unidentified cetacean	0	0	1	1
Delphinidae	0	0	1	1
Delphinus delphis	38	24	22	84
Stenella coeruleoalba	4	2	4	10
Delphinids	0	2	0	2
Delphinidae/Phocoenidae	0	1	3	4
Phocoena phocoena	66	19	7	92
Globicephala melas	1	4	3	8
Grampus griseus	4	2	1	7
Lagenorhynchus acutus	3	4	1	8
Tursiops truncatus	3	2	3	8
Total	**127**	**64**	**50**	**241**

material, Table S1). Several different types of plastic were found in digestive tracts of the delphinid group including plastic bags and wrappers which occurred eight times, unidentified plastic items which occurred nine times, and fisheries related items which occurred six times. Fisheries items were identified in eight of the 23 stomachs which contained macrodebris. However, marine debris was not ingested by any of the animals examined during the bycatch observer programmes.

3.2.2. *Microplastic*

All the individuals which were examined for microplastics ($n = 21$, Table S1), including 19 delphinids and two beaked whales were found to contain at least one microplastic. Microplastics were found in all compartments of the digestive tracts, although the distribution throughout the digestive tract varied between individuals (Fig. 2). No baleen whales were investigated for the presence of microplastics.

A total of 598 plastic particles (0.3–16.7 mm, Fig. 3) were found

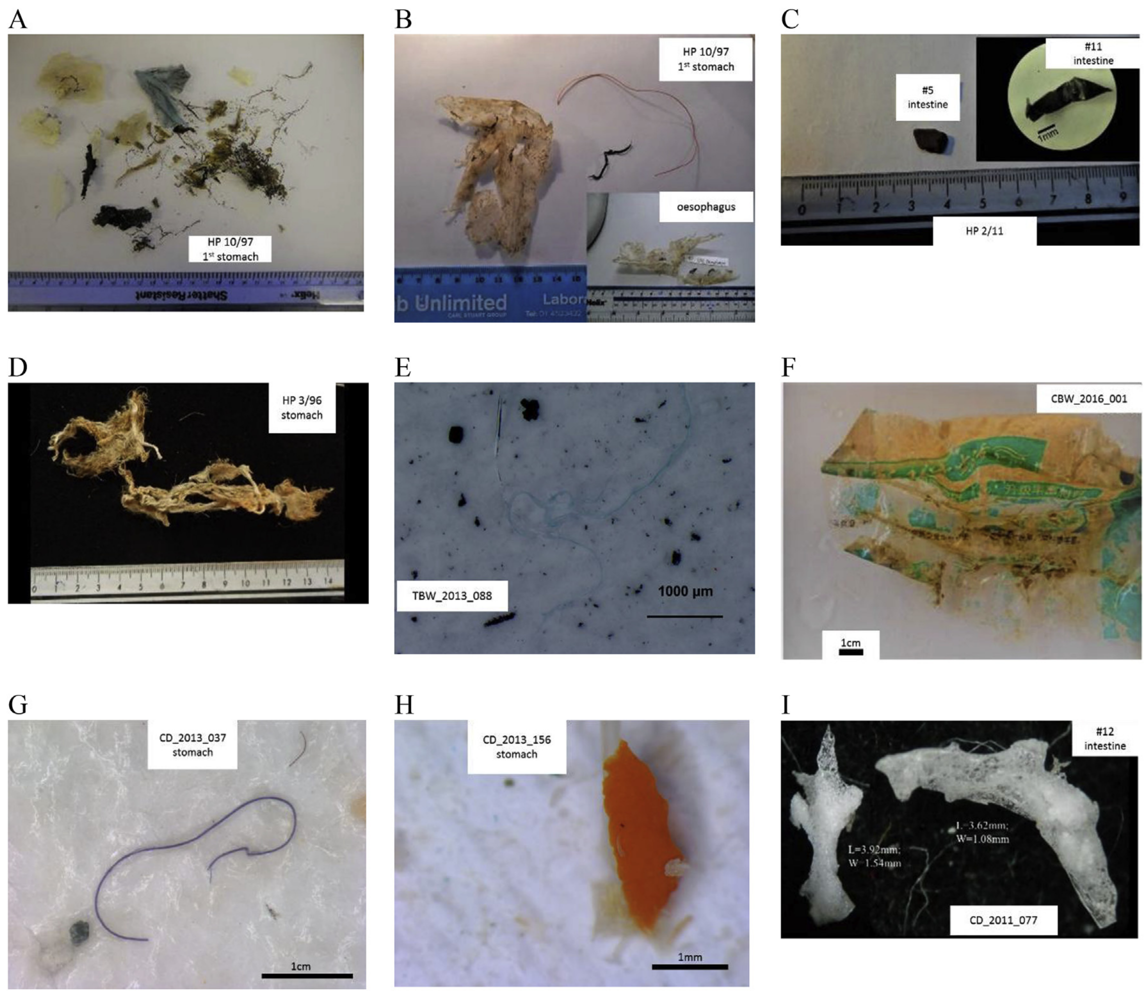

Fig. 1. Examples of macroplastic and microplastic items ingested by cetaceans stranded on Irish coasts between 1990 and 2015. Images A,B,C,D are from coastal species (HP = harbour porpoise), E.F deep diving species (TBW = True's beaked whale; CBW=Cuvier's beaked whale) and G,H,I pelagic species (CD=Common colphin). Labels on images correspond to codes in supplementary material, Table S1.

in cetacean digestive tracts using the method for small plastic items (Lusher et al., 2015). The number of particles per individual ranged from one to 88. The most common item identified were fibres (83.6%, n = 500) while the remaining items were classified as fragments (16.4%, n = 98). Nine different colours of microplastics were identified (Table 3). All yellow fragments (n = 19) came from one individual harbour porpoise, *Phocoena phocoena,* (HP_2013_004). One common dolphin, which was not analysed for microplastics using this method, contained microplastic fragments which were identified during a dietary study (CD_2011_077, Fig. 1c).

3.2.3. *Temporal trends*

No temporal trends in the presence of marine debris ingestion or in interactions with marine debris by cetaceans were identified. There was a peak in interactions and ingestions in 2013, however this might be related to an increase in the number of stranded individuals (Supplementary material, Table S1). When comparing this data set to the one compiled by Baulch and Perry (2014), the incidence of ingestion by common dolphins was 2.5 times higher than that reported in the Atlantic Ocean and on a global scale. Similarly, striped dolphins in the present study had 4.5 times the amount of plastics than global levels and 2.5 times the amount of plastic than levels reported in the Atlantic Ocean. Finally, harbour porpoises had 2.8 times the amount for the Atlantic and 2.1 times the amount reported globally (Fig. 4).

4. Discussion

Marine debris is a serious environmental issue, with the entry, distribution and accumulation of these pollutants in the marine environment significantly impacting habitats and marine biota (Law, 2017). Micro- and macro debris have been identified throughout the marine environment (Lusher, 2015), and marine mammals inhabiting these areas have been found with debris in their digestive tracts (e.g. Baulch and Perry, 2014; CBD, 2016). The results from the present study in Ireland is discussed in a global context.

4.1. *Trends in marine debris*

Levels of marine debris around the world are increasing (e.g. Law et al., 2010) and have been since the beginning of the century (CBD, 2016). Marine debris has also been identified in the Irish marine environment (Lusher et al., 2014; Martin et al., 2017; Moriarty et al., 2016). Predicting future trends around Irish coasts and surrounding waters without knowledge of input, accumulation and end points of plastic is difficult. Jambeck et al. (2015) suggested

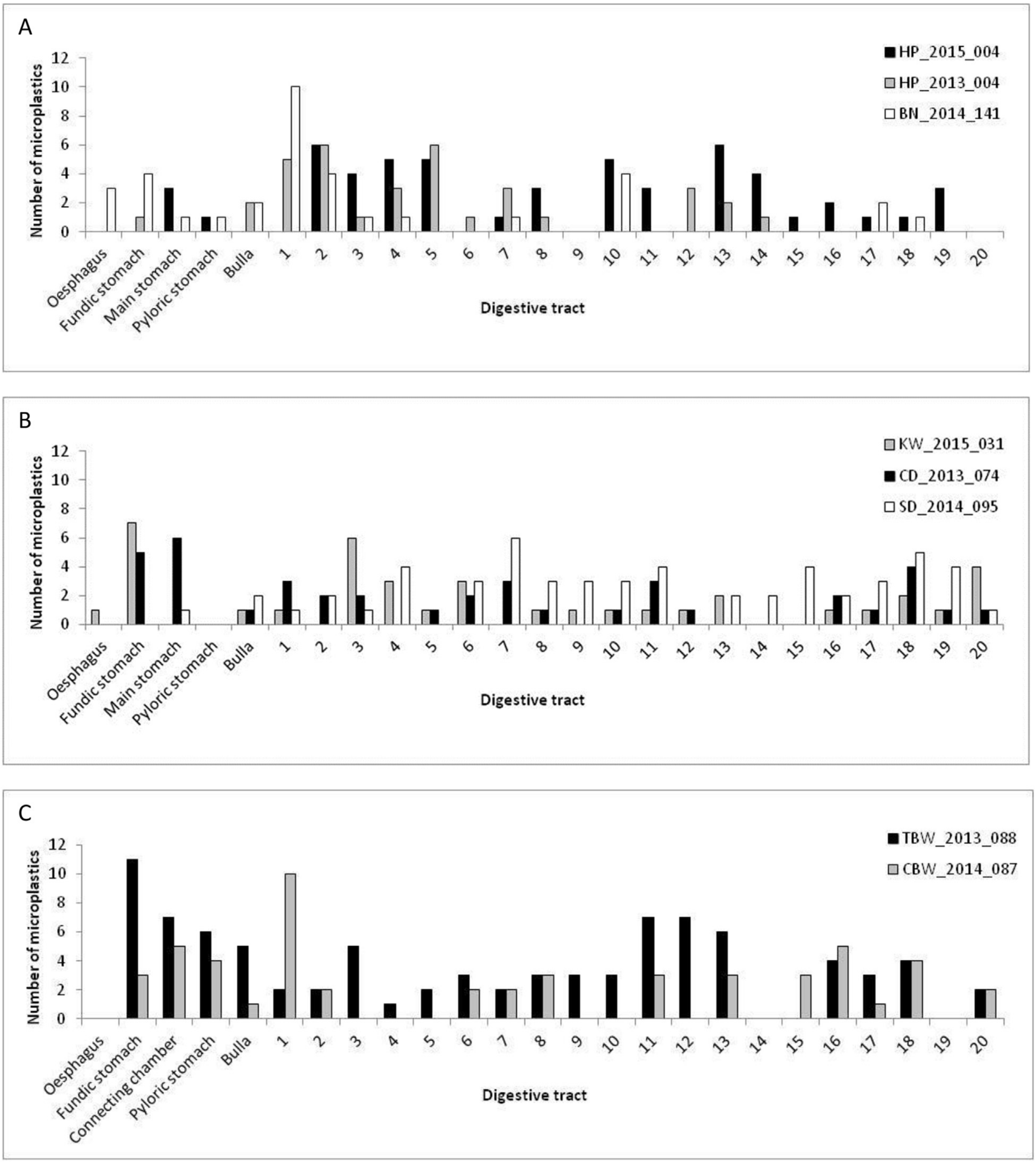

Fig. 2. Example of the distribution of microplastics in the digestive tracts of (A) coastal species, (B) pelagic species and (C) deep diving species. X-axis represents the section of the digestive tract and the numbers 1–20 are the sections of the intestines. The 20 equal length sections were determined by first measuring the entire intestine length and dividing the value by 20.

that without improvements in waste management, the cumulative quantity of plastic entering the ocean from land will increase by an order of magnitude by 2025. Low numbers of post-mortem examinations conducted on stranded cetaceans limited the identification of any temporal trends in plastic ingestion by cetaceans in the present study. A peak in ingested plastic and in the number of animals interacting with fisheries was noted in 2013, but this was likely related to a 15% increase in the number of strandings of that year, rather than an increase in ingestion (McGovern et al., 2016).

Coastal cetaceans were expected to be more exposed to marine debris sources and present higher ingestion rates, while deep diving species would be less exposed. Surprisingly, deep divers contained more plastics than coastal and pelagic individuals, especially plastic bags. Cephalopods are generally the main prey of deep diving species (Hernandez-Milian et al., 2016) and individuals might have confused plastic items for their usual prey. This hypothesis of misidentification was not possible to confirm using statistical methods due to unbalance data. In addition to prey

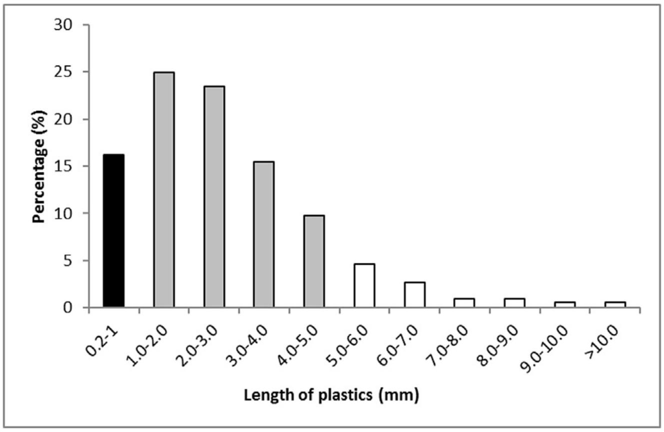

Fig. 3. Size frequency of plastics identified in cetaceans using the method for microplastic analysis. Colour bars represent different size classification of palstic, black bar, standard SI classificaion of micropalstics (<1 mm, Browne 2015), grey 5 mm-1mm which emcompassers the traditional definiation of micropalstics (Thompson et al., 2004) and white macroplastics (>5 mm).

Table 3
Breakdown of microplastic classification based by colour and type of microplastic.

Colour	Fibres	Fragment	Total
Black	92	9	101
Blue	138	37	175
Red	69	5	74
Orange	81	9	90
Yellow	1	19	20
White	3	2	5
Grey	107	2	109
Green	9	10	19
Purple	0	2	2
TOTAL	**500**	**98**	**598**

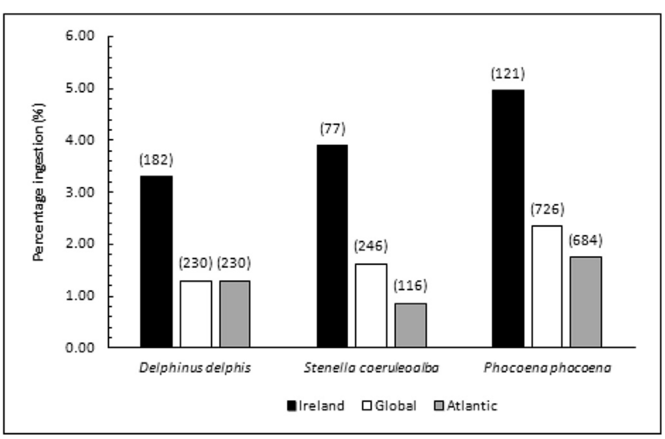

Fig. 4. Comparison of ingestion (%) by three cetacean species (Common dolphin *Delphinus delphis*, Striped dolphin *Stenella coeureoalba* and harbour porpoise *Phocoena phocoena*) between this study and global and Atlantic. Global and Atlantic data obtained from Baulch and Perry (2014). Number in the brackets above columns refer to the numbers of individuals.

confusion, plastic presence in different marine habitats may have influenced interaction. Source of debris to Irish coasts may therefore be a result of localised coastal pollution or long-range transport on ocean currents. For example, accumulation zones in the ocean such as mesoscale gyres and upwelling zones are predicted to concentrate marine debris because of their converging currents (Lusher, 2015); animals which are inhabiting Irish waters may be exposed to localised increases in marine debris due to localised currents and wind conditions as well as ocean scale transport mechanisms.

To the authors knowledge, this is the first study reporting marine debris in fin whales and Risso's dolphin in North Atlantic waters. This is only the second report globally of marine debris ingestion by humpback whales (Besseling et al., 2015) and Risso's dolphin (Shoham-Frider et al., 2002). Incidences of marine debris in True's beaked whale were previously only reported in Brazil (Souza et al., 2005), New Zealand (Constantine et al., 2014), and Ireland (Lusher et al., 2015). Interestingly, common dolphins from Ireland examined in this study had three times the amount of ingested marine debris when compared to the study by Baulch and Perry (2014). Similarly, striped dolphins and harbour porpoises presented twice the incidence of marine debris ingestion.

4.2. Sources of marine debris

Studying marine mammals can be challenging due to: (a) difficulties in collecting data, (b) lack of resources and (c) lack of homogeneity in sampling protocols between regional organisations. These difficulties are added to the challenging process of identifying the origin of marine debris, increasing the complexity of the interactions between cetaceans and marine debris. Generally, it is assumed that marine debris related to fisheries (e.g. hooks, pieces of nets, twine) have a marine origin. However, origins of other items (e.g. plastic bags, plastic sheets) may be difficult to identify because they may be directly released into the ocean or transported to the marine environment from land by wind and streams/rivers. Of all the animals that contained macro debris in this study, 34.8% contained fisheries related items including nets, fish hooks and monofilament lines. Some individuals contained debris which might have originated on land. For example, debris identified in True's beaked whales included a shotgun cartridge and an ice cream wrapper (Gassner et al., 2005; Lusher et al., 2015) both might come from land transported by rivers or through coastal littering. In a wider context, a sperm whale from Spain had a stomach full of plastic which could be sourced to local greenhouses (de Stephanis et al., 2013). Additionally, a Cuvier's beaked whale which stranded near Bergen, West Norway contained 45 plastic bags, food packaging and plastic sheets (Terje Lislevand *pers. comm.*) with unknown origin. In the case of microplastics, we cannot infer the sources in the same way as with macrodebris (Lusher et al., 2015).

It is interesting that only one animal presented yellow fragments which could have come from the same item however we cannot speculate further. Identifying the source of marine debris is difficult, especially for microdebris. Coloration may help in the identification of particles which have a synthetic origin, although this is complicated in the case of fibres which may be made from natural material. A well-established visual identification method was used in this study (Lusher et al., 2014, 2015), which is further supported by only including particles greater than 250 μm. Some particles were subjected to FTIR analysis; however, it was not possible to do this for all potential microplastics therefore this data has not been presented. The likelihood of accurate identification of synthetic particles rather than natural material was further increased due to the use of KOH in dissolving organic material from the samples. Contamination controls were also sufficient and did not indicate airborne contamination.

Expanded polystyrene (EPS) foam is another prolific item of marine debris. EPS is used for food packaging, product packaging and fisheries and aquaculture floats. It therefore has several routes into the marine environment and has been identified on many shorelines worldwide (Galgani et al., 2015). Recent unpublished data collected in Cork, Ireland, showed that 30% of plastic items in the River Lee and 25% of plastic debris collected from a beach were classified as EPS. In addition, Northern fulmar (*Fulmarus glacialis*) chicks from the Blasket Islands (south west of Ireland) contained EPS in their pellets (Hernandez-Milian *pers. obs.*). In this study, none of the animals investigated presented EPS. It was expected that EPS, as a buoyant plastic, could be found in surface waters along with prey species, e.g. herring and sardines. If prey mixes with EPS in the surface waters, ingestion of EPS could occur through incidental capture whilst targeting prey or through secondary ingestion (consuming prey already containing EPS).

4.3. Consequences of interaction

4.3.1. Entanglement

Several reports have described marine mammal entanglement (e.g. Baulch and Perry, 2014; CBD, 2016) however, its identification is still difficult to assess. Entanglement is defined as the process of being wrapped by a passive item; whilst, bycatch is defined as unwanted capture during fishing operations and could imply that an animal is caught in nets or intentionally released from nets by fishers. It can be difficult to distinguish between cetaceans which had died due to entanglement or bycatch related to fisheries, especially when the debris involved was conspicuous. Therefore, some of the animals categorized as “possible entanglement or bycatch” may have been miss-classified during initial post-mortem. A novel aspect of this study is the use of three different categories for the classification of the interaction with fisheries activities prompting the death of individuals.

4.3.2. Ingestion

Ireland's marine mammals have higher incidences of macro-debris ingestion than those reported for mammals in the Atlantic Ocean and on a global scale (Baulch and Perry, 2014; CBD, 2016). It is important to considered that the present study was conducted on a relatively local scale but over a greater temporal scale, and this might give the different values than the patchy data from other studies. Interestingly, areas of marine debris accumulation, such as the Hawaiian Islands, information on marine debris ingestion in marine mammals is scarce (Baulch and Perry, 2014). Ireland is not located in accumulation zones of macro and microdebris but higher values were found; such pollution might be related to seasonal weather conditions or flooding in combination with the country's geographical position, where it is exposed to currents and winds from the Atlantic. Other potential reasons for limited data on a global scale include low rate of strandings, lack of resources or unestablished stranding networks. Generally, there are over 100 stranding events per year along the Irish coast (McGovern et al., 2016), and results in this study cover 25 years of data collected through a well-established stranding scheme. These circumstances might contribute to a more realistic, albeit local representation of debris ingestion by marine mammals.

Sourcing the origin of ingested plastic items is difficult. Firstly, it is difficult to reconstruct the route of transport to the marine environment. Items may have originated on land or were directly introduced into the ocean. Secondly, animals may have ingested items individually, or through ingesting prey which already contained the debris, known as secondary ingestion or trophic transfer. In this study, we were unable to distinguish between direct consumption or secondary ingestion. However, the method used in this study allowed the identification of debris along the whole digestive tract which is unique as most published research to date focuses on stomachs. Interestingly, we identified debris in the intestines of some individuals when debris was absent from their stomachs.

Plastic ingestion has been considered as a consequence of confusion with prey items e.g. Teuthophagus cetaceans and turtles (Kühn et al., 2015; Lusher, 2015). These animals have been reported to usually contain low numbers of prey or no prey in their stomachs. This was not consistent with the present study and some of the individuals with plastic items contained large amounts of recent prey in their digestive tract (e.g. HP 1/03, Table S1). On the other hand, the ingestion of microplastics occurred in all animals investigated, irrespective of whether they had a recent meal. It is likely that plastic particles in marine mammals are a result of trophic transfer from their prey. Studying the number of particles in prey might provide an idea on how many microplastics are indirectly ingested by top predators (e.g. Lusher et al., 2016). The incidence of microplastics in marine mammals may be amplified through trophic transfer.

Another interesting finding was that micro and macroplastics were found along the whole digestive tract. This finding suggests that some plastics may be egested, returning to the marine environment. In the case of deep diving animals (sperm whales, beaked whales), the particles may be released into the deep-sea as faeces sink rapidly (Roman and McCarthy, 2010). Once in the deep-sea plastic may form part of the detritus and become re-mobilised into the food web. Pathologies resulting from marine debris ingestion have been described, such as gastric rupture resulting from impacted debris (e.g. de Stephanis et al., 2013; CBD, 2016); in contrary, this study did not present any pathologies linked to ingested marine debris.

During the last few years, research into the effects of microplastics following uptake by biota have been studied in different organisms including invertebrates (e.g. Wright et al., 2013; Sussarellu et al., 2016) and vertebrates (e.g. Rochman et al., 2013). Generally, microplastic particles have not been linked to sub-lethal effects in organisms however their associated pollutants have (e.g. Rochman et al., 2013). It appears that microparticles act as small sponges attracting different pollutants such as organochlorates and heavy metals. High levels of microplastic ingestion might facilitate pollutant availability and therefore pollutants may bioaccumulate in organisms producing sub-lethal effects. In the case of marine mammals, research has identified plastic derivatives, including phthalates in the blubber of fin whales (Fossi et al., 2012); however, it is unknown whether micro or macroplastic might be the source of these chemicals. Knowledge of the correlation between the incidence of microplastics and pollutant bioaccumulation in top predators should be a priority in future research.

5. Conclusion

Awareness of marine pollution within Ireland has increased in recent years and there has been a large focus by different stakeholders in understanding its implications. This study has provided a thorough evaluation of the interactions between cetaceans and marine debris in Irish waters. It has compiled additional data on macro debris to those collected during a recent global review. In addition, this comprehensive study reports microplastics in several species of cetacean. Although no trends were found in the data, it is important to acknowledge the limitations of different sampling regimes. For example, early studies did not utilise standardised methods for identifying small plastic items. Future studies should consider the approaches presented in this publication as a standardised method to study trends in micro and macroplastic. This study also shows that there were more incidences of plastic ingestion in Irish waters than those reported globally for similar species, suggesting the incidences of marine debris are underestimated elsewhere. Moving forward, compiling international data, in a similar way as presented here, is paramount as it will provide the information required to carry out a global metaanalysis on debris occurrence on both macro and microplastics. In fact, as indicated in our results, the absence of macroplastics does not mean the absence of microplastics. A more in-depth knowledge of this new marine contaminant is required before we can begin to understand the implications for megafauna.

Acknowledgements

AL was funded by an Irish Research Council Postgraduate Scholarship (Project ID: GOIPG/2013/248) and a GMIT 40th anniversary studentship. GHM was funded under the Beaufort Ecosystem Approach to Fisheries Management award, as part of the Irish Government's National Development Plan (NDP), the Beaufort Marine Research Award is grant aided by the Department of Communications, Energy and Natural Resources (DCENR) and the Department of Agriculture, Fisheries and Food (DAFF) under the Strategy for Science Technology and Innovation (SSTI) and the Sea Change Strategy. Funding for sampling was also received from several sources over the years and we gratefully acknowledge the National Parks and Wildlife Service, The Heritage Council of Ireland; European Commission ECFAIR contract FAIR-CT95-0523: Assessment and Reduction of the By-catch of Small Cetaceans of Small Cetaceans (BY-CARE); contract EVK3-2000-00027: Bioaccumulation of persistent organic pollutants in small cetaceans in European waters: transport pathways and impact on reproduction (BIOCET) and Science Foundation Ireland. The authors would like to thank Mick O'Connell from the IWDG for providing the historical data, the IWDG stranding network and all who helped during port-mortem examination. We are grateful to the reviewers who commented on previous drafts of this manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2017.09.070.

References

Baulch, S., Perry, C., 2014. Evaluating the impacts of marine debris on cetaceans. Mar. Pollut. Bull. 80 (1), 210–221.

Besseling, E., Foekema, E.M., Van Franeker, J.A., Leopold, M.F., Kühn, S., Rebolledo, E.B., Heße, E., Mielke, L., IJzer, J., Kamminga, P., Koelmans, A.A., 2015. Microplastic in a macro filter feeder: humpback whale *Megaptera novaeangliae*. Mar. Pollut. Bull. 95 (1), 248–252.

Bravo-Rebolledo, E.L., van Franeker, J.A., Jansen, O.E., Brasseur, S.M., 2013. Plastic ingestion by harbour seals (*Phoca vitulina*) in The Netherlands. Mar. Pollut. Bull. 67 (1), 200–202.

Carretta, J.V., Danil, K., Chivers, S.J., Weller, D.W., Janiger, D.S., Berman-Kowalewski, M., Hernandez, K.M., Harvey, J.T., Dunkin, R.C., Casper, D.R., Stoudt, S., 2016. Recovery rates of bottlenose dolphin (*Tursiops truncatus*) carcasses estimated from stranding and survival rate data. Mar. Mammal Sci. 32 (1), 349–362.

CBD, 2016. Marine Debris: Understanding, Preventing and Mitigating the Significant Adverse Impacts on Marine and Coastal Biodiversity. Technical Series No.83. Secretariat of the Convention on Biological Diversity, Montreal, 78 pages.

Constantine, R., Carroll, E., Stewart, R., Neale, D., Van Helden, A., 2014. First record of True's beaked whale *Mesoplodon mirus* in New Zealand. Mar. Biodivers. Rec. 7.

Curran, E., Hernandez-Milian, G., Rogan, E., Whooley, P., 2014. Common dolphins in the River lee at Cork city. Ir. Naturalists' J. 33 (2), 142.

de Stephanis, R., Giménez, J., Carpinelli, E., Gutierrez-Exposito, C., Cañadas, A., 2013. As main meal for sperm whales: plastics debris. Mar. Pollut. Bull. 69 (1), 206–214.

Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. AMBIO A J. Hum. Environ. 32, 380–384.

Fossi, M.C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., Minutoli, R., 2012. Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*). Mar. Pollut. Bull. 64 (11), 2374–2379.

Galgani, F., Hanke, G., Werner, S., Oosterbaan, L., Nilsson, P., Fleet, D., Kinsey, S., Thompson, R.C., van Franeker, J., Vlachogianni, T., Scoullos, M., 2013. Guidance on Monitoring of Marine Litter in European Seas. Available online. European Commission. http://hdl.handle.net/10508/1649.

Galgani, F., Hanke, G., Maes, T., 2015. Global distribution, composition and abundance of marine litter. In: Marine anthropogenic Litter. Springer International Publishing, pp. 29–56.

Gassner, I., Rogan, E., Bruton, T., 2005. A live stranding of True's beaked whale Mesoplodon mirus True. Ir. Naturalists' J. 28 (4), 170.

Hernandez-Milian, G., 2014. Trophic Role of Small Cetaceans and Seals in Irish Waters. PhD thesis. University College Cork, Ireland, 403pp.

Hernandez-Milian, G., Berrow, S., Santos, M.B., Reid, D., Rogan, E., 2015a. Insights into the trophic ecology of bottlenose dolphins (*Tursiops truncatus*) in Irish waters. Aquat. Mamm. 41 (2), 226–239.

Hernandez-Milian, G., Santos, M.B., Reid, D., Rogan, E., 2015b. Insights into the diet of Atlantic white-sided dolphins (*Lagenorhynchus acutus*) in the Northeast Atlantic. Mar. Mammal Sci. 32 (2), 735–742.

Hernandez-Milian, G., Brophy, J., Rogan, E., 2016. Deep sea predators in Irish waters and their trophic relevance. In: 30th European Cetacean Society Conference. Madeira, Portugal.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Kühn, S., Rebolledo, E.L.B., van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Marine Anthropogenic Litter. Springer International Publishing, pp. 75–116.

Kuiken, T., Garcia-Hartmann, M., 1993. Cetacean pathology: dissection techniques and tissue sampling. In: Proceedings of the European Cetacean Society Workshop, Leiden, the Netherlands, 13–14 September 1991. ECS Newsletter, pp. 1–39.

Law, K.L., 2017. Plastics in the marine environment. Annu. Rev. Mar. Sci. 9, 205–229.

Law, K.L., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329 (5996), 1185–1188.

Lusher, A., 2015. Microplastics in the marine environment: distribution, interactions and effects. In: Marine Anthropogenic Litter. Springer International Publishing, pp. 245–307.

Lusher, A.L., Burke, A., O'Connor, I., Officer, R., 2014. Microplastic pollution in the Northeast Atlantic Ocean. Mar. Pollut. Bull. 88 (1–2), 325–333.

Lusher, A.L., Hernandez-Milian, G., O'Brien, J., Berrow, S., O'Connor, I., Officer, R., 2015. Microplastic and macroplastic ingestion by a deep diving, oceanic cetacean: the True's beaked whale *Mesoplodon mirus*. Environ. Pollut. 199, 185–191.

Lusher, A.L., O'Donnell, C., Officer, R., O'Connor, I., 2016. Microplastic interactions with North Atlantic mesopelagic fish. ICES J. Mar. Sci. J. du Conseil 73 (4), 1214–1225.

Martin, J., Lusher, A., Thompson, R.C., Morley, A., 2017. The deposition and accumulation of microplastics in marine sediments and bottom water from the Irish continental shelf. Sci. Rep. 7, 10772.

McGovern, B., Culloch, R., O'Connell, M., Berrow, S., 2016. Temporal and spatial trends in stranding records of cetaceans on the Irish coast, 2002–2014. J. Mar. Biol. Assoc. U. K. 1–13.

Moriarty, M., Pedreschi, D., Stokes, D., Dransfeld, L., Reid, D.G., 2016. Spatial and temporal analysis of litter in the celtic sea from groundfish survey data: lessons for monitoring. Mar. Pollut. Bull. 103 (1), 195–205.

Nelms, S.E., Duncan, E.M., Broderick, A.C., Galloway, T.S., Godfrey, M.H., Hamann, M., Lindeque, P.K., Godley, B.J., 2015. Plastic and marine turtles: a review and call for research. ICES J. Mar. Sci. J. du Conseil fsv165.

Peltier, H., Dabin, W., Daniel, P., Van Canneyt, O., Dorémus, G., Huon, M., Ridoux, V., 2012. The significance of stranding data as indicators of cetacean populations at sea: modelling the drift of cetacean carcasses. Ecol. Indic. 18, 278–290.

Rochman, C.M., 2015. The complex mixture, fate and toxicity of chemicals associated with plastic debris in the marine environment. In: Marine Anthropogenic Litter. Springer International Publishing, pp. 117–140.

Rochman, C.M., Hoh, E., Kurobe, T., Teh, S.J., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep. 3, 3263.

Rogan, E., Mackey, M., 2007. Megafauna bycatch in drift nets for albacore tuna (*Thunnus alalunga*) in the NE Atlantic. Fish. Res. 86, 6–14.

Roman, J., McCarthy, J.J., 2010. The whale pump: marine mammals enhance primary productivity in a coastal basin. PloS one 5 (10), e13255.

Ryan, C., Berrow, S.D., McHugh, B., O'Donnell, C., Trueman, C.N., O'Connor, I., 2014. Prey preferences of sympatric fin (*Balaenoptera physalus*) and humpback (*Megaptera novaeangliae*) whales revealed by stable isotope mixing models. Mar. Mammal Sci. 30 (1), 242–258.

Shoham-Frider, E., Amiel, S., Roditi-Elasar, M., Kress, N., 2002. Risso's dolphin (*Grampus griseus*) stranding on the coast of Israel (eastern Mediterranean). Autopsy results and trace metal concentrations. Sci. Total Environ. 295 (1–3), 157–166.

Souza, S.P., Siciliano, S., Cuenca, S., Sanctis, B., 2005. A True's beaked whale (*Mesoplodon mirus*) on the coast of Brazil: Adding a new beaked whale species to the western Tropical Atlantic and South America. Lat. Am. J. Aquatic Mamm. 4 (2), 129–136.

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E.J., Le Goïc, N., Quillien, V., Mingant, C., Epelboin, Y., Corporeau, C., 2016. Oyster reproduction is affected by exposure to polystyrene microplastics. Proc. Natl. Acad. Sci. 113 (9), 2430–2435.

UNEP, 2016. Marine plastic Debris and Microplastics – Global Lessons and Research to Inspire Action and Guide Policy Change. United Nations Environment Programme, Nairobi.

van Franeker, J.A., Law, K.L., 2015. Seabirds, gyres and global trends in plastic

pollution. Environ. Pollut. 203, 89–96.
Wall, D., Murray, C., O'Brien, J., Kavanagh, L., Wilson, C., Ryan, C., Glanville, B., Williams, D., Enlander, I., O'Connor, I., McGrath, D., Whooley, P., Berrow, S., 2013. Atlas of the Distribution and Relative Abundance of Marine Mammals in Irish Offshore Waters 2005-2011. IrishWhale and Dolphin Group, Merchants Quay, Kilrush, Co. Clare.
Wells, R.S., Allen, J.B., Lovewell, G., Gorzelany, J., Delynn, R.E., Fauquier, D.A., Barros, N.B., 2015. Carcass-recovery rates for resident bottlenose dolphins in Sarasota Bay, Florida. Mar. Mammal Sci. 31 (1), 355–368.
Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23 (23), R1031–R1033.