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Marine Anthropogenic Litter



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Chapter 4

Deleterious Effects of Litter on Marine Life

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Abstract In this review we report new findings concerning interaction between marine debris and wildlife. Deleterious effects and consequences of entanglement, consumption and smothering are highlighted and discussed. The number of species known to have been affected by either entanglement or ingestion of plastic debris has doubled since 1997, from 267 to 557 species among all groups of wildlife. For marine turtles the number of affected species increased from 86 to 100 % (now 7 of 7 species), for marine mammals from 43 to 66 % (now 81 of 123 species) and for seabirds from 44 to 50 % of species (now 203 of 406 species). Strong increases in records were also listed for fish and invertebrates, groups that were previously not considered in detail. In future records of interactions between marine debris and wildlife we recommend to focus on standardized data on frequency of occurrence and quantities of debris ingested. In combination with dedicated impact studies in the wild or experiments, this will allow more detailed assessments of the deleterious effects of marine debris on individuals and populations.

Keywords Marine debris • Plastic litter • Entanglement • Ingestion • Harm • Review

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4.1 Introduction

For several decades, it has been known that anthropogenic debris in the marine environment, in particular plastic, affects marine organisms (Shomura and Yoshida 1985; Laist 1997; Derraik 2002; Katsanevakis 2008). Plastic production grows at 5 % per year (Andrady and Neal 2009). Part of the material ends up as litter in the marine environment, to such an extent that the issue is considered to be of major global concern (UNEP 2011). Awareness has grown that plastics may become less visible but do not really disappear as they become fragmented into small persistent particles ('plastic soup') (Andrady 2015). Plastic fragmentation can be caused by abiotic factors (Andrady 2011) or through animal digestion processes (Van Franeker et al. 2011). The smaller the particle, the higher the availability to animals at the base of the food chain. The potential deleterious effects from ingestion, have heightened the urgency to evaluate the impact of plastics on the whole marine food chain and, ultimately, the consequences for humans as end consumers (Koch and Calafat 2009; UNEP 2011; Galloway 2015).

The most visible effect of plastic pollution on marine organisms concerns wildlife entanglement in marine debris, often in discarded or lost fishing gear and ropes (Laist 1997; Baulch and Perry 2014). Entangled biota are hindered in their ability to move, feed and breathe. In addition, many marine organisms mistake litter for food and ingest it (Day et al. 1985; Laist 1997). Indigestible debris such as plastics may accumulate in their stomachs and affect individual fitness, with consequences for reproduction and survival, even if not causing direct mortality (Van Franeker 1985; Bjorndal et al. 1994; McCauley and Bjorndal 1999). Marine birds, turtles and mammals have received most attention, but the consequences of entanglement and ingestion on other organism groups, e.g. fish and invertebrates, are becoming more evident. In addition to the issues of entanglement and ingestion, synthetic materials represent a long-lived substrate that may present the possibility of transporting hitch-hiking 'alien' species horizontally to ecosystems elsewhere (for more details see Kiessling et al. 2015) or vertically from the sea surface through the water column to the seafloor. Plastics may also smother water surfaces and sea bottoms where effects may range from suffocating organisms (e.g. Mordecai et al. 2011; Green et al. 2015) to offering new habitats for species that are otherwise unable to settle (e.g. Chapman and Clynick 2006).

Major reviews of the impacts of litter, in particular plastics, on marine life have been undertaken by Shomura and Yoshida (1985), Laist (1997), Derraik (2002) and Katsanevakis (2008). We used the species list of Laist (1997) as a basis for our work and conducted an extensive literature review to add not only birds and mammals, but also fish and invertebrates. Laist (1997) tabulated data on both entanglement and ingestion but focused discussions on the entanglement aspect. Therefore, we paid more attention to descriptions and discussion of the ingestion issue. This includes occurrence of smaller plastics in smaller organisms, including invertebrates but leaves the real microplastic issues to the dedicated chapter in this book (Lusher 2015). The table with species listings for ingestion and entanglement starts with marine birds and mammals because for these animal groups, literature

coverage is far more complete than for lower taxonomic groups, and because this is directly comparable with Laist (1997). Further taxonomic groups are in traditional taxonomic sequence.

Tables 4.1, 4.2 and 4.3 summarise our findings on entanglement and ingestion for groups of species in comparison to the earlier review by Laist (1997). Table 4.4 gives a more specific overview of our findings, but all details for individual species and data sources are provided in our Online Supplement. Data in our tables only relate to observations on wild organisms. This excludes for example fisheries by-catch data for active fishing gear and laboratory experiments. Texts refer to these only where it does not overlap too much with the microplastics chapters in this book and the review by Cole et al. (2011). The main aim of our paper was to compile a factual overview of known records of interference of plastic debris with marine wildlife as a basis for current discussions and future work addressing the scale of impact and policies to be developed.

4.2 Entanglement

Entanglement of marine life occurs all over the world, from whales in the Arctic (Knowlton et al. 2012) and fur seals in the Southern Ocean (Waluda and Staniland 2013), to gannets in Spain (Rodríguez et al. 2013), octopuses in Japan (Matsuoka et al. 2005) and crabs in Virginia, USA (Bilkovic et al. 2014). One of the first entanglement records of marine debris was probably a shark, caught in a rubber automobile tyre in 1931 (Gudger and Hoffman 1931). Hundreds of thousands of marine birds and mammals are known to perish in active fishing gear (Read et al. 2006; Żydelis et al. 2013), but no estimates are available for the actual number of animals becoming entangled in synthetic fisheries debris and other litter. However, from species records in Table 4.1 and the Online Supplement, it appears that the problem is substantial. The percentage of species that have been recorded as entangled among various groups of marine organisms, is high: 100 % of marine turtles (7 of 7 species), 67 % of seals (22 of 33 species), 31 % of whales (25 of 80 species) and 25 % of seabirds (103 of 406). In comparison to the listings by Laist (1997) the number of bird + turtle + mammal species with known entanglement increased from 89 (21 %) to 161 (30 %) (Table 4.1). For other reptiles, fish and invertebrates the percentage of affected species is futile because there are many thousands of species which have not been properly investigated. Often it is considered less worthwhile to publish individual entanglement records for common fishes or invertebrates or inconspicuous small species, than, for example, for a large entangled whale washed ashore.

Temporal entanglement trends are difficult to establish, as they differ between species groups and population changes play an important role (Ryan et al. 2009). Fowler et al. (1992) found a decline in entanglement of northern fur seals (*Callorhinus ursinus*) from 1975 to 1992. In Antarctic fur seals (*Arctocephalus gazella*), Waluda and Staniland (2013) reported a peak in 1994 and then a decrease

Table 4.1 Number of species with documented records of entanglement in marine debris

Species group	Laist (1997)			This study		
	Spp. total	Entanglement		Spp. total	Entanglement	
	(n)	(n)	(%)	(n)	(n)	(%)
<i>Seabirds</i>	312	51	16	406	103	25.4
Anseriformes (marine ducks)	–	–	–	13	5	38.5
Gaviiformes (divers)	–	–	–	5	3	60.0
Sphenisciformes (penguins)	16	6	38	18	6	33.3
Procellariiformes (tubenoses)	99	10	10	141	24	17.0
Podicipediformes (grebes)	19	2	10	23	6	26.1
Pelecaniformes, suliformes, phaethontiformes (pelicans, gannets and boobies, tropicbirds)	51	11	22	67	20	29.9
Charadriiformes (gulls, skuas, terns and auks)	122	22	18	139	39	28.1
<i>Marine mammals</i>	115	32	28	123	51	41.5
Mysticeti (baleen whales)	10	6	60	13	9	69.2
Odontoceti (toothed whales)	65	5	8	65	16	24.6
Phocidae (true seals)	19	8	42	19	9	47.4
Otariidae (eared seals)	14	11	79	13	13	100.0
Sirenia (sea cows, dugongs)	4	1	25	5	2	40.0
Mustelidae (otters)	1	1	100	2	1	50.0
Ursidae (polar bears)	0	0	0	1	1	100.0
Turtles	7	6	86	7	7	100
<i>Sea snakes</i>	–	–	–	62	2	3.2
<i>Fishes</i>	–	34	–	32,554	89	0.27
<i>Invertebrates</i>	–	8	–	159,000	92	0.06
Marine birds, mammals and turtles	434	89	20.5	536	161	30.0
<i>All species</i>	–	136	–		344	

Comparative summary with the earlier major review by Laist (1997). Individual species and sources are documented in the Online Supplement. Observations only concern dead or living animals entangled in marine debris including derelict fishing gear. Between the two reviews, the number of species, in the groups considered, differ because of changes in accepted taxonomic status, and selection of which species groups should be considered to be ‘marine’. For details see the Online Supplement

until 2012. In the same period of time (1978–2000), Cliff et al. (2002) found an increase in entanglement rates of dusky sharks (*Carcharhinus obscurus*).

4.2.1 Ways of Entanglement

The term “ghost fishing” has been established for lost or abandoned fishing gear (Breen 1990). Ghost nets may continue to trap and kill organisms and can damage benthic habitats (Pawson 2003; Good et al. 2010). Important factors, increasing

the risks of entanglement, are the size and structure (Sancho et al. 2003) of the lost nets and their location. For example, nets that are stretched open by structures on the sea bed, tend to catch more organisms (Good et al. 2010). The estimated time, over which lost fishing gear continues to entangle and kill organisms varies substantially and is site and gear specific (Kaiser et al. 1996; Erzini 1997; Hébert et al. 2001; Humborstad et al. 2003; Revill and Dunlin 2003; Sancho et al. 2003; Tschernij and Larsson 2003; Matsuoka et al. 2005; Erzini et al. 2008; Newman et al. 2011). Matsuoka et al. (2005) estimated catch durations of derelict gill- and trammel-nets from different studies between 30 and 568 days. Ghost-fishing efficiency can sometimes decrease exponentially (Erzini 1997; Tschernij and Larsson 2003; Ayaz et al. 2006; Baeta et al. 2009). For example, Tschernij and Larsson (2003) found 80 % of the catch in bottom gill nets in the Baltic Sea during the first three months. Still, the nets continued fishing at a low rate until the end of the experiment after 27 months. Lost fishing gear can carry on trapping, until it is heavily colonised, altering weight, mesh size and visibility (Erzini 1997; Humborstad et al. 2003; Sancho et al. 2003). In deeper waters, ghost fishing seems to continue for longer periods of time, as fouling takes longer (Breen 1990; Humborstad et al. 2003; Large et al. 2009). A reduction of the duration of ghost fishing by using degradable materials unfortunately also affects the operational lifetime of equipment. However, easily replaced degradable escape cords in lobster traps may reduce ghost fishing of lost traps efficiently (Antonelis et al. 2011).

In addition to entanglement in derelict fishing gear, other anthropogenic material such as ropes, balloons, plastic bags, sheets and six-pack drink holders can cause entanglement (e.g. Plotkin and Amos 1990; Norman et al. 1995; Camphuysen 2001; Matsuoka et al. 2005; Gomerčić et al. 2009; Votier et al. 2011; Bond et al. 2012; Moore et al. 2009, 2013; Rodríguez et al. 2013).

Whales and dolphins tend to become entangled around their neck, flippers and flukes, often in several types of fishing gear (Moore et al. 2013; Van der Hoop et al. 2013). Seals become frequently entangled in synthetic fishing gear, packing straps or other loop-shaped items that encircle the neck at young age and create problems during growth (Fowler 1987; Lucas 1992; Allen et al. 2012) (see Fig. 4.2). Seabirds are well known to become entangled around the bill, wings and feet with rope-like materials, which constrains their ability to fly or forage properly (Camphuysen 2001; Rodríguez et al. 2013) (Fig. 4.1). In addition to entanglement in fishing gear and other debris (Bugoni et al. 2001) marine turtles face problems on beaches where hatchlings are prone to entanglement or entrapment in marine debris on their way to the sea (Kasperek 1995; Ozdilek et al. 2006; Triessing et al. 2012). Motile benthic organisms become primarily caught in derelict traps on the seafloor (Adey et al. 2008; Erzini et al. 2008; Antonelis et al. 2011; Anderson and Alford 2014; Bilkovic et al. 2014; Kim et al. 2014; Uhrin et al. 2014) (Fig. 4.3a) although sometimes escape has also been observed (Parrish and Kazama 1992; Godøy et al. 2003). If there is no possibility of escape, animals in these traps and pots die from starvation (Pecci et al. 1978) and serve as bait, which attracts new victims (Kaiser et al. 1996; Stevens et al. 2000; Hébert et al. 2001).



Fig. 4.1 Northern gannet entanglement. On a nest on Helgoland, Germany (*top*), on a beach on Texel, The Netherlands (*bottom left*) and with fishing nets wrapped around the neck (*bottom right*) (Photos: J.A. van Franeker (1, 2) and S. Kühn (3), IMARES)

Behavioural traits can be important factors in becoming entangled (Shaughnessy 1985; Woodley and Lavigne 1991). It has been suggested that sharks become entangled when investigating large floating items and when searching for food associated with clumps of lost fishing gear (Bird 1978). Prey fish, which use debris as a shelter, can increase entanglement risks for predators, such as sharks (Cliff et al. 2002) and fish (Tschernij and Larsson 2003). The ‘playful’ behaviour of marine mammals may increase the risk of entanglement (Mattlin and Cawthorn 1986; Laist 1987; Harcourt et al. 1994; Zavala-González and Mellink 1997; Hanni and Pyle 2000; Page et al. 2004). Zavala-González and Mellink (1997) and Hanni and Pyle (2000) explained a higher incidence of entanglement



Fig. 4.2 Marine Mammal entanglement and plastic ingestion. Stomach contents of Dutch harbour seals (*top*), entangled grey seal (*bottom left*) and harbor seal (Texel, The Netherlands, *bottom center*), Antarctic fur seal investigating a rope (Cape Shirreff, Antarctica, *bottom right*) (Photos: J.A. van Franeker (1, 2, 3) and E. Bravo Rebolledo (6) IMARES; S. de Wolf (4, 5), Ecomare)

in younger California sea lions (*Zalophus californianus*) by playful behaviour and curiosity in combination with lack of experience and a foraging habit closer to the water surface. Age plays a significant role in pinnipeds, as younger seals are more often entangled than adults (Lucas 1992; Henderson 2001; Hofmeyr et al. 2006).

Gannets and many other seabird species use seaweed to build their nests, but are known to frequently incorporate ropes, nets and other anthropogenic debris (Podolski and Kress 1989; Montevecchi 1991; Hartwig et al. 2007; Votier et al. 2011; Bond et al. 2012; Lavers et al. 2013; Verlis et al. 2014) (Fig. 4.1). Marine debris used in nest construction increases the risk of mortal entanglement for both adult birds and chicks (Fig. 4.1). In three of the six North American gannet populations, close to 75 % of the gannet nests contained fishing debris. Its frequency can be linked to the level of gillnet fishing effort in the waters around the colonies (Bond et al. 2012).

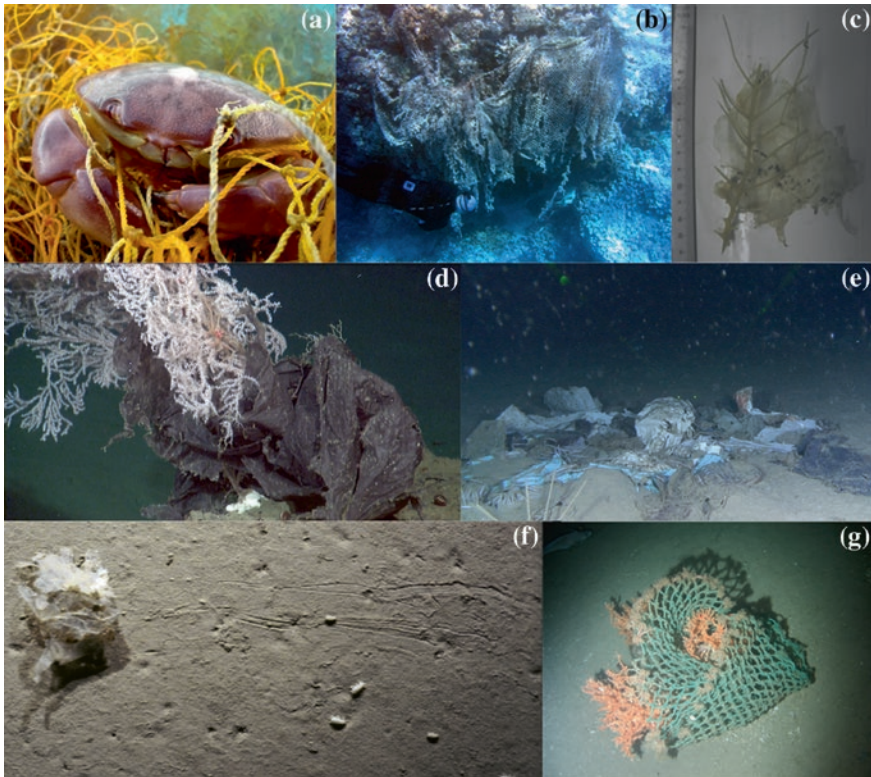


Fig. 4.3 Effects of litter on organisms on the seafloor. **a** Crab entangled in derelict net and **b** fishing net wrapped around coral, NW Hawaiian Islands (Photo: NOAA); **c** plastic fragment entangled in trawled sponge (*Cladorhiza gelida*) from HAUSGARTEN observatory (Arctic), 2,500 m depth (Photo: M. Bergmann, AWI); **d** rubbish bag wrapped around deep-sea gorgonian at 2,115 m depth in Astoria Canyon (Photo: © 2007, MBARI); **e** Mediterranean soft-sediment habitat at 450 m depth smothered with plastic litter (Photo: F. Galgani, AAMP); **f** evidence of plastic fragment causing disturbance and biogeochemical changes at the sediment-water interface by dragging along the seabed of the Molloy Deep, HAUSGARTEN IX, at 5,500 m depth (Photo: M. Bergmann, AWI); **g** cargo net entangled in a deep-water coral colony at 950 m in Darwin Mounds province with entrapped biota (Photo: V. Huvenne, National Oceanography Centre Southampton)

4.2.2 Effects of Entanglement

Entangled organisms may no longer be able to acquire food and avoid predators, or become so exhausted that they starve or drown (Laist 1997). Even if the organism does not die directly, wounds, restricted movements and reduced foraging ability will seriously affect the entangled animal (Arnould and Croxall 1995; Laist 1997; Moore et al. 2009; Allen et al. 2012). In turtles, entanglement is known to cause skin infections, amputations of legs and septic processes (Orós et al. 2005; Barreiros and Raykov 2014). Barreiros and Guerreiro (2014) reported a ring from

a plastic bottle that became fixed around the operculum of a juvenile axillary sea bream (*Pagellus acarne*), which inflicted a deep cut in the anterior part of the fish and caused mortality. Discarded plastic lines and fishing gear, even if not directly drowning the animal, may cause complications in proper foraging or surfacing to breathe (Wabnitz and Nichols 2010). Illustrating the fact that such events may affect even unlikely species, the entanglement of a sea snake (*Hydrophis elegans*) in a ceramic ring caused starvation by restricting the passage of food (Udyawer et al. 2013).

In sharks, plastic entanglement reduced the mouth opening so as to impair foraging and gill ventilation (Sazima et al. 2002). A malformation of the backbone due to long-term entanglement of a shortfin mako shark (*Isurus oxyrinchus*) disturbed natural growth. In addition, biofouling on the rope probably reduced its swimming efficiency, maximum velocity and manoeuvrability (Wegner and Cartamil 2012). Lucas (1992) discovered a dead grey seal (*Halichoerus grypus*) with deformations. The size of the rubber trawl roller suggested that it had been entangled as a juvenile five years before.

Crabs, octopuses, fishes and a wide range of smaller marine biota are known to get caught in derelict traps on the seafloor and die from stress, injuries or starvation, as escape is difficult (Matsuoka 1999; Al-Masroori et al. 2004; Matsuoka et al. 2005; Erzini et al. 2008; Antonelis et al. 2011; Cho 2011). Derelict fishing lines and other gear are often covering structurally complex biota such as sponges, gorgonians (Fig. 4.3b) or (soft) corals (Pham et al. 2013; Smith and Edgar 2014) which suffer broken parts and may be more susceptible to infections and eventually die, as shown for shallow-water (soft) corals and gorgonians (Bavestrello et al. 1997; Schleyer and Tomalin 2000; Asoh et al. 2004; Yoshikawa and Asoh 2004; Chiappone et al. 2005). Contact with soft plastic litter also caused necrosis in the cold water coral *Lophelia pertusa* (Fabri et al. 2014).

Although examples of entanglement and various pathways of negative effects on individuals are abundant, it is rarely possible to assess the proportional damage to populations. However, Knowlton et al. (2012) reported that among a known number of 626 photo-identified individuals of the North Atlantic right whale (*Eubalaena glacialis*), 83 % showed evidence of entanglements in ropes and nets. On average, 26 % of adequately photographed animals acquired new wounds or scars every year. Allen et al. (2012) showed that entanglement reduces the longer-term survival of grey seals significantly. Studies like these, although not attributable with certainty to marine debris alone, do show that entanglement, although not directly obvious, can have a serious impact on wild populations.

4.3 Smothering

Marine debris on the seabed can have various effects on the resident flora and fauna that we do not consider to be ‘entanglement’ but rather describe as ‘smothering’. Smith (2012) suggested that large quantities of litter may impede attempts

to rehabilitate depleted mangrove forests in Papua New Guinea through smothering of seedlings. In the intertidal zone the weight and shading effects of debris may crush sensitive salt marsh vegetation or reduce light levels needed for growth, which can lead to denuded areas in these sensitive protected ecosystems (Uhrin and Schellinger 2011; Viehman et al. 2011). Two species of seagrass (*Thalassia testudinum*, *Syringodium filiforme*) had significantly decreased shoot densities after experimental deployment of traps on the sea bed (Uhrin et al. 2005). The weight of the traps caused blades to become abraded or crushed into the underlying *anoxic sediments*, likely suffocating the plants, reducing photosynthetic rates and leading to eventual senescence of above-ground biomass (Uhrin et al. 2005), which indicates long-lasting effects on ecosystem function and thus biodiversity of these vulnerable habitats.

Estimates on the impact of marine debris on local populations are available for corals: for example, Richards and Beger (2011) found that coral cover decreased significantly as macrodebris cover increased. Yoshikawa and Asoh (2004) reported that 65 % of coral colonies in Oahu, Hawaii were covered with fishing lines, and 80 % of colonies were either entirely or partially dead, which was, again, positively correlated with the percentage of colonies covered with fishing lines.

On one hand some debris may provide shelter for motile animals, and a habitat for sessile organisms, as was experimentally shown by Katsanevakis et al. (2007) and in the deep sea (Mordecai et al. 2011; Schlining et al. 2013). In the Majuro Lagoon, the coral *Porites rus* overgrew debris and appeared to thrive in locations of high debris cover (Richards and Beger 2011). On the other hand, derelict fishing gear, bags and large (agricultural) foils are known to cover parts of the seafloor at all depths (e.g. Galgani et al. 1996; Watters et al. 2010; Van Cauwenberghé et al. 2013; Pham et al. 2014) (Fig. 4.3e). Mordecai et al. (2011) reported anoxic sediments below a plastic bag on the deep seafloor of the Nazaré Canyon and suggested that this would alter the infaunal community underneath as it reduces the exchange of pore water with overlying water masses. Indeed, anoxic sediments, reduced primary productivity and organic matter and significantly lower abundances of infaunal invertebrates were recently recorded below plastic bags experimentally deployed on a beach for 9 weeks (Green et al. 2015). Anoxic sediments below marine litter were also observed at two sites of a mangrove habitat from Papua New Guinea (Smith 2012). Dragged along the seafloor litter may cause further damage to fragile habitat engineers (coral, plants) and change biogeochemical seafloor properties (e.g. Fig. 4.3f). Macroplastics covering larger parts of corals, cannot only cause direct mechanical damage, but also diminish the capacity of phototrophic and heterotrophic nutrition (Richards and Beger 2011) (see also Fig. 4.3b, d). Also, a relationship between marine debris and coral diseases has been observed (Harrison et al. 2011). When corals die and release the debris, it moves on to a new spot and repeats the negative cycle (Donohue et al. 2001; Chiappone et al. 2005; Abu-Hilal and Al-Najjar 2009). In eastern Indonesian areas experimentally smothered by plastic, diatom densities were lower, probably due to the lack of light. However, meiofauna had a higher density beneath smothered test sites than on clean control sites, which was explained by the temporarily decomposing organic matter improving habitat quality for meiofauna (Uneputtu and Evans 2009). Smothering may also limit the nutrition of filter

feeders as it may restrict water circulation and thereby particles reaching the feeding apparatus (see Fig. 4.3b, c, d). In addition, marine debris on beaches can have negative effects on marine biota. Kasparek (1995) found marine turtle nesting sites on beaches in Syria, where the beaches were so polluted that females might not be able to dig a nest at an appropriate site. Litter may also lead to behavioural changes: for example, prolonged food searching time and increased self-burial in intertidal snails (*Nassarius pullus*) is strongly correlated with increased plastic cover, which was also reflected in low snail densities in areas of high litter cover (Aloy et al. 2011). Twenty-two taxa that are affected by smothering with litter are listed in Online Supplement 2 (provided by M. Bergmann) including four grasses, two types of sponges, 14 cnidarian species and one mollusc and crustacean.

4.4 Ingestion of Plastic

Ingestion of plastic by marine organisms is less visible than entanglement. Table 4.2 and Online Supplement 1 show that ingestion of plastic debris has currently been documented for 100 % of marine turtles (7 of 7 species), 59 % of whales (47 of 80), 36 % of seals (12 of 33), and 40 % of seabirds (164 of 406). In comparison to the review by Laist (1997) the number of bird + turtle + mammal species with known ingestion of plastics increased from 143 (33 %) to 233 (44 %). Studies on the ingestion of plastics by fish and invertebrates are largely a recent development. Currently, low proportions of fish and invertebrate species are presented in the tables, but a rapid increase in publications and species numbers are expected in this currently dynamic field of research. Records of plastic ingestion date back to the early days of plastic production in the 1960s. One of the first birds recorded to contain plastic was Leach's storm petrel (*Oceanodroma leucorhoa*) off New Foundland in 1962 (Rothstein 1973). The first report of a leatherback turtle (*Dermochelys coriacea*) with plastic dates back to 1968 (Mrosovsky et al. 2009). While the first record of anthropogenic debris in sperm whales (*Physeter macrocephalus*) was a fish hook found in a stomach in 1895, the first report of ingested plastic in sperm whales dates back to 1979 (de Stephanis et al. 2013). The first fish feeding on plastic was published in 1972 (Carpenter et al. 1972). The ingestion of plastics became a more commonly reported phenomenon from the 1970s onwards (Kenyon and Kridler 1969; Crockett and Reed 1976; Bourne and Imber 1982; Furness 1983; Day et al. 1985). A trend for birds ingesting plastic was probably first noted by Harper and Fowler (1987). Between 1958 and 1959 they found no plastic in prions (*Pachyptila* spp.) but from then on there was an upward trend in plastic consumption until 1977. A peak of plastic ingestion was detected in 1985 and 1995 in a number of long-term studies (Moser and Lee 1992; Robards et al. 1995; Spear et al. 1995; Mrosovsky et al. 2009; Van Franeker et al. 2011). In contrast to the continuing growth of global plastic use and increase in marine activities, the trend of plastic consumption decreased and stabilized from 2000 onwards approaching the 1980s level (Mrosovsky et al. 2009; Van Franeker et al.

Table 4.2 Number of species with documented records of ingestion of marine debris

Species group	Laist (1997)			This study		
	Spp. total	Ingestion		Spp. total	Ingestion	
	(n)	(n)	(%)	(n)	(n)	(%)
<i>Seabirds</i>	312	111	36	406	164	40.4
Anseriformes (marine ducks)	–	–	–	13	1	7.7
Gaviiformes (divers)	–	–	–	5	3	60.0
Sphenisciformes (penguins)	16	1	6	18	5	27.8
Procellariiformes (tubenoses)	99	62	63	141	84	59.6
Podicipediformes (grebes)	19	0	0	23	0	0.0
Pelecaniformes, suliformes, phaethontiformes (pelicans, gannets and boobies, tropicbirds)	51	8	16	67	16	23.9
Charadriiformes (gulls, skuas, terns and auks)	122	40	33	139	55	39.6
<i>Marine mammals</i>	115	26	23	123	62	50.4
Mysticeti (baleen whales)	10	2	20	13	7	53.8
Odontoceti (toothed whales)	65	21	32	65	40	61.5
Phocidae (true seals)	19	1	5	19	4	21.1
Otariidae (eared seals)	14	1	7	13	8	61.5
Sirenia (sea cows, dugongs)	4	1	25	5	3	60.0
Mustelidae (otters)	1	0	0	2	0	0.0
Ursidae (polar bears)	0	0	0	0	0	0.0
<i>Turtles</i>	7	6	86	7	7	100
<i>Sea snakes</i>	–	–	–	62	0	0.0
<i>Fish</i>	–	33	–	32,554	92	0.28
<i>Invertebrates</i>	–	1	–	159,000	6	0.004
Marine birds, mammals and turtles	434	143	32.9	536	233	43.5
<i>All species</i>		177			331	

Comparative summary with the earlier major review by Laist (1997). Individual species and sources are documented in Online Supplement. Observations only concern non-simulated dead or living wild animals found in their natural habitat. We thus exclude experimental studies showing the potential for ingestion by marine species. Between the two reviews, the number of species in the groups considered, differ because of changes in accepted taxonomic status, and selection of which species groups should be considered to be ‘marine’. For details see the Online Supplement

2011; Bond et al. 2013). Figure 4.4 illustrates the ingestion of plastic by northern fulmars.

4.4.1 Ways of Plastic Ingestion

Plastics may be ingested intentionally or accidentally and both pathways deserve further discussion.



Fig. 4.4 Plastic ingestion by northern fulmars (*Fulmarus glacialis*). Unopened stomach with plastic inside (*top*), fulmars at sea chewing on a plastic fragment (*bottom left*), stomach content of a northern fulmar with fragments, foam, sheets and wood (*bottom right*) (Photos: J.A. van Franeker (1, 3) and S. Kühn (2), IMARES)

4.4.1.1 Intentional Ingestion

Why some animals intentionally ingest plastic debris may depend on a range of factors, and these may vary among different animal groups. Although many of these factors interact, it is useful to review at least some of them separately.

Foraging Strategy

In seabirds, plastic ingestion has been linked to foraging strategy by several authors (e.g. Day et al. 1985; Azzarello and Van Vleet 1987; Ryan 1987; Tourinho et al. 2010.) From their study on many different seabird species, Day et al. (1985)

concluded, that pursuit-diving birds have the highest frequency of plastic uptake, followed by surface-seizing and dipping seabirds. Provencher et al. (2010) reported that marine birds, feeding on crustaceans and cephalopods had ingested more plastic than piscivorous seabirds, and those omnivores are most likely to confuse prey and plastic. Seabirds with specialized diets are less likely to misidentify plastic, unless a particular type resembles their prey (Ryan 1987). Many gull species frequent rubbish bins and landfill areas, in addition to foraging in marine habitats and seem prone to ingest debris. However, ingested debris does not often show up in their stomachs during dissections because they clear them daily by regurgitating hard prey remains (Hays and Cormons 1974; Ryan and Fraser 1988; Lindborg et al. 2012). As regurgitation takes place regularly, plastics quantified from boluses reflect the ingestion of the very last period, rather than accumulated debris (Camphuysen et al. 2008; Ceccarelli 2009; Codina-García et al. 2013; Hong et al. 2013). Tubenosed seabirds mostly retain plastic and hard prey items (Mallory 2006) because they possess two stomachs with a constriction (*Isthmus gastris*) between the glandular proventriculus and the muscular gizzard (Furness 1985; Ryan and Jackson 1986). Even when spitting stomach oil to defend themselves or when feeding their chicks, only plastics from the proventriculus are regurgitated but items from the gizzard are retained (Rothstein 1973). Marine turtles frequently ingest plastic bags as they may mistake them for jellyfish, a common component of their diet (Carr 1987; Lutz 1990; Mrosovsky et al. 2009; Tourinho et al. 2010; Townsend 2011; Campani et al. 2013; Schuyler et al. 2014). While accidental plastic ingestion by filter-feeding baleen whales (Mysticeti) might be assumed to be common, Walker and Coe (1990) expected that toothed whales (Odontoceti) would have a low rate of plastic ingestion because they use echolocation or visual cues to locate their prey. However, Laist (1997), Simmonds (2012) and Baulch and Perry (2014) all made extensive descriptions of toothed whales that had ingested plastic. Indeed, our updated literature search showed that 54 and 62 % of the baleen and toothed whales, respectively, ingest plastics. It has also been suggested, that marine mammals could see plastic as a curiosity and while investigating it, they swallow it or become entrapped (Mattlin and Cawthorn 1986; Laist 1987). Large predatory fishes and birds are known to frequently inspect plastic debris and take bites out of larger plastic items. Cadée (2002) observed that 80 % of foamed plastic debris on the Dutch coast showed peckmarks of birds and suggested that the birds mistake polystyrene foam for cuttlebones or other food. Carson et al. (2013) observed bite marks of sharks or large predatory fishes on 16 % of plastic debris beached on Hawaii indicating ‘testing’ of materials. Choy and Drazen (2013) showed that among 595 individuals of seven such large predatory fish species, 19 % of individuals (range per species <1–58 %) had actually ingested plastic. Foraging strategies may vary under different conditions of food availability. Duguy et al. (2000) considered that decreased availability of jellyfish during winter could be the reason for the higher incidence of plastic bags during these months in the diet of turtles.

In conclusion it seems that although indiscriminate omnivorous predators or filter feeders appear most prone to plastic ingestion, there are many examples of

ingestion among species with specialized foraging techniques and specific prey selection.

Color

One of the factors often considered to influence the consumption of marine debris is color as specific colors might attract predators when resembling the color of their prey. In seabirds, this has been suggested for e.g. greater shearwaters (*Puffinus gravis*) and red phalaropes (*Phalaropus fulicarius*) (Moser and Lee 1992). Parakeet auklets (*Aethia psittacula*) on the Alaskan coast, feeding naturally primarily on light-brown crustaceans, consumed mainly darker plastic granules, suggesting they were mistaken for food items (Day et al. 1985). In studies of marine turtles, the issue of color preference is controversial. Lutz (1990) indicated no preferential ingestion of different plastic colors; neither did Campani et al. (2013) in loggerhead turtles. However, others find light-colored and translucent plastics are most commonly ingested, suggesting similarity to their jellyfish prey (Bugoni et al. 2001; Tourinho et al. 2010). Schuyler et al. (2014) indicated such prey-similarity by the combination of translucency and flexibility of plastic bags and found that blue-colored items were less frequently eaten probably because of lower detection rates in open water. An additional visual factor could be shape as floating plastic bags resemble jellyfish. In fur seal scats, the colors of plastic were white, brown, blue, green and yellow (Eriksson and Burton 2003), however, no clear preference was evident.

White, clear, and blue plastics were primarily ingested by planktivorous fish from the North Pacific central gyre but similar color proportions were recorded from neuston samples (Boerger et al. 2010). By contrast, black particles were most prevalent in stomachs of fish from the English Channel but this study included both pelagic and demersal fish (Lusher et al. 2013). While two mesopelagic fish (*Lampris* spp.) species did not favour particular colors *Alepisaurus ferox* seemed to favour white and clear plastic pieces, which may resemble their gelatinous prey (Choy and Drazen 2013). The majority of strands reported from the intestines of Norway lobsters (*Nephrops norvegicus*) were also transparent (Murray and Cowie 2011).

Studies on the color-specific uptake often do not take into account that color may change in the gastrointestinal tract (e.g. Eriksson and Burton 2003). Also, there are rarely quantitative data on the abundance of various color categories in the foraging ranges of the species studied. In general, light colors seem to be most common in floating marine debris ranging from 94 % of the abundance in the Sargasso Sea (Carpenter et al. 1972) and 82–89 % in the South Atlantic (Ryan 1987) to 72 % in the North Pacific (Day et al. 1985). The frequently observed prevalence of translucent or brightly colored objects in stomachs may thus reflect the availability of such items the ambient environment rather than color selectivity.

Age

Among seabirds, it has been well-established that younger northern fulmars have more plastic in their stomachs than adults (Day et al. 1985; Van Franeker et al. 2011). The same has been shown for flesh-footed and short-tailed shearwater (*Puffinus carneipes* and *P. tenuirostris*, respectively, Hutton et al. 2008; Acampora et al. 2014). The chicks of Laysan albatrosses (*Phoebastria immutabilis*) at colonies (Auman et al. 1997) have a much higher load of plastic than adults at sea (e.g. Gray et al. 2012). In marine turtles, Plotkin and Amos (1990) found a decreasing trend in plastic consumption with age and attributed this to the fact that young turtles linger along drift-lines, where plastic accumulates. However, in the Adriatic Sea no clear age or size-related differences were apparent in loggerhead sea turtles (*Caretta caretta*) (Lazar and Gracan 2011; Campani et al. 2013). Schuyler et al. (2013) concludes that turtles ingest most debris during their younger oceanic life stages. Significantly higher levels of plastics were recorded in younger franciscana dolphins (*Pontoporia blainvillei*) off the Argentinian coast (Denuncio et al. 2011). Younger harbour seals (*Phoca vitulina*) in the Netherlands had significantly more plastic in their stomach than older ones (Bravo Rebolledo et al. 2013) (illustrated by Fig. 4.2). There were no differences in the plastic consumption of different age classes of cat fishes (Ariidae) from a Brazilian estuary (Possatto et al. 2011). Similarly, there was no relationship between ingested litter mass and sex, maturity and body length in deep-water blackmouth catsharks (*Galeus melastomus*, Anastasopoulou et al. 2013). By contrast, the mean number of plastic items ingested by planktivorous fish from the North Pacific gyre increased as the size of fish increased, reaching a maximum of seven pieces per fish for the 7-cm size class (Boerger et al. 2010). However, this may also be explained by higher plastic uptake of larger individuals during the capture process in the codend (Davison and Asch 2011). Larger individuals of the Norway lobster had fewer plastic threads in their intestines indicating higher ingestion rates of smaller/younger animals (Murray and Cowie 2011) that also have higher incidence of infaunal prey such as polychaetes (Wieczorek et al. 1999).

In summary, it seems that where age differences were shown, younger animals are most affected. The reasons for this are not clear. In seabirds, this could partly be explained by parental delivery of food by regurgitation to chicks at the nest. In such chicks, elevated loads of plastic could be the consequence of being fed by two parents, each transferring much of its own plastic load, which has accumulated in the proventricular stomach over an extended period of time before breeding. In addition, a less developed grinding action in the gizzards of young birds could slow the mechanical break-down of plastic and removal through the intestines. Some species of albatross and shearwater chicks may lose an excess load of plastic by regurgitating proventricular stomach contents prior to fledging (Auman et al. 1997; Hutton et al. 2008). However, in fulmars the high level of plastic persists in immature birds and only gradually disappears after several years (Jensen 2012) and thus cannot be completely explained by parental feeding and stomach functioning. Perhaps, young animals are less efficient at foraging, and therefore

less specific in their prey selection (Day et al. 1985; Baird and Hooker 2000; Denuncio et al. 2011). One important open question therefore is whether higher loads of plastic in younger animals reflect a learning process or mortality of those individuals that ingested too much plastic. Both explanations are speculative, but the latter suggests serious deleterious effects at the population level.

Sex

To date, there is no evidence that sex affects plastic ingestion. Studies that specifically evaluated male and female ingestion, found no significant differences in the plastic load (e.g. Day et al. 1985; Van Franeker and Meijboom 2002; Lazar and Gracan 2011; Murray and Cowie 2011; Anastasopoulou et al. 2013; Bravo Rebolledo et al. 2013). However, species showing strong sexual dimorphism or sex-dependent foraging ranges or winter distributions may show sex-specific uptake rates.

4.4.1.2 Accidental and Secondary Ingestion

Filter-feeding marine organisms, ranging in size from small crustaceans, to shellfish, fish, some seabirds (prions, *Pachyptila* spp.) and ultimately large baleen whales may be prone to plastic ingestion. These species obtain their nutrition by filtering large volumes of water, which may contain debris in addition to the targeted food source. Although non-food items can be ejected before passage into the digestive system, this is not always the case. In their natural habitat, ingested plastics have been found in filter-feeding crustaceans such as goose barnacles (*Lepas* spp.; Goldstein and Goodwin 2013) and mussels (*Mytilus edulis*, Van Cauwenberghe et al. 2012; Leslie et al. 2013; Van Cauwenberghe and Janssen 2014). Large baleen whales have been long known to occasionally ingest debris (Laist 1997; Baulch and Perry 2014). In France, a young minke whale (*Balaenoptera acutorostrata*) beached with various plastic bags completely filling its stomachs (De Pierrepont et al. 2005). Curiously, we have found no record of plastic ingestion by obligate filter-feeding large fish such as basking shark (*Cetorhinus maximus*) or manta ray (*Manta birostris*). Some bony fish species partially use filter-feeding, but also directional feeding making it difficult to assign the pathway of debris ingestion. Uptake of plastic by filter-feeding fish has been reported for herring (*Clupea harengus*) and horse mackerel (*Trachurus trachurus*) from the North Sea and English Channel (Foekema et al. 2013; Lusher et al. 2013).

Accidental ingestion of a mixture of food and debris is not restricted to filter feeders. In the Clyde Sea, 83 % of Norway lobsters (*Nephrops norvegicus*) had plastic in their stomach, which was attributed either to passive ingestion of sediment while feeding or to secondary ingestion (Murray and Cowie 2011), although it could be argued that the fibres ingested may resemble benthic polychaete prey. Plastics and other non-food items found in stomachs of harbour seals in the Netherlands were considered to have been accidentally ingested when catching

prey fishes (Bravo Rebolledo et al. 2013). A similar route for plastic ingestion was proposed by Di Beneditto and Ramos (2014), who showed that plastic in franciscana dolphins was related to benthic feeding habits, in which disturbance of sediment probably induced accidental intake of plastic debris. Florida manatees (*Trichechus manatus latirostris*) may take up plastic accidentally during foraging on plants (Beck and Barros 1991). Pelagic loggerhead sea turtles may ingest plastic because they feed indiscriminately or graze on organisms settled on floating plastic (McCauley and Bjorndal 1999; Tomas et al. 2002). A special case of such accidental ingestion is known for the Laysan albatross who take up plastic particles in combination with eggs strings of flying fish. The fishes attach their eggs to floating items: previously seaweed, bits of wood or pumice, but nowadays often plastic objects (Pettit et al. 1981). This phenomenon has also been observed in loggerhead turtles. The plastic in their stomachs was sometimes covered by the eggs of the insect *Halobates micans* (Frick et al. 2009).

A final case of unintentional plastic ingestion is that of secondary ingestion, which occurs when animals feed on prey, which had already ingested debris. This may concern both prey swallowed as a whole or scavenging. In seabirds, skuas are known to forage on smaller seabirds that consume plastic (Ryan 1987). Great skuas (*Stercorarius skua*) from the South Atlantic Ocean predate several seabird species, and their regurgitated boluses showed a link with the amount of secondarily ingested plastic and their main prey species (Bourne and Imber 1982; Ryan and Fraser 1988). In the monitoring study on northern fulmars (*Fulmarus glacialis*) in the North Sea intact stomachs from scavenged fulmars or black-legged kittiwakes (*Rissa tridactyla*) were occasionally found, which contained plastic (Van Franeker et al. 2011). A spectacular example of secondary ingestions was provided by Perry et al. (2013) who reported a ball of nylon fishing line in the stomach of a little auk (*Alle alle*), that was found in the stomach of a goose fish (*Lophius americanus*). The presence of small plastic particles in the faeces of fur seals on Macquarie Island was attributed to secondary ingestion through the consumption of myctophid fishes (Eriksson and Burton 2003). High abundance of small plastics in myctophid fishes (Boerger et al. 2010; Davison and Asch 2011), in combination with the fact that this type of fish is a common prey for many larger marine predators, suggest that secondary ingestion may be more common than reported.

4.4.2 Impacts of Plastic Ingestion

Plastic ingestion may directly cause mortality or can affect animals by slower sub-lethal physical and chemical effects which are best considered separately.

4.4.2.1 Direct Mortality Caused by Plastic Ingestion

When the gastrointestinal tract becomes completely blocked or severely damaged ingested plastic may lead to rapid death. Even small pieces can cause the blockage

of the intestines of animals, if orientated in the wrong way (Bjørndal et al. 1994). An ingested straw led to the death of a Magellanic penguin (*Spheniscus magellanicus*) by perforation of the stomach wall (Brandao et al. 2011). Other examples of lethal impacts in seabirds were provided, for example, by Kenyon and Kridler (1969), Pettit et al. (1981) and Colabuono et al. (2009). Cases of mortality among marine turtles have been reported by e.g. Bjørndal et al. (1994), Bugoni et al. (2001), Mrosovsky et al. (2009) and Tourinho et al. (2010). Unlike most birds, turtles seem to pass plastic debris easily into the gut, and therefore most plastics have been found in the intestines rather than the stomach (e.g. Bjørndal et al. 1994; Bugoni et al. 2001; Tourinho et al. 2010, Campani et al. 2013). As a consequence, physical impact in turtles may often be related to gut functioning or damage. In the Mediterranean Sea, the death of a sperm whale of 4.5 t, was attributed to 7.6 kg of plastic debris in its stomach, which was ruptured probably due to the large plastic load (de Stephanis et al. 2013). Often, it is difficult to produce evidence for causal links between ingested debris and mortality, and as a consequence, documented cases of death through plastic ingestion are rare (Sievert and Sileo 1993; Colabuono et al. 2009). A direct lethal result from ingestion probably does not occur at a frequency relevant at the population level. Indirect, sub-lethal effects are probably more relevant.

4.4.3 Indirect Physical Effects of Plastic Ingestion

Impacts that are deleterious for the individual but not directly lethal become relevant to populations if many individuals are affected. Partial blockage or moderate damage of the digestive tract in Laysan albatross chicks was not a major cause of direct mortality, but may contribute to poor nutrition or dehydration (Auman et al. 1997). Since virtually every chick in this population (frequency of occurrence: 97.6 %) had a considerable quantity of plastic in the stomach, debris ingestion must be considered a relevant factor in overall fledging success of the population. Major proportions of tubenosed seabird species and marine turtles ingest plastic on a very regular basis. This raises urgent questions concerning the cumulative physical and chemical impacts at the population level. Sub-lethal physical impacts may have various consequences.

Firstly, stomach volume occupied by debris may limit optimal food intake. For example, tubenosed seabirds have large proventricular stomachs because they depend on irregular patchy food availability. Reduced storage capacity affects optimal foraging at times when this should be possible. Partial blockage of food passage through the digestive tract may cause gradual deterioration of body condition of fish (Hoss and Settle 1990). Efficiency of digestive processes may be reduced when sheet-like plastics or fragments cover parts of the intestinal wall. Sometimes ulcerations are found on stomach walls of organisms that ingested plastic (Pettit et al. 1981; Hoss and Settle 1990). A potentially important physical impact from ingested plastics may be a feeling of satiation as receptors signal

satiety to the brain and reduce the feeling of hunger (Day et al. 1985), which may reduce the drive to search for food (Hoss and Settle 1990). High volumes of plastic can reduce proventricular contraction, responsible for the stimulation of appetite (Sturkie 1976).

All these factors may lead to a deterioration of the body condition of animals. In young loggerhead turtles, McCauley and Bjorndal (1999) found experimental evidence, that volume reduction in stomachs by non-food material caused lower nutrient and energy uptake. Similarly Lutz (1990) found a negative correlation between plastic consumption and nutritional condition in experiments with green turtles (*Chelonia mydas*) and loggerhead turtles. Ryan (1988) provided evidence for a negative effect on uptake of food and growth rate among chickens (*Gallus gallus domesticus*) that had been fed plastic pellets under controlled laboratory conditions, compared to control chickens.

In many non-experimental studies, researchers have looked for correlations between plastic loads and body condition. Some seabird studies indicate negative correlations between ingested plastics and body condition (e.g. Connors and Smith 1982; Harper and Fowler 1987; Donnelly-Greenan et al. 2014; Lavers et al. 2014). However, no such correlation was found by Day et al. (1985), Furness (1985), Sileo et al. (1990), Moser and Lee (1992), Van Franeker and Meijboom (2002) and Vliestra and Parga (2002). In these non-experimental studies, it is always problematic to distinguish cause and consequence: do animals increase ingestion of abnormal items such as plastics when in poor condition, or do they loose condition because of the plastic debris in their stomach? This is even more complicated because many studies are based on corpses of beached animals that often starved before being washed ashore with potentially aberrant foraging activity.

We conclude that the estimated impact from plastic ingestion on body condition is difficult to document in wild populations. However, as mentioned above, experimental studies clearly indicate that eating plastic reduces an individual's body condition. This may not be directly lethal but will translate into negative effects on average survival and reproductive success in populations in which plastic ingestion is a common phenomenon.

4.4.3.1 Chemical Effects from Plastic Ingestion

The chemical substances added during manufacture or adsorbed to plastics at sea are an additional source of concern in terms of sublethal effects. Potential chemical impacts from the ingestion of plastic are not exhaustively discussed in this chapter, as chemical transfer and impacts are discussed in more detail in the contributions by Koelmans (2015) and Rochman (2015). We would like to stress, however, that in larger organisms, plastics often have a long residence time, during which objects may be fragmented to smaller sizes due to mechanical or enzymatic digestive processes. In such conditions, the chemical additives may play a more prominent role than chemicals adsorbed to the surface. We conclude that although research to quantify body burden and consequences of plastic-derived chemicals in

marine organisms is still in its infancy, there is a risk to species frequently ingesting synthetic debris. This will remain a complicated issue due to the widespread presence of many chemicals and their accumulation in marine foodwebs along routes other than plastics alone.

4.4.3.2 Chain of Impacts Related to Plastic Ingestion

By ingesting plastics, marine biota, and in particular seabirds, accidentally facilitate and catalyse the global distribution of plastic through bio-transportation. Studies of polar tubenosed seabirds returning to clean breeding areas after overwintering in more polluted regions are a good example. Similarly, Van Franeker and Bell (1988) found that cape petrels (*Daption capense*) process and excrete some 75 % of their initial plastic load by grinding particles in the gizzard during one month in Antarctica. Plastics are thus excreted as smaller particles in other places than where they were taken up and become available to other trophic levels in marine and terrestrial habitats. Similar data were obtained for northern fulmars and thick-billed murrelets (*Uria lomvia*) in the Canadian high Arctic (Mallory 2008; Provencher et al. 2010; Van Franeker et al. 2011). In the Antarctic, Van Franeker and Bell (1988) also found that 75 % of Wilson's storm petrel (*Oceanites oceanicus*) chicks that died before fledging had plastics in their stomachs, fed to them by their parents and now permanently deposited around Antarctic breeding colonies. Transport of materials may be considerable. Van Franeker (2011) calculated that northern fulmars in the North Sea area (plastic incidence 95 %, average number 35 plastic items, average mass 0.31 g per bird) annually reshape and redistribute ca. 630 million pieces or 6 t of plastic. As fulmars range over large areas, widespread secondary distribution of plastics will occur. Chemicals may be brought to other environments by seabirds (Blais et al. 2005)—potentially partly linked to plastics. From an average plastic mass of 10 g in healthy Laysan albatross chicks on Midway Atoll to about 20 g in chicks that died (Auman et al. 1997) it may be conservatively estimated, that this species with locally ca. 600,000 breeding pairs, annually brings ashore some 6 t of marine plastic debris. Also, some crustaceans reshape and redistribute plastics: Davidson (2012) showed that boring crustacean *Sphaeroma* sp. could release into the environment thousands of small particles per burrow. One of the open questions is how plastic items reach the deep sea despite their low density and therefore low sinking rates. Along with increased density by fouling processes (Ye and Andrady 1991) plastic may also be transported to the deep sea either through sinking of carcasses containing plastics, in marine snow (Van Cauwenberghe et al. 2013) or repackaged in the faeces of zooplankton (Cole et al. 2013) or other pelagic organisms. Vertical export may also be facilitated by migratory behaviour of mesopelagic fish in the water column, which had fed on plastic items (Choy and Drazen 2013). Thus, marine life is as a significant factor in the environmental production and redistribution of secondary microplastics.

4.4.4 Impacts from Species Dispersal

One of the potentially deleterious effects of marine debris is that it offers opportunities for the dispersal, or ‘hitch hiking’ of species around the world. Organisms can colonise non-degradable material and be transported by the currents and winds. Once settled in a new habitat, this can lead to massive population growth of ‘alien species’ that can outcompete original ecosystem components (Kiessling et al. 2015). Oceanic plastics can also provide new or increased habitat opportunities for specialized species such as ocean skaters (Goldstein et al. 2012; Majer et al. 2012) or whole pelagic or benthic communities (Goldberg 1997; Bauer et al. 2008; Zettler et al. 2013; Goldstein et al. 2014). For more details on hitch-hiking species see Kiessling et al. (2015).

4.5 Discussion

The total number of marine species with documented records of either entanglement and/or ingestion has doubled with an increase from 267 species in Laist (1997) to 557 species in this new review (Table 4.3 and Online Supplements). The increase in number of affected species is substantial in all groups. The documented impact for marine turtles increased from 86 to 100 % of species (now 7 of 7 species), for marine mammals from 43 to 66 % of species (now 81 of 123 species) and for seabirds from 44 to 50 % of species (now 203 of 406 species). Among marine mammals the percentage of affected whales increased from 37 to 68 % of species (now 54 of 80 species) and seals from 58 to 67 % of species (now 22 of 32 species) (see Table 4.3).

Laist (1997) addressed groups such as fish and invertebrates only marginally, so comparative figures in such groups (Tables 4.1, 4.2, 4.3) are currently of less use. We may have missed sources, and recently publications have been published at such high frequency that we cannot guarantee completeness as given in full in the online supplement, with derived data in Table 4.4.

We have stopped our additions to the online supplement and thus to derived tables on the 9th of December 2014. We welcome documentation on missed or new records of entanglement or ingestion for future updates. It remains important to continue such documentation of species affected by marine debris. However, given sufficient time and research effort, all species of marine organisms will get documented examples of interaction with marine debris. Any species can become the victim of entanglement. Furthermore, the filter-feeding habits of many lower trophic levels, and secondary ingestion by higher trophic levels, make it almost unavoidable that any species in the marine food web will at some stage pass at least some plastic debris through the intestinal tract.

As a consequence, to improve on current knowledge, future assessments of deleterious effects of debris on marine life require comparable standardized data on frequency of occurrence, ingestion quantification and categorisation of ingested debris. It is only through study of the various impacts (including frequency and quantity) on

Table 4.3 Number of species with documented records of entanglement in, and/or ingestion of marine debris

Species group	Laist (1997)			This study		
	Spp. total	Species affected		Spp. total	Species affected	
	(n)	(n)	(%)	(n)	(n)	(%)
<i>Seabirds</i>	314	138	43.9	406	203	50.0
Anseriformes (marine ducks)	–	1	–	13	5	38.5
Gaviiformes (divers)	–	–	–	5	4	80.0
Sphenisciformes (penguins)	16	6	38.0	18	9	50.0
Procellariiformes (tubenoses)	99	63	64.0	141	85	60.3
Podicipediformes (grebes)	19	2	10.0	23	6	26.1
Pelecaniformes, suliformes, phaethontiformes (pelicans, gannets and boobies, tropicbirds)	51	17	33.3	67	27	40.3
Charadriiformes (gulls, skuas, terns, auks)	122	50	41.0	139	67	48.2
<i>Marine mammals</i>	115	49	43	123	81	65.9
Mysticeti (baleen whales)	10	6	60.0	13	10	76.9
Odontoceti (toothed whales)	65	22	34.0	65	44	66.2
Phocidae (true seals)	19	8	42.0	19	9	42.1
Otariidae (eared seals)	14	11	79.0	13	13	100.0
Sirenia (sea cows, dugongs)	4	1	25.0	5	3	60.0
Mustelidae (otters)	1	1	100.0	2	1	50.0
Ursidae (polar bears)	–	–	–	1	1	100.0
<i>Turtles</i>	7	6	85.7	7	7	100.0
<i>Sea snakes</i>	–	0	–	62	2	3.2
<i>Fish</i>	–	60	–	32,554	166	0.6
<i>Invertebrates</i>	–	9	–	159,000	98	0.1
<i>All species</i>	–	267	–	–	557	–
Marine birds, mammals and turtles	436	193	44.3	536	291	54.3
<i>Species associated with smothering</i>	–	–	–	–	22	–

Comparative summary with the earlier major review by Laist (1997). See notes in captions of Tables 4.1 and 4.2. Numbers of species affected and group percentages are not a simple sum of Tables 4.1 and 4.2 because many species suffer from entanglement as well as ingestion. For details, see the Online Supplement

different species and their interactions, combined with dedicated observational or experimental studies, that we can ultimately gain areal understanding of the many deleterious impacts of marine plastic debris on wild populations. A number of recommendations can be made to assist collection of comparable high-quality data sets:

- Accurate data on frequency of occurrence of entanglement or ingestion of debris require a proper a priori protocol, staff that has experience with identifying (symptoms of) marine debris and adequate samples sizes.
- Concerning frequency of entanglement in debris, protocols for assessment are complicated by the distinction between interaction with active fishing gear and

Table 4.4 Number of species of major groups of marine organisms with documented records of marine debris impacts in natural habitats, separately for entanglement or ingestion and in combination (search closed 9th December 2014)

Species group	Species (n)	Entanglement (n)	Entanglement (%)	Ingestion (n)	Ingestion (%)	Total species affected (n)	Total species affected (%)
<i>Seabirds</i>	406	103	25.4	164	40.4	203	50.0
Anseriformes	13	5	38.5	1	7.7	5	38.5
Anatidae (marine ducks)	13	5	38.5	1	7.7	5	38.5
Gaviiformes	5	3	60.0	3	60.0	4	80.0
Gaviidae (divers, loons)	5	3	60.0	3	60.0	4	80.0
Sphenisciformes	18	6	33.3	5	27.8	9	50.0
Spheniscidae (penguins)	18	6	33.3	5	27.8	9	50.0
Procellariiformes	141	24	17.0	84	59.6	85	60.3
Procellariidae (albatrosses)	21	12	57.1	17	81.0	17	81.0
Diomedidae (petrels, shearwaters, prions)	92	10	10.9	55	59.8	56	60.9
Hydrobatidae (storm petrels)	24	2	8.3	10	41.7	10	41.7
Pelecanoididae (diving petrels)	4	0	0.0	2	50.0	2	50.0
Podicipediformes	23	6	26.1	0	0.0	6	26.1
Podicipedidae (grebes)	23	6	26.1	0	0.0	6	26.1
Phaethontiformes	3	0	0.0	2	66.7	2	66.7
Phaethontidae (tropicbirds)	3	0	0.0	2	66.7	2	66.7
Pelecaniformes	8	4	50.0	2	25.0	5	62.5
Pelecanidae (pelicans)	8	4	50.0	2	25.0	5	62.5
Suliformes	56	16	28.6	12	21.4	20	35.7
Fregatidae (frigatebirds)	5	0	0.0	1	20.0	1	20.0
Sulidae (gannets, boobies)	10	6	60.0	5	50.0	8	80.0

(continued)

Table 4.4 (continued)

Species group	Species (n)	Entanglement (n)	Entanglement (%)	Ingestion (n)	Ingestion (%)	Total species affected (n)	Total species affected (%)
Phalacrocoracidae (cormorants, shags)	41	10	24.4	6	14.6	11	26.8
Charadriiformes	139	39	28.1	55	39.6	67	48.2
Chionidae (shearwaters)	2	0	0.0	1	50.0	1	50.0
Scolopacidae (phalaropes)	3	0	0.0	2	66.7	2	66.7
Laridae (gulls, noddies, skimmers, terns)	102	28	27.5	32	31.4	42	41.2
Stercorariidae (skuas)	7	2	28.6	6	85.7	6	85.7
Alcidae (murrelets, guillemots, murrelets, auks, auklets, puffins)	25	9	36.0	14	56.0	16	64.0
Marine mammals	123	51	41.5	62	50.4	81	65.9
Mysticeti	13	9	69.2	7	53.8	10	76.9
Balaenidae (right whales)	4	3	75	2	50	3	75.0
Neobalaenidae (pygmy right whales)	1	1	100	1	100	1	100.0
Eschrichtiidae (gray whales)	1	1	100	0	0	1	100.0
Balaenopteridae (rorquals)	7	4	57.1	4	57.1	5	71.4
Odontoceti	67	16	23.9	40	59.7	44	65.7
Physeteridae (sperm whales)	1	1	100	1	100	1	100.0
Kogiidae (dwarf and pygmy sperm whales)	2	1	50	2	100	2	100.0
Pontoporiidae (La Plata river dolphins)	1	0	0	1	100	1	100.0
Monodontidae (narwhals, belugas)	2	1	50	0	0	1	50.0

(continued)

Table 4.4 (continued)

Species group	Species (n)	Entanglement (n)	Entanglement (%)	Ingestion (n)	Ingestion (%)	Total species affected (n)	Total species affected (%)
Phocoenidae (porpoises)	6	2	33.3	4	66.7	4	66.7
Delphinidae (oceanic dolphins)	34	10	29.4	19	55.9	22	64.7
Ziphiidae (beaked whales)	21	1	4.8	13	61.9	13	61.9
<i>Pinniped</i>	33	22	66.7	12	36.4	22	66.7
Phocidae (true seals)	19	9	47.4	4	21.1	9	47.4
Otariidae (eared seals)	13	13	100	8	61.5	13	100.0
<i>Sirenia</i>	5	2	40	3	60	3	60.0
Trichechidae (manatees)	2	1	50.0	2	100.0	2	100.0
Dugongidae (dugongs)	2	1	50	1	50	1	50.0
<i>Carnivora</i>	3	2	66.7	0	0.0	2	66.7
Mustelidae (otters)	2	1	50	0	0	1	50.0
Ursidae (polar bears)	1	1	100	0	0	1	100.0
<i>Turtles</i>	7	7	100.0	7	100.0	7	100.0
Carettae	3	3	100.0	3	3.0	3	100.0
Cheloniidae	3	3	100.0	3	3.0	3	100.0
Dermochelyidae	1	1	100.0	1	1.0	1	100.0
Sea snakes	62	2	3.2	0	0.0	2	3.2
Hydrophiidae (sea snakes)	62	2	3.2	0	0.0	2	3.2
<i>Fish</i>	32,554	89	0.27	92	0.28	166	0.51
<i>Elasmobranchii</i>	692	21	3.03	18	2.60	30	4.34
Hexanchiformes (frill and cow sharks)	6	1	16.67	0	0.00	1	16.67
Orectolobiformes (carpet sharks)	44	0	0.00	1	2.27	1	2.27

(continued)

Table 4.4 (continued)

Species group	Species (n)	Entanglement (n)	Entanglement (%)	Ingestion (n)	Ingestion (%)	Total species affected (n)	Total species affected (%)
Lamniformes (mackerel sharks)	16	6	37.50	5	31.25	7	43.75
Charcharhiniformes (ground sharks)	282	11	3.90	8	2.84	14	4.96
Squaliformes (bramble, sleeper, dogfish sharks)	129	1	0.78	3	2.33	4	3.10
Myliobatiformes (stingrays)	215	2	0.93	1	0.47	3	1.40
<i>Holocephali</i>	50	1	2.00	0	0.00	1	2.0
Chimaeriformes (chimaeras)	50	1	2.00	0	0.00	1	2.0
<i>Actinopterygii</i>	22,916	67	0.29	74	0.32	135	0.6
Amiiformes (bowfins)	1	1	100.00	0	0.00	1	100.0
Anguilliformes (eels, morays)	906	1	0.11	0	0.00	1	0.11
Clupeiformes (herrings)	390	2	0.51	2	0.51	3	0.77
Siluriformes (cat fish)	3589	2	0.06	3	0.08	4	0.11
Osmeriformes (smelts)	319	1	0.31	0	0.00	1	0.31
Salmoniformes (salmons)	215	4	1.86	1	0.47	5	2.33
Stomiiformes (light fish, dragon fish)	413	0	0.00	3	0.73	3	0.73
Aulopiformes (grinners)	255	0	0.00	1	0.39	1	0.39
Myctophiformes (lantern fish)	215	0	0.00	12	5.58	12	5.58
Lampriformes (velifers, tube-eyes, ribbon fish)	24	0	0.00	3	12.50	3	12.50
Gadiformes (cod-like)	614	2	0.33	7	1.14	8	1.30
Batrachoidiformes (toad fish)	82	2	2.44	0	0.00	2	2.44
Lophiiformes (angler fish)	353	0	0.00	1	0.28	1	0.28

(continued)

Table 4.4 (continued)

Species group	Species (n)	Entanglement (n)	Entanglement (%)	Ingestion (n)	Ingestion (%)	Total species affected (n)	Total species affected (%)
Atheriniiformes (silversides)	338	0	0.00	1	0.30	1	0.30
Cyprinodontiformes (rivulines, killi fish, live bearers)	1249	1	0.08	0	0.00	1	0.08
Belontiiformes (needle fish)	254	0	0.00	1	0.39	1	0.39
Zeiformes (dories)	33	0	0.00	1	3.03	1	3.03
Scorpaeniformes (scorpion fish, flatheads)	1622	18	1.11	5	0.31	23	1.42
Perciformes (perch-like)	10,837	20	0.18	29	0.27	47	0.43
Pleuronectiformes (flatfish)	778	11	1.41	4	0.51	14	1.80
Tetraodontiformes (puffers, file fish)	429	2	0.47	0	0.00	2	0.47
<i>Invertebrates</i>	159,000	92	0.06	6	0.004	99	0.06
Crustacea	67,000	46	0.07	3	0.00	49	0.07
Echinodermata	7000	21	0.30	0	0.00	21	0.30
Mollusca	85,000	25	0.03	3	0.00	29	0.03
<i>All species*</i>		344		331		557	

*Exclusive 22 species associated with smothering, see online supplement 2

interaction with marine debris. For example, even for experts using standard protocols, it is difficult to distinguish whether wounds are caused by entanglement in active or derelict fishing gear, even when remains of nets or similar are found on the body. Some suggestions are being developed concerning entanglement rates in ghost nets or for bird entanglement in synthetic materials used for nest construction (MSFD-TSGML 2013).

- For ingestion, in addition to frequency of occurrence ('incidence') it is recommended to collect data on quantities of ingested debris not only on the basis of numbers of items but also by mass of categories.
- In such ingestion records, as a minimum it is recommended to separate industrial plastics (pellets) from consumer-waste plastics (see Table 4.5). The latter if possible can be further specified following the categorisation recommended for ingestion by birds, mammals and fishes according to the EU Marine Strategy Directive (MSFD-TSGML 2013), that is into categories of sheetlike, threadlike, foamed, hard fragmented, and other synthetic items, plus categories of non-plastic rubbish.
- For averaged data, information should be provided as 'population averages' with standard error of the mean. Population averages are calculated with the inclusion of individuals without ingested plastics. Additional data can be maximum levels observed, or proportions of animals exceeding a particular limit [such as the 0.1-g critical limit in the Ecological Quality Objective for plastic ingestion by northern fulmars (Van Franeker et al. 2011)] (see Table 4.5). We emphasize this explicit use of population averages because in quite a few of the publications checked for this review averages had been calculated just over those individuals that had plastic, often not specifying that zero values had been omitted.
- Negative species results (e.g. Avery-Gomm et al. 2013; Provencher et al. 2014) are also relevant but again should be based on an adequate sample size of animals studied according to a proper protocol. Thus, records of absence of debris for an individual sample should be as firm as those on presence. From experience in our own research group, we know of claims on absence or near absence of plastics in stomachs or guts of several species of which diets were studied, but without dedicated methods or data recording for marine debris (including zeros). Once proper methods were established for laboratory procedures and data recording, each of those species was found to contain debris regularly (e.g. Bravo-Rebolledo et al. 2013).
- Examples of protocols for ingested debris in intestinal tracts of larger organisms can be found in e.g. MSFD-TSGML (2013), with further information for ingestion by marine birds in Van Franeker et al. (2011) and marine turtles in Camedda et al. (2014). Standard protocols for marine mammals, invertebrates have not yet been established in detail but may largely follow those for seabirds and turtles. In general, these studies consider debris of ≥ 1 mm by using sieves with such mesh size.
- Only when using the above approaches on frequency of occurrence (proportion of animals in populations affected) and gravity of interaction (quantity of ingested material; damage level from entanglement), it becomes possible to design experimental or other dedicated studies that allow estimates of the true impact of plastic ingestion on wildlife populations. This relates to both the physical and chemical types of impacts, and will ultimately require model predictions using demographic characteristics of the species involved (Criddle et al. 2009).

Table 4.5 Recommended mode of data presentation for ingested plastic debris, using the example of plastics ingested by northern fulmars in different sub-regions of the North Sea (modified from Van Franeker and the ‘Save the North Sea Fulmar’ study group, 2013)

Regions		Industrial granules			User plastics			Total plastics				
2007–2011 period	Sample (n)	Incidence (%)	Average number n ± se	Average mass g ± se	Incidence (%)	Average number n ± se	Average mass g ± se	Incidence (%)	Average number n ± se	Average mass g ± se	Geometric mean mass	EcoQO (%) (over 0.1 g)
Scottish Islands	121	47	1.3 ± 0.2	0.03 ± 0.00	90	21.2 ± 3.0	0.32 ± 0.06	90	22.5 ± 3.0	0.35 ± 0.06	0.091	58
East England	51	75	4.2 ± 0.9	0.09 ± 0.02	98	42.2 ± 6.2	0.26 ± 0.06	98	46.4 ± 6.7	0.35 ± 0.07	0.154	76
Channel area	72	82	7.1 ± 1.6	0.15 ± 0.03	99	44.6 ± 8.0	0.39 ± 0.06	99	51.7 ± 9.3	0.54 ± 0.08	0.278	86
SE North Sea	493	57	3.1 ± 0.6	0.07 ± 0.01	94	24.9 ± 1.8	0.29 ± 0.04	95	28.0 ± 2.1	0.36 ± 0.04	0.105	60
Skagerrak	79	53	3.4 ± 0.8	0.07 ± 0.02	94	49.2 ± 14.9	0.24 ± 0.04	94	52.6 ± 15.5	0.31 ± 0.05	0.105	56
North Sea total	816	58	3.3 ± 0.4	0.07 ± 0.01	94	29.5 ± 2.0	0.30 ± 0.03	95	32.8 ± 2.2	0.37 ± 0.03	0.115	62

Given are sample size, percentage of individuals with ingested material (incidence or frequency of occurrence), and population averages (including zero values) with standard error (se) for both number of items (n) and mass. These are specified for industrial plastics and consumer waste separately, and in total. Added to total plastics in this example are geometric mean mass and EcoQO performance that is the percentage of fulmars that had more than the critical level of 0.1 g of total plastic in the stomach

It will take considerable time and effort to collect these data and conduct dedicated studies before firm conclusions can be drawn on the level of detrimental impact of marine plastic debris on wildlife. However, in our opinion the suffering and death of individuals, in combination with the likelihood of higher-level population effects, indicates the need for a rapid reduction of input of plastic debris into the marine environment. If wildlife problems are not convincing: recent studies show that chemical and physical impacts are likely to occur in marine food webs (e.g. Van Cauwenberghe and Janssen 2014; Rochman et al. 2013, 2014), which implies potential impacts on human end consumers (Galloway 2015).

Long-term studies on seabirds have shown that measures to reduce loss of plastics to the environment do have relatively rapid effects. After considerable attention to the massive loss of industrial pellets to the marine environment in the early 1980s, improvements in production and transport methods were reflected in a visible result in the marine environment within one to two decades: several studies from around the globe showed that by the early 2000s the number of industrial granules in seabird stomachs had approximately halved from levels observed in the 1980s (Van Franeker and Meijboom 2002; Vlietstra and Parga 2002; Ryan 2008; Van Franeker et al. 2011; Van Franeker and Law 2015). These examples indicate that it is possible to reduce deleterious impacts from marine plastic debris on marine wildlife in shorter time frames than the longevity of the material might suggest.

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