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Biological Conservation 123 (2005) 151–163
BIOLOGICAL CONSERVATION
www.elsevier.com/locate/biocon

Estimating incidental takes of shearwaters in driftnet fisheries: lessons for the conservation of seabirds

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Received 30 June 2004

Abstract

We consider estimation of the magnitude of incidental fisheries 'bycatch' for two petrel species, sooty shearwaters (*Puffinus griseus*) and short-tailed shearwaters (*Puffinus tenuirostris*). There are clear statistical advantages in estimating bycatch for abundant species such as these, and our results may also guide the conservation and management of rarer species. We used fisheries statistics and observer data to estimate retrospectively the total numbers of sooty and short-tailed shearwaters bycatch in seven large-scale pelagic North Pacific driftnet fisheries between 1952 and 2001. Sensitivity analysis greatly simplified estimation of uncertainty by identifying four driftnet fisheries to be of particular importance in determining the magnitude and precision of the estimated bycatch totals. We estimated that between 1.0 and 12.8 million (95% CI) sooty shearwaters were killed by driftnets between 1952 and 2001. For short-tailed shearwaters we estimated between 4.6 and 21.2 million (95% CI) over the same period. More precise estimation was hampered by the paucity of available observer data, lack of reported detail and inconsistencies among data sources. Estimates may be strongly biased because some dead birds are misidentified or drop out of nets before hauling, or because some records were of live captures that were subsequently released. Improved estimation of overall take and its impact on populations of seabirds requires standardisation of reporting, allowance for potential sampling bias, as well as a clearer definition of the sampling unit and underlying bycatch probability distribution model, and knowledge of potential compensatory changes in population parameters.

Keywords: Shearwater; Fisheries bycatch; Sensitivity; Uncertainty; Demographic compensation

1. Introduction

Studies of the impact of fisheries bycatch on seabird populations have mainly focused on rare species, such as the wandering albatross (*Diomedea exulans*) (Weimerskirch and Jouventin, 1987, 1998; Tuck et al., 2001) and Amsterdam albatross (*Diomedea amsterdamensis*) (Weimerskirch et al., 1997; Inchausti and Weimerskirch, 2001). The extent and effects of fisheries bycatch on more abundant species like sooty ('muttonbird', tītī, *Puffinus griseus*) and short-tailed shearwaters ('Tasmanian muttonbird', yolla, *Puffinus tenuirostris*) are less well studied. Numerous records of sooty and short-tailed shearwater bycatch numbers in North Pacific driftnet fisheries have been published (e.g. Warham et al., 1982; King, 1984; International North Pacific Fisheries Commission, 1991; Northridge, 1991; DeGange et al., 1993; Ogi et al., 1993; Artyukhin and Burkanov, 2000), but overall mortalities with confidence limits have never been estimated thoroughly. Estimation of the numbers killed of these two very abundant species is the

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doi:10.1016/j.biocon.2004.11.003

first step in assessing demographic impacts and eventually could guide management interventions and risk assessment for rarer species.

Sooty shearwater chicks are harvested by Rakiura Māori, the southernmost indigenous people of New Zealand, from their main breeding grounds on the Tītī Islands around Rakiura (Stewart Island), New Zealand (Taiepa et al., 1997; Lyver and Moller, 1999; Moller et al., 2000b). Aborigines and commercial operators harvest short-tailed shearwater chicks in Tasmania, Australia (Skira, 1990). These harvests are culturally and economically important for the participants, but may become unsustainable if sooty and short-tailed shearwater population demographics are affected by high rates of additional mortality from fisheries bycatch. Any changes in shearwater abundance could have profound effects on breeding island ecology, because sooty and short-tailed shearwaters are a keystone species that impact on soil aeration, nutrification and plant regeneration (Moller et al., 2000a; Hawke and Newman, 2004). Thus, there is an urgent need to investigate the impact of fisheries bycatch on the harvested population of shearwaters. This is especially true for sooty shearwater in New Zealand, where chick harvests and populations have been declining (Lyver et al., 1999; Jones, 2002; Scofield and Christie, 2002).

Sooty and short-tailed shearwaters are congeneric species and are long-lived, late-maturing and slow-reproducers. Both species depart from their breeding grounds in austral autumn and overwinter in oceanic regions of the northern hemisphere (Warham, 1990; Skira, 1991; Everett and Pitman, 1993). Between May and September 1952–1993 some of these areas overlapped with fishing grounds of major Asian North Pacific driftnet fisheries (Uhlmann, 2001). Sooty and short-tailed shearwaters are proficient pursuit diving seabirds (Weimerskirch and Sagar, 1996; Weimerskirch and Cherel, 1998) and are particularly vulnerable to accidental entanglement in sub-surface driftnets when they seize fish and other prey species already caught in the nets.

Independent observers stationed on some driftnet fishing vessels have reported characteristics of the catch in terms of size, weight and number of non-target species caught (Fitzgerald et al., 1993). Numbers of bycatch mortalities of sooty and short-tailed shearwaters were observed in the thousands in a single driftnet fishery in 1990 (Johnson et al., 1993; Ogi et al., 1993). Here we provide the first estimate of total bycatch of sooty and short-tailed shearwaters in all driftnet fisheries for the period 1952–2001, together with confidence limits. We do this by reconstructing fishing effort and bycatch data for seven large-scale North Pacific driftnet fisheries. A sensitivity analysis is used to quantify the relative importance of fisheries statistics that most influence both the estimate of total mortality and the uncertainty of this estimate. We use this case study of bycatch of two abundant procellariiforms to outline general lessons for improving the accuracy and precision of future bycatch estimates for a variety of seabird species.

2. Methods

2.1. Building a database from the literature

Records of sooty and short-tailed shearwater mortalities in fisheries were found by first reviewing the migration patterns of the two shearwaters to identify all the fisheries in the birds' path. We then systematically searched library databases and networked with seabird biologists, fisheries managers and conservationists for evidence of bycatch. Altogether 20 of 29 reviewed fisheries incidentally caught these two shearwater species (Uhlmann, 2003). The first simplification of the analysis for this paper was to focus our estimation efforts on the seven North Pacific driftnet fisheries where observed annual mortalities of both sooty and short-tailed shearwaters were at least 10^2 times higher than for any other of the reviewed fisheries. These seven driftnet fisheries were: Japanese tuna large mesh; Japanese salmon land-based; Japanese salmon mothership; Japanese salmon in Russia; Japanese, Korean and Taiwanese squid (Table 1).

Complete records of effort and bycatch for entire periods of active fishing were not available for any of these driftnet fisheries. Therefore, we had to reconstruct missing data by drawing upon information from several sources for the Japanese squid (Gjernes et al., 1990; Johnson et al., 1993; Yatsu et al., 1993), Taiwanese squid (Northridge, 1991; Johnson et al., 1993; Ogi et al., 1993), Korean squid (Gong et al., 1993; Johnson et al., 1993), Japanese land-based salmon (DeGange and Day, 1991; Northridge, 1991; Ogi et al., 1993), Japanese mothership salmon (DeGange et al., 1985; Northridge, 1991) and Japanese salmon in Russia (Artyukhin and Burkanov, 2000) driftnet fisheries.

2.2. Problems with incomplete species identification

Reported bycatch data on sooty and short-tailed shearwaters may not be accurate because fisheries observers often had difficulties in distinguishing these two species in the field and simply recorded both sooty and short-tailed as 'dark shearwaters'.

To obtain an estimate of the actual numbers of sooty shearwaters taken we assumed that the proportion of observed, unidentified dark shearwaters that were sooty shearwaters was the same as the ratio of sooty shearwaters to short-tailed shearwaters in the positively identified groups. This involved the assumption that the probability of classifying a bird as a dark shearwater was the same for sooty and short-tailed shearwaters.

Table 1
General locations, fishing seasons and gear dimensions of Japanese tuna large mesh (JLAMFD), Japanese salmon land-based (JLBSFD); Japanese salmon mothership (JMOSFD), Japanese salmon in Russia (JSFDR), Japanese, Korean and Taiwanese squid driftnet fisheries (JSQFD, KSQFD, TSQFD, respectively)

Source[a]	Fishery	Period of active fishing	Fishing latitude	Area longitude	Fishing season	Length of a net panel (m)	Setting depth (m)	Mesh size (mm)	Number of panels/section	Section length (km)	Number of sections/set	Total length (km)
1, 3	JLAMFD	1970–1991	10–46°N	145°E–145°W	January–May, year-round	32–54	6–13	151–210	96–167	3–5	8–10	30–50
2, 6	JLBSFD	1952–1988	38–44°N	155°E–174°E	May–July	30, 37.5, 47.5	8	110–115	–	–	–	13–15
4, 6	JMOSFD	1952–1988	46–58°N	155°E–175°E	Mid-May–late July	50	8	121,130	330	–	–	15–17
8	JSFDR	1991-today	40–60°N	150°E–170°E	Mid-May–late July	50	8	124–130	–	⩽4	⩽8	⩽32
3, 4, 7	JSQFD	1978–1991	20–46°N	170°E–155°W	May–December	30–52	6–12	105–135	100–180	⩽6	8–10	20–62
3, 4, 5	KSQFD	1979–1991	36–46°N	141°E–170°W	April–December	50	8–12	76–115	150–200	⩽10	5–6	38–88
3, 4	TSQFD	1980–1991	38°–44°N	156°E–166°W	May–December	15–40	9–20	76–110	250–667	⩽10	3–4	12–41

[a] 1, Nakano et al., 1993; 2, DeGange and Day, 1991; 3, Fitzgerald et al., 1993; 4, Jones and DeGange, 1988; 5, Gong et al., 1993; 6, DeGange et al., 1985; 7, Yatsu et al., 1993; 8, Artyukhin and Burkanov, 2000.

2.3. Divergent units of replication, gaps in information and a lack of error estimates

A major challenge for estimating total bycatch is to fill gaps in the fishing records. Many fisheries only presented data for one or a few years, and some provided only effort measures or only total catches for those years. Some reported catches for individual sets of the nets, others for voyages, others aggregated totals for seasons. Some provided a range of capture totals, others just a mean. Apart from DeGange et al. (1985) and Johnson et al. (1993) none of the reports provided a formal error estimate on shearwater bycatch rates or evidence of the shape of the underlying probability distribution in catch effort or catch rate to evaluate the validity of the error estimates or to allow us to calculate our own estimate of uncertainty. Some fisheries used different definitions of catch effort or did not specify which unit applied to their data. For example, the size of 'tans' (one tan is a 50 m long, single panel of driftnet) or number of tans in a set was not always reported. This made it extremely difficult to suggest plausible estimates for the number of sooty and short-tailed shearwaters killed by the seven main fisheries in all the years they operated.

Typically a fishery only reported the observed number of sooty or short-tailed shearwater caught in a subset of years. We calculated the bycatch rate for each year (i) of observed fishing as

$$r_i = x_i/u_i, \tag{1}$$

where x_i is the number of observed shearwaters caught in the ith year of observed fishing and u_i is numbers of tans observed in that fishery in the same year.

Estimates of total (observed plus unobserved) effort for all years (n) of active fishing $u'_1, u'_2, \ldots, u'_n$ were then used to estimate the total bycatch of sooty and short-tailed shearwater (N) for that fishery as

$$N = r(u'_1 + u'_2 + \cdots + u'_n), \tag{2}$$

where r is the mean value of r_i over those years which were observed.

Where published estimates of overall mortalities were derived from the same bycatch rate, the coefficient of variation (CV = standard error/estimate) reported for estimates of bycatch totals were also used for estimates of bycatch rates. If values of bycatch rates for the same fisheries and the same fishing season were available from different sources, or for a number of years, we calculated their mean and standard error (SE).

If accurate information on total fishing effort was unknown or missing for some time period, we chose plausible bounds for the gaps by (i) assuming trends observed before or after the gap years applied during the gap, (ii) extrapolation from the number of observers reported for those years (assuming no change in overall degree of observer coverage), (iii) predicting catch effort

from reports of weight of fish landed for the missing years, or (iv) assuming that equipment and catch rates were the same as for a similar fishery operating at that time. Nevertheless we were forced to assign a somewhat arbitrary range for some fisheries and years when none of these other data were available. In such cases, we specified the uncertainty via a uniform distribution between plausible bounds (detailed in Uhlmann, 2001, Appendix A) that specified the minimum (x) and maximum (y) effort each year. For example 4.7 million tans were deployed in the Japanese large-mesh driftnet fishery in 1990 (Nakano et al., 1993), but no information whatever could be found for the 1973–1989 period. In comparing the Japanese large-mesh fishery with similar driftnet fisheries we assigned a minimum of 1 million tans (as a best estimate of the size of the incipient fishery), and a maximum of 7 million to allow for the possibility that the fishery peaked above the 1990 level in earlier years. We chose extremely broad limits for these bounds so as to be reasonably sure to encompass the plausible actual rates for the missing data. In terms of uncertainty, this choice of distribution was equivalent to having data on effort for which the mean was $(x + y)/2$, with a SE of $(y - x)/\sqrt{12}$ (Kotz and Johnson, 1982–1989).

The initial estimation of the total magnitude of sooty and short-tailed shearwater bycatch for the seven driftnet fisheries combined annual estimates from 1952 to 2001 (Table 2). The time series falls into three distinct periods defined by the entry and exit of the fisheries: (i) before squid driftnetting (1952–1977), (ii) during squid driftnetting (1978–1990) and (iii) after squid driftnetting (1991–2001).

2.4. Sensitivity and uncertainty analyses

In view of the large number of assumptions made to fill data gaps to initially estimate mean and SE in bycatch (Table 2), we placed considerable emphasis on a subsequent 'sensitivity analysis' (Caswell, 2000; de Kroon et al., 2000) to estimate the effects of changes in "input parameters" on our results (Tables 3 and 4). Specifically, we were interested in how changes in the estimates and SE of both bycatch rates and total fishing effort of each driftnet fishery would change (i) the total estimated number of sooty and short-tailed shearwaters killed in three historical periods (1952–1977; 1978–1990; 1991–2001) and (ii) the uncertainty around these estimates.

Our analysis employed two distinct approaches: (a) a sensitivity analysis to quantify the relative importance of each input parameter in determining (i) and (ii) outlined above, and (b) an uncertainty analysis where values between plausible upper and lower bounds of key input parameters were selected randomly using Monte Carlo simulation (Caswell et al., 1998) to provide confidence limits on bycatch estimates.

For the sensitivity analysis, we varied 28 different input parameters (Table 2) by +10% from their estimated value to measure their relative importance in determining total estimated numbers (and SE) of sooty and short-tailed shearwaters bycatch for each of the three time periods (Tables 3 and 4). We calculated the resulting percentage change in the estimate of total bycatch.

We then carried out an uncertainty analysis (Fig. 2) only for those input parameters first identified by the sensitivity analysis as having an order of magnitude

Table 2
Estimates, standard errors (SE) and coefficients of variation (CV) for the input parameters of fishing effort (number of standardised driftnet panel sections = no. of tans) and bycatch rates (number of birds caught per driftnet panel section = birds per tan) of sooty (SOSH) and short-tailed shearwaters (STSH) for seven different driftnet fisheries

	Fishery period	JLAMFD	JLBSFD	JMOSFD	JSFDR	JSQFD	KSQFD	TSQFD
		1973–1990	1953–1988	1952–1988	1990–2001	1978–1990	1980– 1990	1980–1990
Fishing effort (no. of tans)								
Total	Estimate	72,000,000	169,970,400	173,100,000	23,856,000	330,861,598	161, 493,380	92,045,600
	SE	7,348,469	5,058,405	23,746,603	200,000	8,336,087	0	5,454,910
	CV	10%	3%	14%	1%	3%	0%	6%
Mean	Estimate	4,000,000	4,721,400	4,678,378	1,988,000	25,450,892	14,681, 216	8,367,782
	SE	1,732,051	843,067	3,903,918	57,735	2,312,015	0	1,644,717
Bycatch rate (birds per tan)								
SOSH	Estimate	0.00075	0.04143	0.00021	0.00018	0.01100	0.00225	0. 00033
	SE	0.00006	0.03962	0.00002	0.00004	0.00377	0.00028	0.00017
	CV	8%	96%	10%	22%	34%	12%	52%
STSH	Estimate	0	0.02859	0.03888	0.03099	0.00055	0.00004	0.00003
	SE	0	0.00770	0.01233	0.00492	0.00019	0.00001	0.00002
	CV	0	27%	32%	16%	35%	25%	69%

See Table 1 for fisheries codes.

Table 3
Sensitivity analysis results showing the % increase in the total number of sooty (SOSH) and short-tailed shearwater (STSH) bycatch (*N*) when estimates of fishing effort and bycatch rate for each period were increased by 10%

Fishery	Estimate changed	Total bycatch *N* (%)						Parameter ranking					
		1952–1977		1978–1990		1991–2001		1952–1977		1978–1990		1991–2001	
		SOSH	STSH	SOSH	STSH	SOSH	STSH	SOSH	STSH	SOSH	STSH	SOSH	STSH
KSQFD	Effort			0.41	0.03					3	4		
	Bycatch			0.41	0.03					3	4		
TSQFD	Effort			0.03	0.01					5	5		
	Bycatch			0.03	0.01					5	5		
JSQFD	Effort			**7.97**	**1.52**					1	3		
	Bycatch			**7.97**	**1.52**					1	3		
JLBSFD	Effort	**9.92**	**4.07**	1.54	**4.03**			1	2	2	2		
	Bycatch	**9.92**	**4.07**	1.54	**4.03**			1	2	2	2		
JMOSFD	Effort	0.05	**5.93**	0.01	**4.40**			2	1	6	1		
	Bycatch	0.05	**5.93**	0.01	**4.40**			2	1	6	1		
JLAMFD	Effort	0.03		0.04				3		4			
	Bycatch	0.03		0.04				3		4			
JSFDR	Effort					**10.00**	**10.00**					1	1
	Bycatch					**10.00**	**10.00**					1	1

Blank cells indicate % changes less than 0.01%. Bold cells indicate which parameter caused the largest increase in the estimated total bycatch. See Table 1 for fisheries codes.

Table 4
Sensitivity analysis results showing the % increase in the standard error (SE) of the total number of sooty (SOSH) and short-tailed shearwater (STSH) bycatch (*N*) when estimated SE of fishing effort and bycatch rate for each period were increased by 10%

Fishery	SE changed	SE total bycatch *N* (%)						Parameter ranking					
		1952–1977		1978–1990		1991–2001		1952–1977		1978–1990		1991–2001	
		SOSH	STSH	SOSH	STSH	SOSH	STSH	SOSH	STSH	SOSH	STSH	SOSH	STSH
KSQFD	Bycatch			0.01						5			
JSQFD	Effort			**1.56**	0.01					2	6		
	Bycatch			0.48	0.02					3	5		
JLBSFD	Effort	0.59	0.20	0.47	0.28			2	4	4	4		
	Bycatch	**9.72**	0.48	**7.87**	0.68			1	3	1	3		
JMOSFD	Effort		**8.14**		**8.04**				1		1		
	Bycatch		2.12		**1.92**				2		2		
JSFDR	Effort					0.02	0.31					2	2
	Bycatch					**10.00**	**9.72**					1	1

Blank cells indicate % changes less than 0.01%. Bold cells indicate which parameter caused the largest increase in SE of total bycatch. See Table 1 for fisheries codes.

higher influence on outcomes than the remaining inputs (Tables 3 and 4). For this uncertainty analysis, we defined ecologically plausible parameter minima (x_{min}) and maxima (x_{max}) by including information from some sources/fisheries seasons and excluding information from others (Table 5, also refer to Uhlmann, 2001, Appendix B). This was done by (i) including some reported bycatch rates from different sources for the same fisheries while excluding others in order to consider potential measurement errors and/or lack of reported detail. The latter sometimes included competing ways of scaling inter-annual variability or trends to estimate gaps in data in slightly different ways than we used for our initial, median estimates in Table 2. For example, Ogi et al. (1993) reported an order of magnitude higher bycatch rate of sooty shearwaters than reported by DeGange and Day (1991) in the same Japanese salmon land-based fishery. In our initial estimation we averaged the two because inter-annual variation may indeed be very high and both studies may be reliable. The strength of the DeGange and Day (1991) analysis is that estimates are linked to commercial fishing effort and

Table 5
Uncertainty limits of fishing effort (number of standardised driftnet panel sections = no. of tans, in thousands) and bycatch rate (number of birds per driftnet panel = birds per tan) of sooty (SOSH) and short-tailed shearwaters (STSH) for the relevant driftnet fisheries

	Fishery	JSQFD		JLBSFD		JSFDR		JMOSFD	
		Min	Max	Min	Max	Min	Max	Min	Max
Fishing effort (no. of tans, in thousands)		7490	36,367	699	10,075	953	3087	300	9600
Bycatch rate (birds per tan)	SOSH	0	0.03793	0	0.03213	0	0.00913	–	–
	STSH	0	0.00369	0	0.02903	0.00286	0.06286	0.00360	0.09425

See Table 1 for fisheries codes.
Uncertainty limits of bycatch rate equal 95% CI, limits of fishing effort are absolute values.

its reliance on 11 years of information. Ogi et al. (1993) had only one year of data and their predictions of bycatch were not linked to commercial effort data. The alternative outcomes from including one source and not the other, or from including an average of the two, were therefore set up as alternative scenarios for the uncertainty analysis.

All the available observer information was derived from relatively short periods and so was inadequate for us to describe long-term fluctuations in annual or seasonal bycatch magnitude of each species. To allow for some variability, we assumed that (i) the proportion of sooty or short-tailed shearwater captures in the sample of dark shearwaters differed annually by the same amount as the proportions recorded by the subsample of observers that recorded separate totals for each species (DeGange and Day, 1991; DeGange et al., 1993; Johnson et al., 1993; Ogi et al., 1993; Artyukhin and Burkanov, 2000). These proportions ranged between 4% and 73% for sooty shearwaters in the Japanese land-based fisheries; 0% and 10% in the Japanese salmon driftnet fisheries in Russia, 0% and 2% in the Japanese mothership; and between 87% and 98% in the Japanese squid driftnet fishery.

In order to allow as much of the uncertainty as possible, we defined upper (L_U) and lower (L_L) limits of our estimates of bycatch rates (r) as

$$L_L = r_{min} - 1.96\ SE_{max}(r) \quad \text{and}$$
$$L_U = r_{max} + 1.96\ SE_{max}(r), \tag{3}$$

where r_{min}, r_{max} represented predicted parameter ranges; and SE_{max} was the largest (accounting for highest ecologically plausible uncertainty) standard error of estimated bycatch rates. This approach means that we were acknowledging inherent uncertainties from estimates lacking sufficient representative observer data for each fishery. To provide 95% CI of the numbers of sooty and short-tailed shearwater killed in each period, we combined the 26 different uncertainty scenarios for estimated parameter ranges of bycatch rates (normally distributed) and fishing effort (uniformly distributed) for the four key fisheries at random using 1000 Monte Carlo simulations (Caswell et al., 1998).

3. Results

3.1. Total magnitude of sooty and short-tailed shearwater bycatch

Far more sooty shearwater were taken by the Japanese land-based salmon and squid fisheries than by all other driftnet fisheries combined (Fig. 1). Takes of short-tailed shearwaters were high in the Japanese mothership and land-based salmon driftnet fisheries between 1953 and 1977, and in the recent Japanese salmon fishery in Russia between 1993 and 1997 (Fig. 1).

Bycatch of short-tailed shearwaters was much higher than for sooty shearwaters until the 1978–1990 period, when the Japanese squid fishery killed enormous numbers of sooty shearwaters. The international ban on driftnet fisheries in 1991 sharply curtailed bycatch of sooty shearwaters to its present low level.

3.2. Sensitivity analysis

The four driftnet fisheries that were of particular importance in determining the magnitude (Table 3) and precision (see Uhlmann, 2001) of the estimated total bycatch of sooty and short-tailed shearwaters are: the Japanese squid, Japanese land-based and mothership salmon, and Japanese salmon driftnet fisheries in Russia. Different fisheries had different relative importance in determining bycatch for each species, even though the two species are of similar size and ecology. Presumably this reflects differences in distribution at sea during northward migration in relation to fisheries zones.

A given proportional change in fishing effort (t) has the same impact on the estimates of total bycatch as the equivalent proportional change in bycatch rate (r), because total catch is simply the product of the two factors (see E2, Table 3). However, this is not true for the precision of the estimates of total bycatch. Altering the

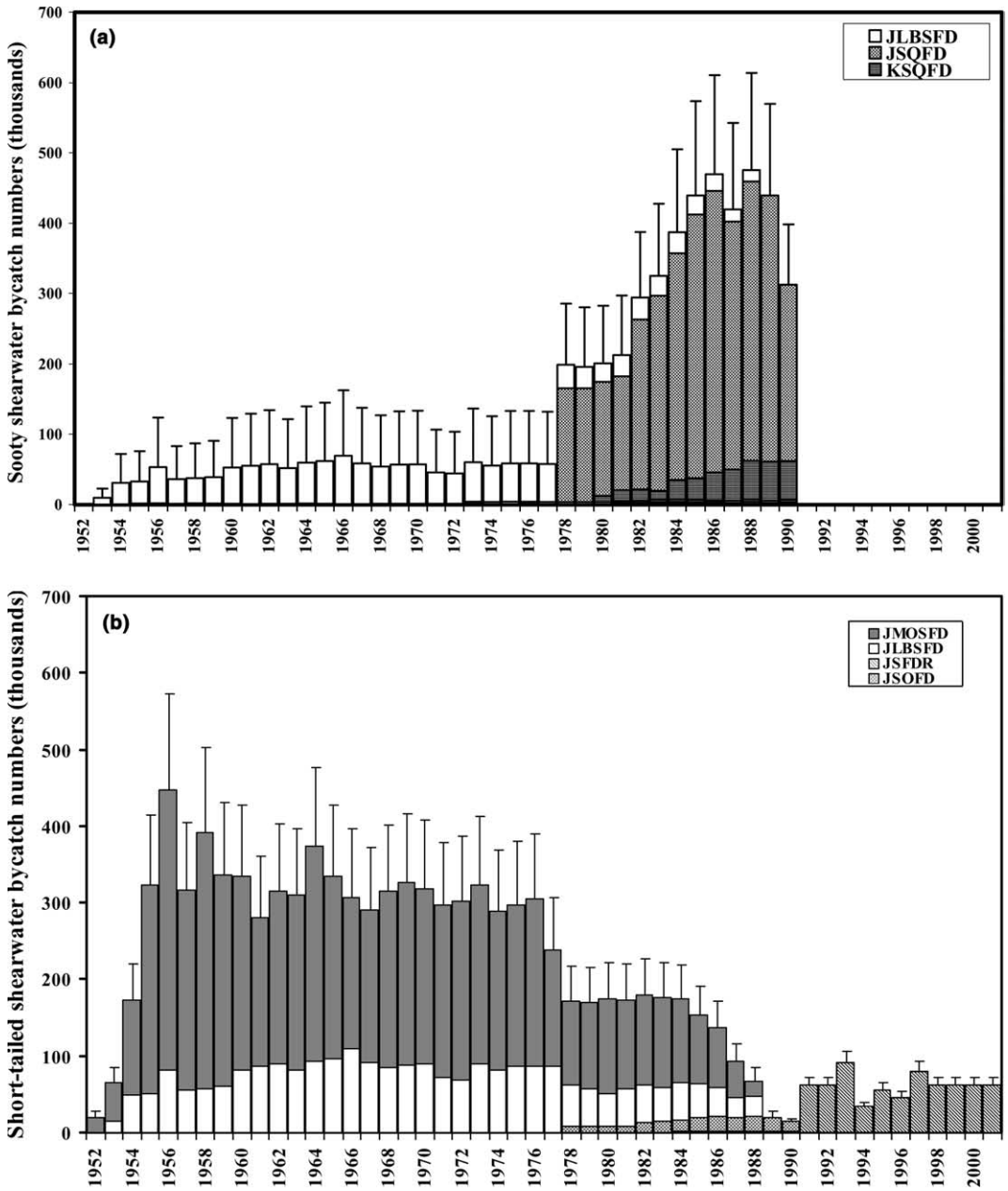

Fig. 1. Estimated annual take of sooty (a) and short-tailed shearwaters (b) (+SE) in driftnet fisheries, 1952–2001.

precision of the estimated fishing effort and bycatch rate of some fisheries had large impacts on the overall precision of the total bycatch estimate (Table 4).

3.3. Uncertainty analysis

Our sensitivity analysis emphasised the paramount importance of a few fisheries in each of the main study periods and of four fisheries overall. Accordingly we focused our uncertainty analysis on those four important fisheries. Plausible scenarios for minimum and maximum parameters often varied by an order of magnitude across these four fisheries (Table 5). It is therefore not surprising that the estimated total number of shearwaters killed, as established by Monte Carlo simulation, varies by a huge margin within its 95% CI of 11.8 and 16.6 million for sooty and short-tailed shearwaters, respectively (Fig. 2).

Sooty shearwaters captured in driftnets of the North Pacific between 1978 and 1990 totalled between 0.5 and 10.5 million (95% CI). Altogether, somewhere between 1.0 and 12.8 (95% CI) million sooty shearwaters could have been taken between 1952 and 2001 (Fig. 2). In the case of short-tailed shearwaters, we estimated that 2.9–16.6 (95% CI) million were killed between 1952 and 1977. Overall mortalities of short-tailed shearwaters

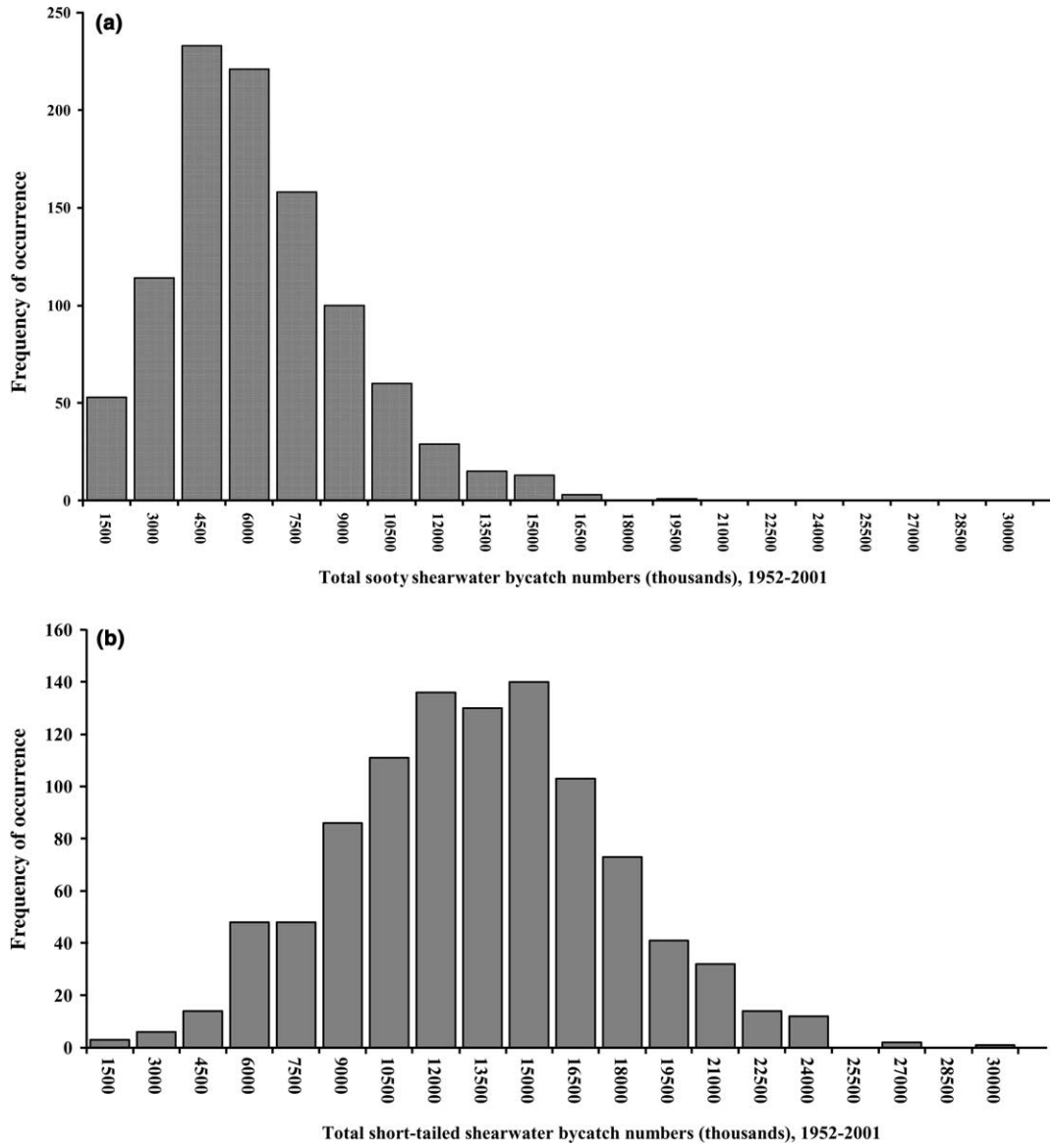

Fig. 2. Distribution of estimates of total take of sooty (a) and short-tailed shearwater (b) in driftnet fisheries, 1952–2001, as determined by simulations in the uncertainty analysis.

from 1952 to 2001 were nearly twice as high as for sooty shearwaters, with a 95% CI of between 4.6 and 21.2 million captures (Fig. 2).

3.4. Potential bias from undetected deaths or survival of released live birds

The above analysis considered variation and uncertainty around fishing effort and bycatch rates assuming that estimates were not biased in any way. However published estimates may underestimate takes if significant proportions of dead birds drop off before the net is hauled, or overestimate take if some shearwaters are misidentified or landed alive and released. To estimate the potential size of these biases, we used the same estimates of proportions of sooty and short-tailed shearwaters that were included in the 'dark shearwaters' as above, but also: (i) assigned a lower limit of 1% of 'dark shearwaters' being some other species (estimated by consulting the literature on relative abundance of species likely to be confused with sooty or short-tailed shearwater), (ii) assigned an arbitrary upper limit of 10% for such misidentifications, (iii) assumed between 0.3% and 13% of the drowned shearwaters drop-off before being landed (the range of rates reported by Ainley et al. (1981), DeGange et al. (1985), and Artyukhin and Burkanov (2000) for similar fisheries), and (iv) estimated that between 7% (Gjernes et al., 1990) and 14% (plausible upper limit accounting for higher species specific released alive rates observed by DeGange et al. (1985)) of the birds decked were released alive and survived.

Multiplying these limits together indicated that our original estimates may have been seriously underestimated or overestimated. Our sooty shearwater bycatch estimates may have been 73–116%, 60–132%, and 80–235% of the real levels for the Japanese squid, Japanese salmon land-based and Japanese salmon in Russia driftnet fisheries, respectively. The equivalent figures for short-tailed shearwater are 36–281%, 71–114%, 80–113% and 84–113% for the Japanese squid; Japanese salmon land-based; Japanese salmon in Russia and Japanese salmon mothership driftnet fisheries, respectively.

4. Discussion

4.1. Total magnitude of sooty and short-tailed shearwater bycatch

We have estimated that the combined driftnet mortality of short-tailed shearwaters was about twice as high as for sooty shearwaters. The former reportedly dominated bycatch samples of the 'Japanese mothership salmon' and 'Japanese salmon in Russia', whereas the latter outnumbered takes in the Japanese squid driftnet fisheries (Fig. 1). Our calculations used to apportion numbers of dark shearwaters are key determinants of this inference and were based on the fragmentary evidence of a few identified sooty and short-tailed shearwater samples alone.

For all but the Japanese squid and mothership salmon driftnet fisheries, it is unknown whether observer sampling covered seasons and places that were representative of the total commercial fishing effort of the fleet. It is also unknown for all fisheries, including the Japanese squid fleet, whether the coverage of vessels represented the entire fleet (Johnson et al., 1993). It is likely that specific vessels received higher coverage due to logistical constraints (e.g. sufficient space offered onboard the vessel for accommodating an observer) (Fitzgerald et al., 1993). Extrapolating from unrepresentative samples of observed fishing operations may over- or underestimate totals (Hilborn and Mangel, 1997).

4.2. Sensitivity and uncertainty analysis

Sensitivity analyses are an important tool in conservation biology for identifying key parameters and thereby to focus management and research (Caswell, 2000; Slooten et al., 2000; Cuthbert et al., 2001). In our case, sensitivity analysis identified those driftnet fisheries that were most important in contributing to the overall historical and present bycatch mortalities of sooty and short-tailed shearwaters in the North Pacific. In the end and after exhaustive review of over 29 fisheries (Uhlmann, 2003), we emphasise just four main fisheries as key contributors to the overall outcome.

Uncertainty analyses are potentially unreliable in that definitions as to the most likely parameter ranges are usually made in the absence of 'reliable' data (Caswell, 2000). Different scientists may cast the judgement of reliable versus unreliable data in different places because it demands a partly intuitive process of trading-off setting parameter limits that are wide enough to encompass ecologically plausible ranges definitely while still narrow enough to usefully guide management and research. We were uncomfortable about choosing arbitrary limits for smaller parts of the overall analysis, and then used simulation in our uncertainty analysis to help ameliorate their potential effects on our conclusions. The same problems of choosing conservative parameter ranges to account for both environmental variability and measurement uncertainties were encountered in a study evaluating bycatch impacts on the endangered Amsterdam albatross (Inchausti and Weimerskirch, 2001).

4.3. A need for description of bycatch probability distributions

So far there have been no descriptions of the probability function underlying a given unit of replication in all the studies of shearwater bycatch. This gap in reporting misses an opportunity to better understand underlying ecology and behaviour that leads to seabirds being drowned. It may be that a Poisson distribution describes the probability function because capture is a rare event and capture of one bird is unlikely to reduce or increase the chances of another bird being ensnared. But it may also be that one set of ecological or fishery practice conditions affect the likelihood of each bird present at a boat or net being caught, while a second set of parameters influence the number of birds attending the boat and net. If so, bycatch models will be best described by a two stage process. Management interventions to solve the problem and distribution of observer coverage might then be optimised by targeting the two separate parts of the problem.

This absence of descriptions of underlying capture probability functions also makes setting error limits on take extremely problematical and hampers model building. In the absence of better information we resorted to using normal distribution assumptions. Simulations assumed uniform distributions between putative upper and lower limits of catch effort. The effect will probably have been to exaggerate the uncertainty evident in Fig. 2. Until actual descriptions are reported, it will be unclear how best to estimate robust uncertainty limits on total bycatch estimates.

In our case, complexity escalates once (a) interest arises to calculate single plausible error limits of total bycatch estimates for individual periods and (b) the unknowns from several different scenarios for key fisheries are aggregated. Calculation of the variance of total

bycatch by summing independent estimates from all fisheries each year by analytical means would result in a very complicated formulae. Monte Carlo methods provide the most traceable and understandable substitute to bypass these complications and describe here the uncertainty in our total bycatch estimates.

4.4. Potential biases

Our crude assessment of the potential biases indicates that several confounding variables might interact to result in both large overestimation or underestimation of the level of take simply from misidentifications, drowned birds not being recovered, or release of live birds. Observer records and published reports should test whether these biases operate and be explicit about whether they have been taken into accounts in the reported figures.

Our analysis involves the usual assumption that the sample units are statistically independent. Unless the data were collected by a random sampling method, this assumption will not be fully met. It was only known for the Japanese squid fisheries whether the observers covered all the key times and places of the fishery (Fitzgerald et al., 1993; Johnson et al., 1993). It is therefore unclear if a representative sample of observations has been reported for the shearwaters in the remaining fisheries of our analysis. Given more detailed information, such as the numbers caught per tan, it might be possible to quantify the effect of this assumption not being true. This issue shows the importance of attempting to collect a random sample (possibly stratified) when estimating bycatch. For historical data it may be possible to allow for any bias caused by non-random sampling, using a model-based approach to estimation (Cochran, 1977).

4.5. Bycatch impacts on sooty and short-tailed shearwater populations

All legal driftnet fisheries but the Japanese salmon driftnet fishery in Russia ceased fishing at the latest by 1993 as a result of enforcement of the UN resolution 44/245 (Nagao et al., 1993). This major decline in current bycatch compared to levels occurring in the 1980s (Fig. 1) is not necessarily evidence that current levels are sustainable. Current risks for sooty and short-tailed shearwaters persist in the Japanese salmon driftnet fishery in Russia, the last remaining large-scale commercial driftnet fishery in the Pacific. Ongoing monitoring and improved reporting is still needed to better assess remaining risk and preventing high levels of bycatch in the future.

The wide range of estimated bycatch totals of sooty and short-tailed shearwater (Fig. 2) makes exact prediction of long-term effects on population demography and growth impossible. Sooty and short-tailed shearwaters are long-lived seabirds with life spans of 21–30 years (Wooller et al., 1990). As a consequence, moderate declines in population size would take many years of population monitoring to emerge. We cannot go back to recreate better estimates for those fisheries identified as key contributors to overall takes. Therefore we are very unlikely to ever be able to evaluate the putative impact of bycatch on sooty shearwater populations except within extremely broad bands of uncertainty.

Even had better estimates of total take been available, we still need a reliable estimate of total species abundance in order to calculate the change in survival wrought by fishery bycatch. Such an estimate for the current population is not yet available, let alone a historical one to match against the period of maximum bycatch. Demographic parameters are also imprecisely estimated and very small levels of uncertainty (e.g. measurement error) in survival rates may greatly affect population change predictions (Hamilton and Moller, 1995; Hunter et al., 2000). Fundamentally important in this regard is whether the bycatch mortality is additive or in some way compensated for (Moller, in press). Also, if the bycatch mortality is disproportionately of one sex and mates are limiting, the surviving partner of a bycatch victim may experience delays in breeding, or reduced productivity until a new compatible mate is found (Bradley et al., 1995). DeGange and Day (1991) reported significantly more females (65%) than males (34%) were caught in the Japanese salmon driftnet fishery in 1984, but other samples have failed to detect gender differences (Uhlmann, 2001).

Length of the bursa fabricii of 275 sooty shearwaters drowned in North Pacific driftnets suggests that 34% are juvenile, 37% immature and 29% are adults (Woods, unpubl. data in Uhlmann, 2001). A simple population projection model using observed survival and reproductive rates suggests that the proportion of juvenile and immature shearwaters in the population as a whole will be much lower than these observed bycatch proportions (Moller, unpubl.). If bycatch mainly kills pre-breeders, the full demographic effect of the added mortality will be lagged and slightly ameliorated because of delay before reduced numbers of breeding adults and their chicks occur. Some of the younger bycatch victims would have died of other natural causes before reaching breeding age. Chick harvests rates (an index of abundance) have continued to decline since the cessation of most pelagic drift netting mortalities (Lyver et al., 1999; Moller, unpubl. data). We do not yet know if this reflects a lag before improved pre-breeder survival following reduction in bycatch, or whether the fishery bycatch was an insignificant impact even at its peak in the 1980s and early 1990s.

The uncertainty in bycatch levels, potential for delayed impact of bycatch effects, amplification or amelioration of the kill's effects, major shifts in bycatch levels

in recent decades and potential climatic warming impacts on foods and survival all combine to make it impossible to infer causes of recent sooty shearwater declines.

4.6. Lessons for the conservation of seabirds

Description and adequate prediction of bycatch levels is an inherently difficult challenge. Wide-ranging procellariids exploit spatially and temporally patchy food supplies and so congregate in the same areas as the fishing boats targeting the same prey species. However, some improvements in risk assessment can be made by better standardisation and more thorough scientific reporting of observer data. Interpretation of observer data in our study was difficult because: (i) observer programs often did not cover all boats operating in the fisheries, (ii) observations were often not replicated in time, (iii) many observers did not differentiate in their identification between sooty and short-tailed shearwater (because they are not easy to distinguish in the field), (iv) the unit of replication for reporting catch effort and mortality has been defined differently in different reports, (v) basic descriptions of statistical error were either absent or varied between studies, making it harder to aggregate results, (vi) the capture rate probability distribution underlying the phenomenon is not described, (vii) we are unsure of the age and sex of the birds killed, (viii) we have imprecise measures of baseline pre-breeder and adult survival in the absence of significant bycatch, (ix) there are no baseline measures of bird numbers to compare bycatch rates against to estimate the degree of added mortality imposed by bycatch, and (x) we do not know whether any added mortality from bycatch may be compensated for by other adjustments in survival, age at first reproduction, or productivity.

Similar difficulties will reduce the power of many other investigations of bycatch impacts on other species. Statistical error estimates were absent from 86% of the 42 studies (Uhlmann, 2003) reviewed as a prelude to the more focussed analysis described here. We hoped that some of these difficulties would have been rectified in recent years as the seabird bycatch risk has received overdue attention. If so, the poor levels of reporting may simply reflect the historical nature of the data we assembled. Unfortunately we could find no clear relationship between reporting of statistical uncertainty and date of publication of these 42 reports (Uhlmann, 2001), so there is no evidence of improvement.

The difficulty of retrospectively and precisely estimating total bycatch for abundant seabirds like sooty and short-tailed shearwater raises the spectre that evaluation of risk to much rarer species may be even less reliable. Bycatch probabilities of rare species will be lower if lower abundance causes lower probabilities of fatal encounters with fishing gear. Sometimes sample sizes of rare species may be too small or even absent to calculate meaningful capture rates (Murray et al., 1993; Inchausti and Weimerskirch, 2001). Accordingly, variances of observed records will be large and transferred into large uncertainties of extrapolated total bycatch. These uncertainties will make any assessments of bycatch impacts on individual populations much more difficult and complex, especially if the information on the provenance of killed birds and accurate estimates of demographic parameters are absent as well (Inchausti and Weimerskirch, 2001). Conclusions on whether mortalities exceed maximum allowable take, and predictions of impact are potentially misleading for management unless robust estimation of uncertainty can be incorporated.

There is circumstantial evidence that fisheries bycatch may have caused population declines of some procellariids (Croxall et al., 1990; Moloney et al., 1994; Weimerskirch et al., 1997; Tuck et al., 2003) but this interpretation is potentially confounded by large-scale oceanic perturbations, potentially exacerbated by climate change. Several, localised albatross populations are stable or even increasing in numbers, despite mortalities in fisheries. Such populations may have increased more over the same period had bycatch not occurred or it may be that the bycatch has an insignificant effect on population dynamics. For example, numbers of the black-browed albatrosses (*Thalassarche melanophrys*) have increased in the recent past in New Zealand (Tennyson et al., 1998) and Australia (Kirkwood and Mitchell, 1992). The same species was found to be in decline on islands in the Southern Indian Ocean (Jouventin and Weimerskirch, 1991). This selective example illustrates that generalisations about overall population trends require careful considerations of localised effects and that differences in the rate of demographic changes are complex even at within-population levels, e.g. for the southern Buller's albatross (Sagar et al., 1999).

Undoubtedly, an environmental precautionary principle (Myers, 1993) suggests stringent effort to reduce bycatch in all fisheries as an urgent priority. A prima facie case for potential risk has been established, but our understanding of the problem and how best to manage it will be assisted more by objective declarations of how little we know even about the numbers killed, let alone the putative impact of those mortalities on procellariid populations. This study emphasises a need for greatly improved bycatch data and seabird population ecology before improved risk assessment is possible.

Acknowledgements

We thank the *Kia Mau Te Titi Mo Ake Tonu Atu* research team and the Rakiura Titi Islands Administering Body for their support during this work. We are grateful

to Chris Wood from the Burke Museum of Natural History and Culture at the University of Washington for sharing records of sooty shearwater bycatch specimens. Sue Baird and Steve Dawson made helpful comments on an earlier draft of the manuscript. This research is primarily funded by New Zealand's Foundation for Research Science and Technology. Sebastian Uhlmann received financial support from the German Academic Exchange Service (DAAD).

References

Ainley, D.G., DeGange, A.R., Jones, L.L., Beach, R.J., 1981. Mortality of seabirds in high-seas salmon gill nets. Fishery Bulletin 79, 800–806.

Artyukhin, Y.B., Burkanov, V.N., 2000. Incidental mortality of seabirds in the drift net salmon fishery by Japanese vessels in the Russian Exclusive Economic Zone, 1993–1997. In: Kondratyev, A.K., Litvinenko, N.M., Kaiser, G.W. (Eds.), Seabirds of the Russian Far East. Canadian Wildlife Service, Ottawa, Canada, pp. 105–116.

Bradley, J.S., Wooller, R.D., Skira, I.J., 1995. The relationship of pair-bond formation and duration to reproductive success in short-tailed shearwaters (*Puffinus tenuirostris*). Journal of Animal Ecology 64, 31–38.

Caswell, H., 2000. Prospective and retrospective analyses: their roles in conservation biology. Ecology 81, 619–627.

Caswell, H., Brault, S., Read, A.J., Smith, T.D., 1998. Harbor porpoise and fisheries: an uncertainty analysis of incidental mortality. Ecological Applications 8, 1226–1238.

Cochran, W.G. (Ed.), 1977. Sampling Techniques, third ed. Wiley, New York, USA.

Croxall, J.P., Rothery, P., Pickering, S.P., Prince, P.A., 1990. Reproductive performance, recruitment and survival of wandering albatrosses (*Diomedea exulans*) at Bird Island, South Georgia. Journal of Animal Ecology 59, 775–796.

Cuthbert, R., Fletcher, D.J., Davis, L.S., 2001. A sensitivity analysis of Hutton's shearwater: prioritizing conservation research and management. Biological Conservation 100, 163–172.

DeGange, A.R., Day, R.H., 1991. Mortality of seabirds in the Japanese land-based gillnet fishery for salmon. Condor 93, 251–258.

DeGange, A.R., Forsell, D.J., Jones, L.L., 1985. Mortality of seabirds in the high-seas Japanese salmon mothership fishery, 1981–1984. US National Marine Fisheries Service, National Marine Mammal Laboratory, 7600 Sand Point Way, Seattle, WA 98115, USA.

DeGange, A.R., Day, R.H., Takekawa, J.E., Mendenhall, V.M., 1993. Losses of seabirds in gill nets in the North Pacific. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D. (Eds.), The Status, Ecology and Conservation of Marine Birds of the North Pacific. Canadian Wildlife Service Special Publications, Ottawa, Canada, pp. 204–211.

de Kroon, H., van Groenendael, J., Ehrlén, J., 2000. Elasticities: a review of methods and model limitations. Ecology 81, 607–618.

Everett, W.T., Pitman, R.L., 1993. Status and conservation of shearwaters of the North Pacific. In: Vermeer, K., Briggs, K.T., Morgan, K.H., Siegel-Causey, D. (Eds.), The Status, Ecology, and Conservation of Marine Birds of the North Pacific. Canadian Wildlife Service Special Publications, Ottawa, Canada, pp. 93–101.

Fitzgerald, S.M., McElderry, H., Hatanaka, H., Watanabe, Y., Park, J.S., Gong, Y., Yeh, S., 1993. 1990–1991 North Pacific high seas driftnet scientific observer programs. International North Pacific Commission Bulletin 53, 77–90.

Gjernes, T., McKinnell, S., Yatsu, A., Hayase, S., Ito, J., Nagao, K., Hatanaka, H., Ogi, H., Dahlberg, M., Jones, L., Wetherall, J., Gould, P., 1990. Final report of squid and bycatch observations in the Japanese driftnet fishery for neon flying squid (*Omnastrephes bartrami*), June–December, 1989 Observer Program. Joint Report of Fisheries Agency of Japan, Canadian Department of Fisheries and Oceans, United States National Marine Fisheries Service, United States Fish and Wildlife Service.

Gong, Y., Kim, Y.S., Hwang, S.J., 1993. Outline of the Korean gillnet fishery in the North Pacific. International North Pacific Fisheries Commission Bulletin 53, 45–59.

Hamilton, S., Moller, H., 1995. Can PVA models using computer packages offer useful conservation advice? Sooty shearwaters (*Puffinus griseus*) in New Zealand as a case study. Biological Conservation 73, 107–117.

Hawke, D.J., Newman, J., 2004. Inventories and elemental accumulation in peat soils of forested seabird breeding islands, southern New Zealand. Australian Journal of Soil Research 42, 45–48.

Hilborn, R., Mangel, M., 1997. The Ecological Detective: Confronting Models with Data. Princeton University Press, Princeton, USA.

Hunter, C.M., Moller, H., Fletcher, D., 2000. Parameter uncertainty and elasticity analysis of a population model: setting research priorities for shearwaters. Ecological Modelling 134, 299–323.

Inchausti, P., Weimerskirch, H., 2001. Risks of decline and extinction of the endangered Amsterdam albatross and the projected impact of long-line fisheries. Biological Conservation 100, 377–386.

International North Pacific Fisheries Commission, 1991. Scientific review of North Pacific high seas driftnet fisheries, Sidney, British Columbia, June 11–14, 1991. Report for presentation to the United Nations Pursuant to resolutions 44/225 and 45/197. Department of Fisheries and Oceans Sciences, P.O. Box 6000, Sidney, Canada BC V8L 4B2.

Johnson, D.H., Shaffer, T.L., Gould, P.J., 1993. Incidental catch of marine birds in the North Pacific high seas driftnet fisheries in 1990. International North Pacific Commission Bulletin 53, 473–483.

Jones, C., 2002. A model for the conservation management of a 'secondary' prey: sooty shearwater (*Puffinus griseus*) colonies on mainland New Zealand as a case study. Biological Conservation 108, 1–12.

Jones, L.L., DeGange, A.R., 1988. Interactions between seabirds and fisheries in the North Pacific ocean. In: Burger, J. (Ed.), Seabirds and Other Marine Vertebrates. Columbia University Press, New York, USA, pp. 269–291.

Jouventin, P., Weimerskirch, H., 1991. Changes in the population size and demography of southern seabirds: management implications. In: Perrins, C.M., Lebreton, J.-D., Hirons, G.J.M. (Eds.), Bird Population Studies: Relevance to Conservation and Management. Oxford University Press, New York, USA, pp. 297–314.

King, W.B., 1984. Incidental mortality of seabirds in gillnets in the North Pacific. ICBP Technical Publication 2, 709–715.

Kirkwood, R.J., Mitchell, P.J., 1992. The status of the black-browed albatross (*Diomedea melanophrys*) at Heard Island. Emu 92, 111–114.

Kotz, S., Johnson, N.L., 1982–1989. Encyclopaedia of Statistical Sciences. Wiley, New York, USA.

Lyver, P.O.'B., Moller, H., 1999. Modern technology and customary use of wildlife: the harvest of sooty shearwaters by Rakiura Mâori as a case study. Environmental Conservation 26, 280–288.

Lyver, P.O.'B., Moller, H., Thompson, C., 1999. Changes in sooty shearwater (*Puffinus griseus*) chick production and harvest precede ENSO events. Marine Ecology Progress Series 188, 237–248.

Moller, H. Are current harvests of seabirds sustainable? Acta Zoologica Sinica (in press).

Moller, H., Frampton, C., Hocken, A.G., McLean, I.G., Saffer, V., Sheridan, L., 2000a. The importance of seabird research for New Zealand. New Zealand Journal of Zoology 27, 255–260.

Moller, H., Horsley, P., Lyver, P.O.'B, Taiepa, T., Davis, J., Bragg, M., 2000b. Co-management by Māori and Pakeha for improved conservation for the 21st century. In: Perkins, A.P., Memon, A. (Eds.), Environmental Planning and Management in New Zealand. Dunmore Press, Palmerston North, New Zealand, pp. 156–167.

Moloney, C.L., Cooper, J., Ryan, P.G., Siegfried, W.R., 1994. Use of a population model to assess the impact of longline fishing on wandering albatross (*Diomedea exulans*) populations. Biological Conservation 70, 195–203.

Murray, T.E., Bartle, J.A., Kalish, S.R., Taylor, P.R., 1993. Incidental capture of seabirds by Japanese southern bluefin tuna longline vessels in New Zealand, 1988–1992. Bird Conservation International 3, 181–210.

Myers, N., 1993. Biodiversity and the precautionary principle. Ambio 22, 74–79.

Nagao, K., Ota, S., Hirono, J., 1993. Regulation of the Japanese high seas driftnet fisheries. International North Pacific Commission Bulletin 53, 39–44.

Nakano, H., Okada, K., Watanabe, Y., Uosaki, K., 1993. Outline of the large-mesh driftnet fishery of Japan. International North Pacific Commission Bulletin 53, 25–37.

Northridge, S.P., 1991. Driftnet fisheries and their impacts on non-target species: a worldwide review. FAO Fisheries Technical Paper No. 320. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Ogi, H., Yatsu, A., Hatanaka, H., Nitta, A., 1993. The mortality of seabirds by driftnet fisheries in the North Pacific. International North Pacific Commission Bulletin 53, 499–518.

Sagar, P.M., Stahl, J.C., Molloy, J., Taylor, G.A., Tennyson, A.J.D., 1999. Population size and trends within two populations of Southern Buller's albatross (*Diomedea bulleri bulleri*). Biological Conservation 89, 11–19.

Scofield, R.P., Christie, D., 2002. Beach patrol records indicate a substantial decline in sooty shearwater (*Puffinus griseus*) numbers. Notornis 49, 158–165.

Skira, I.J., 1990. Human exploitation of the short-tailed shearwater. Papers and Proceedings of the Royal Society of Tasmania 124, 77–90.

Skira, I.J., 1991. Australasian bird reviews – Number 3: the short-tailed shearwater, a review of its biology. Corella 15, 45–52.

Slooten, E., Fletcher, D., Taylor, B.L., 2000. Accounting for uncertainty in risk assessment: case study of Hector's dolphin mortality due to gillnet entanglement. Conservation Biology 14, 1264–1270.

Taiepa, T., Lyver, P., Horsley, P., Davis, J., Bragg, M., Moller, H., 1997. Co-management of New Zealand's conservation estate by Mâori and Pakeha: a review. Environmental Conservation 24, 236–250.

Tennyson, A., Imber, M., Taylor, R., 1998. Numbers of black-browed mollymawks (*Diomedea m. melanophrys*) and white-capped mollymawks (*D. cauta steadi*) at the Antipodes Islands in 1994–95 and their population trends in the New Zealand region. Notornis 45, 157–166.

Tuck, G.N., Polacheck, T., Croxall, J.P., Weimerskirch, H., 2001. Modelling the impact of fishery by-catches on albatross populations. Journal of Applied Ecology, 1182–1196.

Tuck, G.N., Polacheck, T., Bulman, C.M., 2003. Spatio-temporal trends of longline fishing effort in the Southern Ocean and implications for seabird bycatch. Biological Conservation 114, 1–27.

Uhlmann, S., 2001. Incidental takes of sooty (*Puffinus griseus*) and short-tailed shearwaters (*P. tenuirostris*) in fisheries. M.Sc. Thesis, University of Otago, Dunedin, New Zealand. Available from: <www.otago.ac.nz/titi/download.php?au=uhlmann>.

Uhlmann, S., 2003. Fisheries bycatch mortalities of sooty shearwaters (*Puffinus griseus*) and short-tailed shearwaters (*P. tenuirostris*). DOC Science Internal Series 92. Department of Conservation, Wellington, New Zealand.

Warham, J., 1990. The Petrels: Their Ecology and Breeding Systems. Academic Press, London, UK.

Warham, J., Wilson, G.J., Keeley, B.R., 1982. The annual cycle of the sooty shearwater (*Puffinus griseus*) at the Snares Islands, New Zealand. Notornis 29, 269–292.

Weimerskirch, H., Brothers, N., Jouventin, P., 1997. Population dynamics of wandering albatross (*Diomedea exulans*) and Amsterdam albatross *D. amsterdamensis* in the Indian Ocean and their relationships with long-line fisheries: conservation implications. Biological Conservation 79, 257–270.

Weimerskirch, H., Cherel, Y., 1998. Feeding ecology of short-tailed shearwaters: breeding in Tasmania and foraging in the Antarctic?. Marine Ecology Progress Series 167, 261–274.

Weimerskirch, H., Jouventin, P., 1987. Population dynamics of the wandering albatross (*Diomedea exulans*) of the Crozet Islands: causes and consequences of the population decline. Oikos 49, 315–322.

Weimerskirch, H., Jouventin, P., 1998. Changes in population sizes and demographic parameters of six albatross species breeding on the French sub-Antarctic islands. In: Robertson, G., Gales, R. (Eds.), Albatross Biology and Conservation. Surrey Beatty and Sons, Chipping Norton, Australia, pp. 84–91.

Weimerskirch, H., Sagar, P., 1996. Diving depths of sooty shearwaters (*Puffinus griseus*). Ibis 138, 786–788.

Wooller, R.D., Bradley, J.S., Skira, I.J., Serventy, D.L., 1990. Reproductive success of short-tailed shearwaters (*Puffinus tenuirostris*) in relation to their age and breeding experience. Journal of Animal Ecology 59, 161–170.

Yatsu, A., Hiramatsu, K., Hayase, S., 1993. Outline of the Japanese squid driftnet fishery with notes on the by-catch. International North Pacific Commission Bulletin 53, 5–23.