

Preliminary modelling of black petrels (*Procellaria parkinsoni*) to assess population status

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CONTENTS

Abstract	5
<hr/>	
1. Introduction	6
<hr/>	
1.1 Background	6
1.2 Objectives	6
2. Relevant literature on the Procellaria	7
<hr/>	
2.1 Comparative biology	7
2.2 Available demographic data for the Procellaria	8
2.2.1 Breeder survival	8
2.2.2 Rate of skipping breeding	10
2.2.3 Juvenile and pre-breeder survival	10
2.2.4 Age of first breeding	10
2.3 Cory's shearwater demography	11
2.3.1 Breeder survival	11
2.3.2 Breeding success	11
2.3.3 Rate of skipping breeding	11
2.3.4 Juvenile and pre-breeder survival	12
2.3.5 Age of first breeding	12
3. Assessing the current data	13
<hr/>	
3.1 Model structure	13
3.2 Model parameterisation	14
3.3 Sensitivity, elasticity and uncertainty analyses	15
3.4 Model results	16
3.5 Power analysis based on available demographic data	17
3.5.1 Scenario 1—breeding success	17
3.5.2 Scenario 2—breeder survival	18
3.5.3 Scenario 3—pre-breeder survival	19
3.5.4 Scenario 4—rate of skipping breeding	19
3.5.5 Scenario 5—mean stage duration	20
3.5.6 Scenario 6—variance of stage duration	20
4. Interactions with longline fisheries	21
<hr/>	
4.1 Potential for interaction between black petrels and longline fisheries	21
5. Critique of research programme	25
<hr/>	
5.1 Establishing the status of the Great Barrier Island black petrel population	25
5.2 Improving demographic parameter estimates	26
5.2.1 Breeder survival and skipping rates	26
5.2.2 Juvenile and pre-breeder survival and age of first breeding	27
5.2.3 Emigration and immigration	27
5.2.4 Breeding success	28
5.2.5 Stratification of study burrows	28
5.2.6 Monitoring predation levels	29

5.3	Assessing interactions between black petrels and longline fisheries	29
6.	Conclusions and recommendations	31
7.	Acknowledgements	31
8.	References	32
<hr/>		
Appendix 1		
<hr/>		
	Estimating skipping rate	35
	Sensitivity and elasticity coefficients	35
	References	36
<hr/>		
Appendix 2		
<hr/>		
	Location of black petrels recorded in more than one burrow. Burrows marked in bold were used for breeding.	37
<hr/>		
Appendix 3		
<hr/>		
	Selected literature references relevant to <i>Procellaria</i> taxonomy and biology not cited in this report.	39

Preliminary modelling of black petrels (*Procellaria parkinsoni*) to assess population status

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ABSTRACT

We review the literature on the five *Procellaria* species and current data available on black petrels (*Procellaria parkinsoni*) to assess its adequacy for developing a population model for black petrels. Using data from the current monitoring program of black petrels on Great Barrier Island, New Zealand, we were able to make preliminary estimates of mean breeder survival (88.0%, SE = 4.8%) and the mean rate of skipping breeding (22.4%, SE = 12.6%). Population growth rate is estimated to be 0.972 (95% CI = 0.907-1.039) in a deterministic stage-structured matrix model. In sensitivity, elasticity and parameter uncertainty analyses, we found breeder survival to be the most important parameter. Juvenile survival and pre-breeder survival are also important. These results suggest that reducing the bias and increasing the precision of the estimates of these survival parameters should be the focus of future research effort.

A power analysis to assess the gain in precision of the estimate of population growth rate that could be achieved by reducing uncertainty in parameter estimates further emphasised the importance of breeder survival.

Establishing the status of the black petrel population on Great Barrier Island more definitively will require better estimates of breeder survival, and possibly also of juvenile and pre-breeder survival.

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1. Introduction

1.1 BACKGROUND

The black petrel (*Procellaria parkinsoni*) is the smallest and most northerly breeding of its genus. Although formerly widespread in the North Island and northern South Island, this New Zealand endemic is now restricted to Little Barrier and Great Barrier Islands off the coast of the northern North Island. (Imber 1976, 1987; Scofield 1989). Black petrels nest in burrows, generally in forested areas at least 300 m above sea level, and lay a single egg. The breeding season extends from October to July. The restricted breeding range, threat of predation by rats and feral cats, and an unknown level of by-catch from longline fisheries all potentially contribute to the vulnerability of this species.

A survey and monitoring programme was established by the Department of Conservation (DOC) in 1996 to determine current population trends on Great Barrier Island and the causes and timing of mortality (Bell & Sim 1998a, b). The study is monitoring breeding success and the causes of breeding failure in study burrows; banding adults and chicks from study burrows and monitoring predation by rats and feral cats. Census grids (40 × 40 m) have been established to estimate population size and density. Current monitoring is focused on the main colony at Mt. Hobson (Hirakimata), which consists of about 1000 burrows. Little recent work has been conducted at the remaining four colonies on Great Barrier (which range in size from approximately 10 to 100 burrows) or at the colony on Little Barrier Island.

1.2 OBJECTIVES

The objectives of this report are to:

- Review the literature on the five *Procellaria* species, with respect to assessing its relevance in developing a population model for black petrels;
- Evaluate which demographic parameters can be estimated from current data on black petrels;
- Assess the adequacy of the current research program for assessing the population status of Black petrels. In particular, we consider the adequacy of the data as input to a population model.

2. Relevant literature on the *Procellaria*

2.1 COMPARATIVE BIOLOGY

Five species of *Procellaria* petrel are currently recognised:

- Procellaria parkinsoni* Gray 1862 Black petrel
- Procellaria westlandica* Falla 1946 Westland Petrel
- Procellaria cinerea* Gmelin 1789 Grey Petrel
- Procellaria aequinoctialis* Linnaeus 1759 White-chinned Petrel
- Procellaria conspicillata* Gould 1844 Spectacled Petrel

The *Procellaria* are a primitive, monophyletic group (Harper 1978) most closely related to the *Calonectris* shearwaters (Warham 1996). The black petrel is most closely related to the Westland petrel and both species are endemic to New Zealand (Harper 1978). The grey petrel breeds on a few sub-antarctic islands and is recognised by its plumage, vocalisations and behaviour as the most distantly related of the group (Warham 1990, 1996). The white-chinned petrel is widespread and abundant throughout the southern ocean. The recently re-recognised spectacled petrel forms a super-species with the white-chinned petrel (Ryan 1998).

The incubation and fledging periods of these species are not correlated to average body weight (Table 1), which is unusual in procellariiformes. This may be due to the even mix of summer- and winter-breeding species represented in the genus. The two winter-breeding species have longer chick development periods due to lower average temperatures experienced at their breeding grounds (Warham 1990). Differences in breeding seasons, latitudinal distribution, and migratory behaviour negate simple comparisons of demographic rates for the *Procellaria* (Tables 1 and 2).

TABLE 1. MEAN WEIGHT AND TIMING OF THE BREEDING SEASON FOR THE FIVE *Procellaria* SPECIES. (DATA ARE FROM JOUVENTIN et al. 1985; HALL 1987; IMBER 1987; WEIMERSKIRCH et al. 1989; ZOTIER 1990; CHASTEL 1995; E. BELL AND J. SIM UNPUBL. DATA)

SPECIES	MEAN WEIGHT IN GRAMS (n)	BREEDING SEASON	LAYING DATE	INCUBATION PERIOD	FLEDGING PERIOD	BURROW LOCATIONS
Black	744 (~280)	Summer	Early December	57	107	Burrows and natural sites
Westland	1199 (12)	Winter	Peak 23 May	62	120-140	Burrows only
White-chinned	1277 (16)	Summer	Late November	58-59	94-98	Burrows only, wet entrances
Spectacled	1191 (32)	Summer	Late October	?	?	Burrows only
Grey	1131 (37)	Winter	Late March	55-58	110	Burrows only

TABLE 2. LOCATION OF BREEDING GROUNDS, SEASON WHEN BIRDS PRESENT, AND MIGRATORY PATTERNS OF THE FIVE *Procellaria* SPECIES.

SPECIES	BREEDING LOCATIONS	BREEDING SEASON	DEPART THE BREEDING GROUNDS	MIGRATORY	MIGRATE TO
Black	Little and Great Barrier Islands only	Summer	May	Yes	Eastern Tropical Pacific
Westland	Barrytown, Westland only	Winter	Feb.	Yes	Central South Pacific
White-chinned	Mid-high latitude circumpolar	Summer	Aug.	Slightly north	North
Spectacled	Inaccessible Island only	Summer	Autumn	Yes	South American shelf
Grey	High latitude circumpolar	Winter	Dec.-Jan.	Slightly north	North

2.2 AVAILABLE DEMOGRAPHIC DATA FOR THE *Procellaria*

There is still very little known about the demography of the *Procellaria* petrels: Table 3 summarises the available demographic data for this genus. Papers on *Procellaria* biology that were referred to but gave no useful demographic information are given in Appendix 3. There are no published analyses of survival rates of adults or pre-breeders or of age of first breeding, although data may exist that could be used to estimate these parameters.

In addition to reviewing relevant data from previous work on black petrels (Imber 1987; Scofield 1989), we obtained data from the 1996, 1997, 1998, and 1999 breeding seasons* of the current monitoring program (Bell & Sim 1998a, b; E. Bell and J. Sim unpubl. data). We analysed these data to see if preliminary estimates could be made for demographic parameters other than breeding success. For all parameters used as inputs to the population model in Section 3, we adopted the approach described by White (2000) to estimate the mean for that parameter (over the years of data available) and its standard error.

2.2.1 Breeder survival

Breeder survival was estimated using Program Mark (White & Burnham 1999), from the 1996, 1997, 1998 and 1999 banding data on Great Barrier Island (E. Bell and J. Sim unpubl. data). These data were primarily obtained from checks of breeding burrows. Since non-breeders and pre-breeders attend the colony less regularly and spend less time in burrows, they have a much lower probability of recapture than established breeders. Birds that were not known to have bred represented a small portion of the data set and were seldom recaptured. Indeed, non-breeding burrows were only checked until the same non-breeding bird was caught twice. We therefore chose to include only data for birds that were known to have bred at least once during the study (85% of the 536 birds) in our estimates of adult survival. We could have classified birds according to breeding status, and used a multi-state mark-recapture model to allow for differences in

* Note: 1996 = 1996/97 breeding season, 1997 = 1997/98 breeding season etc.

TABLE 3. AVAILABLE DEMOGRAPHIC DATA ON THE FIVE *Procellaria* SPECIES.

SPECIES	BREEDING SUCCESS (%)	SKIPPING BREEDING (%)	POPULATION SIZE	REFERENCE
Black	98 (n = 48, 1996)*		5×10^3	Bell & Sim 1998a & b; E. Bell and J. Sim unpubl. data.
	78 (n = 92, 1997)			
	84 (n = 95, 1998)			
	77 (n = 142, 1999)			
	51 (n = 83, 1977)			Imber 1987.
	60 (n = 188, 1978)			
	70 (n = 28, 1988)		2.3×10^3	Scofield 1989.
67 (n = 54, 1989)				
Westland	39 (20-63)			Department of Conservation unpubl. report. Freeman et al. 1997. Bartle 1987; Department of Conservation 1996.
	50 (38-63)		2×10^4	
White-chinned	36.2 (n = 47), 21.8 (n = 55)			Cooper et al. 1995.
	28.4 (n = 102)			Berruti et al. 1995.
	28.0			Hall 1987.
	< 10.5			Mougin 1970.
		20.9		Chastel 1995.
Spectacled			2×10^3	Ryan 1998.
Grey			1×10^5	Robertson & Bell 1992.
		26.2		Chastel 1995.

* Percent breeding success is biased because the majority of these burrows were selected with chicks already present.

capture probability, but chose not to for ease of analysis. The extra complexity of this option may be warranted in the future when additional data are available.

In mark-recapture modelling it is important to check the most general model for goodness of fit before reducing comparing reduced models using the Akaike Information Criterion (AICc) (White & Burnham 1999). A test of the general Cormack-Jolly-Seber model showed no evidence of lack-of-fit ($\chi^2 = 11.2$, DF = 7; P = 0.13). We then compared this model with three alternatives that assumed constant survival and/or capture rates. The best-fitting model, using AICc, allowed survival rates to vary from year to year but kept capture rate constant (AICc weight = 0.76). Estimates of survival from this model are shown in Table 4. For comparison, we have also included the estimates obtained from the full data set, i.e. including those birds that were not known to have bred (the same model was the best-fitting for these data; AICc weight = 0.85). In each year, the estimate is lower for the full data set, implying a lower apparent survival rate for non-breeders, which could be caused by emigration as well as mortality.

The majority of the current study burrows lie along the present track system (about 72%). These burrows are interspersed with burrows for which the occupancy and identity of any occupants is unknown. Movement of birds to a new breeding burrow, even within a short distance of their original burrow, is therefore likely to go unrecorded. Birds moving to a new breeding burrow will then be lost from the monitored population and presumed to be dead. Unrecorded movement such as this will negatively bias estimates of breeder survival.

TABLE 4. ESTIMATED SURVIVAL RATES FOR BLACK PETRELS Banded OVER FOUR BREEDING SEASONS (1996–99) ON GREAT BARRIER ISLAND.

BREEDING SEASON	BREEDERS		FULL DATA SET	
	SURVIVAL	STANDARD ERROR	SURVIVAL	STANDARD ERROR
1996	0.904	0.062	0.884	0.066
1997	0.886	0.027	0.837	0.030
1998	0.756	0.032	0.737	0.032
1999	0.986	0.032	0.962	0.032
<i>Mean</i>	<i>0.881</i>	<i>0.048</i>	<i>0.852</i>	<i>0.048</i>

Movement of breeding birds among study burrows of 8% to 13% (Appendix 2) has been recorded. As there are more unmonitored than monitored burrows in the Mt. Hobson area, we would expect at least this rate of movement to unmonitored burrows. This will be an important factor to consider in subsequent estimates of breeder survival and rate of skipping breeding.

2.2.2 Rate of skipping breeding

Reliable estimates of the proportion of birds skipping breeding require relatively long-term data. However, we attempted to obtain preliminary estimates of skipping rates from presence and absence data of breeding pairs in burrows. Details of the method we used are given in Appendix 1. The estimate of the mean skipping rate was 22.4% (SE = 12.6%).

2.2.3 Juvenile and pre-breeder survival

Some data exists in the Department of Conservation banding database that may be useful for estimating juvenile and pre-breeder survival rates. Unfortunately, this data has been inaccessible during the term of this contract because of problems with the Department of Conservation computer system.

2.2.4 Age of first breeding

Eighteen birds banded as chicks are known to have returned to Great Barrier Island. Fourteen of those chicks were first recorded breeding at a mean age of 8.5 years (SD = 2.5, n = 14; Table 5). This is likely to be an overestimate of the actual age of first breeding, as eight of the fourteen burrows were not checked in the year prior to a known-age individual first being found. These birds would therefore have had the opportunity to breed at a younger age without being detected. The estimated age of first breeding for only the six burrows checked in prior years is 7.8 years (SD = 2.3, n = 6). Imber (1987) records a single individual breeding at age 6 years on Little Barrier Island

Bird H-30930 was banded as a chick in 1996 and returned to the colony at 4 years of age in the 1999 breeding season. This is the youngest recorded age of first return. However it seems likely that H-28572, which bred at age 5 years, also returned at age 4.

TABLE 5. AGE OF FIRST RECORDED RETURN TO THE COLONY AND FIRST BREEDING OF BLACK PETREL CHICKS BANDED ON GREAT BARRIER ISLAND. SEVEN OF THESE CHICKS WERE TRANSFERRED TO LITTLE BARRIER ISLAND (LBI).

BAND	YEAR BANDED	AGE FIRST KNOWN TO RETURN	AGE FIRST KNOWN TO BREED	NOTES
13641*	1988		9	Transferred to LBI
26991	1986	11	12	Transferred to LBI
23635	1988	10		Control chick
27604*	1989	7	8	Transferred to LBI
27665*	1990		6	Control chick
28572*	1992	4	5	Banded by Terry Greene
27702*	1990		6	Control chick
13618*	1988		8	Transferred to LBI
27666*	1990	6	7	Control chick
27678	1990		7	Transferred to LBI
27689*	1990		7	Control chick
27568	1989		11	Banded by Paul Scofield
27708	1990	10		Control chick
27728	1990		8	Control chick
30930*	1996	4		Banded by Bell and Sim
13634*	1988		12	Transferred to LBI
27058*	1987		13	Transferred to LBI
27032*	1987	4		Banded by Bell and Sim

* Burrows were not checked the year prior to this bird being recorded so age of first known return or breeding is a maximum age.

2.3 CORY'S SHEARWATER DEMOGRAPHY

Given the scarcity of demographic data available for the *Procellaria* and the close phylogenetic relationship and similarity in size between black petrels and Cory's shearwater (*Calonectris diomedea*), we also reviewed information available for the latter species. Cory's shearwaters breed in the northern hemisphere and begin egg-laying in late May. They are a summer breeder with an incubation period of 52-58 days and mean fledging period of 97 days (Mougin et al. 1996).

2.3.1 Breeder survival

Breeder survival between 1978 and 1984 is reported as 0.952 (\pm 0.017, 95% CI) for males, 0.960 (\pm 0.228, 95% CI) for females and 0.956 (\pm 0.017, 95% CI) for the two sexes combined (Mougin et al. 1987, 1993).

2.3.2 Breeding success

Mean breeding success for Cory's shearwater is reported to be 57.9% (n = 1603; Mougin et al. 1997).

2.3.3 Rate of skipping breeding

The proportion of sabbatical (non-breeding) years among possible breeding years for birds that have bred at least once is reported to vary between 9.9% and 16.4%. A total of 1270 sabbaticals were recorded out of 9118 possible bird breeding years (13.9%; Mougin et al. 1984, 1997). There is some indication that

this rate increases with increasing colony size. Fifty-eight percent of sabbaticals lasted one year, 26% lasted two years and 16% lasted three or more years. The mean length of absence was 1.07 years ($n = 455$). The proportion of birds skipping after a successful breeding attempt was 10% (Table 6).

No sexual bias was found in birds skipping breeding in a given year. However, 51.2% of males and 59.5% of females bred with another mate, either in the same burrow or in another burrow, in the year that its partner took a sabbatical (Mougin et al. 1984, 1997). The percentage that returned to their original partner is not reported.

TABLE 6. PERCENTAGE OF CORY'S SHEARWATERS ON SELVAGEM GRANDE THAT WERE BREEDING IN THE YEAR FOLLOWING A SUCCESSFUL BREEDING ATTEMPT (MOUGIN et al. 1997).

YEAR	NUMBER OF BIRDS	BIRDS BREEDING NEXT YEAR (%)
1980	455	89.0
1981	521	89.4
1982	653	89.0
1983	668	89.2
1984	687	92.0
1985	766	89.7
1986	786	90.8

2.3.4 Juvenile and pre-breeder survival

Of four cohorts of chicks banded between 1968 and 1971 (a total of 11 381), 172 were later found to be breeding (1.55%; Mougin et al. 1986). The authors considered this low rate of return to be partly due to migration. Juvenile survival (survival to one year) for Cory's shearwater was estimated to be between 26% and 32.3% with a mean of 28.8% (Mougin et al. 1987). No estimates of pre-breeder survival have been reported. Demographic models of Cory's shearwater have set survival rates of all birds greater than one year old as equal to breeder survival (Mougin et al. 1987, 1996).

2.3.5 Age of first breeding

First breeding has been reported between the ages of 5 and 13, with an overall mean of 9.2 years and standard deviation of 1.7 years (Table 7; Mougin et al. 1993, 1996).

TABLE 7. KNOWN AGE OF FIRST BREEDING OF COREY'S SHEARWATER (MOUGIN et al. 1993).

YEAR OF BIRTH	5	6	7	8	9	10	11	12	13	N	MEAN	SD
1977	1	3	5	6	8	5	2			30	8.8	0.89
1978			1	2	6	5	4	3	2	23	9.7	0.86
1979		1	3	4	8	7	5	4	1	33	9.6	0.90
1980		2	4	4	4	5	7			26	9.5	0.64
Total	1	6	13	16	26	22	18	7	3	112	9.2	1.7

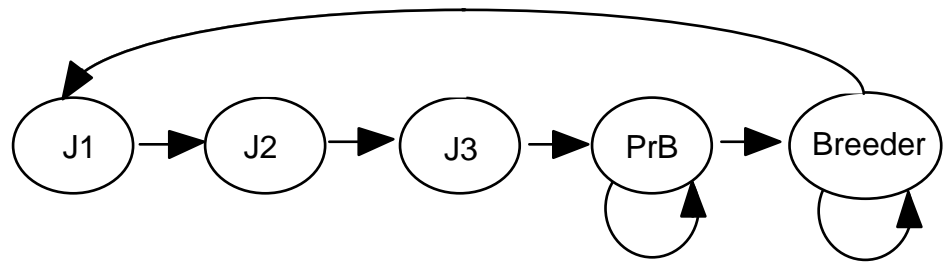
3. Assessing the current data

To assess the adequacy of the current data for demographic modelling, we used it as input to a deterministic model. We then conducted a power analysis to evaluate how the uncertainty in parameter estimates affects our ability to estimate population growth rate.

3.1 MODEL STRUCTURE

We used the deterministic stage-structured model summarised by the life cycle in Figure 1 (Caswell 1989). The three juvenile stages ensure that birds are four years old before entering the pre-breeder stage and therefore cannot breed before the age of five. We chose a relatively simple model as this allowed us to assess the importance of the basic demographic parameters without going beyond the limits of the data. Recent studies indicate that incorporating additional age structure in the model is unlikely to have a significant influence either on confidence intervals for population growth rate or on results of sensitivity analyses (Heppell et al. 2000; Hunter & Fletcher in press).

Figure 1. Life-cycle representation of the model. J1-J3 represent juvenile birds before return to the colony and PrB represents pre-breeders, birds that have not previously bred.



Transitions between stages of the model (represented by arrows in Fig. 1) can be represented by the following equations:

$$N_t^{J^1} = N_{t-1}^{BR} (1 - BR_{skip}) BS J_{Surv}^0$$

$$N_t^{J^2} = N_{t-1}^{J^1} J_{Surv}^1$$

$$N_t^{J^3} = N_{t-1}^{J^2} J_{Surv}^2$$

$$N_t^{PrB} = N_{t-1}^{J^3} J_{Surv}^3 + N_{t-1}^{PrB} PrB_{Surv} (1 - \gamma)$$

$$N_t^{BR} = N_{t-1}^{PrB} PrB_{Surv} \gamma + N_{t-1}^{BR} BR_{Surv}$$

where

$$N_t^a = \text{number of individuals in class } a \text{ at time } t$$

$$J^x = \text{juveniles of age } x$$

$$PrB = \text{pre-breeders}$$

$$R = \text{breeders}$$

BS	= breeding success rate
J_{Surv}	= survival rate of juveniles
PrB_{Surv}	= survival rate of pre-breeders
BR_{Surv}	= survival rate of breeders
BR_{Skip}	= proportion of breeders skipping breeding in a given year
γ	= probability a pre-breeder becomes a breeder, given that it survived

The parameter γ can be estimated to several levels of approximation, depending on the assumptions made regarding the variability in age of first breeding among individuals and the stability of the age structure within the pre-breeder stage (Caswell 1989). The equation

$$\gamma = \frac{1}{\bar{T}} \exp \left[- \ln \left(\frac{\lambda}{PrB_{Surv}} \right) \left(\frac{\bar{T}}{2} - \frac{V(T_i)}{2\bar{T}} \right) \right]$$

estimates γ for a ‘variable stage duration’, which assumes the pre-breeder stage duration varies among individuals with mean \bar{T} and variance $V(T_i)$ and that the age distribution within this stage is stable (Caswell 1989, p. 85). We chose this method because it involves the least assumptions. However, other methods for estimating γ would be expected to give similar results (Caswell 1989; Hunter & Fletcher in press). Note that in what follows we use the term stage duration to mean pre-breeder stage duration.

We chose to use a deterministic model (no year-to-year variation in parameters) rather than a stochastic model (between-year variation in parameters) for a number of reasons. First, the sensitivity analyses and subsequent power analyses (Sections 3.3–3.5) are greatly simplified by use of a deterministic model. Second, although a power analysis based on a stochastic model might highlight the need to estimate between-year variation in a parameter as well as its mean, it is unlikely to alter conclusions as to which parameters are important for estimating population growth rate. Third, only crude estimates of between-year variation in parameters are available, being based on just three or four years of data.

3.2 MODEL PARAMETERISATION

The model has seven input parameters. Estimates and 95% confidence limits (Table 8) were obtained for each of these using the data and results presented in sections 2.2 and 2.3.

For breeding success, we used only the data for 1997–99 (Table 3), as the majority of burrows in 1996 were selected with a chick already present: the estimate for that year therefore corresponds to chick success from hatching rather than from egg laying.

Confidence limits for annual juvenile survival were calculated to give return rates to four years of between 25% and 55% (e.g. $(J_{Surv})^4 = 0.25$). The estimate of juvenile survival was taken as the average of these two rates. Lack of any information on juvenile or pre-breeder survival for either black petrels or Cory’s

TABLE 8. ESTIMATES AND 95% CONFIDENCE LIMITS FOR THE MODEL PARAMETERS. STAGE DURATION IS ESTIMATED AS MEAN AGE OF FIRST BREEDING MINUS 4 YEARS.

	LOWER	ESTIMATE	UPPER
Breeding success	0.375	0.397	0.419
Juvenile survival	0.758	0.827	0.887
Pre-breeder survival	0.784	0.880	0.976
Breeder Survival	0.784	0.880	0.976
Skipping breeding rate	0.000	0.224	0.475
Mean stage duration	4.4	5.2	6.0
Variance of stage duration	1.9	2.6	3.3

shearwater means we have no justification for our choice of these return rates, other than the fact that they represent what would be considered biologically reasonable limits for this species (M. Imber, pers. comm.).

We set survival rates of pre-breeders equal to breeders. This is a common simplifying assumption when lack of data prevents separate estimates for pre-breeders.

We used estimates of age of first breeding for Cory's shearwater since age of first breeding for black petrels was estimated from such a small sample size. Stage duration was taken to be age of first breeding minus the age at which juveniles entered the pre-breeder stage (four years).

We did not include emigration or immigration in the model. The monitored population represents the majority of the black petrel breeding population; the remaining colonies on both Great Barrier and Little Barrier Islands are much smaller. Immigration and emigration rates are therefore both expected to be small.

3.3 SENSITIVITY, ELASTICITY AND UNCERTAINTY ANALYSES

Sensitivity and elasticity analyses have become popular tools in conservation management. They quantify the effect of input parameters on estimates of population growth rate. It is generally inferred that attempts to improve population status management should focus on demographic parameters with the largest sensitivity or elasticity coefficients (Crouse et al. 1987; Menges 1990; Caswell 2000; de Kroon et al. 2000; Heppell et al. 2000).

The sensitivity coefficient for an input parameter measures the absolute change in population growth rate resulting from a unit change in that parameter, while keeping all other parameters fixed. The elasticity coefficient (proportional sensitivity coefficient) for a parameter measures the proportional change in population growth rate resulting from a proportional change in that parameter (de Kroon et al. 1986; Caswell 1989). Sensitivity and elasticity coefficients can both be interpreted as the potential for altering population growth rate by changing parameter values. Sensitivity coefficients rank this potential based on altering each parameter by the same actual amount whereas elasticity coefficients rank it based on altering parameters by the same percentage.

The uncertainty coefficient for a parameter measures the absolute change in population growth rate that results from changing the value for that parameter from its lower to its upper 95% confidence limit. In order to increase the precision of population growth rate estimates, it is best to increase the precision of the estimates of parameters that have large uncertainty coefficients. A parameter for which we have little data may have a low sensitivity/elasticity coefficient and yet have a high uncertainty coefficient. It is important to note that an uncertainty coefficient gives no indication of the effect of any bias in our estimate for that parameter: the potential effect of bias is indicated by the sensitivity and elasticity coefficients.

Details regarding the calculation of these coefficients are given in Appendix 1.

Use of sensitivity and elasticity coefficients involves the assumption that the relationship between population growth rate and each parameter is approximately linear over the biologically plausible range of values for that parameter. In order to check for any strong non-linearities, we also calculated a scaled uncertainty coefficient, the uncertainty coefficient divided by the uncertainty range (the upper minus the lower 95% confidence limit) for each parameter. If the linearity assumption is reasonable, the values of these coefficients will be close to those of the sensitivity coefficients.

Bootstrap confidence intervals for population growth were calculated by performing 1000 runs of the model. For every run, the value of each parameter was selected from a normal distribution with mean and standard error as given by the 95% confidence intervals in Table 8 (Caswell 1989, p. 190).

3.4 MODEL RESULTS

Using our estimates for each parameter, the model predicted a population growth rate for black petrels of 0.972 (0.906–1.038; 95% CI). The sensitivity and elasticity coefficients suggest population growth rate is most strongly influenced by survival rates, particularly breeder survival (Table 9). Breeding success was also quite important for the sensitivity but not the elasticity analysis. For the sensitivity analysis, a 10% increase in breeding success would be needed to achieve the same gains as a 1% increase in breeder survival. For both sensitivity and elasticity analyses, the actual change in a parameter level that could be achieved through management actions also needs to be considered: the changes needed to increase breeding success by 10% may be as costly as those needed to increase breeder survival by 1%.

TABLE 9. SENSITIVITY, ELASTICITY AND PARAMETER UNCERTAINTY COEFFICIENTS FOR MODEL INPUT PARAMETERS.

	SENSITIVITY	ELASTICITY	UNCERTAINTY
Breeding success	0.1372	0.0560	0.0059
Juvenile survival	0.2635	0.2241	0.0331
Pre-breeder survival	0.3279	0.2968	0.0608
Breeder survival	0.5897	0.5337	0.1109
Skipping breeding rate	-0.0702	-0.0162	-0.0334
Mean of stage duration	-0.0055	-0.0296	-0.0083
Variance of stage duration	0.0011	0.0030	0.0003

The high rank of breeder survival emphasises the vulnerability of black petrels to external influences that reduce breeder survival. This is consistent with other demographic studies of seabirds (Weimerskirch et al. 1996; Russell 1999). It suggests that increased adult mortality from threats such as fisheries by-catch, if occurring, will have important consequences for the population.

Only the variance of stage duration showed any indication of a non-linear relationship with population growth. We did not investigate this further as the sensitivity of this parameter was extremely low. The lack of evidence for non-linearities suggests that results for the sensitivity and elasticity analyses should be reasonably robust to larger changes in parameter values.

The rankings of the uncertainty coefficients were similar to those of the sensitivity and elasticity coefficients (Table 9). Survival rates had the greatest influence on the uncertainty in estimating population growth rate. The uncertainty coefficient for breeding success was relatively low compared to its sensitivity and elasticity coefficients, reflecting the fact that it is one of the easier parameters for which to collect data.

3.5 POWER ANALYSIS BASED ON AVAILABLE DEMOGRAPHIC DATA

We performed a power analysis by examining the effect of changing the standard error of the estimated mean for each parameter on the width of the confidence interval for black petrel population growth rate. Six scenarios were considered, each scenario corresponding to three values for the standard error of a particular parameter (Table 10). For each scenario, all other parameters had their mean and standard error set at their current estimates. We used the method of analysis described by White (2000) to predict what the standard error of each mean would be if we had up to 10 years of data. In doing so, for all parameters except breeder survival, we made the assumption that the standard error associated with the estimate of a parameter in any one year in the future would be approximately the average of its standard error in each of the years for which we have data. For breeder survival, we predicted the standard error for each year in the future using the method in Burnham et al. (1987).

For both breeding success and stage duration, the standard error relies solely on the number of years data, not on whether those years are consecutive or not: for example, five years of data might correspond to sampling once every two years for ten years. For breeder survival, we also considered the option of continuing for a further five years with the current capture rate, but sampling only in years 6, 8 and 10. The predicted standard error for this case is 0.035, slightly larger than that obtained by halving the capture rate and sampling in each of the coming five years.

3.5.1 Scenario 1—breeding success

We calculated the change in the standard error of black petrel breeding success expected if the current annual monitoring effort were maintained for 3 (years of data currently available), 5 and 10 years (Table 10). The smaller standard error achieved from collecting additional years of data resulted in a negligible change in the precision of estimated population growth rate (Fig. 2).

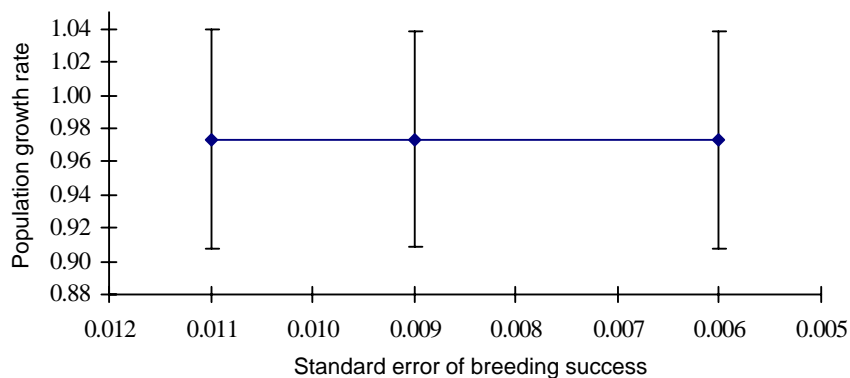
TABLE 10. PARAMETER ESTIMATES, STANDARD ERRORS AND NUMBER OF YEARS OF DATA NEEDED TO ACHIEVE THOSE STANDARD ERRORS USED IN THE POWER ANALYSIS. FOR SURVIVAL RATES, p DENOTES CAPTURE RATE.

PARAMETER	SCENARIO	PARAMETER			95% CONFIDENCE INTERVAL FOR λ		CONFIDENCE INTERVAL WIDTH
		ESTIMATE	SE	YEARS OF DATA	LOWER	UPPER	WIDTH
Breeding success	1	0.40	0.011	3 yrs*	0.908	1.039	0.132
		0.40	0.009	5 yrs	0.908	1.038	0.130
		0.40	0.006	10 yrs	0.908	1.039	0.131
Breeder survival	2	0.88	0.048	5 yrs*	0.908	1.039	0.132
		0.88	0.032	10 yrs 1/2 p	0.923	1.023	0.100
		0.88	0.031	10 yrs-same p	0.921	1.026	0.105
Pre-breeder survival	3	0.88	0.048	5 yrs**	0.908	1.039	0.132
		0.88	0.032	10 yrs 1/2 p **	0.914	1.033	0.120
		0.88	0.031	10 yrs-same p **	0.911	1.036	0.125
Rate of skipping breeding	4	0.22	0.126	3 yrs*	0.908	1.039	0.132
		0.22	0.089	5 yrs	0.909	1.038	0.130
		0.22	0.063	10 yrs	0.910	1.036	0.126
Mean stage duration	5	5.3	0.39	4 yrs	0.908	1.039	0.132
		5.3	0.35	5 yrs	0.909	1.038	0.129
		5.3	0.26	10 yrs	0.909	1.038	0.129
Variance of stage duration	6	2.6	0.36	4 yrs	0.908	1.039	0.132
		2.6	0.32	5 yrs	0.908	1.038	0.130
		2.6	0.24	10 yrs	0.908	1.039	0.131

* The approximate current level of monitoring.

** Years of data for banding and recapture of breeders.

Figure 2. Confidence intervals for black petrel population growth rate versus standard error of breeding success.

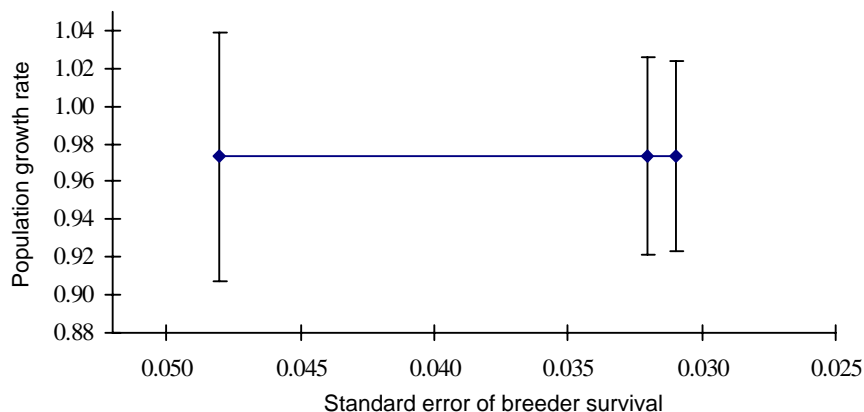


3.5.2 Scenario 2—breeder survival

We set the standard error of breeder survival to reflect both the number of years of data collection and the capture effort. For five years data (current level), this translates to a standard error of 4.8%. Using the same capture rate (to represent the same level of effort) over ten years reduces the standard error to 3.1%. If the capture rate is reduced to half the current level for the next five years, the standard error is 3.2%.

A clear improvement in the width of the confidence interval was observed by increasing the time span over which survival rates were calculated from five to ten years (Fig. 3). This was not surprising as breeder survival had the highest uncertainty coefficient. Little difference was observed in the reduction in the width of the confidence interval when capture rate was reduced by half. This is an important result, as it indicates that there is little to be gained in keeping the capture rate at the current level.

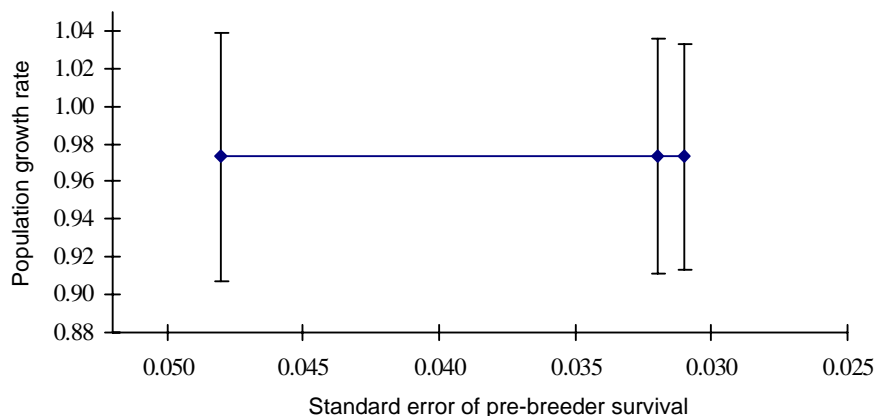
Figure 3. Confidence intervals for black petrel population growth rate versus standard error of breeder survival.



3.5.3 Scenario 3—pre-breeder survival

As we have assumed that pre-breeder survival is equal to that for breeders, we examined the effect of reducing the standard error of pre-breeder survival to the values considered for breeder survival in scenario 2 (Table 10). The reduction in the width of the confidence interval was still noticeable but smaller than that for breeder survival (Fig. 4).

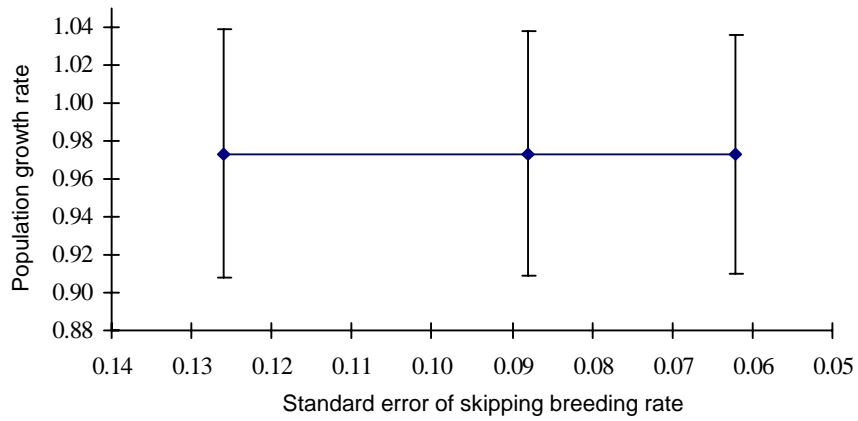
Figure 4. Confidence intervals for black petrel population growth rate versus standard error of pre-breeder survival.



3.5.4 Scenario 4—rate of skipping breeding

We calculated the change in the standard error for the estimated rate of skipping breeding for 3, 5 and 10 years of data at the current annual level of effort (Table 10). Reducing the standard error to these values resulted in little change in the width of the confidence interval for population growth rate (Fig. 5). This suggests that although our estimates for the rate of skipping breeding were imprecise and dependent on several simplifying assumptions, this is likely to have little effect on the precision of the population growth rate estimate.

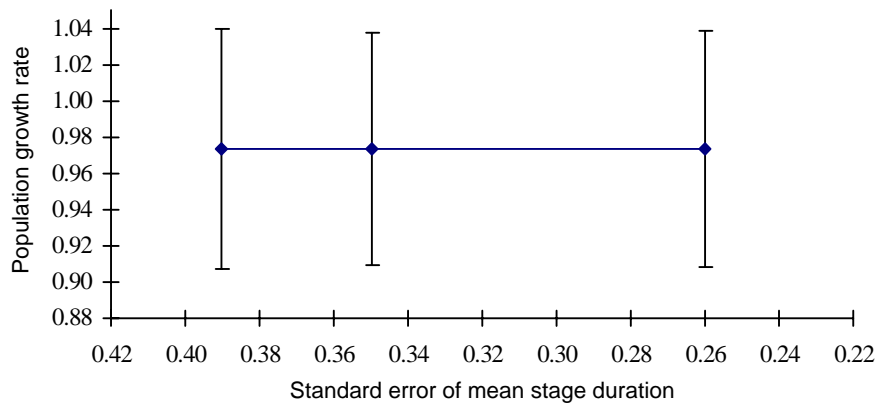
Figure 5. Confidence intervals for black petrel population growth rate versus standard error of rate of skipping breeding.



3.5.5 Scenario 5—mean stage duration

Using the data in Table 7, we calculated the standard error for mean stage duration corresponding to 4, 5 and 10 years of data assuming the same level of effort as for the Cory’s shearwater study from which data for these estimates was used. An average of 28 known-age first breeders were identified each year in that study (Table 7). There was little change in the width of the confidence interval for population growth rate for these smaller standard errors (Fig. 6, Table 10).

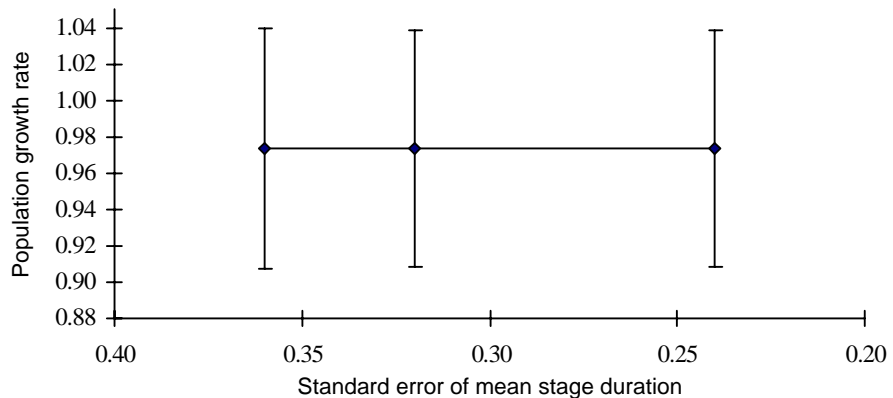
Figure 6. Confidence intervals for black petrel population growth rate versus standard error of the mean stage duration.



3.5.6 Scenario 6—variance of stage duration

Using the data in Table 7, we calculated the standard error for the variance of stage duration corresponding to 4, 5 and 10 years of data assuming the same level of effort as for the Cory’s Shearwater study (Table 10). Reducing the standard error for variance of stage duration did not alter the width of the confidence intervals for population growth rate (Fig. 7).

Figure 7. Confidence intervals for black petrel population growth rate versus standard error of variance of stage duration.



4. Interactions with longline fisheries

4.1 POTENTIAL FOR INTERACTION BETWEEN BLACK PETRELS AND LONGLINE FISHERIES

Between 1980 and 1997 there were between 1.78 and 27.28 million hooks set each year in the New Zealand Exclusive Economic Zone (EEZ) by tuna longline fishing vessels. Currently, approximately half this fishery consists of domestic vessels (Table 11). About one-third of all domestic sets were monitored by scientific observers in 1997. In 1993, five black petrels were reported in the by-catch for the domestic longline fishery. This increased to six in 1994 and eleven in 1996 (J.A. Bartle & I. West in Bell & Sim 1998a, b). The increase may be correlated to an increase in size of the domestic longline fleet. The number of black petrels affected by by-catch from longline fisheries remains largely unknown.

TABLE 11. NUMBER OF HOOKS SET BY DOMESTIC LONGLINE VESSELS IN THE NEW ZEALAND EEZ AND NUMBER OF BLACK PETRELS REPORTED IN THE BY-CATCH BETWEEN 1988 AND 1997. SOURCES: NIWA UNPUBLISHED DATA; BARTLE (2000); BELL & SIM (1998a, b); ROBERTSON (2000).

YEAR	NUMBER OF SETS	NUMBER OF HOOKS (1000S)	PERCENTAGE HOOKS OBSERVED	NUMBER OF BLACK-PETRELS REPORTED IN THE BY-CATCH
1988	497	1427	8.0	No data
1989	760	1650	7.1	No data
1990	686	1261	16.0	0
1991	1059	1954	1.0	No data
1992	1499	2400	19.8	No data
1993	2096	2438	25.1	5 (at least 2 males)
1994	3107	3672	19.7	6
1995	2583	2335	7.0	No data
1996	2617	3174	32.0	11
1997	3431	3890	28.3	1

Black petrels are shelf-edge feeders during the breeding season (Imber 1987). This coincides with the areas most intensively targeted by domestic longline vessels. In addition, most New Zealand domestic longlining occurs between December and July, which coincides with the incubation and chick rearing of black petrels (Figs 8 and 9, Table 12; Imber 1987).

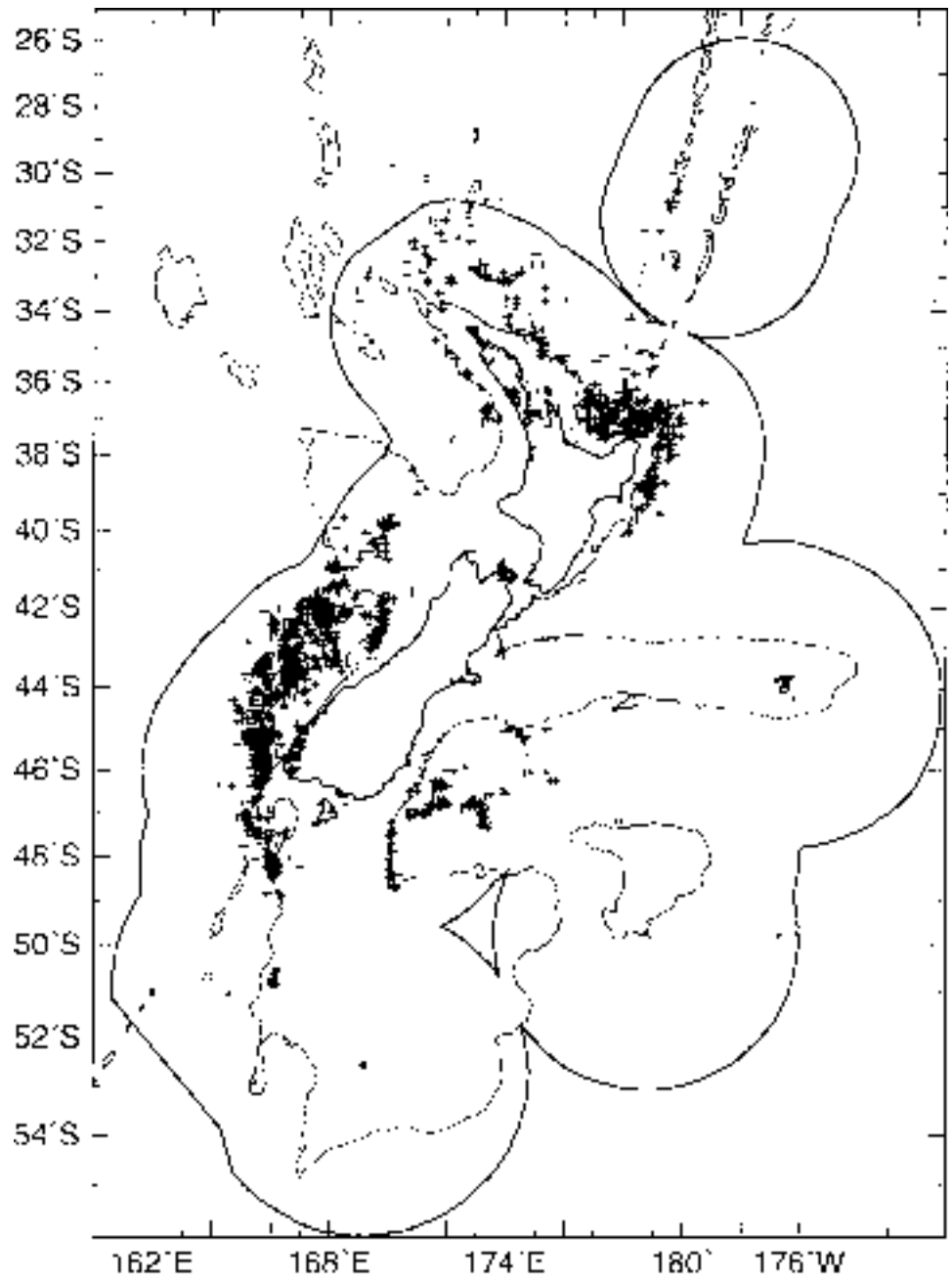


Figure 8a. Domestic longline operations during the period 1991-98: observed positions. Provided by the Ministry of Fisheries and the National Institute of Water and Atmospheric Research Ltd (NIWA).

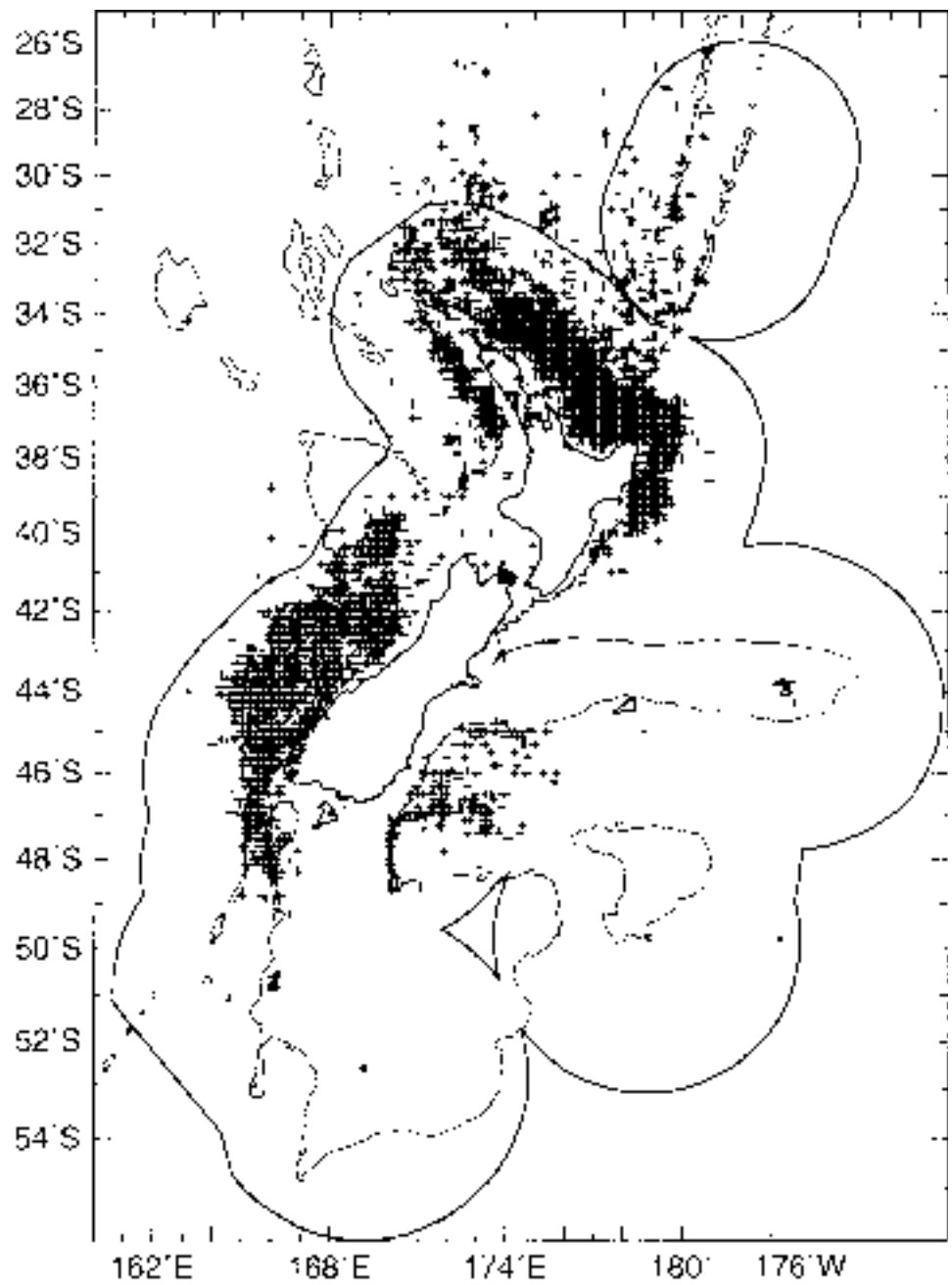


Figure 8b. Domestic longline operations during the period 1991-98: total number of positions. Provided by the Ministry of Fisheries and the National Institute of Water and Atmospheric Research Ltd (NIWA).

TABLE 12. EXPOSURE OF THE FIVE *Procellaria* SPECIES TO LONGLINE FISHERIES.

SPECIES	SEASON AT RISK	SEX AT RISK	AT RISK FROM	NUMBER AFFECTED	REFERENCE
Black	Breeding	Both sexes	Domestic longline fishery, New Zealand.	Unknown	
Westland	Breeding	Both sexes	Hoki fisheries, New Zealand.	Few	Freeman et al 1997; Freeman 1998a, b; Freeman & Smith 1998.
White-chinned	Breeding	Unknown	South Georgia.	2301 p.a.	Dalziell & Porter 1993.
White-chinned	Breeding and non-breeding	Unknown	Domestic bottom trawling, South Africa.	Unknown	Barnes et al. 1996; Robertson 2000.
Spectacled	Breeding and non-breeding	Both sexes	Domestic long-line fishery.	200 p.a.	In Ryan 1998.
Grey	Breeding	Females	New Zealand water. SBFT long-lines.	160 in 1999	Bartle 1990; C.J.R. Robertson pers. comm.

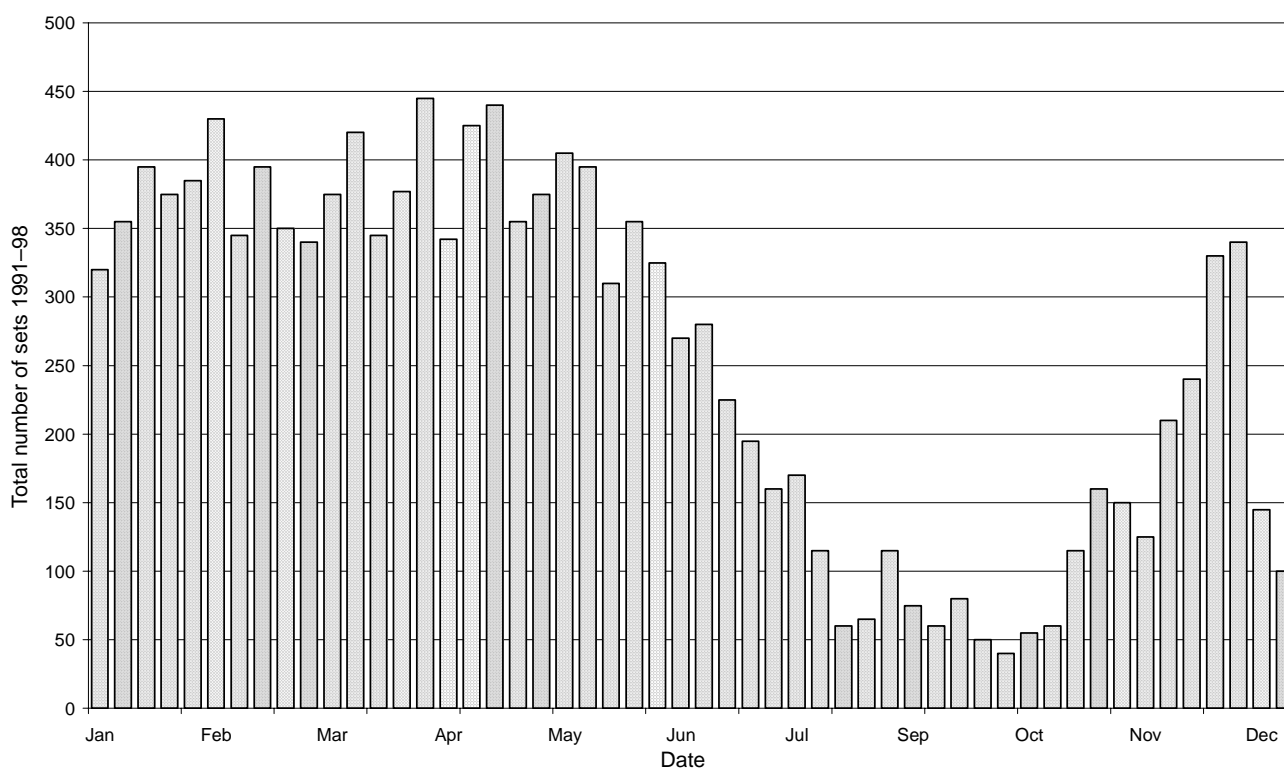


Figure 9. Frequency of domestic longline setting operations during the year. Figures shown are for weekly intervals pooled across all seasons during the period 1991-98. Provided by the Ministry of Fisheries and the National Institute of Water and Atmospheric Research Ltd (NIWA).

5. Critique of research programme

5.1 ESTABLISHING THE STATUS OF THE GREAT BARRIER ISLAND BLACK PETREL POPULATION

Our modelling suggests that with a λ of 0.9720 (906-1.038; 95% CI) it is likely that the black petrel population on Great Barrier Island is declining. However, several potential biases exist in our estimate of population growth rate. Undetected movement of breeding birds between burrows may mean we have underestimated breeder survival, overestimated skipping, and therefore underestimated population growth rate. What little data is available on age of first breeding for black petrels suggests this may be slightly lower than the mean age of first breeding for Cory's shearwater. Using data from Cory's shearwater to estimate this parameter may have negatively biased our estimate of population growth rate. Juvenile and pre-breeder survival rates are still largely unknown and the estimates we used may have negatively or positively biased our population growth estimate. However, with the exception of breeder survival, the effect of these biases is not likely to be large. Altering these parameters in combination; halving the skipping rate, reducing mean age of first breeding to 7.8 and increasing juvenile survival to 0.87 would be required to predict a population growth rate of 1.00.

Breeder survival was the single most important factor affecting population growth rate. Comparative data on adult survival for other *Procellaria* species do not exist. However, our estimate was much lower (0.880) than estimated adult survival for Cory's shearwater (0.956) and adult survival expected for a petrel of this size. Published estimates of breeder survival for the *Procellaria*, when plotted against the natural log of body weight, suggest that the survival rate for an adult petrel weighing 750 grams should be about 0.91 (H. Moller unpubl. analyses). Our estimate for black petrels suggests that either some external influence, such as by-catch, is increasing adult mortality or that our estimate of breeder survival is negatively biased. The reduction of breeder survival by some external influence is suggested by a relatively high amount of movement between burrows for birds whose partners have not been re-caught and are presumed to have died (Appendix 2).

The estimate of population growth obtained from a model such as the one we use here can be compared with one that comes directly from mark-recapture data (Pradel 1996). However, as with breeder survival, reliable estimates will require several more years of data.

5.2 IMPROVING DEMOGRAPHIC PARAMETER ESTIMATES

5.2.1 Breeder survival and skipping rates

A biased estimate of breeder survival would have a large impact on the estimate and precision of population growth rate. This is supported by the high sensitivity, elasticity and uncertainty rankings for this parameter and results of the power analysis. Using an adult survival rate of 0.96 as estimated for Cory's shearwater, with all other parameters set at their mean values (Table 8), increases predicted population growth rate to 1.02.

Improving the reliability and precision of breeder survival estimates can be achieved by continued recapture and banding of birds from breeding burrows. Significant improvements in the ability to estimate population growth may be achieved with as little as five additional seasons of data. Continuing to characterise birds as breeding or non-breeding and banded on the surface or in a burrow will help to improve the accuracy of estimates and may allow separate estimates of non-breeder survival in the future. The power analysis suggests that a similar level of precision in breeder survival estimates (and therefore in population growth rate) can be achieved with only half the capture rate. If there is an approximately linear relationship between capture rate and effort, this implies that monitoring half the study burrows would allow additional time to be spent collecting data for other parameters such as pre-breeder survival. Capturing primarily birds in burrows has led to the current high capture rate; devoting more effort to finding birds on the surface, will naturally lead to a decline in the overall capture rate.

Current estimates for non-breeders are likely to be biased because of the low number of recaptures. Additional banding and recapture of birds on the surface or at take-off rocks will probably be required to achieve a reasonable number of recaptures of non-breeding birds. For many procellariiformes, non-breeders and pre-breeders are more prevalent and there is more general activity of birds on the surface early in the season. Increasing the banding effort of surface birds may therefore require an earlier trip in October or November. The preliminary model we have used assumes that non-breeder survival is the same as for breeders: more data are required to check this assumption.

Populations of long-lived species such as black petrels are often slow to respond to external perturbations. Although changes in adult survival are expected to have a significant impact on the population, the immediate noticeable effects of this may be moderated by the presence of non-breeders or pre-breeders in the population. If a high proportion of non-breeders or pre-breeders are present, breeders lost to the population may be quickly replaced the next season. This would be manifest as a change in the ratio of non-breeding to breeding birds rather than as a lower density or occupancy of breeding birds. An additional advantage of increasing the effort in banding surface birds would be the ability to estimate the ratio of non-breeding to breeding birds.

Movement of breeding birds between burrows will negatively bias breeder survival estimates if undetected. The relatively high degree of movement detected, even though study burrows are not consolidated in one area, suggests that a significant amount of additional undetected movement may also be occurring. Movements of greater than 200 m have been recorded and females are especially prone to large-scale movements (E. Bell pers. comm.). If

additional study burrows are established we recommend they be concentrated in specific areas, as has been recently done on the census grids, to increase the chance of detecting movement of birds between burrows (see Section 5.2.6).

Our estimate of skipping rate is reliant on the assumption that our estimate of breeder survival is unbiased and that no movement of breeding birds occurs between burrows. Skipping rates are likely to be biased low if breeder survival is underestimated. On the other hand, movement will lead to skipping rate being overestimated. Skipping rates could be estimated independently of survival rates by fitting a multi-state mark-recapture model to the banding data. As noted in Section 2.2.1, the extra complexity of this option may be warranted in the future when additional data are available.

5.2.2 Juvenile and pre-breeder survival and age of first breeding

Currently, there are no available data on juvenile or pre-breeder survival or age of first breeding. Our results for these parameters are therefore dependent on the assumptions we have used to estimate them. Our estimates for juvenile survival are very similar to juvenile survival estimated for Cory's shearwater (28.8% to year one then 95.6% in subsequent years = 25.2% to 4 years; Moughin et al. 1987). If our estimate for breeder survival is negatively biased, setting pre-breeder survival equal to this may also have negatively biased pre-breeder survival. However, we have no measure of whether setting pre-breeder survival equal to breeder survival is a valid assumption, even if our breeder survival estimate is not biased. Both juvenile survival and pre-breeder survival were relatively important in predicting population growth rate. Some effort should therefore go into estimating these parameters for black petrels. As these birds are less likely to be present in burrows this will also probably require additional banding and recapture of birds on the surface or at take-off rocks. As stated above, this may need to be done earlier in the season when birds are more active on the surface.

Age of first breeding for Cory's shearwater appears to be slightly higher than for black petrels. By using data for Cory's shearwater we may therefore have underestimated population growth rate. However, this is unlikely to affect our results for the sensitivity or power analyses, as the mean and variance of stage duration had little effect on the estimate or confidence interval for population growth rate. The high amount of effort and long-term commitment required to estimate age of first breeding and the small effect on the model results suggest this parameter need not be a focus of future monitoring effort.

5.2.3 Emigration and immigration

Emigration of pre-breeders from the main colony (Mt. Hobson) to the smaller colonies may occur. Most procellariidae exhibit high site fidelity once they have begun breeding, so this is most likely to occur at the pre-breeder stage. However, emigration of pre-breeders would probably not be distinguishable from mortality unless additional colonies were monitored and would therefore be included in estimates of pre-breeder survival rates. Emigration is thus not likely to be important unless future modelling incorporates dynamics of the smaller colonies. Immigration to the large colony may also occur if black petrels are attracted to the higher levels of vocalisations and activity.

5.2.4 Breeding success

Breeding success is arguably the easiest demographic parameter to measure but is relatively unimportant for demographic modelling. The high emphasis currently placed on monitoring breeding success could be reduced by focusing on this parameter in alternate, or even less frequent, years. This would allow monitoring effort and timing to be focused around other parameters such as adult or pre-breeder survival.

Breeding success estimates are high in comparison to previous studies (Table 3). Imber recorded a breeding success of 50% and 60% in 1977 and 1978 respectively, and Scofield recorded 62% in 1989 (Imber 1987; Scofield 1989). Breeding failure is more prevalent during the incubation than the chick-rearing period (P. Scofield unpubl. data). Current monitoring effort is focused between late incubation/early hatching and fledging. Not monitoring burrows early in the incubation stage may potentially result in overestimating breeding success by missing breeding attempts that fail early in the season. This is likely if eggs are ejected or buried after breeding failure and are thus unlikely to be found. In seasons when breeding success is monitored, the initial check of burrows should be as soon after egg laying is completed as possible. This may require several short trips in November and December as laying is spread over about eight weeks but would minimise the potential to overestimate breeding success. There is a greater risk of abandonment during the incubation period so although the occupancy of burrows could be checked with minimal disturbance, it may not be appropriate to remove and band adults during at this time. To check the effect of overestimating breeding success, we recalculated both the population growth rate and the sensitivity coefficients with the estimate of breeding success set at half its currently estimated value (Table 8; 0.397 c.f. 0.20). This led to an estimate of population growth of 0.941, a decrease of 0.031. The sensitivity coefficient for breeding success increased, while that for juvenile survival decreased to approximately the same value.

Given the relatively high breeding success of black petrel nests in the current monitoring study, monitoring the fate of nests throughout the breeding season to determine the causes of failure is probably unnecessary. This will be important only if high levels of failure are observed in the future and the causes need to be identified to assess appropriate management responses.

5.2.5 Stratification of study burrows

The study burrows are currently widely distributed around the track system. Concentrating future monitoring on burrows in defined areas or blocks, as has recently been done on the census grids, will help to reduce errors due to movement of birds between burrows and will allow measures of spatial variation among areas to be estimated. This would also reduce positive biases in estimates of occupancy and breeding success resulting from establishing the initial study burrows on occupied nests. Establishing the majority of study burrows on successful, occupied nests may explain the higher occupancy of burrows in the current monitoring effort (3:1 occupied to unoccupied) than found in previous studies (1:1 occupied to unoccupied; Imber 1987; Scofield 1989).

The current study is entirely focused on the main colony at Mt. Hobson. This seems to be the most efficient way to establish baseline data on black petrel demography. However, burrow density, predation levels or age structure may differ between the colonies, resulting in differences in demographic parameter values. Extrapolation to areas other than Mt. Hobson will require additional work in some of the smaller colonies.

If the current census grids are to be useful for population estimates, the area to which the density and occupancy estimates are applied needs to be more clearly defined and may need to be stratified by vegetation or other environmental variables. The variation in burrow numbers among census grids (4-22 in 1999) shows that simple extrapolation to the entire 30-ha area of Mt. Hobson above 300 m will result in a large error. However, it seems that the utility of these census grids may lie more in monitoring relative changes in density and occupancy of burrows over time, not in absolute estimates of population size. They are clearly useful for estimating spatial variation among areas and could be used to track changes over time without requiring annual monitoring.

5.2.6 Monitoring predation levels

Loss of eggs or chicks due to rat predation has been relatively low for the past two breeding seasons and even with a relatively high level of rat predation in 1997 breeding success was reasonably high. The purpose of the rat index lines in the current monitoring effort is unclear. Egg or chick predation by rats can be determined without knowing the relative abundance of rats. Determining whether a correlation exists between the relative abundance of rats and rat predation of eggs or chicks does not seem to add much to our understanding of these populations. It seems that the effort put into these index lines would be more effectively directed elsewhere.

Cat predation presents a much greater potential threat to black petrels than predation by rats (Imber 1987; van Rensburg & Bester 1988; Cooper et al. 1995). Larger numbers of birds may be taken in a short time and feral cats are capable of taking large chicks and adults, so could have a much greater impact on the population. Cat sign should be monitored within the study area and trapping or the use of poison baits laid off the track should be investigated as cats are present within the colony during the breeding season (E. Bell pers. comm.)

5.3 ASSESSING INTERACTIONS BETWEEN BLACK PETRELS AND LONGLINE FISHERIES

Small numbers of black petrels have been taken by longline fishing vessels (Table 11) but the extent of interactions between black petrels and longline vessels remains largely unknown. The current monitoring program for black petrels does not address the issues of whether, how and how intensively black petrels interact with longline fisheries.

Changes in by-catch levels may be inferred from survival rates but small changes are likely to be within estimated error limits and go undetected, even though they may still impact on the population. No historical data is available to serve as a baseline comparison. Assessing the extent of these interactions will require

evaluation of the spatial distribution of both longline fishing vessels and black petrel foraging grounds. Whilst it is beyond the scope of this report to design a research program to address these issues we would like to point out some important considerations if future work is to be directed towards modelling the demographic consequences of fisheries by-catch on black petrel populations.

The first step in determining the extent of interactions between black petrels and longline fisheries is to determine the timing and spatial distribution of each at sea. Probably the only way to obtain reliable data for distribution of the birds at sea will be to use satellite telemetry. Information will be needed on where the birds are going, how consistent they are, and whether these patterns change over the season. Some knowledge of where the birds are foraging will enable monitoring of fisheries vessels to be more focused.

The timing of interactions is also likely to be important. Murray et al. (1993) report that more grey petrels are caught at night than during the day by longline fishing vessels. Duckworth (1998) also notes that mutton-birds (i.e. dark petrels and shearwaters) were only caught during night sets on tuna longlines. Night sets are specifically required by the fisheries management authorities to prevent albatross mortality but this mitigation technique may inadvertently lead to higher levels of shearwater and *Procellaria* mortality. The depth to which black petrels dive may also be important in determining the type of interactions that occur, such as the response of black petrels to different baits and line setting practices and for delineating mitigation procedures.

Demographic models usually only involve females (as here) and assume that demographic rates are the same for the two sexes. There is evidence, for at least some species of *Procellaria*, that by-catch rates are higher for females than males. Bartle (1990) reports higher mortality of female than male grey petrels on New Zealand longline fishing vessels. He suggests this may be due to differences in foraging strategies between the sexes and may also apply to other *Procellaria* species. Higher mortality rates for females compared with males has also been reported for Westland petrels, although it is not known if this is the result of by-catch mortality. Differential mortality between the sexes could have significant demographic consequences, especially for species with relatively small populations such as black petrels. The ratio of female to male *Procellaria* washed up on New Zealand beaches may be useful for quantifying differential mortality between the sexes or for observing large changes in mortality rates (Powlesland 1989). Accurate morphometric sexing methods have been established for black petrel (Scofield 1989). Simple and cheap DNA sexing from feathers is also available (D. Lambert pers. comm.). Either of these techniques could be used establish the sex of breeding birds to allow separate survival estimates for males and females. The sex ratio of non-breeders present in the population could also be investigated.

6. Conclusions and recommendations

If monitoring of black petrel populations is continued to establish the status of the population we recommend:

1. Improving estimates of breeder survival by:
 - continuing to monitor and band birds in breeding burrows,
 - monitoring movements of breeding pairs among burrows,
 - increasing banding and recapture effort at take-off sites.
2. Obtaining preliminary estimates of pre-breeder survival by continuing to band fledglings and recapturing bird earlier in the season on the surface or at take-off rocks.

If monitoring of black petrels is continued to establish the extent of interactions with longline fisheries we recommend:

3. Reviewing the evidence for interactions between black petrels and longline fisheries to assess whether the likelihood of by-catch is low or high;
4. Establishing a satellite tracking program to determine foraging distribution of black petrels;
5. Determining the distribution of longline fishery vessels during the black petrel breeding season.

Determining the impact of fisheries by-catch on black petrel populations will require improvements in both estimates of population status and the extent of interactions with fisheries.

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Appendix 1

ESTIMATING SKIPPING RATE

We estimated the probability that a breeding burrow was unoccupied given that it was occupied in the previous year, for both 1998 and 1999. These estimates were 29.6% (SE = 4.8%) and 49.1% (SE = 5.6%) respectively.

An occupied burrow may become unoccupied in the following year because

1. one or more of the pair died;
2. the pair moved to another burrow;
3. the pair skipped breeding.

If we assume no movement between burrows (see Section 2.2.1), one that is occupied becomes unoccupied if either a) both birds survive and they skip breeding or b) at least one of them dies. The probability (p) of an occupied burrow becoming unoccupied can therefore be written as

$$p = BR_{surv}^2 BR_{skip} + (1 - BR_{surv}^2)$$

where BR_{surv} is breeder survival and BR_{skip} is the probability of breeders skipping. Note that this expression also involves the assumption that the birds survive independently.

An estimate of skipping rate is therefore given by

$$BR_{skip} = 1 - \frac{1 - p}{BR_{surv}^2}$$

A standard error for this estimate can be derived using the ‘delta’ method (Kotz & Johnson 1988), and is given by

$$SE(BR_{skip}) = (1 - BR_{skip}) \sqrt{\left\{ \frac{SE(p)}{1 - p} \right\}^2 + \left\{ \frac{2BR_{surv} SE(BR_{surv})}{BR_{surv}^2} \right\}^2}$$

These equations gave estimates of skipping rate of 9.1% (SE = 12.0%) and 34.2% (SE = 10.4%) for 1998 and 1999 respectively.

SENSITIVITY AND ELASTICITY COEFFICIENTS

We calculated the sensitivity coefficient (s_θ) for parameter θ as the first derivative of population growth rate (λ) with respect to that parameter (Tomovic 1963; Caswell 1978; Caswell 1989):

$$s_\theta = \frac{\partial \lambda}{\partial \theta} = \sum_{i,j} \frac{\partial \lambda}{\partial a_{ij}} \frac{\partial a_{ij}}{\partial \theta} \quad \text{where} \quad \frac{\partial \lambda}{\partial a_{ij}} = \frac{v_i w_j}{\langle \mathbf{w}, \mathbf{v} \rangle}$$

and a_{ij} is the element in the i th row and j th column of the transition matrix for the model. The terms v_i and w_i are the i th elements of the left and right eigenvectors of the transition matrix, respectively; $\langle w, v \rangle$ is the scalar product of these eigenvectors (Caswell 1989).

The elasticity coefficient (e_θ) for parameter θ was calculated as:

$$e_\theta = \frac{\theta}{\lambda} s_\theta$$

The uncertainty coefficient (u_θ) for parameter θ was calculated as the absolute change in the predicted population growth rate when the lower and upper 95% confidence limits (θ_L, θ_U) for that parameter were used in the model, divided by the predicted population growth rate when that parameter was set at its estimated value (θ_{Est}) (Hunter et al. 2000):

$$u_\theta = \frac{|\lambda(\theta_L) - \lambda(\theta_U)|}{\lambda(\theta_{Est})}$$

In calculating u_θ all the other parameters were set at their estimated values.

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Appendix 2

LOCATION OF BLACK PETRELS RECORDED IN MORE THAN ONE BURROW. BURROWS MARKED IN BOLD WERE USED FOR BREEDING

BAND	BURROW BIRD RECORDED PRESENT IN					NOTES
	1996	1997	1998	1999	2000	
23635			120	120	55	Very close burrows—approximately 2 m apart (in PTG1), Probable H31042 died 98/99.
25450				156	191	Burrows approximately 10 m apart (both in PTG2), breeding failed in 1999.
25506				160	42	Burrows at least 200 m apart, one on SF track towards summit and other down Shortcut.
25509				185	227	Burrows directly next to each other, have same entrance, one chamber to north and one to the south (both breeding attempts failed).
30859	29	29	29	19	19	Burrow 29 flooded in 1999, burrow 19 approximately 50-75 m away.
30866	68	68	68		102	burrows approximately 5 m apart (in KDG1), breeding not successful in 2000.
H30877	109		opposite 10			Burrows approximately 5 m apart, also non-breeding in new (non-study) burrow.
30884	53	53		53	54	H30884, H31021 and H31022 all changing between burrows 53 and 54 (1 m apart), not sure which birds are parents of chick in 1999 as H31022 may have been forced into 54 (or that may be the case in 2000 where H30884 forced into 54), prob. H21021 and H20122 are parents as they were together in 1998 and 2000—could be fight in 1999.
31011			32	96	96	Burrows approximately 5 m apart (in PTG1), breeding not successful in 1999.
31012			169		83	Burrows approximately 5 m apart.
31022			53	54	53	See comment for H30884.
31027			112		238	Burrows share internal wall, entrances only 1-2 m apart.
31034			96		60	Burrows approximately 10 m apart (in PTG1), breeding not successful in 2000.
31051			96		122	Burrows approximately 10 m apart (in PTG1).
31102		74	74	78	78	Burrows approximately 3 m apart (in KDG1).
31110		39		171	171	Burrows approximately 10 m apart, possibly also in 171 in 1998 (chick raised).
31117		45	45	45	23	Burrows approximately 2-3 m apart, breeding failed in 1998 (dead embryo) and 1999 (rat predation), parents moved to 23 at end of 1999 season and attempted breeding in 2000 (died pipping).
31128		84		127	127	Burrows approximately 200 m apart, was an interloper in 84 in 1998—caused breeding failure (crushed egg) of resident pair, failed breeding in 1999 (infertile).
31134		106		20		Burrows approximately 10 m apart.

APPENDIX 2 continued

BAND	BURROW BIRD RECORDED PRESENT IN					NOTES
	1996	1997	1998	1999	2000	
31136		57	57	57	166	Burrows approximately 20 m apart, still with egg in 2000.
31137		58			207	Burrows approximately 10 m apart (in PTG1).
31142		24	24	24	114	Burrows approximately 50 m apart, breeding unsuccessful in 1997 (abandoned), 1998 (dead embryo) and 1999 (infertile), now raised chick in 2000.
31143		43			173	Burrows 3 m apart, may have been in 173 in 1999 (chick raised), Partner probably died (H31116).
31157		45	45	45	23	See comment for H 31117.
31161		115	5		5	Burrows approximately 10 m apart, probably present in 5 in 1999 also (chick raised).
H31172		103		68	68	Burrows approximately 3 m apart (in KDG1).
31205		96	58	58		Burrows approximately 10 m apart (in PTG1), breeding unsuccessful in 1999 (dead chick), probably present in 2000 (raised chick).
31210		old 2			29	Burrows approximately 50 m apart, old 2 destroyed in slip 98/99, moved to 29 in 2000.
31219		58			157	Burrows approximately 50 m apart, probably raised chick in 1999 in 157 as well as this year.
31246		60	60	123	123	Burrows approximately 4 m apart, partner probably died (H28584) 98/99.
31259		112	86	86	87	Burrows 112 and 86 approximately 4 m apart, burrow 86 and 87 approx 20 m apart, breeding failed 1997 (rat predation (pair already moved into 86 at end of 1997 season), partner probably died (H27678) 99/2000, female moved to 87.
31268		5		100	100	Burrows approximately 20 m apart, partner probably died (H31207) 98/99, female moved to 100.
31287		15	15	96	96	Burrows approximately 40 m apart, partner probably died (H31245) 97/98 (chick died of starvation—partner never returned, female sat on egg and little chick for 22 straight days before leaving to feed, returned after chick had already died (four days later), female moved to 96, breeding failed 1999 (rat predation).

Appendix 3

SELECTED LITERATURE REFERENCES RELEVANT TO *Procellaria* TAXONOMY AND BIOLOGY NOT CITED IN THIS REPORT

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