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The impact of debris on marine life

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ABSTRACT

Marine debris is listed among the major perceived threats to biodiversity, and is cause for particular concern due to its abundance, durability and persistence in the marine environment. An extensive literature search reviewed the current state of knowledge on the effects of marine debris on marine organisms. 340 original publications reported encounters between organisms and marine debris and 693 species. Plastic debris accounted for 92% of encounters between debris and individuals. Numerous direct and indirect consequences were recorded, with the potential for sublethal effects of ingestion an area of considerable uncertainty and concern. Comparison to the IUCN Red List highlighted that at least 17% of species affected by entanglement and ingestion were listed as threatened or near threatened. Hence where marine debris combines with other anthropogenic stressors it may affect populations, trophic interactions and assemblages.

1. Introduction

Marine habitats are spoiled with man-made debris, from the poles to the equator and from shorelines, estuaries and the sea surface to the depths of the ocean (Thompson et al., 2009). The incidence of marine debris is cause for concern for a number of reasons. It is known to be harmful to organisms and to human health (Coe and Rogers, 1997; Derraik, 2002; Gregory, 2009; Rochman et al., 2013), it has potential to increase the transport of organic and inorganic contaminants (Gaylor et al., 2012; Holmes et al., 2012; Mato et al., 2001; Rochman et al., 2012; Teuten et al., 2009), it presents a hazard to shipping, and it is aesthetically detrimental, thus generating negative socio-economic consequences (Mouat et al., 2010). The scale of the marine debris problem and its potential to negatively impact biodiversity has not been widely evaluated.

Marine debris is defined as any persistent manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment (Coe and Rogers, 1997; Galgani et al., 2010). It includes items made or lost by people, and those deliberately discarded into or unintentionally lost in the marine environment including, among others, items of plastic, wood, metal, glass, rubber, clothing and paper (Galgani et al., 2010; OSPAR, 2007). The material types most commonly found in marine debris are glass, metal, paper and plastic (OSPAR, 2007), and it is readily apparent from the published literature that on a global scale, plastic items are consistently among the most numerically abundant types of marine debris (OSPAR, 2007; Thompson et al., 2009; UNEP-CAR/RCU, 2008; UNEP, 2005, 2009). There are a number of transport pathways by which debris enters the marine environment, including rivers, drainage or sewerage systems, and wind, and once there, debris persists, with its durability making it resistant to degradation (Barnes et al., 2009).

Plastic debris is of particular concern due to its abundance, and its persistence in the environment, which makes it a ubiquitous category of marine debris. Global production of plastics has increased considerably over the last few decades from 5 million tonnes per year in the 1960s to 280 million tonnes per year in 2011 (PlasticsEurope, 2012). The absolute quantity of plastic debris that enters the marine environment is, however, unknown. Sampling is typically restricted to the sea surface in coastal waters and shorelines, and temporal trends have been found to vary between regions (Barnes et al., 2009; Derraik, 2002). It is evident, however, that despite efforts to remove debris from the marine environment, and restrictions on dumping at sea, quantities of plastic are increasing in some locations (Harper and Fowler, 1987; Thompson et al., 2004; Goldstein et al., 2012). In many areas quantities are highly variable but stable and for some debris types there is evidence of a decrease, but it seems inevitable that since most plastics will not biodegrade, quantities in the marine environment will increase over time (Andrady, 2011). It is likely that the lack of consistent trends in temporal data represent the movement of debris to compartments where monitoring is minimal such as deep sea sediments Woodall et al. (2014) and offshore

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areas, and also the fragmentation of plastic debris into pieces smaller than those routinely sampled.

The impact of marine debris on marine life is of particular concern, and effects can be wide reaching (Fig. 1), with the consequences of ingestion and entanglement considered to be harmful. Reports in the literature began in the 1960s (Brongersma, 1968; Caldwell et al., 1965; Holgersen, 1961) with fatalities being well documented for birds, turtles, fish and marine mammals (Laist, 1997; Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, 2012). Debris has also been shown to provide an additional surface for the rafting of organisms (Aliani and Molcard, 2003; Barnes and Fraser, 2003; Barnes and Milner, 2005; Carpenter et al., 1972; Winston et al., 1997) which has implications for the transport of non-native species, and to provide new habitat for colonisation (Ayaz et al., 2006; Carr et al., 1985; Donohue et al., 2001; Goldstein et al., 2012; Good et al., 2010; Pace et al., 2007) which may be particularly important where it provides hard substrate in areas that are otherwise predominantly of soft sediment (Pace et al., 2007). It may also cause physical changes to habitats (Aloy et al., 2011; Carson et al., 2011), in particular coral reefs (Al-Jufaili et al., 1999; Chiappone et al., 2005; Chiappone et al., 2002; Donohue et al., 2001; Richards and Beger, 2011). Particular concern is associated with species listed on the IUCN Red List as these are at the greatest risk of extinction from a diverse range of impacts.

The incidence of marine debris and its potential to cause harm has resulted in it being recognised as a global problem (STAP, 2011; Sutherland et al., 2010) and its listing among the major percieved threats to marine biodiversity (Gray, 1997). The problem has been recognised in global and regional agreements such as the decisions of the 11th Conference of the Parties to the Convention on Biological Diversity (CBD COP 11 Decision XI/18), the 10th Conference of the Parties to the Convention on the Conservation of Migratory Species of Wild Animals (CMS Resolution 10.4), the International Convention for the Prevention of Pollution From Ships (MARPOL) Annex V, and the EU Marine Strategy Framework Directive (MSFD). Furthermore, the cumulative impacts of plastic resins on human health and the environment have led to proposals enacting legislation and policies classifying the most harmful types of plastic debris as hazardous waste (Rochman et al., 2013).

Fig. 1. (A) Debris discarded on the shore near a coral reef, Ta'u Island, American Samoa (Courtesy of Wolcott Henry/Marine Photobank). (B) Debris extracted from the carcass of a Laysan Albatross chick, Kure Atoll, Hawaii (Courtesy of Claire Fackler, NOAA Marine Sanctuaries/Marine Photobank). (C) Debris incorporated into the nests of a Northern Gannet (*Morus bassanus*) on Grasholm, UK (Courtesy of Dr. Stephen Votier, Plymouth University). (D). Marine debris and derelict fishing gear among albatross nesting habitat. Midway Atoll, Northwestern Hawaiian Islands (Courtesy of Steven Siegel/Marine Photobank). (E) Turtle entangled in plastic rope in Caribbean (photo: UNEP-CAR/RCU, 2008).

Without sufficient knowledge on the scope of the problem it is, however, difficult to develop legislation that is both adequate and effective.

Literature to date has highlighted the problems associated with the presence of debris in the marine environment and discussed its impacts and implications on marine organisms (Derraik, 2002; Gregory, 2009; Laist, 1997, 1987). The last comprehensive review was conducted by Laist (1997) who reported 267 species interacting with marine debris (becoming entangled or ingesting debris), but provided no synthesis of numbers of individuals impacted, thus restricting our understanding of the scale of the problem. It is evident that high degrees of uncertainty exist relating to marine debris data, including, in particular the amount of debris entering the marine environment, what happens to this debris and the extent of its impact on marine biodiversity. Following this, Derraik (2002) reviewed the pollution of the marine environment by plastic debris, in relation to entanglement and ingestion, use of plastic debris by invasive species, and absorption of pollutants by species. Since this time, however, no further review has been completed, and it is therefore timely to evaluate the extent to which the marine debris problem has changed over time.

This paper therefore aims to provide an update to the work of Derraik (2002) reviewing and synthesising current knowledge of the effects of marine debris on marine organisms, presenting data on the number of individuals and number of species for which literature exists documenting encounters with marine debris and also the number of reports that have been published. The opportunity for this work arose from a report the authors were invited to prepare for the CBD and Scientific and Technical Advisory Panel of the Global Environment Facility (STAP). This formed an extensive review (61 pages) outlining the impact of marine debris on biodiversity together with strategies to address the challenge of marine debris (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, 2012). The current paper presents a succinct summary of some of the key messages from that report and builds upon it, providing a peer reviewed update on (Derraik, 2002). It is intended that the results will contribute to global understanding of the marine debris problem, providing up to date estimates of the numbers of species and individuals affected by marine debris. The results are also compared to species conservation status as defined by IUCN to provide context for the scale and potential consequences of the impacts.

2. Materials and methods

An extensive literature review was conducted, focussing on peer reviewed publications and reports in grey literature. Once collated, the literature was divided into four key topics, namely those 1) documenting ingestion of or entanglement in marine debris by organisms, 2) reporting species rafting on debris, 3) where debris creates new habitat for colonisation, and 4) where it causes physical damage to ecosystems. Electronic key word searches were performed using Web of Science, Google Scholar and Google to identify literature. Key words used for debris included: marine debris, floating marine debris, marine litter, debris, plastic, metal, glass and paper, and for effects included: impact, entanglement, ingestion, rafting, habitat, ecosystem, invasive, alien and biodiversity. The reference list from Laist (1997) and papers which referenced other studies that had not already been captured were also examined and all relevant traceable sources used.

Contact by email was made with key researchers and the coordinators of the UNEP Regional Seas Programmes to identify additional literature, in particular grey literature. Data was compiled in terms of the frequency of different types of encounter, including (where relevant) species name, taxonomic grouping, number of individuals, debris type, type of encounter, and location of encounter. Where additional reference was made to specific impacts or harm these were also noted, for example lacerations, gut obstruction and death.

Once the data were collated, analyses were undertaken to determine the number of papers reporting encounters, number of species involved, number of individuals involved, debris type and report location. The paper did not aim to test hypotheses, but to provide summary statistics on mean levels of encounter, including means and measures of variability where possible. Species were included on the species list when in the original publication they were either 1) identified to species level or 2) identified to a lower taxonomic level but where it could be confirmed that they were not included within those already captured. Species were grouped taxonomically as appropriate for the ingestion/entanglement and rafting categories, with analyses focussing on the groups with the greatest numbers of species and individuals reported.

The literature review process did not include assessment of the reliability of each report. Literature was screened to ensure that the focus was on the most reliable sources, but the conclusions of the authors regarding whether encounters with marine debris had caused harm to the organisms were not questioned. The objective of this work was to present the body of evidence, and it was accepted that some subjectivity in different researcher's assessment of harm was inherent, but unavoidable. The reference list refers only to those references mentioned within this text and is not a full list of all reviewed papers. Those mentioned are characteristic, and indicative of the general trends identified by the review.

Some limitations were identified in the data currently available, with a lack of reports considering low trophic level organisms, and a geographical reporting bias. Furthermore, the differing aims of studies which have reported encounters result in different information being provided; hence not all reports provided detail of the size or number of items ingested, the number of individuals affected or the impact of the encounters and whether harm was caused. It is thought that the impact of microplastic (defined as plastic material <5 mm (Arthur et al., 2009)) in particular is under-represented due to lack of information relating to the size of debris ingested. These limitations are discussed.

3. Results

A total of 340 original publications were identified documenting encounters between marine debris and marine organisms. These reported encounters for a total of 693 species. 76.5% of all reports listed plastic amongst the debris types encountered by organisms making it the most commonly reported debris type. 92% of all encounters between individual organisms and debris were with plastic.

Encounters between organisms and marine debris were first reported in the 1960s (Brongersma, 1968; Caldwell et al., 1965; Holgersen, 1961). Since that time there has been an increased frequency of reporting, both for numbers of species and numbers of individuals effected (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, 2012). The average number of documents reporting ingestion and entanglement encounters as well as those reporting rafting has remained fairly constant since the 1980s (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, 2012).

When considering reporting location, regions with the greatest number of reports included the east coast of North America ($n = 56$), Australasia ($n = 54$), the west coast of North America

(n = 54) and Europe (n = 52). Regions where reporting was low included Antarctica (n = 6), the east and west coasts of Africa (n = 7 and n = 5 respectively) the west coast of South America (n = 6) and the Arctic (n = 5).

3.1. Entanglement and ingestion

Of the 340 original publications examined, a total of 292 reported the incidence of ingestion or entanglement encounters between marine debris and organisms. These reported encounters for 44,006 individuals from 395 species, and represented a 49% increase over the 267 species reported by Laist (1997). Reports of ingestion were made for 13,110 individuals from 208 species and reports of entanglement were made for 30,896 individuals from 243 species. Plastic was the material for which encounters between individuals and debris were most commonly reported for cases of both entanglement and ingestion (92%). When this category was subdivided into debris type it was apparent that the majority of entanglement incidents were encounters between the individual and plastic rope and netting (71%), whereas the majority of ingestion incidents were between the individual and plastic fragments (37%) (Fig. 2a). When the data are considered according to species, encounters were again most strongly associated with plastic rope and netting for cases of entanglement (55%), and with plastic fragments (31%) for ingestion (Fig. 2b). Cases of both entanglement and ingestion were fewest for the debris types: glass, metal and paper (Fig. 2).

Thirty-five percent more papers reported entanglement (n = 178) than ingestion (n = 132), and reports were most commonly made for sea turtles, marine mammals and sea birds. Reports of entanglement in marine debris by species were most numerous for the northern right whale (*Eubalaena glacialis*), (n = 38), the green sea turtle (*Chelonia mydas*), (n = 19), and hawksbill turtle (*Eretmochelys imbricata*), (n = 15), and reports of the incidence of ingestion of marine debris by species were most numerous for the green sea turtle (*C. mydas*), (n = 20), northern fulmar (*Fulmaris glacialis*), (n = 20) and loggerhead turtle (*Caretta caretta*), (n = 18). Species with the greatest number of individuals ingesting debris were the northern fulmar (*F. glacialis*), (n = 3444), Laysan albatross (*Phoebastria immutabilis*), (n = 971) and greater shearwater (*Puffinus gravis*), (n = 895), and with the greatest number of individuals becoming entangled in debris were

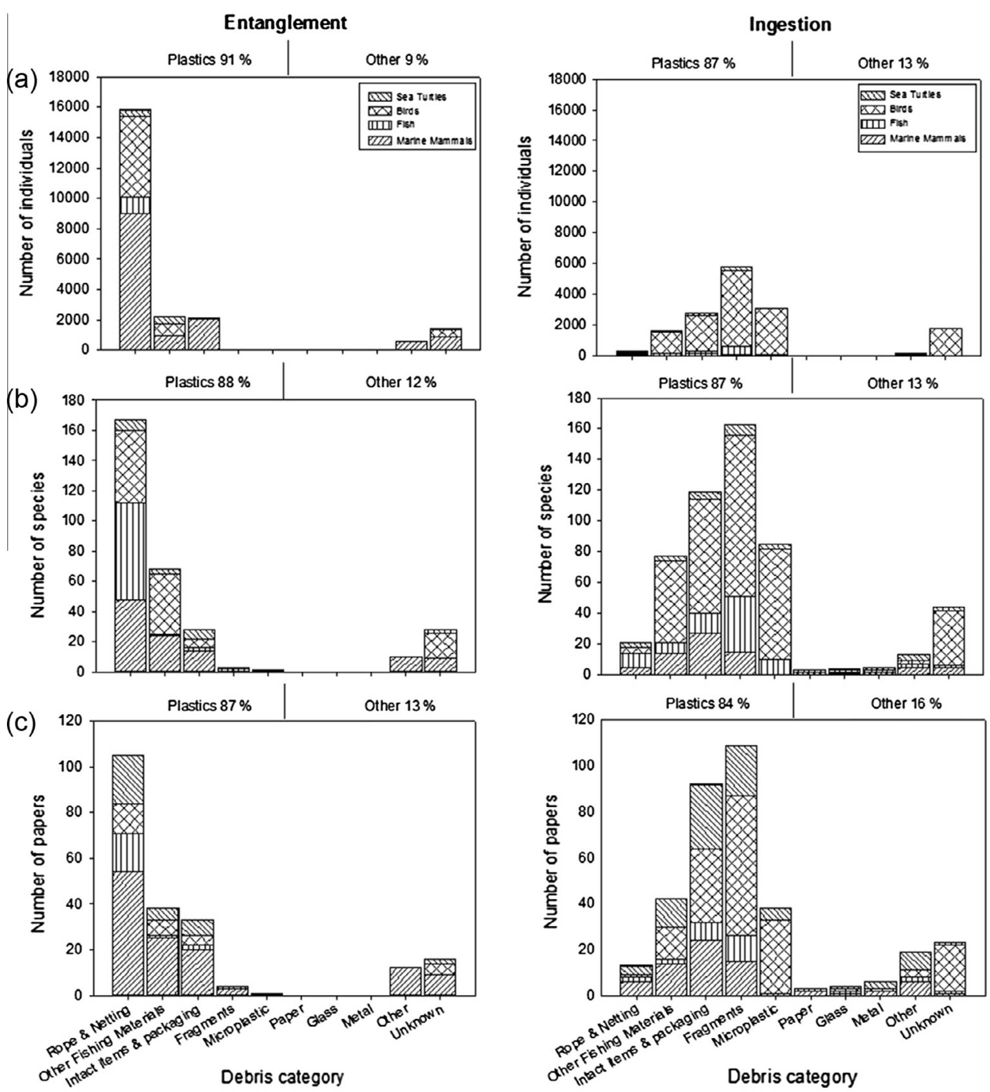

Fig. 2. Reports of entanglement and ingestion caused by marine debris according to number of (a) individuals, (b) species, and (c) documents/papers per debris type (Rope and netting, other fishing materials (mainly lines, pots), intact items and packaging, fragments > 5 mm, microplastic < 4.99 mm), glass, metal, paper, other (e.g. rubber) and unknown. Bars are divided by impact according to taxonomic grouping – marine mammals, birds, fish, sea turtles. The number of species is greater than 395 as it accounts for species encountering more than one debris type, and total number of papers is greater than 292 as it accounts for papers reporting impacts on more than one species. Data presented are for all reported encounters identified in the published literature.

the northern fur seal (*Callorhinus ursinus*), ($n = 3835$), Californian sea lion (*Zalophus californianus*), ($n = 3587$), and Atlantic puffin (*Fratercula arctica*), ($n = 1674$).

Consequences of encounters were considered where documented, suggesting that direct harm or death (defined as where the individual was reported to have been injured or killed as a direct result of the encounter with marine debris) is a more common consequence of entanglement than ingestion, with 79% of cases resulting in direct harm or death for cases of entanglement compared to 4% of cases of ingestion (Fig. 3).

All known species of sea turtle, 54% of all species of marine mammal, and 56% of all species of seabird were affected by entanglement in or ingestion of marine debris and the percentage of encounters has increased for all taxonomic groups since the Laist (1997) review (Table 1). Whilst the number of reports of species of fish encountering marine debris remains low (0.68%), the number of species affected has almost doubled since 1997.

Data on species that had encountered marine debris were cross referenced with species conservation status using the IUCN Red List to determine how many of those already known to be threatened were encountering debris. From this, it was apparent that approximately 17% of species ingesting or becoming entangled in marine debris were listed as near threatened, vulnerable, endangered or critically endangered (Fig. 3). Reports documenting impacts on critically endangered Hawaiian monk seal (*Monachus schauinslandi*), ($n = 215$); endangered loggerhead turtle, ($n = 755$); vulnerable northern fur seal, ($n = 3835$), and near threatened sooty shearwater, ($n = 1122$) were of particular concern due to the numbers of individuals involved (Fig. 4).

3.2. Potential for debris to provide new habitat

Numerous man made surfaces have been added to the marine environment, and marine debris contributes to this. These are most commonly coastal structures such as harbour walls and coastal defences, and artificial reefs which result from purposeful introduction of additional surfaces. Whilst the contribution of marine debris to this is slim, it does represents the addition of hard substrata into the sea, providing new surfaces for colonisation by microorganisms and macrobiota (Harrison et al., 2011; Whal, 1989; Ye and Andrady, 1991), and influencing the relative abundance of organisms within local assemblages (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, 2012). The impact of this will likely be more substantial in areas away from the coastal zone where other man made habitats are scarce.

Six papers were identified that described this, listing a total of 85 taxa (both mobile and sessile) using marine debris as habitat from 12 taxonomic groups (Table 2). Number of individuals was not commonly reported, often as organisms were colonial. Four of the papers reported colonisation of derelict fishing gear by mobile and sessile species (Ayaz et al., 2006; Carr et al., 1985; Donohue et al., 2001; Good et al., 2010), highlighting an effect aside from the destructive 'ghost fishing' with which they are usually associated.

3.3. Dispersal via rafting, including transport of invasive species

The dispersal of species in the marine environment largely depends on oceanic currents, but, increasingly the range of species with no pelagic larval stage has expanded, suggesting that rafting on man-made objects is playing a role in their spread (Thiel and Gutow, 2005). Species have always rafted on natural materials such as wood, sargassum and volcanic pumice (Thiel and Gutow, 2005), but increased industrialisation has opened new pathways such as the transport of organisms in the ballast water of ships and via aquaculture, both of which are known to be substantial contributors to species dispersal, and also to the transport of invasive species (Molnar et al., 2008). Marine debris is now contributing to the rafting and transport of organisms, with the potential for floating debris such as plastic to travel great distances.

Thirty-four reports were identified reporting organisms rafting on debris for 259 species. Numbers of individuals were seldom reported, so values are not presented. When considering the materials comprising the rafting debris, intact items and packaging accounted for 40% of all reported encounters with species, followed by fragments (36%), rope and netting (17%), other fishing material (1.50%) and microplastics (1.50%), (Fig. 5). Of the species identified, only 6 were listed as invasive and were described in a total of 4 reports. It is however, expected that this is an underrepresentation as the number of reports is low and not all reports identified organisms to species level.

3.4. Assemblage level effects

Evidence for assemblage level effects were very limited; suggesting that such effects are difficult to quantify rather than that they do not exist. A total of eight references were identified. These documented and suggested likely effects on coral reefs (Al-Jufaili et al., 1999; Chiappone et al., 2005; Chiappone et al., 2002; Donohue et al., 2001; Richards and Beger, 2011), soft sediment habitats (Uneputty and Evans, 1997) and sandy intertidal sediments (Aloy et al., 2011; Carson et al., 2011).

Chiappone et al. (2005) reviewed the consequences of the loss of fishing gear on coral reef and hard bottom sites in the Florida Keys, finding that hook and line gear was responsible for 84% of impacts to sponges and cnidarians with tissue abrasion causing partial or total mortality. They did not attempt to link the quantity of debris to the damage caused, but it is clear from their assessment that debris had negative impacts on the benthic assemblage. Richards and Beger (2011) identified similar consequences from the presence of marine debris in a lagoon in the Republic of the Marshall Islands, finding that coral cover significantly decreased as debris cover increased, again suggesting assemblage level effects.

In soft sediment habitats, Uneputty and Evans (1997) found that marine debris accumulating on the seabed in Ambon Bay, Indonesia increased the abundance of meiofauna and decreased that of diatoms when compared to areas without debris, although no change was noted for macrofauna.

Not all studies were able to directly link their findings to assemblage level effects, however, but instead identified the potential for these to occur. Aloy et al. (2011) determined experimentally that when plastic cover was 50% the efficiency of the gastropod *Nassarius pullus* in locating and moving towards a food source significantly decreased, but the maximum cover of plastic that they found on the shore was only 0.77%. Similarly, Carson et al. (2011) determined that the quantity of plastic fragments in beach sediments altered the sediment's thermal properties, and although they did not identify an assemblage level impact they hypothesised that this could have significant consequences for beach organisms, particularly those such as sea turtles whose eggs have temperature dependent sex determination. Hence, rather than identifying a current assemblage level effect, both authors have identified the potential for this to be the case in the future.

4. Discussion

It is apparent that a wide range of species are affected by ingestion and entanglement in marine debris and that the frequency of encounters has increased over time. While it seems inevitable that

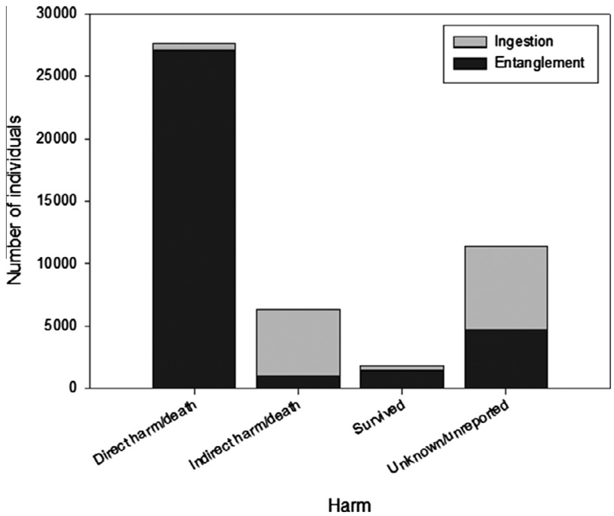

Fig. 3. Incidence of ingestion of or entanglement in marine debris, indicating the consequence of the encounter where described. 'Direct harm/death' is defined as where the encounter was reported to have directly caused injury or death, 'indirect harm/death' as where the encounter contributed to injury or death but was not the direct cause (for example, sub-lethal effects) and 'survived' as where the encounter did not have an adverse effect on the individual. Data presented are for all reported encounters identified in the published literature.

the biological and ecological performance of some individuals will be compromised, at present there is no clear evidence of population level consequences of encounters between plastic and marine life. It should be noted, however, that there are few clear examples of population level effects from any single form of man-made contamination as it is very difficult to link such changes in natural populations to single causative agents (but see Gibbs et al., 1987). A lack of evidence does not therefore necessarily imply a lack of effect.

This review has identified that the effects of entanglement are more commonly reported than those of ingestion, with a much greater percentage of encounters linked to direct harm or death of individuals. This however, rather than suggesting that entanglement is a greater problem than ingestion, may serve to highlight that the effects of entanglement are more readily obvious, allowing more conclusive reporting of harm with entanglement. Impacts of entanglement include drowning, suffocation, lacerations, a decreased ability to catch food, and an inability to effectively avoid predators (Derraik, 2002; Gregory, 1991; Laist, 1997, 1987). The detection of ingestion effects is harder and typically requires necropsy. Effects commonly outlined include starvation due to gut obstruction, a false feeling of satiation, reduced fitness, and, potential toxicity caused by absorption of toxins from plastic debris (Bjorndal et al., 1994; Gregory, 1991; Ryan et al., 1988; Spear et al., 1995).

The severity of the impact of both ingestion and entanglement will vary according to the type of debris and will vary between species and also between individuals, with some able to withstand more than others. Despite this, it is apparent that there will be negative consequence for the individual.

The consequences of ingestion also depends upon feeding habitats, with, for example, sea birds that commonly ingest hard, sharp, items of prey being better able to tolerate ingestion of hard items of debris than those used to softer prey items (Baltz and Morejohn, 1976; Bourne and Imber, 1980). Some species will regurgitate indigestible items, and therefore will regurgitate debris, resulting in less impact than those in which debris accumulates in the gut. Where accumulation in the gut occurs, the result may be death, caused at least in part by sublethal effects such as reduced feeding capacity (Ryan, 1988). Sub-lethal effects are particularly difficult to quantify, highlighting the complexities in ascertaining whether debris ingestion has caused the individuals death, been a contributing factor, or is unrelated.

A further consequence of ingestion of marine debris, in particular microplastic debris may be the provision of a pathway facilitating the transport of chemicals to organisms (Oehlmann et al., 2009; Rochman et al., 2012; Teuten et al., 2009). Microplastics are defined as pieces or fragments of plastic less than 5 mm in diameter (Arthur et al., 2009; Barnes et al., 2009), and their abundance is increasing in the oceans (Goldstein et al., 2012; Thompson et al., 2004). The finding that 10% of all ingestion reports documented encounters with microplastics highlights their importance as a component of marine debris, as supported by their recent identification as one of the top emerging global issues (Sutherland et al., 2010; UNEP Year Book, 2011). To date, studies into harmful toxicological effects associated with ingestion are limited, with none having confirmed a link at environmental concentrations of debris. Ryan et al. (1988) did however, identify a positive correlation between the amount of polychlorinated biphenyls (PCBs), DDT, DDE and dieldrin in the fat tissue and eggs of breeding female Great Shearwaters, suggesting that if there are toxicological effects, these could be passed to offspring and may therefore be far reaching.

The small size of microplastics means that they have a large surface area to volume ratio, and consequently the capacity to facilitate the transport of contaminants. This applies both to those incorporated in the plastic as part of the manufacturing process such as monomers, oligomers, bisphenol-A, phthalate plasticisers, flame retardants and antimicrobials (Lithner et al., 2011), and those adsorbed such as persistent bioaccumulative and toxic substances present in the oceans from other sources (Mato et al., 2001; Rochman et al., 2012; Teuten et al., 2009). It is clear that there is potential for the transfer of contaminants from the plastic to the organism once ingested (Teuten et al., 2007, 2009), but the extent to which the transfer of toxic substances to organisms is facilitated by microplastic particles, the consequences of this transfer, and the importance of this pathway in relation to other pathways is not yet fully understood (Cole et al., 2011; Teuten et al., 2009). In addition to toxicological effects, recent laboratory experiments have indicated the potential for microplastic ingestion to have physical effects compromising food assimilation (Wright et al., 2013).

Examination of encounters according to species highlighted that all known species of sea turtle and more than half of all known species of marine mammal and sea bird have ingested or become entangled in marine debris. However, only a small proportion of fish species have been affected, and it is important to note that while these are important statistics, it must be recognised that the proportion of species known to encounter debris will decrease as the taxonomic diversity of the species group increases. Hence, the more species in a taxonomic group, the bigger the sampling effort required to adequately determine the number of species affected. Studies of fish, for example, are often opportunistic following fisheries studies, with ingestion in particular not commonly recorded as it requires necropsy. There is variation among studies which likely results from differences in the species examined the sampling location, and methodology. Some studies, such as that of Lusher et al. (2013) found that all ten fish species sampled in the English Channel, UK and 37% of all individuals had ingested microplastic, whereas Anastasopoulou et al. (2013) only found evidence of debris ingestion in five out of 24 species sampled in the Ionian Sea, Eastern Mediterranean.

Encounters with marine debris are of particular concern for species which are recognised to be threatened, and with 17% of all species reported here listed as near threatened, vulnerable, endangered or critically endangered on the IUCN Red List it is evident

Table 1
Number of species with records of entanglement and ingestion documented in Laist (1997), the number reported here and the total number of species identified worldwide. The percentage of the total number of known species that are reported entangled or ingesting is given in brackets. NB This value will also be affected by the number of species within a taxonomic group. For groups with fewer species less sampling effort would be required to demonstrate that all or a large percentage of the species were affected. Sources for total number of identified species: Laist (1997), First Census of Marine Life (2010).

Species group	Number of known species	Number of species with entanglement records		Number of species with ingestion records		Total number of species with either entanglement or ingestion records	
		Laist (1997)	This study	Laist (1997)	This study	Laist (1997)	This study
Marine mammals	115	32 (28%)	52 (45%)	26 (23%)	30 (26%)	49 (43%)	62 (54%)
Fish	16,754	34 (0.20%)	66 (0.39%)	33 (0.20%)	50 (0.30%)	60 (0.36%)	114 (0.68%)
Seabirds	312	51 (16%)	79 (25%)	111 (36%)	122 (39%)	138 (44%)	174 (56%)
Sea turtles	7	6 (86%)	7 (100%)	6 (86%)	6 (86%)	6 (86%)	7 (100%)

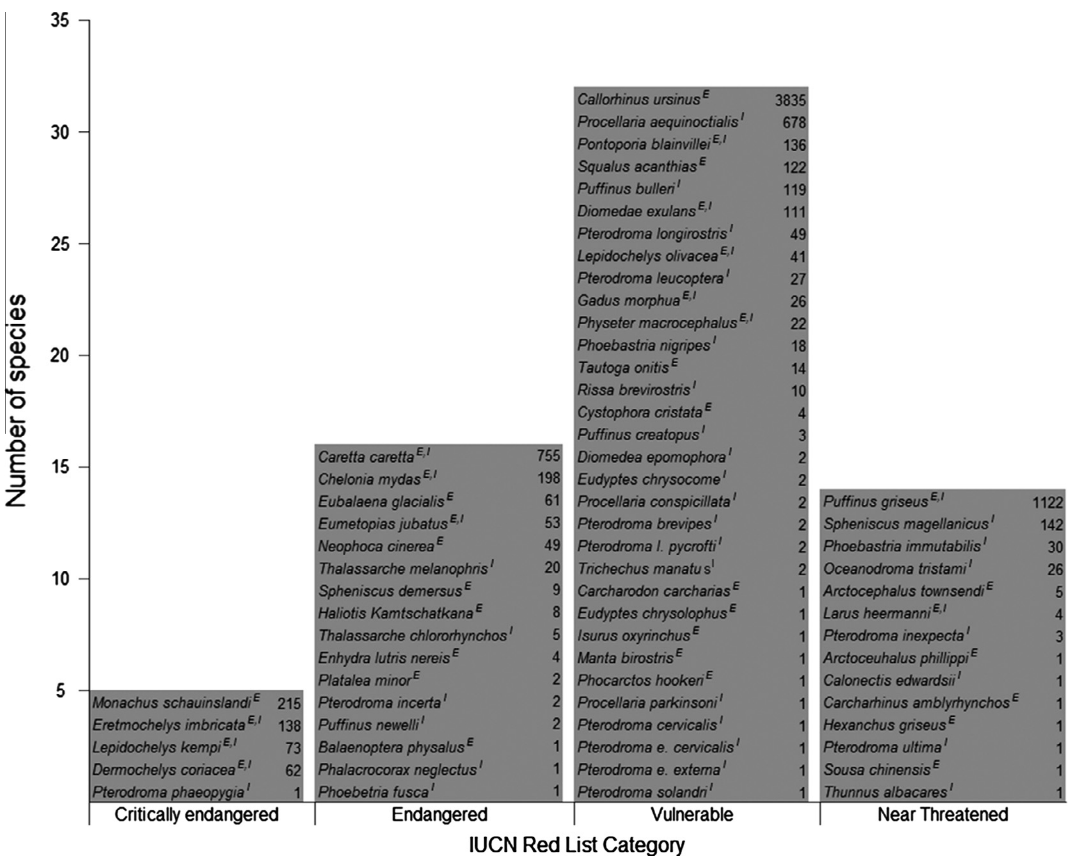

Fig. 4. Number of species listed as near threatened, vulnerable, endangered or critically endangered on the IUCN Red List for which impacts of marine debris through entanglement or ingestion effects have been recorded. Species are listed in order of number of impacted individuals from largest to smallest. [E] denotes that the species has been impacted by entanglement, and [I] that it has been impacted by ingestion. For critically endangered species, 1 represents entanglement, 1 ingestion and 3 both entanglement and ingestion; for endangered species, 6 represent entanglement, 6 ingestion, and 3 both entanglement and ingestion; for vulnerable species, 9 represent entanglement, 18 ingestion, and 5 both entanglement and ingestion; and for near threatened species, 5 represent entanglement, 7 ingestion, and 2 both entanglement and ingestion. Data presented are for all reported encounters identified in the published literature.

that marine debris may be contributing to the potential for species extinction.

The main focus of the literature to date has been on entanglement and ingestion of marine debris. The provision of an additional source of rafting material for species may, however, also have negative consequences, with Barnes (2002) estimating that debris might have substantially increased the propagation of fauna in subtropical and high latitudes. Where species are invasive this could be problematic, and whilst unlikely to be a major pathway for transport, rafting on marine debris may provide an additional and in some locations, substantial method for the spread of invasive species (Gregory, 2009).

Despite lack of solid evidence to confirm it, for species where there is a clear record of marine debris encounters affecting substantial numbers of individuals there is concern for population level effects. For example van Franeker et al. (2011) who have studied the northern fulmar population in the North Sea over than last 33 years determined that approximately 95% of individuals washed ashore dead contained plastic debris, and that of these, 58% contained quantities exceeding the OSPAR Ecological Quality Objective critical level of 0.1 g per individual. Whilst they did not identify specific negative impacts on the fulmars resulting from the ingestion of plastic debris, it seems likely that they are occurring. The strength of this data has led to the suggestion that plastic content in this population could be used as a monitoring indicator to assess spatial and temporal changes in surface debris concentrations on a regional basis within the north-eastern Atlantic. Similarly, due to the finding that plastic was retained in the stomachs of petrels for months, (Furness, 1985; Ryan and Jackson, 1987), it has been suggested that these species could be a useful proxy for

Table 2
Number of taxa and number of papers by taxonomic group that report the use of marine debris as a habitat. Unknown represents those species identified by Pace et al. (2007) as no species list was presented.

Taxonomic group	Number of taxa	Number of papers
Bivalves	1	1
Bryozoans	1	1
Cephalopods	1	1
Cnidaria	3	2
Crustaceans	14	3
Echinoderms	6	3
Fish	10	1
Gastropods	1	1
Pelagic insects	1	1
Polychaetes	2	1
Porifera	1	1
Seagrass and algae	2	1
Unknown	47	1

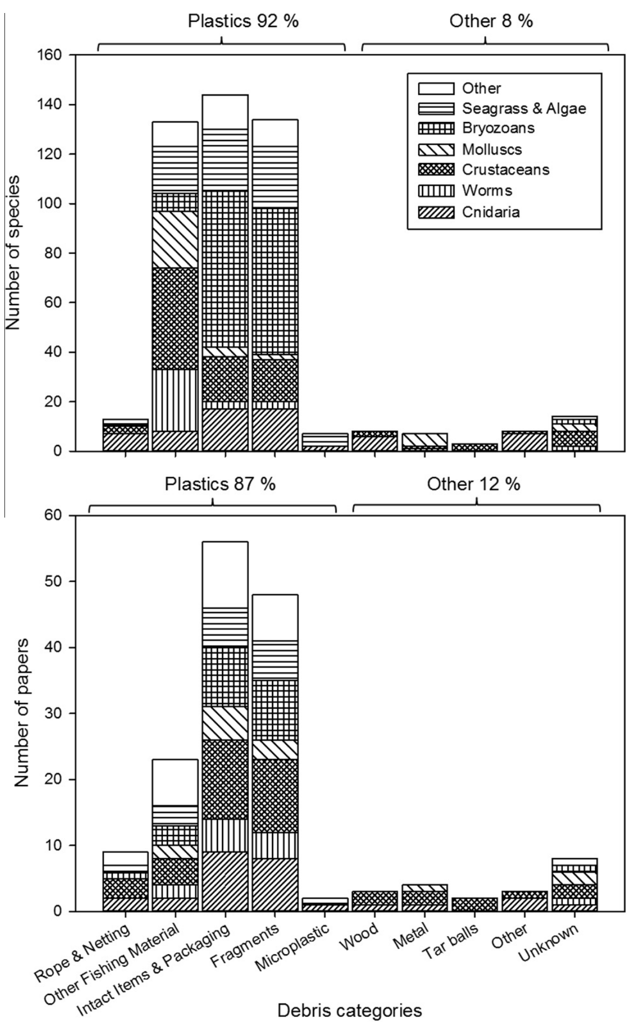

Fig. 5. Incidence of rafting on marine debris reported by number of (a) species and (b) papers per taxonomic grouping – mammals, birds, fish, sea turtles, crustaceans, cephalopods, bivalves, gastropods and echinoderms. Bars are divided by impact per debris type (rope and netting, other fishing materials (mainly lines, pots), Intact items and packaging, fragments > 5 mm, microplastic < 4.99 mm, wood, metal, tar balls and type not reported). Number of individuals was not commonly reported in the literature and so has not been included. Total number of species is greater than 259 as it accounts for species being reported for more than one debris type, and total number of papers is greater than 34 as it accounts for reports of more than one taxon per paper. Data presented are for all reported encounters identified in the published literature.

monitoring changes in the composition of plastic across the Atlantic and southwest Indian Oceans (Ryan, 2008). Other populations known to extensively ingest marine debris include the Norway lobster (*Nephrops norvegicus*) in the Clyde Sea, UK where Murray and Cowie (2011) determined that 83% of the individuals contained microplastic debris, and green turtle and seabirds in Brazil where Tourinho et al. (2010) determined that 100% of dead stranded green turtles and 40% of dead stranded sea birds contained human made debris.

There is limited evidence of effects at the assemblage level. In areas where debris provides isolated hard habitat, however, species which would not otherwise have been present are able to colonise which may have consequences for surrounding biota. Where this occurs in the water column or in areas of soft sediment, the species associated with the debris are likely to be different from those otherwise present, thus potentially altering the species assemblage and increasing overall diversity (Pace et al., 2007). An increase in microplastic debris in the water column might also provide opportunity for species to increase in abundance. Goldstein et al. (2012), for example, found a positive correlation between abundance of microplastics and abundance of the eggs of the pelagic insect *Halobates sericeus* in the North Pacific Subtropical Gyre. Despite the lack of a positive correlation between microplastic abundance and recruitment, the increased abundance of microplastics was seen to overcome substrate limitation for oviposition, suggesting that oceanic microplastic pollution may have consequences for organisms associated with hard substrates.

5. Conclusions

This review has reported the number of species and individuals encountering marine debris and the number of reports documenting these encounters. The finding that for some species, a substantial proportion of a population may be involved, along with the number of species that are also on the IUCN Red List, and the increased incidence of encounter highlights that marine debris is likely to represent an additional and escalating anthropogenic factor affecting marine habitats and biodiversity. Hence, it is possible that where marine debris combines with other anthropogenic stressors it may contribute towards population or species level effects, and may also indirectly affect trophic interactions and assemblages which could be particularly important if a keystone species is involved.

It must be recognised that whilst this paper examines the known extent of the impact of marine debris on marine organisms there are reporting limitations. Few reports currently consider low trophic level organisms, but this does not necessarily indicate that they are not affected by marine debris, rather that any impacts are, as yet, not fully described. Globally, a reporting bias is evident, with the lack of reports from areas such as Asia, Africa and the Polar Regions probably also resulting from underreporting rather than a lack of occurrence. Lack of data on the size of debris ingested may also indicate that encounters with microplastic may be more widespread than is currently documented.

The findings presented here are considered an underestimate of the impacts of marine debris on biota, and while this highlights a clear need for further research in order to more fully understand the global patterns and the extent of debris impacts on biodiversity this is not a reason to delay efforts focussed on effective mitigation or input reduction.

Addressing the marine debris problem presents challenges similar to those associated with many other threats to biodiversity, such as habitat loss and degradation, climate change, nutrient loading, and over-exploitation and unsustainable use of resources. Unlike many other environmental issues that currently challenge

the marine environment, however, the benefits to society associated with items typically found as marine debris can be fully realised without the need for end of life material to accumulate in the oceans. Whilst a broad range of instruments are used to address the problem from sectoral land or sea based perspectives it is evident from the current trends that their effectiveness is relatively low considering the global scale of the marine debris challenge (Goldstein et al., 2012; Rochman et al., 2013; STAP, 2011; Thompson et al., 2009; UNEP Year Book, 2011). There is wide recognition that marine debris does not belong, nor does it need to be in the marine environment. Finding effective solutions requires a holistic approach, considering the entire life cycle of items that become marine debris including green chemistry and design and manufacturing as well as effective waste management and prevention and removal of marine debris (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, 2012). Hence finding ways to ensure greater engagement and effectiveness of solutions perhaps requires a higher priority than additional research to further the evidence about the impacts of the debris itself.

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