

Long-term decline in fledging body condition of Flesh-footed Shearwaters (*Ardenna carneipes*)

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Marine systems are under increasing pressure from anthropogenic activities. In recent decades, the deteriorating condition of the world's seabird populations suggests these pressures have reached a tipping point. For young birds, body mass can significantly influence survival in the critical period between nest departure and recruitment to the breeding population. On Lord Howe Island, we measured Flesh-footed Shearwater (*Ardenna carneipes*) fledglings in the colony and adjacent beaches to determine how body condition changed during 2010–2022. Overall, we found chick body mass as well as wing, culmen, and head + bill length declined over time with larger declines observed in beach-washed birds. Culmen and head + bill length declined by 0.17 and 0.23 mm/year, respectively, and body mass by 16.1 g/year. The number of chicks fledging at <400 g has increased sharply in recent years, meaning significant numbers of birds are unlikely to survive after departing the island. Our results point to a deepening of the division in the shearwater population: adult birds who can successfully provision sufficient nutrient reserves so their chick fledges successfully, and those who cannot. In this latter group, failure at the fledging stage (beached birds) is resulting in birds in increasingly poor condition, the likes of which were seldom documented 13 years ago.

Keywords: long-term monitoring, morphology, plastic ingestion, seabird health, time series.

Introduction

Marine systems are under increasing and often intense pressure from anthropogenic activities that encompass all corners of the globe and include noise, chemical and physical pollutants, habitat destruction through offshore development, and invasive species (Halpern *et al.*, 2008; Halpern *et al.*, 2019). These pressures do not occur in isolation, instead, the impact on marine species can be cumulative and even synergistic (Côté *et al.*, 2016; Halpern *et al.*, 2019). In recent decades, the deteriorating condition of many of the world's seabird populations (Dias *et al.*, 2019) indicates that for many species, and in many parts of the globe, these pressures have reached a tipping point and are resulting in population declines, decreased resilience to new pressures (Falchieri *et al.*, 2022), and even extirpation or extinction (e.g. Jones *et al.*, 2008).

Across years and locations, how species respond to factors such as ocean warming or changes in prey availability can differ depending on their diet, ability to adjust time budgets, and other factors (Piatt *et al.*, 2007; Paiva, 2022). As top predators, understanding seabirds' responses is fundamental to biodiversity conservation due to their threatened populations, importance in marine ecosystems, and society's reliance on seabirds as bioindicators of ocean health (Orgeret *et al.*, 2022). For many studies, young seabirds are more accessible, thus it is important to understand how anthropogenic pressures that impact adult seabirds can modify the relationship with their chicks by altering parental body condition and provisioning (O'Dwyer *et al.*, 2006; Doody *et al.*, 2008; Divoky *et al.*, 2021), and consequently affecting chick growth and survival (Major *et al.*, 2006).

Among birds, survival rates between nest departure and recruitment to the breeding population can be variable but

are an important parameter in population dynamics (Maness and Anderson, 2013). Chick body mass significantly influences survival during this period, with relatively small increases in departure mass leading to substantially improved survival (Sagar and Horning, 1998; Ronget *et al.*, 2018). In seabirds, chicks with shorter wings are also less likely to survive to recruitment (Morrison *et al.*, 2009; Maness and Anderson, 2013). For adult seabirds, the timing of breeding is generally inflexible (Keogan *et al.*, 2018), and in many Procellariiformes, adult birds depart the colony prior to chick fledging so that chicks must rely on their own body reserves for some period before they, too, depart (Brooke, 2004). Chicks can also prioritize some areas for growth over others during times of nutritional stress, such as Atlantic Puffins (*Fratercula arctica*) who prioritized growth in wing length and head size over other measures, including body mass and tarsus (Øyan and Anker-Nilssen, 1996). Chicks' fledgling size is therefore a function of parental provisioning, the length of time between parental abandonment and fledging, and individual resource allocation within chicks.

Lord Howe Island, Australia, is the largest Flesh-footed Shearwater (*Ardenna carneipes*) population globally and has declined substantially in the past decade (Lavers *et al.*, 2019a). Pressures on the island include loss of habitat and invasive species, though a recent campaign may have succeeded in removing both house mice (*Mus musculus*) and black rats (*Rattus rattus*) (Harper *et al.*, 2020). Bycatch in domestic and international fisheries causes the mortality of large numbers of birds in some years (Reid *et al.*, 2012; Reid *et al.*, 2013b). The population is highly affected by plastic pollution (Lavers *et al.*, 2021) and metal contaminants relative to other Flesh-footed Shearwater colonies with Lord Howe Island birds having ele-

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vated mercury concentrations compared with populations in western Australia and New Zealand (Bond and Lavers, 2011). We captured and measured fledglings on the colony surface and on adjacent beaches to determine how body condition at fledgling has changed over more than a decade of environmental change and population pressures.

Methods

Between late-April and mid-May 2010–2022, we recorded morphometrics of fledgling Flesh-footed Shearwaters as part of a long-term monitoring programme on Lord Howe Island, New South Wales, Australia (31.53°S, 159.07°E; Supplementary Table S1; Lavers *et al.*, 2021). As fledging and other breeding parameters are highly synchronous in this species and other Procellariiform seabirds (Marchant and Higgins, 1990), the Flesh-footed Shearwater chicks were all captured at 80–90 d of age. Chicks were captured by hand, either randomly sampled from the colony at night (“colony birds”) from three of the six colonies on the island or recorded on the beach in the early morning after an unsuccessful fledging attempt (“beach-washed”). Beach-washed birds were also collected from one of three locations along the beach: retrieved from shallow water along the shoreline, along the high-tide mark, or in the fore-dune. Most of the birds in the latter two groups were either too lethargic/emaciated or died before reaching the water. For each bird, we recorded body mass (± 10 g) using a spring balance, flattened and straightened wing chord (± 1 mm) using a stopped ruler, and head + bill, and culmen length (± 0.1 mm) using Vernier callipers. Measurements were recorded by the same, experienced team members (JL, AB) for the duration of the study. For colony birds, a numbered, metal band was applied to the leg.

All statistical analyses were conducted in R 4.2.1 (R Core Team, 2022). We examined the relationships between chick body mass, wing chord length, and head + bill and culmen length using mixed models, and included whether the chick was from the colony or beach-washed as a fixed factor, and year as a random categorical factor to account for interannual variability that might be caused by confounding factors such as food availability, which is presumably influenced by broader oceanographic conditions. To examine changes over time, we used linear models with the year as a continuous variable.

Sagar and Horning (1998) reported that for Sooty Shearwaters (*Ardenna griseus*), chicks that recruited into the breeding population had a minimum fledging mass of 564 g (69% of the adult body mass of 819 g; Warham, 1982). Extrapolating this to Flesh-footed Shearwaters on Lord Howe (mean adult body mass: 583 g; author’s unpublished data) would imply a minimum fledging mass of 400 g of recruits. We examined the proportion of all chicks that exceeded this threshold annually and used a linear regression to evaluate change over time. In all analyses, results were considered significant when $p < 0.05$, and we report Cohen’s d as a measure of effect size (Cohen, 2013), using Sawilowsky (2009) guidance on interpretation.

Results

Chicks that were beach-washed ($n = 499$) had lower body mass than birds from the colony ($n = 663$; $\chi^2_1 = 1034.9$, $p < 0.001$) with a huge effect size ($d = 2.11$, 95% CI: 1.94–2.28), and in both groups fledging mass declined over

time ($F_{1,1158} = 655.55$, $p < 0.001$), though at a more rapid rate for beached birds (interaction term: $F_{1,1158} = 4.92$, $p = 0.027$; Figure 1a). Overall, the mean mass of birds captured in the colony declined from 687 g in 2010 to 540 g in 2022, a reduction of 12.3 g/year, while for beached birds the decline was from 488 to 278 g, a reduction of 17.5 g/year.

Chicks’ wing chord was also shorter in beached birds ($n = 496$) than colony birds ($n = 629$; $\chi^2_1 = 467.9$, $p < 0.001$; Figure 2) with a large effect size ($d = 1.43$, 95% CI: 1.27–1.59, and changed over time in both groups ($F_{1,1121} = 129.83$, $p < 0.001$), though in different directions (interaction term: $F_{1,1121} = 56.57$, $p < 0.001$). In colony birds, the mean wing chord increased from 287 to 299 mm (ca. 1 mm/year), while in beached birds it declined from 280 to 248 mm, a decrease of 2.7 mm/year (Figure 1b).

Culmen length did not differ between beached and colony birds ($\chi^2_1 = 0.4$, $p = 0.53$; Figure 2) with no effect size ($d = 0.04$, 95% CI: -0.10–0.18), and declined across both groups ($F_{1,1127} = 113.66$, $p < 0.001$) at the same rate (interaction term: $F_{1,1127} = 0.029$, $p = 0.86$). In colony birds, the mean culmen length decreased from 41.6 to 39.5 mm, while in beached birds it went from 41.4 to 39.1 mm; in both cases, a decrease of ~ 0.19 mm/year (Figure 1c).

Finally, head + bill length was shorter in beached birds ($n = 477$) than colony birds ($n = 634$; $\chi^2_1 = 19.7$, $p < 0.001$), but with a small/medium effect size ($d = 0.30$, 95% CI: 0.15–0.44). It also declined over time ($F_{1,1107} = 61.20$, $p < 0.001$), and there was no significant difference between the two groups (interaction term: $F_{1,1107} = 3.01$, $p = 0.08$). The mean head + bill length of colony birds decreased from 93.3 to 91.7 mm (-0.12 mm/year), and beached birds decreased from 93.0 to 90.0 mm (-0.23 mm/year; Figure 1d).

Over the course of our study, the proportion of fledglings from all sources >400 g declined significantly ($F_{1,10} = 29.9$, $p < 0.001$) from 100% in 2010 and 2011 to 27% in 2021 and 36% in 2022, at a rate of -5.1% per year (Figure 3).

Discussion

On Lord Howe Island, body mass of Flesh-footed Shearwater chicks has declined markedly over the past 13 years (Figure 1a). This was especially the case in chicks found beach-washed; their low body mass (and thus energy reserves) likely contributed to the unsuccessful fledging attempt. Even in “good” years (such as 2010), beach-washed birds (many of which are still alive) were around 30% smaller than birds encountered at random in the colony. More recently, the condition of beach-washed birds has declined such that their body mass was only $\sim 40\%$ of colony birds [i.e. they were 60% smaller with beached birds commonly found weighing as little as 170–210 g during 2021 and 2022; the mean \pm SD adult body mass is 583 ± 97 g (authors’ unpublished data)]. Because fledglings are becoming smaller, as time has gone on, individual birds have an increasing and substantial amount of growth they must achieve in order to “catch up” to equivalent-aged chicks from a decade ago before reaching the age of recruitment.

In seabirds, fledglings and pre-breeders often experience high mortality as this critical period hinges upon flight and foraging capacity, which improve slowly over time (Corbeau *et al.*, 2020). Wing loading ratio, a measure of bird wing and body size, has a significant effect on flight efficiency; therefore, the length of a bird’s wing is fundamental to the speed

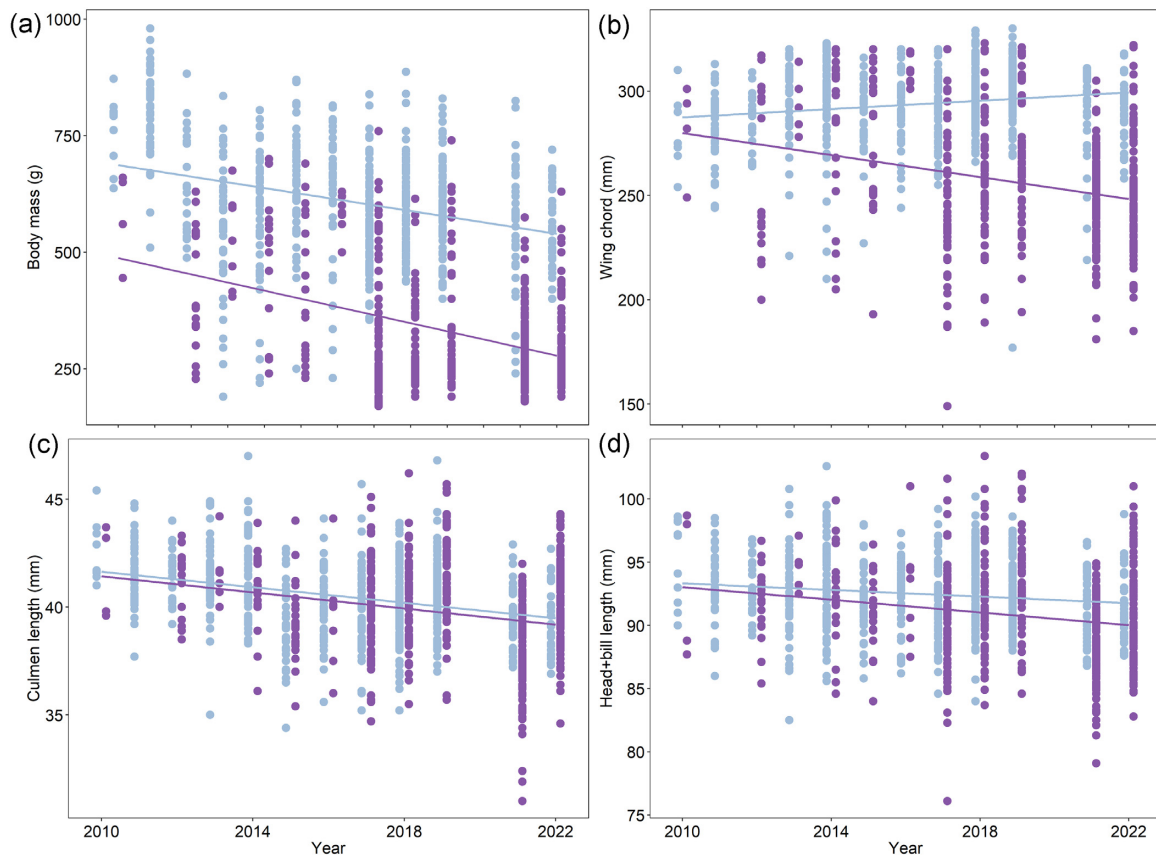


Figure 1. Trend in fledging Flesh-footed Shearwater body mass (g; panel a), wing chord length (mm; b), culmen length (mm; c), and head + bill length (mm; d) on Lord Howe Island during 2010–2022 ($p < 0.001$ for all measurements; please also refer to the Results section). Light blue: colony birds; dark purple: beachwashed birds.

and distance it can travel (Brewer and Hertel, 2007) and the depth it can dive to pursue prey (Watanabe *et al.*, 2011). Unsurprisingly, in Tufted Puffins (*Fratercula cirrhata*), wing length at fledging was a strong predictor of juvenile survival, where birds with longer wings had higher survival rates (Morrison *et al.*, 2009), a pattern also seen in Nazca Boobies (*Sula grantii*), though this may be driven by sex differences (Maness and Anderson, 2013). In Flesh-footed Shearwaters, as with many seabirds, the wing chord continues to grow after fledging until it reaches adult size (312 ± 20 mm; authors' unpublished data; Powell *et al.*, 2007). We saw reductions in wing chord length of 32 mm (>10% of adult wing length) between 2010 and 2022 in beached birds (Figure 2), and a slight increase in the wing chord of chicks captured in the colony. This suggests that the allocation of resources to wing growth differs between these two sources of chicks (Øyan and Anker-Nilssen, 1996), and further emphasizes the poor nutritional condition of beached birds. Beached birds are those who have attempted to fledge, but have failed with many being pushed back to shore by currents or wind. Birds with shorter and less-developed wings would be less able to fly or swim strongly (Figure 2), so the difference between beached and colony birds is unsurprising.

Both measurements of shearwater head size (culmen and head + bill length) declined significantly over time in our study, with larger reductions observed for beach-washed birds (Figure 1). Reduced head size measurements (linked with gape size) can impact both the size and number of fish seabirds are

able to consume during prey capture events (Swennen and Duiven, 1977; Hulsman, 1981; van Heezik, 1990). Such alterations to the foraging ability of fledgling shearwaters could be detrimental to young birds that are inexperienced at flying and feeding themselves and may also be experiencing low energy reserves (i.e. low body mass; Figure 1). Birds with smaller heads (which are likely to be smaller overall) may be less able to compete with larger seabirds, such as albatrosses (Heswall *et al.*, 2021), which is likely as Flesh-footed Shearwaters are a gregarious, ship-following species (Bartle, 1974; Wood, 1990). It may also indicate incomplete cognitive development as the cranium volume will be lower. This in turn could affect foraging efficiency and migratory behaviour, and ultimately individuals' survival (Wagnon and Brown, 2020).

Together, these results point to a division in the shearwater population: those who can successfully provision sufficient nutrient reserves so that their chick fledges successfully, and those who cannot. While such divisions also exist in putative healthy seabird populations (e.g. synchronous breeding pairs experience better fledging success; Cleeland, 2011), the failure of Flesh-footed Shearwaters at the fledging stage (as beached birds) is clearly resulting in birds in increasingly poor condition (Figure 2), the likes of which were seldom documented 13 years ago. The consequences for the adult population are as yet unknown, as most of the birds in our study have not yet had time to recruit to the breeding population (age of first breeding is 4–5 years; authors pers. obs.). However, change in adult bird body size as a response to environmental pressures,



Figure 2. (a) Fledgling Flesh-footed Shearwaters on Lord Howe Island in May 2022: (left) a healthy chick collected in the colony (hit by a motor vehicle) and (right) a similar age bird found washed up on the beach with substantially lower body mass, shorter wing length, and downy feathers. (b) Fledgling Flesh-footed Shearwaters on Lord Howe Island in May 2022: (left) a healthy chick collected in the colony (hit by a motor vehicle) and (right) a similar age bird found washed up on the beach with substantially lower body mass, shorter wing length, and downy feathers.

mainly climate change, is well documented in many species over short ecological time scales (Weeks *et al.*, 2020) and could impact the utility of other management tools like discriminant functions to predict the sex of bycaught birds (Thalman *et al.*, 2007).

The most recent assessment of Flesh-footed Shearwater population size on Lord Howe Island found a significant decline over the past decade (Lavers *et al.*, 2019a), following a long period of decline since the late-1970s (Fullagar *et al.*, 1974; Priddel *et al.*, 2006; Reid *et al.*, 2013a). Our body condi-

tion data, as well as data on other population pressures such as contaminants (Bond and Lavers, 2011; Bond and Lavers, 2020; Szabo *et al.*, 2020) and plastics (Lavers *et al.*, 2014; Puskic *et al.*, 2019; Lavers *et al.*, 2019b, 2021; Charlton-Howard *et al.*, 2023; Keys *et al.*, 2023; Rivers-Auty *et al.*, 2023) overlap much of this same period and suggest a population under increasing pressure, which may explain some of the recent decline in numbers. A paper by Wilcox *et al.* (2021) suggested the Flesh-footed Shearwater population increased substantially over roughly the same period (2008–2015), and we

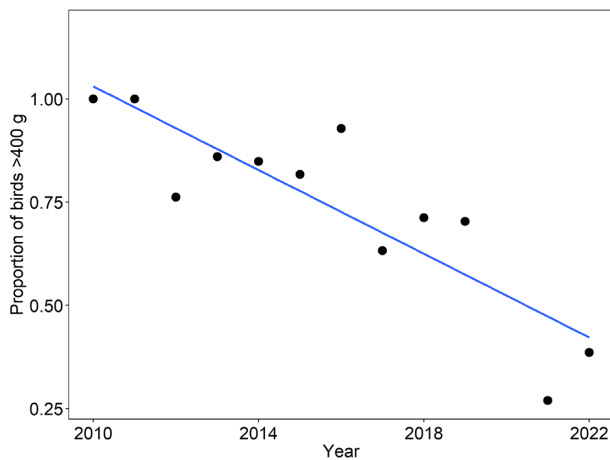


Figure 3. Proportion of fledging Flesh-footed Shearwaters encountered on Lord Howe Island with a body mass >400 g during 2010–2022.

recognize the reductions in fisheries bycatch (Reid *et al.*, 2012) and road mortality (Wilcox *et al.*, 2021) that have lessened pressures on the shearwaters. However, the suggestion that this iconic species of Lord Howe Island is secure ignores a substantial corpus of literature, to which our current study adds. The assessment by Wilcox *et al.* (2021) also contrasts with substantial feedback from the Lord Howe Island community, which suggests the number of Flesh-footed Shearwater burrows and birds has declined (community members' pers. comm.). In Aotearoa New Zealand, a larger number of Flesh-footed Shearwaters recorded at some breeding islands has been attributed to more targeted monitoring and advances in technology rather than an increase in the population (Burgin and Lamb, 2022). Our results for Lord Howe Island provide support for this with more birds detected using higher resolution burrow inspection cameras (Lavers *et al.*, 2019a).

Beached birds are overall in poorer condition, and their condition has declined faster than in colony birds. This is perhaps unsurprising, as beached birds are beached for a reason, usually a lack of energy reserves, starvation, or incomplete development. They also have higher plastics burdens (Lavers *et al.*, 2021), and therefore the concomitant stresses that accompany it (Lavers *et al.*, 2019b; Charlton-Howard *et al.*, 2023; Rivers-Auty *et al.*, 2023), thus the cause/effect relationship between body condition and plastics (are they in poor condition because they have been fed plastics, or are they fed plastics because they are in such poor condition to begin with) remains elusive.

Ultimately, the consequences of the fledging body condition declines reported here are not yet known. The huge proportion of birds that are potentially unlikely to recruit to the breeding population is worrying, and would support the conclusions of Lavers *et al.* (2019a) that the population is more likely to be in decline. Globally, seabirds are under increasing pressure from well-established and emerging stressors on individuals and populations. Understanding the period between fledging and recruitment is an area with significant research gaps and little knowledge, but one that has demonstrable impacts on breeding populations. For declining species, and those with low fecundity, it is increasingly urgent to diagnose and mitigate the causes of these declines. For Flesh-footed Shearwaters, the driving force behind population trends and the clear decline in fledging body condition are unknown,

but given the alleviation of many of the previously identified threats (invasive species, fisheries bycatch, and road mortality), other pressures should be examined (Gaze, 2000).

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Supplementary Data

Supplementary material is available at the ICESJMS online version of the manuscript.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution

J.L.L.—Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, and Writing-Original draft.

A.L.B.—Data curation, Funding acquisition, Investigation, Project administration, Formal analysis, and Writing-Original draft.

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Data availability

Data are available on figshare: <https://figshare.com/s/0764d6ceef0f8ec79085>

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