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Decline in the distribution and abundance of flesh-footed shearwaters (*Puffinus carneipes*) on Lord Howe Island, Australia

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ABSTRACT

The flesh-footed shearwater (*Puffinus carneipes*) is a migratory seabird that ranges widely across the Pacific and Indian Oceans. The principal breeding populations are in Australia and New Zealand. The only breeding site in eastern Australia is on Lord Howe Island. Despite it being afforded a high level of legislative protection, the population on Lord Howe Island has declined substantially during the last few decades. The total extent of nesting habitat in 2002 was 24.3 ha, a reduction of 13.4 ha (35.6%) since 1978. Loss of nesting habitat was associated with increased urbanisation, the adverse impact of which extended beyond the footprint of buildings and gardens. In 2002, overall burrow density was 0.123 per m^2 and the total number of burrows was estimated to be 29,853 ± 5867, a decline of about 19.0% since 1978. A substantial decline in burrow density was evident in the colony where loss of habitat to urbanisation had been greatest. In 2002, 58% of burrows were occupied by breeding birds, and the total population size was estimated to be 17,462 breeding pairs. Breeding success (the proportion of eggs that produced fledglings) was 50%, but was lowest in the most urbanised colony. To avert further declines in the population of flesh-footed shearwaters on Lord Howe Island major changes in land use practices, enforced through appropriate legislation, are needed, together with reductions in the level of seabird bycatch in fisheries operations and in the amount of plastics that litter the world's oceans.

1. Introduction

The flesh-footed shearwater (*Puffinus carneipes*) is a pelagic trans-equatorial migrant (Marchant and Higgins, 1990). It breeds in dense colonies on islands within the Australasian region. The principal breeding colonies are in south-western Western Australia (Ross et al., 1996), in New Zealand (Taylor, 2000), on St. Paul Island in the Indian Ocean (Roux, 1985), and on Lord Howe Island, the only breeding site in eastern Australia (Fullagar et al., 1974). During the austral winter flesh-footed shearwaters range north through the western Pacific Ocean to the Aleutian Islands with small numbers off North America, north through the Indian Ocean, and west to the southern tip of Africa (del Hoyo et al., 1992).

The global conservation status of the flesh-footed shearwater is Least Concern (BirdLife International, 2005). Within

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Australia, the species is afforded a high level of protection under relevant legislation. It is listed as a Migratory Species under the Environment Protection and Biodiversity Conservation Act, 1999 (Commonwealth of Australia) and as a Vulnerable Species under the Threatened Species Conservation Act, 1995 (New South Wales). The population on Lord Howe Island is further protected through the island's listing as a World Heritage Area.

Although several cursory studies have been undertaken (Warham, 1958; McKean, 1963; Fullagar et al., 1974; Dyer, 2001), the flesh-footed shearwater has not been studied in any detail. On Lord Howe Island birds are ashore between September and May, with eggs laid sometime between November and January, and young thought to fledge during May (Hutton, 1991). Like most small and medium sized Procellariiformes flesh-footed shearwaters lay a single egg each year which is not replaced if lost (Warham, 1990). Precise laying dates on Lord Howe Island are not known, but the peak hatching period is 24–27 January (Dyer, 2001), a few days earlier than occurs in Western Australia (Warham, 1958).

In 1971, a preliminary survey of the distribution of flesh-footed shearwater burrows on Lord Howe Island was undertaken as part of a broader environmental survey of the island (Recher and Clark, 1974). This preliminary assessment suggested that the total extent of nesting habitat was about 28 ha (Fullagar et al., 1974). This, together with an estimate of burrow density obtained by counts within 40 small (15 m × 15 m) plots, gave an estimated population size of about 17,500 breeding pairs (Fullagar et al., 1974). Recognising that (1) the full extent of the colonies may not have been known, and (2) the plot counts were probably biased towards counts made in high-density areas, a more thorough survey was conducted in 1978 (Fullagar and Disney, 1981). The distribution of burrows was more accurately mapped, and burrow density more reliably estimated. Provisional analysis of these data (Fullagar and Disney, 1981) suggested a colony area of about 40.6 ha, plus 4.3 ha that contained only remnant colonies, and 0.7 ha that contained burrows that had been abandoned recently. Population size was estimated at 20,000–40,000 breeding pairs. Although the implication was that the colonies had grown between 1971 and 1978, this was not the case; it was simply that, in 1978, they were more correctly delineated (Fullagar and Disney, 1981).

Aside from these two surveys, there are no other data from which to determine population trends, and no measures of adult survival or breeding success. Anecdotal evidence suggests that the population declined during the middle of last century due to harvesting of nestlings for human consumption (mutton-birding) and clearing of nesting habitat for pastoralism and housing (Fullagar et al., 1974).

This study investigated the distribution and abundance of flesh-footed shearwater burrows on Lord Howe Island during the 2002–2003 breeding season. Findings were compared with those from the 1978 survey, the full details of which are presented here for the first time. Breeding success, burrow occupation rate and breeding population size were also estimated. Changes in the distribution and abundance of flesh-footed shearwaters on Lord Howe Island between 1978 and 2002 are discussed in relation to both local and global threats.

2. Study site and methods

2.1. Study site

Lord Howe Island (31°30′S, 159°05′E) is a 1455-ha oceanic island in the South Pacific Ocean, 495 km east of the Australian mainland. The island is crescent-shaped, with a 6-km long coral reef on the western side enclosing a lagoon. The southern mountains, rising to 875 m, are separated from the northern hills (209 m) by an area of lowland, much of which has been cleared for agriculture and settlement. About 20% of the island, including most of the lowlands, is composed of calcarenite derived from coral; the rest is basaltic (Pickard, 1983). See Pickard (1983) for a detailed description of vegetation communities.

Flesh-footed shearwaters on Lord Howe Island nest in single-species colonies at low elevations, chiefly within the area intensively settled by people (Fullagar et al., 1974). The birds excavate burrows, up to 3 m long, in sandy soils (Dyer, 2001). Most burrows occur along the eastern side of the island, within 500 m of the coast (Fig. 1). A much smaller number of burrows occur in a single colony on the western side of the island. Fullagar et al. (1974) described six more-or-less discrete colonies (Fig. 1), hereafter referred to as Neds Beach, Stevens Point, Middle Beach, Clear Place, Little Mutton-bird Ground and Hunter Bay. There are no known colonies on any of the smaller islets within the Lord Howe Island Group and, given the lack of suitable soils for burrowing on most, it is unlikely that any colonies occur there (Fullagar et al., 1974).

Pigs (*Sus scrofa*) and goats (*Capra hircus*) were released onto Lord Howe Island by whalers in the early 1800s. Pigs were eradicated in 1981 (Miller and Mullette, 1985). An attempt to eradicate goats in 1999 failed (Parkes et al., 2002), although the few animals left, possibly all females, appear not to be breeding. Cats (*Felis catus*) were introduced to Lord Howe Island in 1845 (Hutton, 1991). The feral population, confined to the settlement area and northern hills, was eradicated in 1980 (Miller and Mullette, 1985). In 1982, the Lord Howe Island Board prohibited the keeping of domestic cats, allowing existing pets to be retained only if they were desexed. In 2003, a single domestic cat remained. Residents are permitted to keep certain breeds of domestic dogs but there are strict regulations to prevent them from roaming or interfering with wildlife. The house mouse (*Mus domesticus*) arrived on the island about 1860 and is now common and widespread (Hindwood, 1940). Black rats (*Rattus rattus*) arrived in 1918 when the trading vessel *Makambo* struck a rock and was deliberately beached (Hindwood, 1940). The rats spread rapidly and are now common throughout the island. The degree to which mice or rats prey on flesh-footed shearwater eggs and chicks is unknown. For economic reasons, rats are heavily controlled in areas of palm forest in an effort to reduce damage to the seed of the kentia palm (*Howea forsterana*). The export of kentia palm seedlings is a major source of income for Lord Howe Island.

2.2. Location and extent of colonies

In 1978, the nesting grounds were inspected on foot and, with the aid of a stereoscope, the boundaries of each colony

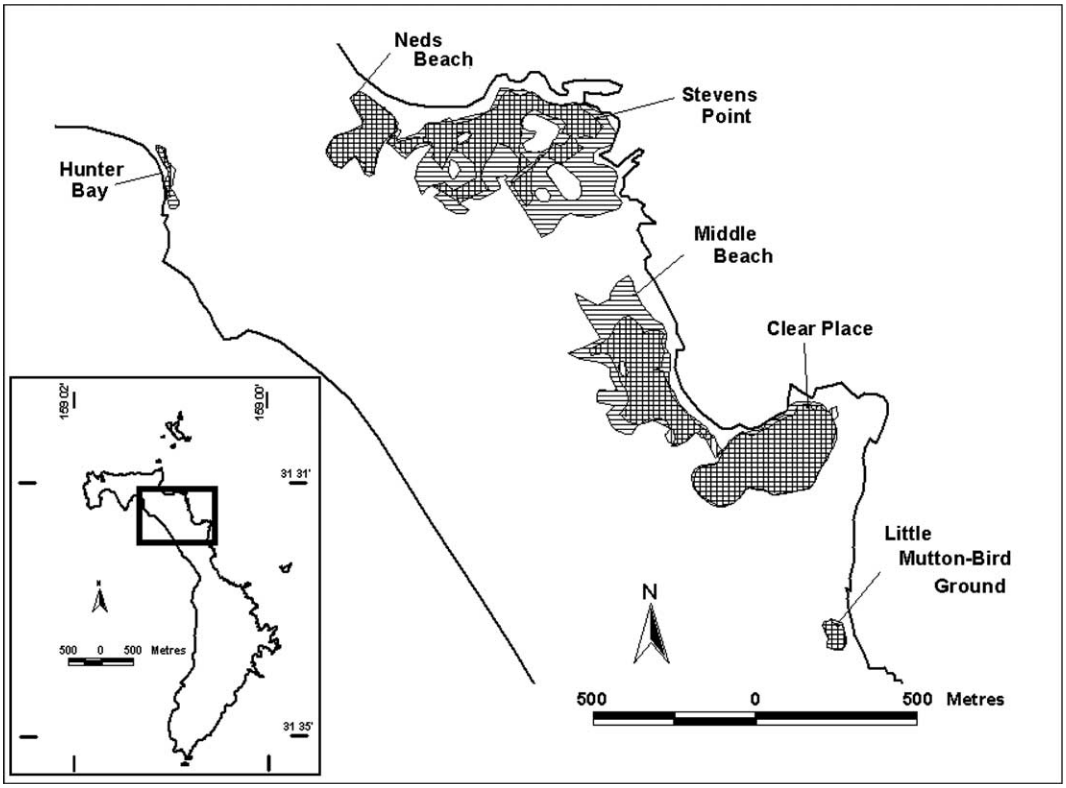

Fig. 1 – Location of the nesting grounds of the flesh-footed shearwater on Lord Howe Island in 1978 (horizontal hatching) and 2002 (vertical hatching).

were plotted onto aerial photographs. The nesting grounds were inspected again in 2002 and changes in the extent of each colony noted and plotted onto contemporary aerial photographs. Colony boundaries from both surveys were then mapped onto a geographic information system (Arcview GIS 3.3) and the area of each colony calculated for each survey.

2.3. *Burrow density in 1978*

In October 1978, burrow density was estimated using the Point-centred Quarter Method (Mueller-Dombois and Ellenberg, 1974). This technique, used primarily for measuring the density of trees in a forest, is based on the principle that density can be calculated from the average distance to the item of interest (in this case burrows) from randomly located sampling points.

A series of 22 randomly placed transects of variable length were used to sample the five most extensive colonies (Neds Beach, Stevens Point, Middle Beach, Clear Place and Little Mutton-bird Ground). Sampling points along each transect were chosen randomly, the distance from one point to the next being a random distance between 0.3 and 15.2 m (1–50 ft). At each point the nearest burrow in each of four compass quadrants (northeast, southeast, southwest and northwest) was located and the distance between the sampling point and the burrow entrance measured and recorded. Due to its small size the sixth colony (Hunter Bay) was counted in its entirety.

The density of burrows (D_i) along each transect was calculated by the equation

$$D_i = 1/\bar{d}^2,$$

where $\bar{d}$ is the mean distance from each sampling point to the nearest burrow in each quadrant (Mueller-Dombois and Ellenberg, 1974). The density of burrows in each colony (D_c) was then calculated from the densities for each transect (D_i), the relative contribution of each transect being proportional to the number of sampling points on that transect:

$$D_c = \sum_{i=1}^{n} D_i * N_i/N_t,$$

where n is the number of transects in the colony and

$$N_t = \sum_{i=1}^{n} N_i.$$

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.

2.4. *Burrow density in 2002*

In October 2002, a series of 18 randomly placed transects of variable length sampled the five most extensive colonies. Sampling effort in each colony was approximately proportional to the area of the colony. Total transect length was 2.9 km and overall sampling effort was about 5% of the total nesting habitat. Burrows were counted within 2 m either side of a measuring tape placed along the length of each transect. The small Hunter Bay colony was again counted in its entirety. The length of each transect was noted, and the area of each transect (A_i) and the density of burrows within each transect (D_i) calculated. The density of burrows in each colony (D_c) was then calculated from the densities for each transect (D_i), the relative contribution of each transect being proportional to the area of that transect:

$$D_c = \sum_{i=1}^{n} D_i * A_i / A_t,$$

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.

2.5. Burrow length

In the last week of November 2002, 50 burrows in each of four large colonies (Neds Beach, Stevens Point, Middle Beach and Clear Place) and 25 burrows in each of two small colonies (Little Mutton-bird Ground and Hunter Bay) were randomly selected and marked with a numbered plastic tag. Tags were attached to the nearest tree root or trunk by a stainless steel wire. Flesh-footed shearwaters are energetic burrowers, capable of moving large volumes of soil. The method used to mark burrows was an attempt to avoid the loss of makers through burial; it was reasonably, but not entirely, successful (see Section 3).

Each of the 250 marked burrows was inspected with the aid of a burrowscope (Dyer and Hill, 1991); a miniature video camera attached to the end of a 4-m long flexible tube. A video image was projected onto a display monitor. When the camera reached the end of the burrow, burrow length was measured to the nearest 0.1 m using divisions marked on the external casing of the burrowscope.

2.6. Timing of egg laying

Determination of breeding success requires the timing of egg laying to be known. Shearwaters that are trans-equatorial migrants generally exhibit very high breeding synchrony within a colony, with most eggs laid within a few days of one another (Warham, 1990). For flesh-footed shearwaters, however, the timing of laying can vary between populations (Marchant and Higgins, 1990). In colonies along the west coast of Australia, eggs are laid in the last week of November and the first week of December (Warham, 1958). On Lord Howe Island, previous observations of eggs laid on the surface suggested that laying there may not start until early December. To clarify the timing of egg laying on Lord Howe Island, the 50 marked burrows at Neds Beach were inspected every second day between 2 and 10 December 2002 and again on 3 January 2003.

The timing of egg laying in 2002–2003, together with data from other studies, were used to estimate the breeding schedule, incubation period and the period between hatching and fledging.

2.7. Breeding success

All 250 marked burrows were inspected once during 3–6 January 2003 and again during 9–12 April 2003. At each inspection the contents of each burrow were recorded. The January inspection followed egg laying and the April inspection preceded fledging. Burrow markers were removed in April. Breeding success was calculated as the proportion of eggs present in January that produced near-fledged nestlings in April. Those burrows with eggs in January, but which could not be relocated in April were excluded from the calculation.

Some burrows containing near-fledged nestlings in April had no egg recorded in them in January. Manipulation of the burrowscope around bends was not always possible and buried obstacles sometimes restricted the field of view, resulting in some eggs being missed. Near-fledged nestlings were much less likely to be overlooked, as unlike most eggs they were generally not at the rear of the burrow. Also, nestlings were active, inquisitive and, attracted by movement and light, often approached the burrowscope camera. Missed eggs (and subsequent chicks) were omitted from the calculation of breeding success but were included in the calculation of occupancy rate, productivity and population size.

2.8. Occupancy rate

Occupancy rate (O), the proportion of burrows occupied by a breeding pair, was estimated for each colony using the formula:

$$O = \frac{E + \frac{F_{ne}}{BS}}{N},$$

where E is the number of burrows that contained an egg in January; F_{ne} is the number of burrows that contained a fledgling in April but where no egg was recorded in January; BS is the breeding success; and N is the number of burrows sampled.

This calculation takes account of any eggs missed during the January inspection. Birds in burrows, but without eggs, were assumed to be non-breeding birds and were omitted from the calculation. Burrows that could not be located in both January and April were also excluded. Occupancy rate for the population was calculated by dividing the total number of breeding pairs (see below) by the total number of burrows.

2.9. Productivity

The productivity of each colony (the number of fledglings produced per burrow) was calculated as the proportion of marked burrows (both occupied and unoccupied in January) that contained a nestling in April. Burrows that could not be relocated in April were excluded from the calculation. The number of fledglings produced by each colony was then estimated as the product of the productivity of the colony and the number of burrows within the colony. The total number of fledglings produced on Lord Howe Island was calculated by summing data from each colony.

2.10. Population size

The number of breeding pairs in each colony (also equivalent to the number of eggs produced) was calculated as the product of the number of burrows and occupancy rate. Population size was calculated by summing the number of pairs in each colony.

3. Results

3.1. Location and extent of colonies

The locations of the nesting grounds of flesh-footed shearwaters on Lord Howe Island in both 1978 and 2002 are shown in Fig. 1. Detailed digital spatial information maps for each survey are included as supplementary data to this publication. In 1978, the six colonies together comprised a total area of 37.8 ha (Table 1). The most extensive colony was Stevens Point (16.4 ha). An additional area of about 4.3 ha between Stevens Point and Middle Beach had been cleared but still contained small numbers of active burrows. Remnant hummocks of spoil from old burrows indicated that this area was once densely colonised. An additional 0.7-ha clearing within Stevens Point contained burrows that had been abandoned only recently. The area of each colony delineated in 1978 had been measured previously with the use of a planimeter, and the total area of intact colonies reported as 40.6 ha (Fullagar and Disney, 1981), compared to 37.8 ha measured digitally. Much of the previous error was due to overestimating the size of the two smallest colonies (Table 1).

In 2002, the six colonies together comprised a total area of 24.3 ha (Table 1), a decline of 13.4 ha (35.6%) since 1978. Clear Place (8.0 ha) was the most extensive colony in 2002, compared with Stevens Point (16.4 ha) in 1978. More than 95% of the overall loss of nesting habitat was associated with reductions in the extent of Stevens Point and Middle Beach (Fig. 1): Stevens Point contracted by 9.0 ha (54.9%) and Middle Beach by 3.8 ha (40.9%). Loss of nesting habitat in these two colonies was associated with increased urban development. Generally, few burrows occurred under dwellings, in gardens or along driveways. The absence of burrows in areas of suitable nesting habitat surrounding these modified environments indicated that the adverse impact of construction and habitation extended beyond the footprint of buildings and gardens.

The colony at Hunter Bay contracted by 14.4% but the area lost was relatively small (0.05 ha). Proportional decreases in the extent of other colonies (Clear Place, Neds Beach and Little Mutton-bird Ground) were less substantial (Table 1) and were probably associated with errors in defining the edge of the colony rather than any real loss of habitat. Similar errors may have also affected the delineation of Stevens Point and Middle Beach, but the habitat losses in these two colonies were an order of magnitude greater than these potential errors.

A small number of active burrows (<100) still persisted in the cleared area between Stevens Point and Middle Beach in 2002. All other burrows were in lowland palm forest dominated by kentia palms or in rainforest dominated by greybark (*Drypetes australasica*) and blackbutt (*Cryptocarya triplinervis*). All colonies were on calcarenous soils. The boundaries of nesting habitat were often delineated by a transition from calcarenite-derived sandy soils to basalt-derived clay soils, the latter of which are presumably unsuitable for burrowing.

3.2. Burrow density in 1978

In 1978, a total of 525 sample points was examined (Table 2). The mean distance separating these points along the transects was 7.5 m. Mean burrow density varied between 0.071 burrows per m^2 at Little Mutton-bird Ground and 0.153 burrows per m^2 at Clear Place (Table 2), but the differences were not significant (ANOVA, $F_{4,17} = 1.963$, $p = 0.146$). The overall density of burrows (mean ± SE) was 0.098 ± 0.016 per m^2.

The total number of burrows on Lord Howe Island was estimated to be 36,850 ± 6108. The colony with most burrows (12,849 ± 1860 burrows, 34.9% of the total) was Clear Place (Table 2). The colonies with least burrows were Little Mutton-bird Ground (347 ± 169) and Hunter Bay (134), which together accounted for only 1.3% of all burrows. There was no significant relationship between burrow density and the area of the colony (linear regression, $F_{1,4} = 3.027$, $p = 0.157$).

3.3. Burrow density in 2002

Sampling intensity in 2002 (the total area of the transects as a proportion of the total area of the colonies) was 4.8% (Table 3). Mean burrow density varied between 0.077 burrows per m^2 at Stevens Point and 0.168 burrows per m^2 at Clear Place (Table

Table 1 – Area and reduction of flesh-footed shearwater colonies on Lord Howe Island between 1978 and 2002

Date	Method	Units	Colony						Total
			SP	MB	CP	NB	LMBG	HB	
1978	Planimeter	(ha)	15.8	9.1	10.0	3.4	1.1	1.2	40.6
1978	Digitally	(ha)	16.43	9.34	8.38	2.75	0.49	0.36	37.75
2002	Digitally	(ha)	7.41	5.53	8.00	2.61	0.46	0.31	24.31
Reduction	Digitally	(ha)	9.02	3.82	0.38	0.14	0.03	0.05	13.45
% Reduction	Digitally		54.9	40.9	4.6	5.1	6.7	14.4	35.6

SP, Stevens Point; MB, Middle Beach; CP, Clear Place; NB, Neds Beach; LMBG, Little Mutton-bird Ground; HB, Hunter Bay. Colonies sizes for 1978 were calculated, from the same aerial photos, by planimeter (Fullagar and Disney, 1981) and digitally (this study).

Table 2 – Density and abundance of flesh-footed shearwater burrows within each of the six colonies on Lord Howe Island in 1978

	Colony						Total
	SP	MB	CP	NB	LMBG	HB	
Sampling points	179	162	119	54	11		525
Burrow density							
Mean (burrows per m^2)	0.127	0.092	0.153	0.113	0.071	0.037	0.098
SE (burrows per m^2)	0.012	0.016	0.022	0.021	0.035		0.016
Burrows							
Number	11,860	8561	12,849	3099	347	134	36,850
SE	2035	1460	1860	584	169		6108
Proportion (%)	32.2	23.2	34.9	8.4	0.9	0.4	100.0

SP, Stevens Point; MB, Middle Beach; CP, Clear Place; NB, Neds Beach; LMBG, Little Mutton-bird Ground; HB, Hunter Bay. Data for Hunter Bay were derived from a total count of burrows, all other estimates were calculated using the Point-centered Quarter Method at random sampling points along random transects of unequal length.

Table 3 – Density and abundance of flesh-footed shearwater burrows within each of the six colonies on Lord Howe Island in 2002, and changes in abundance since 1978

	Colony						Total
	SP	MB	CP	NB	LMBG	HB	
Transects							
n	5	5	4	2	2		18
Area (m^2)	3752	3188	3048	996	640		11,624
Sampling intensity	0.051	0.058	0.038	0.038	0.140		0.048
Burrow density							
Mean (burrows per m^2)	0.077	0.126	0.168	0.127	0.078	0.039	0.123
SE (burrows per m^2)	0.008	0.022	0.046	0.012	0.011		0.024
Burrows							
Number	5686	6984	13,412	3297	358	119	29,853
SE	623	1222	3649	323	51		5867
Proportion (%)	19.0	23.4	44.9	11.0	1.2	0.4	100.0
Change since 1978							
Number	−6175	−1577	563	199	11	−15	−6998
Proportion (%)	−52.1	−18.4	4.4	6.4	3.1	−11.2	−19.0

SP, Stevens Point; MB, Middle Beach; CP, Clear Place; NB, Neds Beach; LMBG, Little Mutton-bird Ground; HB, Hunter Bay; *n*, number of transects. Sampling intensity is the area of the transects as a proportion of area of the colony. Data for Hunter Bay were derived from a total count of burrows, all other estimates were calculated from counts along random transects of unequal lengths.

3), although these differences were not significant (ANOVA, $F_{4,13} = 2.375$, $p = 0.106$). Within each colony, burrow density was highly variable. This was particularly evident in Clear Place, where patches of low burrow density were associated with calcarenite outcrops and skeletal soils. Overall burrow density was 0.123 ± 0.024 burrows per m^2.

Burrow densities within each colony (Fig. 2) did not differ significantly between 1978 and 2002 (paired *t*-test, $t = 0.8108$, $p = 0.4543$). Given the use of different methodologies and lack of knowledge regarding inter-annual variation, any comparison of density estimates between surveys should be interpreted cautiously. Of particular interest, however, is the relative density of each colony in each of the two surveys (Fig. 2). While all other colonies recorded similar or higher burrow densities in 2002, Stevens Point recorded a substantial decline (a fall of 0.05 burrows per m^2), suggesting a decline in relative burrow density for this colony between 1978 and 2002.

The total number of burrows on Lord Howe Island in 2002 was estimated to be 29,853 ± 5867 (Table 3). The largest colony was Clear Place (13,412 ± 3649 burrows) which accounted for 44.9% of all burrows. The smallest colonies (Little Mutton-bird Ground and Hunter Bay) together accounted for only 1.6% of all burrows. There was no significant relationship between burrow density and the area of the colony (linear regression, $F_{1,3} = 2.774$, $p = 0.171$).

Data from the two surveys (Tables 2 and 3) indicate that between 1978 and 2002 the number of flesh-footed shearwater burrows on Lord Howe Island declined by 6998 (19.0%). Most of these burrows (6175) were lost from Stevens Point, a decline in this colony of 52.1% (Table 3). Another 1577 burrows were lost from Middle Beach (a decline of 18.4%), and 15 from

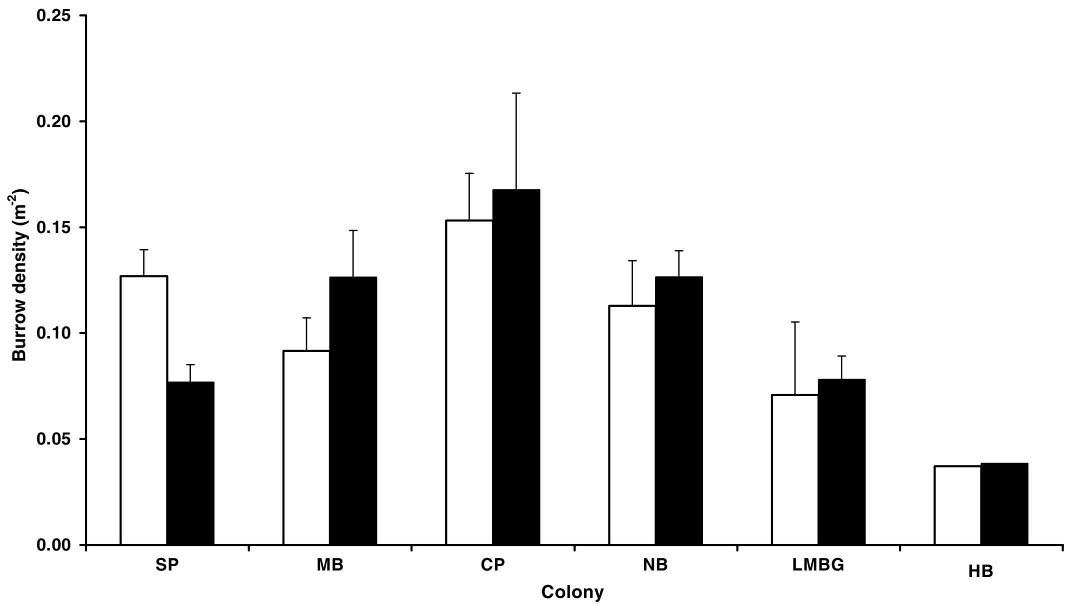

Fig. 2 – Burrow densities in flesh-footed shearwater colonies on Lord Howe Island in 1978 and 2002. SP, Stevens Point; MB, Middle Beach; CP, Clear Place; NB, Neds Beach; LMBG, Little Mutton-bird Ground; HB, Hunter Bay. 1978, unshaded columns; 2002, shaded columns.

Hunter Bay. Small increases in burrow numbers were recorded in Clear Place, Neds Beach and Little Mutton-bird Ground (563, 199 and 11, respectively). Again, given the use of different methodologies and lack of knowledge regarding inter-annual variation, any differences in burrow estimates between surveys should be interpreted cautiously.

3.4. *Burrow length*

Although some burrows had more than one entrance, each burrow was a single tunnel, which although sometimes convoluted, always terminated in a single nest chamber. There was no evidence of a complex network of interconnecting tunnels and chambers like that described for a particular colony of sooty shearwater (*Puffinus griseus*) by Hamilton (2000). Overall, mean burrow length was 1.2 ± 0.1 m (range 0.2–3.4 m) (Table 4). Burrow length differed between colonies (ANOVA, $F_{6,242} = 10.08$, $p < 0.01$) with burrows at Clear Place being about 0.5 m shorter than those elsewhere (Student–Newman–Keuls test for unequal sample sizes). The longest burrow recorded was 3.4 m, at Stevens Point. Occupied burrows were not significantly different in length to empty burrows either within each colony or pooled across all colonies (ANOVAs, all $p > 0.15$).

3.5. *Timing of egg laying*

Eggs were laid in 18 of the 42 burrows monitored repeatedly at Neds Beach. Twelve (67%) were laid by 6 December, three (16%) between 6 and 10 December, and three (16%) sometime between 10 December and 3 January (Table 5). The median date of laying was 5–6 December and the duration of laying exceeded 8 days.

Based on the median laying date (this study) and the peak hatching period of 24–27 January (Dyer, 2001), and assuming no variation in the timing of breeding between years, the incubation period for this species is estimated to be approximately 52–55 days. If young on Lord Howe Island fledged at about 92 days of age, as they do in Western Australia (Warham, 1958), fledging would coincide with the last week of April. Thus nestlings counted during the April survey (9–12 April 2003) were probably 2–4 weeks off fledging.

3.6. *Breeding success*

Of the 250 marked burrows, one could not be relocated during 3–6 January 2003. Of the 249 burrows that were found, 116 contained eggs (Table 6). Eleven burrows contained a bird (or birds) without eggs; these were assumed to be non-breeding

Table 4 – Length of flesh-footed shearwater burrows at six colonies on Lord Howe Island in January 2003

Burrow length	Colony						Total
	SP	MB	CP	NB	LMBG	HB	
Mean (m)	1.3	1.3	0.8	1.3	1.4	1.4	1.2
SE (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Range (m)	0.2–3.4	0.5–2.4	0.3–1.8	0.5–2.5	0.8–2.8	1.0–2.6	0.2–3.4

SP, Stevens Point; MB, Middle Beach; CP, Clear Place; NB, Neds Beach; LMBG, Little Mutton-bird Ground; HB, Hunter Bay.

Table 5 – Contents of 42 flesh-footed shearwater burrows, checked in December 2002 and January 2003

Contents	Date					
	December 2002					January 2003
	2	4	6	8	10	3
Empty	37	29	28	27	24	20
Bird(s) no egg	1	7	2	1	3	4
Bird and egg	4	5	10	13	14	17
Egg only	0	1	2	1	1	0
Egg lost	0	0	0	0	0	1

Burrows were all within the Neds Beach colony.

Table 6 – The contents of flesh-footed shearwater burrows at six colonies on Lord Howe Island in April 2003 together with estimates of breeding success, productivity, fledgling production, occupancy rate and the number of breeding pairs

	Colony						Total
	SP	MB	CP	NB	LMBG	HB	
Burrows with eggs in January	19	29	29	20	11	8	116
Nestling present in April	5	16	16	10	3	6	56
Not relocated in April	2	1	0	0	0	0	3
Breeding success (fledglings/egg)	0.29	0.57	0.55	0.50	0.27	0.75	0.50
Burrows without eggs in January	31	21	21	29	14	17	133
Nestlings present in April	1	4	0	3	0	2	10
Not relocated in April	2	2	0	0	0	1	5
Productivity (fledglings/burrow)	0.13	0.43	0.32	0.27	0.12	0.33	0.27
Fledglings	742	2972	4292	875	43	40	8963
Occupancy rate	0.44	0.74	0.58	0.53	0.44	0.44	0.58
Breeding pairs	2521	5201	7779	1750	158	53	17462

Breeding success is the proportion of eggs that produced nestlings. Productivity is the proportion of all burrows (occupied and unoccupied in January) that produced fledglings in April. Occupancy rate is the proportion of burrows that contained a breeding pair. SP, Stevens Point; MB, Middle Beach; CP, Clear Place; NB, Neds Beach; LMBG, Little Mutton-bird Ground; HB, Hunter Bay.

birds. When inspected again in April 2003, a further eight marked burrows could not be relocated. Of those nests known to contain eggs in January and which were located in April ($n = 113$), 56 contained well-developed nestlings (Table 6). Thus, breeding success (the proportion of eggs that produced fledglings) was calculated to be 50%. This estimate does not take into account eggs lost prior to the first inspection or mortalities of fledglings between the April survey and final departure. Consequently, it is likely to be an overestimate and should be interpreted accordingly. Breeding success did not differ between colonies ($\chi^2 = 8.029$, df = 5, $p > 0.10$), although larger sample sizes may indicate otherwise. Ten nestlings found during April were from marked burrows that were recorded as being unoccupied in January (i.e., not containing an egg).

3.7. *Productivity*

Overall productivity was 27% (Table 6), but varied significantly between colonies ($\chi^2 = 14.152$, df = 5, $p < 0.025$). Based on the contribution of each cell in the contingency table, productivity was particularly low at Stevens Point (13%) and high at Middle Beach (43%).

The number of fledglings produced by each colony was calculated from the productivity of the sampled burrows (Table 6) and the number of burrows each colony contained (Table 3). Overall, the population is estimated to have produced a total of 8963 fledglings (Table 6), the largest contributions coming from Clear Place (4292 fledglings, 47.9% of total output) and Middle Beach (2972, 33.2%).

3.8. *Occupancy rate*

Based on the number of nestlings in burrows that were thought not to contain an egg ($n = 10$) and breeding success (50%), it is estimated that approximately 20 eggs failed to be detected during the January inspection. The formula used to calculate occupancy rate took account of these missed eggs. Occupancy rates (Table 6) varied between colonies ($\chi^2 = 11.852$, df = 5, $p < 0.05$). The occupancy rate for Middle Beach (0.74) was substantially greater than that in any other colony (0.44–0.58). Occupation rates in all colonies other than Middle Beach were similar ($\chi^2 = 2.708$, df = 4, $p > 0.5$). The overall occupancy rate (0.58) was identical to that obtained by Dyer (2001) using counts of eggs and newly hatched chicks. Unlike this study, however, Dyer found the proportion of occupied burrows relatively consistent across all colonies (0.52–0.62).

3.9. *Population size*

The size of the flesh-footed shearwater population on Lord Howe Island during the 2002–2003 season was estimated to be 17,462 breeding pairs (Table 6). The largest colonies were Clear Place (7779 breeding pairs, 44.6% of the total population) and Middle Beach (5201, 29.8%). Stevens Point and Neds Beach contained 2521 and 1750 breeding pairs, respectively, or 14.4% and 10.0% of the total population. The colonies at Little Mutton-bird Ground and Hunter Bay were small (158 and 53 breeding pairs, respectively) and together accounted for only 1.2% of the population.

4. Discussion

4.1. *Population trends on Lord Howe Island*

Since settlement in 1834, there has been a marked contraction in the nesting grounds of flesh-footed shearwaters on Lord Howe Island. Much of the lowland forest in which shearwaters once nested has been cleared to provide pasture for cattle and building sites for the island's residents and tourists. The once large, and probably unbroken, colony along the eastern coastline has been reduced and fragmented (Fullagar et al., 1974). Evidence of past shearwater colonies – the remnant hummocks of spoil from old burrows – still persists in some pastures. The 1978 survey identified at least 5.0 ha of cleared land that previously contained dense colonies of flesh-footed shearwaters. Since 1978 the total area of nesting habitat has been reduced by a further 13.4 ha (35.6%). The colonies most affected during this period were Stevens Point and Middle Beach, where the loss of nesting habitat was associated with increasing urbanisation, the impact of which generally extended beyond the footprint of buildings and gardens. Unintended disturbance and trampling, together with minor noise and light pollution, may have contributed to discouraging birds from nesting adjacent to habitation. The impact of lighting on Lord Howe Island, however, is likely to be less significant than in most other communities. For aesthetic reasons and because power generation capacity is limited, external lighting on Lord Howe Island is extremely minimal. Street lighting, for example, is largely non-existent and where lights do occur they are of low wattage and positioned close to the ground. In some instances, the exclusion of birds from areas surrounding habitation may be due to more wilful interference. Breeding shearwaters are noisy and it has been alleged that burrows (and birds) in close proximity to inhabited buildings have been deliberately destroyed, although the veracity of such allegations has yet to be substantiated.

In 2002–2003, the mean density of flesh-footed shearwater burrows within the six colonies on Lord Howe Island was 0.123 burrows per m^2. Two years earlier Dyer (2001) estimated the density of flesh-footed shearwater burrows in four of the six colonies on Lord Howe Island (Middle Beach, Clear Place, Hunter Bay and Neds Beach) by counting burrows within small plots (10 m × 10 m) at the time of hatching (late January). Dyer made no assessment of the extent of nesting habitat nor produced any estimate of population size. For each colony, burrow densities recorded by Dyer (2001) were substantially greater than those recorded in this study. Dyer (2001) recorded densities as high as 0.71 burrows per m^2 whereas the maximum burrow density recorded on any transect in this study was 0.254 burrows per m^2. Burrow density in 2002 was extremely patchy and the high densities obtained by Dyer (2001) were probably the result of sampling small areas of habitat where burrows were particularly dense.

Data from the 1978 and 2002 surveys suggest that the mean density of flesh-footed shearwater burrows within colonies increased during this period (from 0.098 burrows per m^2 to 0.123 per m^2). However, the level of annual variation is unknown and density estimates for each survey were derived using two different sampling techniques, hence comparison between these estimates must be interpreted cautiously. Notwithstanding, the apparent increase in the density of burrows was insufficient to offset the loss of nesting habitat, resulting in a net reduction (19.0%) in the number of burrows on Lord Howe Island between 1978 and 2002. Assuming that the occupancy rate has remained unchanged, it follows that the breeding population of shearwaters has declined by a similar proportion over the same period. This study provides the baseline data from which to track future population trends on Lord Howe Island.

4.2. *Global population trends*

The global population of flesh-footed shearwaters is estimated to be 300,000 individuals (Fishpool and Evans, 2001). Although the population in eastern Australia has declined in recent years, global population trends have not been quantified. In Western Australia, where the population numbers 100,000–200,000 pairs (Ross et al., 1996), introduced predators have destroyed all mainland colonies (Warham, 1958). Colonies persist on at least 20 offshore islands (Marchant and Higgins, 1990). In recent years fishing effort in waters off Western Australia has increased (Department of Agriculture, Fisheries and Forestry, 2003), with unknown effects on shearwater colonies. In New Zealand, where the breeding population numbers 25,000–50,000 pairs, some colonies have increased recently while others have been extirpated by introduced predators (Taylor, 2000). Little is known about population trends for the small colony of about 600 pairs on St. Paul Island (Roux, 1985).

Other Procellariiformes breeding in the South Pacific have also undergone declines in abundance or contraction in breeding ranges. For example, beach patrol records indicate a substantial decline in sooty shearwater numbers in New Zealand since 1961 (Scofield and Christie, 2002). These authors suggest that a rise in sea-surface temperatures and the associated movement of the sub-Antarctic Front are major contributing factors.

4.3. *Breeding success*

Procellariiformes are long-lived, have high adult survival and low fecundity (a clutch size of one), and first breed at considerable age (Warham, 1990). For such k-selected species (Pianka, 1970) small changes in adult mortality rates can have substantial effects on population size, whereas changes in fecundity have much less effect (Caughley, 1977). Determination of age-specific mortality (or survival) rates requires long-term studies of marked individuals. Unfortunately, modern seabird research, particularly that funded by government, is generally based on short-term projects (Weimerskirch, 2002). In the absence of demographic data, breeding success can be a valuable indicator of ecological circumstance (Nelson, 1978). The breeding success of Gould's petrel (*Pterodroma leucoptera*), for example, increased from less than 20% to more than 50% when their principal predator, pied currawongs (*Strepera graculina*), was heavily culled (Priddel and Carlile, 1997). The significance of the pied currawong as a predator of Gould's petrel is thought to be a recent manifestation, the result of habitat change in the breeding site of the petrel brought about by the introduction of the European rabbit (*Oryctolagus cuniculus*) (Priddel and Carlile, 1995).

Overall breeding success for flesh-footed shearwaters on Lord Howe Island in 2002–2003 was 50%. No other estimate of breeding success exists for flesh-footed shearwaters but generally, for other Procellariiformes, 40–50% of eggs yield flying young (Warham, 1990). Although breeding success can vary between species, populations and years, this initial estimate for flesh-footed shearwaters on Lord Howe Island appears consistent with a reasonably productive population.

4.4. *Threats on Lord Howe Island*

The apparent decline in the population of flesh-footed shearwaters on Lord Howe Island during the middle of last century was attributed to harvesting of nestlings for human consumption (mutton-birding) and clearing of nesting habitat for pastoralism and housing (Fullagar et al., 1974). Harvesting is no longer practiced, but this study has demonstrated that the loss of nesting habitat has continued despite the species' high level of legislative protection.

Trampling of burrows by domestic cattle and the encroachment of kikuyu grass (*Pennisetum clandestinum*) have affected some shearwater burrows on Lord Howe Island, but these threats are confined essentially to areas of nesting habitat that has been cleared. If availability of nesting habitat was the prime factor limiting the size of the flesh-footed shearwater population, the decrease in shearwater abundance between 1978 and 2002 could be explained as a direct consequence of the loss of nesting habitat. However, given the low density of burrows in some areas of apparently suitable habitat and an occupancy rate of less than 60% it seems unlikely that all available nesting habitat is fully occupied. It is probable that additional threats are operating, either on land or at sea.

Past threats on Lord Howe Island include predation by both pigs and cats, but feral populations of these species were eradicated in the early 1980s. Currently, the only potential mammalian predator of seabirds on Lord Howe Island is the black rat. This exotic pest is known to take the eggs, chicks and adults of several burrowing Procellariiformes, particularly the smaller species, causing substantial reductions in reproductive output (Moors and Atkinson, 1984; Atkinson, 1985). The productivity of flesh-footed shearwaters on Lord Howe Island during 2002–2003 was not suggestive of a population suffering a high rate of predation, and there was no direct evidence of rats preying on flesh-footed shearwater eggs or chicks. A few dead adults were encountered (in Neds Beach and Stevens Point), but these were near roads and appeared to have died as a result of collisions with vehicles. In New Zealand, colonies of flesh-footed shearwaters persist on islands where black rats or Norway rats (*Rattus norvegicus*) are present, but the largest colonies occur on islands that are free of both rats and mustelids (Taylor, 2000).

4.5. *Global threats*

Flesh-footed shearwaters face significant threats whilst at sea. They are incidentally killed in driftnets and during longline fishing operations, and they ingest considerable quantities of plastics, presumably mistaking it for food. The cumulative impacts of these threats are not understood. Intensive, longitudinal studies are needed to assess more fully, and where possible mitigate, these threats.

During the austral winter, flesh-footed shearwaters migrate across the equator to the North Pacific (Lindsey, 1986). Driftnet fishing in these waters between 1978 and 1992 killed millions of 'dark shearwaters' (Ogi, 1984; Northridge, 1991; DeGange et al., 1991; Johnson et al., 1993; Ogi et al., 1993; Artyukhin and Burkanov, 2000; Uhlmann, 2003; Uhlmann et al., 2005). Although most of these birds were sooty and short-tailed shearwaters, in 1990 this bycatch was estimated to include approximately 1000 flesh-footed shearwaters (Johnson et al., 1993). In 1993, a United Nations resolution banned all driftnet fishing on the high seas (Nagao et al., 1993). However, large-scale driftnet fishing still persists in inshore waters in the North Pacific (Artyukhin and Burkanov, 2000; Spiridonov and Nikolaeva, 2004).

Longline fishing is recognised as a serious threat to many seabirds, causing declines in populations around the globe (Moloney et al., 1994; Croxall, 1998; Gales, 1998; Tuck et al., 2001; Inchausti and Weimerskirch, 2001). Between 1986 and 1995 flesh-footed shearwaters comprised 9.6% of the bycatch recorded on Japanese longline vessels operating within the Australian Fishing Zone (Gales et al., 1998). Immature males were caught regularly in April and adults returning from migration were caught in September (Gales et al., 1998). The Japanese longlining fleet withdrew from Australian waters in 1997 to be replaced by an expanding domestic fishery, the Australian Eastern Tuna and Billfish Fishery. Since 1998 this fishery has concentrated much of its fishing effort during the austral summer to waters off the east coast of Australia, between latitudes 25°S and 30°S (Baker and Wise, 2005). Flesh-footed shearwaters breeding on Lord Howe Island are known to forage in these waters (McKean and Hindwood, 1965). It has been estimated that between 1998 and 2002 the driftnet fishery killed as many as 4500 flesh-footed shearwaters annually, many of which are likely to have come from the population on Lord Howe Island (Baker and Wise, 2005). Banded individuals from Lord Howe Island have also been taken on longlines set in the North Pacific (McKean and Hindwood, 1965; Purchase, 1971).

The presence of sizeable quantities (7–33 ml) of plastic within the skeletal remains of 18 dead fledglings on Lord Howe Island (Hutton, 2004) indicates that the ingestion of plastic may be an additional threat for flesh-footed shearwaters. Plastic ingestion can have a range of lethal and sublethal consequences for seabirds (Peakall, 1970; Colton et al., 1974; Mauchline, 1980; Raymont, 1983; Ryan and Moloney, 1988; Baker et al., 2002). Nestlings are particularly susceptible because they tend not to regurgitate until they are almost fully fledged, so plastic accumulates in their gut. The physical presence of plastic in the gut prevents the bird from receiving a full load of food at each feed. Also, by preventing stomach contraction, an important cue in the stimulation of hunger, nestlings may have depressed appetite and diminished feeding activity (Sturkie, 1965; Ryan, 1988; Auman et al., 1998). The lower nutrient intake can result in reduced fitness or death. Body fat, a measure of energy reserves, is negatively correlated with the number of pieces of plastic in the stomach of petrels (Ryan, 1987). Plastic accumulation in seabirds is also correlated with polychlorinated biphenyls (PCBs) levels in body tissues (Ryan et al., 1988). High PCB loads can lower steroid hormone levels causing delayed ovulation and other reproductive problems (Hoffman et al., 1996). The degree to which plastic ingestion affects nestling mortality of flesh-footed shearwaters is unknown, and the extent of the problem on Lord Howe Island merits further investigation.

4.6. *Management implications*

The flesh-footed shearwater is afforded a high level of protection under relevant Australian legislation. Despite this protection, the only population of this species in eastern Australia has declined substantially during the last few decades. A clear factor in this decline has been the loss of nesting habitat through the clearing of lowland forest for pastoralism and housing; more than 45% of the original nesting habitat has been lost.

Future land-use decisions will be of vital importance to the survival of flesh-footed shearwaters on Lord Howe Island. A modern airport on the island, completed in 1974, has reduced reliance on local pastoralism and consequently the clearing of lowland forest to create pasture for stock has ceased. The demand for new dwellings, however, is escalating, potentially putting further pressure on the shearwater population. The Draft Regional Environmental Plan for Lord Howe Island (Department of Infrastructure, Planning and Natural Resources, 2004) allows for 25 new dwellings to be constructed on the island over the next two decades. Areas designated for future development include current nesting habitat of the flesh-footed shearwater. Large sections of Stevens Point and small sections of both Neds Beach and Clear Place are proposed for development (Zone 2 Settlement; Department of Infrastructure, Planning and Natural Resources, 2004). Land under this zoning aims to "provide opportunities for limited residential and commercial development while also avoiding or minimising environmental damage and protecting areas that comprise significant habitat for species of animals that are native to the island or contain significant native vegetation". Given the past loss of substantial nesting habitat, together with low burrow density and low productivity in sites affected by earlier developments, it is hard to justify the inclusion of any shearwater nesting habitat in future development plans.

Major changes in land use practices, enforced through appropriate legislation, are needed to avert further declines in the population of flesh-footed shearwaters on Lord Howe Island. On an island of such World Heritage significance, the focus should not be on destroying more shearwater nesting habitat, but on restoring what has already been lost. In particular, the reduced reliance on local pastoralism has created the opportunity to rehabilitate some grazing leases as nesting habitat for the flesh-footed shearwater through direct planting of native vegetation. Subsequent recolonisation of these areas by shearwaters can either be allowed to occur naturally or hastened by the translocation of fledglings. Although some small weed-infested areas adjacent to grazing leases have been rehabilitated by weed removal and direct planting, the possibility of restoring large areas of cleared land has yet to be realised. The decline in local pastoralism also creates a significant opportunity to adopt a more environmentally responsible approach to the housing issue. Rather than clear more areas of lowland forest, new dwellings should be constructed within existing pastures and the area around them revegetated and, in time, recolonised.

At-sea threats are also contributing to the decline of the flesh-footed shearwater. Mortality in the Australian domestic longlining fishery alone is currently at a level that threatens the persistence of the population on Lord Howe Island (Baker and Wise, 2005). Other fisheries to the east of Lord Howe Island or in the north Pacific are also likely to be contributing to this decline. The uncertainty regarding the level of impact highlights the need to improve the monitoring and reporting of seabird bycatch in all fisheries. Although some progress has been made, further development and implementation of mitigation measures to reduce the level of seabird bycatch in fisheries operations is warranted. Initiatives to reduce the amount of plastics that currently litter the world's oceans may also be beneficial.

At present, the global population of flesh-footed shearwaters is evaluated as Least Concern under IUCN Red List criteria (BirdLife International, 2005). Stochastic modelling using current bycatch estimates predicts the population on Lord Howe Island will decline by 50% within 55 years (Baker and Wise, 2005), thus meeting the IUCN criteria for listing as vulnerable or endangered (IUCN, 2001). Although the current threats are likely to be global, there is presently insufficient information from other populations to warrant a change to the species' current conservation status. Monitoring of population trends within the large colonies in Western Australia and New Zealand is needed to assess the current level of threat and to determine the appropriate global status of flesh-footed shearwaters.

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