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Northern fulmars as biological monitors of trends of plastic pollution in the eastern North Pacific

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ABSTRACT

Marine plastic debris is a global issue, which highlights the need for internationally standardized methods of monitoring plastic pollution. The stomach contents of beached northern fulmar (*Fulmarus glacialis*) have proven a cost-effective biomonitor in Europe. However, recent information on northern fulmar plastic ingestion is lacking in the North Pacific. We quantified the stomach contents of 67 fulmars from beaches in the eastern North Pacific in 2009–2010 and found that 92.5% of fulmars had ingested an average of 36.8 pieces, or 0.385 g of plastic. Plastic ingestion in these fulmars is among the highest recorded globally. Compared to earlier studies in the North Pacific, our findings indicate an increase in plastic ingestion over the past 40 years. This study substantiates the use of northern fulmar as biomonitors of plastic pollution in the North Pacific and suggests that the high levels of plastic pollution in this region warrant further monitoring.

1. Introduction

Since the 1950s, plastic production rates and input of plastic into the marine environment have increased dramatically and plastic is now recognized globally as a major form of marine pollution (Barnes et al., 2009; Moore, 2008; PlasticsEurope, 2010). Marine plastic pollution has significant environmental, economic, cultural, and aesthetic costs (see UNEP, 2009 for review). Of particular concern is the detrimental impact of plastic pollution on marine animals via entanglement or ingestion (Derraik, 2002; Gregory, 2009). Plastic ingestion can result in direct mortality or a range of sub-lethal effects such as gastrointestinal blockage, lacerations, reduced feeding (Laist, 1987; Ryan, 1988; Sievert and Sileo, 1993; Azzarello and Van Vleet, 1987), or absorption of toxic compounds (Mato et al., 2001; Teuten et al., 2009). Although population level impacts of plastic entanglement and ingestion on marine taxa are not yet fully understood, to date over 260 species (including invertebrates, turtles, fish, seabirds and mammals) have been reported to ingest or become entangled in plastic debris (Boerger et al., 2010; Laist, 1997).

Plastic pollution is so pervasive that it is now found in every ocean of the world, including those formerly thought of as pristine, such as the Arctic Ocean and Southern Ocean (Provencher et al., 2010; Ainley et al., 1990). In 2009, the UNEP challenged the global community to improve methods to monitor trends in plastic pollution (UNEP, 2009). Although many countries have documented plastic debris in the marine environment, no standard technique has been used, and the lack of consistent methodology has made it difficult to monitor trends or to compare plastic pollution between different regions of the world (Ryan et al., 2009). This highlights the need for a reliable, internationally standardized method of monitoring trends in plastic pollution. One such method, which has been implemented with success in the historically polluted, industrial North Sea, uses mass of plastic ingested by beached northern fulmars (*Fulmarus glacialis glacialis*) as an indicator for tracking temporal and geographical trends in the abundance and composition of small-sized plastic pollution (van Franeker and Meijboom, 2002; van Franeker et al., 2011).

Northern fulmars are procellariid seabirds belonging to three subspecies (*Fulmarus glacialis rodgersii*, *F. g. glacialis*, *Fulmarus glacialis auduboni*), each with distinct breeding locations and vast migratory ranges in the Northern Pacific, High Arctic and Northern Atlantic (Hatch and Nettleship, 1998). Northern fulmars are particularly suitable as biomonitors of trends in plastic pollution because, like many petrels, they forage exclusively at

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sea, have vast migratory ranges and a non-selective surface foraging ecology that makes them prone to ingest plastic (van Franeker and Meijboom, 2002). Northern fulmars are also suitable because they have a tendency only to regurgitate indigestible items such as plastic when they are feeding chicks (Ryan, 1988), and so the retention time for ingested plastics in the non-breeding season is in the order of weeks to months (Ryan and Jackson, 1987; van Franeker et al., 2011). As a result, the stomach content of a single northern fulmar provides a quantitative 'snapshot' sample of small-sized plastic pollution from a large offshore area (100s of km^2). Finally, although age and breeding status may bias the amounts of ingested plastic in this species, the condition, cause of death, and sex have not been found to affect the amount of plastic ingested in beached birds (van Franeker and Meijboom, 2002; van Franeker et al., 2005) which means that beached northern fulmar are an ideal biomonitor for plastic pollution in coastal areas where they are prone to washing up on beaches in sufficient numbers ($n > 40$, van Franeker and Meijboom, 2002). Where northern fulmars are not available, other petrel species may be suitable, as many of the key characteristics are common to other procellariids.

In the present study we document plastic ingestion in beached northern fulmar (*F. g. rodgersii*) from the eastern North Pacific, a region that is lacking current baseline data. We compare our results to levels of plastic ingestion for northern fulmar previously documented globally, report our findings in comparison to the North Sea Ecological Quality Objective (EcoQO) for marine litter, and show how beached fulmars may be used to monitor of trends in plastic pollution in the North Pacific.

2. Methods

2.1. Study area and specimen collection

The eastern North Pacific is characterized by three major oceanographic regimes: the Gulf of Alaska Gyre in the north, the California Current System in the south, and a Transition zone between the two, which extends roughly from northern Vancouver Island to mid-northern Washington (described by Favorite et al., 1976). From October 2009 to April 2010 a total of 67 fresh, beached northern fulmar carcasses were collected. Thirty-six fulmar were collected on the west coast of Vancouver Island, British Columbia (BC), Canada (49°03′26.17″N, 125°43′56.90″W; Fig. 1). Thirty-one fulmars were collected from beaches in the United States of America; five from Grayland Beach and Long Beach in southern Washington (46°47′4.21″N, 124°5′48.40″W), and 26 from beaches in Clatsop County, northern Oregon (46°5′32.00″N, 123°56′21.26″W). The stomach contents of beached fulmars collected in southwestern BC are considered indicative of plastic pollution in the northern Transition Zone and southern Gulf of Alaska Gyre, whereas fulmars collected in northwestern USA are considered representative of plastic pollution found in the southern Transition Zone and northern California Current System

2.2. Quantification of plastic ingestion

Necropsies were conducted to determine cause of death, sex, and age. Age was determined based on the presence or absence of the bursa; a primary immune organ that atrophies away once sexual maturity is reached. Fulmars with a bursa present were classified as juveniles, and those without bursa were classified as adults. Stomachs were removed and the contents were analyzed and quantified according to the protocol as described by van Franeker (2004). Briefly, the proventriculus and gizzard of each bird was opened along their length and the contents were flushed out over a 0.5 mm sieve. Plastic items were separated from prey items before being dried. The incidence (i.e., proportion of sample fulmars to ingest plastic) was recorded, and plastic contents were weighed using an analytical scale (accurate to 0.0001 g). Individual plastic items were counted and categorized as user plastic (e.g., fragments, sheets, rubber, sponge, balls of plastic fibers, Styrofoam) or industrial plastic (small symmetrical virgin plastic pellets, or 'nurdles').

2.3. Statistical analyses

Regions were defined as British Columbia (BC), representing the southern Gulf of Alaska Gyre and the Transition Zone, and Washington/Oregon combined (WA/OR), representing the Transition Zone and the northern California Current System. Differences in incidence and number of plastic pieces found in the fulmars were tested between sex, age and region, using Generalized Linear Models (GLiMs) with Maximum Likelihood to estimate the variance components. Variation in incidence was modeled using "Proc Genmod," with a negative binomial distribution link-function that best fit our over-dispersed data. Age- and region-specific variation in the number of industrial plastic pieces relative to total number of plastic pieces (=industrial plus user plastic pieces) per individual was tested using "Proc Genmod" with a logit link function for binomial data. Post-hoc comparisons of fixed effects within this model were tested using LSMEANS statements, and results of these comparisons are presented with χ^2-values, degrees of freedom, and *p*-values. Differences in plastic load (mass) between sex, age and region were tested using an ANOVA ("Proc GLM"). All analyses were based on data pooled over sex, as there was no significant variation for any of the response variables with sex (male, female, unknown). Statistical analyses were carried out using SAS V. 9.2 (2008), *p*-values of less than 0.05 are considered significant. The EcoQO was calculated as the percentage of northern fulmars found to have ingested $\geqslant 0.1$ g of plastic.

3. Results

Necropsy revealed that all of the fulmars were in poor general body condition based on significant reduction in pectoral muscle mass and fat reserves. The immediate cause of death was drowning (heavy wet lungs and frothy fluid in terminal airways). Traumatic injury was ruled out. The sex ratio was 32 males: 33 females: 2 fulmars of unknown sex. The age ratio was 24 adults: 33 juveniles: 10 fulmars of unknown age. For the pooled study regions, plastic was found in the stomachs of 92.5% of northern fulmars. The average number of plastic ingested by fulmars was 36.8 ± 9.8 SE pieces per bird (range 0–454 pieces), and the average mass was 0.385 ± 0.087 SE g (range 0–3.656 g; see Table 1 for regional data). Incidence rates did not vary significantly between sample regions, between adult and juvenile or for data pooled between regions and there were no significant interactions. The number of plastic pieces per fulmar was significantly higher in BC ($\chi^2_{1,54} = 12.7$, $p = 0.0004$), compared to WA/OR. The number of plastic pieces per individual was higher in juvenile fulmars ($\chi^2_{1,24} = 3.81$, $p = 0.0095$) than in adults controlling for regional variation in numbers per individual. The mass of plastic ingested by fulmars did not differ significantly between regions. Overall, 54% of all fulmars sampled were found to have exceeded the EcoQO target, having ingested >0.1 g of plastic.

For the pooled study area, 95.7% of ingested plastic pieces ($N = 2326$) were user plastics such as twine, rope, fishing line, Styrofoam, hard pieces of discarded plastic such as bottle caps, fiber sponge and candy wrapper (i.e. sheet plastic). The remaining 4.3% ($N = 107$) of plastic pieces were industrial pre-production pellets. The proportion of industrial plastic pieces varied significantly

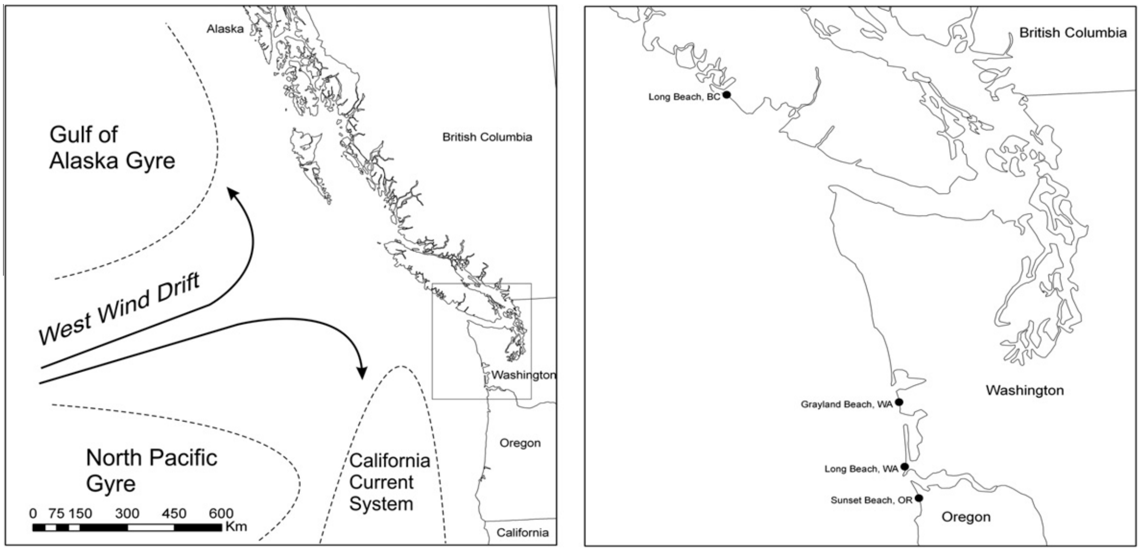

Fig. 1. Large-scale oceanographic currents (left panel) associated with study sites (right panel). The "Transition Zone" occurs where the west wind current splits off into the Gulf of Alaska Gyre to the north and the California current system to the south (as per Favorite et al., 1976). The Transition Zone tends to shift north during the summer and south during the winter.

Table 1
Incidence, mass of plastic and number of particles in stomachs of fulmars beached in the eastern North Pacific (regions combined) and for each of the regions from which fulmars were recovered (BC fulmars and USA fulmars: WA & OR fulmars combined) from October 2009 to April 2010. Number data is also shown as the percentage of user and industry plastics, and mass data as the percentage of stomachs with more than 0.1 g of plastic (EcoQO performance; OSPAR, 2008).

Location (*n*)	Incidence (%)	Average mass *g* ± se	Average number *n* ± se	Proportion of plastic pieces		% Over 0.1 g (EcoQO target)
				User plastic (%)	Industry plastic (%)	
Eastern North Pacific (67)	92.5	0.385 ± 0.087	36.8 ± 9.8	95.7	4.3	54
British Columbia, Canada (36)	97.2	0.354 ± 0.087	52.9 ± 17.2	96.7	3.3	61
Washington & Oregon, USA (31)	87.1	0.326 ± 0.126	18.1 ± 5.5	92.1	7.86	45

between age categories ($\chi^2_{1,48}$ = 12.0, p = 0.0005), however this variation was not consistent between regions. In BC, adults had ingested a smaller proportion of industrial plastics than juveniles (χ^2 = 14.3, df = 1, p = 0.0002), and there was no difference found between adults and juveniles in the WA/OR fulmars. Comparing regions, both adult and juvenile northern fulmar in BC had lower proportions of industrial plastic than northern fulmar in WA/OR (χ^2 = 19.2, df = 1, $p < 0.0001$; χ^2 = 4.12, df = 1, p = 0.042, respectively).

4. Discussion

4.1. Global comparisons of plastic ingestion

Despite the close proximity to the North Pacific Central Gyre, which has garnered significant attention for its high levels of plastic pollution over the past decade (Moore et al., 2001; Ingraham and Ebbesmeyer, 2001; Boerger et al., 2010), plastic pollution in the eastern North Pacific has not been considered an issue of concern. We found that the proportion of fulmars found to ingest plastic (92.5%), and the mass of plastic ingested in the present study (0.385 ± 0.087 SE g), are comparable to what has recently been reported for fulmars collected in the heavily industrialized and polluted North Sea (95%, 0.28 ± 0.02 g; van Franeker et al., 2011). According to our findings, fulmars from the eastern North Pacific have higher plastic loads than most other regions, including the Canadian Arctic (Mallory et al., 2006; Mallory, 2008; Provencher et al., 2009), and the Atlantic Ocean (Moser and Lee, 1992; Table 2). However, comparisons of our results with other studies must be made cautiously because sample differences, such as the proportion of juveniles or the breeding status of adults, can influence plastic load (Ryan, 1988; Spear et al., 1995). This highlights the need for an international consensus on standardized methods, which will facilitate temporal and regional comparisons.

In the North Sea, the mass of plastic in beached fulmar stomachs is monitored and compared against the EcoQO target for marine litter, which represents an ecologically clean and healthy North Sea. The EcoQO target is defined as "*... less than 10% of northern fulmars having 0.1 g or more plastic in the stomach in samples of 50–100 beached fulmars...*," and is used to monitor trends in plastic pollution and monitor the success of policy measures to reduce marine litter (OSPAR, 2008). In the North Sea, 58% of the fulmars sampled from 2003 to 2007 exceeded 0.1 g of ingested plastic (Fig. 2; van Franeker et al., 2011). If we apply this target to the eastern North Pacific, 54% of fulmars ingested >0.1 g of plastic, exceeding the North Sea EcoQO target of 10% by a wide margin. This provides further evidence that plastic ingestion in northern fulmars from the eastern North Pacific is high, and may be approaching the levels documented in fulmars from the North Sea. We believe that the high levels of plastic ingestion observed in the present study indicate concomitant plastic pollution off the southwestern coast of Canada and the northwestern coast of the USA. This is consistent with findings by Williams et al. (2011) who estimated high densities of floating plastic based on visual surveys during ship-based transects from southern British Columbia to Hecate Strait, north of Vancouver Island.

4.2. Spatial and temporal trends of plastic pollution in the North Pacific

Within the eastern North Pacific, we did not find any significant differences in the incidence of plastic ingestion or the mass of ingested plastic between fulmars from BC, which represent the southern Alaska Gyre and Transition Zone, and fulmars from

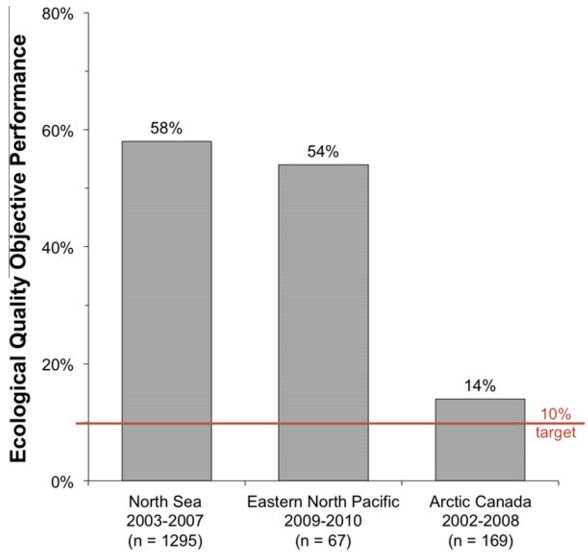

Fig. 2. Comparison of the Ecological Quality Objective performance (% of fulmars found to ingest >0.1 g of plastic) in relation to the 10% OSPAR North Sea target for fulmars from the North Sea (van Franeker et al., 2011), eastern North Pacific, and Canadian Arctic (Mallory et al., 2006; Mallory, 2008; Provencher et al., 2009 and additional information from these authors cited in van Franker et al., 2011.).

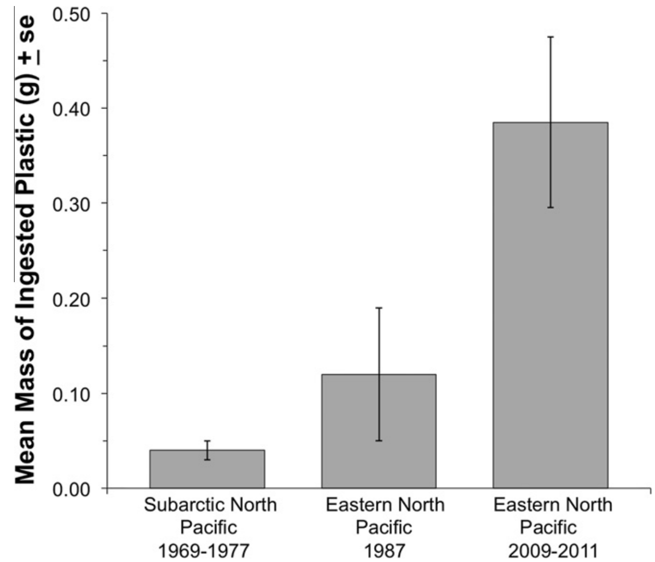

Fig. 3. Increasing trend in the mean mass of ingested plastics found in the digestive tracts of northern fulmar for eastern North Pacific in 2009–2010 ($N = 67$; current study), compared to earlier published findings in the eastern North Pacific ($N = 3$; Blight and Burger, 1997) and in the subarctic North Pacific ($N = 38$; Day, 1980).

Washington and Oregon, which represent the Northern California Current System and Transition Zone. The absence of a regional difference in incidence and mass is likely due to the small sample sizes, long retention time of plastics and to the vast migratory ranges of these fulmars which breed in the subarctic North Pacific, and migrate south along the continental shelf to Baja California. However, the number of plastic pieces ingested was significantly higher in fulmars recovered from BC waters, which may be driven by the fact that a few fulmars had a high proportion of Styrofoam in their digestive tracts, which tends to break down into many small pieces relatively quickly. For this reason it has been proposed that the interpretation of data and statistical analysis should be based on incidence and mass of plastic, rather than the number of pieces (van Franeker and Meijboom, 2002; OSPAR, 2008). We adhered to this standard and, finding no significant differences in the incidence or mass of plastic ingestion between regions, we discuss our findings with regards to the eastern North Pacific.

Plastic ingestion in northern fulmar was first investigated by Day (1980), at breeding colonies south of the Alaska Peninsula, who reported that 57.9% of fulmar collected between 1969 and 1977 had ingested plastic. This effort was repeated in 1988–1989 by Robards et al. (1995) who documented a 26.3% increase in the incidence of plastic ingestion among fulmars over the 11-year period. Our 2009–2010 study shows that the incidence of plastic ingestion among northern fulmars from the same breeding populations (Hatch et al., 2010) is 92.5%, which is an 8% increase beyond the most recent report in 1989, or a total increase of 34% over the past four decades (Table 2). We also find that the mass of ingested plastic has increased dramatically from 0.04 g in 1969–1977 ($n = 38$, Day, 1980), to 0.12 g in 1987 ($n = 3$, Blight and Burger *unpublished*) to 0.385 g in 2009–2010 ($n = 67$, Table 2, Fig. 3). As previously mentioned, conclusions about the magnitude of increase in plastic ingestion based on comparisons with these earlier studies must be made with caution. Nevertheless, our results provide strong evidence that there has been an increase in plastic ingestion by fulmar over the past 40 years in the North Pacific, which probably reflects an increase in the amount of plastic pollution in this region.

In addition to the increase in incidence and amount of plastic ingested by fulmars, our results indicate a shift in the type of plastic consumed, from predominantly industry plastics to predominantly user plastics (Fig. 4). For example, Robards et al. (1995) reported that 35% of ingested plastics in fulmars from 1988 to 1989 were industrial plastics and 65% were user plastics. In contrast, we found that 96% of ingested plastics were user plastics and only 4% were industrial plastics, suggesting a change in the proportion of industrial plastics in the marine environment. A similar decrease in the proportion of industrial plastics has been reported for procellariid species from the South Atlantic Ocean (Ryan, 2008), the North Pacific (Vlietstra and Parga, 2002) and for northern fulmars in the North Sea (van Franeker et al., 2005). This shift in the type of plastic consumed may be explained by a combination of factors,

Table 2
Incidence and mass of plastic ingested by northern fulmars, as reported by various studies in the Pacific, Arctic and Atlantic Oceans.

Region	Pacific				Arctic			Atlantic	
	Eastern North Pacific[a]	Eastern North Pacific[b]	Subarctic North Pacific[c]	Subarctic North Pacific[d]	Arctic[e] (Davis Strait)	High Arctic[f]	Arctic[g]	North Atlantic[h]	North sea[i]
N	67	3	38	19	102	25	25	42	1295
Year	2009–2010	1987	1969–1977	1988–1989	2002	2003–2004	2008	1975–1989	2003–2007
Incidence	92%	100%	58%	84%	36%	31%	87%	86%	95%
Mass (g) ± SE	0.385 ± 0.087	0.12 ± 0.07	0.04 ± 0.01	N/A	N/A	0.31 ± N/A	0.124 ± 0.162	2.12 ± N/A	0.28 ± 0.02

[a] Current study; [b] Blight and Burger (1997) including unpublished data; [c] Day (1980); [d] Robards et al. (1995); [e] Mallory et al. (2006); [f] Mallory (2008); [g] Provencher et al. (2009); [h] Moser and Lee (1992); [i] van Franeker et al. (2011).

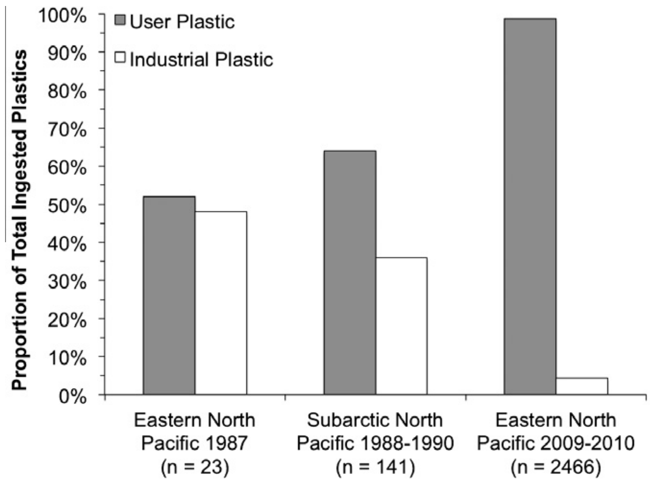

Fig. 4. Shift in relative abundance of user plastic and industry plastic found in the digestive tracts of northern fulmar for eastern North Pacific (67 fulmars, 2326 pieces; current study), compared to earlier published findings in the eastern North Pacific (3 fulmars, 23 pieces; Blight and Burger, 1997), and subarctic North Pacific (19 fulmars, 141 pieces; Robards et al., 1995).

including fragmentation of user plastics into smaller and smaller pieces, an accumulation of user plastics over time, or due to a lower rate of input of industrial plastics into the marine environment (Thompson et al., 2004).

4.3. Plastic type and sources

The origin of plastic debris, the mechanism of entry, and the process by which plastics circulate through the marine environment are key issues to be considered for successful management of marine plastic pollution. Plastic pollution in the marine environment originates from a variety of sources at the local scale (e.g., waste discharges from ships; Horsman, 1982), the regional scale (e.g., waste discharges into rivers, storm drains and sewage systems; Ross et al., 1991), and the global scale (e.g., large-scale oceanic currents and gyres; Day et al., 1985). In convergent gyre systems such as the North Pacific Central Gyre, global "downstream effects" (Day et al., 1985) are likely to influence plastic input, since plastics discarded throughout the Pacific enter major oceanic currents that feed this gyre (Robards et al., 1995). Conversely, local and regional sources of plastic may play a more important role in determining the concentration of plastic pollution in the study area simply because the oceanography of the Gulf of Alaska Gyre and California Current System are divergent, or at least non-convergent, and do not concentrate debris the way convergent gyres do. Although the migratory patterns and over-wintering foraging areas of northern fulmars sampled here may overlap somewhat with convergent gyre systems, we believe that the plastic ingestion documented here is more representative of the divergent large-scale oceanographic systems that dominate in the regions where the beached fulmars for this study were collected. For this reason, local and regional sources of plastic, such as maritime traffic transiting the area and density of urban areas, probably play a more important role in plastic pollution in the eastern North Pacific. Further study will be necessary to fully understand pollution pathways, so that effective management strategies can be developed and implemented (Thompson et al., 2009).

4.4. Conclusions and perspectives

In the present study we have demonstrated the utility of northern fulmar as biomonitors of trends in the abundance and composition of plastic pollution in the North Pacific. We have established a robust baseline of plastic ingestion for northern fulmar from the eastern North Pacific and our results indicates that there has been an increase in the incidence and mass of plastic ingested over the past 40 years. The high levels of plastic ingestion in northern fulmar from the eastern North Pacific are approaching the levels reported for fulmar from the historically polluted North Sea, suggesting that similarly high levels of plastic pollution occur in both regions (van Franeker et al., 2011; Williams et al., 2011). The need for internationally standardized methods of monitoring plastic pollution has been recognized globally (UNEP, 2009). We propose that in the North Pacific, and other areas with significant and regular deposition of northern fulmars, a yearly monitoring program similar to that in the North Sea (van Franeker et al., 2005) could provide a cost-effective and standardized method of monitoring trends in plastic pollution.

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