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The impact of pelagic longline fishing on the flesh-footed shearwater *Puffinus carneipes* in Eastern Australia

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Abstract

The flesh-footed shearwater (*Puffinus carneipes*) is a medium-sized seabird (ca. 700 g) that is incidentally killed during longline fishing operations. We examined the levels of bycatch in Australia's Eastern Tuna and Billfish Fishery and developed a model to examine the impact of this fishery on the eastern Australian population of flesh-footed shearwaters, which breeds at only one site, Lord Howe Island. Observed bycatch rates for flesh-footed shearwaters were 0.378 birds/1000 hooks for night sets, and 0.945 birds/1000 hooks for day sets. The mean number of birds killed from 1998 to 2002 was estimated to be 1794–4486 birds per year, with the estimated total killed over this period ranging from 8972 to 18,490 birds. Models incorporating both density-independent and density-dependent scenarios were applied to levels of bycatch representative of that observed in the fishery. Density-independent scenarios showed that fishing mortality levels caused declines in the majority of simulated populations. In contrast, density-dependent scenarios produced populations that were more resilient to fishing mortalities. Although some modelling scenarios led to population growth, under most stochastic simulations median population halving and quasi-extinction times were less than 55 and 120 years, respectively. We conclude that the level of bycatch observed in the fishery is most likely unsustainable and threatens the survival of the Lord Howe Island population. This situation can be improved only with the development and implementation of mitigation measures that will halt or greatly reduce the level of bycatch currently observed. Improved knowledge on a range of demographic parameters for the species, combined with a clearer idea of the at-sea distribution of breeding and non-breeding shearwaters, will greatly assist in improving understanding and the management of this population.

Keywords: Flesh-footed shearwater; *Puffinus carneipes*; Seabird bycatch; Age-structured model; Lord Howe Island

1. Introduction

Tens of thousands of seabirds are accidentally killed each year on longline hooks set in the world's oceans. Seabird bycatch during longline fishing occurs when birds are attracted to fishing vessels by discards and baits and ingest baited hooks during the setting or, less commonly, hauling of the longline. The hooked birds are subsequently pulled under the water by the weight of the line and drown. The impact of longline fishing activities on seabirds is regarded as a serious threat, causing widespread declines in populations across the world (Alexander et al., 1997; Croxall, 1998; Gales, 1998).

Longline fishing is used to target pelagic and demersal finfish and shark species. Its use as a fishing technique in the southern oceans commenced in the 1950s and today operates in almost all Australian waters. Bycatch of seabirds during longline fishing operations is listed under Australian legislation as a key threatening process which could endanger 14 species of seabirds

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(Environment Australia, 1998). In 1998 a Threat Abatement Plan was finalised to manage this threat (Environment Australia, 1998).

The objective of the Threat Abatement Plan is to reduce seabird bycatch in all Australian fisheries to below 0.05 seabirds per 1000 hooks. Based on the level of fishing effort in Australian waters in 1998 (12 million hooks), achievement of this objective equates to a reduction of up to 90% of seabird bycatch, which was considered achievable within the five-year life of the Plan (Environment Australia, 1998).

At the time the threat abatement plan was written the only available data for seabird bycatch in Australian pelagic tuna fisheries were those collected by fishery observers on Japanese longline vessels. These vessels fished under licence in the Australian Fishing Zone from 1986 until 1997 (Caton, 2003). This data set was extensive, with over 10 million hooks observed. Bycatch levels in this fishery were estimated at 0.15 birds per 1000 hooks set (Gales et al., 1998). The most commonly caught birds at that time were albatrosses (74%), with the species composition differing according to season and area (Gales et al., 1998). Flesh-footed shearwaters (*Puffinus carneipes*) comprised 9.6% of the bycatch recorded on these Japanese longline vessels.

Longline fishing in Australian domestic tuna and billfish fisheries commenced in 1986 but effort was limited for many years. Following the withdrawal of Japanese longline vessels from the Australian Fishing Zone in 1997, fishing effort in the domestic fishery increased substantially, rising from 6.7 million hooks set in 1997 to over 17 million hooks in 2001 (Caton, 2003). Most of this effort was concentrated off the east and west coasts of Australia between latitudes 25° to 40°, and around Tasmania. With no fisheries-independent observer program established, there were few data on the composition and rate of seabird bycatch in these longline fisheries (Brothers et al., 1999).

During the Austral summers of 2001/02 and 2002/03, the performance of an underwater setting chute (a device designed to set baited hooks at a depth of 5–7 m below the water's surface) and various line-weighting regimes, were evaluated in a series of at-sea trials in the Eastern Tuna & Billfish fishery. These measures were implemented to minimise seabird bycatch in the fishery. The trials occurred off eastern Australia, between latitudes 28° to 37° South and were monitored by independent fishery observers. A total of 461,311 hooks was observed, with 278 seabirds caught at an overall rate of 0.6 birds per 1000 hooks. All of the 20 vessels participating in the trial caught seabirds. The principal species caught was the flesh-footed shearwater, which comprised 254 (91%) of all birds taken (Australian Fisheries Management Authority, unpublished).

The flesh-footed shearwater is a medium-sized seabird (ca. 700 g), and is provided with protected status under Australian legislation. It frequents Australian and New Zealand waters during September to May, when it breeds, and migrates to the northern hemisphere between June and August. More than 80% of the world's estimated population of approximately 220,000 pairs (Brooke, 2004) breeds in Australian waters (Baker et al., 2002).

Although the level of bycatch observed in the trials was based on a small number of observed hooks, it raised concerns as to the viability of the eastern Australian population of flesh-footed shearwaters. This population breeds at only one site, Lord Howe Island (31°30′ S, 159°05′ E), and was estimated to comprise 17,500 breeding pairs in 2002 (D. Priddel, N. Carlile, P. Fullagar, I. Hutton and L. O'Neill, unpublished). In order to gain an understanding of the impacts of longline fishing on this population, an age-structured model was developed. Using this model a number of different levels of fishing mortality was investigated to determine those that would threaten the survival of the Lord Howe Island population.

2. Methods

2.1. Fishing effort and bycatch rates

Fishing effort in the Eastern Tuna and Billfish Fishery for the period 1996 to 2002 was assessed from shot-by-shot data, where information from each individual shot is recorded, provided in logbooks submitted by fishers to the Australian Fisheries Management Authority. Effort (number of hooks set) was collated into seasonal (Austral summer, defined as the period September–May) and annual totals, to examine the spatial and temporal changes within the fishery.

Bycatch rates of flesh-footed shearwaters were determined from observer data collected during seabird bycatch mitigation trials conducted in the Eastern Tuna and Billfish Fishery from 2001 to 2003. The data were stratified by time of set (night and day) and area (5° latitude bands). Time of set is known to influence bycatch of seabirds in many fisheries (Brothers et al., 1999) and was defined as the time that line-setting first commenced, with night being the hours between nautical dusk and nautical dawn, and day being all other times. Mean bycatch rates are expressed as the number of birds observed caught per 1000 hooks, and confidence intervals estimated by bootstrapping (randomly resampling the observed data 1000 times), as recommended by Uhlmann et al. (2005) for seabird bycatch data. The bycatch rates derived from the data most likely underestimate mortality as birds may have been eaten by predators or fallen off hooks prior to line hauling. However the deliberate cutting of seabirds from the line, observed in some fisheries (Gales et al., 1998), is unlikely to have occurred in this fishery in the presence of an observer.

Bycatch rates and distribution of fishing effort were used to estimate the number of birds killed each year and to calculate the overall fishing-related mortality on the flesh-footed shearwater population. The number of birds killed was estimated by multiplying observed bycatch rates by the mean fishing effort between latitudes 25°S–35°S during the Austral summers of 1998 to 2002. Fishing-related mortality rates were derived by dividing the estimate of the total adult population size at 2002/03 (see below for estimate) by estimates of the mean number of birds killed under a number of scenarios. Three scenarios were examined to assess the impact of fishing-related mortality on the population:

- Scenario 1 assumes the observed bycatch rate for night sets in 5° latitude bands is representative of all hooks set in latitude bands 25°S–35°S. This scenario was used to reflect a situation where all fishing activities would occur during the night.
- Scenario 2 assumes the observed bycatch rate for day sets in 5° latitude bands is representative of all hooks set in latitude bands 25°S–35°S. This scenario was used to reflect a situation where all fishing activities would occur during the day.
- Scenario 3 assumes the observed bycatch rate for all sets (day and night) in 5° latitude bands is representative of all hooks set in latitude bands 25°S–35°S. This scenario was used to reflect the current situation where fishing activities occur during the day and night.

2.2. Basis for selection of parameters

The demography of flesh-footed shearwaters is poorly known and longitudinal data sets are not available to assist in selecting model inputs. Therefore estimates of population parameters were 'borrowed' from research carried out on congeners of similar size (short-tailed and sooty shearwaters, *Puffinus tenuirostris*, *P. griseus*). These species have biological and ecological characteristics similar to the flesh-footed shearwater in that they breed in southern Australia in the Austral summer, and migrate to the northern Pacific Ocean from May to August (Serventy and Curry, 1984; Marchant and Higgins, 1990; Hamilton and Moller, 1995).

2.3. Assumptions

A number of assumptions were made in developing the model.

- Flesh-footed shearwaters are found off the east coast of Australia within the Australian Fishing Zone between 25°S to 35°S (Fraser Island to the New South Wales/Victoria border), during the months of September to May (Lindsey, 1986). It is assumed that all birds found in this area are from the Lord Howe Island population.
- The flesh-footed shearwater population on Lord Howe Island is stable in the absence of fisheries-related mortality. The Lord Howe Island population was estimated to comprise 17,500 breeding pairs in the 2002/03 breeding season (D. Priddel, N. Carlile, P. Fullagar, I. Hutton and L. O'Neill, unpublished). Assuming that 25% of adults of breeding age do not breed in any one year (Wooller et al., 1990), the total adult population was estimated to comprise 47,000 adults.
- Flesh-footed shearwaters are assumed to live to 40 years of age and breed for the first time at seven years old. Survival and fecundity at age estimates (Table 1) were based on published data for the short-tailed shearwater (Wooller et al., 1989, 1990; Bradley and Wooller, 1990, 1991a,b; Bradley et al., 1991, 1999, 2000) and sooty shearwater (Hamilton and Moller, 1995). Fecundity means the successful fledging of a female chick and incorporates the assumption that 25% of the adult female population do not breed in a given year (Wooller et al., 1990).
- All but 2 of 149 birds autopsied (R. Gales, unpublished) were sexually mature. We have assumed that both sexes have an equal probability of being hooked, although a sample of 139 birds was slightly male biased 78:61. However an additional 10 birds could not be accurately sexed because of the condition of the corpses but were thought to be females. If they are included with the other birds as females, the sex

Table 1
Survival and fecundity parameters used to model the impact of longline fishing on the Lord Howe Island population of flesh-footed shearwaters

Age	Stage	Survival		Fecundity	
		Average	Random	Average	Random
1	Fledged	0.500	U (0.48, 0.52)	NA	NA
2–6	Pre-breeders	0.320	U (0.30, 0.34)	NA	NA
7–40	Adults	0.940	U (0.93, 0.95)	0.263	U (0.225, 0.3)

Shearwater population size was estimated at 47,000 adults (ages 7–40). U represents a uniform distribution. NA is not applicable.

ratio is 1.1:1. Of 12 birds caught by the Japanese fleet in eastern Australia, the sex ratio was 1:1 (R. Gales, unpublished).
- All longline vessels operating in this area during this period have an equal probability of encountering this species. We assume that fishing effort will remain constant for the foreseeable future. The Australian Fisheries Management Authority is proposing to limit effort by restricting the number of hooks set each year in a management plan currently being developed. Annual effort is likely to be capped at 13.5 million hooks although the management plan is unlikely to restrict where effort is directed (Australian Fisheries Management Authority, unpublished).

2.4. Age-structured models

The development of a simple age-structured model (Caughley, 1977; Krebs, 2001) was considered appropriate, as information on flesh-footed shearwaters is poorly known, necessitating the use of data from other shearwaters with similar biological and ecological characteristics to provide model inputs.

The model was developed where the female population size ($N^{\rm f}_{y,a}$) each year y and age a was calculated from the survival to age at first breeding (s_J), adult survival (s) and fishing-related mortality rate (F) by

$$N^{\rm f}_{y,a} = \begin{cases} N^{\rm f}_{y,1} & a = 1, \\ s_J N^{\rm f}_{y-1,1} & a = 7, \\ s(1-F)N^{\rm f}_{y-1,a-1} & 7 < a \leqslant 40. \end{cases}$$

Fishing was assumed to impact only the adult population, which includes all individuals seven years or older. Total number of individuals fledged ($N^{\rm f}_{y,1}$) each year y that survive to age one was calculated from a constant fecundity (b) by $N^{\rm f}_{y,1} = b\sum_{a=7}^{40} N^{\rm f}_{y-1,a}$. The initial female population ($N^{\rm f}_{0,a}$) was simulated in the absence of fishing until a stable age structure was achieved and recalibrated such that this population was composed of 17,500 breeding pairs. The total adult female population was calculated as $N^{\rm f}_{y} = \sum_{a=7}^{40} N^{\rm f}_{y,a}$. Population halving time ($y_{0.5}$) and quasi-extinction time, defined here as an 80% reduction in population size ($y_{0.8}$) were used as reference points to describe the population's state and define critical levels of fishing on a population, and corresponded to $N_{y_{0.5}} = 0.5N_0$ and $N_{y_{0.8}} = 0.2N_0$, respectively.

Data demonstrating a density-dependent relationship between survival and abundance in shearwaters are equivocal (Barker et al., 2002), but there is some evidence that populations of the wandering albatross *Diomedea exulans*, show a density-dependent response to declines in the breeding population size (Croxall et al., 1990; Tuck et al., 2001). Juvenile natural mortality rate was selected as the density-dependent demographic component where juvenile survival rates increase when the numbers of breeding pairs decrease (Tuck et al., 2001). The ecological basis for this would be a decrease in the intraspecific competition for resources such as food (Weimerskirch, 1992). In the absence of a clear understanding of the mechanism of population regulation in shearwaters, density dependence was implemented following that of Tuck et al. (2001) where s^*_J and the density dependent survival to age of first breeding calculated as

$$s^*_J = s^k_J / s^{6(k-1)} \text{ where } k = (N^{\rm f}_y / N^{\rm f}_0)^{\gamma}.$$

The "6" comes into the equation because juveniles must survive for six years until they reach breeding age. The γ term controls the level of compensation (e.g., $\gamma = 0$ implies density-independent survival to age of first breeding). Tuck et al. (2001) found γ in the range 2.7–6.5 for wandering albatrosses on Bird Island, South Georgia and Possession Island, Crozet Islands. However, values of $\gamma > 1$ appeared to overestimate substantially the effect of density dependence for shearwaters when compared with density independent modelling, indicating their unsuitability for modelling in this species. There are some distinct demographic differences between flesh-footed shearwaters and wandering albatrosses, most notable being the biennial breeding strategy of wandering albatrosses and their greater age at first breeding. It therefore appeared sensible to assume lower values for γ than those used by Tuck et al. (2001) and, accordingly, we set $\gamma = 0.5$ for stochastic modelling.

Deterministic and stochastic population survival and fecundity parameters were considered. The deterministic parameters represented average levels of survival at age and fecundity obtained from the literature (Table 1). Stochastic parameter values were randomly selected from a uniform distribution on the interval determined by the range of estimates obtained from the literature (Table 1). A uniform distribution was used, as there was no information on which to base an alternative assumption.

Stochastic simulations were carried out using the model and a Monte Carlo process with age-specific survival and fecundity randomly selected from between the low and high age-specific survival and fecundity parameter values (Table 1). The impact of longline fishing mortality on an initial population unaffected by fishing was tested in 1000 runs of the model for each of the three fishing-related mortality scenarios outlined above (Methods, Section 2.1).

3. Results

3.1. Fishing effort and bycatch rates

Fishing effort in the Eastern Tuna and Billfish Fishery has increased substantially since the fishery commenced

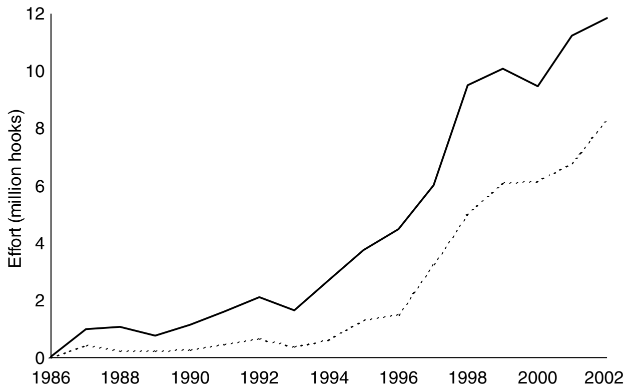

Fig. 1. Annual effort (million hooks) in the Eastern Tuna and Billfish Fishery from 1986 to 2002 for latitudes 25°S–35°S inclusive (dotted line) and the total fishery (solid line).

in 1986, and particularly between 1997 and 2002 (Fig. 1). Much of the effort since 1998 has been directed toward the area between latitudes 25°S–35°S during the Austral summer when flesh-footed shearwaters are present (Figs. 1 and 2).

Observed bycatch rates for flesh-footed shearwaters in the seabird bycatch mitigation trials were generally high (Table 2), and ranged from 0 to 1.009 birds/1000 hooks within the distributional range of the species. Bycatch was higher when hooks were set during the day rather than at night. The total observed bycatch rate for the fishery between latitudes 25°S–35°S was 0.378 birds/1000 hooks for night sets, and 0.945 birds/1000 hooks for day sets (Table 2). Although observer effort is low, no birds were observed caught north of latitude 25°S, and only eight caught south of latitude 35°S (Table 2).

Estimates of the number of birds killed each year, based on the product of the observed bycatch rate multiplied by the amount of effort in the fishery, ranged from a mean of 1794–4486 birds for the period 1998 to 2002 (Table 3). The total number of birds killed over this five-year period ranged from 8972–18,490. The calculated fishery-related mortality rates for the three scenarios were 3.8%, 9.6% and 7.9% for Scenarios 1–3, respectively.

3.2. Deterministic simulations

The model was used to simulate the flesh-footed shearwater population on Lord Howe Island subjected to fishery-related mortality levels from an initial population unaffected by fishing mortality. Deterministic simulations were carried out for the range of fishery-related mortality levels from 0% to 100% (Fig. 3). In the absence of fishing mortality the simulated population increased. Conversely, the impact of fishing mortality greater than 2% caused declines in all simulated density independent models, with density dependence providing greater resilience (Fig. 3). The mortality level of 0.05 birds per 1000 hooks, specified by Australia's Threat Abatement Plan as a maximum permissible bycatch level, produced a fishing-related mortality rate of 0.65% and an increase in the simulated populations, assuming that fishing does not exceed the observed 2002 level.

3.3. Stochastic simulations

Stochastic simulations were carried out using randomly selected age specific survival and fecundity (Table 1). Simulations were carried out for each of the three scenarios of fishing-related mortality (Table 3).

Under most density-independent simulations populations declined rapidly (Fig. 4). The impact of longline fishing mortality was to cause a decline generally under all three scenarios with median halving times of 54, 12 and 16 years for Scenarios 1a to 3a, respectively. The median times to quasi-extinction for the three scenarios were 111, 29 and 37 years. However, under Scenario 1 where fishing related mortality was 3.8%, 25% of simulations showed positive population growth (Fig. 4).

In contrast, density-dependent scenarios (assuming $\gamma = 0.5$) produced populations that were more robust to fishing mortality (Fig. 4). Under Scenario 1b 28.1% of populations grew, and median halving and quasi-extinction times were >1000 years indicating that under this scenario the risk of extinction would be minimal. However, under Scenarios 2b and 3b median halving times were 15 and 21 years, respectively. The median times to quasi-extinction were 51 and 118 years for scenarios 2b and 3b, respectively.

4. Discussion

The bycatch of flesh-footed shearwaters in the Eastern Tuna and Billfish Fishery is currently at a level that threatens the persistence of the eastern Australian population. Between 1998 and 2002 the mean fishing effort within the shearwaters breeding distribution each summer has exceeded 4.7 million hooks, and it is likely this level will be maintained or increased in the foreseeable future. The overall bycatch rate is high when compared with contemporary rates in other fisheries, such as those observed in the demersal toothfish fishery in the sub-Antarctic (Scientific Committee for the Conservation of Antarctic Marine Living Resources, 2003). These bycatch rates have led to an estimated 1794–4486 shearwaters being killed annually over that time, which has resulted in increased mortality at the population level of 3.8%–9.6%.

Under most stochastic modelling scenarios presented here the level of seabird bycatch observed in the fishery is unsustainable. The eastern Australian flesh-footed shearwater population is predicted to decline by 50% under most scenarios (Fig. 4) within 55 years, and by 80% (quasi-extinction) within 120 years. On this basis the population would meet the IUCN criteria for listing as

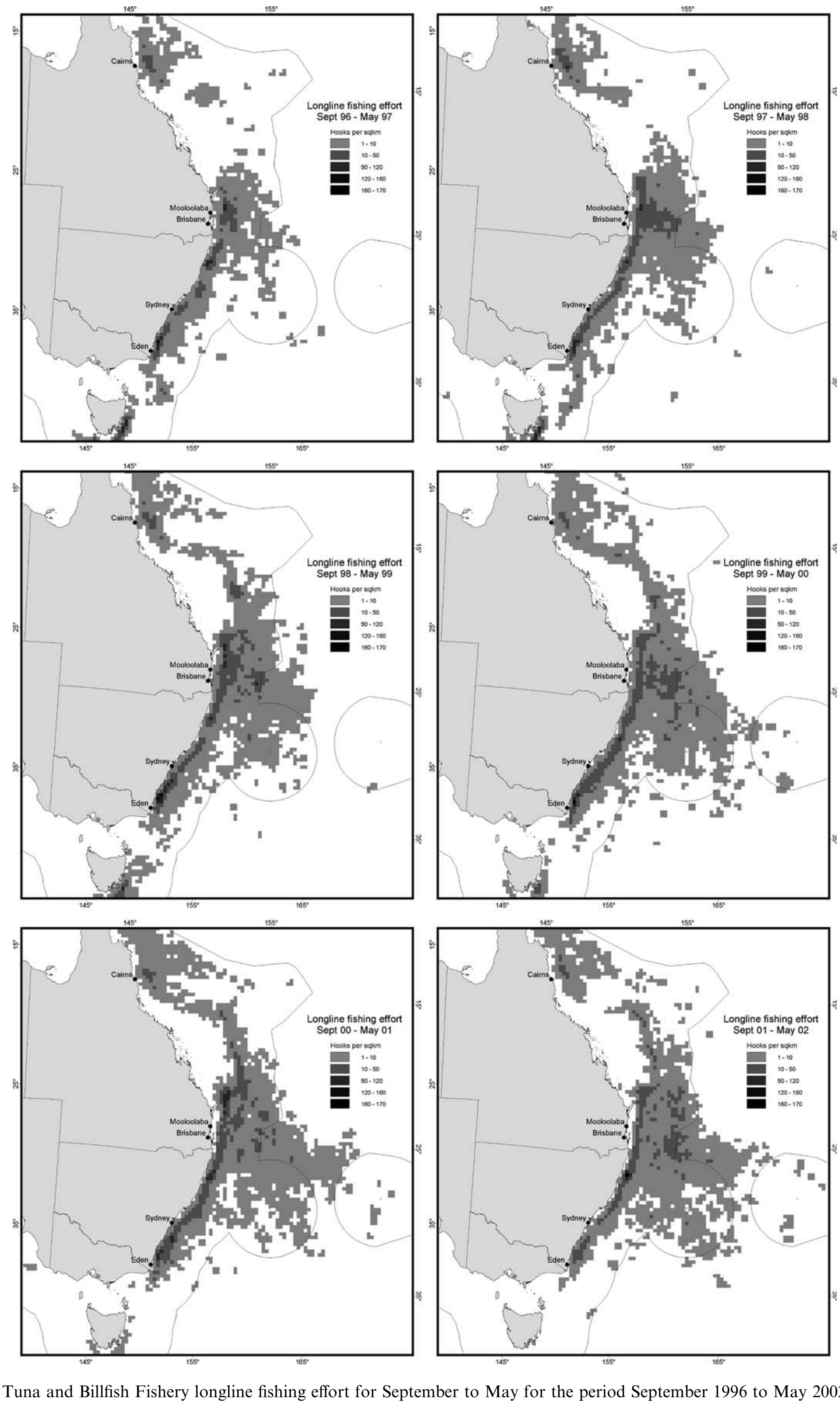

Fig. 2. Eastern Tuna and Billfish Fishery longline fishing effort for September to May for the period September 1996 to May 2002. Effort in grids with less than five vessels has been removed.

Table 2
Bycatch rates of flesh-footed shearwaters observed during mitigation trials in the Eastern Tuna and Billfish Fishery during the Austral summer (September–May) from 2000 to 2003

Area	Time of set	Hooks observed (number)	Birds caught	Bycatch rate (birds/1000 hooks)	Confidence Intervals (95%)
20°S – 25°S	night	3,555	0	0.000	
20°S – 25°S	day	0	0	0.000	
20°S – 25°S	total	3,555	0	0.000	
25°S – 30°S	**night**	**9,510**	**0**	**0.000**	
25°S – 30°S	**day**	**18,141**	**4**	**0.220**	**(0.05, 0.44)**
25°S – 30°S	**total**	**27,651**	**4**	**0.145**	**(0.04, 0.29**
30°S – 35°S	**night**	**83,023**	**35**	**0.422**	**(0.2, 0.72)**
30°S – 35°S	**day**	**205,201**	**207**	**1.009**	**(0.63, 1.54)**
30°S – 35°S	**total**	**288,224**	**242**	**0.840**	**(0.4, 1.69)**
35°S – 40°S	night	26,090	0	0.000	
35°S – 40°S	day	115,791	8	0.069	(0.03, 0.13)
35°S – 40°S	total	141,881	8	0.056	(0.01, 0.1)
25°S – 35°S	**night**	**92,533**	**35**	**0.378 (1)**	**(0.17, 0.64)**
25°S – 35°S	**day**	**223,342**	**211**	**0.945 (2)**	**(0.6, 1.42)**
25°S – 35°S	**total**	**315,875**	**246**	**0.779 (3)**	**(0.51, 1.09)**

Fishing areas have been stratified by 5° latitude bands. The shaded area indicates the distributional range of birds during the bird's breeding season. The numbers in parentheses represent the bycatch rate for each of three scenarios (see text).

Table 3
Estimated fishing-related mortality of flesh-footed shearwaters in the East Coast Tuna and Billfish Fishery during the period 1998 to 2002

Year	Number of hooks set by area during Austral summer (1000 hooks)			Estimated number of birds killed Scenarios		
	25°S–30°S	30°S–35°S	Total	1	2	3
1998	2863	999	3862	1460	3650	3008
1999	3215	1163	4378	1655	4137	3410
2000	2956	1517	4473	1691	4227	3484
2001	3256	1627	4883	1846	4614	3804
2002	4021	2119	6140	2321	5802	4783
Total	16,311	7425	23,736	8972	22,431	18,490
Mean	3262	1485	4747	1794	4486	3698
Estimated annual fishing bycatch rates (%)				3.8%	9.6%	7.9%

The number of birds killed each year was estimated by multiplying the bycatch rates for each of three scenarios (see text, and Table 2) by the mean number of hooks set between latitudes 25°S and 35°S during the Austral summer (September–May). Estimates of annual mortality are for a population of 47,000 breeding adults.

Vulnerable or Endangered (International Union for Conservation of Nature and Natural Resources, 2001).

All models assumed that fishing mortality was only impacting breeding birds, but this assumption is based on a small autopsy sample of bycatch birds. It is possible that juvenile birds are also impacted and, if this is the case, then recruitment into the breeding population will be affected. Recruitment levels have been observed to have a large influence on the growth rate of populations in other modelling studies (Cuthbert et al., 2001). Longline fishing impacts on recruitment of flesh-footed shearwaters will therefore accelerate population decline.

Additional mortality from other fisheries was also not considered in our modelling, but this may also be contributing to a decline in the population. Eastern Australian shearwaters may be impacted by other fisheries located either adjacent to the breeding grounds, or in the north Pacific where the population is present from June to August. There are large bigeye tuna (*Tunnus obesus*) fishing grounds located to the east of Lord Howe Island that are currently utilised by the Japanese distant-water longline fleet (Tuck et al., 2003). The overlap of breeding birds from the Australian population and this fishery is likely but has not been substantiated. Bycatch of flesh-footed shearwaters banded on Lord Howe Island has been recorded from salmon and squid driftnet fisheries in the north Pacific (Australian Bird and Bat Banding Scheme, unpublished). The level of bycatch from these fisheries was estimated at 999 flesh-footed shearwaters in 1990 (Johnson et al., 1993) although

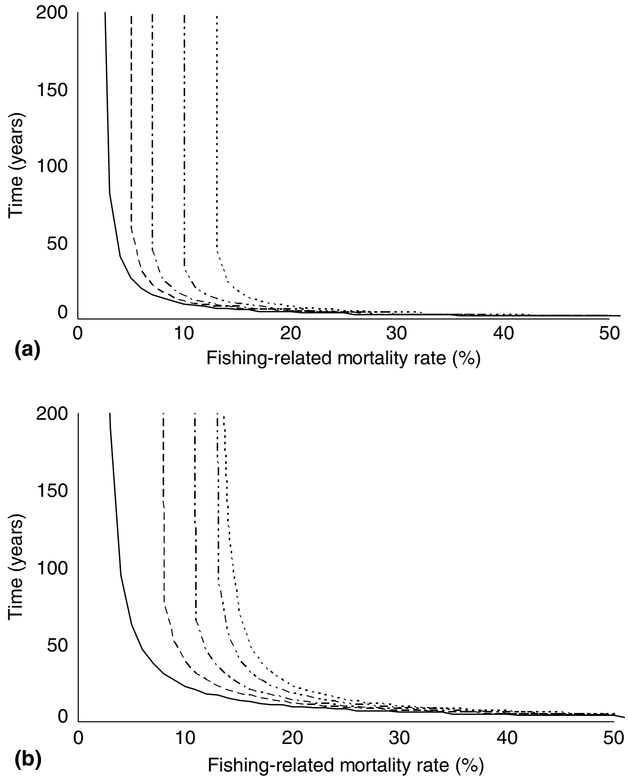

Fig. 3. The population halving time (a) and years to quasi-extinction (b) resulting from fishing-related mortality (0% to 100%) on the Lord Howe Island population of flesh-footed shearwater. The solid line represents density independent population, while the dashed and dotted lines represent density-dependent populations where $\gamma = 0.5$, 1, 2, 5 from left to right, respectively

not all of these birds can be assumed to be from the Australian population. While high-seas driftnet fishing has now ceased, inshore set nets fisheries in northern Pacific waters are still operational and may catch flesh-footed shearwaters.

The level and composition of seabird bycatch observed in the Eastern Tuna and Billfish Fishery differed greatly from that reported for Japanese vessels operating within Australia's Fishing Zone (Gales et al., 1998; Brothers et al., 1999). While over 90% of seabirds caught in the Eastern Tuna and Billfish Fishery were flesh-footed shearwaters, bycatch on Japanese vessels comprised mainly albatross species, with flesh-footed shearwaters forming only 9.6% of carcasses examined (Gales et al., 1998). While there are obvious temporal and spatial differences in the Japanese and Australian fleet characteristics, a striking difference between both fleets is the type of bait used. Japanese vessels use large squid baits, where Australian vessels have widely adopted the use of live fish bait since the mid 1990s (Australian Fisheries Management Authority, unpublished). It is possible that live bait is more attractive and available to flesh-footed shearwaters, which have greater diving capabilities than albatrosses. The impact of bait-type on bycatch of shearwaters and other seabird species merits further investigation.

4.1. Management implications

Data limitations and the spatial scale of interactions are the two key points that need to be addressed to understand the effects of fisheries bycatch on an organism (Lewison et al., 2004) and both of these are relevant to this species. There is an immediate requirement to obtain demographic data for flesh-footed shearwaters and improve understanding of the spatial scale of fisheries interactions, which will assist in reducing the uncertainty identified in our modelling. In addition, as the results of the modelling are highly contingent on the magnitude of density-dependence, knowledge of how this operates in this species is also essential to our understanding of the viability of this population.

Notwithstanding this uncertainty, it is evident that bycatch of flesh-footed shearwaters in the Eastern Tuna & Billfish Fishery is most likely unsustainable. There is clear evidence from other fisheries that seabird bycatch can be greatly reduced when appropriate mitigation measures are applied during fishing operations (Scientific Committee for the Conservation of Antarctic Marine Living Resources, 2003). Unfortunately, mitigation measures such as mandatory night-setting of longlines have not worked for flesh-footed shearwaters in the Eastern Tuna and Billfish Fishery. The observed bycatch rate for all night-set lines within the fishery was 0.378 birds/1000 hooks, and even higher (0.422 birds/1000 hooks) in areas adjacent to the birds breeding site (between latitudes 30°S–35°S) where fishing effort is high. Although these rates are lower than that observed for day sets, they are not sufficiently low to ensure population viability in the medium to long term at current fishing levels.

There is therefore an urgent need to develop a suite of mitigation measures that will halt or greatly reduce the level of bycatch currently being experienced. The initial purpose of the ongoing mitigation trials was to examine the efficacy of mitigation measures such as underwater setting gear, and 38 or 60 g weighted swivels on branchlines used in combination with twin bird-scaring lines. These measures were not successful in reducing bycatch substantially during daylight sets and resulted in higher bycatch rates than those observed in night sets. Other measures that warrant investigation include the application of more weight to branchlines, or the imposition of seasonal closures between latitudes 25°S–35°S, and particularly between 30°S and 35°S, for part or all of the flesh-footed shearwater breeding season. The use of seasonal closures has proven extremely effective in managing bycatch problems in other fisheries, and their introduction around major seabird-breeding sites is the main reason that seabird bycatch has been reduced to extremely low

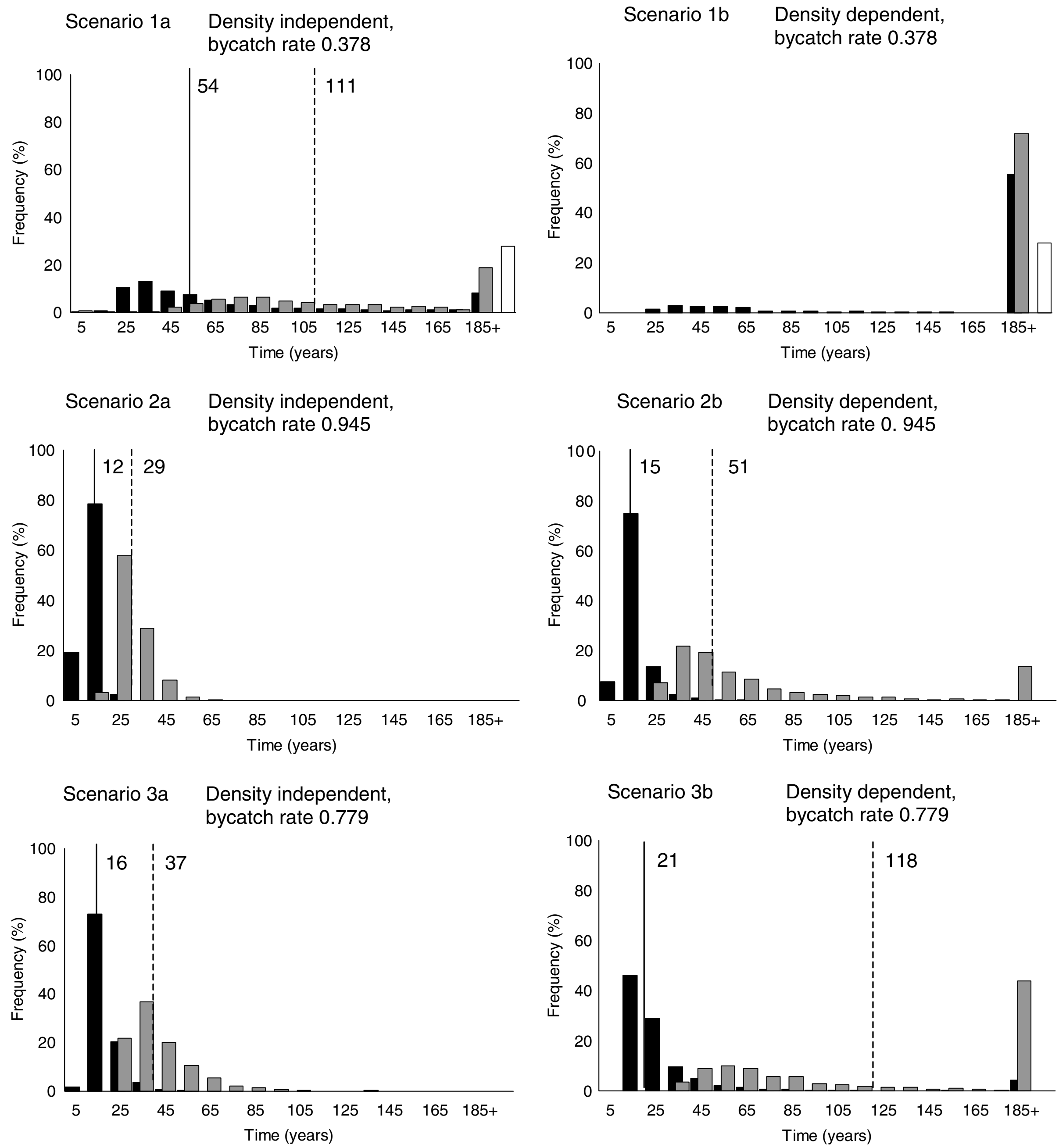

Fig. 4. Stochastic simulations for three scenarios (Table 3). The filled bars represent halving times and shaded bars represent years to quasi-extinction. Median halving and quasi-extinction times are represented by solid and dashed lines, respectively (note medians exceed 1000 years in scenario b). The open bars represent the percentage of increasing populations. Scenarios 1a–3a represent density independent scenarios and 1b–3b represent density dependent scenarios where $\gamma = 0.5$.

levels (>0.002 birds/1000 hooks) in Antarctic demersal toothfish fisheries (Scientific Committee for the Conservation of Antarctic Marine Living Resources, 2003).

It should be noted that although the Lord Howe Island shearwater population is relatively small, low levels of bycatch within the fishery can be sustained. If bycatch could be reduced to less than 0.05 birds per 1000 hooks at current effort levels, it would not only meet the seabird target bycatch level required by the Australian government (Environment Australia, 1998), but also ensure the population was not adversely impacted by this threat alone. At present, this does not appear to be an easy task. Fishing methods which rely on lightweight gear for operational effectiveness, and which are deployed in areas where seabirds with highly developed diving capabilities such as shearwaters and white-chinned petrels (*Procellaria aequinoctialis*) are present, represent the greatest challenge to those seeking to minimise bycatch problems.

Achieving this goal will require a dedicated approach by all stakeholders in the fishery, but the experiences of the Commission for the Conservation of Antarctic Marine Living Resources (Scientific Committee for the Conservation of Antarctic Marine Living Resources, 2003) in a fishery with an historically high level of bycatch demonstrate that this is entirely achievable.

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