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Changes in technology and imperfect detection of nest contents impedes reliable estimates of population trends in burrowing seabirds

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ABSTRACT

One of the most fundamental aspects of conservation biology is understanding trends in the abundance of species and populations. This influences conservation interventions, threat abatement, and management by implicitly or explicitly setting targets for favourable conservation states, such as an increasing or stable population. Burrow-nesting seabirds present many challenges for determining abundance reliably, which is further hampered by variability in the quality of previous surveys. We used burrow scopes to determine the population status of Flesh-footed Shearwaters (*Ardenna carneipes*) at their largest colony on Lord Howe Island, Australia, in 2018. We estimated a breeding population of 22,654 breeding pairs (95% CI: 8159–37,909). Comparing burrow scope models used in 2018 found more than half of burrow contents (20/36 burrows examined) were classified differently. If this detection probability is applied retroactively to surveys in 2002 and 2009, we estimate that the Flesh-footed Shearwater population on Lord Howe has decreased by up to 50% in the last decade, but uncertainty around previous surveys' ability to reliably determine burrow contents means a direct comparison is not possible. The decline in burrow density between 2018 and previous years adds further evidence that the population may not be stable. Our results highlight a need for regular surveys to quantify detection probability so that as video technology advances, previous population estimates remain comparable. We urge caution when comparing population counts of burrowing seabirds using different technologies, to ensure comparisons are meaningful.

1. Introduction

Seabirds are among the fastest declining groups of birds (Croxall et al., 2012), with populations affected negatively by introduced predators, bycatch in fisheries, pollution, habitat loss, depletion of food prey, climate change, and human exploitation (Cury et al., 2011; Phillips et al., 2016; Žydelis et al., 2013). While mitigation measures have been implemented, assessing their efficacy requires accurate assessments of population sizes over time, and the number of breeding pairs is also a key indicator for many species' recovery and management plans (Commonwealth of Australia, 2018).

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Determining population sizes of seabirds can be challenging, particularly for species that breed in burrows or crevices underground (Savard and Smith, 1985; Schumann et al., 2013). Unlike surface-nesting species where visual observations can be used to estimate the number of breeding pairs, burrow-nesting species are more difficult to survey – not all burrows are necessarily occupied, and determining occupancy is a field of much discussion and methodological refinement (Harding et al., 2005; Johnson, 2008; Jones et al., 2003; Renner et al., 2006).

A variety of methods have been used to assess burrow occupancy, including examination of burrow characteristics (e.g., fresh digging, presence of cobwebs or vegetation; Abbott, 1981; Dyer, 2001), response to audio playback of conspecific vocalizations (Hamilton, 1998; Ratcliffe et al., 1998), physically removing birds from burrows ("grubbing"; Ambagis, 2004), or using video cameras with external displays (burrow scopes) to view burrow contents (Dyer and Hill, 1991; Rexer-Huber et al., 2014). All methods have varying degrees of reliability and rates of detection, which can also vary through the breeding season, with environmental conditions (e.g., moon phase, rainfall), or with the quality of technology.

Burrow scopes are often considered the most reliable, because they do not rely on individuals' response to a stimulus, like playback, are less invasive than 'grubbing' (Ambagis, 2004), and are less subjective than examining burrow characteristics (Rexer-Huber et al., 2014). But detection is not perfect, and some burrows may be too long, or too angled to assess the contents reliably (Lyver et al., 1998). Rapid technological advances in video quality and transmission method have improved the quality of the imagery, and the cost of equipment has decreased. Consequently, the ability of different burrow scope models to detect an active nest varies considerably, which makes comparisons among surveys challenging (much as with conventional survey techniques for surface-nesting species; e.g., ACAP, 2009).

Previous surveys to determine population estimates for seabirds have used a variety of techniques in the field, and statistical approaches, which make quantitative assessments of population trends challenging. In the most basic, estimates were intuited from the authors' experience without a quantitative basis (e.g., Fullagar, 1978; Swales, 1965). Later, representative surveys or complete censuses of breeding colonies provided point estimates of breeding population size, but assumed perfect detection (e.g., Mitchell et al., 2004; Sowls et al., 1978). More recently, methods that assume imperfect detection and incorporate error in estimates explicitly have provided more robust estimates of population trends (e.g., Kéry and Schaub, 2012).

In eastern Australia, the world's largest population of Flesh-footed Shearwaters (*Ardenna carneipes*) on Lord Howe Island has declined by 1.3% per annum from 1978 to 2009 (Reid et al., 2013a). In 2017, the species was up-listed to Near Threatened on the IUCN Red List after similar declines were highlighted at colonies in Western Australia and New Zealand (BirdLife International, 2018b; Lavers, 2015; Waugh et al., 2013). Mitigation employed at a handful of breeding sites, including significant reductions in by-catch in the Australian domestic fishery (Reid et al., 2012) has proven insufficient to reverse population declines (Gaze, 2000; Reid et al., 2013a). Emerging threats, such as the ingestion of plastic and associated chemicals, may now be exhibiting pressure on populations (Bond and Lavers, 2011; Lavers et al., 2014) and contributing to lack of recovery.

Here we investigated the distribution and abundance of Flesh-footed Shearwaters on Lord Howe Island during the 2018 breeding season, nine years after the most recent survey (Reid et al., 2013a), and investigated what impact different camera technologies might have on detection probabilities. Our aims were to provide updated estimates of burrow density, occupancy, colony area, and breeding success to compare with the three earlier surveys (1978, 2002, and 2009; Fullagar and Disney, 1981; Priddel et al., 2006; Reid et al., 2013a) and determine whether the population is continuing to decline. Using two burrow scope models, we predict the newer version with higher quality video will influence detection probability significantly compared to the burrow scope models used in 2002 and 2009, with potential implications for population trend estimates.

2. Methods

2.1. Study site

Lord Howe Island, New South Wales (31.55°S, 159.09°E) is a UNESCO World Heritage-listed island in the central Tasman Sea, approximately 650 km off the east coast of Australia. About 20% of the island, including most of the north-central lowlands, is composed of calcarenite derived from coral with the remainder of the island largely comprised of basalt (Pickard, 1983). The sandy, calcarenite soils support kentia palm (*Howea forsteriana*) forest where Flesh-footed Shearwaters primarily dig their 1–3 m long burrows in single-species colonies (Priddel et al., 2006). Four of the five main colonies (Middle Beach, Ned's Beach, Old Settlement Beach, Steven's Point; Fig. 1) are located within an area intensively settled by Lord Howe Island's ~350 human residents.

2.2. Shearwater survey methods

The five major colonies on Lord Howe Island have been surveyed three times previously, in 1978, 2002, and 2009 (Fullagar and Disney, 1981; Priddel et al., 2006; Reid et al., 2013a). The survey methods employed in 1978 were constrained by access to technology (e.g., no burrow scope or GPS), with the authors relying on aerial photographs to delineate colony boundaries and assumptions regarding burrow occupancy rates (Fullagar and Disney, 1981).

Fig. 1. Map of Lord Howe Island with location of Flesh-footed Shearwater breeding colonies and roads in 1978 (Fullagar and Disney, 1981), 2002 (Priddel et al., 2006), and 2018. Data from 2009 were not available.

During 1–8 January 2018, we undertook an island-wide survey using methods comparable to those used by Priddel et al. (2006) and Reid et al. (2013a). The area of each colony was measured by walking the perimeter with a hand held GPS (accuracy 3–10 m). Burrow density was estimated using straight-line transects through each colony (except Old Settlement Beach, also known as Hunter Bay, where it was possible to count all burrows). The 17 transects used in this study were previously used by Reid et al. (2013a). Each transect was 60–100 m in length, depending on habitat and obstacles, and was divided along its length into 10 m sections. All burrows within 2 m either side of each transect were recorded. The transects were evenly separated and oriented from colony edges through the centre of the colony, covering a total of 1.6 km, or around 2.4% of the total colony area.

Burrow density was estimated using the area of each transect (A_i) and the density of burrows within each transect (D_i). For each colony, the density of burrows (D_c) was then calculated from each transect:

$$D_c = \sum_{i=1}^{n} D_i \times \frac{A_i}{A_t}$$

where n is the number of transects in the colony and,

$$A_t = \sum_{i=1}^{n} A_i$$

The number of burrows in each colony was calculated as the product of the density of burrows in the colony (D_c) and the area of the colony.

In prior studies, burrow occupancy (the proportion of burrows occupied by a breeding pair) was determined using a basic burrow scope (specifications not reported; Priddel et al., 2006; Reid et al., 2013a). Other techniques, such as 'grubbing', using one's arm to determine nest contents, are not suitable for determining occupancy in this species as burrow length is typically >1 m (Dyer, 2001; Powell et al., 2007), thus the nesting chamber is not within reach. For this study, twenty randomly selected burrows per transect (except for three transects where burrow density was too low; $n = 194$ burrows) were inspected using an EMS2015 Gopher Tortoise Camera System (Environmental Management Services, Canton, Georgia, USA) with a Sony 960H ExView Super HAD CCD II camera (1080p resolution, 1920 × 1080 pixels, 30 frames per second) and sealed head containing a ring of six white LEDs lights for illumination which relayed to a 15 cm colour LCD monitor, and wirelessly transmitted to a head-mounted display (Fatshark Dominator V3 goggles, 720p resolution, 800 × 480 pixels, 30 frames per second). Burrows were classified as active (adult or egg present), empty, or unknown (i.e., the contents could not be determined reliably).

Forty-six burrows were marked with uniquely numbered pegs in January (2–3 weeks prior to hatching) in order to provide information on breeding success. These same burrows were inspected again on 10 April 2018 (2–3 weeks prior to fledging) following Priddel et al. (2006). In both instances, the contents of the burrow were recorded using the EMS2015 burrow scope as above.

2.3. Assessing detection probability

On 5 January 2018, 36 shearwater burrows were marked with uniquely numbered pegs in the Ned's Beach colony. Working as two independent teams, we inspected each burrow twice using two different scope designs: the EMS2015 with head-mounted display (detailed above) and a second scope (Taupe model scope which transmits wirelessly to a 752 × 582 pixel black and white screen; Sextant Technologies, Wellington, New Zealand; Fig. 2). The contents of each burrow were recorded (as above) with the order selected randomly such that half of the burrows were first inspected by the Sextant scope while the remaining burrows were first inspected by the EMS2015.

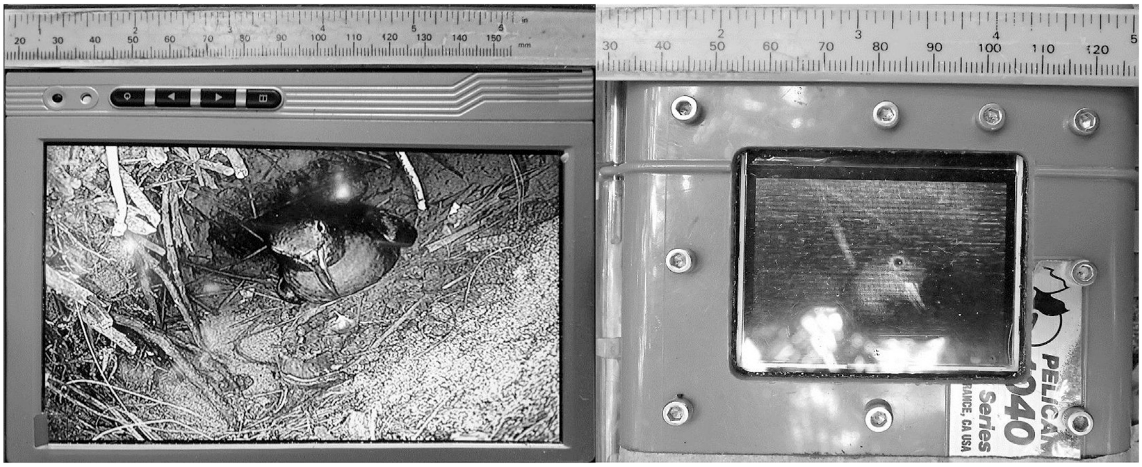

Fig. 2. Left panel: adult Flesh-footed shearwater detected in its burrow on Lord Howe Island in January 2018 using the EMS2015 Gopher Tortoise Camera System (display screen: 1080p resolution, 1920 × 1080 pixels). Right panel: the same adult Flesh-footed shearwater in the same burrow detected using the Sextant Technologies scope (display screen: 752 × 582 pixels).

2.4. Statistical analysis

Analyses were conducted in R 3.5.1 (R Core Team, 2018). We tested for differences in the occupancy rate and density of active burrows (active burrows/m^2) in 2018 using general linear models, with Tukey's HSD for multiple comparisons when main effects were significant ($p < 0.05$).

We estimated the population of each colony by performing 10,000 bootstraps, sampling a density of active burrows from a normal distribution with the mean, SD, and range from our data (constrained to positive integers), and multiplying this by the total colony area across the island. We report the mean estimate (±SE) and 95% confidence intervals. We then calculated the annual rate of population change as

$$\lambda = \sqrt[n]{\frac{N_0 - N_t}{N_t}}$$

Where λ is the annual population growth rate, n is the number of years between population estimates from year N_0 and N_t. We then used λ to extrapolate the population change over three generations (55 years) under IUCN Red List criterion A2 (Birdlife International 2018a).

We compared the performance of the two burrow scope models by looking at the proportion of burrows that were classified differently between the two. Because determining the true status of each burrow by independent means was impossible, we assumed that the EMS2015 burrow scope reflected the contents of the burrow accurately (see Results). We then calculated the supposed population estimate using both burrow scopes as detailed above.

3. Results

3.1. Shearwater colony area

Flesh-footed Shearwaters breed in five distinct colonies on Lord Howe Island (Fig. 1), with perhaps an additional ~50 pairs in a recently colonized area around Signal Point (south of the jetty). Colony size ranged from 0.41 ha (Little Muttonbird Ground; Reid et al., 2013a) to 8.10 ha (Steven's Point), and totalled 31.63 ha (Table 1, Fig. 1).

Table 1
Burrow density (mean ± SE), abundance, and occupancy (eggs burrow^{-1}) for the six Flesh-footed Shearwater colonies on Lord Howe Island, adapted from Priddel et al. (2006) and Reid et al. (2013a). CI = 95% Confidence Interval. All estimates assume perfect detection of burrow contents and, as this paper discusses, are therefore not necessarily directly comparable.

Year	Site	Area (ha)	Burrow density (m^{-2})	Occupancy rate (%)	Estimated # of pairs (CI)
1978	Clear Place	8.38	0.153 ± 0.022	N/A	N/A
2002	Clear Place	8.00	0.168 ± 0.046	58	7779
2009	Clear Place	7.73	0.148	N/A	N/A
2018	Clear Place	7.12	0.234 ± 0.084	72	13,363 (3743-24,186)
1978	Hunter Bay	0.36	0.037[a]	N/A	N/A
2002	Hunter Bay	0.31	0.039[a]	44	53
2009	Hunter Bay	0.41	0.061[a]	N/A	N/A
2018	Hunter Bay	0.27	0.043[a]	50	116
1978	Little Muttonbird Ground	0.49	0.071 ± 0.035	N/A	N/A
2002	Little Muttonbird Ground	0.46	0.078 ± 0.011	44	158
2009	Little Muttonbird Ground	0.41	0.015	N/A	N/A
2018	Little Muttonbird Ground	0.41	0.065 ± 0.013	29	69 (5–132)
1978	Middle Beach	9.34	0.092 ± 0.016	N/A	N/A
2002	Middle Beach	5.53	0.126 ± 0.022	74	5201
2009	Middle Beach	5.88	0.131	N/A	N/A
2018	Middle Beach	7.81	0.097 ± 0.021	55	3814 (1601–5776)
1978	Ned's Beach	2.75	0.113 ± 0.021	N/A	N/A
2002	Ned's Beach	2.61	0.127 ± 0.012	53	1750
2009	Ned's Beach	2.89	0.125	N/A	N/A
2018	Ned's Beach	3.51	0.091 ± 0.009	52	1526 (1120–1900)
1978	Steven's Point	16.43	0.127 ± 0.012	N/A	N/A
2002	Steven's Point	7.41	0.077 ± 0.008	44	2521
2009	Steven's Point	7.41	0.061	N/A	N/A
2018	Steven's Point	8.33	0.093 ± 0.017	52	3766 (1570–5799)
1978	Whole island	37.75	0.098 ± 0.016	N/A	20,000–40,000
2002	Whole island	25.31	0.123 ± 0.024	53 ± 5[b]	17,462
2009	Whole island	24.73	0.110 ± 0.008	67 ± 4	16,267 (11,649–21,250)[c]
2018	Whole island	31.63	0.071 ± 0.019	53 ± 5	22,654 (8156–37,909)

[a] All burrows individually counted within this small colony.
[b] Occupancy data collected for three sites in 2009, but reported as whole island by Reid et al. (2013a).
[c] Variation is reported as the 95% credible interval.

3.1.1. Burrow occupancy and density

In total, we surveyed 17 transects comprising 6240 m^2. There was no difference in occupancy rate among colony sites ($F_{5,13} = 2.056$, $p = 0.14$), and overall, occupancy was 0.530 ± 0.197% (range: 0.000–0.841%). The density of active burrows was also not significantly different across the island ($F_{4,13} = 2.80$, $p = 0.07$), with 0.071 ± 0.081 (range: 0.000–0.355) active burrows/m^2.

3.1.2. Population size and breeding success

Colony size ranged from 69 pairs (95% CI: 5–132 pairs) at Little Muttonbird Ground, to 13,363 pairs (95% CI: 3743-24,186 pairs) at Clear Place (Table 1). We estimated the total breeding population of Flesh-footed Shearwaters on Lord Howe Island as 22,654 breeding pairs (95% CI: 8156–37,909 pairs; Table 1). Of the 46 burrows with eggs in January, the EMS2015 scope could not determine the contents of four, found 15 to be empty, and the remaining 25 (62.5%) contained a chick in April 2018.

3.1.3. Comparison of burrow scope models

Of the 36 burrows examined, the EMS2015 could not determine the contents of seven, found five to be empty, and the remaining 24 (66.7%) were classified as active. The Sextant scope could not determine the contents of 24 burrows (including six of the seven where the contents could not be determined by the EMS2015), determined that three were empty, and nine (25.0%) were active. Together, the contents of 20/36 burrows (56%) differed between the two burrow scope models.

3.1.4. Accounting for detection probability

If we had used the Sextant scope to assess occupancy, our population estimate would have been 8155 breeding pairs (95% CI: 2936-13,657 pairs), a 50.1% decline since 2009. If we assume that detection in 2002 and 2009 (assumed to be perfect) was similar to that found using the Sextant burrow scope (an earlier design/model, see Fig. 2 and Methods), then total population estimates would be 49,006 and 45,186 breeding pairs, respectively, and our mean estimate of 22,654 breeding pairs using the EMS2015 in 2018 also represents a 50.1% reduction. In this extreme scenario, a 5.5% reduction per annum since 2009, the Lord Howe Island Flesh-footed Shearwater population is predicted to decline by 97% in three generations (55 years; BirdLife International 2018b). Because we cannot assess detection probability retroactively, but we assume it to be lower in 2002 and 2009 than with the EMS2015 burrow scope in 2018, we conclude that the population has declined by an unknown but possibly significant amount in the last decade.

4. Discussion

Results of the 2018 Flesh-footed Shearwater survey suggest the total population on Lord Howe Island was 22,654 breeding pairs (8156–37,909; Table 1). While this number appears to be similar to previous estimates (Priddel et al., 2006; Reid et al., 2013a), the population is unlikely to be stable over time, however. The survey in 2018 found a greater colony area, and lower burrow density, while previous surveys likely underestimated true occupancy because of technological challenges (Fig. 2). Previous estimates of colony area were derived from annotated aerial photographs (1978, 2002), or using the same GPS methods as in this study (2009). Anecdotally, island residents have reported shearwaters moving into new areas, and colony extents increasing in the last decade, but this seems to be accompanied by a reduction in active burrow density (authors personal observations), as occurs when populations are declining (e.g., Rexer-Huber et al., 2014). Small-scale habitat restoration and more precise methods, including using GPS and excluding residential areas where birds do not nest, likely contributed to changes in colony extent, particularly around Middle Beach.

Information on detection probability is increasingly recognised as an important factor when monitoring biological populations (Buckland et al., 2008). The assumption of perfect detection is especially problematic for burrow-nesting seabirds where it can be difficult to record individuals reliably due to fragile habitat, complex burrow structure (making the nest contents difficult to access), and significant variation in the number of adult birds attending the colony (Harding et al., 2005). On Lord Howe Island, the proportion of active shearwater burrows detected varied greatly depending on the type of burrow scope used (EMS2015: 66.7%, Sextant: 25.0%; Fig. 2), due in part to the high-resolution, colour screen available on the EMS2015 and issues with wireless connectivity when the Sextant scope was used to survey especially long/deep burrows. Consequently, the estimated population size (8155 breeding pairs) based on the Sextant scope is less than half the predicted 22,654 pairs from the EMS2015 model. The difference in population size calculated based on burrow occupancy values generated using the two scopes highlights the importance of regular surveys that carefully document detection probability and improvements in technology in addition to changes in protocols.

Despite our findings, we emphasize that each species and site is unique, requiring different solutions to monitor populations effectively. The long burrows (1–3 m), and breeding habitat (soft sandy soil in palm forests with complex tree root structures) of Flesh-footed Shearwaters on Lord Howe Island present considerable difficulties for monitoring population size and demography. Burrow scopes such as those used in previous surveys represented the best available technology at the time, and remain suitable for many applications today. Researchers should be aware that burrow scope properties (i.e., power source, transmitter strength) and factors such as nesting chamber (burrow) depth, entrance structure, and tortuosity can directly affect burrow scope performance and will be species and site specific. Our main argument is that unless the contents of all survey burrows can be determined unequivocally (i.e., no burrows have unknown contents), and reproducibly (i.e., different observers determining the contents come to the same conclusion), then comparisons over multiple surveys using different technologies, or estimating population numbers or trends is likely to be fraught with challenges around imperfect detection (Kéry and Schmidt, 2008). Studies of burrowing seabird populations should therefore ensure that imperfect detection is evaluated, and reproducibility is assessed and reported, and analyses should make use of the increasing body of statistical methods that include detection probability explicitly (Kéry et al., 2009; Royle et al., 2005).

4.1. Breeding success and the demographics of population trends

Despite the apparent population decrease and reduction in burrow density, we found generally good reproductive success (62.5%), comparable to that in previous years (2002: 50%, 2009: 60%; Priddel et al., 2006; Reid et al., 2013a). Among seabirds and other long-lived species, population trends are usually most influenced by adult survival (Croxall and Rothery, 1991), with breeding success being influential in driving population trends in extreme cases where breeding failure occurs in multiple years (e.g., Caravaggi et al., 2018; Wanless et al., 2007). Shearwaters from Lord Howe Island have been severely affected by fisheries bycatch, both locally and on the high seas (Reid et al. 2012, 2013b), road-kill (Reid et al., 2013a), and by high contaminant burdens (Bond and Lavers, 2011; Lavers et al., 2014). While no adult survival data exist for this colony, it can be highly variable, ranging from 63 to 84% in Western Australia (Lavers et al., 2018) to 76–94% in New Zealand (Barbraud et al., 2014; Waugh and Taylor, 2012). Identifying the life history stage that most influences the population trajectory is crucial to identifying effective mitigation measures and ensuring the survival of local populations (Wanless et al., 2009).

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Appendix A. Supplementary data

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