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Seabirds, gyres and global trends in plastic pollution

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ABSTRACT

Fulmars are effective biological indicators of the abundance of floating plastic marine debris. Long-term data reveal high plastic abundance in the southern North Sea, gradually decreasing to the north at increasing distance from population centres, with lowest levels in high-arctic waters. Since the 1980s, pre-production plastic pellets in North Sea fulmars have decreased by ~75%, while user plastics varied without a strong overall change. Similar trends were found in net-collected floating plastic debris in the North Atlantic subtropical gyre, with a ~75% decrease in plastic pellets and no obvious trend in user plastic. The decreases in pellets suggest that changes in litter input are rapidly visible in the environment not only close to presumed sources, but also far from land. Floating plastic debris is rapidly "lost" from the ocean surface to other as-yet undetermined sinks in the marine environment.

1. Introduction

Ingestion of marine debris by wildlife, and that of plastics by seabirds in particular, has been widely documented. Reviews (e.g. Laist, 1997; Derraik, 2002; Katsanevakis, 2008; Kühn et al., in press) illustrate the extent of plastic ingestion, but do not evaluate spatial patterns and trends in abundance of marine litter. The northern fulmar *Fulmarus glacialis* was among the earliest seabird species reported to ingest marine plastic debris. Fulmars belong to the tubenosed bird families of albatrosses and petrels (Procellariiformes). They only come ashore to breed and never forage on land or in fresh water but exclusively far out to sea. Fulmars have a wide distribution over the northern North Atlantic and Pacific Oceans with a population estimated at 15–30 million individuals (BirdLife International, 2014). Early papers suggested temporal and spatial differences in accumulated plastics in fulmar stomachs. An abundance of 1–2 particles per fulmar stomach in the North Sea in the early 1970s (Bourne, 1976) changed to more than 10 plastic particles per stomach by the 1980s (Furness, 1985; Van Franeker, 1985). Van Franeker (1985) observed an average of 12 plastic particles in fulmars from the North Sea, but less than 5 in fulmars from the presumably cleaner arctic breeding locations of Bear Island (74°N–19°E) and Jan Mayen (71°N–8°W). Similarly, the difference of only 2.8 plastic particles in fulmars from Alaska (Day, 1980; Day et al., 1985) compared to 11.3 particles in fulmars from California (Baltz and Morejohn, 1976) was explained by higher pollution in waters off the densely populated California coast. Close relatives of the fulmar living in the Antarctic had still lower levels of ingested plastics, in which species migrating to northern areas during winter contained more plastic than the resident species living in pristine Antarctic waters year round (Van Franeker and Bell, 1988).

These early studies assumed that plastic abundance in seabird stomachs reflected local or regional pollution levels, which could then be used to map spatial patterns and to monitor changes over time in ocean plastic pollution. However, as most datasets were no more than instantaneous point measurements, there was little insight into potentially biasing variables affecting quantities of plastics in bird stomachs. A first evaluation of such variables found that trends over time (1980s–2000) in beached fulmars from the Netherlands were not affected by body condition, sex of the birds, seasonal variations, or likely breeding region (Van Franeker and Meijboom, 2002). Only age of birds was found to be a factor in plastic ingestion, with young and immature birds consistently having a higher average plastic load in the stomach than adults. For monitoring purposes, when age composition of samples shows no structural change towards older or younger birds over time, samples of combined age groups can be used.

Fulmars are now a formal marine litter indicator in OSPAR (Oslo/Paris Convention for the Protection of the Marine

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Environment of the North-East Atlantic) and the European MSFD (Marine Strategy Framework Directive) (OSPAR, 2008, 2010; EC, 2008, 2010; Galgani et al., 2010; MSFD-TSGML, 2013) with results published in peer reviewed literature (Ryan et al., 2009; Van Franeker et al., 2011). The policy target or 'Ecological Quality Objective (EcoQO)' for an ecologically acceptable level of marine debris in the North Sea has been defined as fewer than 10% of beached fulmars in the North Sea having more than 0.1 g of plastic (OSPAR, 2010). Here we present new information on temporal and spatial scales in plastic pollution in fulmar stomachs, which will refine their use as an indicator. Few datasets can conclusively determine that seabird stomach contents accurately reflect environmental abundance of plastic marine debris. In the North Sea, there are no direct measurements of abundance of plastic debris in seawater and, although predicted by oceanographic models (Maximenko et al., 2012; Van Sebille et al., 2012), few data exist to confirm the lower abundance of floating plastic debris at high latitudes (Cozar et al., 2014; Ryan et al., 2014).

While not co-located, one dataset covering an almost similar time span as the North Sea fulmar study does exist: Sea Education Association (SEA) has sampled small floating plastics in the western North Atlantic Ocean and Caribbean Sea since 1986. In an analysis of data from 1986 to 2008, Law et al. (2010) found the highest abundances of plastics in the centre of the North Atlantic subtropical gyre, as predicted by models.

In this paper, we present a comparative analysis of North Sea fulmar data and SEA data through 2012. The densely populated and industrialised North Sea area is primarily a source of marine debris, where winds and currents export floating debris and prevent local accumulation (Neumann et al., 2014). In contrast, the North Atlantic subtropical gyre is distant from major sources, yet accumulates floating marine debris.

2. Methods

2.1. Fulmar study

Fulmars used in long-term studies within the North Sea are birds found dead on beaches. For the Netherlands, data are available from 1979 onwards; other North Sea countries have participated since 2002. From elsewhere, fulmars accidentally killed in long-line fisheries and stomachs of birds hunted for human consumption have been used. Early Arctic (Van Franeker, 1985) and Antarctic studies (Van Franeker and Bell, 1988) used birds collected for the Zoological Museum of Amsterdam.

Standard methods for bird dissections in the monitoring program are described in Van Franeker (2004). Stomach contents are rinsed in a sieve with a 1 mm mesh and sorted under a binocular microscope. The 1 mm mesh was selected because smaller particles are extremely rare in the stomach (Bravo Rebolledo, 2011) and because smaller meshes clog easily. Plastic items were visually identified under binocular microscope and categorized as either industrial or user plastics. Industrial plastics are often referred to as pre-production or resin pellets, 'nurdles' or 'mermaids tears' and are the raw granular stock from which user objects are made by melting the granules, with additives giving the plastic its desired characteristics. User plastics are often fragments of larger objects. Subcategories of litter are counted and dried at room temperature for at least 2 days before weighing to an accuracy of 0.0001 g. Data allow analyses for subcategories of litter or higher groupings by: i) the percentage of birds having litter in the stomach (incidence or frequency of occurrence), ii) number of items, or iii) total mass of litter. Number and mass are always given as population averages, meaning that all birds, including those with zero debris in the stomach, are included in the calculation.

Methodological details are provided in Van Franeker et al. (2011) and the Online Supplement. In the current analysis, time series for the Netherlands have been updated with results up to 2012 (total 973 birds). For other locations around the North Sea, data in 2012 were not yet available and data are presented up to 2011.

2.2. Gyre study

SEA has sampled small floating plastics in the western North Atlantic and Caribbean Sea since 1986. For the current analyses earlier published data (through 2008 in Law et al., 2010) were extended through 2012. Samples were collected with neuston nets and archived by SEA undergraduate students and faculty scientists. SEA cruises mostly follow annually repeated cruise tracks. The neuston net has a 1.0 m $\times$ 0.5 m mouth, a 335-µm mesh, and is towed at the air-sea interface, in principle sampling half its height submerged (25 cm). The net is towed off the port side of the vessel to avoid interference by the ship's wake. Tow duration is typically 30 min at an estimated speed of two knots, giving a nominal tow length of one nautical mile (1.852 km). However, sampling may differ by conditions, and actual tow length was measured either with a taffrail log towed behind the ship or from GPS coordinates. Plastic particle concentration is computed as total number of pieces collected, divided by the tow area (tow length*1-m net width), and reported in units of pieces per km^2. The area sampled during a tow is a small fraction of a square kilometre; when scaled up, the minimum non-zero concentration recorded is ~540 pieces km^{-2} (one piece in a 1.85 km-long tow). Potential bias from the small sampling area was tested by comparing averages from individual tows (with associated standard errors (SE)) to averages derived from counts of grouped data (total number of items divided by total area sampled in a year; no SE). Differences were relatively minor, so here we use values from individual tows. Similar to fulmar data, all calculations for averages include the net tow observations with zero plastics. The dataset contained 7165 net tows but observations east of 50°W (only visited twice; 91 tows), early records that did not distinguish between industrial and user particles (230 tows), and likely data entry errors with more than 10 industrial particles but zero user particles (27 tows) were omitted. The remaining dataset had 6817 net tows east of 50°W from 1987 to 2012. The analyses in this paper focus on 2624 records in arbitrarily chosen limits of the most frequently sampled high density area referred to as the central gyre, between 20°N and 40°N and 60°W to 80°W. Plastic densities in this centre were about three times higher than those outside and are expected to more clearly show proportional abundances and trends over time. The Online Supplement provides details of backgrounds of data restrictions and tabulates results also for the unrestricted dataset.

Data graphs for both datasets use 5-year running averages, each time calculated from all individual birds or net tows within the period (i.e. not from annual averages). We refrained from using annual averages because of occasional small samples, short-term variations and individual outliers. In running average graphs, the lines connecting data-points are only provided as a simple visualisation of patterns or trends and have no statistical meaning.

Temporal trends were evaluated by GAMM (Generalized Additive Mixed Models) using R version 3.0.3 (R Core Team, 2014; Wood, 2011). Where GAMM estimates 'Effective Degrees of Freedom (edf) as 1, the correlation may be considered linear (Wood, 2001). Higher edf indicates more complicated non-linear relationships (Zuur et al., 2009). Significance of all trends was tested by simple linear regression, fitting log-transformed values of plastic abundance from individual birds or neuston tows on the year of collection using Genstat 17th Edition. The test statistic is a t-score for slope

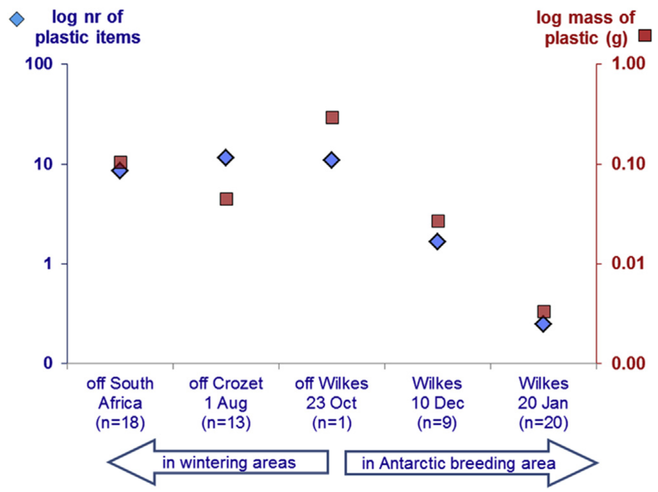

Fig. 1. Change in abundance of plastic debris in stomach contents of cape petrels after return from northern wintering areas to their Antarctic breeding area in Wilkes Land (66°S–110°E) from late October onwards.

and standard error of the slope estimated by the regression. For evaluation of regional differences, plastic data were fitted in a negative binomial generalized linear model with region included as a factor, and the test statistic is a t-score based on residual variance for the region (Genstat 17th Edition).

3. Results

3.1. Fulmar study

In order for stomach contents to reflect location-specific pollution levels, birds must forage in a certain area for time periods long enough to integrate debris encounters, and plastics must disappear from the stomach quickly enough to ensure that amounts of debris regain a new local balance when the birds migrate to another area. Lacking straightforward data on those issues, an indirect approach is used that a) evaluates information on the residence time and clearance rates of plastics from stomachs and b) investigates the consistency in small-scale spatial patterns of stomach contents.

3.2. Retention time of plastics in stomachs

Unlike gulls, fulmarine petrels do not usually regurgitate indigestible hard items. They only spit out stomach contents in fear, in fights, or when feeding their chicks. When they do spit, only materials from the glandular first stomach (proventriculus) are lost as the narrow passage to the second muscular stomach (gizzard) prevents materials in the gizzard from returning to the proventriculus (Ryan and Jackson, 1986). Most plastic particles accumulate in the muscular gizzard, where all hard food or debris items are ground up until they wear down or fragment into sizes small enough to pass into the intestines. In a study of several species of Antarctic fulmarine petrels, Van Franeker and Bell (1988) evaluated changes in stomach contents throughout the breeding season. The non-polluted character of the local Antarctic area was demonstrated by the fact that the non-migratory species had virtually no plastic in the stomach in any time of the breeding season, whereas species migrating north in winter, such as the cape petrel *Daption capense*, returned with considerable amounts of ingested plastic. In their Antarctic breeding area between December and January, cape petrels lost 80–90% of plastics from their stomachs in just over one month. However, cape petrels start to arrive in Antarctica in late October: one late October bird from the study area had a stomach content similar to that of cape petrels collected in winter off South Africa (Ryan, 1987) and the Crozet Islands (Van Franeker and J.-K. Jensen, unpublished). Plastic abundance in these 'pre-breeding' cape petrels, compared to birds collected in the Antarctic breeding location in December, indicates that during this initial ~1.5 months of local foraging the number and mass of plastic items decreased by 80%–90% (Fig. 1; details in Online Supplement). We conclude that the rapid losses of plastics were the result of size reductions in the birds' gizzards and eventual excretion, and that little or no plastic was ingested while foraging in the Antarctic. A similar rapid reduction was observed for squid beaks in the stomachs of all species of fulmarine petrels in the study. Squid beaks are made of chitin, a natural equivalent of synthetic polymers, and of similar resistance. Squid are prevalent in winter foraging grounds but are

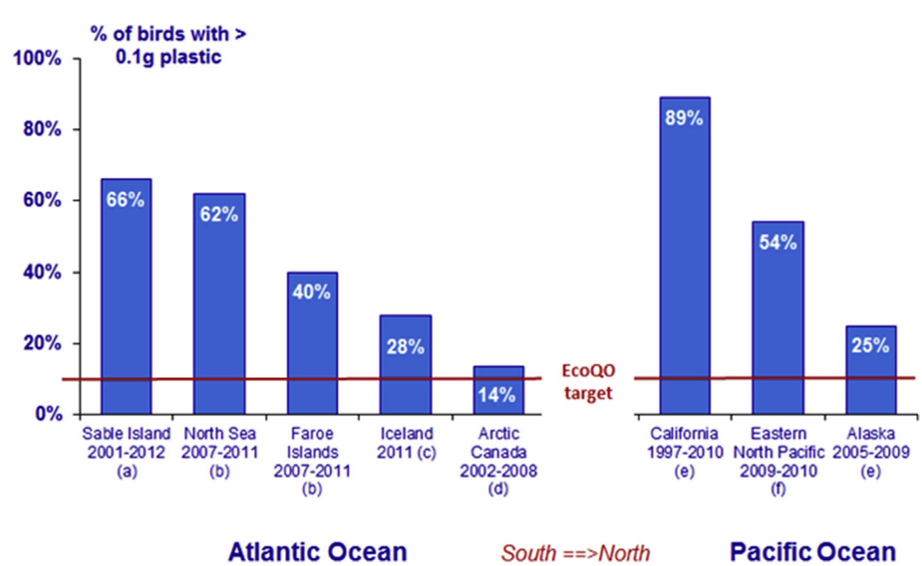

Fig. 2. Latitudinal patterns in fulmar EcoQO performance (proportion of fulmars having >0.1 g plastic in the stomach) in North Atlantic and Pacific Oceans. (a) Bond et al. (2014), (b) this study, (c) Kühn and Van Franeker (2012), (d) combined from Mallory et al. (2006), Mallory (2008) and Provencher et al. (2009) with additional information from the authors, (e) Nevins et al. (2011), (f) Avery-Gomm et al. (2012). Details in Online Supplement.

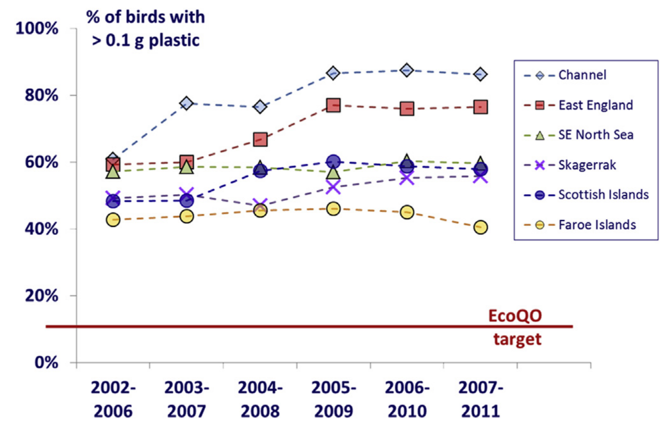

Fig. 3. Regional trends in fulmar EcoQO performance (proportion of fulmars having > 0.1 g plastic in the stomach) over time in North Sea regions and the Faroe Islands (Updated from Van Franeker and the SNS Fulmar Study Group (2013); details in Online Supplement).

rare near the breeding colonies (cf. Jarman et al., 2013). Squid beaks disappeared at an average rate of 72% between December and January (details in Online Supplement), consistent with observations of ingested plastic.

3.3. Consistency in regional patterns

For northern fulmars, large-scale spatial patterns in stomach contents observed in the 1980s have been confirmed by recent studies that used the EcoQO methods. In the North Sea, on average about 60% of fulmars exceed the critical EcoQO level of 0.1 g of plastic. Further north, around the Faroe Islands, this figure decreases to about 40%. Incidental data from locations at greater distance from populated industrialized areas support continuation of this pattern in both the North Atlantic and in the North Pacific (Fig. 2).

Data for EcoQO performance within the North Sea reveal relatively consistent spatial patterns at even smaller subregional scales (Fig. 3). The 5-year running averages for EcoQO performance do suggest small changes over time such as increases in the Channel area and northeast England, but none of the trends is significant. Ingested plastic mass in fulmars from the Channel area differed significantly from that in the Faroes ($p < 0.001$) and SE-North Sea ($p = 0.026$), but not from the other regions, likely due to lower sample sizes. The major point illustrated is that differences between sub-regions within the North Sea are fairly consistent, with highest plastic abundance in fulmars from the Channel and lower average plastic abundances in more northern sub-regions and the Faroe Islands, with increasing distance from heavily industrialized and populated areas.

3.4. Time trends 1980s to 2012 in fulmar plastic ingestion

Plastic abundance in fulmar stomachs from the Netherlands has shown strong but erratic changes from the 1980s onwards. In the standard EcoQO approach, plastic abundance is evaluated in terms of mass because mass is considered to be more ecologically relevant than numerical abundance (Van Franeker et al., 2011). Numerical and mass trends do not always match because particles of user plastics in fulmar stomachs have become smaller over time (Online Supplement). The data (1979–2012, $n = 973$) suggest an increase in ingested plastic from the mid-1980s to peak values in the mid-1990s in both mass and number, followed by a decrease in mass towards the turn of the century, but not in number. Finally, over the past decade, number and mass of plastics are apparently stable. These non-linear patterns in total plastic abundance (industrial plus user plastics) are visible in 5-year running averages (Fig. 4) but GAMM analysis only supports non-linear change in number of particles ($edf = 1.7$, $p = 0.06$) and not in mass ($edf = 1$, $p = 0.07$; Online Supplement). Linear regression of total plastics over the entire time series suggests a strong and significant numerical increase ($p < 0.001$, Fig. 4A), but a weakly significant decrease in mass ($p = 0.03$, Fig. 4B). Remarkable differences exist between industrial and user plastics. User plastics dominate the overall pattern (Fig. 5A and B) and follow non-linear changes described by GAMM for both number of particles ($edf = 2.3$, $p = 0.005$) and mass ($edf = 2.9$, $p = 0.009$). However, GAMM analyses indicate that temporal trends in industrial plastic (Fig. 5A and B) should be considered linear (number of particles $edf = 1$, $p = 0.07$; mass $edf = 1$, $p = 0.15$). Linear regression indicates a highly significant decrease of industrial plastics ($p < 0.001$ for both mass and number). This decrease represents an almost 75% reduction in average number of industrial plastics in stomachs of fulmars found in the Netherlands (from ±8 industrial plastics per stomach in the first half of the 1980s to less than 3 in the 2000s).

3.5. Time trends 1987–2012 in plastic abundance in the North Atlantic subtropical gyre

In the central part of the gyre, total plastic abundance by number of particles (Fig. 6) followed a complex non-linear pattern

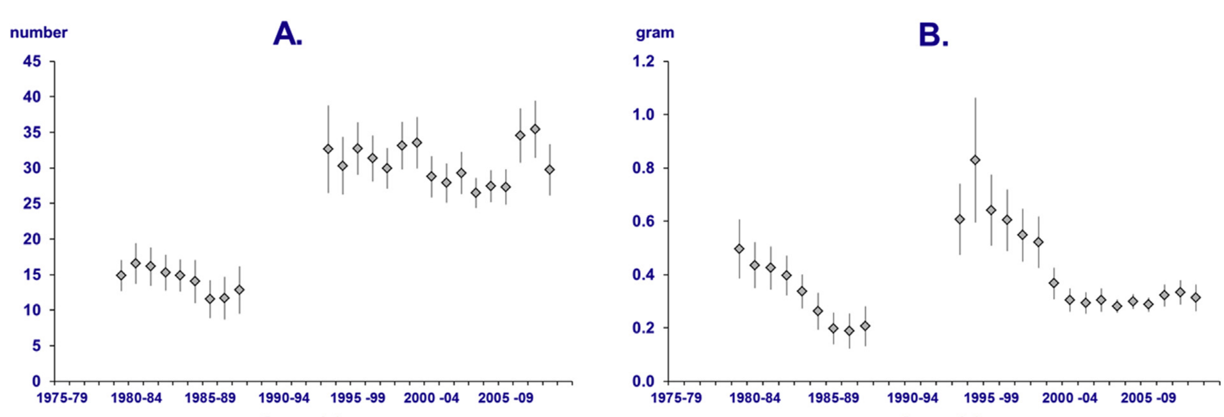

Fig. 4. Changes in A. numerical abundance and B. mass of plastics in fulmars from the Netherlands since the 1980s. Data show arithmetic averages ±standard error (SE) by running 5-year averages (i.e. data points shift one year ahead at a time; sample size for 5 year periods is ≥ 21 during the 1980s and ≥204 from the 1990s onward. Data in the early 1990s were omitted because sample sizes were ≤10 birds. Details in Online Supplement.

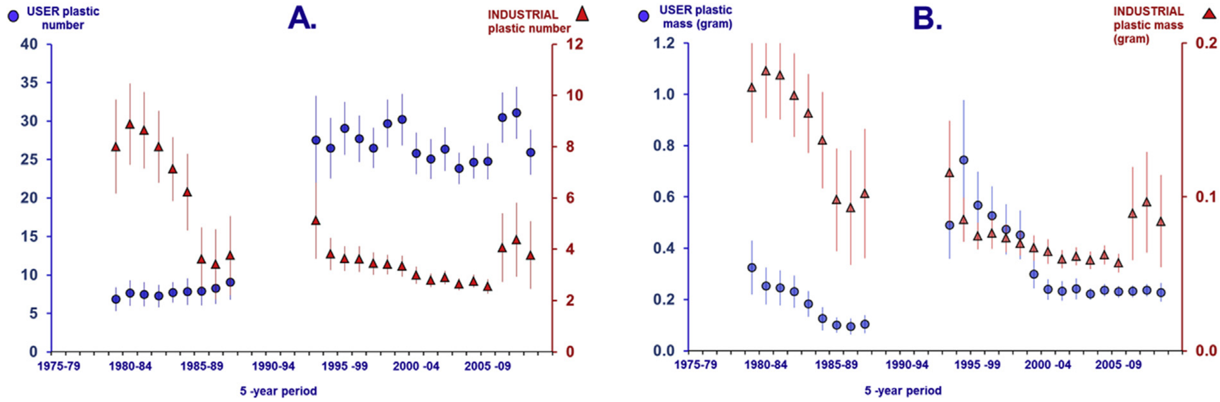

Fig. 5. Dissimilar trends in A. numerical abundance and B. mass of industrial and user plastics in fulmars from the Netherlands since the 1980s. Data show arithmetic averages ±SE by running 5-year averages. For industrial plastics, high arithmetic averages and large standard errors in the last three pentads were caused by 2 excessive outliers in 2010 and 2011. Additional log transformation in tests for trends reduces the impact of these outliers, see Online Supplement.

over the period 1987–2012 (n = 2624) with strong variability and potential peak values in the early 2000s (GAMM: edf = 6.2, $p < 0.001$; Online Supplement). However, as in contents of fulmar stomachs, this pattern is composed (Fig. 7) of a dominant trend in the abundant user plastics with similar non-linear complexity (edf 6.1, $p < 0.001$) but a linear correlation indicated for the number of industrial plastics (edf = 1, $p < 0.001$). By linear regression, the total number of particles and the number of user plastics have shown no significant change, but industrial plastics have decreased at a highly significant rate ($p < 0.001$).

Abundance data as number per km^2 obscures the fact that even in the centre of the gyre an average of only 1.05 industrial plastics and 18.3 user plastics per tow were observed over the entire time record, illustrating the large number of tows with zero plastics. As a consequence, trends can be more strongly visualised in the frequency of occurrence of particles in individual tows (Fig. 8). Within the central gyre, the percentage of net tows that contained one or more industrial plastics dropped from ~50% in the 1980s to 10–20% in recent survey years, a highly significant decrease over 25 years of data ($p < 0.001$). Overall, the density of industrial plastics in the central gyre has decreased by about 75% from roughly 1000 to around 250 particles per km^2. User plastics are found in about 80% of net tows without significant changes over time.

4. Discussion

Early papers estimated retention times for plastics in seabird stomachs from 2 to 3 months for ‘soft’ objects to 10–15 months for “hard” particles (Day, 1980). From a wider range of observations, Day et al. (1985) concluded that it took an average of 6 months or more for plastic particles to disappear through wear in the gizzard, with great variation in rates depending on the number, size, and type of particles. An even longer retention time for plastic pellets was inferred by Ryan and Jackson (1987) from experimental work on chicks of white-chinned petrels (*Procellaria aequinoctialis)*; they estimated a half-life of at least one year for plastics in the stomachs of these chicks.

Our data on cape petrels demonstrate that these are serious overestimates of residence time of plastics in stomachs of petrels, as supported by studies of seabirds in the Canadian Arctic after their return from winter ranges. Northern fulmars collected at Nunavut in the high Arctic (n = 102; data derived from Mallory, 2008) showed an overall 90% decrease in the average number of plastic particles in the stomach over summer from 8.6 particles/bird in May, to 3.2 in June, 1.2 in July, and 0.8 in August. The June and July data represent monthly reductions of more than 60%, a similar order of magnitude to our findings. The lowered reduction

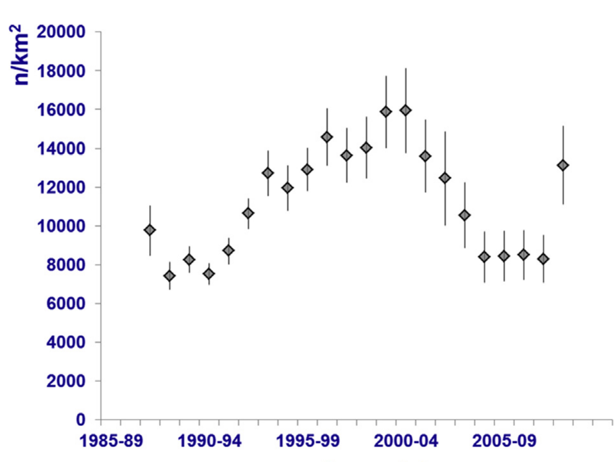

Fig. 6. Numerical abundance of plastic particles (n/km²) in the central area of the North Atlantic subtropical gyre (20–40°N, 60–80°W) from 1987 to 2012 in 5-year running averages ±SE (minimum sample size per 5 years is 237 tows; total tows 2624).

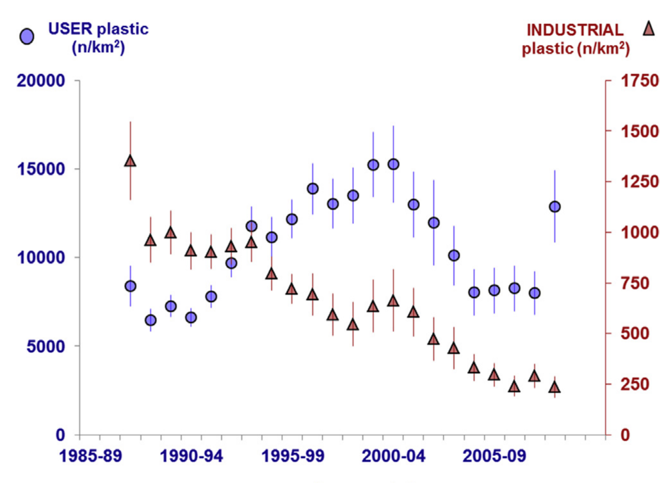

Fig. 7. Numerical abundances of industrial and user plastics (n/km²) in the central area of the Atlantic gyre (20-40°N, 60–80°W) from 1987 to 2012 in 5 year running averages ±SE (minimum sample size per 5 years = 237 tows; total tows = 2624).

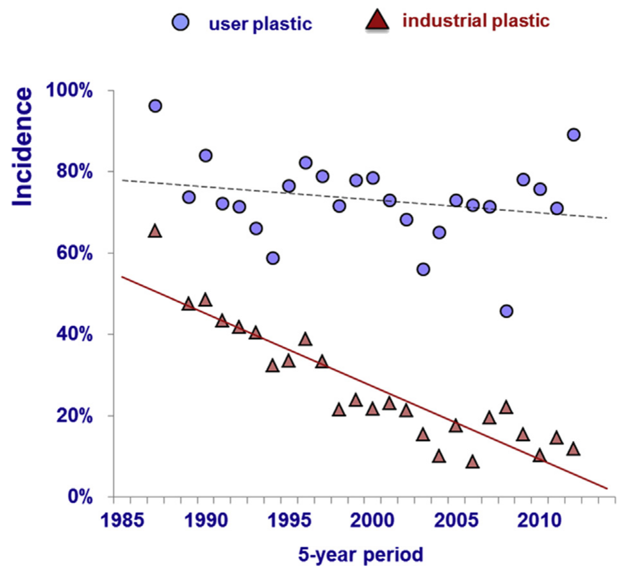

Fig. 8. Annual incidences of industrial and user plastics in SEA net tow data from the central gyre (20-40°N, 60–80°W) from 1987 to 2012 (n = 2624).

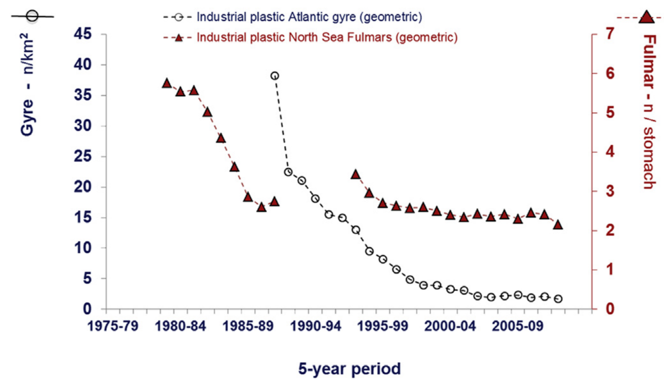

Fig. 9. Comparative trends in numerical abundance of industrial plastics in stomachs of North Sea fulmars and surface densities in the North Atlantic subtropical gyre by running geometric means over 5-year periods.

rate towards the end of summer (July–August: 33%) may reflect highly wear-resistant plastics remaining in the stomach or low rates of local ingestion. In a different species, 13% of thick-billed murres *(Uria lomvia)* arrived in their high Arctic breeding colony with plastic in the stomach, while 2 months later no bird at the same location had any plastic (Provencher et al., 2010).

The studies of birds moving from polluted wintering areas to clean(er) foraging zones justify the conclusion that for species comparable in size and morphology to fulmars, the loss rate of plastics from their stomachs may be conservatively estimated to be on the order of 75% per month for harder types of plastic. It is reasonable to assume that softer sheet-like and foamed plastics disappear at faster rates. Consequently, it is likely that fulmars can accumulate or lose – quantities characteristic of local pollution levels within a few weeks, with faster changes possible for softer materials.

Fulmars cover distances of around 30 km in an hour, up to a maximum of 70 km (Falk and Møller, 1995; Weimerskirch et al., 2001; Mallory et al., 2008; Edwards et al., 2013). Theoretically, such flight speeds enable birds to cover much of the North Sea in a few days. However, continuous fast movements are energetically expensive, and in practise seabirds tend to stay for longer periods once in chosen foraging areas. From tracking studies during the breeding season, foraging ranges of breeding fulmars have been estimated at only 47.5 ± 17.7 (sd) km away from the colony (Thaxter et al., 2012), in spite of the fact that the maximum observed distance of a breeding bird away from the colony was around 2400 km during a 15-day journey in the early egg phase (Edwards et al., 2013). Winter foraging patterns are less well known. Tracking data show wide dispersal potential, but also indicate fairly limited daily travel distances. Mallory et al. (2008) recorded an average travel distance of 84 km/day for high-Arctic Canadian fulmars, but this included the fast initial southward migration and thus strongly overestimates movement in the winter foraging zone. Individual tracks of Pacific fulmars (Hatch et al., 2010) showed considerable variability in wintering patterns, but quite a few birds showed behaviour of staying relatively sedentary once in chosen locations, sometimes returning to the same small area in subsequent winters. Fulmar tracking data indicating relative short daily movements are consistent with our findings on spatial gradients in plastics abundance (Fig. 3) and stomach residence time of plastics. On average, stomach contents of fulmars reflect the local conditions to which they adapt on time scales of a few weeks or possibly even days.

Our analyses indicate similarity in long-term trends in plastic abundance ingested by a bio-indicator in the North Sea, one of the source areas for plastic debris in the North Atlantic, and surface densities in the North Atlantic subtropical gyre, a long-term accumulation area (Law et al., 2010; Maximenko et al., 2012; Van Sebille et al., 2012). Although Moret-Ferguson et al. (2010) examined plastic mass in a subset of the gyre data, we have insufficient information to compare fulmar and gyre data using plastic mass, and thus focus on numerical abundances.

Industrial plastics show highly significant decreases throughout the period of observation, strongest in initial years but continuing into an overall reduction of about 75% in both datasets over two to three decades (Fig. 9). These data are consistent with the 'spot' observations on abundance of industrial plastics in seabird stomach contents in other areas. In the western Atlantic, Moser and Lee (1992) reported half of the plastic items in fulmar stomachs as industrial during the early 1980s, whereas Bond et al. (2014) in recent years classified only 6% as industrial plastics. In the North Pacific, industrial plastics in stomachs of short-tailed shearwaters (*Puffinus tenuirostris*) nearly halved from the 1970s to the period 1997–2001 (Vlietstra and Parga, 2002). In the South Atlantic and Indian Oceans, Ryan (2008) reported 44%–79% decreases in the abundance of industrial plastic particles in 5 tubenosed seabird species from the 1980s to 1999–2006. Thus, there is convincing evidence for a

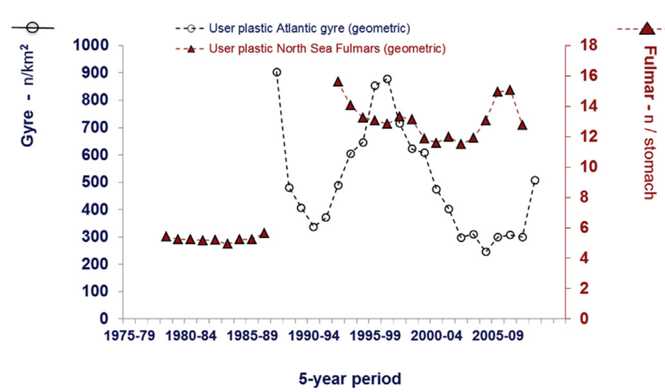

Fig. 10. Comparative trends in numerical abundance of user plastics in stomachs of North Sea fulmars and surface densities in the North Atlantic subtropical gyre by running geometric means over 5-year periods.

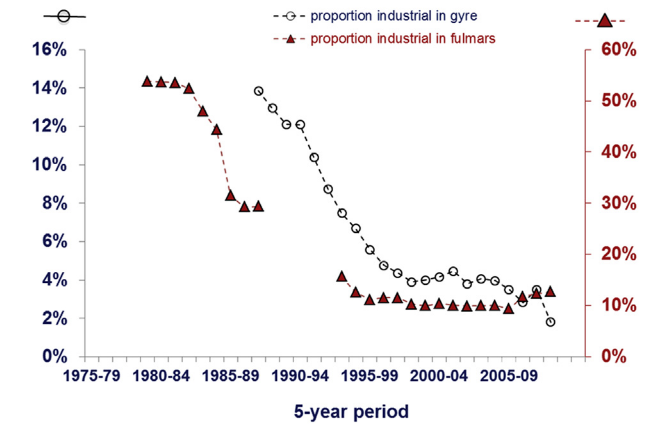

Fig. 11. Numerical proportion of industrial plastics among all plastic particles in the central Atlantic gyre and in northern fulmars of the North Sea by running 5-year periods (arithmetic average number of industrial plastics divided by arithmetic average total number of plastic particles).

strongly reduced abundance of industrial plastics in the surface of the global oceans from the 1980s into the 21st century. Our North Sea fulmar data show that input of industrial plastics in one of the major areas of global plastic production (PlasticsEurope, 2013) has been reduced.

User plastics, on the other hand, have shown a complex pattern of increases and decreases in numerical abundance in both fulmars and the gyre. Fulmars showed an initial strong numerical increase and subsequent stability, whereas abundance in the gyre fluctuated without an evident long-term trend (Fig. 10).

The different patterns for industrial and user plastics have led to a considerable change in composition of plastic in both the gyre and in fulmars. During the first half of the 1980s fulmars had about equal numbers of industrial and user plastic particles in their stomachs; currently, user plastics outnumber industrial plastics by a factor of 10. In the gyre, initially about one in seven particles was an industrial pellet, but recently only one in about 50. Fig. 11 suggests that the major changes in these ratios occurred before the turn of the century, and that recently proportions remain fairly stable.

A tentative explanation for the decrease in industrial plastics might be found in a response to publicity in the 1970s and 1980s revealing a global oceanic presence of virgin industrial pellets (Colton et al., 1974; Wong et al., 1974; Gregory, 1978; Shiber, 1979, 1982; Morris, 1980) and their ingestion by a wide range of marine wildlife (e.g. Bourne and Imber, 1982; Connors and Smith, 1982; Day et al., 1985). For the 1980s, no information exists on dedicated measures by industry or transport sectors, but in 1991 the dedicated Operation Clean Sweep campaign was started (U.S. EPA, 1993). The similarity in results of fulmar and gyre data, and published information on seabirds elsewhere, suggests that the observed trends are embedded in a wider and more general reduction in the input of industrial pre-production pellets to the marine environment.

Our analysis shows that reduced input of marine debris in source areas has observable effects even in accumulation areas far offshore within a limited number of years. This implies that plastics disappear from the sea surface on relatively short time scales. Recent publications (Cozar et al., 2014; Eriksen et al., 2014) reported lower than expected accumulation of plastic debris in all 5 global subtropical gyres. Eriksen et al. (2014) estimated that around 270.000 tons of micro- and macro plastic debris floats in the global oceans. That quantity represents only about 5% of the minimum of the estimated annual input of plastic waste into the oceans from land (4.8 million tons; Jambeck et al., 2015). Our time series for industrial plastics provide firm evidence that such a mismatch has a realistic basis and is not due to potential errors in measurements or models. We do not know to what extent losses from the ocean surface represent export to other oceanic compartments or to land, reductions in size to below our level of observation, or possibly true degradation. Ingestion and stomach processing by wildlife may well play a role in size reductions and displacement. The hypothesis that a reduced (but continuing) rate of input of plastics leads to reduced numbers of particles in marine surface waters does not mean that current input levels do not cause harm to food-chains or ecosystems. The critical question, 'Where is all the plastic?' (Thompson et al., 2004), including the uncertainty on impacts, remains unanswered. However, our observations do suggest that a reduction in the input of plastic debris to the sea is an observable and effective way to at least begin solving this pollution problem.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2015.02.034.

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ONLINE SUPPLEMENT

To:

Seabirds, gyres and global trends in plastic pollution.

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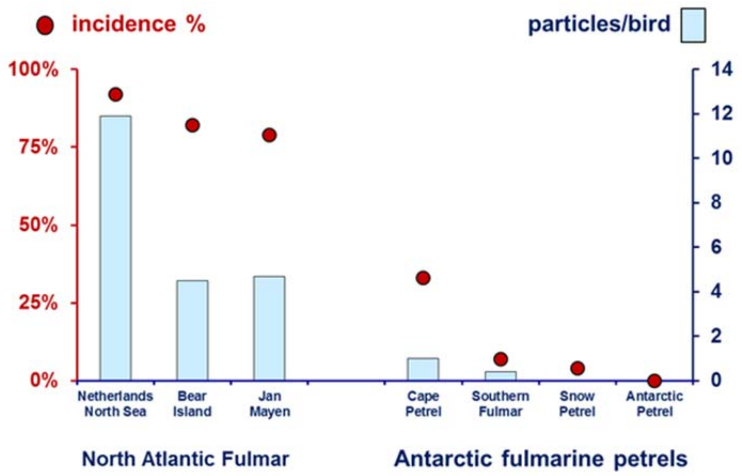
Contents

1. Supplementary information with introduction

In the early 1980's Van Franeker (1985) observed an average of nearly 12 particles of plastic in stomachs of Northern Fulmars *Fulmarus glacialis* from the North Sea, but less than 5 particles in fulmars from the presumably cleaner, breeding locations of Bear Island (74°N-19°E) and Jan Mayen (71°N-8°W) in polar environments of the northern Atlantic Ocean. Southern hemisphere relatives of the fulmar breeding in the Antarctic (Ardery Island, Windmill Islands, Wilkes Land, 66°S-110°E) had still lower levels of ingested plastics in which differences between species appeared linked to migratory behaviour (Van Franeker & Bell 1988). Fulmarine petrels that never leave the Antarctic seasonal sea ice zone, such as the Antarctic Petrel (*Thalassoica antarctica*) and Snow Petrel (*Pagodroma nivea*), had zero or almost zero plastics in the stomach, whereas species known to migrate to more populated parts of the world during winter such as the Southern Fulmar (*Fulmarus glacialoides*) and especially the Cape Petrel (*Daption capense*) appeared to hold plastics in their stomach during the migration.



Supplement Figure 1 Frequency of occurrence (incidence) and abundance by number of plastic particles in stomachs of ecologically and morphologically similar species of fulmarine petrels around the world in the 1980s. Stomach contents matched 'expected' differences between polluted industrialized areas and remote areas with likely lower pollution levels.

Supplement Table 1 Abundance of plastics in stomachs of Arctic and Antarctic petrels in the 1980s (from Van Franeker 1985 and Van Franeker & Bell 1988)

	n	Incidence %	particles/bird	mg/bird
	North Atlantic Fulmar populations 1982-1984			
Netherlands North Sea	65	92%	11.9	-
Bear Island	22	82%	4.5	-
Jan Mayen	29	79%	4.7	-
	Antarctic fulmarines - Windmill Islands 1984-1987			
Cape Petrel	30	33%	1	20.1
Southern Fulmar	27	7%	0.4	10.6
Snow Petrel	27	4%	+	0.1
Antarctic Petrel	11	0%	0	0
	Wilsons Storm Petrel - Windmill Islands 1984-1987			
Wilsons Storm Petrel adults	4	75%	1.8	4.8
Wilsons Storm Petrel chicks	16	75%	5	16.4

Full **definition of the Ecological Quality Objective** on plastic particles in seabird stomachs (OSPAR 2010b):

> *"There should be less than 10% of northern fulmars (*Fulmarus glacialis*) having more than 0.1 g plastic particles in the stomach in samples of 50 to 100 beach-washed fulmars found from each of 4 to 5 areas of the North Sea over a period of at least five years".*

The OSPAR EcoQO approach has not set a date for reaching such level of 'ecological quality'. The fulmar approach has been copied in the European Marine Strategy Directive as one of the indicators for its descriptor 10 on Marine Litter. The equivalent wording for the EcoQO target is 'Good Environmental Status (GES)' which should be achieved by 2020. Because of this date, some countries are considering a temporary weaker target definition (e.g., significant reduction in 2020)

2. Supplementary information with 'Methods Fulmar study'

Fulmar monitoring for the Save the North Sea project started in 2002 and has participants that collect beached fulmars at a number of locations around the North Sea. For comparative purposes, from the Faroe Islands, stomachs from birds hunted, drowned in longline fisheries or collected for toxicological work by the local Food & Environmental Agency have also been used.

Supplement Figure 2

Fulmar-Litter study sites in the Save the North Sea Project (SNS). Colour of symbols indicates regional grouping into Scottish Islands (red), East England (blue), Channel area (white), Southeastern North Sea (yellow), and Skagerrak area (white). Not all locations are equally active. The Faroe Islands study area is considered as an external reference monitoring site for the North Sea.

Dissection

Bird corpses are stored frozen until analysis. At dissections, a full series of data is recorded to determine sex, age, breeding status, likely cause of death, origin, condition index and other issues. Age, the only variable found to influence litter quantities in stomach contents, is largely determined on the basis of development of sexual organs (size and shape) and presence of *Bursa of Fabricius* (a gland-like organ positioned near the end of the gut which is involved in immunity systems of young birds; it is well developed in chicks, but disappears within the first year of life or shortly after).

Stomach procedure
After dissection, stomachs of birds are opened for analysis. Stomachs of Fulmars have two 'units': initially food is stored and starts to digest in a large glandular stomach (the *proventriculus*) after which it passes into a small muscular stomach (the *gizzard*) where harder prey remains can be processed through mechanical grinding. In early phases of the project, data for the two individual stomachs were recorded separately, but for the purpose of reduction in monitoring costs, the contents of proventriculus and gizzard are now combined.
Stomach, contents are carefully rinsed in a sieve with a 1 mm mesh and then transferred to a petri dish for sorting under a binocular microscope. The 1 mm mesh is used because smaller meshes become clogged with mucus from the stomach wall and with food-remains. Analyses using smaller meshes were found to be extremely time consuming and particles smaller than 1 mm seemed rare in the stomachs, and when present contribute little to plastic mass.
If oil or chemical types of pollutants are present, these may be sub-sampled and weighed before rinsing the remainder of stomach content. If sticky substances hamper further processing of the litter objects, hot water and detergents are used to rinse the material clean as needed for further sorting and counting under a binocular microscope.
Categorization of debris in stomach contents
The following categorization is used for plastics and other rubbish found in the stomachs, with acronyms between parentheses:

1. **PLASTICS (PLA)**
   - 1.1. **Industrial plastic pellets (IND).** These are small, often cylindrical-shaped granules of ± 4 mm diameter, but also disk and rectangular shapes occur. Various names are used, such as pellets, beads or granules. They can be considered as “raw” plastic or a half-product in the form of which plastics are usually first produced (mostly from mineral oil). The raw industrial plastics are then usually transported to manufacturers that melt the granules and mix them with a variety of additives (fillers, stabilizers, colorants, anti-oxidants, softeners, biocides, etc.) that depend on the user product to be made. For the time being, included in data output for this category are a relatively small number of very small, usually transparent spherical granules also considered to be a raw industrial product.
   - 1.2. **User plastics (USE)** (all non-industrial remains of plastic objects) differentiated in the following subcategories:
     - 1.2.1. **sheetlike user plastics (she)**, as in plastic bags, foils etc., usually broken up in smaller pieces;
     - 1.2.2. **threadlike user plastics (thr)** as in (remains of) ropes, nets, nylon line, packaging straps etc. Sometimes ‘balls’ of threads and fibres form in the gizzard;
     - 1.2.3. **foamed user plastics (foa)**, as in foamed polystyrene cups or packaging or foamed polyurethane in matrasses or construction foams;
     - 1.2.4. **fragments (fra)** of more or less hard plastic items as used in a huge number of applications (bottles, boxes, toys, tools, equipment housing, toothbrushes, lighters etc.);
     - 1.2.5. **other (oth)**, for example cigarette filters, rubber, elastics etc. Items that are ‘plastic-like’ or do not fit into a clear category.
2. **RUBBISH (RUB)** other than plastic:
   - 2.1. **paper (pap)** including silver paper, aluminium foil etc., so various types of non-plastic packaging material;
   - 2.2. **kitchenfood (kit)** for human food wastes such as fried meat, chips, vegetables, onions etc., probably mostly originating from ships’ galley refuse;
   - 2.3. **various rubbish (rva)** is used for e.g. pieces of timber (manufactured wood); paint chips, pieces of metals etc.;
   - 2.4. **fish hook (hoo)** from either sport-fishing or long-lining.

To be able to sort out items of debris categories 1 and 2, all other materials in the stomachs have to be sorted. *Optional categories used include:*

3. **POLLUTANTS (POL)**
   Items indicating industrial or chemical waste remains such as slags (the remains of burning ovens, e.g. remains of coal or ore after melting out the metals); tar-lumps (remains of mineral oil); chemical (lumps or ‘mud’ of paraffin-like materials or sticky substances arbitrarily judged to be unnatural and of chemical origin) and feather-lumps (indicating excessive preening by the bird of feathers sticky with oil or chemical pollutants).
4. **NATURAL FOOD REMAINS (FOO)**

Numbers of specific items may be recorded in separate subcategories (fish otoliths, eye-lenses, squid-jaws, crustacean remains, jelly-type prey remains, scavenged tissues incl. feathers, insects, other).

5. **NATURAL NON-FOOD REMAINS (NFO)**
   Numbers of subcategories e.g. plant-remains, seaweed, pumice, stone and other may be recorded.

Acronyms
In addition to the acronyms used for (sub)categories as above, further acronyms may be used to describe datasets. Logarithmic transformed data are initiated by 'ln' (natural logarithm); mass data are characterized by capital G (gram) and numerical data by N (number). For example lnGIND refers to the dataset that uses ln-transformed data for the mass of industrial plastics in the stomachs; acronym NUSE refers to a dataset based on the number of items of user plastics.

Particle counts and category weights
For the main categories 1 (plastic) and 2 (rubbish) we record for each bird and each (sub)category:

- The number of particles (N=count of number of items in each (sub)category)
- mass (W=weight in grams) using Sartorius electronic weighing scale after at least a two day period of air drying at laboratory temperatures. For marine litter (categories 1 to 3 above), this is done separately for all subcategories. In the early Fulmar study we also weighed the natural-food and natural-non-food categories as a whole, but this was discontinued in 2006 to reduce costs. Weights are recorded in grams accurate to the 4th decimal (= tenth of milligram).

On the basis of these records, data can be presented in different formats:

Incidence
The simplest form of data presentation is by presence or absence. Incidence (Frequency of occurrence) gives the percentage of investigated stomachs that contained the category of debris discussed. The quantity of debris in a stomach is irrelevant in this respect.

Arithmetic Average
Data for numbers or mass are frequently shown as averages with standard errors (se) calculated for a specific type of debris by location and specified time period. Averages are calculated over all available stomachs in a sample, so including those that contained no plastic ('population averages'). Especially when sample sizes are smaller, arithmetic averages may be influenced by short term or local variations or extreme outliers. An option then is to pool data over a larger area or longer time period. An alternative to reduce the influence of outliers is by logarithmic transformation of data.

Geometric Mean
Sample sizes may not be large enough to average out the impact of occasional extreme outliers. Therefore, data are often additionally presented as geometric means, calculated from logarithmic data values. Logarithmic transformation reduces the role of the higher values, but as a consequence the geometric mean is usually considerably lower than the arithmetic mean for the same data. In mass data for plastics in the Fulmar stomachs, geometric means are only about one third to half of the arithmetic averages. Geometric means thus do not properly reflect absolute values, but are useful for comparative purposes between smaller sample sizes, for example when looking at annual data rather than at 5-year-periods. Logarithmic transformation cannot deal with the value zero, and thus the common approach chosen is to add a small value (e.g. 0.001g in mass data) to all data points, and then subtracting this again when the mean of log values is back-calculated to normal value. However, this implies that geometric means are less reliable with an increasing number of zero values in a dataset. The natural logarithm (ln) is used to compute geometric means.

EcoQO performance
OSPAR (2010b) words its Ecological Quality Objective (EcoQO) for levels of litter (plastic) in stomachs of fulmars (the '*Fulmar-Litter-EcoQO*') as: *"There should be less than 10% of northern fulmars (Fulmarus glacialis) having more than 0.1 gram plastic particles in the stomach in samples of 50 to 100 beach-washed fulmars from each of 4 to 5 different areas of the North Sea over a period of at least 5 years".*
Thus, the information requested for OSPAR and the EcoQO focuses on the category of 'total plastic' and pooled data for 5-year periods over larger areas, and a simple decision rule for each stomach if the plastics in it weigh more than 0.1 gram or less, including zero.
EcoQO compliance or performance is defined as the percentage of birds in a sample that has 0.1 g or more plastic mass in the stomach. The OSPAR target is thus to reduce that percentage to under 10%. The EcoQO format is a highly simplified form of data-presentation but through that simplicity escapes

the problems faced by more sophisticated procedures as a consequence of excessive outliers or a large proportion of zero values in a data set. In the background however, details of various subcategories of litter continue to play an important role for correct interpretation of the EcoQO metric.

Data pooling

To avoid erratic information on the level of ingested plastics from short term variations, data are frequently pooled into 5-year periods. Such pooled data for 5-year periods are ***not*** derived from the annual averages, but are calculated from all individual birds over the full 5-year period. For data presentation, the ***Current Situation*** of plastic ingestion is defined as the figures for incidence and number or mass abundance for the most recent 5-year period, not the figures for the recent single year. Time related changes are illustrated in graphs by running 5-year averages, each time shifting one year and thus overlapping for four years.

For pooling study locations in the North Sea, the OSPAR EcoQO target definition has triggered a grouping into five areas or regions (Fig. 1): the Scottish Islands (Shetland and Orkney), East England (northeast and southeast England), the Channel (Normandy and Pas de Calais), South-Eastern North Sea (Belgium, Netherlands and Germany), and the Skagerrak (Skagen, Denmark, Lista, Norway and Swedish west coast)

Statistical tests

Data from dissections and stomach content analysis are recorded in Excel spreadsheets and next stored in Oracle relational database. GENSTAT 17 was used for statistical tests (http://www.vsni.co.uk/software/genstat/). As concluded in the pilot study (Van Franeker & Meijboom 2002) and later reports, statistical trend analyses for EcoQO purposes are conducted using mass data.

Tests for trends over time are based on linear regressions fitting ln-transformed plastic mass values for individual birds on the year of collection. Logarithmic transformation is needed because the original data are strongly skewed and need to be normalized for the statistical procedures. The natural logarithm (ln) is used. Tests for '**long term' trends** use the full data set; **'recent' trends** only use the past ten years of data. This 10-year period was derived from the pilot study (Van Franeker & Meijboom 2002), which found that in the Dutch situation a series of about eight years was needed to potentially detect significant change. To be on the safe side in our approach, this period was arbitrarily increased to a standard period of 10 years for tests of current time related trends. The test statistic is a t-score (t) defined by t = b1 / SE where b1 is the slope of the sample regression line, and SE is the standard error of the slope.

Statistical tests of regional differences are conducted in GENSTAT 17th edition, using mass data from individual birds over the most recent 5-year period. Regional differences in ingested plastic mass were evaluated by fitting a negative binominal generalized linear model with region as a factor with a log ratio link function and estimated dispersion parameter. The test statistic is a t-score for residual variance for the region.

Summary of Fulmar data presentation and analysis:

- **Incidence** – Incidence represents the percentage of birds having plastic in the stomach
- **Average ± se** – These refer to straightforward arithmetic averages from all available samples (population average), usually given with standard errors.
- **Geometric mean** – Refers to geometric means calculated using data transformation (natural logarithm) reducing influence of extreme outliers.
- **EcoQO performance** – The % of birds having more than 0.1 gram of plastic in the stomach.
- **Pooled data -** Data are mostly presented as pooled over 5-year periods to avoid incidental short-term fluctuations. The **'Current level of plastic ingestion'** is defined by pooled data for the most recent 5 years, not by an annual figure. **Graphs** often use the pooled data for 5 years, but shifting one year by data point. Data points and connecting lines only intend to visually illustrate trends over time or geographic patterns and have no statistical relevance.
- **Statistics -** Statistical analyses are solely based on the mass of plastic using ln-transformed data from individual birds. Tests for significance of trends over time are based on linear regressions of ln-transformed data against year of collection. The **long-term trend** is derived from the full dataset, the **Recent trend** from only the most recent 10 years of data. Regional differences were fitted in a negative binomial generalized linear model with region included as a factor and test statistic a t-score based on residual variance for the region (Genstat 17th Edition).

3. Supplementary information with Results retention time in fulmar stomachs

Supplement Table 2 Details of plastics in the stomachs of Cape Petrels in sub-Antarctic or temperate winter areas and an Antarctic breeding area (Windmill Islands, Wilkes Land, 66°S-110°E) to illustrate disappearance rate of plastics from stomachs when feeding in clean Antarctic waters (derived from van Franeker and Bell 1988). The single October bird compares well to winter samples of Cape Petrels from near South Africa (Ryan 1987) and from near the Crozet Islands (Van Franeker & J.-K. Jensen unpublished)

CAPE PETREL	off S. Africa (Ryan 1987)	at sea off Crozet Islands 1 Aug 1998	off Windmill Islands 23 Oct 1986	pre-breed combined estimate	Windmill Islands 1-10 Dec-1986	Windmill Islands 20-Jan-1986	pre-breed to December decrease %	December to January decrease %
sample size	*18*	*13*	*1*	***32***	***9***	***20***		
plastic incidence	83%	100%	100%	**91%**	**56%**	**20%**	*38%*	*64%*
average number of items per bird	8.60	11.46	11.00	**9.84**	**1.67**	**0.25**	*83%*	*85%*
average mass per bird (g)	0.106	0.045	0.294	**0.15**	**0.027**	**0.003**	*82%*	*88%*

Note: *In the 1986/87field season on Ardery Island, among bird bones around Skua nests (a species predating on fulmarine petrels) two remains of Cape Petrels were found with bands from New Zealand indicating wintering in more temperate waters with higher plastic pollution levels.*

Supplement Table 3 Decrease in squid beak abundance in stomachs of fulmarine petrels in the Windmill Islands, Antarctica 1985-1987 from early incubation period to middle of the breeding season; derived from Van Franeker et al., 2001*, Table 7).). Snow Petrels had low abundance of squid beaks to start with, because they winter in the sea ice close to the breeding areas.

	December		*January*		
	n	**avg nr of squid beaks in stomach**	*n*	**avg nr of squid beaks in stomach**	**% decrease**
Southern Fulmar	*6*	**9.5**	*21*	**3.6**	**62%**
Antarctic Petrel	*5*	**7.6**	*6*	**1.2**	**84%**
Cape Petrel	*9*	**11.1**	*20*	**1.1**	**90%**
Snow Petrel (major)	*4*	**1.5**	*13*	**0.9**	**40%**
Snow Petrel (nivea)	*7*	**1.6**	*2*	**1**	**38%**
fulmarine petrels combined	*31*	**6.8**	*62*	**1.9**	**72%**

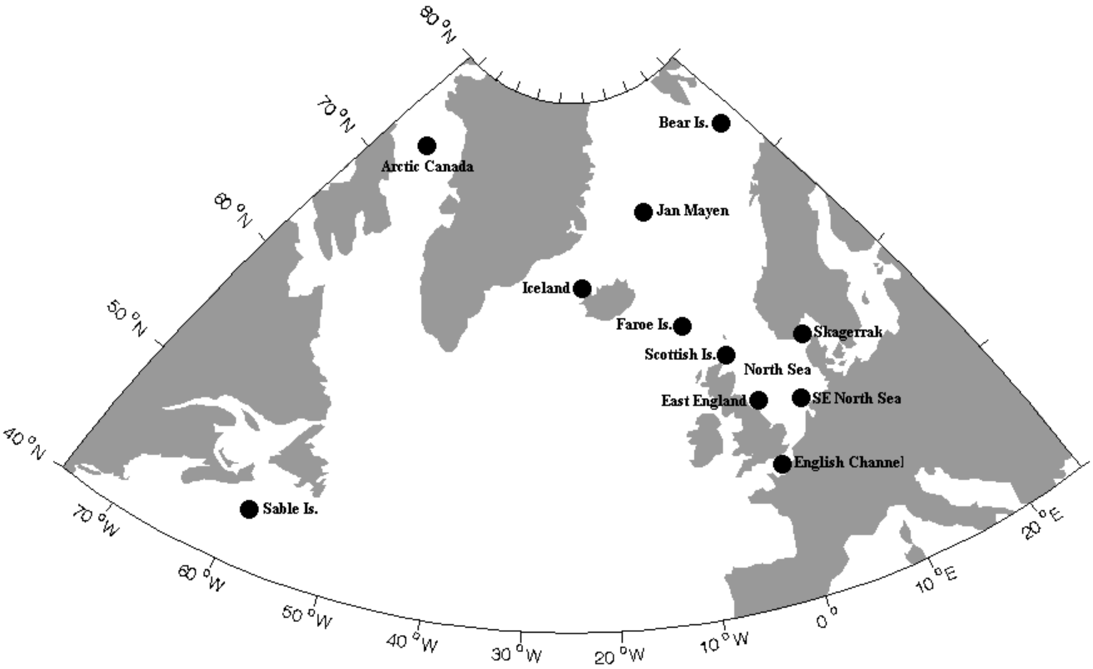
(* Van Franeker, J.A., Williams, R., Imber, M.J., Wolff, W.J., 2001. Diet and foraging ecology of Southern Fulmar *Fulmarus glacialoides*, Antarctic Petrel *Thalassoica antarctica*, Cape Petrel *Daption capense* and Snow Petrels *Pagodroma nivea* ssp on Ardery Island, Wilkes Land, Antarctica.. Chapter 11 (58pp) in: J.A. van Franeker Mirrors in ice. PhD-Thesis, University of Groningen. Alterra, Texel. ISBN 90-367-1352-8.)

Notes on rates of disappearance of plastic debris from stomachs in other species
The conclusion for fulmars and allies that an estimated 75% of harder plastics in a stomach are ground within a month to dust and sizes small enough to pass in to the intestines cannot be generalized, as this will depend on the size, stomach morphology and feeding habits of the species

studied. For Northern Fulmars, preliminary data (Bravo-Rebolledo 2011) indicate that particles need to wear down to approximately 2 mm in diameter before passage from gizzard to intestine becomes possible. Once small enough for such passage, the remaining bits can make their way through the intestines in a matter of hours and are excreted back into the environment, only in a smaller size range than originally ingested. The speed of intestinal passage means that hard items including plastics are only incidentally found in the intestines of fulmarine petrels.

This situation can be different even in related and morphologically similar, but differently sized seabirds. For example, chicks of Wilsons Storm-petrels (*Oceanites oceanicus*) found in the Windmill Island area in Antarctica during the mid-1980s had considerable quantities of plastic in the stomach, mainly the gizzard (Van Franeker & Bell 1988; Online Supplement Table 1). The bulk of these plastics came from ingestion of plastics by the parent birds in wintering areas at least ~3 months earlier, and had no relation to local pollution levels. However, to be fed to chicks, plastics must have been residing in the parental proventriculus, where no grinding occurs, over the egg incubation period, and once in gizzards of chicks, the small size of these birds may require that plastics have to be ground to much smaller sizes before they can pass into the intestines. Industrial granules have their original size mostly in the range of 4 to 5 mm. Fulmars likely can excrete the granules earlier at relatively larger residual size than storm petrels. Average mass of remaining pellets in stomachs of fulmars from the North Sea is around 0.023 gram, whereas pellets remaining in Wilsons Storm-petrels in the Antarctic were extremely worn and only weighed ~0.005 g on average

4. Supplementary information with Results 'Consistency in regional patterns'



Supplement Figure 3 Map of the north Atlantic showing locations mentioned in relation to spatial patterns of plastic ingestion by northern fulmars (Supplement Table 4 and Supplement Table 5).

Supplement Table 4 Large-scale latitudinal patterns in plastic ingestion in Northern Fulmars from different areas in the North Atlantic and Pacific Oceans. Data from a) Bond et al. 2014, b) this study, c) Kühn & van Franeker 2012, d) combined from Mallory et al 2006, Mallory 2008, Provencher et al 2009 and personal information, e) Nevins et al. 2011, and f) Avery-Gomm et al. 2012)

	North Sea 2007-2011	Faroe Islands 2007-2011	Iceland 2011	Atl. Arctic Canada 2002-2008	California	Eastern North Pacific	Alaska
n	*816*	*699*	*58*	*169*		*67*	
incidence	**95%**	**91%**	**79%**	**40%**	**94%**	**93%**	**63%**
nr of plastic particles per stomach	**32.8**	**11.3**	**6.0**	**2.5**		**36.8**	
se	*2.2*	*0.6*	*1.0*			*9.8*	
mass of plastic per stomach (g)	**0.37**	**0.15**	**0.13**	**0.03**		**0.39**	
se	*0.03*	*0.01*	*0.04*			*0.09*	
EcoQO performance *	**62%**	**40%**	**28%**	**14%**	**89%**	**61%**	**25%**

** EcoQO performance = percentage of birds having more than 0.1g of plastic in the stomach*

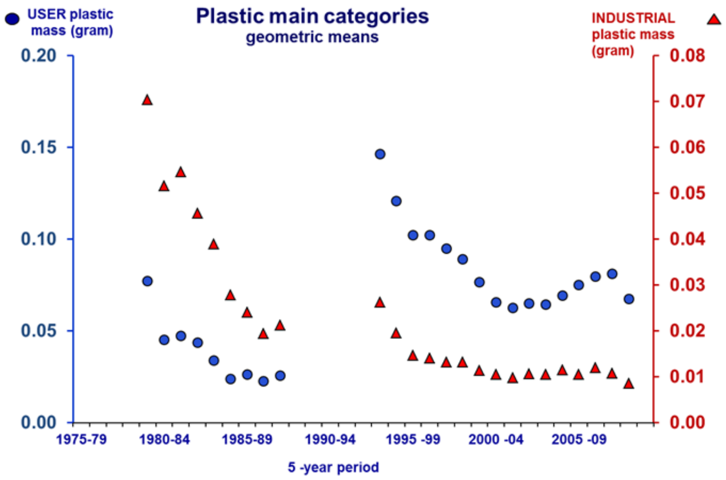
Supplement Table 5 Regional EcoQO performance (proportion of Fulmars having > 0.1 g plastic in the stomach) in sub-regions within the North Sea, and on Faroe Islands, in running 5-year periods 2002 to 2011, as displayed in Figure 3 of the main paper.

period	Channel	East England	SE North Sea	Skagerrak	Scottish Islands	Faroe Islands
2002-2006	61%	59%	57%	49%	48%	43%
2003-2007	78%	60%	59%	50%	48%	44%
2004-2008	77%	67%	58%	47%	57%	45%
2005-2009	86%	77%	57%	53%	60%	46%
2006-2010	87%	76%	60%	55%	59%	45%
2007-2011	86%	76%	60%	55%	58%	40%

5. Supplementary information on results for trends in ingested plastics

Supplement Table 6 Running 5-year averages of plastic abundance in Fulmars from the Netherlands since the 1980s. Data show incidence, and arithmetic averages ± se for number of particles and mass for each of the major categories and total of plastics in running 5-year averages (i.e. data points shift one year ahead at a time). For all plastics combined, geometric mean mass and EcoQO performance are added. Five-year periods shaded grey should not be used because of small sample sizes (n<20).

NETHERLANDS		Industrial granules			User plastics			Total plastics				
5-year period	*sample n*	Inc. %	avg number n ± se	avg mass g ± se	Inc. %	avg number n ± se	avg mass g ± se	Incidence %	average number n ± se	average mass g ± se	Geometric mean mass	EcoQO % *(over 0.1g)*
1979-1983	*23*	87%	8.0 ± 1.8	0.17 ± 0.04	87%	6.9 ± 1.5	0.32 ± 0.10	**100%**	**14.9 ± 2.2**	**0.50 ± 0.11**	**0.298**	**91%**
1980-1984	*42*	79%	8.9 ± 1.6	0.18 ± 0.03	88%	7.7 ± 1.7	0.25 ± 0.07	**95%**	**16.5 ± 2.9**	**0.43 ± 0.09**	**0.154**	**74%**
1981-1985	*45*	80%	8.6 ± 1.5	0.18 ± 0.03	89%	7.5 ± 1.6	0.25 ± 0.07	**96%**	**16.1 ± 2.7**	**0.42 ± 0.08**	**0.159**	**76%**
1982-1986	*49*	78%	8.0 ± 1.4	0.17 ± 0.03	88%	7.3 ± 1.4	0.23 ± 0.06	**94%**	**15.3 ± 2.5**	**0.40 ± 0.07**	**0.137**	**71%**
1983-1987	*61*	77%	7.1 ± 1.2	0.15 ± 0.03	84%	7.7 ± 1.3	0.18 ± 0.05	**90%**	**14.9 ± 2.2**	**0.34 ± 0.06**	**0.100**	**66%**
1984-1988	*43*	72%	6.2 ± 1.5	0.14 ± 0.03	81%	7.8 ± 1.7	0.13 ± 0.04	**86%**	**14.0 ± 3.0**	**0.26 ± 0.07**	**0.062**	**53%**
1985-1989	*27*	74%	3.6 ± 1.2	0.10 ± 0.03	78%	7.9 ± 1.8	0.10 ± 0.03	**85%**	**11.5 ± 2.6**	**0.20 ± 0.06**	**0.063**	**56%**
1986-1990	*24*	71%	3.4 ± 1.4	0.09 ± 0.04	75%	8.3 ± 2.0	0.10 ± 0.03	**83%**	**11.7 ± 3.0**	**0.19 ± 0.07**	**0.052**	**50%**
1987-1991	*21*	71%	3.8 ± 1.5	0.10 ± 0.04	76%	9.0 ± 2.3	0.10 ± 0.04	**86%**	**12.8 ± 3.3**	**0.21 ± 0.07**	**0.063**	**57%**
1988-1992	*6*	50%	3.5 ± 2.1	0.09 ± 0.06	100%	9.5 ± 4.4	0.14 ± 0.07	**100%**	**13.0 ± 4.8**	**0.23 ± 0.12**	**0.122**	**67%**
1989-1993	*5*	60%	4.2 ± 2.5	0.11 ± 0.06	100%	11.0 ± 5.0	0.15 ± 0.09	**100%**	**15.2 ± 5.2**	**0.26 ± 0.14**	**0.150**	**80%**
1990-1994	*1*	0%	0.0 ± 0.0	0.00 ± 0.00	100%	11.0 ± 0.0	0.14 ± 0.00	**100%**	**11.0 ± 0.0**	**0.14 ± 0.00**	**0.140**	**100%**
1991-1995	*3*	67%	1.0 ± 0.6	0.02 ± 0.01	100%	6.0 ± 2.5	0.07 ± 0.04	**100%**	**7.0 ± 2.1**	**0.08 ± 0.03**	**0.072**	**33%**
1992-1996	*10*	80%	2.6 ± 0.9	0.06 ± 0.02	100%	20.3 ± 11.1	0.16 ± 0.08	**100%**	**22.9 ± 11.2**	**0.22 ± 0.09**	**0.081**	**50%**
1993-1997	*41*	76%	5.1 ± 1.5	0.12 ± 0.03	98%	27.5 ± 5.8	0.49 ± 0.13	**98%**	**32.6 ± 6.1**	**0.61 ± 0.13**	**0.217**	**76%**
1994-1998	*115*	71%	3.8 ± 0.6	0.09 ± 0.01	96%	26.5 ± 3.9	0.74 ± 0.23	**97%**	**30.3 ± 4.0**	**0.83 ± 0.23**	**0.184**	**73%**
1995-1999	*222*	65%	3.6 ± 0.5	0.07 ± 0.01	96%	29.1 ± 3.4	0.57 ± 0.13	**97%**	**32.7 ± 3.7**	**0.64 ± 0.13**	**0.151**	**67%**
1996-2000	*258*	64%	3.6 ± 0.5	0.08 ± 0.01	97%	27.7 ± 3.0	0.53 ± 0.11	**98%**	**31.3 ± 3.2**	**0.60 ± 0.12**	**0.149**	**67%**
1997-2001	*304*	63%	3.5 ± 0.4	0.07 ± 0.01	97%	26.5 ± 2.6	0.47 ± 0.10	**97%**	**29.9 ± 2.8**	**0.55 ± 0.10**	**0.137**	**63%**
1998-2002	*329*	63%	3.4 ± 0.4	0.07 ± 0.01	97%	29.7 ± 3.1	0.45 ± 0.09	**98%**	**33.1 ± 3.3**	**0.52 ± 0.10**	**0.130**	**62%**
1999-2003	*294*	60%	3.3 ± 0.4	0.07 ± 0.01	97%	30.2 ± 3.4	0.30 ± 0.06	**98%**	**33.5 ± 3.6**	**0.37 ± 0.06**	**0.112**	**59%**
2000-2004	*318*	58%	3.0 ± 0.3	0.06 ± 0.01	94%	25.8 ± 2.7	0.24 ± 0.04	**95%**	**28.8 ± 2.9**	**0.30 ± 0.04**	**0.095**	**59%**
2001-2005	*331*	57%	2.8 ± 0.3	0.06 ± 0.01	94%	25.1 ± 2.6	0.23 ± 0.04	**95%**	**27.9 ± 2.7**	**0.29 ± 0.04**	**0.091**	**57%**
2002-2006	*304*	58%	2.9 ± 0.3	0.06 ± 0.01	93%	26.4 ± 2.8	0.24 ± 0.04	**94%**	**29.3 ± 3.0**	**0.30 ± 0.04**	**0.094**	**61%**
2003-2007	*309*	59%	2.6 ± 0.2	0.06 ± 0.01	92%	23.8 ± 2.0	0.22 ± 0.02	**93%**	**26.5 ± 2.1**	**0.28 ± 0.02**	**0.092**	**61%**
2004-2008	*290*	60%	2.8 ± 0.3	0.06 ± 0.01	92%	24.7 ± 2.1	0.24 ± 0.02	**93%**	**27.4 ± 2.2**	**0.30 ± 0.03**	**0.096**	**62%**
2005-2009	*227*	59%	2.6 ± 0.3	0.06 ± 0.01	94%	24.8 ± 2.3	0.23 ± 0.02	**95%**	**27.3 ± 2.5**	**0.29 ± 0.03**	**0.102**	**58%**
2006-2010	*212*	61%	4.1 ± 1.3	0.09 ± 0.03	93%	30.5 ± 3.2	0.23 ± 0.02	**94%**	**34.5 ± 3.8**	**0.32 ± 0.04**	**0.107**	**62%**
2007-2011	*204*	59%	4.4 ± 1.4	0.10 ± 0.03	94%	31.1 ± 3.4	0.24 ± 0.02	**95%**	**35.5 ± 4.0**	**0.33 ± 0.04**	**0.110**	**60%**
2008-2012	*223*	56%	3.8 ± 1.3	0.08 ± 0.03	93%	26.0 ± 2.9	0.23 ± 0.04	**94%**	**29.7 ± 3.6**	**0.31 ± 0.05**	**0.091**	**54%**



Supplement Figure 4 Geometric mean of mass of industrial and user plastics in Fulmars from the Netherlands since the 1980s, illustrating the impact that strong outliers can have on even 5-year arithmetic averages: (i.e., the high values for industrial plastics in recent years in Fig.5 in the main paper are not seen here in the geometric means).

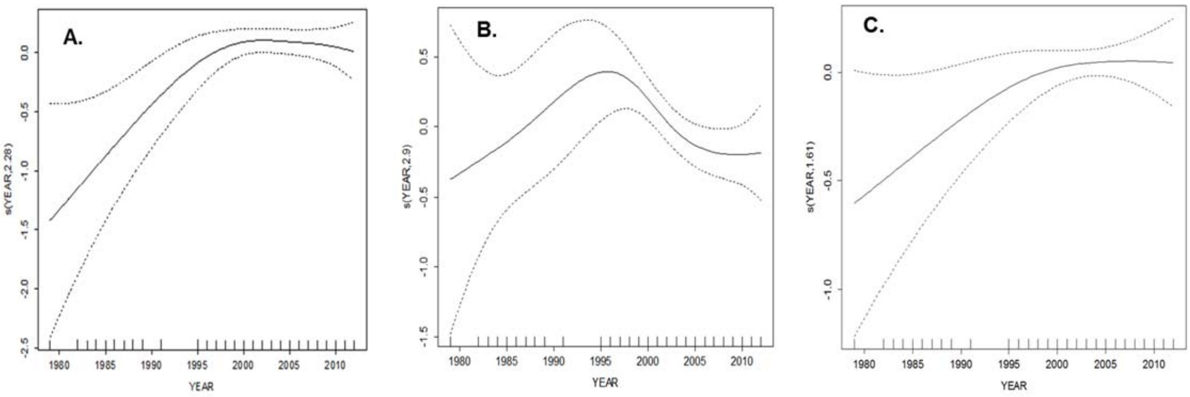
SURVEY BY GAMM OF TIME TRENDS IN PLASTICS IN FULMAR STOMACHS

Because of its policy perspective, the Fulmar EcoQO approach (Van Franeker et al., 2011) has its main focus on the direction and significance of recent trends (past 10 years) as reflected by linear regression analyses of mass of plastic. However, for the long-term changes in particle number and mass considered in this paper, data patterns in long-term trends are the main focus, and these were evaluated by Generalized Additive Mixed Models (GAMM) using R software Version 3.0.3. Where GAMM indicates estimated degrees of freedom (edf) at or close to value 1, the trend can be considered as a linear relationship. Higher edf values indicate more complicated non-linear trends. Data in Supplement Table 7 show that changes over the time-period 1979-2012 for number and mass of industrial plastics are best considered as linear correlations, but that user plastics have undergone more complicated non-linear changes, which however differ for number of user particles and user plastic mass (Supplement Figure 5 A, B). For all plastics combined, trends for numerical abundance (Supplement Figure 5 C) are similar to those of user plastics, but a linear relation is indicated for mass.
The GAMM patterns match those revealed by the running 5-year averages for user plastics in fulmar stomachs (Figure 5 in the paper): the number of particles increased strongly in early years, and remained fairly constant after the 1990s. However, mass data do show a similar initial increase, but then decreased as a consequence of reduced sizes of user plastics in fulmar stomachs.

Supplement Table 7 Output from GAMM analyses for trends in plastic abundance by number or mass in fulmar stomachs 1979-2012 (n=973). Shown are results for only term 'year'. Additional smooth terms such as age and sex were also tested but produced no different conclusions. Bracketed letters refer to graphs showing non-linear trends in Supplement Figure 6.

GAMM analysis ~year	SIGNIFICANCE OF SMOOTH TERM YEAR			
	edf	F	p	
Number of industrial pellets	**1**	3.466	0.063	
Mass of industrial pellets	**1**	2.052	0.152	
Number of user particles	**2.3**	5.006	0.005	*(A)*
Mass of user particles	**2.9**	3.977	0.009	*(B)*
Total nr of plastic particles	**1.6**	3.071	0.058	*(C)*
Total mass of plastics	**1**	3.358	0.067	

Supplement Figure 5 Non-linear trends over time for plastics in fulmar stomachs in the Netherlands North Sea 1979-2012, as suggested by GAMM for A. number of user particles, B. user plastic mass, and C. total number of plastic particles



Supplement Table 8 Linear regression results for plastic abundance in stomachs of fulmars in the Netherlands 1979-2012. Note that GAMM analyses indicate that only industrial plastics (by number and mass) and total plastics (by mass) follow linear trend patterns, whereas the others show variable non-linear patterns (plus or minus signs indicate increasing resp. decreasing linear trends and significance levels as ns=not significant and number of symbols reflecting significance levels at p<0.05, p<0.01 and p<0.001)

A.

LONG TERM TRENDS 1979-2012 FOR NUMBER OF PLASTIC PARTICLES

in Fulmar stomachs, the Netherlands

	n	Constant	estimate	s.e.	t	p	
Industrial plastics (lnNIND)	*973*	48.5	-0.0238	0.0045	-5.29	**<0.001**	- - -
User plastics (lnNUSE)	*973*	-44.8	0.0236	0.0061	3.90	**<0.001**	+++
All plastics combined (lnNPLA)	*973*	-14.7	0.0086	0.0061	1.43	0.154	*ns*

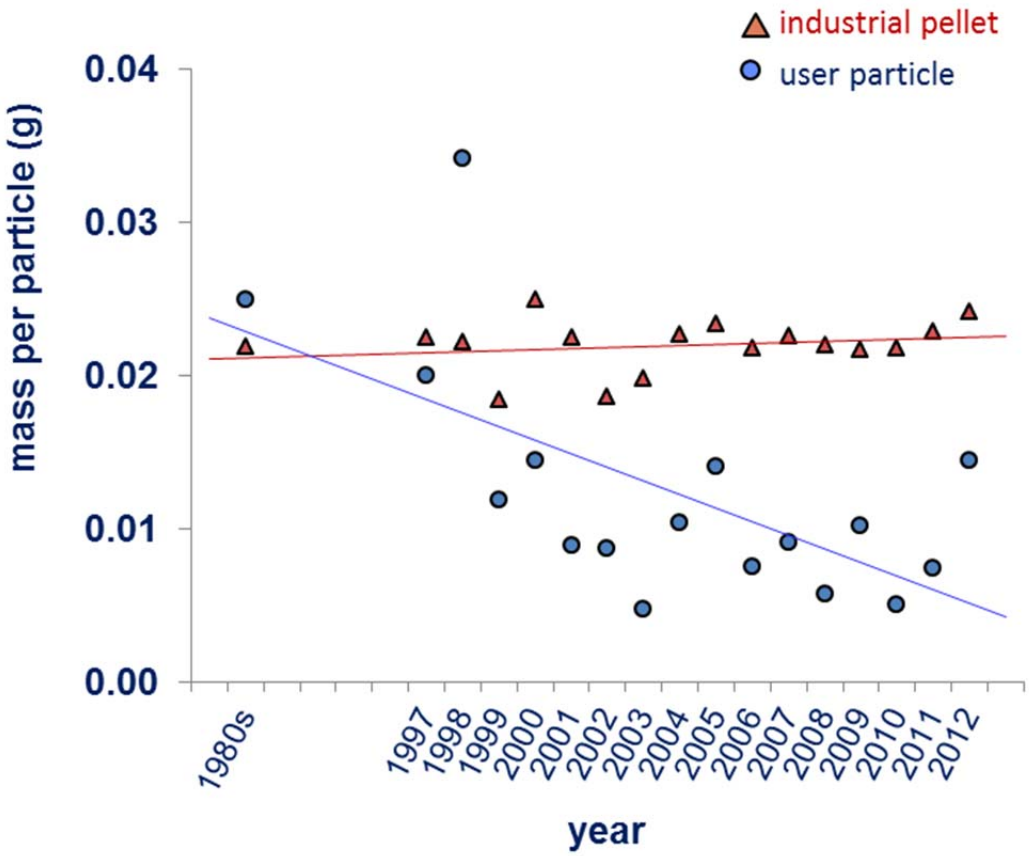
B.

LONG TERM TRENDS 1979-2012 FOR PLASTIC MASS

in Fulmar stomachs, the Netherlands

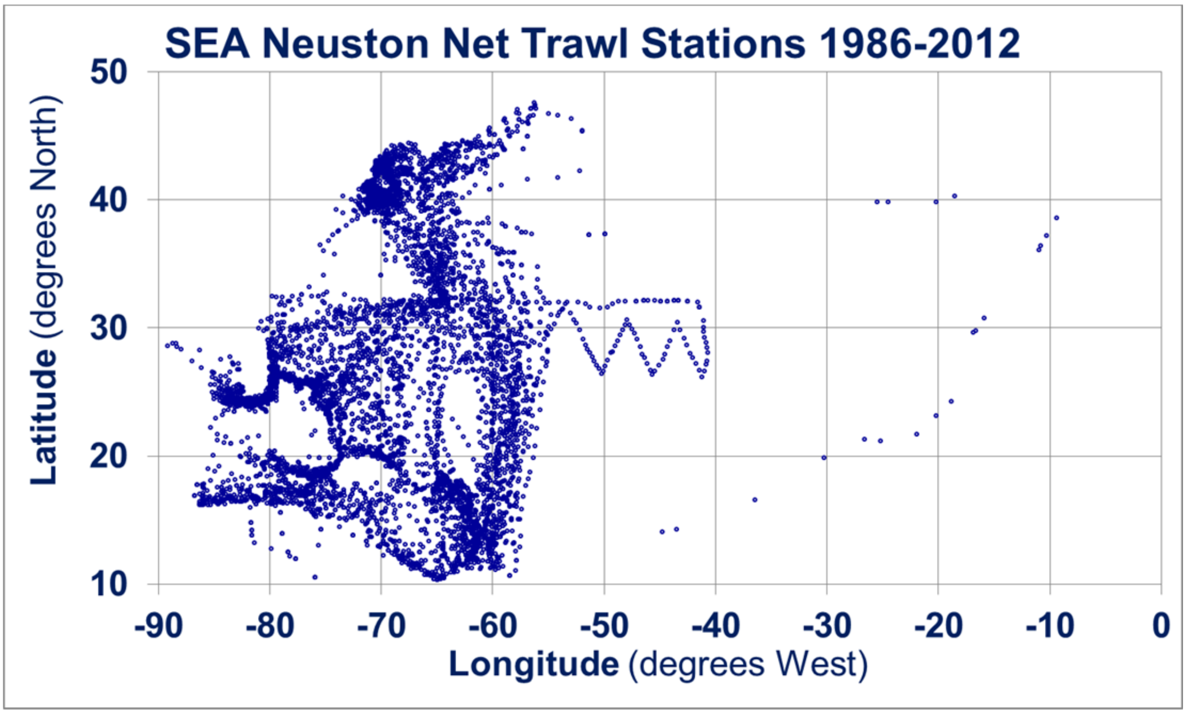
	n	Constant	estimate	s.e.	t	p	
Industrial plastics (lnGIND)	*973*	93.1	-0.0486	0.0105	-4.63	**<.001**	- - -
User plastics (lnGUSE)	*973*	-14.0	0.0057	0.0090	0.63	0.531	*ns*
All plastics combined (lnGPLA)	*973*	34.1	-0.0182	0.0088	-2.07	0.039	-

Data analyses are complicated by the fact that user plastic particles have shown a change in particle size over time. This is evident from Fulmar data (see Supplement Figure 6), but was also reported for the North Atlantic subtropical gyre by Moret-Ferguson et al. (2010).

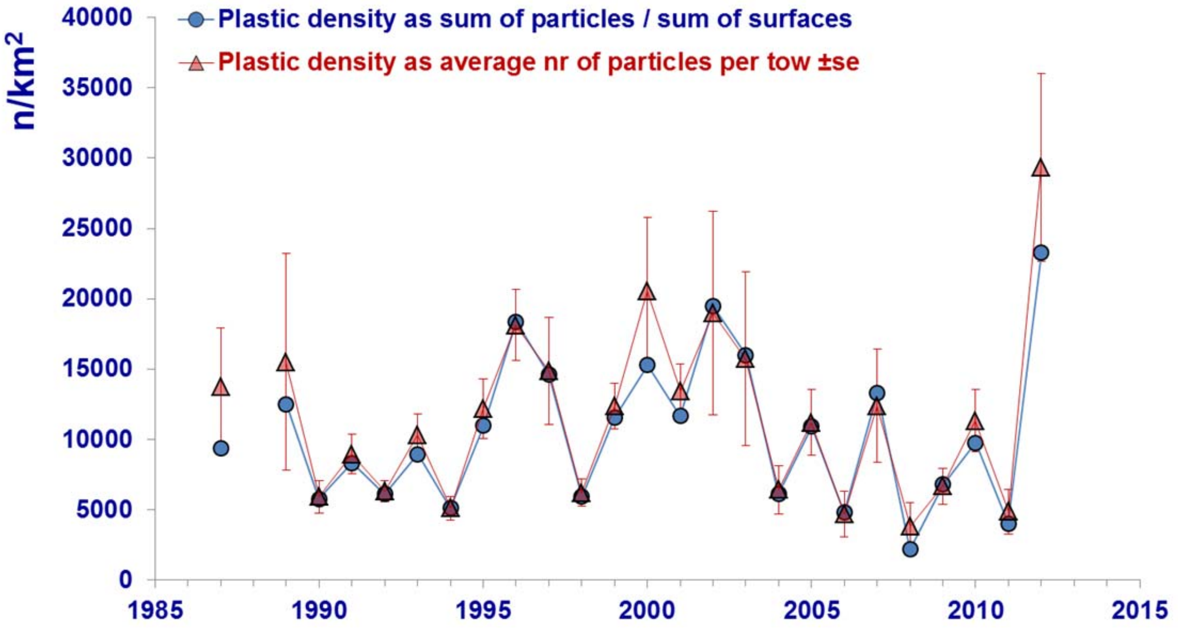


Supplement Figure 6 Changes over time in user plastic particle size (mass), but not in industrial pellets in stomachs of fulmars from the Netherlands. Data derived from annual sums of mass divided by number of particles. We are currently studying the size and mass of individual particles, but these data are not yet available.

6. Supplementary information on data selection for the North Atlantic subtropical gyre.

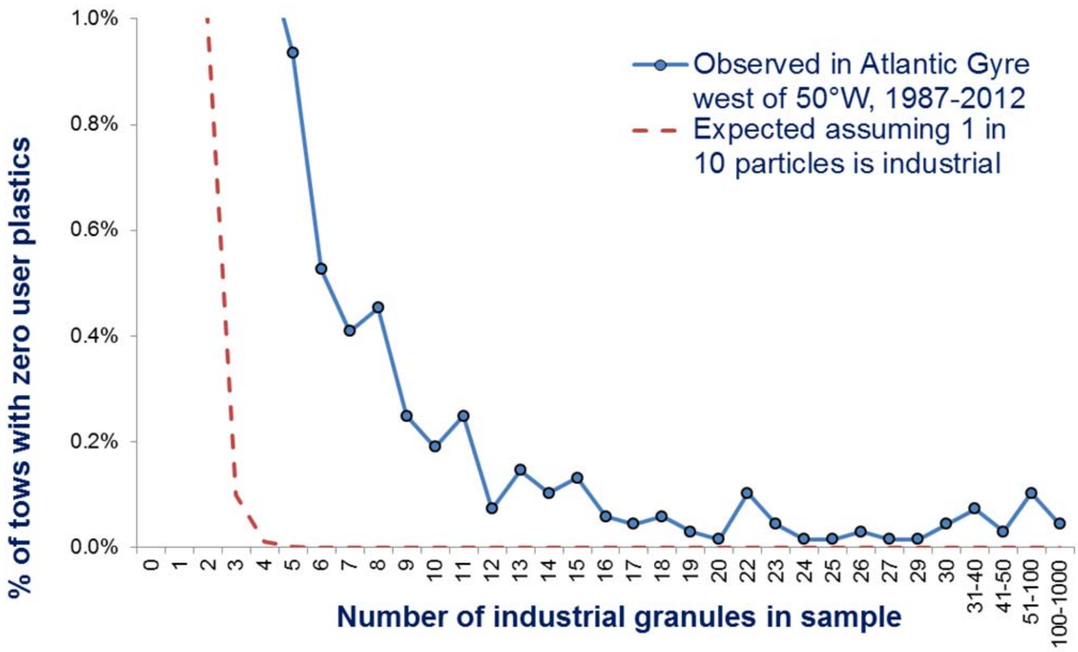


Supplement Figure 7 SEA neuston net trawl station positions 1986-2012. One-time transects east of 50°West were ignored. Data analysis focused on the 'central gyre' arbitrarily defined as area 20-40°N and 60-80°W, which avoids the shelf and Caribbean areas and which has average plastic debris densities about three times the level seen in the other, 'peripheral' areas.



Supplement Figure 8 Data survey to explore impact of large number of zero observations and extreme outliers on average densities calculated as either 'sum of particles / sum of area surveyed' per year (circles, no standard errors) or as averages calculated from individual tow densities during the year (triangles ± standard errors). (Data for all of the Atlantic Gyre west of

50°W, and no exclusion of likely erroneous sample counts with industrial >=10 but user=0). We conclude that both modes of calculation produce very similar averages, and here the individual tow calculation with standard errors for the means is preferred.



Supplement Figure 9 Background of exclusion of tow data when more than 10 industrial granules were reported but zero user plastic particles. The percentage of industrial granules among all plastic particles in the gyre averages below 7%. Assuming a 10% occurrence, the likelihood to obtain a tow with 4 industrial particles but zero user plastics approaches zero (red dashed line). We excluded tows that reported 10 or more industrial granules but zero user plastics as such combinations are utterly unlikely and suspected of being data entry errors. The line for observed frequencies is based on all counts west of 50°W; 6844 tows; 5429 industrial granules and 78697 user particles in nets).

7. Supplementary information North Atlantic subtropical gyre results

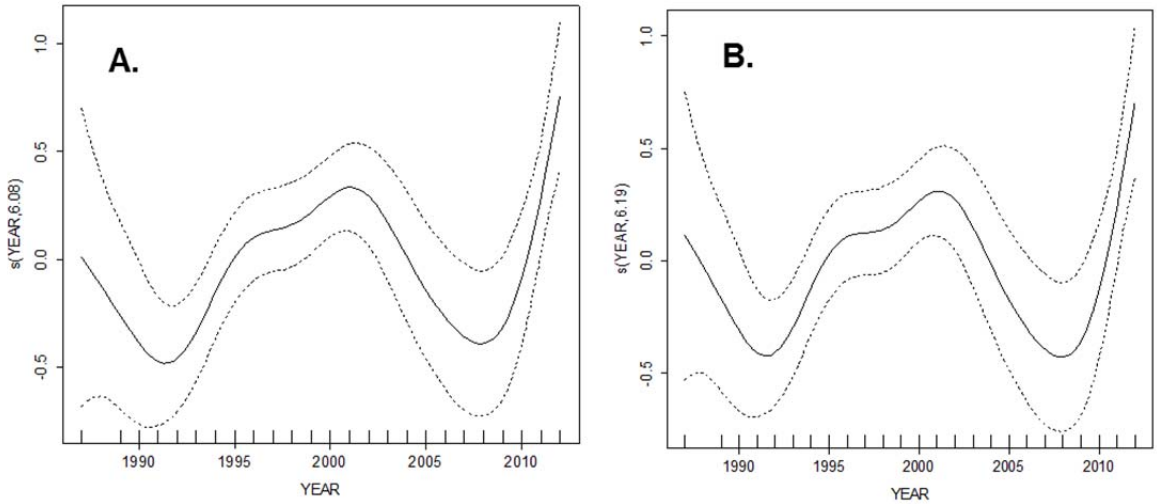
Supplement Table 9 5-year running averaged data and linear regression results for the central part of the North Atlantic subtropical gyre, excluding tows with more than 10 industrial granules but zero user plastics. This dataset was mostly used in the paper to illustrate trends. See next pages for comparative information on full data set and annual figures for central part and periphery of the gyre

Central Atlantic Gyre - *5-year running averages* (area 20°N-40°N and 60°W-80°W, unlikely entries with > 10 industrial but 0 user plastics excluded)

			INDUSTRIAL PELLETS			USER PARTICLES			TOTAL PLASTICS			
Period	*Nr of tows*	*Surface sampled (km2)*	Incidence (% of tows)	n/km^2 ± se	geom. mean n/km2	Incidence (% of tows)	n/km^2 ± se	geom. mean n/km2	Incidence (% of tows)	n/km^2 ± se	geom. mean n/km2	*Proportion Industrial*
1985-89												
1986-90												
1987-91	*237*	*0.41*	50%	1352 ± 193	38	81%	8405 ± 1143	904	81%	9757 ± 1301	1089	*14%*
1988-92	*384*	*0.67*	44%	962 ± 112	22	74%	6467 ± 615	481	76%	7429 ± 695	614	*13%*
1989-93	*540*	*0.95*	43%	1000 ± 107	21	72%	7264 ± 605	407	74%	8265 ± 661	544	*12%*
1990-94	*623*	*1.10*	41%	910 ± 91	18	69%	6618 ± 505	337	72%	7528 ± 543	459	*12%*
1991-95	*722*	*1.27*	39%	903 ± 84	16	70%	7804 ± 637	371	73%	8707 ± 662	515	*11%*
1992-96	*780*	*1.35*	38%	930 ± 89	15	72%	9697 ± 774	489	75%	10627 ± 795	671	*9%*
1993-97	*746*	*1.27*	36%	951 ± 96	13	74%	11762 ± 1134	605	77%	12713 ± 1164	826	*8%*
1994-98	*734*	*1.26*	32%	798 ± 83	10	75%	11148 ± 1129	646	77%	11946 ± 1158	845	*7%*
1995-99	*804*	*1.36*	30%	721 ± 72	8	78%	12183 ± 1077	855	80%	12903 ± 1102	1089	*6%*
1996-00	*805*	*1.37*	28%	694 ± 105	7	78%	13886 ± 1445	879	80%	14580 ± 1464	1067	*5%*
1997-01	*821*	*1.42*	25%	594 ± 102	5	76%	13041 ± 1392	716	78%	13634 ± 1410	873	*4%*
1998-02	*750*	*1.31*	22%	547 ± 108	4	74%	13491 ± 1573	622	77%	14038 ± 1581	779	*3%*
1999-03	*665*	*1.14*	22%	636 ± 128	4	73%	15247 ± 1837	608	76%	15883 ± 1846	762	*3%*
2000-04	*553*	*0.95*	20%	664 ± 153	3	71%	15286 ± 2164	474	73%	15950 ± 2174	610	*3%*
2001-05	*465*	*0.80*	19%	606 ± 117	3	69%	12991 ± 1858	402	72%	13597 ± 1871	530	*4%*
2002-06	*333*	*0.57*	16%	474 ± 107	2	67%	11972 ± 2406	298	70%	12446 ± 2414	407	*3%*
2003-07	*326*	*0.56*	15%	428 ± 104	2	68%	10111 ± 1681	311	71%	10539 ± 1687	416	*4%*
2004-08	*326*	*0.57*	16%	333 ± 64	2	66%	8057 ± 1297	245	71%	8390 ± 1301	362	*3%*
2005-09	*325*	*0.59*	17%	296 ± 58	2	68%	8143 ± 1282	300	72%	8439 ± 1287	412	*3%*
2006-10	*329*	*0.61*	16%	241 ± 50	2	69%	8262 ± 1266	307	72%	8503 ± 1270	407	*3%*
2007-11	*352*	*0.67*	16%	290 ± 59	2	69%	8000 ± 1206	300	73%	8290 ± 1210	411	*3%*
2008-12	*366*	*0.72*	14%	236 ± 51	2	74%	12894 ± 2019	507	76%	13130 ± 2023	617	*2%*

Supplement Table 10 Output from GAMM analyses for trends in plastic abundance by number in the central part of the North Atlantic subtropical gyre, n=2624 tows 1987-2012. Additional smooth terms such as latitude and longitude were also tested but produced no different conclusions. Where GAMM indicates estimated degrees of freedom (edf) at or close to value 1, the trend can be considered as a linear relationship (A) and (B) refer to plotted trends in **Supplement Figure 10**.

GAMM analysis ~year	SIGNIFICANCE OF SMOOTH TERM YEAR			
	edf	F	p	
Number of industrial pellets	**1**	35.97	<0.001	
Number of user particles	**6.1**	6.383	<0.001	*(A)*
Total nr of plastic partices	**6.2**	5.849	<0.001	*(B)*



Supplement Figure 10 Complex non-linear trends over time as suggested by GAMM for user plastic (A) and total plastic (B) abundance in the central part of the North Atlantic subtropical gyre. Extreme outliers in individual years render any analysis complicated.

Supplement Table 11 Linear regression results for numerical plastic abundance in central part of the North Atlantic subtropical gyre. GAMM analysis indicates indeed linear fit for industrial pellets, but a complicated non-linear pattern for user particles, which in linear analysis shows no noticeable overall change (plus or minus signs indicate increasing resp. decreasing linear trends and significance levels as ns=not significant and number of symbols reflecting significance levels at p<0.05, p<0.01 and p<0.001)

Linear regression on densities of plastics in the central N.Atlantic Subtropical Gyre *1987-2012*

	n	Constant	estimate	s.e.	t	p	
Industrial plastics	*2624*	258.5	-0.1283	0.0098	-13.05	**<0.001**	**- - -**
User plastics	*2624*	24.9	-0.0093	0.0122	-0.76	0.448	*ns*
All plastics combined	*2624*	30.7	-0.0121	0.0119	-1.01	0.313	*ns*

Supplement Table 12 Annual averaged data for **A)** Central gyre, **B)** peripheral areas around the gyre, and **C)** ALL tows in the North Atlantic gyre west of 50°W including unlikely tows with more than 10 industrial granules but zero user plastics.

A)

***Central Atlantic Gyre* - annual averages** *(area 20°N-40°N and 60°W-80°W, unlikely entries with >10 industrial but 0 user plastics excluded)*

YEAR	Nr of tows	Surface sampled (km2)	INDUSTRIAL PELLETS Incidence (% of tows)	INDUSTRIAL PELLETS n/km^2 ± se	INDUSTRIAL PELLETS geom. mean n/km2	USER PARTICLES Incidence (% of tows)	USER PARTICLES n/km^2 ± se	USER PARTICLES geom. mean n/km2	TOTAL PLASTICS Incidence (% of tows)	TOTAL PLASTICS n/km^2 ± se	TOTAL PLASTICS geom. mean n/km2	Proportion Industrial
1985												
1986												
1987	*52*	*0.09*	65%	1826 ± 474	126	96%	11948 ± 3686	3445	**96%**	**13774 ± 4128**	**4038**	***14%***
1988	*0*											
1989	*19*	*0.03*	47%	2861 ± 1400	41	74%	12653 ± 6390	525	**74%**	**15514 ± 7687**	**604**	***20%***
1990	*62*	*0.11*	48%	705 ± 143	29	84%	5231 ± 1060	874	**86%**	**5936 ± 1158**	**1131**	***12%***
1991	*104*	*0.17*	43%	1226 ± 246	24	72%	7748 ± 1264	521	**73%**	**8974 ± 1426**	**616**	***13%***
1992	*199*	*0.36*	42%	723 ± 94	19	71%	5592 ± 696	379	**74%**	**6315 ± 751**	**508**	***12%***
1993	*156*	*0.27*	40%	1095 ± 250	18	66%	9227 ± 1438	270	**70%**	**10322 ± 1511**	**403**	***11%***
1994	*102*	*0.19*	32%	793 ± 240	9	59%	4319 ± 790	134	**63%**	**5112 ± 857**	**196**	***15%***
1995	*161*	*0.27*	34%	803 ± 147	11	76%	11402 ± 2103	749	**80%**	**12204 ± 2129**	**1089**	***7%***
1996	*162*	*0.26*	39%	1239 ± 257	18	82%	16883 ± 2469	1747	**83%**	**18122 ± 2525**	**2058**	***7%***
1997	*165*	*0.27*	33%	774 ± 156	10	79%	14085 ± 3715	940	**81%**	**14860 ± 3820**	**1231**	***5%***
1998	*144*	*0.26*	22%	326 ± 79	3	72%	5885 ± 927	353	**74%**	**6211 ± 956**	**426**	***5%***
1999	*172*	*0.28*	24%	436 ± 80	5	78%	11934 ± 1590	943	**80%**	**12369 ± 1607**	**1167**	***4%***
2000	*162*	*0.29*	22%	668 ± 406	3	78%	19870 ± 5217	864	**79%**	**20537 ± 5230**	**983**	***3%***
2001	*178*	*0.32*	23%	729 ± 233	4	73%	12715 ± 1897	635	**75%**	**13444 ± 1948**	**768**	***4%***
2002	*94*	*0.16*	21%	538 ± 167	4	68%	18467 ± 7225	377	**75%**	**19005 ± 7240**	**643**	***2%***
2003	*59*	*0.09*	15%	1011 ± 485	2	56%	14716 ± 6147	121	**56%**	**15727 ± 6185**	**139**	***6%***
2004	*60*	*0.09*	10%	320 ± 165	1	65%	6112 ± 1715	215	**70%**	**6432 ± 1705**	**335**	***4%***
2005	*74*	*0.14*	18%	305 ± 128	2	73%	10899 ± 2337	623	**74%**	**11204 ± 2349**	**716**	***2%***
2006	*46*	*0.08*	9%	125 ± 75	1	72%	4552 ± 1610	275	**74%**	**4677 ± 1628**	**325**	***3%***
2007	*87*	*0.16*	20%	373 ± 128	3	71%	12014 ± 4021	447	**77%**	**12387 ± 4014**	**724**	***3%***
2008	*59*	*0.10*	22%	486 ± 184	4	46%	3369 ± 1514	32	**54%**	**3854 ± 1632**	**65**	***13%***
2009	*59*	*0.12*	15%	118 ± 55	2	78%	6550 ± 1263	656	**78%**	**6667 ± 1262**	**679**	***2%***
2010	*78*	*0.16*	10%	70 ± 26	1	76%	11263 ± 2203	661	**76%**	**11333 ± 2210**	**664**	***1%***
2011	*69*	*0.14*	15%	417 ± 190	2	71%	4448 ± 1587	252	**75%**	**4864 ± 1613**	**365**	***9%***
2012	*101*	*0.20*	12%	165 ± 55	1	89%	29195 ± 6679	2840	**89%**	**29360 ± 6687**	**2926**	***1%***

B)

periphery of the Atlantic Gyre (outside 0°N- 40°N and 60°W - 80°W) - Annual Averages unlikely entries w ith >10 industrial but 0 user plastics excluded)

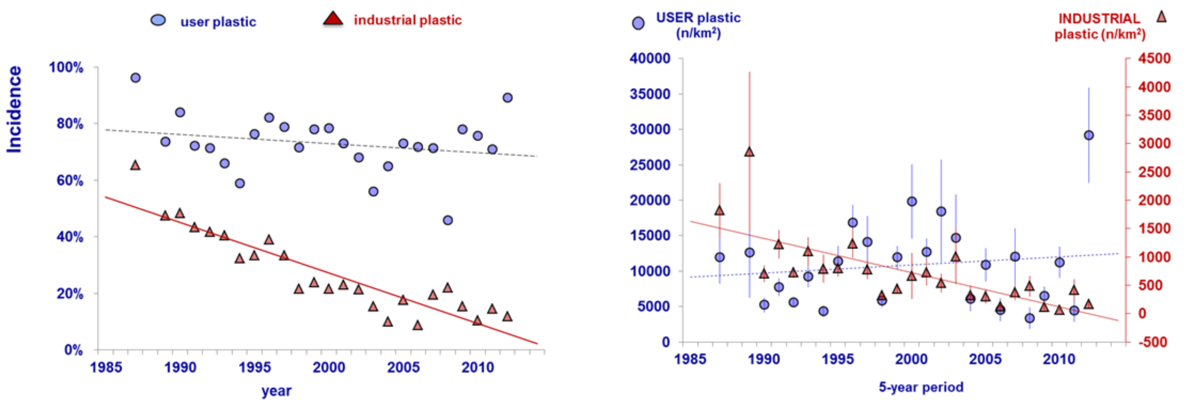
Period	Nr of tows	Surface sampled (km2)	INDUSTRIAL PELLETS Incidence (% of tows)	INDUSTRIAL PELLETS n/km² ± se	INDUSTRIAL PELLETS geom. mean n/km2	USER PARTICLES Incidence (% of tows)	USER PARTICLES n/km² ± se	USER PARTICLES geom. mean n/km2	**TOTAL PLASTICS Incidence (% of tows)**	**TOTAL PLASTICS n/km² ± se**	**TOTAL PLASTICS geom. mean n/km2**	***Proportion Industrial***
1985	*0*											
1986	*0*											
1987	*60*	*0.12*	13%	119 ± 52	1	50%	1789 ± 726	38	**53%**	**1908 ± 725**	**51**	***5%***
1988	*0*											
1989	*72*	*0.14*	13%	428 ± 303	1	78%	3688 ± 760	411	**78%**	**4116 ± 881**	**436**	***9%***
1990	*8*	*0.01*	25%	607 ± 472	6	63%	1282 ± 637	91	**63%**	**1890 ± 1090**	**101**	***32%***
1991	*188*	*0.34*	21%	444 ± 105	3	53%	2036 ± 324	54	**58%**	**2480 ± 398**	**80**	***19%***
1992	*296*	*0.52*	19%	401 ± 74	3	56%	2882 ± 381	76	**59%**	**3283 ± 420**	**101**	***13%***
1993	*206*	*0.37*	13%	218 ± 54	2	35%	981 ± 203	12	**37%**	**1199 ± 229**	**15**	***19%***
1994	*208*	*0.38*	13%	154 ± 34	1	42%	1097 ± 171	21	**46%**	**1251 ± 186**	**28**	***13%***
1995	*183*	*0.34*	10%	147 ± 56	1	55%	2100 ± 320	68	**57%**	**2247 ± 343**	**81**	***7%***
1996	*245*	*0.38*	14%	217 ± 53	2	54%	4467 ± 921	72	**57%**	**4684 ± 944**	**94**	***5%***
1997	*218*	*0.36*	12%	224 ± 62	1	46%	3501 ± 810	38	**47%**	**3724 ± 833**	**42**	***7%***
1998	*270*	*0.47*	8%	129 ± 40	1	41%	2323 ± 519	22	**43%**	**2452 ± 543**	**26**	***5%***
1999	*175*	*0.28*	12%	261 ± 94	1	57%	2635 ± 425	78	**58%**	**2897 ± 453**	**91**	***9%***
2000	*274*	*0.50*	13%	237 ± 55	1	52%	2561 ± 375	54	**57%**	**2799 ± 394**	**80**	***8%***
2001	*193*	*0.33*	13%	223 ± 62	1	58%	3785 ± 878	91	**61%**	**4008 ± 910**	**117**	***6%***
2002	*151*	*0.26*	9%	260 ± 156	1	40%	2389 ± 534	22	**44%**	**2649 ± 577**	**29**	***13%***
2003	*141*	*0.24*	10%	187 ± 61	1	55%	3220 ± 879	66	**57%**	**3407 ± 887**	**81**	***6%***
2004	*133*	*0.21*	7%	110 ± 44	1	32%	783 ± 153	9	**37%**	**893 ± 156**	**14**	***11%***
2005	*162*	*0.28*	16%	557 ± 303	2	66%	8142 ± 2497	213	**70%**	**8699 ± 2511**	**296**	***7%***
2006	*124*	*0.22*	10%	80 ± 24	1	57%	2289 ± 393	75	**58%**	**2369 ± 399**	**85**	***3%***
2007	*166*	*0.31*	12%	188 ± 58	1	49%	3198 ± 908	40	**55%**	**3387 ± 907**	**65**	***6%***
2008	*102*	*0.19*	13%	140 ± 46	1	43%	661 ± 126	19	**49%**	**801 ± 138**	**31**	***19%***
2009	*89*	*0.18*	6%	64 ± 38	0	57%	4828 ± 1967	84	**57%**	**4892 ± 1975**	**85**	***1%***
2010	*209*	*0.42*	13%	208 ± 48	2	71%	20240 ± 2943	485	**71%**	**20449 ± 2964**	**509**	***1%***
2011	*193*	*0.38*	8%	76 ± 23	1	74%	3949 ± 571	317	**76%**	**4025 ± 574**	**362**	***2%***
2012	*127*	*0.23*	4%	49 ± 25	0	68%	15119 ######	212	**68%**	**15169 ± 10515**	**213**	***0%***

C)

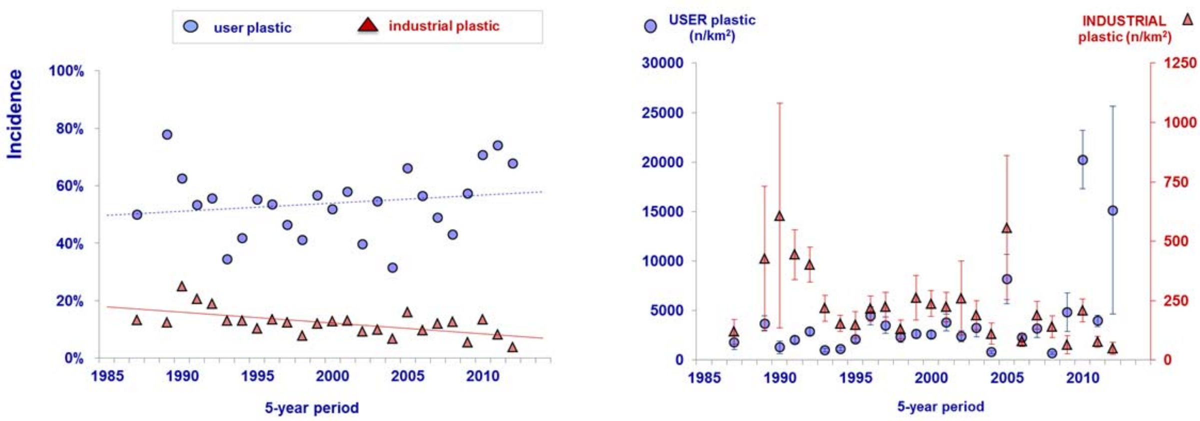
Atlantic Gyre - Annual data for all tows west of 50°W (including unlikely high industrial -zero user counts)

YEAR	Nr of tows	Surface sampled (km2)	INDUSTRIAL PELLETS Incidence (% of tows)	INDUSTRIAL PELLETS n/km^2 ± se	INDUSTRIAL PELLETS geom. mean n/km2	USER PARTICLES Incidence (% of tows)	USER PARTICLES n/km^2 ± se	USER PARTICLES geom. mean n/km2	TOTAL PLASTICS Incidence (% of tows)	TOTAL PLASTICS n/km^2 ± se	TOTAL PLASTICS geom. mean n/km2	TOTAL PLASTICS Proportion Industrial
1985	*0*											
1986	*0*											
1987	*112*	*0.22*	38%	911 ± 235	14	71%	6506 ± 1811	312	**73%**	**7417 ± 2025**	**392**	***12%***
1988	*0*											
1989	*91*	*0.17*	20%	936 ± 387	3	77%	5560 ± 1488	433	**77%**	**6496 ± 1786**	**466**	***14%***
1990	*70*	*0.13*	46%	693 ± 136	24	81%	4780 ± 953	675	**83%**	**5474 ± 1043**	**859**	***13%***
1991	*292*	*0.51*	29%	723 ± 113	7	60%	4070 ± 520	122	**63%**	**4793 ± 596**	**166**	***15%***
1992	*497*	*0.88*	28%	557 ± 61	7	62%	3956 ± 364	143	**65%**	**4512 ± 396**	**197**	***13%***
1993	*362*	*0.64*	25%	596 ± 114	5	48%	4534 ± 665	46	**51%**	**5130 ± 704**	**64**	***12%***
1994	*313*	*0.57*	20%	680 ± 202	3	47%	2137 ± 294	37	**52%**	**2817 ± 364**	**57**	***24%***
1995	*348*	*0.62*	22%	650 ± 138	4	64%	6379 ± 1017	198	**68%**	**7029 ± 1038**	**287**	***10%***
1996	*407*	*0.64*	24%	624 ± 110	5	65%	9409 ± 1166	258	**67%**	**10033 ± 1198**	**322**	***6%***
1997	*384*	*0.64*	22%	475 ± 78	4	60%	8040 ± 1680	150	**62%**	**8515 ± 1728**	**182**	***6%***
1998	*415*	*0.74*	13%	222 ± 45	1	52%	3553 ± 473	57	**54%**	**3775 ± 492**	**70**	***6%***
1999	*350*	*0.57*	19%	630 ± 243	3	67%	7182 ± 846	257	**69%**	**7813 ± 884**	**335**	***8%***
2000	*437*	*0.79*	16%	421 ± 156	2	62%	8972 ± 1985	151	**65%**	**9393 ± 1993**	**206**	***4%***
2001	*371*	*0.65*	18%	465 ± 117	3	65%	8070 ± 1043	231	**68%**	**8535 ± 1074**	**289**	***5%***
2002	*245*	*0.43*	14%	367 ± 115	2	51%	8558 ± 2827	65	**56%**	**8925 ± 2837**	**96**	***4%***
2003	*200*	*0.33*	12%	430 ± 151	1	55%	6611 ± 1942	79	**57%**	**7042 ± 1959**	**95**	***6%***
2004	*197*	*0.31*	10%	377 ± 136	1	41%	2390 ± 558	24	**48%**	**2767 ± 567**	**44**	***16%***
2005	*243*	*0.42*	19%	1438 ± 557	3	66%	8747 ± 1812	253	**72%**	**10185 ± 1875**	**437**	***13%***
2006	*170*	*0.31*	9%	92 ± 27	1	61%	2902 ± 524	107	**62%**	**2994 ± 531**	**122**	***3%***
2007	*253*	*0.47*	15%	252 ± 58	2	57%	6230 ± 1524	92	**63%**	**6482 ± 1522**	**149**	***4%***
2008	*162*	*0.29*	17%	306 ± 84	2	44%	1643 ± 564	23	**51%**	**1949 ± 609**	**42**	***18%***
2009	*148*	*0.30*	10%	85 ± 32	1	66%	5514 ± 1284	191	**66%**	**5600 ± 1289**	**196**	***1%***
2010	*287*	*0.58*	13%	171 ± 35	1	72%	17801 ± 2236	527	**73%**	**17971 ± 2251**	**547**	***1%***
2011	*262*	*0.52*	10%	166 ± 54	1	73%	4080 ± 591	298	**76%**	**4246 ± 598**	**363**	***4%***
2012	*228*	*0.43*	8%	101 ± 28	1	77%	21354 ± 6561	669	**77%**	**21455 ± 6567**	**680**	***0%***

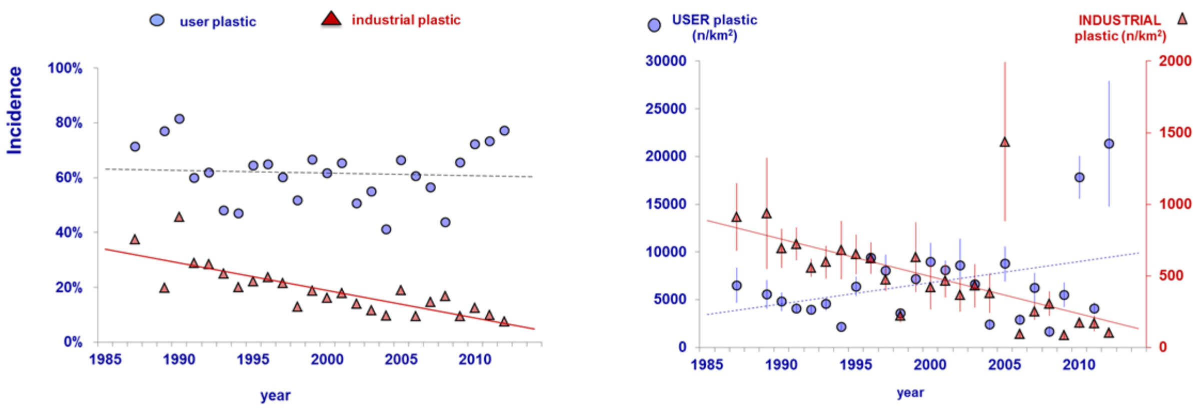
A. Centre



B. Periphery



C. Total



Supplement Figure 11 Annual figures for incidence and densities of industrial and user plastic in the North Atlantic subtropical gyre. A. central part of gyre b. peripheral parts of gyre C. total (cf. Supplement Table 12)

Supplement Table 13 Linear tests for trends in annual densities of industrial and user plastic in the North Atlantic subtropical gyre. A. central part of gyre b. peripheral parts of gyre C. total (cf. Supplement Table 12). Industrial plastics decreasing in all three datasets. Increase in user plastics suggested from data in periphery probably linked to few outliers in recent years, and not present in the overall data set combining central and peripheral data.

A.

Linear regression on annual densities of plastics in the central N.Atlantic Gyre *(1987-2012; 2624 hauls)*

	n	Constant	estimate	s.e.	t	p	
Industrial plastics	25	**121385**	**-60.30**	**11.60**	**-5.22**	**<0.001**	**- - -**
User plastics	25	**-216304**	**114.00**	**167.00**	**0.68**	**0.503**	ns
All plastics combined	25	**-94919**	**53.00**	**170.00**	**0.31**	**0.758**	ns

B).

Linear regression on annual densities of plastics in the periphery of the North Atlantic Gyre (1987-2012; 4193 hauls)

	n	Constant	estimate	s.e.	t	p	
Industrial plastics	25	**18711**	**-9.24**	**3.47**	**-2.66**	**0.014**	**-**
User plastics	25	**-612586**	**308.00**	**108.00**	**2.86**	**0.009**	+ +
All plastics combined	25	**-593876**	**299.00**	**109.00**	**2.75**	**0.011**	+

C.

Linear regressions on annual densities of plastics in the North Atlantic Gyre *(1987-2012; 6844 hauls)*

	n	Constant	estimate	s.e.	t	p	
Industrial plastics	25	**52677**	**-26.09**	**6.93**	**-3.77**	**0.001**	**- - -**
User plastics	25	**-436546**	**222.00**	**117.00**	**1.89**	**0.071**	ns
All plastics combined	25	**-383870**	**196.00**	**118.00**	**1.65**	**0.112**	ns

8. Photographs of samples

Photo examples of Fulmar stomach contents

Sample NMD-2010-001 with plastics from proventricular stomach contents on left, and gizzard contents on the right. Preproduction plastic pellets for each subsample on top right are 4 to 5 mm in diameter.

Sample FAE-2011-X29, with single preproduction plastic pellet (diameter 4-5mm) at top left.

Photo examples of SEA neuston net plastic particles

photo: SEA - G. Proskurowski

photo SEA - J. Donahue