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Sheryl Hamilton

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Determining burrow occupancy, fledging success and land-based threats to mainland and near-shore island sooty shearwater (*Puffinus griseus*) colonies

SHERYL HAMILTON

Department of Zoology
University of Otago
P. O. Box 56
Dunedin, New Zealand

Current address: P. O. Box 133, Leigh, Warkworth,
New Zealand

Abstract A specialised infra-red camera “burrowscope” was used to determine the burrow occupancy rate of sooty shearwaters at three Nugget Point colonies, two Taiaroa Head colonies and one Tuhawaiki Island colony in 1992/93, and the results compared to those given by less reliable methods.

At three Nugget Point colonies, fledging success ranged from 0–41%. One of these colonies also suffered high mortality of adults, most likely attributable to mammalian predation, during the nest preparation and egg-laying period. At the Taiaroa Head and Tuhawaiki Island colonies, low predator abundance may have been an important factor contributing to the high fledging success (64–100%). Several years of monitoring reproductive and survival parameters are needed to verify the status of mainland colonies and the impacts of various possible threats to their survival and productivity.

Keywords sooty shearwater; *Puffinus griseus*; predation; burrow occupancy; methodology

INTRODUCTION

Large numbers of sooty shearwater (*Puffinus griseus*; Family Procellariidae) breed in colonies on offshore islands around New Zealand (Warham & Wilson 1982). However, many of the mainland colonies that once existed on headlands on both the North and South Islands have disappeared (Jackson 1957). Those small mainland colonies that still persist (Hamilton et al. 1997) are the remnants surviving from extinctions in historic time, most likely attributable to mammalian predation or habitat alteration. Because sooty shearwaters are slow-reproducing (laying only one egg per year in a nest down a burrow), long-lived seabirds, declines in their breeding colonies may be slow and difficult to detect. Therefore, a long-term monitoring programme to quantify the impact of different possible threats to the reproductive and survival rates of mainland sooty shearwaters has been established by a research team at the University of Otago, Dunedin.

Maintaining sooty shearwater populations on mainland New Zealand is important for aesthetic, tourism and cultural reasons, since these colonies are much more accessible to human observers than those found on offshore islands. Muttonbirding (the harvesting of chicks), which is an activity important to southern Maori people for provisions and as an integral part of their culture (Wilson 1979; Taiepa et al. 1997), is currently legal only during a restricted season on some offshore islands around Stewart Island. Sustainable harvesting of selected mainland colonies could be possible if the factors determining their productivity could be controlled. This requires reliable information on the numbers of breeding adults and the mortality rates of adults and chicks at each colony.

The burrows of sooty shearwaters can be more than two metres long. This makes it difficult accurately to identify burrow occupants and the presence or absence of a nest. Methods for determining burrow occupancy used in the past have included monitoring only short, accessible burrows (Warham et al. 1982); excavating inspection holes down to the

nesting chamber (Sinclair 1981), which can be temporarily plugged, for example, with soil-filled plastic bags (Johnstone & Davis 1990); and using fibre optics (Warham 1982) or infra-red camera (Dyer & Hill 1991) equipment. Some previous sooty shearwater surveys have defined occupied burrows as those giving off the "musky" odour of the Procellariidae (*C. Lalas*, pers. comm.) and some surveys have identified occupied burrows as those which were frequently visited, using "barricades" at burrow entrances as indicators of activity (Richdale 1963; Warham & Wilson 1982). Unfortunately there are no published data on whether or not the use of barricades correctly indicates burrow occupancy, or on the time lapse between barricade disturbance, or on seasonal variation in rate of barricade disturbance (Warham & Wilson 1982). Unless the proportion of burrows being used by pre-breeders is known, counts of active burrows do not give an accurate estimate of the breeding population (Dyer & Hill 1992).

As the remaining mainland colonies of sooty shearwater on the South Island of New Zealand are relatively small (Hamilton et al. 1997), any restriction of sample sizes, for example, to short burrows or to those with easy access, severely limits a study of shearwater breeding biology. Excluding long burrows might also bias the results, if, for example, burrows of different lengths are occupied by birds with different breeding experience. Occupants of longer burrows may also be less susceptible to predation. There are few mainland colonies available to study, and the proportion of short burrows varies enormously between colonies. Accordingly it is imperative to find a method of determining burrow occupancy applicable to every burrow in any colony.

In this paper, I assess five possible methods for determining sooty shearwater burrow occupancy (defined as the proportion of nesting chambers containing a nesting attempt, i.e., an egg laid) for mainland and near-shore island sooty shearwater breeding colonies in Otago, New Zealand. I then report the data gathered by the best of the methods tried on burrow occupancy and fledging success for the 1992/93 breeding season, and the possible land-based threats to sooty shearwaters and their productivity.

METHODS

Study sites

Three colonies were >100 m apart at Nugget Point (Nuggets A, C, D), two were on Taiaroa Head (A, on private property, and B, within the Nature Re-

serve), and one was on Tuhawaiki (Jacks) Island (Fig. 1). The main terms used to describe burrow status and to categorize birds are defined in Appendix A.

Methods for estimating burrow occupancy

I compared five methods for identifying the occupants of a burrow.

- a) *Sign*: During the regular checking of each burrow entrance, I recorded the presence or absence of the characteristic musky, shearwater smell, faeces, scratches in the substrate from adult birds, feathers and/or down, fresh diggings, soil and/or vegetation blockages, and egg shell remains.
- b) *Pecks*: According to Harrison (1992), a stick (c. 1 m long) inserted down the burrow entrance will elicit a pecking response from a bird occupant. Occasionally, it is possible to feel the outline of an egg in the nesting chamber.
- c) *Barricading* (Richdale 1963; Warham & Wilson 1982; Gaston & Collins 1988): A barricade consists of four or five small sticks inserted vertically, 20 cm inside the burrow entrance. Records of barricade knockdown on subsequent days indicate which burrows were entered and how frequently occupied burrows were entered over a period of time. At Nuggets C, I checked the barricades on "confirmed occupied" burrows every day from 10 to 23 December 1992 (during incubation), 15 to 27 February 1993 (early chick stage), and 9 April to 1 May 1993 (late chick stage), to get a cumulative rate of barricade knock-down over a period of time for each breeding stage. At Nuggets A, I checked the barricades on "confirmed occupied" burrows during mid-February and in early April.
- d) *Hatches*: Before egg-laying, I excavated observation holes (diameter c. 15 cm) down to the nesting chamber of 30 burrows, and covered them with a 30 cm × 30 cm wooden slab (diagram in Walls 1978). Twenty of these "hatches" were established on burrows at Taiaroa Head A, and ten at Nuggets D. However, no chicks were produced from the nests with observation hatches at Nuggets D. I made direct observations of the nests at Taiaroa Head A 18 times between 12 December 1992 and 19 April 1993.
- e) *Burrowscope*: The Department of Conservation lent me some specialised infra-red camera equipment (a "burrowscope") designed for inspecting the contents of burrows (Dyer & Hill 1991) for approximately two weeks in February/March 1993 and approximately two weeks in May 1993. An infra-red camera contained in one end of a

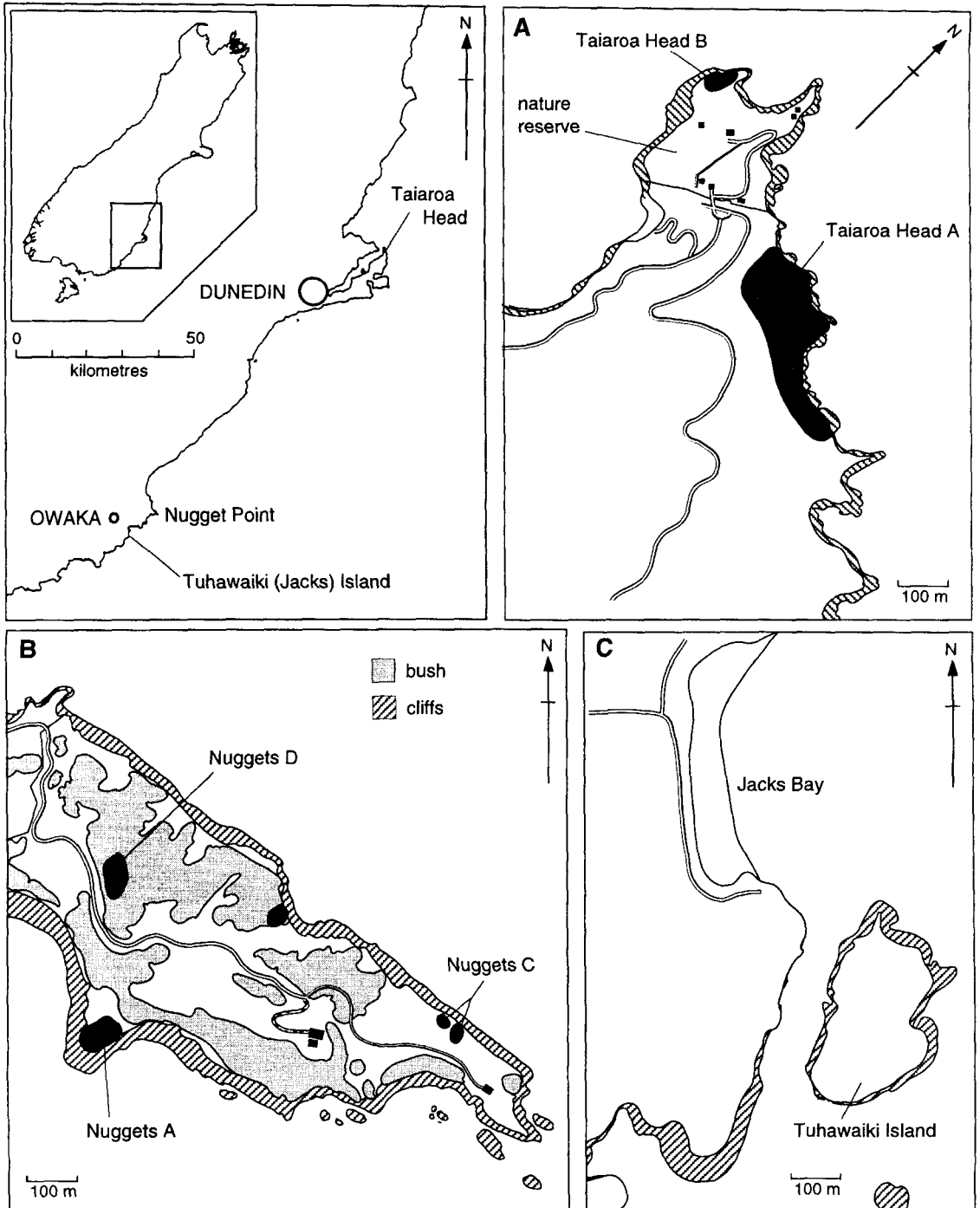


Fig. 1 The sooty shearwater study locations along the Otago coastline (general map first published in Hamilton et al. 1997) and individual study colonies at (A) Taiaroa Head, (B) Nugget Point, and (C) Tuhawaiki Island.

three metre length of tube (diameter c. 5 cm), pushed down the tunnel of the burrow via the entrance, projected an image of the burrow contents onto a video monitor outside.

Burrow occupancy and fledging success estimates for Otago breeding colonies in 1992/93

At each colony, I counted all burrows, and individually marked study burrows. Burrows identified as having two entrances leading to the same chamber counted as one burrow; whereas those with a single entrance leading into two nesting chambers counted as two separate burrows. At the larger colonies, Taiaroa Head A and Tuhawaiki Island, I marked and monitored all burrows within a sub-section of the colony (arbitrarily chosen as being easily accessible) as well as a number of burrows (23 and 10 respectively) spread through the rest of the colony that were known to contain a nest. I checked all marked burrows, using each of the methods described above, once a week at the Nugget Point and Taiaroa Head A colonies, and once a month at Tuhawaiki Island and Taiaroa Head B, from November 1992 until mid-May 1993. Burrows were classified as "unoccupied", "confirmed occupied" or "unknown" (see Appendix A) during each visit.

I estimated the predation risk at each breeding colony (Table 1) from the presence/absence of predators in the locality of the colony and from known levels of predator trapping effort (Appendix A). I defined the rates of burrow occupancy (%) for each visit as the minimum and maximum number of "occupied" burrows as a proportion of the marked study burrows (excluding the extra burrows which were marked at Taiaroa Head A and Tuhawaiki Island). I compared burrow occupancy (%) between colonies with high and low vulnerability to predation using a one-factor ANOVA, transforming the data using $\sin^{-1}\sqrt{(x/100)}$ (where x = % occupancy), then estimated the minimum and maximum number of occupied burrows at each colony by extrapolation (i.e., applying the minimum and maximum occupancy rates from study burrows to the total number of burrows at that colony).

I used observation "hatches" and the "burrowscope" to follow chick survival directly. I estimated fledging success (i.e., number of fledglings as a proportion of chicks hatched) at Nuggets A and C, Taiaroa Head A and B, and Tuhawaiki Island by calculating the number of chicks alive after 20 April 1993 (i.e., the beginning of fledging) as a proportion of the number of burrows occupied in the early chick stage (February). I also visited Taiaroa Head, Nug-

gets A and Nuggets C at night during the fledging period to band any chicks which came to the surface. Fledging success (%) was compared between colonies with high and low vulnerability to predation using a one-factor ANOVA, transforming the data using $\sin^{-1}\sqrt{(x/100)}$ (where x = % fledging success). At all colonies, I recorded any observed mortality (adult or chick) and the likely cause of death.

RESULTS & DISCUSSION

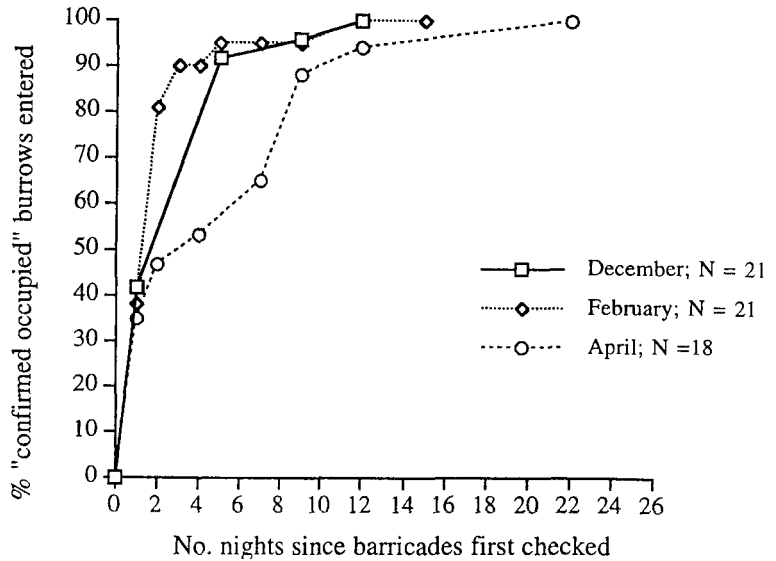
Effectiveness of different methods for determining burrow occupancy

Sign: At Nuggets C, for four consecutive days in December (incubation stage), there was no difference in the number of burrows which smelt musky between 19 "confirmed occupied" burrows (\bar{x} = 7.3, SD = 5.4) and 19 "unoccupied" burrows (\bar{x} = 3.5, SD = 3.9) (Mann Whitney U test). For six consecutive days in January (young chick stage), there was a significant difference in the number of burrows which smelt musky between 22 "confirmed occupied" burrows (\bar{x} = 12.3, SD = 3.1) and 22 "unoccupied" burrows (\bar{x} = 7.3, SD = 2.0) (Mann Whitney U test). Burrows may smell more strongly and consistently later in the season after longer burrow occupation. However, not all "confirmed occupied" burrows smelt musky all the time (38% for December and 56% for January), and some "unoccupied" burrows occasionally smelt musky during at least one check (18% in December and 33% in January). Total burrow occupancy estimates based on smell varied by approximately 50% within a week at one colony in December.

The problems of using burrow smell as a shearwater survey method were further compounded when rabbits (*Oryctolagus cuniculus*) or blue penguins (*Eudyptula minor*) used the same burrows. The smell from these other animals usually masked the musky smell of shearwaters. Determining whether a burrow smells musky is also subject to weather conditions (e.g., smell was less obvious when the ground was wet) and observer variability. Past sooty shearwater surveys in Otago have estimated burrow occupancy solely from the proportion of musky-smelling burrows, and this limits their usefulness as baseline data. However, the musky smell may be a helpful adjunct to other methods of indicating occupancy.

"Faeces", "scratches", or "feathers/down" did not appear in burrow entrances frequently enough (< 10% for any day "confirmed occupied" burrows at

Fig. 2 The cumulative frequency of the proportion of sooty shearwater burrows being entered since the first day of checking in mid-December, mid-February and early April at Nuggets C.



Nuggets C were checked) to be useful as indicators of burrow use. These signs were also often left around “unoccupied” burrows possibly by pre-breeding birds. J. A. Bartle (pers. comm.) suggests that burrow digging after an egg had been laid in the burrow indicates the activity of pre-breeders rather than breeding birds. However, I found “fresh diggings” at both “unoccupied” and “confirmed occupied” burrows throughout the breeding season. At some colonies, diggings could as well be the work of species other than shearwaters (eg., rabbits).

In the majority of burrows recorded with an egg, egg remains were found in the tunnel, presumably after adults cleared out the nesting chamber. There may have been other burrows from which egg remains were not cleared from the nesting chamber, or were not brought near enough to the burrow entrance to be visible from the outside. There are no data on how long egg remains last or whether their durability is affected by substrate type or weather conditions. Therefore, it is possible that some egg remains found at burrow entrances could have been from previous seasons. As eggs are sometimes laid outside burrows, possibly by non-breeders (Warham et al. 1982), egg remains at burrow entrances may not necessarily indicate viable nesting attempts.

The tunnel entrance to 13% of “confirmed occupied” burrows at Nuggets C appeared to be overgrown during incubation (i.e., blocked with vegetation growth or debris). Richdale (1963) also observed that some burrows containing an incubat-

ing bird were not easily seen as the entrance was overgrown with vegetation. Debris or vegetation growth at burrow entrances says nothing about occupancy throughout the season: parents sometimes do not return for several days, and entrances can appear disused after a short period (Harrison 1992).

Pecks: Occupied burrows were “burrowscoped” to confirm the identity of the occupant, and then regularly checked by probing with a stick down the burrow to elicit a peck confirming the presence of a bird. However, this was possible only for shorter (<1.5 m long), fairly straight burrows, in which chick survival could be followed with reasonable confidence using the “pecking” method. Also, the number of times chicks pecked at a stick varied considerably. Chicks known to be alive and occupying a burrow pecked at the stick on less than half of all possible occasions. For example, for nine survey days in February at Nuggets C, on average only 36% of chicks pecked when their burrows were probed with a stick (N = 16 chicks, SD = 18.5, range 6–69%). One chick did not peck the stick on any of the nine days. The frequency of pecking may be related to the age or aggressiveness of the chick.

Barricading: At Nuggets C ≥95% of “confirmed occupied” burrows had been entered after eight nights since the barricade was erected during incubation, after five nights during the early chick stage, and after 16 nights during the late chick stage (Fig. 2). Presumably parents enter burrows more frequently in February to feed young chicks than they

do when merely making incubation shift changes. In April, chicks are probably being fed less frequently (but in larger amounts) than in February.

Variation in barricade disturbance between colonies appeared to be small. During the early chick stage, $\geq 95\%$ of "confirmed occupied" burrows at Nuggets A had been entered after six nights (compared with five nights for Nuggets C) but by April 1993, all burrow activity at Nuggets A had ceased following 100% chick mortality. The proportions of barricades disturbed by non-breeders, other animals (eg., rabbits), or chicks, particularly close to fledging (late April onwards), all introduce unknown errors in activity estimates based on this method.

Hatches: The cheapest and most effective method of observing the occupants of a long burrow (> 0.7 m long: i.e., exceeding approximate arm length) is to install an observation hole over the nesting chamber, covered with a wooden "hatch". Hatches are also the easiest way to extract chicks from longer burrows for weighing or other handling. However, hatches are practical only for burrows in flatter areas that do not have too much soil depth above the nesting chamber and that are unobstructed by rocks and tree roots. Establishing a hatch interferes with the birds' burrow construction work and, therefore, may affect burrow occupancy or cause birds to change the location of the nesting chamber, although this is untested.

Burrowscope: The "burrowscope" is the best method for determining the occupants of burrows more than 0.7 metres long and without interfering with the burrow construction (i.e., by digging an observation hole). It would also be useful in testing the impact of observation holes on the burrow occupancy and breeding success of burrow occupants. However, the particular "burrowscope" I used during the 1992/93 season was impractical for checking the occupancy of a large number of burrows, as it was relatively cumbersome and difficult to manoeuvre down long or curving tunnels. Instead, a "burrowscope" with a smaller, lighter camera would be more useful, even though there is still a limit on the length of burrow it can investigate.

Burrow occupancy estimates for Otago breeding colonies

The total number of burrows at colonies on the mainland ranged from 21 to at least 620 (Table 1). On Tuhawaiki Island, the minimum number of burrow entrances was 1050.

A nesting attempt (i.e., an egg laid) was confirmed in only one of the 60 study burrows at Nuggets D

Table 1 Colony status and burrow occupancy from six sooty shearwater breeding colonies along the Otago coast in 1992/93 (see Appendix A for description of terms), with the total number of occupied burrows in 1992/93 and the total number of occupied burrows estimated in the 1980s (C. Lallas, pers. comm.).

Colony	Estimated vulnerability to predation	Marked study burrows	Unoccupied burrows	Egg stage only	Chick stage	Unknown status	Occupied burrows (% burrow occupancy)	Total number of burrows	Total occupied burrows	1980s occupied burrows
Nuggets A	High	116	68	4	25	25	29-54 (25-47%)	122	31-57	90
Nuggets C	High	69	27	6	22	14	28-42 (41-61%)	69	28-42	40
Nuggets D	High	60	59	1	0	0	1 (2%)	60	1	120
Taiaroa Head A	Probably low	104	46	4	35	19	39-58 (38-56%)	620	236-347	150-300
Taiaroa Head B	Low	21	8	0	11	2	11-13 (52-62%)	21	11-13	-
¹ Tuhawaiki Island	Low	44	17	2	19	6	21-27 (48-61%)	¹ >1050	504-640	2 983

¹ Part of the colony was not surveyed during the 1992/93 season.

² Figure adjusted to include only the section of the island surveyed during the 1992/93 season.

(Table 1). There was high mortality of adult sooty shearwaters, probably from predation, at this colony early on in the breeding season, and very little activity was observed at the colony after 9 January 1993. The total burrow occupancy at Nuggets D in 1992/93 (i.e. the proportion of nest attempts) was probably < 2%.

Minimum burrow occupancy (“confirmed occupied” burrows only) ranged from 25–52% for the remaining five colonies, and maximum burrow occupancy (including burrows of “unknown” status) ranged from 47–62% (Table 1). The highest burrow occupancy was recorded at Taiaroa Head B (range 52–62%) and Tuhawaiki Island (48–61%), and the lowest burrow occupancy at all the Nugget Point colonies.

The number of occupied burrows in the 1992/93 breeding season compared with those estimated by C. L alas in the 1980s showed a decrease at Nuggets A, D and Tuhawaiki Island and an increase at Taiaroa Head A (Table 1). However, L alas identified occupied burrows from their musky smell which is not an accurate indicator of the proportion of burrows containing nests. If adult breeding pairs return to the same burrow each year (Warham 1990) and lengthen that burrow from year to year during nest preparation, then long burrows of “unknown” status may have been occupied by older, more experienced breeding pairs that have proportionately more successful nests. Therefore, the lack of information on “unknown” status burrows probably underestimates total colony success. Clearly, comparing estimates of breeding success derived from current technology with those from historical data are unreliable. The historical information available is helpful to determine the proportion of known colonies still persisting, but not to estimate trends in colony or population size.

Mammalian predators were thought to be absent from Tuhawaiki Island (\approx 500 m offshore), since no evidence of predators has been observed there by the Department of Conservation staff (Brian Murphy, pers. comm.) (Table 1). However, as stoats (*Mustela erminea*) are able to swim up to 1100 m (Taylor & Tilley 1984) and rats (*Rattus rattus* and *R. norvegicus*) about 300 m (Taylor 1984), Tuhawaiki Island is not safe from colonization by predators. Mainland colonies are very vulnerable to predators (Table 1), but at Taiaroa Head B, predation risk is reduced by a long-term, intensive predator trapping programme operated within the Nature Reserve to protect the Northern Royal Albatross (*Diomedea*

epomophora sanfordi). This work probably also reduces predator numbers in the areas surrounding the Nature Reserve (i.e., at Taiaroa Head A, Fig. 1).

The mean minimum occupancy rate for mainland colonies highly vulnerable to predation (33%, SD = 11.3, N = 2) was not significantly different from those less vulnerable (46%, SD = 7.2, N = 3) ($P > 0.1$; one-factor ANOVA) (Table 1). The mean maximum occupancy rate for colonies suffering high levels of predation (54%, SD = 9.9, N = 2) was not significantly different from that at colonies where predation was infrequent (60%, SD = 3.2, N = 3) ($P > 0.1$; one-factor ANOVA).

Fledging success

Sooty shearwater fledging success (number of fledglings as a proportion of hatchlings) at five Otago colonies (not including Nugget D where no chicks were hatched) varied from 0–100% (Table 2). The colonies at Nugget Point (Nuggets A and C) had the lowest fledging success, and Taiaroa Head (A and B) and Tuhawaiki Island had high fledging success. Chick survival at Nuggets C and A was 41% and 0% respectively (Table 2). Colonies with high vulnerability to predation had a lower average fledging success (20.5%, SD = 29, N = 2) than did colonies with low vulnerability (83%, SD = 18, N = 3) (Tables 1 & 2). This was not significantly different (95% CI, $P = 0.0542$; one-factor ANOVA), but that result may be influenced by the small sample sizes.

Egg loss at sooty shearwater colonies in 1992/93 appeared to be quite low, but could easily have been underestimated as it was difficult to determine whether burrows contained eggs without disturbing the adults. For example, Serventy & Curry (1984) reported that, during nest checks of short-tailed shearwaters (*Puffinus tenuirostris*), chicks, which were easier to locate than eggs, were sometimes found in burrows where no egg had been recorded.

Adult mortality at Nuggets D

I observed high adult mortality, attributed to predation from cats (*Felis catus*), stoats or ferrets (*Mustela furo*), at Nuggets D between 7 November 1992 and 9 January 1993. During this period, I removed one dead adult from each of 12 burrow entrances, two from each of two entrances, and three dead adults from one burrow entrance. A further two dead adults were found in the open, unassociated with any burrow entrance. Therefore, a total of 21 carcasses (ten of which were fresh enough to be autopsied) were removed from a colony containing 60 burrows. All the ten freshly dead birds were

reproductively mature adults, five males and five females, with well developed gonads. No adults were seen at Nuggets D after 9 January and no chicks were fledged from any nests there in 1993 (Table 2). There was also evidence of extensive adult and chick predation at Nuggets D in the mid-1980s (C. Lalas, pers. comm.).

Most adult corpses were found half in and half out of a burrow entrance, usually with a head and/or neck wound, although this does not necessarily infer that those individual birds had been nesting in that particular burrow. Pre-breeders or unpaired adults may spend a higher proportion of their time at the surface than do breeding birds, and may therefore be more vulnerable to predators. Some birds also sleep on the surface (pers. obs.), so could have been killed outside any burrow. Many predators drag prey off into holes to feed (Campbell et al. 1984) which would explain the three adult carcasses that were found, over a period of time, at one burrow entrance. In addition, ferrets can use pre-existing burrows as nurseries. For example, on 17 November 1992, after I had extracted an adult sooty shearwater carcass from a burrow entrance in Nuggets D, I saw an adult ferret inside, as it moved further down the tunnel. On 29 November 1992, a lactating female ferret was kill-trapped within 20 m of this burrow (D. Karna-Holmes, pers. comm.), and five days later I found a dead ferret kit in the same burrow entrance, indicating that the trapped female had been using the burrow as a breeding den.

Sooty shearwaters are long-lived seabirds with delayed maturity and low productivity (Warham 1990), so any accelerated adult mortality would potentially have a high impact on the breeding population (Hamilton & Moller 1995). There are no historic data to show how often the Nuggets D colony suffers the severe adult mortality which I

observed in 1992/93 but, if it is frequent, that colony may no longer be a self-sustaining unit. However, assuming high predation is a relatively recent phenomenon, and, as young birds do not return to breed for at least three or four years (Warham 1990), recruitment back into this population may still be possible if predation declines or is controlled in the meantime. Several years of monitoring the survival of sooty shearwaters is required to place the impact from severe adult mortality events such as these into perspective.

Chick mortality

Minimum chick predation rates (proportion of chicks preyed upon) at Nuggets A and C were 43 and 41% respectively (Table 2). These figures may be underestimates, as they do not include chicks that went missing with no known cause of death. Chick predation was worst at Nuggets A between 22 February and 30 April 1993, when the chicks were relatively young and confined to their burrows. However, at Nuggets C, chick predation was concentrated during the 4–5 weeks prior to fledging (9 April to approximately 15 May 1993), when the chicks came to the surface at night to exercise their wings before fledging. By comparison, predation of black petrel (*Procellaria parkinsoni*) chicks, presumably by feral cats, is most frequent after they begin emerging to exercise their wings (Imber 1975). Some sooty shearwater chicks whose deaths were attributed to predation may have died from other causes and then been scavenged, posthumously, by predators. Chicks that went missing ("presumed dead", Table 2) may have been dragged away by predators or died of other causes down the burrow.

In contrast to Nugget Point, the colonies at Taiaroa Head and Tuhawaiki Island had extremely high fledging success, with no chick mortality attrib-

Table 2 Sooty shearwater chick survival at Otago breeding colonies in 1992/93. Figures in parentheses are a percentage of the total number of chicks. See Appendix A for description of terms.

Colony	Total number of chicks	Presumed fledged	Presumed dead	Confirmed dead	Causes of "confirmed dead" mortality		
					Preyed upon	Collapsed burrows	Unknown cause of death
Nuggets A	28	0	10 (36%)	18 (64%)	12 (43%)	0	6 (21%)
Nuggets C	22	9 (41%)	3 (14%)	10 (45%)	9 (41%)	0	1 (4%)
Nuggets D	0	0	0	0	0	0	0
Taiaroa Head A	¹ 58	37 (64%)	17 (29%)	4 (7%)	0	2 (3.5%)	2 (3.5%)
Taiaroa Head B	11	11 (100%)	0	0	0	0	0
Tuhawaiki Island	¹ 29	25 (86%)	2 (7%)	2 (7%)	0	0	2 (7%)

¹ Includes extra study burrows outside of study section known to contain a nest.

utable to predation (Table 2). At Taiaroa Head B, 100% of chicks fledged. Tuhawaiki Island, assumed to be predator-free, had the second highest fledging success of 86%. Taiaroa Head A, with a relatively high fledging success of 64% (Table 2), is by far the largest extant mainland colony (236–347 occupied burrows, Table 1).

The low predation levels at Taiaroa Head were probably due to long-term year-round predator trapping within, and surrounding, the Nature Reserve there. On the other hand, bird predation may be naturally low in the sand dune habitats of Taiaroa Head because the large local rabbit population serves as an alternate food source for predators (Bruce 1991; Ratz et al. 1992; Fechney et al. 1993). Conversely, rabbits may have had an influence in reducing the sooty shearwater population on Macquarie Island through grazing of the tussock, *Poa foliosa*, and thereby increasing the risk of cat and skua (*Stercorarius skua lonnbergi*) predation (Brothers 1984). It is not therefore possible to generalise about the influence of rabbit numbers on bird predation.

At Nugget Point, predator trapping was undertaken during the yellow-eyed penguin (*Megadyptes antipodes*) breeding season from November until late December in order to clear predators from the penguin nesting area (Ratz et al. 1992). However, reinvasion of predators is rapid as soon as trapping stops (Ratz et al. 1992), and the sooty shearwater breeding season (October until May) is largely unprotected.

Burrow collapse

At least 27 burrows collapsed during the breeding season at the Taiaroa Head A colony, due either to human trampling (both by study observers and by tourists) and/or stock (sheep). Two chicks from the study area at Taiaroa Head A probably died when their burrows collapsed (Table 2). In the sand dune environment at this colony, burrows collapsed easily, but many new ones were being dug both at the beginning of the season and during the breeding season. High rabbit density at Taiaroa Head (pers. obs.) may increase the risk of burrow collapse, by denuding the landscape of vegetation as well as by increasing the number of holes in the ground.

CONCLUSIONS

The “burrowscope” was the best method for determining burrow occupancy in the long, and often obstructed and convoluted, sooty shearwater burrows. However, some problems remained, related to

the difficulty of pushing the camera past obstructions and around corners. Aside from establishing observation hatches, the other methodologies tested were useful only as an indicator of occupancy rather than as an accurate measure of nesting attempts. Refining and developing the construction of the “burrowscope” may be the key for following the breeding success of burrow-nesting seabirds in the future, but the accuracy of data obtained using a “burrowscope” needs to be tested.

Burrow occupancy and fledging success were higher at colonies less vulnerable to predation (although this was not statistically significant). If most of the remaining mainland populations suffer the levels of sooty shearwater chick and adult predation observed in 1992/93, it is unlikely that they can survive long-term (Hamilton & Moller 1995). However, if enough birds bred on the large offshore island colonies immigrate to the mainland, they may be able to sustain many of the small mainland colonies of sooty shearwaters in Otago. Along with predation, starvation may have added to the chick mortality in 1992/93: muttonbirders reported unusually small chick sizes on the offshore Rakiura Titi (Muttonbird) Islands during the same season (Margaret Bragg and Nash Norton, pers. comm.). Many underweight and undersized fledglings were washed up on Dunedin beaches at the end of the breeding season (Hamilton 1993), although these need not necessarily have been from Otago coast colonies.

Many breeding seabirds encounter years when chick survival rates are depressed and breeding success is extremely low or even zero (Wooller et al. 1992). The longevity of seabirds minimizes the deleterious effects of rare catastrophic breeding years, because the disadvantage is spread over a long reproductive life span (Wooller et al. 1992). However, catastrophic adult mortality, as recorded in the predation outbreak at Nuggets D, is more likely to have a large negative impact on the long-term survival of colonies at which it depletes the breeding population (Hamilton & Moller 1995). Any predator control should be planned to protect adults when they are most vulnerable, i.e., during courtship and nest preparation (November/December). Predator trapping to protect chicks is an additional operation, which would probably need to run for a much longer period (i.e., from late February to May). Breeding colonies of sooty shearwaters need to be monitored over many successive years before any concrete conclusions can be reached as to the importance of predation and other threats to colony survival.

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APPENDIX A

- “egg stage only” = nesting chambers (NC) confirmed to contain an egg but in which no chick was found in later searches
- “chick stage” = NC containing a chick
- “unknown burrows” = NC too long to accurately determine status but which were actively used (i.e. potentially occupied)
- “confirmed occupied” = NC containing an egg (i.e., a confirmed nesting attempt)
- “unoccupied burrows” = NC with no confirmed nesting attempt
- “occupied burrows” (range): minimum = confirmed occupied NC
maximum = confirmed occupied plus unknown status
- “% burrow occupancy” (range) = number of occupied NC (minimum and maximum) as a proportion of NC studied
- “fledglings” = chicks alive after 20 April (beginning of fledging) and from burrows in which no carcass was found after that date
- “presumed dead” = chicks that went missing but no carcass was recovered
- “confirmed dead” = chicks whose carcasses were recovered
- “unknown cause of death” = chick carcasses where cause of death undetermined
- “preyed upon” = carcasses having signs of predator-inflicted neck and/or head wounds
- “fledging success” = number of chicks assumed fledged as a proportion of the number of chicks confirmed hatched