Marine Pollution Bulletin 102 (2016) 134–141

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea

Christoph D. Rummel [a,*], Martin G.J. Löder [a,1], Nicolai F. Fricke [b], Thomas Lang [b], Eva-Maria Griebeler [c], Michael Janke [a], Gunnar Gerdts [a]

[a] Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Biologische Anstalt Helgoland (BAH), Kurpromenade, D-27498 Helgoland, Germany
[b] Thünen Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, Institute of Fisheries Ecology, Germany
[c] Johannes Gutenberg-University Mainz, Institute of Zoology, Department of Ecology, Germany

ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form 12 November 2015
Accepted 17 November 2015
Available online 29 November 2015

Keywords:
Marine debris
Plastic
Fish
Ingestion
North Sea
Baltic Sea

ABSTRACT

Plastic ingestion by marine biota has been reported for a variety of different taxa. In this study, we investigated 290 gastrointestinal tracts of demersal (cod, dab and flounder) and pelagic fish species (herring and mackerel) from the North and Baltic Sea for the occurrence of plastic ingestion. In 5.5% of all investigated fishes, plastic particles were detected, with 74% of all particles being in the microplastic (<5 mm) size range. The polymer types of all found particles were analysed by means of Fourier transform infrared (FT-IR) spectroscopy. Almost 40% of the particles consisted of polyethylene (PE). In 3.4% of the demersal and 10.7% of the pelagic individuals, plastic ingestion was recorded, showing a significantly higher ingestion frequency in the pelagic feeders. The condition factor *K* was calculated to test differences in the fitness status between individuals with and without ingested plastic, but no direct effect was detected.

1. Introduction

The ongoing littering of plastic has recently gained more and more attention in the scientific community (Andrady, 2011) and politics (Galgani et al., 2013). Since plastic waste is not biodegradable, its durability is uncertain and it may persist for even centuries (Andrady, 1994; Barnes et al., 2009). Through the loss by inappropriate waste management and dumping onshore and offshore, plastic debris often reaches the marine environment where it may accumulate (Barnes et al., 2009; Hammer et al., 2012; Thompson et al., 2009). Plastic debris may drift for years and may degrade due to physical abrasion, weathering and UV-radiation (Derraik, 2002; Klemchuk, 1990; Thompson et al., 2004; Winslow et al., 1966). The ongoing degradation results in small fragments (Thompson et al., 2004) called microplastics (particles <5 mm, following the definition by Arthur et al. (2009)). Plastic particles are available for ingestion by a wide range of marine species as studies on fur seals, seabirds, sperm whales and others demonstrated (Azzarello and Van Vleet, 1987; de Stephanis et al., 2013; Eriksson and Burton, 2003; Wright et al., 2013), but they may also enter the food chain at lower trophic levels (Cole et al., 2013; Engler, 2012; Farrell and Nelson, 2013; Ryan et al., 1988). The ingestion of plastic is believed to affect the condition of animals negatively by causing false feeling of satiation or leading to internal blockage or lesion of the digestive tract (Foekema et al., 2013; Ryan, 1988). Further, plastic ingestion may modulate the bioavailability of adhered, sorbed or additive chemicals (Chua et al., 2014; Rochman et al., 2013, 2014; Teuten et al., 2009) but this might be negligible compared to uptake through ambient water and prey (Koelmans et al., 2014). Depending on the polymer density, plastic debris may be positively, neutrally or negatively buoyant which may affect the capability of ingestion by organisms (Eriksson and Burton, 2003; Lusher et al., 2013). Carpenter et al. (1972) reported the first discovery of plastic ingestion by teleost fish and several subsequent studies investigated the occurrence of plastic particles in fish (Boerger et al., 2010; Choy and Drazen, 2013; Dantas et al., 2012; Jackson et al., 2000; Jantz et al., 2013; Joyce et al., 2002; Possatto et al., 2011). Observations of such ingestions in North Sea fish were made by Lusher et al. (2013) and Foekema et al. (2013) in 36.5% and 2.6%, respectively of all investigated fish. For the Baltic Sea, no systematic studies with focus on plastic ingestion by fish exist and observations were only made occasionally (Skóra et al., 2012). Prior to our main study, 30 Atlantic mackerels (*Scomber scombrus*) were caught during sport fishing events at the "Steingrund" around the island Helgoland in summer 2013. At least 10% of the fishes contained a striking amount of long, thick and coloured synthetic fibres in the gastrointestinal tract (GIT) (Fig. 1). Motivated by this observation, this study was conducted to investigate the occurrence of plastic ingestion by fish from the North Sea and Baltic Sea with special focus on feeding-guild and species-specific differences. Besides the

* Corresponding author at: Helmholtz Centre for Environmental Research — UFZ, Department of Cell Toxicology, Permoserstraße 15, D-04318 Leipzig, Germany.
E-mail addresses: christoph.rummel@ufz.de (C.D. Rummel), Martin.Loeder@uni-bayreuth.de (M.G.J. Löder), nicofricke@gmx.de (N.F. Fricke), Thomas.Lang@ti.bund.de (T. Lang), em.griebeler@uni-mainz.de (E.-M. Griebeler), Michael.janke@awi.de (M. Janke), gunnar.gerdts@awi.de (G. Gerdts).
[1] Current affiliation: University of Bayreuth, Animal Ecology I, Germany.

http://dx.doi.org/10.1016/j.marpolbul.2015.11.043

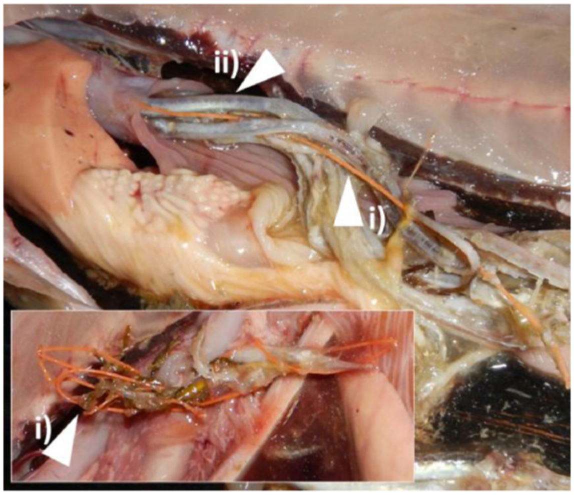

Fig. 1. Mackerels which were caught at Helgoland "Steingrund" during sport fishing having ingested orange PE and PP fibres (i) (data not included in this study). Presumably, they were taken up due to prey resemblance with juvenile Syngnathidae (ii). The fibres likely originate from fishing gear.

reporting of plastic ingestion, we investigated potential effects on the fishes' fitness status and characterized the plastic particles' polymer types and geographical distribution.

2. Material and methods

2.1. Fish sampling

Previously mentioned observations on fibres in mackerels are not included in the description of sampling and data analysis of the main study since they were sampled and processed differently. For the North and Baltic Sea survey, five different fish species were investigated. Demersal fish species were the common dab *Limanda limanda* (Linnaeus, 1758), the European flounder *Platichthys flesus* (Linnaeus, 1758) and the Atlantic cod *Gadus morhua* (Linnaeus, 1758). The Atlantic herring *Clupea harengus* (Linnaeus, 1758) and the Atlantic mackerel *Scomber scombrus* (Linnaeus, 1758) were the two pelagic species investigated. Samples from the station Helgoland "Tiefe Rinne" (Fig. 2, a red box) were taken during cruises with the research vessel "Uthörn" on the 19th of June and 24th of July 2013. All other samples were taken during the 367th cruise of the fisheries research vessel Walther Herwig III (WH III) between the 30th of August and 11th of September 2013.

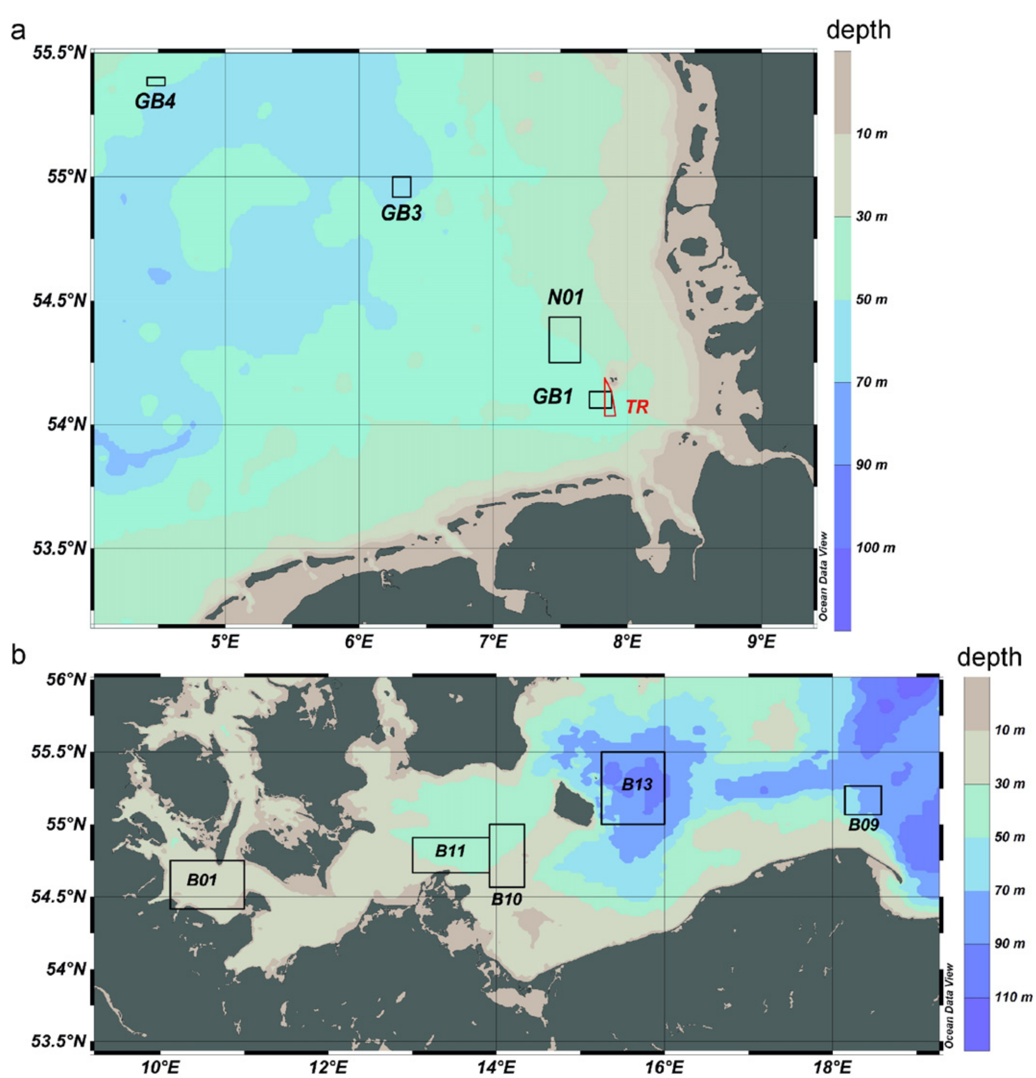

Fig. 2. Sampling stations in the North Sea (a) and Baltic Sea (b). Abbreviations represent the annually visited standard sampling stations used by the Thünen Institute of Fisheries Ecology in the North Sea (N), German Bight (GB) and Baltic Sea (B); black boxes: 367th cruise of FRV Walther Herwig III; red box: cruises with RV Uthörn at "Tiefe Rinne" (TR).

Fish were caught at five study stations each in the North and the Baltic Sea (Fig. 2 a, b) by means of bottom or pelagic trawling. If possible, 30 fish including at least 15 demersal and 15 pelagic specimens were taken per station (detailed information see Table 1 in Supporting Information (SI)). A total number of 290 fish were investigated (North Sea $n = 148$; Baltic Sea $n = 142$). We recorded the fish's total length (measured to the cm below) and the gutted weight to estimate the fitness status of all fish. On-board, the total GITs were removed and stored in sample bags at −40 °C for subsequent analysis in the laboratory.

2.2. Analysis in the laboratory

The frozen GIT was rinsed from the outside with distilled water to prevent cross-contamination. After cutting the thawed GIT open, the gut content was scraped out using a scalpel and suspended in distilled water. To minimize the turbidity for subsequent visual observation, we size-separated the suspension using a sieve of 500 μm mesh size. The fraction <500 μm was not investigated in this study since this would require a different protocol described elsewhere (Löder et al. in preparation). During visual observation of the >500 μm fraction under the stereomicroscope, we separated all potential plastic particles; still, if particles <500 μm diameter were present in the >500 μm fraction they were also included in the counts. We adopted the criteria for identification of potential synthetic materials from Noren (2007). The particles polymer type was identified applying attenuated total reflectance (ATR) (Tensor 27 spectrometer equipped with a Platinum ATR device by Bruker Optics; IR-spectrum 4000–400 cm^{-1}) and focal plane array (FPA) based micro FT-IR spectroscopy (Hyperion 3000 FT-IR microscope by Bruker Optics; IR-spectrum 3200–1250 cm^{-1}). The polymer type identification was done by comparing absorbance spectra to a reference spectra library applying the software OPUS 7.2 (Löder et al., 2015). We recorded the size, colour and shape (fragment, film, fibre or spherule) of all verified particles. Precautionary steps to prevent contamination of samples by microscopic material included wearing lab coat (100% cotton) and gloves, cleaning of instruments and dishes with ethanol and verifying the absence of contaminating microplastics on the dissecting set under the stereomicroscope prior to the analyses (Remy et al., 2015; Sanchez et al., 2014). Further, we covered the samples with aluminium foil or a glass lid when possible. The shape category "fibre" was only recorded after thorough comparison with the controls (see section below), since considerable amounts of fibres in the samples were identified as background contamination originating from ambient laboratory air.

2.3. Controls

To estimate the quantity of background contamination from ambient laboratory air, we simulated the processing of GITs (dissection, filtration and observation under the stereomicroscope) for 10 individual procedural blank controls using distilled water. Furthermore, ambient air samples were taken with focus on contaminating synthetic fibres. In ambient air and procedural blank controls the length, diameter and colour of detected contaminating fibres were recorded. Together, these results were compared to the fibres detected in environmental samples which were only recorded if the particle differed distinctively from the controls. To exclude false positives, we analysed reference material from the ship (i.e. vessel coating, fishing gear) and laboratory equipment (e.g. gloves, instruments) applying FT-IR spectroscopy.

2.4. Statistical analysis

To test for significant differences in the uptake of plastic particles between demersal and pelagic fish a Wilcoxon rank sum test was applied using R 3.2.0. This test was also conducted in R to assess differences in the number of plastic particles ingested by fish between the North Sea and Baltic Sea. Differences between groups were considered significant if $p < 0.05$. To investigate a possible effect of plastic ingestion on the fitness or physical condition of a fish, we calculated Fulton's condition factor (CF) K (Nash et al., 2006) (see formula below) for all fish. For each species, the median K value of the individuals with and without plastic ingestion was calculated.

$$K = \frac{W}{L^3} * 100$$

K	Fulton's CF
W	gutted weight (g)
L	vital length (cm)

Maps and diagrams were generated using the software Ocean Data View 4.5.7 (ODV) and the software package GraphPad PRISM V6.04, respectively. For detailed information concerning fishing, fish data and plastic particles see SI (Tables SI 1– 4).

Table 1
Fish data from the North Sea and Baltic Sea: species composition, sample size, average gutted weight (W) and vital length (L) with respective standard deviation and corresponding plastic ingestion as individual counts and percentages.

Location	Species	Sample size (n)	Sampling station	Avg W (g)	Stdev W (g)	Avg L (cm)	Stdev L (cm)	Ind. with ingested plastic	Overall % of ind. with ingested plastic
Total North Sea	Cod	7	TR,	45	14	18	2	0	0
	Dab	74	GB1, N01, GB3, GB4, TR	108	29	23	2	4	5.4
	Flounder	16	GB1, TR	256	107	28	4	0	0
	Herring	13	GB3, TR	102	33	23	2	0	0
	Mackerel	38	GB1, N01, GB3, TR	172	45	28	2	5	13.2
	All species	148						9	6.1
Total Baltic Sea	Cod	74	B01, B11, B10, B13, B09	448	172	38	7	1	1.4
	Dab	15	B01	98	19	22	1	0	0
	Flounder	20	B11, B10	299	91	32	13	2	10.0
	Herring	20	B10, B13	58	16	21	2	0	0
	Mackerel	13	B01, B11	245	88	30	2	4	30.8
	All species	142						7	4.9
Total North Sea and Baltic Sea	Cod	81	TR, B01, B11, B10, B13, B09	413	200	37	7	1	1.2
	Dab	89	GB1, N01, GB3, GB4, TR, B01	106	28	22	2	4	4.5
	Flounder	36	GB1, TR, B11, B10	280	99	29	4	2	5.6
	Herring	33	GB3, TR, B10, B13	75	32	22	2	0	0
	Mackerel	51	GB1, N01, GB3, TR, B01, B11	191	66	28	2	9	17.7
	All Species	290						16	5.5

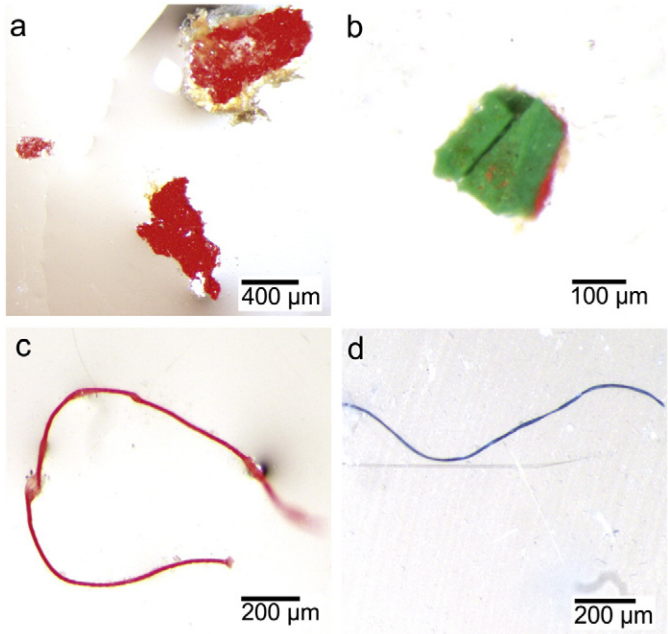

Fig. 3. Detected particles, research vessel coating and fibres, from GIT samples which were identified as false positives. Consequently, they were excluded from the total counts of detected plastics. a, b: Red and green particles of WH III coating with largest cross-section of approximately 1.2 mm and 0.2 mm, respectively; c, d: blue and red fibres approximately of about 1.7 mm and 1.8 mm length, respectively.

3. Results

3.1. Controls

Eight particles in the shape of fragments, mostly green or red, were identified as residues of coating of the research vessel WH III (Fig. 3 a, b). Consequently, these eight particles were excluded from the total counts of detected plastic particles. They were found in the gut content and had a size range of a 200 µm up to 2.2 mm. During the analyses of fish GIT samples we detected more than 160 prevailing blue and black fibres in the size range of approx. 150 µm up to 3 mm length and 5–30 µm in diameter (Fig. 3 c, d). The ten individual procedural blank controls showed fibres in a similar distribution of colour and size as the fibres detected in the field samples. Furthermore, in the ambient air samples, similar observations concerning small coloured fibres were made. The determination of absorption spectra of these particular small fibres applying micro FT-IR resulted in very weak spectra due to the small fibre diameter and did thus not lead to material identification. Consequently, detected fibres from the fish samples similar to the ones described above were excluded from the total counts of fibres and were considered as background contamination. Only fibres that differed in length and/or diameter from the fibre background contamination were counted as environmental microplastics.

3.2. Plastic ingestion by marine fish

In the North Sea and Baltic Sea survey, a total amount of 23 plastic particles were detected in the GITs of sampled fish. Plastic ingestion occurred in 16 individuals (5.5%) out of 290 investigated, whereas the frequency differed between demersal and pelagic fish species (Table 1). Out of 206 sampled demersal fish, seven individuals (3.4%) had ingested one plastic particle, resulting in a mean number of 0.03 +/− 0.18 plastic items (mean and S.D.) per fish. No demersal individual was detected having ingested more than one particle (Fig. 4 a). With 16 plastic items detected in nine out of 84 sampled fish, the pelagic feeders displayed a mean number of 0.19 +/− 0.61 items per fish. This resulted in a plastic ingestion frequency of 10.7% of all pelagic fish investigated in this study (Fig. 4 a). Pelagic feeding species ingested a statistically significant higher amount of plastic particles than bottom feeding species ($W = 8001.5$, $n = 290$; $p < 0.05$).

Species-specific counts of fish that had ingested at least one plastic particle were one cod, four dabs, two flounders and nine mackerels that had ingested at least one plastic particle (Fig. 4 b). Three individual mackerels had ingested two particles while up to three items could be recorded for two individuals. No plastic particle was detected in the digestive tract of herring. With more than 17% of all investigated individuals, mackerel displayed the highest frequency of ingestion across all species (Table 1). Due to a low sample sizes of species statistical analyses on differences in ingestion frequencies were not possible. The median K values of fish that had and had not ingested plastic debris did not differ significantly for any of the species. However, the two flounders that had ingested plastic particles showed a lower CF (median $K = 0.96$) than the other individuals that had not (median $K = 1.1$). For a single cod which had ingested a large rubber strap (Fig. 5), a low CF ($K = 0.65$) was recorded, while the median of the CF of cod individuals that had not ingested plastic was $K = 0.74$.

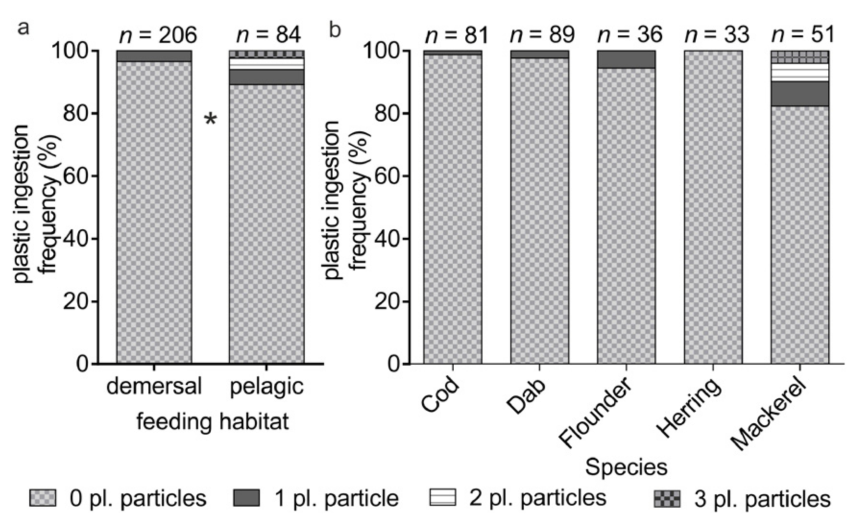

Fig. 4. Frequency of individuals (%) having ingested zero, one, two or three plastic particles grouped according to their feeding habitats (A) or at species level (B). Legend is applicable to both graphs. a: Ingestion of plastic particles was significantly higher in pelagic species (10.7%) than in demersal species (3.4%) with $p < 0.05$ (*) ($W = 8001.5$, $n = 290$, $p = 0.0112$); b: frequency of plastic ingestion across different species. The highest ingestion rate was observed for the species mackerel (17.7%) while herring was not affected.

Fig. 5. A cod hauled at sampling station B09 in the Baltic Sea, Gdańsk Bay, which had ingested a 5 cm × 50 cm rubber strap seen below the individual. Crumbled up, the rubber strap filled the entire stomach.

3.3. C Characterization, polymer types and geographical distribution of plastic particles

3.3.1. Characterization

The smallest detected microplastic particle was 180 μm at the largest cross-section. A rubber strap of 50 cm length detected in a cod was the largest and most distinct macroplastic particle detected in this study (Fig. 5). Six macroplastic particles and 17 microplastic particles were detected overall. Thus, nearly 74% of the detected particles were microplastics. Two of the macroplastic particles were fibres of ten and 20 mm length, respectively. The remaining four particles were fragments, with three of them barely exceeding the 5 mm threshold. In the different shape categories, 13 fragments represented the major proportion of plastic particles with more than 50%. The most frequent colours of synthetic polymers detected in fish were clear and white, with six and four particles, respectively. This observation is followed by five blue and four black particles, while the remaining single particles displayed a yellow, green, red or brown colour (Fig. 6 a).

3.3.2. Polymer types and geographical distribution

A total of 54 potential plastic particles were visually pre-sorted from the gut content. Of these, 23 particles were verified as synthetic polymers by means of FT-IR spectroscopy which results in a 40% hit-rate. Eight different polymer types could be identified (Fig. 6 b). Nine plastic items of polyethylene (PE) were recorded (approx. 40%). Five particles (22%) were detected as polyamide (PA), while three particles of polypropylene (PP) were found (approx. 13%). Two particles were verified as polystyrene (PS). One particle each of the polymer type polyethylenterephtalate (PET), polyester (PEST), polyurethane (PU) and rubber were detected. The remaining 31 non-synthetic particles consisted of mostly chitin, keratin as well as unidentified material. The two innermost stations TR in the North Sea and B01 in the Baltic Sea showed the highest frequency of plastic ingestion with seven detected particles each (Fig. 6 b). No significant difference between the occurrence of plastic particles in the GIT of fishes from the North Sea (13 particles) and the Baltic Sea (10 particles) could be determined ($W = 10.386$, $n = 290$, $p = 0.667$). Further, no pattern in the spatial distribution of polymer types was obvious.

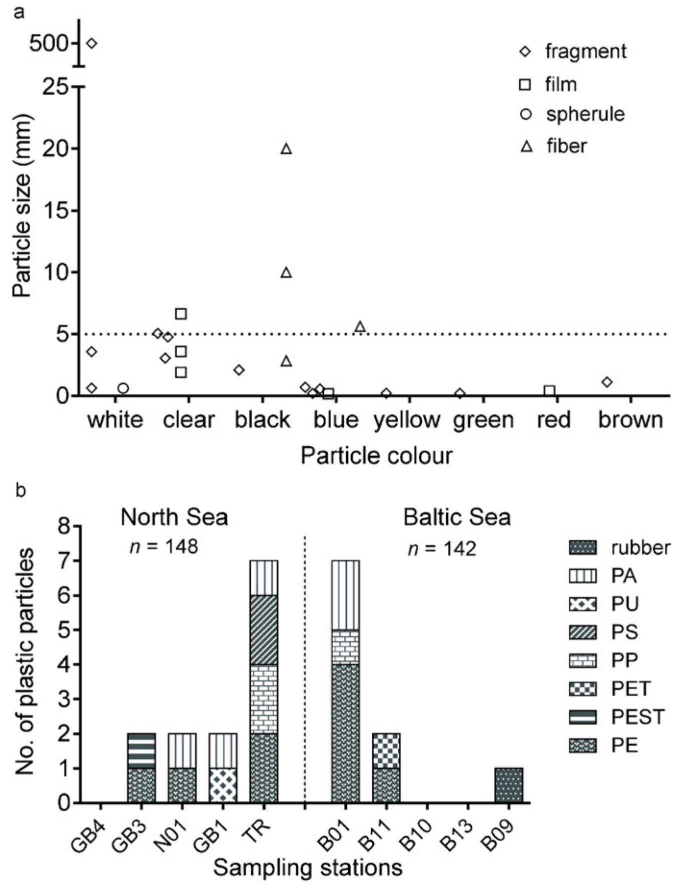

Fig. 6. Size, colour and shape of all detected plastic particles and the geographical distribution with individual counts of identified polymer type. a: Nearly 74% of all detected plastic particles were in the microplastic size range (dotted line represents the 5 mm microplastic threshold). Prevailing colours were white, clear, black and blue; fragments made up over 50% of all particles shape. b: In the North Sea and Baltic Sea, the total amount of detected plastic particles was thirteen and ten, respectively. Stations TR and B01 showed the highest detection rates, while polyethylene (PE) and polyamide (PA) were the prevailing polymer types identified by means of Fourier transform infrared (FT-IR) spectroscopy.

4. Discussion

4.1. Controls

Due to the use of controls, we could exclude a false positive detection of small coloured particles identified as vessel coating and of small fibres possibly originating from ambient air (Fig. 3 a–d). Post-capture ingestion (net feeding) may pose serious bias problems in dietary studies, often falsifying subsequent analysis of gut contents (Lancraft and Robinson, 1980). In this study, we assume that net feeding occurred occasionally during hauling. Red and green fragments of vessel coating probably got scraped from the hull during net hauling. Other studies excluded net feeding also due to mesh size (Davison and Asch, 2011), but still we consider it as a possible source of contamination or at least a possible source of falsification. After excluding most of the fibres as potential contamination, the major share of particles were fragments. In other studies, small fibres dominated with up to over 68% of all identified plastic items (Lusher et al., 2013). Our observations concerning high amounts of fibres and the subsequent identification as background contamination is also in accordance with other scientists, e.g. Foekema et al. (2013). These findings are reinforced by similar detections of also mainly blue and black fibres identified as background contamination by Davison and Asch (2011) and Nuelle et al. (2014). Remy et al. (2015) identified the majority of fibres detected in a litter macrofauna community as artificial fibres (i.e. viscose) and not petrochemical based synthetic fibres by means of Raman spectroscopy. Raman spectroscopy facilitates the measurements in the sub-micron size range (Löder and Gerdts, 2015; Löder et al., 2015). The micro-FT-IR spectroscopy approach we used does not allow for the measurement of structures below 20 μm. Due to this fact a comparison of our results with the results of Remy et al. (2015) is not possible. However, our exclusion of the majority of fibres might be a conservative approach and could thus underestimate actual numbers. Summarizing, we point at the existing problem of cross- and background contamination, wherefore special precautions such as working at a clean bench are recommended in future studies.

4.2. Plastic ingestion by fish

The uptake of small positively or neutrally buoyant particles (e.g. density PE = 0.92–0.97 g/cm^3; PA = 1.01–1.18 g/cm^3) by mackerels probably occurs accidentally during normal feeding activity (Lusher et al., 2013). In contrast, the casual detection of numerous fibres in the samples taken during recreational sport fishing at Helgoland "Steingrund" (Fig. 1) leads to the assumption that these fibres were mistaken as prey while feeding on Syngnathidae since these are part of a mackerel's diet (van Damme and Couperus (2008), personal communication M. Janke (2013)). The fibres (here PE and PP with densities <1 g/cm^3) drift passively at the sea surface and concentrate at small scale accumulation zones (created by wind, currents and seawater density gradients); the same has been observed sometimes for the juvenile Syngnathidae around Helgoland. Mackerels are opportunistic feeders that can ingest prey either by individual selection of organisms or by passive filter feeding (Pepin et al., 1988). The detected coloured fibres, probably originating from fishing gear of commercial fisheries, look like juvenile Syngnathidae that hatch in the period between May and August (Edwards et al., 2011) (Fig. 1). The detection of two or three particles in a single individual could indicate that mackerel (or other filter feeding fish) may be more vulnerable to ingest plastic than other marine fish species due to its unselective filter feeding behaviour and/or due to its feeding habitat, mainly the pelagic zone and sea surface, where floating or neutrally buoyant plastic particles may be available for ingestion. Herring, an unselective filter feeder, did not show any plastic ingestion, however most of the digestive tracts were empty. Their stage of maturity was about spawning, where herring reduces the feeding activity (Damme et al., 2009; Rijnsdorp, 1990; Wilkins, 1967). In contrast a flatfish, such as flounder, feeds with the mouthful of mud and sand which is sifted through the gill rakers to obtain the infauna (Summers, 1980). High amounts of sediment were detected in both flatfish species, dab and flounder, thus, plastic particles mixed in the sediment may be taken up accidentally while feeding (Claessens et al., 2011). The large rubber strap found in cod was probably resulting from unselective opportunistic feeding behaviour since cod feeds "on anything or almost anything" (Brook, 1886). Foekema et al. (2013) observed the highest frequency of plastic ingestion in cod (13% of examined individuals), yet we detected only a single individual having ingested plastic. Another survey found no difference in the amount of ingestion when comparing all pelagic (38% with ingestion) and demersal (35% with ingestion) species (Lusher et al., 2013) while we observed a statistically significant difference between both groups. The evaluation of the amounts of detected plastic particles remains difficult since gut content analyses are 'snapshots' of the recently ingested food and literature for further comparison is missing. The amount of affected fish may change over time since marine plastic underlies a large spatial and temporal heterogeneity (Ryan et al., 2009).

4.3. Effects of plastic ingestion

Little is known about the effects of plastic ingestion on fish and most of the recent studies focused on plastic detection in the digestive tract solely, but the further impact remains unclear (Choy and Drazen, 2013; Davison and Asch, 2011; Lusher et al., 2013; Possatto et al., 2011; Ramos et al., 2012; Sanchez et al., 2014). For the species cod we detected a slightly lower CF in the individual that had ingested a large fragment compared to the unaffected individuals. Regurgitation of the large rubber strap was probably not possible due to the size of the fragment and the way it was stuck in the stomach. The low individual CF could result from a prolonged period of starvation of which likely the individual would have died sooner or later, as a result of internal blockage by the rubber strap. Further, during a potential delay of the evacuation time, additives and chemicals sorbed to the plastic may hypothetically also leach out for a prolonged period of time. We conclude that plastic pieces of this size represent a serious threat to fishes if ingested. A mechanical threat by microplastics such as abrasions in the gut is not likely to occur since undigested entire mussel shells found in dab and flounder would certainly be excreted as a whole. Therefore, we consider an accumulation of microplastics in the gut of adult flatfish as unlikely. Flounder that had ingested microplastics had a lower CF than individuals without ingested plastics. But we argue that the sample size was insufficient to confirm the hypothesis that microplastic ingestion reduces the energy status of a fish. In this study, no direct effects of microplastic ingestion on the condition of fish could be determined. The measurement of plastic-related mortality remains difficult because disabled or dead animals are likely to be consumed by predators or decompose rapidly (Laist, 1987), hence, they remain undetected by our sampling method applied.

4.4. Characterization of plastic

The verification of potential plastic particles applying ATR and FPA based micro FT-IR spectroscopy or a similar identification technique is essential for the generation of reliable data. In this study, the IR spectroscopy facilitated a robust quantification of plastic particles. Previous studies verified visually pre-sorted particles only sporadically by spectroscopy techniques or even all particles were classified as synthetic polymers by applying the visual criteria for identification solely (Anastasopoulou et al., 2013; Foekema et al., 2013). This could lead to an overestimation of detections and is of limited confidence considering our 40% hit rate. Further, as a result of the exclusive analyses of the >500 μm fraction we most likely underestimated the total amount of microplastic particles, as potentially an unknown number of microplastics remained in the <500 μm fraction. The remaining 60% non-plastic particles in the analysed fraction most likely originated from crustacean exuviae (chitin), bird feathers (keratin) or other organic material. The analysis of plastic characteristics does not lead to the presumption of colour- or size-specific preferences by fish of plastics as prey items. Moreover, the particle properties reported here reflect amounts of plastic production demand (Plastics*Europe*, 2012, 2013), and common litter compositions regarding polymer type, shape, colour and size and are comparable with other studies, even with those from different parts of the globe (Davison and Asch, 2011). Nine (in the North Sea) and seven (in the Baltic Sea) affected individuals in our study reveal comparable incidences of ingestion in both seas especially with respect to similar sample sizes (Table 1). Still, these results can only be seen indicatively because species-specific sample sizes were low and species composition at each sampling station was heterogeneous (see SI Tables 3, 4). Both seas are commercially important and many European states border these waters. Hence, we argue that the discharge of plastic debris by anthropogenic activity is likely to be of similar magnitude in North Sea and Baltic Sea. For the North Sea, i.e. the Jade system of the southern North Sea, higher amounts of plastic particles in surface waters were reported when compared to data from the Baltic Sea (Dubaish and Liebezeit, 2013; Noren, 2007). However, this result might be due to different sampling techniques. In the present study, the highest plastic ingestion frequencies were recorded at the most nearshore stations TR in the North Sea and B01, Kiel Bight, in the Baltic Sea (Fig. 6 b). This is consistent with earlier studies that reported higher plastic abundance in coastal waters than in offshore waters, which is most likely due to land-based human activities as the major source of plastic in the marine environment (Barnes et al., 2009; Browne et al., 2011, 2010; Collignon et al., 2012; Desforges et al., 2014; Dubaish and Liebezeit, 2013). To our knowledge, this study documents the first plastic ingestions by cod, flounder and mackerel in the Baltic Sea, indicating that the Baltic Sea should be under a similar focus as other marine regions. One incidental detection of plastic in the Baltic Sea (Gdańsk Bay, close to station B09) was reported for the twaite shade *Alosa fallax* (Clupeidae) (Lacépède, 1803) by Skóra et al. (2012). In conclusion, the present study demonstrated the occurrence of plastic ingestion by fish from the North and Baltic Sea with special focus on polymer verification to determine robust ingestion frequencies and possible background contamination. Potential effects need to be seen indicatively since individual sample size was low. Long-term exposure experiments targeting the potential bioaccumulation and toxicity of plastic associated pollutants need to be addressed in future studies.

Notes

The authors declare no competing financial interest.

Acknowledgements

We would like to thank the crew and scientific staff on the vessels WH III and Uthörn. For detailed polymer type analysis we thank Mikhail Malanin and the Leibniz Institute of Polymer Research Dresden. Our sincere thanks also go to the anonymous reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.marpolbul.2015.11.043.

References

Anastasopoulou, A., Mytilineou, C., Smith, C.J., Papadopoulou, K.N., 2013. Plastic debris ingested by deep-water fish of the Ionian Sea (Eastern Mediterranean). Deep-Sea Res. I Oceanogr. Res. Pap. 74, 11–13. http://dx.doi.org/10.1016/j.dsr.2012.12.008.

Andrady, A.L., 1994. Assessment of environmental biodegradation of synthetic polymers. J. Macromol. Sci. Polym. Rev. 34, 25–76. http://dx.doi.org/10.1080/15321799408009632.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. http://dx.doi.org/10.1016/j.marpolbul.2011.05.030.

Arthur, C., Baker, J., Bamford, H., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris, NOAA Technical Memorandum NOS-OR&R-30.

Azzarello, M.Y., Van Vleet, E.S., 1987. Marine birds and plastic pollution. Mar. Ecol. Prog. Ser. 37, 295–303.

Barnes, D., Galgani, F., Thompson, R., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364, 1985–1998.

Boerger, C.M., Lattin, G.L., Moore, S.L., Moore, C.J., 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Mar. Pollut. Bull. 60, 2275–2278. http://dx.doi.org/10.1016/j.marpolbul.2010.08.007.

Brook, G., 1886. Preliminary report on the food of the cod. Rep. Fishery Bd. Scotl. 4, 134–147.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179. http://dx.doi.org/10.1021/es201811s.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol. 44, 3404–3409. http://dx.doi.org/10.1021/es903784e.

Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., 1972. Polystyrene spherules in coastal waters. Science 178, 749–750. http://dx.doi.org/10.1126/science.178.4062.749.

Choy, C.A., Drazen, J.C., 2013. Plastic for dinner? Observations of frequent debris ingestion by pelagic predatory fishes from the central North Pacific. Mar. Ecol. Prog. Ser. 485, 155–163. http://dx.doi.org/10.3354/meps10342.

Chua, E.M., Shimeta, J., Nugegoda, D., Morrison, P.D., Clarke, B.O., 2014. Assimilation of polybrominated diphenyl ethers from microplastics by the marine amphipod, *Allorchestes compressa*. Environ. Sci. Technol. 48, 8127–8134. http://dx.doi.org/10.1021/es405717z.

Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204. http://dx.doi.org/10.1016/j.marpolbul.2011.06.030.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47, 6646–6655. http://dx.doi.org/10.1021/es400663f.

Collignon, A., Hecq, J.H., Glagani, F., Voisin, P., Collard, F., Goffart, A., 2012. Neustonic microplastic and zooplankton in the North Western Mediterranean Sea. Mar. Pollut. Bull. 64, 861–864. http://dx.doi.org/10.1016/j.marpolbul.2012.01.011.

Damme, C.J.G.V., Dickey-Collas, M., Rijnsdorp, A.D., Kjesbu, O.S., 2009. Fecundity, atresia, and spawning strategies of Atlantic herring (*Clupea harengus*). Can. J. Fish. Aquat. Sci. 66, 2130–2141. http://dx.doi.org/10.1139/F09-153.

Dantas, D.V., Barletta, M., da Costa, M.F., 2012. The seasonal and spatial patterns of ingestion of polyfilament nylon fragments by estuarine drums (Sciaenidae). Environ. Sci. Pollut. Res. 19, 600–606. http://dx.doi.org/10.1007/s11356-011-0579-0.

Davison, P., Asch, R.G., 2011. Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. Mar. Ecol. Prog. Ser. 432, 173–180. http://dx.doi.org/10.3354/meps09142.

de Stephanis, R., Gimenez, J., Carpinelli, E., Gutierrez-Exposito, C., Canadas, A., 2013. As main meal for sperm whales: plastics debris. Mar. Pollut. Bull. 69, 206–214. http://dx.doi.org/10.1016/j.marpolbul.2013.01.033.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852. http://dx.doi.org/10.1016/S0025-326X(02)00220-5.

Desforges, J.-P.W., Galbraith, M., Dangerfield, N., Ross, P.S., 2014. Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. Mar. Pollut. Bull. 79, 94–99. http://dx.doi.org/10.1016/j.marpolbul.2013.12.035.

Dubaish, F., Liebezeit, G., 2013. Suspended microplastics and black carbon particles in the Jade system, southern North Sea. Water Air Soil Pollut. 224, 1–8. http://dx.doi.org/10.1007/s11270-012-1352-9.

Edwards, M., Helaouet, P., N, H., Beaugrand, G., Fox, C., Johns, D.G., Licandro, P., Lynam, C., Pitois, S., Stevens, D., Coombs, S., 2011. Fish Larvae Atlas of the NE Atlantic. Results From the Continuous Plankton Recorder survey 1948-2005. Sir Alister Hardy Foundation for Ocean Science, Plymouth, U.K.

Engler, R.E., 2012. The complex interaction between marine debris and toxic chemicals in the ocean. Environ. Sci. Technol. 46, 12302–12315. http://dx.doi.org/10.1021/es3027105.

Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. Ambio 32, 380–384. http://dx.doi.org/10.2307/4315405.

Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). Environ. Pollut. 177, 1–3. http://dx.doi.org/10.1016/j.envpol.2013.01.046.

Foekema, E.M., De Gruijter, C., Mergia, M.T., van Franeker, J.A., Murk, A.J., Koelmans, A.A., 2013. Plastic in North Sea fish. Environ. Sci. Technol. 47, 8818–8824. http://dx.doi.org/10.1021/es400931b.

Galgani, F., Hanke, G., Werner, S., De Vrees, L., 2013. Marine litter within the European marine strategy framework directive. ICES J. Mar. Sci. 70, 1055–1064. http://dx.doi.org/10.1093/icesjms/fst122.

Hammer, J., Kraak, M.S., Parsons, J., 2012. Plastics in the marine environment: the dark side of a modern gift. In: Whitacre, D.M. (Ed.), Reviews of Environmental Contamination and Toxicology. Springer, New York, pp. 1–44.

Jackson, G.D., Buxton, N.G., George, M.J.A., 2000. Diet of the southern opah *Lampris immaculatus* on the Patagonian Shelf, the significance of the squid *Morotheutis igens* and anthropogenic plastic. Mar. Ecol. Prog. Ser. 206, 261–271. http://dx.doi.org/10.3354/meps206261.

Jantz, L.A., Morishige, C.L., Bruland, G.L., Lepczyk, C.A., 2013. Ingestion of plastic marine debris by longnose lancetfish (*Alepisaurus ferox*) in the North Pacific Ocean. Mar. Pollut. Bull. 69, 97–104. http://dx.doi.org/10.1016/j.marpolbul.2013.01.019.

Joyce, W.N., Campana, S.E., Natanson, L.J., Kohler, N.E., Pratt, H.L., Jensen, C.F., 2002. Analysis of stomach contents of the porbeagle shark (*Lamna nasus* Bonnaterre) in the northwest Atlantic. ICES J. Mar. Sci. 59, 1263–1269. http://dx.doi.org/10.1006/jmsc.2002.1286.

Klemchuk, P.P., 1990. Degradable plastics: a critical review. Polym. Degrad. Stab. 27, 183–202. http://dx.doi.org/10.1016/0141-3910(90)90108-J.

Koelmans, A.A., Besseling, E., Foekema, E.M., 2014. Leaching of plastic additives to marine organisms. Environ. Pollut. 187, 49–54. http://dx.doi.org/10.1016/j.envpol.2013.12.013.

Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Mar. Pollut. Bull. 18, 319–326. http://dx.doi.org/10.1016/S0025-326X(87)80019-X.

Lancraft, T.M., Robinson, B.H., 1980. Evidence of postcapture ingestion by mid water fishes in trawl nets. Fish. Bull. 77, 713–715.

Löder, M.G.J., Gerdts, G., 2015. Methodology used for the detection and identification of microplastics—a critical appraisal. In: Bergmann, M., Gutow, L., KLages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham Heidelberg New York Dordrecht London, pp. 201–227.

Löder, M.G.J., Kuczera, M., Mintenig, S., Lorenz, C., Gerdts, G., 2015. Focal plane array detector-based micro-Fourier-transform infrared imaging for the analysis of microplastics in environmental samples. Environ. Chem. 12, 563–581. http://dx.doi.org/10.1071/EN14205.

Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99. http://dx.doi.org/10.1016/j.marpolbul.2012.11.028.

Nash, R.D.M., Valencia, A.H., Geffen, A.J., 2006. The origin of Fulton's condition factor — setting the record straight. Fisheries 31, 236–238.

Noren, F., 2007. Small plastic particles in coastal Swedish waters. *KIMO* Report, pp. 1–11.

Nuelle, M.-T., Dekiff, J.H., Remy, D., Fries, E., 2014. A new analytical approach for monitoring microplastics in marine sediments. Environ. Pollut. 184, 161–169. http://dx.doi.org/10.1016/j.envpol.2013.07.027.

Pepin, P., Koslow, J.A., Pearre Jr., S., 1988. Laboratory study of foraging by Atlantic mackerel, *Scomber scombrus*, on natural zooplankton assemblages. Can. J. Fish. Aquat. Sci. 45, 879–887. http://dx.doi.org/10.1139/f88-106.

PlasticsEurope, 2012. Plastics — The Facts 2012 An Analysis of European Plastics Production, Demand and Waste Data for 2011. Association of Plastics Manufacturers, Brussel.

PlasticsEurope, 2013. Plastics — The Facts 2013 An Analysis of European Latest Plastics Production, Demand and Waste Data. Association of Plastics Manufacturers, Brussel.

Possatto, F.E., Barletta, M., Costa, M.F., do Sul, J.A., Dantas, D.V., 2011. Plastic debris ingestion by marine catfish: an unexpected fisheries impact. Mar. Pollut. Bull. 62, 1098–1102. http://dx.doi.org/10.1016/j.marpolbul.2011.01.036.

Ramos, J.A.A., Barletta, M., Costa, M.F., 2012. Ingestion of nylon threads by Gerreidae while using a tropical estuary as foraging grounds. Aquat. Biol. 17, 29–34. http://dx.doi.org/10.3354/ab00461.

Remy, F., Collard, F., Gilbert, B., Compère, P., Eppe, G., Lepoint, G., 2015. When microplastic is not plastic: the ingestion of artificial cellulose fibers by macrofauna living in seagrass *Macrophytodetritus*. Environ. Sci. Technol. 49, 11158–11166. http://dx.doi.org/10.1021/acs.est.5b02005.

Rijnsdorp, A.D., 1990. The mechanism of energy allocation over reproduction and somatic growth in female North Sea plaice, *Pleuronectes platessa* L. Neth. J. Sea Res. 25, 279–289. http://dx.doi.org/10.1016/0077-7579(90)90027-E.

Rochman, C., Hoh, E., Kurobe, T., Teh, S., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep. 3, 3263. http://dx.doi.org/10.1038/srep03263.

Rochman, C.M., Lewison, R.L., Eriksen, M., Allen, H., Cook, A.-M., Teh, S.J., 2014. Polybrominated diphenyl ethers (PBDEs) in fish tissue may be an indicator of plastic contamination in marine habitats. Sci. Total Environ. 476–477, 622–633. http://dx.doi.org/10.1016/j.scitotenv.2014.01.058.

Ryan, P.G., 1988. Effects of ingested plastic on seabird feeding — evidence from chickens. Mar. Pollut. Bull. 19, 125–128. http://dx.doi.org/10.1016/0025-326X(88)90708-4.

Ryan, P.G., Connell, A.D., Gardner, B.D., 1988. Plastic ingestion and PCBs in seabirds: is there a relationship? Mar. Pollut. Bull. 19, 174–176. http://dx.doi.org/10.1016/0025-326X(88)90674-1.

Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364, 1999–2012. http://dx.doi.org/10.1098/rstb.2008.0207.

Sanchez, W., Bender, C., Porcher, J.-M., 2014. Wild gudgeons (*Gobio gobio*) from French rivers are contaminated by microplastics: preliminary study and first evidence. Environ. Res. 128, 98–100. http://dx.doi.org/10.1016/j.envres.2013.11.004.

Skóra, M., Sapota, M., Skóra, K., Pawelec, A., 2012. Diet of the twaite shad *Alosa fallax* (Lacépède, 1803) (Clupeidae) in the Gulf of Gdansk, the Baltic Sea. Ocean Hydro 41, 24–32. http://dx.doi.org/10.2478/s13545-012-0024-0.

Summers, R.W., 1980. The diet and feeding behaviour of the flounder *Platichthys flesus* (L.) in the Ythan estuary, Aberdeenshire, Scotland. Estuar. Coast. Mar. Sci. 11, 217–232. http://dx.doi.org/10.1016/S0302-3524(80)80042-9.

Teuten, E., Saquing, J., Knappe, D., Barlaz, M., Jonsson, S., Bjorn, A., Rowland, S., Thompson, R., Galloway, T., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P., Tana, T., Prudente, M., Boonyatumanond, R., Zakaria, M., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364, 2027–2045. http://dx.doi.org/10.1098/rstb.2008.0284.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838. http://dx.doi.org/10.1126/science.1094559.

Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009. Our plastic age. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364, 1973–1976. http://dx.doi.org/10.1098/rstb.2009.0054.

van Damme, C.J.G., Couperus, A.S., 2008. Mass occurrence of snake pipefish in the North-east Atlantic: result of a change in climate? J. Sea Res. 60, 117–125. http://dx.doi.org/10.1016/j.seares.2008.02.009.

Wilkins, N.P., 1967. Starvation of the herring, *Clupea harengus* L.: survival and some gross biochemical changes. Comp. Biochem. Physiol. 23, 503–518. http://dx.doi.org/10.1016/0010-406X(67)90402-1.

Winslow, F.H., Hellman, M.Y., Matreyek, W., Stills, S.M., 1966. Autoxidation of semicrystalline polyethylene. Polym. Eng. Sci. 6, 273–278. http://dx.doi.org/10.1002/pen.760060317.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492. http://dx.doi.org/10.1016/j.envpol.2013.02.031.