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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

* 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 $\times$ 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