Temporal trends and interannual variation in plastic ingestion by Flesh-footed Shearwaters (*Ardenna carneipes*) using different sampling strategies

Jennifer L. Lavers[1]*, Ian Hutton[2], and Alexander L. Bond[3]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, 20 Castray Esplanade, Battery Point, Tasmania, 7004 Australia
[2]Lord Howe Island Museum, P.O. Box 157, Lord Howe Island, New South Wales, 2898 Australia
[3]Bird Group, Department of Life Sciences, The Natural History Museum, Tring, Hertfordshire, United Kingdom, HP23 6AP
*Corresponding author. E-mail address: Jennifer.Lavers@utas.edu.au (J.L. Lavers)

ABSTRACT

The world's oceans are under increasing pressure from anthropogenic activities, including significant and rapidly increasing inputs of plastic pollution. Seabirds have long been considered sentinels of ocean health, providing data on physical and chemical pollutants in their marine habitats. However, long-term data that can elucidate important patterns and changes in seabird exposure to marine pollutants are relatively limited but are urgently needed to identify and support effective policy measures to reduce plastic waste. Using up to 12 years of data, we examined the benefits and challenges of different approaches to monitoring plastic in seabirds, and the relationship between plastic and body size parameters. We found the mass and number of ingested plastics per bird varied by sample type, with lavage and road-kill birds containing less plastic (9.17-9.33 pieces/bird) than beach-washed or otherwise dead birds (27.62-32.22 pieces/bird). Beached birds therefore provide data for only a particular subset of the population, mostly individuals in poorer body condition, including those severely impacted by plastics. In addition, the mass and number of plastics in beached birds were more variable, therefore the sample sizes required to detect a change in plastic over time were significantly larger than for lavaged birds. The use of lavaged birds is rare in studies of plastic ingestion due to ethical and methodological implications, and we recommend future work on ingested plastics should focus on sampling this group to ensure data are more representative of a population's overall exposure to plastics.

Keywords: Body condition; Long-term trends; Marine debris; Monitoring program; Tasman Sea

Capsule: Long-term data on plastic ingestion in shearwaters highlights significant changes over time, and the importance of different sampling strategies

1. Introduction

The depletion of wildlife (IPBES, 2019), spread of invasive species (Bellard et al., 2016) and unsustainable inputs of pollutants (Borrelle et al., 2020; Lamborg et al., 2014) provides increasing evidence that the ocean, on which all life depends, is being altered drastically by human activities. Nowhere is safe: a concept highlighted by anthropogenic marine debris, now ubiquitous from the Arctic ice sheets (Obbard et al., 2014) to Antarctic waters (Waller et al., 2017). Visited by humans only a handful of times, the Marianas Trench (4 km depth) and even Mars (206 million km from Earth) now contain our plastic waste (NASA, 2012; Qui, 2016). Plastic pollution was highlighted during the United Nations Conference on Sustainable Development (Rio+20), where participant governments "commit to take action to achieve significant reductions in marine debris by 2025 to prevent harm to the coastal and marine environment" (United Nations, 2012). However, most of the Rio+20 targets are voluntary and progress has been hampered by an inability to agree on monitoring and management frameworks, and ambiguous stakeholder engagement mechanisms (Borrelle et al., 2017; Cutter et al., 2013). Addressing this requires robust quantitative data on indicator species to provide critical insights into trends in the quantity and impact of plastic, and allowing for measures of progress over time (O'Hanlon et al., 2017).

As apex predators, seabirds are widely regarded as indicators of ocean health (Burger and Gochfeld, 2004; Parsons et al., 2008). Countless studies have reported debris ingestion and entanglement rates for seabirds (Kühn and van Franeker, 2020) as these metrics are thought to reflect the amount or distribution of plastic pollution in the marine environment (Fossi and Depledge, 2014; Ryan and Fraser, 1988). Though there have been several recent studies that have evaluated trends in plastic ingestion over time (Bond et al., 2012b; Lavers and Bond, 2016a; Lavers et al., 2018; Moser and Lee, 1992; Perold et al., 2020; Robards et al., 1995), they are still uncommon and often opportunistic. A notable exception is the long-term monitoring of ingested plastic by the Northern Fulmar (*Fulmarus glacialis*) which has provided valuable insights into changes in the composition and abundance of debris in the North Sea (van Franeker and Kühn, 2019; van Franeker and Law, 2015).

In Australia, data on the frequency of ingestion of marine debris by Flesh-footed Shearwaters (*Ardenna carneipes*) provided some of the earliest evidence of plastic accumulation in the Tasman Sea during 2005-2011 (Hutton et al., 2008; Lavers et al., 2014). High prevalence of plastic ingestion was linked to morbidity and mortality of shearwater fledglings, and the transfer of plastic associated co-pollutants such as mercury and polybrominated diphenyl ethers (PBDEs) (Bond and Lavers, 2011; Lavers et al., 2014; Szabo et al., 2020). Ingestion of plastics by adult Flesh-footed Shearwaters foraging at sea is likely influenced by factors such as particle abundance and colour

(Lavers and Bond, 2016b), and may contribute to the ongoing decline and recent uplisting of this species to Near Threatened on the IUCN Red List of Threatened Species (BirdLife International, 2021; Lavers et al., 2014; Lavers et al., 2019a).

Seabirds, including shearwaters, are well known for their role as biological pathways, transporting nutrients from the ocean to the land by depositing organic material in their colonies (Vizzini et al., 2016; Wait et al., 2005). With debris accumulating in our oceans (Eriksen et al., 2014), and seabird populations in decline (Croxall et al., 2012), seabirds are unwittingly contributing to the degradation of their own habitat by depositing fewer nutrients, and increasing quantities of chemical and physical pollutants (Blais et al., 2005; Choy et al., 2010; Provencher et al., 2018). With the decline of Flesh-footed Shearwaters on Lord Howe Island comes a concomitant decline in nutrients, which are thought to have maintained the globally Vulnerable kentia palm (*Howea forsteriana*) forest where the shearwaters breed (Hutton, pers. obs.), and an increase in the quantity of plastic (Buxton et al., 2013; Grant et al., 2021) and associated pollutants.

Here we investigate changes in the amount and composition of plastic being consumed by Flesh-footed Shearwaters on Lord Howe Island using data collected from four sources (beach-washed birds, road-kill, necropsied (other), and lavaged live birds) collected during 2005-2021. Our objectives were to identify within- and among-year trends in the quantity of plastic ingested by this sentinel species, quantify the relationship between plastic and body size in young shearwaters , and suggest refinements for future monitoring of plastic ingestion in this and other highly-affected species.

2. Methods

2.1. Sampling birds

Flesh-footed Shearwater fledglings (80-90 days old) were captured by hand at night on the colony surface on UNESCO World Heritage-listed Lord Howe Island, New South Wales (31.33°S, 159.05°E) from late-April until mid-May during 2005-2021.

To minimise disturbance to colonies, nightly capture effort was distributed across three sites (Ned's Beach, Middle Beach, and Clear Place colony) and birds were captured within 10 m of well-defined walking paths or roads. Individual birds were selected one at a time, at random, within this area and returned to a central processing station located outside of the colony. Body mass (±10 g) was determined using a spring balance, wing chord (flattened; ± 1 mm) using a stopped ruler, and culmen and head + bill length using Vernier callipers (± 0.1 mm). Not all measurements were taken from all individuals in all years because of animal welfare considerations or logistical constraints;

however, measurements were recorded by the same researcher to ensure consistent data across years.

Ingested plastic was collected by stomach flushing (lavage category) following procedures outlined by Duffy and Jackson (1986). In brief, water (approximately 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 (i.e., once the stomach was completely filled), the bird was inverted over a container to collect anything expelled. Lavage removes plastics from the proventriculus only, though in severely impacted birds it can only recover 78-94% of pieces (Hutton et al., 2008; Lavers et al., 2014).

Freshly deceased (< 24 hours) shearwater carcasses were collected from local beaches after unsuccessful fledging attempts (beach-washed category) and from roadsides (road-kill category) each morning during late-April to mid-May 2005-2021. Additional birds (referred to as "Other") were provided through a range of sources, including birds found dead by researchers and community members in the colony and community. All dead birds were measured, weighed, and necropsied, with ingested items processed following the procedures outlined below. Unlike lavage, we were able to retrieve all plastics from both the proventriculus and gizzard of necropsied birds (Lavers et al., 2014).

Plastic items > 1 mm were washed, dried, and weighed (items from the proventriculus and gizzard separately) to the nearest 0.01 g using an electronic balance. Items were then sorted by colour (white, blue, green, red, yellow, and black) and type following the categories outlined by Provencher et al. (2017; industrial pellets, user plastic, foam, threads, sheet plastic, and other), with the exception of plastic strapping, which more closely resembled plastic fragments in our study system.

2.2. Statistical methods

We examined changes in the prevalence, number of pieces, and mass of plastics over time using a binomial (logit link), negative binomial (log link; see below), and Gaussian generalized additive model, respectively (Wood, 2017). Error structures were based on data (presence/absence, count, and ratio). In all cases, we used restricted maximum likelihood to determine the cubic spline smoothing parameters, and the number of knots was determined by generalized cross-validation during model fitting. In all cases, our sampling unit was the individual bird.

To compare lavage and necropsied birds directly, we ran similar GAMs including the sample source (lavage, necropsy) and compared the odds ratio (number of pieces) and parameter estimates (mass of plastics) for only plastics found in the proventriculus, which is sampled using both techniques.

The relationship between ingested plastic mass and number of items on Flesh-footed Shearwater fledgling body mass, head+bill, culmen, and wing chord length was investigated using general linear models that included the effect of ingested plastic mass and sampling year. All analyses were done in R 4.0.5 (R Core Team, 2020) using the packages *vegan* (Oksanen et al., 2020), *lubridate* (Grolemund and Wickham, 2011), *mgcv* (Wood, 2019), and *tidyverse* (Wickham et al., 2019), differences were considered statistically significant when $p < 0.05$ and values are reported as mean ± SD.

We conducted a power analysis to determine the sample sizes needed for future monitoring to detect 5-100% change in prevalence, the number of pieces, and mass of plastic over time (Lavers and Bond, 2016a; van Franeker and Meijboom, 2002) using the equation below:

$$n = 2 \times \left\{ \frac{\left| z_{\alpha/2} - z_{\pi} \right| \times \frac{\mathrm{CV}}{100} \times \mu_{\mathrm{I}}}{\mu_I - 100} \right\}^2$$

where *n* is the required annual sample size, z is the t-value, α is the Type I error rate, π is the Type II error rate, μ_I is the difference to detect (where a 5% change is μ_I = 10, a 10% change is μ_I = 110, etc.), and CV is the coefficient of variation (SD/mean) of the time series. We set α = 0.05 and π = 0.90, meaning $z_{\alpha/2} - z_{\pi}$ = 3.242, which is a power of 80% to detect any trend (Provencher et al., 2015; van Franeker and Meijboom, 2002).

Lastly, we compared the colour and type of ingested plastics among years and sampling types using the Jaccard Similarity Index (Bloom, 1981; Jaccard, 1912), which calculates the similarity in pairwise comparisons of proportions of groups in two samples, ranging from 0 (no overlap) to 1 (completely identical). Values > 0.60 generally indicate significant overlap (Bond et al., 2012a).

3. Results

We sampled 718 birds using lavage, and examined a total of 172 beach-washed, 80 road-killed, and 146 otherwise dead birds by necropsy during 2005-2021 (Table S1). Sample numbers change annually in relation to capture effort, not bird abundance.

3.1 Frequency of occurrence of ingested plastic

The frequency of occurrence (%FO; prevalence) of plastics in necropsied birds was 88.7% (361/407) and was 49.2% (353/718) in lavaged birds (Figure 1; Table S2). The FO of plastic ingestion in lavaged birds ranged from 39.1% in 2014 to 85.2% in 2005. There was a non-linear and decreasing trend in the proportion of lavaged birds that had ingested plastics (χ^2 = 27.35, effective df = 3.86, p <

0.001), and a nearly linear but non-significant decrease in the frequency of plastic ingestion in relation to sampling date (χ^2 = 3.50, effective d = 1.00, p= 0.06; Figure S1). Both models had k = 9 knots. Conversely, there was no significant trend in the frequency of plastic ingestion in necropsied birds over years (χ^2 = 0.807, effective df = 2.06, p = 0.64; Figure S2) or with day of year (χ^2 = 0.52, effective df = 1.00, p = 0.47). Again, both models had k = 9 knots.

3.2 Number of pieces ingested

Lavaged and road-kill birds had slightly fewer pieces of plastic on average (mean ± SE: 8.61 ± 2.72 and 8.72 ± 3.13 pieces, respectively) compared to beach-washed or otherwise dead birds (29.62 ± 15.49 and 25.86 ± 12.77 pieces, respectively; Figure 2, Table S3). Using a Poisson distribution, residuals were overdispersed. This was overcome using a negative binomial error structure for subsequent models of plastic number. There was significant inter-annual variation in the number of plastic pieces ingested by lavaged birds, peaking in 2011-2012, followed by a rapid decrease in 2014, and with an overall decreasing trend (z = 100.45, effective df = 8.59, p < 0.001; Figure 3), and with annual peaks around 7 May (z = 5.15, effective df = 1.00, p = 0.023; Figure 4). In necropsied birds, the number of pieces peaked in 2011-2012 before declining rapidly, and then gradually rising again from 2017-2021 (z = 86.38, effective df = 8.38, p < 0.001; Figure 3), while within years, there was no trend (z = 1.225, effective df = 1.87, p = 0.59; Figure 4). Birds that were necropsied had 1.38× (± 0.13 SE) more pieces in their proventriculus than birds that were lavaged (z = 1.99, p = 0.046).

3.3 Mass of ingested plastics

The mass of plastic ingested followed a similar pattern to the number of pieces: lavaged (mean ± SE: 0.80 ± 0.29 g) and road-kill birds (1.17 ± 0.74 g) tended to have less plastic than beach-washed (4.34 ± 2.62 g) or otherwise dead birds (4.15 ± 2.10 g; Figure 3, Table S4). Among lavaged birds, the mean mass of ingested plastic ranged from 0.04 g in 2015 to 2.93 g in 2016 (Table S4). For the mass of plastic ingested by lavaged birds, there was no effect of day of year F = 0.015, effective df = 1.00, p = 0.91; Figure S4), but there was significant variation among years (F = 3.00, effective df = 6.02, p = 0.004; Figure S3). The mass of plastics declined to 2013 before rising again to 2016, and then declining and remining stable (Figure S3). There was a similar pattern for necropsied birds: no relationship with day of year (F = 0.54, effective df = 1.00, p = 0.46; Figure S4), and significant variation among years, but largely driven by high values in 2012 and remining relatively stable thereafter (F = 15.33, effective df = 7.71, p < 0.001; Figure S3). Necropsied birds also had a higher plastic mass than lavaged birds when looking at only the proventriculus (t_1 = 3.39, p < 0.001; β ± SE: 0.917 ± 0.270). Thus, necropsied birds had 9.0% more plastic by mass than lavaged birds.

3.4 Colour of ingested plastic

The composition of ingested plastics was very similar among years, with a high Jaccard Index for colour (lavage: 0.817 ± 0.060, range: 0.667-0.936; necropsy: 0.788 ± 0.078, range: 0.610-0.943; Tables S5, 6, 9 and 11). Among all years, lavaged shearwaters ingested primarily white plastic (74.5%), with smaller contributions of green (8.5%), blue (7.0%), black (4.7%), yellow (2.9%), and red (2.3%). The same pattern was present in necropsied birds (pooled among all sources), white was again the most common colour (81.5%), followed by green (7.2%), blue (6.1%), black (4.6%), red (2.9%), and yellow (1.9%). Lavaged and necropsied birds were virtually identical in colour composition (Jaccard Index: 0.898).

3.5 Plastic type

The type of plastic was also highly similar among years (Jaccard Index: 0.765 ± 0.201, range: 0.320-0.977), except for 2014, which differed from all others (Tables S7, S8, 10 and 12). In 2014, birds ingested considerably more industrial pellets (51.5%), and fewer fragments (48.5%). Overall, shearwaters ingested 91.7% fragments, 5.6% industrial pellets (nurdles), and <1% foam, threads, sheets, and other. And while the same types were observed in necropsied birds (fragments: 95.3%, industrial pellets: 7.2%, form, threads, sheets, and other <1%), there was more interannual variation (Jaccard Index: 0.608 ± 0.261, range: 0.180-0.952), largely driven by years with smaller sample sizes in 2013-2015 (Table S1). Overall, there was no difference in the types of plastics found in lavaged compared to necropsied birds (Jaccard Index: 0.943).

3.6 Relationship between ingested plastic and body condition

Accounting for year of sampling, the mass of ingested plastic was unrelated to chick fledging body mass ($F_{1,636}$ = 0.124, p = 0.73), culmen length ($F_{1,564}$ = 0.02, p = 0.88), or head+bill length ($F_{1,565}$ = 0.85, p = 0.36) in lavaged birds, and unrelated to body mass ($F_{1,373}$ = 2.45, p = 0.12), culmen length ($F_{1,380}$ = 0.55, p = 0.46), head+bill length ($F_{1,364}$ = 0.09, p = 0.76) and wing chord ($F_{1,378}$ = 0.01, p = 0.91) in necropsied birds, accounting for sampling method. The only significant relationship was between wing chord and ingested plastic mass in lavaged birds ($F_{1,559}$ = 7.78, p = 0.005; Figure 1), which showed a negative overall relationship (β ± SE: -71.5 ± 153.4), which was primarily driven by 2011 and 2016 (Figure 1). No interaction terms containing the mass of ingested plastic were significant in any model.

3.7 Power analysis

Based on the sample sizes of lavaged birds in each year (Table S1), and the coefficient of variation we observed from 2005-2021, we would require sample sizes of 247, 3064, and 4166 to detect a 10% change in the prevalence, number of pieces, and mass of plastic respectively. With an annual sample size of 60 ± 35 birds, we can detect a 20-25% change in the prevalence of plastic each year, but the high variability in the number of pieces and mass of plastic mean we could only detect changes of 285% and 400% respectively with current efforts (Figure 2). The same general patterns occurred among other sample types but requiring more annual samples given the increased variation in the coefficients of variation for the number of plastic pieces and mass of ingested plastics, but fewer samples for frequency of occurrence (Figure 2).

4. Discussion

The results of our study indicate the proportion of Flesh-footed Shearwater fledglings containing plastic decreased slightly from 85% in 2005 to 73% in 2019 (Table S2), though this change was not significant. The mass and number of ingested plastics per bird varied by source (sample type), with lavage and road-kill birds containing slightly fewer pieces than beach-washed or otherwise dead birds (Figure 2, Table S3).

4.1 Source of samples

Analysis of beached Short-tailed Shearwaters (*Ardenna tenuirostris*) and those collected as a result of light pollution (collisions; assumed to be a random sample of the population) suggests monitoring studies based solely on beached birds could overestimate plastic ingestion as these birds exhibit consistently higher plastic loads, poorer body condition and reduced isotopic variability, meaning this group is not representative of the population (Rodríguez et al., 2018). Similar patterns have been observed in Wedge-tailed Shearwaters (*A. pacifica*) with significantly poorer blood chemistry and morphometric parameters recorded in stranded fledglings compared to putatively healthy birds (Work and Rameyer, 1999), and on Lord Howe Island, beached Wedge-tailed Shearwaters weighed less, and were more likely to contain plastics (Lavers et al., 2018). On Lord Howe Island, 85% of necropsied Flesh-footed Shearwaters contained an average of 4.47-4.81 g of ingested plastic compared to only 0.38-1.29 g in just over 50% of lavaged birds (Table S2), demonstrating that beached birds provide data on only a particular subset of the population, and most likely individuals that are in poorer body condition or severely impacted by plastics (Table S13). This is counter to what was found in Northern Fulmars *Fulmarus glacialis*, where beached birds and a random sample from ship strikes and oiling events contained similar plastic burdens (van Franeker and Meijboom, 2002), highlighting the species-specific nature of this bias. The ingestion of plastic has previously been linked with reduced health and condition of Flesh-footed Shearwater fledglings (Lavers et al., 2014; Lavers et al., 2019b) and is correlated with reduced wing chord length in lavaged birds in this study (Figure 1). These negative impacts may contribute to the likelihood of these same birds being detected on beaches as poorer overall health and shorter wings likely influences their survival post-fledging (Lavers et al., 2014; Morrison et al., 2009; Sievert and Sileo, 1993).

We found that lavaged birds had lower plastic than necropsied birds, when considering only the proventriculus. Lavage is assumed to remove the majority of plastics from the proventriculus, and indeed it does so in most cases (Gales, 1987; Ryan, 1987). Hutton et al. (2008) posited that ca. 5% of plastics remained in the proventriculus after lavage. This value almost certainly varies with the volume of plastic (higher volumes are more difficult to remove with lavage). We found that necropsy detected 1.38× more plastic pieces, but that this amounted to only 9% of additional plastic mass compared to lavaged birds.

4.2 Patterns within and among years

The fledging period is a critical stage in a seabird's transition to independence, and is strongly influenced by phenology, such as hatching date (Dittmann et al., 2001; Harris et al., 1992). Birds in better condition have the energy reserves to support rapid and timely departure, while the body mass of the remaining chicks still in the nest often declines as the season progresses (i.e., with later departure date; Gaston, 2003). For Flesh-footed Shearwaters, fledging body condition likely follows this pattern, however this does not appear to be solely driven by plastic ingestion, as the number and mass of ingested items was not influenced by day of year. Instead, body mass in Flesh-footed Shearwaters and most other Procellariforms, declines during the protracted (~10 day) pre-fledging period (Oka et al., 2002) once the adult birds have ceased provisioning and initiated their post-breeding migration (Mauck and Ricklefs, 2005).

There was no consistent pattern over time in the frequency or number of ingested plastics in either lavage or necropsied Flesh-footed Shearwaters, however, the mass of plastic ingested by lavaged birds varied with year. In the South Atlantic, incorporation of debris in the nests of three albatross species was similarly variable, with particular types and amounts of debris peaking only in some species and in some years (Perold et al., 2020). In contrast, a consistent decline of ∼75% in the abundance of ingested nurdles has been observed in North Sea Northern Fulmars since the 1980s, while user plastics (e.g., fragments) varied without a strong overall change (van Franeker and Law, 2015). Similar trends were found in floating plastics in the North Atlantic subtropical gyre, suggesting the plastic types ingested by fulmars mirrors the abundance of debris in their foraging grounds (van Franeker and Law, 2015). Detailed information on plastics in the Tasman Sea where Flesh-footed

Shearwaters forage are limited (Reisser et al., 2013; Rudduck et al., 2017), however the ingestion of considerably more nurdles (51.5%), and fewer fragments (48.5%) in 2014 suggests there may have been a spillage event leading to increased availability of nurdles in the Tasman Sea.

4.3. Other factors influencing plastic ingestion trends and impacts

Our study demonstrates that plastic ingestion by breeding birds provisioning chicks is a flexible behaviour in Flesh-footed Shearwaters (Figure 3, Table S2-S4). This is perhaps the first time this has been recorded in seabirds, as other long-term studies broadly show consistency in plastic loads through time (e.g., Lavers et al., 2018; van Franeker and Law, 2015). While chick provisioning with plastic items is probably linked to environmental conditions, at present, a lack of data on the spatial and temporal patterns of oceanic plastic abundance, including in the Tasman Sea offshore of Lord Howe Island (Eriksen et al., 2014; Rudduck et al., 2017), limit our ability to directly link the abundance or types of polymers in the marine environment with trends and impacts observed in wildlife, including seabirds. Other unexplored factors may also play a significant role in driving inter-annual variation, but our understanding of the mechanisms is also hampered by a lack of data. For example, it is unclear whether adult (parent) bird foraging behaviour or body condition influences the amount of plastic fed to chicks. In many seabirds, adult body condition varies within and among years, and influences chick provisioning (Chastel et al., 1995). The availability of prey can also influence adult foraging behaviour and chick provisioning (Cohen et al., 2014). Thus, disentangling whether adults in poorer condition actively seek out more plastic from the ocean's surface or provision their chick with more plastic will be challenging. Answering this important question will require robust data on prey availability and plastic density in key seabird foraging areas that does not currently exist but would be a valuable avenue for future research.

4.4 Recommendations for future study design

While global plastic production continues to increase (Borrelle et al., 2020), in many cases the sample sizes required to detect a change in plastic ingestion in Flesh-footed Shearwaters, given the annual variability observed, was too low (Figure 2). The exception being the frequency of occurrence, where variation is lower (Table S2). In general, the variation found in lavaged birds was lower than that of necropsied birds, except for frequency of occurrence, and so future work on the number and mass of ingested plastics should focus on this sampling group. The use of lavaged birds is rare in studies of plastic ingestion (Provencher et al., 2017), as this requires extensive licensing, ethical approvals, and training. However, compared to many necropsied birds, it can provide a large random sample of the population that does not rely on opportunistic and unpredictable events. This allows more *a priori* hypothesis testing and importantly, predetermined sample sizes based on power analyses to ensure that the study design can deliver the desired aims in a statistically robust way. In contrast, relying on beach-washed or otherwise dead birds will only be opportunistic, though these birds provide a unique opportunity to investigate the relationship between ingested plastic and breeding failure (poor fledging success). Given the variance and power to detect trends, but also the ease with which samples can be obtained, sampling of Flesh-footed Shearwaters should continue to examine both live birds using lavage, and dead birds from a variety of sources using necropsy to gain a more holistic assessment of the pressures, and responses, to plastic pollution.

5. Conclusions

For decades, researchers have relied on the wide-ranging habits of marine birds to sample remote corners of our seas, reliably returning to their island breeding sites. The birds have become our eyes and ears, providing a global "avian pulse" on the health of the oceans. In the lab, we interpret data collected by the birds, and in doing so, translate their story. Recommendations are made, and trends are highlighted, as has been done here. Our results have clear implications for existing and future long-term monitoring programs of seabird plastic ingestion, particularly those involving beach-based birds which may not be representative of a population's overall exposure to plastics. For researchers, it is essential to identify the type(s) of sample most appropriate to the question being asked. As a random sample of the population, lavage and road-kill birds are suitable for monitoring baselines/averages of presumably healthy members of a population while beach-washed birds may be suitable for other research questions such as assessing the pathology or cause of death where plastic may be a factor.

Like the proverbial, "canary in the coal mine", seabird populations worldwide have been sounding the alarm on ocean health for years (Dias et al., 2019; Gorta et al., 2019; Khan, 2018). Countless papers document rapidly increasing plastic debris in our oceans (Borrelle et al., 2020; Jambeck et al., 2015) with diverse and increasing consequences for marine wildlife (Kühn and van Franeker, 2020), even in the absence of well quantified population-level impacts (Senko et al., 2020). Impacts of pollution and nutritional condition, and variation at the individual level should not be discounted (Merrick and Koprowski, 2017; Richardson et al., 2019), and yet there is no evidence to suggest the pace of change in waste management and policy or behaviour change in our society reflects the urgency with which mitigation and prevention is needed. Long-term monitoring of Flesh-footed Shearwaters and Northern Fulmars are considered the flagships of seabird plastics studies, but after more than 20 years of data collection and reporting, what we desire most is evidence these data are leading to meaningful change.

Acknowledgements

Special thanks to Detached Cultural Organization, Sea World Research & Rescue Foundation (SWR/4/2015), Sydney Sea Life Foundation, Natural History Museum, Trading Consultants Ltd (V. Wellington), L. Brice, L. Mortensen, C. Noone, and the W.V. Scott Charitable Trust for providing funding for this project. Samples were collected with the permission of the Lord Howe Island Board (permit no. LHIB 07/12, 02/14, and 07/18) under the approval of the University of Tasmania Animal Ethics Committee (permit no. A10874, A11586, A13836, A16357, and A18480) and New South Wales Office of Environment & Heritage (licence no. SL100619 and SL102382). Logistical support was provided by the Australian Bird and Bat Banding Service and Lord Howe Island community, especially T. Adams, L. Brice, and J. & C. Shick. Assistance in the field was provided by generous volunteers, particularly P. Clive, the Two Hands Project (S. Stuckenbrock & P. Sharp) and members of the Adrift Lab team. Comments from three anonymous reviewers improved earlier drafts.

Literature cited

Bellard, C., Cassey, P., Blackburn, T.M., 2016. Alien species as a driver of recent extinctions. Biology Letters 12, 20150623.
BirdLife International, 2021. IUCN Red List for birds species factsheet: *Ardenna carneipes*.
Blais, J.M., Kimpe, L.E., McMahon, D., Keatley, B.E., Mallory, M.L., Douglas, M.S.V., Smol, J.P., 2005. Arctic seabirds transport marine-derived contaminants. Science 309, 445-445.
Bloom, S.A., 1981. Similarity indices in community studies: Potential pitfalls. Marine Ecology Progress Series 5, 125-128.
Bond, A.L., Jones, I.L., Williams, J.C., Byrd, G.V., 2012a. Diet of auklet chicks in the Aleutian Islands, Alaska: similarity among islands, inter-species overlap, and relationships to ocean climate. Journal of Ornithology 153, 115-129.
Bond, A.L., Lavers, J.L., 2011. Trace element concentrations in feathers of Flesh-footed Shearwaters (*Puffinus carneipes*) from across their breeding range. Archives of Environmental Contamination and Toxicology 61, 318-326.
Bond, A.L., Montevecchi, W.A., Guse, N., Regular, P.M., Garthe, S., Rail, J.-F., 2012b. Prevalence and composition of fishing gear debris in the nests of Northern Gannets (*Morus bassanus*) are related to fishing effort. Marine Pollution Bulletin 64, 907-911.
Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H.P., De Frond, H., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515-1518.
Borrelle, S.B., Rochman, C.M., Liboiron, M., Bond, A.L., Lusher, A., Bradshaw, H., Provencher, J.F., 2017. Opinion: Why we need an international agreement on marine plastic pollution. Proceedings of the National Academy of Sciences 114, 9994-9997.
Burger, J., Gochfeld, M., 2004. Marine birds as sentinels of environmental pollution. EcoHealth 1, 263-274.
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. Marine Pollution Bulletin 74, 420-424.
Chastel, O., Weimerskirch, H., Jouventin, P., 1995. Body condition and seabird reproductive performance: a study of three petrel species. Ecology 76, 2240-2246.
Choy, E.S., Kimpe, 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.

Cohen, L.A., Pichegru, L., Grémillet, D., Coetzee, J., Upfold, L., Ryan, P.G., 2014. Changes in prey availability impact the foraging behaviour and fitness of Cape Gannets over a decade. Marine Ecology Progress Series 505, 281-293.

Croxall, J.P., Butchart, S.H.M., Lascelles, B., Stattersfield, A.J.J., Sullivan, B.J.J., Symes, A., Taylor, P., 2012. Seabird conservation status, threats and priority actions: a global assessment. Bird Conservation International 22, 1-34.

Cutter, A., Lingán, J., Cornforth, J., Bonham, S., 2013. Fulfilling the Rio+20 promises: Reviewing progress since the UN Conference on Sustainable Development. Natural Resources Defense Council, New York.

Dias, M.P., Martin, R.E., Pearmain, E.J., Burfield, I.J., Small, C., Phillips, R.A., Yates, O., Lascelles, B., Borboroglu, P.G., Croxall, J.P., 2019. Threats to seabirds: A global assessment. Biological Conservation 237, 525-537.

Dittmann, T., Ludwigs, J.-D., Becker, P.H., 2001. The influence of fledgling number and hatching order on return rates of Common Terns *Sterna hirundo*. Atlantic Seabirds 4, 179-186.

Duffy, D.C., Jackson, S., 1986. Diet studies of seabirds: a review of methods. Colonial Waterbirds 9, 1-17.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE 9, e111913.

Fossi, M.C., Depledge, M.H., 2014. Exploring the potential of large vertebrates as early warning sentinels of threats to marine ecosystems, human health and wellbeing. Marine Environmental Research 100, 1-2.

Gales, R.P., 1987. Validation of the stomach-flushing technique for obtaining stomach contents of penguins. Ibis 129, 335-343.

Gaston, A.J., 2003. Influence of chick mass and date at departure from the colony on adult characteristics in Ancient Murrelets (*Synthliboramphus antiquus*), a precocial seabird. The Auk 120, 818-826.

Gorta, S.B.Z., Smith, J.A., Everett, J.D., Kingsford, R.T., Cornwell, W.K., Suthers, I.M., Epstein, H., McGovern, R., McLachlan, G., Roderick, M., Smith, L., Williams, D., Callaghan, C.T., 2019. Pelagic citizen science data reveal declines of seabirds off south-eastern Australia. Biological Conservation 235, 226-235.

Grant, M.L., Lavers, J.L., Hutton, I., Bond, A.L., 2021. Seabird colonies as a sink for marine plastic debris. Environmental Pollution 276, 116734.

Grolemund, G., Wickham, H., 2011. Dates and times made easy with *lubridate*. Journal of Statistical Software 40, 25.

Harris, M.P., Halley, D.J., Wanless, S., 1992. The post-fledging survival of young Guillemots *Uria aalge* in relation to hatching date and growth. Ibis 134, 335-339.

Hutton, I., Carlile, N., Priddel, D., 2008. Plastic ingestion by Flesh-footed Shearwaters, *Puffinus carneipes*, and Wedge-tailed Shearwaters, *Puffinus pacificus*. Papers and Proceedings of the Royal Society of Tasmania 142, 67-72.

IPBES, 2019. Global assessment report on biodiversity and ecosystem services, in: Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (Eds.). IPBES secretariat, Bonn, Germany.

Jaccard, P., 1912. The distribution of the flora in the alpine zone. New Phytologist 11, 37-50.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768-771.

Khan, F.R., 2018. Ecotoxicology in the Anthropocene: Are we listening to nature's scream? Environmental Science & Technology 52, 10227-10229.

Kühn, S., van Franeker, J.A., 2020. Quantitative overview of marine debris ingested by marine megafauna. Marine Pollution Bulletin 151, 110858.

Lamborg, C.H., Hammerschmidt, C.R., Bowman, K.L., Swarr, G.J., Munson, K.M., Ohnemus, D.C., Lam, P.J., Heimburger, L.E., Rijkenberg, M.J.A., Saito, M.A., 2014. A global ocean inventory of anthropogenic mercury based on water column measurements. Nature 512, 65-68.

Lavers, J.L., Bond, A.L., 2016a. Ingested plastic as a route for trace metals in Laysan Albatross (*Phoebastria immutabilis*) and Bonin Petrel (*Pterodroma hypoleuca*) from Midway Atoll. Marine Pollution Bulletin 110, 493-500.

Lavers, J.L., Bond, A.L., 2016b. Selectivity of Flesh-footed Shearwaters for plastic colour: evidence for differential provisioning in adults and fledglings. Marine Environmental Research 113, 1-6.

Lavers, J.L., Bond, A.L., Hutton, I., 2014. Plastic ingestion by Flesh-footed Shearwaters (*Puffinus carneipes*): Implications for chick body condition and the accumulation of plastic-derived chemicals. Environmental Pollution 187, 124-129.

Lavers, J.L., Hutton, I., Bond, A.L., 2018. Ingestion of marine debris by Wedge-tailed Shearwaters (*Ardenna pacificus*) on Lord Howe Island during 2005-2018. Marine Pollution Bulletin 133, 616-621.

Lavers, J.L., Hutton, I., Bond, A.L., 2019a. Changes in technology and imperfect detection of nest contents impedes reliable estimates of population trends in burrowing seabirds. Global Ecology and Conservation 17, e00579.

Lavers, J.L., Hutton, I., Bond, A.L., 2019b. Clinical pathology of plastic ingestion in marine birds and relationships with blood chemistry. Environmental Science & Technology 53, 9224-9231.

Mauck, R.A., Ricklefs, R.E., 2005. Control of fledging age in Leach's Storm-Petrel, *Oceanodroma leucorhoa*: chick development and prefledging mass loss. Functional Ecology 19, 73-80.

Merrick, M.J., Koprowski, J.L., 2017. Should we consider individual behavior differences in applied wildlife conservation studies? Biological Conservation 209, 34-44.

Morrison, K.W., Hipfner, J.M., Gjerdrum, C., Green, D.J., 2009. Wing length and mass at fledging predict local juvenile survival and age at first return in Tufted Puffins. The Condor 111, 433-441.

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

NASA, 2012. NASA: Curiosity has found plastic on Mars, Mars Science Laboratory Status Report. NASA Jet Propulsion Lab, University of California.

O'Hanlon, N.J., James, N.A., Masden, E.A., Bond, A.L., 2017. Seabirds and marine plastic debris in the northeastern Atlantic: A synthesis and recommendations for monitoring and research. Environmental Pollution 231, 1291-1301.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2, 315-320.

Oka, K., Hitoshi, S., Haruta, N., Maruyama, N., 2002. Streaked Shearwater *Calonectris leucomelas* chick growth and fledging performance in two breeding seasons on Mikurajima. Yamashina Institute for Ornithology Research Report 34, 39-59.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2020. Vegan: R functions for vegetation ecologists. R package version 2.5-7.

Parsons, M., Mitchell, I., Butler, A., Ratcliffe, N., Frederiksen, M., Foster, S., Reid, J.B., 2008. Seabirds as indicators of the marine environment. ICES Journal of Marine Science 65, 1520-1526.

Perold, V., Schoombie, S., Ryan, P.G., 2020. Decadal changes in plastic litter regurgitated by albatrosses and giant petrels at sub-Antarctic Marion Island. Marine Pollution Bulletin 159, 111471.

Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Bravo Rebolledo, E.L., Hammer, S., Kühn, S., Lavers, J.L., Mallory, M.L., Trevail, A.M., van Franeker, J.A., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Analytical Methods 9, 1454-1469.

Provencher, J.F., Bond, A.L., Mallory, M.L., 2015. Marine birds and plastic debris in Canada: a national synthesis and a way forward. Environmental Reviews 23, 1-13.

Provencher, J.F., Vermaire, J.C., Avery-Gomm, S., Braune, B.M., Mallory, M.L., 2018. Garbage in guano? Microplastic debris found in faecal precursors of seabirds known to ingest plastics. Science of The Total Environment 644, 1477-1484.

Qui, J., 2016. Man-made pollutants found in Earth's deepest ocean trenches, Nature.

R Core Team, 2020. R: a language and environment for statistical computing. Version 4.0.3 [computer program]. R Foundation for Statistical Computing, Vienna, Austria.

Reisser, J., Shaw, J., Wilcox, C., Hardesty, B.D., Proietti, M., Thums, M., Pattiaratchi, C., 2013. Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways. PLoS ONE 8, e80466.

Richardson, K.M., Parlato, E.H., Walker, L.K., Parker, K.A., Ewen, J.G., Armstrong, D.P., 2019. Links between personality, early natal nutrition and survival of a threatened bird. Philosophical Transactions of the Royal Society B: Biological Sciences 374, 20190373.

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.

Rodríguez, A., Ramírez, F., Carrasco, M.N., Chiaradia, A., 2018. Seabird plastic ingestion differs among collection methods: Examples from the Short-tailed Shearwater. Environmental Pollution 243, 1750-1757.

Rudduck, O.-A., Lavers, J.L., Fischer, A.M., Stuckenbrock, S., Sharp, P.B., Banati, R.B., 2017. Inter-annual variation in the density of anthropogenic debris in the Tasman Sea. Marine Pollution Bulletin 124, 51-55.

Ryan, P.G., 1987. The incidence and characteristics of plastic particles ingested by seabirds. Marine Environmental Research 23, 175-206.

Ryan, P.G., Fraser, M.W., 1988. The use of Great Skua pellets as indicators of plastic pollution in seabirds. Emu 88, 16-19.

Senko, J.F., Nelms, S.E., Reavis, J.L., Witherington, B., Godley, B.J., Wallace, B.P., 2020. Understanding individual and population-level effects of plastic pollution on marine megafauna. Endangered Species Research 43, 234-252.

Sievert, P.R., Sileo, L., 1993. The effects of ingested plastic on growth and survival of albatross chicks, in: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D. (Eds.). Canadian Wildlife Service Special Publication, Ottawa.

Szabo, D., Lavers, J.L., Shimeta, J., Green, M.P., Mulder, R.A., Clarke, B.O., 2020. Correlations between per- and polyfluoroalkyl substances (PFASs) and body morphometrics in fledgling shearwaters impacted by plastic consumption from a remote Pacific island. Environmental Toxicology and Chemistry 40, 799-810.

United Nations, 2012. The future we want: Resolution adopted by the General Assembly on 27 July 2012. 66/288. United Nations General Assembly, New York.

van Franeker, J.A., Kühn, S., 2019. Fulmar litter EcoQO monitoring in the Netherlands – Update 2018, Wageningen Marine Research Report C077/19 & RWS Centrale Informatievoorziening BM 19.16, Utrecht, The Netherlands.

van Franeker, J.A., Law, K.L., 2015. Seabirds, gyres and global trends in plastic pollution. Environmental Pollution 203, 89-96.

van Franeker, J.A., Meijboom, A., 2002. Marine litter monitoring by Northern Fulmars (a pilot study), Alterra-rapport 401, Wageningen, pp. 1-72.

Vizzini, S., Signa, G., Mazzola, A., 2016. Guano-derived nutrient subsidies drive food web structure in coastal ponds. PLoS ONE 11, e0151018.

Wait, D.A., Aubrey, D.P., Anderson, W.B., 2005. Seabird guano influences on desert islands: soil chemistry and herbaceous species richness and productivity. Journal of Arid Environments 60, 681-695.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: An emerging area of research. Science of The Total Environment 598, 220-227.

Wickham, H., Averick, M., Bryan, J., Chang, W., D'Agnostino McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Lin Pederson, T., Miller, E., Milton Bache, S., Müller, K., Ooms, J., Robinson, D., Paige Seidel, D., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H., 2019. Welcome to the tidyverse. Journal of Open Source Software 4, 1686.

Wood, S.N., 2017. Generalized additive models: an introduction with R. CBC Press, Boca Raton.

Wood, S.N., 2019. mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation. R package version 1.8-31. https://cran.r-project.org/web/packages/mgcv/mgcv.pdf.

Work, T.M., Rameyer, R.A., 1999. Mass stranding of Wedge-tailed Shearwater chicks in Hawaii. Journal of Wildlife Diseases 35, 487-495.

Figure 1. The wing chord of Flesh-footed Shearwater fledglings was negatively related to the mass of ingested plastics in lavaged birds in some years, but not others

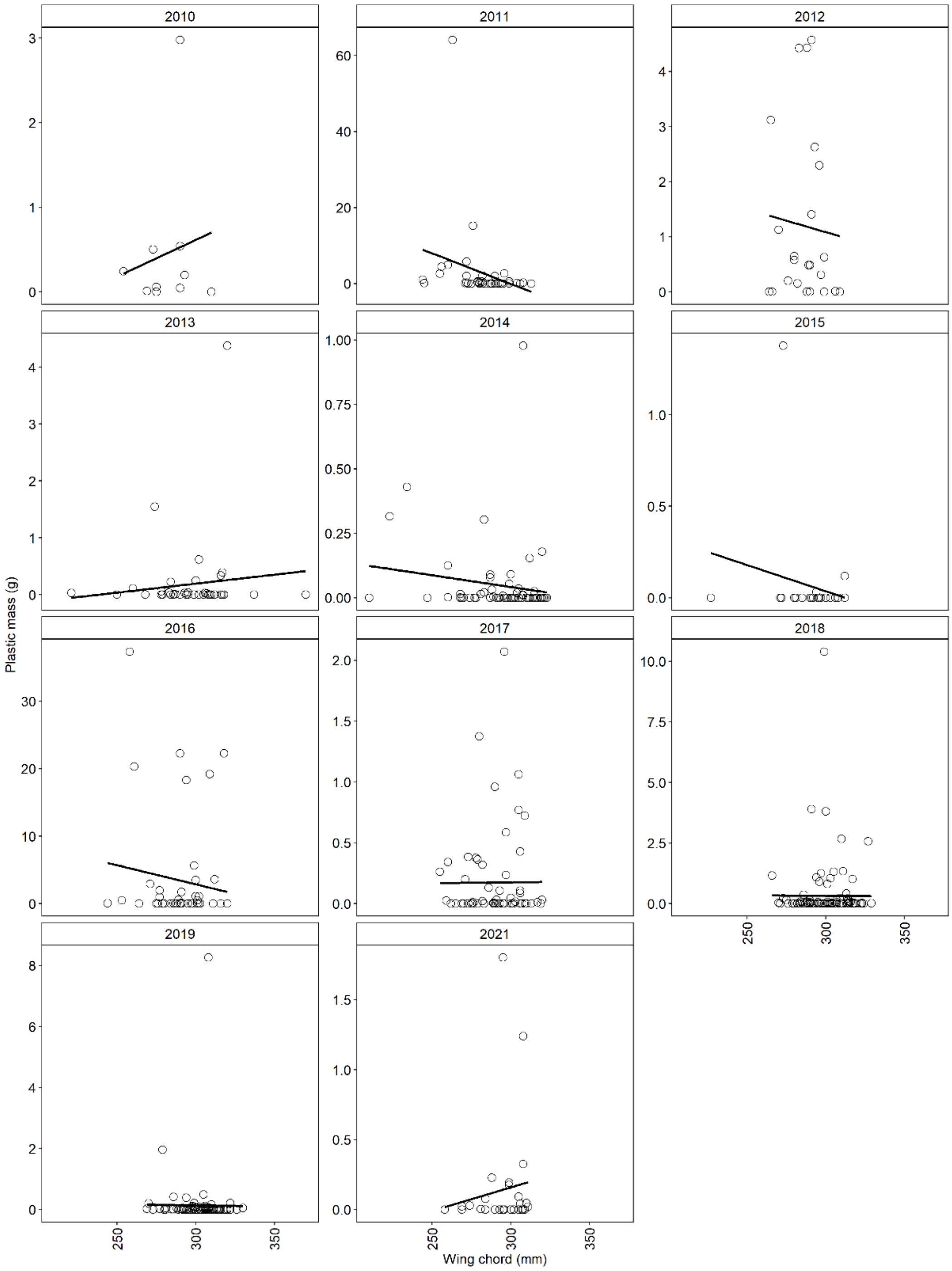

Figure 2. Power analysis graphs for ingested plastic by Flesh-footed Shearwater fledglings on Lord Howe Island during 2005-2021. Showing the number of individuals required to detect changes in plastic ingestion by source (sample type; see Methods). Frequency of occurrence (%FO), number of plastic items ingested, and mass (g) of ingested plastic.

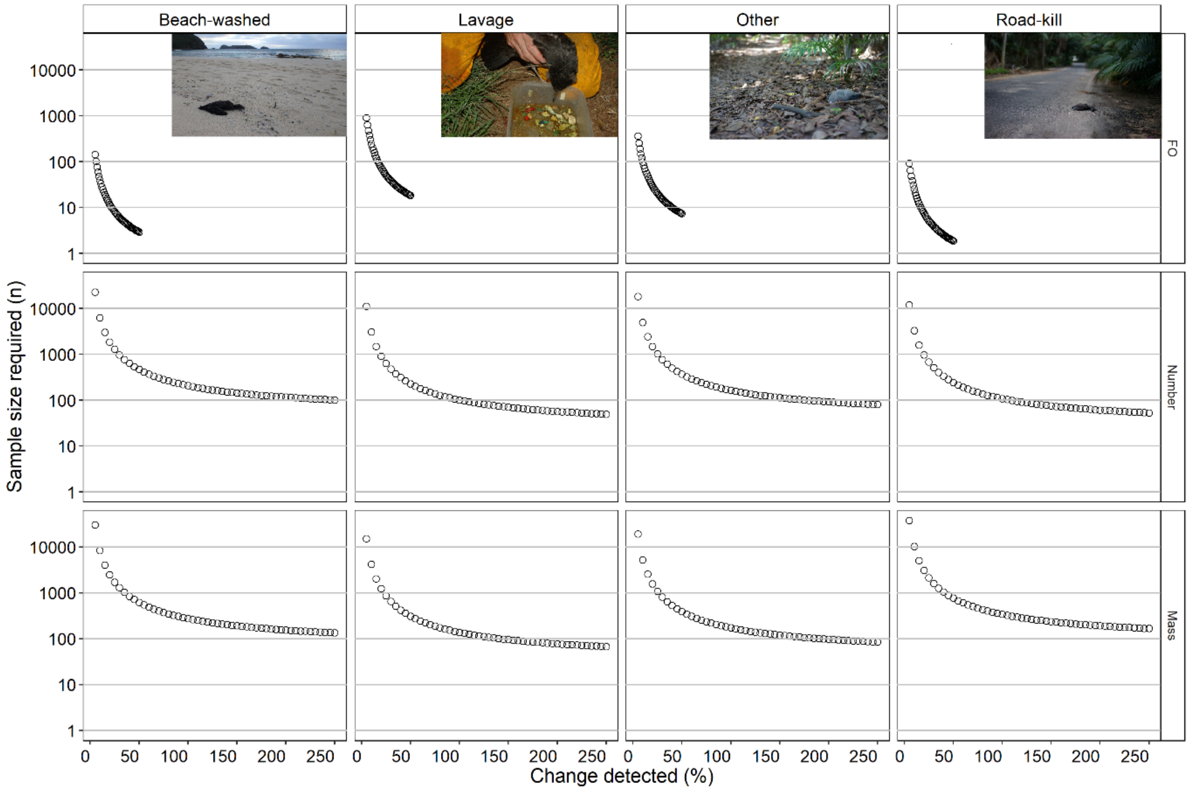

Figure 3. Number of ingested plastics in Flesh-footed Shearwater fledglings on Lord Howe Island during 2005-2021 by year and source (lavage of live birds, necropsy of recently deceased birds) showing the GAM-fitted curve (top panels) and boxplots with median, interquartile range (grey boxes), 95% percentiles (whiskers) and final outliers (bottom panels). The top two panels omit 35 cases (3%) of high numbers of plastics for visualisation only.

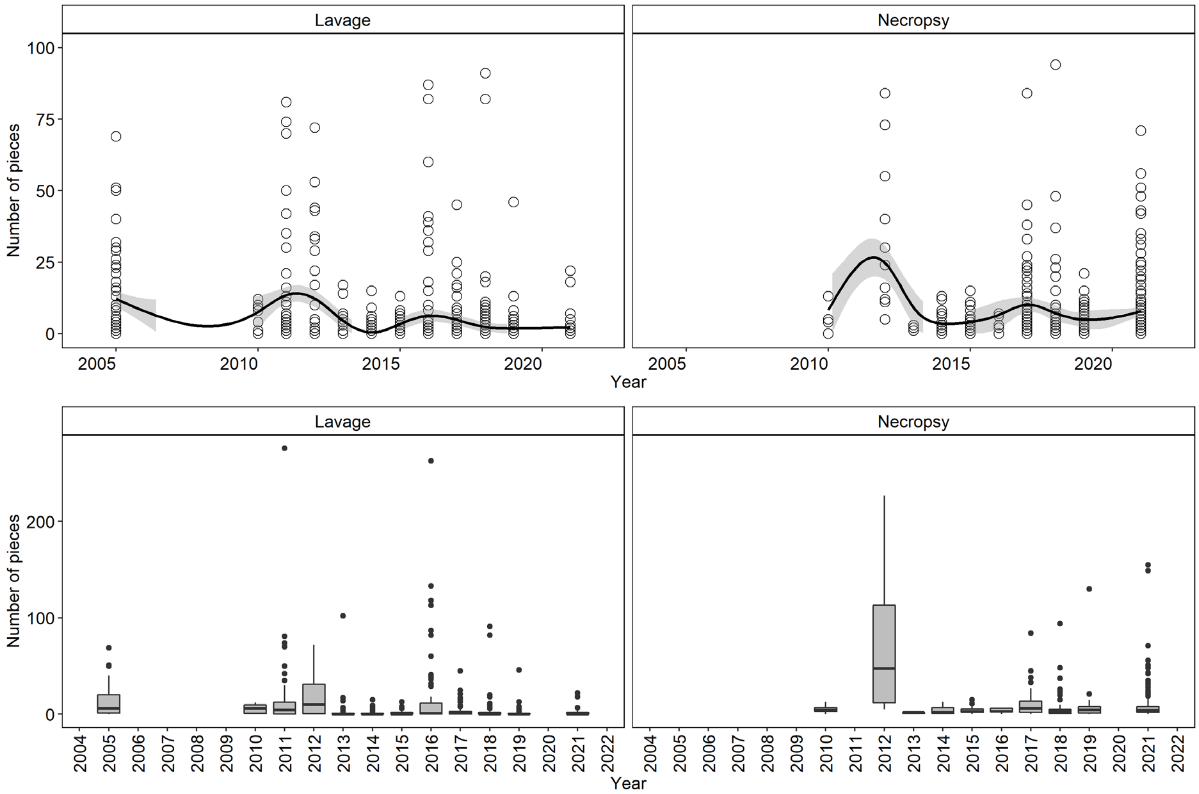

Figure 4. Number of ingested plastics in Flesh-footed Shearwater fledglings on Lord Howe Island during 2005-2021 by day of year and source (lavage of live birds, necropsy of recently deceased birds).