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Article *in* Emu · December 1998

DOI: 10.1071/MU98042

CSIRO Publishing

Emu

Volume 98, 1998

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Birds Australia

Published by CSIRO Publishing
for the Royal Australasian Ornithologists Union

www.publish.csiro.au/journals/emu

EMU Vol. 98, 305-316, 1998

0158-4197/98/04305 + 11
10.1071/MU98042
Received 22-6-1998, accepted 4-10-1998

The Influence of Environmental Factors and Mitigation Measures on By-Catch Rates of Seabirds by Japanese Longline Fishing Vessels in the Australian Region

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Summary: Most seabirds caught and killed by longline fishing are captured during line setting. Data collected by Australian observers on Japanese longline vessels from April 1992 to March 1995 were used to investigate the influence of various environmental factors and mitigation measures on seabird catch rates. Generalised linear models were used to test the significance of the effect of each factor. The environmental factor that most influenced the seabird catch rate was whether line setting was carried out at night or during the day. From the data examined, the chance of catching seabirds during day sets was five times greater than for night sets. For night sets, the chance of catching seabirds during the full half-phase of the moon was five times greater than during the new half-phase. The area and season fished were also significant, while wind, cloud and sea conditions were not. Considerable variation in the seabird by-catch rate among vessels was found. This was probably due to differences in their implementation of mitigation measures, as well as the clumped distribution of seabirds by area and time. Although the by-catch rate was significantly different among years, the differences were small in comparison to other factors. An examination of the influence of mitigation measures for sets made during the day in summer in the Tasmanian area showed that the level of bait thawing and unidentified factors related to individual vessels were most significant in determining the seabird by-catch rate, followed by the use of a bait throwing device. For this data set, the amount of cloud cover had an influence, while moon phase, sea conditions and wind strength did not. The effect of using bird scaring tori poles and lines was not examined, as these were used during all sets examined in detail.

Recent declines in the population size of several albatross species (e.g. Tomkins 1985; Weimerskirch & Jouventin 1987; Croxall et al. 1990) and estimates of seabird by-catch from commercial fishing operations (e.g. Brothers 1991; Murray et al. 1993; CCAMLR 1994; Klaer & Polacheck 1995) have led to the recognition that longline fishing is a threat to the long-term viability of some seabird populations, notably albatrosses. A number of international treaties, conventions and agreements have acknowledged this threat and recommended action to reduce albatross by-catch by longline fisheries (e.g. Bonn Convention 1995, 1997; International Union for Conservation of Nature and Natural Resources 1996). In 1995, the Australian Government listed pelagic tuna longlining as a key threatening process for seabirds (particularly albatrosses) under the Australian Government Endangered Species Protection Act.

Analysis of Australian Fishing Zone (AFZ) observer records from 1992 to 1995 showed that Japanese longline vessels in the southern Australian region caught at least 2800 to 3600 seabirds each year, and 78% of these were albatrosses (Klaer & Polacheck 1995, 1997a). Black-browed Albatross *Diomedea melanophrys* and Shy Albatross *D. cauta* were caught in the greatest numbers, and catches of Yellow-nosed Albatross *D. chlororhynchos*, Wandering Albatross *D. exulans* and Grey-headed Albatross *D. chrysostoma* were also high (Klaer & Polacheck 1995, 1997a).

Mitigation measures designed to reduce the catch of seabirds by longline fishing have also been recommended (e.g. Brothers 1991; CCAMLR 1994; Alexander et al. 1997). These measures include setting lines at night; trailing bird scaring lines and streamers behind fishing vessels during line setting ('tori poles' and 'tori lines'); using machines to cast baits clear of the vessel wash during line setting; weighting lines more heavily so that they sink more quickly; thawing bait; using bait that sinks more readily; closing fishing areas or seasons; and not dumping offal near the fishing lines during setting and hauling.

Environmental conditions would have an influence on longline catch rates of seabirds for a number of reasons. In any area and time, environmental conditions can change the chance of catching seabirds by a fishing vessel by influencing the abundance of seabirds in the same area as the fishing vessel, whether seabirds in the area are actively foraging for food or the efficiency of mitigation measures being used by the fishing vessel. The chance of catching seabirds would be highest in areas and times where large numbers of susceptible birds are actively foraging, and conditions reduce the efficiency of mitigation measures in use.

The effect of mitigation measures and environmental factors on the catch rates of seabirds by Japanese longline vessels in the Australian region has not been measured. It has been shown that setting longlines at night rather than during the day is an effective method that may be used to reduce incidental catches of seabirds (Brothers 1991; Murray et al. 1993; Klaer & Polacheck 1995). Cross-tabulations of seabird by-catch rates by environmental conditions and the use of seabird by-catch mitigation measures were presented in Klaer & Polacheck (1995). However, the relative importance of the various factors in influencing seabird by-catch rates has not been analysed. This paper presents such an analysis of the available Australian observer data from April 1992 to March 1995.

Methods

A fishing year was defined to start in April and end in March the following year, with the winter season generally from April to September and the summer season from October to March. These seasons delimit the movements of the Japanese fishing fleet (Sainsbury et al. 1994; Klaer & Polacheck 1995). The seasonal distribution of seabirds differs by species, but many have distinct summer and winter distributions (see Marchant & Higgins 1990).

Allocation of time of capture

To determine whether an event occurred during the night or day at any point on the globe requires the time, and the position in latitude and longitude of the event. The following describes how the time of capture was estimated for each seabird recorded by observers.

Almost all seabirds retrieved dead on hauling of a longline are hooked during line setting while the bait is close to the water surface (Brothers 1991). Baits normally sink out of reach of seabirds within a short time, so it follows that the time of capture for most seabirds is close to the time that the hook was set. The actual capture is not usually observed and recorded as the line is set, and must be estimated from recorded events during line hauling.

Time of capture (t) was estimated using a method similar to that used by Murray et al. (1993). Using the time of an event during the haul t_{ev} (in this case the observed landing of a seabird) in relation to the time of haul start (t_{hs}) and end (t_{he}), the time of the event during the set (t) is estimated as a proportion of the time between set start (t_{ss}) and set end (t_{se}) as follows:

$$t = t_{ss} + (t_{se} - t_{ss})\left(x - \frac{(t_{ev} - t_{hs})}{(t_{he} - t_{hs})} \right)$$

The value for x was set to 1 if the line was hauled from the end of the line last set, and to 0 if from the start of the set. Most hauls (93% of all observed hauls) were made from the end of the set.

This method assumes that the line is both set and hauled at a reasonably constant rate. A number of events during hauling may lead to delays, including line breaks, line tangles and retrieval of large tuna. When a line break is encountered during the haul, the vessel may recommence hauling on a section of line that is out of sequence with the line set (C. Ramirez pers. comm.). The assumption is therefore not always met, which means that some fishing effort and incidental kills may be mis-classified as to whether they took place during night or day. The consequence of any such mis-classifications will be to reduce the probability of detecting a significant difference in catch rates between day and night and to under-estimate the magnitude of any effect. To minimise the amount of mis-classification due to gear problems, sets that took more than 10 h to set or more than 15 h to haul were excluded from the analyses (setting normally takes about 6 h and hauling about 12 h).

Calculation of day and night

From first light to sunrise and sunset to last light are periods of twilight. Preliminary examination of seabird catch rates found that catch rates during twilight are usually more similar to catch rates during the day than at night (Klaer & Polacheck 1995). For this study, times of capture were defined only in terms of night or day, delimited by the time of evening and morning nautical twilight. The latter was calculated from the position (latitude and longitude), the date, and algorithms by Doggett et al. (1990) to produce the times of astronomical events in Greenwich Mean Time.

For each observed set, observers recorded the start and end time for each observation period during the haul, as there was often more than one observation period. Observers recorded the total hooks observed during a haul, but not the number of hooks observed in each observation period during the haul. These were estimated by multiplying the proportion of total observation time that occurred during an observation period by total observed hooks for the haul. Using the same method as that used to allocate time of capture, start and end times for observation periods during the haul were translated to corresponding times during the set. Using start and end times for observed hooks during the set, and the calculated times for nautical twilight, it was possible to estimate for any observed hook, whether the hook was set during the night or day. It was also possible to estimate how many hooks were set and how many birds were caught during night and day for each set.

Selection of sets

The geographical starting positions of all observed sets are shown in Figure 1. Observations from only the southern regions (south-east Indian Ocean, southern Australia, Tasmania and south-east Australia) were included in the analyses in this paper, because there are few albatrosses and very low seabird catch rates in northern waters (Klaer & Polacheck 1995, 1997a). Therefore, sets from northern waters can provide little information on factors affecting seabird by-catch rates.

Sets for which critical information was either not recorded or there was an unresolvable inconsistency were also excluded. Records for sets made using monofilament mainline rather than traditional Kuralon were excluded as it was found that monofilament appeared to substantially increase seabird catch rates when it was introduced in 1993, but this effect was not as apparent for 1994 (Klaer & Polacheck 1997a). Altogether, about 30% of the observed sets were rejected (Table 1). Records were mostly rejected because the time zone had not been recorded. This information is critical for estimating the time at which hooks were set, as the Australian Fishing Zone spans four hours in longitude (GMT +7 h to GMT +10 h). On Japanese longline vessels the observers usually record set times according to Japan time (GMT +9 h), but sometimes use local or other time zones. It was only during the 1992 fishing year that observers began recording the time zone used on the vessel.

Because mis-recording of information for a set is likely to be independent of factors affecting seabird catch rates, filtering should have produced an unbiased random sample of the records. A valid time of capture was subsequently obtained for all birds recorded captured for valid sets, avoiding the introduction of a bias

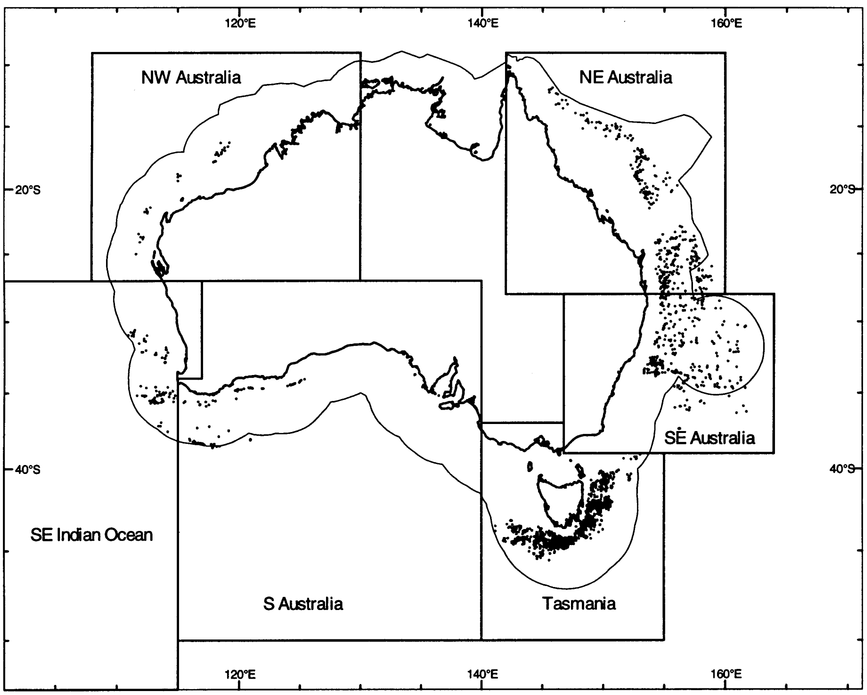

Figure 1 Position of observed Japanese longline sets from 1 April 1992 to 31 March 1995.

through additional rejection of whole set records based on invalid bird capture times.

Our intention in this study was to examine the relative effect of various factors on the seabird catch rate, assuming that the observed catch rate was a reliable indicator of the actual seabird kill rate. There are various reasons why estimates of the number of seabirds killed by longlining are underestimated when based on the number of birds that observers record hooked on the line during hauling (Klaer & Polacheck 1997a). If the level of underestimation was constant across the factors that we examined in this study, then our results also apply to seabird kill rates. There is no available information that we could use to quantify this kind of bias for most of the factors examined, if it does exist.

Generalised linear models (GLMs)

In the statistical analyses, an event is defined as the setting of a longline and a trial is the setting of a single hook. The response variable examined was the number of seabirds (0 or 1) caught per hook in a set. Therefore, a logistic regression procedure (see McCullagh & Nelder 1983) was chosen to model the process of capturing seabirds. The distribution of the response variable was assumed to be binomial and the logit link function (McCullagh & Nelder 1983) was used. For the purposes of the GLM, the 1420 valid sets detailed in Table 1 were divided into portions of the set that were made during the night and day. This division produced 2291 valid events for the analysis. In this paper, the GLM carried out using all available data is referred to as the full GLM, and the GLM carried out using selected data is referred to as the subset GLM.

To simplify the analysis and to allow presentation of cross-tabulations, all factors of interest were reduced to a small number of discrete classes as shown in Table 2. All of this information comes directly from information recorded by the observers. The year, time of capture, moon phase and season were derived from time, date and position recordings. The area was derived from position recordings. The wind, cloud and sea conditions were recorded using the Beaufort scale, percentage cover and metres swell respectively. Mitigation measures were recorded directly using the same classes and explanations shown in Table 2. A cross-tabulation showing the number of records available for analysis per factor class for the full GLM is given in Appendix 1.

The linear form of the model used was:

$$\ln\left(\frac{\pi}{1-\pi}\right)=\sum_{j=1}^{p}\beta_j$$

where π = probability of catching a seabird on a hook,

Table 1 Japanese longline observer per-set data used for time of capture calculations, with reasons for the rejection of certain records based on incompleteness or inconsistency.

Reason for rejection[1]	Sets				Birds			
	1992	1993	1994	Total	1992	1993	1994	Total
Total number of records	634	884	532	2050	252	429	196	877
Time zone not recorded	223	61	20	304	60	36	0	96
Incomplete or inconsistent observation period durations[2]	8	24	39	71	0	0	2	2
Monofilament gear	0	32	32	64	0	140	1	141
Haul time > 15 hours	19	22	22	63	20	4	5	29
Mismatch of calculated observed hooks[3]	11	27	8	46	3	17	5	25
Haul start or end time not recorded	17	7	16	40	1	0	0	1
Observation period overlap[4]	9	6	5	20	0	1	1	2
No hooks observed	9	7	2	18	0	0	0	0
Set time > 10 hours	1	3	0	4	3	1	0	4
Number valid	337	695	388	1420	165	230	182	577
Percent valid	53	79	73	69	66	54	93	66

[1] Only the first reason for the rejection of a record is included in this summary, so the table does not show the total number of records failing each criterion. [2] After adding times for each observation period, total time less than or equal to 0. [3] Total hooks observed from all observation periods differs from the recorded total hooks observed by more than 40%. [4] Times of start and end of observation periods overlap.

p = total number of factors,
β = the value of a factor, and
j = factor index.

In assessing the goodness of fit of the model to the data, the log-likelihood ratio statistic or deviance was scaled to approximate a chi-squared distribution by dividing by a scaling value (McCullagh & Nelder 1983). The scaling value was calculated by dividing the Pearson chi-square value for the maximal model by the degrees of freedom for the maximal model. The maximal model is the model that includes all factors of interest (note this distinction from the full model that includes all of the data). The influence and statistical significance of the inclusion of each factor is determined by comparison of the unexplained deviance and degrees of freedom of a model that does not include the factor with the unexplained deviance and degrees of freedom of the maximal model. A calculated scale value greater than 1.0 indicates either a poorly fitting model, or over-dispersion in the data. A scale value close to 1.0 indicates that the data are consistent with the underlying model and error structure. Over-dispersion, which is common in GLM applications (McCullagh & Nelder 1983), indicates a clumping of events.

Table 2 Observed vessel, environmental and seabird by-catch mitigation factors included in the GLM analyses and discrete classes defined for each factor.

Factor	Classes	Explanation
Vessel	Various	Unique identifiers for each fishing vessel
Year	1992	1 April 1992 to 31 March 1993
	1993	1 April 1993 to 31 March 1994
	1994	1 April 1994 to 31 March 1995
Time of capture	Night	Nautical dusk to nautical dawn
	Day	Nautical dawn to nautical dusk
Moon phase	Full	From mid-phase to mid-phase through full
	New	From mid-phase to mid-phase through new
Area	SE Australia	
	Tasmania	
	Southern Australia	
	SE Indian Ocean	
Season	Winter	April to September
	Summer	October to March
Wind	Low	Beaufort scale 0 to 3
	Medium	4 to 6
	High	Over 6
Cloud	Low	0 to 35% coverage
	Medium	36 to 65%
	High	66 to 100%
Sea	Low	0 to 2.5 m swell
	Medium	2.6 to 4.5 m
	High	Over 4.5 m
Tori pole*	Yes	Tori pole in use during line setting
	No	No tori pole
Bait thawing*	Poor	Bait not thawed
	Fair	Bait partly thawed
	Good	Bait well thawed
Bait thrower*	Yes	Bait thrower in use during line setting
	No	No bait thrower

* Information for these factors was not recorded in much of the data set (see Appendix 1), so these factors were not examined in the full GLM. Bait thawing and bait thrower factors were examined using the subset GLM.

Results

Generalised linear models

A cross-tabulation of the sample sizes (in sets) used for the GLM analyses is given in Appendix 1. Sample numbers are highest in the Tasmanian region generally. As observers are deployed to obtain similar coverage rates by area and time strata, this is mainly because of the higher total fishing effort in this region by Japanese vessels during the years examined.

Results for the full GLM are given in Table 3. The maximal model included vessel, time of capture, moon phase, time of capture by moon phase interactions, area, season, area/season interactions, wind, cloud, sea condition and year as factors. After exclusion of non-significant factors, the final model included vessel, time of capture by moon phase interactions, time of capture, area, season and year.

The scale value obtained here of 1.284 (2809/2187) suggests that there is some over-dispersion in these data. In our case this means that for some reason, if a seabird is caught on a hook during a set, then the capture of further birds is more likely than a random distribution of events would indicate. Over-dispersion is not surprising, as the spatial and temporal distribution of seabirds is probably highly clustered within the large area and time strata used for the GLM. Murray et al. (1993) examined small-scale differences in seabird capture rates by area and concluded that catch rates differed among areas that were closely spaced (within 100 nautical miles). The environmental factors that most affect seabird catch rates are time of day (day/night sets) ($P < 0.001$), area fished ($P < 0.001$) and season

Table 3 Measures of the effect of including vessel and environmental factors on model deviance, and the significance of exclusion of each factor in alternative models for the full GLM.

Model	Nominal		Change			χ^2
	d.f.	Deviance	*d.f.*	Deviance	Scaled deviance	*P* value
Null model	2290	2316.21				
Maximal model	2187	1082.47				
Vessel	2272	1610.00	85	527.53	410.72	< 0.001
Time*Moon	2188	1096.17	1	13.70	10.67	< 0.01
Time	2189	1239.07	2	142.90	111.26	< 0.001
Moon	2189	1096.19	2	0.02	0.02	ns
Area*Season	2190	1084.32	3	1.85	1.44	ns
Area	2193	1121.63	6	37.31	29.05	< 0.001
Season	2191	1128.33	4	44.01	34.26	< 0.001
Wind	2189	1082.90	2	0.43	0.34s	ns
Cloud	2189	1084.01	2	1.54	1.20	ns
Sea	2189	1083.16	2	0.69	0.54	ns
Year	2189	1090.90	2	8.43	6.56	< 0.05
Final model	2196	1086.87	9	4.40	3.43	ns

d.f. = degrees of freedom. Indented excluded factors indicate that both the factor and the interaction term which included that factor were excluded.

fished ($P < 0.001$) (Table 3). Of less importance but still highly significant is an interaction of time of day and moon phase ($P < 0.01$), and the year was significant ($P < 0.05$). Effects that were not significant in the full model were moon phase alone, area/season interactions, wind, cloud and sea conditions.

The vessel factor was highly significant ($P < 0.001$), indicating that there are substantial differences among vessels in their seabird by-catch rates, independent of the environmental factors included in the model. Differences among vessels in their capacity to catch seabirds would include the type and quality of seabird mitigation measures employed. The full model does not include mitigation factors, as only a small fraction of the available data per longline set includes information on all mitigation measures used (see Appendix 1). However, as it would be reasonable to expect that the procedures used by particular vessels across different sets would not vary as greatly as inter-vessel differences, procedural differences related to mitigation measures would tend to be attributed directly as vessel effects in the full model. Anecdotal accounts from fisheries observers also report that the quality of implementation of various mitigation measures such as bird scaring poles and lines varies considerably among vessels (Klaer & Polacheck 1995).

About 53% of the null model deviance is explained by the full model. This indicates that over half of the variation in seabird by-catch can be explained by the six significant factors included in the model and suggests that these factors are important variables that need to be considered in assessing by-catch rates. While substantial variation remains unexplained by the model, this is not surprising given the high degree of spatial and temporal clustering of seabirds.

Transformed values shown in Table 4 are presented as odds ratios (r), and are the odds of an event occurring under one condition divided by the odds of an event occurring under another. The condition used as the comparison standard does not have an odds ratio assigned in the table. The odds ratio in Table 4 for time of setting is the odds of a bird being caught at night divided by the odds of a bird being caught during the day: $r = o_n/o_d = 0.21$. These ratios allow the calculation of relative probabilities. For example, if the probability of catching seabirds at night (p_n) is one per thousand hooks, the probability is 0.001 and the odds are 1:999, $o_n = p_n/(1 - p_n) = 0.001/(1.0 - 0.001) = 0.001001$. In the case of relatively rare events (as in seabird captures),

Table 4 Parameter estimates produced by the final model of the full GLM, standard errors of the estimates (Est. *s.e.*), transformations of the estimates to odds ratios (anti-log of the estimates) and 95% confidence intervals for the odds ratios using ± 1.96 times the standard error.

Factor	Class	Estimate	Est. *s.e.*	Odds ratio	Min 95%	Max 95%
Time	Day	0.00	—			
	Night	–1.58	0.33	0.21	0.11	0.40
Time * Moon	Day – full	0.00	—			
	Day – new	0.05	0.12	1.05	0.82	1.34
	Night – full	0.00	—			
	Night – new	–1.70	0.71	0.18	0.04	0.75
Area	S Aus	2.20	0.53	9.04	3.14	26.06
	SE Aus	0.11	0.43	1.12	0.48	2.64
	SE Ind	0.04	1.01	1.04	0.14	7.87
	Tas	0.00	—			
Season	Summer	1.13	0.23	3.10	1.96	4.89
	Winter	0.00	—			
Year	1992	–0.33	0.24	0.72	0.45	1.17
	1993	0.18	0.25	1.19	0.72	1.98
	1994	0.00	—			

The estimated standard error was adjusted to account for a scaling factor other than 1.0 by multiplying by the square-root of the scaling factor (1.284).

the odds of an event occurring and the probability of the event are almost the same. This means that we can use the odds ratios to estimate the ratio of the probabilities. Therefore, if the probability of catching a seabird at night is 0.001, then the probability of catching a seabird during the day $p_d = p_n/r = 0.001/0.21 = 0.0048$, or 4.8 birds per thousand hooks. Night catch rates were approximately one fifth of day catch rates, irrespective of other factors such as moon phase.

The moon had little influence on day catch rates by moon phase ($r = 1.05$). Night sets during the new moon, however, had about one fifth of the probability of catching seabirds as sets made during the full moon ($r = 0.18$). It also follows (after some algebra) that night sets during the new moon have about one-fifteenth of the probability of catching seabirds as day sets, and night sets during the full moon about one-third.

For areas, Southern Australia produced a much higher catch rate than Tasmania ($r = 9.04$); SE Australia ($r = 1.12$) and SE Indian Ocean ($r = 1.04$) were similar in catch rates to the Tasmanian area. For season, summer produced a higher catch rate than winter ($r = 3.10$). For year, 1992 produced a slightly lower catch rate than 1994 ($r = 0.72$), while 1993 was slightly higher ($r = 1.19$).

Parameter estimates for each vessel are not shown in Table 4 as there were 86 vessels in the analysis, and estimates for each are not important except for highlighting the large variation among vessels in their ability to catch seabirds. This relates in part to differences among vessels in mitigation strategies that might have been used.

As there are strong area, season and time of day effects, to exclude such influences and examine the effects of mitigation measures implemented by individual fishing vessels in detail, a subset GLM was conducted using a subset of the full data from a stratum where all of these factors were constant. The stratum chosen was the Tasmanian region during the day in summer, as it had the largest number of observations suitable for analysis in combination with a relatively high catch rate of seabirds (see Appendix 1). This combination improves the ability of the GLM to detect significant differences in mitigation effects. Results from the GLM using this subset of the data are given in Table 5. The sample size is small for this analysis (141 observed sets), as a requirement was that all classes for each factor were recorded, i.e. no factor was recorded as unknown. To keep the sample size as large as possible, the year effect found to be just significant in the full GLM was ignored, allowing examination of data from this stratum for all years.

We could not examine the effect of tori poles and lines in the subset GLM because all sets made during the Tasmanian summer used them. The maximal model did not include a vessel effect in the subset GLM, as it was expected that differences among vessels would be captured by observed differences in mitigation measures used. As the type and quality of mitigation measures used normally remain fairly constant during the time each vessel is observed, there would be confounding due to the high correlation between mitigation measures employed and the vessel. There are insufficient data available to examine interactions of vessel and mitigation effects.

Bait thawing was the most significant measured factor ($P < 0.001$), followed by use of a bait thrower ($P < 0.01$) and then cloud cover ($P < 0.05$). Moon phase, wind and sea conditions were not significant. The high significance of the re-introduction of a vessel effect indicates that there may be additional important factors affecting the seabird by-catch rates of individual vessels that have not been measured and included in the model. This may, for example, be due to differences among vessels in the quality of mitigation measures used and the fine-scale spatial clustering of seabirds within this region. Interestingly, the scaling value for the subset GLM was 269/130 = 2.07, which is more over-dispersed than the full GLM. This suggests that

Table 5 Subset GLM (Tasmanian region day sets during summer): contribution of various environmental and mitigation factors to the model fit.

Model	Nominal		Change			χ^2
	d.f.	Deviance	*d.f.*	Deviance	Scaled deviance	*P* value
Null model	140	316.48				
Maximal model	130	262.55				
Moon	131	264.30	1	1.75	1.45	ns
Bait thawing	132	276.47	2	13.92	11.56	< 0.001
Bait thrower	131	273.23	1	10.67	8.87	< 0.01
Wind	132	265.53	2	2.98	2.48	ns
Cloud	132	271.07	2	8.52	7.08	< 0.05
Sea	132	264.03	2	1.47	1.23	ns
+ Vessel	114	147.06	16	115.49	95.95	< 0.001

d.f. = degrees of freedom.

Table 6 Parameter estimates produced by the final model of the subset GLM, standard errors of the estimates (Est. *s.e.*), transformations of the estimates to odds ratios (anti-log of the estimates) and 95% confidence intervals for the odds ratios using ± 1.96 times the standard error.

Factor	Class	Estimate	Est. *s.e.*	Odds ratio	Min 95%	Max 95%
Bait thawing	Poor	0.00	—			
	Fair	–0.68	0.35	0.51	0.25	1.01
	Good	–0.68	0.51	0.51	0.18	1.41
Bait thrower	No	0.70	0.46	2.01	0.81	5.02
	Yes	0.00	—			
Cloud	High	–0.44	0.32	0.64	0.34	1.21
	Med	0.00	—			
	Low	–0.35	0.40	0.70	0.32	1.56

The estimated standard error was adjusted to account for a scaling factor other than 1.0 by multiplying by the square-root of the scaling factor (2.07).

the spatial and temporal distribution of seabirds may be more variable in this stratum than others.

Odds ratios given in Table 6 show fair and good thawing decrease the seabird by-catch rate in comparison with poorly thawed bait ($r = 0.51$). Not using a bait thrower increases the seabird by-catch rate in comparison with using one ($r = 2.01$). Both higher ($r = 0.64$) and lower ($r = 0.70$) levels of cloud cover decrease the seabird by-catch rate in comparison with medium cover. Of the significant effects, cloud cover was the least significant, and was not found to be significant at all in the full GLM. As there was also no consistent trend in the effect of cloud cover, the result for cloud cover should be treated with caution.

Examination of the Tasmanian winter stratum in a similar manner was unsuccessful because of even greater dispersion shown by the results and the smaller number of birds captured.

Cross-tabulations of seabird by-catch by significant environmental factors

Tables 7 to 10 present cross-tabulations of seabird by-catch information in relation to the environmental factors found to be significant using the full GLM.

Table 7 shows that more than half of all observations available for analysis were in the Tasmanian region. Most observations were made during winter, and there was a reasonably even distribution of total observations made during the night and day, and during new and full moon half-phases.

Table 8 shows that the distribution of observed hooks corresponds reasonably well with the distribution of observed sets given in Table 7. An indication of the proportion of fishing effort during the night per area/season stratum is given in the last column. The mean percentage of hooks set at night varies considerably by area and season. This variation is not explained by seasonal variation in the local time of sunrise (e.g. SE Indian Ocean Summer is 55% night, Tasmanian Summer is 1% night) but appears to reflect different fishing strategies used by the Japanese fleet in different areas and seasons.

Table 9 shows that a total of 577 seabirds were observed caught in southern regions of Australia from 1992 to 1994. Of these, 554 were caught during the day and 23 at night. Of those caught at night, 19 of the 23 were caught on the full half-phase of the moon. More seabirds were observed caught during summer, despite lower fishing effort during summer than for winter.

Table 10 gives an overall seabird catch rate of 0.18 for all observed sets. The catch rate during the day was 0.252 birds per thousand hooks. For hooks set at night, the catch rate was 0.022 — a reduction of 91% compared to the day catch rate. During the new moon, the night catch rate was 0.006 — a reduction of 98% compared to the day rate.

Summer catch rates were considerably higher than the winter catch rates in all areas. The highest observed catch rate in any stratum occurred in the southern Australian region during the day in summer. Interestingly, the proportion of hooks set at night in this stratum was the highest of all summer strata at 59% (Table 7).

Table 7 Total numbers of observed sets made in various environmental conditions for the full GLM data set.

Area	Season	Day New moon	Day Full moon	Night New moon	Night Full moon	Total
Southern Australia	Summer	22	20	18	21	81
	Winter	1	1	0	0	2
SE Australia	Summer	13	6	3	0	22
	Winter	77	106	59	51	293
SE Indian Ocean	Summer	5	1	5	1	12
	Winter	0	0	0	9	9
Tasmania	Summer	161	180	1	8	350
	Winter	431	343	436	312	1522
Total		710	657	522	402	2291

Table 8 Total numbers of observed hooks set (in thousands) in various environmental conditions for the full GLM data set.

Area	Season	Day		Night		Total	% night
		New moon	Full moon	New moon	Full moon		
Southern Australia	Summer	24	15	24	33	95	59
	Winter	3	2	0	0	5	0
SE Australia	Summer	28	12	3	0	44	8
	Winter	138	205	38	37	418	18
SE Indian Ocean	Summer	10	0	11	2	23	55
	Winter	0	0	0	17	17	100
Tasmania	Summer	385	427	1	8	821	1
	Winter	497	450	563	324	1834	48
Total		1085	1112	639	421	3257	33

Table 9 Total numbers of seabirds observed caught in various environmental conditions for the full GLM data set.

Area	Season	Day		Night		Total
		New moon	Full moon	New moon	Full moon	
Southern Australia	Summer	32	17	0	15	64
	Winter	1	1	*	*	2
SE Australia	Summer	11	2	0	*	13
	Winter	10	19	0	0	29
SE Indian Ocean	Summer	2	0	0	0	2
	Winter	*	*	*	0	0
Tasmania	Summer	179	178	0	1	358
	Winter	65	37	4	3	109
Total		300	254	4	19	577

* = strata in which there were no observations.

Discussion

The results of our study show that the rate of seabird by-catch during the day is consistently higher than that at night, as reported by Brothers (1991) and Murray et al. (1993). This is also consistent with the results of foraging behaviour studies (e.g. Harrison et al. 1991; Pitman and Balance 1992 (cited in Murray et al. 1993)), that suggest that albatrosses and petrels feed mainly during the day. Satellite tracking of Wandering Albatross (Jouventin & Weimerskirch 1990; Weimerskirch and Wilson 1992; Weimerskirch et al. 1997) and the use of activity recorders (Weimerskirch et al. 1997) also indicate that they more actively forage by flying during the day, while at night they rest or wait for prey at the water surface. On nights of bright moonlight, foraging by flight is more likely.

Overall, night catch rates were 91% less than the day catch rates by Japanese longline in the southern Australian region from 1992 to 1994. GLM results indicate that the chance of catching seabirds during the day was generally five times greater than at night. At night, the chance of seabird catches during the full moon was five times greater than during new moon.

The most important factor affecting by-catch rates of seabirds in southern Australian waters is whether the longline is set during the night or day. If avoiding catching birds were the only objective, then setting lines at night would be the most effective single strategy of the mitigation measures examined here. However,

Table 10 Seabird by-catch rate in birds per ’000 hooks in various environmental conditions for the full GLM data set.

Area	Season	Day		Night		Total
		New moon	Full moon	New moon	Full moon	
Southern Australia	Summer	1.34	1.16	0.00	0.45	0.67
	Winter	0.38	0.40	*	*	0.39
SE Australia	Summer	0.39	0.16	0.00	*	0.30
	Winter	0.07	0.09	0.00	0.00	0.07
SE Indian Ocean	Summer	0.20	0.00	0.00	0.00	0.09
	Winter	*	*	*	0.00	0.00
Tasmania	Summer	0.46	0.42	0.00	0.13	0.44
	Winter	0.13	0.08	0.01	0.01	0.06
Total		0.28	0.23	0.01	0.05	0.18

These catch rates are simply a division of observed birds caught from Table 9 by observed hooks set from Table 8. Totals are therefore weighted according to the fishing effort applied in each cell. * = strata where there were no observations.

the objectives of the fishing fleet are a complicated mix of maximising the value of fish caught, maximising operational efficiency and complying with management requirements. In mid-winter at 43°S, the local time of nautical dawn is 0620 h and dusk is 1740 h (12 h 40 min of darkness). In mid-summer at 43°S, the local time of nautical dawn is 0300 h and dusk is 2100 h (6 h of darkness). The average time to complete a set calculated from observer data was 5 h and 15 min. It is, therefore, physically possible to complete line setting entirely at night in any stratum within the Australian region. Whether night setting affects catch of commercial species is not clear (Klaer & Polacheck 1997b). It is also not clear whether night setting might increase the by-catch of non-target fish species, particularly shark.

From the data examined, only a third of all observed hooks were set at night in southern regions of Australia. A considerable reduction in the total by-catch of seabirds would almost certainly be achieved if the proportion of night setting were higher.

Murray et al. (1993) found that the impact of day and night setting may, however, be species-specific; and did not recommend an increase in night setting in northern New Zealand waters until the likely impact on Grey Petrels *Procellaria cinerea* had been assessed. Such analyses are difficult due to the sparse nature of seabird captures. Our analyses indicate that there is only just sufficient data to examine the influence of day and night setting for all seabirds combined. For Australian waters therefore, the impact on any particular species or species group of a shift to more night setting can not yet be well determined by statistical analysis. Continued collection of observations as well as accurate identification of species caught would make such an analysis possible in the future.

Mitigation measures related to procedures used on vessels during line setting were effective at reducing seabird by-catch. Thawing of bait so that it sinks more readily was shown to be an effective mitigation measure. The use of a bait thrower that throws baits clear of the vessel wash, thus also allowing more efficient sinking, was also shown to be effective. The level of cloud cover was shown to be a significant factor in the subset GLM, but not in the full GLM. Whether the level of cloud cover has a significant influence on seabird by-catch rates is unclear.

Seabird by-catch rates vary significantly among vessels, even when an attempt is made to account for observed differences in some of the mitigation measures used. The patchy distribution of seabirds in space and time may account for some of this variation. However, observer accounts of differences in the quality of mitigation measures such as the construction of tori poles and lines (Klaer & Polacheck 1995) suggests that some of this variability is probably due to these differences. This also suggests that seabird by-catch could potentially be further reduced by ensuring that all vessels use mitigation measures of sufficient quality.

Acknowledgements

This paper presents the work in this area carried out by the CSIRO in support of the Ecologically Related Species Working Group of the Commission for the Conservation of Southern Bluefin Tuna during 1996 and 1997. We thank the members of the working group for their comments, and the Australian Fisheries Management Authority (AFMA) for partial financial support for the analyses. Cesar Ramirez (AFMA Observer Program) provided technical advice on details of the observer databases; Thim Skousen (AFMA) gave background information on Japanese longline logbook databases; Wade Whitelaw (CSIRO) gave technical details of observer data collection procedures; Andrew Betlehem and Miroslaw Ryba (both CSIRO) helped process the AFMA observer and logbook data; Kathy Haskard (CSIRO) gave advice on interpreting the GLM results. We also acknowledge the important contribution made by the AFZ observers who collected most of the information used in this paper. Jim Hone (University of Canberra) provided useful criticisms of drafts of this manuscript.

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Appendix 1 Sample size in number of sets within each cell of the full GLM data set combined over all years.

Area	Season	Time	Moon	Sets	Hooks	Birds	CPUE	Bait thawing				Bait thrower			Tori pole			Wind			Cloud			Sea		
								Good	Fair	Poor	Unkn	Yes	No	Unkn	Yes	No	Unkn	Low	Med	High	Low	Med	High	Low	Med	High
S Aus	Sum	Night	New	18	23 719	0	0.000	0	0	0	18	1	6	11	7	0	11	12	6	0	4	8	6	17	1	0
S Aus	Sum	Night	Full	21	32 987	15	0.610	0	0	0	21	8	1	12	9	0	12	13	8	0	3	7	11	20	1	0
SE Ind	Sum	Night	New	5	10 636	0	0.000	0	0	0	5	0	0	5	0	0	5	4	1	0	2	3	0	5	0	0
SE Ind	Sum	Night	Full	1	1818	0	0.000	0	0	0	1	0	0	1	0	0	1	1	0	0	1	0	0	1	0	0
SE Ind	Win	Night	Full	9	17 092	0	0.000	0	0	0	9	0	0	9	0	0	9	5	4	0	4	3	2	9	0	0
SE Aus	Sum	Night	New	3	3316	0	0.000	1	0	0	2	0	1	2	0	1	2	1	2	0	0	1	2	3	0	0
SE Aus	Win	Night	New	60	39 238	0	0.000	6	0	0	54	0	11	49	8	3	49	31	27	2	30	21	9	55	4	1
SE Aus	Win	Night	Full	50	35 732	0	0.000	3	1	0	46	3	2	45	5	0	45	18	30	2	20	18	12	43	6	1
Tas	Sum	Night	New	1	710	0	0.000	0	0	0	1	0	0	1	0	0	1	0	1	0	0	0	1	1	0	0
Tas	Sum	Night	Full	8	7779	1	0.427	0	7	0	1	0	7	1	6	0	2	4	3	1	2	3	3	8	0	0
Tas	Win	Night	New	447	576 793	4	0.017	23	83	10	331	10	247	190	219	25	203	199	209	39	150	144	153	381	58	8
Tas	Win	Night	Full	301	310 156	3	0.007	12	50	11	228	5	114	182	97	21	183	158	117	26	79	124	98	261	35	5
S Aus	Sum	Day	New	22	23 927	32	0.872	2	0	0	20	0	11	11	11	0	11	16	6	0	6	10	6	21	1	0
S Aus	Sum	Day	Full	22	19 241	18	1.136	1	0	0	21	7	2	13	9	0	13	12	10	0	3	9	10	22	0	0
S Aus	Win	Day	New	1	2604	1	0.384	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	1	1	0	0
S Aus	Win	Day	Full	4	9885	6	0.571	0	1	0	3	1	0	3	1	0	3	3	1	0	1	1	2	3	1	0
SE Ind	Sum	Day	New	5	10 127	2	0.165	4	0	0	1	0	4	1	4	0	1	5	0	0	3	1	1	5	0	0
SE Ind	Sum	Day	Full	1	103	0	0.000	0	0	0	1	0	0	1	0	0	1	1	0	0	1	0	0	1	0	0
SE Aus	Sum	Day	New	13	28 242	11	0.391	1	0	0	12	0	1	12	1	0	12	5	7	1	4	4	5	13	0	0
SE Aus	Sum	Day	Full	6	12 390	2	0.191	0	0	0	6	0	0	6	0	0	6	2	3	1	3	2	1	6	0	0
SE Aus	Win	Day	New	78	139 467	10	0.076	9	0	0	69	0	14	64	10	4	64	40	34	4	39	28	11	70	6	2
SE Aus	Win	Day	Full	105	203 793	19	0.092	10	3	0	92	3	16	86	20	0	85	42	57	6	46	34	25	94	1	1
Tas	Sum	Day	New	161	385 174	179	0.469	13	52	9	87	26	72	63	98	0	63	81	64	16	35	55	71	137	18	6
Tas	Sum	Day	Full	180	427 137	178	0.413	13	47	8	112	9	74	97	82	0	98	70	82	28	48	65	67	154	21	5
Tas	Win	Day	New	442	509 536	65	0.106	24	75	9	334	12	241	189	222	19	201	193	205	44	146	145	151	369	61	12
Tas	Win	Day	Full	332	43 ,847	37	0.077	12	64	11	245	12	126	194	116	21	195	173	130	29	87	133	112	287	38	7

S Aus = Southem Australia; SE Ind = SE Indian 0cean; Tas = Tasmania; SE Aus = SE Australia (see Fig. 1); Unk = unknown; CPUE = mean birds per 1000 hooks for each set.