Agreement on the Conservation of Albatrosses and Petrels

Joint Twelfth Meeting of the Seabird Bycatch Working Group and Eighth Meeting of the Population and Conservation Status Working Group

Lima, Peru, 8 August 2024

Updated fisheries risk assessment framework for seabirds in the Southern Hemisphere

Edwards, C.T.T.; Peatman, T.; Roberts, J.O.; Devine, J.A.; Hoyle, S.D.

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SUMMARY

The Spatially Explicit Fisheries Risk Assessment (SEFRA) framework has been developed in New Zealand for quantitative assessment of the risk to a variety of megafauna, including seabirds. It uses spatial and temporal overlap between the distribution of seabirds and fishing effort to construct a measure of the opportunity for interaction. The relationship between this opportunity and actual captures is estimated using a regression, with observed captures providing the response variable and overlap providing the input covariate. The regression of captures onto overlap is described by an estimated term known as the catchability. This catchability can then be applied to the total overlap (from observed and unobserved fishing effort) to predict total captures. Captures are converted to death via a mortality multiplier, and this in turn is used to estimate the risk. Species for which the number of fishery related deaths exceeds capacity of the population to regenerate are considered to be at risk.

Many of the New Zealand endemic and indigenous seabird species are subject to incidental catch by fisheries outside the New Zealand Exclusive Economic Zone (EEZ). A comprehensive assessment of the risk therefore needs to include these global pressures. The current project represents the most recent published iteration of attempts to quantify the risk to New Zealand's seabirds in the entire Southern Hemisphere.

Compared with previous iterations, the most significant advance is that bottom longline and trawl effort data have been represented, rather than focusing on surface longline effort only. However, observer capture data were only available from within the New Zealand EEZ, meaning that catchability could only be estimated from a very small fraction of the possible captures. Because of regulated mitigation measures within the New Zealand EEZ, the application of this catchability to fishing effort globally is likely not representative of the global captures and risk.

RECOMMENDATIONS

We recommend that SBWG and PaCSWG:

1. note that future work to assess the impact of fisheries on seabirds needs to include observational data (that is at least representative) from fleets that overlap with assessed species to get an accurate estimate of catchability.
2. note that work is currently underway with CCSBT to estimate impact from member nations surface longline fisheries using observational data from Japan, New Zealand and Taiwan.
3. consider developing a guiding framework for the application of risk assessment approaches such as SEFRA and the inferences made from these analyses on the sustainability of seabird bycatch levels from fisheries.

Actualización del marco de evaluaciones de riesgo de pesquerías para las aves marinas en el hemisferio sur

RESUMEN

El marco de Evaluaciones de Riesgo de Pesquerías Espacialmente Explícito (SEFRA) se ha desarrollado en Nueva Zelanda para la evaluación cuantitativa del riesgo para una variedad de megafauna, incluidas las aves marinas. Utiliza la superposición espacial y temporal entre la distribución de las aves marinas y el esfuerzo pesquero para construir una medida de oportunidad de interacción. La relación entre esta oportunidad y las capturas reales se estima mediante una regresión, en la que las capturas observadas proporcionan la variable de respuesta y la superposición proporciona la covariable de entrada. La regresión de las capturas a la superposición se describe mediante un término estimado conocido como "capturabilidad". Esta capturabilidad se puede aplicar a la superposición total (del esfuerzo pesquero observado y no observado) para predecir las capturas totales. Las capturas se convierten en muertes a través de un multiplicador de mortalidad, que a su vez se utiliza para estimar el riesgo. Se consideran en riesgo las especies cuyo número de muertes relacionadas con pesquerías supera la capacidad de regeneración de la población.

Muchas de las especies de aves marinas endémicas y autóctonas de Nueva Zelanda son objeto de captura secundaria en pesquerías situadas fuera de la zona económica exclusiva (ZEE) de Nueva Zelanda. Por lo tanto, una evaluación exhaustiva del riesgo debe incluir estas presiones mundiales. El proyecto actual representa la iteración publicada más reciente de los intentos de cuantificar el riesgo para las aves marinas de Nueva Zelanda en todo el hemisferio sur.

En comparación con las iteraciones anteriores, el avance más significativo es que se han representado los datos sobre el esfuerzo del palangre de fondo y de la pesca de arrastre, en lugar de centrarse únicamente en el esfuerzo del palangre de superficie. Sin embargo, los datos de captura de observadores solo estaban disponibles dentro de la ZEE de Nueva Zelanda, lo que significa que la capturabilidad solo podía estimarse a partir de una fracción muy pequeña de las capturas posibles. Debido a las medidas de mitigación reguladas

dentro de la ZEE de Nueva Zelanda, es probable que la aplicación de esta capturabilidad al esfuerzo pesquero a nivel mundial no sea representativa de las capturas y el riesgo mundiales.

RECOMENDACIONES

Se recomienda al GdTCS y al GdTPEC realizar las siguientes acciones:

1. Tomar nota de que el trabajo futuro para evaluar el impacto de las pesquerías en las aves marinas debe incluir datos de observación (que sean al menos representativos) de flotas que se superpongan con las especies analizadas para obtener una estimación precisa de la capturabilidad.
2. Tomar nota de que actualmente se está trabajando con la CCSBT para estimar el impacto de las pesquerías con palangre de superficie de las naciones miembros utilizando datos de observación de Japón, Nueva Zelanda y Taiwán.
3. Considerar la posibilidad de elaborar un marco rector para la aplicación de enfoques de evaluaciones de riesgos como SEFRA y las inferencias extraídas de estos análisis sobre la sostenibilidad de los niveles de captura secundaría de aves marinas procedentes de las pesquerías.

Mise à jour du cadre d’évaluation des risques liés aux pêcheries pour les oiseaux de mer dans l’hémisphère Sud

RÉSUMÉ

Le cadre d’évaluation spatialement explicite des risques liés à la pêche (SEFRA) a été développé en Nouvelle-Zélande pour l’évaluation quantitative du risque pour différentes variétés de mégafaune, dont les oiseaux de mer. Il utilise le chevauchement spatial et temporel entre la répartition des oiseaux de mer et l’effort de pêche pour établir une mesure des occasions d’interaction. La relation entre ces occasions et les captures réelles est estimée à l’aide d’une régression, les captures observées fournissant la variable de réponse et le chevauchement fournissant la covariable d’entrée. La régression des captures avec le chevauchement est décrite par un terme estimé connu sous le nom de capturabilité. Cette capturabilité peut ensuite être appliquée au chevauchement total (avec l’effort de pêche observé et non observé) afin d’établir des prévisions en matière de captures totales. Les captures sont converties en décès via un multiplicateur de mortalité, qui est ensuite utilisé pour estimer le risque. Les espèces pour lesquelles le nombre de décès liés à la pêche dépasse la capacité de régénération de la population sont considérées comme étant en danger.

De nombreuses espèces d’oiseaux de mer endémiques et indigènes de Nouvelle-Zélande font l’objet de captures accidentelles par des pêcheries situées en dehors de la zone économique exclusive (ZEE) de la Nouvelle-Zélande. Toute évaluation complète du risque doit donc nécessairement prendre en compte ces pressions globales. Le projet actuel est la version la plus récente publiée des tentatives visant à quantifier le risque pour les oiseaux de mer de Nouvelle-Zélande dans l’ensemble de l’hémisphère sud.

Par rapport aux itérations précédentes, l'avancée la plus significative est que les données sur l'effort de pêche démersale à la palangre et au chalut ont été représentées, plutôt que de se concentrer uniquement sur l'effort de pêche à la palangre de surface. Les données de capture des observateurs n'étaient cependant disponibles que dans la ZEE de la Nouvelle-Zélande : la capturabilité n'a donc pu être estimée qu'à partir d'une très petite fraction des captures possibles. En raison de la réglementation en matière de mesures d'atténuation dans la ZEE de la Nouvelle-Zélande, l'application de cette capturabilité à l'effort de pêche à l'échelle mondiale n'est probablement pas représentative des captures et des risques mondiaux.

RECOMMANDATIONS

Nous recommandons que le GTCA et le GTSPC :

1. notent que les travaux futurs visant à évaluer l'impact des pêcheries sur les oiseaux de mer doivent inclure des données d'observation (au moins représentatives) provenant de flottes en chevauchement avec les espèces évaluées afin d'obtenir une estimation précise de la capturabilité.
2. notent que des travaux sont en cours avec la CCSBT pour estimer l'impact des pêcheries palangrières de surface des pays membres à l'aide de données d'observation provenant du Japon, de la Nouvelle-Zélande et de Taïwan.
3. envisagent d'élaborer un cadre directeur pour l'application d'approches d'évaluation des risques comme le SERFA et les déductions tirées de ces analyses sur la durabilité des niveaux de captures accessoires d'oiseaux de mer liées aux pêcheries.

Fisheries New Zealand

Updated sheries risk assessment framework for seabirds in the Southern Hemisphere

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EXECUTIVE SUMMARY

Edwards, C.T.T.[1]; Peatman, T.[2]; Roberts, J.O.[3]; Devine, J.A.[4]; Hoyle, S.D.[4] (2023).
Updated fisheries risk assessment framework for seabirds in the Southern Hemisphere.

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The Spatially Explicit Fisheries Risk Assessment (SEFRA) framework has been developed in New Zealand for quantitative assessment of the risk to a variety of megafauna, including seabirds. It uses spatial and temporal overlap between the distribution of seabirds and fishing effort to construct a measure of the opportunity for interaction. The relationship between this opportunity and actual captures is estimated using a regression, with observed captures providing the response variable and overlap providing the input covariate. The regression of captures onto overlap is described by an estimated term known as the catchability. This catchability can then be applied to the total overlap (from observed and unobserved fishing effort) to predict total captures. Captures are converted to death via a mortality multiplier, and this in turn is used to estimate the risk. Species for which the number of fishery related deaths exceeds capacity of the population to regenerate are considered to be at risk.

Many of the New Zealand endemic and indigenous seabird species are subject to incidental catch by fisheries outside the New Zealand Exclusive Economic Zone (EEZ). A comprehensive assessment of the risk therefore needs to include these global pressures. The current project represents the most recent iteration of attempts to quantify the risk to New Zealand's seabirds in the entire Southern Hemisphere. In order to expand its relevance, species of interest to the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) and the Agreement on the Conservation of Albatrosses and Petrels (ACAP) have also been included.

Compared with previous iterations, the most significant advance is that bottom longline and trawl effort data have been represented, rather than focusing on surface longline effort only. However, observer capture data were only available from within the New Zealand EEZ, meaning that catchability could only be estimated from a very small fraction of the possible captures. Because of strong mitigation measures within the New Zealand EEZ, the application of this catchability to fishing effort globally is likely not representative of the global captures and risk. The results presented here should therefore only be considered preliminary. Given this caveat, the current project identifies Westland petrel (Procellaria westlandica), White-chinned petrel (Procellaria aequinoctialis), New Zealand white-capped albatross (Thalassarche cauta steadi), Southern Buller's albatross (Thalassarche bulleri bulleri), Salvin's albatross (Thalassarche salvini), Northern royal albatross (Diomedea sanfordi), and Amsterdam albatross (Diomedea amsterdamensis), as the species at highest risk.

A number of other features of the SEFRA framework have been updated, based on recent updates to the domestic seabird risk assessment. They are described here with the intention of providing a foundation for future work.

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1. INTRODUCTION

A Spatially Explicit Fisheries Risk Assessment (SEFRA) framework is used in New Zealand to estimate the risk to seabirds (and other protected species) from commercial fishing (Sharp 2019). The approach is designed to accommodate multiple species and fisheries simultaneously, constructing risk profiles as a function of spatial and temporal overlap. Application has been primarily within the New Zealand Exclusive Economic Zone (EEZ; e.g., Richard & Abraham 2015, Richard et al. 2017, 2020), but, since seabirds migrate widely across the southern hemisphere, a comprehensive assessment of the fisheries risk needs to account for all the fishing effort that may be encountered as they move through international waters. This has motivated application of the method in this wider context.

This paper presents an update to the approach of Abraham et al. (2019), itself based on previous work by Abraham et al. (2017) and Waugh et al. (e.g., Waugh et al. 2008a,b, 2013, 2015) extending the New Zealand risk assessment beyond the EEZ into international waters. In so doing it has included other species not resident in New Zealand. Previous work has concentrated on bird captures by tuna surface longline fisheries, and we have further developed the approach by also including global bottom longline and trawl fisheries. However, in contrast to previous work, observer capture data were only available from within the New Zealand EEZ. No capture data from high-seas fisheries were available, but could be included in future iterations of the work.

2. METHODOLOGY

The SEFRA approach implements a quantitative risk assessment framework in which both the susceptibility of a population to anthropogenic mortality and the productivity of the population are combined to estimate risk. From this definition, it shares conceptual similarities with Productivity Susceptibility Analyses (PSA; e.g., Hobday et al. 2011) and is similarly designed to estimate an instantaneous measure of current risk, rather than changes in the population over time. However, whereas PSA analyses are qualitative, SEFRA attempts a quantitative assessment. By using strongly informed priors on model parameters and integrating over catches and known biological information from multiple species and fisheries simultaneously, SEFRA generates an estimate of seabird deaths. This is then compared with a limit reference point that approximates the number of deaths that the population can sustain whilst meeting management objectives. Using SEFRA terminology, this reference point is referred to as the Population Sustainability Threshold (PST; Sharp 2019).

The SEFRA approach is quasi-spatial, in the sense that spatial overlap of the population and fishing effort are used to construct a covariate input into the model. Parameterisation of the capture rate per unit of overlap occurs via a fit to fisheries observer capture data, and total captures are calculated by multiplication of the total overlap (including the unobserved component) with this estimated rate (referred to as the catchability). Deaths are calculated from the predicted captures using a mortality multiplier that accounts for the probability of dead capture and cryptic mortality.

Following estimation of the total deaths, the risk ratio per species is:

$$\text{Risk Ratio}_s = \frac{\text{Total deaths}_s}{\text{PST}_s}$$

The risk is represented as a probability:

$$\text{Risk}_s = P[\text{Risk Ratio}_s > 1]$$

which is equal to the probability that deaths exceed the PST. A management objective for protected species is typically formulated as a requirement that risk should not exceed a pre-specified value. For example, the PST may be set at a level considered to be consistent with recovery of the population to a certain level, within a certain time frame, and the management objective could state that the risk of exceeding this level should be less than, say, 5%. In this case we could write:

$$\text{Management Objective}_s = P[\text{Risk Ratio}_s > 1] < 0.05$$

The PST is a function of both the population size and productivity and can be tuned using the parameter f so as to be consistent with the desired management outcome:

$$PST_s = f \quad r_s \; \frac{1}{2} \; N_s$$

where r_s is the maximum intrinsic population growth rate (i.e., under optimal conditions and in the absence of density dependent contraints), and N_s is the total population size, which we assume in the current setting to be the total number of adults. The Potential Biological Removal (PBR) of Wade (1998) and Moore et al. (2013) is numerically equivalent to the PST, with the exception that the PBR uses a minimum point quantile of the population size, and a point estimate of the maximum growth rate, whereas the PST includes uncertainty in both values. The PST further excludes the recovery factor, replacing it with a more generic term f (Sharp 2019).

3. DATA

Biological data were compiled and reviewed by earlier projects, specifically Peatman et al. (2023) for New Zealand species and Abraham et al. (2017) for non-New Zealand species. These were supplemented by additional data in the current work: the biological inputs for non-New Zealand species were reviewed and updated where necessary, and new maps of the biological species distributions were generated (Devine et al. In press).

Biological inputs are included in the modelling framework with and without uncertainty. Number and rate parameters are represented as distributions, referred to as priors because the parameters themselves are estimated, despite there being limited information with which they can be updated during the model fit. The model also includes fixed data inputs that are treated as point estimates since they include no uncertainty. These describe the spatial availability of birds to fishing, most importantly the spatial density distribution, but also the probabilities of being in the southern hemisphere or away from the nest when breeding and therefore vulnerable to the fishing effort being considered.

To fit the model, we used observer data from New Zealand commercial fisheries for the calendar years 2006 to 2020, this being a period of reasonably consistent observer data collection. The use of calendar years, rather than fishing years, facilitates the inclusion of fisheries capture and effort data from jurisdictions outside of New Zealand. We calculated the overlap between observer fishing effort and the biological population and estimated the relationship between this overlap and the number of captures. This capture rate per unit of overlap is referred to as the catchability, and it allows us to predict the total captures across the unobserved portion of the fishing effort. Precise definition of these terms is given in Section 4. Not all captures are dead, and not all dead birds are caught. We therefore construct a *mortality multiplier* to account for the probability of death at capture, and cryptic deaths that may not be observable even with an observer present. These multipliers are used to scale up the predicted captures to the predicted deaths.

The model requires structural assumptions that concern the grouping of bird species and fishing effort. This is necessary so that information can be shared across members of each group when estimating the catchability $q_{f;z}$, which is specific to the fishery f and species group z. Species were grouped according to their behaviour and assumed vulnerability to fishing, which may be a function of their feeding behaviour, their willingness to travel large distances to a fishing vessel, and their aggression when there. The list of species assessed, along with their catchability grouping, is given in Table 1.

Fishery groups were defined according to their perceived risk to birds and are dependent on the available covariate data associated with the effort. Devine et al. (In press) collated effort data from Regional Fisheries Management Organisations (RFMOs) in the southern hemisphere (Table 2), as well as the Global Fishing Watch (GFW) database. The GFW data were used to supplement the RFMO data because they provided a near continuous global effort layer. Covariates that could be used to define fishery groups include: RFMO, method, and target. At present groups are based on the fishing method only, namely bottom longline (BLL), surface longline (SLL), and trawl. Squid jig effort was available for use but excluded as no capture data could be sourced for this method.

Table 1: Species and catchability groups used in the southern hemisphere risk assessment model. Species codes are from the FAO-ASFIS species list (https://www.fao.org/fishery/en/species/search).

Species code	Common name	Scientific name	Catchability group
DIW	Gibson’s albatross	Diomedea antipodensis gibsoni	Wandering albatross
DQS	Antipodean albatross	Diomedea antipodensis antipodensis	Wandering albatross
DIX	Wandering albatross	Diomedea exulans	Wandering albatross
DBN	Tristan albatross	Diomedea dabbenena	Wandering albatross
DAM	Amsterdam albatross	Diomedea amsterdamensis	Wandering albatross
DIP	Southern royal albatross	Diomedea epomophora	Royal albatross
DIQ	Northern royal albatross	Diomedea sanfordi	Royal albatross
DCR	Atlantic yellow-nosed albatross	Thalassarche chlororhynchos	Small albatross
TQH	Indian yellow-nosed albatross	Thalassarche carteri	Small albatross
DIM	Black-browed albatross	Thalassarche melanophris	Small albatross
TQW	Campbell black-browed albatross	Thalassarche impavida	Small albatross
DCU	Shy albatross	Thalassarche cauta	Small albatross
TWD	New Zealand white-capped albatross	Thalassarche cauta steadi	Small albatross
DKS	Salvin’s albatross	Thalassarche salvini	Small albatross
DER	Chatham Island albatross	Thalassarche eremita	Small albatross
DIC	Grey-headed albatross	Thalassarche chrysostoma	Small albatross
DIB	Southern Buller’s albatross	Thalassarche bulleri bulleri	Small albatross
DNB	Northern Buller’s albatross	Thalassarche bulleri platei	Small albatross
PHU	Sooty albatross	Phoebetria fusca	Sooty albatross
PHE	Light-mantled sooty albatross	Phoebetria palpebrata	Sooty albatross
MAI	Southern giant petrel	Macronectes giganteus	Large petrel
MAH	Northern giant petrel	Macronectes halli	Large petrel
PCI	Grey petrel	Procellaria cinerea	Medium petrel
PRK	Black petrel	Procellaria parkinsoni	Medium petrel
PCW	Westland petrel	Procellaria westlandica	Medium petrel
PRO	White-chinned petrel	Procellaria aequinoctialis	Medium petrel
PCN	Spectacled petrel	Procellaria conspicillata	Medium petrel

Table 2: Regional Fishery Management Organisations (RFMOs) that have provided shing effort data to Devine et al. (In press). Fishing methods were: surface longline (SLL); bottom longline (BLL); and trawl. These data were augmented by data from the Global Fishing Watch database (global shingwatch.org), which included effort from all methods. Data from the South East Atlantic Fisheries Organisation (SEAFO) were requested but not made available for the current project.

RFMO		Fishing method
CCSBT	Commission for the Conservation of Southern Blue n Tuna	SLL
IATTC	Inter-American Tropical Tuna Commission	SLL
ICCAT	International Commission for the Conservation of Atlantic Tunas	SLL
IOTC	Indian Ocean Tuna Commission	SLL
WCPFC	Western and Central Paci c Fisheries Commission	SLL
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources	Trawl; BLL
SIOFA	Southern Indian Ocean Fisheries Agreement	Trawl; BLL
SPRFMO	South Paci c Regional Fisheries Management Organisation	Trawl; BLL

With reference to the glossary of terms listed in Table 3, the key SEFRA data inputs can be summarised as follows:

- Biological demographic parameters: optimum adult survivorship (S_s^{opt}) and the current age at rst breeding (A_s^{curr}) are used to estimate the maximum intrinsic growth rate (r_s) under current environmental conditions from allometric relationships;

- Population size: the number of breeding pairs (N_s^{BP}), summed across all colonies in the southern hemisphere, and the probability of breeding (P_s^{B}), are used to estimate the adult population size, which is combined with r_s to calculate the PST;

- Population distribution: the relative number of birds in grid cell x for each month m of the year is used to calculate $d_{s;m;x}$;

- Fixed biological inputs: for each species the model requires the probability that birds are within the spatial domain of southern hemisphere sheries (P_s^{SH}) and the probability of being on the nest (P_s^{nest}), which are used to scale the number of adult birds that are available to shing gear;

- Fishing effort: for each shing group f, the cumulative shing effort ($e_{f;m;x}$) is multiplied by $d_{s;m;x}$ and the number of available adult birds and summed across x and m to calculate the density overlap ($O_{f;s}$), which provides an input model covariate assumed to be related to the spatial and temporal overlap of shing with the bird population;

- Captures: the observed captures ($C^o_{f;s}$), summed over space, are used to t the model, allowing it to subsequently predict total observable captures as a function of the catchability $q_{f;z}$ and total overlap $O_{f;s}$;

- Mortality: a multiplier $k_{f;z}$ is used to convert model predicted captures into deaths on the assumption that some birds are observed dead at capture, that overall only a fraction of the captures are recorded, and that the realised number of deaths per capture is higher than that estimated from observer data.

The approach therefore integrates over a large amount of information to summarise a complicated system of interactions and captures. It is, however, forgiving in that it can be easily scaled to the data available: approximate inputs can be accommodated when few data are available; and will become more reliable as more or better data are added. In the current work we use observed capture and effort data from within the New Zealand EEZ to estimate the catchabilities, and global effort across the southern hemisphere, with which we estimate total captures and deaths.

4. METHODS

4.1 Numbers available to fishing

The number of adults per species (s) is defined using the number of breeding pairs summed across all colonies globally, and the probability of breeding:

$$N_s^{adults} = 2 \frac{N_s^{BP}}{P_s^B} \tag{1}$$

The number of adults available to fishing gear during any month of the year is determined by the probability that they are in the southern hemisphere (SH), the probability that they are breeding, and whether they are likely to be attending the nest whilst doing so. The number of available adults per species and month (m) is:

$$N_{s,m} = N_s^{adults} \left(1 - P_s^B P_{s,m}^{nest}\right) P_{s,m}^{SH} \tag{2}$$

Outside the breeding season, $P_{s,m}^{nest} = 0$, and all adults are available to fishing gear.

Table 3: Summary of model terms. See also Edwards et al. (2023a) and Peatman et al. (2023).

Notation	Description
Subscripts	
f	Fishing group
s	Species
z	Species group
m	Month
x	Raster grid cell
Estimated parameters	
N_s^{BP}	Number of breeding pairs
P_s^{B}	Annual probability of breeding
S_s^{opt}	Annual optimum survivorship
A_s^{curr}	Current age at first breeding
$b_f, b_f, b_{z\|f}$	Catchability coefficients
$g_0; g_f, g_z$	Survivorship coefficients
p_z^{net}	Probability of net capture
Derived parameters	
N_s^{adults}	Total number of adults
$N_{s;m}$	Number of adults available to fishing
S_s^{A}	Survivorship to A_s^{curr}
$D_{s;m;x}$	Density of adults available to fishing
$q_{f;z}$	Catchabilty
$u_{f;z}$	Vulnerability
$Y_{f;z}$	Probability alive given capture
$T_{f;s}$	Number of interactions
$C_{f;s}$	Number of observable captures
Input covariates	
$P_{s;m}^{SH}$	Probability of an adult being in the southern hemisphere
$P_{s;m}^{nest}$	Probability of a breeding adult being on the nest
$d_{s;m;x}$	Relative density of adults per square kilometre
$a_{f;m;x}$	Fishing effort
$K_{f;z}$	Capture multiplier
$k_{f;z}$	Mortality multiplier
w	Probability of post-release survivorship
Derived covariates	
$O_{f;s}$	Density overlap
Observational data	
$C_{f;s}^{0}$	Number of observed captures
$C_{f;s}^{LIVE\,0}, C_{f;s}^{DEAD\,0}$	Number of observed live and dead captures
$C_{f;s}^{NET\,0}, C_{f;s}^{WARP\,0}$	Number of observed net and warp captures

4.2 Spatial distribution and overlap

The spatial distribution of the species is treated as a fixed data input and described using a density term $d_{s;m;x}$, which is derived from the number of individuals of species s within grid cell x in month m. Specifically, if $y_{s;m;x}$ is the number of birds in grid cell x, then:

$$d_{s;m;x} = \frac{y_{s;m;x}}{A_x \sum_x y_{s;m;x}} \tag{3}$$

The value $y_{s;m;x} / \sum_x y_{s;m;x}$ is treated as the multinomial sampling probability of an individual being in grid cell x during that month. The absolute density, in number of birds per square kilometre, is therefore:

$$D_{s;m;x} = d_{s;m;x} \times N_{s;m} \tag{4}$$

If fishing effort for each fishery group f is allocated to grid cell x, and assuming a uniform distribution of birds and fishing effort within that cell, then we can construct an overlap metric that measures the opportunity for interaction between a bird population and fishing effort:

$$\text{overlap}_{f;s;m;x} = \underbrace{\text{effort}_{f;m;x}}_{a_{f;m;x}} \times d_{s;m;x} \tag{5}$$

The overlap is analogous to the fishing exposure index of Queiroz et al. (2019) and provides a measure of the relative exposure of a bird population to fishing effort. A naive application of this metric, for example, by assuming exposure is equally proportional to captures across species and fishing fleets, allows relative risk to be quantified. However, SEFRA includes estimation of the different catchabilties between fleets and bird species. This requires the density overlap:

$$\underbrace{\text{density overlap}_{f;s}}_{O_{f;s}} = \sum_{m;x} a_{f;m;x} \times D_{s;m;x} \tag{6}$$

for which we introduce the notation $O_{f;s}$ and $a_{f;m;x}$ (Sharp 2019).

4.3 Expected captures

The rate of interaction per unit of density overlap is described by the vulnerability $u_{f;z}$, which is defined at the level of the fishing group f and species s (see catchability groups in Table 1). The total number of interactions per fishery group and species is expected to be:

$$\underbrace{\text{interactions}_{f;s}}_{T_{f;s}} = u_{f;z} \times O_{f;s} \tag{7}$$

Some interactions lead to captures that are observable, and for this we require the catchability ($q_{f;z}$):

$$\underbrace{\text{observable captures}_{f;s}}_{C_{f;s}} = q_{f;z} \times O_{f;s} \tag{8}$$

The probability of surviving capture is defined using the parameter $Y_{f;z}$. Specifically, the probability of a capture being dead is $1 - Y_{f;z}$, which can be used to predict the number of dead captures:

$$\underbrace{\text{dead captures}_{f;s}}_{C^{\text{DEAD}}_{f;s}} = C_{f;s} \times (1 - Y_{f;z}) \tag{9}$$

The number of live captures is $C^{\text{LIVE}}_{f;s}$.

Finally, we introduce the prime notation to indicate something that has been observed. The observed fishing effort $a'_{f,m,x}$ and observed density overlap $O'_{f,s}$ are used to calculate the expected number of observed captures:

$$\underbrace{\text{observed captures}_{f,s}}_{C'_{f,s}} = q_{f,z} \, O'_{f,s} \qquad (10)$$

Similarly the number of observed dead and live captures are $C^{DEAD'}_{f,s}$ and $C^{LIVE'}_{f,s}$, respectively.

4.4 Regression equations

The model is fitted to the observed number of captures and deaths. If $C'_{f,s}$ is the observed number of captures for fishery group f and species, then the expectation is:

$$m_{f,s} = q_{f,z} \, O'_{f,s}$$

and the likelihood is abbreviated as:

$$C'_{f,s} \sim \text{Poisson}(m_{f,s})$$

The probability of live capture is included as a separate likelihood, using the number of live captures. Because $C^{LIVE'}_{f,s} + C^{DEAD'}_{f,s} = C'_{f,s}$, we can write:

$$C^{LIVE'}_{f,s} \sim \text{Binomial}(C'_{f,s}, Y_{f,z})$$

For the trawl fishery, we also distinguish between net and warp captures. In this case $C^{NET'}_{f,s} + C^{WARP'}_{f,s} \leq C'_{f,s}$, as some trawl captures have no information on where the capture occurred, and therefore:

$$C^{NET'}_{f,s} \sim \text{Binomial}(C^{NET'}_{f,s} + C^{WARP'}_{f,s}, p^{net}_{z})$$

The probability of being a live capture is conditional on it being a net capture: $Y_{f,z} = Y^{net}_{f,z} \, p^{net}_{z}$, because all warp captures are assumed to be dead, i.e., $Y^{warp}_{f,z} = 0$.

The catchability itself is a function of fishery group (f) and species group (z) covariates:

$$\log(q_{f,z}) = b_0 + b_f + b_{z|f} \qquad (11)$$

where the fishery group coefficient b_f is centred on the intercept term, with deviations around this intercept constrained to sum to zero. Species group coefficients ($b_{z|f}$) were specific to the fishery group and were similarly constrained to sum to zero. This allowed the catchability per species group to deviate from the fishery group effect in a fishery group-specific manner.

The probability of live captures is:

$$\text{logit}(Y_{f,z}) = g_0 + g_f + g_z \qquad (12)$$

where g_0 is an intercept term and with coefficients g_f and g_z similarly constrained to sum to zero.

4.5 Prediction of total interactions and deaths

During the fitting process we estimate the catchability $q_{f,z}$, which describes the rate of observed capture per unit of density overlap. If the presence of an observer does not influence the capture rate then $q_{f,z}$ is also the the rate of observable capture for unobserved effort.

The vulnerability describes the rate of interaction per unit of density overlap. Captures are a subset of the interactions. A different but partially overlapping subset of these interactions will be deaths. Not all deaths will be observable because they can be cryptic (unobservable even where an observer present). The relationship between captures, interactions, and deaths is described by Edwards et al. (2023a) with reference to the data used to estimate the cryptic multipliers. Here we summarise how these multipliers are used following prediction of O from a fit to the data.

To predict interactions based on the number of captures, we need a capture multiplier, $K_{f;z}$, that accounts for the fact that not all captures are observable. The interaction equation is:

$$
\begin{aligned}
T_{f;s} &= u_{f;z} \, O_{f;s} \\
&= q_{f;z} \, O_{f;s} \, K_{f;z}
\end{aligned}
\tag{13}
$$

Typically, whether a bird has died as a result of interaction with the fishery will influence how likely it is to be observed. The estimated probability of live capture $Y_{f;z}$ therefore forms part of the derivation of $K_{f;z}$ (see below).

To predict deaths from captures we use the mortality multiplier $k_{f;z}$. Since deaths are a subset of interactions $k_{f;z} \leq K_{f;z}$. In general the number of deaths is:

$$
D_{f;s} = q_{f;z} \, O_{f;s} \, k_{f;z} \tag{14}
$$

The mortality multiplier specifically relates the number of predicted observable captures to the number of deaths. It includes observable dead captures, the rate of cryptic capture per observable capture, and the probability that these cryptic captures lead to death (cryptic mortality). It also includes the death of live captures post-release.

An important part of the derivation of $K_{f;z}$ and $k_{f;z}$ involves the specification of cryptic multipliers for different fishery groups and capture types, which we summarise here. Cryptic mortality groups and associated input values per species are listed in Table 4. Cryptic capture groups have been defined according to the data used to estimate these multipliers. Net capture probabilities were estimated per cryptic capture group, because of the relevance of net captures to the rate of cryptic capture, with net captures having a much lower cryptic capture rate than warp captures. Cryptic capture rates are usually defined in the literature with reference to unobservable death (cryptic mortality), and we are therefore also reliant on the estimated parameter $Y_{f;z}$ in our derivations, to distinguish birds that are caught alive. We further assume a probability w to account for the post-release death for a live capture, and include these deaths in the mortality multiplier.

For the longline fisheries (SLL and BLL), we assume that captures at haul-back are observed and alive, and that captures at setting are all dead and lost at a rate of $k^{longline}$ (Table 4). We use $k^{longline}$ to calculate the total interactions and deaths as:

$$
T_{f;s} = q_{f;z} \, O_{f;s} \, \underbrace{\left(Y_{f;z} + (1 - Y_{f;z}) \, k^{longline}\right)}_{K_{f;z}} \tag{15}
$$

$$
D_{f;s} = q_{f;z} \, O_{f;s} \, \underbrace{\left(Y_{f;z} \, (1 - w) + (1 - Y_{f;z}) \, k^{longline}\right)}_{k_{f;z}} \tag{16}
$$

For the trawl fishery, we similarly have alive and dead captures, in this case split between net captures and warp captures. We assume the same k^{net} value for all net captures, both alive and dead:

$$
T^{net}_{f;s} = q_{f;z} \, O_{f;s} \, p^{net}_{z} \, k^{net} \tag{17}
$$

For warp captures, which take place with estimated probability $1 - p_z^{net}$, all captures are dead. However, birds may interact with the warps and not be caught and still die, either through aerial collisions or surface strikes. In this case the multipliers are species group-specific, with subscript z:

$$T_{f;s}^{warp} = q_{f;z} \, O_{f;s} \, (1 - p_z^{net}) \, k_z^{warp} \qquad (18)$$

For the trawl fishery overall, the summation is:

$$T_{f;s} = q_{f;z} \, O_{f;s} \, p_z^{net} \, k^{net} + (1 - p_z^{net}) \, k_z^{warp} \qquad (19)$$

and the deaths are:

$$D_{f;s} = q_{f;z} \, O_{f;s} \, p_z^{net} \, k^{net} \, (1 - \Psi_{f;z}^{net} \, w) + (1 - p_z^{net}) \, k_z^{warp}$$

All deaths were generated using posterior predictive simulation from a Poisson distribution conditioned on the expected value. The number of total deaths per species is a summation of the deaths across the fishery group:

$$D_s = \sum_f D_{f;s} \qquad (20)$$

This is compared with the PST_s to calculate the species-specific risk.

Table 4: Cryptic mortality multipliers for longline ($k^{longline}$), net (k^{net}) and warp (k_z^{warp}) captures. Cryptic multipliers were estimated externally and provided to the model as distributions (Edwards et al. 2023a). The mortality multiplier $k_{f;z}$ is a function of the probability of live capture $Y_{f;z}$ and the probabilty of net capture p_z^{net} (Section 4.5). Estimates of $k_{f;z}$ are illustrated in Figure 12.

			$k^{longline}$		k^{net}		k_z^{warp}		p_z^{net}	
Code	Common name	Cryptic group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
DIW	Gibson's albatross	Large seabirds	1.44	[0.97,2.07]	1.30	[1.10,1.69]	21.25	[13.53,31.60]	0.70	[0.68,0.72]
DQS	Antipodean albatross	Large seabirds	1.42	[0.98,1.97]	1.30	[1.11,1.68]	21.31	[13.71,31.90]	0.70	[0.68,0.72]
DIX	Wandering albatross	Large seabirds	1.41	[0.97,2.00]	1.30	[1.10,1.67]	21.12	[13.46,30.79]	0.70	[0.68,0.72]
DBN	Tristan albatross	Large seabirds	1.42	[0.98,1.96]	1.30	[1.10,1.71]	21.21	[13.51,31.79]	0.70	[0.68,0.72]
DAM	Amsterdam albatross	Large seabirds	1.42	[1.00,2.03]	1.30	[1.11,1.69]	21.19	[13.63,31.99]	0.70	[0.68,0.72]
DIP	Southern royal albatross	Large seabirds	1.43	[0.98,2.05]	1.30	[1.10,1.67]	21.29	[13.67,32.03]	0.70	[0.68,0.72]
DIQ	Northern royal albatross	Large seabirds	1.42	[0.96,2.04]	1.30	[1.09,1.67]	21.34	[13.52,32.99]	0.70	[0.68,0.72]
DCR	Atlantic yellow-nosed albatross	Large seabirds	1.43	[0.97,2.06]	1.30	[1.11,1.66]	21.12	[13.51,31.20]	0.70	[0.68,0.72]
TQH	Indian yellow-nosed albatross	Large seabirds	1.41	[0.97,2.03]	1.30	[1.10,1.65]	21.36	[13.43,32.67]	0.70	[0.68,0.72]
DIM	Black-browed albatross	Large seabirds	1.42	[0.95,2.00]	1.30	[1.10,1.73]	21.02	[13.51,31.58]	0.70	[0.68,0.72]
TQW	Campbell black-browed albatross	Large seabirds	1.42	[1.01,2.01]	1.30	[1.10,1.71]	21.50	[13.74,31.78]	0.70	[0.68,0.72]
DCU	Shy albatross	Large seabirds	1.42	[0.98,1.99]	1.30	[1.10,1.70]	21.17	[13.76,31.90]	0.70	[0.68,0.72]
TWD	New Zealand white-capped albatross	Large seabirds	1.42	[0.98,2.03]	1.30	[1.10,1.67]	20.99	[13.59,31.44]	0.70	[0.68,0.72]
DKS	Salvin's albatross	Large seabirds	1.41	[0.95,2.06]	1.30	[1.10,1.72]	21.07	[13.85,30.97]	0.70	[0.68,0.72]
DER	Chatham Island albatross	Large seabirds	1.42	[0.99,1.98]	1.30	[1.09,1.69]	21.27	[13.56,32.53]	0.70	[0.68,0.72]
DIC	Grey-headed albatross	Large seabirds	1.41	[0.98,2.01]	1.30	[1.10,1.72]	21.30	[13.41,30.88]	0.70	[0.68,0.72]
DIB	Southern Buller's albatross	Large seabirds	1.41	[0.95,2.00]	1.30	[1.09,1.68]	21.22	[13.75,31.27]	0.70	[0.68,0.72]
DNB	Northern Buller's albatross	Large seabirds	1.41	[0.98,1.97]	1.31	[1.10,1.73]	21.06	[13.73,32.58]	0.70	[0.68,0.72]
PHU	Sooty albatross	Large seabirds	1.41	[0.96,2.03]	1.29	[1.10,1.68]	21.21	[13.80,31.95]	0.70	[0.68,0.72]
PHE	Light-mantled sooty albatross	Large seabirds	1.42	[0.98,1.97]	1.30	[1.10,1.66]	20.93	[13.62,31.73]	0.70	[0.68,0.72]
MAI	Southern giant petrel	Large seabirds	1.42	[0.96,1.98]	1.30	[1.10,1.73]	21.20	[13.83,31.70]	0.70	[0.68,0.72]
MAH	Northern giant petrel	Large seabirds	1.43	[0.98,2.03]	1.29	[1.10,1.68]	20.95	[13.55,31.26]	0.70	[0.68,0.72]
PCI	Grey petrel	Medium seabirds	1.43	[0.96,2.07]	1.30	[1.10,1.76]	182.33	[60.67,451.44]	0.99	[0.99,1.00]
PRK	Black petrel	Medium seabirds	1.42	[0.95,2.00]	1.30	[1.10,1.68]	183.31	[60.71,424.38]	0.99	[0.99,1.00]
PCW	Westland petrel	Medium seabirds	1.44	[0.96,1.99]	1.30	[1.10,1.72]	188.88	[63.10,427.30]	0.99	[0.99,1.00]
PRO	White-chinned petrel	Medium seabirds	1.43	[0.98,2.07]	1.29	[1.09,1.67]	178.67	[54.16,421.83]	0.99	[0.99,1.00]
PCN	Spectacled petrel	Medium seabirds	1.41	[0.97,2.02]	1.29	[1.10,1.70]	182.15	[61.12,424.19]	0.99	[0.99,1.00]

4.6 Derivation of PST reference points

Given the adult population size, which is specified as a prior distribution for each species, for the PST we are required to estimate an accompanying distribution for $r_s = \ln(\lambda_s)$. This was achieved using allometric theory as follows. Mean generation time is first approximated as:

$$\bar{T} = A + \frac{S}{\lambda - S}$$

Allometric theory defines the optimal generation time such that:

$$T_{[opt]} \ln(\lambda) = k$$

where $k \approx 1$ is a constant. Therefore under constant fecundity and assumed optimal conditions we can write:

$$\frac{k}{\ln(\lambda)} = A + \frac{S^{opt}}{\lambda - S^{opt}}$$

$$\Rightarrow \quad \lambda = \exp\left(k\left(A + \frac{S^{opt}}{\lambda - S^{opt}}\right)^{-1}\right)$$

which must be solved numerically. This provides the so-called demographic-invariant solution for λ (Niel & Lebreton 2005) that has been used for applications of the SEFRA methodology to date (e.g., Abraham et al. 2017).

We assume that we have information on the optimum survivorship (S_s^{opt}) and use the current age at first breeding (A_s^{curr}) as indicative of the current environmental conditions. These are estimated parameters within the model, each with strongly informed priors. Priors are listed in Appendix A and per species in Appendix B.

4.7 Parameter estimation

All estimation was performed within a Bayesian framework using rstan (Stan Development Team 2020). Two chains were run for 4000 iterations each, with the first half discarded. Posterior samples from estimated parameters were inspected visually to ensure convergence of the model. All biological parameters were treated as estimable: N_s^{BP}, P_s^B, S_s^{opt}, A_s^{curr}; with strongly informed priors. Predictor coefficients for the catchability (b_f and b_{zjf}; Equation 11) and post-capture survival (g_f and g_z; Equation 12) were given standard normal priors. The intercept terms b_0 and g_0, as well as the probability of a net capture (p_z^{net}), were given improper uninformative priors.

4.8 Risk assessment inputs

Structural groupings for the species groups are given in Table 1. Biological fixed data inputs are listed in Appendix A, and priors for estimated parameters per species are listed in Appendix A. The spatial distributions per species per month were developed by Devine et al. (In press) and are provided here in Appendix B.

Fishing groups were specified according to the different fishing methods considered: BLL, SLL, and trawl. When estimating the catchabilities, we used catch and effort data collected from within the New Zealand EEZ and reported to Fisheries New Zealand, Wellington, New Zealand. These data have been reviewed in detail by Edwards et al. (2023a). Observed captures per species group and fishery group are illustrated in Figure 1 and listed in Table 5. There are no noticeable changes over time in the number of captures. However, there are clear differences in the number of captures per shing method. Trawl captures predominate, particularly for small albatross and medium petrels. Longline catches are fewer, with SLL catching more of the larger albatross (wandering and royal albatrosses) and BLL catching more petrels.

Global shing effort data for the different groups were collected from the different RFMOs by Devine et al. (In press). Effort values per year and shing method are listed in Tables 6 to 8, with their spatial distributions summarised in Figure 2. These global effort layers do not include effort reported to Fisheries New Zealand, although some RFMO effort data will be from vessels operating within the New Zealand EEZ, particularly for the SLL sheries.

Finally, observed captures and dead captures per species and method are listed in Tables 9 and 10, respectively, and overlap, which provides a covariate for the model t and prediction of captures, is listed in Tables 11 and 12. These overlap values are calculated using Equation 5. Spatial overlap between the species distribution and global shing effort is given graphically per species in Appendix C. Overlap is a relative measure of the probability of interaction between shing and an individual but is not scaled to represent a true probability of occurrence, and although non-negative it does not have a theoretical maximum value. It therefore only provides a relative indication of the potential for capture between species within a given method. It cannot be compared between methods, because different effort units are used.

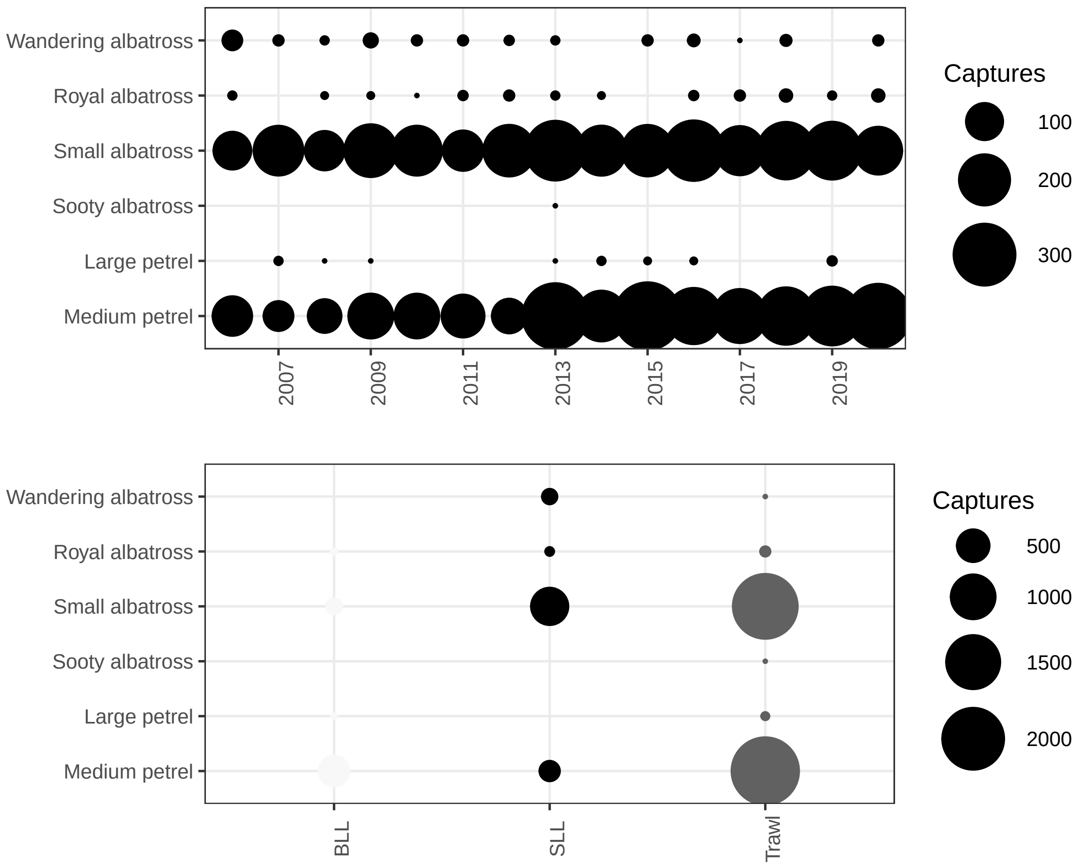

Figure 1: Observed captures per species group per year (top panel) and per species group per shery group (bottom panel).

Table 5: Number of observed seabird captures by species group and method, between 2006 and 2020.

Group name	BLL	SLL	Trawl	Total	Total per year
Medium petrel	429	167	2 405	3 001	200
Small albatross	89	670	2 209	2 968	198
Wandering albatross	0	83	1	84	6
Royal albatross	6	17	27	50	3
Large petrel	4	0	13	17	1
Sooty albatross	0	0	1	1	0
Total	528	937	4 656	6 121	
Total per year	35	62	310	408	

Table 6: Surface longline effort (thousand hooks). Observed effort is from the New Zealand EEZ between 2006 and 2020. Total effort is from the global data collated by Devine et al. (In press) for years 2017 to 2019.

	Total Hooks		Observed Hooks	
Year	New Zealand	Global	New Zealand	Global
2006	3 673		732	
2007	3 672		1 005	
2008	2 268		435	
2009	3 208		957	
2010	2 988		655	
2011	3 153		663	
2012	3 063		697	
2013	2 774		574	
2014	2 522		779	
2015	2 430		741	
2016	2 358		327	
2017	2 118	792 776	329	
2018	2 317	769 097	294	
2019	2 039	808 162	151	
2020	1 863		191	
Total	40 446	2 370 034	8 529	0
Total per year	2 696	790 011	569	

Table 7: Bottom longline effort (thousand hooks). Observed effort is from the New Zealand EEZ between 2006 and 2020. Total effort is from the global data collated by Devine et al. (In press) for years 2017 to 2019.

	Total Hooks		Observed Hooks	
Year	New Zealand	Global	New Zealand	Global
2006	35 498		3 270	
2007	38 570		2 064	
2008	40 806		3 157	
2009	37 390		4 735	
2010	40 809		2 477	
2011	40 685		1 388	
2012	37 698		1 792	
2013	33 439		1 195	
2014	39 883		2 796	
2015	39 449		1 364	
2016	43 781		3 409	
2017	46 436	96 284	5 192	
2018	38 556	119 095	4 341	
2019	40 977	123 403	3 955	
2020	31 673		2 779	
Total	585 647	338 782	43 913	0
Total per year	39 043	112 927	2 928	

Table 8: Trawl effort (tows). Observed effort is from the New Zealand EEZ between 2006 and 2020. Total effort is from the global data collated by Devine et al. (In press) for years 2017 to 2019.

	Total Tows		Observed Tows	
Year	New Zealand	Global	New Zealand	Global
2006	105 501		6 861	
2007	101 276		8 316	
2008	86 745		9 027	
2009	88 952		10 096	
2010	94 007		7 929	
2011	82 918		8 306	
2012	85 246		9 615	
2013	85 344		12 514	
2014	82 243		12 658	
2015	77 776		13 968	
2016	78 220		12 719	
2017	78 897	1 457 503	14 063	
2018	73 482	1 547 523	14 788	
2019	69 399	1 528 285	14 429	
2020	48 050		12 045	
Total	1 238 056	4 533 311	167 334	0
Total per year	82 537	1 511 104	11 156	

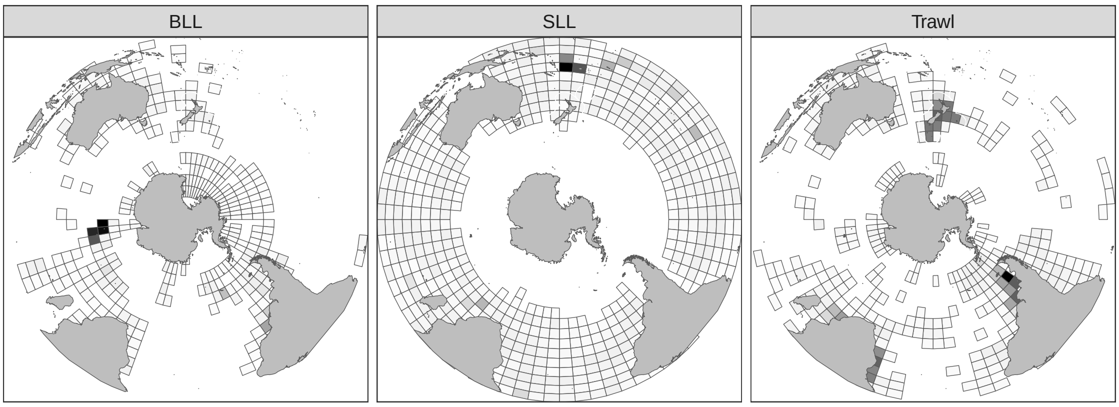

Figure 2: Summary of southern hemisphere effort distributions for each shing method. Effort has been rescaled to a maximum of one to allow their distributions to be compared. Overlap of shing effort with species-speci c biological distributions is illustrated in Appendix C. The boundary of the New Zealand EEZ is shown in red, this being the region from which observed capture data were available.

Table 9: Number of observed seabird captures within the New Zealand EEZ by species and method, between 2006 and 2020.

Code	Common name	BLL	SLL	Trawl	Total
DIW	Gibson's albatross	0	34	1	35
DQS	Antipodean albatross	0	43	0	43
DIX	Wandering albatross	0	6	0	6
DBN	Tristan albatross	0	0	0	0
DAM	Amsterdam albatross	0	0	0	0
DIP	Southern royal albatross	6	13	26	45
DIQ	Northern royal albatross	0	4	1	5
DCR	Atlantic yellow-nosed albatross	0	0	0	0
TQH	Indian yellow-nosed albatross	1	0	0	1
DIM	Black-browed albatross	1	4	2	7
TQW	Campbell black-browed albatross	4	26	17	47
DCU	Shy albatross	0	0	0	0
TWD	New Zealand white-capped albatross	12	232	1 251	1 495
DKS	Salvin's albatross	44	8	465	517
DER	Chatham Island albatross	15	0	18	33
DIC	Grey-headed albatross	0	1	0	1
DIB	Southern Buller's albatross	6	375	422	803
DNB	Northern Buller's albatross	6	24	34	64
PHU	Sooty albatross	0	0	0	0
PHE	Light-mantled sooty albatross	0	0	1	1
MAI	Southern giant petrel	0	0	2	2
MAH	Northern giant petrel	4	0	11	15
PCI	Grey petrel	17	38	92	147
PRK	Black petrel	94	47	32	173
PCW	Westland petrel	17	45	39	101
PRO	White-chinned petrel	301	37	2 242	2 580
PCN	Spectacled petrel	0	0	0	0
Total		528	937	4 656	6 121
Total per year		35	62	310	408

Table 10: Number of observed dead seabird captures within the New Zealand EEZ by species and method, between 2006 and 2020.

Code	Common name	BLL	SLL	Trawl	Total
DIW	Gibson’s albatross	0	28	1	29
DQS	Antipodean albatross	0	29	0	29
DIX	Wandering albatross	0	5	0	5
DBN	Tristan albatross	0	0	0	0
DAM	Amsterdam albatross	0	0	0	0
DIP	Southern royal albatross	1	6	12	19
DIQ	Northern royal albatross	0	4	0	4
DCR	Atlantic yellow-nosed albatross	0	0	0	0
TQH	Indian yellow-nosed albatross	1	0	0	1
DIM	Black-browed albatross	1	4	0	5
TQW	Campbell black-browed albatross	3	24	16	43
DCU	Shy albatross	0	0	0	0
TWD	New Zealand white-capped albatross	4	206	865	1 075
DKS	Salvin’s albatross	40	7	318	365
DER	Chatham Island albatross	15	0	12	27
DIC	Grey-headed albatross	0	1	0	1
DIB	Southern Buller’s albatross	1	239	307	547
DNB	Northern Buller’s albatross	5	22	28	55
PHU	Sooty albatross	0	0	0	0
PHE	Light-mantled sooty albatross	0	0	0	0
MAI	Southern giant petrel	0	0	2	2
MAH	Northern giant petrel	1	0	6	7
PCI	Grey petrel	16	38	62	116
PRK	Black petrel	37	44	12	93
PCW	Westland petrel	15	41	25	81
PRO	White-chinned petrel	290	35	1 421	1 746
PCN	Spectacled petrel	0	0	0	0
Total		430	733	3 087	4 250
Total per year		29	49	206	283

Table 11: Observed overlap by species for bottom-longline (BLL), surface-longline (SLL), and trawl shing methods between 2006 and 2020. The summed overlap is only included as a diagnostic for construction of the data. Missing values indicate zero overlap.

Common name	BLL	SLL	Trawl	Sum
Gibson’s albatross	0.002	0.002	0.016	0.020
Antipodean albatross	0.003	< 0.001	0.011	0.015
Wandering albatross	< 0.001	< 0.001	0.001	0.001
Tristan albatross				
Amsterdam albatross				
Southern royal albatross	0.004	0.001	0.019	0.024
Northern royal albatross	0.009	< 0.001	0.024	0.033
Atlantic yellow-nosed albatross				
Indian yellow-nosed albatross		< 0.001	< 0.001	< 0.001
Black-browed albatross	< 0.001	< 0.001	< 0.001	< 0.001
Campbell black-browed albatross	0.003	< 0.001	0.012	0.015
Shy albatross				
New Zealand white-capped albatross	0.004	0.001	0.023	0.029
Salvin’s albatross	0.004	< 0.001	0.017	0.022
Chatham Island albatross	0.003	< 0.001	0.007	0.010
Grey-headed albatross	< 0.001	< 0.001	< 0.001	< 0.001
Southern Buller’s albatross	0.005	0.001	0.021	0.027
Northern Buller’s albatross	0.005	0.001	0.021	0.027
Sooty albatross				
Light-mantled sooty albatross	< 0.001		< 0.001	< 0.001
Southern giant petrel				
Northern giant petrel				
Grey petrel	0.002	< 0.001	0.004	0.006
Black petrel	0.001	< 0.001	0.003	0.004
Westland petrel	0.007	0.002	0.029	0.038
White-chinned petrel	< 0.001	< 0.001	0.001	0.001
Spectacled petrel				
Sum	0.053	0.010	0.210	0.274
Sum per year	0.007	0.001	0.028	0.037

Table 12: Total overlap by species for bottom-longline (BLL), surface-longline (SLL), and trawl shing methods between 2017 and 2019. The summed overlap is only included as a diagnostic for construction of the data. All species had positive overlap with all of the methods.

Common name	BLL	SLL	Trawl	Sum
Gibson's albatross	0.001	0.008	0.082	0.090
Antipodean albatross	0.001	0.002	0.076	0.079
Wandering albatross	0.009	0.008	0.016	0.033
Tristan albatross	< 0.001	0.006	0.008	0.014
Amsterdam albatross	0.003	0.014	0.003	0.020
Southern royal albatross	0.002	0.002	0.133	0.136
Northern royal albatross	0.004	0.001	0.239	0.243
Atlantic yellow-nosed albatross	0.002	0.004	0.019	0.025
Indian yellow-nosed albatross	0.003	0.006	0.007	0.015
Black-browed albatross	0.010	0.001	0.095	0.107
Campbell black-browed albatross	< 0.001	< 0.001	0.069	0.070
Shy albatross	0.001	0.002	0.040	0.044
New Zealand white-capped albatross	0.001	0.004	0.115	0.120
Salvin's albatross	0.001	0.001	0.110	0.112
Chatham Island albatross	< 0.001	0.002	0.060	0.062
Grey-headed albatross	0.005	0.003	0.031	0.039
Southern Buller's albatross	0.001	0.005	0.110	0.115
Northern Buller's albatross	0.001	0.005	0.110	0.115
Sooty albatross	0.003	0.007	0.005	0.016
Light-mantled sooty albatross	0.005	0.001	0.002	0.008
Southern giant petrel	0.006	0.002	0.063	0.071
Northern giant petrel	0.011	0.002	0.085	0.097
Grey petrel	0.006	0.001	0.031	0.038
Black petrel	< 0.001	0.013	0.030	0.043
Westland petrel	0.001	0.004	0.148	0.153
White-chinned petrel	0.008	0.004	0.143	0.155
Spectacled petrel	0.009	0.005	0.050	0.063
Sum	0.093	0.114	1.878	2.086
Sum per year	0.062	0.076	1.252	1.390

4.9 Data limitations

For the current project, which only uses New Zealand observer data, no capture data were available for species that do not enter the New Zealand EEZ. Tristan albatross (Diomedea dabbenena) and Amsterdam albatross (Diomedea amsterdamensis) are good examples, since they do not enter the pacific ocean (Appendix B). Species catchability groups allowed catchability estimates to be shared across species. For example, catchability can be estimated for the Wandering albatross species group (Table 1) using capture data from Gibson's albatross (Diomedea antipodensis gibsoni), Antipodean albatross (Diomedea antipodensis antipodensis), and Wandering albatross (Diomedea exulans), and this estimate is shared across species within that group. This feature of the model may become more important in future if capture data that have not been identified to species level are included.

A second type of missing data concerns known errors in the species distribution inputs. Specifically, instances in which birds are observed to be caught within the New Zealand EEZ but the input bird distributions do not predict any overlap with New Zealand fishing effort. Southern giant petrel (Macronectes giganteus) and Northern giant petrel (Macronectes halli) both have observed captures within the New Zealand EEZ but a lack of representative input data on their distributions leads to calculation of zero observed overlap (Tables 9 and 11). A catchability could therefore not be estimated for these species. Because of strong behavioral differences, they form their own species group (Table 1), and for this group therefore, catchability will be obtained from the fishing group coefficient and intercept term only, with species group coefficient set to its prior value (i.e., b_{zjf} 0; Equation 11). Global captures can be predicted, but because of this deficiency in the data no captures can be predicted for the New Zealand EEZ.

Only observed captures for species with a positive observed overlap were retained when preparing the data for analysis, since only these data can be used to parameterise the model. The giant petrel species are therefore excluded from model fit diagnostics.

4.10 Risk assessment outputs

Fit of the risk assessment model to observed captures, including partitions of the observed captures into alive/dead and net/warp captures, allows us to estimate the catchability ($q_{f,z}$). Assumptions concerning cryptic capture and mortality allow these catchabilities to be converted into vulnerabilties ($u_{f;z}$) and annual deaths (D_s). From comparison of the catchability and vulnerability terms, the model outputs provide an indication of the relative risk to each species and species group, by each fishery group. Only fishery groups sharing the same effort metric can be compared (i.e., longline fishery groups can be compared with other longline fishery groups). Since the model uses spatial and temporal overlap as an input covariate, comparison of the fishery groups in this way will account for their encounter rate with birds, but only to the extent that spatial input data are an accurate representation of this determinant of capture.

Application of the estimated catchabilities to total overlap allows calculation of the total observable captures and total deaths, including cryptic mortalities. These deaths can then be used to assess the risk through comparison with the PST reference point, generating a metric that allows comparison of the risk between species. Consistent with previous iterations, risk was calculated using annual captures averaged over the most recent three years of global effort data (2017 to 2019 inclusive). In presentation of the results we assume that the PST tuning parameter $f = 0.5$ throughout (Abraham et al. 2019).

5. RESULTS

5.1 Convergence diagnostics

Summary statistics were constructed for estimated model parameters to assess model convergence. These were as follows:

$$
\begin{aligned}
q(\text{intercept}) &= b_0\\
q(\text{species}) &= \| b_z \|\\
q(\text{method}) &= \| b_f \|\\
\text{Prob. live capture} &= \| g_0; g_f; g_z \|\\
\text{Prob. net capture} &= \| p_z^{net} \|
\end{aligned}
$$

where $\| \cdot \|$ is the Euclidean norm of the enclosed parameter vector. Trace plots for the catchability summary diagnostics are shown in Figure 3. For biological parameters, we used the following summary statistics:

$$
\begin{aligned}
\text{Number of breeding pairs} &= \| N_s^{BP} \|\\
\text{Prob. breeding} &= \| P_s^{B} \|\\
\text{Age breeding} &= \| A_s^{curr} \|\\
\text{Survivorship} &= \| S_s^{opt} \|
\end{aligned}
$$

These are shown in Figure 4. In both Figures 3 and 4 it can be seen that the model converges well.

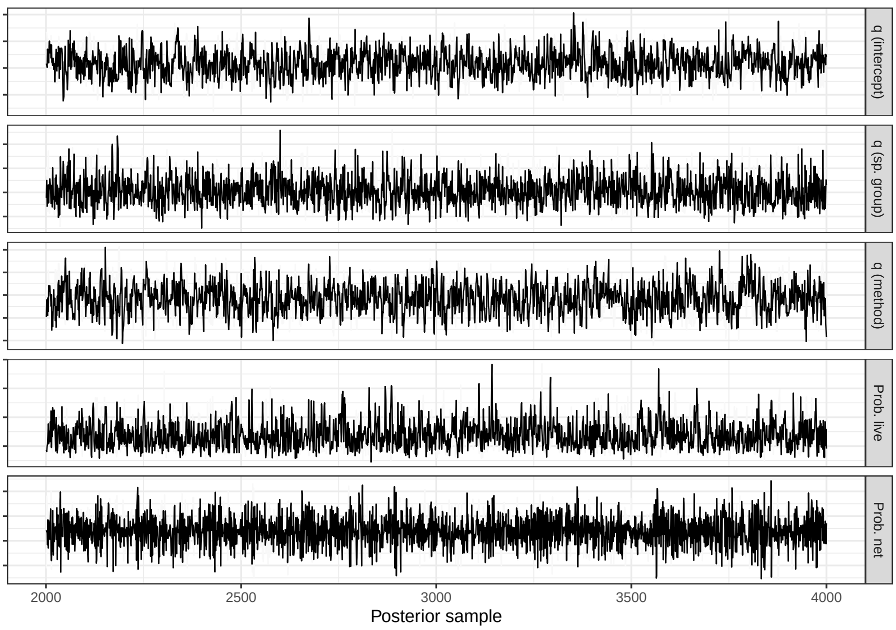

Figure 3: Trace plots of catchability predictors, illustrated using the summary statistics: b_0, $\| b_f \|$, $\| b_z \|$, probability of live capture ($\| g_0; g_j; g_z \|$), and probability of net capture ($\| p_z^{net} \|$).

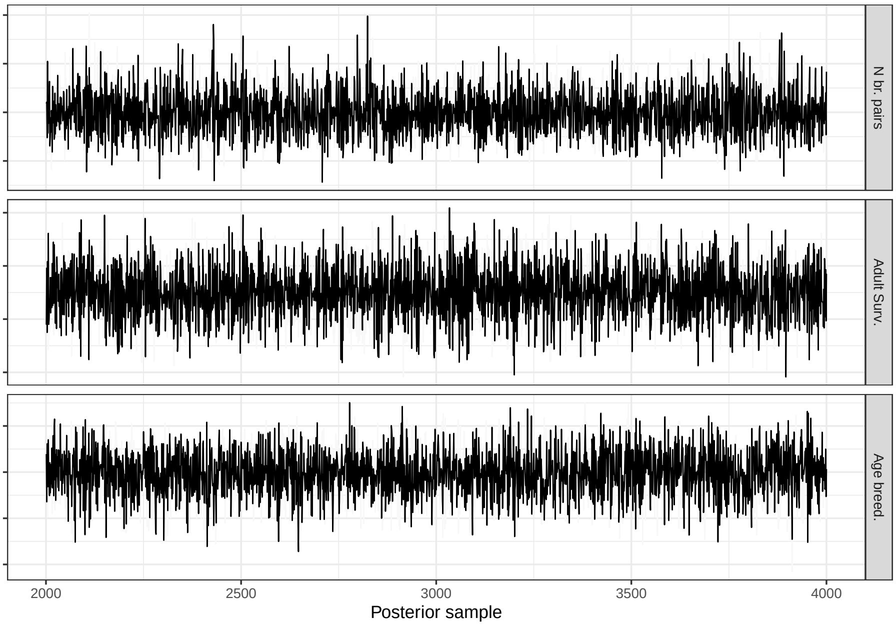

Figure 4: Trace plots for summary statistics of estimated biological parameter vectors: number of breeding pairs ($||N_s^{BP}||$), probability breeding ($||P_s^{B}||$), current age of first breeding ($||A_s^{curr}||$), and survivorship ($||S_s^{opt}||$).

5.2 Model fit

For diagnosing the model fit, we demonstrate the ability of the model to predict the data. Figure 5 provides an illustration of the predicted average annual captures per species and fishery group, indicating that overall the fit is good. Figure 6 similarly shows the prediction of the sum of observed captures ($C'_{f,s}$) by fishery group and species group, which is the resolution used by the model when estimating the catchability. Figure 7 shows prediction of the probability of non-zero records in the data being presented to the model. As an illustration of the high resolution model fit by species, the predicted and empirical numbers of observed captures (C'_s) are given per species in Table 13.

In estimating the probability of live capture $Y_{f,z}$, the model fits to observed live captures $C_{f,s}^{LIVE\,'}$ using a binomial distribution conditioned on $C'_{f,s}$. The predicted and empirical numbers of observed dead captures ($C_s^{DEAD\,'}$) are given per species in Table 14. Good prediction of observed live captures is shown in Figure 8.

A binomial distribution is also used to estimate p_z^{net}, the probability of a capture being a net capture for the trawl fishery, per species group. Derived predictions of the number of net and warp captures are shown in Figure 9. The estimated probabilities of net capture per cryptic capture group are given in Table 4.

Because the model has been constructed with a monthly time step, we diagnosed prediction of the captures per month for each method and fishery group (Figure 10). There are strong seasonal differences in the number of captures, particularly for medium petrels and shearwaters in the trawl fisheries, and small albatrosses in the SLL fisheries. The model predicts these seasonal changes well, which indicates that the monthly structure of the model is warranted and allows it to be used to predict seasonal changes in risk if required.

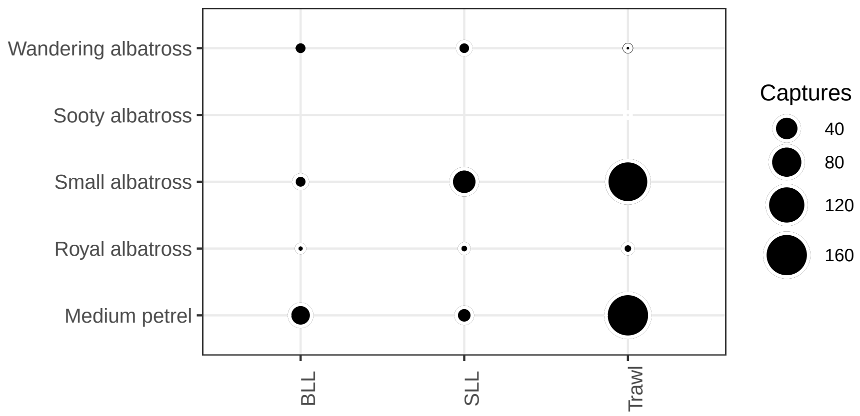

Figure 5: Model t to observed average annual captures ($C^0_{f;z}$) per species and shery group combination, between 2006 and 2020. Model predicted values are represented by the posterior median of the sum accross species per group, and shaded in blue. Empirical values are represented by red circles. Giant petrel species are excluded (see Section 4.9).

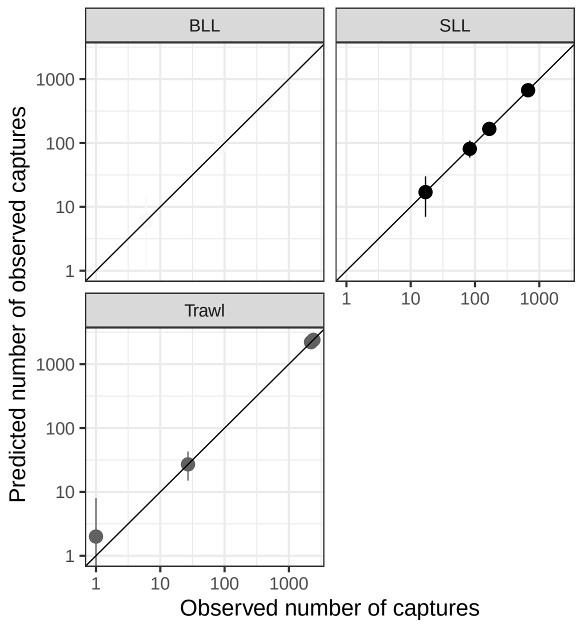

Figure 6: Model t to the number of observed captures$C^0_{f;z}$ for each shing method. Zero values are omitted. Captures are summed across species within each species group, between 2006 and 2020, and each point represents a unique combination of species group and shery group. Median and 95% quantile values are shown.

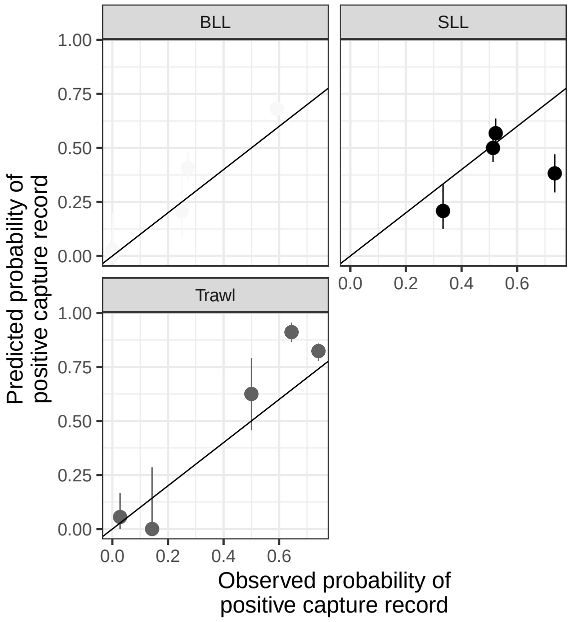

Figure 7: Model t to the probability of observed capture per capture record $P[C^{0}_{f;z} > 0]$. Values are shown for each shing method. Each point represents calculation of the probability across species within each species group and shery group. Median and 95% quantile values for this probability are shown.

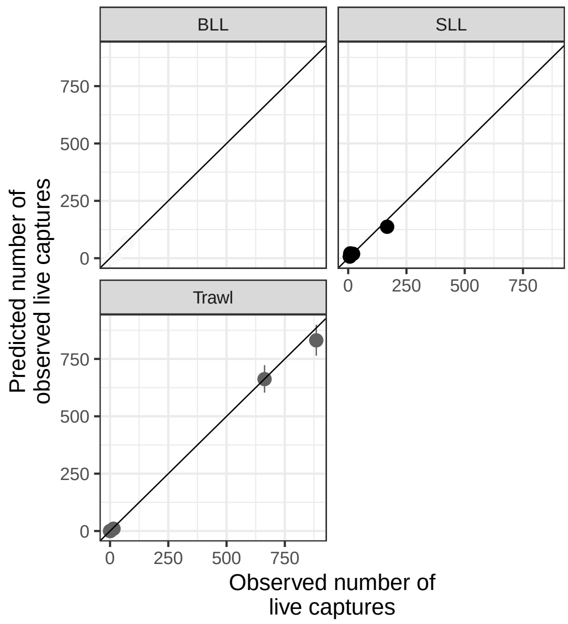

Figure 8: Model t to observed number of live captures $C^{LIVE\,0}_{sg}$ for each shing method. Captures are summed across species within each species group, between 2006 and 2020, and each point represents a unique combination of species group and shery group.

Table 13: Model fit to observed captures per species C^0_s, summed from 2006 to 2020: empirical value, posterior, and R for each species. Captures of giant petrel (MAI and MAH) where excluded from the model fit because of missing distribution data for these species (i.e., data inputs indicate zero observed overlap with New Zealand fisheries; see Section 4.9).

			Posterior		
Code	Species	Observed	Median	95% CI	R
DIW	Gibson's albatross	35	56	[41,74]	1.00
DQS	Antipodean albatross	43	25	[16,36]	1.00
DIX	Wandering albatross	6	3	[1,7]	1.00
DBN	Tristan albatross	0	0	[0,0]	
DAM	Amsterdam albatross	0	0	[0,0]	
DIP	Southern royal albatross	45	39	[26,53]	1.00
DIQ	Northern royal albatross	5	12	[6,20]	1.00
DCR	Atlantic yellow-nosed albatross	0	0	[0,0]	
TQH	Indian yellow-nosed albatross	0	0	[0,0]	1.00
DIM	Black-browed albatross	7	37	[25,49]	1.00
TQW	Campbell black-browed albatross	47	40	[28,54]	1.00
DCU	Shy albatross	0	0	[0,0]	
TWD	New Zealand white-capped albatross	1 495	1 482	[1 394,1 573]	1.00
DKS	Salvin's albatross	517	517	[466,572]	1.00
DER	Chatham Island albatross	33	20	[11,32]	1.00
DIC	Grey-headed albatross	1	1	[0,3]	1.00
DIB	Southern Buller's albatross	803	784	[721,852]	1.00
DNB	Northern Buller's albatross	64	86	[68,106]	1.00
PHU	Sooty albatross	0	0	[0,0]	
PHE	Light-mantled sooty albatross	1	0	[0,3]	1.00
MAI	Southern giant petrel	2			
MAH	Northern giant petrel	15			
PCI	Grey petrel	147	193	[164,225]	1.00
PRK	Black petrel	173	131	[106,158]	1.00
PCW	Westland petrel	101	110	[87,135]	1.00
PRO	White-chinned petrel	2 580	2 559	[2 441,2 678]	1.00
PCN	Spectacled petrel	0	0	[0,0]	

Table 14: Model t to observed dead captures per species, $C_s^{\mathrm{DEAD}0}$, summed from 2006 to 2020: empirical value, posterior and R for each species. Dead captures of giant petrel (MAI and MAH) where excluded from the model t because of missing distribution data for these species (i.e., data inputs indicate zero observed overlap with New Zealand sheries; see Section 4.9).

			Posterior		
Code	Species	Observed	Median	95% CI	R
DIW	Gibson's albatross	29	42	[29,57]	1.00
DQS	Antipodean albatross	29	18	[11,28]	1.00
DIX	Wandering albatross	5	2	[0,6]	1.00
DBN	Tristan albatross	0	0	[0,0]	
DAM	Amsterdam albatross	0	0	[0,0]	
DIP	Southern royal albatross	19	18	[10,29]	1.00
DIQ	Northern royal albatross	4	4	[1,9]	1.00
DCR	Atlantic yellow-nosed albatross	0	0	[0,0]	
TQH	Indian yellow-nosed albatross	0	0	[0,0]	1.00
DIM	Black-browed albatross	5	25	[16,35]	1.00
TQW	Campbell black-browed albatross	43	27	[18,38]	1.00
DCU	Shy albatross	0	0	[0,0]	
TWD	New Zealand white-capped albatross	1 075	1 057	[986,1 128]	1.00
DKS	Salvin's albatross	365	362	[321,405]	1.00
DER	Chatham Island albatross	27	13	[6,22]	1.00
DIC	Grey-headed albatross	1	0	[0,2]	1.00
DIB	Southern Buller's albatross	547	555	[502,609]	1.00
DNB	Northern Buller's albatross	55	61	[46,76]	1.00
PHU	Sooty albatross	0	0	[0,0]	
PHE	Light-mantled sooty albatross	0	0	[0,2]	1.00
MAI	Southern giant petrel	2			
MAH	Northern giant petrel	7			
PCI	Grey petrel	116	136	[112,160]	1.00
PRK	Black petrel	93	90	[71,110]	1.00
PCW	Westland petrel	81	77	[59,96]	1.00
PRO	White-chinned petrel	1 746	1 728	[1 632,1 821]	1.00
PCN	Spectacled petrel	0	0	[0,0]	

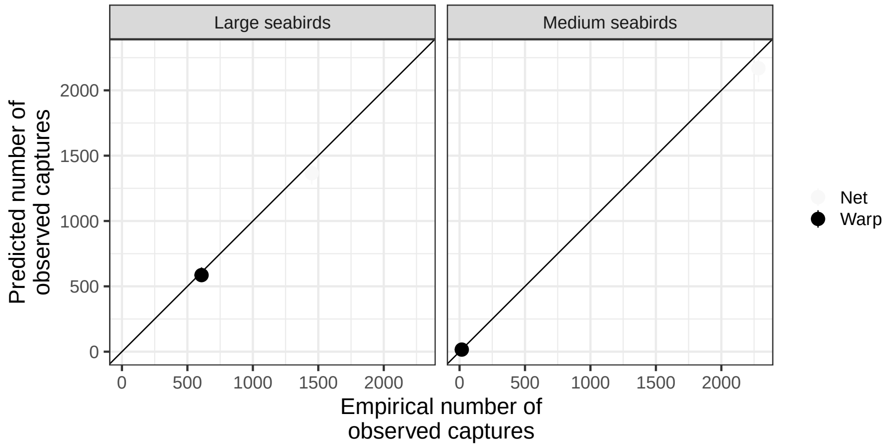

Figure 9: Model t to number of observed net and warp trawl captures for each net capture group. Captures are summed across species within each group, between 2006 and 2020, and each point represents a unique combination of net capture group and shery group.

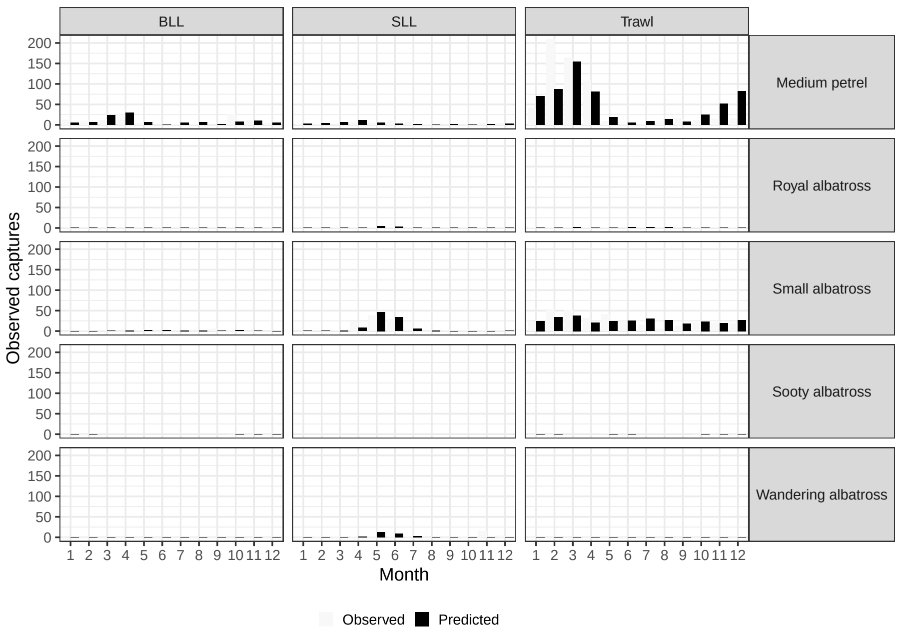

Figure 10: Observed and model predicted captures (C^{0}_{fs}) aggregated by month, species group, and method (with month 1 equal to January). Mean posterior predicted values are shown.

5.3 Estimated catchabilities and vulnerabilities

Catchability is the rate of capture per unit of density overlap. The vulnerability uses the capture multiplier $K_{f;z}$ to account for the fact that not all captures are observable:

$$u_{f;z} = q_{f;z} K_{f;z} \tag{21}$$

The number of interactions is larger than the number of captures, and some of these interactions will lead to death, either directly or following live release. Because the catchability is estimated from the data, it provides a reliable metric of the relative risk of capture associated with a particular shery. However, because of cryptic capture and death it will likely be an underestimate of the relative risk. The vulnerability is less well estimated, but provides a conservative upper limit to the relative risk. To estimate death we use the mortality multiplier $k_{f;z}$ (Equation 14).

Catchabilities and vulnerabilities per species group and shery group combination are shown in Tables 15 and 16. From these, we can identify the species groups that are most likely to be caught by the different shery groups. For the BLL and trawl shery groups, catchabilities are highest for the medium petrels. For SLL, catchabilities are high for the medium petrels, but also for the great albatross species, particularly the wandering albatross. The same pattern across species groups within each of the shery groups is evidence for the vulnerabilities.

Taking the geometric mean across species groups, we calculated the catchability per shery group. These are shown alongside the geometric means of the vulnerabilities per group in Figure 11. The differences between catchability and vulnerability are an indication of the proportion of the shery related interactions and mortalities that are unobservable. From Figure 11 we can see that the SLL groups have a higher catchability and vulnerability than the BLL shery groups. In the trawl shery, there is notably a much higher discrepancy between the vulnerabilities and the catchabilities, compared with longlines. This indicates the higher importance of cryptic capture for prediction of captures and deaths by the trawl eets. The importance of cryptic mortalities is illustrated in Figure 12. These are a function of the input values listed in Table 4 and also the estimated net capture rates and probabilities of live capture.

Table 15: Catchability per species group and shery group ($q_{f;z}$, log10-scale). Catchability is a measure of the expected number of captures per unit of density overlap. Cells values are shaded from the lowest (white) to the highest (dark grey).

	BLL		SLL		Trawl	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
Wandering albatross	-1.96	[-2.59,-1.45]	0.54	[0.44,0.64]	-2.08	[-2.57,-1.73]
Royal albatross	-1.57	[-1.87,-1.32]	-0.25	[-0.45,-0.06]	-1.47	[-1.63,-1.32]
Small albatross	-1.86	[-1.96,-1.77]	-0.38	[-0.44,-0.32]	-1.14	[-1.20,-1.09]
Sooty albatross	-1.42	[-2.27,-0.64]	-0.12	[-1.00,0.76]	-1.00	[-1.70,-0.44]
Large petrel	-1.39	[-2.29,-0.49]	-0.11	[-1.00,0.77]	-1.16	[-2.02,-0.31]
Medium petrel	-0.53	[-0.61,-0.46]	0.26	[0.17,0.34]	-0.34	[-0.41,-0.28]

Table 16: Vulnerability per species group and fishery group ($u_{f;z}$, log10-scale). Vulnerability is a measure of the number of interactions (captures and cryptic captures) per unit of density overlap. Cells values are shaded from the lowest (white) to the highest (dark grey).

	BLL		SLL		Trawl	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
Wandering albatross	-1.84	[-2.48,-1.34]	0.66	[0.55,0.76]	-1.23	[-1.71,-0.86]
Royal albatross	-1.49	[-1.79,-1.23]	-0.17	[-0.38,0.02]	-0.62	[-0.80,-0.44]
Small albatross	-1.75	[-1.85,-1.65]	-0.26	[-0.33,-0.20]	-0.29	[-0.36,-0.22]
Sooty albatross	-1.34	[-2.18,-0.55]	-0.03	[-0.92,0.84]	-0.15	[-0.86,0.43]
Large petrel	-1.30	[-2.20,-0.39]	-0.01	[-0.90,0.89]	-0.31	[-1.17,0.55]
Medium petrel	-0.41	[-0.50,-0.33]	0.38	[0.29,0.48]	0.07	[-0.06,0.21]

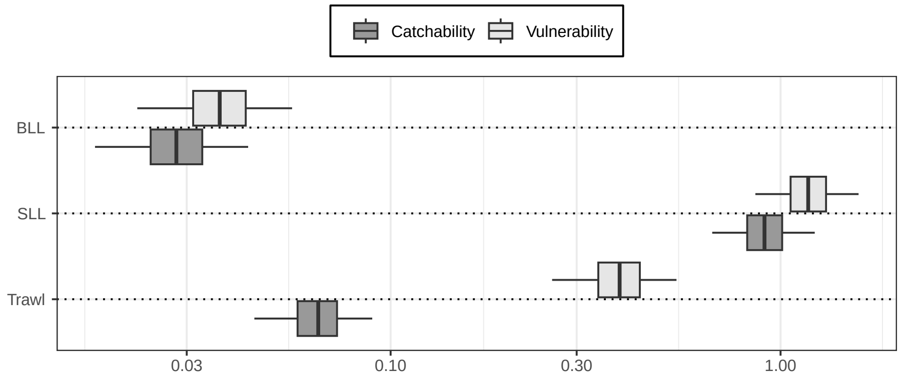

Figure 11: Marginal catchability (q_f) and vulnerability (u_f) per fishing group assuming a geometric mean across species. Values are given on a log10-scale. Boxplots show the median and 75% and 95% posterior quantiles.

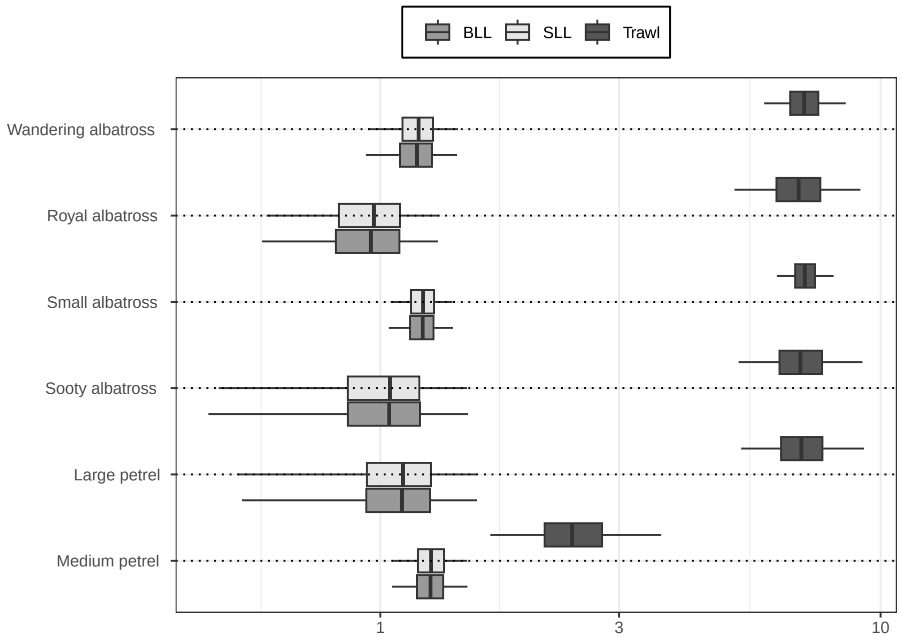

Figure 12: Mortality multipliers ($k_{f;z}$) per fishing group and species group. Values are given on a log-10 scale. Boxplots show the median and 75% and 95% posterior quantiles.

5.4 Estimated biological values

Prior updates for the number of breeding pairs (N_s^{BP}) and the probability of breeding (P_s^B) are illustrated per species in Figures 13 and 14, respectively. The posteriors are also listed in Table 17 alongside the age of first breeding (A_s^{curr}) and optimum survivorship (S_s^{opt}).

It can be seen that there is little information in the data with which to update the prior values. Exceptions to this are the P_s^B values for New Zealand white-capped albatross (TWD), Salvin's albatross (DKS), Chatham Island albatross (DER), Southern Buller's albatross (DIB), Black petrel (PRK), and White-chinned petrel (PRO), which are noticeably lower than the priors. These are all species that are indigenous to New Zealand and were included in the domestic seabird risk assessment (Edwards et al. 2023b). In Edwards et al. (2023b), only P_s^B priors for New Zealand white-capped albatross (TWD) and Salvin's albatross (DKS) were updated, and to a much smaller degree. This difference between the current and domestic risk assessments suggests that the structural data and inputs are inconsistent, because the model formulation is otherwise the same (and uses the same code). If P_s^B is less than the prior, this indicates that the model is able to improve fit to the capture data by reducing the number of birds breeding and increasing non-breeders in the population: a lower P_s^B will increase the predicted number of birds that are available for capture (Equation 2). The same number of observed captures can then be achieved with a lower catchability. One explanation could therefore be that the data inputs for the current risk assessment underestimate the availability of birds for New Zealand species, requiring that the model compensates by lowering the estimate for P_s^B.

In Figure 15 we illustrate the estimation of r_s using the demographic invariant (DI) method. Using this value, and the estimated number of adults, we are able to calculate the PST reference point per species (Table 18). All biological values within the model are consistent. Updates to N_s^{BP}, for example, will be consistent with estimates of the catchability ($q_{f,z}$), and updates to N_s^{BP}, P_s^B, and S_s^{opt} will be consistent with estimates of r_s and the PST.

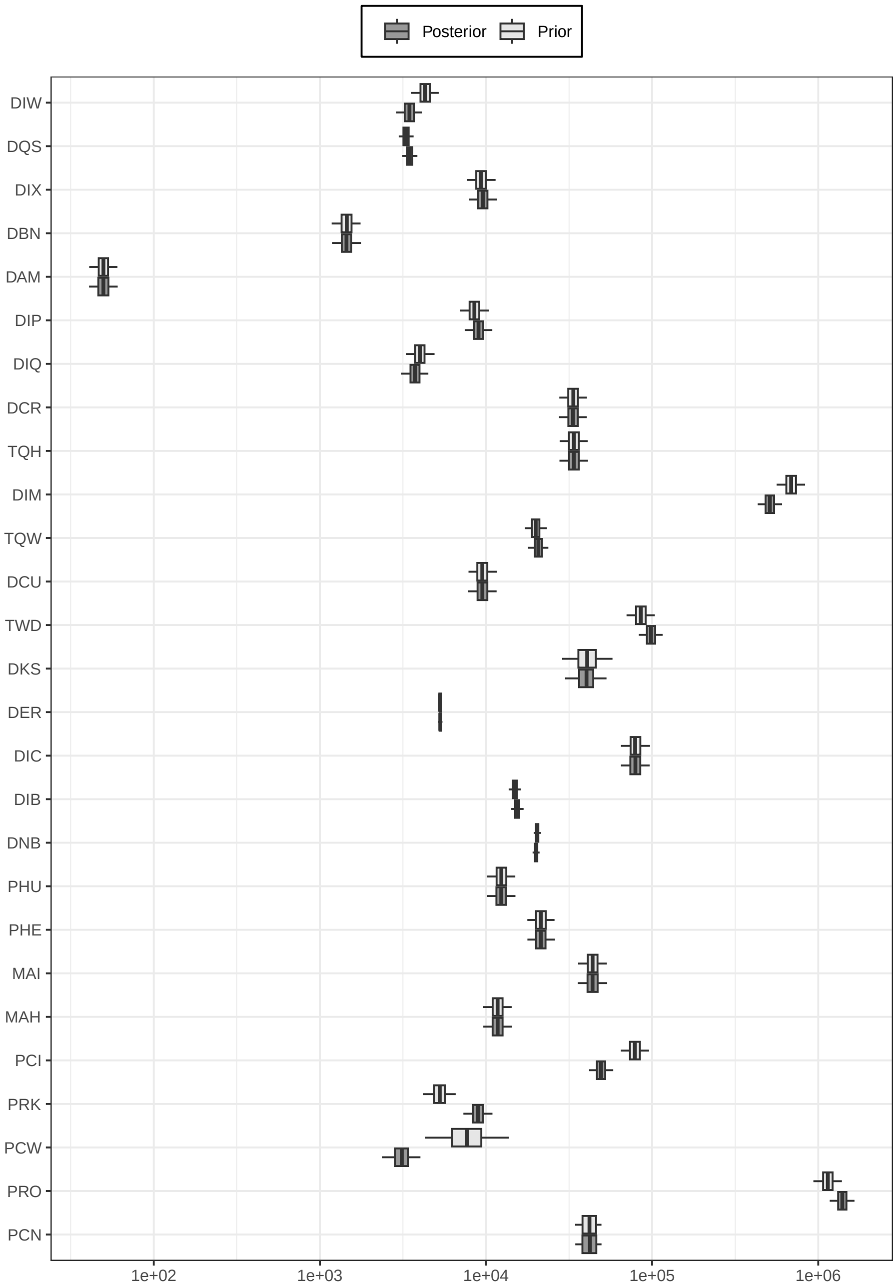

Figure 13: Prior and posterior densities for the number of breeding pairs (N_s^{BP}; log10-scale) for each species (see Table 1). Boxplots show the median and 75% and 95% posterior quantiles.

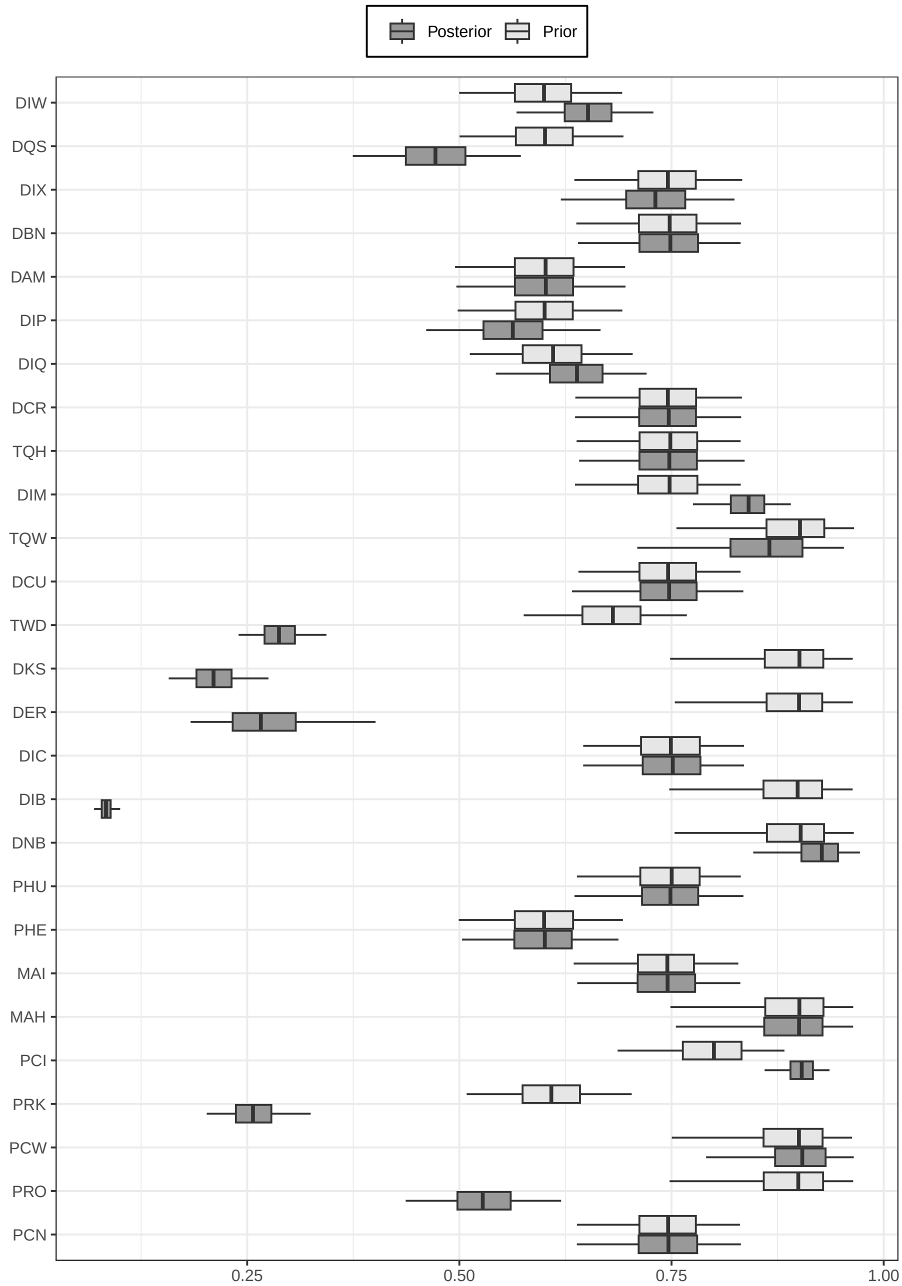

Figure 14: Prior and posterior densities for the proportion breeding (P_s^B) for each species (see Table 1). Boxplots show the median, and 75% and 95% posterior quantiles.

Table 17: Posterior summary statistics for the annual number of breeding pairs (N_s^{BP}), proportion of adults breeding (P_s^B), current age at first reproduction (A_s^{curr}) and optimum survivorship (S_s^{opt}).

		N_s^{BP}		P_s^B		A_s^{curr}		S_s^{opt}	
Code	Common name	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
DIW	Gibson's albatross	3 472	[2 877,4 115]	0.65	[0.57,0.73]	11.0	[10.0,12.0]	0.95	[0.95,0.96]
DQS	Antipodean albatross	3 480	[3 135,3 863]	0.47	[0.37,0.57]	10.0	[7.1,12.9]	0.95	[0.95,0.96]
DIX	Wandering albatross	9 613	[7 917,11 667]	0.73	[0.62,0.82]	10.0	[7.2,12.9]	0.95	[0.95,0.96]
DBN	Tristan albatross	1 454	[1 185,1 770]	0.75	[0.64,0.83]	10.0	[7.1,12.8]	0.95	[0.95,0.96]
DAM	Amsterdam albatross	50	[41,61]	0.60	[0.50,0.70]	11.5	[10.1,12.9]	0.95	[0.95,0.96]
DIP	Southern royal albatross	9 054	[7 445,10 913]	0.56	[0.46,0.67]	10.0	[9.1,11.0]	0.95	[0.95,0.96]
DIQ	Northern royal albatross	3 753	[3 090,4 497]	0.64	[0.54,0.72]	10.0	[9.0,10.9]	0.95	[0.95,0.96]
DCR	Atlantic yellow-nosed albatross	33 565	[27 500,40 369]	0.74	[0.64,0.83]	9.0	[6.1,11.8]	0.95	[0.93,0.97]
TQH	Indian yellow-nosed albatross	33 991	[27 680,41 114]	0.74	[0.64,0.84]	9.0	[6.1,11.9]	0.95	[0.93,0.97]
DIM	Black-browed albatross	512 885	[431 924,605 680]	0.84	[0.78,0.89]	9.0	[7.1,10.9]	0.95	[0.93,0.97]
TQW	Campbell black-browed albatross	20 705	[17 896,23 732]	0.86	[0.71,0.95]	9.5	[6.2,12.8]	0.95	[0.93,0.97]
DCU	Shy albatross	9 560	[7 799,11 582]	0.74	[0.63,0.83]	12.0	[9.2,14.9]	0.95	[0.93,0.97]
TWD	New Zealand white-capped albatross	98 668	[83 067,115 634]	0.29	[0.24,0.34]	12.0	[9.2,14.9]	0.95	[0.93,0.97]
DKS	Salvin's albatross	40 561	[29 927,53 137]	0.21	[0.16,0.28]	12.0	[9.1,14.8]	0.95	[0.93,0.97]
DER	Chatham Island albatross	5 309	[5 158,5 467]	0.27	[0.18,0.40]	12.0	[9.2,14.9]	0.95	[0.93,0.97]
DIC	Grey-headed albatross	79 690	[64 875,96 591]	0.75	[0.65,0.84]	9.9	[7.1,12.8]	0.95	[0.93,0.97]
DIB	Southern Buller's albatross	15 438	[14 192,16 838]	0.08	[0.07,0.10]	12.0	[9.1,14.9]	0.95	[0.93,0.97]
DNB	Northern Buller's albatross	20 037	[19 077,21 016]	0.92	[0.85,0.97]	12.0	[9.2,14.8]	0.95	[0.93,0.97]
PHU	Sooty albatross	12 428	[10 162,15 038]	0.75	[0.64,0.83]	12.0	[9.2,14.8]	0.95	[0.93,0.97]
PHE	Light-mantled sooty albatross	21 503	[17 753,25 983]	0.60	[0.50,0.69]	12.0	[9.1,14.9]	0.95	[0.93,0.97]
MAI	Southern giant petrel	44 051	[35 635,53 658]	0.74	[0.64,0.83]	7.5	[7.0,8.0]	0.95	[0.93,0.96]
MAH	Northern giant petrel	11 809	[9 631,14 340]	0.89	[0.76,0.96]	8.0	[6.1,9.9]	0.94	[0.93,0.96]
PCI	Grey petrel	49 496	[41 736,58 345]	0.90	[0.86,0.94]	7.0	[5.1,8.9]	0.94	[0.92,0.95]
PRK	Black petrel	8 991	[7 309,10 936]	0.26	[0.20,0.32]	6.6	[6.2,7.0]	0.94	[0.92,0.95]
PCW	Westland petrel	3 128	[2 362,4 030]	0.90	[0.79,0.96]	6.5	[4.1,8.9]	0.93	[0.92,0.95]
PRO	White-chinned petrel	1 400 401	[1 171 989,1 652 494]	0.53	[0.44,0.62]	6.5	[4.1,8.8]	0.94	[0.92,0.95]
PCN	Spectacled petrel	42 075	[34 472,49 585]	0.74	[0.64,0.83]	6.5	[4.1,8.9]	0.93	[0.92,0.95]

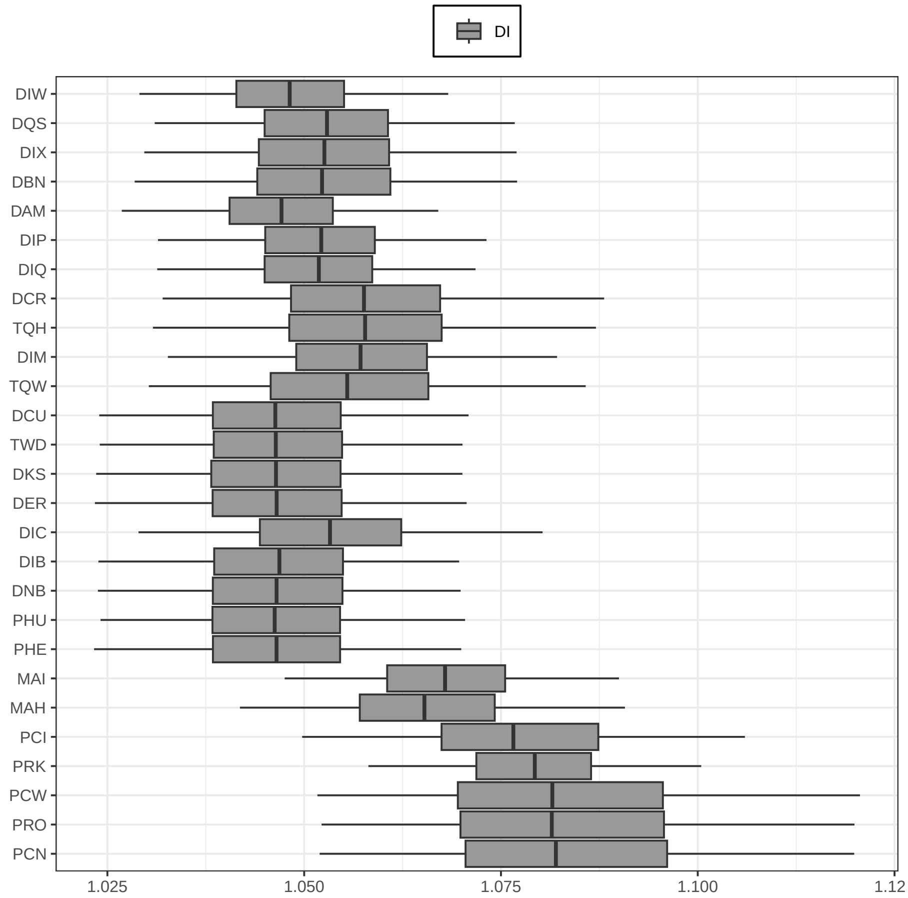

Figure 15: Estimation of l_s for each species (Table 1) using the demographic invariant (DI) method. Associated r_s values for each estimate are listed in Table 18.

Table 18: Posterior productivity and population size estimates used to calculate PST reference points for each species, assuming $f = 0.5$. Numbers are given in units of a thousand individuals.

Code	Common name	N_S (thousand)		r_S		PST_S	
		Mean	95% CI	Mean	95% CI	Mean	95% CI
DIW	Gibson's albatross	11	[9,13]	0.05	[0.03,0.07]	126.29	[72.57,189.31]
DQS	Antipodean albatross	15	[12,19]	0.05	[0.03,0.07]	192.40	[108.97,293.44]
DIX	Wandering albatross	26	[21,34]	0.05	[0.03,0.07]	339.91	[183.92,518.40]
DBN	Tristan albatross	4	[3,5]	0.05	[0.03,0.07]	50.21	[26.10,78.85]
DAM	Amsterdam albatross	0	[0,0]	0.05	[0.03,0.06]	1.93	[1.02,2.94]
DIP	Southern royal albatross	32	[25,42]	0.05	[0.03,0.07]	410.60	[235.08,615.42]
DIQ	Northern royal albatross	12	[9,15]	0.05	[0.03,0.07]	149.57	[85.63,220.30]
DCR	Atlantic yellow-nosed albatross	91	[71,115]	0.06	[0.03,0.08]	1 277.68	[678.86,2 020.66]
TQH	Indian yellow-nosed albatross	92	[72,117]	0.06	[0.03,0.08]	1 290.41	[670.95,2 018.20]
DIM	Black-browed albatross	1 224	[1 027,1 444]	0.06	[0.03,0.08]	17 023.84	[9 497.79,24 937.08]
TQW	Campbell black-browed albatross	49	[41,59]	0.05	[0.03,0.08]	661.42	[352.28,1 033.75]
DCU	Shy albatross	26	[20,33]	0.05	[0.02,0.07]	293.58	[145.67,468.12]
TWD	New Zealand white-capped albatross	686	[590,798]	0.05	[0.02,0.07]	7 819.58	[4 037.20,11 864.36]
DKS	Salvin's albatross	384	[325,453]	0.05	[0.02,0.07]	4 367.12	[2 188.36,6 693.60]
DER	Chatham Island albatross	40	[26,58]	0.05	[0.02,0.07]	459.40	[205.68,790.65]
DIC	Grey-headed albatross	214	[169,271]	0.05	[0.03,0.08]	2 787.81	[1 446.18,4 410.93]
DIB	Southern Buller's albatross	370	[313,434]	0.05	[0.02,0.07]	4 221.55	[2 151.15,6 475.60]
DNB	Northern Buller's albatross	44	[40,48]	0.05	[0.02,0.07]	495.73	[252.02,748.27]
PHU	Sooty albatross	33	[26,42]	0.05	[0.02,0.07]	379.92	[192.15,604.99]
PHE	Light-mantled sooty albatross	72	[56,93]	0.05	[0.02,0.07]	820.58	[398.93,1 311.01]
MAI	Southern giant petrel	119	[94,152]	0.07	[0.05,0.09]	1 962.50	[1 274.65,2 795.84]
MAH	Northern giant petrel	27	[21,34]	0.06	[0.04,0.09]	424.68	[259.22,634.54]
PCI	Grey petrel	110	[93,129]	0.07	[0.05,0.10]	2 041.04	[1 291.22,2 892.84]
PRK	Black petrel	70	[57,87]	0.08	[0.06,0.10]	1 335.72	[928.93,1 836.05]
PCW	Westland petrel	7	[5,9]	0.08	[0.05,0.11]	138.72	[80.27,212.59]
PRO	White-chinned petrel	5 317	[4 499,6 270]	0.08	[0.05,0.11]	105 987.19	[65 303.64,156 869.05]
PCN	Spectacled petrel	114	[88,143]	0.08	[0.05,0.11]	2 274.92	[1 333.84,3 504.12]

5.5 Model predictions

Given the estimated catchabilities, the number of adult birds available for capture and total overlap, we can estimate the total annual captures (Table 19). These values represent an average across the most recent three years of global effort data (2017 to 2019 inclusive). Using the mortality multipliers in Figure 12 we can further predict the average number of deaths and the risk. These are listed per species in Table 19, with the risk also illustrated in Figure 16. Risk ratio values of greater than one indicate that the current deaths exceed the PST. According to the model, there is a high probability that this is true for Westland petrel (PCW), White-chinned petrel (PRO), New Zealand white-capped albatross (TWD), Southern Buller's albatross (DIB), Salvin's albatross (DKS), Northern Buller's albatross (DNB), Northern royal albatross (DIQ), Amsterdam albatross (DAM), Black petrel (PRK), and Gibson's albatross (DIW), all of which have a median risk ratio greater than or close to one (Table 19).

Predicted annual deaths per species per method are listed in Table 20. Because these deaths will include cryptic mortalities, the proportion of deaths that are cryptic are listed in Table 21. It is calculated as:

$$\text{Proportion cryptic} = \frac{D_{f;s} - C^{DEAD}_{f;s}}{D_{f;s}} \qquad (22)$$

The proportion of deaths that are cryptic will depend on the cryptic mortality multipliers listed in Table 4, the proportion of net captures (in the trawl fishery with net captures having a lower cryptic mortality component than warp captures), and the proportion of captures that are live (since live captures will likely suffer some post-release cryptic mortality). For the longline fisheries, cryptic captures for the BLL and SLL fisheries are the same (Table 4), with overall cryptic mortalities again determined by both cryptic capture and post-release mortality of live birds. For the trawl fisheries, the proportion of captures that are net captures is listed in Table 4 for the different cryptic capture groups. These are lowest for the large albatross, with approximately 70% of captures occurring in the net, and over 90% for the other cryptic mortality groupings. The relative low probability of net capture for the large albatross will lead to a much higher rate of cryptic mortality, and this is what is predicted by the model. For the medium petrels, cryptic mortalities are lower, since they are more likely to be caught in the net and less likely to succumb to unobservable warp strikes. Overall, cryptic mortalities are highest for the trawl fisheries, accounting for up to 90% of the total deaths.

Deaths are disaggregated by fishery group in Table 20. The same information for all species is illustrated graphically in Figure 17. These provide an indication of the fishery groups responsible for the overall risk to each species listed in Table 19. To indicate the spatial distribution of risk, we provide spatial maps of the posterior predicted density overlap and deaths in Figures 18 and 19. Finally, we disaggregated deaths by RFMO, using the location of captures to allocate deaths to the RFMO. Deaths were not allocated to RFMO based on the source of the effort data, because RFMO data were incomplete and overlapping (Devine et al. In press). Because RFMO boundaries overlap, the sum of the deaths per RFMO may exceed the total deaths. For the BLL and Trawl fisheries, RFMO data were supplemented with data from the Global Fishing Watch database (Devine et al. In press), and a high proportion of this effort falls outside of BLL and Trawl fishery RFMO boundaries (CCAMLR, SEAFO, SIOFA, and SPRFMO; Table 2). In Figure 20, the different RFMO spatial definitions are shown. We also report deaths from these non-RFMO grid cells, which included large portions of the south western Atlantic ocean.

Table 19: Posterior predicted annual captures, deaths, risk ratio, and risk per species, between 2017 and 2019, ranked from highest to lowest median risk ratio. Risk ratio is calculated assuming that f = 0:5. Red: risk ratio with a median over 1 or upper 95% credible limit (u.c.l.) over 2; dark orange: median over 0.3 or u.c.l. over 1; light orange: median over 0.1 or u.c.l. over 0.3; yellow: u.c.l. over 0.1 (Richard et al. 2020).

		C_S		D_S		Risk ratio		Risk
Code	Common name	Mean	95% CI	Mean	95% CI	Median	95% CI	P[Risk ratio > 1]
PCW	Westland petrel	151	[122,184]	359	[191,681]	2.48	[1.24,5.62]	0.996
PRO	White-chinned petrel	116 151	[111 331,120 911]	268 700	[156 845,495 589]	2.42	[1.25,5.35]	0.997
TWD	New Zealand white-capped albatross	2 222	[2 098,2 350]	13 203	[8 931,18 934]	1.68	[0.95,3.60]	0.958
DIB	Southern Buller's albatross	1 187	[1 095,1 280]	7 078	[4 769,10 348]	1.68	[0.95,3.46]	0.958
DKS	Salvin's albatross	1 022	[931,1 117]	6 831	[4 535,9 969]	1.55	[0.87,3.34]	0.925
DNB	Northern Buller's albatross	126	[104,150]	736	[475,1 108]	1.47	[0.81,3.19]	0.891
DIQ	Northern royal albatross	29	[18,45]	190	[96,336]	1.23	[0.60,2.60]	0.720
DAM	Amsterdam albatross	2	[0,4]	2	[0,5]	1.14	[0.29,2.99]	0.598
PRK	Black petrel	773	[641,917]	1 336	[868,2 111]	0.98	[0.61,1.72]	0.470
DIW	Gibson's albatross	88	[66,113]	118	[74,179]	0.94	[0.52,1.79]	0.411
DER	Chatham Island albatross	62	[38,93]	387	[201,660]	0.83	[0.45,1.82]	0.308
MAH	Northern giant petrel	117	[13,483]	630	[41,3 010]	0.77	[0.10,7.14]	0.414
DIP	Southern royal albatross	57	[40,78]	319	[174,529]	0.77	[0.38,1.58]	0.232
PCN	Spectacled petrel	825	[564,1 168]	1 710	[901,3 228]	0.72	[0.39,1.54]	0.183
DIM	Black-browed albatross	1 794	[1 437,2 197]	11 691	[7 308,17 815]	0.68	[0.39,1.33]	0.113
TQW	Campbell black-browed albatross	65	[49,83]	450	[280,687]	0.68	[0.37,1.36]	0.132
DIX	Wandering albatross	162	[107,237]	198	[112,317]	0.57	[0.31,1.14]	0.054
PCI	Grey petrel	503	[434,573]	1 109	[655,2 002]	0.52	[0.29,1.12]	0.044
DBN	Tristan albatross	19	[11,29]	23	[12,39]	0.44	[0.22,0.92]	0.017
MAI	Southern giant petrel	305	[34,1 281]	1 670	[110,8 305]	0.44	[0.06,4.16]	0.237
DIC	Grey-headed albatross	249	[184,329]	1 166	[720,1 815]	0.42	[0.23,0.85]	0.009
DCU	Shy albatross	21	[13,31]	118	[63,199]	0.39	[0.20,0.88]	0.016
DQS	Antipodean albatross	43	[30,58]	70	[39,115]	0.36	[0.18,0.74]	0.004
PHU	Sooty albatross	91	[7,510]	123	[14,547]	0.21	[0.04,1.56]	0.057
DCR	Atlantic yellow-nosed albatross	57	[39,81]	226	[133,360]	0.18	[0.10,0.36]	0.000
TQH	Indian yellow-nosed albatross	56	[39,81]	127	[77,195]	0.10	[0.06,0.20]	0.000
PHE	Light-mantled sooty albatross	42	[6,185]	75	[12,245]	0.07	[0.01,0.33]	0.001

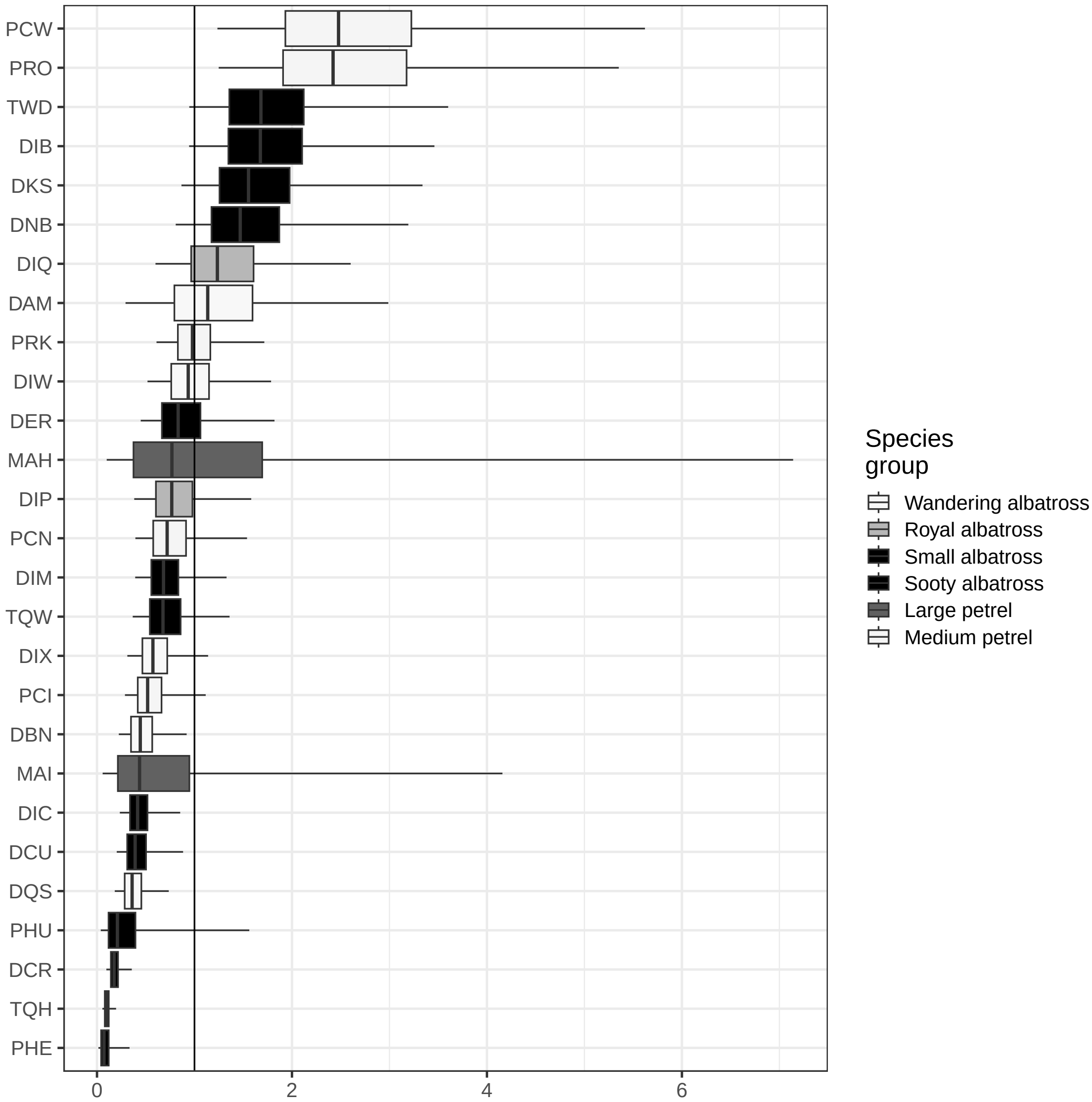

Figure 16: Posterior distributions of the risk ratios per species, ranked from highest to lowest median risk ratio (Table 19). Species codes are given and correspond to the names listed in Table 1. Boxplots show the median, and 75% and 95% posterior quantiles.

For BLL, we provide estimates of the total deaths for CCAMLR, SIOFA, SPRFMO, and SEAFO (Table 22), per species group. Deaths were highest for the medium petrels in the non-RFMO and then CCAMLR regions. For trawl sheries, we provide estimates for the same RFMOs (Table 23). Medium petrels again had the highest number of deaths, but in the non-RFMO and then SPRFMO regions. Mortality for small albatross was also signi cant. For both the BLL and Trawl sheries, it is notable that most of the deaths occur in non-RFMO regions.

For the SLL sheries, we predict deaths for IOTC, ICCAT, IATTC, WCFPC, and CCSBT (Table 24). CCSBT had the highest number of deaths; but it is also the largest RFMO in the southern hemisphere. For CCSBT, we also provide deaths per CCSBT statistical area (Figure 21, Table 25). These predict the highest number of SLL deaths in the Indian and Atlantic oceans (statistical areas 9 and 10).

Table 20: Posterior predicted annual deaths per species and method between 2017 and 2019, ranked from highest to lowest median risk ratio. Colours are de ned as per Table 19.

		BLL		SLL		Trawl	
Code	Common name	Mean	95% CI	Mean	95% CI	Mean	95% CI
PCW	Westland petrel	1	[0,2]	16	[10,24]	314	[195,583]
PRO	White-chinned petrel	4 454	[3 251,6 065]	15 056	[10 885,20 661]	230 276	[147 435,410 984]
TWD	New Zealand white-capped albatross	2	[1,5]	510	[378,688]	12 406	[8 943,17 450]
DIB	Southern Buller's albatross	1	[0,3]	274	[200,372]	6 632	[4 819,9 388]
DKS	Salvin's albatross	1	[0,3]	79	[57,110]	6 598	[4 747,9 338]
DNB	Northern Buller's albatross	0	[0,1]	32	[22,46]	685	[474,994]
DIQ	Northern royal albatross	0	[0,1]	2	[0,4]	179	[104,299]
DAM	Amsterdam albatross	0	[0,0]	2	[1,4]	0	[0,0]
PRK	Black petrel	1	[0,3]	598	[419,840]	663	[413,1 238]
DIW	Gibson's albatross	0	[0,0]	100	[68,144]	14	[2,39]
DER	Chatham Island albatross	0	[0,0]	11	[6,18]	360	[213,592]
MAH	Northern giant petrel	3	[0,29]	13	[1,104]	282	[36,2 009]
DIP	Southern royal albatross	0	[0,1]	11	[6,19]	295	[181,476]
PCN	Spectacled petrel	73	[47,110]	272	[177,425]	1 234	[713,2 393]
DIM	Black-browed albatross	39	[25,59]	164	[115,234]	11 222	[7 718,16 220]
TQW	Campbell black-browed albatross	0	[0,0]	2	[0,4]	433	[296,642]
DIX	Wandering albatross	1	[0,3]	186	[115,286]	5	[0,15]
PCI	Grey petrel	59	[41,84]	87	[61,123]	873	[563,1 602]
DBN	Tristan albatross	0	[0,0]	21	[13,35]	0	[0,3]
MAI	Southern giant petrel	7	[1,56]	33	[4,265]	738	[98,5 640]
DIC	Grey-headed albatross	5	[2,9]	115	[77,167]	1 008	[669,1 522]
DCU	Shy albatross	0	[0,0]	6	[3,10]	107	[64,175]
DQS	Antipodean albatross	0	[0,0]	46	[30,69]	19	[4,50]
PHU	Sooty albatross	1	[0,6]	39	[4,298]	24	[3,99]
DCR	Atlantic yellow-nosed albatross	0	[0,2]	36	[23,56]	180	[112,287]
TQH	Indian yellow-nosed albatross	1	[0,2]	54	[35,83]	67	[39,110]
PHE	Light-mantled sooty albatross	3	[0,20]	14	[2,114]	27	[4,109]

Table 21: Posterior predicted annual cryptic deaths per species and method, expressed as a proportion of total deaths (Equation 22), ranked from highest to lowest median risk ratio. Colours are de ned as per Table 19.

		BLL		SLL		Trawl	
Code	Common name	Mean	95% CI	Mean	95% CI	Mean	95% CI
PCW	Westland petrel	0.32	[0.00,0.50]	0.33	[0.10,0.50]	0.72	[0.56,0.85]
PRO	White-chinned petrel	0.33	[0.10,0.50]	0.33	[0.10,0.50]	0.72	[0.56,0.85]
TWD	New Zealand white-capped albatross	0.35	[0.12,0.51]	0.35	[0.12,0.51]	0.90	[0.86,0.93]
DIB	Southern Buller's albatross	0.34	[0.00,0.51]	0.35	[0.12,0.51]	0.90	[0.86,0.93]
DKS	Salvin's albatross	0.35	[0.05,0.51]	0.35	[0.14,0.52]	0.90	[0.86,0.93]
DNB	Northern Buller's albatross	0.00	[0.00,0.45]	0.35	[0.13,0.51]	0.90	[0.86,0.93]
DIQ	Northern royal albatross	0.37	[0.00,0.62]	0.48	[0.21,0.64]	0.93	[0.90,0.95]
DAM	Amsterdam albatross	0.00	[0.00,0.00]	0.36	[0.12,0.52]	0.00	[0.00,0.00]
PRK	Black petrel	0.33	[0.00,0.50]	0.33	[0.10,0.50]	0.72	[0.57,0.85]
DIW	Gibson's albatross	0.00	[0.00,0.36]	0.36	[0.14,0.53]	0.90	[0.86,0.93]
DER	Chatham Island albatross	0.00	[0.00,0.43]	0.35	[0.12,0.51]	0.90	[0.86,0.93]
MAH	Northern giant petrel	0.40	[0.01,0.67]	0.41	[0.14,0.67]	0.91	[0.86,0.95]
DIP	Southern royal albatross	0.42	[0.00,0.63]	0.48	[0.22,0.64]	0.93	[0.90,0.95]
PCN	Spectacled petrel	0.33	[0.11,0.50]	0.33	[0.11,0.51]	0.72	[0.56,0.85]
DIM	Black-browed albatross	0.36	[0.14,0.52]	0.35	[0.12,0.51]	0.90	[0.86,0.93]
TQW	Campbell black-browed albatross	0.00	[0.00,0.37]	0.35	[0.11,0.51]	0.90	[0.86,0.93]
DIX	Wandering albatross	0.32	[0.00,0.52]	0.36	[0.14,0.53]	0.90	[0.00,0.93]
PCI	Grey petrel	0.33	[0.10,0.50]	0.33	[0.10,0.50]	0.72	[0.57,0.85]
DBN	Tristan albatross	0.00	[0.00,0.00]	0.36	[0.14,0.52]	0.00	[0.00,0.91]
MAI	Southern giant petrel	0.40	[0.10,0.68]	0.41	[0.15,0.67]	0.91	[0.86,0.95]
DIC	Grey-headed albatross	0.35	[0.13,0.51]	0.35	[0.12,0.51]	0.90	[0.86,0.93]
DCU	Shy albatross	0.00	[0.00,0.43]	0.35	[0.12,0.52]	0.90	[0.86,0.93]
DQS	Antipodean albatross	0.00	[0.00,0.38]	0.37	[0.15,0.53]	0.90	[0.86,0.93]
PHU	Sooty albatross	0.39	[0.00,0.69]	0.43	[0.17,0.71]	0.92	[0.86,0.95]
DCR	Atlantic yellow-nosed albatross	0.31	[0.00,0.51]	0.35	[0.13,0.52]	0.90	[0.86,0.93]
TQH	Indian yellow-nosed albatross	0.33	[0.00,0.50]	0.35	[0.13,0.51]	0.90	[0.86,0.93]
PHE	Light-mantled sooty albatross	0.43	[0.04,0.72]	0.43	[0.17,0.71]	0.92	[0.87,0.95]

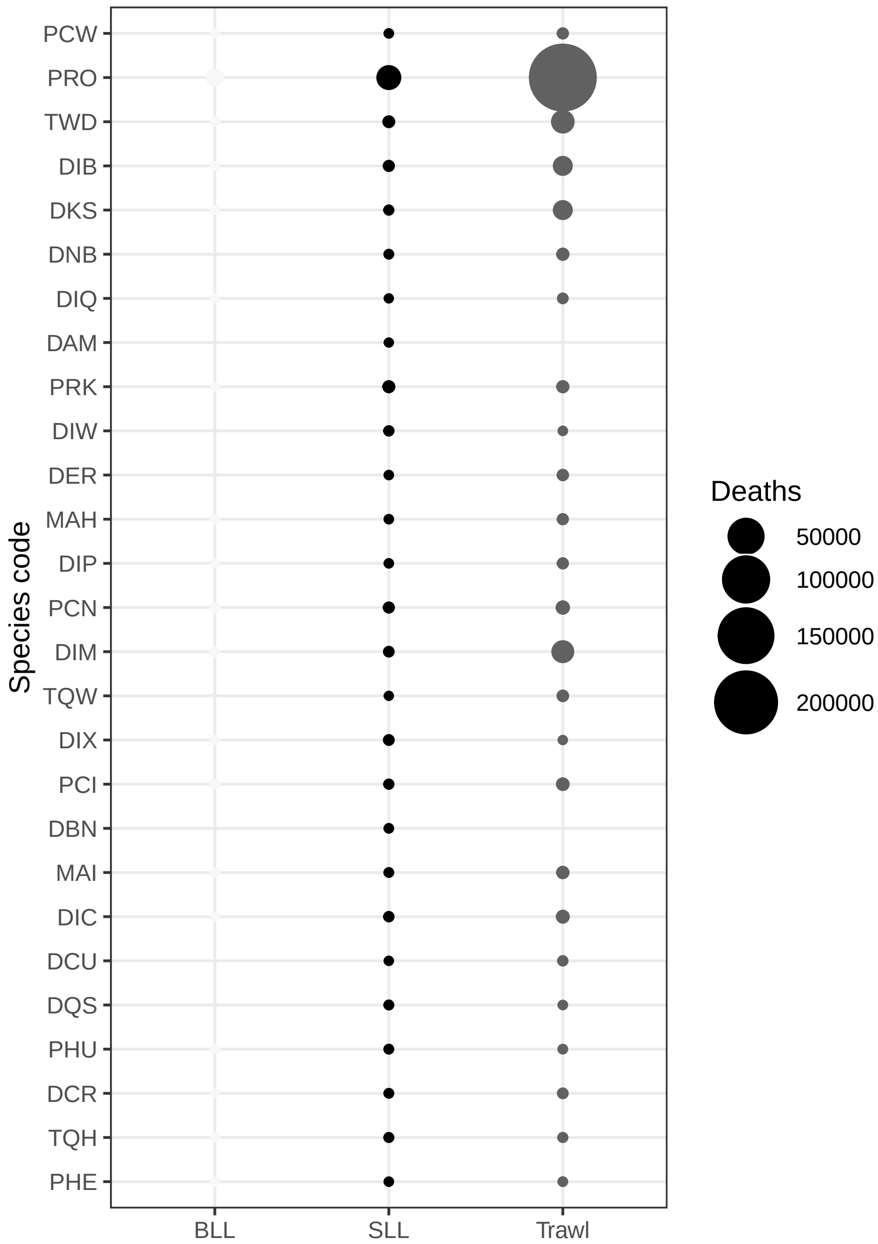

Figure 17: Predicted annual deaths (D) per species and fishery group combination, with species ranked from highest to lowest risk. Species codes are given and correspond to the names listed in Table 1.

Figure 18: Annual average of the posterior density overlap (Equation 6) summed across months per 5 5 grid cell, method, and species group. The mean of the posterior is shown on a log10-scale.