Seabird breeding islands as sinks for marine plastic debris

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Abstract

Seabirds are apex predators in the marine environment and well-known ecosystem engineers, capable of changing their terrestrial habitats by introducing marine-derived nutrients via deposition of guano and other allochthonous inputs. However, with the health of the world's oceans under threat due to anthropogenic pressures such as organic, inorganic, and physical pollutants, seabirds are depositing these same pollutants wherever they come to land. Using data from 2018-2020, we quantify how the Flesh-footed Shearwater (*Ardenna carneipes*) has inadvertently introduced physical pollutants to their colonies on Lord Howe Island, a UNESCO World Heritage site in the Tasman Sea and their largest breeding colony, through a mix of regurgitated pellet (bolus) deposition and carcasses containing plastic debris. The density of plastics within the shearwater colonies ranged between 1.32 – 3.66 pieces/m^2 (mean ± SE: 2.18 ± 0.32), and a total of 688,480 (95% CI: 582,409 – 800,877) pieces are deposited on the island each year. Our research demonstrates that seabirds are a transfer mechanism for marine-derived plastics, reintroducing items back into the terrestrial environment, thus making seabird colonies a sink for plastic debris. This phenomenon is likely occurring in seabird colonies across the globe and will increase in severity as global plastic production and marine plastic pollution accelerates without adequate mitigation strategies.

Capsule: Seabirds transport significant quantities of plastic to remote island

1. Introduction

Seabirds are well-known vectors for the movement of beneficial nutrients from their marine feeding grounds to their terrestrial breeding and roosting sites (Anderson and Polis, 1999; Zmudczynska-Skarbek and Balazy, 2017). Seabirds deposit these marine-derived nutrients (MDN), primarily nitrogen and phosphorous, via their guano, but also through the deposition of other allochthonous inputs such as eggs, carcasses and regurgitates (Ellis, 2005; Zwolicki et al., 2013). The addition of these MDN in colonies can create local 'hotspots' of biological productivity (Signa et al., 2012), whereby the soils are fertilized by guano and other inputs, which, in turn, stimulates primary and secondary production in the surrounding environment (Gonzalez-Bergonzoni et al., 2017; Payne and Moore, 2006; Sanchez-Pinero and Polis, 2000). The effects of large seabird colonies on terrestrial environments can be profound, particularly on remote, offshore islands where external nutrient subsidies are limited (Buelow et al., 2018).

However, it is not just nutrients that are transported by seabirds. Species at higher trophic levels often contain high concentrations of organic and inorganic pollutants due to bioaccumulation and biomagnification (Michelutti et al., 2009). These contaminants can come from the seabirds' prey (Corsolini and Sara, 2017), or from the ingestion of marine plastics that leach toxic chemicals (Lavers and Bond, 2016a; Tanaka et al., 2015). In the same manner as nutrients, seabirds transfer and deposit these contaminants in their terrestrial colonies, often in significant quantities (Blais et al., 2005). Transport of chemical pollutants by seabirds has been the focus of recent scientific interest, with an influx of papers exploring this topic in seabird species all over the globe (for example, see: Cheng et al., 2016; De La Pena-Lastra et al., 2019; Espejo et al., 2017; Otero et al., 2018; Shoji et al., 2019).

In contrast, there are few papers quantifying the transport of physical pollutants (i.e., plastics) from marine to terrestrial environments via seabirds (except see Bourdages et al., 2020; Buxton et al., 2013; Provencher et al., 2018), despite the abundance of literature regarding interactions between seabirds and plastics. Plastic pollution is ubiquitous throughout the world's oceans (Barnes et al., 2009; Cozar et al., 2014) and is a considerable threat to marine life (Gall and Thompson, 2015), particularly seabirds (Baak et al., 2020). Negative interactions include the entanglement in, and ingestion of, plastic pieces (Kühn et al., 2015). Ingestion of plastics can occur when an organism mistakes it for prey, due to its shape, colour, or scent (Savoca et al., 2016), or through secondary ingestion from the uptake of prey that contains ingested plastics (Hammer et al., 2016). The ingestion of marine plastic debris is reported for 44% of seabird species worldwide (Kuhn and van Franeker, 2020) and is predicted to increase in coming years, in line with increases in plastic production and subsequent pollution of the marine environment (Borrelle et al., 2020; Wilcox et al., 2015).

The ingestion of plastics by seabirds does not necessarily constitute the end-point for those plastics. Some seabirds are able to expel ingested items through regurgitating a pellet (bolus; Hays and Cormons, 1974; Fig. 1A), during feeding of chicks (with some spillage occuring; Carey, 2011), or via guano deposition (Provencher et al., 2018). Seabirds can excrete significant quantities of micro-plastics (<5 mm diameter; Barnes et al., 2009) via their guano, with one study estimating that Northern Fulmars (*Fulmarus glacialis*) and Thick-billed Murres (*Uria lomvia*) deposited 3.3 and 45.5 million plastic particles/year, respectively, within the study colonies during the breeding period (Bourdages et al., 2020). Additionally, plastics can be deposited in colonies through the death and subsequent decomposition of individuals containing ingested plastics (Hutton, 2004; Fig. 1B).

Procellariform seabirds (shearwaters, petrels, and albatrosses) are more prone to plastic ingestion than all other orders of seabirds (Roman et al., 2016), with Flesh-footed Shearwaters (*Ardenna carneipes*) documented to ingest considerable quantities. A recent study reported 21 ± 45 SD plastic items per bird (Lavers et al., 2019b), and estimated that in the past decade alone, the population may have declined by up to 50% in part due to the ingestion of plastics (Lavers et al., 2019a). Flesh-footed Shearwaters may therefore transport significant quantities of plastics to their terrestrial breeding grounds. Using plastic density data collected from the shearwater colony during 2018-2020, coupled with data from Lavers et al. (2019a) our aim was to quantify the annual deposition rate of plastics by Flesh-footed Shearwaters on Lord Howe Island.

2. Materials and Methods

2.1. Study site

Lord Howe Island (31°33'S, 159°05'E) is in the Tasman Sea, approximately 500 km off the east coast of Australia. The island supports diverse flora and fauna species with a high level of endemism, and was registered on the UNESCO World Heritage List in 1982 in recognition of the global significance of the island and its biodiversity (Hutton et al., 2007). Lord Howe Island is home to dense aggregations of seabirds, including around 22,000 pairs of Flesh-footed Shearwaters which breed in underground burrows in six colonies dispersed over the northern-half of the island (Ned's Beach, Middle Beach, Clear Place Point, Old Settlement Beach, Steven's Point, Little Muttonbird Ground; Lavers et al., 2019a)

2.2. Plastics sampling method

Five permanent 10 × 10 m quadrats were established in the Flesh-footed Shearwater colony at Clear Place Point in 2016. This colony was chosen as it is located at the top of a cliff, thus plastics found within the colony originate from the shearwaters, rather than from oceanic deposition, and it is a single species colony meaning plastics have not been deposited by other seabird species. Additionally, this colony is the most distant from the island's settlement, so it is unlikely that plastics in the colony were deposited either intentionally or unintentionally by humans, irrespective of this, the plastics deposited in the colony are typical of marine plastics and have weathered edges and slight discolouration caused by prolonged UV exposure (Marti et al., 2020; Fig. 1D). Initial cleaning and removal of all plastics (i.e., the 'standing stock'), suggested as best practice (Ryan et al., 2009), was completed during 2016 and 2017, prior to the first year of sampling in 2018.

Plastics from within each quadrat were collected at the end of the Flesh-footed Shearwater breeding season each year (mid-May) during 2018-2020. First, leaf litter (i.e., palm fronds and other large branches) from each quadrat were removed so that the sandy substrate was visible. All plastic items were then collected by hand from each quadrat. To do this, quadrats were swept twice from edge to edge by a team of up to six people moving in a line 2 m apart. The second collection was made perpendicular to the first to ensure all pieces were collected. Plastics were categorised into standardised classes following Lavers et al. (2014); van Franeker et al. (2004). Plastics were sorted into two broad type categories: industrial pellets (i.e., nurdles) and user plastics, with the latter further categorised into: hard fragments (including small pieces of packaging strap), sheet-like, threadlike, foamed, and other (e.g., melted plastic). Plastic colour categories used were white, blue/purple, green, yellow/orange, red/pink, and black/brown. The total mass of plastics per quadrat was weighed to 0.0001 g using an electronic balance. When boluses were encountered inside quadrats, the number and mass of plastic items found within each bolus was added to the total for the quadrat. Finally, the number of Flesh-footed Shearwater burrows in each quadrat was recorded.

2.3. Colony area and burrow density

The total surface area and burrow density for the six Flesh-footed Shearwater colonies on Lord Howe Island was estimated in 2018 and reported by Lavers et al. (2019a). In brief, the area of each colony was measured by walking the boundary with a handheld GPS (accuracy 3-10 m). Burrow density was estimated by using straight-line 2 m transects through each colony and counting the number of burrows (total transect area surveyed: 6240 m^2).

2.4. Statistical analysis

All analyses were conducted in R 4.0.2 (R Core Team, 2020). All data are reported as mean ± standard error (SE) in standardized measurements (i.e., items/m^2 and g/m^2). We compared the colours and types of plastics across years (pooling plastics from all five quadrats) with Jaccard's Index (J) of similarity, whereby a value of $J = 0$ indicates a complete dissimilarity and a value of $J = 1$ indicates a complete similarity. Results are significant when $J > 0.6$ (Real and Vargas, 1996). We tested for differences in the count of plastics across years using a generalized linear mixed-effects model with Poisson distribution, and used a general linear mixed-effects model to compare the mass of plastics across years. In both instances, quadrat was treated as a random effect and year was treated as a fixed effect. Burrow counts were only recorded for one quadrat in 2019. As such, we used a subset of our data (all quadrats in 2018 and 2020, and only Q3 in 2019) to determine if burrow count effected the count or mass of plastics. We used a generalized linear mixed-effects model with Poisson distribution, and a general linear mixed-effects model, respectively. Results were considered significant when $p < 0.05$.

To estimate the annual deposition rate of plastics to Lord Howe Island we extrapolated the count and mass of plastics in the quadrats to the total Flesh-footed Shearwater breeding area (all six colonies) by bootstrapping 10,000 iterations, and then calculating the annual deposition rate by multiplying this by the total colony area (31.63 ha; reported in Table 1 Lavers et al., 2019a). We present this as mean with 95% confidence intervals.

3. Results

3.1. Quadrat data over the years

Over the three years of sampling (2018 – 2020), 3265 pieces of plastics weighing a total of 783.45 g were collected from the five quadrats (Table 1). The mean across all quadrats and years was 2.18 ± 0.18 pieces/m^2 (range = 1.32 – 3.66 pieces/m^2) and 0.52 ± 0.04 g/m^2 (range = 0.29 – 0.95 g/m^2). The maximum number and mass of plastics in any given quadrat was recorded in 2018 in quadrat 2 with a total of 366 pieces weighing 95.06 g (3.66 pieces/m^2; 0.95 g/m^2). There was a significant difference in the count of plastics across years (χ^2 = 16.77, df = 2, $p < 0.05$), with a decrease in plastics in 2020. However, 2018 and 2019 had the exact same number of plastic items recorded (1143 pieces total; Table 1). The mass of plastics deposited across years was not significantly different (χ^2 = 1.70, df = 2, $p = 0.43$), nor did the density of burrows significantly affect plastic count (χ^2 = 0.87, df = 1, $p = 0.35$) or mass (χ^2 = 1.77, df = 1, $p = 0.18$).

Fragments were the most frequently encountered item across all years, accounting for 99.85% of all debris (Table 2; Fig. 1D). Minimal amounts of all other plastic types were recorded (< 3 items/category). Plastic type was highly similar across years, as indicated by Jaccard's Index, with all pairwise comparisons above the significance level (J = 0.99 – 1.00). White plastics accounted for 70.60% (n = 2305) of all items, followed by green (13.26%; n = 1043), and blue (10.84%; n = 710; Table 2). However, the proportions of colours remained similar across years (J = 0.86 – 0.94).

3.2. Annual plastic deposition

We estimate that the Flesh-footed Shearwaters are transporting and depositing 688,480 (95% CI: 582,409 – 800,877) pieces of plastics to their colonies on Lord Howe Island every year, weighing an estimated 165,204.00 g/year (95% CI: 141,060.50 – 192,763.60 g/year). This is the equivalent of 30.4 pieces (95% CI: 25.7 – 35.4 pieces) and 7.29 g (95% CI: 6.23 – 8.51 g) per breeding pair. Over the three years that our study took place (2018-2020), we estimate that the shearwaters have deposited 2,065,439 (95% CI: 1,747,226 - 2,402,631) pieces of plastics weighing 495.61 kg (95% CI: 423.18 – 578.29 kg).

4. Discussion

Seabirds are recognized as one of the most significant vectors for the movement of essential nutrients out of all animals on Earth (Marmen et al., 2017), yet they are also known to transport substantial quantities of pollutants as well (Celis et al., 2015; Signa et al., 2013). While most of the literature has focused on inorganic and organic pollutants, there is evidence some seabirds can transport plastics and other debris items from the marine environment to terrestrial environments (Bourdages et al., 2020; Provencher et al., 2018). Our study reinforces this concept, with the Flesh-footed Shearwaters on Lord Howe Island depositing substantial quantities of plastics every year.

The plastics commonly encountered within the shearwater colony were typical of both marine debris and plastics ingested by procellariform seabirds. White plastics accounted for a large percentage of all colours (70.60%; 2305 pieces). This corresponds with reported amounts, where 68% of all plastics ingested by the same species on Lord Howe Island were white in colour (Lavers et al., 2014), while white is the most common colour ingested by procellariform seabirds, such as Black-footed Albatross (*Phoebastria nigripes*; 75% of ingested plastics; Hyrenbach et al., 2017) and Bonin Petrel (*Pterodroma hypoleuca*; 64% of ingested plastics; Lavers and Bond, 2016a). White is one of the most abundant colours of floating marine plastics, and this increases with distance from land (Marti et al., 2020). It is possible that the abundance of white plastics both ingested by Flesh-footed Shearwaters and found within their colonies is correlated to their foraging locations. The same could be said about the intensity of hard plastic fragments encountered within our study. This type of plastic accounted for 99.85% (3260 pieces) of the total. This is again in line with both ingestion studies in seabirds (Hidalgo-Ruz et al., 2020) and marine plastic debris studies, where fragments dominate in the open ocean (Hammer et al., 2012; Moret-Ferguson et al., 2010).

Previous studies on the deposition of plastics by seabirds have reported exceptionally low amounts in comparison with our results. During 2011-2012, Buxton et al. (2013) reported a mean density of 0.013 items/m^2 in one colony that contained Flesh-footed Shearwaters, but also Little Shearwaters (*Puffinus assimilis*) and Grey-faced Petrels (*Pterodroma gouldi*), whereas a more recent study of two Flesh-footed Shearwater breeding colonies in Western Australia found only a single nurdle (Paterson and Dunlop, 2018). Differences in plastic loads could be attributed to varying plastic ingestion rates for this species. The shearwater population on Lord Howe Island is well-known to ingest significant quantities of plastics with 75 – 100% of sampled birds containing debris items (adults: 2.25 ± 2.22 pieces, fledglings: 17-21 ± 45 SD; Hutton et al., 2008; Lavers and Bond, 2016b; Lavers et al., 2014; Lavers et al., 2019b). However, in Western Australia, ingestion rates are still relatively high with 13% of adults (n = 136) and 100% of fledglings (n = 7) containing plastics (1.73 ± 1.22 pieces and 18.83 ± 34.45 SD, respectively; Lavers and Bond, 2016b). Little is known about the populations of Flesh-footed Shearwaters in New Zealand in regards to the severity of plastic ingestion, however, anecdotal information suggests 44% of adult birds recovered from fishing gear contained plastics (Bond and Lavers, 2011).

Possible differences observed between these three populations could also be attributed to foraging range and plastic densities in the marine environment. Flesh-footed Shearwaters breeding on Lord Howe Island forage in the Tasman Sea (Reid et al., 2012), while populations in eastern New Zealand typically forage within ~350km of their breeding islands in the western Pacific Ocean (Waugh et al., 2016), and those breeding along the southern coast of Western Australia forage within coastal waters (Lavers et al., 2018; Powell, 2009). Previous studies examining plastic concentrations in these regions are limited and suggest concentrations vary across years, with slightly higher concentrations recorded off Western Australia (1099.3 – 2852.6 pieces/km^2; Reisser et al., 2013) compared to the Tasman Sea (248 – 685 pieces/km^2; Reisser et al., 2013; Rudduck et al., 2017). This information conflicts with the ingestion rates for this species and suggests that there may be differences in foraging behaviours and strategies between the three shearwater colonies (e.g., as demonstrated in Laysan Albatrosses (Phoebastria immutabilis); Young et al., 2009), which in turn would influence plastic ingestion and subsequent deposition.

Burrow density has been suggested as an influencing factor determining the amount of plastics in a given colony, as demonstrated by Buxton et al. (2013) who found a positive relationship between the number of burrows and deposited plastics. However, in our study, burrow density did not affect the overall plastic count or mass. There are several other factors that may explain plastic deposition rates in seabird colonies. Most procellariform chicks regurgitate a single bolus prior to fledging (Carey, 2011; Hyrenbach et al., 2017). However, there is limited information on bolus production and deposition for many species, including Flesh-footed Shearwaters, thus it is unknown whether chicks regurgitate their boluses in the immediate vicinity of their burrow (i.e., within the same quadrat where burrows were counted). Chicks disperse over short distances around their burrows before fledging (Miskelly et al., 2009). In addition, plastics deposited through carcass decomposition, which could potentially contain higher amounts of plastics in comparison to boluses, occur where the bird dies, which could happen anywhere (e.g., within a colony, on a beach; Fig. 1B, C). Together, these two sources of plastic are independent of burrow location and may help explain the lack of relationship between burrow density and the number or mass of plastic items.

While our study has focused on meso- (5-20 mm diameter; Barnes et al., 2009) and macro-plastics (>20 mm) deposition through three main pathways (spillage, boluses, carcasses; Fig. 1), there is increasing evidence to suggest that seabirds can excrete micro-plastics (<5 mm) via their guano (Bourdages et al., 2020; Provencher et al., 2018). We did not account for micro-plastics transported and deposited by guano in our study, but given the high amounts of macro-plastics deposited by Flesh-footed Shearwaters, and the presence of small micro-plastics in the birds themselves (Lavers et al., 2019c), it is highly likely that they are also excreting plastics through their guano and from carcass decomposition. This would add a layer of complexity to the current study but would yield important results.

Previous studies have identified four possible sinks for marine plastics: 1) biofouling (fouled plastics can have higher densities than seawater, resulting in sinking), 2) ingestion by wildlife, 3) nano-fragmentation (leading to sinking), and 4) shore deposits (Cozar et al., 2014). While marine organisms, particularly seabirds, do ingest plastics, our study indicates wildlife is not always the end point for these items. Additional reservoirs for plastics include debris used as nesting material by seabirds (Grant et al., 2018; Jagiello et al., 2019). Several seabirds collect nest material from the sea surface (e.g., Northern Gannets (*Morus bassanus*); O'Hanlon et al., 2019), transporting plastics to their terrestrial breeding colonies. We suggest that seabirds are vectors for marine-derived plastics, whereas their colonies are the sinks. With many seabird species residing on remote, uninhabited islands, plastics are frequently being introduced to otherwise pristine environments, creating ‘plastic islands’ in the process. This suggests policies and legislation currently in place to protect seabird breeding islands including World Heritage status or marine parks (Lord Howe Island has both) do not prevent the deposition of plastic items by birds on land.

5. Conclusion

Our results clearly demonstrate the pollution of terrestrial habitats with plastics resulting from the deposition of boluses and decomposition of seabird carcasses at seabird breeding sites. While this study focused on Flesh-footed Shearwaters from one breeding island, this phenomenon is likely occurring in seabird colonies worldwide for the 180 species that ingest plastics (Kuhn and van Franeker, 2020). This is alarming, particularly when considering that plastics are not inert and can change soil physiochemical properties (e.g., lowered pH; Boots et al., 2019), soil microbial activity (de Souza Machado et al., 2018), affect nitrogen cycling processes (Seeley et al., 2020), and cause oxidative stress and initiate avoidance behaviour in soil invertebrates (Pflugmacher et al., 2020). This raises the question; what is happening within the colonies on Lord Howe Island and on other seabird islands? Not only are they becoming sinks for marine-derived plastics, but there is potential for negative impacts on soil communities leading to cascading effects on terrestrial ecosystems. Current mitigation strategies are not sufficient, thus there is a serious need to improve strategies already in place and create new policies to combat marine pollution (Borrelle et al., 2017). However, prevention is better than cure, and in this case, preventing plastics from entering marine environments is of paramount importance (Law, 2017), for it is easier to prevent plastics from entering these environments than it is to remove them (Schmaltz et al., 2020).

CRediT authorship contribution statement

Megan L. Grant: Formal Analysis; Investigation; Writing – Original Draft; Writing – Review and Editing; Visualization; Funding Acquisition. **Jennifer L. Lavers:** Investigation; Writing – Review and Editing; Project administration; Supervision; Funding Acquisition. **Ian Hutton:** Conceptualization; Methodology; Resources; Investigation; Writing – Review and Editing. **Alexander L. Bond:** Formal Analysis; Investigation; Writing – Review and Editing; Project administration; Supervision; Funding Acquisition.

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7. Figures

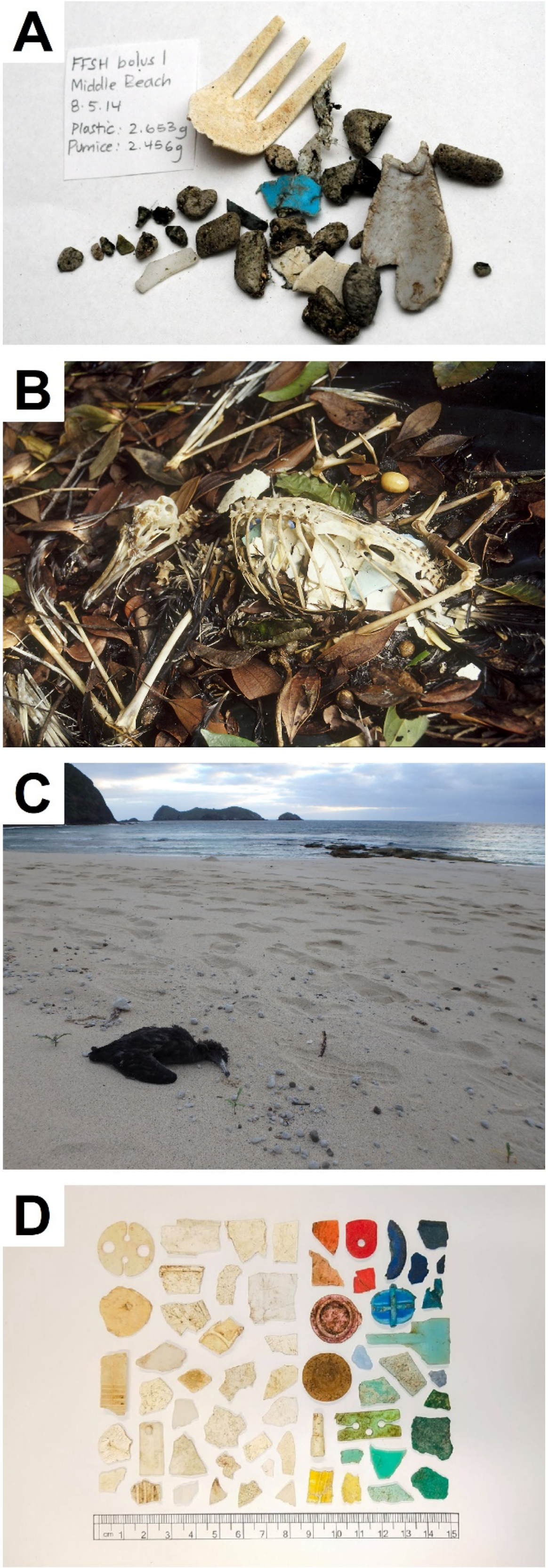

Fig. 1. Plastics can be deposited within seabird colonies through regurgitation and bolus production (panel A), or from the death and decomposition of birds with ingested plastics

(panel B). Not all birds die within colonies, however, with some washing up on beaches (panel C). Plastics commonly encountered within the colonies were hard plastic fragments in the meso-plastic size class (5-20 mm), with few macro-plastics (>20 mm; panel D). Source: S. Stuckenbrock (A; 2014), I. Hutton (B; 2002), A. Bond (C; 2017), M. Grant (D; 2021).

8. Tables

Table 1

Summary statistics of plastics recovered from five permanent 10 × 10 m quadrats within the largest Flesh-footed Shearwater (*Ardenna carneipes*) colony (Clear Place Point) on Lord Howe Island during 2018-2020. N = the total number of plastics per year from all five quadrats. Data are reported in standardised metrics (m^{-2}). Years that share the same superscript have plastic densities that are not significantly different from each other. There was no significant difference in plastic mass among years.

		Density (pieces/m^2)		Mass (g/m^2)	
Year	**N**	**Mean ± SE**	**Range**	**Mean ± SE**	**Range**
2018	1143	2.29 ± 0.39^{a}	1.64 - 3.66	0.59 ± 0.10	0.40 - 0.95
2019	1143	2.29 ± 0.27^{a}	1.40 - 2.90	0.51 ± 0.06	0.30 - 0.65
2020	979	1.96 ± 0.33^{b}	1.32 - 2.99	0.46 ± 0.06	0.29 - 0.60
Overall	**3625**	**2.18 ± 0.32**	**1.32 - 3.66**	**0.52 ± 0.07**	**0.29 - 0.95**

Table 2

The summary and frequency of occurrence (FO; %) of types and colours of plastics recorded in quadrats over 2018-2020. Fragments were the most ubiquitous type, whereas there was more variation in colour.

	Category	**N**	**FO (%)**
Type	Fragment	3260	99.85
	Sheet	2	0.06
	Thread	1	0.03
	Other	1	0.03
	Nurdle	1	0.03
	Foam	0	0.00
Colour	White	2305	70.60
	Green	433	13.26
	Blue	354	10.84
	Red	116	3.55
	Yellow	38	1.16
	Black	19	0.58