Environmental Pollution 159 (2011) 2609–2615

Contents lists available at ScienceDirect

Environmental Pollution

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

Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea

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ARTICLE INFO

Article history:
Received 7 January 2011
Received in revised form
31 May 2011
Accepted 4 June 2011

Keywords:
Fulmarus glacialis
Plastic ingestion
Marine debris
Environmental monitoring
OSPAR EcoQO
MSFD-GES

ABSTRACT

The abundance of plastics in stomachs of northern fulmars from the North Sea is used in the OSPAR Ecological Quality Objective (EcoQO) for marine litter. The preliminary EcoQO defines acceptable ecological quality as the situation where no more than 10% of fulmars exceed a critical level of 0.1 g of plastic in the stomach. During 2003–2007, 95% of 1295 fulmars sampled in the North Sea had plastic in the stomach (on average 35 pieces weighing 0.31 g) and the critical level of 0.1 g of plastic was exceeded by 58% of birds, with regional variations ranging from 48 to 78%. Long term data for the Netherlands since the 1980s show a decrease of industrial, but an increase of user plastics, with shipping and fisheries as the main sources. The EcoQO is now also used as an indicator for Good Environmental Status in the European Marine Strategy Framework Directive.

1. Introduction

Marine debris can have serious economic and ecological consequences. Even on a local scale, such as the Shetland Islands in Scotland, the economic damage can exceed a million Euro's annually (Hall, 2000; Lozano and Mouat, 2009; Mouat et al., 2010). The ecological damage from marine litter is sometimes dramatically illustrated by entangled wildlife. Less apparent are the consequences of the ingestion of plastics and other types of litter, common among a wide range of marine organisms (Laist, 1987, 1997; Derraik, 2002). Plastics gradually break down to microscopic sizes and there is a growing concern that 'micro-plastics' may enter the base of marine food webs via sediment- or filter-feeding organisms (Thompson et al., 2004, 2009; Browne et al., 2008; Graham and Thompson, 2009). These concerns are exacerbated by evidence that plastics, in addition to having many embedded chemicals, also adsorb toxic pollutants from the surrounding water, thus potentially boosting bioaccumulation of dangerous contaminants in the food web by ingestion (Endo et al., 2005; Hale et al., 2010; Teuten et al., 2007; Moore, 2008; Arthur et al., 2009; Teuten et al., 2009). The potential toxic danger of plastic ingestion thus affects the higher food web levels not only

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doi:10.1016/j.envpol.2011.06.008

directly, but also indirectly through the consumption of contaminated prey.

Several early international policy measures attempted to reduce input of litter into the marine environment, such as the 1972 London Dumping Convention, the MARPOL Convention 73/78, and the 1992 Oslo and Paris Conventions for the protection of the marine environment of the northeast Atlantic (OSPAR). In the absence of significant improvement, new policy initiatives were developed by, for example, the EC Directive 2000/59/EC on Port Reception Facilities (EC, 2000), the Bergen Declaration of the North Sea Ministerial Conference (2002) and most recently by the inclusion of litter in the European Marine Strategy Framework Directive (EC, 2008, 2010). Emphasizing the need for policy aims to be quantifiable, the North Sea Ministers decided to establish a system of Ecological Quality Objectives for the North Sea (EcoQO's) to be implemented by OSPAR and ICES (International Council for the Exploration of the Sea). For marine litter, ICES had proposed an EcoQO based on the abundance of plastics in stomachs of seabirds (e.g., ICES-WGSE, 2001). Studies from the North Atlantic and North Pacific had shown that the northern fulmar (*Fulmarus glacialis*) commonly ingests litter and accumulates plastic in the stomach (Bourne, 1976; Baltz and Morejohn, 1976; Day et al., 1985; Furness, 1985; van Franeker, 1985; Moser and Lee, 1992; Robards et al., 1995; Blight and Burger, 1997). Synthetic debris may sometimes be ingested because it somehow resembles prey (Derraik, 2002), but in many instances it is unclear what triggers the ingestion of plastic objects. Unlike many other seabird species, for example gulls, fulmars feed only at sea, never on land and normally do not regurgitate hard prey remains. Indigestible food parts accumulate in the muscular part of the stomach to be slowly ground down to a size that may pass into the gut. Consequently, the abundance of hard prey remains in the stomach, including plastics, provides an integrated picture of ingestion over a period of time before death. Different quantities of plastic in stomachs of fulmars from the North Sea and from the Arctic (van Franeker, 1985), and differences among related species in the Antarctic (van Franeker and Bell, 1988; Ainley et al., 1990) provided early evidence for this basic assumption. In combination with the fulmar's high abundance and wide distribution (Del Hoyo et al., 1992; Hatch and Nettleship, 1998) these features make the species an optimal candidate for the ecological monitoring of litter in the marine environment.

Since the initial identification of the 'Seabird-Plastic-EcoQO' by ICES and the North Sea Ministers, close co-operation has grown between researchers around the North Sea. The work started with a pilot study in the Netherlands, investigating the usage of beached fulmars as an indicator of the effectiveness of Dutch shipping and harbor policies to minimize waste disposal at sea (van Franeker and Meijboom, 2002). The pilot project assessed potential sources of bias influencing stomach contents, adequate sample size and the most appropriate metric to use. Internationally, monitoring of plastics in fulmars started as a part of the 'Save the North Sea' campaign (Save the North Sea, 2004; van Franeker et al., 2005). In a number of research reports (most recent: van Franeker and the SNS Fulmar Study Group, 2008) and policy documents (most recent: OSPAR, 2008) the metrics, data presentation and target definition of the Fulmar-Plastic-EcoQO have gradually been evaluated and matured to a level ready for formal implementation. Although formally still a 'proposed' EcoQO, OSPAR (2010a,b) presents it as being implemented. The EcoQO is based on the mass of plastics in fulmar stomachs, with the preliminary target for acceptable ecological conditions defined as:

"There should be less than 10% of northern fulmars having 0.1 g or more plastic in the stomach in samples of 50–100 beached fulmars from each of 5 different regions of the North Sea over a period of at least 5 years".

The OSPAR target level is an arbitrary political choice, matching pollution levels in environments where anthropogenic influence is expected to be low. Data are lacking to identify a target that represents a no-effect level for fulmars or any other ecosystem component.

The purpose of this article is to disseminate the concept of the Fulmar-Plastic-EcoQO as a tool to quantify trends and geographic patterns in marine litter, which will provide a sound basis for policy decisions in combination with increased public awareness. Similar tools are required for implementation of the 'Good Environmental Status (GES)' requirement in the Marine Strategy Framework Directive (MSFD) (EC, 2008).

2. Materials and methods

In the Netherlands, volunteers of the Dutch Seabird Group (Nederlandse Zeevogelgroep NZG) involved in Beached Bird Surveys have collected dead fulmars for this study since the early 1980s. Other organizations such as coastal bird rehabilitation centers also assist in collecting. Similar sampling began in all countries bordering the North Sea following the start of the Save the North Sea project in 2002, with participating groups in Shetland, Orkney, eastern England, the French Channel, Belgium, Germany, Denmark, Norway and Sweden. These groups ranged from volunteer birders to governmental research institutes and municipal beach cleaning projects. The Faroe Islands have participated in the project as a reference area outside the North Sea. Sampling locations were grouped into the following North Sea regions: Scottish Islands, eastern England, Channel area, southeast North Sea (Belgium, Netherlands, Germany) and Skagerrak area (Denmark, Sweden, Norway).

Fulmar corpses were stored frozen until processed in batches in the laboratory. Standard dissection methods structured the recording of a broad range of data needed to assess sex, age, breeding status, body condition, probable cause of death, origin, and other potentially relevant issues. Thorough attention was given to age-related characters because age was the only variable previously found to influence the quantity of litter in stomachs (van Franeker and Meijboom, 2002). Assessments used developmental stages of sexual organs (size, shape, color) and the presence and size of the Bursa of Fabricius (a gland-like organ near the end of the gut involved in immunity systems of young birds, but disappearing within the first year of life or shortly after). Supporting information on age was derived from plumage details and timing of moult. Complete information on dissection methods and forms used is provided in the project dissection manual (van Franeker, 2004; plus addenda in Online supplement).

After removal of the stomach, contents were 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 was 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, contributing little to plastic mass. Plastic items were categorized into industrial- or user plastics. Industrial plastics are the raw granular stock from which all sorts of user objects can be made by melting the granules and adding different substances to give the plastic its desired characteristics. User plastics are the debris of all sorts of consumer products. User plastics and non-plastic rubbish are described in further subcategories (see Online supplement) that are not a part of the formal EcoQO but do play a role in assessments of sources of litter. After sorting, the plastic and rubbish were left to become completely air-dry in open petri-dishes for a number of days. Then, for each individual stomach, the precise number of items and their combined mass was recorded for each subcategory of plastic and litter. Weights were recorded using electronic Sartorius weighing scales to an accuracy of 0.0001 g. Further details of procedures are provided in the Online supplement. Data from dissections and stomach content analysis were initially recorded in Excel spreadsheets and then stored in Oracle relational database. The stomach data allow analyses for subcategories of litter or higher groupings by i) the percentage of birds having the litter in the stomach (incidence or frequency of occurrence) or ii) number of items or iii) mass. As proposed in the Dutch pilot study (van Franeker and Meijboom, 2002) and the international EcoQO (OSPAR, 2008), the main interpretation of data and statistical analyses were based on mass of plastic. The following conventions and definitions apply:

- The 'current situation' is defined as the most recent 5-year period, 2003–2007 for the purposes of this article, in which data are calculated from all individuals within that period (i.e., not from annual averages)
- EcoQO compliance or performance is defined as the percentage of birds in a sample that had 0.1 g or more plastic mass in the stomach
- Statistical tests for significance of temporal trends are conducted by linear regressions fitting ln-transformed plastic mass values for individual birds on the year of collection
- 'Recent trend' is defined as the trend over the past 10 years
- 'Long term trend' refers to the full dataset (for the Netherlands from the first individual in 1979)

For evaluation of regional differences, data from individual birds over the most recent 5- year period were fitted in a negative binomial generalized linear model and tested by likelihood ratio test (Venables and Ripley, 2002).

Annual averages are of limited use because small sample sizes, short-term variations and individual outliers can have a strong effect on results. Thus, as in the EcoQO target definition, 5-year periods are used as the basic unit for data presentation in tables and figures. Time related changes are illustrated by running 5-year averages, each time shifting one year and thus overlapping for four years. Where needed, short-term inter-annual comparisons are based on geometric means, derived from logarithmically transformed data. See the Online supplement for details illustrating the skewed distribution of mass data and the relation to arithmetic averages, geometric means and the critical level of 0.1 g used in the EcoQO.

3. Results

3.1. Long term litter trends based on Dutch data

The incidence of plastic in stomachs of fulmars from the Netherlands averaged 91% in the 1980s, increased to about 98% around the year 2000 and has since stabilized at a level slightly below 95% (Table 1). The average number of plastic particles per bird was c. 15 in the 1980s, increased to over 30 around the turn of the century and currently averages 26. Greater differences exist in average mass of plastic: initially, as with the number of items, mass of plastic doubled from 0.34 g in the 1980s to 0.64 g in the late 1990s. However, whereas the number of particles decreased only slightly in subsequent years, the mass of plastic in the stomachs halved to a now fairly stable level of 0.28 g of plastic per beached fulmar, slightly below the 1980s level. A similar but more dampened time trend may be seen in geometric mean masses for 5-year periods, and in gradual changes in the EcoQO percentage of birds exceeding the critical limit of 0.1 g of plastic in the stomach. Remarkably, the EcoQO percentage did not reveal an obvious change from the 1980s to the late 1990s despite the marked changes in numbers of particles and mass. This is probably related to the size and mass differences between industrial and user plastics and their changing proportions (see below). However, after the mid-1990s the percentage of birds exceeding the critical level of 0.1 g did show a 10% decrease although this has not continued in the most recent periods. (Table 1, Fig. 1 and Online supplement Table 2 for statistical details).

For the overall mass of plastics (industrial plus user) in the stomachs of Dutch fulmars, the regressions for long term trends show no significant change as linear tests do not take the initial increase and subsequent decrease into account. Restricted to the period after the mid-1990s, the short-term (10-year) trends for mass of plastic were initially significantly downwards (e.g., $p < 0.001$ for 1996–2005), but have stabilized and are no longer significant in the most recent test for 1998–2007. Trends in abundance for the two major types of plastic were very different (Fig. 2). Measured over the full time frame of 1979–2007, industrial plastic has decreased significantly. User plastics have increased but not with consistent significance in all age groups of birds (Online supplement Table 2). The main change occurred from the 1980s to 1990s: when industrial plastic mass in stomachs decreased by half (decrease1979–2000 $p < 0.001$) but user plastics tripled (increase 1979–2000 $p < 0.001$). Both categories showed decreases after the mid-1990s that were significant initially (1996–2005 decreases $p = 0.007$ for industrial and $p < 0.001$ for user plastic) but currently show no further change (both not significant for 1998–2007).

3.2. Current litter levels in the wider North Sea

Analyses of time related trends for North Sea areas other than the Netherlands are not yet available as data collection in most of those areas began in 2002 and 2003 and the minimum period for trend analysis is taken as 10 years. Data presented here are for the 'current' 5-year period in our analysis, i.e., 2003–2007. The fulmar stomachs reveal clear spatial patterns of litter pollution in the North Sea (Table 2 and Fig. 3 and Online supplement). The Likelihood ratio test of the negative binomial model for the five regions indicated significant differences (LR stat 11.1832; df = 4; $p = 0.025$). The abundance of plastics was highest in fulmars from the Channel area, and gradually decreased northwards along both the eastern and western coasts of the North Sea. The Channel area differed significantly from the neighboring regions of East England (LR Stat 4.7074; df = 1; $p = 0.030$) and the SE North Sea (LR Stat 5.0886; df = 1; $p = 0.024$). The decreases from East England to the Scottish Islands and from the SE North Sea to the Skagerrak were not significant.

4. Discussion

Initial evaluation of the time series of Dutch fulmars (van Franeker and Meijboom, 2002) found that only the age composition of samples of beached birds might cause bias in analyses for trends over time, with younger birds having more plastic in the stomach than older birds. Data added after the pilot study showed that the age difference is consistent to a level that all different age groups can be combined into a single monitoring unit. The annual geometric mean mass of plastics shows the same long-term pattern, and the same short-term annual fluctuations for adults and non-adults, in spite of the substantial difference between these groups (Fig. 4). Thus, as long as age composition of samples is considered, any risks of age-related bias can be controlled for and policy reports may use simple "all age" derived graphs such as in Fig. 1. The details of, and reasons for the higher loads of plastics in younger birds are unclear. Preliminary data from

Table 1
Incidence, number of particles and mass of plastics in stomachs of fulmars beached in the Netherlands in the 1980's and 'running' 5-year periods since 1995. Mass data are also shown as geometric mean mass, and as percentage of stomachs with more than 0.1 g of plastic (EcoQO performance).

5-year period	n	Incidence %	Average number $n \pm$ se	Average mass g $\pm$ se	Geometric mean mass (g)	Over 0.1 g EcoQO %
1980s	69	91%	14.6 ± 2.0	0.34 ± 0.06	0.11	67%
1995–1999	222	97%	32.7 ± 3.7	0.64 ± 0.13	0.15	67%
1996–2000	258	98%	31.3 ± 3.2	0.60 ± 0.12	0.15	67%
1997–2001	304	97%	29.9 ± 2.8	0.55 ± 0.10	0.14	63%
1998–2002	329	98%	33.1 ± 3.3	0.52 ± 0.10	0.13	62%
1999–2003	294	98%	33.5 ± 3.6	0.37 ± 0.06	0.11	59%
2000–2004	318	95%	28.8 ± 2.9	0.30 ± 0.04	0.09	59%
2001–2005	331	95%	27.9 ± 2.7	0.29 ± 0.04	0.09	57%
2002–2006	304	94%	29.3 ± 3.0	0.30 ± 0.04	0.09	61%
2003–2007	309	93%	26.5 ± 2.1	0.28 ± 0.02	0.09	61%

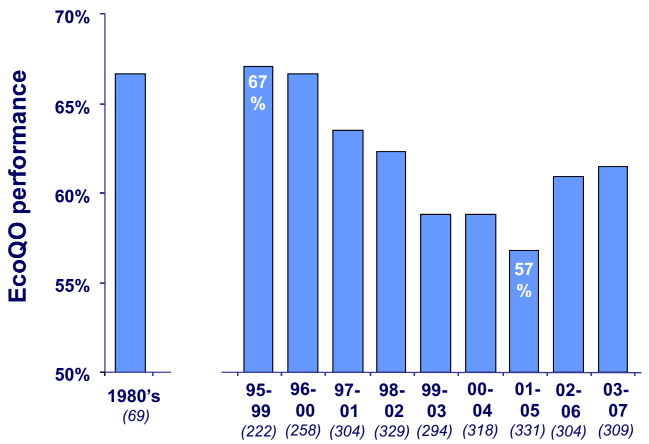

Fig. 1. EcoQO performance in the Netherlands 1980–2007 – Trend in the percentage of beached fulmars having more than 0.1 g of plastic in the stomach (running average over 5-year periods, each bar shifting one year; number of birds in brackets below each bar). Note that the *Y*-axis only shows the 50–70% range whereas the OSPAR target for the EcoQO is that less than 10% of birds should have more than 0.1 g of plastic in the stomach.

an ongoing study on seasonal changes on the Faroe Islands suggest that breeding adults may lose part of their plastics burden by feeding it to chicks, but the effects are short-term and insufficient to fully explain the differences between age groups.

Insights into the temporal aspects of fulmar monitoring data can be derived from Fig. 4. An aberrant peak in plastic abundance occurred in 2002 but the consistency of the pattern between age groups indicates a real event rather than an accidental outlier. Such consistency often persists even for smaller sample sizes, which might suggest that the power analyses in van Franeker and Meijboom (2002) and the OSPAR (2008) recommendations for an annual sample size of c. 40 birds per location, the use of 5-year averages and a minimum of 10 years for statistical tests for trends over time may be overly cautious. However, we emphasize that caution must be maintained in information that is used for long-term policy decisions, especially when short-term events such as that in 2002 are not properly explained: possibly flooding in central Europe caused increased riverine input of litter into the North Sea in 2002, but we found no way to substantiate this quantitatively. Thus, although we believe that annual geometric means will generally reflect true developments, management decisions should only rely on longer-term data evaluations. For the long term, there are no comparative datasets in the North Sea area. However, for the period after 2002, results from beach surveys around the North Sea confirm the finding from the Fulmar monitoring in showing that there is no change in the amount of beached debris (OSPAR, 2010a).

Questions concerning the spatial resolution of fulmar plastic monitoring are gradually being clarified. Starting with the Save the North Sea project in 2002, monitoring was expanded to a wide range of locations around the North Sea. In theory, the flying abilities of fulmars allow them to travel over much or all of the North Sea in a single or in a very few days. This led to the expectation that local differences of pollution within the North Sea area were unlikely to be clearly reflected in fulmar stomach contents. However, even though we only have 5–6 years of data, and less for some locations, data combined into regions reveal a clear pattern in mass of plastics in the fulmar stomachs in the North Sea. Highest levels occur in the English–French Channel area, and these decrease northwards, reaching a minimum for the North Sea around the Scottish Islands (Fig. 3 and Table 2). Such a pattern shows that the bulk of debris in the North Sea must be of relatively local origin, and cannot be attributed to a 'background noise' of litter drifting in from distant sources such as the western Atlantic. Warm Gulf Stream water flows into the North Sea around both the north and south of the UK, and elevated levels of litter in the Channel and southern North Sea compared to the Scottish Islands provide evidence for litter sources that are predominantly local. The geographic pattern and variations in subcategories of litter indicated that shipping and fisheries play a major role in the pollution of the North Sea with plastic (van Franeker et al., 2005), a conclusion confirmed by a large inventory of litter on the beaches

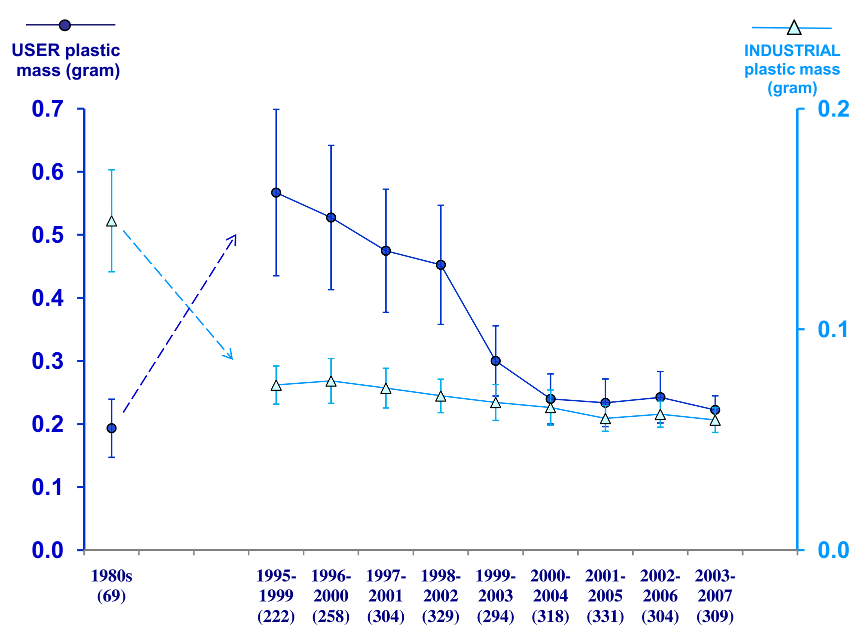

Fig. 2. Trends for industrial and user plastics in the Netherlands 1980–2007 – Running 5-year average mass ± standard error for the two main categories of plastic in stomachs of beached fulmars from the Netherlands.

Table 2
Incidence, number of particles and mass of plastics in stomachs of fulmars beached in different North Sea regions during the 5-year period 2003–2007. Mass data are also shown as geometric mean mass, and as percentage of stomachs with more than 0.1 g of plastic (EcoQO performance).

Region	*n*	Incidence %	Average number $n \pm$ se	Average mass g $\pm$ se	Geometric mean mass (g)	Over 0.1 g EcoQO %
Scottish Islands	95	92%	18.9 $\pm$ 3.0	0.20 $\pm$ 0.03	0.06	48%
East England	60	95%	35.0 $\pm$ 6.9	0.23 $\pm$ 0.03	0.11	60%
Channel area	107	100%	56.7 $\pm$ 8.3	0.44 $\pm$ 0.06	0.23	78%
SE North Sea	842	94%	30.4 $\pm$ 3.0	0.30 $\pm$ 0.02	0.09	58%
Skagerrak area	191	95%	47.7 $\pm$ 8.6	0.36 $\pm$ 0.11	0.08	50%
North Sea total	1295	95%	34.5 $\pm$ 2.5	0.31 $\pm$ 0.02	0.09	58%

of Texel in the Netherlands in 2005 (van Franeker, 2005). These findings for the North Sea conflict with an opinion that globally most marine debris has a land-based origin (MEPC, 2009).

The spatial differentiation of stomach contents over relatively small scales implies that, despite potentially high mobility, the average fulmar in the average situation spends ‘prolonged’ periods of time within a restricted sea area, enough time to accumulate a (on average) characteristic level of litter in the stomach. Of course if storm-driven winter movements or synchronous returns to colonies are followed by sudden mortality, stomach contents may incidentally not reflect local conditions. Such incidents may distort the occasional annual value, but not the average multi-year picture.

Concerning the aspect of stomach contents not always reflecting the ‘local’ situation, it is relevant to know how long it takes a fulmar to accumulate an amount of plastic characteristic for the foraging area. We have no way to determine this directly, but can make a rough assessment of time scales from the rate of disappearance of plastics from stomachs. Early publications indicated long residence times for plastics in seabird stomachs, Day et al. (1985) suggesting an average of 6 months or more for plastic particles to disappear through wear in the gizzard and subsequent passage through the gut, while Ryan and Jackson (1987) estimated a half-life of at least one year for plastic granules in the stomachs of White-chinned Petrels *Procellaria aequinoctialis*. However, these are probably serious overestimates. van Franeker and Bell (1988) observed that Cape Petrels *Daption capense* returning to clean Antarctic waters after wintering in northern, more polluted environments lost 80–90% of plastics from their stomachs in just over a month. As described in the Online supplement, disappearance rates for squid beaks in several species of Antarctic fulmarine petrels (van Franeker et al., 2001) and datasets on plastics in high Arctic Canadian fulmars (Mallory, 2008) and thick-billed murres *Uria lomvia* (Provencher et al., 2010) accord with such rapid rates of disappearance. From these data, disappearance rates of plastics from stomachs can be conservatively estimated at over 75% per month. In the North Sea, where soft foamed and sheet-like plastics are commonly ingested, disappearance may be considerably faster, and it is reasonable to assume that fulmars lose or accumulate characteristic local pollution levels within time frames of at most a very few weeks or even a number of days.

The main purpose of this paper was to provide insight into the reliability of the Fulmar EcoQO approach as a scientific instrument for policy decisions concerning marine litter. Nevertheless, major conclusions on trends, regional patterns, sources of litter and potential meaning for policy decisions should be discussed here too.

Within the Dutch time series, the pattern of plastic litter, peaking in the 1990s followed by a sharp downward trend back to earlier levels, appears dominated by a high figure for 1997 (Fig. 4). Nevertheless if in the standard 10-year analysis (1997–2006 decrease $p < 0.001$) all 1997 data are left out, the trend remains significant (1998–2006 decrease $p = 0.003$). In arithmetic annual averages for mass of plastics (Supplement Table 1) the value for the large 1998 sample exceeds that for 1997, indicating that the pattern is not caused by a single odd year.

The most remarkable change in the long term dataset concerns the reduced pollution by industrial plastic, unfortunately compensated for by an increase in user plastic debris (Fig. 2.). This phenomenon was previously documented by van Franeker and Meijboom (2002) and has also been observed in the north Pacific (Vlietstra and Parga, 2002), and in the south Atlantic and southwest

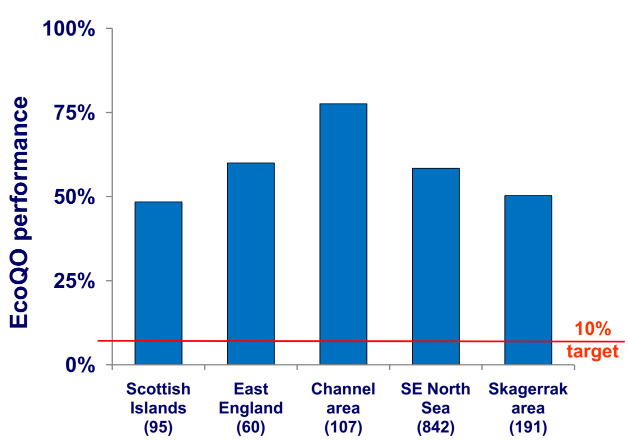

Fig. 3. EcoQO performance in North Sea regions 2003–2007 – Percentages of beached fulmars having more than 0.1 g of plastic in the stomach over the 2003–2007 5-year period in different regions around the North Sea.

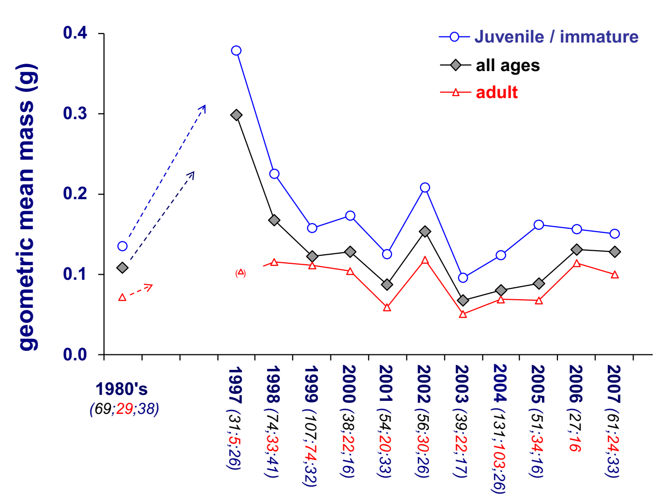

Fig. 4. Annual geometric means for mass of plastics in stomachs of beached fulmars from the Netherlands 1982–2007 for all age groups combined (including birds of unknown age), adult birds and non-adults, with sample sizes (all ages; adults; non-adults) in brackets in the *x*-axis labels. Data-points are shown for sample sizes of 10 stomachs or more.

Indian Ocean (Ryan, 2008). The economic value of raw industrial plastic may have been an incentive to reduce losses from industrial processing plants and during transport. Increased container transport as well as improved waste water treatment will have reduced loss of granules to the environment. Unfortunately, economic incentives are largely lacking as a stimulus to reduce the discarding of consumer plastics. Consequently, the current overall plastic pollution level may be similar to that in the 1980s, but its composition and origin have changed markedly. Such findings stress the importance of recording subcategories of plastics, even if the EcoQO considers all plastics together.

Being aware of the role of shipping, the European Commission decided that global rules for ships in MARPOL Annex V were insufficiently effective, and introduced a Directive to enhance proper waste disposal at harbors (EC, 2000). In the Netherlands, the fulmar monitoring has been financed as a tool to evaluate the effectiveness of this Directive after its implementation in 2004. As yet, fulmar data from the Netherlands show no significant improvements in the marine litter situation in the North Sea since implementation of the Directive, a finding corroborated by the OSPAR Beach Litter Surveys (OSPAR, 2010a). An evaluation of the effectiveness of the Directive should, however, take into account increases in shipping traffic and in the proportion of plastics in wastes.

The EcoQO target for 'acceptable ecological quality' has been defined by OSPAR as the situation where less than 10% of fulmars carry more than 0.1 g of plastic (OSPAR, 2008). In the North Sea, currently 58% (48–78% depending on area) of fulmars exceed this level (Table 2). The considerable gap between the current situation and the target is of concern and raises the question of whether the EcoQO target is realistic, even in the long term (no target date was set by OSPAR). The Save the North Sea study has used stomachs of fulmars from the Faroe Islands as an outside reference; currently 44% of Faroe birds exceed the critical level of 0.1 g of plastic (Fig. 5 and details in Online supplement). At present, the EcoQO target is only approached by fulmars in the eastern Canadian Arctic, where data suggest regional averages of 40% incidence, 2.5 particles and 0.03 g per bird, and 14% of birds exceeding 0.1 g of plastic in the stomach (Mallory et al., 2006; Mallory, 2008; Provencher et al., 2009). The true local pollution level is probably lower, because some birds were sampled early in the breeding season and probably contained plastics from wintering areas further south (see Discussion on disappearance rates in Online supplement).

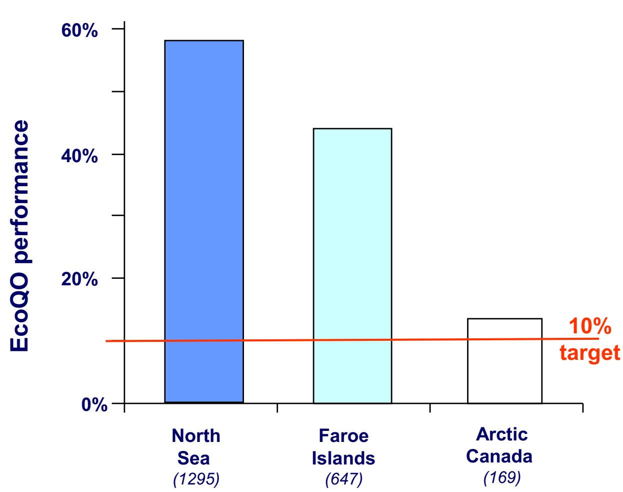

Fig. 5. EcoQO performance in North Sea 2003–2007 and reference areas in relation to the OSPAR EcoQO target. Canadian data calculated from Mallory et al. (2006), Mallory, (2008), Provencher et al. (2009) and personal information from these authors.

Increased pollutant loads have been observed in soils below high arctic breeding colonies of fulmars (Choy et al., 2010), in which a contribution from excrement containing digested plastics seems a reasonable assumption. The long term OSPAR EcoQO target for the North Sea can be seen as realistic, because the target level already exists in relatively clean areas of the North Atlantic.

The EcoQO approach for the North Sea has also been adopted as an indicator for Good Environmental Status (GES) in the European Marine Strategy Framework Directive (MSFD) (EC, 2008; Galgani et al., 2010; EC, 2010). In some European marine areas the Fulmar EcoQO is directly applicable, although copying the undated OSPAR target to the MSFD date of 2020 could be considered too ambitious. If so, an alternative target such as a 'significant' or 'fixed percentage' decrease could be formulated for the short-term. Fulmars do not inhabit all the regions covered by the MSFD and feasibility studies of plastic ingestion by other seabird species, marine mammals, sea-turtles, fish or invertebrates will be needed to establish a Europe-wide monitoring system for the impacts of marine litter.

Marine organisms like the fulmar continuously integrate litter levels in their environment in a way that is virtually impossible to replicate by direct physical measurements (Ryan et al., 2009). EcoQO trends (Fig. 1) and patterns (Fig. 3) provide policy makers with a statistically robust basis for urgently needed management decisions aiming at improving the quality of European marine environments.

Acknowledgements

Fulmar monitoring in the Netherlands is supported financially by the Netherlands Ministry of Infrastructure and the Environment. The international part of the study developed during the Save the North Sea campaign 2002–2004, which was co-funded by the EU Interreg IIIB program for the North Sea. The idea of an EcoQO based on the abundance of plastics in seabird stomachs was initiated by the ICES Working Group on Seabird Ecology and guided in several workgroups within ICES and OSPAR. Continuation of the international fulmar work up to the analyses of data from 2007 was supported by the NYK Group Europe Ltd. Preliminary data from the Faroe Islands in this report were derived from an ongoing diet and litter study funded by Chevron Upstream Europe, supported in the field by Poul-Johannes Simonsen. Mark Mallory and Jennifer Provencher provided unpublished details of their Canadian data. Geert Aarts advised on statistics for regional differences.

Beached fulmars are mainly collected by volunteers, too many to be named individually, but without whom a project such as this would have been impossible. This publication is therefore dedicated to all our helpers around the North Sea.

Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.envpol.2011.06.008.

References

Ainley, D.G., Fraser, W.R., Spear, L.B., 1990. The Incidence of Plastic in the Diets of Antarctic Seabirds. NOAA Technical Memo. NMFS. NOAA-TM-NMFS-SWFSC-154: 682–691.

NOAA Technical Memorandum NOS-OR&R-30. In: Arthur, C., Baker, J., Bamford, H. (Eds.), Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. Sep 9–11, 2008. NOAA, Silver Spring, 530 pp.

Baltz, D.M., Morejohn, G.V., 1976. Evidence from seabirds of plastic pollution off central California. Western Birds 7, 111–112.

Blight, L.K., Burger, A.E., 1997. Occurrence of plastic particles in seabirds from the eastern North Pacific. Marine Pollution Bulletin 34, 232–325.

Bourne, W.R.P., 1976. Seabirds and pollution. In: Johnston, R. (Ed.), Marine Pollution. Academic Press, London, pp. 403–502.

Browne, M.A., Sissanayake, A., Galloway, T.S., Lowe, D.M., Thompson, R.C., 2008. Ingested microscopic plastic translocates to the circulatory system of the Mussel, *Mytilus edulis* (L.). Environmental Science and Technology 42, 5026–5031.

Choy, E.S., Krimpe, L.E., Mallory, M.L., Smol, J.P., Blais, J.M., 2010. Contamination of an arctic terrestrial food web with marine-derived persistent organic pollutants transported by breeding seabirds. Environmental Pollution 158, 3431–3438.

Day, R.H., Wehle, D.H.S., Coleman, F.C., 1985. Ingestion of plastic pollutants by marine birds. in: R.S. Shomura and H.O. Yoshida (Eds.), Proceedings of the Workshop on the Fate and Impact of Marine Debris, 26–29 November 1984, Honolulu, Hawaii. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-54. pp. 344–386.

Del Hoyo, J., Elliott, A., Sargatal, J. (Eds.), 1992. Handbook of the Birds of the World. Vol. 1 (Ostrich to Ducks). Lynx Editions, Barcelona.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44, 842–852.

EC, 28 Dec 2000. Directive 2000/59/EC of the European Parliament and of the Council of 27 November 2000 on port reception facilities for ship-generated waste and cargo residues. Official Journal of the European Communities L 332, 81–90.

EC, 25 Jun 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Official Journal of the European Union L 164, 19–40.

EC, 2010. Commission decision of 1 September 2010 on criteria and methodological standards on Good environmental status of marine waters (notified under document C(2010) 5956) (Text with EEA Relevance) (2010/477/EU). Official Journal of the European Union L 232, 14–24.

Endo, S., Takizawa, R., Okuda, K., Takada, H., Chiba, K., Kanehiro, H., Ogi, H., Yamashita, R., Date, T., 2005. Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: variability among individual particles and regional differences. Marine Pollution Bulletin 50, 1103–1114.

Furness, R.W., 1985. Plastic particle pollution: accumulation by Procellariiform seabirds at Scottish colonies. Marine Pollution Bulletin 16, 103–106.

Galgani, F., Fleet, D., van Franeker, J., Katsanevakis, S., Mouat, J., Oosterbaan, L., Poitou, I., Hanke, G., Thompson, R., Amato, E., Birkun, A., Janssen, C., 2010. Properties and quantities of marine litter do not cause harm to the coastal and marine environment. Report on the identification of descriptors for the good environmental status of European seas regarding marine litter under the marine Strategy framework Directive. MSFD GES Task Group 10, final report 19/04/2010, 50 pp.

Graham, E.R., Thompson, J.T., 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. Journal of Experimental Marine Biology and Ecology 368, 22–29.

Hale, S.E., Martin, T.J., Goss, K.U., Arp, H.P.H., Werner, D., 2010. Partitioning of organochlorine pesticides from water to polyethylene passive samplers. Environmental Pollution 158, 2511–2517.

Hall, K., 2000. Impacts of Marine Debris and Oil: Economic and Social Costs to Coastal Communities. KIMO, c/o Shetland Islands Council, Lerwick, 104 pp.

Hatch, S.A., Nettleship, D.N., 1998, No. 361 (31 pp.). In: Poole, A., Gill, F. (Eds.), Northern Fulmar (*Fulmarus glacialis*). The Birds of North America, Inc., Philadelphia, P.A.

ICES-WGSE 2001. Report of the working group on seabird ecology. Ices Headquarters, 16–19 March 2001. ICES CM 2001/C:05. Copenhagen. 68pp.

Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Marine Pollution Bulletin 18, 319–326.

Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris Sources, Impacts and Solutions. Springer Series on Environmental Management. Springer Verlag, New York, pp. 99–140, 432 pp.

Lozano, R.L., Mouat, J., 2009. Marine Litter in the North-East Atlantic Region, Assessment and Priorities for Response. OSPAR/KIMO/UNEP. Biological Diversity and Ecosystems Nr 386. OSPAR, London, 127 pp.

MEPC, 2009. Interpretations of and amendments to MARPOL and related instruments. Report of the Correspondence group for the review of MARPOL Annex V. Submitted by Canada. Marine environment protection Committee MEPC 59/6/3. 11 pp. + 4 annexes.

Mallory, M.L., 2008. Marine plastic debris in northern fulmars from the Canadian high Arctic. Marine Pollution Bulletin 56, 1486–1512.

Mallory, M.L., Roberston, G.J., Moenting, A., 2006. Marine plastic debris in northern fulmars from Davis Strait, Nunavut, Canada. Marine Pollution Bulletin 52, 813–815.

Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environmental Research 108, 131–139.

Moser, M.L., Lee, D.S., 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colonial Waterbirds 15, 83–94.

Mouat, J., Lozano, R.L., Bateson, H., September 2010. Economic Impacts of Marine Litter. KIMO Report. KIMO, Shetland, 105 pp.

North Sea Ministerial Conference, Bergen Declaration. Ministerial Declaration of the Fifth International Conference on the Protection of the North Sea. Bergen, Norway, 20–21 March 2002. NSMC Secretariat, Bergen. 50 pp.

OSPAR, 2008. Background Document for the EcoQO on Plastic Particles in Stomachs of Seabirds. OSPAR Commission, Biodiversity Series Publication Number: 355/2008. OSPAR, London, 18 pp.

OSPAR, 2010a. Quality Status Report 2010. OSPAR Commission, London, 175 pp.

OSPAR, 2010b. The OSPAR System of Ecological Quality Objectives for the North Sea: a Contribution to OSPAR's Quality Status Report 2010. OSPAR Publication 404/2009. OSPAR Commission London, en Rijkswaterstaat VenW, Rijswijk, 16 pp. (Update, 2010).

Provencher, J.F., Gaston, A.J., Mallory, M.L., 2009. Evidence for increased ingestion of plastics by northern fulmars (*Fulmarus glacialis*) in the Canadian Arctic. Marine Pollution Bulletin 58, 1092–1095.

Provencher, J.F., Gaston, A.J., Mallory, M.L., O'Hara, P.D., Gilchrist, H.G., 2010. Ingested plastic in a diving seabird, the thick-billed murre (*Uria lomvia*), in the eastern Canadian Arctic. Marine Pollution Bulletin 60, 1406–1411.

Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific. Marine Pollution Bulletin 30, 151–157.

Ryan, P.G., 2008. Seabirds indicate changes in the composition of plastic litter in the Atlantic and south-western Indian Oceans. Marine Pollution Bulletin 56, 1406–1409.

Ryan, P.G., Jackson, S., 1987. The lifespan of ingested plastic particles in seabirds and their effect on digestive efficiency. Marine Pollution Bulletin 18, 217–219.

Ryan, P.G., Moore, C.J., Van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B 364, 1999–2012.

Save the North Sea, 2004. Reduce Marine Litter: 'Save the North Sea' Project Results. Keep Sweden Tidy Foundation, Stockholm, 17 pp.

Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., 2007. Potential for plastics to transport hydrophobic contaminants. Environmental Science and Technology 41, 7759–7764.

Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, U., Imamura, A., Saha, M., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B 364, 2027–2045.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304 (5672), 838.

Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H. (Eds.), 2009. Plastics, the Environment and Human Health. Philosophical Transactions of the Royal Society B Vol. 364 (nr 1526 Theme Issue) Pages 1969–2166.

Van Franeker, J.A., 1985. Plastic ingestion in the North Atlantic fulmar. Marine Pollution Bulletin 16, 367–369.

Van Franeker, J.A., 2004. Save the North Sea – Fulmar Study Manual 1: Collection and Dissection Procedures. Alterra Rapport 672. Alterra, Wageningen, 38 pp.

Van Franeker, J.A., 2005. Schoon Strand Texel 2005: Onderzoeksresultaten van de Schoonmaakactie van het Texelse Strand op 20 april 2005. Alterra Speciale Uitgave 2005/09. Alterra, Texel, 23 pp.

Van Franeker, J.A., the SNS Fulmar Study Group, 2008. Fulmar Litter EcoQO Monitoring in the North Sea – Results to 2006. IMARES report nr C033/08. Wageningen IMARES, Texel, 53 pp.

Van Franeker, J.A., Bell, P.J., 1988. Plastic ingestion by petrels breeding in Antarctica. Marine Pollution Bulletin 19, 672–674.

Van Franeker, J.A., Meijboom, A., 2002. Litter NSV – Marine Litter Monitoring by Northern Fulmars: a Pilot Study. ALTERRA-Rapport 401. Alterra, Wageningen, 72 pp.

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 (58 pp.) in: J.A. van Franeker, Mirrors in Ice. PhD-Thesis, University of Groningen. Alterra, Texel.

Van Franeker, J.A., Heubeck, M., Fairclough, K., Turner, D.M., Grantham, M., Stienen, E.W.M., Guse, N., Pedersen, J., Olsen, K.O., Andersson, P.J., Olsen, B., 2005. 'Save the North Sea' Fulmar Study 2002–2004: A Regional Pilot Project for the Fulmar-Litter-EcoQO in the OSPAR Area. Alterra-rapport 1162. Alterra, Wageningen, 70 pp.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S, fourth ed. Springer, New York, 503 pp.

Vlietstra, L.S., Parga, J.A., 2002. Long-term changes in the type, but not the amount, of ingested plastic particles in short-tailed shearwaters in the southeastern Bering sea. Marine Pollution Bulletin 44, 945–955.