Environmental Pollution 187 (2014) 124–129

Contents lists available at ScienceDirect

Environmental Pollution

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

Plastic ingestion by Flesh-footed Shearwaters (*Puffinus carneipes*): Implications for fledgling body condition and the accumulation of plastic-derived chemicals

Jennifer L. Lavers[a,*,1], Alexander L. Bond[b], Ian Hutton[c]

[a] *Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, Tasmania 7005, Australia*
[b] *Environment Canada, 11 Innovation Boulevard, Saskatoon, Saskatchewan S7N 3H5 Canada*
[c] *Lord Howe Island Museum, PO Box 157, Lord Howe Island, New South Wales 2898 Australia*

A R T I C L E I N F O

Article history:
Received 15 September 2013
Received in revised form
17 December 2013
Accepted 20 December 2013

Keywords:
Body condition
Flesh-footed Shearwater
Marine debris
Plastic ingestion
Trace metals

A B S T R A C T

To provide much needed quantitative data on the lethal and sublethal effects of plastic pollution on marine wildlife, we sampled breast feathers and stomach contents from Flesh-footed Shearwater (*Puffinus carneipes*) fledglings in eastern Australia. Birds with high levels of ingested plastic exhibited reduced body condition and increased contaminant load ($p < 0.05$). More than 60% of fledglings exceed international targets for plastic ingestion by seabirds, with 16% of fledglings failing these targets after a single feeding (range: 0.13–3.21 g of plastic/feeding). As top predators, seabirds are considered sentinels of the marine environment. The amount of plastic ingested and corresponding damage to Flesh-footed Shearwater fledglings is the highest reported for any marine vertebrate, suggesting the condition of the Australian marine environment is poor. These findings help explain the ongoing decline of this species and are worrying in light of increasing levels of plastic pollution in our oceans.

1. Introduction

Despite the implementation of strict international legislation aimed at reducing the amount of marine debris originating from ocean- and land-based sources (e.g., MARPOL Annex V), it continues to accumulate worldwide with an estimated 20 million new items entering the ocean each day (Barnes, 2005; Gregory, 2009). Ingestion of plastic debris by seabirds that presumably mistake it for food was first reported in Laysan Albatross (*Phoebastria immutabilis*) in the early 1960s (Kenyon and Kridler, 1969), though the report of part of a candle in a Wilson's Storm-petrel (*Oceanites oceanicus*) in 1838 is perhaps the first documented case of seabirds ingesting anthropogenic waste (Couch, 1838). By the mid-1990s more than 111 (35%) of the world's seabird species had been recorded with plastic in their stomachs (Laist, 1997). Since then, the number of seabird species recorded ingesting debris has continued to increase rapidly (Robards et al., 1995; van Franeker et al., 2011), and our understanding of species' susceptibility and the effects of plastic ingestion progresses each year (Avery-Gomm et al., 2013; CBD, 2012; Provencher et al., 2010). Within species, the proportion of the population affected has also been increasing, often to the point where all individuals contain some plastic (Carey, 2011; Hyrenbach et al., 2012).

The ingestion of plastic debris has been shown to negatively impact seabirds in a number of ways, including nutritional deprivation (i.e., starvation; Dickerman and Goelet, 1987; Pierce et al., 2004), reduced body mass (Auman et al., 1998; Ryan, 1987a; Sievert and Sileo, 1993; Spear et al., 1995), decreased fat deposition (Auman et al., 1998; Connors and Smith, 1982), and damage to or obstruction of the gut (e.g., ulcers; Pettit et al., 1981; Pierce et al., 2004). Ingested plastic has also been shown to suppress the appetite and reduce growth rates in birds and other wildlife (Danner et al., 2009; Ryan, 1988; Sievert and Sileo, 1993). Plastic also attracts and accumulates organic pollutants (e.g., polychlorinated biphenyls, PCBs) and trace metals (e.g., cadmium, chromium, lead) at more than 1000× ambient seawater concentrations (Ashton et al., 2010; Holmes et al., 2012; Lee et al., 2013; Massee et al., 1981; Mato et al., 2001; Nakashima et al., 2012). Once ingested, debris can leach contaminants into the animal's blood stream (Browne et al., 2013; Tanaka et al., 2013) which may result in stomach ulcerations, liver damage, neurological and reproductive effects, and in some cases, death (Fig. 1; Bouland et al., 2012; Colabuono et al., 2010; Day et al., 1985; Ryan et al., 1988;

* Corresponding author.
E-mail address: Jennifer.Lavers@utas.edu.au (J.L. Lavers).
[1] Present address: School of Biological Sciences, Monash University, Building 17, Clayton, Victoria 3800, Australia.

0269-7491/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envpol.2013.12.020

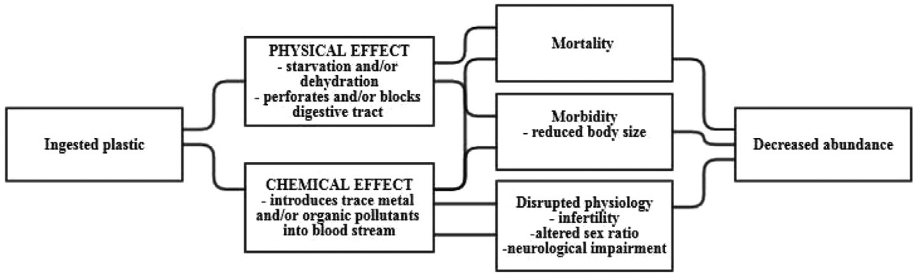

Fig. 1. Potential pathways through which ingested plastic can affect marine wildlife.

Wolfe et al., 2009). As a group, seabirds are the most heavily affected marine vertebrate with regards to plastics (Laist, 1997) and are also declining faster than any other group of birds (Butchart et al., 2004; Croxall et al., 2012). Repeated years of low breeding success and juvenile survival have been implicated in the decline of some marine species, including birds, likely the result of high mortality due to the ingestion of plastic (McCauley and Bjorndal, 1999; Priddel et al., 2006). Consequently, the ingestion of plastic debris by marine vertebrates is listed as a Key Threatening Processes under the *Environment Protection and Biodiversity Conservation Act 1999* in Australia (DEWHA, 2009).

On Lord Howe Island in eastern Australia, the world's largest population of Flesh-footed Shearwaters (*Puffinus carneipes*) has been declining for more than two decades (Priddel et al., 2006; Reid et al., 2013). Known threats have included bycatch in long-line fisheries and loss of nesting habitat (Baker and Wise, 2005; Brown and Baker, 2009). Both threats have been largely mitigated, but the population shows no signs of recovery (Reid et al., 2013). A recent study of plastic ingestion by Flesh-footed Shearwaters found 79% of fledglings contained considerable quantities of plastic debris (Hutton et al., 2008). While this behaviour of ingesting plastic debris has been implicated in the ongoing population decline (Hutton et al., 2008; Priddel et al., 2006; Reid et al., 2013), the mechanisms by which this may affect population size have not been investigated. Our goal was therefore to assess the relationship between plastic load, trace element concentrations, and chick body condition in Flesh-footed Shearwaters fledglings and the possible contribution plastic may make to the decline of this species.

2. Materials and methods

2.1. Sample collection

Flesh-footed Shearwater fledglings were captured by hand at night on the colony surface on Lord Howe Island, New South Wales (32.53°S, 159.08°E) from 19 to 24 April 2011 (approx. 80 days of age). Body mass (±10 g) was determined using a spring balance, wing chord (flattened; ±1 mm) using a stopped ruler, and head + bill length using vernier calipers (±0.1 mm). Ingested plastic was collected by stomach flushing following procedures outlined by Duffy and Jackson (1986). In brief, seawater (approx. 150 ml) at ambient temperature was gently pumped into the proventriculus through a tube, thus displacing any food or plastic items. Once fluid and stomach contents began to flow back up the throat (e.g., once the stomach was completely filled), the bird was inverted over a container to collect anything expelled. Plastic items were dried, weighed to the nearest 0.001 g using an electronic balance, and sorted by colour.

Four breast feathers were collected from each fledgling. Fledgling feathers were the preferred tissue as they are grown in a relatively short window (Pettit et al., 1984), have been found to be the best indicator of whole-body metal burden (Furness et al., 1986), and represent exogenous input, with a minimal body pool of most elements (Braune and Gaskin, 1987). Feathers were stored in sterile polyethylene bags and stored at −20 °C prior to analysis.

2.2. Trace element analysis

Feathers were washed in a 2:1 chloroform:methanol solution to remove external contamination (Paritte and Kelly, 2009). Two feathers per bird, or approximately 15–25 mg, were weighed accurately into clean Savillex 15 ml Teflon screw-cap vessels. We analysed two feathers per sample as individual feathers can be highly variable in metal concentrations (Bond and Diamond, 2008). About 1 ml of 8 M HNO_3 (Fisher Scientific, 16 M, distilled in-house using Teflon stills) was added, the vessel capped tight, and placed on a hotplate at 70 °C. After 60 min, an additional 1 ml of 8 M HNO_3 was added and the feathers were pushed down with clean disposable plastic pipettes until submerged fully in the acid. After 24 h, the hotplate was cooled to 50 °C, then 1 ml of H_2O_2 (Fisher Scientific, 30% certified, American Chemical Society) was added and the vessel caps removed. When most of the reaction had taken place, the vessels were recapped and left on hotplate for 3 h at 70 °C. Solutions were then transferred to clean, sealed containers, and taken up to volume with distilled, deionised water to dilute the sample 500×. For inductively coupled plasma mass spectrometry (ICP-MS) analysis, 1 ml of the sample solution was pipetted into clean 10 ml tubes, and 4 ml distilled, deionised water added to make a final tube dilution of approximately 2500×.

Trace element concentrations were measured in a PerkinElmer ELAN DRCII ICP-MS (Rf power: 1200 W, ICP-MS plasma gas flow: 15 L/min, auxiliary gas flow: 1 L/min, nebuliser gas flow: 1 L/min, sample uptake rate: 3.055 ml/min). Data acquisition was at peak-hopping mode, and each analyte mass was measured for 6 s. The protocol used was based on Friel et al. (1990). Procedural blanks and secondary reference materials were included for every 15–20 samples. The secondary materials used are certified human hair samples 10H-08 from the Centre de Toxicologie du Québec, Institut National de Santé Publique du Québec. Secondary reference materials were certified for concentrations Be, Al, V, Cr, Mn, Co, Ni, Cu, Zn, As, Se, Mo, Ag, Cd, Sn, Sb, I, Ba, Hg, Tl, Pb, Bi, and U, and we restricted our statistical analysis to those elements that could be analysed reliably as assessed by the recovery of reference materials. We therefore excluded I, Mn, Mo, and Ni from our analysis. Recovery of the secondary reference material ranged from 85 to 137% among all runs. Values were corrected for background levels using procedural blanks. For each element, we used the keratin reference material with the same magnitude of concentration as the unknowns to correct for recovery. Comprehensive quality assurance and quality control (QA/QC) details are provided in the supplementary material (Table S1).

2.3. Statistical methods

The relationship between ingested plastic mass and number of items on Flesh-footed Shearwater fledgling body mass, wing chord length, and trace metal concentrations was investigated using linear regression in RStudio (v 0.96.330, Boston, Massachusetts, USA). Outliers with a Cook's Distance above three were excluded from the analysis (Kim and Storer, 1996). Differences were considered statistically significant when $p < 0.05$ and values are reported as mean ± SD.

3. Results

We detected measurable concentrations of 17 trace elements in breast feathers from Flesh-footed Shearwater fledglings (Table 1).

Mean mass and wing chord of Flesh-footed Shearwater fledglings ($n = 38$) was 763 ± 129 g and 275.8 ± 35.2 mm, representing 114% and 86% of adult size, respectively (JLL unpublished data). Ninety percent ($n = 34$) of fledglings contained plastic. Overall, fledglings contained 17.5 ± 44.9 pieces of plastic weighing 2.7 ± 10.6 g (Table 2). One bird weighing only 445 g had 276 pieces of plastic in its stomach weighing 64.1 g and accounting for 14.4% of the bird's body mass. The majority of ingested plastic was white (68%, $n = 461$), followed by blue (12%, $n = 84$), black/brown (8%, $n = 55$), green (7%, $n = 50$), red/pink (3%, $n = 21$), and yellow (1%, $n = 4$).

Flesh-footed Shearwater fledgling body mass was negatively related with the mass of ingested plastic ($\beta = -6.05$, $r^2 = 0.21$, $p < 0.01$, Fig. 2a) as well as the number of pieces ingested

Table 1
Trace element concentrations in Flesh-footed Shearwater fledgling breast feathers from Lord Howe Island during April 2011. Sample size (number of samples above the limit of detection) is provided in parentheses.

Element	Concentration (μg/g)
Aluminium (Al)	112.53 ± 72.79 (37)
Antimony (Sb)	0.02 ± 0.08 (11)
Barium (Ba)	0.82 ± 1.16 (37)
Beryllium (Be)	0.76 ± 0.08 (2)
Bismuth (Bi)	0.03 ± 0.01 (9)
Arsenic (As)	0.22 ± 0.13 (29)
Cadmium (Cd)	0.49 ± 0.17 (6)
Chromium (Cr)	1.82 ± 2.51 (9)
Cobalt (Co)	33.28 ± 22.27 (38)
Copper (Cu)	14.64 ± 16.99 (38)
Lead (Pb)	0.30 ± 0.29 (37)
Mercury (Hg)	2.40 ± 1.70 (37)
Silver (Ag)	0.62 ± 1.04 (8)
Thallium (Tl)	0.01 ± 0.01 (3)
Tin (Sn)	22.62 ± 7.70 (37)
Uranium (U)	0.05 ± 0.06 (11)
Zinc (Zn)	91.70 ± 11.23 (37)

($\beta = -3.52$, $r^2 = 0.11$, $p = 0.03$, Fig. 2d). Wing chord was also negatively influenced by the number of pieces ingested ($\beta = -1.42$, $r^2 = 0.24$, $p < 0.01$, Fig. 2e), but not plastic mass ($\beta = -0.24$, $r^2 = 0.02$, $p = 0.53$, Fig. 2b). Head + bill length was negatively influenced by the number of pieces ingested ($\beta = -0.11$, $r^2 = 0.13$, $p = 0.02$, Fig. 2f) and was not significant for plastic mass ($\beta = -0.35$, $r^2 = 0.04$, $p = 0.12$, Fig. 2c).

The mass of ingested plastic was positively related to the concentration of chromium (Cr) and silver (Ag) in fledgling breast feathers (Cr: $\beta = 0.99$, $r^2 = 0.40$, $p = 0.04$; Ag: $\beta = 1.36$, $r^2 = 0.91$, $p < 0.01$). The number of plastic items ingested was not related to the concentration of any of the trace elements in fledglings, including for Cr and Ag (Cr: $\beta = 0.11$, $r^2 = 0.24$, $p = 0.11$; Ag: $\beta = 0.13$, $r^2 = 0.26$, $p = 0.09$).

4. Discussion

The results of our study indicate the proportion of the Flesh-footed Shearwater fledglings on Lord Howe Island affected by the ingestion of plastic debris has increased from 79% in 2005–2007 (Hutton et al., 2008) to 90% in 2011. Between 6 and 22% of plastic items remain inside fledglings after stomach flushing (Lavers pers. obs., Hutton et al., 2008), therefore the mass and frequency of plastic ingestion reported here are considered underestimates. The frequency of plastic ingestion by seabirds has been used as an indicator of the condition of the marine environment and the risk to seabird health. For Northern Fulmars (*Fulmarus glacialis*) in the North Sea, an Ecological Quality Objective (EcoQO) target of no more than 10% of birds with 0.1 g of plastic has been established (OSPAR, 2008; van Franeker et al., 2005). If the EcoQO was applied to Flesh-footed Shearwater fledglings, adjusting the value to 0.12 g of plastic in 10% of birds following Bond and Lavers (2013) and assuming a 0.65 kg fulmar and 0.76 kg shearwater, then 23/38 (61%) of the birds in our study fall above this threshold (Table 2). Assuming shearwater chicks are fed every four days for 80 days (Warham, 1958) and that any ingested plastic is retained, six (16%) of the fledglings in this study fail the EcoQO after a single feeding (range: 0.13–3.21 g of plastic per feeding; Table 2).

Table 2
Mass and number of plastic items ingested by Flesh-footed Shearwater fledglings on Lord Howe Island during April 2011.

Plastic	Whole season	Per feeding[a]	Per day[b]
Number of items	17.5 ± 44.9 (0–276)	0.9 ± 2.2 (0–13.8)	0.2 ± 0.6 (0–3.5)
Mass (g)	2.70 ± 10.55 (0–64.10)	0.13 ± 0.53 (0–3.20)	0.03 ± 0.13 (0–0.80)

[a] One feeding every four days (Warham, 1958).
[b] Chicks are fed for a total of 80 days (Warham, 1958).

The colour of ingested plastic appears to have changed with around 85% of items ingested during 2005–2007 being white (Hutton, 2004) compared with 68% in this study. While the percentage of ingested white plastic has declined over time, it remains the dominant plastic colour, likely due to an abundance of light-coloured plastic items (e.g., white, transparent) in the marine environment (Day et al., 1990; Moser and Lee, 1992). Selection for plastic colour by seabirds is thought to be based on the degree of similarity to potential prey items and conspicuousness at sea (Blight and Burger, 1997; Moser and Lee, 1992; Ryan, 1987b). The diet of Flesh-footed Shearwaters is poorly known (Marchant and Higgins, 1990), however limited data from Lord Howe Island suggest fledgling diet is mainly squid (authors, pers. obs.) so adult birds may mistake white plastic floating on the ocean surface for their preferred prey.

Small numbers of Flesh-footed Shearwater adults and fledglings die each year on Lord Howe Island as a result of perforations to the stomach lining by large or sharp items of plastic (Lavers unpublished data; Hutton et al., 2008). Mortality has also been reported for Short-tailed Shearwaters (*P. tenuirostris*) (Carey, 2011) and Laysan Albatrosses (Fry et al., 1987; Sievert and Sileo, 1993). The results of this study suggest that fledglings that do not die as a direct result of plastic ingestion, do suffer sublethal effects. Fledglings with increased plastic loads exhibited significantly reduced body mass, wing chord, and head bill length. Poor body condition has been linked to reduced nutrient intake and a corresponding decline in seabird populations (Kitaysky et al., 2006; Øyan and Anker-Nilssen, 1996) and likely results from reduced stomach capacity as a result of Flesh-footed Shearwaters ingesting plastic. This morbidity may negatively impact juvenile survival, and therefore population viability (Kitaysky et al., 2006), particularly during the first few months at sea when young birds must compensate for temporary food shortages due in part to reduced foraging efficiency (McClung et al., 2004; Sagar and Horning, 1998; Stienen and Brenninkmeijer, 2002). Sagar and Horning (1998) established a threshold of 564 g for a similarly-sized Sooty Shearwater (*P. griseus*) fledgling to survive its first year at-sea. Based on this value, at least four (11%) of the 38 Flesh-footed Shearwaters assessed in this study would not be expected to survive their first year at sea (body mass: 464 ± 93 g). This is likely due in part to having ingested large amounts of plastic as the average mass (21 ± 82 g) and number of plastic items (94 ± 30) ingested by these four ‘underweight’ birds was well above mean values for ‘healthy’ birds (plastic mass: 0.59 ± 1.05 g; number of items: 8 ± 10; Table 2).

Plastic products inherently contain a wide array of chemicals used in the manufacturing process (Cadore et al., 2008; Carpenter and Smith, 1972). In the marine environment, plastic accumulates high concentrations of metals and organochlorines on its surface (Ashton et al., 2010; Holmes, 2013; Holmes et al., 2012; Mato et al., 2001; Nakashima et al., 2012). Whether ingested plastic can pass these contaminants on to marine wildlife once it has been ingested has been the source of much discussion, largely because the relative contributions of plastic- and trophic-derived contaminants can be difficult to quantify (Bakir et al., 2012; Holmes, 2013; Ryan et al., 1988). However, a recent study by Tanaka et al. (2013) showed anthropogenic polybrominated diphenyl ether (PBDE) congeners that could be obtained only from ingested plastic were transferred to Short-tailed Shearwater tissues. Advances in the isotopic analysis of trace metals (e.g., mercury) to attribute sources (e.g., prey or plastic) could be beneficial for future studies (Day et al., 2012).

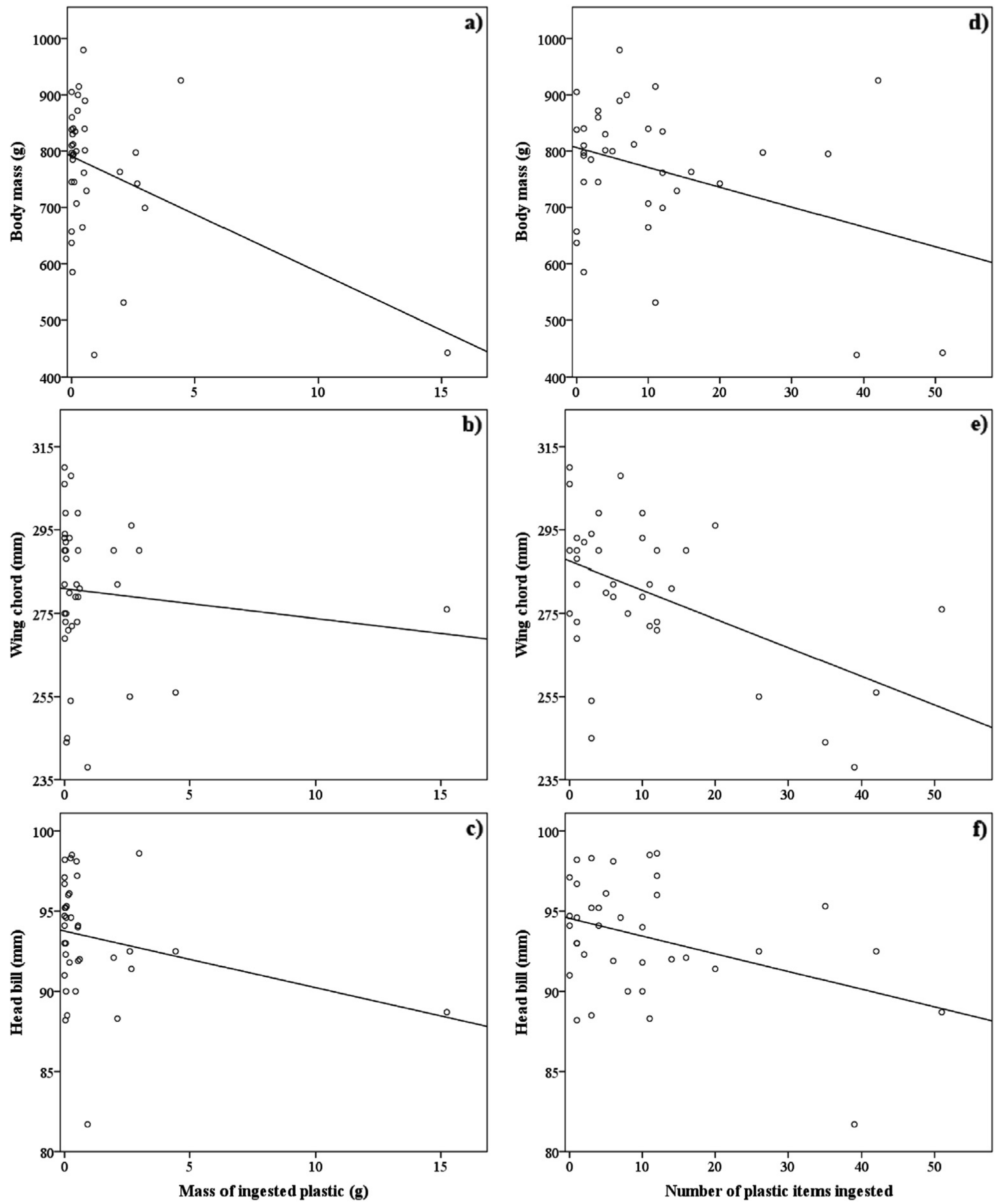

Fig. 2. Relationship between the mass of ingested plastic (left column) and number of items ingested (right column) and Flesh-footed Shearwater fledgling body mass, wing chord, and head bill. A single outlier with 276 pieces of ingested plastic weighing 64.1 g has been excluded.

The degree to which metals adhere to plastic is influenced by factors such as pH (Bryan, 1971) and may limit our ability to establish causal relationships between the amount of plastic ingested and the concentration of metals in feathers. However, in Flesh-footed Shearwaters, high concentrations of chromium (1.82 ± 2.51 μg/g) and silver (0.62 ± 1.04 μg/g; Table 1) were positively related with the mass of ingested plastic ($p < 0.05$). No relationship was detected for number of plastic items ingested ($p > 0.05$), possibly due to mechanical abrasion in the stomach which may break brittle plastic into many pieces, thereby obscuring the relationship. While chromium can arise from natural sources (e.g., through the ingestion of prey), it has also been show to adsorb readily onto weathered plastic fragments and pellets ('nurdles') typical of the types of plastic items ingested by seabirds, including Flesh-footed Shearwaters (Burger, 1993; Cadore et al., 2008; Holmes, 2013; Holmes et al., 2012; Nakashima et al., 2012; Rochman et al. 2014). Chromium can bioaccumulate in avian tissues, and levels exceeding 2.8 μg/g in feathers are thought to be associated with adverse neurotoxic effects (Burger and Gochfeld, 1995, 2000; Eisler, 1986; Gilani and Marano, 1979; Ridgeway and Karnofsky, 1952). Three (33%) of the nine Flesh-footed Shearwater fledglings in our study that were above the level of detection (approximately 3.0 μg/g) exceeded this threshold (range: 3.67–6.12 μg/g; Table 1), therefore increased chromium levels may contribute to reduced body condition, and perhaps juvenile survival, in these birds. There is little information available for bulk silver concentrations in marine birds (except see Borgå et al., 2006) and its toxicity in wildlife in general is poorly understood. Silver nanoparticles (between 1 and 100 nm), however, have well-documented toxicological effects at the cellular and subcellular level (Ahamed et al., 2008; de Lima et al., 2012; Kawata et al., 2009). Silver nanoparticles form complexes with proteins, particularly those with sulphur-containing amino acids, which are prevalent in keratins (Bell and Kramer, 1999; Crewther et al., 1965), but much remains to be understood about how the effects of nanosilver, if any, manifest in birds and other wildlife (Behra et al., 2013).

Table 3
Toxicity effect levels, lowest observed adverse effects levels (LOAEL), bioaccessible concentrations (C_{BA}), and mass of plastic required on a daily basis for adverse effects to be possible in terms of metal toxicity (M_{adv}) reported for selected trace metals.

Element	Effect level (μg/g)[a]	LOAEL (μg/g/day)[b]	C_{BA}[c]	M_{adv} (g)[c]
Arsenic	N/A	12.8	N/A	N/A
Cadmium	2.00	20.03	25.5	0.0006
Chromium	2.80	5.00	38.9	0.0001
Lead	4.00	11.3	79.5	0.0001
Mercury	5.00	0.9	N/A	N/A

[a] Based on values reported by Burger (1993).
[b] Based on values reported by Sample et al. (1996).
[c] Based on formulae provided by Holmes (2013).

Based on the lowest observed adverse effect level (LOAELs) for metals in piscivore birds (Sample et al., 1996), it is possible to estimate the daily intake of plastic necessary to present a toxicologically important dose of metals. The LOAEL for chromium (5.00 μg/g/day; Table 3; Sample et al., 1996) normalised to 0.76 kg (the mean mass of Flesh-footed Shearwater chicks), and the bioaccessible metal concentration for white plastic, C_{BA} (Cr: 38.9 μg/g; Holmes, 2013), can be used to calculate the mass of plastic required on a daily basis for adverse effects (M_{adv}) to arise from metal toxicity. Using the formula $M_{adv} = \text{LOAEL}/C_{BA}$, the mass of plastic ingested daily thought to confer damage to shearwaters through contamination with chromium is less than 0.0001 g (Table 3). Using this value, 89% of Flesh-footed Shearwater fledglings in this study would be expected to suffer morbidity or mortality due to exposure to chromium from ingested plastic. All Flesh-footed Shearwater fledglings were below hypothesised effect levels for cadmium, mercury, and lead in feathers of marine birds (Tables 1 and 3; Burger, 1993; Burger and Gochfeld, 2000), the only other elements where predicted effect levels exist.

5. Conclusions

Despite growing awareness of the quantity of plastic pollution in our oceans, the majority of studies have so far focused on qualitative descriptions of the type, colour, amount, and provenance of plastic items with quantitative data on the lethal and sublethal effects of plastic ingestion lacking for any marine species. This research highlights, for the first time, the adverse effects of plastic ingestion, and associated trace metal exposure on seabird body condition and provides significant insight into the impact ingested plastic may have on fledgling survival. The main conclusion drawn is that the risk posed to Flesh-footed Shearwaters on Lord Howe Island from ingested plastic is significant and has increased over a short period of time. Ingested plastic likely poses serious threats to Flesh-footed Shearwaters in Western Australia (Lavers unpublished data) and New Zealand (Buxton et al., 2013). Together these data help explain the ongoing decline of this species across its range (Lavers, submitted for publication; Reid et al., 2013; Waugh et al., 2013).

Acknowledgements

Special thanks go to Birdlife Tasmania, Environment Canada, the National Sciences and Engineering Research Council of Canada, Save our Shearwaters Foundation, Trading Consultants Ltd, V. Wellington, the W.V. Scott Charitable Trust for generously providing funding for this project. Samples were collected with the permission of the Lord Howe Island Board under the approval of the University of Tasmania Animal Ethics Committees (A0010874). Analytical support was provided by L. Hewa and comments from I. Molnar, and two anonymous reviewers improved earlier drafts.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2013.12.020.

References

Ahamed, M., Karns, M., Goodson, M., Rowe, J., Hussain, S.M., Schlager, J.J., Hong, Y., 2008. DNA damage response to different surface chemistry of silver nanoparticles in mammalian cells. Toxicol. Appl. Pharmacol. 233, 404–410.
Ashton, K., Holmes, L., Turner, A., 2010. Association of metals with plastic production pellets in the marine environment. Mar. Pollut. Bull. 60, 2050–2055.
Auman, H.J., Ludwig, J.P., Giesy, J.P., Colborn, T., 1998. Plastic ingestion by Laysan Albatross chicks on Sand Island, Midway Atoll, in 1994 and 1995. In: Robertson, C.J.R., Gales, R. (Eds.), Albatross Biology and Conservation. Surrey Beaty & Sons, Chipping Norton.
Avery-Gomm, S., Provencher, J.F., Morgan, K.H., Bertram, D.F., 2013. Plastic ingestion in marine-associated bird species from the eastern North Pacific. Mar. Pollut. Bull. 72, 257–259.
Baker, G.B., Wise, B.S., 2005. The impact of pelagic longline fishing on the Flesh-footed Shearwater *Puffinus carneipes* in Eastern Australia. Biol. Conserv. 126, 306–316.
Bakir, A., Rowland, S.J., Thompson, R.C., 2012. Competitive sorption of persistent organic pollutants onto microplastics in the marine environment. Mar. Pollut. Bull. 64, 2782–2789.
Barnes, D.K.A., 2005. Remote islands reveal rapid rise of southern hemisphere sea debris. Dir. Sci. 5, 915–921.
Behra, R., Sigg, L., Clift, M.J.D., Herzog, F., Minghetti, M., Johnston, B., Petri-Fink, A., Rothen-Rutishauser, B., 2013. Bioavailability of silver nanoparticles and ions: from a chemical and biochemical perspective. J. R. Soc. Interface 10, 1–18 (article number 20130396).
Bell, R.A., Kramer, J.R., 1999. Structural chemistry and geochemistry of silver-sulfur compounds: critical review. Environ. Toxicol. Chem. 18, 9–22.
Blight, L.K., Burger, A.E., 1997. Occurrence of plastic particles in seabirds from the eastern North Pacific. Mar. Pollut. Bull. 34, 323–325.
Bond, A.L., Diamond, A.W., 2008. High within-individual variation in total mercury concentration in seabird feathers. Environ. Toxicol. Chem. 27, 2375–2377.
Bond, A.L., Lavers, J.L., 2013. Effectiveness of emetics to study plastic ingestion by Leach's Storm-petrels (*Oceanodroma leucorhoa*). Mar. Pollut. Bull. 70, 171–175.
Borgå, K., Campbell, L., Gabrielsen, G.W., Norstrom, R.J., Muir, D.C., Fisk, A.T., 2006. Regional and species specific bioaccumulation of major and trace elements in Arctic seabirds. Environ. Toxicol. Chem. 25, 2927–2936.
Bouland, A.J., White, A.E., Lonabaugh, K.P., Varian-Ramos, C.W., Cristol, D.A., 2012. Female-biased offspring sex ratios in birds at a mercury-contaminated river. J. Avian Biol. 43, 244–251.
Braune, B.M., Gaskin, D.E., 1987. Mercury levels in Bonaparte's Gulls (*Larus philadelphia*) during autumn molt in the Quoddy Region, New Brunswick, Canada. Arch. Ecol. Contam. Toxicol. 16, 539–549.
Brown, D., Baker, L., 2009. The Lord Howe Island biodiversity management plan: an integrated approach to recovery planning. Ecol. Manag. Restor. 10, S70–S78.
Browne, Mark A., Niven, Stewart J., Galloway, Tamara S., Rowland, Steve J., Thompson, Richard C., 2013. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr. Biol. 23, 2388–2392.
Bryan, G.W., 1971. The effects of heavy metals (other than mercury) on marine and estuarine organisms. Proc. R. Soc. Lond. Ser. B Biol. Sci. 177, 389–410.
Burger, J., 1993. Metals in avian feathers: bioindicators of environmental pollution. Rev. Environ. Toxicol. 5, 203–311.
Burger, J., Gochfeld, M., 1995. Growth and behavioral effects of early postnatal chromium and manganese exposure in Herring Gull *Larus argentatus* chicks. Pharmacol. Biochem. Behav. 50, 607–612.
Burger, J., Gochfeld, M., 2000. Metal levels in feathers of 12 species of seabirds from Midway Atoll in the northern Pacific Ocean. Sci. Total Environ. 257, 37–52.
Butchart, S.H.M., Stattersfield, A.J., Bennun, L.A., Shutes, S.M., Akçakaya, H.R., Baillie, J.E.M., Stuart, S.N., Hilton-Taylor, C., Mace, G.M., 2004. Measuring global trends in the status of biodiversity: red list indices for birds. PLoS Biol. 2, e383.
Buxton, R.T., Currey, C.A., Lyver, P.O.B., Jones, C.J., 2013. Incidence of plastic fragments among burrow-nesting seabird colonies on offshore islands in northern New Zealand. Mar. Pollut. Bull. 74, 420–424.
Cadore, S., Matoso, E., Santos, M.C., 2008. A espectrometria atomica e a determinacao de elementos metalicos em material polimerico (Atomic spectrometry and the determination of metals in polymeric materials). Quimica Nova 31, 1533–1542.
Carey, M.J., 2011. Intergenerational transfer of plastic debris by Short-tailed Shearwaters (*Ardenna tenuirostris*). Emu 111, 229–234.
Carpenter, E.J., Smith Jr., K.L., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240–1241.
CBD, 2012. Impacts of Marine Debris on Biodiversity: Current Status and Potential Solutions. Technical Series No. 67. Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel, Montreal.
Colabuono, F.I., Taniguchi, S., Montone, R.C., 2010. Polychlorinated biphenyls and organochlorine pesticides in plastics ingested by seabirds. Mar. Pollut. Bull. 60, 630–634.
Connors, P.G., Smith, K.G., 1982. Oceanic plastic particle pollution: suspected effect on fat deposition in Red Phalaropes. Mar. Pollut. Bull. 13, 18–20.

Couch, J., 1838. A letter on the occurrence of Wilson's Petrel (*Procellaria wilsonii*) on the British coast. Proc. Linn. Soc. Lond. 1, 2–3.
Crewther, W.G., Fraser, R.D., Lennox, F.G., Lindley, H., 1965. The chemistry of keratins. Adv. Protein Chem. 20, 191–346.
Croxall, J.P., Butchart, S.H.M., Lascelles, B., Stattersfield, A.J., Sullivan, B.J., Symes, A., Taylor, P., 2012. Seabird conservation status, threats and priority actions: a global assessment. Bird Conserv. Int. 22, 1–34.
Danner, G.R., Chacko, J., Brautigam, F., 2009. Voluntary ingestion of soft plastic fishing lures affects brook trout growth in the laboratory. N. Am. J. Fish. Manag. 29, 352–360.
Day, R.D., Roseneau, D.G., Berail, S., Hobson, K.A., Donard, O.F., Vander Pol, S.S., Pugh, R.S., Moors, A.J., Long, S.E., Becker, P.R., 2012. Mercury stable isotopes in seabird eggs reflect a gradient from terrestrial geogenic to oceanic mercury reservoirs. Environ. Sci. Technol. 46, 5327–5335.
Day, R.H., Shaw, D.G., Ignell, S.E., 1990. The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1985–88. In: Shomura, R.S., Godfrey, M.L. (Eds.), Proceedings of the Second International Conference on Marine Debris, Honolulu, Hawaii.
Day, R.H., Wehle, D.H.S., Coleman, F.C., 1985. Proceedings of the workshop on the fate and impact of marine debris. In: Shomura, R.S., Yoshida, H.O. (Eds.), Ingestion of Plastic Pollutants by Marine Birds, pp. 344–386. Honolulu.
de Lima, R., Seabra, A.B., Durán, N., 2012. Silver nanoparticles: a brief review of cytotoxicity and genotoxicity of chemically and biogenically synthesized nanoparticles. J. Appl. Toxicol. 32, 867–879.
DEWHA, 2009. Threat Abatement Plan for the Impacts of Marine Debris on Vertebrate Marine Life. Department of the Environment, Water, Heritage and the Arts, Canberra.
Dickerman, R.W., Goelet, R.G., 1987. Northern Gannet starvation after swallowing styrofoam. Mar. Pollut. Bull. 18, 293.
Duffy, D.C., Jackson, S., 1986. Diet studies of seabirds: a review of methods. Colon. Waterbirds 9, 1–17.
Eisler, R., 1986. Chromium Hazards to Fish, Wildlife, and Invertebrates: a Synoptic Review. In: Contaminant Hazard Reviews Report No. 6. U.S. Fish and Wildlife Service, Maryland, USA.
Friel, J.K., Skinner, C.S., Jackson, S.E., Longerich, H.P., 1990. Analysis of biological reference materials, prepared by microwave dissolution, using inductively coupled plasma mass spectrometry. Analyst 115, 269–273.
Fry, D.M., Fefer, S.I., Sileo, L., 1987. Ingestion of plastic debris by Laysan Albatrosses and Wedge-tailed shearwaters in the Hawaiian Islands. Mar. Pollut. Bull. 18, 339–343.
Furness, R.W., Muirhead, S.J., Woodburn, M., 1986. Using bird feathers to measure mercury in the environment: relationships between mercury content and moult. Mar. Pollut. Bull. 17, 27–30.
Gilani, S.H., Marano, M., 1979. Chromium poisoning and chick embryogenesis. Environ. Res. 19, 427–431.
Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings-entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos. Trans. R. Soc. Lond. B 364, 2013–2025.
Holmes, L.A., 2013. Interactions of Trace Metals with Plastic Production Pellets in the Marine Environment. School of Geography, Earth and Environmental Sciences. University of Plymouth, Plymouth, UK.
Holmes, L.A., Turner, A., Thompson, R.C., 2012. Adsorption of trace metals to plastic resin pellets in the marine environment. Environ. Pollut. 160, 42–48.
Hutton, I., 2004. Plastic perils for seabirds. Nat. Aust. 28, 52–59.
Hutton, I., Carlile, N., Priddel, D., 2008. Plastic ingestion by Flesh-footed Shearwaters, *Puffinus carneipes*, and Wedge-tailed Shearwaters, *Puffinus pacificus*. Pap. Proc. R. Soc. Tasman. 142, 67–72.
Hyrenbach, K.D., Titmus, A.J., Hester, M., Vanderlip, C., Chang, C.-W., 2012. Boluses reveal species-specific and colony based differences in plastic ingestion by Black-footed and Laysan Albatross. In: 39th Annual Pacific Seabird Group Conference, Hawaii.
Kawata, K., Osawa, M., Okabe, S., 2009. In vitro toxicity of silver nanoparticles at noncytotoxic doses to HepG2 human hepatoma cells. Environ. Sci. Technol. 43, 6046–6051.
Kenyon, K.W., Kridler, E., 1969. Laysan Albatrosses swallow indigestible matter. Auk 86, 339–343.
Kim, C., Storer, B.E., 1996. Reference values for Cook's distance. Commun. Stat. Simul. Comput. 25, 691–708.
Kitaysky, A.S., Kitaiskaia, E.V., Piatt, J.F., Wingfield, J.C., 2006. A mechanistic link between chick diet and decline in seabirds? Proc. R. Soc. B Biol. Sci. 273, 445–450.
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: Marine Debris: Sources, Impacts, and Solutions.
Lavers, J.L., 2014. A review of concurrent threats to Flesh-footed Shearwaters (*Puffinus carneipes*): words of warning from a top marine predator in decline. ICES J. Mar. Sci. (submitted for publication).
Lee, H., Shim, W.J., Kwon, J.-H., 2013. Sorption capacity of plastic debris for hydrophobic organic chemicals. Sci. Total Environ. 470–471, 1545–1552.
Marchant, S., Higgins, P.J., 1990. Handbook of Australian, New Zealand, and Antarctic Birds. In: Ratites to Ducks, vol. 1. Oxford University Press, Melbourne.
Massee, R., Maessen, F.J.M.J., De goeij, J.J.M., 1981. Losses of silver, arsenic, cadmium, selenium and zinc traces from distilled water and artificial sea-water by sorption on various container surfaces. Anal. Chim. Acta 127, 181–193.
Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ. Sci. Technol. 35, 318–324.
McCauley, S.J., Bjorndal, K.A., 1999. Conservation implications of dietary dilution from debris ingestion: sublethal effects in post-hatchling loggerhead sea turtles. Conserv. Biol. 13, 925–929.
McClung, M.R., Seddon, P.J., Massaro, M., Setiawan, A.N., 2004. Nature-based tourism impacts on Yellow-eyed Penguins *Megadyptes antipodes*: does unregulated visitor access affect fledging weight and juvenile survival? Biol. Conserv. 119, 279–285.
Moser, M.L., Lee, D.S., 1992. A fourteen years survey of plastic ingestion by western North Atlantic seabirds. Colon. Waterbirds 15, 83–94.
Nakashima, E., Isobe, A., Kako, S.i., Itai, T., Takahashi, S., 2012. Quantification of toxic metals derived from macroplastic litter on Ookushi Beach, Japan. Environ. Sci. Technol. 46, 10099–10105.
OSPAR, 2008. Background Document for the EcoQO on Plastic Particles in Stomachs of Seabirds. Biodiversity Series publication number: 355/2008. OSPAR Commission, London.
Øyan, H.S., Anker-Nilssen, T., 1996. Allocation of growth in food-stressed Atlantic Puffin chicks. Auk 113, 830–841.
Paritte, J.M., Kelly, J.F., 2009. Effect of cleaning regime on stable-isotope ratios of feathers in Japanese Quail (*Coturnix japonica*). Auk 126, 165–174.
Pettit, T.N., Byrd, G.V., Whittow, G.C., Seki, M.P., 1984. Growth of the Wedge-Tailed Shearwater in the Hawaiian Islands. Auk 101, 103–109.
Pettit, T.N., Grant, G.S., Whittow, C.G., 1981. Ingestion of plastics by Laysan albatross. Auk 98, 839–841.
Pierce, K.E., Harris, R.J., Larned, L.S., Pokras, M.A., 2004. Obstruction and starvation associated with plastic ingestion in a Northern Gannet *Morus bassanus* and a Greater Shearwater *Puffinus gravis*. Mar. Ornithol. 32, 187–189.
Priddel, D., Carlile, N., Fullagar, P., Hutton, I., O'Neill, L., 2006. Decline in the distribution and abundance of Flesh-footed Shearwaters (*Puffinus carneipes*) on Lord Howe Island, Australia. Biol. Conserv. 128, 412–424.
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. Mar. Pollut. Bull. 60, 1406–1411.
Reid, T., Hindell, M., Lavers, J.L., Wilcox, C., 2013. Re-examining mortality sources and population trends in a declining seabird: using Bayesian methods to incorporate existing information and new data. PLoS One 8, e58230.
Ridgeway, L.P., Karnofsky, D.A., 1952. The effects of metals on the chick embryo: toxicity and production of abnormalities in development. Ann. N. Y. Acad. Sci. 55, 203–215.
Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific. Mar. Pollut. Bull. 30, 151–157.
Rochman, C.M., Hentschel, B.T., Teh, S.J., 2014. Long-term sorption of metals is similar among plastic types: Implications for plastic debris in aquatic environments. PLoS One 9, e85433.
Ryan, P.G., 1987a. The effects of ingested plastics on seabirds: correlation between plastic load and body condition. Environ. Pollut. 46, 119–125.
Ryan, P.G., 1987b. The incidence and characteristics of plastic particles ingested by seabirds. Mar. Environ. Res. 23, 175–206.
Ryan, P.G., 1988. Effects of ingested plastic on seabird feeding: evidence from chickens. Mar. Pollut. Bull. 19, 125–128.
Ryan, P.G., Connel, A.D., Gardner, B.D., 1988. Plastic ingestion and PCB's in seabirds: is there a relationship? Mar. Pollut. Bull. 19, 174–176.
Sagar, P.M., Horning, D.S., 1998. Mass-related survival of fledgling Sooty Shearwaters *Puffinus griseus* at The Snares, New Zealand. Ibis 140, 329–331.
Sample, B.E., Opresko, D.M., Suter II, G.W., 1996. Toxicological Benchmarks for Wildlife: 1996 Revision. Report ES/ER/TM-86/R3. US Department of Energy, Office of Environment.
Sievert, P.R., Sileo, L., 1993. The effects of ingested plastic on growth and survival of albatross chicks. In: Vermee, r.K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D. (Eds.), The Status, Ecology, and Conservation of Marine Birds of the North Pacifc. Canadian Wildlife Service Special Publication, Ottawa.
Spear, L.B., Ainley, D.G., Ribic, C.A., 1995. Incidence of plastic in seabirds from the tropical Pacific, 1984–91 – relation with distribution of species, sex, age, season, year, and body weight. Mar. Environ. Res. 40, 123–146.
Stienen, E.W.M., Brenninkmeijer, A., 2002. Variation in growth in Sandwich Tern chicks *Sterna sandvicensis* and the consequences for pre- and post-fledging mortality. Ibis 144, 567–576.
Tanaka, K., Takada, H., Yamashita, R., Mizukawa, K., Fukuwaka, M.-a., Watanuki, Y., 2013. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69, 219–222.
van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Hansen, P.L., Heubeck, M., Jensen, J.K., Le Guillou, G., Olsen, B., Olsen, K.O., Pedersen, J., Stienen, E.W., Turner, D.M., 2011. Monitoring plastic ingestion by the Northern Fulmar *Fulmarus glacialis* in the North Sea. Environ. Pollut. 159, 2609–2615.
van Franeker, J.A., Heubeck, M., Fairclough, K., Turner, D.M., Grantham, M., Stienen, E.W.M., Guse, N., Pedersen, J.C., 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. In: Alterra-rapport 1162. Alterra, Wageningen.
Warham, J., 1958. The nesting of the shearwater *Puffinus carneipes*. Auk 75, 1–14.
Waugh, S.M., Tennyson, A., Taylor, G., Wilson, K.-J., 2013. Population sizes of shearwaters (*Puffinus* spp.) breeding in New Zealand, with recommendations for monitoring. Tuhinga 24, 159–204.
Wolfe, M.F., Schwarzbach, S., Sulaiman, R.A., 2009. Effects of mercury on wildlife: a comprehensive review. Environ. Toxicol. Chem. 17, 146–160.

Supplementary material

Table S1. Recovery of certified reference materials (CRM; 10H-08) used to determine concentrations in Flesh-footed Shearwater fledgling breast feathers (n = 38).

Element	Measured (µg/g)	Certified (µg/g)	% Recovery
Ag	2.63	2.04	1.29
Al	101.8	91.1	1.11
As	0.254	0.226	1.12
Ba	8.94	7.54	1.18
Be	0.410	0.447	0.92
Bi	0.90	0.75	1.20
Cd	2.54	1.84	1.38
Co	0.515	0.473	1.09
Cr	3.81	4.66	0.82
Cu	31.2	27.4	1.14
Hg	5.3	4.4	1.20
I	9.95	2.25	4.42
Mn	10.95	6.07	1.80
Mo	0.463	0.194	2.39
Ni	1.58	1.09	1.45
Pb	5.04	4.06	1.24
Sb	0.116	0.114	1.02
Sn	28.9	6.4	4.52
Tl	0.144	0.127	1.14
U	1.30	1.12	1.16
Zn	231	172	1.34