RAPID INCREASE IN SIZE OF WEDGE-TAILED SHEARWATER *ARDENNA PACIFICA* COLONY FOLLOWING RAT ERADICATION

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ABSTRACT

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Invasive mammalian predators have devastating effects on seabird nesting colonies. A census was conducted on breeding Wedge-tailed Shearwaters *Ardenna pacifica* in 2016 and 2021 on D'Arros Island, Seychelles, which has been rat-free since 2003. Results were compared with an earlier population estimate to assess population growth following the rat eradication. Compared to counts in 2009, we estimated a 10-fold increase in breeding population size, with 2768 (95% confidence interval (CI) 2424–3112) and 2406 (95% CI 2143–2667) breeding pairs in 2016 and 2021, respectively. While the estimated increase is partly attributable to differences in the timing of the conducted census between the two studies, we also observed an increase in the areal extent of the population, from 3.00 to 3.85 ha (0.0300–0.0385 km^2), and an increase in nesting density. Cumulatively, this indicates a true population increase.

Key words: *Ardenna pacifica*, Wedge-tailed Shearwater, invasive species, population census, biodiversity, phenology, Seychelles

INTRODUCTION

Invasive predatory species constitute a global threat to biodiversity (Maxwell *et al.* 2016), causing numerous extinctions, often among endemic island species (Tershy *et al.* 2015). Oceanic island species are particularly vulnerable (Croxall *et al.* 2012, Jones *et al.* 2016) because they lack anti-predator adaptations such as behavioural responses as defence mechanisms (Atkinson 1985, Vitousek 1988). Low-latitude islands tend to be biodiversity hotspots (Myers *et al.* 2000) and are particularly vulnerable to invasive predatory species (Harper & Bunbury 2015).

Humans have introduced three species of rat, the Black or Ship Rat *Rattus rattus*, the Brown or Norway Rat *R. norvegicus* and the Pacific Rat *R. exulans* to more than 80% of the world's islands (Atkinson 1985, Harper & Bunbury 2015). Rats are not only one of the most prolific invasive mammals, but they are also the invasive species with the greatest impact on seabirds (Dias *et al.* 2019). This is particularly true for seabird species that nest in burrows (Atkinson 1985, Igual *et al.* 2006, Jones *et al.* 2008). The threat of rats to seabirds is of particular concern when considering the poor conservation status of a large proportion of seabird species globally (Croxall *et al.* 2012, Paleczny *et al.* 2015). However, seabird populations have been shown to rapidly recover after rat eradication (Pascal *et al.* 2008, Vanderwerf *et al.* 2014) or rat population control efforts (Igual *et al.* 2006).

The management of invasive species can have major benefits to seabird populations (Brooke *et al.* 2018). For example, the eradication or control of invasive species has resulted in both improved productivity through increased breeding and/or fledging success (Smith *et al.* 2002, Millus *et al.* 2007, Rayner *et al.* 2007, Pascal *et al.* 2008) and increases in the number of breeding pairs (Vanderwerf *et al.* 2014, Le Corre *et al.* 2015). Previous studies on seabirds have also demonstrated increased burrow density and colony size (Nordström *et al.* 2004, Buxton *et al.* 2016), improved adult survival rates (Smith *et al.* 2002, Keitt & Tershy 2003), and recolonization by previously extirpated species following invasive mammal eradication (Buxton *et al.* 2016, Connan *et al.* 2022).

Wedge-tailed Shearwaters *Ardenna pacifica* (hereafter WTS or shearwaters) are colonial breeders and usually nest in self-excavated burrows (Whittow 2020). They are distributed throughout the tropical Indian and Pacific oceans and have an estimated global population size of over five million adults (Brooke 2004). In the tropical Western Indian Ocean, WTS synchronously start breeding in late August to early September (Kappes *et al.* 2013), with little annual temporal variation (Surman *et al.* 2012).

Most breeding grounds for WTS in the Western Indian Ocean are in Seychelles (~60%, Kappes *et al.* 2013), which also provides important foraging habitat for this species within the region (Le Corre *et al.* 2012). In 2009, Kappes *et al.* (2013) conducted a census of breeding WTS on D'Arros Island (hereafter D'Arros) in Seychelles, estimating a population size of approximately 254 breeding pairs.

In this study, we updated the WTS population size at D'Arros Island after rat eradication in 2003, assessing changes from the population size reported by Kappes *et al.* (2013). While there were no pre-eradication population counts for comparison, we expected to find steep growth between the two censuses for three reasons: (1) rodents significantly impact seabird breeding success (Thibault 1995, Jones *et al.* 2008, Pascal *et al.* 2008); (2) the third largest population of breeding WTS in the Western Indian Ocean is only 2 km away from the D'Arros population and may be acting as a source population for D'Arros, which has a lower nest density

(Kappes *et al.* 2013); and (3) the delayed recruitment of juveniles into the adult population means there could be a lag in population recovery (WTS start breeding at age four; Maclean 1993). We also determined the peak incubation period for WTS on D'Arros, which is essential for future comparability of population estimates.

METHODS

We conducted two censuses of WTS on D'Arros Island, Seychelles (05°24′59″S, 053°17′51″E; Fig. 1). The first census took place 04–16 November 2016 and the second 15–23 November 2021. Additionally, a sample census was conducted from 15 October to 22 December 2021 to identify the peak incubation period on D'Arros for comparative purposes. Approval to undertake this study was granted by the Seychelles Ministry of Environment. D'Arros is mostly covered by overgrown coconut *Cocos nucifera* plantations, interspersed with *Casuarina litorea* and a dense littoral growth of *Scaevola taccada* (Stoddart & Coe 1979).

Six shearwater coastal nesting areas had previously been identified on D'Arros (Kappes *et al.* 2013). Within these known areas and newly located nesting areas, we mapped each nesting area with either a Garmin eTrek® 10 (2016) or 73 (2021) handheld GPS. Colony surface area was calculated in ArcGIS® 10.5 (ESRI 2016). As per Kappes *et al.* (2013), a combination of direct counts and area-based estimates were used to estimate the total number of WTS breeding on D'Arros. Direct counts focused on areas with relatively low burrow densities, and area-based estimates were conducted in high-density areas. In high-density areas, where it was impractical to walk without collapsing burrows due to their close proximity to one another, the latter approach was motivated by both time constraints and cautionary measures to avoid collapsing burrows while sampling.

In the low-density areas, we summed the number of direct counts of occupied burrows. For the high-density areas, we randomly selected circular plots (three in areas 5 and 6; Fig. 2) for surveying. Once a plot was selected, a wooden pole was placed into the ground and a 3.99 m rope was used to demarcate a circular 50-m^2 survey site. The starting location was marked and all burrows with entrances falling inside the circle were inspected for evidence of occupation. From these plots, we calculated the number of breeding pairs in the high-density areas as the mean density multiplied by the colony area. Due to the small number of plots in the high-density areas, a conservative number of breeding pairs was estimated using the Poisson confidence interval.

Following Kappes *et al.* (2013) and to facilitate comparison, breeding burrows included all burrows where breeding activity for the current season could be identified. Signs of breeding activity included incubating adults, chicks, recently broken eggshells, or abandoned eggs. Non-breeding burrows included all burrows where no signs of breeding were detected and comprised empty burrows or burrows with an adult or pair without an egg. Since most of the

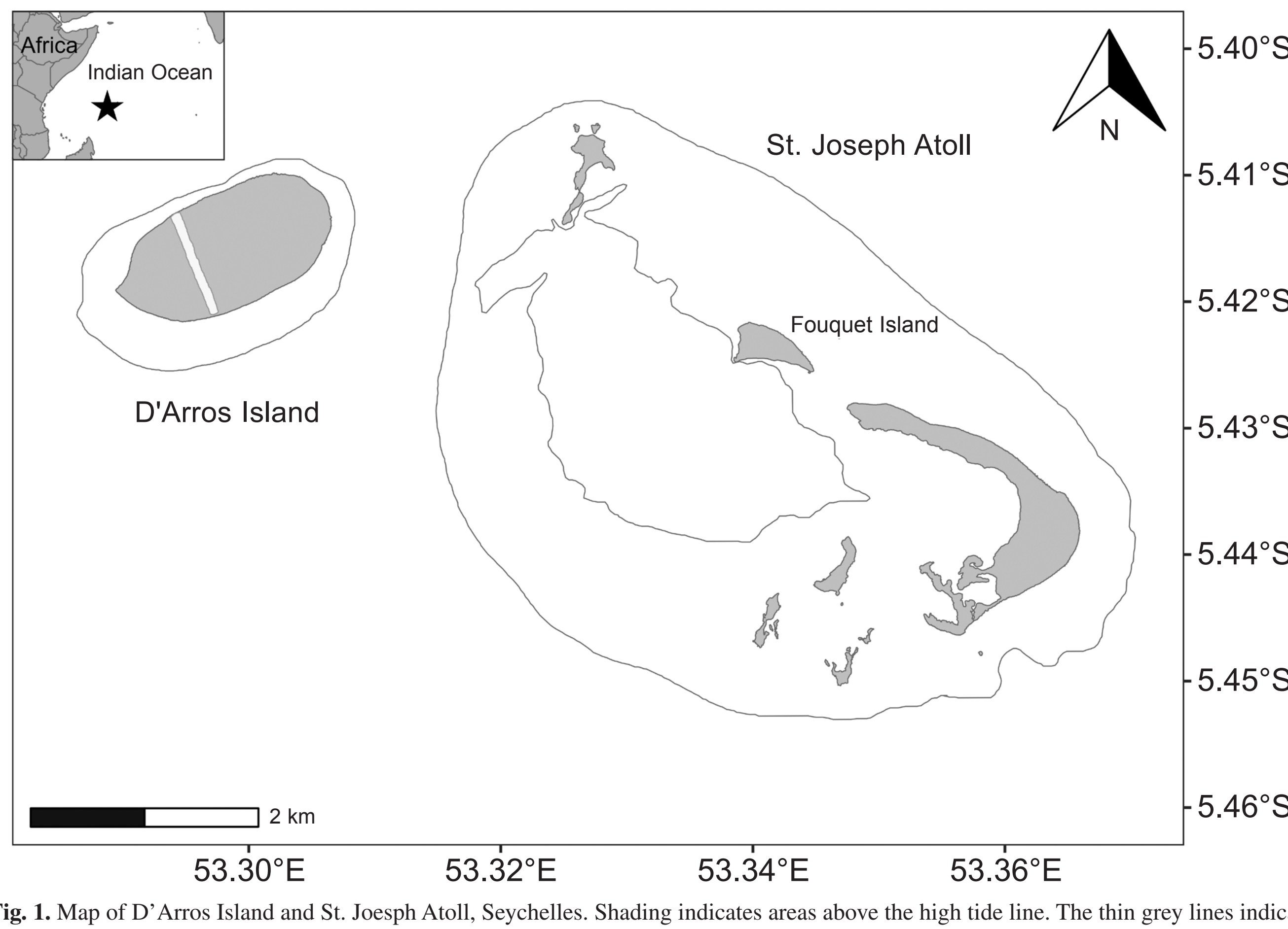

Fig. 1. Map of D'Arros Island and St. Joesph Atoll, Seychelles. Shading indicates areas above the high tide line. The thin grey lines indicate the low tide line; the white polygon inside the atoll is a lagoon at low tide.

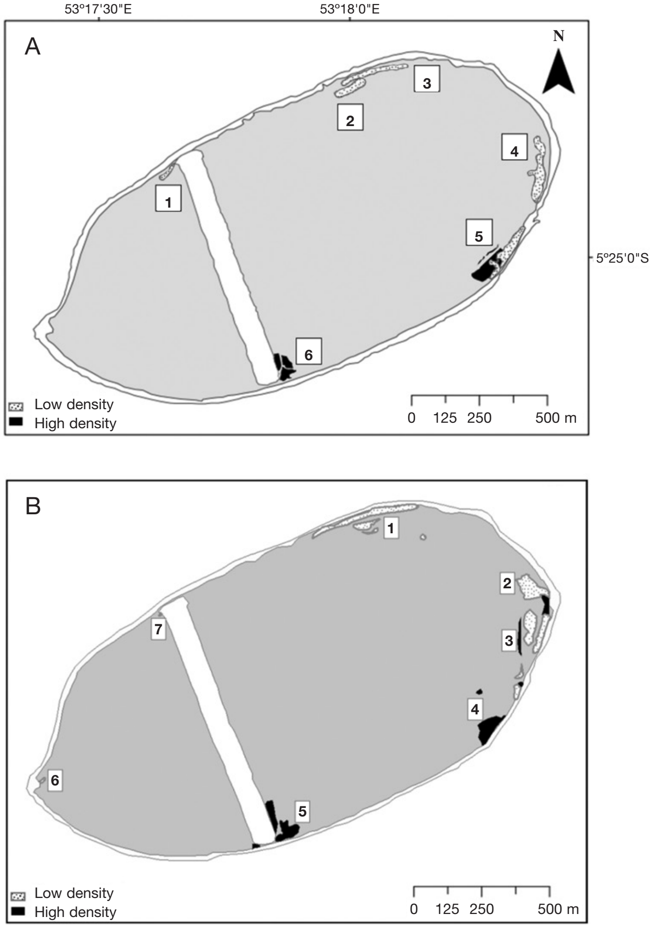

Fig. 2. A map of the Wedge-tailed Shearwater *Ardenna pacifica* colony sites censused on D'Arros Island, Seychelles, in November (A) 2016 and (B) 2021. The dotted areas indicate where direct counts were conducted (low burrow density) and the solid black areas indicate where area-based estimates were conducted (high burrow density). Plot numbers indicate the nesting areas of breeding birds located on the island. Solid grey shading indicates areas above the high tide line. The white areas surrounding the island consist of sandy beach (i.e., intertidal zone), and the white area across the island is the airstrip. The areas in white are not inhabited by shearwaters.

surveyed burrows were deep (> 70 cm) with many obstacles, such as plant roots and shells, an HD Endoscope (Potensic®) with a 5-m flexible cord (hereafter, burrow-scope) was used to inspect the burrows. In 2016, the cord for the endoscope was marked with tape in 10-cm increments to determine the depth of the burrows. In 2016 to confirm nest occupancy for burrows that were initially found empty but showed potential signs of recent activity, we used call play-back to confirm the status of the burrow (Burger & Lawrence 2001). If call play-back resulted in a response, the burrow was checked again to confirm nest occupancy.

To identify the peak incubation period for the WTS breeding on D'Arros, we censused a section of the study site in October, November, and December of 2021. Direct counts were made across one low-density area and three high-density circular plots (50 m^2 each). The proportion of breeding to non-breeding burrows were compared across these months.

RESULTS

Location of colonies

The total colony area on D'Arros was estimated to be 3.40 ha (0.034 km^2) across six colony sites in 2016 and 3.85 ha across seven colony sites in 2021 (Fig. 2). The latter estimate included a very small nesting area located in the northwest of the island that was previously unidentified. During both years, WTS were heard vocalizing at night inside the dense coconut palm vegetation, however, no nests were found in these areas and were not included in the census. The average (± standard deviation) burrow depth was 0.8 ± 0.4 m, with a maximum depth of 2.1 m (n = 634). Some burrows formed V- or Y-shaped tunnels, making it difficult to locate the position of the nests.

Census

Based on the direct counts on D'Arros during early November 2016 (n = 844; Table 1), most of the WTS burrows were occupied by an adult incubating an egg (56.6%) with very few adults in burrows that were not incubating (0.2%); chicks were present in just 2% of breeding burrows (Table 1). From the direct counts in 2021 (n = 570; Table 1), there was higher uncertainty regarding the breeding status of birds seen in burrows (24.7%), and it could not be confirmed whether an adult was incubating. Birds, however, generally did not budge, suggesting that they were most likely on eggs. A higher percentage of burrows were found empty (57.5%) and fewer adults were identified with eggs (13.0%) during 2021. Overall, it was estimated that there were 2768 (95% confidence interval (CI) 2424–3112) and 2406 (95% CI 2143–2667) breeding pairs of WTS at the beginning of November 2016 and 2021, respectively (Table 2).

Monthly differences in nest status in 2021

Repeat counts from the sample census (low-density direct count: n = 1, high-density circle plot: n = 3) identified November as the peak incubation period on D'Arros (Table 3). The proportion of burrows occupied by incubating birds in November was significantly higher than in October (Student's t-test: $t_{4.78} = -2.61$, P = 0.05) and December ($t_{3.00} = -5.99$, P = 0.01; Fig 3).

TABLE 1
Status of Wedge-tailed Shearwater *Ardenna pacifica* burrows with known contents at D'Arros Island, Seychelles, 04–16 November 2016 and 15–23 November 2021, given as number of burrows (% of total)

Year	Adult/pair, egg	Adult/pair, no egg	Chick	Egg, no adult	Empty	Adult/pair, unconfirmed status	Total number of burrows
2016	478 (56.6)	2 (0.2)	9 (1.1)	4 (0.5)	330 (39.1)	21 (2.5)	844
2021	74 (13.0)	not assessed	22 (3.9)	5 (0.9)	328 (57.5)	141 (24.7)	570

DISCUSSION

This study used a combination of direct and indirect (i.e., area-based estimates) counts to determine the population size of WTS on D'Arros Island, Seychelles, seven years after the census by Kappes *et al.* (2013) and 13 years after rats had been eradicated. Following Kappes *et al.* (2013), we estimated 2768 and 2406 breeding pairs in 2016 and 2021, respectively, nearly 10 times larger than estimated in 2009. Additionally, we found that total colony area increased from 3.00 ha in 2009 (Kappes *et al.* 2013) to 3.85 ha in 2021. The breeding burrow densities in 2016 (21–1866 pairs/ha) and 2021 (17–2391 pairs/ha) were comparable to those found on other islands in Seychelles (2488 pairs/ha, Burger & Lawrence 2001; 98–2830 pairs/ha, Kappes *et al.* 2013); on Heron Island, Australia

TABLE 2
Wedge-tailed Shearwater *Ardenna pacifica* census results on D'Arros Island, Seychelles, during the incubation period in November 2016 and 2021[a]

Season Count method	Colony site	Colony area (ha)	Number of plots	% Area coverage	Breeding burrows (pairs/ha)	Non-breeding burrows (pairs/ha)	Breeding pairs	Confidence interval (95%)
2016 Direct counts	1	0.09			21	0	2	
	2	0.33			45	66	15	
	3	0.41			158	242	64	
	4	0.74			255	446	189	
	5	0.59			290	462	171	
2016 High-density estimates	5	0.76	3	1.97	1945 ± 28	3112 ± 36	1478	1437–1519
	6	0.47	3	3.20	1866 ± 645	2933 ± 1477	849	546–1152
2016 Total		**3.40**	**6**				**2768**	**2424–3112**
2021 Direct counts	1	0.96			42	179	40	
	2	0.58			17	52	10	
	3	0.68			53	84	36	
	6+7	0.03			67	1	2	
2021 High-density estimates	2	0.24	1	4.17	1196	3000	287	-
	3	0.11	1	9.09	2391	4000	263	-
	4	0.58	3	1.72	1522 ± 427	3950 ± 685	883	354–1412
	5	0.67	2	1.49	1320 ± 227	3100 ± 1100	885	603–1167
		3.85	**8**				**2406**	**2143–2667**

[a] The burrow densities for direct counts are represented as the mean only, and the high-density estimates are represented as the mean ± standard error.

TABLE 3
Status of Wedge-tailed Shearwater *Ardenna pacifica* burrows with known contents at D'Arros Island, Seychelles, during October–December 2021[a]

Month sampled	Adult/pair, egg	Adult/pair, no egg	Chick	Egg, no adult	Empty	Total burrows	Total breeding burrows
High-density plots (*n* = 3)							
October	2 ± 1	6 ± 3	0 ± 0	0 ± 0	12 ± 5	20 ± 7	2 ± 1
November	5 ± 1	2 ± 2	1 ± 1	1 ± 0	9 ± 2	19 ± 3	7 ± 1
December	0 ± 0	1 ± 1	1 ± 1	0 ± 0	17 ± 3	20 ± 2	1 ± 1
Low-density area (*n* = 1)							
October	6	5	0	0	38	49	6
November	7	18	0	0	37	62	7
December	0	3	7	0	41	56	7

[a] One low-density direct-count plot and three high-density circle plots were resampled each month to assess the change in the burrow occupancy/status. Estimates are represented as mean ± standard deviation.

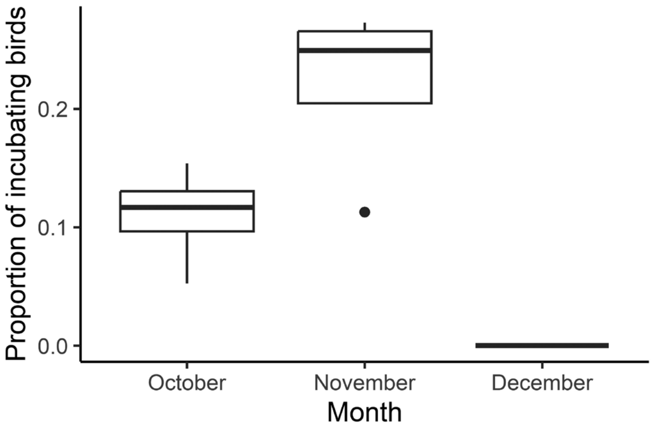

Fig. 3. Boxplot of the proportion of incubating Wedge-tailed Shearwater *Ardenna pacifica* burrows within sample plots (*n* = 4) sampled during October–December 2021 on D'Arros Island, Seychelles.

(500–2000 pairs/ha, Hill *et al.* 1996); and in Hawai'i (2800 pairs/ha, Shallenberger 1973).

The estimated increase in the number of breeding shearwater pairs is likely a result of the successful eradication of Brown Rats in 2003 (Rocamora 2019). Possibly, the eradication of rats six years prior to the Kappes *et al.* (2013) census resulted in a rapid and significant increase in breeding success (Smith *et al.* 2002, Smith *et al.* 2006, Marie *et al.* 2014, Vanderwerf *et al.* 2014). This would have resulted from the delayed recruitment of juveniles into the breeding population; WTS typically breed by age four (Maclean 1993). Surprisingly, even in the absence of rats, hatching success in 2021 (13 nests monitored between November and December) appeared low (54%). Whether this is an artefact of low sample numbers or conditions in the particular year is unknown, but the additional cumulative impact of rat predation would certainly have been significant.

Immigration could also have contributed to population growth (Ogden 1994). The neighbouring St Joseph Atoll includes Fouquet Island, which is known for its high population density of WTS (~2620 pairs/ha). Fouquet Island is approximately 2 km from D'Arros and accounts for at least 16% (~28 655 breeding pairs) of the WTS population in the Western Indian Ocean (Kappes *et al.* 2013). The breeding population of WTS in the St Joseph Atoll may be acting as a source population for D'Arros (Buxton *et al.* 2014), and WTS may be recruiting to and/or recolonizing D'Arros from St Joseph Atoll to avoid competition for nesting sites on nearby densely populated islands. A future study in the St Joseph Atoll will be necessary to confirm the current population density of WTS in the atoll.

WTS have been shown to not change their breeding phenology, even if environmental conditions become suboptimal (Surman *et al.* 2012). Therefore, it is unlikely there were differences in breeding phenology between the two studies. While the previous census took place in October, when birds in most nests were believed to be breeding (Kappes *et al.* 2013), we found that the peak incubation period in 2021 was a month later, even though sample sizes were small; November had ~50% more incubating birds on average than in October. This census also found fewer empty burrows (30% and 12% in 2016 and 2021, respectively) than Kappes *et al.* (2013). Despite the mismatch of sampling periods, the dramatic change in estimated population size suggests a true increase in the number of breeding pairs of WTS on D'Arros.

Advances in technology to assess nest occupancy clearly benefited the study (Ambagis 2004). In this study, most WTS burrows were deeper than arm's length (> 70 cm) and were convoluted; some adults also laid their egg behind a sand barrier. Those characteristics would have complicated detection without a burrow-scope. To some extent, the increase in population size could have been the result of different sampling techniques, in particular, the use of burrow-scope and call play-back in the current study vs. grubbing (i.e., assessing the contents of a burrow by probing with a hand or stick, see Kappes *et al*. 2013). This makes comparing censuses that use different sampling techniques problematic (Lavers *et al.* 2019). However, the overall burrow density per hectare and total colony area were substantially larger in the current study, confirming at least some level of population increase.

Our findings suggest that the WTS population on D'Arros increased after the eradication of rats. Nonetheless, although the release from rat predation was largely responsible for the population recovery, other factors relevant to the conservation management of the population could have come into play (Sutherland & Dann 2012). The continued monitoring of this population is encouraged to better understand factors driving these changes. Though logistical constraints may prohibit an annual census on D'Arros, we suggest that selected and representative sub-sections of the colony be monitored annually to enable detection of long-term population trends. Furthermore, the ringing of both breeding adults and fledglings in St Joseph Atoll would be useful to assess potential immigration to D'Arros, should the former serve as a source population. With high densities, care would need to be taken to avoid burrow damage (Baker *et al.* 2010, Kennedy & Pachlatko 2012).

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