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Project 68: Estimation of seabird mortality across the WCPFC Convention Area

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Executive Summary

Project 68 aims to: estimate total annual seabird mortalities in WCPFC fisheries; assess mortality per year since the first WCFPC seabird CMM and assess whether there is any detectable trend; describe the methods used, including treatment of data gaps; identify limitations in available data; and, given available data, generate advice on what further level of seabird assessment can be conducted.

Total longline seabird bycatch and mortalities were estimated using a Monte Carlo simulation modelling framework. Bycatch rate distributions for the simulation models were estimated using Generalised Additive Models of bycatch rate (individuals per '000 hooks). Seabird condition at-vessel models were used to estimate distributions of proportions of bycatch that were alive at-vessel. Purse seine bycatch and mortalities were estimated using a non-parametric bootstrapping procedure. Additionally, species-specific seabird bycatch for southern hemisphere longline fisheries was estimated based on the overlap between fishing effort and estimated seabird distributions.

Estimated annual mortalities of seabirds in longline and purse seine fisheries from 2015 to 2018 were between 13,000 and 19,000 individuals (95 % confidence intervals 10,800 to 25,000). Approximately two-thirds of the estimated seabird mortalities were accounted for by longline fisheries north of 20°N, with approximately one-quarter of mortalities accounted for by longline fisheries south of 30°S. Seabird mortalities in the purse seine fishery were estimated to be approximately one individual per annum. Total capture estimates from the overlap method were similar to those obtained from the GAM-based estimates. The species with the highest estimated captures were white-capped albatross, Buller's albatross and white-chinned petrel.

Estimates of bycatch and mortality were not adjusted to reflect cryptic mortalities, i.e. fishery induced mortalities that are not detectable by observers. Furthermore, seabird bycatch and mortalities were not estimated for fleets and areas with insufficient representative observer data to robustly estimate seabird mortalities. These fleets included: purse seine fleets operating in temperate regions; domestic purse seine and longline fleets operating in the far-west of the WCPFC Convention Area (WCPFC-CA); effort by small-scale Asian longline fleets in EEZs in the northwest of the WCPFC-CA; and the pole and line and troll fisheries.

A range of limitations in available observer data are discussed. In particular, it was not possible to obtain robust estimates of seabird mortalities pre-2015, due to the low levels of available observer coverage of key longline fleets operating in high latitude areas for this period. A range of additional analyses are suggested that could be undertaken with available data. These include extending the overlap-based analysis to estimate the risk to populations resulting from estimated bycatch rates.

We invite SC to note:

- The estimates of seabird mortalities for WCPFC longline and purse seine fisheries obtained through Project 68.
- The difficulty in obtaining robust estimates of seabird mortalities pre-2015, primarily due to insufficient observer coverage for key longline fleets in high latitude areas in these years. This precludes the detection temporal trends in seabird mortalities.

- The estimates of seabird mortalities do not account for fishery-induced mortalities from all longline and purse seine effort in the WCPFC-CA, due to a lack of, or limited availability of, representative observer coverage. Furthermore, the mortality estimates do not account for cryptic mortality.
- The suggested additional analyses that could be undertaken with available information.
- The summary of limitations in available data that constrained the analyses presented here, and potential analyses of seabird bycatch data more generally.

Furthermore, we recommend:

- The overlap analysis for the Southern Hemisphere be extended to a full risk assessment to estimate risk to populations resulting from fishery induced mortalities.
- An equivalent overlap analysis and risk assessment be undertaken for the Northern Hemisphere, to enable both species specific estimation of mortalities and estimation of resulting risk to populations.
- SC consider that the addition of UTC set times to WCPFC ROP longline minimum standard data fields would be required for analyses of seabird bycatch data to include mitigation measures.

1 Introduction

The Convention on the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean (Convention) entered into force in June 2004 creating one of the first regional fisheries management organisations to be established since the 1995 adoption of the United Nations Fish Stocks Agreement (Fish Stocks Agreement).

The objective of the Convention is to ensure, through effective management, the long-term conservation and sustainable use of highly migratory fish stocks in the western and central Pacific Ocean (WCPO) in accordance with the 1982 United Nations Convention on the Law of the Sea (UNCLOS) and the Fish Stocks Agreement. The Convention also clearly indicates that the Western and Central Pacific Fisheries Commission has responsibilities in assessing the impact of fishing and environmental factors on non-target species and species belonging to the same ecosystem or dependent upon or associated with the target stocks (article 5d), to minimize catch of non-target species (article 5e), to protect biodiversity (article 5f), and to adopt, when necessary, Conservation and Management Measures (CMMs) for non-target species to ensure the conservation of such species (article 6c).

1.1 Project History

Commission members, Cooperating Non-Members and Participating Territories (CCMs) are required to report information to the Scientific Committee to enable estimation of seabird mortalities in fisheries to which the Convention applies (e.g. CMM 2007-04). The Twelfth Scientific Committee (SC12) developed terms of reference (scope of work) for the estimation of seabird mortality across the WCPO Convention area, which were endorsed and approved by the Commission in December 2016, on the basis that the ABNJ Tuna Project may be able to provide co-funding. In 2017 OFP-SPC developed a paper for the Thirteenth Scientific Committee (SC13) providing a project outline, a summary of seabird bycatch data held by SPC and an outline of the proposed methodology for estimation (Peatman et al., 2017a). In 2017, SC13 reiterated the scope of the project and increased its rank from medium to high priority. WCPFC 14 approved the scope and proposed budgets. FAO signed a Letter of Agreement with WCPFC in February 2018 to provide the co-funding. The Scientific Service Provider was contracted to undertake Project 68 in late April 2018. A short note on progress was reported to SC14 (Peatman & Smith, 2018), with an update report provided to FAO in February 2019.

1.2 Project Scope

The scope of work for this project included:

a) Fulfil the requirement under the WCPFC seabird CMMs to estimate the total number of seabirds being killed per year in WCPFC fisheries;
b) Assess mortality per year over the ten years since the first WCPFC seabird CMM, and assess whether there is any detectable trend;
c) Describe the methods used to estimate total mortality, including treatment of data gaps;

d) Identify the limitations in the data available, allowing the SC to generate advice to the Commission on what improvements are needed to enable better analyses to be made, and;
e) Generate advice on what further level of seabird assessment at species or species-group level can be conducted, given the amount and quality of data currently available.

1.3 Regional management context

The Commission has adopted six CMMs with requirements for seabird mitigation measures in WCPO longline fisheries. The evolution in seabird mitigation requirements is summarised in Appendix B (Table 6). Seabird mitigation was first required in WCPO longline fisheries through CMM 2006-02. CMM 2006-02 introduced obligations for seabird mitigation for: longline vessels larger than 24m LOA operating north of 23°N from 30th June 2008; longline vessels larger than 24m LOA operating south of 30°S from 1st January 2008; and, longline vessels smaller than 24m LOA operating south of 30°S from 31st January 2009. CMM 2007-04 introduced technical specifications for the mitigation measures. CMM 2012-07 strengthened the mitigation measure options for longline vessels operating south of 30°S, effective 1st July 2014, requiring vessels to use at least two of: weighted branch lines; night setting with minimal lighting; and, tori lines. CMM 2015-03 introduced mitigation measure requirements for longline vessels smaller than 24m LOA operating north of 23°N. CMM 2018-03 introduced mitigation requirements for longline vessels operating between 25°S and 30°S, effective 1st January 2020, and included hook-shielding devices in the mitigation options for all regions.

The CMMs have also included reporting obligations for CCMs, through annual reports submitted to the Scientific Committee. Since 2008, CMMs have been required to provide information on seabird interactions as part of Part I reports to enable the Scientific Committee to estimate seabird mortalities[1]. CMMs have also been required to provide, as part of Part II reports, information on mitigation measures that their vessels are required to use, and their specifications. CMM 2012-07 introduced reporting templates and guidelines for provision of information in Part I reports. CMM 2017-03 reinforced the requirement for CMMs to provide information on mitigation measure usage as part of Part I reports submitted from 2018 onwards, and introduced reporting templates for this information[2]. CMM 2018-03 amended the Part I reporting templates to require mitigation measure usage to be provided separately for effort north of 23°N, 23°N to 25°S, 25 to 30°S, and south of 30°S.

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[1] Publicly available at www.wcpfc.int.

[2] The requirement for CCMs to provide in their Part I reports the information on mitigation use was first included in CMM 2012-07, but no corresponding table guideline was provided. Limited information on mitigation measure usage was provided before 2018 in Part I reports.

2 Methods

All exploratory data analyses, catch rate models and catch estimation simulation models were undertaken in R version 3.4.1 (R Core Team, 2017). The package 'RODBC' was used for extractions from SPC databases (Ripley and Lapsley, 2017). Multi-core processing was used where possible, using the package 'parallel' (R Core Team, 2017) to reduce computation time. R packages 'tidyr' (Wickham & Henry, 2018) and 'dplyr' (Wickham et al., 2017) were used extensively in data preparation and manipulation, with 'ggplot2' (Wickham, 2009) used for data visualisation and generation of some figures contained in this report.

In the context of this work, we define 'seabird' as any species covered by the following families (grouped by order): Procellariiformes – *Diomedeidae*, *Procellariidae*, *Pelacanoididae*, *Hydrobatidae* and *Oceanitidae*; Suliformes – *Sulidae*, *Phalacrocoracidae* and *Fregatidae*; Phaethontiformes – *Phaethontidae*; Charadriiformes - *Stercorariidae*, *Laridae* and *Alcidae*. Observer records of 'birds – unspecified' were also included, on the assumption that these records were highly likely to be species in the families listed above.

2.1 Data sources

SPC holds aggregate catch and effort data for longline fisheries in the WCPFC Convention Area (WCPFC-CA), stratified by year, month, flag, fleet, and 5° square, *i.e.* 'L_BEST' strata. The aggregate catch and effort data were used to provide total longline effort in the WCPFC-CA. SPC also holds hook between float-specific aggregate catch and effort data for longline fisheries, i.e. L_BEST_HBF data. L_BEST_HBF data were used to identify effort from the Hawaii-based US swordfish fishery and remove this effort from the L_BEST dataset. This was necessary in order to use seabird observations from the US swordfish fishery directly, given 100 % observer coverage for the fishery.

Observers represent the only source of information of interactions between the majority of WCPO fisheries and seabirds, as interactions are rarely recorded in vessel logsheet data. SPC holds observer data from a variety of observer programmes, including WCPFC's regional observer programme (ROP), and national observer programmes. In this report we used all observer data held in SPC's master observer database located in the WCPFC-CA, with the exception of observer data from the historic Papua New Guinea and Solomon Islands shark-fisheries which are not covered in aggregate catch and effort data held by SPC. There were a limited number of records with missing information or erroneous values for key variables i.e. set position. These values were interpolated using within-trip moving averages. For the estimates reported herein, data from SPC's aggregate catch and effort and observer data holdings were extracted on 3rd July 2019.

2.2 Estimation of seabird mortalities in longline fisheries

Observer data were used to parameterise models of seabird bycatch rate and condition at-vessel for WCPO longline fisheries. The fitted bycatch rate models were used to predict bycatch per unit effort (BPUE) for longline fisheries, which was then applied to aggregate longline effort data to estimate seabird bycatch numbers. The proportions of seabirds dead at-vessel were estimated using the catch condition models, and applied to the bycatch estimates to estimate mortalities at-vessel. The estimates can then considered to be bycatch and mortalities at-vessel that would have been recorded with full observer coverage. As such the estimates do not account for cryptic mortality, including post-release mortality.

The US, NZ and Australian longline fleets account for a large proportion of observed effort in the higher latitude areas of the WCPO, and have constrained areas of operation relative to the WCPFC-CA. As such it is difficult to model bycatch rates of seabirds across the entire WCPFC-CA whilst explicitly accounting for spatial and flag effects, due to excessive multi-collinearity between the location of observed effort and vessel flag. Furthermore the composition of seabird communities demonstrates strong regional variability. We split the WCPFC-CA in to three regions: 'north Pacific' - the region north of 10°N; south Pacific - the region south of 25°S; and, the equatorial Pacific - the region between 10°N and 25°S. Region-specific bycatch rate and condition at-vessel models were then fitted to observer data. Comparison of predicted and observed bycatches indicated that initial models fitted relatively poorly to observations at the lower-latitude limits of the south and north Pacific models. The fit of the north Pacific model at the southern boundary was improved by including observations between 5 and 10°N from flags with observed effort north of 10°N, and the models were used to estimate bycatch north of 10°N. A similar approach was taken for the south Pacific models, which were fitted to observations south of 20°S and used to estimate bycatch south of 25°S.

For each region, we fitted bycatch per unit effort (BPUE) and catch condition models for all seabirds combined. These models were used to obtain the 'best estimate' of total seabird mortality. Order, family and genus-specific models were then fitted for the south Pacific and north Pacific, along with species-specific models for Laysan and black-footed albatrosses (*Phoebastria immutabilis* and *P. nigripes* respectively) in the north Pacific. These finer resolution models allowed for consideration of differences between different species groups, e.g. differences in spatial and temporal distributions in catches.

2.2.1 BPUE models

Generalised additive models (GAMs) of bycatch rates were fitted to set-level observer data using the 'mgcv' R package (Wood, 2017). Negative binomial distributed errors were assumed to account for over-dispersion common in observed seabird bycatch data, with a log link function. Explanatory analyses identified strong spatial, seasonal and temporal variation in seabird bycatch rates, and apparent variation in bycatch rates between longline fleets. As a result, variables considered for inclusion in the models were: flag, to account for differences in seabird mitigation options implemented by different fleets; year and quarter (1 = Jan to Mar, 2 = Apr to Jun, 3 = Jul to Sep, 4 = Oct to Dec), to account for temporal and seasonal variation in bycatch rates; and, seasonally-varying spatial effects to account for spatial-temporal variation in seabird distributions. All explanatory variables were included where possible in all catch rate models, though some models were simplified in cases of relatively low levels of observed bycatch. Latitudinal effects were included for the south and north Pacific, with a Markov random field accounting for any remaining spatial correlation in catch rates. We note that the choice of explanatory variables was limited to those available in aggregate longline catch and effort data. As such variables known to influence seabird bycatch rates, for example set time relative to nautical dawn and dusk, and moon phase (e.g. Melvin et al., 2013), were not included.

The specification of the most complex model was:

$$E[Y_i] = \mu_i \qquad\qquad Var[Y_i] = \mu_i + \frac{{\mu_i}^2}{\theta}$$

$$\ln \mu_i = \ln(thooks_i) + \beta_0 + flag_i + quarter_i + f_1(year_i) + f_2(latBin_i) + f_q(grid_i)$$

where Y_i denotes observed bycatch rate (individuals per thousand hooks), subscript i refers to set id, $flag$ and $quarter$ are categorical variables, f_1 and f_2 represent thin plate regression splines, f_q represents a (reduced rank) quarter-specific Markov random field (MRF) of set location, $latBin_i$ is the latitude rounded to the nearest 5° (to match the resolution of the aggregate effort data), and θ is an overdispersion parameter. The grid size of the MRF was increased in size in areas of limited observer coverage.

The final model specifications are provided in Table 1. In cases where model simplification was required, it was assumed that the main driver of bycatch rates was the overlap between fishing effort and seabird density. As such, spatial and seasonal effects were preferred over other explanatory variables. Year effects were not included in all South Pacific models, due to high multi-collinearity between flag and year. The genus-level model for shearwaters (*Puffinus* spp.) in the South Pacific had a quarter-invariant MRF and no flag effect, due to the relatively low level of observed catches. The genus-level model for great albatrosses (*Diomedea* spp.) in the South Pacific had a quarter-invariant MRF, in part due to the relatively low numbers of observed catches and an apparent lack of seasonality in spatial variation in bycatch rates. It was necessary to combine observations from flags with relatively low numbers of records for both north and south Pacific models. The flag groupings are described in Section 3.1. Following Ochi et al. (2018), Japanese longline effort in the south Pacific was separated into two components: fishing inside the New Zealand EEZ through charter agreements; and, fishing in the high seas. We included observations from the US swordfish fishery in north Pacific bycatch rate models but created a separate flag effect for the fishery ('US-shlw') given the weak but significant difference in bycatch rates for the US swordfish and tuna fisheries detected in exploratory model runs.

The quarter effect was replaced by a direct summer/winter season effect for the equatorial Pacific model, where 'summer' refers to quarters 2 and 3 in the northern hemisphere and quarters 1 and 4 in the southern hemisphere and vice versa for 'winter'. A flag effect was not included in the equatorial Pacific model, with the observed spatial variation in catch rates assumed to be more strongly influenced by the overlap of fishing effort and seabird distributions than by differences in gear configuration and fishing practises between longline fleets. We note that differences in seabird bycatch rates between fleets are less likely in the equatorial region compared to the higher latitude areas, where fleets can choose from a suite of mitigation measures.

2.2.2 Condition at-vessel models

Logistic-regression models of condition at-vessel were fitted to individual-level observations using the R package 'gamlss' (Rigby and Stasinopoulos, 2005). Condition models were fitted at the level of class, order, family and genus, and for the north Pacific, species. All models included flag effects to account for the effect of differences in fishing operations between fleets that impact whether seabirds were caught at setting or on haul back, i.e. primarily the timing of setting and hauling in relation to local times of sunrise and sunset. Family, genus and species effects were included in family, genus and species-level models, to account for differences in condition at-vessel between species or species groups, *e.g.* differences in feeding behaviour etc. Observations from the US swordfish fishery were excluded, as estimates of condition at-vessel were not required for this fleet due to 100 % observer coverage, and seabird conditions at-vessel in the swordfish fishery are not representative of the tuna fishery.

2.2.3 Bycatch and mortality estimation

A Monte Carlo simulation modelling framework was used to estimate bycatch and mortality at-vessel for longline fisheries. For each bycatch rate and condition GAM, 1,000 random draws of parameters were taken from the multivariate normal distribution defined by the vector of mean parameter values $\boldsymbol{\beta}$ and their covariance matrix $\boldsymbol{\Sigma}$, $N_k(\boldsymbol{\beta}, \boldsymbol{\Sigma})$ where k is the number of estimated parameters. The random draws of parameter values were then used to generate estimates of bycatch rates and proportion of catch alive-at vessel for each L_BEST stratum, and median estimates and confidence intervals computed. Seabird bycatch and mortalities were estimated for 2015 to 2017, as there were insufficient observer data to obtain robust estimates of bycatch rates for specific key longline fleets pre-2014 (covered in more detail in Section 4). We did not attempt to estimate seabird mortalities for longline fisheries for which SPC holds little or no representative observer data, *i.e.* domestic longline fisheries of Indonesia, the Philippines and Vietnam, and small-scale longline fisheries of Japan and Taiwan operating inside their respective EEZs. Seabird bycatch and mortality was estimated for all effort, both observed and unobserved, with the exception of the US swordfish fishery for which 100 % observer coverage is available.

2.3 Estimation of seabird mortalities in purse seine fisheries

Estimates of seabird bycatch and mortalities for purse seine fisheries were obtained by using non-parametric bootstrapping (Efron and Tibshirani, 1994). One thousand estimates of seabird bycatch and mortality rates (individuals caught/killed per set) were obtained by resampling from observations, and these rates applied to the number of unobserved sets to estimate unobserved bycatch and mortality. These estimates were combined with observed bycatch and mortalities to obtain total estimates for the purse seine fishery. We did not attempt to account for any variation in seabird catch rates, e.g. spatial and temporal variation, given the rarity of observed seabird captures. Furthermore, we did not attempt to estimate seabird mortalities for purse seine fisheries for which SPC holds little or no representative observer data, *i.e*. the domestic purse seine fisheries of Indonesia, the Philippines and Vietnam, and the temperate purse seine fisheries of Japan and New Zealand.

2.4 Estimation of seabird mortalities in pole and line and troll fisheries

Pole and line, and troll fisheries, account for the majority of remaining catch in tuna fisheries in the WCPFC-CA, excluding longline and purse seine fisheries. SPC holds little or no recent observer data to inform seabird mortalities in pole and line and troll fisheries, particularly when considering data collected since the early 2000s. As such, we have not attempted to estimate seabird mortalities in these fisheries, and instead provide an overview of information available in the literature in Section 4.

2.5 Estimating captures using an overlap method

We used a method based on overlap between seabirds and fisheries to estimate the species-specific bycatch of seabirds in southern hemisphere WCPFC longline fisheries, following the estimation methods used in the Spatially Explicit Fisheries Risk Assessment (SEFRA; Richard and Abraham 2013a, 2013b; Richard et al., 2017; Ochi et al., 2018; Birdlife South Africa 2019; see Appendix A for a detailed description). All albatrosses and petrels listed by the Agreement for the Conservation of Albatrosses and Petrels (ACAP) that breed south of 20°S (*Diomedea*, *Thalassarche*, *Phoebetria*, *Procellaria* and *Macronectes* species) were included in the estimation. There were some observed captures of species, such as flesh-footed shearwater, that were not ACAP listed. Across all observed captures, however, 98.1% of all observed captures were either of species that were included in the overlap method estimation, or were of unidentified seabirds.

A core assumption of the overlap method is that the number of observed captures of a seabird species is proportional to the local abundance of that species. The constant of proportionality is the product of a susceptibility parameter (which was assumed to be the same for taxa within taxa groups, see Table A1 in Appendix A) and a catchability (which is assumed to be the same within the fleets used in the longline BPUE models). For each taxon, the local abundance was estimated using weighted sums of distributions derived from tracking data, and heuristic distributions based on tracking data and on assumptions of seabird density close to colonies (BirdLife International and Handbook of the Birds of the World, 2018; Abraham et al., 2019). The model also includes parameters to allow unidentified seabirds to be appropriately allocated to taxa groups.

The susceptibility and catchability parameters were estimated using observer data from between 2012 and 2017. Bayesian inference was used to learn from a generalised linear mixed model (GLMM) coded in the software Stan (Carpenter et al., 2015). The posterior parameters samples were then used to estimate species-specific seabird bycatch during the 2016 fishing year, by applying the fitted model to WCPFC effort data. We estimate the total captures (without distinguishing between live and dead captures), and no account is taken of the cryptic mortality. In the risk assessment work (e.g. Richard et al., 2017; Ochi et al., 2018), the captures are compared with an estimate of population productivity. This comparison was not made here, and so the potential impact of the captures on seabird populations was not considered.

Across the dataset used for fitting the model (between 2012 and 2017, the same period used in a comparable analysis; Abraham et al., 2019), there were 1,371 observed captures that could be identified to the taxa group level, 583 that were recorded as unidentified albatross, 85 as unidentified Procellaridae, and 21 as unidentified seabirds. In addition, there were 7 captures of unidentified *Procellaria*, which were treated as Procellaridae so that there were only three classes of unidentified seabirds within the model.

3 Results

3.1 Summary of the modelled datasets

Longline fishing effort is widely distributed throughout the WCPFC-CA (Appendix C Figure 12). Observer coverage of longline fisheries since 2008 has mainly been concentrated in the region surrounding the Hawaiian Islands, the EEZs of Pacific Island Countries and Territories in the tropical region, and the Tasman Sea and EEZs of Australia and New Zealand (Appendix C Figure 13 & Figure 14). Observer coverage in the longline fishery has generally increased through time. Observer coverage from 2015 to 2018 was more widely distributed across the WCPFC-CA, with a large increase in coverage in the high seas region of the northwest Pacific (Figure 2 & Figure 3). However, there were still areas with limited observer coverage, particularly the high seas region west of 175°W between 25 and 30°S.

Four flags have accounted for the majority of longline effort in the northern higher latitudes of the WCPFC-CA: Japan, Taiwan, the US and Vanuatu. These fleets accounted for 99 % of total longline effort north of 25°N from 2008 to 2018, with Japan, Taiwan and the US accounting for 54, 32 and 10 % respectively. SPC's observer data holdings for the north Pacific models included 68,438 sets, with observed captures of 2,654 seabirds (Appendix D Table 7). Over 95 % of the observed seabird captures were Laysan albatrosses (45 %), black-footed albatrosses (41 %) and albatrosses (unspecified – 10 %) (Appendix D Table 10). The US fleet accounted for over 80 % of total observed sets in the north Pacific modelled dataset (Appendix D Table 7), whilst accounting for a relatively low proportion of total effort in the region. Observer coverage of vessels flagged to Taiwan and Japan in the region north of 25°N was available from 2012 and 2015 respectively.

The modelled dataset for the equatorial Pacific model was restricted to 2008 to 2018. We note that observer coverage, observed seabird captures, and nominal bycatch rates, were all markedly lower pre-2008. The modelled dataset for the equatorial Pacific models included 54,495 sets, with observed captures of 257 seabirds (Appendix D Table 11). One quarter of the observed seabird captures were recorded at genus or species level (Appendix D Table 13).

Seven flags accounted for 99 % of total longline effort in the WCPFC-CA south of 30°S from 2008 to 2018: Japan (27 %); Taiwan (20 %); Vanuatu (15 %); New Zealand (14 %); China (12 %); Australia (9 %), and the EU (3 %). SPC's observer data holdings for the south Pacific models included 18,515 sets, with observed captures of 2,675 seabirds (Appendix D Table 15). Observer coverage for Japan vessels operating in the high seas, and Taiwan vessels, was limited to 2015 and 2011 onwards respectively. There was limited observer data available for Vanuatu and China, and no available coverage of EU effort (Appendix D Table 16). Two-thirds of observed seabird captures were recorded at a species or species-complex level, though unspecified albatrosses accounted for one quarter of total observed seabird captures (Appendix D Table 18). Albatrosses accounted for 80 % of total observed captures, of which the majority were mollymawks (or unspecified albatrosses).

Here we provide a broad overview of the purse seine observer dataset. A more thorough summary of SPC's purse seine observer data holdings is available in Peatman et al. (2017b). Observer data was available for 330,787 sets from 2008 to 2018, with observed interactions with 259 individuals (Table 2). Of these, 189 individuals were recorded as having interacted with the primary fishing gear, but were not landed on deck. Two hundred and twenty four individuals were alive-at-vessel, with the condition at-vessel of the remaining 35 individuals unknown. At release, five individuals were dead, 222 were alive and 32 were in an unknown condition. Sixty two percent of the observed bycatch was accounted for by unidentified seabirds, with the remainder recorded at the family or species level.

SPC's longline observer data holdings include information on seabird mitigation measures used by vessels. However, it is not possible to determine exactly which mitigation measures were used, as the observer data does not cover all mitigation types. Information on night setting is particularly limited in the higher latitude regions, as the ROP minimum standard data fields for longliners are not sufficient to determine the local time of setting and hauling. SPC's observer data holdings include around 12,000 observed sets either north of 23°N or south of 30°S between 2015 and 2018, and it is possible to determine the time of setting and hauling relative to local times of sunrise and sunset for 27 sets.

3.2 Longline BPUE and condition at-vessel models

The 'all seabirds' north Pacific bycatch rate model detected strong spatial and seasonal variation in bycatch rates (Figure 4, Figure 7). Bycatch rates generally increased with increasing latitudes, and were higher in the first and second quarter of the year. Bycatch rates were particularly high in quarters 1 and 2 in close proximity to the northwestern Hawaiian islands. An increasing trend in bycatch rates was detected through time (Figure 4). Species-specific bycatch rate models suggested that this increasing trend in bycatch rates from 2012 onwards was predominantly driven by black-footed albatross. There was substantial between-flag variation in catch rates, though estimates of some flag effects were imprecise due to low levels of available observer coverage (Figure 4). There was also strong between-flag variation in condition at-vessel (Appendix G Figure 22).

The 'all seabirds' equatorial Pacific bycatch rate model detected relatively low spatial and seasonal variation in bycatch rates (Figure 5, Figure 8). Bycatch rates were generally higher west of 170°E, and in the east of 160°W south of 10°S. A generally increasing trend in bycatch rates was detected from 2008 onwards, though with a decline in bycatch rates from 2014 to 2018 (Figure 5). There was some between-flag variation in condition-at vessel, though estimates of flag effects were generally imprecise (Appendix G Figure 23).

The 'all seabirds' south Pacific bycatch rate model detected strong spatial and seasonal variation in bycatch rates (Figure 6, Figure 9). Bycatch rates were generally higher further south. Bycatch rates in the Tasman Sea were highest in the fourth quarter, and to a lesser extent the first quarter, and were lowest in the third quarter. Conversely, bycatch rates north of 30°S were lowest in the first and fourth quarters (Figure 9). Condition at-vessel models demonstrated strong between-flag variation (Appendix G Figure 24). Family-level condition models suggested that albatrosses had a higher probability of being alive at-vessel compared to petrels & shearwaters (Appendix G Figure 25).

3.3 Estimated seabird bycatch and mortalities

Estimated longline and purse seine seabird bycatch and mortalities in the WCPFC-CA are provided in Table 5. However, it is important to note that the estimates do not cover all reported effort (refer to Section 4 for more information).

Estimated longline seabird bycatch from 2015 to 2018 was between 14,700 and 20,600 individuals per year (95% confidence intervals ranging from 12,000 to 28,600 - Table 4). The majority (65 %) of total bycatch was from fishing north of 20°N, whilst fishing south of 30°S accounted for 23 %. The remainder was accounted for by fishing between 25°S and 20°N (9 %) and fishing between 25°S and 30°S (4%). The majority of bycatch was estimated to be dead at-vessel, with estimates of mortality ranging from 13,000 to 19,000 individuals per year (95 % CIs ranging from 10,800 to 25,000). The proportions dead at-vessel were relatively low for the region between 25°S and 20°N (75 %), compared to fishing elsewhere (95 %). Estimated longline seabird mortalities in the northern hemisphere were highest in the region between 20°N to 30°N and to the east of the Kuroshio current extension, i.e. 145 to 165°E (Figure 10). In the southern hemisphere the highest bycatch levels were accounted for by fishing effort in the west of the Tasman Sea, south of 40°S. However, there was strong seasonality in the spatial distribution of mortalities (Figure 12).

Estimated seabird interactions in the large-scale equatorial purse seine fishery from 2008 to 2018 were generally between 10 and 30 individuals per year, with the exception of 2013 and 2017 with estimates of 180 and 75 individuals respectively (Table 3). The majority of bycatch was estimated to be alive at-vessel and at-release, with estimates of mortalities ranging from 0 to 3 individuals per year (95 % CIs spanning 0 - 5).

3.4 Summary of overlap results

The overlap method results are provided in Appendix A. There were no issues with model convergence (Appendix A, Figure A1). The estimated relative catchability of the different fleets was highest for Japan (5.1; 95 % c.i.: 1.7 to 11.7) (Appendix A, Table A2). However, the relative catchability of the Japanese fleet fishing in New Zealand waters was low (0.12; 95 % c.i.: 0.03 to 0.31). The Australian fleet had the lowest relative catchability, 0.07 (95 % c.i.: 0.001 to 0.32).

The total estimated captures of ACAP-listed albatrosses and petrels captures in the WCPFC area in the Southern Hemisphere was 4,384 (95 % credible interval: 4,124 to 4,647). Of these captures, the majority (4,124; 95 % c.i.: 3,888 to 4,360) were south of 30°S, with 158 (95 % c.i.: 125 to 199) between 30°S and 25°S, and 102 (95 % c.i.: 57 to 164) captures between 25°S and the equator. There is strong spatial variation in the estimated captures with a mean of 2,323 captures (53 % of all captures) occurring within two 5-degree cells in the southern Tasman Sea (centred on a latitude of 42.5°S and longitudes of 152.5°E and 157.5°E, respectively).

The species with the highest estimated captures were white-capped albatross (1,249 captures; 95 % c.i.: 1,113 to 1,389); Buller's albatross (1,143 captures; 95 % c.i.: 1,006 to 1,281); and white-chinned petrel (614 captures; 95 % c.i. 504 to 732) (Appendix A, Table A3). Of the great albatrosses (*Diomedea* spp), the species with the highest captures was Gibson's albatross (224 captures; 95 % c.i.: 167 to 288).

4 Discussion

The simulation models estimated annual mortalities of seabirds in longline and purse seine fisheries from 2015 to 2018 to be in the region of 13,000 to 19,000 individuals per annum (95 % CIs spanning 10,800 to 25,000). However, it is important to note that the simulation models did not include all reported longline and purse seine effort. In particular, approximately 15 % of total reported longline effort was excluded from north Pacific simulations due to the removal of effort from small-scale vessels of Japan and Taiwan in areas with no available observer coverage. Additionally, the estimates of purse seine mortalities do not cover fisheries operating in higher latitude regions, due to limited available representative observer data. We note that purse seine fishing in higher latitude regions may pose greater risk to seabirds than the large-scale equatorial purse seine fishery given the respective areas of operation. Furthermore, the mortality estimates do not include cryptic mortality, and so should be interpreted as mortalities that would have been observed with full observer coverage, which will be lower than total mortalities resulting from interactions with fisheries.

It was not possible to generate robust WCPFC-CA wide estimates of seabird bycatch at a family, genus or species level using the simulation modelling framework outlined in Sections 2.2 and 2.3, due to the difficulties in accounting for seabird captures that were not recorded at a sufficiently high resolution. Using the overlap methodology allows for species-level estimates to be made. However, this relies strongly on the seabird distributions, and on the assumption that the captures are proportional to the local abundance of each species. This is necessarily a simplification. For example, the model does not account for variations in behaviour due to breeding stage. Overall, capture estimates from the overlap method were similar to the estimates from the GAM model - in the region south of 30 °S, the credible interval from the overlap model was entirely within the confidence interval from the GAM model. In the region between 30 °S and 25 °S, estimates from the overlap method were considerably lower, however, with 158 (95 % c.i.: 125 to 199) estimated captures in 2016, compared with estimated captures of 668 (95% c.i.: 347 to 1,621) from the GAM modelling framework. The seabird distributions require information from juvenile, adult breeding, and adult non-breeding birds. Because of the logistics of seabird tracking, the tracking data are biased towards the adult life-stages: across the 26 albatross and petrel taxa included in a southern-hemisphere wide analysis, only nine had more than 10,000 hours of tracking data from juvenile birds (Abraham et al., 2019). Juvenile birds may forage in different regions than adults (for example, juvenile grey-headed albatross in the Indian Ocean are foraging in areas that are not widely used by adult birds[3]). Because of this fundamental lack of distribution information, the overlap method may have significant, but unknown, gaps. However, the overlap method was fully Bayesian, and inference and posterior predictive simulation was integrated within the same framework, which should better represent parameter uncertainty and correlation between parameters in the simulation stage. Future efforts should aim to integrate the two approaches.

Across the WCPFC-CA, approximately two-thirds of the estimated seabird mortalities were accounted for by longline fisheries north of 20°N, with approximately one-quarter of mortalities accounted for by longline fisheries south of 30°S. The difference in seabird mortalities between the two regions was

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[3] Unpublished data from British Antarctic Survey:
http://www.bas.ac.uk/project/grey-headed-albatross-juvenile-tracking/

predominantly driven by the levels of fishing, with effort north of 20°N four times greater than effort south of 30°S.

There was strong seasonality in the spatial variation in estimated bycatch rates which, combined with seasonality in the distribution of fishing effort, resulted in seasonality in the distribution of mortalities. Bycatch rates in the north Pacific were highest in the first and second quarter in the region around the northwestern Hawaiian Islands, where the largest breeding colonies of Laysan and black-footed albatrosses are located. The timing of the peak in bycatch rates coincides with the period of chick provisioning by breeding adults. This suggests that the simulation modelling framework is capable of detecting and accounting for biologically plausible spatial and seasonal variation in bycatch rates of seabirds, with sufficient observer coverage. It is more challenging to put seasonal and spatial variation in estimated bycatch rates in context for the south Pacific given the diversity of species, though the areas with high bycatch rates are generally consistent with areas where densities of seabirds are thought to be highest (e.g. Waugh et al., 2012).

We are not aware of any earlier WCPFC-CA wide estimates of seabird bycatches or mortalities in the literature. However, Anderson et al. (2011) estimated global seabird mortalities in pelagic and demersal longline fisheries to be at least 160,000 individuals per year, and possibly more than 320,000 per year. A recent estimate of seabird bycatch in southern hemisphere CCSBT surface longline fisheries, using the same overlap methodology that was used here, estimated that there were 41,078 (95% c.i.: 39,432 to 42,746) captures of ACAP listed species. Global estimates of seabird bycatch in pelagic longline fisheries south of 20°S from the final ABNJ global seabird bycatch assessment were in the region of 20,000 to 50,000 individuals per year (Birdlife South Africa, 2019). The ABNJ Global Seabird Bycatch Assessment made the assumption that the catchability of all high-seas fleets was the same as the Japanese fleet. Applying the same assumption to this analysis would result in a substantial increase in estimated seabird mortality, as the catchabilities of the other high-seas fleets were lower than Japan. The reasons for the variation in the catchability between fleets are not understood. However, if there has been under-reporting of seabird bycatch by any fleet, then this would directly result in an underestimate of the total estimated seabird bycatch.

Flag-specific seabird bycatch estimates are available for New Zealand, US and Australia. Our estimates of bycatch for NZ longliners, 620 and 390 individuals for the 2013/2014 and 2014/15 fishing years, are generally comparable to those in Abraham and Richard (2018), at 650 and 560. Our estimates of bycatch for the US deep-set tuna fishery, 460 and 720 for 2015 and 2016, are also comparable to those in McCracken (2017), at 530 and 670 individuals. Our estimates for Australian longliners are lower than those recorded in vessel logbooks (Patterson et al., 2019), though had high uncertainty due to the low numbers of observed seabird interactions from Australian longliners in our modelled dataset.

We chose to only estimate seabird mortalities for longline fisheries for the time period 2015 to 2018, as we considered available observer data pre-2015 to be insufficient to obtain robust region-wide estimates. Observer coverage was limited or lacking pre-2015 for key longline fleets operating across large areas of the high seas north of 25°N, an area with extensive longline effort, and in the high seas south of 25°S. In particular, observer coverage for Taiwanese vessels operating in high latitudes was limited to 2012 onwards, and observer coverage for Japanese vessels operating in high latitudes was limited to 2015 onwards, with the exception of Japanese vessels operating in the New Zealand EEZ through charter agreements. With regards to the south of the WCPFC-CA, strengthened mitigation requirements were required for longline fishing south of 30°S from 1st July 2014 (through CMM 2012-07). As such, there were no observer data available for the Japanese fleet operating in the high seas south of 30°S in the period when CMM 2007-04 was in effect. We note that Japanese vessels operating in the NZ EEZ were required from 2007 onwards to set at night and use tori lines, or use weighted branch lines and tori lines if setting during the day, due to NZ domestic management (Ministry for Primary Industries, 2017).

The scope of work for this work covers all fisheries to which the WCPF Convention applies. We have estimated seabird mortalities for longline and purse seine fisheries operating in the WCPFC-CA, representing the vast majority of catch in the WCPFC-CA (e.g. Williams and Reid, 2018). We did not attempt to estimate seabird bycatch for pole and line and troll fisheries. Pole and line fishing in the WCPFC-CA is predominantly accounted for by vessels flagged to Japan and Indonesia, accounting for > 99 % of total pole and line fishing days from 2008 to 2018. Pole and line fisheries are generally considered to pose low risk to seabird populations (e.g. Gilman and Lundin, 2010). However, it is difficult to find quantitative information to estimate the magnitude of pole and line bycatch of seabirds in the WCPFC-CA. We note that seabird bycatch has recently been observed in pole and line fisheries in the Indian Ocean, though the level of sampling was insufficient to robustly estimate bycatch rates (Miller et al., 2017). Furthermore, observed seabird mortalities have been attributed to pole and line fisheries in the Atlantic Ocean resulting from the actions taken by crew to scare seabirds away during fishing operations (Bugoni et al., 2008). However, it is not clear to what extent these are representative of pole and line fisheries in the WCPFC-CA.

Seabird bycatch has been observed historically in troll fisheries in the WCPFC-CA. However, observed bycatch rates are low, e.g. 5 mollymawks caught in the sub-tropical convergence zone fishery east of New Zealand across 4,000 observed days (Bailey et al., 1996) and the level of effort in the WCPFC-CA is limited. SPC does not hold recent observer data for troll fisheries in the WCPFC-CA. However, the perceived risk of the troll fisheries is low (Akroyd and McLoughlin, 2017).

4.1 Limitations in available observer data

We focus discussion here on available data for the longline fishery, given the low level of estimated mortalities, and high levels of observer coverage in the large-scale equatorial purse seine fishery.

As mentioned in the beginning of Section 4, we did not estimate seabird mortalities for all longline fleets operating in the WCPFC-CA, as representative observer data were limited or lacking for some fisheries. In particular, we did not estimate seabird mortalities for small-scale longline fisheries of Japan and Taiwan operating in regions with no available observer coverage. These fisheries are estimated to pose relatively high risk to seabird populations due to the overlap between fishing effort and seabird distributions (Waugh et al., 2012). Data to support comprehensive analyses of these fisheries may not be available to WCPFC in the future as the WCPFC ROP does not cover the full spatial range of the fisheries.

We did not attempt to estimate seabird bycatch in high latitude areas pre-2015, due to low levels of available observer coverage for key longline fleets during this period and differences in WCPFC management measures in force at the time. In the context of using the observer data to detect trends in seabird capture and mortality rates, it is also problematic that the longest time series of observer data for high-latitude fisheries are available for fleets for which domestic management have been driving seabird mitigation, rather than WCPFC CMMs, i.e. the Hawaii-based US fleet, and vessels flagged to NZ and Australia. We note that review of Part I Annual Reports indicates that there are observer data for some of the key longline fleets operating in the WCPFC-CA that are not available in SPC observer data holdings, particularly for the period 2008 to 2014. We note it was not possible to identify any trends in fishery-induced seabird mortalities in the WCPFC-CA given the short time series of estimated mortalities. Access to additional historic observer data would be beneficial in future analyses, and may provide sufficient information to estimate bycatches pre-2015. However we note that any identified temporal trends in mortalities would likely be difficult to interpret in the context of assessing mitigation measure effectiveness.

SPC's longline observer data holdings are unbalanced, in the sense that temporal and spatial coverage varies substantially between fleets. This, coupled with the fact that some longline fleets operate in areas with relatively limited effort from other fleets, may result in insufficient information in observer data to appropriately separate seasonal and spatial variation in catch rates from between-flag variation without fishery independent information on seabird densities. In particular, we note that observer coverage has been limited for longline fishing in the high seas in latitudes from 25 to 35°S.

The fitted models for the north and south Pacific demonstrated substantial between-flag variability in bycatch rates. Furthermore, some flags had relatively low estimated bycatch rates in both models, having accounted for where and when fishing took place. The cause of this is not clear. Relatively low bycatch rates could reflect more effective seabird mitigation relative to other fleets, or observers failing to detect or record seabird captures. Theoretically, it could also simply reflect difficulties in separating flag effects from seasonal and spatial variation in bycatch rates, but this appears unlikely, particularly in the north Pacific. The flag-specific catchability parameters from the south Pacific overlap method are broadly consistent with the flag effects in the bycatch rate GAMs, and are primarily informed by the overlap between fishing effort and estimated seabird density distributions. However, there is some indication in the overlap analysis that the disparity in flag-specific catchabilities decreased in the period 2015 - 2017, which might reflect increased detection and/or reporting of seabird captures.

SPC's longline observer data holdings cannot be used to determine exactly which mitigation measures were implemented by vessels, as some key mitigation options are not covered by ROP minimum standard data fields, i.e. night-setting. Comprehensive information on set-level mitigation use is a prerequisite for assessing the relative effectiveness of different mitigation options and combinations on commercial vessels. We note that mitigation use was reported by CCMs in 2018 Part I reports, and from 2019 onwards will be provided on a regional basis. However, information at aggregated levels will be of less use than set-level information in an analysis context for fleets which employ varied mitigation measure combinations.

As discussed above, the estimates of mortalities here do not include cryptic mortality. Brothers et al. (2010) reported that approximately 50 % of seabirds captured during setting were not attached to gear at haulback, based on observations from surface longliners operating in the Indian Ocean, Southern Ocean, central Pacific Ocean and Coral Sea. It is not clear how representative these estimates of seabird loss are for the longline fisheries in the WCPFC-CA.

It is difficult to interpret the estimated mortalities from the simulation model at a species level, and even a genus level, due to the relatively high proportion of observed seabird captures that were recorded at a family level. In particular, it is not clear to what extent the estimated spatial distribution in mortality estimates reflect differences in reporting between fleets, e.g. genus level vs family level. This is particularly problematic for the southwest sector of the WCPFC-CA, where the diversity in species is highest (e.g. Waugh et al., 2012). The overlap method can account for differing resolutions of seabird identification (e.g. identifications to a family, genus or species level) and provide species-specific bycatch estimates. However, improving the resolution of seabird identification would also reduce uncertainty in species specific catch estimates in an overlap analysis. We note that observers in both New Zealand and Japan's observer programmes have collected carcasses, or taken photos of captured individuals, to enable later identification of seabirds by experts. We recommend that those members continue to provide these post-capture identifications of seabirds as part of observer data submissions, and ideally the observer's identification too as this could facilitate interpretation of observer-based species identification in observer programmes where post-capture identifications are unavailable. Having these data available from other members would improve the quality of seabird bycatch data.

Vessel information has not always been provided historically in non-standard longline observer data submissions to SPC. This precludes the use of vessel effects in seabird bycatch rate models. We note that exploratory analyses indicated strong apparent variation in seabird bycatch rates between trips. Furthermore, residual diagnostics demonstrated autocorrelation in residuals for catch rate models of 'all seabirds', particularly for the south Pacific models (Appendix F Figure 21). Random vessel effects provide one approach to address this, by explicitly accounting for the structure of the observer data, i.e. repeated observations from a vessel. As such, it would be helpful to have vessel identifiers available for the full observer dataset in future analyses of seabird bycatch, along with longline bycatch analyses more generally.

Here we provide an overview of the data limitations discussed above, and where relevant suggestions on how they might be addressed:

- There are short time-series of available observer data for key longline fisheries operating in high latitude areas of the WCPFC-CA. We note that observer coverage for these fisheries has increased since 2015. Submission of historical data, where available, would improve observer coverage pre-2015.

- SPC holds limited or no representative observer data for: small-scale Asian fleets operating in EEZs in the northwest of the WCPFC-CA; longline fisheries in the high seas between 25°S and 35°S; temperate purse seine fisheries; domestic purse seine and longline fisheries in the west of the WCPFC-CA; and, pole and line and troll fisheries. We note that the different fisheries above have different operational constraints regarding observer placement, and some will likely be lower priority than others from a seabird perspective.

- The unbalanced nature of the longline observer dataset, with varying temporal and spatial coverage between fleets, also creates potential difficulties in differentiating between spatial/seasonal variation in bycatch rates and flag effects. Higher observer coverage in areas with limited data would address this, as would including fisheries independent information on seabird density distributions.

- There are varying levels of identification for observed seabird captures, particularly in the South Pacific where there is a relatively high proportion of seabird captures identified to a family level. Continued submission of formal identification (autopsy based) and photo-based identification by relevant observer programmes will ensure that SPC observer data has the best available identification. There may also be potential for other observer programmes to task observers with photographing seabird bycatch. We also note that seabird training guides are currently being updated for the WCPFC ROP.

- There are a number of seabird species caught in WCPFC fisheries that do not have FAO codes, along with species groups, for example wandering type albatrosses, that do not have species codes. Reporting formats for these species vary between WCPFC members and observer programmes. It would be beneficial for reporting to be standardised amongst members.

- ROP minimum standard data fields do not cover all seabird mitigation options, and as such it is not possible to definitively determine which mitigation options were used for observed effort. In particular we note that the ROP minimum standard data fields do not allow determination of the time of setting and hauling of longlines relative to local dawn and dusk (and so whether a line was set at night), which affects both capture rates of seabirds and condition at-vessel. The coverage of all mitigation options in minimum standard data fields is a prerequisite to the use of mitigation information in analyses, and would not have any material impact on observer workload.

- There is limited information available on cryptic mortality rates for longline fisheries in the WCPFC-CA. This would require dedicated experiments, targeted at fisheries which are thought to account for the greatest number of mortalities, or ideally that are thought to pose the greatest risks to seabird populations.

- There is some evidence of flags that have significantly lower bycatch rates of seabirds than others, having accounted for when and where fishing takes place, for both the GAM bycatch rate models and the overlap analysis. This could reflect either more effective mitigation, or low rates of observers detecting and recording seabird captures. If there is under-reporting of seabird bycatch then the estimates presented here will be underestimates. We note that the total estimates of seabird mortalities are sensitive to flag-specific catch rates.

- SPC does not hold vessel identifiers for large proportions of longline data in high latitude fisheries. This precludes the use of vessel effects in bycatch rate models. There is some evidence that vessel effects would improve the model fits. We note that the vessel identifiers would ideally be provided for contemporary and historic data, and from a bycatch modelling perspective could be anonymous identifiers.

4.2 Suggestions for further work with existing datasets

There are additional analyses that could be undertaken with available data, as well as avenues for potential improvement to the current modelling approach.

The overlap-based analysis undertaken here could be extended to estimate the risk to populations resulting from the estimated bycatch rates (e.g. Richard et al., 2017; Ochi et al., 2018; Abraham et al., 2019; Birdlife South Africa, 2019). The risk analysis would allow for prioritising of any management response based on the impact of the fisheries populations on the seabird species, rather than on the number of seabirds caught. The overlap-based approach could also be implemented for the North Pacific, at least for *Phoebastria* albatrosses. Access to available tracking data would be beneficial in informing best-available estimates of seabird density distributions. There remain significant gaps in our knowledge of seabird distributions, particularly for juvenile and adult non-breeding birds. These may lead to errors in the spatial distribution of estimated captures from the overlap-based model. While the overlap-based analysis allows for estimates of bycatch at the species level, these estimates are dependent on the reliability of both the distribution information and population abundance estimates.

It would be preferable to restructure the GAM bycatch rate models to explicitly account for the structure of the observer data, i.e. repeated observations from a vessel. Comprehensive vessel identifiers would be a prerequisite for this. A hierarchical approach could also be used to allow all available observations to contribute towards estimates of seabird bycatch rates and mortalities at a genus or species level, e.g. by nesting species (or genus) specific models within genera (or families) and so on, building on the genus or species level model specifications presented here. This would be best undertaken by fitting models using Bayesian inference. Bayesian inference would also facilitate the inclusion of prior information in estimation of seabird bycatch rates in general and better represent and propagate parameter uncertainty. Existing catch rate models, and the south Pacific overlap-based analysis, could be used to estimate bycatch and mortalities at a fishery and/or sub-regional scale.

As discussed in Section 4, we note that short time series of available observer data for key fleets was problematic in the context of estimating longer time series of mortalities. With continued observer coverage at current levels, and increased observer coverage in areas with limited or no available observer data to date, it is reasonable to expect that the current modelling framework would deliver more precise and accurate annual estimates of seabird mortalities from 2015 onwards. Furthermore, as noted above in Section 4, some CCMs have historic longline observer data in high latitude regions that has not been provided to WCPFC. We note that access to this data in future analyses may allow robust estimates of mortality to be generated for years pre-2015, and so provide contrast between the mitigation regimes of CMM 2012-07 and CMM 2007-04 south of 30°S.

4.3 Recommendations

We invite SC to note:

- The estimates of seabird mortalities for WCPFC longline and purse seine fisheries obtained through Project 68.
- The difficulty in obtaining robust estimates of seabird mortalities pre-2015, primarily due to insufficient observer coverage for key longline fleets in high latitude areas in these years. This precludes the detection temporal trends in seabird mortalities.
- The estimates of seabird mortalities do not account for fishery-induced mortalities from all longline and purse seine effort in the WCPFC-CA, due to a lack of, or limited availability of, representative observer coverage. Furthermore, the mortality estimates do not account for cryptic mortality.
- The suggested additional analyses that could be undertaken with available information.
- The summary of limitations in available data that constrained the analyses presented here, and potential analyses of seabird bycatch data more generally.

Furthermore, we recommend:

- The overlap analysis for the Southern Hemisphere be extended to a full risk assessment to estimate risk to populations resulting from fishery induced mortalities.
- An equivalent overlap analysis and risk assessment be undertaken for the Northern Hemisphere, to enable both species specific estimation of mortalities and estimation of resulting risk to populations.
- SC consider that the addition of UTC set times to WCPFC ROP longline minimum standard data fields would be required for analyses of seabird bycatch data to include mitigation measures.

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References

Abraham, E.R., Carneiro, A., Fahmi, Z., Inoue, Y., Kathena, J.N., Kim, D.N., Lee, S.I., Maree, B., Oshima, K., Parsa, M., Rice, J., Sant'Ana, R., Sharma, R., Small, C., Tsuji, S., Wanless, R., Winker, H. and Wolfaardt, A. 2018 Update on the seabird component of the Common Oceans Tuna Project Seabird Bycatch Assessment Workshop. WCPFC-SC14-2018/ EB-IP-05.

Abraham, E.R., Julie Roux, M., Richard, Y. and Walker, N., 2017. Assessment of the risk of southern hemisphere surface longline fisheries to ACAP species. WCPFC-SC13-2017/ EB-IP-13.

Abraham, E.R. and Richard, Y. 2017. Summary of the capture of seabirds in New Zealand commercial fisheries, 2002-03 to 2013–14. *New Zealand Aquatic Environment and Biodiversity Report No. 184*.

Abraham, E.R and Richard, Y. 2018. Estimated captures of seabirds in New Zealand trawl and longline fisheries, 2002-03 to 2014-05. *New Zealand Aquatic Environment and Biodiversity Report* No. 197.

Abraham, E., Richard, Y., Walker, N., Gibson, W., Ochi, D., Tsuji, S., Kerwath, S.,Winker, H., Parsa, M., Small, C., Waugh, S. 2019. Assessment of the risk of surface longline fisheries in the Southern Hemisphere to albatrosses and petrels, for 2016. Report prepared for the 13th Meeting of the Ecologically Related Species Working Group (ERSWG13) of the Commission for the Conservation of Southern Bluefin Tuna (CCSBT-ERS/1905/17).

Akroyd, J. and McLoughlin, K. 2017. MSC Sustainable Fisheries Certification. New Zealand Albacore Tuna Troll. Public Certification Report, February 2017.

Anderson, O.R., Small, C.J., Croxall, J.P., Dunn, E.K., Sullivan, B.J., Yates, O. and Black, A., 2011. Global seabird bycatch in longline fisheries. *Endangered Species Research*, **14**, 91-106.

Bailey, K., Williams, P. and Itano, D, 1996. By-catch and discards in Western Pacific tuna fisheries: a review of SPC data holdings and literature. Oceanic Fisheries Programme Technical Report No. 34.

BirdLife International and Handbook of the Birds of the World (2018). Bird species distribution maps of the world. Version 2018.1. Available at http://datazone.birdlife.org/species/requestdis.

Birdlife South Africa (2019). Report of the Final Global Seabird Bycatch Assessment Workshop. 25 February–1 March 2019. Kruger National Park, South Africa. WCPFC-SC14-2018/EB-WP-12.

Brothers, N., Duckworth, A.R., Safina, C. and Gilman, E.L. 2010. Seabird bycatch in pelagic longline fisheries is grossly underestimated when using only haul data. *PLoS ONE* 5(8): e12491.

Bugoni, L., Neves, T.S., Leite Jr, N.O., Carvalho, D., Sales, G., Furness, R.W., Stein, C.E., Peppes, F.V., Giffoni, B.B. and Monteiro, D.S., 2008. Potential bycatch of seabirds and turtles in hook-and-line fisheries of the Itaipava Fleet, Brazil. Fisheries Research, **90**, 217-224.

Carpenter, B., Gelman, A., Hoffman, M.D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., and Riddell. A. 2017. Stan: A probabilistic programming language. Journal of Statistical Software 76. DOI 10.18637/jss.v076.i01

Debski, I., Pierre, J. and Knowles, K. 2016. Observer coverage to monitor seabird captures in pelagic longline fisheries. WCPFC-SC12-2016/EB-IP-07.

Efron, B., and Tibshirani, R. J. 1994. An Introduction to the Bootstrap. Monographs on Statistics and Applied Probability. Chapman & Hall/CRC. 456 pp.

Gilman, E., Lundin, C. 2010. Minimizing Bycatch of Sensitive Species Groups in Marine Capture Fisheries: Lessons from Commercial Tuna Fisheries. IN: Grafton, Q., Hillborn, R., Squires, D., Tait, M., Williams, M. (Eds.). Handbook of Marine Fisheries Conservation and Management. Oxford University Press.

Miller, K.I., Nadheeh, I., Jauharee, A.R., Anderson, R.C. and Adam, M.S., 2017. Bycatch in the Maldivian pole-and-line tuna fishery. *PloS one*, **12**, e0177391.

Melvin, E. F., Guy, T. J., and Read, L. B., 2013. Reducing seabird bycatch in the South African joint venture tuna fishery using bird-scaring lines, branch line weighting and nighttime setting of hooks. *Fisheries Research*, **147**, 72-82.

McCracken, M., 2017. Hawaii Longline Fishery Seabird and Sea Turtle Bycatch Within the IATTC Convention Area. PIFSC Data Report DR-17-028. https://doi.org/10.7289/V5/DR-PIFSC-17-028.

Ministry for Primary Industries, 2017. Fisheries Assessment Plenary, November 2017: stock assessments and stock status. Compiled by the Fisheries Science Group, Ministry for Primary Industries, Wellington, New Zealand. 500p.

Ochi, D., Abraham, E.R., Inoue, Y., Oshima, K., Walker, N., Richard, Y., and Tsuji, S, 2018. Preliminary assessment of the risk of albatrosses by longline fisheries. WCPFC-SC14-2018/EB-WP-09.

Patterson, H, Hobsbawn, P & Larcombe, J 2019. Annual report for the Western and Central Pacific Fisheries Commission Part 1: Information on fisheries, research and statistics 2018, ABARES, Canberra, July. CC BY 3.0

Peatman, T., Smith, N., and Caillot, S. 2017a. A short note on the development of WCPFC seabird bycatch estimates for Project 68. WCPFC-SC13-2017/EB-IP-18.

Peatman, T., and Smith, N. 2018. A short note on the development of WCPFC seabird bycatch estimates for Project 68. WCPFC-SC14-2018/EB-WB-03.

Peatman T., Allain V., Caillot S., Williams P. and Smith N. 2017b. Summary of purse seine fishery bycatch at a regional scale, 2003-2016. 13th Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, WCPFC-SC13, Rarotonga, Cook Islands, 9-17 August 2017, WCPFC-SC13-2017/ST-WP-05.

R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Richard, Y.; Abraham, E.R.; Berkenbusch, K., 2017. Assessment of the risk of commercial fisheries to New Zealand seabirds, 2006–07 to 2014–15. New Zealand Aquatic Environment and Biodiversity Report No. 191. Ministry for Primary Industries, Wellington, New Zealand.

Richard, Y.; Abraham, E.R., 2013a. Risk of commercial fisheries to New Zealand seabird populations. New Zealand Aquatic Environment and Biodiversity Report No. 109. Ministry for Primary Industries, Wellington, New Zealand.

Richard, Y.; Abraham, E. R., 2013b. Application of Potential Biological Removal methods to seabird populations. New Zealand Aquatic Environment and Biodiversity Report No. 108. Ministry for Primary Industries, Wellington, New Zealand.

Richard, Y. and Abraham, E.R., 2015. Assessment of the risk of commercial fisheries to New Zealand seabirds, 2006–07 to 2012–13. *New Zealand Aquatic Environment and Biodiversity Report No 162*.

Ripley B. & Lapsley, M., 2017. RODBC: ODBC Database Access. R package version 1.3-15. https://CRAN.R-project.org/package=RODBC.

Waugh, S.M., Filippi, D.P., Kirby, D.S., Abraham, E. and Walker, N., 2012. Ecological Risk Assessment for seabird interactions in Western and Central Pacific longline fisheries. *Marine Policy*, **36**, 933-946.

Wickham H., 2009. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wickham H. & Henry L., 2018. tidyr: Easily Tidy Data with 'spread()' and 'gather()' Functions. R package version 0.8.0. https://CRAN.R-project.org/package=tidyr.

Wickham H., R. Francois, L. Henry & K. Müller, 2017. dplyr: A Grammar of Data Manipulation. R package version 0.7.3. https://CRAN.R-project.org/package=dplyr.

Williams, P. and Reid, C. 2018. Overview of Tuna Fisheries in the Western and Central Pacific Ocean, including Economic Conditions – 2017. WCPFC-SC14-2018/GN-WP-01.

Tables

Table 1 Bycatch rate model specification for WCPO longline fisheries.

Model	year	qtr	season	flag	latitude	MRF	quarter-varying MRF	season-varying MRF
North Pacific (north of 10N)								
All seabirds	x	x		x	x		x	
Order - Procellariiformes	x	x		x	x		x	
Family - *Diomedeidae*	x	x		x	x		x	
Genus - *Phoebastria*	x	x		x	x		x	
Species - *Phoebastria immutabilis*	x	x		x	x		x	
Species - *Phoebastria nigripes*	x	x		x	x		x	
Equatorial Pacific (10N to 25S)								
All seabirds	x		x					x
South Pacific (south of 25S)								
All seabirds		x		x	x		x	
Order - Procellariiformes		x		x	x		x	
Family - *Diomedeidae*		x		x	x		x	
Family - *Procellariidae*		x		x	x		x	
Genus - *Diomedea*		x		x	x	x		
Genus - *Thalassarche*		x		x	x		x	
Genus - *Procellaria*		x		x	x		x	
Genus - *Puffinus*		x			x	x		
Genus - *Procellaridae* nei		x		x	x	x		

Table 2 Observed purse seine sets and seabird bycatch from 2008 to 2018.

Year	Observed sets	Observed interactions
2008	6,314	1
2009	10,840	1
2010	33,208	1
2011	32,553	6
2012	38,339	2
2013	43,622	167
2014	40,905	17
2015	37,166	3
2016	33,243	4
2017	26,022	57
2018	28,575	0
Total	**330,787**	**259**

Table 3 Estimated annual seabird interactions and mortalities (individuals) for large-scale tropical purse seine fisheries in the WCPFC-CA, and 95 % confidence intervals.

Year	Interactions	Mortalities
2008	26.8 (5 - 72)	0.5 (0 - 1.5)
2009	25.6 (5 - 69)	0.5 (0 - 1.4)
2010	14.6 (3 - 38)	0.3 (0 - 0.8)
2011	20.6 (8 - 46)	3.3 (3 - 4.5)
2012	16.1 (4 - 41)	1.3 (1 - 1.8)
2013	178.3 (170 - 342)	0.2 (0 - 0.5)
2014	29.1 (19 - 50)	0.2 (0 - 0.7)
2015	10.6 (4 - 24)	1.2 (1 - 1.4)
2016	13.5 (6 - 30)	0.2 (0 - 0.5)
2017	75.2 (60 - 107)	0.4 (0 - 1.3)
2018	17.0 (3 - 47)	0.3 (0 - 1.0)

Table 4 Estimated annual (a) seabird bycatch and (b) mortalities (individuals) for longline fisheries in the WCPFC-CA, disaggregated by region, and 95 % confidence intervals.

a)

Region	2015	2016	2017	2018
N of 20N	11,342 (9,065 - 16,558)	13,717 (11,151 - 18,090)	13,889 (10,791 - 21,782)	8,239 (5,830 - 15,190)
25S to 20N	2,406 (1,892 - 3,059)	1,719 (1,355 - 2,206)	1,361 (1,045 - 1,797)	984 (687 - 1,422)
30S to 25S	676 (363 - 1,803)	668 (347 - 1,621)	711 (360 - 1,892)	599 (347 - 1,380)
S of 30S	3,357 (2,895 - 4,855)	4,110 (3,562 - 5,126)	4,502 (3,939 - 5,160)	4,747 (4,123 - 5,647)
Total	17,998 (15,348 - 24,118)	20,404 (17,623 - 25,115)	20,618 (17,315 - 28,615)	14,723 (12,025 - 21,601)

b)

Region	2015	2016	2017	2018
N of 20N	10,431 (8,460 - 14,801)	12,959 (10,616 - 16,575)	12,499 (9,962 - 18,356)	7,148 (5,151 - 12,018)
25S to 20N	1,718 (1,326 - 2,210)	1,292 (1,012 - 1,667)	1,028 (785 - 1,381)	724 (512 - 1,042)
30S to 25S	633 (338 - 1,723)	638 (324 - 1,559)	672 (329 - 1,822)	553 (313 - 1,301)
S of 30S	3,210 (2,761 - 4,671)	3,951 (3,413 - 4,907)	4,336 (3,782 - 4,976)	4,570 (3,971 - 5,456)
Total	16,102 (13,840 - 21,117)	19,068 (16,439 - 22,934)	18,662 (15,772 - 24,850)	13,133 (10,864 - 18,487)

Table 5 Estimated annual (a) seabird bycatch and (b) mortalities (individuals) for fisheries in the WCPFC-CA, disaggregated by region for longline, and 95 % confidence intervals.

a)

Fishery	**2015**	**2016**	**2017**	**2018**
Longline				
N of 20N	11,342 (9,065 - 16,558)	13,717 (11,151 - 18,090)	13,889 (10,791 - 21,782)	8,239 (5,830 - 15,190)
25S to 20N	2,406 (1,892 - 3,059)	1,719 (1,355 - 2,206)	1,361 (1,045 - 1,797)	984 (687 - 1,422)
30S to 25S	676 (363 - 1,803)	668 (347 - 1,621)	711 (360 - 1,892)	599 (347 - 1,380)
S of 30S	3,357 (2,895 - 4,855)	4,110 (3,562 - 5,126)	4,502 (3,939 - 5,160)	4,747 (4,123 - 5,647)
Purse seine	10.6 (4 - 24)	13.5 (6 - 30)	75.2 (60 - 107)	17.0 (3 - 47)
Pole and line	Not estimated	Not estimated	Not estimated	Not estimated
Troll	Not estimated	Not estimated	Not estimated	Not estimated
Total*	18,012 (15,370 - 24,129)	20,417 (17,636 - 25,127)	20,691 (17,395 - 28,700)	14,746 (12,052 - 21,632)

** Total of longline and purse seine estimates*

b)

Fishery	**2015**	**2016**	**2017**	**2018**
Longline				
N of 20N	10,431 (8,460 - 14,801)	12,959 (10,616 - 16,575)	12,499 (9,962 - 18,356)	7,148 (5,151 - 12,018)
25S to 20N	1,718 (1,326 - 2,210)	1,292 (1,012 - 1,667)	1,028 (785 - 1,381)	724 (512 - 1,042)
30S to 25S	633 (338 - 1,723)	638 (324 - 1,559)	672 (329 - 1,822)	553 (313 - 1,301)
S of 30S	3,210 (2,761 - 4,671)	3,951 (3,413 - 4,907)	4,336 (3,782 - 4,976)	4,570 (3,971 - 5,456)
Purse seine	1.2 (1 - 1.4)	0.2 (0 - 0.5)	0.4 (0 - 1.3)	0.3 (0 - 1.0)
Pole and line	Not estimated	Not estimated	Not estimated	Not estimated
Troll	Not estimated	Not estimated	Not estimated	Not estimated
Total*	16,103 (13,841 - 21,119)	19,068 (16,439 - 22,934)	18,662 (15,773 - 24,850)	13,133 (10,864 - 18,487)

** Total of longline and purse seine estimates*

Figures

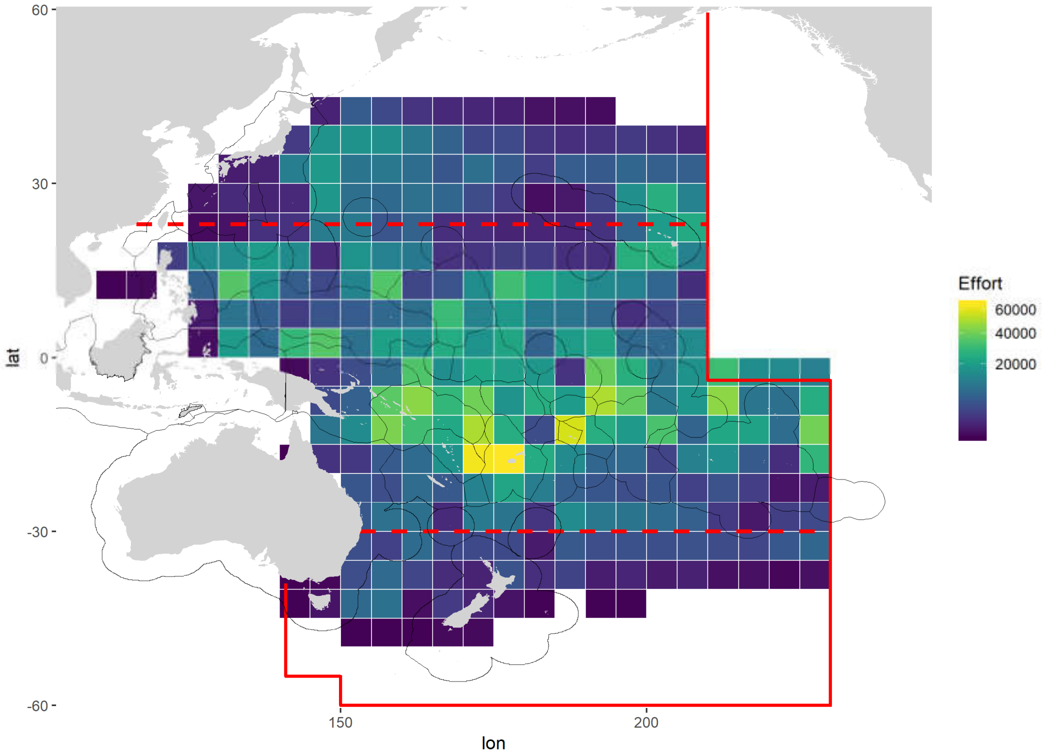


Figure 1 Reported longline effort ('000 hooks) in the WCPO from fleets included in the simulation model, 2015 – 2018. The red lines show the WCPFC convention boundaries and the red dashed lines show the 30°S and 23°N lines of longitude.

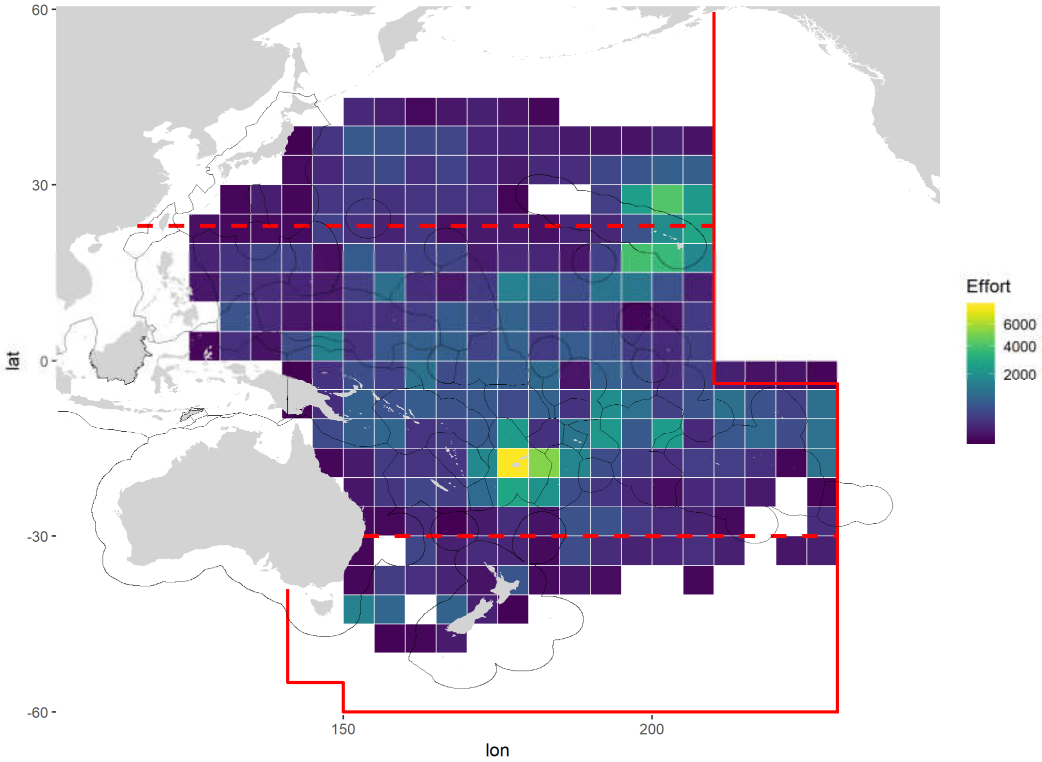


Figure 2 Longline effort with observer onboard ('000 hooks) in the WCPO used to fit bycatch rate models, 2015 – 2018. The red lines show the WCPFC convention boundaries and the red dashed lines show the 30°S and 23°N lines of longitude.

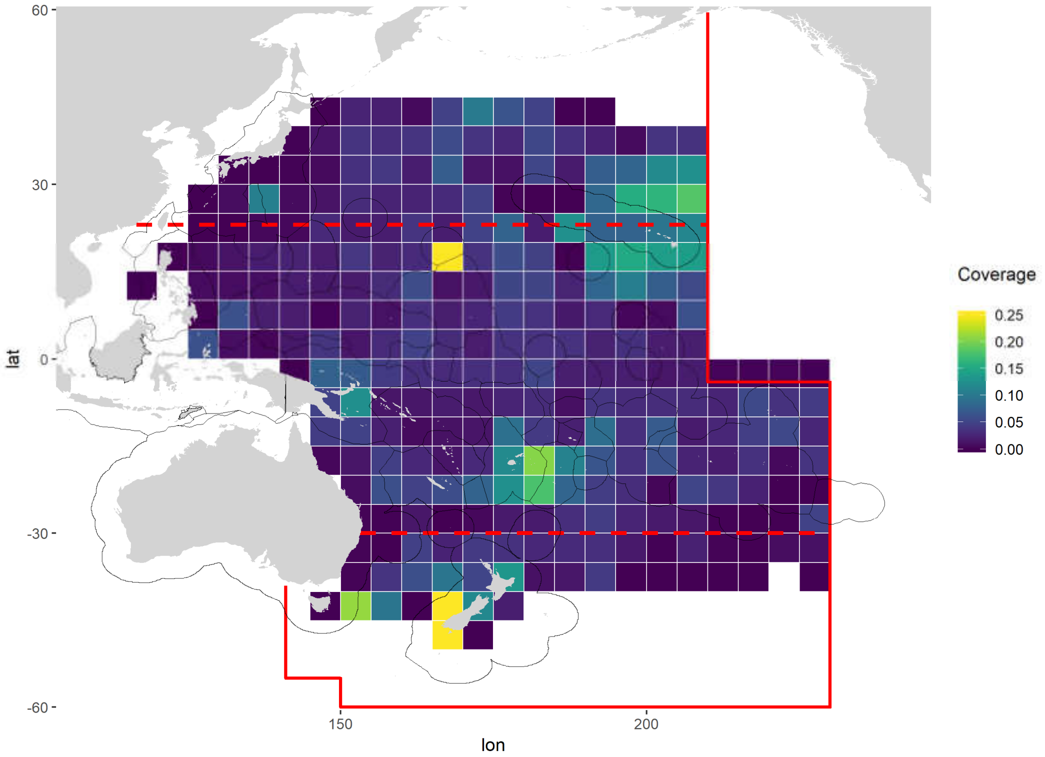


Figure 3 Observer coverage (proportion of hooks with observer onboard) for longline fleets included in the simulation model, 2015 – 2018. The red lines show the WCPFC convention boundaries and the red dashed lines show the 30°S and 23°N lines of longitude.

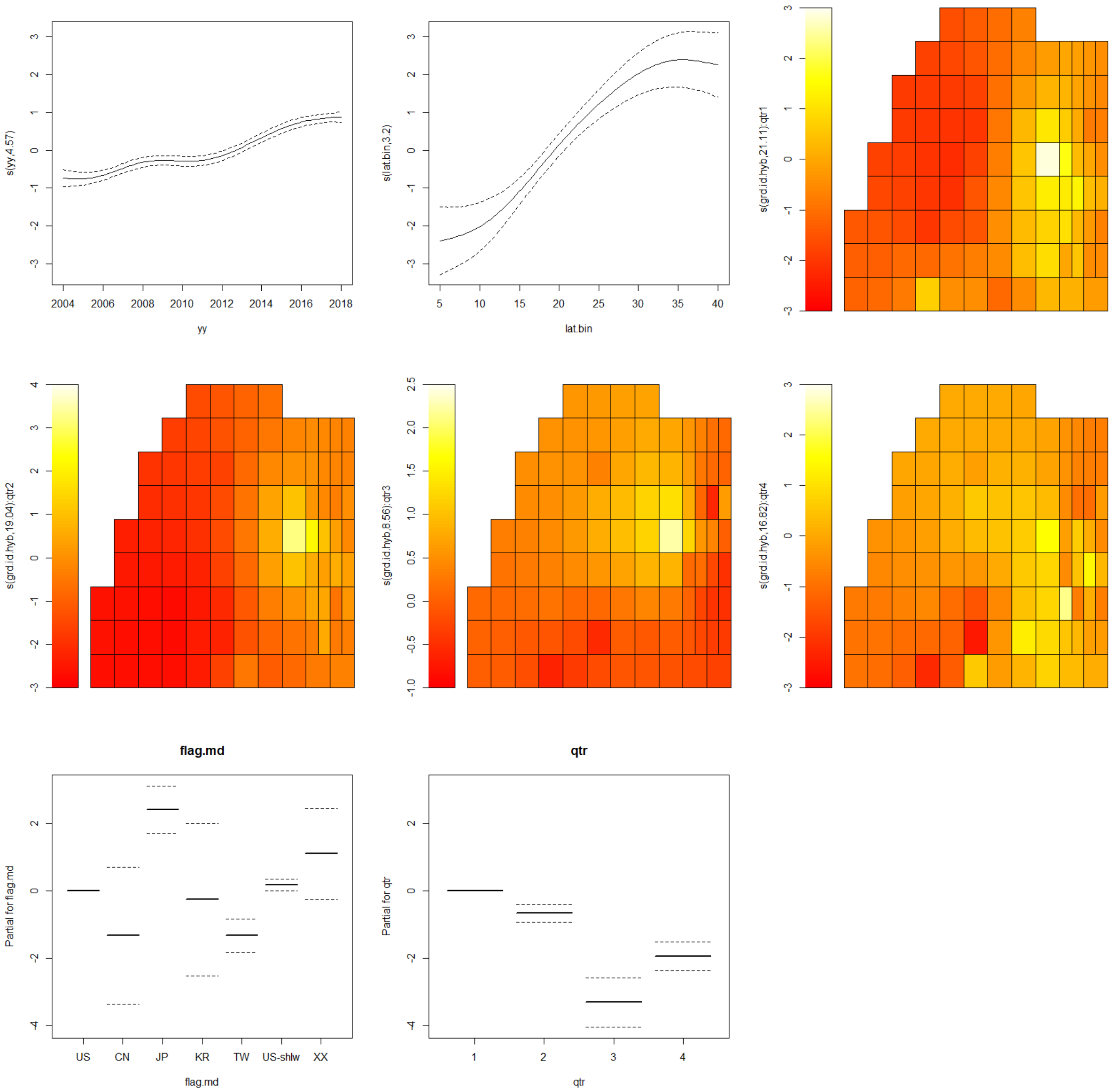


Figure 4 Effect plot for the bycatch rate model for all seabirds in the north Pacific: year (top right); latitude (top centre); spatial smooth (Markov random field) for quarters 1 (top left), 2 (middle left), 3 (middle centre) and 4 (middle right); flag (bottom left); and quarter (bottom centre).

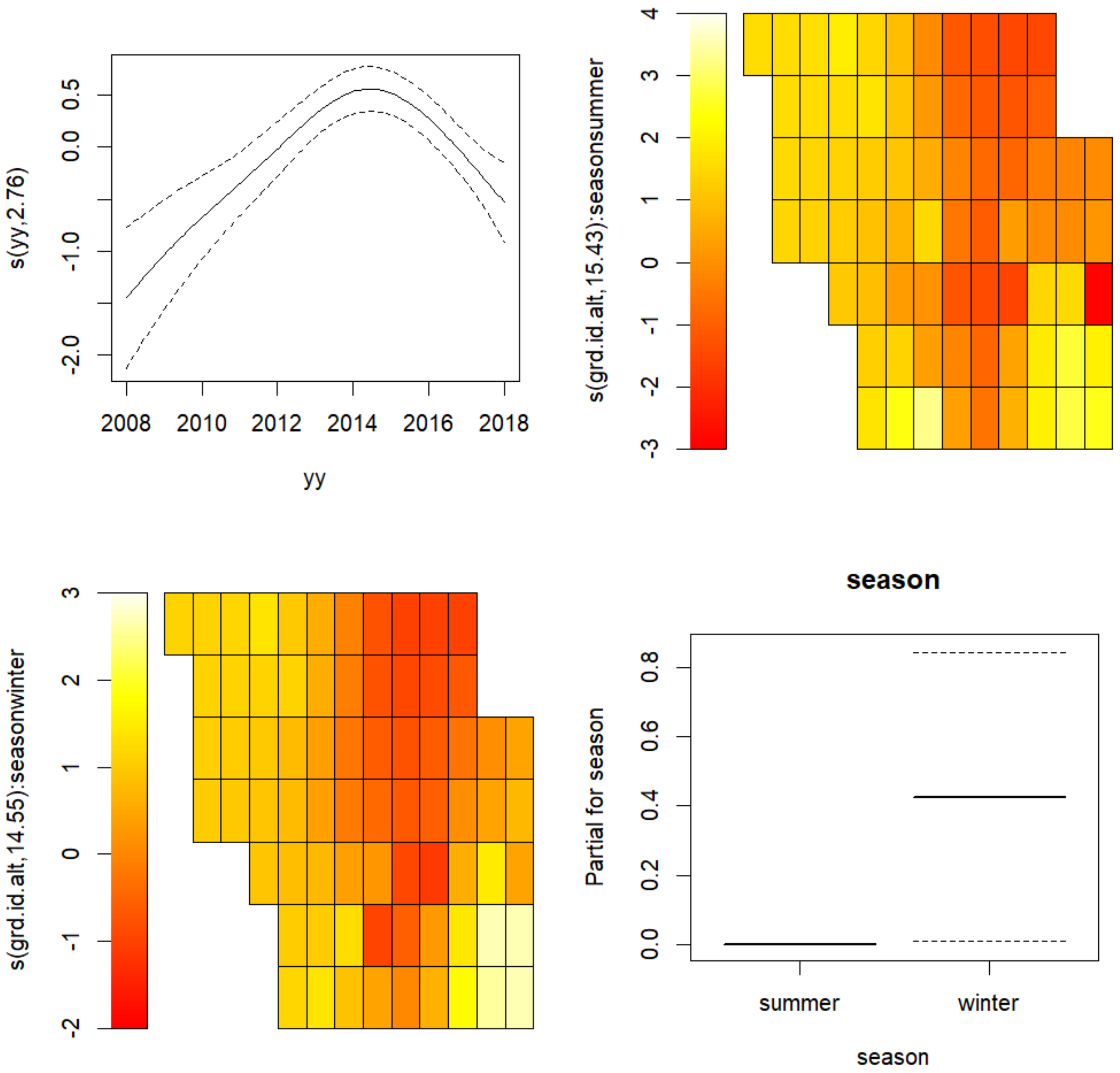


Figure 5 Effects plot for the bycatch rate model for 'all seabirds' in the equatorial Pacific: year (top right); spatial smooth (Markov random field) for summer (top right) and winter (bottom left); and season (bottom right).

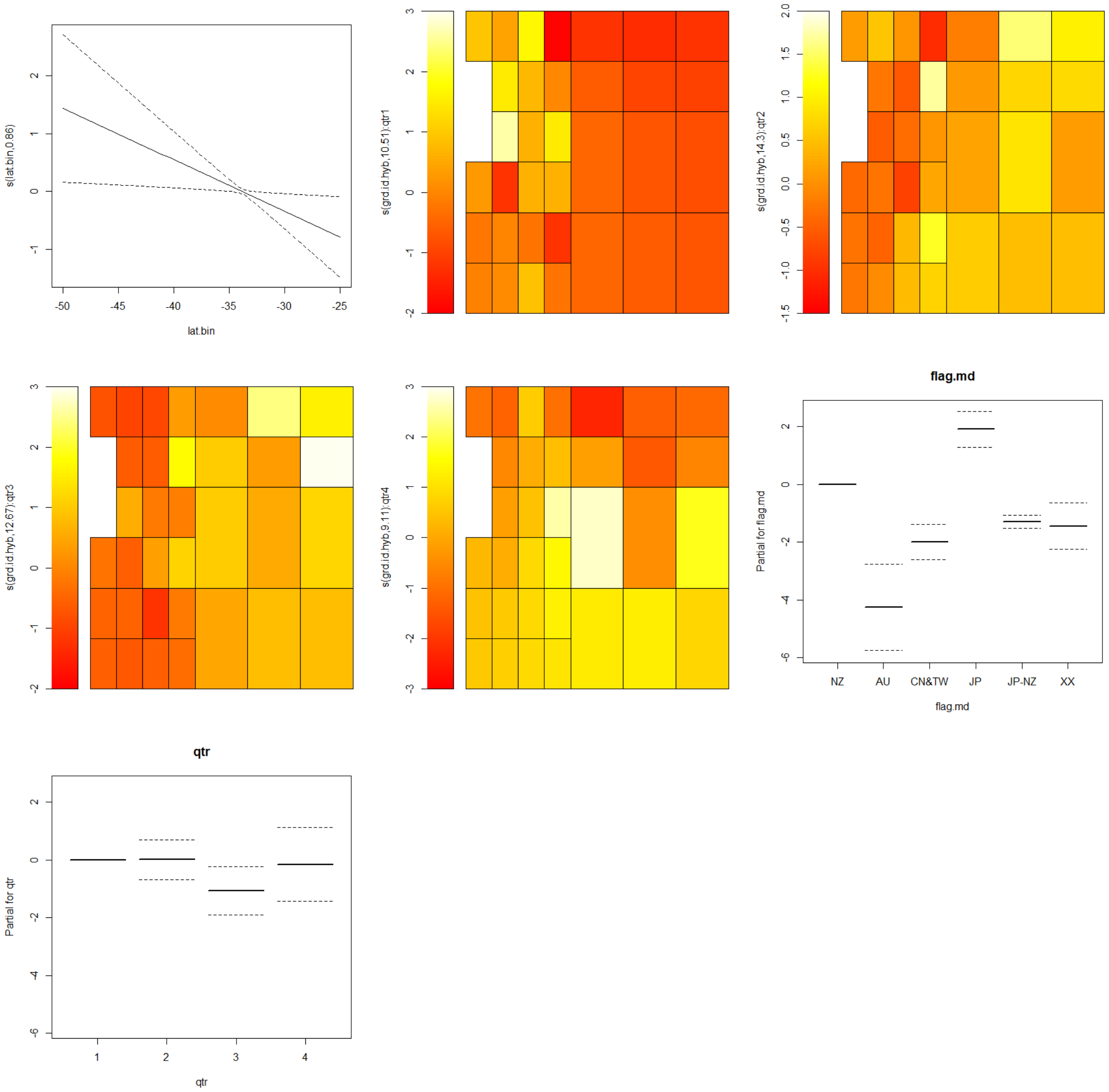


Figure 6 Effect plot for the bycatch rate model for all seabirds in the south Pacific: latitude (top right); spatial smooth (Markov random field) for quarters 1 (top centre), 2 (top right), 3 (middle left) and 4 (middle centre); flag (middle right); and quarter (bottom centre). Flag.md = 'JP-NZ' refers to Japanese vessels operating in the NZ EEZ through charter agreements.

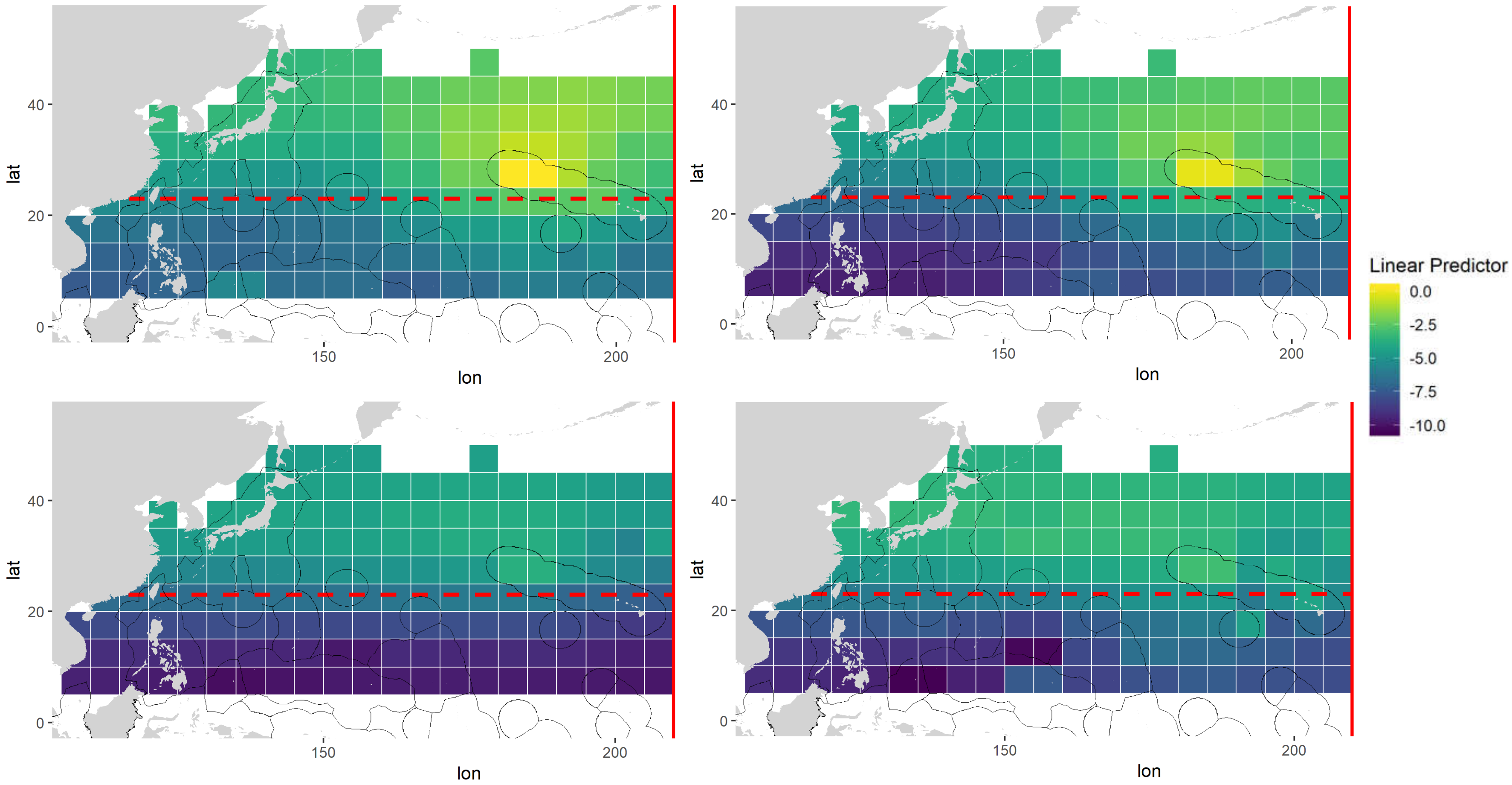


Figure 7 Linear predictor from the 'all seabirds' north Pacific model for quarter 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right). Reference levels for other explanatory variables: flag = US, year = 2017. The red lines show the WCPFC convention boundaries and the red dashed line shows 23°N.

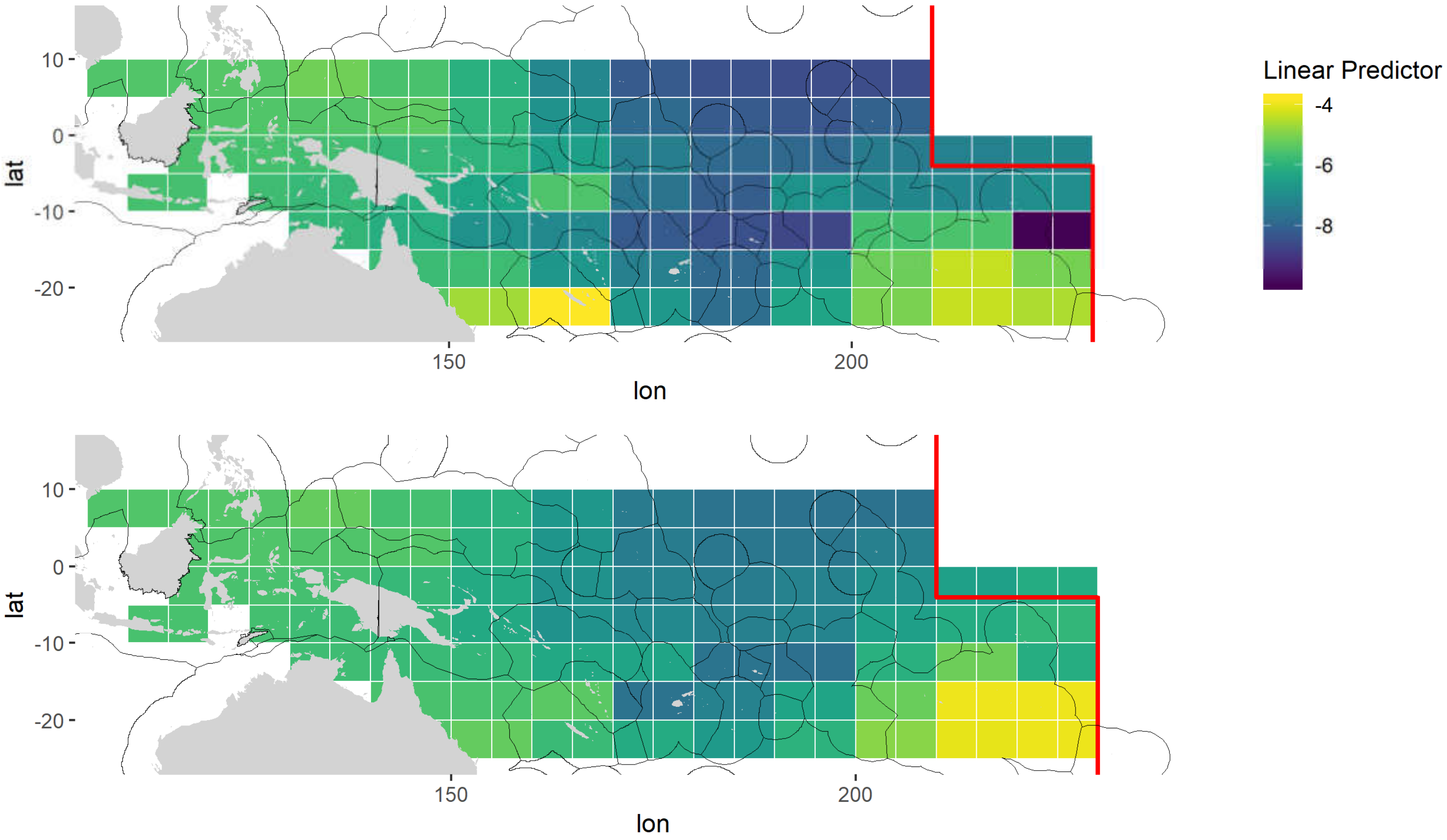


Figure 8 Linear predictor from the 'all seabirds' equatorial Pacific model for summer (top) and winter (bottom). Reference levels for other explanatory variables: year = 2017. . The red lines show the WCPFC convention boundaries.

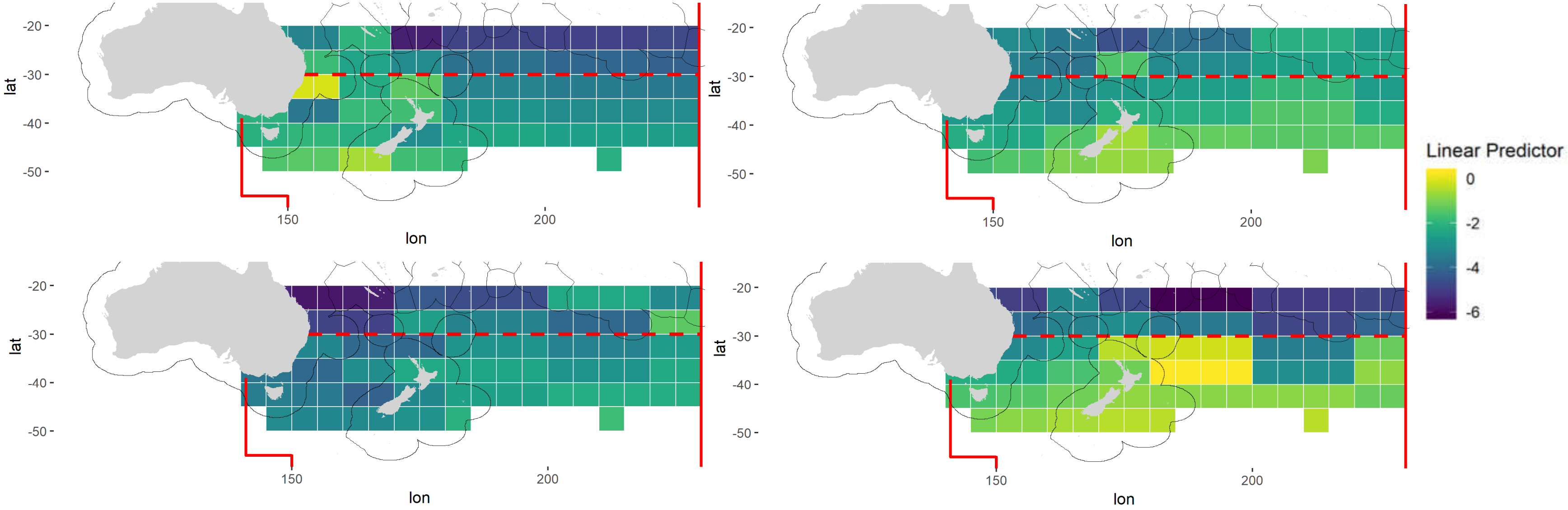
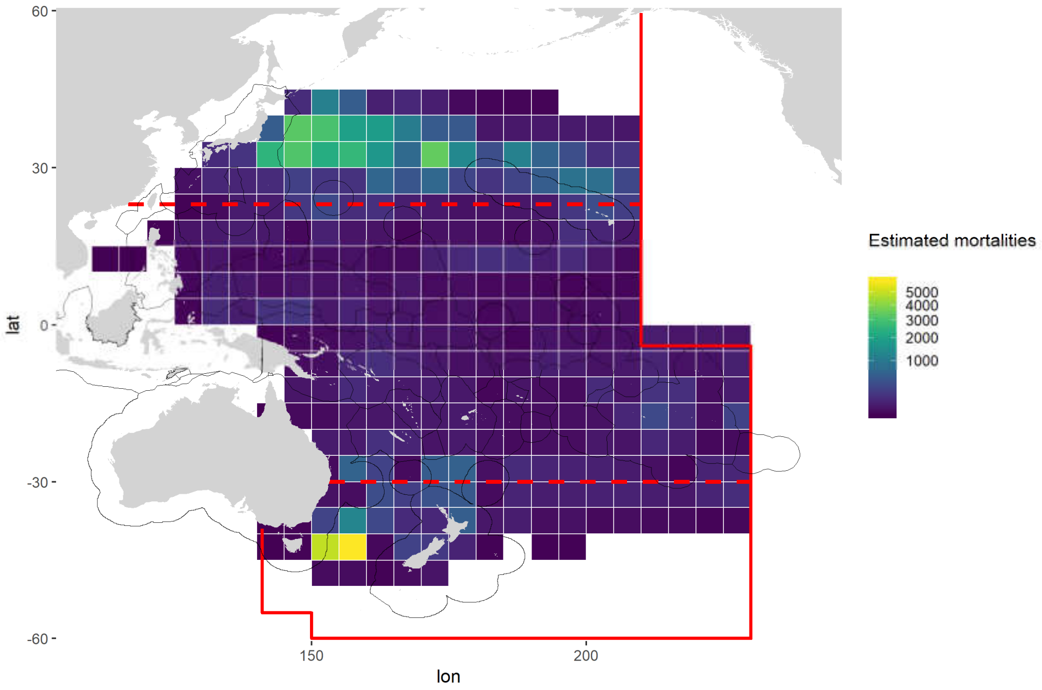


Figure 9 Linear predictor from the 'all seabirds' south Pacific model for quarter 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right). Reference levels for other explanatory variables: flag = NZ. The red lines show the WCPFC convention boundaries and the red dashed line shows 30°S.

a)



b)

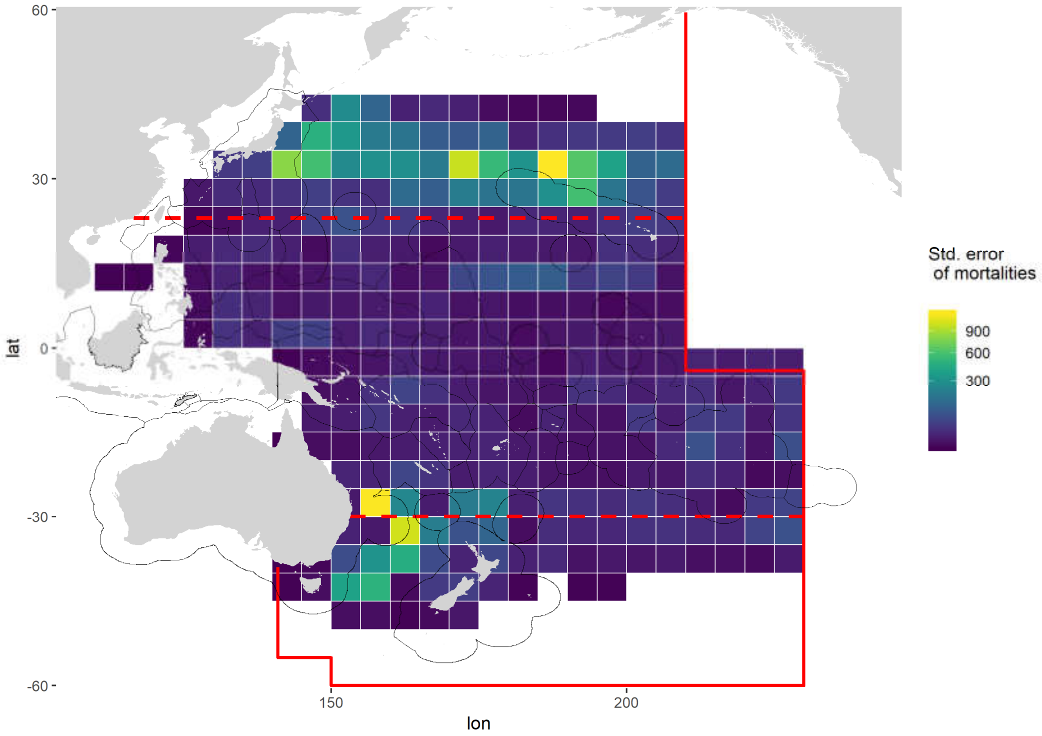


Figure 10 Estimated a) seabird mortalities at-vessel (individuals) by longline fisheries, 2015-2018 and b) standard errors in estimates. The red lines show the WCPFC convention boundaries and the red dashed lines show the 30°S and 23°N lines of longitude.

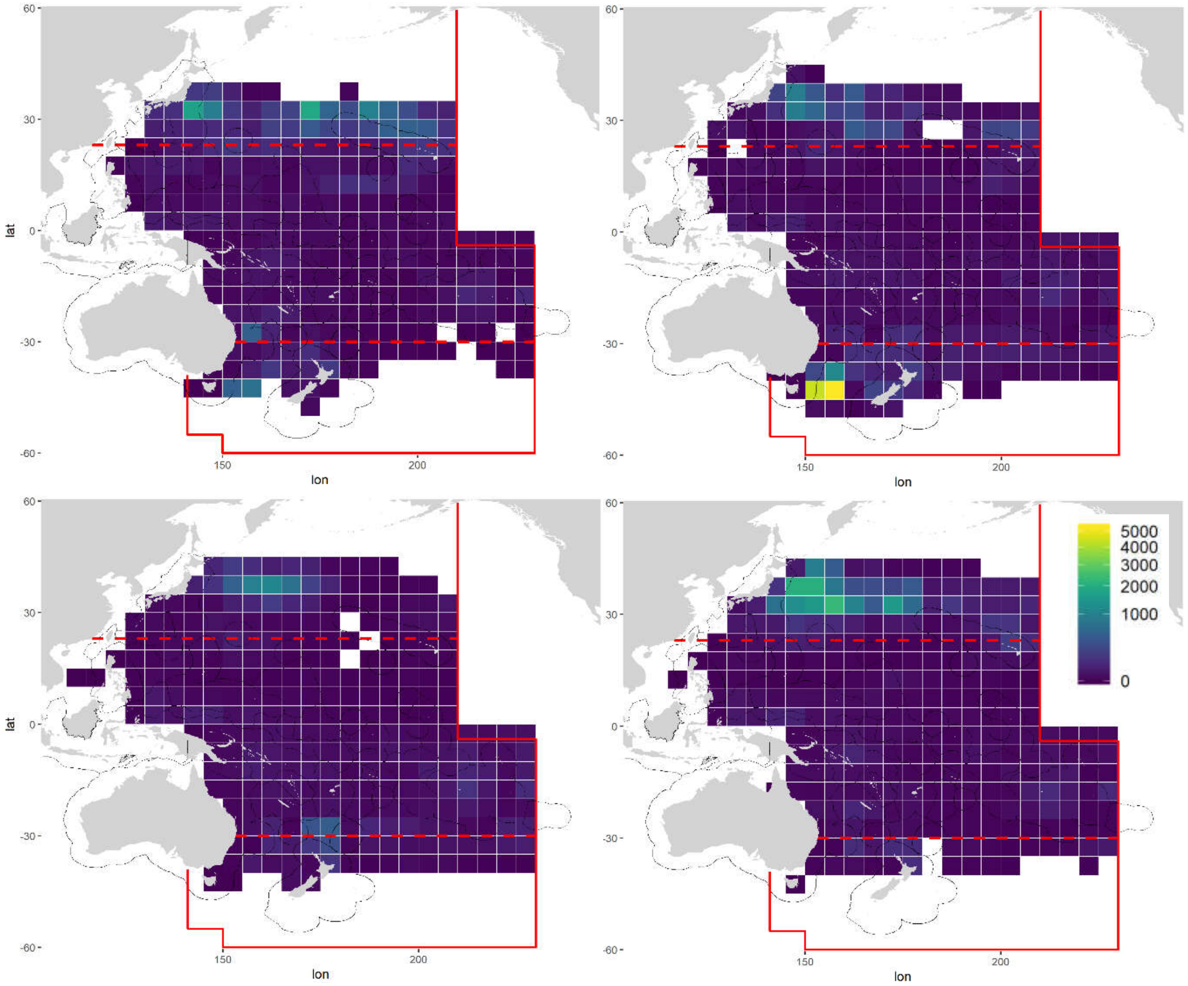


Figure 11 Estimated seabird mortalities by longline fisheries, 2015-2018 for quarter 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right). The red lines show the WCPFC convention boundaries and the red dashed lines show the 30°S and 23°N lines of longitude.

Appendix A

Overlap-based estimation of seabird bycatch

New Zealand has been utilising and refining a spatially explicit assessment of risk to seabirds from commercial fishing (e.g., Richard and Abraham 2013a; Richard et al., 2017). The method uses overlap between seabird distributions and fishing effort to estimate bycatch of seabird species. The risk assessment method was applied to surface-longline fishing, first by using New Zealand bycatch data to estimate seabird bycatch in surface-longline fishing throughout the Southern Hemisphere (Abraham et al 2017a,b); second by using observer data from New Zealand and Japan to estimate the bycatch of great albatross species in surface-longline fishing throughout the Southern Hemisphere (Daisuke et al., 2018). These studies were intended to demonstrate the method, while acknowledging limitations in the input data, in particular in the distributions of seabirds, and in the use of observer data from a limited number of fleets. The risk assessment method was also used as part of a Common Oceans project, led by Birdlife International, to estimate seabird bycatch of species listed by the Agreement on the Conservation of Albatrosses and Petrels (ACAP) (Birdlife South Africa, 2019).

In this analysis, we adapted work presented to the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) Ecologically Related Species Working Group (ERSWG) 13 by Abraham et al. (2019), to estimate seabird bycatch for 21 albatross and petrel taxa that breed in the Southern Hemisphere (Table A1). These taxa are the 20 species listed by the Agreement for the Conservation of Albatrosses and Petrels (ACAP), which breed south of 20°S, and which overlap with WCPFC fisheries, with Antipodean albatross being split into two subspecies.

Estimating annual captures. The total number of incidental captures of seabirds was estimated by assuming that, for similar species, and for similar fisheries, the number of incidental captures of protected species is proportional to the overlap between the density of the populations and the fishing. Here, the density overlap (θ) between a species (s) and the fishing effort within a group of fisheries (*f*) was calculated by summing the product of fishing intensity, population size and the relative density of a species at the location of the fishing:

$$\theta_{sf} = N_s O_{sf}$$

$$O_{sf} = \sum_i p_{si} h_{fi}$$

where N_s is the total population size, O_{sf} is the population-independent overlap, *i* is an index of the fishing events within the fisheries group, p_{si} is the relative population density at the location of the fishing (p has units of km^{-2} and is calibrated to integrate to one over the Southern Hemisphere), and h_{fi} is the number of hooks associated with the fishing event.

Captures of seabirds are recorded by observers when they are onboard fishing vessels. The expected number of incidents is assumed to be proportional to the density overlap. The mean capture rate recorded by observers (μ'_{sf}) is then given by:

$$\mu'_{sf} = q_{sf} \theta'_{sf}$$

where q_{sf} is the vulnerability of a species, *s*, to capture in a fleet, *f*, per unit of density overlap, θ'_{sf}. The prime symbol was used to indicate observed quantities.

In this analysis, it was assumed that the vulnerability could be represented as a combination of a susceptibility, q_g, that was assumed to be the same for all seabirds within each species group g (see Table A1), and a catchability, q_f that was assumed to be the same for all seabirds within each fleet:

$$q_{sf} = q_{g(s)} q_f \varepsilon_{g(s)f}$$

where the term ε_{gf} represents the interaction between the catchability and the susceptibility. There were sixteen seabird species groups (see Table A1) included in the modeling. The fleets were the same six fleets that were included in the GAM modelling: Japan high seas, China and the fishing entity of Taiwan, Australia, New Zealand joint venture, New Zealand domestic, and all other flags.

Not all captured seabirds could be identified to the species group level: some captures were only recorded as unidentified seabirds, and some captures were only identified to the family level (either albatrosses or petrels). From the mean capture rate, the number of observed captures identified to the taxa-group level, C'_{gf}, is given by:

$$C'_{gf} \sim Poisson\left(p_{observable} p_f^{bird} p_{F(g)f}^{family} \mu'_{gf}\right)$$

The probability, $p_{observable}$, is the probability that an incident that occurred while an observer was on the vessel would be recorded; not all incidental captures are recorded, for example, as captured bird may fall off the hook before being brought on board. In this study we assume that $p_{observable}$= 1and so we are not accounting for cryptic mortality. In previous applications of the risk assessment to surface longline fishing, we used a mean value for $p_{observable}$ of 0.48 (95% c.i.: 0.41–0.55) based on a study by Brothers et al. (2010). The probability p_f^{bird} is the probability that a capture is identified to a level better than a seabird (estimated separately for each fishery), and p_{Ff}^{family} is the probability that a capture is identified to a level better than the family, *F* (estimated separately for each seabird family and fishery). The number of observed unidentified seabird captures, S'_f, can then be estimated as:

$$S'_f \sim Poisson\left(\left(1 - p_f^{bird}\right) \sum_g \mu'_{gf}\right)$$

and the number of seabird captures that are only identified to the family level, F'_{Ff}, can be estimated as:

$$F'_{Ff} \sim Poisson\left(p_f^{bird}\left(1 - p_{Ff}^{family}\right) \sum_{g \in F} \mu'_{gf}\right)$$

The model was fitted to the data and estimated using Bayesian methods, within the software Stan. The standard deviation of the susceptibility and catchability parameters was drawn from a (-1, 1) lognormal prior (with this prior, the prior of the susceptibility and catchability parameters has a 95 % credible interval of 0.16 to 6). The model was fitted using four Markov chain Monte Carlo (MCMC) chains, with a warmup period of 3000 iterations; posteriors were calculated from 6000 further iterations, retaining a sample value every 3 iterations. Convergence and mixing were visually assessed from the MCMC trace of the parameters, and by requiring that the $\hat{R}$ parameter (which compares variation within chains and between chains) was less than 1.1 for all parameters.

Having fitted the model, the number of annual captures of a taxa *s* in fishing effort in the fishing group *g* could be estimated from the fitted vulnerability and the overlap as:

$$EAC \sim Poisson(p_{observable} q_{sf} \theta_{sf})$$

Seabird distributions. Seabird distributions were derived from tracking data following methods similar to those by Carneiro et al. (2019), but with several key differences, reflecting the requirements of the analysis. Tracking data were obtained from a request to tracking data owners, through the Birdlife International Seabird Tracking Database (http://www.seabirdtracking.org/). Seabird distributions were prepared for all ACAP-listed albatross and petrel species breeding south of 20 °S (with Gibson's and Antipodean albatross treated separately), for a total of 26 distinct taxa.

Each deployment was first processed to remove the first three days (to reduce a bias caused by seabirds being tagged at the colony). Second, any gaps of longer than 24 hours in the tracking data were discarded, by splitting the deployment into separate tracks. Third, each track was interpolated regularly in time (hourly intervals) to obtain a set of points that were equally-spaced in time. The number of interpolated points falling within each 5-degree square was counted, and this gridded track distribution was normalised to integrate to one. Because this analysis was at a 5-degree scale, no kernel density estimation was carried out, as the resolution of the 5-degree grid is lower than typical kernel densities. Because of the coarse spatial scale, tracks with positions derived from Global Positioning System (GPS) or Geolocators (GLS) were treated in the same way.

For each species and breeding site, the tracks were grouped into tracks from breeding, non-breeding, and juvenile seabirds. Tracks that were initially for breeding seabirds, but that continued outside their breeding season, were split with each part assigned to the corresponding life-stage. Furthermore, for petrels, tracks of breeding seabirds were split at 3000 km from their colony, with the portion of the tracks beyond this distance being assigned to non-breeding seabirds.

For each species and site, the tracking distribution of juveniles with less than 15 tracks or 5000 tracking points was derived from the average of the distribution of non-breeding adults and of the distribution of juveniles, weighted by the respective number of points in each distribution.

Tracking data were not available or insufficient for some combinations of species, site, and population class and so range maps were also required. For juveniles and non-breeding adults, a simple distribution with a uniform density across the range of the species was derived, based on range maps (BirdLife International and Handbook of the Birds of the World 2018). These range maps were the same for all breeding sites. For breeding adults, the range map was supplemented by adding breeding seabirds, based on an exponential decay function around the colony, so that 90% of their movement occurred within 1500 km from the colony.

For all species, sites and classes, the distribution was derived as a weighted average of the tracking and range distributions, weighted by the number of hourly points used to derive the tracking distribution (the range distribution was assigned a weight of 5000). For species, sites and classes with considerable tracking data, the range maps had little weight.

A simple demographic matrix model (with number of breeding pairs, age at first breeding, juvenile survival, adult survival, proportion of successful/unsuccessful breeding seabirds and non-breeding seabirds breeding the following year or not) was used to estimate the proportion of the population at each breeding site that were juvenile, adult breeders or adult non-breeders, within each of the quarterly periods. The gridded track distributions were weighted by the proportion of seabirds in each class, and then combined to provide a normalised distribution for each species and breeding site.

Finally, the population-weighted distributions from each colony were combined to obtain a distribution for the species as a whole.

Across all taxa, there were 7.2 million hours of tracking data available to the analysis. Of the 26 taxa, there were 24 taxa that had at least some tracking data available (no tracking data was requested for either of the two giant petrel species). There were 2.2 million hours of tracking data available for black-browed albatross, and 1.8 million hours available for wandering albatross. Nevertheless, there were three species (southern royal albatross, Campbell black-browed albatross and spectacled petrel) that had less than 10 000 hours of tracking data. Distinguished by life stage, there were 21 species with more than 10 000 hours of tracking data available for breeding adults; 18 species with more than 10,000 hours of tracking data available for non-breeding adults; and 9 species with more than 10,000 hours of tracking data available for juveniles.

Table A1: Taxa included in the current analysis of bycatch of seabirds in the Southern Hemisphere WCFPC region. The 20 species are listed by the Agreement for the Conservation of Albatrosses and Petrels (ACAP), have breeding colonies in the Southern Hemisphere, and overlap with WCFPC fisheries. Note that in this analysis, Antipodean albatross is represented as two subspecies, Antipodean and Gibson's albatrosses, so the analysis includes 21 taxa. Taxa were grouped to estimate their vulnerability to capture in surface-longline fisheries.

Taxa group	Taxa	Scientific name
Wandering albatrosses	Wandering albatross	*Diomedea exulans*
	Antipodean albatross	*Diomedea antipodensis antipodensis*
	Gibson's albatross	*Diomedea antipodensis gibsoni*
Royal albatrosses	Southern royal albatross	*Diomedea epomophora*
	Northern royal albatross	*Diomedea sanfordi*
Yellow-nosed albatrosses	Indian yellow-nosed albatross	*Thalassarche carteri*
Black browed albatrosses	Black-browed albatross	*Thalassarche melanophris*
	Campbell black-browed albatross	*Thalassarche impavida*
Grey-headed albatross	Grey-headed albatross	*Thalassarche chrysostoma*
Buller's albatross	Buller's albatross	*Thalassarche bulleri*
Shy albatrosses	Shy albatross	*Thalassarche cauta*
	White-capped albatross	*Thalassarche steadi*
Chatham Island albatross	Chatham Island albatross	*Thalassarche eremita*
Salvin's albatross	Salvin's albatross	*Thalassarche salvini*
Sooty albatrosses	Light-mantled sooty albatross	*Phoebetria palpebrata*
Giant petrels	Southern giant petrel	*Macronectes giganteus*
	Northern giant petrel	*Macronectes halli*
White-chinned petrel	White-chinned petrel	*Procellaria aequinoctialis*
Westland petrel	Westland petrel	*Procellaria westlandica*
Black petrel	Black petrel	*Procellaria parkinsoni*
Grey petrel	Grey petrel	*Procellaria cinerea*

Table A2: Summary of the posterior distribution of the vulnerability parameters (the catchability, susceptibility and the standard deviation of their distributions). For each parameter, the table gives the mean and 95 % credible interval of the posterior distribution.

Parameter		Mean	95 % c.i.	
Catchability, q_f	Australia	0.07	0	0.32
	China and Taiwan	0.3	0.08	0.8
	Japan	5.06	1.68	11.66
	New Zealand domestic	2.53	0.83	6.03
	New Zealand joint venture	0.12	0.03	0.32
	Other	0.88	0.18	2.52
Susceptibility, q_g	Royal albatrosses	0.69	0.1	2.29
	Wandering albatrosses	1.54	0.36	4.39
	Phoebetria species	0.88	0.12	3.02
	Chatham Island albatross	0.81	0.02	3.89
	Buller's albatross	7.03	1.58	19.86
	grey-headed albatross	0.53	0.07	1.79
	Salvin's albatross	0.28	0.03	0.99
	Black-browed albatrosses	1.55	0.38	4.27
	Shy albatrosses	1	0.24	2.79
	Yellow-nosed albatrosses	0.13	0	0.59
	Macronectes species	0.18	0.01	0.68
	grey petrel	1.42	0.26	4.58
	Westland petrel	5.95	1.05	18.88
	black petrel	15.6	2.35	49.53
	white-chinned petrel	0.71	0.17	2.01
Standard deviation	Catchability	1.97	0.98	3.82
	Susceptibility	1.59	0.88	2.59
	Catchability-susceptibility interaction	0.99	0.65	1.48

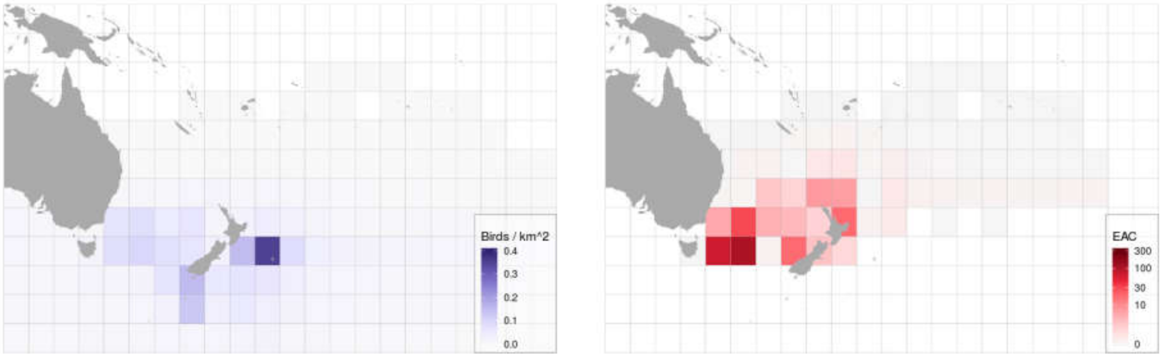
Figure A1. Traces of the chains of the vulnerability parametres (the catchability, for each fishery group, and the susceptibility for each taxa group). The traces show 2000 samples from each of the four chains.

Table A3: Estimated annual captures of each taxon. For each taxon, the table gives the mean and 95 % credible interval af the annual captures within the WCPFC region, estimated from the overlap model.

Taxon	Mean	95 % c.i.
White-capped albatross	1249	1113 – 1389
Buller’s albatross	1143	1006 – 1281
White-chinned petrel	614	504 – 732
Black-browed albatross	522	420 – 632
Gibson’s albatross	224	167 – 288
Campbell black-browed albatross	223	174 – 276
Black petrel	150	76 – 273
Westland petrel	64	37 – 96
Grey petrel	37	15 – 72
Antipodean albatross	31	18 – 46
Light-mantled sooty albatross	29	10 – 55
Wandering albatross	22	12 – 33
Shy albatross	21	12 – 31
Grey-headed albatross	18	4 – 42
Salvin’s albatross	11	1 – 30
Southern royal albatross	7	1 – 18
Indian yellow-nosed albatross	5	0 – 19
Southern giant petrel	5	0 – 15
Northern royal albatross	4	0 – 11
Chatham Island albatross	3	0 – 13
Northern giant petrel	2	0 – 8

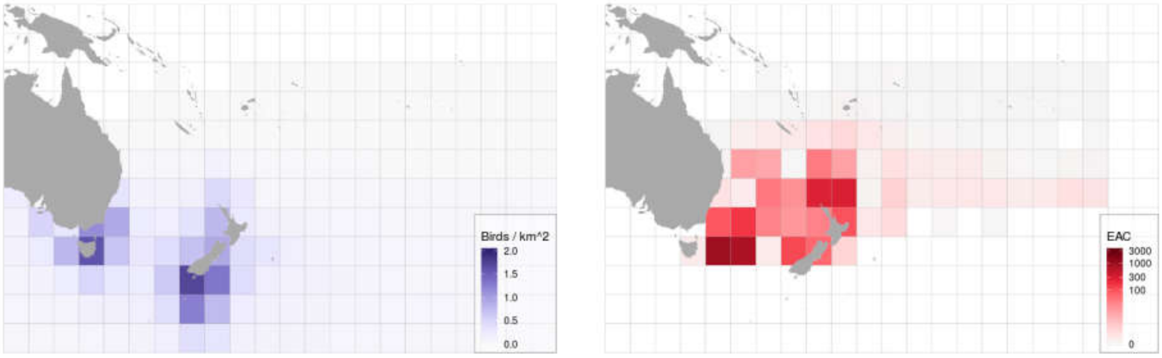
(a) Distribution of *Diomedea*

(b) Captures of *Diomedea*



(c) Distribution of *Thalassarche*

(d) Captures of *Thalassarche*



(e) Distribution of *Phoebetria*

(f) Captures of *Phoebetria*

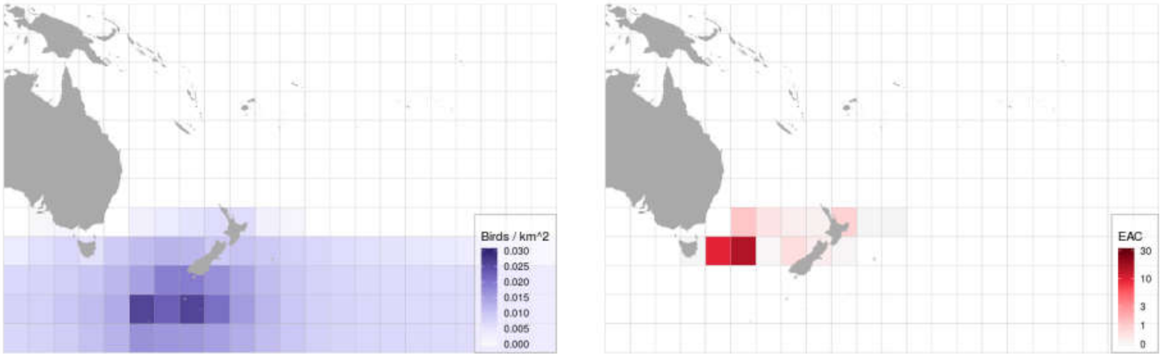
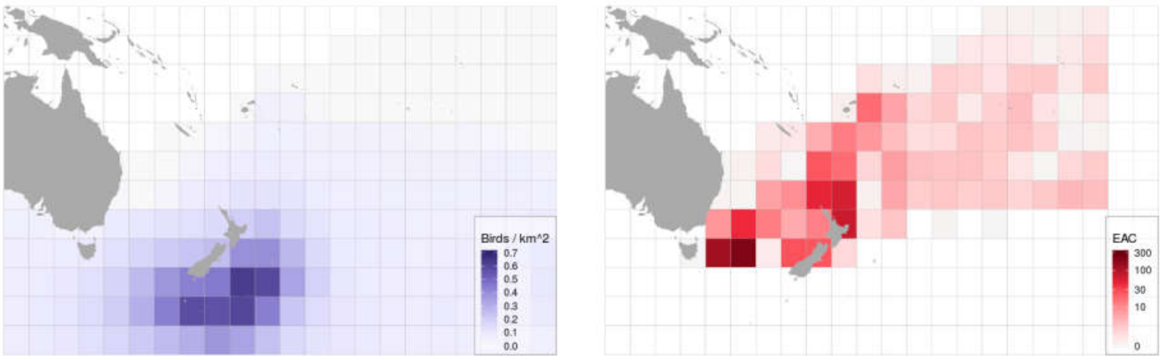
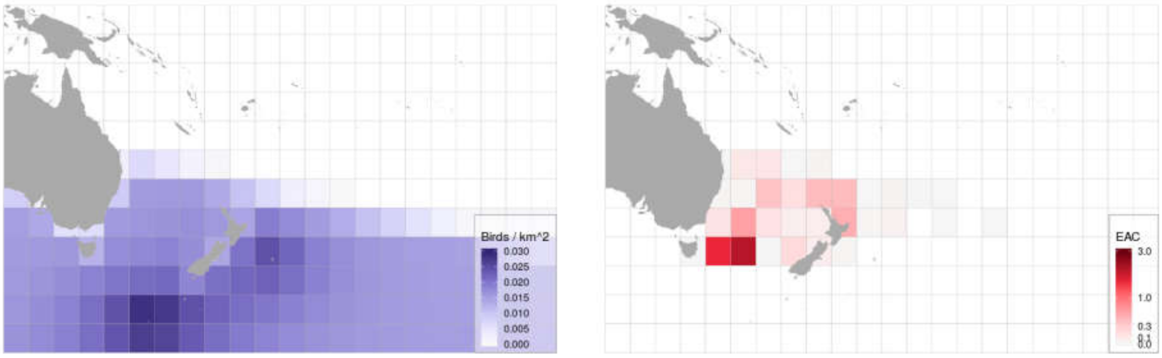


Figure A2: Distribution of albatross within each genus (a, c, e), and the estimated annual captures (EAC) of albatross within each genus using the overlap method (b, d, f). The distribution is the sum of the density of all species within each genus (birds/ km^2). The captures are the mean of the sum of the captures of each species in the genus, within each 5-degree cell.


(g) Distribution of *Procellaria*

(h) Captures of *Procellaria*


(i) Distribution of *Macronectes*

(j) Captures of Macronectes

Figure A3: Distribution of petrels within each genus (a, c, e), and the estimated annual captures (EAC) of petrels within each genus using the overlap method (b, d, f). The distribution is the sum of the density of all species within each genus (birds/ km^2). The captures are the mean of the sum of the captures of each species in the genus, within each 5-degree cell.

Appendix B

Table 6 Summary of the evolution of seabird mitigation options in WCPFC CMMs.

CMM	Applicability	Mitigation options	Column A	Column B	Date in force
CMM 2006-02 & CMM 2007-04	North of 23N, LoA ≥ 24m	At least two mitigation measures, including at least one from Column A. Side-setting only applicable north of 23N	i) Side setting with bird curtain and weighted branch lines* ii) Tori line iii) Night setting iv) Weighted branch lines	i) Tori line ii) Blue-dyed bait iii) Deep setting line shooter iv) Underwater setting chute v) Management of offal discharge	30th June 2008
	South of 30S, LoA ≥ 24m				1st January 2008
	South of 30S, LoA < 24m				31st January 2009
CMM 2012-07	North of 23N, LoA ≥ 24m	At least two mitigation measures, including at least one from Column A.	As above for CMM 2007-04	i) Tori line ii) Blue-dyed bait iii) Deep setting line shooter iv) Management of offal discharge	1st July 2014
	South of 30S	At least two of: weighted branch lines; night setting; and, tori lines	Not applicable	Not applicable	1st July 2014
CMM 2015-03 & CMM 2017-06	North of 23N, LoA ≥ 24m	At least two mitigation measures, including at least one from Column A.	As above for CMM 2012-07	As above for CMM 2012-07	1st January 2017
	North of 23N, LoA < 24m	At least one mitigation measure from Column A			
	South of 30S	At least two of: weighted branch lines; night setting; and, tori lines	Not applicable	Not applicable	1st January 2017
CMM 2018-03	North of 23N, LoA ≥ 24m	At least two mitigation measures, including at least one from Column A.	i) Side setting with bird curtain and weighted branch lines* ii) Tori line iii) Night setting iv) Weighted branch lines v) Hook-shielding devices*	As above for CMM 2012-07	1st January 2019
	North of 23N, LoA < 24m	At least one mitigation measure from Column A			
	25S to 30S (with exemptions)	At least one of: i) weighted branch lines; ii) tori lines; or iii) hook-shielding devices	Not applicable	Not applicable	1st January 2020
	South of 30S	Hook-shielding devices OR at least two of: weighted branch lines; night setting; and, tori lines.	Not applicable	Not applicable	1st January 2019

Note: mitigation options with *'s can be used as a stand-alone measure

Appendix C

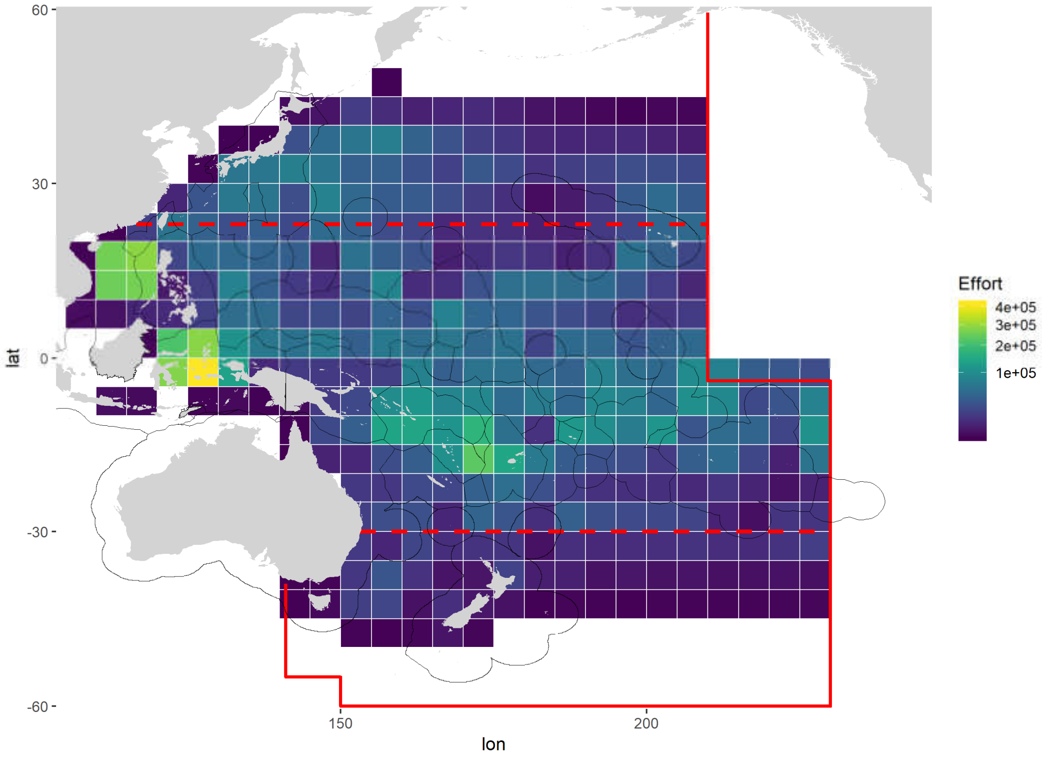


Figure 12 Reported longline effort ('000 hooks) in the WCPFC-CA, 2008 - 2018.

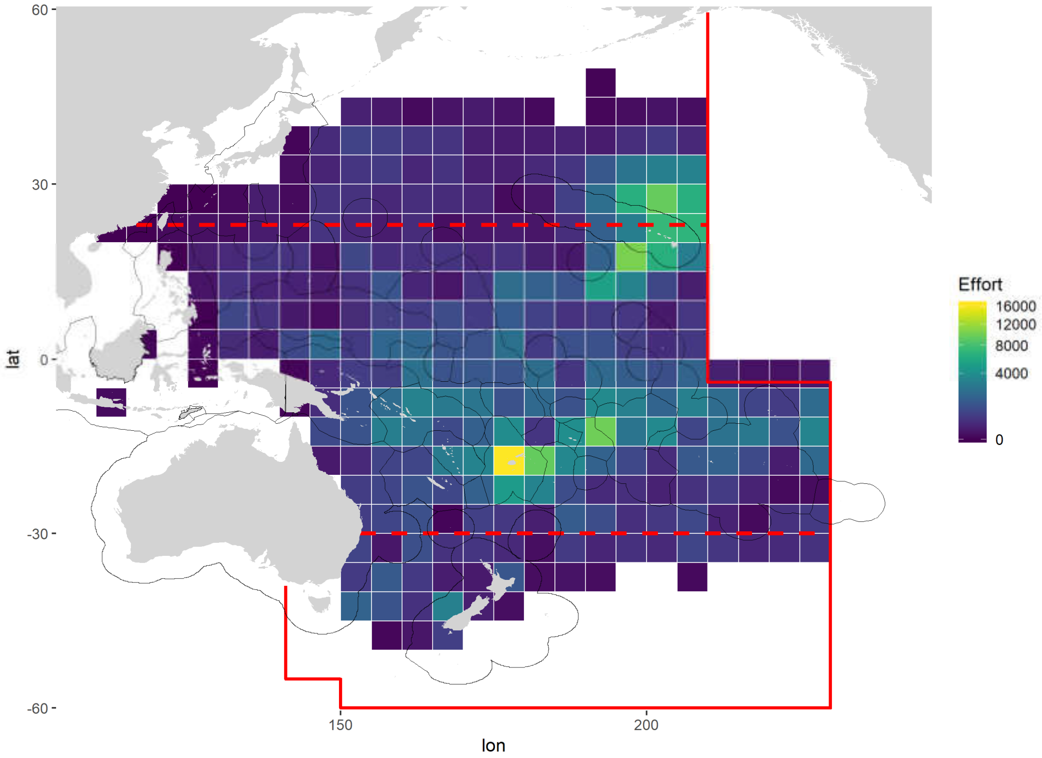


Figure 13 Longline effort with observer onboard ('000 hooks) in the WCPFC-CA, 2008 - 2018.

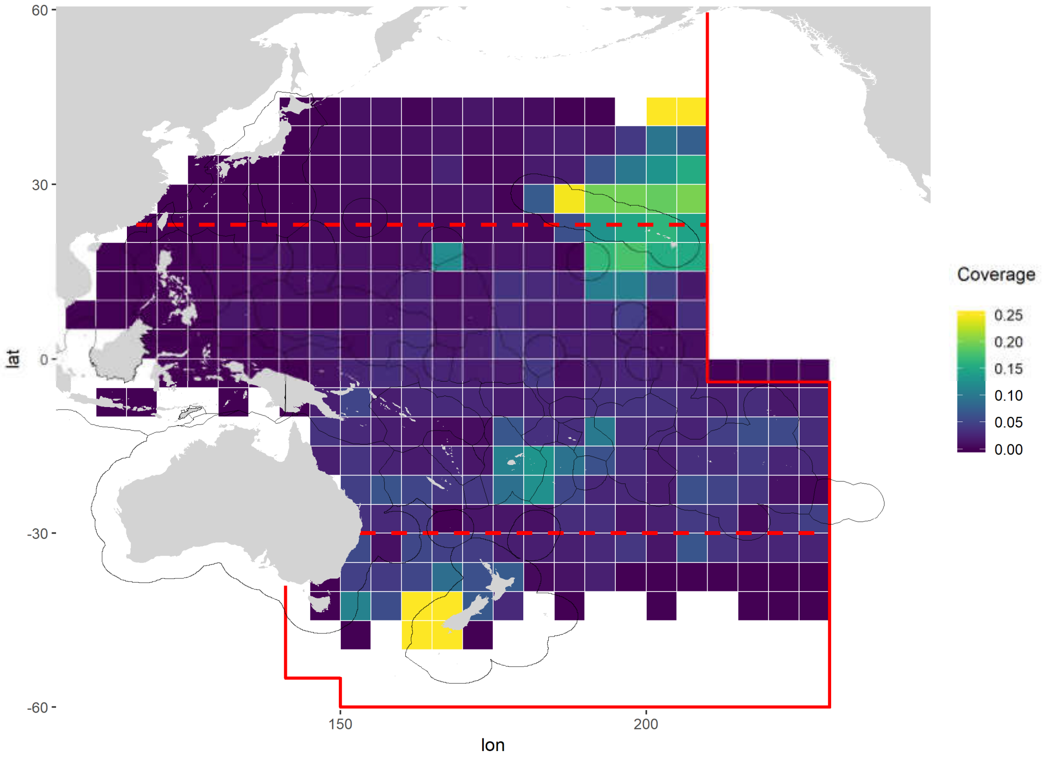


Figure 14 Longline observer coverage (proportion of hooks with observer onboard) for longline fleets in the WCPFC-CA, 2008 – 2018.

Appendix D

North Pacific longline modelled dataset

Table 7 Observed effort (sets and '000 hooks) and seabird bycatch (individuals) by (a) year and (b) flag in the dataset for the north Pacific 'all seabirds' model. Flag groupings used in the model are also provided ('flag effect').

a)

	Observed effort		
Year	**Sets**	**'000 hooks**	**Bycatch**
2004	4,017	7,861	10
2005	5,583	9,559	86
2006	4,609	8,577	31
2007	5,010	9,154	71
2008	4,281	8,148	95
2009	4,351	8,074	142
2010	3,817	7,084	118
2011	3,877	7,789	108
2012	4,160	8,721	144
2013	4,030	8,567	171
2014	4,149	8,728	115
2015	3,329	6,570	374
2016	5,398	11,456	508
2017	6,343	13,326	453
2018	5,484	12,940	228

b)

		Observed effort		
Flag	**Flag effect**	**Sets**	**'000 hooks**	**Bycatch**
US	US	45,144	104,513	1,017
US	US-shlw	11,016	10,664	681
JP	JP	2,986	6,098	918
TW	TW	6,006	8,937	33
CN	CN	1,423	2,566	1
KR	KR	653	1,261	0
MH	XX	479	926	1
FM	XX	667	1,407	1
others	XX	64	183	2
Totals		68,438	136,556	2,654

Table 8 Observed sets by flag effect and year in the dataset for the north Pacific models.

Year	US	JP	TW	CN	KR	MH	FM	others	Total
2004	3,776	12	18	163	0	0	48	0	4,017
2005	5,367	52	0	130	0	0	31	3	5,583
2006	4,103	19	6	338	56	0	87	0	4,609
2007	4,456	28	35	431	11	0	49	0	5,010
2008	4,092	0	66	54	0	11	46	12	4,281
2009	4,260	0	47	36	0	8	0	0	4,351
2010	3,725	0	73	3	0	0	0	16	3,817
2011	3,690	0	146	41	0	0	0	0	3,877
2012	3,840	0	259	14	47	0	0	0	4,160
2013	3,307	14	464	69	165	0	11	0	4,030
2014	3,522	0	436	86	9	0	96	0	4,149
2015	1,564	1,193	539	0	0	0	33	0	3,329
2016	3,506	831	701	14	55	186	89	16	5,398
2017	3,411	828	1,880	44	0	167	13	0	6,343
2018	3,541	9	1,336	0	310	107	164	17	5,484

Table 9 Numbers of seabirds in the modelled north Pacific dataset recorded for ‘seabirds unidentified’, or at a family, genus and species level.

Level of reporting	n
Seabirds unidentified	84
Family	277
Genus	7
Species	2,286

Table 10 Numbers of seabirds in the modelled north Pacific dataset by species / species group.

Scientific name	English name	Family	Order	n
Phoebastria immutabilis	Laysan albatross	*Diomedeidae*	Procellariiformes	1188
Phoebastria nigripes	Black-footed albatross	*Diomedeidae*	Procellariiformes	1087
Diomedeidae	Albatrosses	*Diomedeidae*	Procellariiformes	269
Birds unspecified	Birds unspecified	NA	NA	84
Others				26

Equatorial Pacific longline modelled dataset

Table 11 Observed effort (sets and ’000 hooks) and seabird bycatch (individuals) by (a) year and (b) flag in the dataset for the equatorial Pacific ‘all seabirds’ model. Flag groupings used in the model are also provided (‘flag effect’).

a)

	Observed effort		
Year	**Sets**	**'000 hooks**	**Bycatch**
2008	1,539	3,854	0
2009	1,775	3,957	5
2010	2,542	5,768	14
2011	3,737	8,479	11
2012	4,651	10,686	17
2013	7,996	14,951	40
2014	6,293	12,617	38
2015	6,114	12,581	54
2016	7,110	15,604	25
2017	6,757	14,666	31
2018	5,981	14,043	22

b)

	Observed effort		
Flag	**Sets**	**'000 hooks**	**Bycatch**
FJ	10,021	26,519	19
TW	16,690	26,497	62
US	6,143	17,416	1
PF	3,843	7,779	103
CN	3,319	6,995	5
KR	2,797	6,208	4
VU	2,208	4,843	6
JP	1,557	3,445	4
SB	1,689	3,890	12
NC	1,737	3,313	29
FM	1,264	3,089	6
AU	661	935	0
others	2,566	6,276	6
Totals	**54,495**	**117,206**	**257**

Table 12 Observed sets by flag and year in the dataset for the equatorial Pacific models.

Year	FJ	TW	US	PF	CN	KR	VU	JP	SB	NC	FM	AU	others	Total
2008	314	136	348	190	90	0	0	0	0	85	25	61	290	1,539
2009	207	162	405	453	66	0	41	12	0	210	0	124	95	1,775
2010	168	170	1,056	432	213	0	121	0	0	227	0	84	71	2,542
2011	265	939	1,102	325	355	77	237	0	74	170	0	102	91	3,737
2012	113	1,551	709	392	821	335	5	0	473	122	8	72	50	4,651
2013	798	2,491	695	420	776	670	1,212	14	465	103	71	119	162	7,996
2014	1,202	2,040	561	395	636	304	121	95	263	144	326	54	152	6,293
2015	1,646	2,195	151	304	23	454	181	371	141	103	267	45	233	6,114
2016	2,155	2,420	375	273	165	244	153	486	9	142	357	0	331	7,110
2017	1,097	3,147	476	401	114	2	41	572	0	180	13	0	714	6,757
2018	2,056	1,439	265	258	60	711	96	7	264	251	197	0	377	5,981

Table 13 Numbers of seabirds in the equatorial Pacific dataset recorded for ‘seabirds unidentified’ or at a family, genus and species level.

Level of reporting	n
Seabirds unidentified	46
Family	150
Genus	2
Species	59

Table 14 Numbers of seabirds in the modelled equatorial Pacific dataset by species / species group.

Scientific name	English name	Family	Order	n
Procellariidae	Petrels and shearwaters	*Procellariidae*	Procellariiformes	103
Diomedeidae	Albatrosses	*Diomedeidae*	Procellariiformes	22
Daption capense	Cape petrel	*Procellariidae*	Procellariiformes	15
Phoebastria nigripes	Black-footed albatross	*Diomedeidae*	Procellariiformes	18
Sulidae	Boobies and gannets	*Sulidae*	Ciconiiformes	15
Laridae	Laridae	*Laridae*	Charadriiformes	10
Birds unspecified	Birds unspecified	NA	NA	46
Others				28

South Pacific longline modelled dataset

Table 15 Observed effort (sets and '000 hooks) and seabird bycatch (individuals) by (a) year and (b) flag in the dataset for the south Pacific 'all seabirds' model. Flag groupings used in the model are also provided ('flag effect'). 'JP-NZ' refers to Japanese vessels operating in the NZ EEZ through charter agreements.

a)

	Observed effort		
Year	**Sets**	**'000 hooks**	**Bycatch**
2003	1,037	2,285	105
2004	1,031	2,019	56
2005	853	1,363	47
2006	970	1,787	115
2007	862	1,572	111
2008	1,052	1,768	47
2009	1,029	1,832	66
2010	666	1,088	126
2011	771	1,347	26
2012	952	2,186	52
2013	1,433	2,289	33
2014	1,712	2,695	36
2015	1,530	3,284	561
2016	1,761	3,533	1,073
2017	1,649	3,485	99
2018	1,207	2,449	122

b)

		Observed effort		
Flag	**Flag effect**	**Sets**	**'000 hooks**	**Bycatch**
NZ	JP-NZ	1,947	5,595	375
TW	CN&TW	3,594	6,132	40
AU	AU	3,861	4,786	5
NZ	NZ	3,283	4,631	726
JP	JP	936	2,427	1,466
CN	CN&TW	137	387	1
VU	CN&TW	60	221	3
others	XX	4,697	10,804	59
Totals		18,515	34,982	2,675

Table 16 Observed sets by flag and year in the dataset for the south Pacific models.

Year	NZ	TW	AU	JP	CN	VU	others	Total
2003	488	0	367	0	0	0	182	1,037
2004	460	0	438	0	0	0	133	1,031
2005	337	0	439	0	0	0	77	853
2006	289	0	360	0	0	0	321	970
2007	406	0	336	0	0	0	120	862
2008	236	0	531	0	1	0	284	1,052
2009	406	5	348	0	0	0	270	1,029
2010	284	0	159	0	0	0	223	666
2011	229	53	274	0	0	0	215	771
2012	250	345	234	0	8	0	115	952
2013	246	662	223	0	99	18	185	1,433
2014	274	917	113	0	12	0	396	1,712
2015	322	363	39	368	0	0	438	1,530
2016	327	506	0	384	17	0	527	1,761
2017	354	584	0	184	0	22	505	1,649
2018	322	159	0	0	0	20	706	1,207

Table 17 Numbers of seabirds in the south Pacific dataset recorded for ‘seabirds unidentified’, or at a family, genus, species complex and species level.

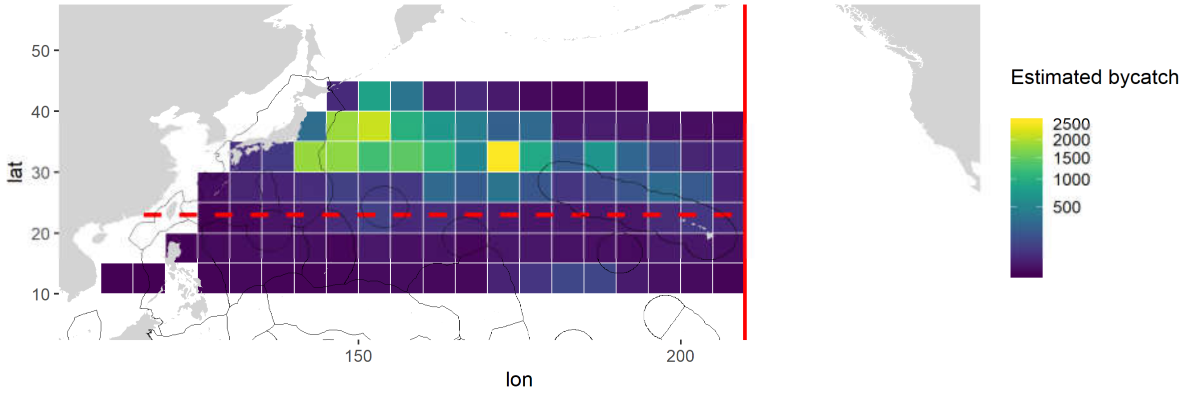
Level of reporting	n
Seabirds unidentified	37
Family	750
Genus	46
Species complex	425
Species	1,417

Table 18 Numbers of seabirds in the modelled south Pacific dataset by species / species group.

Scientific name	English name	Family	Order	n
Diomedeidae	Albatrosses nei	*Diomedeidae*	Procellariiformes	657
Thalassarche bulleri	Buller's albatross	*Diomedeidae*	Procellariiformes	598
Thalassarche cauta, T. salvini, T. eremita & T.steadi	Shy-type albatrosses	*Diomedeidae*	Procellariiformes	289
Thalassarche steadi	White-capped albatross	*Diomedeidae*	Procellariiformes	197
Procellaria aequinoctialis	White-chinned petrel	*Procellariidae*	Procellariiformes	147
Thalassarche melanophris	Black-browed albatross	*Diomedeidae*	Procellariiformes	95
Diomedea exulans, D. antipodensis, D. gibsoni & D. amsterdamensis	Wandering albatross complex	*Diomedeidae*	Procellariiformes	93
Procellariidae	Petrels and shearwaters nei	*Procellariidae*	Procellariiformes	90
Thalassarche impavida	Campbell albatross	*Diomedeidae*	Procellariiformes	76
Procellaria parkinsoni	Parkinson's petrel	*Procellariidae*	Procellariiformes	46
Procellaria cinerea	Grey petrel	*Procellariidae*	Procellariiformes	42
Procellaria westlandica	Westland petrel	*Procellariidae*	Procellariiformes	39
Procellaria spp	Petrels nei	*Procellariidae*	Procellariiformes	39
Thalassarche melanophris & T. impavida	Black-browed albatrosses	*Diomedeidae*	Procellariiformes	33
Diomedea exulans	Wandering albatross	*Diomedeidae*	Procellariiformes	31
Thalassarche salvini	Salvin's albatross	*Diomedeidae*	Procellariiformes	20
Puffinus carneipes	Flesh-footed shearwater	*Procellariidae*	Procellariiformes	18
Puffinus griseus	Sooty shearwater	*Procellariidae*	Procellariiformes	17
Thalassarche chrysostoma	Grey-headed albatross	*Diomedeidae*	Procellariiformes	15
Daption capense	Cape petrel	*Procellariidae*	Procellariiformes	13
Diomedea gibsoni	Gibson's albatross	*Diomedeidae*	Procellariiformes	10
Phoebetria palpebrata	Light-mantled sooty albatross	*Diomedeidae*	Procellariiformes	10
Birds unspecified	Birds unspecified	NA	NA	37
Others				63

Appendix E

a)



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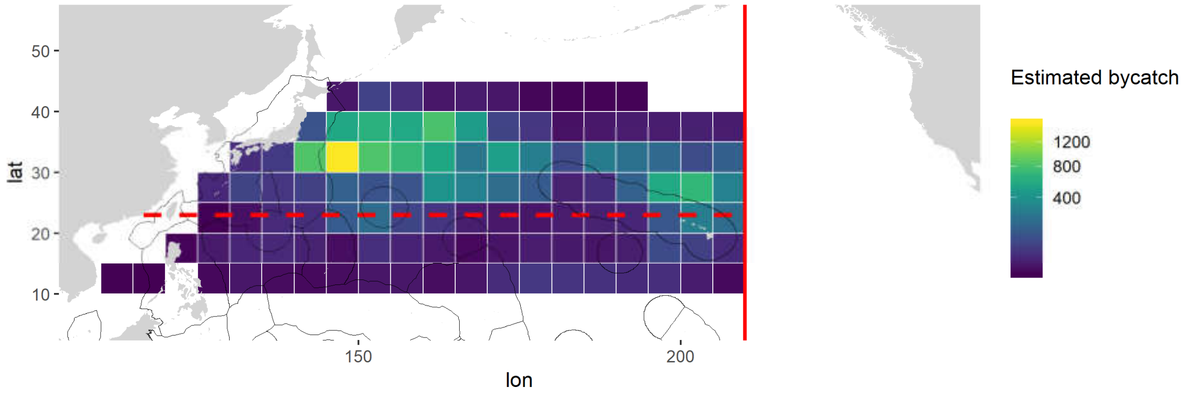


Figure 15 Indicative spatial distributions of estimated bycatch of a) Laysan albatross (*Phoebastria immutabilis*) and b) black-footed albatross (*Phoebastria nigripes*) by longline fisheries in the north of the WCPFC-CA, 2015-2018.

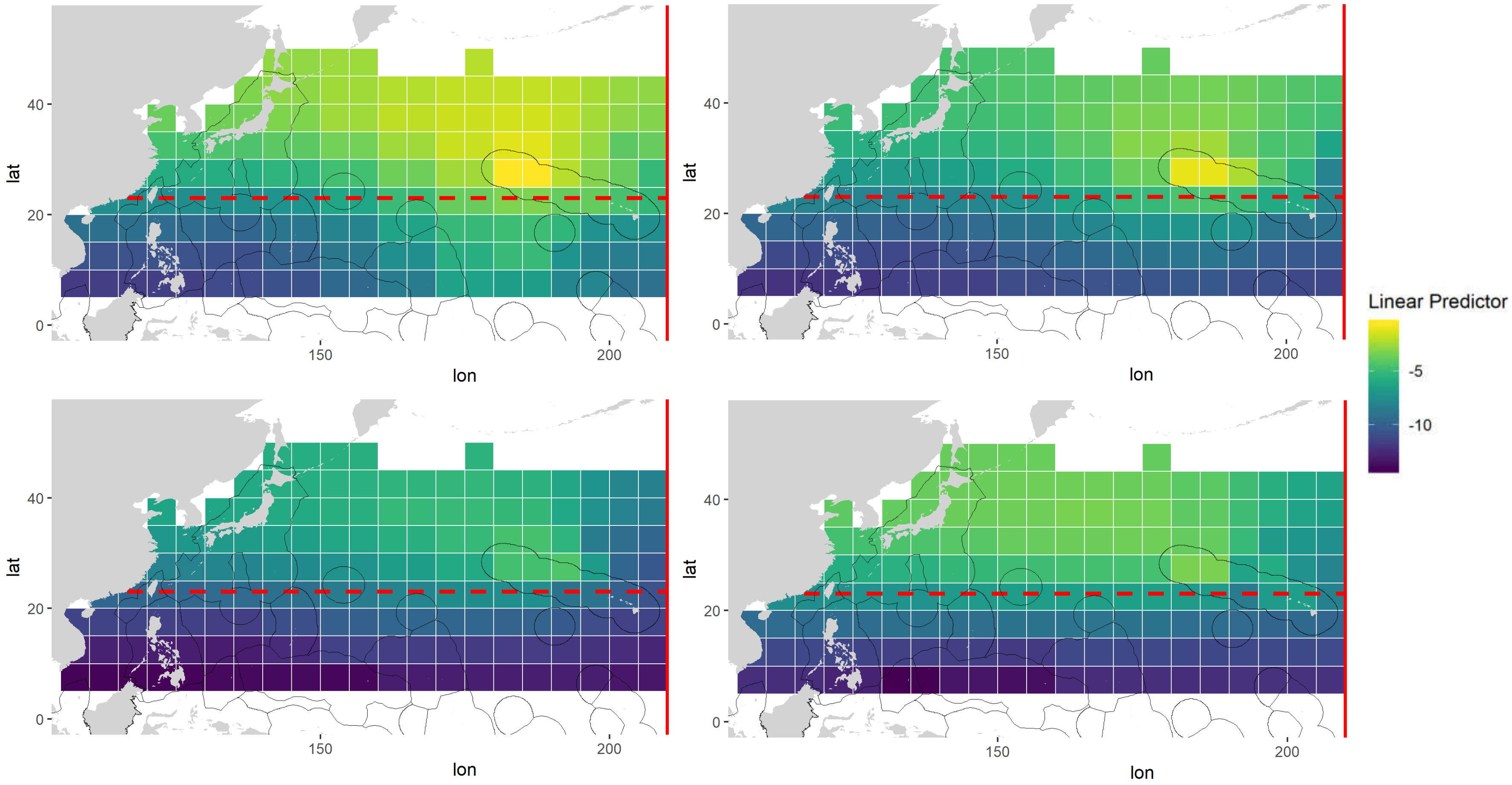


Figure 16 Linear predictor from the north Pacific Laysan albatross (*Phoebastria immutabilis*) model for quarter 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right). Reference levels for other explanatory variables: flag = US, year = 2017.

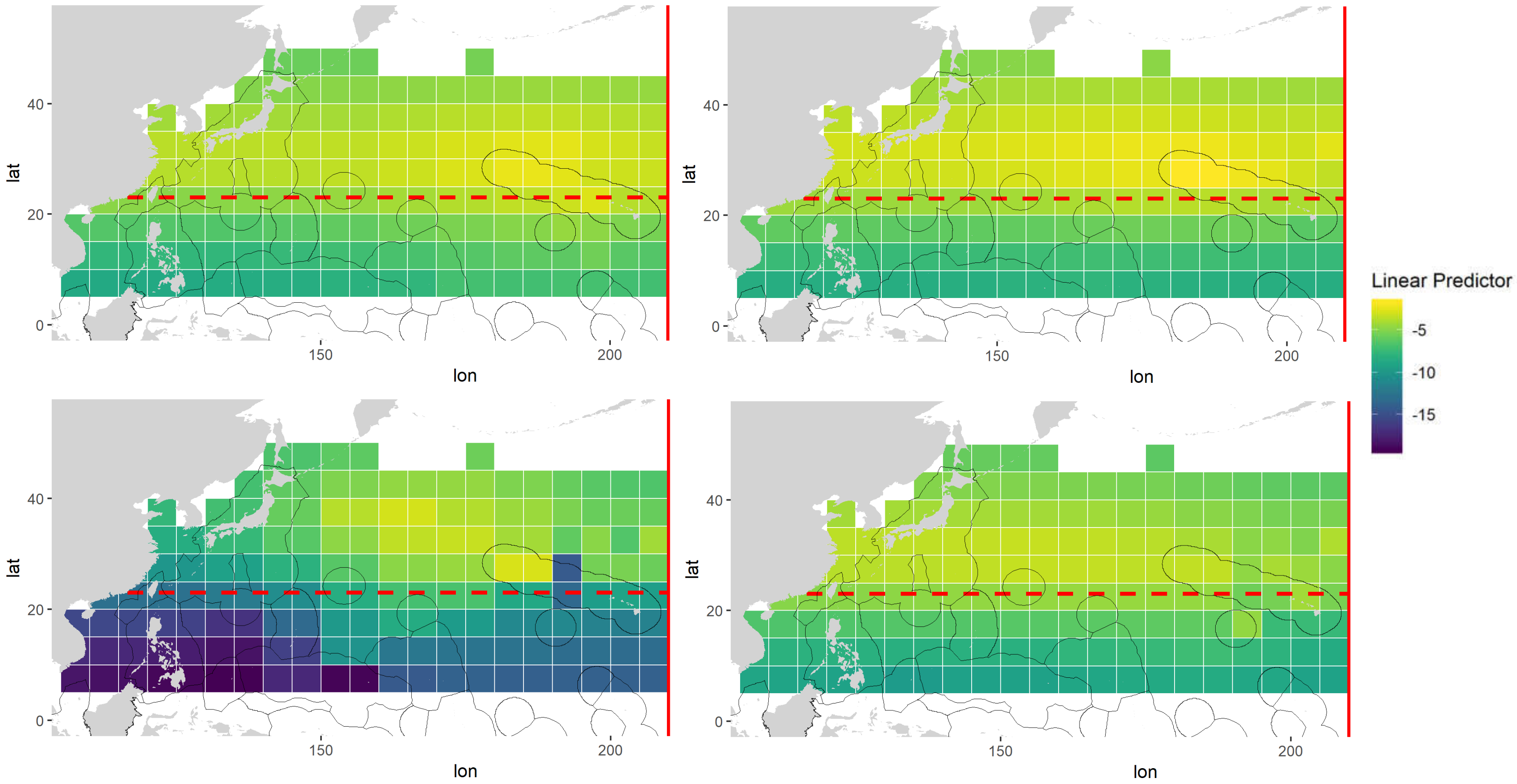
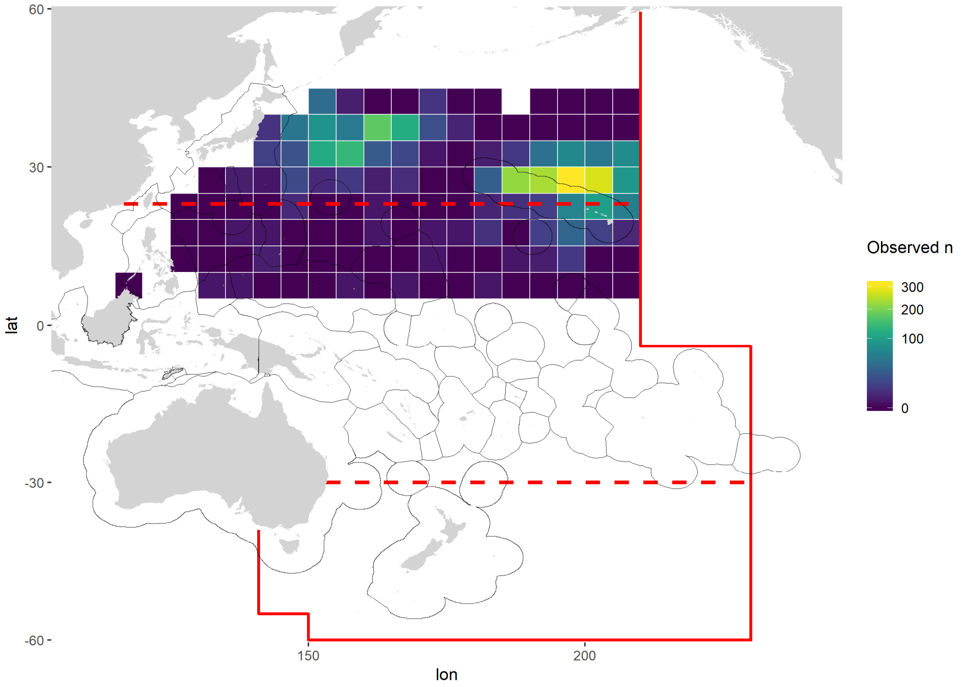


Figure 17 Linear predictor from the north Pacific black-footed albatross (*Phoebastria nigripes*) model for quarter 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right). Reference levels for other explanatory variables: flag = US, year = 2017.

Appendix F



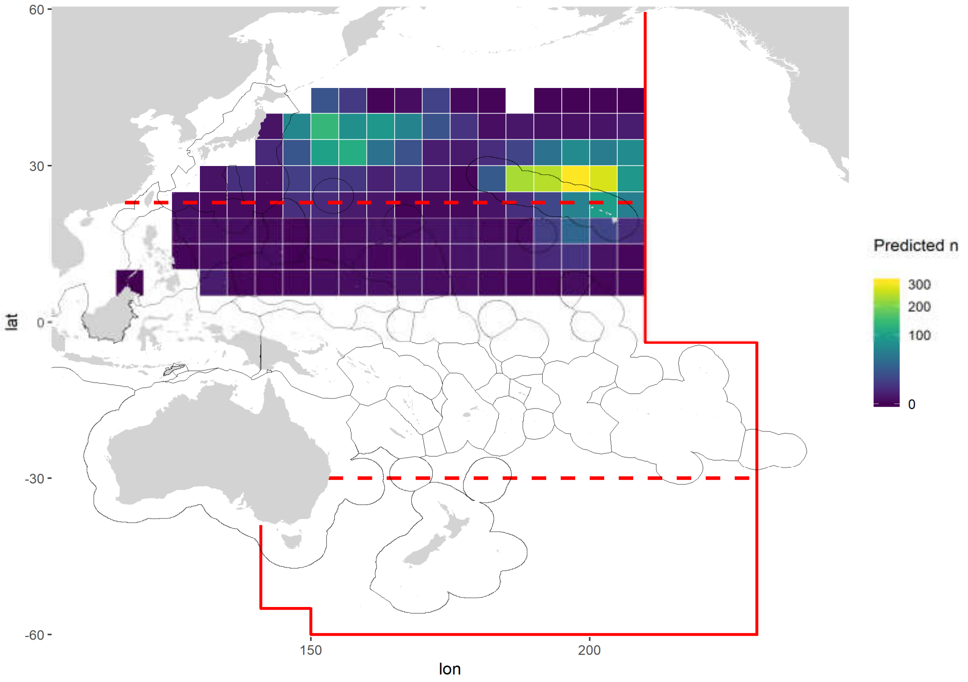


Figure 18 Observed (top) and predicted (bottom) bycatch for the dataset used to fit the bycatch rate model for all seabirds in the north Pacific.

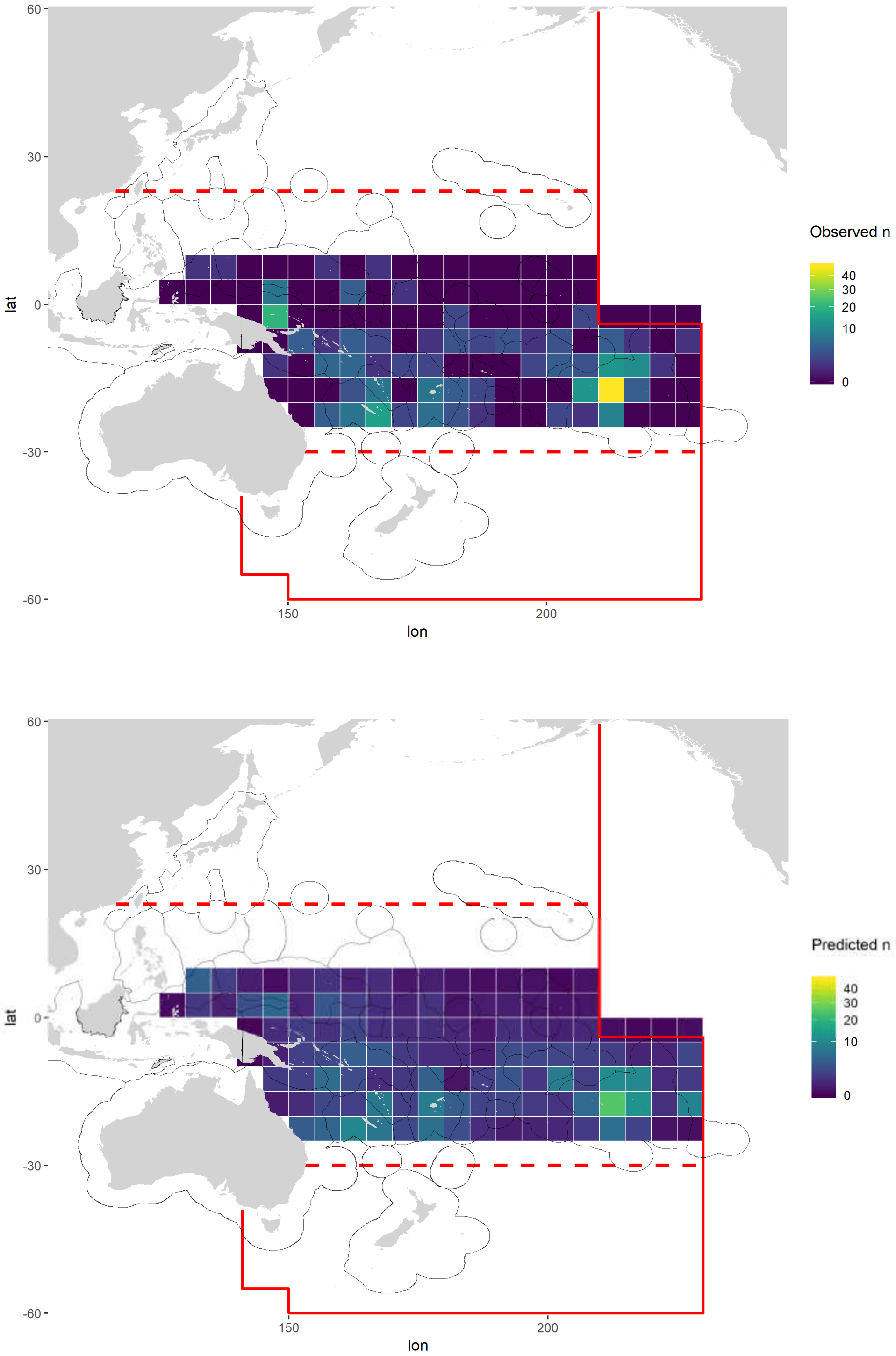


Figure 19 Observed (top) and predicted (bottom) bycatch for the dataset used to fit the bycatch rate model for all seabirds in the equatorial Pacific.

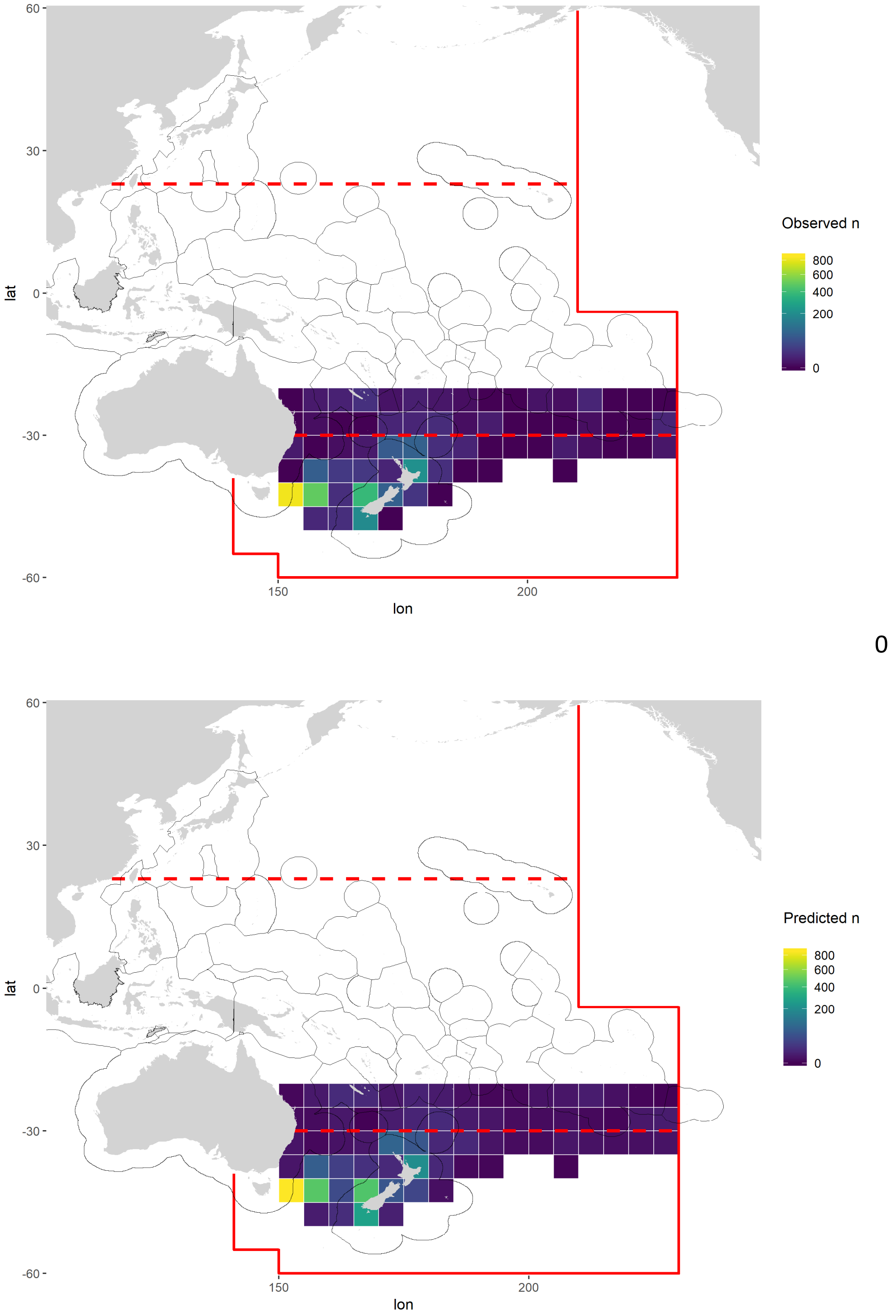


Figure 20 Observed (top) and predicted (bottom) bycatch for the dataset used to fit the bycatch rate model for all seabirds in the south Pacific.

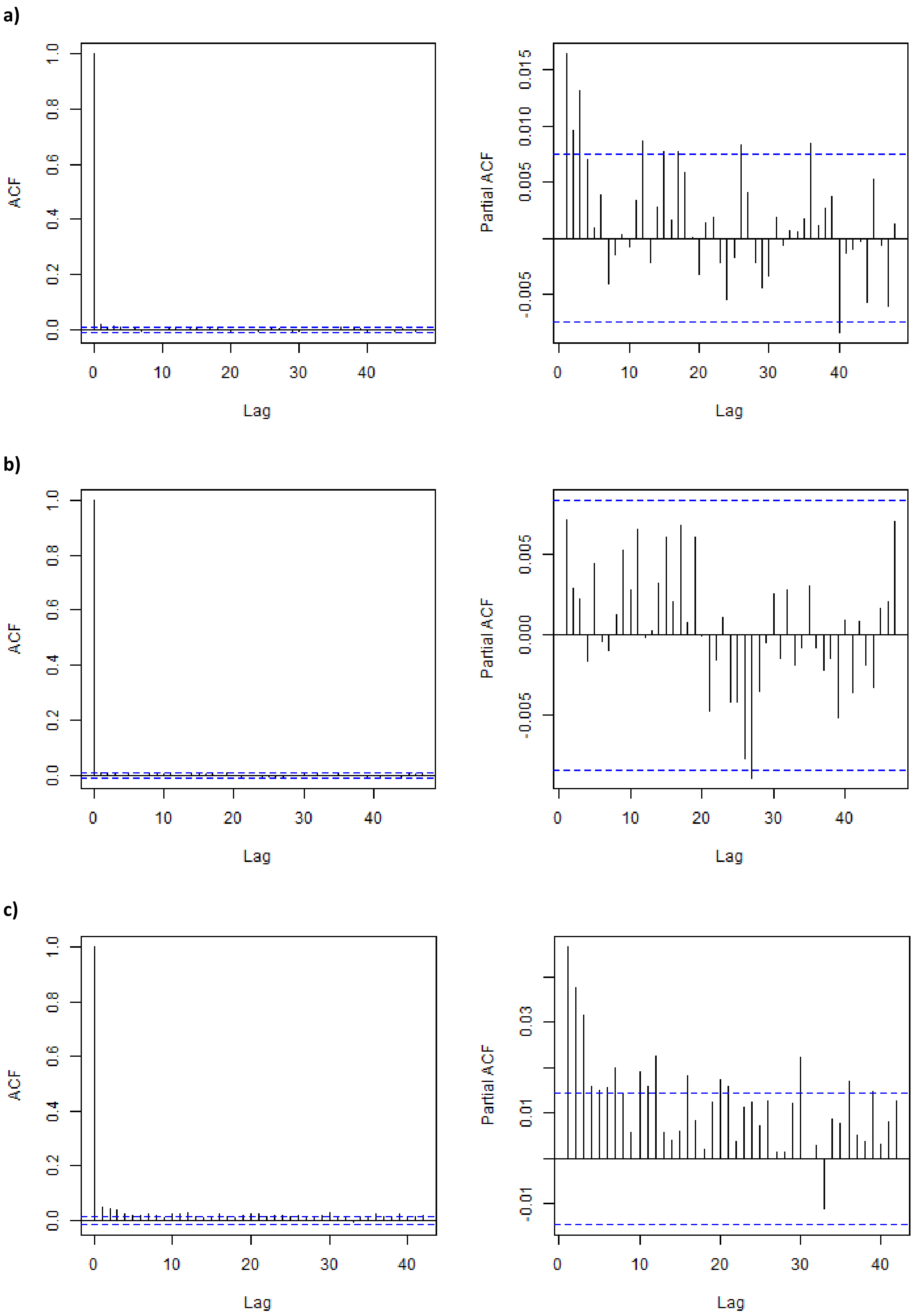


Figure 21 Auto-correlation function (left) and partial auto-correlation function (right) plots of quantile residuals for 'all seabird' models for the (a) north Pacific, (b) equatorial Pacific and (c) south Pacific.

Appendix G

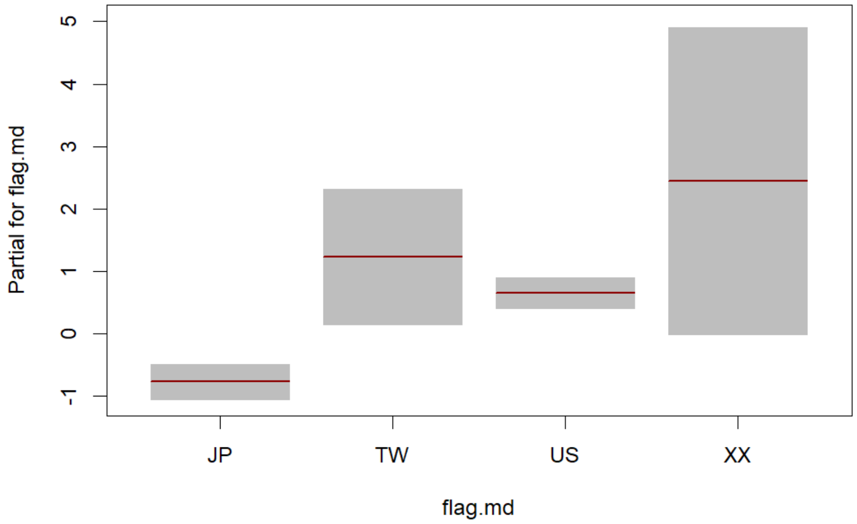


Figure 22 Effect plot from the condition at-vessel model for 'all seabirds' in the north Pacific. Y-axis is the linear predictor, i.e. logit transformed probability of being alive at-vessel. All other flags were grouped in 'XX'.

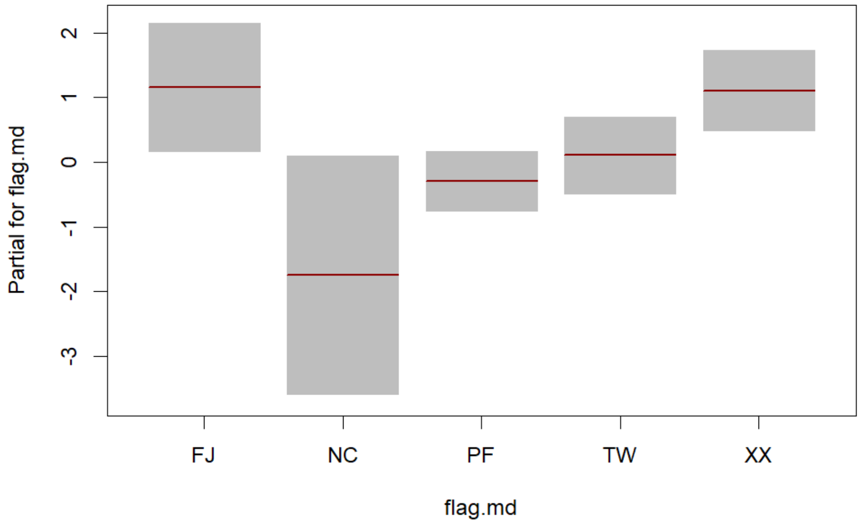


Figure 23 Effect plot from the condition at-vessel model for 'all seabirds' in the equatorial Pacific. Y-axis is the linear predictor, i.e. logit transformed probability of being alive at-vessel. All other flags were grouped in 'XX'.

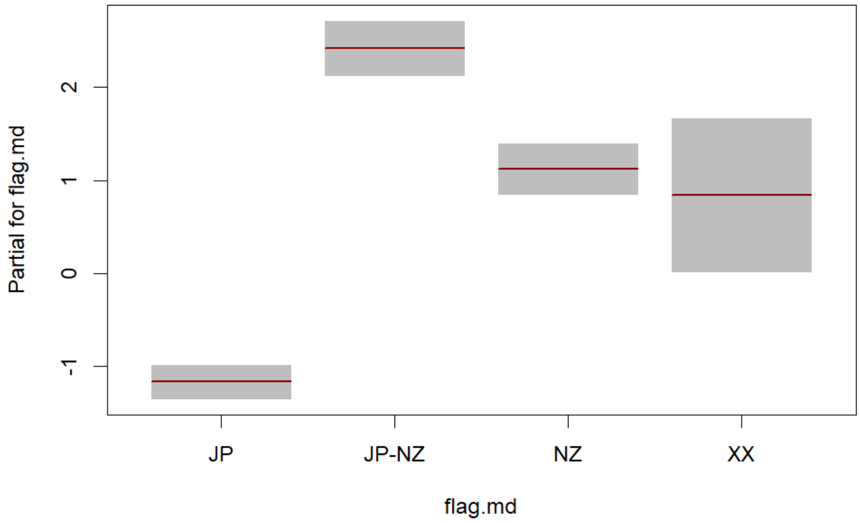


Figure 24 **Effect plot from the condition at-vessel model for 'all seabirds' in the south Pacific. Y-axis is the linear predictor, i.e. logit transformed probability of being alive at-vessel. All other flags were grouped in 'XX'.**

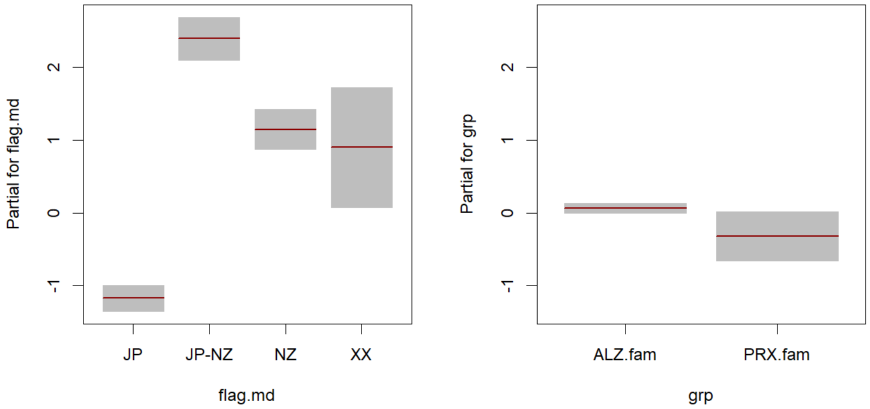


Figure 25 **Effect plot from the family level condition at-vessel model for the south Pacific. Y-axis is the linear predictor, i.e. logit transformed probability of being alive at-vessel. All other flags were grouped in 'XX'. 'ALZ.fam' refers to albatrosses (*Diomedeidae*) and 'PRX.fam' refers to petrels & shearwaters (*Procellariidae*).**