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Meta-analysis of standardised interaction rates reveals relative performance of seabird bycatch mitigation methods for pelagic longline fisheries in the light of the review of CMM 2018-03

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ABSTRACT

Bycatch in commercial pelagic longline fisheries is a prominent driver of seabird declines globally. A range of different seabird bycatch mitigation methods exist that can address this challenge to marine biodiversity. However, to date, comparing the relative effectiveness of different bycatch mitigation methods has been challenged by the context-specificity of experimental trials and large-scale studies using observer data.

Here, we build on a recent statistical development that leverages the context-specificity of bycatch mitigation studies, rather than being limited by it. We calculated relative Standardised Interaction Rates (*rSIR*) per mitigation method under either WCPFC CMM 2018-03 specifications (separated between Hemispheres when appropriate) or current ACAP best practice. Specifically, we calculated *rSIR* for 44 bycatch mitigation studies that met our meta-analyses criteria within a Bayesian modelling framework. This allowed us to account for sample sizes of different studies, while generating adequate levels of uncertainty.

Our results provide an intuitive 0-1 metric (1 = worst performing) that enables the evaluation of the relative performance of different mitigation methods. Our analyses highlight the poor performance of I) blue-dyed bait, II) weighted branch lines under CMM 2018-03 specifications (contrasting with high performance of weighted branch lines under ACAP best practice specifications), and III) tori lines as per CMM 2018-03 Northern Hemisphere specifications.

Our approach allows for upscaling to assess the performance of combinations of different bycatch mitigation methods and highlights the significant increase in bycatch mitigation performance that can be achieved by adopting ACAP best practice.

The evidence presented indicates that ACAP best practice reduces seabird bycatch more effectively than the current minimum requirements in CMM 2018-03. Adopting ACAP best practice in the WCPFC Convention Area could result in bycatch mitigation performance improvements of 61% for the area south of 30°S, 81% for the area 25°-30°S, and 73% for the area north of 23°N (as measured in relative standardised interaction rates).

It is recommended that WCPFC SC20:

- **Notes** the analysis of the performance of seabird mitigation methods for commercial pelagic longline fisheries using relative standardised interaction rates, which demonstrated the poor performance of some seabird mitigation methods (e.g., blue-dyed bait) and the need to improve specifications of other seabird mitigation methods (e.g., current branch line weighting and Northern Hemisphere tori line specifications).
- **Notes** the ranking of individual seabird bycatch mitigation methods under ACAP best practice specifications, from best to worst performing (based on relative standardised interaction rates): 1) hook-shielding devices, 2) weighted branch lines, 3) night setting, and 4) tori lines, and notes the ranking of combinations of two out of three Southern Hemisphere mitigation methods: 1) weighted branch lines with tori lines, 2) weighted branch lines with night setting, and 3) tori lines with night setting.
- **Notes** that this analysis shows that the use of ACAP best practice could improve the performance of seabird bycatch mitigation methods by 61% for the area South of 30°S, 81% for the area between 25°S and 30°S, and 73% for the area North of 23°N.

INTRODUCTION

Seabird bycatch, including in commercial pelagic longline fisheries (hereafter pelagic longline fisheries), is a primary driver of seabird declines and a challenge to ensure the sustainability of the industry. To address this global challenge, a wide range of bycatch mitigation methods have been developed specifically for pelagic longlines to prevent birds from becoming hooked, or entangled, and subsequently drown. Such mitigation methods include (see Pierre 2023 for a comprehensive review):

I) Setting hooks at night, when birds are less active,
II) Weighting branch lines, so hooks sink quicker out of the range in which they are accessible to diving seabirds,
III) Tori lines, which scare birds away from accessing sinking hooks,
IV) Hook-shielding devices, which shield the barb of the hook until a certain depth is reached, and
V) Underwater bait setters, which set hooks under water and out of range of most seabirds.

Each of these methods have been developed through a range of experimental trials around the globe to:

I) Assess their effectiveness in terms of reducing seabird bycatch to the lowest achievable levels,
II) Assess the impacts on target catch,
III) Assess the impacts on bycatch of other non-target species (e.g., sea turtles),
IV) Evaluate the practicability of their implementation, and
V) Establish clear specifications and minimum performance standards.

Only once adequate performance has been confirmed under these criteria, can a method be considered for ACAP best practice advice (ACAP 2023). While this has resulted in clear and defensible best practice advice, the direct comparisons of effectiveness between different methods and different combinations of methods has remained elusive.

Comparing different trials and studies of various bycatch mitigation methods has long been challenging, particularly because of the context-specificity of individual studies. Studies or trials are often subject to local confounding factors, such as weather, sea state, seabird abundance, seabird species composition, fishing practices, latitude etc, even when studies are large-scale (e.g., Jiminez *et al*. 2020, Gilman *et al*. 2016). While individual studies often go through great lengths to account for these factors, and can do so successfully (e.g., Gilman *et al*. 2023), these confounding factors result in challenges of evaluating the effectiveness of seabird bycatch mitigation methods across studies. Thus, even using standardised metrics like bycatch per unit effort (BPUE), usually per 1,000 hooks, have not resulted in a commonly accepted performance metric (e.g., Ochi 2023). A clear, accessible, and easily interpretable metric to quantity the direct, or relative, effectiveness of different bycatch mitigation methods and combinations thereof across studies has thus remained a challenging construct.

To facilitate meaningful assessments when reviewing seabird bycatch mitigation policies, however, particularly when these cover large sections of ocean, a clear and accessible metric of effectiveness would be required. This is exemplified by the current review of the WCPFC *Conservation and Management Measure to mitigate the impact of fishing for highly migratory fish stocks on seabirds* (CMM 2018-03; WCPFC 2018), which covers the entire Western and Central Pacific Ocean (WCPO), a section of ocean that is characterised by differing seabird communities, among a range of other key differing factors. Central to this review is a comparison of bycatch mitigation methods and their specifications listed under CMM 2018-03 and those listed under ACAP best practice (ACAP 2023).

To overcome the challenge of a missing performance metric for seabird bycatch mitigation methods and facilitate a meaningful review of CMM-2018-03, we here build on a recent statistical development (Bell *et al*. 2024), which exploits the context-specificity of different trials and studies, rather than being limited by them, and generates a relatively simple, clear, and easy-to-interpret relative performance metric ranging from between 0 and 1.

Specifically, we here:

I) Complete a meta-analysis and document the development of relative standardized interaction rates (*rSIR*) as a performance metric suitable to evaluate the relative effectiveness of different mitigation methods and their specifications across studies and,

II) Estimate *rSIR* within a Bayesian framework for each of the relevant bycatch mitigation methods, specifications, and combinations thereof under either WCPFC CMM 2018-03 or ACAP best practice.

METHODS

Selection of relevant and suitable seabird bycatch mitigation studies

To identify studies suitable to evaluate the relative performance of different seabird bycatch mitigation methods for pelagic longlines under either current ACAP best practice specifications (ACAP 2023) or the specifications as per WCPFC CMM 2018-03 (for both the Southern and the Northern Hemisphere; WCPFC 2018), we first conducted a structured literature review. We went through considerable lengths to reduce influences of publication biases on our analyses as much as possible. Specifically, we compiled all papers listed in the independent review conducted by Pierre (2023). Additionally, we reviewed all papers on seabird bycatch mitigation methods submitted to WCPFC SC since its inception, and if any additional studies were identified, these were added to our compilation of papers. Then, we conducted a standard scientific literature search using Google Scholar. As a final step, we compiled all the information in a SharePoint folder[3], which we shared with all those who had signalled interest in the review of CMM 2018-03, and invited all interested parties to share any additional work that was not yet included both in writing and during the two informal intersessional meetings (February and May 2024).

[3] Access to this SharePoint folder can be requested by contacting Johannes Fischer via jfischer@doc.govt.nz

Following the compilation of relevant papers, we then retained those in which:

I) The study evaluated the performance of bycatch mitigation methods through comparison and included at least two treatments, so that relative performance (including comparisons to no mitigation) could be assessed,
II) Specifications of bycatch mitigation methods were adequately detailed and followed either current ACAP best practice (ACAP 2023) and/or WCPFC CMM 2018-03 (for the Southern and/or Northern Hemisphere; WCPFC 2018),
III) Reported interaction rates allowed for standardization (e.g., reported bycatch/contact/attack rates per unit effort, usually per 1,000 hooks), and
IV) Sample sizes of each treatment were reported in a standardised fashion (i.e., 1,000s of hooks) so that studies could be weighted accordingly.

Following these steps, we identified 44 relevant and suitable papers, which are listed in Supplementary Material 1. As a final step, we cross-referenced these papers with those used by Bell *et al*. (2024) to ensure that no papers had been missed. Our compiled papers included both papers documenting experimental studies (n = 35) as well as papers that summarized/analysed observed fishing effort during standard fishing practices (n = 9). Jointly, these papers cover 84.1 million pelagic longline hooks and the seabird interactions recorded with these across all major ocean basins on planet Earth.

Estimation of relative standardized interaction rates

We estimated relative Standardized Interaction Rates (*rSIR*) for each seabird bycatch mitigation treatment in the studies described in the retained papers following the methodology developed by Bell *et al*. (2024), but we expanded upon this approach by estimating *rSIR* within a Bayesian framework to account for the influence of different sample sizes among studies and propagate uncertainty surrounding the estimates. Specifically, we first standardized the reported interaction rates per unit effort (*IPUE*) for each bycatch mitigation treatment as follows:

$$1)\quad rSIR_{i,j} = \frac{IPUE_{ij}}{max_i(IPUE_j)},$$

in which, $IPUE_{ij}$ refers to the interaction rate per unit effort (bycatch/contact/attack rate, usually per 1,000 hooks) per mitigation method $_i$ per study/trial $_j$. If a paper reported adequately on several studies/trials that differed considerably on spatial (i.e., in different ocean basins, e.g., Sullivan *et al*. 2017) or that employed different fishing approaches (e.g., tuna and swordfish gear; Gilman *et al*. 2003, 2007), these studies/trials were considered separately. Through this approach, the treatment (bycatch mitigation method) with the highest reported *IPUE* per study received an *rSIR* of 1, and each other treatment in the same study was scaled according to this. It should also be noted that due to this standardisation approach, the relationship between *rSIR* and *IPUE* was not linear (see Supplementary Material 2), as the standardisation process introduces an upper limit to *rSIR*, while *IPUE* can technically range from 0 to infinity.

However, still, in short, the better a bycatch mitigation method performed comparatively, the closer to 0 its *rSIR* value was, and the poorer a bycatch mitigation method performed, the closer to 1 its *rSIR* value was. Our approach, following Bell *et al*. (2024), thus leveraged the context-specificity of individual bycatch mitigation studies, rather than being limited by it, and allowed for subsequent evaluation of relative performance of different methods and specifications across studies.

We fitted a series of GLMs and stochastic nodes to the collated data to estimate *rSIR* per bycatch mitigation method under ACAP best practice (ACAP 2023) or WCPFC CMM 2018-03 specifications (WCPFC 2018) as following:

2) $Logit\left(rSIR_{i,s}\right) = \alpha_i + \theta_{i,s}^{\beta} \times spec_{i,j}$,
3) $(rSIR_{i,j} \times n_{hooks_{i,j}}) \sim Binomial(rSIR_{i,s}, n_{hooks_{i,j}})$,

in which $rSIR_{i,s}$ is the relative Standardized Interaction Rate per bycatch mitigation method *i* with specifications *s*, α_i is the intercept, $\theta_{i,s}^{\beta}$ is a vector of coefficients for the fixed effects of mitigation method $_i$ with specifications $_s$, $spec_{i,j}$ is the design matrix of the relevant specifications of mitigation method $_i$ in study $_j$, and $n_{hooks_{i,j}}$ is the sample size per mitigation method $_i$ in study $_j$ (but to ensure that single studies did not dominate estimates, we restricted the maximum value to 500,000 hooks). Preliminary attempts to extend this modelling approach with random effects (e.g., for different data types) resulted in non-convergence, potentially due to overfitting issues, and thus we retained a GLM approach. In addition, our analyses were not informative (i.e., credible intervals 0-1) for bycatch mitigation methods evaluated by single studies, and thus we excluded the only suitable study evaluating underwater bait setters (Robertson *et al*. 2018) and the only suitable study evaluating line shooters (Lokkeborg 2003). Despite these minor shortcomings, this extension of the Bell *et al*. (2024) approach allowed us to account specifically for different sample sizes (e.g., hundreds of hooks; e.g., Cocking *et al*. 2008; vs. tens of millions of hooks; e.g., Jimenez *et al*. 2020) and thus the potential different levels of confidence in the presented evidence, while also generating uncertainty as appropriate around the *rSIR* estimates.

To extend these *rSIR* estimates for individual mitigation methods to the combinations of mitigation methods (with either ACAP best practice or WCPFC CMM 2018-03 Southern/Northern Hemisphere specifications), we calculated the product of the relevant $rSIR_{i,s}$ estimates *sensu* Bell *et al*. (2024). This step was required as there was not a sufficiently large enough sample size of studies/trials evaluating each combination of mitigation methods with varying specifications (e.g., see Pierre 2023). Following the estimation *rSIR* for individual mitigation methods and combinations thereof, we calculated the relative gains that could be achieved when changing WCPFC CMM 2018-03 Southern/Northern Hemisphere specifications to ACAP best practice specifications. For this, and in the face of uncertainty, we also calculated the probability of one bycatch mitigation method with a certain set of specifications, or combination thereof, outperforming the other, and considered a probability of $P < 0.05$ significant.

To fully quantify the relative differences in bycatch mitigation performance between ACAP best practice and the *status quo* in the WCPFC Convention Area, we calculated the mean *rSIR* for minimum requirements under WCPFC CMM 2018 for the areas south of 30°S, 25°-30°S, and north of 23°N, and ACAP best practice. To assess if our *rSIR* estimates truly provided guidance for the best choice of bycatch mitigation options even in the face of uncertainty, we generated cumulative density functions of each *rSIR* estimate and assessed stochastic dominance following Canessa *et al.* (2016). In short, if cumulative density functions do not cross, first order stochastic dominance exists, and the specifications with the lower *rSIR* estimate is indeed the better performing, and therefore, the logical choice over the other specifications, despite existing uncertainty. If first order stochastic dominance was confirmed, we calculated the relative improvements in bycatch mitigation methods that could be achieved in the WCPFC Convention Area per different relevant latitudinal bands.

We fitted our models within the Bayesian modelling programme OpenBUGS (Spiegelhalter *et al*. 2014). Specifically, we used vague priors only (N[0, 0.01]) and fitted models using two MCMC chains of 100,000 iterations following a burn-in of 50,000 iterations. We assessed convergence by evaluating trace plots visually and by confirming that $\hat{R}$<1.05. We report our estimates as medians with 95% credible intervals (CIs) unless otherwise stated.

RESULTS

Estimates of relative standardised interaction rates (*rSIR*) for mitigation methods and combinations thereof for both the Southern and Northern Hemispheres under either ACAP best practice specifications or WCPFC CMM 2018-03 specifications can be found in Fig. 1. *rSIR* for no mitigation use was estimated at 0.894 (0.859-0.923), as in some cases, other mitigation methods (particularly blue-dyed bait) performed worse than no mitigation. The *rSIR* estimate for no mitigation equates to a mean interaction rate (*IPUE*) per 1,000 hooks of 3.143 (and a mean bycatch per unit effort (*BPUE*) per 1,000 hooks of 1.339).

Relative performance of Southern Hemisphere mitigation methods

Estimates of *rSIR* of Southern Hemisphere bycatch mitigation methods under ACAP best practice specifications were as following: tori lines = 0.413 (0.330-0.499), night setting = 0.407 (0.372-0.443), weighted branch lines = 0.275 (0.204-0.354), and hook-shielding devices = 0.086 (0.009-0.295). While informative values of *rSIR* for underwater bait setters could not be estimated using Equation 2 & 3, the raw *rSIR* value for underwater bait setters was 0.138. *rSIR* estimates of Southern Hemisphere mitigation methods following WCFCP CMM 2018-03 specifications were the same as ACAP best practice specifications for tori lines and night setting, while for weighted branch lines *rSIR* = 0.574 (0.522-0.625) and hook-shielding devices *rSIR* = 0.039 (0.001-0.228).

The adoption of ACAP best practice specifications in WCPFC in the Southern Hemisphere could result in an average relative improvement of 18% (11-25%) for single bycatch mitigation methods, which is predominantly driven by improvements in weighted branch line specifications (relative improvements of 52%; 43-61%). However, adopting ACAP specifications for hook-shielding devices could result in a reduction of relative performance of 124% (-789-30%) as WCPFC CMM 2018-03 specifications do not allow the Smart Tuna Hook (Baker & Candy 2014) which reduced the performance of hook-shielding devices under ACAP specifications and increased uncertainty.

Relative improvements that could be provided by an adoption of ACAP best practice specifications were also evident in the various combinations of bycatch mitigation methods (Table 1). Adopting ACAP best practice specifications in WCPFC in the Southern Hemisphere could result in an average relative improvement of 38% (33-44%) for combinations of two mitigation methods and 52% (47-58%) for the combination of all three mitigation methods.

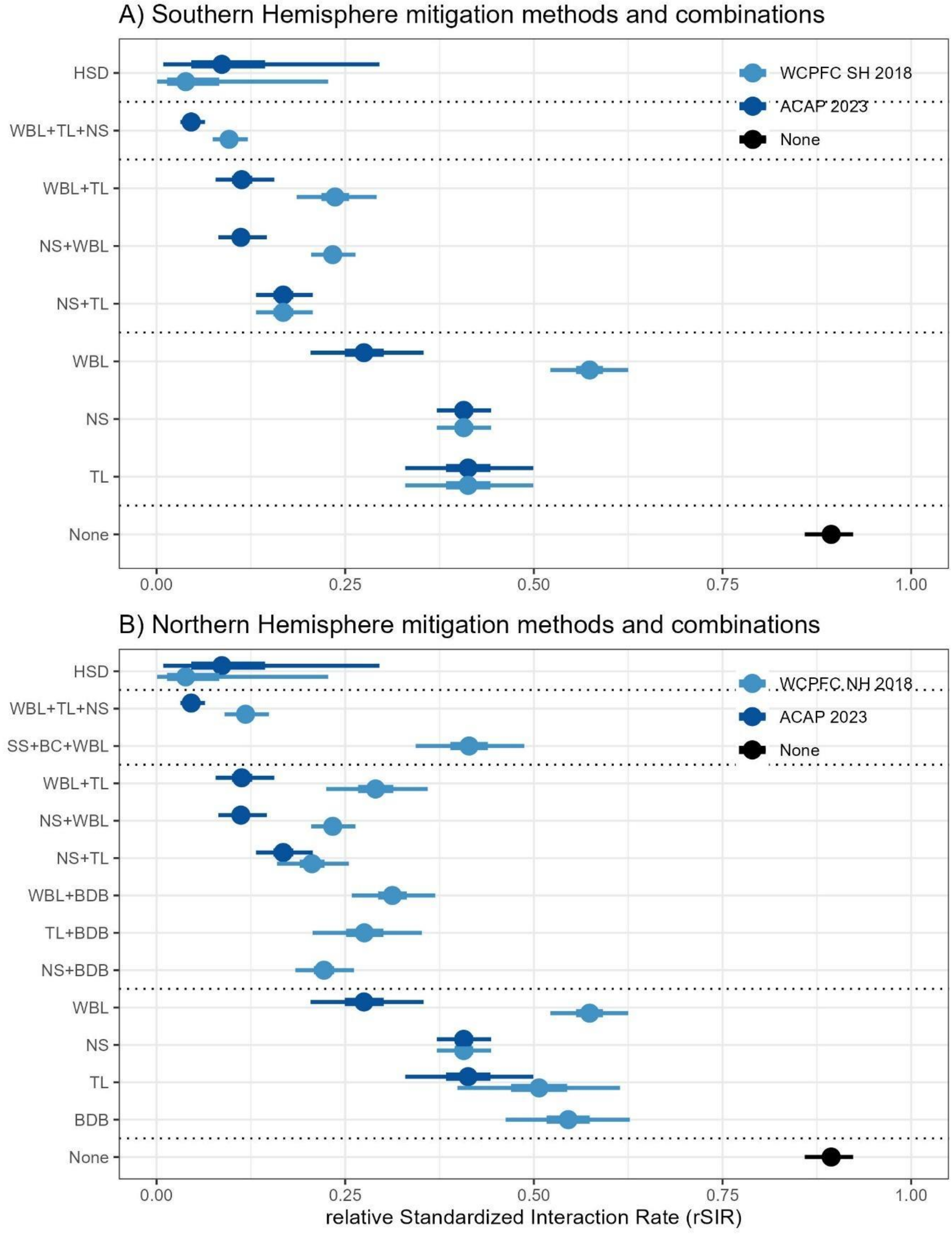

Fig. 1. Relative effectiveness of Southern (A) and Northern (B) Hemisphere seabird bycatch mitigation methods under ACAP best practice or WCPFC CMM 2018-03 specifications. HSD = hook-shielding devices; WBL = weighted branch lines; TL = tori lines; NS = night setting, SS = side setting; BC = bird curtain; BDB = blue-dyed bait. Dotted lines indicate different levels of combinations of mitigation methods (including stand-alone methods). Symbols represent medians, 50%, and 95% CIs.

Table 1. Relative gains or losses in *rSIR* in pairwise comparisons when adopting ACAP best practice specifications in WCPFC in the Southern Hemisphere, for 2/3 and 3/3 combinations of bycatch mitigation methods, as well as stand-alone methods (i.e., hook-shielding devices). NS = night setting, TL = tori lines, WBL = weighted branch lines, HSD = hook-shielding devices. *Italic* indicates $P > 0.05$.

		ACAP best practice 2023				
		NS+TL	**NS+WBL**	**WBL+TL**	**WBL+TL+NS**	**HSD**
WCPFC CMM 2018-03 SH	**NS+TL**	0% (0; 0%)	33% (29; 38%)	33% (25; 41%)	73% (69; 76%)	*48%* *(-43; 93%)*
	NS+WBL	28% (21; 36%)	52% (46; 58%)	52% (41; 62%)	80% (85; 76%)	*63%* *(-12; 96%)*
	WBL+TL	29% (28; 30%)	53% (50; 56%)	52% (45; 60%)	81% (78; 83%)	*63%* *(-1; 95%)*
	WBL+TL+NS	*-75%* *(-71; 77%)*	-16 (-21; -10%)	-17 (-29; -5%)	52% (47; 58%)	*10%* *(-144; 88%)*
	HSD	*-335%* *(-13,080; 9%)*	*-190%* *(-8,099; 36%)*	*-192%* *(-7,744; 31%)*	*-19%* *(-3,057; 72%)*	-124% (-789; -30%)

Relative performance of Northern Hemisphere mitigation methods

Estimates of *rSIR* of Northern Hemisphere bycatch mitigation methods following WCFCP CMM 2018-03 specifications were as following: weighted branch lines = 0.574 (0.522-0.625), blue-dyed bait = 0.546 (0.463-0.627), tori lines = 0.507 (0.339-0.614), side setting bird curtains and weighted branch lines = 0.414 (0.343-0.487), night setting = 0.407 (0.372-0.443), and hook-shielding devices = 0.039 (0.001-0.228). While informative values of *rSIR* for line shooters could not be estimated using Equation 2 & 3, the raw *rSIR* values for line shooters was 0.406.

The adoption of ACAP best practice specifications in WCPFC in the Northern Hemisphere could result in an average relative improvement of 29% (21-35%) for single bycatch mitigation methods, which is predominantly driven by improvements for weighted branch line specifications (relative improvements of 52%; 43-61%) and for tori lines (relative improvements of 19%; 17-19%), as well as the removal of blue-dyed bait.

Relative improvements of an adoption of ACAP best practice specifications in WCPFC in the Northern Hemisphere were also evident in the various combinations of bycatch mitigation methods (Table 2). Adopting ACAP best practice specifications in WCPFC in the Northern Hemisphere could result in an average relative improvement of 49% (45-53%) for combinations of two mitigation methods and 87% (85-89%) for the combination of three mitigation methods.

Table 2. Relative gains or losses in *rSIR* in pairwise comparisons when adopting ACAP best practice specifications in WCPFC in the Northern Hemisphere, for 2/3 and 3/3 combinations of bycatch mitigation methods, as well as stand-alone methods (i.e., hook-shielding devices). BDB = blue-dyed bait, NS = night setting, TL = tori lines, WBL = weighted branch lines, SS = side setting, BC = bird curtain, HSD = hook-shielding devices. *Italic* indicates $P > 0.05$.

		ACAP best practice 2023				
		NS+TL	**NS+WBL**	**WBL+TL**	**WBL+TL+NS**	**HSD**
WCPFC CMM 2018-03 NH	**BDB+NS**	24% (21; 28%)	50% (44; 55%)	49% (40; 57%)	79% (75; 83%)	*61% (-13; 95%)*
	BDB+TL	39% (36; 41%)	59% (58; 60%)	59% (56; 62%)	83% (82; 85%)	69% (16; 96%)
	BDB+WBL	46% (44; 49%)	64% (60; 68%)	64% (68; 70%)	85% (83; 88%)	72% (20; 97%)
	NS+TL	19% (17; 19%)	46% (43; 49%)	45% (39; 51%)	78% (75; 80%)	*58% (-16; 94%)*
	NS+WBL	28% (21; 36%)	52% (45; 60%)	52% (41; 62%)	80% (76; 85%)	*41% (-12; 96%)*
	WBL+TL	42% (41; 42%)	62% (59; 64%)	61% (57; 65%)	84% (82; 86%)	70% (18; 96%)
	SS+BC+WBL	59% (58; 62%)	73% (70; 76%)	73% (68; 77%)	89% (87; 91%)	79% (39; 97%)
	WBL+TL+NS	-42% (-46; -39%)	5% (2; 9%)	*4% (-5; 13%)*	61% (57; 65%)	*27% (-98; 90%)*
	HSD	*-335% (-13,080; 9%)*	*-190% (-8,099; 36%)*	*-192% (-7,744; 31%)*	*-19% (-3,057; 72%)*	-124% (-789; -30%)

Relative gains of adopting ACAP best practice in the WCPFC Convention Area

Estimates of *rSIR* for the minimum requirements under WCPFC CMM 2018 for the areas south of 30°S, 25°-30°S, and north of 23°N, and ACAP best practice are shown in Fig. 2A (*rSIR* for ACAP best practice = 0.067 (0.026-0.171), for WCPFC >30°S = 0.172 (0.142-0.222), for WCPFC 25°-30°S = 0.345 (0.305-0.412), and for WCPFC >23°N = 0.251 (0.220-0.287). Density distributions of *rSIR* estimates overlapped, indicating uncertainty, but cumulative density functions did not cross (Fig. 2B), indicating first order stochastic dominance and thus provided confidence in the order of performance despite the existing uncertainty. In other words, ACAP best practice was truly a better choice over WCPFC CMM 2018-03 requirements in terms of bycatch mitigation.

Changing the minimum requirements in the Southern Hemisphere under WCPFC CMM 2018-03 south of 30°S to current ACAP best practice could result in a relative improvement in the performance of seabird bycatch mitigation methods of 61% (27-85%). Similarly, changing the minimum requirements WCPFC CMM 2018-03 25°-30°S to current ACAP best practice could result in a relative improvement of 81% (60-93%). Changing the minimum requirements in the Northern Hemisphere under WCPFC CMM 2018-03 north of 23°N to current ACAP best practice could result in a relative improvement in the performance of seabird bycatch mitigation methods of 73% (44-90%).

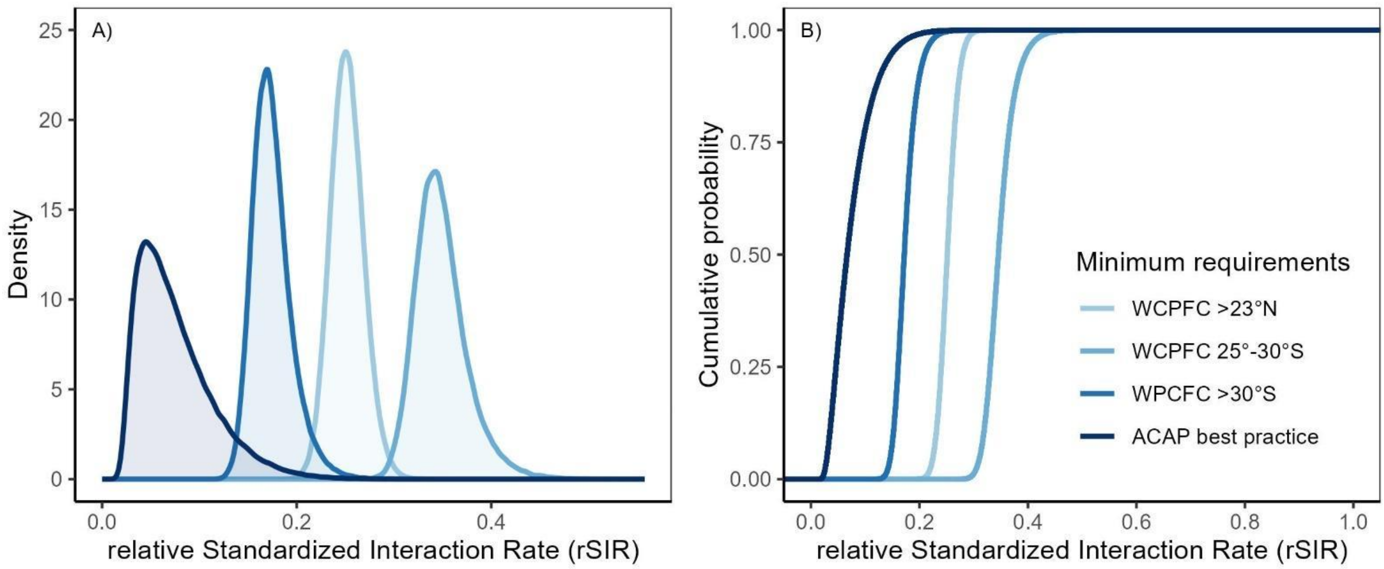

Fig. 2. Density plots (A) and cumulative density functions (B) of relative standardized interaction rates for minimum requirements of bycatch mitigation methods and combinations under WCPFC CMM 2018 for the areas south of 30°S, 25°-30°S, and north of 23°N, and ACAP best practice. The density plot (A) illustrates the distribution of the MCMC iterations of the *rSIR* estimates, similar to a histogram. If cumulative density functions (B) do not cross, first order stochastic dominance exists, and the specifications with the lower *rSIR* estimate (the left most line) is indeed the better performing, despite uncertainty.

DISCUSSION

Robust, cross-cutting, quantitative evidence of the relative performance of seabird bycatch mitigation methods, and their combinations, has long been evasive, hindering the recognition, adoption, and implementation of the best-performing bycatch mitigation methods around the world. We here provide a solution to this long-standing challenge in the form of relative standardised interaction rates (*rSIR*) which provide a relatively simple, intuitive metric, ranging from 0 to 1 (in which 1 is the worst-performing). By estimating this metric in a Bayesian modelling framework, we improved on earlier work (Bell *et al*. 2024) by accounting for sample size differences in studies and generating adequate uncertainty, and thus providing more confidence in the results.

Through our approach we were able to quantify the relative performance of all bycatch mitigation methods and their combinations, relevant to pelagic longlines in the WCPO, under either ACAP best practice specifications or WCPFC CMM 2018-03 Northern/Southern Hemisphere specifications. Our results highlight current shortcomings of the requirements under WCPFC CMM 2018-03 (blue-dyed bait, poor specifications of weighted branch line specifications, and poor Northern Hemisphere specifications of tori lines). In addition, we provide accessible metrics (i.e., %) of potential gains in seabird bycatch mitigation effectiveness if ACAP best practice were to be used rather than the minimum standards specified in CMM 2018-03: 61% for >30°S, 81% for 25°-30°S, and 73% for >23°N. Consequently, these results are of great utility and relevance to the current review of WCPFC CMM 2018-03.

Our analyses demonstrate that blue-dyed bait is an ineffective bycatch mitigation method. A range of studies have also highlighted that blue-dyed bait is ineffective, subject to weather conditions, and vastly outperformed by other more effective methods (Gilman *et al*. 2003, Cocking *et al*. 2008, Gilman *et al*. 2008, Chaloupka *et al*. 2021, Gilman *et al*. 2022). Previous work has also highlighted that blue-dyed bait is generally perceived as impractical (dyeing requires extra time and labour, the required thawing increases bait loss and decreases bait quality, and dyeing is often messy and may stain target catch) and may decrease target catch rate (Ochi *et al*. 2011). Our analyses further highlighted the poor performance of blue-dyed bait is reflected in the combinations of several mitigation methods, where the addition of blue-dyed bait adds little if any gain in mitigation effectiveness.

The current specifications of branch line weighting under WCPFC CMM 2018-03 limit the effectiveness of this mitigation method. Our results illustrate that a 52% gain in relative performance of seabird bycatch mitigation effectiveness could be achieved if ACAP best practice for weighted branch lines were adopted instead of the current WCPFC CMM 2018-03 specifications. These gains are largely attributable to improved sink rates of hooks, ensuring that hooks are outside of the (usual) dive range of seabirds sooner (and ideally within the aerial extent of a tori line; see Düssler *et al*. 2024). Consequently, hook sink rates are directly correlated to IPUE, with sink rates ≥0.5 m/s approaching 0 IPUE (Peterson *et al*. 2008). Barrington *et al*. (2016) provided clear mechanistical evidence for which branch line specifications achieve sink rates ≥0.5 m/s, ultimately forming the current ACAP best practice advice. Here we add to this body of evidence by showing that the *rSIR* of weighted branch lines under ACAP best practice is significantly lower than the *rSIR* of weighted branch lines under WCPFC specifications. Additionally, a range of studies have shown that ACAP best practice weighted branch line specifications do not affect target catch rate (Pierre 2023).

Crew safety has been a long-standing consideration for the implementation of weighted branch lines. Specifically, weights can increase the risk that fly backs (i.e., when hooks and/or weights fly back to the vessel due to a shark biting off the hook, or a hook tearing out of the mouth of a fish), creating serious health and safety concerns of this bycatch mitigation method. However, considerable efforts have been invested into the design of safer branch line weighting designs that allow weights to slide down the branch line in the case of a fly-back, providing a much safer option than weighted swivels (e.g., see Sullivan *et al*. 2012, Robertson *et al*. 2013, Santos *et al*. 2019). Indeed, a sliding weight of 60g at 1 m from the hook was found to almost always slide right off the branch line during a simulated bite off, and in a tear out the collision between recoiling hook and sliding weight often sheared the hook from the line, resulting in both the hook and the weight being lost (Rawlinson *et al.* 2018). Comprehensive safety advice has been developed by ACAP (https://acap.aq/resources/bycatch-mitigation/mitigation-advice). Branch line weighting is now becoming commonly adopted in various fisheries, including in high-risk areas such as New Zealand. Consequently, the specifications of weighted branch lines in WCPFC CMM 2018-03 could be adapted to safe (sliding) weights with ACAP best practice specifications.

The current specifications of tori lines in the Northern Hemisphere under WCPFC CMM 2018-03 also limit the effectiveness of this mitigation method. Our results illustrate that a 19% gain in relative performance of seabird bycatch mitigation effectiveness could be achieved if ACAP best practice for tori line specifications were adopted instead of the current WCPFC CMM 2018-03 specifications.

Our estimates are somewhat complicated by the grouping of all Northern Hemisphere tori line designs into one category, rather than further compartmentalising the limited data into small vessel tori lines and large vessel tori lines under either ACAP best practice specifications or WCPFC CMM 2018-03 specifications (separation between which is further complicated by overlapping definitions of small vs large vessels; 35 vs 24 m). Consequently, our results should be interpreted as an estimate across both vessel size categories, and such an interpretation aligns well with previous studies. Specifically, larger vessel tori lines have been shown to perform well in the Northern Hemisphere under the current WCPFC CMM 2018-03 specifications (e.g., Chaloupka *et al*. 2021, Gilman *et al*. 2021). Conversely, small vessel tori lines with current WCPFC CMM 2018-03 Northern Hemisphere specifications, particularly streamerless tori lines, lack compelling evidence that they are effective in terms of seabird bycatch mitigation, despite considerable research effort (e.g., Katsumata *et al*. 2015, Ochi 2022, Ochi 2023). The poor performance of streamerless (and short streamer) tori lines under Northern Hemisphere specifications is likely caused by the limited aerial extent of these tori lines, as no minimum requirements exist. While achieving adequate aerial extent (i.e., ≥75 m; ACAP 2023) can be challenging, particularly on small vessels, extensive work in New Zealand has shown that it is not impossible, and that in fact, simple approaches can ensure appropriate aerial extents are achieved (Pierre & Goad 2016, Goad 2017). Consequently, the specifications of the Northern Hemisphere tori lines could be adapted to include an adequate aerial extent requirement in order to improve their effectiveness.

Our analyses did not cover all possible mitigation methods that are included in WCPFC CMM 2018-03. A lack of data precluded our ability to include some methods. Specifically, only one empirical study exists that evaluates the effectiveness of line shooters (Lokkeborg 2003). Raw *rSIR* estimates for line shooters based on this study equate to 0.407, which is similar to the performance of night setting. However, it should be noted that this study took place in an area that is not representative of the WCPO in terms of seabird community: the North Atlantic, where only two Procellariiformes occur that are not considered very vulnerable to seabird bycatch. Studies that succeeded Lokkeborg (2003) subsequently highlighted that line shooters may in fact increase seabird bycatch risk, rather than decrease it, as they slow the sink rates of hooks (Robertson *et al*. 2010). Consequently, no compelling evidence exists to consider line shooters an effective seabird bycatch mitigation method.

Offal discharge is a key factor in attracting seabirds to fishing operations, where they may then be at risk of bycatch. Offal discharge management is one of the few options to reduce seabird bycatch during hauling (Rexer-Huber & Parker 2019). As such, responsible management of offal discharge should a standard consideration over all periods of fishing operations. However, there is an absence of current evidence supporting this method as an effective primary bycatch mitigation method for the setting period and notably, there is potential for strategic offal discharge to increase bycatch (McNamara *et al*. 1999, Cherel *et al*. 1999, ACAP 2023). This lack of evidence is reflected in the absence of offal management as an option in the Southern Hemisphere under WCPFC CMM 2018-03.

Only one study exists that evaluates the performance of underwater bait setters (Roberston *et al*. 2018). Our raw *rSIR* of 0.138 indicates high performance, similar to hook-shielding devices, of these devices and aligns with ACAP (2023) in considering underwater bait setters an effective seabird bycatch mitigation method.

Our analyses also highlighted shortcomings in the current requirements of combinations of seabird bycatch mitigation methods in different latitudinal bands. In the area south of 30°S, WCPFC CMM 2018-03 requires the use of two out of three mitigation options or hook-shielding devices, while it requires the use of one out of two options (weighted branch lines or tori lines) or hook-shielding devices in 30°-25°S, and none north of 25°S. However, recent research provided clear evidence that a range of vulnerable seabird species, including Antipodean Albatross (*Diomedea antipodensis antipodensis*), Gibson's Albatross (*D. a. gibsoni*), Black Petrels (*Procellaria parkinsoni*), and Salvin's Albatross (*Thalassarche salvini*) regularly occur in the area of 30°S-25°S, and even visit the area north of 25°S, where they are exposed to increased fishing effort (e.g., Darby *et al*. 2024, Fischer *et al*. 2024).

Our results provide crucial information on how bycatch mitigation requirements could be improved in these latitudinal zones. Specifically, our analyses also provide insights into the order of performance of single mitigation methods (from best to least performing: I) hook-shielding devices, II) weighted branch lines, III) night setting, and IV) tori lines) as well as for combinations of mitigation methods (from best to least performing: I) weighted branch lines and tori lines, II) weighted branch lines and night setting, and III) night setting and tori lines). Most crucially, we show that adopting ACAP best practice could provide relative improvements of bycatch mitigation performance of 61% for the area south of 30°S and 81% for the area 25°-30°S.

CONCLUSION

Given the population status of many of the albatross and petrel species vulnerable to bycatch in pelagic longline fisheries within the WCPO (Fischer *et al*. 2024), improving the performance of bycatch mitigation methods is imperative. We here provide numerical guidance through a novel modelling approach to inform the consideration of different mitigation methods and their combinations. This has allowed us to identify options including for example, removal of ineffective bycatch mitigation methods, improvements of current specifications of mitigation methods, and improvements of the required combinations of mitigation methods per latitudinal bands. The greatest improvements would occur if ACAP best practice combinations and specifications were required. Such improvements will help reduce seabird bycatch in the WCPO, revert the current population declines, enable the protection of seabirds as an important element of the marine environment, and ultimately, ensure the sustainability of pelagic longline fisheries in the WCPO.

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REFERENCES

ACAP. 2023. Updated ACAP advice on reducing the bycatch of albatrosses and petrels in WCPFC fisheries. WCPFC-SC19-EB-IP-21.

Baker & Candy. 2014. Proof of concept experiment to demonstrate the efficacy of the 'Smart Tuna Hook'. Latitude 42 Environmental Consultants, Hobart, Australia.

Barrington *et al*. 2016. Categorising branch line weighting for pelagic longline fishing according to sink rates. SBWG7 Doc 07. Seventh Meeting of the Seabird Bycatch Working Group. La Serena, Chile, 2-4 May 2016. Agreement on the Conservation of Albatrosses and Petrels, Hobart.

Bell *et al*. 2024. Effectiveness of conservation and management measures for reducing seabird bycatch on pelagic longlines in the South Atlantic. ICCAT-SC-ECO SCRS/2024/079.

Canessa *et al*. 2016. Stochastic dominance to account for uncertainty and risk in conservation decisions. Conservation Letters 9: 260-266.

Chaloupka *et al*. 2021. Could tori lines replace blue-dyed bait to reduce seabird bycatch risk in the Hawaiian deep-set fishery? Western Pacific Regional Fishery Management Council, Honolulu, Hawaii.

Cherel *et al*. 1999. Interactions between longline vessels and seabirds in Kerguelen waters and a method to reduce seabird mortality. Biological Conservation 75: 63-70.

Cocking *et al*. 2008. Seabird bycatch mitigation and blue-dyed bait: A spectral and experimental assessment. Biological Conservation 141: 1354-1364.

Darby *et al*. 2024. Overlap between pelagic longline fisheries and Black Petrels in the WCPFC Convention Area. WCPFC-SC20-EB-IP30.

Düssler *et al*. 2024. Diving ecology of selected seabird species from the Southern and Northern Western and Central Pacific Ocean. WCPFC-SC20-EB-IP29.

Fischer *et al*. 2024. An update on the New Zealand large-scale seabird monitoring and tracking programme with improved insights into trends, distribution, and overlap with pelagic longline fisheries. WCPFC-SC20-EB-WP10.

Gilman *et al*. 2003. Performance assessment of underwater setting chutes, side setting, and blue-dyed bait to minimize seabird mortality in Hawaii longline tuna and swordfish fisheries. Western Pacific Regional Fishery Management Council, Honolulu, USA.

Gilman *et al*. 2007. Comparison of three seabird bycatch avoidance methods in Hawaii-based pelagic longline fisheries. Fisheries Science 73: 208-210.

Gilman *et al*. 2008. Reducing seabird bycatch in the Hawaii longline tuna fishery. Endangered Species Research 5: 309-323.

Gilman *et al*. 2016. Risk factors for seabird bycatch in a pelagic longline fishery. PLoS ONE 11: e0155477.

Gilman *et al*. 2021. Tori lines mitigate seabird bycatch in a pelagic longline fishery. Reviews in Fish Biology and Fisheries 31: 653-666.

Gilman *et al*. 2023. Adjusting time-of-day and depth of fishing provides an economically viable solution to seabird bycatch in an albacore tuna longline fishery. Scientific Reports 13: 2621.

Goad. 2017. Tori line designs for small longline vessels. Department of Conservation, Wellington, New Zealand.

Jimenez *et al*. 2020. Towards mitigation of seabird bycatch: large-scale effectiveness of night setting and tori lines across multiple pelagic longline fleets. Biological Conservation 247: 108642.

Katsumata *et al*. 2015. At-sea experiment to develop the mitigation measures of seabirds for small longline vessels in the western North Pacific. WCPFC-SC11-EB-WP-10.

Lokkeborg. 2003. Review and evaluation of three mitigation measures – bird-scaring line, underwater setting and line shooter, to reduce seabird bycatch in the Norwegian longline fishery. Fisheries Research 60: 11-16.

McNamara *et al*. 1999. Hawaii longline seabird mortality mitigation project. WESPAC, Honolulu, USA.

Ochi *et al*. 2011. A comparison of two blue-dyed bait types for reducing incidental catch of seabirds in the experimental operations of the Japanese southern bluefin tuna longline. WCPFC-SC7-EB-WP-09.

Ochi. 2022. Consideration for tori-line and tori-pole design suitable for small-scale tuna longline vessels in the North Pacific based on experimental results. WPCFC-SC18-EB-WP-04 (Rev.01).

Ochi. 2023. Supplemental information for SC18-EB-WP04: statistical comparison of bycatch mitigation performance with and without streamers in tori-lines for small LL vessels. WCPFC-SC19-EB-IP-10.
Peterson *et al*. 2008. Seabird bycatch in the pelagic longline fishery off southern Africa. *In* Petersen *et al*. (*eds.*). Understanding and mitigating vulnerable bycatch in Southern African trawl and longline fisheries. WWF South Africa, Cape Town, South Africa.
Pierre & Goad. 2016. Conservation Services Programme Project MIT2014-02: Improving tori line performance in small-vessel longline fisheries. Department of Conservation, Wellington, New Zealand.
Pierre. 2023. Mitigation of seabird bycatch in pelagic longline fisheries: best practice measures, evidence, and operational considerations. WCPFC-SC19-EB-IP15.
Rawlinson *et al*. 2018. The relative safety of weighted branch lines during simulated fly backs (cut offs and tear outs), Final Report. AMC Search, Launceston, Tasmania 50p.
Rexer-Huber & Parker. 2019. Characterisation of discard management in small-vessel trawl and longline fisheries. Department of Conservation, Wellington, New Zealand.
Richard *et al.* 2024a. Antipodean Albatross multi-threat risk assessment. WCPFC-SC20-EB-IP26.
Richard *et al.* 2024b. Assessing interannual variability in Antipodean Albatross distribution. WCPFC-SC20-EB-IP28.
Roberston *et al*. 2010. Effect of line shooter and mainline tension on the sink rates of pelagic longlines and implications for seabird interactions. Aquatic Conservation: Marine and Freshwater Ecosystems 20: 419-427.
Robertson *et al*. 2013. New branch line weighting regimes to reduce the risk of seabird mortality without affecting fish catch. Aquatic Conservation: Marine and Freshwater Ecosystems 23: 885-900.
Robertson *et al*. 2018. Setting baited hooks by stealth (underwater) can prevent the incidental mortality of albatrosses and petrels in pelagic longline fisheries. Biological Conservation 225: 134-143.
Santos *et al*. 2019. Improved line weighting reduces seabird bycatch without affecting fish catch in the Brazilian longline fishery. Aquatic Conservation: Marine and Freshwater Ecosystem 29: 442-449.
Spiegelhalter *et al.* 2014. OpenBUGS user manual. Version 3(2).
Sullivan *et al*. 2012. Safe Leads for safe heads: safer line weights for pelagic longline fisheries. Fisheries Research 134: 125-132.
Sullivan *et al*. 2017. At-sea trialling of the Hookpod: a ‘one-stop’ mitigation solution for seabird bycatch in pelagic longline fisheries. Animal Conservation 21: 159-167.
WCPFC. 2018. Conservation and Management Measure 2018-03: Conservation and management measure to mitigate the impact of fishing for highly migratory fish stocks in the Western and Central Pacific Ocean. WCPFC15.

SUPPLEMENTARY MATERIAL 1.

Table 1. Studies including in our relative standardized interaction rate (*rSIR*) analyses, including which mitigation methods and which associated specifications each study evaluated. UBS = Underwater Bait Setter, SS+BC+WBL = Side-setting with Bird Curtains and Weighted Branch Lines. ACAP refers to the specifications as per current ACAP Best Practice (ACAP 2023) and WCPFC NH and SH refer to the Northern and Southern Hemisphere specifications as per WCPFC CMM 2018-03 (WCPFC 2018). ✓ indicates that a bycatch mitigation method with either ACAP or WCPFC CMM 2018-03 specifications was applied, while (✓) indicates that a bycatch mitigation method was applied but did not meet either specification (or insufficient information was reported) and was therefore not included in the *rSIR* estimation. Studies conducted (partially) within the WCPO are highlighted in **bold**.

None	**Night setting**	**Weighted branch lines**		**Tori lines**		**Hook-shielding devices**		**UBS**	**Blue-dyed bait**	**Line shooter**	**SS+BC+WBL**	**n_{hooks} (x 1,000)**	**Ocean basin(s)**	**Reference**
	ACAP = WCPFC	ACAP	WCPFC SH/NH	ACAP = WCPFC SH[1,2]	WCPFC NH[2]	ACAP	WCPFC SH/NH	ACAP	WCPFC NH	WCPFC NH	WCPFC NH			
	✓		✓			✓						34	S Atlantic	Baker & Candy 2014
✓	✓											**461**	**S Pacific**	**Baker & Wise 2005**
✓		✓			✓				✓			**6**	**N Pacific**	**Boggs 2001**
					✓							**109**	**S Pacific**	**Brothers 1991**
					✓				✓			**241**	**N Pacific**	**Chaloupka *et al*. 2021, E Gilman pers. comm. 2024**
			(✓)						✓			**1**	**S Pacific**	**Cocking *et al*. 2008**
✓				✓								103	S Atlantic	Domingo *et al*. 2017
✓	✓			(✓)								**2,436**	**S Pacific**	**Duckworth 1995**
✓	✓			(✓)								**2,866**	**S Pacific**	**Gales *et al*. 1998, Klaer & Polacheck 1998, Brothers *et al*. 1999**

None	**Night setting**	**Weighted branch lines**		**Tori lines**		**Hook-shielding devices**		**UBS**	**Blue-dyed bait**	**Line shooter**	**SS+BC+ WBL**	**n_{hooks} (x 1,000)**	**Ocean basin(s)**	**Reference**
	ACAP = WCPFC	ACAP	WCPFC SH/NH	ACAP = WCPFC SH[1,2]	WCPFC NH[2]	ACAP	WCPFC SH/NH	ACAP	WCPFC NH	WCPFC NH	WCPFC NH			
			✓ (& ✓)	✓								156	S Atlantic	Gianuca *et al*. 2011
			✓			✓	✓					82	S Atlantic	Gianuca *et al*. 2021
									✓		**✓**	**50**	**N Pacific**	**Gilman *et al*. 2003, 2007**
	(✓)	**✓**	**✓**								**✓**	**9,064**	**N Pacific**	**Gilman *et al*. 2008**
✓									**✓**		**✓**	**22,515**	**N Pacific**	**Gilman *et al*. 2016**
✓					**✓**				**✓**			**393**	**N Pacific**	**Gilman *et al*. 2021, E Gilman pers. comm. 2024**
✓	**✓**											**2,216**	**Pacific**	**Gilman *et al*. 2023**
	✓	**✓**		**✓**		**✓**	**✓**					**92**	**S Pacific**	**Goad *et al*. 2019**
		✓	✓									7	S Atlantic	Jimenez *et al*. 2013
✓	✓	✓		✓								75	S Atlantic	Jimenez *et al*. 2018
✓	✓			(✓)								36,400	S Atlantic	Jimenez *et al*. 2020
✓					**✓**							**27**	**N Pacific**	**Katsumata *et al*. 2015, Ochi 2023**
	(✓)			**✓**	**✓**							**314**	**N Pacific**	**Kuo *et al*. 2023**
✓				(✓)	(✓)					✓		58	N Atlantic	Lokkeborg 2003

None	**Night setting**	**Weighted branch lines**		**Tori lines**		**Hook-shielding devices**		**UBS**	**Blue-dyed bait**	**Line shooter**	**SS+BC+WBL**	***n_{hooks}* (x 1,000)**	**Ocean basin(s)**	**Reference**
	ACAP = WCPFC	ACAP	WCPFC SH/NH	ACAP = WCPFC SH[1,2]	WCPFC NH[2]	ACAP	WCPFC SH/NH	ACAP	WCPFC NH	WCPFC NH	WCPFC NH			
		(✓)							**✓**			**10**	**S Pacific**	**Lyndon & Starr 2004**
✓	**(✓)**				**✓**				**✓**			**12**	**N Pacific**	**McNamara *et al*. 1999**
	(✓)	✓ (& ✓)		✓ (& ✓)								123	S Indian	Melvin *et al*. 2013
	✓	✓		✓								169	S Indian	Melvin *et al*. 2014
	(✓)	**(✓)**	**(✓)**	**✓**								**445**	**S Pacific**	**Meyer & MacKenzie 2022**
✓				(✓)	(✓)				✓			156	S Atlantic	Minami & Kiyota 2003, Ochi *et al*. 2011
✓			**(✓)**		**✓**							**60**	**N Pacific**	**Ochi *et al*. 2013**
					✓							**30**	**N Pacific**	**Ochi 2022, 2023**
	✓			(✓)	(✓)							**4,400**	S Atlantic, S Indian	Peterson 2008
	(✓)		(✓)					✓				18	S Atlantic	Robertson *et al*. 2018
		✓										600	S Atlantic, S Indian	Rollinson *et al*. 2016
	(✓)	✓	✓									26	S Atlantic	Santos *et al*. 2019
					✓							**99**	**N Pacific**	**Sato *et al*. 2013**

None	Night setting	Weighted branch lines		Tori lines		Hook-shielding devices		UBS	Blue-dyed bait	Line shooter	SS+BC+WBL	n_{hooks} (x 1,000)	Ocean basin(s)	Reference
	ACAP = WCPFC	ACAP	WCPFC SH/NH	ACAP = WCPFC SH[1,2]	WCPFC NH[2]	ACAP	WCPFC SH/NH	ACAP	WCPFC NH	WCPFC NH	WCPFC NH			
			✓	✓								204	S Pacific	Sato *et al*. 2014
			✓			✓	✓					**59**	S Atlantic, S Indian, **S Pacific**	**Sullivan *et al*. 2017**
✓											✓	**20**	**N Pacific**	**Yokata & Kyota 2006**

[1] WCPFC CMM 2018-03 specifications for tori lines in the Southern Hemisphere only differ from ACAP (2023) specifications in terms of 1 m of minimum attachment height, and as specifications in studies are not always provided in sufficient detail, the Southern Hemisphere tori specifications under WCPFC CMM 2018-03 and under ACAP Best Practice (2023) are here considered equal.
[2] We did not differ between large vessel and small vessel tori line specifications to not further compartmentalise data.

REFERENCES

ACAP. 2023. Updated ACAP advice on reducing the bycatch of albatrosses and petrels in WCPFC fisheries. WCPFC-SC19-EB-IP-21.

Baker & Candy. 2014. Proof of concept experiment to demonstrate the efficacy of the ‘Smart Tuna Hook’. Latitude 42 Environmental Consultants, Hobart, Australia.

Baker & Wise. 2005. Impact of pelagic longline fishing on the flesh-footed shearwater *Puffinus carneipes* in Eastern Australia. Biological Conservation 126: 306-316.

Boggs. 2001. Deterring Albatrosses from contacting baits during swordfish longline sets. Proceedings – Seabird Bycatch: Trends, Roadblocks, and Solutions. AK-SG-01-01.

Brothers *et al*. 1999. The influence of environmental variables and mitigation measures on seabird bycatch in the Japanese tuna longline fishery within the Australian Fishing Zone, 1991-1995. Biological Conservation 88: 85-101.

Brothers. 1991. Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. Biological Conservation 55: 255-268.

Chaloupka *et al*. 2021. Could tori lines replace blue-dyed bait to reduce seabird bycatch risk in the Hawaiian deep-set fishery? Western Pacific Regional Fishery Management Council, Honolulu, Hawaii.

Cocking *et al*. 2008. Seabird bycatch mitigation and blue-dyed bait: A spectral and experimental assessment. Biological Conservation 141: 1354-1364.

Domingo *et al*. 2017. Effectiveness of tori line use to reduce seabird bycatch in pelagic longline fishing. PLoS ONE 12: e0184465.

Duckworth. 1995. Analyses of factors which influence seabird bycatch in the Japanese southern bluefin tuna longline fishery in New Zealand waters, 1989-93. Fisheries New Zealand, Wellington, New Zealand.

Gales *et al*. 1998. Seabird mortality in the Japanese tuna longline fishery around Australia, 1988-1995. Biological Conservation 86: 37-56.

Gianuca *et al*. 2011. The effect of leaded swivel position and light toriline on bird attack rates in Brazilian pelagic longline. Fourth Meeting of Seabird Bycatch Working Group, ACAP, Guayaquil, Ecuador.

Gianuca *et al*. 2021. Trialling the new Hookpod-mini, configured to open at 20 m depth, in pelagic longline fisheries off southern Brazil. Tenth Meeting of the Seabird Bycatch Working Group, ACAP, virtual meeting.

Gilman *et al*. 2003. Performance assessment of underwater setting chutes, side setting, and blue-dyed bait to minimize seabird mortality in Hawaii longline tuna and swordfish fisheries. Western Pacific Regional Fishery Management Council, Honolulu, USA.

Gilman *et al*. 2007. Comparison of three seabird bycatch avoidance methods in Hawaii-based pelagic longline fisheries. Fisheries Science 73: 208-210.

Gilman *et al*. 2008. Reducing seabird bycatch in the Hawaii longline tuna fishery. Endangered Species Research 5: 309-323.

Gilman *et al*. 2016. Risk factors for seabird bycatch in a pelagic longline fishery. PLoS ONE 11: e0155477.

Gilman *et al*. 2021. Tori lines mitigate seabird bycatch in a pelagic longline fishery. Reviews in Fish Biology and Fisheries 31: 653-666.

Gilman *et al*. 2023. Adjusting time-of-day and depth of fishing provides an economically viable solution to seabird bycatch in an albacore tuna longline fishery. Scientific Reports 13: 2621.

Goad *et al*. 2019. Hookpod-mini: a smaller potential solution to mitigate seabird bycatch in pelagic longline fisheries. Endangered Species Research 39: 1-8.

Jimenez *et al*. 2013. Effect of reduced distance between the hook and weight in pelagic longline branchlines on seabird attack and bycatch rates and on the catch of target species. Fifth meeting of the Seabird Bycatch Working Group, ACAP, La Rochelle, France.

Jimenez *et al*. 2019. Mitigating bycatch of threatened seabirds: the effectiveness of branch line weighting in pelagic longline fisheries. Animal Conservation 22: 376-385.

Jimenez *et al*. 2020. Towards mitigation of seabird bycatch: large-scale effectiveness of night setting and tori lines across multiple pelagic longline fleets. Biological Conservation 247: 108642.

Katsumata *et al*. 2015. At-sea experiment to develop the mitigation measures of seabirds for small longline vessels in the western North Pacific. WCPFC-SC11-EB-WP-10.

Klaer & Polacheck. 1998. The influence of environmental factors and mitigation measures on bycatch rates of seabirds by Japanese longline fishing vessels in the Australian region. Emu 98: 305-316.

Kuo *et al*. 2023. Tori line experiment on Taiwanese tuna longline fishing vessels in the North Pacific Ocean. WCPFC-SC19-2023/EB-IP0-20.

Lokkeborg. 2003. Review and evaluation of three mitigation measures – bird-scaring line, underwater setting and line shooter, to reduce seabird bycatch in the Norwegian longline fishery. Fisheries Research 60: 11-16.

Lyndon & Starr. 2004. Effect of blue dyed bait on incidental seabird mortalities and fish catch rates on a commercial longliner fishing off East Cape, New Zealand. New Zealand Seafood Industry Council, Wellington, New Zealand.

McNamara *et al*. 1999. Hawaii longline seabird mortality mitigation project. WESPAC, Honolulu, USA.

Melvin *et al*. 2013. Reducing seabird bycatch in the South Africa joint venture tuna fishery using bird-scaring lines, branch line weighting and nighttime setting of hooks. Fisheries Research 147: 72-82.

Melvin *et al*. 2014. Best practice seabird bycatch mitigation for pelagic longline fisheries targeting tuna and related species. Fisheries Research 149: 5-18.

Meyer & MacKenzie 2022. Factors affecting protected species captures in domestic surface longline fisheries. Fisheries New Zealand, Wellington, New Zealand.

Minami & Kiyota. 2002. Effect of blue-dyed bait and tori pole streamer on the reduction of incidental take of seabirds in the Japanese southern bluefin tuna longline fisheries. CCSBT-ERS-0402-08.

Ochi *et al*. 2011. A comparison of two blue-dyed bait types for reducing incidental catch of seabirds in the experimental operations of the Japanese southern bluefin tuna longline. WCPFC-SC7-EB-WP-09.

Ochi *et al*. 2013. At-sea experiment to evaluate the effectiveness of multiple mitigation measures on pelagic longline operations in western north Pacific. WCPFC-SC9-EB-WP-11 (Rev.01).

Ochi. 2022. Consideration for tori-line and tori-pole design suitable for small-scale tuna longline vessels in the North Pacific based on experimental results. WPCFC-SC18-EB-WP-04 (Rev.01).

Ochi. 2023. Supplemental information for SC18-EB-WP04: statistical comparison of bycatch mitigation performance with and without streamers in tori-lines for small LL vessels. WCPFC-SC19-EB-IP-10.

Peterson *et al*. 2008. Seabird bycatch in the pelagic longline fishery off southern Africa. *In* Petersen *et al*. (*eds*.). Understanding and mitigating vulnerable bycatch in Southern African trawl and longline fisheries. WWF South Africa, Cape Town, South Africa.

Robertson *et al*. 2018. Setting baited hooks by stealth (underwater) can prevent the incidental mortality of albatrosses and petrels in pelagic longline fisheries. Biological Conservation 225: 134-143.

Rollinson *et al*. 2016. Lumo Leads: a potential, new, safe line weighting technique to reduce seabird bycatch for pelagic longline fisheries. IOTC-2016-WPEB12-33 Rev 1.

Santos *et al*. 2019. Improved line weighting reduces seabird bycatch without affecting fish catch in the Brazilian longline fishery. Aquatic Conservation: Marine and Freshwater Ecosystem 29: 442-449.

Sato *et al*. 2013. Comparison of the effectiveness of paired and single tori lines for preventing bait attacks by seabirds and their bycatch in pelagic longline fisheries. Fisheries Research 140: 14-19.

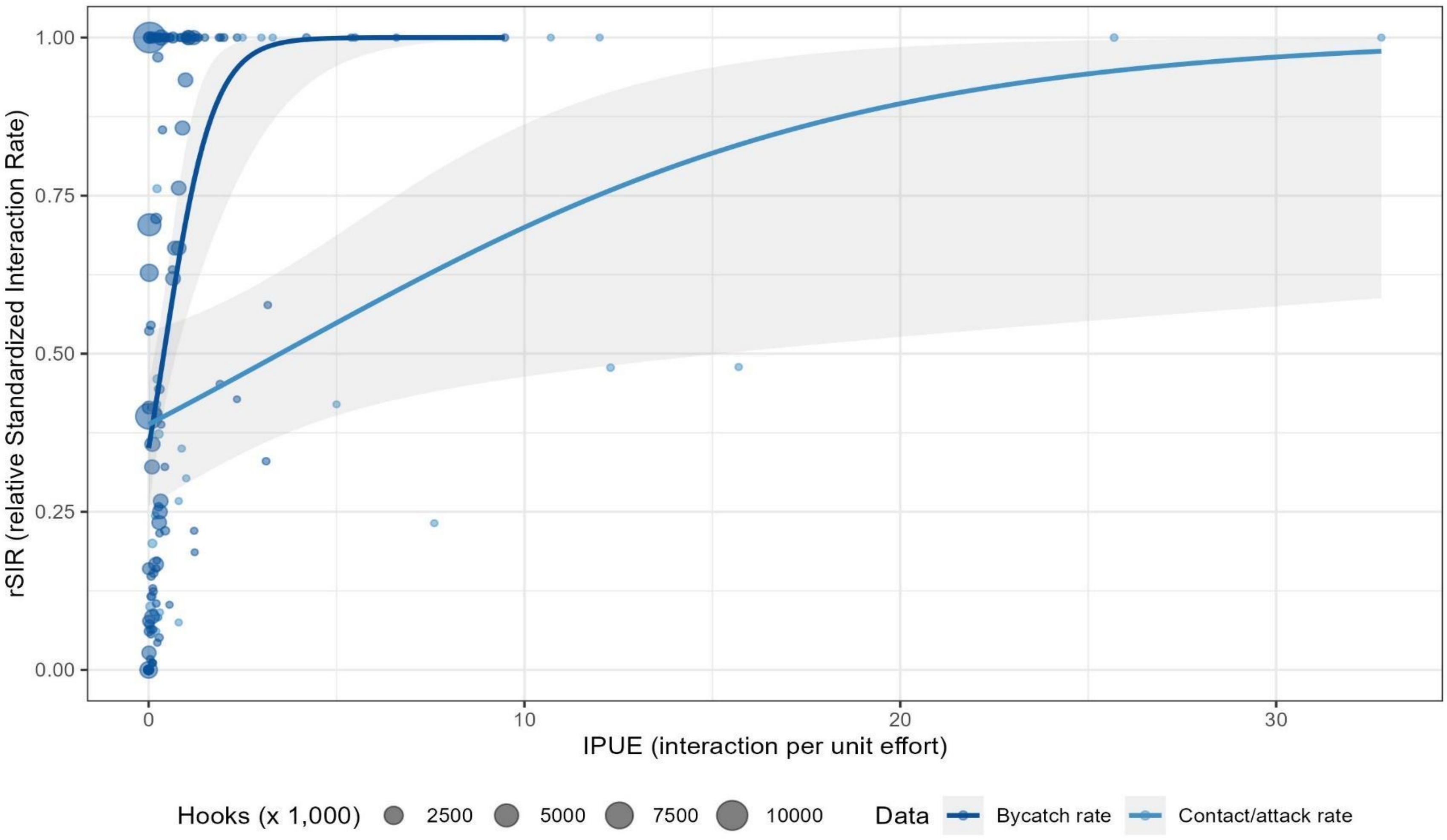
Sato *et al*. 2014. Tori-lines with weighted branch lines reduce seabird bycatch in eastern South Pacific longline fishery. Aquatic Conservation: Marine and Freshwater Ecosystems 26: 95-107.

Sullivan *et al*. 2017. At-sea trialling of the Hookpod: a ‘one-stop’ mitigation solution for seabird bycatch in pelagic longline fisheries. Animal Conservation 21: 159-167.

Yokata & Kiyota. 2006. Preliminary report of side-setting experiments in a large sized longline vessel. WCPFC-SC2-EB-WP15.

WCPFC. 2018. Conservation and Management Measure 2018-03: Conservation and management measure to mitigate the impact of fishing for highly migratory fish stocks in the Western and Central Pacific Ocean. WCPFC15.

SUPPLEMENTARY MATERIAL 2.



Supplementary Figure 1. Non-linear relationship between *rSIR* and *IPUE* for individual studies/trials as illustrated by GLMs with a quasi-binomial error distribution and a logit-link function for the different data types that were used in our analyses.