**Supplementary Material**

Seabird bycatch vulnerability in pelagic longline fisheries based on modelling of a long-term dataset

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**Contents**

Appendix S1.Additional methods and results

Table S1 Species ranking based on their relative ability to locate and take baits from baited hooks in pelagic longline fisheries.

Table S2. Seabird species codes.

Table S3. Wind score.

Table S4*.* Incidence of different types of observed seabird interactions across different levels of competition.

Table S5. Mean and 95% credible interval of model estimated captures across different levels of competition.

Table S6. Incidence of different types of observed seabird interactions across different body size classes.

Table S7 Mean and 95% credible interval of model estimated captures across different levels of body size classes.

Table S8. Classification performance of seabird interaction observations during gear deployment.

Figure S1 Estimates of species-specific bycatch loss rate (*ploss*) based on the selected model (M2d).

# **Appendix S1. Additional methods and results**

## Seabird interaction and outcome confirmation observation protocol

The observation protocol was developed in 1988 by Brothers (1991). It involves two linked observation components, one at gear deployment (the line setting stage) and one at gear retrieval (the hauling stage). Time and other positional aids, such as the interaction location relative to line surface float distances, are used to link an observed seabird interaction during gear deployment to a retrieved carcass during gear retrieval. In contrast, a routine observer program protocol only collects samples during gear retrieval.

Hooks in sight were observed simultaneously, independent of each other, and for simplicity, we only describe the observation on a single baited hook in the following. During gear deployment, a bait-taking attempt from a seabird is categorized into one of five types based on whether it leads to a capture and also the observation uncertainty. The **indeterminate type** has the most uncertainty, and it will be assigned if an individual is seen to successfully take the bait but circumstances do not allow further confirmations; an individual of the **possibly caught type** is observed to successfully take the bait, momentarily display one of the typical capture responses, the full set of which is available at Brothers *et al.* (2010), but circumstances do not allow the final confirmation of the capture; an individual of the **observed caught type** displays clear evidence of struggle and its inability to escape the line. Bait-taking attempts of types mentioned above would eventually lead to a bycatch event with decreasing uncertainty. Meanwhile, the attempt is of the **successful type** if an individual was observed to successfully remove the bait from the hook and not be caught in the process; it is of the **unsuccessful type** if the individual made no contact with the fishing gear during the attempt. All five types of observed interactions were used in the model.

Possibly caught type and observed caught type are capture types; successful type and unsuccessful type are non-capture types. A misclassification happens when a capture event (C in Figure 1 in the main text) was classified into one of the non-capture types or when a non-capture event (N in Figure 1 in the main text) was classified into one of the capture types. The rate of misclassification can be used to assess the error rate associated with seabird interaction observations. The rate of misclassification of the current study was on average c. 2% (Table A8). Note that the proportion of misclassified interactions for each interaction type varies among different species because of their differing bycatch vulnerability. On the other hand, for carcass retrieval observations, their error rate is represented by bycatch loss (c. 50%). In addition, for both types of observations, the level of uncertainty involved is high: for interaction observations, the observer was uncertain of the outcome for around half of capture events (Table A8); for carcass retrieval observations, the loss rate varied substantially with species identity (Figure A1). To properly account for the high level of uncertainty in both types of observations, it becomes necessary to collect linked observations from both.

The last in sequence of the seabirds interacting with a baited hook is of the most conservation importance. A baited hook may be pursued by a single individual or multiple individuals. When multiple individuals compete over the same baited hook, the bait-taking attempt of each individual registers as a separate count of interaction, and all the attempts were recorded. While multiple bycatch incidences on the same hook are theoretically possible, they have not been observed in the field, and in this study, we simply assume that a baited hook may catch at most one individual. In addition, the existence of a following interaction on a given hook implies that the previous interaction does not result in a capture, for example, an embedded hook would prevent additional bait-taking interactions. Only the last individual interacted with a hook is subject to bycatch with an unknown outcome. During gear retrieval, a carcass is either retrieved from the observed hook or not, and this confirms the outcome of the interaction. Therefore, in this study, we are only concerned with the last observed attempt with each hook.

About the observability of underwater bait-taking events, note that all observations are based on behavioural responses of seabirds towards baited hooks above or on the surface of the water, and underwater attacks cannot be observed *directly*. However, each underwater attack attempt, i.e., the underwater dive pursuit, and its outcome can be observed and accounted for when the bird that dived returns to the surface. Such bait-taking attempts will impose more observation uncertainty as compared to attempts occurring close to the surface.

Deliberate discarding is not one of our various explanations of failure to reconcile all observations of set capture in this study. When a section of the haul could not be observed, the crew were requested to retain all carcasses hauled. With the time of day noted, the carcass with branchline attached was kept for further examination. However, with up to 15 crew involved in gear retrieval and long-established habits for discarding birds, it was necessary to verify daily that any captured bird had been accounted for. Occasionally, a carcass was not retained, but even if this occurred, deliberately reliable crew advised of such an incidence. If results from this study were used to upscale the observed bycatch, it would not include those that might have been deliberately discarded for capture concealment which could at times be significant (Gales *et al.* 1998 ). If bycatch concealment was being practiced successfully in the presence of a not so diligent observer, the upscaling would need to further take deliberate discarding into account.

## Risk factors

Species competition score was used to measure the level of competition at the time of interaction. It was calculated as the sum of species-specific abundance of seabirds around the vessel at a given time instance weighted by their respective bait-taking capability score. Spot counts were conducted at either 15- or 30-min intervals throughout the duration of gear deployment within 500m astern and 250m to port and starboard. The weight for each observed seabird species ranges from 0 to 10 based on their capacity to engage in bait-taking interactions, with 0 for those that do not interact with fishing operations and 10 for those most adept at bait locating and recovery (Table A1). Observed species competition score ranged from 0 to 1,045 units. Four levels of competition severity were used to represent 4 levels of competition (low competition: less than 200 units, medium competition: larger than or equal to 200 and less than 400 units, high competition: larger than or equal to 400 and less than 600 units, and extra-high competition: larger than or equal to 600 units).

The feeding behaviour and the typical adult body size of species were based on literature review. While all the seabirds are capable of taking baits at or just under the surface and have some diving capacity, some species are proficient divers, able to fully submerge to seize items at some distance below the surface. In this study, a species was treated as a proficient diver if diving was recognized as a primary/main foraging strategy in the literature and/or supported by direct observation in the field. All the seabird species that participate in bait-taking are effectively scavenging, but some species regularly scavenge as a primary foraging strategy. In this study, a species was a regular scavenger if scavenging was recognized as a primary/main foraging strategy in the literature. Being treated as a regular scavenger or not in this study measures whether it is common for the species to scavenge for food in general. The typical adult body size (beak to tail length) of the 22 seabird species examined ranged from 34 cm to 121 cm. Twenty-two species were ordered by body size and organized into four categories with similar numbers of species within each size category: small-sized (5 species), medium-sized (5 species), large-sized (6 species) and extra-large-sized (6 species).

Physical environment may also affect seabird capture rate. The physical oceanic condition was used to represent the roughness of the physical environment at the time of the bait-taking attempt. It was calculated as the sum of wind score and sea score. Wind score was determined by wind speed and wind direction with respect to the vessel ranging from 1 (calm) to 8 (rough) (Table A3), and sea score was based on Douglas sea scale with the observed values ranging from 2 (slight waves) to 8 (very rough conditions). Three levels of oceanic condition were used to represent calm, intermediate and rough conditions, i.e., less than 4, larger than or equal to 4 and less than 8, and greater than or equal to 8. Most of the interactions occurred when the condition was intermediate (46%), and the least interactions occurred when the condition was calm (23%).

As the observations covered in this study include fishing trips from multiple geographical regions, including Southern Indian Ocean, Coral Sea, Southern Ocean and North Central Pacific, differences in fishing practices, adopted mitigation measures, and the composition of the seabird complex among different regions may have an additional effect on seabird capture rate. A total of 1,573 interactions were observed from the Eastern South Indian Ocean, 159 from the Coral Sea, 587 from the Southern Ocean, and 655 from the North Central Pacific.

Fishing practices and the effectiveness of various mitigation measures may have changed substantially over the 16 years covered in the original study as may have the distribution and abundance of seabirds relative to the fishing effort. To investigate the temporal effect on bycatch vulnerability, interactions observed between 1988 and 2003 were divided into three periods, i.e., from 1988 to 1992, from 1993 to 1997, and from 1998 to 2003. A total of 2,141 interactions were observed during the 1st period, 123 interactions during the 2nd period, and 832 interactions during the 3rd period.

## Species ranking based on bait-taking capacity

The following information on species ranking is based on Brothers (2008). All seabird species encountered during the experiment were given a ranking from 0 to 10 to reflect their relative ability in first locating and then successfully taking baits based on behavioural characteristics. In increasing order, the behavioural response of each species in bait-taking interactions is as follows.

Rank 0 species did not interact with fishing operations. Consequently, these species did not contribute to the risk score. These species were coded as OTH (Table A1), and they included over 30 species, including storm petrels, little shearwater.

Rank 1 species were rarely encountered in this study. When they were present, these individuals showed limited interest in fishing activity, and tended not to follow the fishing vessel. Species in this group interact little or not at all with the same or other species.

Rank 2 species includes only great-winged petrel. This species is unique in that when present in abundance, they tend to feed amicably and safely without being hooked. When present among other species, great-winged petrels tend to avoid conflict and assume a secondary role in bait-taking events. Although a capable diver, this species prefers near-surface bait recovery attempts.

Rank 3 species include the larger species of albatross, the royal and the wandering, both of which are equally inept at bait location and recovery. They lack aerial agility and do not submerge fully in dive attempts. Such limitations put these species at considerable disadvantage, and they are often out-competed by most other species in bait-taking events.

Rank 4 species include cape petrel and grey petrel. Cape petrels are abundant, and they have a specific role as one of the most important species for determining the location where a bait is still accessible. They are aggressive among their own species but are readily intimidated by most other species. Seldom actually caught, this species is however indirectly responsible for the capture of many other species. Grey petrel is also a locator of baits and have limited surface dive capability.

Ranks 5 to 8 species are13 albatrosses, with the ranking reflecting their relative aggressiveness, agility and diving capabilities. Two albatross species from the northern hemisphere have two remarkably similar counterparts in the southern hemisphere. Shy albatross (south) and black-footed albatross (north) are a close match, and also the pair black-browed albatross (south) and Laysan albatross (north). Both pairs of species exhibit similar physical attributes, and behavioural responses toward the bait, their own species and other species. Rank 6 species are fast and manoeuvrable in flight and have well developed diving capabilities, but they tend to be readily intimidated and either relinquish baits or abort bait-taking attempts.

Ranks 9 and 10 species are among the most aggressive and persistent in bait-taking attempts. Grey petrel in rank 9 is very similar to white-chinned petrel in behavioural attributes, but grey petrel is much more timid and easily intimidated whereas white-chinned petrel will fight aggressively. Black petrel most resembles grey petrel and along with white-chinned petrel all three species in contrast to shearwaters are equally adept in all aspects both in day and at night. Antarctic skua are the most aggressive, persistent and successful species in bait-taking. This species may be more alert than other species to potential danger when removing bait from a hook, and is the species least often caught.

## Ecological traits of seabirds

A table of ecological traits of seabirds commonly found interacting with pelagic longline fisheries in Indian Ocean, Southern Ocean, Coral Sea and Central Pacific Ocean based on literature review and/or direct field observations was compiled. Species traits include the typical size and weight of adult birds, the body size class, whether the species is a proficient diver, and whether the species is a regular scavenger. On rare occasions, when the identity of the seabird initiating an interaction cannot be confirmed, it is assigned an “UNK” identity. Here, we make a simplifying assumption that birds with an unknown identity has an average body size and weight across all known species. This dataset is available at <https://doi.org/10.6084/m9.figshare.9755231.v3>.

## Hypothesis testing

Eight hypotheses on the variability of bycatch vulnerability were tested against the null, which assumed a constant vulnerability (*p0*). Here, the domain of  is on the interval [0, 1], and we used the probit link function to transform the domain onto the real line, i.e., . The use of a probit link simplified the choice of a flat prior for *c*, which was the standard normal because of the probability integral transformation between variables *c* and . All the following hypotheses were formed by adding predictors to. It has been shown that bycatch loss rate (*ploss*) is highly species specific (Zhou *et al.* 2020). In all the candidate models, the bycatch loss rate for species *n* with a probit link was , where the prior of the species effect  was the standard normal for each species (group).

The first hypothesis tested for the effect of species competition on bycatch vulnerability. Model M1 assumed that competition level affected the capture rate of an interaction with no restrictions on the particular form of the response, e.g., a linear response. In M1, the bycatch vulnerability of an interaction occurred in a level *i* competition environment was , where the prior of competition level effect (*cmp*) was the standard normal for each level {low, medium, high, extra-high}.

The next three hypotheses examined how species identity, mediated through ecological traits, affects bycatch vulnerability. First, we tested whether being a proficient diver or a regular scavenger had any effect on bycatch vulnerability. In M2a, the capture rate of species *n* in a level *i* competition environment with a probit link was, where diver(*n*) was an indicator function of species identity *n*,

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and in M2b, the capture rate of species *n* in a level *i* competition environment with a probit link was , where scavenger(*n*) was an indicator function of species identity *n*,

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and the priors were , , , and , such that the prior distribution on is flat.

The next hypothesis tested for the effect of the typical adult body size of the species on its bycatch vulnerability. In M2c, the capture rate of an interaction initiated by a species from body size class *j* in a level *i* competition environment with a probit link was , where the prior of body size effect (*size*) was  for each size {small, medium, large, extra-large, the prior of competition effect was , and the prior on variance component was .

To examine the full species effect, the species identity of bird initiating the interaction was incorporated into model M2d. The capture rate of species identity *n* in a level *i* competition environment with a probit link was, where the prior of the species effect  was  for each species (group), the prior of competition effect was , and the prior on variance component was . See Table A*2* for a list of species names (identities). The species effect for those with an unknown identity was estimated as a separate category alongside with other identified species groups.

The next three models examined any additional effect from physical oceanic conditions and spatial-temporal factors. In M3-5, the capture rate of species *n* in a level *i* competition environment with factor *x* at the time of the interaction and a probit link was , where in M3 the prior of the effect of physical condition was  for each condition *k*{calm, intermediate and rough}, in M4 the prior of the spatial effect was  for each region *l*{Indian Ocean, Coral Sea, Southern Ocean and Pacific Ocean}, in M5 the prior of the temporal effect was  for each period *m*{1988-1992, 1993-1997, 1998-2003}, the prior of the species effect  was  for each species (group), the prior of competition effect was , and the prior on variance component was .

## Model fitting and selection

A Bayesian approach was used for parameter estimation. To simulate MCMC (Markov Chain Monte Carlo) samples from the posterior distribution, we used JAGS 4.3 (Plummer 2003) in the statistical program R 4.0.2 (R Core Team 2020). Convergence was checked by visual inspection and Gelman-Rubin convergence diagnostic less than 1.1 (Gelman and Rubin 1992).

Model performance was measured based on deviance information criterion (DIC),

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where deviance *D* was twice the negative log-likelihood,  was the posterior mean of the deviance, and  was an estimate of the effective number of parameters in the model based on the algorithm proposed by Plummer (2002). The model with the minimum DIC is the recommended model, and as a rule of thumb, a less than 2 difference in DIC relative to the recommended model suggests substantial evidence for the model, differences between 3 and 7 indicate that the model has considerably less support, whereas a larger than 10 difference indicates that the model is very unlikely (Burnham and Anderson 2003).

## Alternative explanation for the Effect of body size on bycatch vulnerability

Alternatively, the low bycatch vulnerability of species with a small body size may be related to their relatively small gape size and how far a bird is capable of opening its beak. Species with a small gape cannot swallow whole baits, and the typical larger pelagic longline hooks may inhibit their ingestion, reducing internal hooking risks, and at the same time, expose larger species to greater risk of capture. The same can perhaps be said of other smaller species such as shearwaters which can scavenge in large numbers and dive proficiently, but for their comparative vulnerability to be better understood, more extensive interaction data are required.

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Table S1. Species ranking based on their relative ability to locate and take baits from baited hooks in pelagic longline fisheries. See Table S2 for species codes.

|  |  |
| --- | --- |
| Ranking | Species codes |
| 0 | OTH |
| 1 | ANP, ANF, MOT, SPP, WHP |
| 2 | GWP |
| 3 | RAN, RAS, WAL |
| 4 | CAP, GPE |
| 5 | BFA, SHY |
| 6 | BUL, LMS, SAL, SOT |
| 7 | GHA, YNA |
| 8 | BBA, LAY |
| 9 | BKP, GRP, SHW, SKU |
| 10 | FFS, WCP |

Table S2. Seabird species codes.

|  |  |  |
| --- | --- | --- |
| Code | Common name(s) | Scientific name(s) |
| ANF | Antarctic Fulmar | *Fulmarus glacialoides* |
| ANP | Antarctic Petrel | *Thalassoica antarctica* |
| BBA | Black-browed Albatross (2 species) | *Thalassarche melanophris* and *T. impavida* |
| BFA | Black-footed Albatross | *Phoebastria nigripes* |
| BKP | Black petrel (including Westland) | *Procellaria parkinsoni,* and *P. westlandica* |
| BUL | Buller's Albatross | *Thalassarche bulleri* |
| CAP | Cape Petrel | *Daption capense* |
| FFS | Flesh-footed Shearwater | *Ardenna carneipes* |
| GHA | Grey-headed Albatross | *Thalassarche chrysostoma* |
| GPE | Giant Petrel (2 species) | *Macronectes giganteus* and *M. halli* |
| GRP | Grey Petrel | *Procellaria cinerea* |
| GWP | Great-winged Petrel | *Pterodroma macroptera* |
| LAY | Laysan Albatross | *Phoebastria immutabilis* |
| LMS | Light-mantled Sooty Albatross | *Phoebetria palpebrata* |
| MOT | Mottled Petrel | *Pterodroma inexpectata* |
| RAN | Northern Royal Albatross | *Diomedea sanfordi* |
| RAS | Southern Royal Albatross | *Diomedea epomophora* |
| SAL | Salvin's Albatross | *Thalassarche salvini* |
| SHW | Shearwater (including Sooty, Short-tailed and wedge-tailed) | *Ardenna grisea, A. tenuirostris* and *A. pacificus* |
| SHY | Shy Albatross (2 species) | *Thalassarche cauta* and *T. steadi* |
| SKU | Subantarctic Skua | *Stercorarius antarcticus* |
| SOT | Sooty Albatross | *Phoebetria fusca* |
| SPP | Soft-plumaged Petrel | *Pterodroma mollis* |
| WAL | Wandering Albatross (4 species) | *Diomedea exulans, D. antipodensis, D. dabbenena* and *D. amsterdamensis* |
| WCP | White-chinned Petrel | *Procellaria aequinoctialis* |
| WHP | White-headed Petrel | *Pterodroma lessonii* |
| YNA | Yellow-nosed Albatross (2 species) | *Thalassarche chlororhynchos* and *T. carteri* |

Table S3. Wind score.

|  |  |  |
| --- | --- | --- |
| Wind speed (knots) | Wind direction (onto vessel) | |
| Port | Starboard |
| 0 - 10 | 2 | 1 |
| 10 - 20 | 4 | 2 |
| 20 - 30 | 6 | 2 |
| 20 - 40 | 8 | 2 |
| >40 | 8 | 2 |

Table S4*.* Incidence of different types of observed seabird interactions across different levels of competition.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Types of observed interactions |  | Competition level | | | |
|  | Low | Medium | High | Extra-high |
| Observed caught | Count | 83 | 61 | 22 | 9 |
|  | Percentage | 47.43% | 34.86% | 12.57% | 5.14% |
| Possibly caught | Count | 54 | 24 | 1 | 0 |
|  | Percentage | 68.35% | 30.38% | 1.27% | 0.00% |
| Indeterminate | Count | 145 | 45 | 10 | 70 |
|  | Percentage | 53.70% | 16.67% | 3.70% | 25.93% |
| Successful | Count | 905 | 211 | 29 | 9 |
|  | Percentage | 78.42% | 18.28% | 2.51% | 0.78% |
| Unsuccessful | Count | 1031 | 257 | 28 | 15 |
|  | Percentage | 77.46% | 19.31% | 2.10% | 1.13% |

Note: Seven observed interactions have missing interaction type information and they account for the difference in the total number of observed interactions between this table and Table 3 in the main text. In addition, one observed interaction has missing competition score, and it has been excluded from both tables.

Table S5. Mean and 95% credible interval of model estimated captures across different levels of competition.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Competition level | | | |
|  | Low | Medium | High | Extra-high |
| Mean | 202.78 | 107.95 | 31.60 | 78.27 |
| 95% credible interval | (164.82, 239.37) | (85.17, 132.85) | (21.68, 41.76) | (68.42, 86.52) |

Table S6. Incidence of different types of observed seabird interactions across different body size classes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | Typical adult body size class | | | |
|  |  | Small | Medium | Large | Extra-large |
| Observed caught type | Count | 10 | 22 | 87 | 56 |
|  | Percentage | 5.71% | 12.57% | 49.71% | 32.00% |
| Possibly caught type | Count | 13 | 14 | 20 | 32 |
|  | Percentage | 16.46% | 17.72% | 25.32% | 40.51% |
| Indeterminate type | Count | 21 | 117 | 40 | 92 |
|  | Percentage | 7.78% | 43.33% | 14.81% | 34.07% |
| Successful type | Count | 375 | 204 | 231 | 344 |
|  | Percentage | 32.50% | 17.68% | 20.02% | 29.81% |
| Unsuccessful type | Count | 189 | 267 | 437 | 439 |
|  | Percentage | 14.19% | 20.05% | 32.81% | 32.96% |

Note: Seven observed interactions have missing interaction type information and they account for the difference in the total number of observed interactions between this table and Table 4 in the main text.

Table S7 Mean and 95% credible interval of model estimated captures across different levels of body size classes.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Typical adult body size class | | | |
|  | Small | Medium | Large | Extra-large |
| Mean | 23.73 | 134.50 | 124.29 | 137.98 |
| 95% credible interval | (13.17, 35.37) | (117.09, 155,78) | (101.70, 149.14) | (109.44, 167.36) |

Table S8. Classification performance of seabird interaction observations during gear deployment. Misclassifications for both non-capture (N) and capture (C) events were marked in red.

|  |  |  |  |
| --- | --- | --- | --- |
| State variable | Interaction types | Classification performance | |
| Median | 95% credible interval |
| Non-capture  (N) | Observed caught | 0.4% | (<0.1%, 1.1%) |
| Possibly caught | 1.7% | (1.1%, 2.5%) |
| Indeterminate | 2.0% | (0.84%, 3.1%) |
| Successful | 44.4% | (42.3%, 46.4%) |
| Unsuccessful | 51.3% | (49.3%, 53.6%) |
| Capture  (C) | Observed caught | 38.2% | (32.2%, 43.3) |
| Possibly caught | 8.1% | (4.9%, 11.8%) |
| Indeterminate | 50.8% | (44.7%, 56.4%) |
| Successful | 1.5% | (0.2%, 3.6%) |
| Unsuccessful | 0.6% | (<0.1%, 2.6%) |

A screenshot of a cell phone

Description automatically generated

Figure S1 Estimates of species-specific bycatch loss rate (*ploss*) based on the selected model (M2d). Species (groups) marked with \* have no more than 10 observed records. See Table S2 for a list of the species included. On each row, solid diamond marks median estimate, solid interval marks interquartile range estimate, and dashed line marks a 95% credible interval.