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Seabirds, gyres and global trends in plastic pollution

Jan A. van Franeker [a, *], Kara Lavender Law [b]

[a] IMARES, Wageningen-UR, P.O. Box 167, 1790 AD Den Burg (Texel), Netherlands
[b] Sea Education Association, P.O. Box 6, Woods Hole, MA 02543, USA

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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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* Corresponding author.
E-mail address: jan.vanfraneker@wur.nl (J.A. van Franeker).

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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 × 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

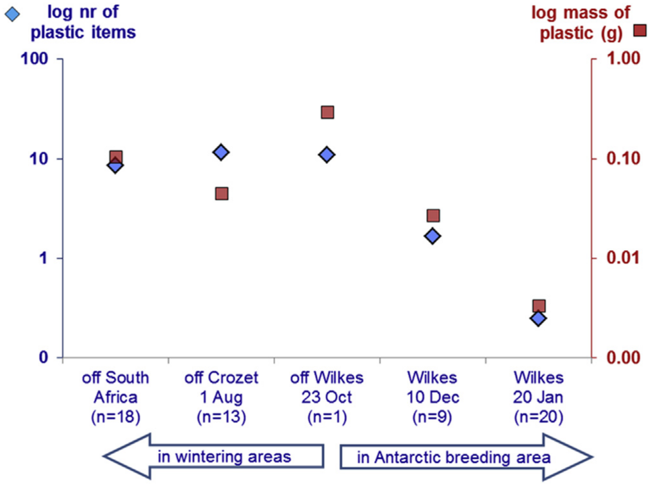

Fig. 1. Change in abundance of plastic debris in stomach contents of cape petrels after return from northern wintering areas to their Antarctic breeding area in Wilkes Land (66°S–110°E) from late October onwards.

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

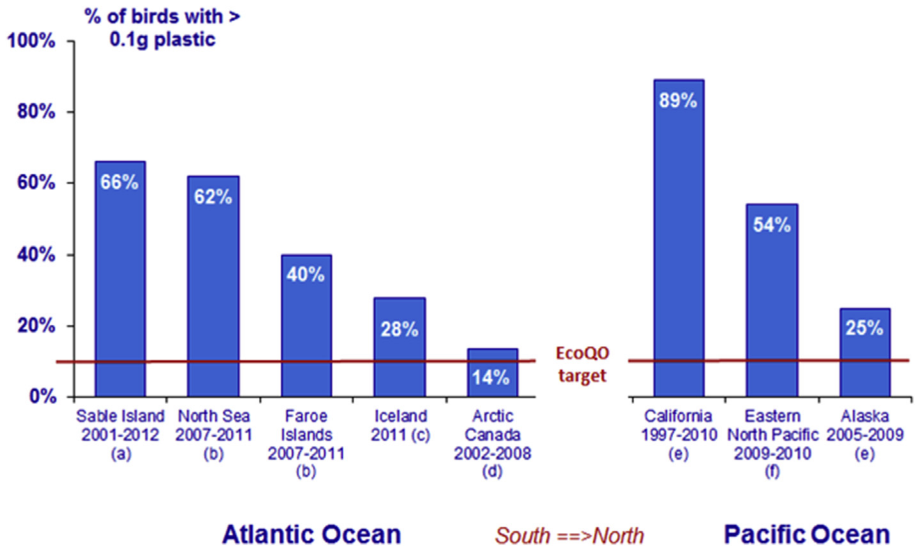

Fig. 2. Latitudinal patterns in fulmar EcoQO performance (proportion of fulmars having >0.1 g plastic in the stomach) in North Atlantic and Pacific Oceans. (a) Bond et al. (2014), (b) this study, (c) Kühn and Van Franeker (2012), (d) combined from Mallory et al. (2006), Mallory (2008) and Provencher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

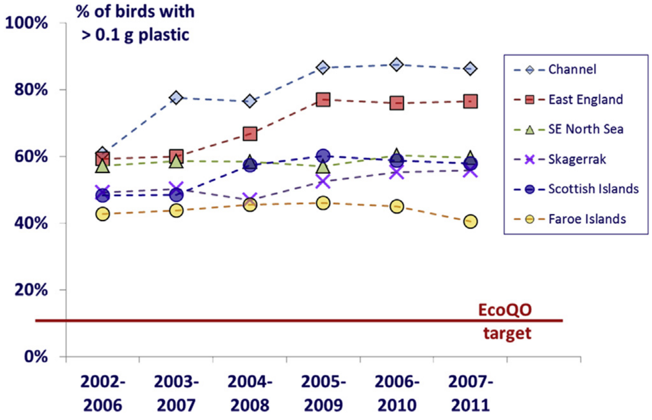

Fig. 3. Regional trends in fulmar EcoQO performance (proportion of fulmars having $>$ 0.1 g plastic in the stomach) over time in North Sea regions and the Faroe Islands (Updated from Van Franeker and the SNS Fulmar Study Group (2013); details in Online Supplement).

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

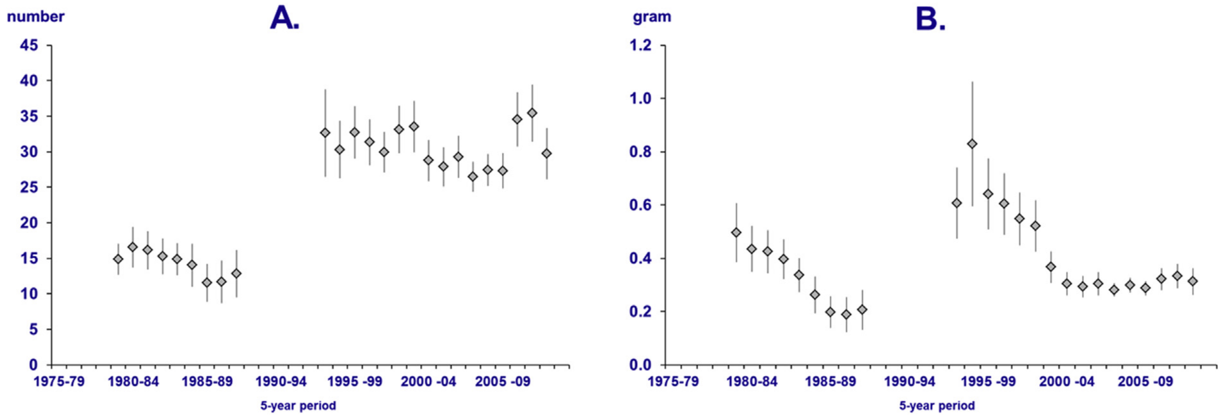

Fig. 4. Changes in A. numerical abundance and B. mass of plastics in fulmars from the Netherlands since the 1980s. Data show arithmetic averages ±standard error (SE) by running 5-year averages (i.e. data points shift one year ahead at a time; sample size for 5 year periods is ≥ 21 during the 1980s and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

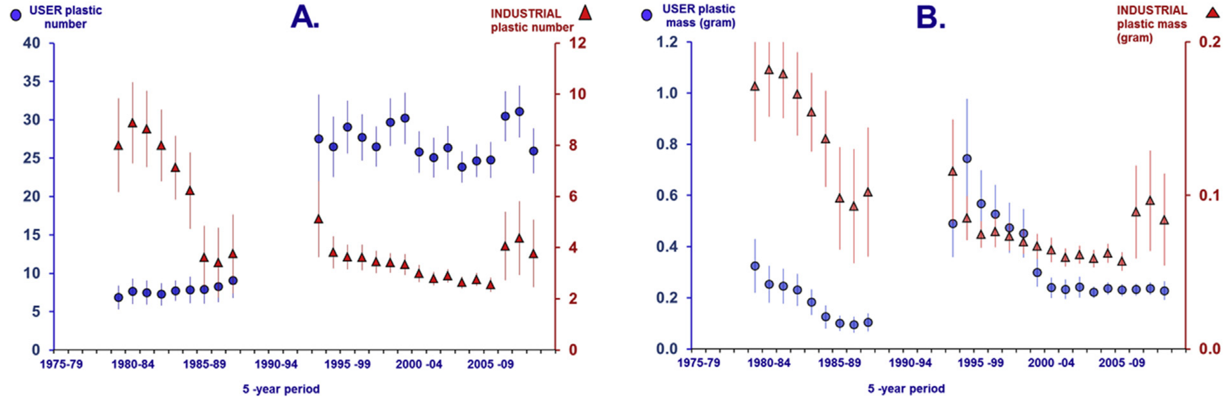

Fig. 5. Dissimilar trends in A. numerical abundance and B. mass of industrial and user plastics in fulmars from the Netherlands since the 1980s. Data show arithmetic averages ±SE by running 5-year averages. For industrial plastics, high arithmetic averages and large standard errors in the last three 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

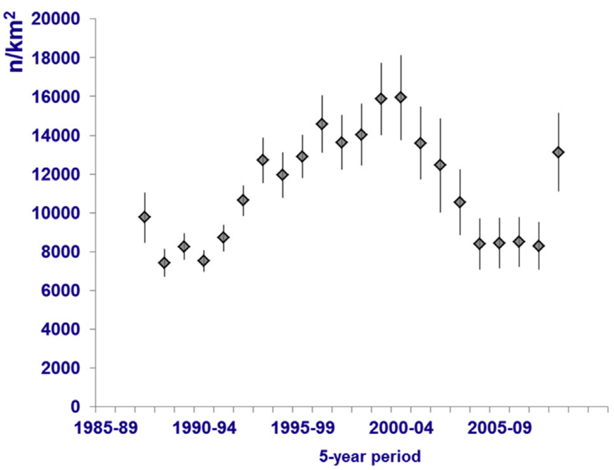

Fig. 6. Numerical abundance of plastic particles (n/km^2) in the central area of the North Atlantic subtropical gyre (20–40°N, 60–80°W) from 1987 to 2012 in 5-year running averages ±SE (minimum sample size per 5 years is 237 tows; total tows 2624).

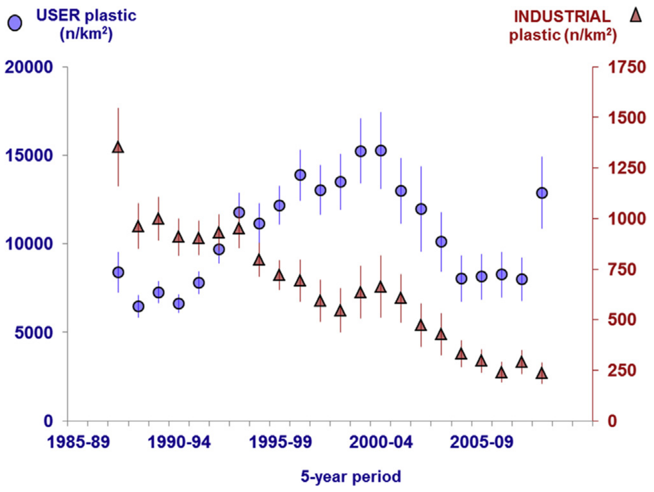

Fig. 7. Numerical abundances of industrial and user plastics (n/km^2) in the central area of the Atlantic gyre (20-40°N, 60–80°W) from 1987 to 2012 in 5 year running averages ±SE (minimum sample size per 5 years = 237 tows; total tows = 2624).

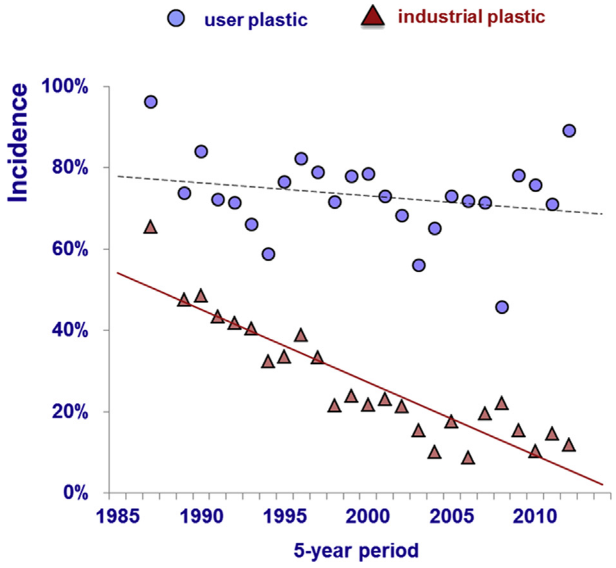

Fig. 8. Annual incidences of industrial and user plastics in SEA net tow data from the central gyre (20-40°N, 60–80°W) from 1987 to 2012 (n = 2624).

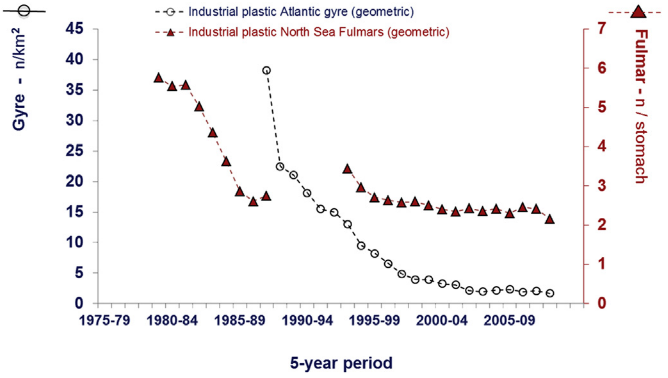

Fig. 9. Comparative trends in numerical abundance of industrial plastics in stomachs of North Sea fulmars and surface densities in the North Atlantic subtropical gyre by running geometric means over 5-year periods.

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

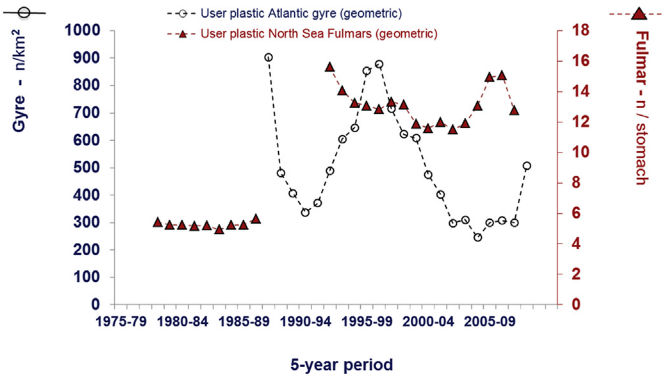

Fig. 10. Comparative trends in numerical abundance of user plastics in stomachs of North Sea fulmars and surface densities in the North Atlantic subtropical gyre by running geometric means over 5-year periods.

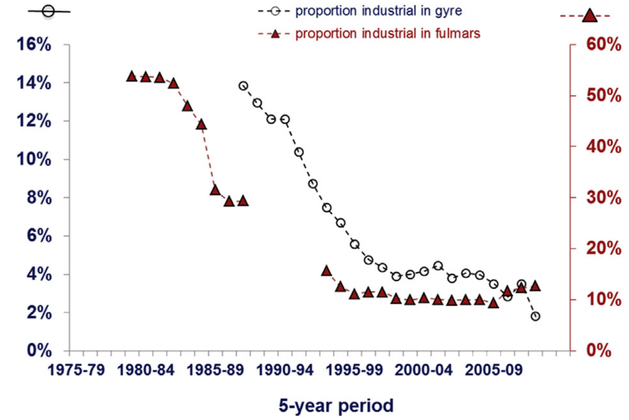

Fig. 11. Numerical proportion of industrial plastics among all plastic particles in the central Atlantic gyre and in northern fulmars of the North Sea by running 5-year periods (arithmetic average number of industrial plastics divided by arithmetic average total number of plastic particles).

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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