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EFFECTIVENESS OF CONSERVATION AND MANAGEMENT MEASURES FOR REDUCING SEABIRD BYCATCH ON PELAGIC LONGLINES IN THE SOUTH ATLANTIC

J. Bell[1]*, A. Bertoldi Carneiro[2], A. Bielli[1], S. Jiménez[3], S. Oppel[2], R. Phillips[4], H. Wade[2], O. Yates[2], S. Griffiths[5] and S. Reeves[1]

SUMMARY

The ICCAT Sub-Committee for Ecosystems and Bycatch (SC-ECO) has been tasked to review Conservation and Management Measures (CMMs) designed to reduce incidental seabird bycatch on pelagic longlines in the south Atlantic. Here we evaluate the evidence for different combinations and specifications of the CMMs between current ICCAT specifications and best practice guidance from the Agreement on the Conservation of Albatrosses and Petrels (ACAP). We apply an ecological risk assessment approach to five populations of four at-risk seabird species in the Atlantic to understand patterns in bycatch rates between different CMMs. Updating to current best practice guidelines reduced seabird mortality by 43-75 % when maintaining the current approach where operators are allowed to select two of three possible CMMs. Mandating all three CMMs simultaneously, or using hook shielding devices, reduced mortality by 83-96 % compared with existing measures. None of the proposed amendments are expected to significantly affect catch rates of target species or other non-retained bycatch species.

RÉSUMÉ

Le Sous-comité des écosystèmes et des prises accessoires de ICCAT (SC-ECO) a été chargé d'examiner les mesures de conservation et de gestion (CMM) conçues pour réduire les prises accessoires d'oiseaux de mer sur les palangres pélagiques dans l'Atlantique Sud. Nous évaluons ici les preuves des différentes combinaisons et spécifications des CMM entre les spécifications actuelles de l'ICCAT et les lignes directrices des meilleures pratiques de l'Accord sur la conservation des albatros et des pétrels (ACAP). Nous appliquons une approche d'évaluation des risques écologiques à cinq populations de quatre espèces d'oiseaux de mer à risque dans l'Atlantique pour comprendre les tendances des taux de prises accessoires entre les différentes CMM. La mise à jour des lignes directrices des meilleure pratiques a permis de réduire la mortalité des oiseaux de mer de 43 à 75% en maintenant l'approche actuelle où les opérateurs sont autorisés à sélectionner deux des trois CMM possibles. L'utilisation obligatoire des trois CMM simultanément, ou l'utilisation de dispositifs d'hameçons encastrés, réduit la mortalité de 83-96% par rapport aux mesures existantes. Aucune des modifications proposées ne devrait affecter de manière significative les taux de capture des espèces cibles ou d'autres espèces de prises accessoires non retenues.

RESUMEN

El Subcomité de ecosistemas y capturas fortuitas de ICCAT (SC-ECO) ha examinado sus medidas de conservación y ordenación (CMM) para la reducción de la captura incidental de aves marinas en palangres pelágicos en el sur del Atlántico. En este documento se evalúan diferentes combinaciones y especificaciones de CMM, comparando las actuales especificaciones ICCAT y las directrices sobre mejores prácticas del Acuerdo sobre la Conservación de Albatros y Petreles (ACAP). Aplicamos un método de evaluación de riesgo ecológico a cinco poblaciones de cuatro especies de albatros y petreles en riesgo en el Atlántico para comprender patrones de tasas de captura fortuita para diferentes combinaciones de CMM. Actualizar las CMM según las directrices de mejores prácticas actuales reduce la mortalidad de aves marinas entre 43-75 %, bajo la condición actual donde los operadores tienen la libertad de seleccionar dos de las tres CMM disponibles. El uso simultáneo de tres CMM, o de dispositivos de protección de anzuelos,

[1] Centre for Environment, Fisheries, and Aquaculture Science, Lowestoft, UK; Email: Corresponding author: james.bell@cefas.gov.uk
[2] BirdLife International, Cambridge, UK
[3] Agreement on the Conservation of Albatrosses and Petrels, Hobart, Tasmania, Australia
[4] British Antarctic Survey, Cambridge, UK
[5] Inter-American Tropical Tuna Commission, La Jolla, CA, USA

reduce la mortalidad entre 83-96% en comparación a las medidas existentes. Ninguno de los cambios aquí propuestos afecta significativamente la captura de las especies objetivo o de otras especies de captura fortuita no retenidas.

KEYWORDS

Seabirds, Pelagic Longline, Bycatch, Line Weighting, Bird-scaring Lines, Night setting, Hook Shielding Devices, South Atlantic

Introduction

Fishing activity poses the greatest threat to seabirds globally (Dias *et al*., 2019), with pelagic longlining accounting for a major proportion of seabird bycatch (Gilman & Kobayashi, 2005; Huang, 2011; Tuck *et al*., 2011; Jiménez *et al.*, 2020; Votier *et al*., 2023). In pelagic longlining, most seabird bycatch occurs during setting, when birds swallow the hook or are entangled, then drowned when the line sinks (Da Rocha *et al*. 2021; Jiménez *et al.* 2014). There are a range of means by which seabird bycatch rates can be reduced including; branch line weighting to increase hook sink rate (e.g. Melvin *et al*., 2013; Jiménez *et al*., 2018), setting gear at night when seabirds are less active (e.g. Brothers *et al*., 1999; Jiménez *et al*., 2020; Kroodsma *et al*., 2023), and 'bird-scaring' or tori lines that deter birds from entering the risk area astern of the vessel where hooks are still sinking (e.g. Melvin *et al.*, 2013; Rollinson *et al.*, 2016; Jiménez *et al.*, 2020). In recent years, there have also been technological developments of mitigations such as underwater bait setting devices, whereby hooks and bait are enclosed within a chute during setting (Robertson *et al*., 2015, 2018), or hook shielding devices, which enclose the hook barb and prevents animals becoming hooked until the hook has reached a target depth (Sullivan *et al.*, 2018, 2021).

The Agreement on the Conservation of Albatrosses and Petrels (ACAP) periodically reviews the evidence base for these measures and publishes best practice guidance on the selection and specification of appropriate methods (ACAP, 2023, see also Pierre, 2023). Reporting rates of seabird mortality at sea are inconsistent and generally cannot provide the requisite level of granularity for conservation stewardship (e.g. even if the species is correctly identified, its provenance may be unknown). For this reason, it is necessary within ICCAT, and other regional fisheries management organisations, to consider risk-based approaches to setting conservation measures for relevant fisheries.

The Conservation and Management Measures (CMMs) currently applicable in south Atlantic pelagic longlining are detailed in ICCAT Rec. 07-07 and 11-09:

- Per Rec. 11-09, in areas south of 25ºS, at least two of the following measures shall be applied:
    - No setting of lines before nautical dusk or after nautical dawn. Deck lighting to be kept to a minimum;
    - Bird-scaring (tori) line(s) are deployed during setting (specification dependent upon vessel length); or
    - Branch line weights are deployed (minimum weight varies, depending on distance between weight and hook).
- Per Rec. 07-07, in areas between 20 and 25ºS, bird-scaring lines at least must be deployed (with certain exceptions).

In May 2023 at the SC-ECO annual meeting, BirdLife International and ACAP proposed a review of these CMMs to take account of subsequent developments in the best practice advice from ACAP, especially that:

1. The specification of CMMs in Recs 07-07 and 11-09 be streamlined and updated to the standards outlined in ACAP (2023); and

2. Hook Shielding Devices (HSDs) should be introduced as an alternative measure to the three measures already established, following the adoption of these devices into Western and Central Pacific Fishery Commission (WCPFC) measures in 2018, and IOTC in 2023.

This proposal was supported by scientific representatives from the UK, Brazil, Uruguay, and others. A task to initiate a review of seabird conservation measures was subsequently included in the 2024 SCRS workplan (section 5 of ICCAT, 2024). It was also further resolved in subsequent meetings to include a review of Rec. 07-07.

In support of the proposed review of Recs 07-07 and 11-09, the UK, in partnership with researchers within the ACAP and BirdLife International network, has prepared a modelling study using the ecological risk assessment of the sustainability of fisheries (EASI-Fish) approach (Griffiths *et al*., 2019) that evaluates the performance of different CMMs within an ICCAT-specific context for five populations of four seabird species. The UK Overseas Territories of South Georgia and the South Sandwich Islands, Tristan da Cunha, and the Falkland Islands are key nesting sites for several globally threatened seabird species (**Figure 1**). For this reason, the UK is keen to see that best practice for seabird bycatch mitigation is observed within the ICCAT Convention Area. The purpose of this submission is to make best use of the available ICCAT, ACAP, and academic data sources, to place the issue of seabird bycatch mortality within as much of an Atlantic-specific context as is practical. This approach was taken to help address concerns that previous studies have not been appropriately tailored to ICCAT's Convention Area or the fishing activity patterns therein.

It has historically been difficult to review these approaches within an Atlantic-specific context, in part owing to the lack of robust data on bycatch rates. However, there have been several advancements since the last iteration of the ICCAT CMMs in 2011, both in the best practice guidance for mitigating seabird bycatch and in analytic methodologies to understand bycatch risk. In keeping with a precautionary approach to management (ICCAT Res. 15-12) and the need to periodically review and update CMMs (Rec. 11-09, para. 8), we have undertaken this evaluation. Besides HSDs, we have not reviewed any alternate CMMs (e.g. mandating the use of thawed or dyed bait) as there is insufficient evidence that other methods are effective, and they are not recommended as best practice by ACAP (2023). The only other method recommended by ACAP is the use of 'underwater bait setting devices'. We have not included such devices in this study for lack of suitable evidence available at the time of writing, and because it was considered out of scope following discussions at the SCRS and Commission in 2023. This is not to say however that such devices should necessarily be discounted as possible future options for longline CMMs in the ICCAT Convention Area.

Methods

Fisheries Data

To calculate the overlap between seabird foraging locations and fishing activity in the ICCAT Convention Area (south of 20°S), this study uses spatial data to delimit the distribution of effort by ICCAT pelagic longline fleets from three sources; ICCAT Task 2 & EffDis, and Global Fishing Watch (GFW). The two sources were compared for the period between 2012 and 2020, and we found good agreement between both the ICCAT and GFW data among several of the major national fleets in terms of the major fishing areas and the relative amount of time/effort expended within these areas. Data from GFW, being of higher resolution (1 degree square used here, compared with 5 degrees square from ICCAT data), was used in the final estimation of the distribution of fishing effort within the overlapping regions of fishing effort and seabird foraging areas. The distribution of seven fleets (Japan, Korea, Chinese Taipei, South Africa, Brazil, Namibia, and Spain) was explicitly used in overlap calculations (see below), comprising 75.3% of the total fishing effort (hooks deployed between 2012-2020, per ICCAT EffDis). The remainder was included as a 'minor fleets' grouping, which was an amalgam of fishing effort by any other flag state for the same period, since these generally were only small components of total effort and/or varied more substantially between years.

Although longline gear may extend many tens of kilometres in length once deployed, the risk area for seabird bycatch is close to the vessel itself during setting of lines and whilst the hooks are still near the surface. Consequently, the spatial resolution of GFW data, bounded by the spatial extent of ICCAT Task 2 records, is more suited to this understanding these finer scale interactions. The effort data used includes fishing by vessels targeting southern bluefin tuna in the ICCAT Convention Area, but that is otherwise managed by CCSBT (see peaks of fishing effort by Japan and Rep. of Korea between 40-45°S, **Figure 2**).

Some model information used in similar applications of EASI-Fish (IATTC, 2023), for instance maximum setting depth of longline hooks, was unnecessary in the present study. Here, all fleets were assumed to set hooks deeper than at least 20 m and so, the only relevant information is the sink rate of hooks through the uppermost portion of the water column, after which any bait is beyond the detection or diving limit of the assessed seabird species. White-chinned petrels are the deepest diving of the species reviewed here, reaching a maximum reported depth of 16 m, and capable of diving at 2.0 $m.s^{-1}$ (Frankish *et al*., 2021a; Rollinson *et al*., 2014), which is less than the shallowest reported hook setting depth of pelagic longlines in the south Atlantic (main line depth at least 18 m; Afonso *et al.*, 2012). Albatrosses by comparison typically only dive at most 5 – 8 m (Bentley *et al*., 2021) and adequate line weighting is a straightforward means to reduce bycatch mortality passively, without requiring that operators to adjust fishing tactics.

Seabird Data

The spatial distribution of seabird foraging areas, summed across breeding and nonbreeding seasons, was taken from Carneiro *et al.* (2020). Data were available for all species and populations at 5-degree square resolution either quarterly or as an annual average. The annual average distribution (covering the period 2007-2016) was used here for five populations of four species (**Table 1; Figure 3**). These species, all of which are declining globally, were selected as they are common components of bycatch and have significant overlap with pelagic longline activity in the south Atlantic (Bugoni *et al.*, 2008; Jiménez *et al.*, 2011, 2020), and for which biological information is readily available. White-chinned petrels are especially vulnerable to bycatch in the south Atlantic (Laich & Favero, 2007) and elsewhere (Baird, 2004, 2005). The four species reviewed here comprised 47.2 % of the total bycatch reported in Jiménez *et al.* (2020), of which the vast majority (85.0 %) was white-chinned petrels.

Overlap was calculated, per fleet and species as the proportion of overlap between polygons of fishing effort and year-round bird foraging distribution, ignoring the lowermost 5% of observations (data from ICCAT Task 2, and Carneiro *et al*., 2020). Seasonal patterns in fishing effort and bird distribution were not considered. Bird foraging distribution (Carneiro *et al.*, 2020), and fishing effort (apparent hours fished, $1^{\circ 2}$, following Kroodsma *et al.*, 2018) were clipped to a polygon containing 95 % of the distribution of fishing effort as reported to ICCAT (Task 2 data), and then calculating the proportion of each within the remaining area. This was done to minimise overestimation of overlap between hotspots of seabird foraging and fishing effort (i.e. to take account of the relative distribution of each within their respective extents). Of the species reviewed here, Atlantic yellow-nosed and Tristan albatrosses, and white-chinned petrels had the greatest overlap with ICCAT pelagic longline effort. Some breeding populations included in Carneiro *et al.* (2020), such as wandering albatross at Crozet Islands or white-chinned petrels at the Antipodean Islands, were excluded at this stage as they showed little or no overlap with fishing in the ICCAT Convention Area.

Biological data (growth rates, maximum age etc.) for the seabird species were collated from a literature search (**Appendix 1**). Unless stated, standard deviation in parameter estimates was given as 10% of the mean value. Regarding growth, seabirds differ substantially from tunas or billfishes in that they achieve their asymptotic size by the time of fledging (ca. 3-9 months after hatching, depending on species), during which time they are not vulnerable to bycatch. In the context of the EASI-Fish model, the result is that growth curves and the estimation of parameters such as selectivity-at-age have minimal impact upon estimates of fishing mortality, i.e. all fledged birds are assumed to be vulnerable to bycatch. There are some ontogenetic differences in foraging range and susceptibility to bycatch (e.g. Frankish *et al*. 2020; Frankish *et al*, 2021b; Gimeno *et al*., 2022), but these are challenging to constrain directly, particularly as there is limited tracking data from juvenile and immature birds (Carneiro *et al*. 2020).

To represent ontogenetic differences in competition and foraging skill, mortality-at-age (M-at-age) was estimated to vary as a step function between juveniles (individuals aged 5 years or less) and adults for each species, following published literature (**Appendix 1**). As with fishes, M-at-age is difficult to discern directly and published estimates (**Appendix 1**) are likely to include a component of fishing mortality, especially for white-chinned petrels, which account for high proportions of total seabird mortality in the southern hemisphere (Baird, 2004, 2005; Barbraud *et al*., 2008).

Mitigation Measures

In line with the proposal to SC-ECO in 2023 (SCRS/2023/078), subsequently accepted into the ICCAT 2024 SCRS workplan, we reviewed the current measures (line weighting, night setting, and bird-scaring lines, following ICCAT Rec. 11-09), comparing them to equivalent measures as specified by ACAP (2023) as well as HSDs as an alternate measure (**Table 2**). Currently, fleets are required to use two of three measures (i.e. following any of scenarios Status Quo scenarios SQ1-3 in **Table 2**) when fishing south of 25°S, or bird-scaring lines when fishing between 20-25°S (per ICCAT Rec. 07-07, with certain exemptions). We did not examine scenarios of fishing between 20-25°S using only a single measure. The spatial component of our analysis aims to estimate the relative performance increase of a northward extension of the measures currently in place for fishing south of 25°S. The scenarios considered are detailed in **Table 2**.

Regarding night setting, ICCAT Rec. 11-09 and ACAP best practice (ACAP, 2023) do not differ substantively (**Appendix 3**) and so estimates for bycatch reduction through night setting were applied equally across the different scenarios (i.e. excluding scenarios SQ2 and ACAP2, which assume that no night setting of hooks occurs). In practice, this means that the present study effectively focuses more upon how changes to the specification of branch line weighting and bird-scaring lines might influence bycatch rates.

For lack of operational information, our study explicitly assumes all fleets comply fully with the measures as specified within each scenario. Presuming the parameter estimation otherwise accurately represents species vulnerability to bycatch, assuming perfect compliance means that the model likely underestimates at-sea bycatch rates. For instance, regarding night setting, Kroodsma *et al.* (2023) estimated that globally, just 3 % of longline sets occur entirely at night, excepting in areas where night setting is required or encouraged as part of the measures adopted by the relevant RFMO. Even in such areas, estimated rate of lines being set entirely at night is only 5.5%, with setting beginning on average around three to four hours before sunrise. Setting times for pelagic longlines are typically 6.5 hours (+/- 1.5 s.d., Tuck *et al.*, 2003; Gandini and Frere, 2012; Melvin *et al.*, 2013). As an example, at 30^{o}S dawn occurs between 04:51 in December and 06:56 in July, meaning that setting would typically have to begin by approximately between 22:00 – 00:30 to be likely to be completed before dawn, which creates an operational constraint for vessels that is perhaps difficult to persistently achieve. That said, some hooks set at night are still better than none, and Brothers *et al*. (1999) found a consistent decrease in seabird bycatch rate with an increasing proportion of hooks set at night. It would certainly be counter-productive to discourage operators from setting at least a proportion of hooks overnight simply because they cannot consistently meet a requirement for complete night setting.

Under current ICCAT specifications (Rec. 11-09) where night setting is not mandated at all times, without knowledge of how bird-scaring lines or branch line weighting was applied by an individual vessel, it is not possible to know whether this rate represents widespread non-compliance, or simply that operators find it too challenging to restrict setting of hooks to night-time only and the practicalities of night setting as a required practice need closer attention. If night setting were to be a mandatory condition, then the method of monitoring timing of line setting outlined in Kroodsma *et al.* (2023) could be a very efficient, cost-effective measure to remotely monitor compliance with CMMs.

Here we also provide an evaluation of the relative performance if Recs 07-07 and 11-09 were to be combined into a single set of measures applied to the entire ICCAT Convention Area south of 20^{o}S but note that the majority of the observed distribution of the five populations in this study (**Table 1; Figure 3**) occurs south of 25^{o}S. Atlantic yellow-nosed albatross was the most northerly distributed population, with the tracked portion of population (largely adults) spending around 8% of its time between 20-25^{o}S (**Figure 3**). White-chinned petrels (from Prince Edward Islands), and Tristan albatross respectively spent 1.5 and 1.2% of their total distribution within this latitudinal band in the Atlantic. Juvenile birds are under-represented in the tracking data used here (data from Carneiro *et al*., 2020) but several studies have indicated that juvenile birds on average spend more time further north (summarised in Gianuca *et al*., 2017; Carneiro *et al*., 2020), meaning that the present study likely underestimates the relative reductions in seabird bycatch that could be achieved by extending Rec. 11-09 to 20^{o}S. For example, comparing scenario SQ1 (status quo measures), with its counterpart ACAP1, in both scenarios, a vessel is presumed to be deploying weighted branch lines, setting only at night, in accordance with either the specifications of ICCAT Rec. 11-09, or ACAP (2023) respectively (see **Appendix 3** for full details for CMM specifications). Any estimated difference in seabird mortality then arises primarily from the degree to which the specifications of these different standards of measures influence real-world bycatch rates.

Model set-up

We use an age-structured implementation of the EASI-Fish model previously reviewed by SC-ECO in 2023 (Griffiths *et al*., 2019; IATTC, 2023). This model was selected for its suitability to species for which direct 'catch' observations are comparatively rare or believed to be under- or mis-reported. The EASI-Fish model includes functionality for estimating biological reference points, such as the ratio of F vs. F_{msy}[6] to determine the vulnerability status of the population (Griffiths *et al*. 2019). However, this was not included in this study since the goal was to understand differences between CMMs, with the overall goal of minimising bycatch mortality. This is distinct from applications of this model to retained species, where the goal may rather be to determine sustainable levels of exploitation, or to assess vulnerability status for the purposes of prioritising species for research and/or management purposes.

[6] F = Fishing mortality rate, F_{msy} = Fishing mortality rate at maximum sustainable yield.

For seabirds specifically, there is concern that under-reporting of bycatch is widespread (e.g. Brothers *et al*., 2010), and that the available data are not representative of species composition or total bycatch. The disparities between direct observer reports and official ICCAT data certainly serve to underline this source of uncertainty (Jiménez *et al*., 2020; ICCAT, 2023). The EASI-Fish model approach was selected because it does not depend on these observations and instead estimates fishing mortality of each species based on estimable parameters relating to their overlap with relevant fisheries, and the susceptibility to bycatch. Within the Commission for the Conservation for Southern Bluefin Tuna (CCSBT), a similar risk assessment type approach is currently being undertaken by the Ecologically Related Species Working Group (ERSWG), termed the 'Spatially Explicit Fisheries Risk Assessment (SEFRA), see Edwards *et al.* (2023) for most recent status report of this analysis.

This implementation of EASI-Fish model calculates a proxy for instantaneous fishing mortality (F)-at-age as a product of series of parameters. The estimation of F is expressed as the product of a set of parameters relating to overlaps between fishing activity and foraging distribution, and the proportion of the seabird population that is vulnerable to capture, including error distributions (**Table 3**). Here, F is effectively a residual likelihood of mortality within a given period, once all other relevant, estimable parameters have been discounted.

F-at-age rates per population were calculated per fleet as follows, tailoring the EASI-Fish approach (Griffiths *et al.*, 2019) to the specific terms relating to seabird susceptibility to pelagic longlining (Eqns. 1-3; with parameters given in **Table 3**):

Equation 1 (finite fishing mortality):

$$finiteF = \sum_{fleet,(\frac{max.\ age}{nclass\ age})} s * o\ * a_{seas} *\ a_{spat} * e_{fixed} *\ e_{timed} * avm * ((1 - avm) * prm)$$

Equation 2 (adjusted finite fishing mortality):

$$adj.finiteF = \sum_{fleet} (finiteF * q) * E$$

Equation 3 (instantaneous fishing mortality):

$$Inst.F = \sum_{fleet} -\log{(1 - adj.finiteF)}$$

Estimates of F were subsequently reported as the mean value across the total age range of each population (Eq. 1), to account for differences in selectivity- and maturity-at-age. Age-related estimations were calculated per 0.5 years (hence, finiteF per fleet of a species with a longevity of 20 years would be the mean of 40 estimates of finiteF-at-age).

Seabirds are wide-ranging and can cover large distances (100s of km) per day. The spatial resolution of fleet activity (1^{o2}, 85.5 km^2 at 40^oS) was greater than the attraction distance for albatrosses attending fishing vessels (up to 30 km, Collet *et al*., 2015; Kroodsma *et al*., 2023). Catchability (q) — here being a gear efficiency parameter — was estimated using the 'domain of potential interaction' (Griffiths *et al.* 2007) that uses gear length and animal movement characteristics to calculate the effective fishing area of a passive fishing gear, such as gillnets and longlines. Here, the rate at which birds attending a vessel within a given cell was calculated as the length of the set (typically 90-100km, Brothers *et al*., 1999; Bugoni *et al*., 2008; Afonso *et al*., 2012; Melvin *et al*., 2013, 2014; Fernandez-Carvalho *et al*., 2015) multiplied by the attraction radius around a vessel (30km), resulting in a mean q of 0.82 (i.e. the area of attraction of a single set, and therefore chance a bird will attend, is typically around 82% of the area over which fishing effort is gridded).

The main means by which the model outputs differ between scenarios is through the estimation of encounterability, which is expressed as a function of the combination of CMMs applied in each scenario. To estimate encounterability per CMM scenario (**Table 2**) we collated the available information on seabird bycatch rates from papers where the authors adequately reported the specification of the gears as deployed. Gear specifications were categorised as either meeting ICCAT 2011 standards (following Rec. 11-09), ACAP best practice guidance (ACAP, 2023), or 'Other' (i.e. a given CMM was applied but below the standard of ICCAT Rec. 11-09, or ACAP guidance, e.g. a branch line was weighted but to a lesser degree, or further from the hook, than specified by either ICCAT or ACAP). Bycatch per unit effort (BPUE) data were collated for night setting, line weighting, bird-scaring lines, and hook shielding devices (**Table 3**). We used all suitable studies reviewed in ACAP (2023) or arising from a standard Web of Science search string[7], that provided the requisite information from two or more gear set ups. All studies used, that reported the composition of seabird bycatch, included one or more of the species evaluated here

[7] Search string (accessed 01/02/2024): (seabird* OR "sea bird" OR "sea birds") AND (bycatch OR "by-catch" OR "incidental catch*" OR "incidental capture*") AND (mitigat* OR prevent* OR reduc*) AND longlin*

(**Table 1**) but some of the BPUE data was necessarily from outside of the Atlantic. In total, 13 of the 19 papers used contained data that was either wholly or partly collected in the south Atlantic. BPUE rate data were standardised across studies (max rate observed = 1), to estimate the relative difference between CMMs ('standardised interaction rate' hereafter), and to reduce the influence of discrepancies between studies. Empirical BPUE observations can be difficult to compare because of a range of factors, such as abundance and composition of seabird assemblages attending a vessel (Brazeiro *et al.* 2011; De la Cruz *et al*., 2022), and the area and season in which fishing occurred, but the standardisation process reduces these observations to second-order values that reflect relative differences within individual studies. For instance, Melvin *et al*. (2013) compared bird scaring lines deployed at-sea as specified by ICCAT Rec. 11-09 or ACAP (2023) and found that the latter resulted in around a 24 % decrease in bycatch rates (standardised interaction rate of 1 under Rec. 11-09 specifications, compared with 0.761 under ACAP (2023)). Melvin *et al*. (2013) also observed that combining night-setting and bird-scaring lines reduced standardised bycatch rates by 78 %.

The two encounterability parameters (see **Table 3**) represent the expected interaction rate, given CMM combination and specifications, of a seabird with a baited hook. Encounterability was divided into two components:

- Fixed encounterability – a function of the standardised interaction rates of night setting and/or bird scaring lines, per the specification used in each scenario.
- Timed encounterability – a function of the hook sink rate (taken to be proportional to the standardised interaction rate of branch line weighting under either ICCAT or ACAP specifications) and the diving depth of each species. Timed encounterability was therefore greatest for white-chinned petrels, the deepest diving of the species we assessed.

Since the estimate of encounterability decreases with each additional measure, scenarios SQ4 and ACAP4 (use of all three CMMs to their respective specifications) was expected to be lower than any pair of CMMs (i.e. overall encounterability SQ4 is bound to be less than in any of SQ1-3, and equivalently for ACAP4 compared with ACAP1-3). The empirical degree to which pairwise combinations of CMMs to a given specification interact with one another remains unknown or at least poorly understood. Assuming that adding additional CMMs does not negatively impact bycatch rates and given the method we outline above, we expect that these efforts will have been, at most, a slight under-estimation of the resultant bycatch mortality rates of introducing a third CMM over any two as currently required.

Parameter estimation & sensitivity testing

Individual parameters were resampled from within a beta distribution (Sinharay, 2010) with a fixed standard deviation about the mean (set at 10% of the mean if error unknown) inclusive. Parameters defined below (**Table 3**). The final set of model solutions was a product of at least 10k iterations or continued until the standard error of instantaneous F had converged (most recent 1k iterations +/- 0.2% of all previous iterations). Larger solution sets (up to 50k iterations) were trialled, but this did not improve precision.

Given that the only material difference between scenarios, and upon which the conclusions of this study rely, are the two encounterability terms (e_{timed} and e_{fixed}), sensitivity testing was restricted to these parameters only. Other parameters vary by fleet and/or population, but mean values and error rates were fixed between scenarios. We examined the impact of the 50% over- and under-estimation of all encounterability parameters, using model solution sets of 5k iterations.

Results

Performance of individual measures

Standardised bycatch rates of individual measures varied between Rec. 11-09 CMMs and ACAP (2023) guidelines. CMMs applied to ACAP (2023) guidelines reduced bycatch by 43.1 – 74.5 % compared with standards outlined in Rec. 11-09.

Lines weighted according to ACAP (2023) had a mean standardised interaction rate of 0.193 (+/- s.d. 0.272), compared with an interaction rate under current CMMs of 0.339 (+/- s.d. 0.412). Equivalent differences in bird scaring line configuration resulted in a drop in the standardised interaction rate from 0.608 (+/- s.d. 0.283) under Res. 11-09 specifications to 0.272 (+/- s.d. 0.332) under ACAP (2023) best practice guidelines.

Differences in standardised interaction rate during night setting (after dusk, per ICCAT 2011, or ACAP 2023) resulted in a drop in a mean standardised interaction rate of 0.311 (+/- s.d. 0.305), applied equally to all scenarios that involved night setting.

Field trials of hook shielding devices alone resulted in a standardised interaction rate of 0.041 (+/- s.d. 0.070), or approximately a 21-fold improvement in bycatch rates compared with gears typically used by the observed vessels.

Best performing combinations of current CMMs

The best performing combinations of CMMs under existing or proposed CMM specifications were all three measures (SQ4 and ACAP4) or hook shielding devices (ACAP5).

Given the uncertainty in the estimation of the various interaction terms, there was considerable overlap in the estimated bycatch mortality between several scenarios. Scenarios ACAP1-2, SQ1-3, and ACAP4-5 were generally similar across species. Similarly performing CMM scenarios can be grouped, across species approximately as follows in **Figure 4**. Scenarios that included night setting had smaller differentials between ICCAT and ACAP specifications, since these requirements do not materially differ.

Atlantic yellow-nosed and Tristan albatrosses from Gough Island, and white-chinned petrels from South Georgia were the most vulnerable to bycatch (**Figure 5**). Without attempting to validate against observer reports, bycatch mortality rates (for breeding birds) were estimated at 1,100-1,600 individuals per year under current measures for Atlantic yellow-nosed albatross, and potentially 33,000-77,500 individuals in the case of white-chinned petrels from South Georgia, which is the largest population of any reviewed here (**Table 1**). For both populations however, mortality estimates under the best-performing scenarios (ACAP4 & ACAP5) were estimated to be limited to fewer than 100 and 3,000 birds annually for Atlantic yellow-nosed albatross and white-chinned petrels from South Georgia respectively, representing around a 90% or greater reduction in bycatch mortality against existing measures.

Relative gains

Updating the CMMs from current (SQ1-3) to ACAP (2023) guidelines (ACAP1-3) resulted in a mean reduction in bycatch rates across all species of between 31.4 – 68.9 % (**Table 4**). Adopting all three measures to ACAP specifications (ACAP4) was estimated to reduce bycatch rates by 82.5 – 92.1 % against perfect compliance with existing measures. Implementing hook shielding devices across all fleets was estimated to reduce bycatch mortality by between 96.5 – 98.9 % (**Table 4**).

When including fishing activity between 20-25^{o}S, Of the populations reviewed here, all populations, except white-chinned petrels from South Georgia, were found to have significantly higher mortality estimates in at least some of the scenarios (**Figure 5**). Distribution of juvenile birds is less certain, but evidence suggests that some species may spend more time foraging further north as juveniles, which makes these estimates potentially more conservative.

Sensitivity

Sensitivity to encounterability values was consistent across scenarios, and proportional to the magnitude of the estimate of instantaneous F. Varying encounterability parameters by a factor of 0.5 and 1.5 resulted in relative differences in total estimated F of between 0.560 - 0.564, and 2.241 - 2.257 respectively (**Appendix 4**). Sensitivity to parameters is thus only expected to impact our estimates substantially if there are systematic differences in the data reporting between observer data published for CMMs as specified by ICCAT or ACAP.

Discussion

The analyses presented in this paper are intended to inform the review of the existing ICCAT seabird measures as requested by ICCAT SCRS. We have modelled the relative impact of the existing ICCAT measures, compared to the current best practice specifications of seabird mitigation measures as summarised by ACAP (2023). Our analysis used the EASI-Fish approach (Griffiths *et al*., 2019), which we consider appropriate, given the extent and nature of the data available to support or validate the analysis. To support the SC-ECO in use of these results for developing recommendations to the SCRS and Commission, we consider below the limitations of the data and model used, and the wider context in which any updated CMMs may be implemented. The real-world rates of seabird bycatch cannot be directly estimated, since it remains unknown to what degree each of the possible CMM combinations are implemented, and we can conclude only that it would be within the range of status quo scenarios above. In each, we assumed that all vessels had adopted the same CMM combination, meaning that between the scenarios they represent the maximum and minimum expected mortality rates.

Current ACAP best practice guidance (ACAP, 2023) is that pelagic longline fishing vessels either:

- Implement night setting, branch line weighting, and bird-scaring lines, to the specification in ACAP (2023) during all sets, or
- Implement hook shielding devices, configured to open after the device has reached 10 metres depth or been in the water more than ten minutes, are implemented for all hooks.

Comparisons with at-sea observations

We have made every effort to ensure that ICCAT data have led this analysis, and only used other information to supplement or enhance the estimation of model parameters. Per the guidance of the SCRS Chair (Brown, pers. comms. 2023), a supporting paper will be submitted to SC-Stats which will provide the requisite information for CPC scientists to satisfy themselves that the way in which additional methods and data have been incorporated here (primarily distribution data sourced from Carneiro *et al.*, (2020)) is appropriate.

Real-world rates of seabird mortality through ICCAT pelagic longlining fisheries are unknown, and under-reporting is likely extensive. For the period 2019-21, ICCAT observer reports record a total of 1,115 birds caught in the south Atlantic (of which 96% of species relevant to this study were discarded dead) by vessels flagged to three nations (Brazil, South Africa, and Japan). Other fishing nations apparently reported zero seabird bycatch and the actual rate of seabird mortality remains unknown. Estimates (e.g. Anderson *et al*., 2011) are both contentious, and highly challenging to validate. However, it is clear from the results presented here that updating the specifications of the existing CMMs in the south Atlantic, and introducing the option for vessels to use HSDs, stands to significantly decrease seabird mortality from ICCAT fisheries in the future.

Fernández-Costa *et al.* (2018) reported total bycatch of 38 birds from 7.6 million observed hooks between 1993-2017 from Spanish longliners targeting swordfish in the north and south Atlantic, all of which were reported to have been setting lines only at night (annual interaction rate, where it occurred, ranged 0.01 – 0.67). The majority of this fishing effort was north of the distribution of the majority of albatrosses and petrels, but all seabird interactions observed occurred south of 15^{o}S, Alternative estimates of seabird bycatch from longlining globally range 160,000 – 320,000 birds a year (Anderson *et al*., 2011), of which around 41,000 were since estimated to be of albatrosses and petrels caught in the southern hemisphere by pelagic longlining (Abraham *et al*., 2019).

This information deficit was the primary reason for adopting the EASI-Fish approach, through which we estimate mortality as a product of relevant interaction probabilities, including the rate of rare events for which sufficient operational data may never be available. However, the lack of operational data makes the results impossible to fully validate, and therefore we suggest that this analysis is limited to providing recommendations based on the difference in estimated F (ΔF_{est}) between CMM scenarios.

Jiménez *et al.* (2020) reported 8,472 seabird captures from 28 species on board vessels flagged to Brazil, Portugal, South Africa, and Uruguay, as well as some Japanese vessels operating within the Uruguayan and South African EEZs. A total of 37.2 million hooks were observed between 2002-2016, from 583 fishing trips. In the period 2012-2020, an average total reported 38.7 million hooks in the southern Atlantic were set annually by all fleets (ICCAT Task 2 data). Jiménez *et al*. (2020) noted considerable temporal variation in bycatch rates as the implementation of CMMs improved over time among the fleets observed. However, given the similar level of total longline fishing activity, it might reasonably be expected that a similar order of magnitude of seabird mortality would occur annually within the South Atlantic, assuming bycatch rates among the fleets observed in Jiménez *et al.* (2020) are representative of unobserved fishing activity among other fleets or elsewhere in the South Atlantic. It is difficult to determine the accuracy of the EASI-Fish model estimates, since we do not know the ratio of different CMM combinations applied as a proportion of effort across the ICCAT Convention Area but, taking the estimates from Jiménez *et al*. (2020), it is likely that our analysis overestimates bycatch mortality, especially for white-chinned petrels from South Georgia. We reiterate that the present analysis should be considered relativistic and that accurately determining at-sea bycatch mortality rates remains highly challenging.

Of the captures reported in Jiménez *et al.* (2020), 3842 (45 %) were of white-chinned petrels which we below assume were solely from South Georgia (as the Prince Edward Islands population is approximately 1% the size of that of South Georgia; **Table 1**). Taking estimated mortality rates from Brazilian, Japanese, and South African longliners, and from the minor fleets (since fishing activity by Uruguay or Portugal was not explicitly examined here), our analysis expects bycatch mortality rates ranging across CMM combinations between 0.011 – 0.024, or 19,300 – 42,400 mature birds annually from among the fleets observed in Jiménez *et al*. (2020). This equates to a 5.0 – 11.1 times greater estimate of total mortality than inferred from observer reports. This is the most definitive validation of our approach that we can evidence from the available information.

Assuming that our estimates are approximately ten times greater than the real-world situation, we estimate that approximately 3,400 – 7,500 individuals of the four species assessed here are killed through bycatch upon pelagic longlining within the ICCAT Convention Area south of 25°S annually. Taking the differentials in F between scenarios (**Table 4**), adopting ACAP (2023) best practice might therefore be expected to reduce seabird mortality by between 1,700 – 5,700 seabirds per year under the current 'two of three CMMs' approach, or between 2,800 – 6,900 seabirds per year if all three CMMs were implemented concurrently. Full implementation of hook shielding devices would be expected to reduce bycatch mortality to fewer than 500 white-chinned petrels annually, with bycatch rates of wandering or Tristan albatrosses reduced to fewer than 5 individuals annually. Though we did not explicitly model any other seabird species, the potential for bycatch reduction is expected to be proportionately applicable across the other 24 species recorded as bycatch in Jiménez *et al*. (2020).

The performance of different combinations of CMMs remains a key source of uncertainty but we note that real-world data are lacking for the CMMs as detailed in ICCAT Rec. 11-09. There is however empirical evidence for the measures as detailed in ACAP (2023), which uses observations from at-sea field trials of different gears and found that the different combinations discussed here reduce seabird mortality between 83 – 100 % relative to the controls in each study (Melvin *et al*., 2014; Jiménez *et al*., 2018). Of these combinations, night setting together with bird-scaring lines performed most poorly, and all other CMM combinations (**Table 2**) found BPUE reductions of 99 – 100 %.

For the purposes of this study, all fleets are assumed to have been applying CMMs fully compliant with either the relevant specification (status quo scenarios following Rec. 07-07 and 11-09) or best practice guidance (ACAP scenarios) and therefore represents 'best case' estimates of mortality, rather than being more precautionary, as directed by ICCAT Res. 15-12. In practice, the implementation of each CMM is likely to be imperfect and will negatively affect its performance.

In the EASI-Fish framework, estimation of mortality rates is via the product of independent parameters, and therefore sensitivity was proportional the magnitude of the parameter, and relative sensitivity was consistent across species and scenarios (**Appendix 3**). A refinement of the encounterability parameters would be possible given more access to additional field trial data that compares the efficacy of different CMM combinations, or between the specifications outlined in current regulations vs. best practice guidance (Votier *et al*., 2023).

Impacts of fishing on South Atlantic seabird populations

Our estimates assume that, per scenario, that all fleets are implementing the same combination of CMMs and with perfect adherence to the relevant specifications. In practice however, there will be substantial variation between and within fleets in the implementation of specific CMMs, as well as in other factors affecting bycatch rates (e.g. hook size; Jiménez *et al.*, 2012). Though our estimates are only risk-based, and not validated against real-world observations for the reasons discussed above, the present work evidences the significant role of ICCAT longline fishing in driving global seabird population decline.

A key consideration in evaluating the potential impacts of fisheries bycatch on seabird populations is estimating the levels of fishing mortality expected to cause population declines. Barbraud *et al.* (2008) estimated that the Crozet Islands population of white-chinned petrels, approximately 170k individuals, would start to be 'severely affected' by mortality rates of >8k individuals per year, or 4.7 % of the population (equivalent to an instantaneous F of 0.047). However, and as with the present study, these estimations are fundamentally limited by the lack of suitable validation data to estimate the relative proportions of fishing mortality versus other sources of natural or anthropogenic mortality (Pardo *et al.*, 2017). The five populations studied here were estimated to be subject to a range in F (from pelagic longline fishing within the ICCAT Convention Area only) of 0.004 – 0.059 under existing CMM combinations (SQ1-3), with the lowest being South Georgia wandering albatross (SQ1), and the highest being Atlantic yellow-nosed albatross (SQ2) (**Figure 5**). Both Atlantic yellow-nosed albatross (from Tristan) and white-chinned petrels (from South Georgia) exceeded the threshold established in Barbraud *et al.* (2008), without the inclusion of fishing activity by other gears in the ICCAT Convention Area, or any fishing elsewhere.

Excepting Atlantic yellow-nosed albatross, all species reviewed here are distributed across several oceanic basins, so mortality through interactions with ICCAT fleets is only a portion of the total bycatch mortality of these species. Tuck *et al.* (2015) however noted subsequently that there is considerable within-species and temporal variation in bycatch susceptibility, which makes it difficult to directly infer, on this basis alone, that a given F means that bycatch is directly driving population declines of seabirds. In this study, we have attempted to estimate bycatch mortality by pelagic longlining in the Atlantic only, and the real extent of bycatch mortality will certainly be higher if we could account for bycatch mortality by other gears in the Atlantic, or by any fishing activity elsewhere in the Pacific or Indian oceans.

However, many of these population size estimates are now many years out of date (**Table 1**). Following ICCAT Res. 15-12, SC-ECO should consider rates of decline, as well as absolute population size estimates of the most vulnerable species, when proposing updates to the CMMs.

Of the species considered here, only the more northerly-nesting species (Tristan and Atlantic, yellow-nosed albatrosses, both nesting on Gough Island) were found to be substantially impacted by fishing activity between 20-25^{o}S, although wandering albatross and white-chinned petrels also indicated increased mortality when the spatial domain of the model was extended north. Tristan albatross is classified as Critically Endangered by IUCN, evidencing that there is a clear need to extend the implementation of effective mitigation measures further north.

Impacts on catch rates of other species

A number of the papers reviewed examined the potential impact upon catch rates of commercial species (typically tunas and billfishes) from one or more of the CMMs evaluated here (Melvin *et al.*, 2013, 2014; Sullivan *et al.*, 2017; Debski *et al.*, 2018; Jiménez *et al.*, 2018; Santos *et al*., 2019; Gilman *et al.*, 2023). No study found evidence that revising the existing CMMs to the level of ACAP (2023) guidelines would significantly affect catch rates of target species.

We have not systematically reviewed any potential effects of the proposed CMMs upon bycatch of other species groups in the South Atlantic (i.e. turtles, sharks, or cetaceans). However, in their literature review, Swimmer *et al*. (2020) found no evidence of increased catch of other non-target taxa when seabird mitigation measures (line weighting, hook shielding devices, night setting, BSL) are used, and suggested that the use of hook-shielding devices might help reduce sea turtle bycatch.

To our knowledge, only a small number of studies assess the impact of specific seabird bycatch mitigation measures on other non-target taxa. Jiménez *et al*. (2019) reported that the use of BSLs and weighted branch lines tested during experimental trips had no negative outcomes for vulnerable taxa (elasmobranchs, teleosts, sea turtles and fur seals). Additionally, according to Rodrigues *et al*. (2022), night setting has the potential to reduce the probability of capturing loggerhead turtles (*Caretta caretta*) and shortfin mako sharks (*Isurus oxyrinchus*) in the South Atlantic Ocean pelagic longline fishery, as these species were typically captured during partially nocturnal sets. However, the study also shows that blue sharks were mostly captured during fully nocturnal sets, highlighting the need for full consideration of the specific impacts for each fishery. Finally, a study investigating underwater setting in Uruguay reported catch rates for sea turtles (*Caretta caretta, Lepidochelys olivacea and Dermochelys coriacea* combined) as 1.36/1000 hooks on baits set at the surface compared to 1.56/1000 hooks on baits set underwater (Robertson *et al*., 2018), but no information was provided on whether the difference was statistically significant.

Accordingly, and given that the proposed CMMs only materially influence catchability of seabirds whilst the gear is being deployed, we consider it unlikely that any ensuing updates to the measures in ICCAT Rec. 11-09 or 07-07 will significantly influence catch rates or target species, or non-seabird bycatch rates (Jiménez *et al.*, 2019; Santos *et al.*, 2019; Rodrigues *et al*., 2022).

Best practice in mitigating seabird bycatch

The study by ACAP (2023) represents the current 'state of the art' in terms of the measures available to mitigate bycatch of seabirds in longline fisheries. Within the EEZs of some ICCAT CPCs, such as South Africa and Tristan da Cunha (UK), additional measures are in place so that seabird mortality by longlining is controlled through limits upon bycatch, rather than population-derived biological reference points as is commonly used in fisheries management. These limits are based on the BPUE and/ or the absolute numbers of birds killed by an individual permit holder within a single season (0.05 birds/ 1000 hooks, or 50 birds in total; Rep. of South Africa, 2008; Winker *et al*. 2019). These limits help to incentivise vessel skippers to ensure effective implementation of the available mitigation measures, so as to avoid suspension of their licence. There is scope for implementing similar limits within ICCAT pelagic longline fisheries. The suitability of a metric based upon an absolute number of birds killed may be compromised by under-reporting of seabird mortality, but this could be addressed by using data from scheduled observer coverage periods or mandatory on-board remote electronic monitoring.

This approach would also serve to underpin some of the work of SC-ECO towards Ecosystem Report Cards, by providing definitive information against which to report performance of ICCAT fisheries.

Revision of ICCAT measures

Current ICCAT seabird mitigation measures are compared with those summarised by ACAP (2023) in **Appendix 3**. The analyses summarised here have indicated that implementing mitigation measures to the ACAP (2023) standard would be more effective. The individual measures contained in the two approaches are considered further below.

Line Weighting

The proposed amendment to line weighting regulations has the dual advantages of being a passive mitigation, thus not requiring additional labour at sea, and being comparatively straightforward to inspect as part of Port State Control Measures, unlike night setting or the use of bird-scaring lines, compliance monitoring of which depends on operational data collection by observers.

Revising the measures in Recs 11-09 and 07-07 such that line weighting, to at least the specifications in ACAP (2023), be implemented during all sets, would achieve a substantial reduction in seabird bycatch with minimal impact on fishing operations.

Bird-scaring lines

Bird-scaring lines, also known as tori lines, are currently one of the measures included in ICCAT recommendations. ACAP (2023) guidance involves more detailed specification of how to set-up and use bird-scaring lines and was more effective in reducing seabird bycatch than the existing measures.

Night-setting

In the case of night-setting, Brothers *et al*., (1999) found that bycatch rates of seabirds decreased by approximately 2 % for every 1 % of hooks that were deployed at night, up to a maximum total reduction in bycatch of 85 % when all hooks were deployed at night. Absolute rates vary with weather and moon phase (Jiménez *et al*. 2018, 2020), and between species (e.g. white-chinned petrels are more active at night than albatrosses and consequently, night setting is considered less effective as a means to reduce bycatch for this species (Phalan *et al*., 2007; Frankish *et al*., 2021a; ACAP, 2023)). We did not estimate the effect of moon-phase or weather directly in our study because of the small sample sizes, and lack of comparable estimates for combinations of CMMs following Rec. 11-09. Kroodsma *et al*., (2023) also showed that the proportion of night setting varies throughout the South Atlantic basin and so, it seems probable that the performance of night setting, as a means to reduce seabird bycatch varies, also between fleets and across the ICCAT Convention Area, to a degree not captured here.

We note, particularly at higher latitudes during the summer, deploying all hooks at night can be operationally challenging for vessel operators, hence the need to deploy multiple CMMs concurrently. Some remote monitoring of setting periods can be possible (see Kroodsma *et al*., 2023) but this has yet to be incorporated into management within ICCAT.

Hook Shielding devices

Hook shielding devices are now an accepted measure both in WCPFC (Debski *et al.*, 2018; WCPFC CMM 2018-03), and IOTC (Res. 12/06 amended in 2023), and the current analysis has indicated that they perform similarly or better to implementing all three existing measures to ACAP (2023) guidelines) for all species (F ranges < 0.001 – 0.003 and 0.001 – 0.005 respectively). As such, permitting the use of hook-shielding devices alongside, or as an alternative to, other measures are expected to be highly beneficial in reducing seabird bycatch on pelagic longline fisheries.

During the 2023 meeting of SC-ECO, it was noted that there is a potential issue with conferring commercial advantage to a single manufacturer of HSDs. Although the analysis presented here includes several HSD types (various HookPods designs and the Smart Tuna Hook), only HookPods are currently commercially available. From a scientific perspective, the field studies have established that hook-shielding devices are in general an effective measure, and current best practice guidelines do not endorse any specific brand. It is also arguable that, by permitting their use and thus creating a wider market base for these devices, ICCAT could encourage innovation.

Comparable work elsewhere

Within the CCSBT Ecologically Related Species working group (ERSWG), a similar analysis is underway – the Spatially Explicit Fisheries Risk Assessment (SEFRA) led by New Zealand. The latest version of this analysis (Edwards *et al*., 2023) is due to be discussed at the next ERSWG meeting in June 2024. As with the present study, the SEFRA aims to estimate total captures, by calculating overlap between fishing effort and threatened seabird species, but instead covers an area of the southern hemisphere more broadly and includes other fishing gears. Just as the present study refers principally to seabirds of concern within UKOT populations, the SEFRA focuses upon seabird species nesting on New Zealand islands. The SEFRA evaluates risk over time, from several gears to its assessed species, and compares to at-sea observer reports (but from fishery observer data collected within the New Zealand EEZ only, which are then extrapolated to the southern hemisphere more broadly). Unlike the method presented here, the SEFRA does not provide a comparison of mortality under different CMM scenarios and, although better able to capture real-world mortality rates, will not provide a similar basis upon which to review the existing measures (Fischer, pers. comms, 2024).

The number of seabird captures observed in pelagic longline fishing in the New Zealand EEZ averaged 62 birds per year between 2006-2020, from an average of 569,000 hooks observed annually (Edwards *et al*., 2023). BPUE within the New Zealand observer reports was therefore 0.11 birds per thousand hooks. The mean observed BPUE in the Atlantic from the studies reviewed here was 0.86 birds per thousand hooks (estimates ranged < 0.01 – 6.40, including studies using best-performing CMMs). The SEFRA is validated against at-sea observations from the New Zealand EEZ and, through extrapolation, assumes that these are representative of bycatch rates elsewhere or among different fleets. The EASI-Fish approach presented here does not rely on direct catch reports and so represents an alternate interpretation of the risk to seabirds from pelagic longline fishing. This of course makes it challenging to validate, hence we focus our recommendations on the relative differences between scenarios, rather than asserting that any estimates of mortality rates are accurate reflections of real-world absolute bycatch mortality.

CCSBT fleets are distributed further south than the majority of ICCAT pelagic longlining and extend eastwards to the southwest Pacific. CCSBT fleets thus overlap more with more southerly distributed seabird species such as wandering albatross, and many others not specifically reviewed here, such as black-browed, southern royal, or grey-head albatrosses. A key consideration, for comparison between the SEFRA and this study, pertains to differences between ICCAT and CCSBT. CCSBT is unique among tuna RFMOs in that its' remit applies only to Southern Bluefin Tuna, and that it has no Convention Area (a.k.a. area of competence). The result of this is that CCSBT fleets (which are included within the present study for the portion of their fishing that occurs in the ICCAT Convention Area) are beholden to the regulations of whichever RFMO Convention Area in which they are active (i.e. ICCAT, IOTC or WCPFC). Increasing the standard of CMMs applied to pelagic longlining by CCSBT fleets is likely to be highly beneficial to reducing seabird bycatch mortality in the Atlantic. Although the SEFRA is ongoing, unlike the present study it does not apply specifically to the ICCAT's Convention Area or its fleets, and so bears less direct relevance to the current SCRS review of ICCAT seabird CMMs.

In the North Atlantic, García-Barón *et al.* (2022) compared vulnerability of seabird species to artisanal tuna fisheries using the Ecological Risk Assessment for the Effects of Fishing (ERAEF) approach (Hobday *et al.*, 2011). The spatial distribution of risk to great shearwaters varied between years, following the position of oceanographic fronts as key foraging locations, and García-Barón *et al.* (2022) found that trollers posed a higher risk to great shearwaters than baitboats among French and Spanish fleets.

The key difference to consider between the present study versus the SEFRA or ERAEF approaches (García-Barón *et al.* 2022; Edwards *et al.,* 2023) is that our analysis is explicitly designed to provide estimates of total seabird bycatch mortality under different scenarios of CMM combinations and specifications. This, we hope, will equip ICCAT members with the knowledge and confidence to update CMM specifications and advance ICCAT fisheries management towards its goal of ecosystem-based fisheries management.

Sources of estimation error

We have demonstrated above that our model over-estimates real-world catch rates (of white-chined petrels by a subset of ICCAT longline fleets) by a factor of between 5.0 – 11.1 times. The model is based on a number of assumptions and decisions that, as described variously above, will include some sources of over- and under-estimation, which we summarise in **Table 5**.

Bycatch through pelagic longlining in the Atlantic is of course not the only source of anthropogenic mortality for southern hemisphere seabirds (Edwards *et al*., 2023). These results represent only a subset of total bycatch mortality of these seabird species. However, these the results are the first attempt to quantify the performance (i.e. rate of seabird bycatch) of existing and best practice CMM specifications throughout the Atlantic. As a relative indicator of CMM performance and an evidence base for determining possible updates to ICCAT Recs 07-07 and 11-09, the present study is robust. We have used ICCAT data where possible, supplemented by academic studies or grey literature, to examine the role of ICCAT pelagic longline fisheries in driving global seabird declines.

Conclusions

Recalling ICCAT Res. 15-12 (on the implementation of a precautionary approach to fisheries management in the ICCAT convention area; ICCAT, 2015), we suggest that the present study and references therein represent the best available scientific advice for the implementation of measures to minimise the bycatch of seabirds within the ICCAT Convention Area. Though we examined only four species, the results are expected to be widely transferrable to the other albatross and petrel species within the South Atlantic. We also encourage CPCs to strengthen their reporting of seabird bycatch through their observer programmes and from vessel operators, both of bycatch rates but also which CMMs they tend to adopt.

Based on ΔF between scenarios, and the lack of evidence for impact upon target species catch rates affecting fishing efficiency, we propose that ICCAT Recs 11-09 and 07-07 be updated to reflect current best practice. We conclude that:

1. All individual CMMs and pairwise combinations resulted in substantial reductions in seabird bycatch mortality when specifications were revised to meet current best practice guidelines (ACAP, 2023).

2. This analysis predicts that hook-shielding devices perform similarly to, or better than, implementing all three existing measures to ACAP (2023) guidelines for all species. As such, permitting the use of hook-shielding devices alongside, or as an alternative to, other measures is expected to be highly beneficial in reducing seabird bycatch on pelagic longline fisheries.

3. Revising the measures in Recs 11-09 and 07-07 such that line weighting, to at least the specifications in ACAP (2023), be implemented during all sets, would achieve a substantial reduction in seabird bycatch with minimal impact on fishing operations.

4. Although the majority of seabird foraging in the South Atlantic occurs south of 30°S, some seabird populations are still exposed to substantial bycatch risk between 20-25°S, particularly among juveniles.

5. Within the EEZs of some ICCAT CPCs additional measures are in place so that seabird mortality by longlining is controlled through limits upon bycatch. These limits help incentivise operators to ensure effective implementation of conservation measures.

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Table 1. Summary of species and populations modelled in this study. *Species does not breed elsewhere. Atlantic yellow-nosed albatross breeds elsewhere within the Tristan da Cunha archipelago but data from Gough constitutes the majority of the population and is considered representative of all breeding populations.

Species	*Population & Location*	*Population size estimate of breeding birds*	*IUCN Status (of species)* *Trend (of population size; BirdLife, 2024)*
Atlantic yellow-nosed albatross (*Thalassarche chlororhynchos*)	Gough Island, Tristan da Cunha (40° S, 10° W)	35 – 73k (ACAP, 2009b ; Ryan *et al*., 2011, Bratt 2023)	*Endangered* Declining at Gough Island (0.2-1.2 % yr^{-1}) and elsewhere (1.1-5.0 % yr^{-1})
Tristan albatross (*Diomedea dabbenena*)	Gough Island, Tristan da Cunha* (40° S, 10° W)	3.0 – 4.0k (Oppel *et al.* 2022)	*Critically Endangered* Declining (1.0-1.2 % yr^{-1})
Wandering albatross (*Diomedea exulans*)	South Georgia (54° S, 37° W)	2.6k (Poncet *et al*., 2017)	*Vulnerable* Declining (1.4-4.1 % yr^{-1})
White-chinned petrel (*Procellaria aequinoctialis*)	South Georgia (54° S, 37° W)	1.18 – 2.37M (Martin *et al*., 2009)	*Vulnerable* Declining (1.6-1.9 % yr^{-1}) at South Georgia. No estimate of population trend available from Prince Edward Islands.
	Prince Edward Islands (47° S, 38° W)	9 – 15k (Ryan *et al*., 2012)	

Table 2. Summary of CMM scenarios considered in this study in support of the review of ICCAT Rec. 11-09. All scenarios run for both fishing south of 20º and 25ºS. Full specifications of CMM design for each of ICCAT (2011) and ACAP (2023) in **Appendix 3**. SQ = Status Quo (CMMs implemented to current standards); BLW = Branch line weighting; BSL = Bird-scaring lines; HSD = Hook shielding devices; and NS = Night setting.

Scenario	CMMs applied		CMMs applied at least as specified by…
SQ1		BLW + NS	ICCAT Rec. 07-07 ICCAT Rec. 11-09
SQ2		BLW + BSL	
SQ3		NS + BSL	
SQ4		BLW + NS + BSL	Extension of current ICCAT Recs but without changing specification of CMMs
ACAP1		BLW + NS	Updating existing CMM combinations to ACAP (2023) specifications
ACAP2		BLW + BSL	
ACAP3		NS + BSL	
ACAP4		BLW + NS + BSL	ACAP Best Practice Guidance (ACAP, 2023)
ACAP5		HSD	

Table 3. Calculation of parameters used to estimate fishing mortality of seabirds. GFW = Global Fishing Watch.

Parameter	Definition/ calculation	Source of information
Effort (*E*)	Relative longline effort per flag state (hooks set, 2012-20) as a proportion of the most active fleet	ICCAT Task 2 EffDis
Overlap (*o*)	Overlap of polygons (convex hull from raster layers gridded at 5^{o2}) containing 95% of ICCAT fishing activity and bird distribution (biased against juvenile birds as discussed above).	ICCAT Task 2 EffDis; Carneiro *et al*., 2020
Spatial availability (a_{spat})	Relative apparent fishing effort and seabird foraging time within overlapping area, using 1^{o2} GFW data and 5^{o2} tagging data respectively	Kroodsma *et al*. 2018; Carneiro *et al*., 2020
Seasonal availability (a_{seas})	Year-round distribution of fishing effort and seabird foraging areas. Fixed value = 1	ICCAT Task 2 EffDis; Carneiro *et al*., 2020
Catchability (*q*)	Proportion of fishing effort cell (1^{o2}, GFW) covered by 'attraction area' which was taken as length of longline x max. attraction distance.	Afonso *et al*., 2012; Brothers *et al*., 1999; Bugoni *et al*., 2008; Collet *et al*., 2015; Fernandez-Carvalho *et al*., 2015; Gales *et al*., 1998; Griffiths *et al*., 2007; Melvin *et al*., 2013, 2014
Selectivity (*s*)	Knife-edge function of age-at-fledging. Selectivity = 0 prior to fledging, and 1 thereafter.	**Appendix 1**
Time-dependent encounterability (e_{timed})	Proportion of birds interacting with hooks, as a function of bird diving depth and line weighting, derived from standardised interaction rate information from published BPUE values per line weighting specification. For scenarios SQ3 and ACAP3, where line weighting was not specified, the standardised interaction rate from vessels using line weighting regimes below ICCAT 2011 standards, rather than assuming that lines were unweighted.	Baker *et al*., 2016; Brothers *et al*., 1999; Duckworth, 1995; Gales *et al*., 1998; Gianuca *et al*., 2011, 2021; Gilman *et al*., 2005, 2008; 2023; Jiménez *et al*., 2014, 2018, 2020; Melvin *et al*., 2013, 2014; Santos *et al*., 2019; Sullivan *et al*., 2017; Robertson *et al*. 2018; Rollinson *et al*., 2016
Fixed encounterability (e_{fixed})	Proportion of birds interacting with hooks as a function of performance of bird-scaring lines, hook shielding devices, and night setting, derived from standardised interaction rate information from published BPUE values per CMM type and specification.	
At-vessel mortality (*avm*)	Proportion of hooked seabirds (*Diomedea*, *Thalassarche*, or *Procellaria* spp.) discarded dead from ICCAT pelagic longline fisheries. Mean value = 0.96 (+/- s.d. 0.0103)	ICCAT, 2023
Post-release mortality (*prm*)	Proportion of hooked seabirds released alive that subsequently die through bycatch injury or trauma. Mean value = 0.40 (+/- s.d. 0.1)	Phillips and Wood, 2020

Table 4. ΔF percent change in estimated bycatch mortality matrix.

	To					
From	SQ4	ACAP1	ACAP2	ACAP3	ACAP4	ACAP5
SQ1	-39.3	-43.1			-84.5	-97.8
SQ2	-68.9		-74.5		-92.1	-98.9
SQ3	-31.4			-55.3	-82.5	-97.5
SQ4					-74.5	-96.5

Table 5. Summary of potential error sources for bycatch mortality estimation. *Some studies have reported reduced seabird bycatch over time among individual fleets (e.g. Jiménez *et al.* 2020) but data generally lacking to assess each fleet.

Potential sources of error	**Bias direction**
Assumes that bycatch rates do not vary spatially or over time (2012-2020)	Uncertain*
Analysis does not account for all factors relating to susceptibility per species (Jiménez *et al.* 2020). These differences may be driven by characteristics of individual vessels, or seabird behavioural or ontogenetic differences such as: • competition among attending bird assemblages (e.g. size-based or between species); • diurnal-nocturnal differences in foraging between species, and influence of moon cycles or weather; • relationship between bird gape and hook size; or • influence of other individual-level vessel fishing methods (e.g. bait choice)	Uncertain
Real-world trials of some CMMs (e.g. HSDs; Sullivan *et al.* 2017) outperform model estimates. Data not used directly, owing to small sample sizes.	Over-estimation
Scenarios assume that CMMs are implemented perfectly by all fleets throughout the ICCAT Convention Area	Under-estimation
Juvenile birds under-represented in tracking data but are generally found further north than adults (Gianuca *et al.,* 2017; Carneiro *et al*., 2020)	Under-estimation
Assumes that adding a third CMM linearly decreases bycatch rates	Under-estimation

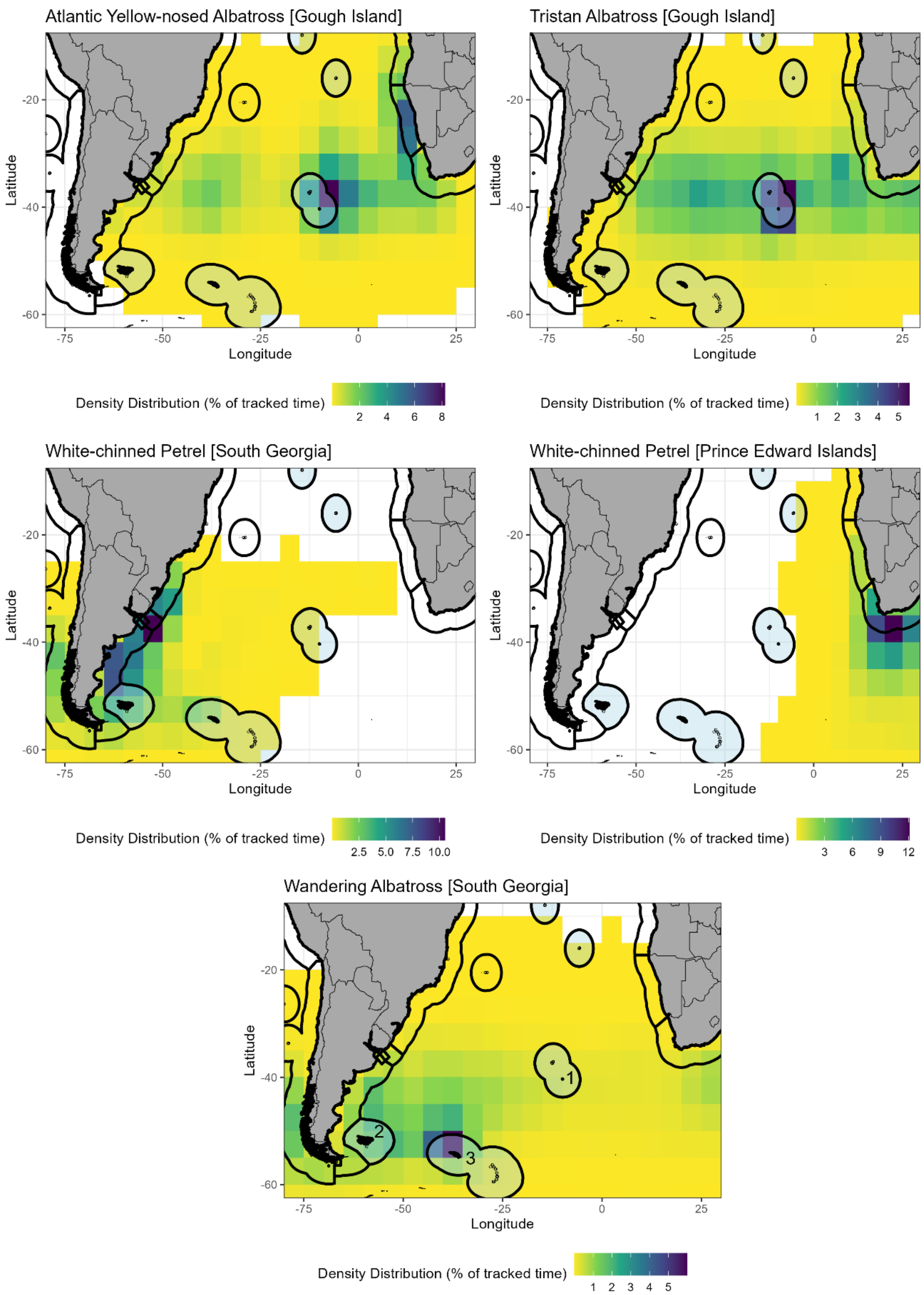


Figure 1. Distribution of the five seabird populations reviewed here (data from Carneiro *et al.* 2020). UKOTs (shaded areas) that host significant populations of seabirds are highlighted on the bottom panel: 1 = Gough Island, part of the Tristan da Cunha islands and the territory of Ascension, St Helena, and Tristan da Cunha; 2 = Falkland Islands; and 3 = South Georgia, part of the territory of South Georgia and the South Sandwich Islands. Prince Edward Islands (South Africa) not depicted as the islands lie outside of the ICCAT Convention Area, but their population of white-chinned petrels forage extensively in the south-east Atlantic.

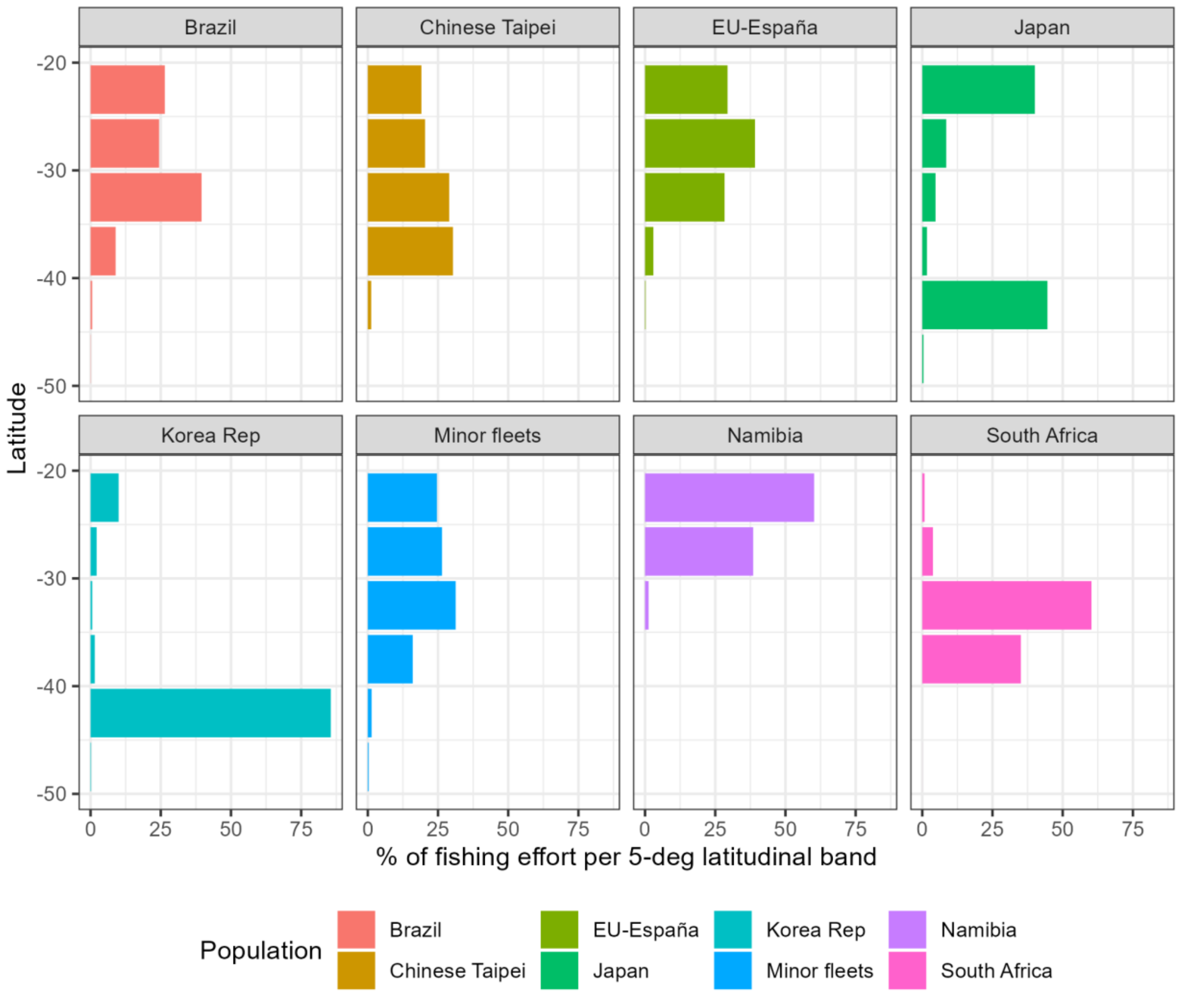


Figure 2. Latitudinal distribution of total fishing effort south of 20º S in the ICCAT Convention area per flag state modelled here (ICCAT EffDis, 2012-2020).

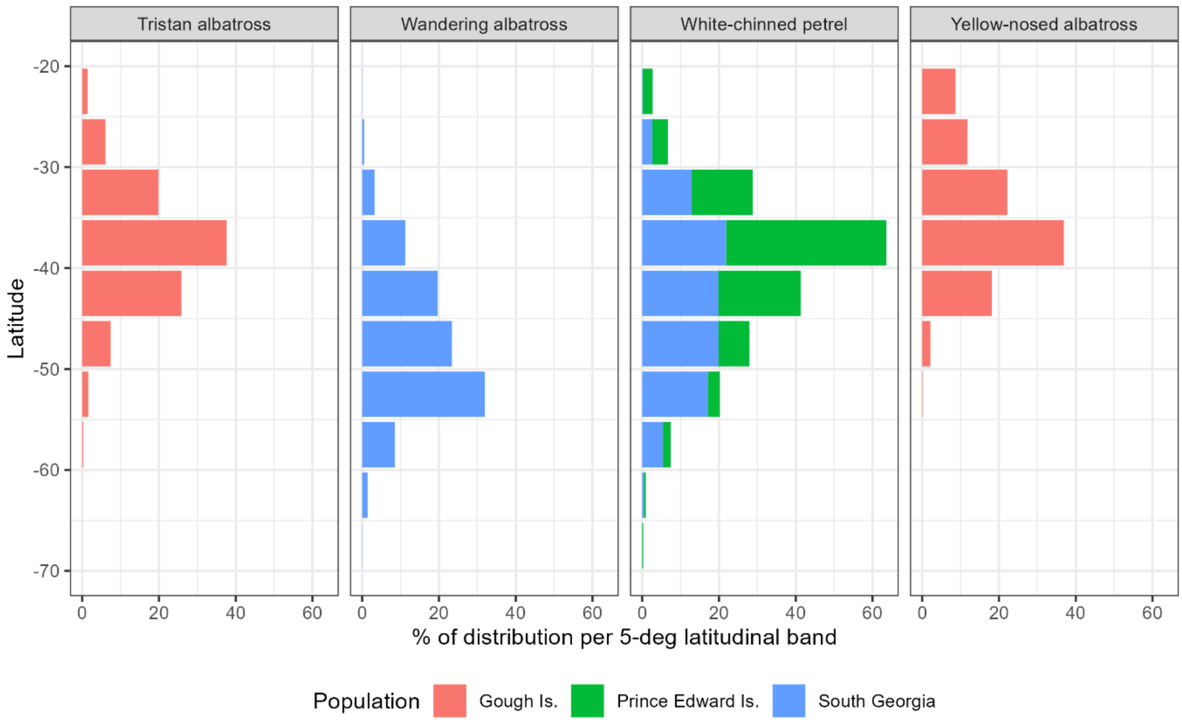


Figure 3. Average annual distribution (% of total) by latitude per seabird population within the Atlantic. All populations range elsewhere in the Pacific and/or Indian Oceans (**Figure 1**).

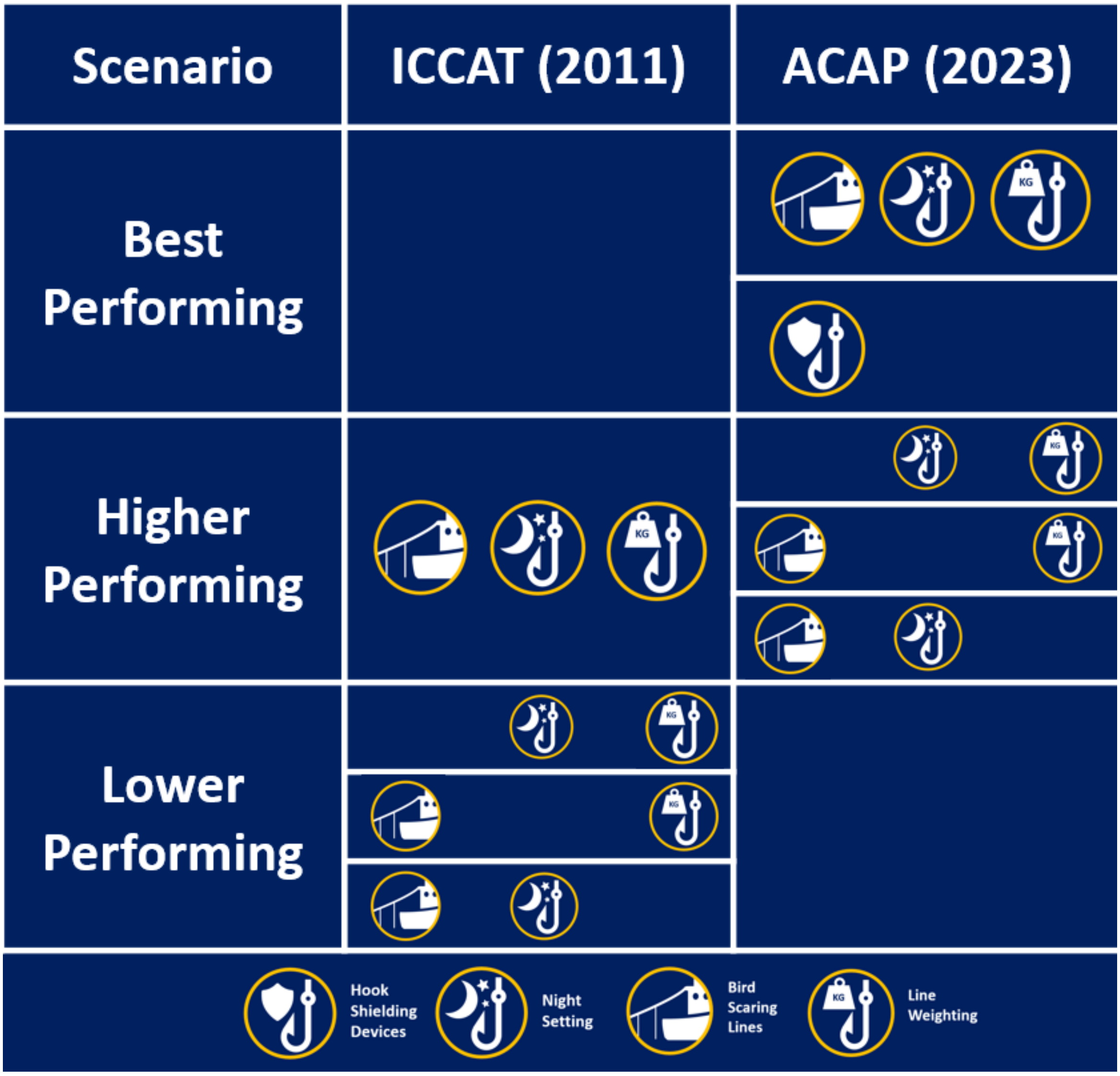


Figure 4. CMM combinations grouped into tiers of performance level (rows) and respective specifications (columns) for reducing seabird bycatch mortality on pelagic longlines.

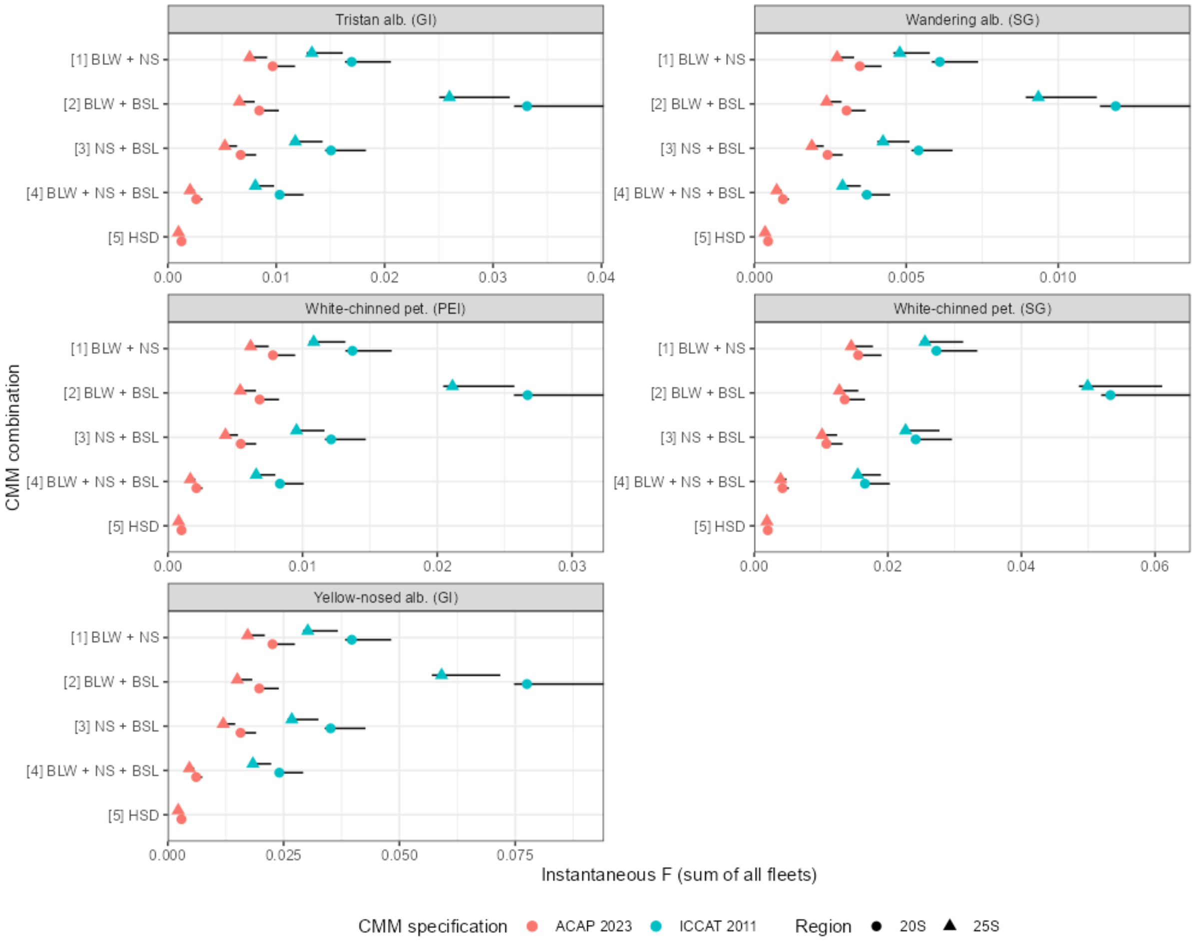


Figure 5. Estimated instantaneous fishing mortality rates per population, region, and CMM scenario (mean +/- 95% confidence intervals). Region = Model spatial domain either south of 20°S or south of 25°S. CMM specification = Specification of CMMs as per ICCAT (Rec. 11-09) or ACAP (2023). GI = Gough Island; PEI = Prince Edward Islands; SG = South Georgia. Numbers in [ ] refer to scenario numbers (see **Table 2**).

Appendix 1

Seabird life history data

Summary of species' life history data used in the EASI-Fish model. Estimates of these life history parameters did not vary significantly between populations. [1]Quantitative estimate not available for this species, longevity estimated from conspecific species (*P. conspicillata*).

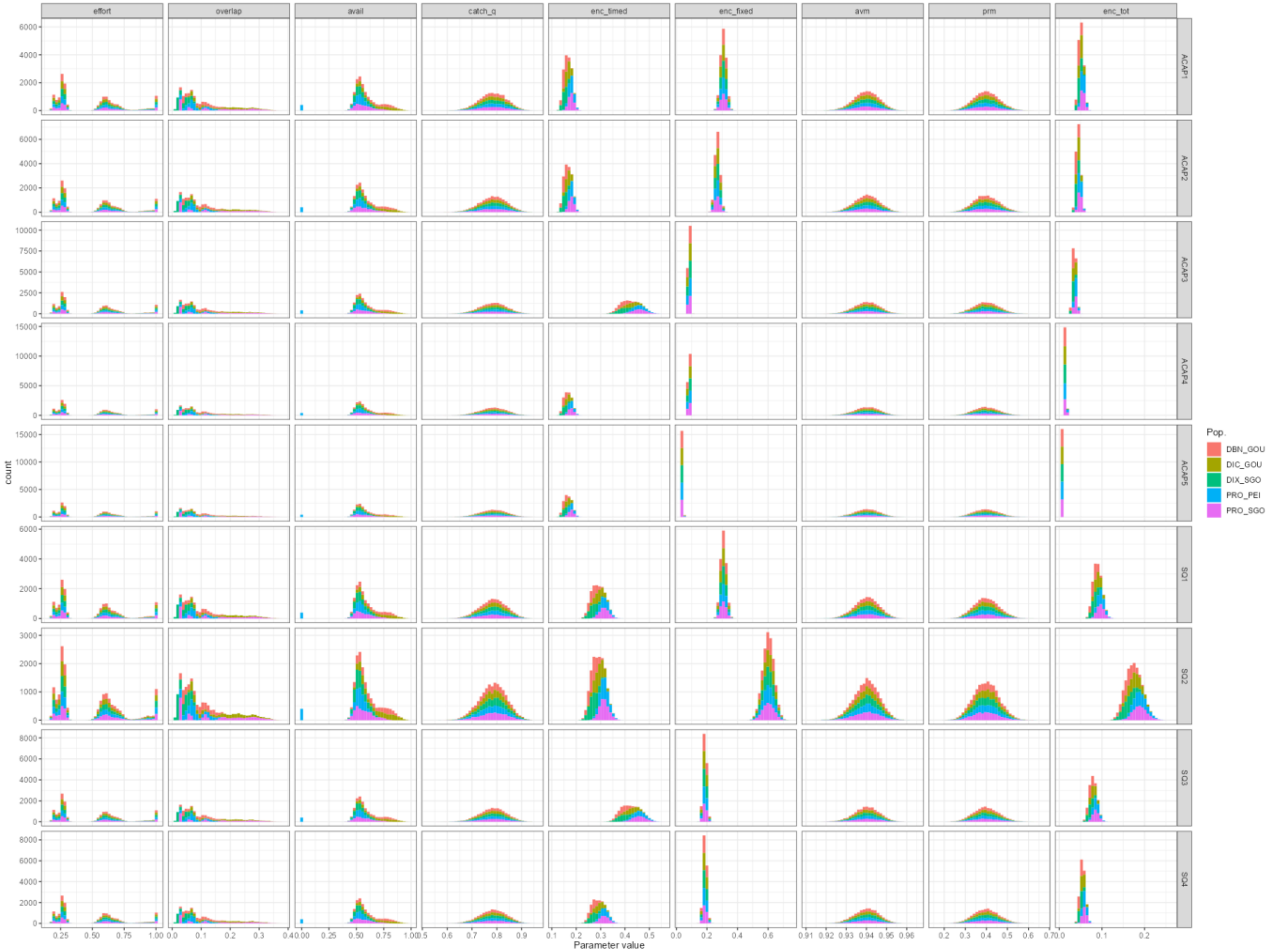
Species	*Life history parameter*						*References*
	Mean longevity (years)	*Age-at-fledging (years)*	*Age at maturity (years)*		*Natural mortality*		
			1%	*50%*	*Juvenile*	*Adult*	
Atlantic yellow-nosed Albatross (*T. chlororhynchos*)	37	0.32	6	10	0.120	0.080	Hagen, 1982; Weimerskirch *et al*., 2000; Cuthbert *et al*. 2003; ACAP factsheet[8]; NZ Birds Encyclopaedia[9]
Tristan albatross (*D. dabbenena*)	38	0.69	4	10	0.242	0.074	Neves *et al*., 2000; Cuthbert *et al*., 2004; ACAP, 2009a; Ryan, 2009; Reid *et al*., 2013
Wandering albatross (*D. exulans*)	50	0.76	10	11	0.078	0.058	Weimerskirch *et al*., 2014; BirdLife International, 2024
White-chinned petrel (*P. aequinoctialis*)	26[1]	0.26	4	6	0.170	0.105	Harrison, 1983; Marchant & Higgins, 1990; Huin, 1994; Barbraud *et al*., 2008; Martin *et al*., 2009; Rollinson *et al*., 2014; BirdLife International, 2024

[8] https://www.acap.aq/acap-species/290-atlantic-yellow-nosed-albatross/file

[9] https://nzbirdsonline.org.nz/species/atlantic-yellow-nosed-mollymawk

Appendix 2

Parameter distributions



Distributions of parameters used to estimate F per scenario. Avail = Availability; catch_q = Catchability (q); Enc_timed = Encounterability (timed); Enc_fixed = Encounterability (fixed); Enc_tot = Sum of fixed and timed encounterability; avm = at-vessel mortality; and prm = post-release mortality. Total encounterability for illustration purposes only. DBN_GOU = Tristan albatross, Gough Island; DIC_GOU = Atlantic yellow-nosed albatross, Gough Island; DIX = Wandering Albatross, South Georgia; and PRO_PEI & PRO_SGO = white-chinned petrels at the Prince Edward Islands and South Georgia respectively.

Appendix 3

CMM specifications

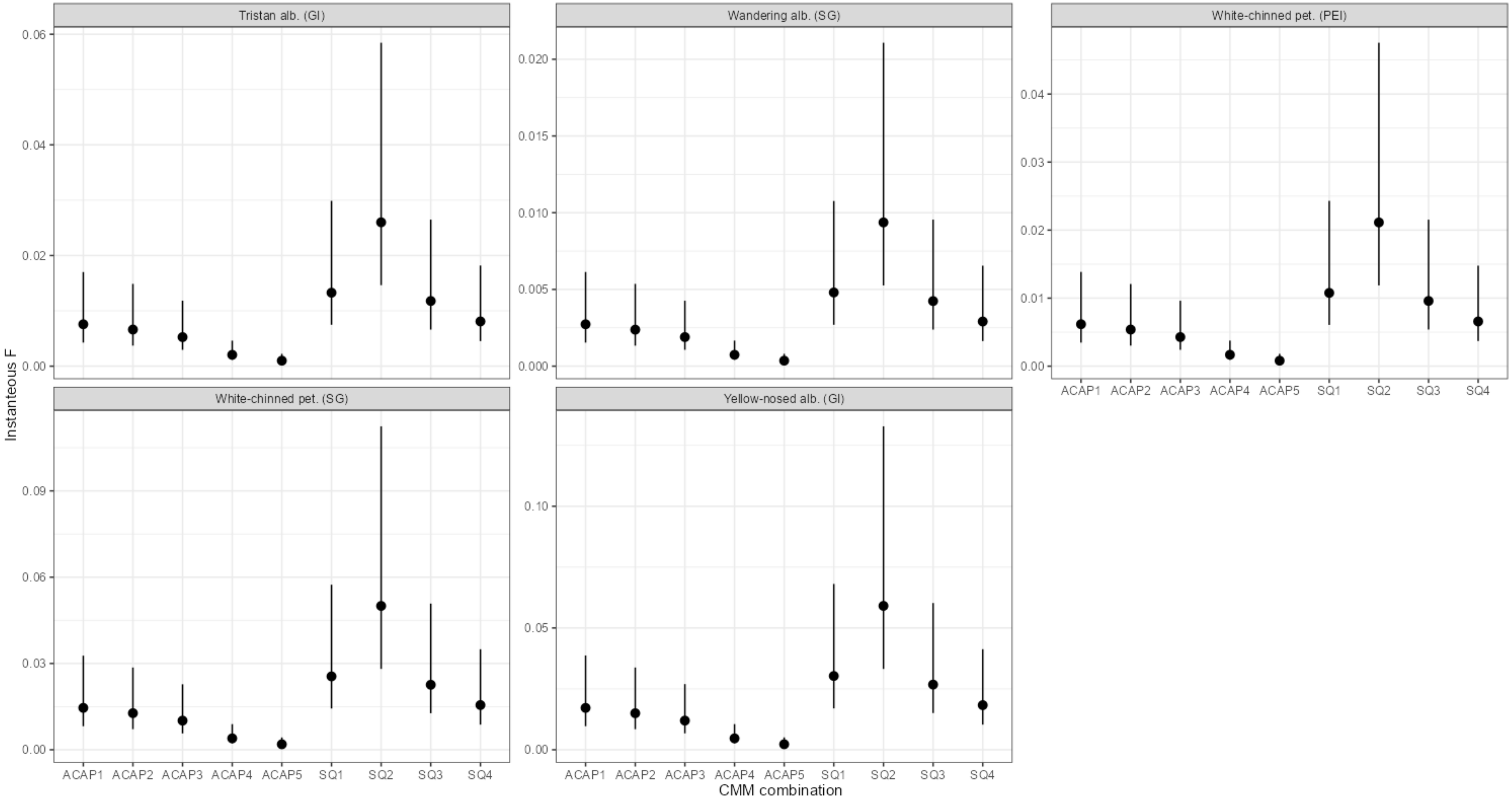
Comparison of CMM specifications as required by ICCAT (Rec. 11-09) or recommended by ACAP (2023). LOA = Length Over All (metres) of vessel

CMM	ICCAT (2011)	ACAP (2023)
Line Weighting	Greater than a total of 45 g attached within 1 m of the hook or; Greater than a total of 60 g attached within 3.5 m of the hook or; Greater than a total of 98 g weight attached within 4 m of the hook.	40 g or greater attached within 0.5 m of the hook; or 60 g or greater attached within 1 m of the hook; or 80 g or greater attached within 2 m of the hook.
Bird-Scaring (tori) Lines	**LOA <35m:** - Deploy at least 1 bird-scaring line. - Aerial extent must be greater than or equal to 75m. - Long and/or short (but greater than 1m in length) streamers must be used and placed at intervals as follows: -- Short: intervals of no more than 2m OR Long: intervals of no more than 5m for the first 55 m of bird scaring line	**LOA <35m:** 1. a design with a mix of long and short streamers that includes long streamers placed at 5 m intervals over at least the first 55 m of the BSL. Streamers may be modified over the first 15 m to avoid tangling, and 2. a design that does not include long streamers. Short streamers (no less than 1 m in length) should be placed at 1 m intervals along the length of the aerial extent. ACAP Summary Advice for Reducing Impact of Pelagic Longline Fisheries on Seabirds In all cases, streamers should be brightly coloured. To achieve a minimum recommended aerial extent of 75 m, BSLs should be attached to the vessel such that they are suspended from a point a minimum of 6 m above the water at the stern
	LOA >35m: - Deploy at least 1 bird-scaring line. Where practical, vessels are encouraged to use a second tori pole and bird scaring line at times of high bird abundance or activity; both tori lines should be deployed simultaneously, one on each side of the line being set. - Aerial extent of bird-scaring lines must be greater than or equal to 100 m. - Long streamers of sufficient length to reach the sea surface in calm conditions must be used. - Long streamers must be at intervals of no more than 5m.	**LOA >35m:** Simultaneous use of two BSLs, one on each side of the sinking longline, provides maximum protection from bird attacks under different wind conditions. The setup for BSLs should be as follows: ▪ BSLs should be deployed to maximise the aerial extent, which is a function of vessel speed, height of the attachment points to the vessel, drag, and weight of bird scaring line materials. ▪ To achieve a minimum recommended aerial extent of 100 m, BSLs should be attached to the vessel such that they are suspended from a point a minimum of 8 m above the water at the stern. ▪ BSLs should contain a mix of brightly coloured long and short streamers placed at intervals of no more than 5 m. Long streamers should be attached to the line with swivels to prevent streamers from wrapping around the line. All long streamers should reach the sea-surface in calm conditions. ▪ Baited hooks should be deployed within the area bounded by the two BSLs. If using bait-casting machines, they should be adjusted so as to land baited hooks within the area bounded by the BSLs. If large vessels use only one BSL, it should be deployed windward of the sinking baits. If baited hooks are set outboard of the wake, the BSL attachment point to the vessel should be positioned several metres outboard of the side of the vessel that baits are deployed.

Night Setting	Setting only occurs between nautical dusk and dawn	Setting only occurs between nautical twilight and dawn
Hook Shielding Devices	Not currently accepted	Device shields the hook until it reaches 10 metres depth or has been submerged for at least 10 minutes. Minimum branch line weighting standards detailed above are achieved. Currently accepted devices: • Hookpod-LED • Hookpod-mini • Smart Tuna Hook

Appendix 4

Sensitivity testing



Sensitivity of F estimation when varying encounterability parameters +/- 50% of their expected value. Point = mean sum instantaneous F per scenario and line range illustrates difference in positive and negative sensitivity tests. Parameter sensitivity strongly proportional to its magnitude.