DECLINE OF SOOTY SHEARWATERS, *PUFFINUS GRISEUS*, ON THE SNARES, NEW ZEALAND

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(with two text-figures and six tables)

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The number of Sooty Shearwater, *Puffinus griseus,* burrow entrances on North East Island of The Snares, New Zealand, declined from 3 288 000 (95% CI = 3.1–3.5 million) entrances between 1969 and 1971, to 2 061 000 (95% CI = 1.9–2.2 million) between 1996 and 2001. This represents a decline of 37% over 27 years, or 1.72% per year (95% CI = 1.35%–2.12%). It is not known whether burrow occupancy has also declined. Possible reasons f●r decline include fisheries bycatch, climate change, and losses on other islands to predation by introduced mammals and harvest of chicks (muttonbirding). Reliable population estimates of other Sooty Shearwater populations will be importanr f●r establishing baseline estimates against which future population trends can be evaluated. If the decline in burrow numbers represents a similar decline in Sooty Shearwater numbers on The Snares and elsewhere, the decline reported here is substantial and enough to warrant listing of the Sooty Shearwater as a "vulnerable" species, according to criterion A3 designated by the International Union f●r Conservaion of Nature and Natural Resources (IUCN) in 2001.

Key Words: Sooty Shearwater, *Puffinus griseus,* The Snares, population decline, fisheries bycatch, climate change, predation, harvest.

INTRODUCTION

Marine birds are sensitive to perturbations in climate, prey abundance and food-web structure. In recent decades increasing pressure has been put on the world's oceans from fisheries and global environmental changes associated with a burgeoning human population (Worm *et al.* 2006). Seabirds are increasingly being used as sensitive indicators of the state of the world's oceans (Furness & Camphuysen 1997). Seabird population decline is widespread, with 50% of taxa in the largest group of marine birds, the Procellariiformes, listed by the IUCN as threatened, vulnerable or endangered (Collar *et al.* 1994).

Procellariiformes are long-lived, monogamous species with low reproductive output and delayed maturation (Warham 1990, 1996). Their populations are particularly sensitive to any fluctuation in adult survival (Danchin *et al.* 1995, Hamilton & Moller 1995, Russell 1999). Demographic consequences of a significant mortality of breeding birds can therefore be rapid and severe, and recovery slow, e.g., the near extinction of the Black Petrel *Procellaria parkinsoni* G.R. Gray, 1862, on Little Barrier Island (Imber 1987). Maturation is delayed, so any change in fledging or juvenile survival may take a generation or more to be detectable in population trends (Fletcher *et al.* unpubl. data).

Sooty Shearwater (Tītī), *Puffinus griseus* (J.F. Gmelin, 1789), is a highly abundant trans-equatorial migrant seabird that plays a major role in the ecology of the islands of southern New Zealand and South America, where it breeds (Shaffer *et al.* 2006). The current total New Zealand population size is estimated to be 19–23 million individuals (Newman *et al.* unpubl. data). Chicks ("muttonbirds") are harvested by Rakiura *Māori* (indigenous people) (see Kitson & Moller 2008). Approximately 360 000 chicks have been harvested annually in recent years (Newman *et al.* 2008). However, of indicators of Sooty Shearwater decline has been found. Harvest rates of Sooty Shearwater chicks on Poutama Island decreased by 42–47%, or 3.6% to 3.9% per year, between 1989 and 1998 (Lyver *et al.* 1999). Furthermore, a 64.4% decline was found in the number of adult Sooty Shearwaters found dead on beaches in New Zealand between 1961 and 1999, or 1.3%● per year (95% CI = 0.3% to 1.7% per annum) (Scofield & Christie 2002). Declines have also been recorded elsewhere; for example Sooty Shearwater numbers in the Californian current system declined by 90%, or 7.4% per year, between 1987 and 1995 (Veit *et al.* 1997).

Driftnet fishing for squid and salmon occurred in the North Pacific from 1978 until the end of 1992 (Uhlmann 2002, 2003, Uhlmann *et al.* 2005). Estimates of the impact of these fisheries on marine ecosystems vary. Sooty Shearwater and Short-tailed Shearwater, *Puffinus tenuir●stris* (Temminck, 1835), were the largest component of the bycatch, both numerically and in biomass. Shearwaters may still be a major component of the bycatch in salmon fisheries in the North Pacific (Artyukhin & Burkanov 2000). Ogi *et al.* (1993) predicted a population growth rate (λ) of between 0.993 and 0.972 for the breeding stock of Sooty Shearwaters during the period driftnet fisheries operated. However, this estimate has not been confirmed by actual estimates of population trends at their breeding colonies (Warham 1996) and all the inputs to Ogi *et al.*'s (1993) model were from Short-tailed Shearwater.

The Snares (48°01'S, 166°36'E) is a group of small islands lying 105 km south-southwest of Stewart Island, New Zealand. Surveys conducted between 1969 and 1971 estimated that collectively these islands had a population of 2.75 million breeding pairs of Sooty Shearwater (Warham & Wilson 1982). Our study repeats the counts undertaken by Warham & Wilson (1982) on North East Island, the largest of The Snares islands. Burrow counts previously undertaken in 1986/87 at 30 permanently marked vegetation plots are also repeated in this study. Our primary aim is to determine whether a measurable decline in the Sooty Shearwater breeding population has occurred in the decades since the original surveys were undertaken. We also estimate the generation time of Sooty Shearwaters from recently available population parameters and ask whether any decline observed on The Snares has reached the critical threshold that would lead to the species being listed as threatened according to IUCN (2001) criteria.

MATERIALS AND METHODS

Study site

North East Island, also referred to elsewhere as Main Island, is 238.1 ha in area. The principal habitat types on the island are *Olearia lyallii* Hook.f. (tree daisy) forest, and maritime tussock grassland dominated by *Poa astonii* Petrie and *P. tennantiana* Petrie (Warham & Wilson 1982, Hay *et al.* 2004).

Burrow entrance counts

We define a burrow entrance as a single entrance leading to one or more tunnels (following Warham & Wilson 1982). Entrances may have more than one occupied tunnel and individual nests frequently have more than one entrance (McKechnie *et al.* 2007, Hamilton 2000). Assuming that the probability of detecting entrances in different areas and times does not change, this will not affect interpretation of relative trends in shearwater abundance.

There are about 10 000 breeding pairs of Mottled Petrels, *Pterodroma inexpectata* (J.R. Forster, 1844), on The Snares (Warham *et al.* 1977). Mottled Petrel and Sooty Shearwater burrow entrances can be difficult to tell apart. Warham & Wilson (1982) do not state how they separated Mottled Petrel and Sooty Shearwater burrows in their study; however we found that Mottled Petrel burrows were always in dry, open, well-drained sites. Additionally, no Mottled Petrel burrows were found in soil with a depth of greater than c. 50 cm, and tunnels were rarely longer than an arm's length. Furthermore, burrow entrances of Mottled Petrels were smaller than those of Sooty Shearwater (Scott 2005, Scott *et al.* 2006), and were almost always in areas where *Poa* tussock was prevalent; only one occupied Mottled Petrel burrow was found more than 5 m from the *Poa* tussock strip that encircles the island.

We assumed that all burrow entrances with a maximum greatest entrance width of less than 7 cm were Common Diving-Petrel, *Pelecanoides urinatrix* (J.F. Gmelin, 1789). An estimate of the number of diving petrel burrows recorded during these surveys is given in Miskelly *et al.* (2001).

1969–71 surveys

Warham & Wilson (1982) sampled 51 quadrats, each 10 x 10 m and randomly placed off marked tracks, between 1969 and 1971. They assessed habitat type and estimated planar habitat size from a map produced in 1971 from aerial photographs (Hay *et al.* 2004). Random number tables were used to obtain distances along and off the track for quadrat placement. The approximate position of these tracks is given in Figure 1 of Warham (1967); however the locations of the quadrats were not permanently marked.

Permanent vegetation quadrats, 1986/87

The University of Canterbury established 30 10 x 10 m permanently marked vegetation quadrats in the summer of 1986/87. Only 23 quadrats contained recognisable burrows that were occupied. The primary purpose of these quadrats was to map vegetation change, but burrow entrance positions were plotted and the total numbers of entrances was counted.

Burrow entrance surveys, 1996–2001

In all 357 sampling units, with a combined area of 2.25 ha, were surveyed for burrow entrance density during the late incubation period between 1996 and 2001. Four methods of plot establishment and size were used to address related research questions, described elsewhere (Scofield 2000, Charleton 2002).

Quadrats positioned from tracks

Random numbers were used to select a distance along and off the track system for placement of 10 x 10 m plots in Dec–Jan 1996 (n = 60).

Transects positioned from tracks

In Dec–Jan 1996, random numbers were used to select a distance along and off the track system for placement of 2-m-wide transects. Transects followed a randomly-assigned direction until 20 used burrow entrances were included and transect length was then recorded to provide an estimate of entrance density (n = 45).

Quadrats positioned along transects across the island

Three randomly-placed line transects were chosen, running approximately north-south, east-west and southeast-northwest across the entire island (fig. 1). Plots measuring 10 x 10 m were placed every 100 paces along the transects in January 2000 (n = 101).

Circular plots along transects near coast

Random numbers were used to obtain start points for 18 transects (nine each on the east and west coast) that ran perpendicular to the coast. Circular plots of 3 m radius were placed at intervals of 3, 15, 27, 54, 76, 113 and 174 paces from the coast in January 2001 (n = 151).

In addition to the 357 sampling units above, the Sooty Shearwater burrow entrances within the 23 University of Canterbury permanent vegetation quadrats recorded with burrow entrances in 1986/87 were counted in December 1998.

The locations of all sampling units on North East Island are shown in figure 1. We assessed vegetation type, whether the ground cover was open or closed and recorded the number of Sooty Shearwater entrances that were open, and the number of Common Diving-Petrel and Mottled Petrel entrances in each sampling unit. The position of each sampling unit was recorded using a Trimble Geo-explorer II ® differential GPS unit and mapped in Geographical Information System MapInfo 6.0™, on a base map supplied by Land Information New Zealand. Vegetation boundaries and types were digitised from a map produced from aerial photographs taken in 1971 (Hay *et al.* 2004). This allowed the land area under each vegetation type to be calculated and mapped. During the 2000 and 2001 surveys, this map was "ground truthed" in the field to determine changes in

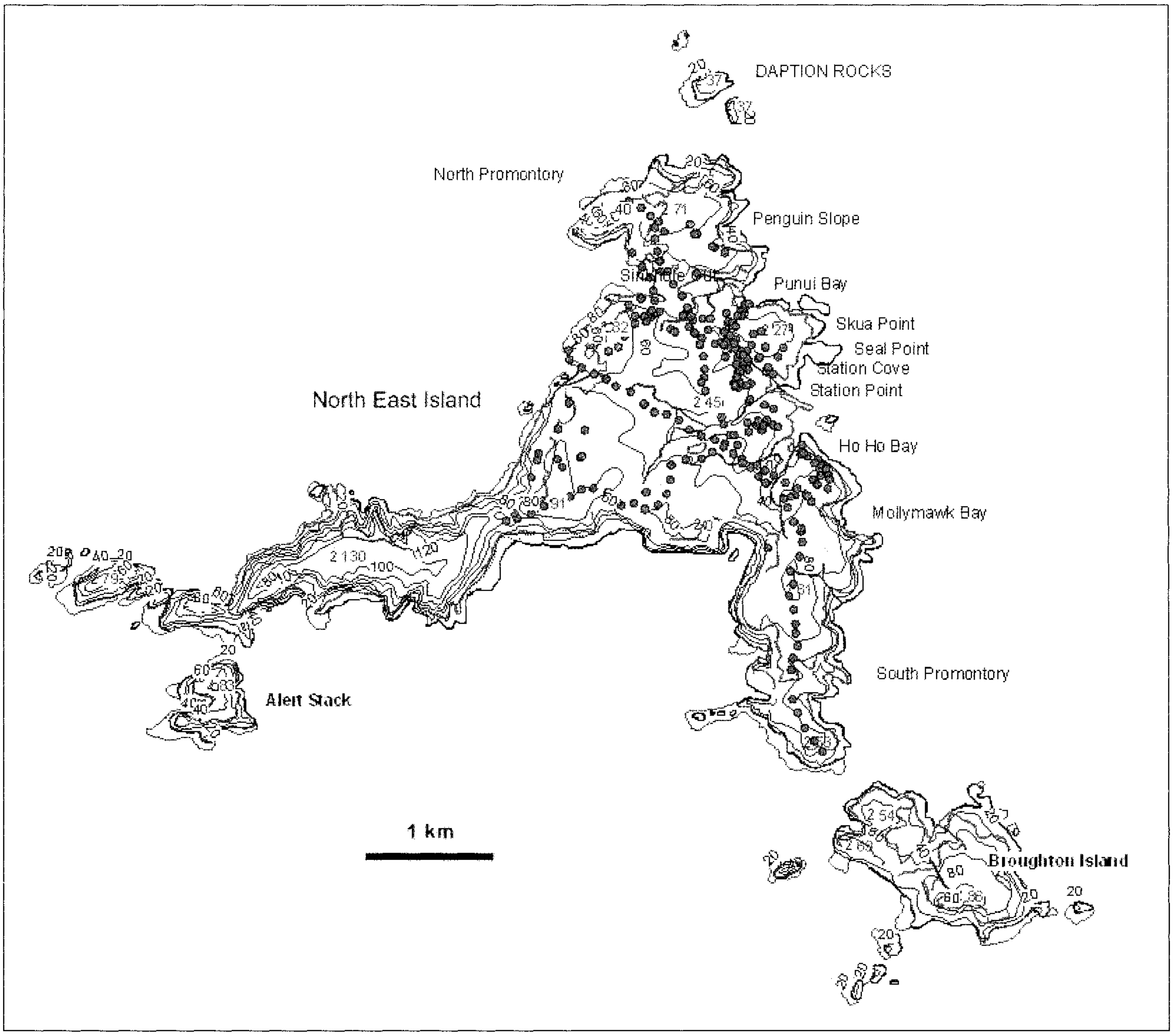

FIG. 1 — North East Island, The Snares, with locations of sampling units (circles) surveyed for Sooty Shearwater burrow entrances 1996–2001.

vegetation cover since 1971. Changes in vegetation cover were found to be minor, with a small decrease in the area classified as *Olearia* forest and increase in the area classified as *Hebe elliptica* shrubland (table 1). The estimated area of the island available for Sooty Shearwater burrows excluded the area occupied by penguin colonies. A survey of Snares Crested Penguin, *Eudyptes robustus* Oliver, 1953, detailing colony sizes and locations undertaken in October 2000 (D. Houston, unpubl. data) was used to exclude these areas from the estimated burrowable area of the island.

Burrow occupancy

The proportion of Sooty Shearwater burrows in which breeding was evident (egg or chick) is referred here as the "occupancy rate". This has been assessed in three general and five specific ways throughout the studies compared here.

1. Contents of collapsed nesting chambers

Whilst carrying out fieldwork on The Snares it is difficult to avoid accidentally collapsing burrows that are often situated in fragile soils. Warham & Wilson accidentally collapsed 54 nesting chambers between 3 December 1970 and 24 February 1971. During our study, 86 burrow chambers were collapsed between 26 December 1999 and 20 January 2000; and 62 chambers between 10 January and 5 February 2001. All burrows were carefully reconstructed using available materials, but first the contents (egg or chick) were determined.

2. Burrowscoping

A burrowscope consists of a miniature surveillance camera on the end of a long tube that projects an image of the nesting chamber onto a monitor on the surface (Lyver *et al.* 1998). We used burrowscopes to estimate burrow occupancy on the 45 2-m-wide transects (900 burrow entrances) positioned from tracks between December–April 1996 and 1998.

3. Measures of passage into and out of burrow entrances in January

Comparisons are possible between two methods: (i) Horning (1976) and Warham & Wilson (1982) estimated occupancy by observing the disturbance of fine wires placed across the 31 burrow entrances between 4 and 22 January 1972. (ii) We used an electronic burrow monitoring system (based

TABLE 1
Sooty Shearwater burrows by vegetation type on North East Island, The Snares

Vegetation type	Cover[1] (%)		Burrow density [2] (m^{-2})		Area (ha)		Est. no. of burrows (thousands)		S.E. (thousands)	
Period	1[3]	2[4]	1	2	1	2	1	2	1	2
Olearia forest[5]	61.7	55.9	1.16	0.71	146.8	133.0	1704	948	104	29
Poa tussock	32.1	32.5	1.95	1.23	76.5	77.3	1490	950	44	26
Brachyglottis[6] forest	1.4	1.9	0.46	0.70	3.3	4.6	15	32	3.8	4.1
Hebe elliptica	4.8	9.7	0.68	0.57	11.5	23.2	78	131	1.7	15
Total	–	–	–	–	238.1	238.1	3288	2061	113	42

[1] Cover is the percentage of the island covered by that vegetation type.
[2] Burrow density is the estimated mean density of burrow entrances.
[3] Period 1 data were collected between 1969 and 1971 (from Warham & Wilson 1982).
[4] Period 2 data were collected between 1996 and 2001.
[5] Includes vegetation from areas in which *Olearia* was present with other vegetation.
[6] Formerly *Senecio*.

on an off-the-shelf burglar alarm system) to record the date and time of entrance and exit events from manual triggering of switches placed in the burrow entrance (Moller *et al.* 2003a). One panel could monitor 16 separate entrances and up to four panels were used simultaneously during this study. Thirty-two of these automated entrance monitors operated at two study sites near Punui Bay between 10–22 January 1999 and 4–22 January 2000.

4. Measures of passage into and out of entrances in April

(i) Horning (1976) and Warham & Wilson (1982) estimated occupancy of 100 entrances chosen at random under *Olearia* forest near Punui Bay in April 1970. In early April, they determined occupancy by feeling for an occupant by hand or by using a long wire.
(ii) In late April, the knocking down of thin wires placed in the burrow entrance, evidence of fresh digging, presence of nestling down in the tunnel, and observation of birds entering these 100 entrances were all used to assess occupancy.
(iii) We used the electronic entrance monitoring system to quantify use of 15 occupied and 17 unoccupied burrows between 1–30 April 1998; and 11 occupied and 21 unoccupied burrows between 1–30 April 1999.

Surface egg density

Some Sooty Shearwater eggs are laid on the ground outside burrow entrances ("surface eggs"). These can be easily distinguished from eggs which have been ejected from burrows, as the latter are generally dirty and stained by incubation and rolling. Warham *et al.* (1982) estimated the number of surface eggs at two sites of differing burrow entrance density near Punui Bay throughout the 1970 egg laying period. We searched six sites in 1998, varying in size from 100–1600 m^2, which were randomly located within *Olearia* habitat type and in reasonable proximity to the research hut in the Boat Harbour. One of the six sites was excavated for another study in 1996 (Hamilton 2000).

Statistical methods

We used single factor ANOVA to compare the burrow entrance density estimates obtained using four sampling methods (quadrats, transects, quadrats from line transects and circular plots) in the *Olearia* vegetation type. We used stratified sampling methods (Cochran 1977) to estimate the standard error associated with the estimate of the total number of burrows in the different time periods, the strata being the different vegetation types. All analyses were carried out in a Microsoft Excel spreadsheet.

Generation time

One of the IUCN (2001) criteria used to determine whether a species is classed as "vulnerable" is a decline of ≥50% over the last 10 years or three generations (criterion A1). We estimated the generation time (T) of Sooty Shearwater using a standard formula, based on the assumption that all breeding adults have the same reproductive rate and the same survival rate, i.e.,

$$T = \alpha + [s/(\lambda - s)]$$

where α is the age at first breeding (assumed the same for all birds), s is the breeder survival rate, and λ is the population growth rate (Gaillard *et al.* 2005). There are no published data on the age at first breeding for Sooty Shearwater, so we used an estimate for a closely-related species, Short-tailed Shearwater (Bradley *et al.* 1989).

RESULTS

Burrow entrance counts

During the survey period 1969–71, the density of Sooty Shearwater burrow entrances in different vegetation types ranged between 0.46 and 1.95 entrances per m^2 (Warham & Wilson 1982, table 1). Using aerial photographs and a vegetation map, Warham & Wilson (1982) estimated the total planar area of North East Island to be 280 ha. Excluding areas devoid of soil, they estimated the burrowable area of the island to be 238.1 ha. The area occupied by Snares Crested Penguins was not considered by Warham & Wilson (1982) (K-J. Wilson pers. comm.). The October 2000 survey of Snares Crested Penguins counted 25 851 nests. Each penguin nest occupied approximately 1 m^2 (D. Houston pers. comm.), so penguins make c. 2.6 ha unavailable to Sooty Shearwaters.

Three of the methods used to survey burrow entrances in 1996–2001 were not specifically stratified to sample representative vegetation types. Burrow density from all four methods (quadrats, transects, quadrats from line transects and circular plots) could therefore only be compared in the *Olearia* vegetation type. There was evidence for a difference in the burrow density estimates found using the four counting methods ($F= 4.66$, with 3 and 168 d.f.; $P = 0.004$), but the differences were small (table 2). Thus, we combined the burrow entrance density estimates from the four methods to generate the most accurate estimate of burrow density possible for 1996–2001. The density of burrow entrances in different vegetation types ranged from 0.57 to 1.23 entrances per m^2 (table 1). The estimated total number of Sooty Shearwater burrow entrances on North East Island during our study between 1996 and 2001 is 2.06 million (95% CI = 1.9 to 2.2 million) (table 1).

Changes in burrow entrance density

We estimate a decrease of approximately 1.23 million Sooty Shearwater burrow entrances (95% CI = 0.95–1.51 million) has occurred between 1969/1971 and 1996/2001. This represents a decline of 37% over 27 years, or 1.72% per year (95% CI = 1.35–2.12%).

Burrow entrance density for the 23 permanent vegetation quadrats that contained burrow entrances in 1986 decreased from 1.34 entrances per m^2 (SE = 0.23) to 1.09 entrances per m^2 (SE = 0.20) between 1986 and 1998, respectively. The 95% CI for the decrease was 0.05–0.45 entrances per m^2. This represents a decline of 19% over 12 years, equivalent to an annual decline of 1.71% per year (95% CI = 0.51–3.09%).

Conservation status of Sooty Shearwater

Bradley *et al.* (1989) report an estimate of age at first breeding for Short-Tailed Shearwater of 7.0 years (SE = 1.1). They also provide an estimate of adult survival rate of 0.92 (SE = 0.01). The only published estimate of breeder survival rate for Sooty Shearwater is 0.87 (95% CI: 0.80–0.94), given by Scofield *et al.* (2001).

If we use the estimates of the age at first breeding (α) and breeder survival rate (s) from Bradley *et al.* (1989), together with the estimate of $\lambda = 0.983$ (95% CI: 0.979–0.987) implied by a 1.7% decline in burrow density, we obtain an estimate of the generation time (T) of 21.6 years (95% CI: 17.2–29.3). We used parametric bootstrapping, with 10 000 replicates, to determine the confidence interval for T and for the decline over three generations (Davison & Hinkley 1997). On this basis, we estimate that the observed 1.7% annual decline of Sooty Shearwater burrow entrances equates to a 67% decline over three generations (95% CI: 54–81%). Using the estimate of adult survival for Sooty Shearwater from Scofield *et al.* (2001), we get a value for T of 14.7 years (95% CI: 10.7–28.5), which leads to an estimated 53% decline over three generations (95% CI: 40–78%).

TABLE 2
Sooty Shearwater burrow entrance density on North East Island, The Snares during 1996-2001, for sampling units classified as having the *Olearia* vegetation type

Sampling unit[1]	Burrow density[2] (m^{-2})	S.E.	n
Quadrats	1.15	0.11	6
Transects	1.05	0.05	25
Quadrats from line transects	1.16	0.04	38
Circular plots	0.98	0.03	103

[1] Four types of sampling units were used.
[2] Burrow Density is the estimated mean density of burrow entrances.
Does not include observations from areas in which *Olearia* was present with other vegetation (cf. table 1).

Burrow occupancy

There is no evidence of a decline in the occupancy of nest chambers that were accidentally collapsed between 1971 and 1999/2000 (table 3; greatest difference $\chi^2 = 1.66$; d.f. = 1; $P = 0.20$).

Similarly, there was little difference in the frequency of entrance events in January of 1972, 1999 and 2000 ($\lambda^2 = 1.359$; d.f. = 1; $P = 0.244$). Entrances containing an egg or chick were entered an average of 59.7% of nights, whereas those without eggs or chicks were entered 79.2% of nights ($t = 2.055$, d.f. = 26, $P < 0.05$; fig. 2). Entrances in which breeding had failed, or in which an egg had never been laid, had very frequent visits, whilst those that contained a chick were less frequently visited. We conclude that frequency of entrance events in January cannot reliably indicate occupancy, so comparison between 1972 and recent estimates of activity cannot indicate changes in burrow occupancy.

Eighty-six per cent of entrances investigated in April 1972 had some indication of use that Horning (1976) and Warham &Wilson (1982) interpreted as indicative of occupation by a chick. Between 1 and 30 April 1999, 36.1% (s.d.=10.0%,

TABLE 3
Occupancy rate (%) of burrows accidentally collapsed on North East Island, The Snares

	1971[1] (n=54)	1999 (n=86)	2000 (n=62)
Adult on egg	55.6	45.3	45
Adult, no egg	-	19.8	8
Two adults, no egg	-	1.2	3
One or two adults, no egg	18.5	-	-
Abandoned egg	0.0	1.2	6
Occupancy rate	74.1	67.5	61.3
Mottled Petrel[2]	0.0	1.2	0

[1] Data for 1971 are from Warham & Wilson (1982).
[2] Data are for Sooty Shearwaters unless otherwise indicated.

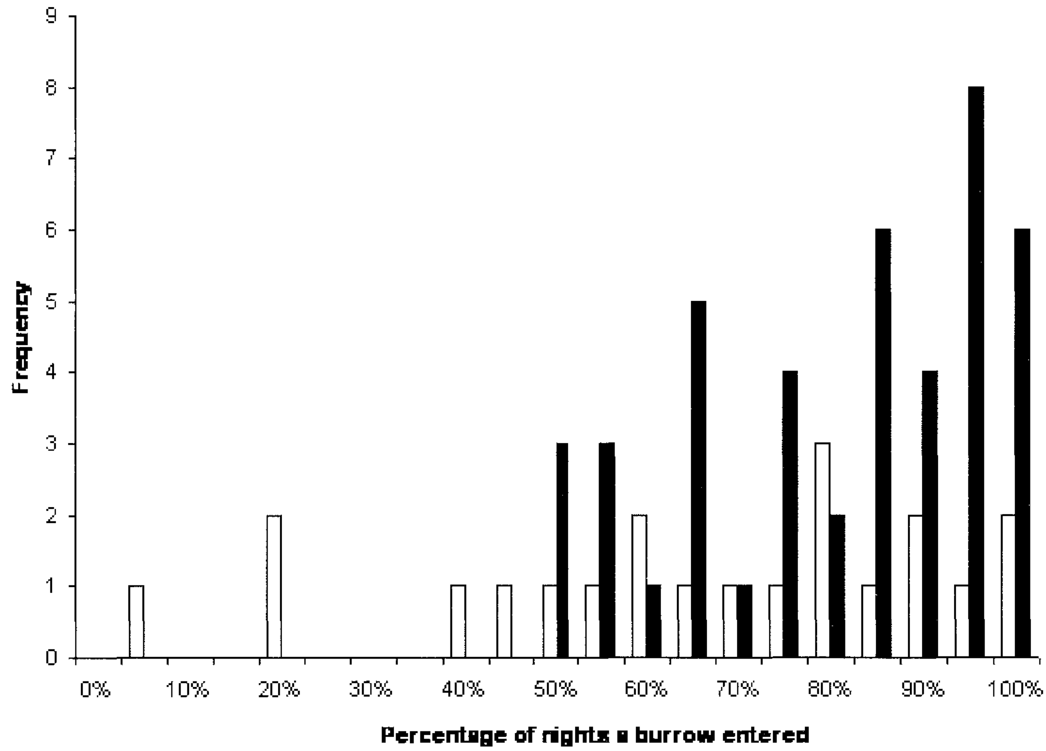

FIG. 2 — Frequency of Sooty Shearwater burrow entrance events per night, North East Island, The Snares. Dark bars represent burrows without chicks, open bars burrows with chicks. Sixty-four burrows were monitored over 19 nights; 4–22 January 2000 (From Moller et al. *2003a).*

range 18.8–56.3%) of 32 entrances monitored each night were active. Overall 94% of 32 burrows were visited at least once. Fifteen of these entrances contained chicks or eggs in the 1999/2000 season and 11 did so in April 1999. Non-breeders were absent from the colony during this period (Richdale 1954, R.P. Scofield unpublished. data). It would appear therefore that the true level of occupancy in 1972 may have been closer to half that reported. Explanations for overestimation of occupancy in 1972 include detection of wandering chicks or breeding adults which have holed up overnight in empty burrows after they have fed their chicks. The latter behaviour has been observed in Sooty Shearwaters elsewhere (G. Taylor pers. comm). Given this result, it is significant that only 42 entrances (51% of the 82 thought to be occupied) had direct evidence that a burrow was occupied (a chick was felt by hand or with a wire) in 1972. There was no evidence that the occupancy estimate in 1972 was different from the average burrowscope estimates of occupancy in the late chick phase in 1996–2000 ($t = -1.685$; d.f = 8, $P = 0.13$; tables 4, 5).

Methodological variations make interpretation of the above results extremely difficult. Furthermore, published estimates of occupancy on The Snares using burrowscopes with similar operators and methods indicate high variability between years and sites (table 4, Hunter 2001). Therefore, it is not possible to infer changes over time in average burrow occupancy from the data available.

Surface egg density

There was no evidence of a decline in surface egg density between 1970 and 1998 ($t = 0.015$; d.f. = 6; $P > 0.89$; table 6). Similarly, there was no evidence that the mean number of surface eggs per burrow entrance changed ($t = 0.0.32$; d.f. = 6; $P > 0.76$; table 6).

DISCUSSION

Burrow occupancy

Our monitoring of entrances of occupied and empty burrows using an electronic system showed that estimates of traffic in and out of entrances is not a reliable indicator of occupancy by breeding Sooty Shearwaters, especially in the middle of the breeding season. Hamilton (1998) reached a similar conclusion from her mainland New Zealand studies using stick barricades at burrow entrances. Entrances that were visited frequently are more likely to contain failed breeders or prospecting birds than breeders (fig. 2). The supposition that burrows with activity at the entrance in April contained chicks (Horning 1976, Warham & Wilson 1982) was based on the assumption that chicks in the period from first emergence to fledging are faithful to their natal burrow. Traditional Ecological Knowledge of the Rakiura muttonbirders (Charleton 2002) and radio-tracking (C.M. Hunter unpubl. data) showed that chicks wander and explore other burrows from mid- to late April. Entrances in areas close to "take-off points" such as Punui Bay on North East Island, where one of our automatic monitoring plots was concentrated, are likely to have the highest level of unoccupied burrow visitation.

There is the potential for bias in the estimation of burrow occupancy rates from the inspection of collapsed burrows. Burrows close to the surface are more likely to collapse. If these burrows are favoured for breeding, then occupancy

TABLE 4
Occupancy rate (%) of Sooty Shearwater burrows on North East Island, The Snares, from burrowscope data, by breeding stage and vegetation type (from Hunter 2001)

Year	Breeding stage	Estimated burrow occupancy rate (%)		
		Poa tussock	*Olearia* forest	Fern
1996	Incubation	42.2	65.9	50.5
1997	Incubation	11.1	28.8	17.1
1998	Incubation	25.9	34.3	36.7
1996	Early chick	30.7	48.3	34.9
1997	Early chick	5.6	12.8	6.0
1996	Late chick	43.8	48.1	33.2
1997	Late chick	10.8	11.6	1.0
1998	Late chick	21.9	22.9	16.2

TABLE 5
Indications of Sooty Shearwater occupancy in 100 monitored burrows on The Snares, in April 1972 (from Horning 1976)

	Only indication of occupancy	Additional indication of occupancy		
		Down	Bird felt with wire loop	Digging
No indication of occupancy = 14				
Bird felt with wire loop	36	1	–	1
Bitten hand	6	–	–	–
Wire fence disturbed	15	13	3	–
Fresh digging	6	–	–	–
Down in burrow mouth	4	–	–	–
Bird seen entering burrow	1	–	–	–

TABLE 6
Density of Sooty Shearwater eggs laid on the ground outside burrow entrances ("surface eggs") at sites on North East Island, The Snares, in 1970 and 1998

Site	Area (m^2)	Burrow entrance density (m^{-2})	Number of surface eggs	Surface egg density (m^{-2})	Surface eggs per burrow entrance
1998					
A	600	0.52	8	0.013	0.026
B	400	1	9	0.023	0.023
C[1]	100	0.91	4	0.040	0.044
D	650	0.61	11	0.017	0.028
Low burrow density	600	0.81	7	0.012	0.014
High burrow density	1600	1.1	20	0.013	0.011
1970[2]					
Low burrow density	3160	0.73	58	0.018	0.025
High burrow density	2860	1.06	55	0.019	0.018

[1] Disturbed site (Hamilton *et al.* 1998).
[2] Data for 1970 are from Warham *et al.* (1982).

rates may be overestimated. Conversely, if these burrows are less favoured, then occupancy could be underestimated. Additionally, areas with greater breeding success may have more burrows closer to the surface. Estimates of burrow occupancy from detection of chicks when felt by hand or with the use of a wire also have limited accuracy. A comparison gave no evidence for a difference between Warham & Wilson's (1982) and our burrow occupancy estimates. However, these comparisons will have had low statistical power because of the large variation in occupancy between years (table 4 and McKechnie *et al.* 2007) which results from large inter-annual variation in the proportion of adults laying eggs and breeding success (Newman *et al.* 2008, Newman *et al.* in press). Therefore we have no evidence that there has been decline or increase in burrow occupancy.

Density of breeding burrow entrances provides a stable index of breeding density that smoothes out inter-annual variation in burrow occupancy (Newman *et al.* 2008). There is also a close relationship between absolute chick density (as estimated by the burrowscope) and burrow entrance density on different islands and within family muttonbirding territories (Newman *et al.* 2008). Therefore it is most likely that changes in burrow entrance density that we observed on North East Island reflect a commensurate change in actual density of Sooty Shearwater breeding pairs during the interval between our studies.

Decline of Sooty Shearwaters

Our study confirms that the number of Sooty Shearwater burrow entrances on North East Island, The Snares, has declined markedly in the past 30 years. Although there was no evidence that the number of surface eggs has also declined, results for this measure are inconclusive because of large variation in the number of surface eggs between areas and the small number of areas and years sampled. The Traditional Ecological Knowledge of the Rakiura muttonbirders records that the number of surface eggs fluctuates markedly between years (H. Moller unpubl. data), so a much longer run of observations will be needed to determine whether or not the number of surface eggs has changed.

There is strong evidence that the decline documented here is not restricted to The Snares islands and that the causes of the decline may also be affecting other populations of Sooty Shearwaters and other shearwater species. A 90% decline in Sooty Shearwater numbers observed in the Californian current system over the period 1987–1994 (Veit *et al.* 1997) has been attributed to water temperature variations and climate change, but changes in bird distribution within the counting zone may have contributed (Oedekoven *et al.* 2001). Declines in Sooty Shearwater populations documented on the New Zealand mainland (Hamilton *et al.* 1997, Jones 2000) have been attributed primarily to predation by introduced small mammals. Various islands in the Hauraki Gulf of the North Island of New Zealand held small populations of Sooty Shearwaters until at least the 1960s (Falla 1934 and Department of Conservation banding records) that have now gone (R. Pierce, A. Booth and G. Taylor pers. comm., R.P. Scofield unpubl. data). An estimated 80 breeding pairs were recorded on Motunau Island, North Canterbury, in 1962 (Taylor 1967) although Scofield (2000 unpubl. data) found this population to be virtually extinct. It is significant that some of these declines or local extinctions have occurred in the absence of introduced predators or harvest, as observed in this study on The Snares and recently on Whenua Hou (Lyver *et al.* 1999). Recent declines in closely-related species, incuding Short-tailed Shearwater (Walsh *et al.* 1997), Fleshy-footed Shearwater, *Puffinus carneipes* (Gould, 1844), (Scofield 2000) and Pink-footed Shearwater, *Puffinus creatopus* (Coues, 1864), (Ainley *et al.* 1995), have also been documented.

Possible reasons for the Sooty Shearwater decline

It is impossible to isolate a single cause for the decline in Sooty Shearwaters. Although the North Pacific squid fishery ceased in 1992 (Uhlmann *et al.* 2005), salmon gill net fisheries have continued throughout the North Pacific and these fisheries still take large numbers of shearwaters (Artyukhin & Burkanov 2000). Approximately 40% of shearwaters killed in the Japanese squid driftnet fishery were of breeding age (Ogi *et al.* 1991a, b). Shearwaters are long-lived, monogamous species with a low reproductive output (Warham 1990, 1996). They take one or more seasons to develop a pair bond and only ever lay one egg per season (Richdale 1963, Skira 1991). Sensitivity analyses of shearwater demography have shown that population growth rate is most sensitive to any change in the rate of mortality of breeding age birds (Hamilton & Moller 1995, Hunter *et al.* 2000). Ryan & Boix-Hinzen (1999) found a consistent male bias in fisheries bycatch for a number of petrel species taken off South Africa. Sooty Shearwaters are killed in New Zealand trawl fisheries and although the full extent of this mortality has not been quantified, it is known that the proportion of killed birds which are male is high (Robertson 2000). For example, 83% (95% binomial confidence intervals 72.2–94.2%) of a spatially – and temporally – representative sample of Sooty Shearwaters (n=205) taken mostly in the New Zealand squid trawl fishery were males (C.J.R. Robertson and R.P. Scofield, unpubl. data). If this sex-biased mortality was due to competitive exclusion, a similar bias would be expected in the North Pacific bycatch; however the available data on the sex ratio of shearwaters killed in the North Pacific are not consistent (Gould *et al.* 2000).

Climate fluctuations such as the El Nino/La Nina Southern Oscillation and the Pacific Decadal Oscillation trigger short-term and medium-term shifts in wind and currents (Mantua *et al.* 1997, Salinger & Mullan 1999) that impact on bird productivity and potentially survival, movements and distribution (Veit *et al.* 1997, Lyver *et al.* 1999, Shaffer *et al.* 2006). Diet sampling and tracking studies show that Sooty Shearwaters forage at the highly productive upwelling region at the Sub-Antarctic Front (SAF), the boundary between the cool, sub-Antarctic waters and the warmer sub-tropic waters (Weimerskirch 1998, Shaffer *et al.* 2006). It is believed that inter-annual and long-term increases in global heat mass may push the SAF southwards. Sea surface temperature (SST) has been increasing in the waters between 45°S and 20°S since 1961 (Hurrell & Trenberth 1999) and average SST and chlorophyll *a* measured near Marion Island has increased (Hunt *et al.* 2001), probably as a result of the SAF moving southward. Decline in the number of Rockhopper Penguins, *Eudyptes chrysocome* (J.R. Forster, 1781), since 1940 on Campbell Island (Cunningham & Moors 1994), Amsterdam Island (Guinard *et al.* 1998) and the Falklands (Bingham 1998), and associated declining oceanic productivity (Hilton *et al.* 2006), may relate in part to the position of the SAF.

Accidental introduction of Black Rats, *Rattus rattus* (Linnaeus, 1758), to Taukihepa (Big South Cape) in 1963 (Bell 1978) may have suppressed Sooty Shearwater populations (Scofield & Christie 2002, Moller *et al.* 2003b). Additionally, the introduction of Weka, *Gallirallus australis* (Sparrman, 1786), an endemic rail, to several Tītī Islands in the early twentieth century may have added to ongoing harvest pressure on chicks (see Kitson & Moller 2008). However, the factors regulating shearwater populations and potential compensation for these added predation and harvest impacts are unknown (Moller 2006) and, in general, the impacts of added chick losses are likely to be much lower than predation of adults (Hamilton & Moller 1995, Hunter & Caswell 2005, Wilcox & Donlan 2007, Finkelstein *et al.* 2008). If a high level of inter-island movement is typical for Sooty Shearwater populations, as seen for Short-tailed Shearwater (Skira 1991), The Snares population may be affected by population declines occurring elsewhere, potentially driven by predation by rats and Weka and harvesting of chicks.

New Zealand Sea Lions, *Phocarctos hookeri* (Gray, 1844), haul out up to 500 m from where they come ashore on The Snares, but reports of this species breeding here are rare. Sea Lions can compact the soil, crush burrow entrances and create wallows and mud pools. Most of our sampling units were situated within 500 m of Sea Lion haul-out locations. Populations of New Zealand Sea Lions are increasing (McNally 2001, 2002), and while we have little direct evidence of Sooty Shearwater failure attributable to sea lions, potential impacts on breeding success cannot be ruled out.

Implications of Sooty Shearwater decline on the ecology of The Snares

Sooty Shearwaters are a keystone species in the ecology of The Snares and other islands on which they breed (Warham 1996, Moller *et al.* 2000, Hawke & Newman 2005). A decrease in burrow numbers will reduce soil aeration, erosion, evaporation of surface moisture, nutrient cycling, and composting, and may alter vegetation regeneration patterns. The impacts of a Sooty Shearwater decline on three threatened or endangered plants on The Snares (*Lepidium oleraceum* G. Forst., *Anisotome acutifolia* (Kirk) Cockayne and *Stilbocarpa robusta* (Kirk) Cockayne) are unknown. There are about 310 Southern Skua, *Catharacta lonnbergi* Matthews, 1912, on The Snares that consume a considerable number of Sooty Shearwaters (Miskelly *et al.* 2001). A reduction in overall Sooty Shearwaters may result in an increase in predation by skua on less common species. Reduced competition for burrows sites may allow marginalised species such as Mottled Petrels, Common Diving-Petrels, Broad-billed Prions, *Pachyptila vittata* (Forster, 1777), and Fairy Prions, *Pachyptila turtur* (Kuhl, 1820), to expand, and reduce egg failure in Snares Island Snipe *Coenocorypha aucklandica huegeli* (G.R. Gray, 1845) caused by Sooty Shearwater disturbance (Miskelly 1999).

CONCLUSION

Conservation status of Sooty Shearwater

The decline of Sooty Shearwater on The Snares is substantial and will potentially have far-reaching ecological consequences. One of the IUCN (2001) criteria used to class a species as "vulnerable" is a documented decline of 50% over the last 10 years or three generations (criterion A1, IUCN 2001). Our study documented the decline of Sooty Shearwater on North East Island during the past 27 years, between the initial and recent survey, but could not apportion the decline between the last 10 years and those preceding. Additionally, the 27-year period is equivalent to only one or two generations of this species. Therefore the documented decline does not meet the threshold specified under this criterion. An alternative criterion is a reduction of >30%, projected or expected within the next 10 years or three generations, whichever is the longer (criterion A3, IUCN 2001). The average rate of decline observed over the study interval exceeds the rate that would be necessary to halve the population in three generations, at least when our maximal estimate of generation time is used (21.6 years). The environmental precautionary principle suggests that we use this longer estimate of generation time for risk assessment. Even if the shorter estimate is used (14.7 years), the mean estimate is for a 53% decline over three generations, if the observed rate continues. These estimates clearly meet the requirements of this alternative criterion.

A more reliable long-term record of occupancy estimates will be crucial to determining whether decreases in burrow numbers translate to decreases in Sooty Shearwater breeding populations. Rigorous estimates of other Sooty Shearwater populations would also be beneficial for establishing whether the declines we observed on The Snares are occurring at the same rate throughout the species range, including the large breeding populations in Chile (Reyes-Arriagada *et al.* 2006). Recent reductions in shearwater bycatch (Uhlmann *et al.* 2005) and eradication of rats from four Sooty Shearwater breeding colonies (Moller *et al.* 2003b, Coote & Blackwell 2006) may slow past declines, but other threats like climate change and harvesting continue. Clearly there is cause for concern for this abundant and important island ecosystem engineer species and the conservation values it affects. Ongoing and intensified monitoring of species abundance throughout the range of the Sooty Shearwater is required.

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