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Update to the risk assessment for New Zealand seabirds

New Zealand Aquatic Environment and Biodiversity Report No. 314

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***New Zealand Aquatic Environment and Biodiversity Report No. 314.* 66 p.**

This report details an implementation of the Spatially Explicit Fisheries Risk Assessment (SEFRA) framework to seabirds in the New Zealand Exclusive Economic Zone, attempting to quantify the impact of New Zealand commercial fisheries on New Zealand populations of seventy-one seabird species. As part of the project both the biological and fishery input data have been updated, as well as the structure of the model itself. The input data have been reviewed in accompanying New Zealand Environment and Biodiversity reports, and in the current report we provide details of the updated model structure as well as an initial implementation.

The most important structural change to the model was to use of a monthly time step consistent across all species, rather than relying on breeding / non-breeding partitions for each species, which may have different breeding seasons. This change greatly improved the ease of model application across species, and allowed improved seasonal resolution, whilst simultaneously increasing the computational requirements. A second notable update was to exclude cryptic capture from the regression equations used to fit the model. This allowed a more stable fit to the data, more transparent diagnosis of the capture predictions, and increased flexibility in application of the cryptic capture multipliers following the fit.

The SEFRA approach uses a limit reference to measure the likely risk of population decline given estimated deaths. This reference point is dependent on the intrinsic growth rate for each species. As a further update to the model, we proposed a revision to how this reference point is estimated.

Model diagnostics were favourable: the model converged well and was able to accurately predict the observed capture data. We tabulated the model predictions of capture, death and risk per species. Partitions by method and fishery group are also presented. Overall, the results are noticeably different from previous iterations of the assessment. Given the magnitude of the changes implemented, this is not surprising. The top at-risk species were concluded to be southern Buller's albatross (XBM), Salvin's albatross (XSA), white-capped albatross (XWM), black petrel (XBP), Westland petrel (XWP), Chatham Island albatross (XCI), flesh-footed shearwater (XFS), northern Buller's albatross (XNB), Gibson's albatross (XAU), Antipodean albatross (XAN), white-chinned petrel (XWC), southern royal albatross (XRA). Only the southern Buller's albatross was estimated to have a risk metric of greater than one, indicating that current captures are higher than what can be sustained by the population over the long term.

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1. INTRODUCTION

New Zealand has been developing and implementing a Spatially Explicit Fisheries Risk Assessment (SEFRA) framework to estimate the risk to seabirds (and other protected species) from commercial fishing (Sharp 2019). From previous applications within the New Zealand Exclusive Economic Zone (EEZ; e.g., Richard & Abraham 2015, Richard et al. 2017, 2020), it has proven to be a useful tool for prioritisation of research and possible management intervention towards the most at-risk seabird species or species groups.

The motivation for the current work was the need to review and update the biological inputs for the SEFRA model, as well as to promote the continual development and refinement of the approach. This will contribute directly to performance objectives under the updated National Plan of Action (NPOA) - Seabirds (Fisheries New Zealand & Department of Conservation 2020).

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 population metrics over time. However, whereas PSA analyses are typically qualitative, SEFRA attempts a quantitative assessment through an inclusive approach to the available information: using strongly informed priors on model parameters and integrating over catches and known biological information from multiple species and fisheries simultaneously. In this way, a quantitative estimate of seabird deaths is generated, which is compared to a reference point that approximates the number of deaths that the population can sustain. Using SEFRA terminology, this reference point is referred to as the Population Sustainability Threshold (PST; e.g.,, Roberts et al. 2019, Large et al. 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. Paramaterisation 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 an estimated probability of dead capture, and an assumed cryptic mortality multiplier.

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

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

The PST is:

$$\text{PST}_s = \phi \cdot r_s \cdot \frac{1}{2} \cdot N_s$$

where r (also referred to as r_{max}) is the maximum intrinsic population growth rate (i.e., under optimal conditions and in the absence of density dependent contraints), and N is the total population size, which we assume in the current setting to be the total number of adults. The parameter ϕ is a tuning parameter set by management (Sharp 2019). 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: ϕ.

Within the remit of the current project, a number of modifications were made to both the data and the model structure. Some of these were first implemented by Webber (2020). When compared with previous work by Richard & Abraham (2015), Richard et al. (2017, 2020), they can be summarised as follows:

- Capture and effort data: Updated data from the Protected Species Capture database (version 6) were used, covering the years 2006/07 to 2019/20.

- Monthly time step: Previously breeding and non-breeding seasons were considered on a species-specific basis, noting that the breeding season differs between species. To simplify the model structure and inputs, as well as to provide a higher temporal resolution, the model was re-structured to take monthly inputs with which to calculate the overlap between fishing effort and the population. Both breeders and non-breeders are combined within each month, with spatial maps constructed to account for the proportion of birds on the nest or available for capture (Peatman et al. 2023).

- Adults only: Captures within New Zealand are predominantly adults, and an independent review recommended that the risk assessment be applied to adults only (Lonergan et al. 2017). Although the PBR methodology constructs a reference point based on the total population size (e.g., Curtis et al. 2015), this would place a downward bias on the estimate of risk. Because captures are primarily of adults, a PST estimated using the total population would assume an unexploited segment of the population regardless of the magnitude of fishery related deaths. We have therefore used a PST based on adults only.

- Fit to captures: The model no longer includes cryptic captures in the capture equation. This is intended to improve the interpretability of model fit diagnostics. Previously, cryptic multipliers were included as part of the model fit, so that vulnerability was being estimated by fitting the model to unobserved cryptic captures. Instead, we have treated the cryptic capture multipliers as scalars by which we convert predicted captures to total deaths following the model fit. This is described in further detail in Section 4.

- Cryptic capture: Cryptic capture rates were reviewed and updated were necessary, for defined cryptic capture species groups. A key determinant of cryptic capture rates in the trawl fishery concerns the probability of net capture. From limited experimental observation, cryptic captures are assumed to be lower for net captures compared with warp captures. To reflect this, net capture probabilities were estimated for the same cryptic capture groups. The empirical data suggest that net capture probabilities have increased since 2000/01, but have been reasonably consistent since 2006/07 (Edwards et al. 2023), and we therefore estimated a constant net capture probability over time.

- Biological input data: Distributional maps have been updated for Gibson's albatross, Antipodean albatross, New Zealand white-capped albatross, Salvin's albatross, Chatham Island albatross, southern Buller's albatross, northern Buller's albatross, black petrel, Westland petrel, white-chinned petrel, flesh-footed shearwater and yellow-eyed penguin (referenced by Peatman et al. 2023, ; see Table 1 for species scientific names). Maps for the remaining species used by Richard et al. (2020), for breeders and non-breeders, were converted to a monthly time step. In addition, biological inputs were reviewed and updated (Peatman et al. 2023).

- Structural assumptions: Species and fishery groups were updated based on perceived differences in species behaviour and fishing practices (Edwards et al. 2023). Temporal disaggregation of the fishery groups was attempted, to account for perceived changes in the observer recording practices and behaviour and structure of the fishing fleets (Edwards et al. 2023). However temporal structure was not supported by the data (i.e., the model did not converge), indicating that captures per unit overlap have been reasonably consistent since 2006/07. This conclusion is supported by graphical representations of the capture per unit overlap, disaggregated by fishery group, provided by Edwards et al. (2023).
- Productivity: The approach used for estimation of the intrinsic growth rate (r_s) was updated to reflect current best practice (Dillingham et al. 2016). This is described in more detail in Section 4.6.

3. DATA

Biological data were compiled and reviewed as part of this project and detailed by Peatman et al. (2023) for New Zealand species. 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 treated as 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 on the nest when breeding breeding, and being within the EEZ. These are further detailed by Peatman et al. (2023).

To fit the model, we used observer data from commercial fisheries for the years 2006/07 to 2019/20. 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. Because not all captures are observable, cryptic mortality multipliers are used to scale 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. Birds 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. A similar logic was followed for the marine mammal risk assessment (MacKenzie et al. 2023). However, given the information content of the seabird capture data, we were able to include a species-specific random effect to allow variation around the species group-specific value. We therefore used the species-specific subscript notation $q_{f,s}$. Fishery groups are defined according to their perceived risk to birds, usually based on the fishing method and gear type. These are justified in detail by Peatman et al. (2023) and Edwards et al. (2023). The list of species assessed, along with their catchability grouping, is given in Table 1. In addition, we provide cryptic capture groupings, that 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 mortality than warp captures. The fishery groups are listed in Table 2.

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}), current age at first breeding (A_s^{curr}), survivorship to the age at first breeding (S_s^A) and female fecundity are used to estimate the maximum intrinsic growth rate r_s from demographic theory;
- Population size: the number of breeding pairs (N_s^{BP}), summed across all New Zealand colonies, is used to estimate the adult population size, which is combined with r_s to calculate the PST;
- Population distribution: the relative density of birds ($d_{s,m,x}$), at grid location x for each month m of the year;
- Fixed biological inputs: for each species the model requires the probability that birds are within the spatial domain of New Zealand fisheries (P_s^{NZ}) 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 fishing gear;
- Fishing effort: fisheries are split into discrete groups, and for each fishing group f, the cumulative fishing effort ($a_{f,m,x}$) 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 ($\mathbb{O}_{f,s}$), which provides an input model covariate assumed to be related to the spatial and temporal overlap of fishing with the bird population;
- Captures: the observed captures ($C'_{f,s}$), summed over space, are used to fit the model, allowing it to subsequently predict total observable captures as a function of the catchability $q_{f,s}$ and total overlap $\mathbb{O}_{f,s}$;
- Cryptic mortality: a multiplier $\kappa_{f,z}$ is used to convert model predicted captures into deaths on the assumption that only a fraction of the captures are recorded and that the realised capture rate 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.

Table 1: Species and capture groups used in the risk assessment model (continued next page). Cryptic groups were also used to estimate the probability of net capture.

Species code	Common name	Scientific name	Catchability group	Cryptic group
XAU	Gibson’s albatross	*Diomedea antipodensis gibsoni*	Great albatross	Large seabirds
XAN	Antipodean albatross	*Diomedea antipodensis antipodensis*	Great albatross	Large seabirds
XRA	Southern royal albatross	*Diomedea epomophora*	Great albatross	Large seabirds
XNR	Northern royal albatross	*Diomedea sanfordi*	Great albatross	Large seabirds
XCM	Campbell black-browed albatross	*Thalassarche impavida*	Mollymawk and Small albatross	Large seabirds
XWM	New Zealand white-capped albatross	*Thalassarche cauta steadi*	Mollymawk and Small albatross	Large seabirds
XSA	Salvin’s albatross	*Thalassarche salvini*	Mollymawk and Small albatross	Large seabirds
XCI	Chatham Island albatross	*Thalassarche eremita*	Mollymawk and Small albatross	Large seabirds
XGM	Grey-headed albatross	*Thalassarche chrysostoma*	Mollymawk and Small albatross	Large seabirds
XBM	Southern Buller’s albatross	*Thalassarche bulleri bulleri*	Mollymawk and Small albatross	Large seabirds
XNB	Northern Buller’s albatross	*Thalassarche bulleri platei*	Mollymawk and Small albatross	Large seabirds
XLM	Light-mantled sooty albatross	*Phoebetria palpebrata*	Mollymawk and Small albatross	Large seabirds
XNP	Northern giant petrel	*Macronectes halli*	Large petrel	Large seabirds
XGP	Grey petrel	*Procellaria cinerea*	Medium petrel	Medium seabirds
XBP	Black petrel	*Procellaria parkinsoni*	Medium petrel	Medium seabirds
XWP	Westland petrel	*Procellaria westlandica*	Medium petrel	Medium seabirds
XWC	White-chinned petrel	*Procellaria aequinoctialis*	Medium petrel	Medium seabirds
XFS	Flesh-footed shearwater	*Puffinus carneipes*	Medium shearwater	Medium seabirds
PUPA	Wedge-tailed shearwater	*Puffinus pacificus*	Small shearwater	Small seabirds
XBS	Buller’s shearwater	*Puffinus bulleri*	Small shearwater	Small seabirds
XSH	Sooty shearwater	*Puffinus griseus*	Medium shearwater	Medium seabirds
XFL	Fluttering shearwater	*Puffinus gavia*	Small shearwater	Small seabirds
XPH	Hutton’s shearwater	*Puffinus huttoni*	Small shearwater	Small seabirds
PUAS	Little shearwater	*Puffinus assimilis*	Small shearwater	Small seabirds
XCA	Snares Cape petrel	*Daption capense australe*	Small petrel	Small seabirds
XFP	Fairy prion	*Pachyptila turtur*	Prion	Small seabirds
XPR	Antarctic prion	*Pachyptila desolata*	Prion	Small seabirds
XPV	Broad-billed prion	*Pachyptila vittata*	Prion	Small seabirds
PTPY	Pycroft’s petrel	*Pterodroma pycrofti*	Small petrel	Small seabirds
PTCO	Cook’s petrel	*Pterodroma cookii*	Small petrel	Small seabirds
PTAX	Chatham petrel	*Pterodroma axillaris*	Small petrel	Small seabirds
XMP	Mottled petrel	*Pterodroma inexpectata*	Small petrel	Small seabirds
PTCE	White-naped petrel	*Pterodroma cervicalis*	Large petrel	Medium seabirds
PTNE	Kermadec petrel	*Pterodroma neglecta*	Large petrel	Medium seabirds
XGF	Grey-faced petrel	*Pterodroma macroptera gouldi*	Large petrel	Medium seabirds
PTMA	Chatham Island taiko	*Pterodroma magentae*	Large petrel	Medium seabirds

Table 1: Continued

Species code	Common name	Scientific name	Catchability group	Cryptic group
XWH	White-headed petrel	*Pterodroma lessonii*	Large petrel	Medium seabirds
PTMO	Soft-plumaged petrel	*Pterodroma mollis*	Small petrel	Small seabirds
XDP	Common diving petrel	*Pelecanoides urinatrix*	Small petrel	Small seabirds
XSD	Whenua Hou diving petrel	*Pelecanoides whenuahouensis*	Small petrel	Small seabirds
XWF	New Zealand white-faced storm petrel	*Pelagodroma marina maoriana*	Small petrel	Small seabirds
XWB	White-bellied storm petrel	*Fregetta grallaria grallaria*	Small petrel	Small seabirds
XFT	Black-bellied storm petrel	*Fregetta tropica*	Small petrel	Small seabirds
PEAL	Kermadec storm petrel	*Pelagodroma albiclunis*	Small petrel	Small seabirds
PEMA	New Zealand storm petrel	*Pealeornis maoriana*	Small petrel	Small seabirds
XYP	Yellow-eyed penguin	*Megadyptes antipodes*	Penguin	Diving seabirds
EUIR	Northern little penguin	*Eudyptula minor f. iredalei*	Penguin	Diving seabirds
EUAL	White-flippered little penguin	*Eudyptula minor f. albosignata*	Penguin	Diving seabirds
EUMI	Southern little penguin	*Eudyptula minor f. minor*	Penguin	Diving seabirds
EUCH	Chatham Island little penguin	*Eudyptula minor f. chathamensis*	Penguin	Diving seabirds
EUFI	Eastern rockhopper penguin	*Eudyptes chrysocome filholi*	Penguin	Diving seabirds
XFC	Fiordland crested penguin	*Eudyptes pachyrhynchus*	Penguin	Diving seabirds
EURO	Snares crested penguin	*Eudyptes robustus*	Penguin	Diving seabirds
EUSC	Erect-crested penguin	*Eudyptes sclateri*	Penguin	Diving seabirds
XGT	Australasian gannet	*Morus serrator*	Other seabirds	Diving seabirds
XMB	Masked booby	*Sula dactylatra*	Other seabirds	Diving seabirds
XPS	Pied shag	*Phalacrocorax varius varius*	Shag	Diving seabirds
XBC	Little black shag	*Phalacrocorax sulcirostris*	Shag	Diving seabirds
XKS	New Zealand king shag	*Leucocarbo carunculatus*	Shag	Diving seabirds
XSI	Otago shag	*Leucocarbo chalconotus*	Shag	Diving seabirds
XFX	Foveaux shag	*Leucocarbo stewarti*	Shag	Diving seabirds
XCS	Chatham Island shag	*Leucocarbo onslowi*	Shag	Diving seabirds
LERA	Bounty Island shag	*Leucocarbo ranfurlyi*	Shag	Diving seabirds
LECO	Auckland Island shag	*Leucocarbo colensoi*	Shag	Diving seabirds
LECA	Campbell Island shag	*Leucocarbo campbelli*	Shag	Diving seabirds
XPP	Spotted shag	*Stictocarbo punctatus*	Shag	Diving seabirds
XPF	Pitt Island shag	*Stictocarbo featherstoni*	Shag	Diving seabirds
CALO	Subantarctic skua	*Catharacta antarctica lonnbergi*	Other seabirds	Medium seabirds
XBG	Southern black-backed gull	*Larus dominicanus dominicanus*	Other seabirds	Medium seabirds
HYCA	Caspian tern	*Hydroprogne caspia*	Other seabirds	Small seabirds
GYCA	White tern	*Gygis alba candida*	Other seabirds	Small seabirds

Table 2: Fishery groups used in the risk assessment model. The methods are bottom longline (BLL), surface longline (SLL), set net (SN) and Trawl.

Method	Fishery group	Identifier
BLL	Large Autoline with IWL	1
BLL	Large Autoline	2
BLL	Small Autoline (LIN, RIB)	3
BLL	Small Autoline	4
BLL	Small Manual (heavy)	5
BLL	Small Manual (light)	6
BLL	Small Manual (LIN, RIB)	7
SLL	Large SLL	8
SLL	Small SLL (tuna and swordfish)	9
SN	SN (unclassified)	10
Trawl	Deepwater	11
Trawl	Large Freezer	12
Trawl	Large Fresher	13
Trawl	Mackerel	14
Trawl	Scampi	15
Trawl	Small inshore (17-28m)	16
Trawl	Small inshore (less than 17m)	17
Trawl	Southern Blue Whiting	18
Trawl	Squid	19

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

Notation	Description
Subscripts	
f	Fishing group
s	Species
z	Species group
m	Month
x	Raster grid
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
β_f, β_z, $\varepsilon_{s\|f}$	Catchability coefficients
$\gamma_0, \gamma_f, \gamma_z$	Survivorship coefficients
π_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}
$\mathbb{D}_{s,m,x}$	Density of adults available to fishing
$q_{f,s}$ and $q_{f,z}$	Catchabilty (the species group catchability is the geometric mean of the catchability across species)
$\upsilon_{f,s}$ and $\upsilon_{f,z}$	Vulnerability (the species group vulnerability is the geometric mean of the vulnerability across species)
$\Psi_{f,z}$	Probability alive given capture
$T_{f,s}$	Number of interactions
$C_{f,s}$	Number of observable captures
Input covariates	
$P_{s,m}^{\mathrm{NZ}}$	Probability of an adult being in the New Zealand EEZ
$P_{s,m}^{\mathrm{nest}}$	Probability of a breeding adult being on the nest
$d_{s,m,x}$	Relative density of adults per km^2
$a_{f,m,x}$	Fishing effort
$K_{f,z}$	Cryptic capture multiplier
$\kappa_{f,z}$	Cryptic mortality multiplier
ω	Probability of post-release survivorship
Derived covariates	
$\mathbb{O}_{f,s}$	Density overlap
Observational data	
$C'_{f,s}$	Number of observed captures
$C_{f,s}^{\mathrm{LIVE}\prime}$, $C_{f,s}^{\mathrm{DEAD}\prime}$	Number of observed live and dead captures
$C_{f,s}^{\mathrm{NET}\prime}$, $C_{f,s}^{\mathrm{WARP}\prime}$	Number of observed net and warp captures

4. STATISTICAL 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:

$$N_s^{\text{adults}} = 2 \cdot \frac{N_s^{\text{BP}}}{P_s^{\text{B}}}$$

The number of adults available to fishing gear within the EEZ at any point of the year is determined by 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:

$$N_{s,m} = N_s^{\text{adults}} \cdot (1 - P_s^{\text{B}} \cdot P_{s,m}^{\text{nest}}) \cdot P_{s,m}^{\text{NZ}}$$

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

4.2 Spatial distribution and overlap

The spatial distribution of the species within the EEZ 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 location x in month m (Peatman et al. 2023). Specifically, if $y_{s,m,x}$ is a relative number of birds in grid x, usually derived from empirical data, then:

$$d_{s,m,x} = \frac{y_{s,m,x}}{A_x \cdot \sum_x y_{s,m,x}}$$

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 x during that month. The absolute density, in number of birds per square kilometre, is therefore:

$$\mathbb{D}_{s,m,x} = d_{s,m,x} \cdot N_{s,m}$$

If fishing effort for each fishery group f is allocated to grid x, and assuming a uniform distribution of birds and fishing effort within that grid, then the overlap is a measure of the possibility for interaction per grid:

$$\text{overlap}_{f,s,m,x} = \underbrace{\text{effort}_{f,m,x}}_{a_{f,m,x}} \cdot d_{s,m,x}$$

and the density overlap is:

$$\underbrace{\text{density overlap}_{f,s}}_{\mathbb{O}_{f,s}} = \sum_{m,x} a_{f,m,x} \cdot \mathbb{D}_{s,m,x}$$

for which we introduce the notation $\mathbb{O}_{k,s}$ and $a_{f,m,x}$ (Sharp 2019). The density overlap is proportional to the opportunity for interaction between birds of species s and fishing group f, when considered across their full spatial distributions and accounting for monthly changes in these distributions during the year.

4.3 Expected captures

The rate of interaction per unit of density overlap is described by the vulnerability $\upsilon_{f,s}$, 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:

$$\underbrace{\text{interaction}_{f,s}}_{T_{f,s}} = \upsilon_{f,s} \cdot \mathbb{O}_{f,s}$$

The observable interactions are referred to as captures and are a function of the catchability ($q_{f,s}$) and are therefore expected to be:

$$\text{captures}_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s}$$

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

$$\underbrace{\text{dead captures}_{f,s}}_{C^{\text{DEAD}}_{f,s}} = \underbrace{\text{captures}_{f,s}}_{C_{f,s}} \cdot (1 - \Psi_{f,z})$$

The number of observable 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 $\mathbb{O}'_{f,s}$ are used to calculate the expected number of observed captures:

$$\underbrace{\text{observed captures}_{f,s}}_{C'_{f,s}} = q_{f,s} \cdot \mathbb{O}'_{f,s}$$

Similarly the number of observed dead and live captures are $C^{\text{DEAD}\prime}_{f,s}$ and $C^{\text{LIVE},\prime}_{f,s}$, 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 s, then the expectation is:

$$\mu_{f,s} = q_{f,s} \cdot \mathbb{O}'_{f,s}$$

and the likelihood is:

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

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

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

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

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

All trawl warp captures are assumed to be dead.

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

$$\log(q_{f,s}) = \beta_f + \beta_z + \varepsilon_{s|f}$$

where the fishery group coefficient β_f is centred on a method-specific intercept term, with deviations around this intercept constrained to sum to zero. Species group specific coefficients (β_z) were similarly constrained to sum to zero. The species-specific term $\varepsilon_{s|f}$ was treated as a random effect centred on zero and nested within each fishery group. This allows the catchability to deviate from the fixed fishery and species group effects in a manner dependent on the information content of the data. When reporting estimates for the species group-specific value $q_{f,z}$, we take the geometric mean across the random effects, which is equivalent to setting $\varepsilon_{s|f} = 0$. The probability of live captures is:

$$\text{logit}(\Psi_{f,z}) = \gamma_0 + \gamma_f + \gamma_z$$

with coefficients γ_f and γ_z similarly constrained to sum to zero.

4.5 Prediction of total interactions and deaths

During the fitting process we estimate the catchability $q_{f,s}$, which describes the rate of observed capture relative to the density overlap. If the presence of an observer does not influence the capture rate then $q_{f,s}$ is also 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, and not all deaths will be captures because they are not all observable. The relationship between observable captures and total interactions and deaths is described by Edwards et al. (2023) with reference to the data used to estimate the cryptic multipliers. Here we summarise how these multipliers are used following prediction of C from a fit to the data.

To predict interactions based on the number of captures, we need a *cryptic capture* multiplier: $K_{f,z}$, that accounts for the fact that not all captures will be observed even if an observer is present. The interaction equation is:

$$\begin{aligned} T_{f,s} &= \upsilon_{f,s} \cdot \mathbb{O}_{f,s} \\ &= q_{f,s} \cdot \mathbb{O}_{f,s} \cdot K_{f,z} \end{aligned}$$

To predict deaths from captures as a subset of these interactions we use the *cryptic mortality* multiplier $\kappa_{f,z}$. Since deaths are a subset of interactions $\kappa_{f,z} \leq K_{f,z}$. In general the number of deaths is:

$$D_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot \kappa_{f,z}$$

The cryptic mortality multiplier specifically relates the number of predicted observable captures to the number of deaths. It includes both the number of cryptic captures per observable capture, and the probability that these interactions lead to death. In the current work we further expand this definition to include the death of live captures that can occur post release.

The derivation of $K_{f,z}$ and $\kappa_{f,z}$ 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. Whether a capture is cryptic is typically dependent on whether it is alive or dead, and we are therefore reliant on the estimated parameter $\Psi_{f,z}$ in our derivations. We further assume a probability multiplier ω to describe the probability of post-capture death for a live interaction.

For the longline fishery (SLL and BLL), we assume that captures at haul-back are alive, and that captures at setting are lost at a rate of k^{longline}. We use available information on the cryptic captures that take place during setting to calculate the total interactions and deaths as:

$$T_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot \underbrace{\left(\Psi_{f,z} + (1 - \Psi_{f,z}) \cdot k^{\text{longline}}\right)}_{K_{f,z}}$$

$$D_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot \underbrace{\left(\Psi_{f,z} \cdot (1 - \omega) + (1 - \Psi_{f,z}) \cdot k^{\text{longline}}\right)}_{\kappa_{f,z}}$$

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:

$$T^{\text{net}}_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot \pi^{\text{net}}_{z} \cdot k^{\text{net}}$$

For warp captures, which take place with estimated probability $1 - \pi^{\text{net}}_{z}$, 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:

$$T^{\text{warp}}_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot (1 - \pi^{\text{net}}_{z}) \cdot k^{\text{warp}}_{z}$$

For the trawl fishery overall, the summation is:

$$T_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot \left(\pi^{\text{net}} \cdot k^{\text{net}} + (1 - \pi^{\text{net}}) \cdot k^{\text{warp}}_{z})\right)$$

and the deaths are:

$$\begin{aligned} D_{f,s} = q_{f,s} \cdot \mathbb{O}_{f,s} \cdot \big(&\pi^{\text{net}} \cdot k^{\text{net}} \cdot (1 - \Psi_{f,z} \cdot \omega) + \\ &(1 - \pi^{\text{net}}) \cdot k^{\text{warp}}_{z}\big) \end{aligned}$$

All deaths were generated using posterior predictive simulation from a Poisson distribution conditioned on the expected value. As for previous iterations of the risk assessment, deaths were predicted as an annual average across the most recent three years of data: 2017/18 to 2019/20. The total average deaths per species is a summation of the deaths across fishery group:

$$D_s = \sum_f D_{f,s}$$

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

Table 4: Cryptic mortality multipliers for longline, net and warp captures (continued on next page). Their derivation is described in full by Edwards et al. (2023). Estimated probabilities of net capture are also shown, since these are relevant to the prediction of cryptic mortalities.

		$k^{longline}$		k^{net}		k_s^{warp}		π_z^{net}	
Code	Cryptic group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XAU	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.11	[13.52-31.59]	0.72	[0.70-0.74]
XAN	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.10	[13.50-31.49]	0.72	[0.70-0.74]
XRA	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.10	[13.47-31.53]	0.72	[0.70-0.74]
XNR	Large seabirds	1.42	[0.97-2.02]	1.30	[1.10-1.70]	21.09	[13.44-31.49]	0.72	[0.70-0.74]
XCM	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.12	[13.47-31.60]	0.72	[0.70-0.74]
XWM	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	21.09	[13.42-31.50]	0.72	[0.70-0.74]
XSA	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.11	[13.49-31.51]	0.72	[0.70-0.74]
XCI	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.08	[13.44-31.44]	0.72	[0.70-0.74]
XGM	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.11	[13.46-31.49]	0.72	[0.70-0.74]
XBM	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.09	[13.48-31.46]	0.72	[0.70-0.74]
XNB	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.11	[13.44-31.55]	0.72	[0.70-0.74]
XLM	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.07	[13.40-31.51]	0.72	[0.70-0.74]
XNP	Large seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	21.09	[13.43-31.57]	0.72	[0.70-0.74]
XGP	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	184.00	[59.49-438.18]	0.99	[0.99-0.99]
XBP	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	185.09	[59.48-441.30]	0.99	[0.99-0.99]
XWP	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	184.61	[59.82-438.70]	0.99	[0.99-0.99]
XWC	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	184.24	[59.62-438.33]	0.99	[0.99-0.99]
XFS	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	185.21	[59.84-440.32]	0.99	[0.99-0.99]
PUPA	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.13	[44.77-366.81]	0.89	[0.78-0.97]
XBS	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	147.95	[44.72-364.89]	0.89	[0.78-0.97]
XSH	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	185.02	[59.82-442.97]	0.99	[0.99-0.99]
XFL	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.32	[44.75-367.62]	0.89	[0.78-0.97]
XPH	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.14	[44.74-370.00]	0.89	[0.78-0.97]
PUAS	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	147.29	[44.70-362.64]	0.89	[0.78-0.97]
XCA	Small seabirds	1.42	[0.97-2.02]	1.30	[1.10-1.70]	148.14	[44.96-367.54]	0.89	[0.78-0.97]
XFP	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.09	[44.49-364.47]	0.89	[0.78-0.97]
XPR	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.20	[44.80-366.64]	0.89	[0.78-0.97]
XPV	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.00	[45.21-366.41]	0.89	[0.78-0.97]
PTPY	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.21	[44.77-367.72]	0.89	[0.78-0.97]
PTCO	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.59	[44.71-371.14]	0.89	[0.78-0.97]
PTAX	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.01	[44.81-366.53]	0.89	[0.78-0.97]
XMP	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.27	[44.63-366.82]	0.89	[0.78-0.97]
PTCE	Medium seabirds	1.42	[0.97-2.00]	1.30	[1.10-1.71]	184.69	[59.43-441.67]	0.99	[0.99-0.99]
PTNE	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	184.86	[59.35-441.24]	0.99	[0.99-0.99]
XGF	Medium seabirds	1.42	[0.97-2.00]	1.30	[1.10-1.70]	184.47	[59.61-441.55]	0.99	[0.99-0.99]
PTMA	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	184.85	[59.67-444.03]	0.99	[0.99-0.99]
XWH	Medium seabirds	1.42	[0.97-2.00]	1.30	[1.10-1.70]	184.41	[59.25-436.29]	0.99	[0.99-0.99]
PTMO	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.04	[45.24-368.23]	0.89	[0.78-0.97]
XDP	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.00	[45.03-366.55]	0.89	[0.78-0.97]
XSD	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.37	[44.77-367.92]	0.89	[0.78-0.97]
XWF	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.17	[45.02-367.72]	0.89	[0.78-0.97]
XWB	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	148.24	[44.77-368.06]	0.89	[0.78-0.97]
XFT	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	147.83	[44.57-365.36]	0.89	[0.78-0.97]
PEAL	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	147.95	[44.68-365.02]	0.89	[0.78-0.97]
PEMA	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	147.82	[44.68-366.39]	0.89	[0.78-0.97]
XYP	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EUIR	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EUAL	Diving seabirds	1.42	[0.97-2.02]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EUMI	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EUCH	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EUFI	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XFC	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EURO	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
EUSC	Diving seabirds	1.42	[0.97-2.00]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XGT	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XMB	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XPS	Diving seabirds	1.42	[0.97-2.02]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]

Table 4: Continued

		$k^{longline}$		k^{net}		k_s^{warp}		π_z^{net}	
Code	Cryptic group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBC	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XKS	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XSI	Diving seabirds	1.42	[0.97-2.02]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XFX	Diving seabirds	1.42	[0.97-2.00]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XCS	Diving seabirds	1.42	[0.97-2.02]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
LERA	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
LECO	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
LECA	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XPP	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
XPF	Diving seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	0.00	[0.00-0.00]	0.97	[0.90-1.00]
CALO	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	184.12	[59.51-442.31]	0.99	[0.99-0.99]
XBG	Medium seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.70]	184.31	[59.31-439.49]	0.99	[0.99-0.99]
HYCA	Small seabirds	1.42	[0.97-2.01]	1.30	[1.10-1.71]	148.29	[44.87-367.90]	0.89	[0.78-0.97]
GYCA	Small seabirds	1.42	[0.97-2.00]	1.30	[1.10-1.70]	147.70	[44.56-366.54]	0.89	[0.78-0.97]

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 is achieved using two competing methods following the approach of Dillingham et al. (2016), which proposes to use the intersection of the two methods as the most likely value. A similar approach has been used for marine mammals (Edwards et al. 2018, Roberts et al. 2019, MacKenzie et al. 2023).

The first method, based on the derivation by Euler (1760) and Lotka (1907), then simplified by Myers et al. (1997) and Skalski et al. (2008), estimates λ as the solution to the equation:

$$0 = S^{opt} \cdot \lambda^{A-1} - \lambda^{A} + b \cdot S_{A}^{opt}$$

where b is the fecundity (number of females born per breeding female per year), A is the age at first breeding, S^{opt} is the optimal survivorship (i.e., in the absence of density dependent limitations), $S_{A}^{opt} = S_{egg} \cdot S_{juv}^{A-1}$ is the survivorship to age A, S_{egg} is the survivorship of age zero individuals (eggs), and S_{juv} is the juvenile survivorship. This approach is frequently used in the ecological literature (reviewed by Cortés & Travis 2016).

An alternative method (with lower data requirements) is provided by 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:

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

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

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

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

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).

For the current analysis, we combine the Euler-Lotka (EL) and demographic-invariant (DI) methods, limiting the uncertainty by selecting values for λ_s that are compatible with both λ_s^{DI} and λ_s^{EL} estimators (Dillingham et al. 2016, Edwards et al. 2018, Roberts et al. 2019, MacKenzie et al. 2023).

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 withing the model, each with strongly informative priors. Egg and juvenile survival values were obtained using assumed multipliers to S_s^{opt} and used to calculate S_A^{opt}. The probability of breeding P_s^{B} and the clutch size were used to estimate the fecundity b, with the clutch size treated as a fixed input value (Peatman et al. 2023).

Within the model, λ_s was treated as an estimated parameter with competing priors equal to λ_s^{DI} and λ_s^{EL}. These priors required equations for λ_s^{DI} and λ_s^{EL} to be solved numerically within the model with each posterior sample of S_s^{opt}, A_s^{curr} and P_s^{B}. This heirarchical struture ensured that λ_s was estimated at the intersection between the two competing EL and DI estimators.

4.7 Parameter estimation

All estimation was performed within a Bayesian framework using rstan (Stan Development Team 2020). Two chains were run for 2000 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 (Peatman et al. 2023). Predictors of the catchability ($q_{f,s}$) and post-capture survival ($\Psi_{f,z}$), as well as the probability of a net capture (π_s^{net}), were given uninformative priors.

4.8 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 ($q_{f,s}$). Assumptions concerning cryptic capture and mortality allow these catchabilities to be converted into vulnerabilties ($\upsilon_{f,s}$). From comparison of the catchability and vulnerability terms, the model fit in the first instance provides 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, and trawl fishery groups can be compared with other trawl 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 (observed and unobserved), 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. Consistent with previous iterations, risk was calculated using annual captures averaged over the most recent three years of data only (2017/18 to 2019/20). In presentation of the results we assume that the PST tuning parameter $\phi = 1$ throughout.

5. RESULTS

5.1 Convergence diagnostics

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

$$\begin{aligned} \mathrm{q}\,(\mathrm{method}) &= ||\beta_f|| \\ \mathrm{q}\,(\mathrm{species}) &= ||\beta_z|| \\ \mathrm{Prob.\,live\,capture} &= ||\gamma_0, \gamma_f, \gamma_z|| \\ \mathrm{Prob.\,net\,capture} &= ||\pi_z^{net}|| \end{aligned}$$

where $||.||$ is the Euclidean norm of the enclosed parameter vector. Trace plots for the catchability summary diagnostics are shown in Figure 1.

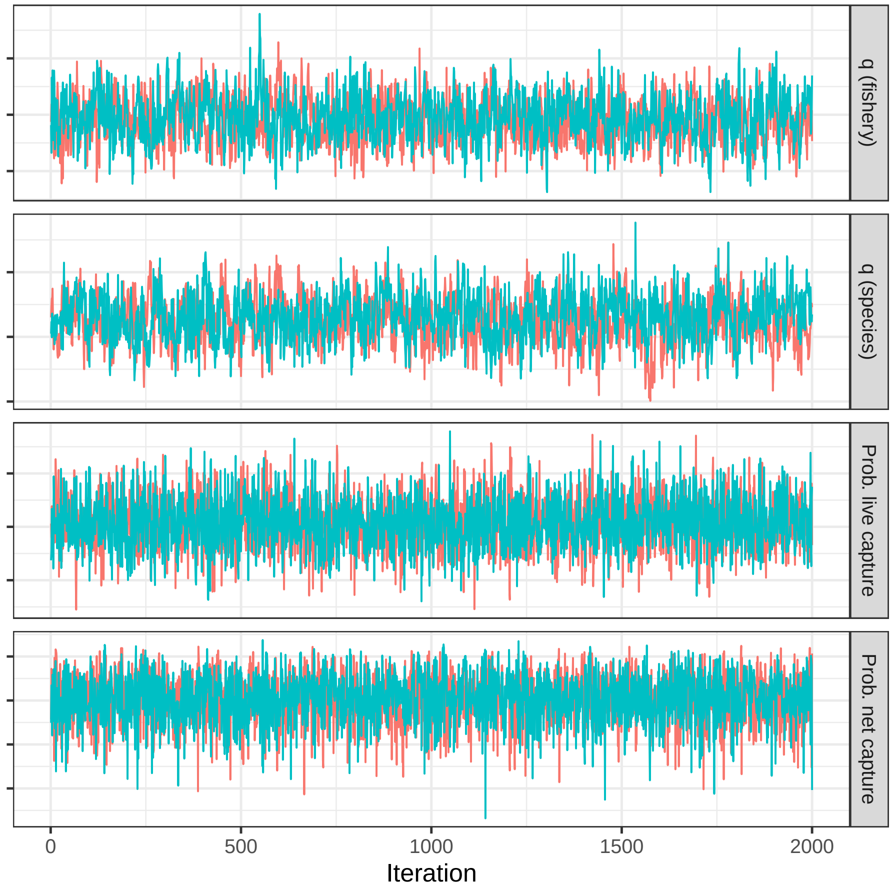

Figure 1: Trace plots of catchability predictors, illustrated using the summary statistics: $||\beta_f||$, $||\beta_z||$, probability of live capture ($||\gamma_0, \gamma_j, \gamma_z||$) and probability of net capture ($||\pi_z^{net}||$).

For biological parameters, we used the following summary statistics:

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

These are shown in Figure 2. In both Figures 1 and 2 it can be seen that the model converges well.

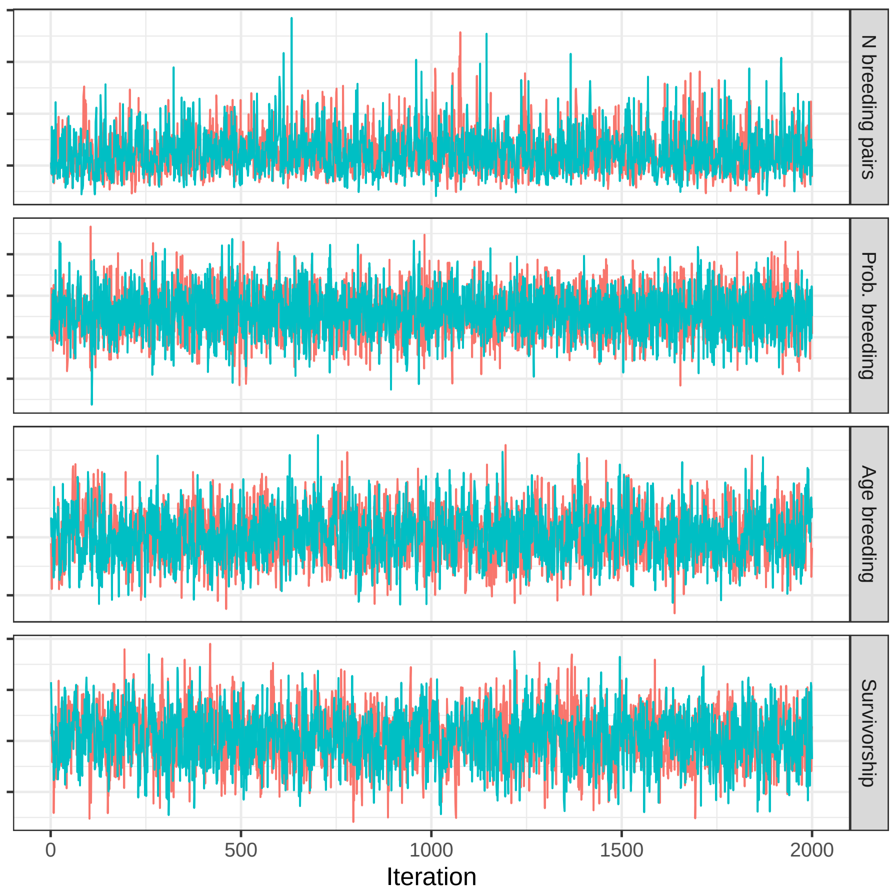

Figure 2: Trace plots for summary statistics of estimated biological parameter vectors: number of breeding pairs ($||N_s^{\text{BP}}||$), probability breeding ($||P_s^{B}||$), current age of first breeding ($||A_s^{\text{curr}}||$) and survivorship ($||S_s^{\text{opt}}||$).

5.2 Model fit

For diagnosing the model fit, we demonstrate ability of the model to predict the data. Figure 3 provides an illustration of the predicted average annual captures per species and fishery group, indicating that overall the fit is good.

Figure 4 shows the prediction of the sum of observed captures ($C'_{f,s}$) by fishery group and species group, which is the resolution of the fixed effects used by the model when estimating the catchability. From Figure 4, there is some underestimation of the captures at low capture numbers, but at higher numbers the fit is good. Figure 5 shows prediction of the probability of non-zero records in the data being presented to the model. The model is over-estimating the probability of a positive data record. This is likely due to aggregation of the capture data prior to it being presented to the model, which will lead to over-dispersion if the data are not drawn from identical distributions. The Poisson likelihood assumption is therefore only approximate, but provides reliable model convergence and is considered sufficient in the current context. 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 5.

In estimating the probability of live capture Ψ_{fz}, the model fits to observed live captures $C^{\mathrm{LIVE}\prime}_{fs}$ using a binomial distribution conditioned on C'_{fs}. The predicted and empirical numbers of observed dead captures ($C^{\mathrm{DEAD}\prime}_{s}$) are given per species in Table 6. Good prediction of observed live captures are shown in Figure 6.

A binomial distribution is also used to estimate π^{NET}_{z}, 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 7. The estimated probabilities of net capture per cryptic capture group are given in Table 4.

Given that density overlap ($\mathbb{O}_{fs}$) is used as an input covariate for prediction of captures, we constructed the diagnostic shown in Figure 8 using the observed overlap $\mathbb{O}'_{fs}$. Since the density overlap is a linear predictor of captures, the cumulative sum of the captures should be increasae linearly with the cumulative sum of the overlap. Departures from linearity indicate that captures are skewed towards higher or lower overlap values. For example, if the cumulative sum of captures increases faster than the cumulative sum of the overlap (i.e., is above the diagonal line of equivalence) then this indicates that captures are occuring disproportionaly in regions of low overlap. Similarly, if the cumulative sum of captures increases more slowly than the cumulative sum of the overlap (i.e., is below the diagonal line of equivalence) then captures are concentrated in regions of high overlap. From empirical values in Figure 8, we can see that for the BLL and SLL fisheries captures appear to be concentrated in regions where the overlap is low. In contrast, overlap is a better predictor of captures for the trawl fishery groups, with the exception of medium petrels.

Regardless of whether overlap is a good spatial match to the distribution of captures, if the model is predicting the captures correctly then the cumulative sum of the predicted captures should follow a similar relationship to the cumulative sum of the empirical data. We can therefore use the correspondence between the empirical and predicted values to diagnose whether captures are being predicted correctly over space. We can see from Figure 8 that this appears to be true in most cases with reasonable quantities of informative data, with information content of the data for the model fit indicated by the width of the 95% credibility intervals. For example the capture of medium petrels in the BLL, SLL and trawl fisheries all show a close correspondence between observed and predicted values. There are also instances of a poor model fit; for example great albatross in the SLL fishery. In this case the data indicate a higher concentration of captures in regions of low overlap, whereas the model predicts a closer correspondence between overlap and captures. Such discrepancies may warrant further investigation at the level of the fishery group and species.

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 9). There are stong seasonal differences in the number of captures, particularly for medium petrels and shearwaters in the trawl fisheries, and mollymawks and small altabross in the SLL fisheries. The model predicts these seasonal changes well, indicating that the monthly structure of the model is warranted and allowing it to be used to predict seasonal changes in risk if required.

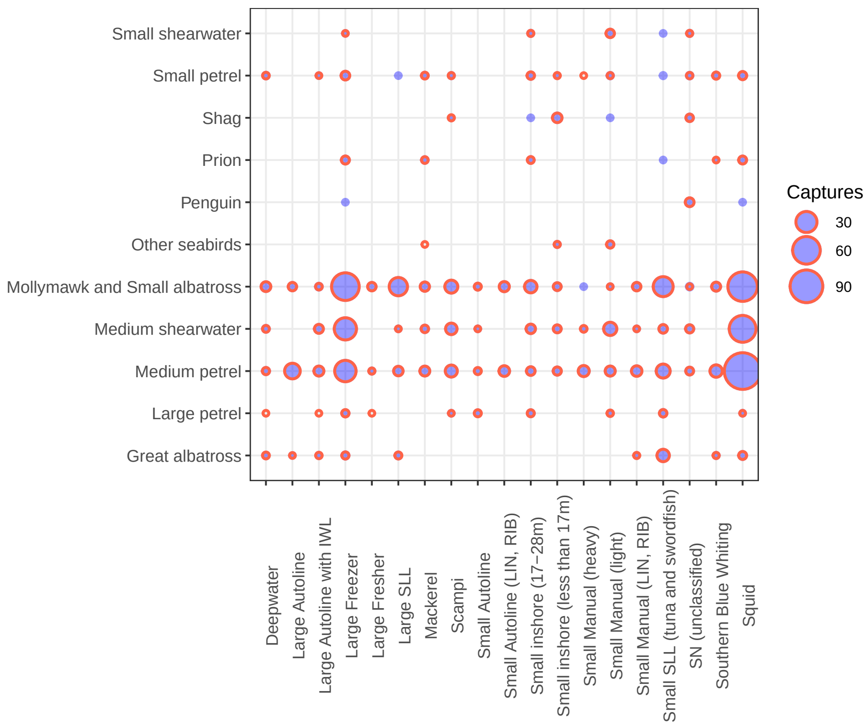

Figure 3: Model fit to observed average annual captures ($C'_{f,z}$) per species and fishery group combination, between 2006/07 and 2019/20. Model predicted values are represented by the posterior median of the sum accross species per group, and shaded in blue. Empirical values are represented by red circles.

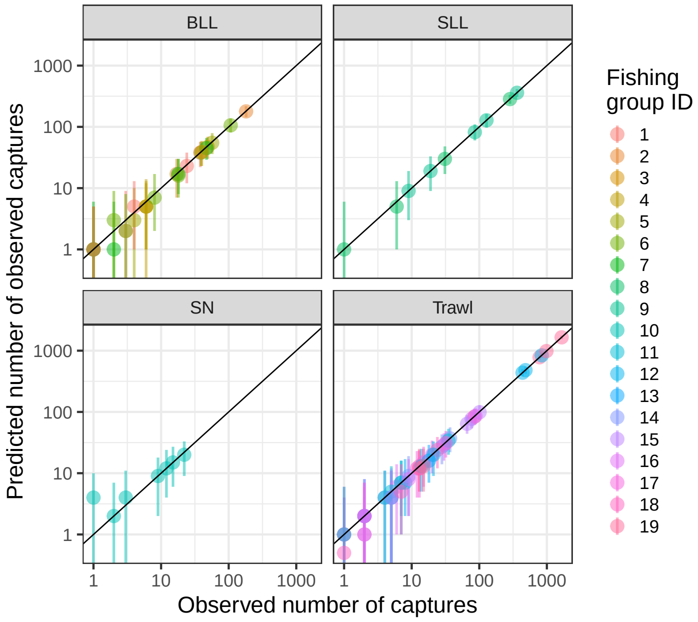

Figure 4: Model fit to the number of observed captures $C'_{f,z}$ for each fishing method. Zero values are omitted. Captures are summed across species within each species group, between 2006/07 and 2019/20, and each point represents a unique combination of species group and fishery group. Median and 95% quantile values are shown.

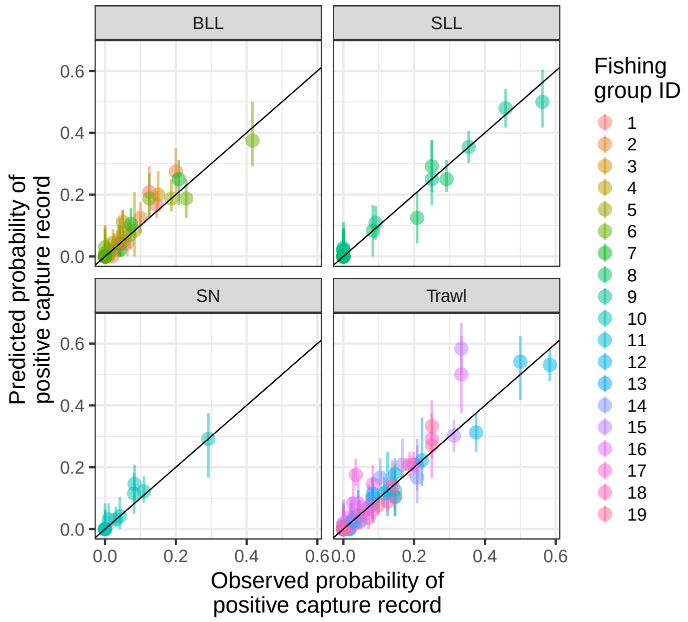

Figure 5: Model fit to the probability of observed capture per capture record $\mathbb{P}[C'_{f,z} > 0]$. Values are shown for each fishing method. Each point represents calculation of the probability across species within each species group and fishery group. Median and 95% quantile values for this probability are shown.

Table 5: **Model fit to observed captures per species C'_s, summed from 2006/07 to 2019/20: empirical value, posterior and $\hat{R}$ for each species (continued on next page).**

		Posterior		
Species	Observed	Median	95% CI	$\hat{R}$
Gibsons albatross	35	35	[22–49]	1.00
Antipodean albatross	42	41	[27–58]	1.00
Southern royal albatross	43	42	[29–59]	1.00
Northern royal albatross	5	6	[2–13]	1.00
Campbell blackbrowed albatross	44	45	[32–62]	1.00
New Zealand whitecapped albatross	1430	1428	[1342–1515]	1.00
Salvins albatross	513	508	[458–561]	1.00
Chatham Island albatross	33	30	[18–43]	1.00
Greyheaded albatross	1	5	[1–11]	1.00
Southern Bullers albatross	785	781	[715–847]	1.00
Northern Bullers albatross	59	59	[42–78]	1.00
Lightmantled sooty albatross	1	6	[2–12]	1.00
Northern giant petrel	15	10	[4–19]	1.00
Grey petrel	139	140	[114–169]	1.00
Black petrel	171	168	[138–201]	1.00
Westland petrel	103	105	[82–129]	1.00
Whitechinned petrel	2508	2502	[2385–2621]	1.00
Fleshfooted shearwater	186	182	[152–213]	1.00
Wedgetailed shearwater	0	0	[0–0]	1.00
Bullers shearwater	16	15	[7–26]	1.00
Sooty shearwater	1373	1377	[1291–1465]	1.00
Fluttering shearwater	7	8	[3–16]	1.00
Huttons shearwater	0	2	[0–5]	1.00
Little shearwater	0	1	[0–4]	1.00
Snares Cape petrel	12	9	[3–17]	1.00
Fairy prion	20	22	[12–33]	1.00
Antarctic prion	10	12	[5–21]	1.00
Broadbilled prion	7	8	[3–15]	1.00
Pycrofts petrel	0	0	[0–2]	1.00
Cooks petrel	0	3	[0–8]	1.00
Chatham petrel	0	0	[0–0]	1.00
Mottled petrel	4	6	[2–12]	1.00
Whitenaped petrel	0	0	[0–1]	1.00
Kermadec petrel	0	0	[0–1]	1.00
Greyfaced petrel	21	24	[14–37]	1.00
Chatham Island taiko	0	0	[0–0]	1.00
Whiteheaded petrel	1	4	[1–10]	1.00
Softplumaged petrel	0	0	[0–1]	1.00
Common diving petrel	38	38	[25–53]	1.00
Whenua Hou diving petrel	0	0	[0–0]	1.00
New Zealand whitefaced storm petrel	14	13	[6–23]	1.00
Whitebellied storm petrel	0	0	[0–0]	1.00
Blackbellied storm petrel	4	4	[1–10]	1.00
Kermadec storm petrel	0	0	[0–0]	1.00
New Zealand storm petrel	0	0	[0–1]	1.00
Yelloweyed penguin	17	15	[7–25]	1.00
Northern little penguin	0	1	[0–4]	1.00
Whiteflippered little penguin	0	0	[0–2]	1.00
Southern little penguin	0	1	[0–4]	1.00
Chatham Island little penguin	0	0	[0–2]	1.00
Eastern rockhopper penguin	0	0	[0–3]	1.00
Fiordland crested penguin	5	4	[1–10]	1.00
Snares crested penguin	0	1	[0–3]	1.00
Erectcrested penguin	0	1	[0–3]	1.00
Australasian gannet	1	1	[0–4]	1.00
Masked booby	0	0	[0–0]	1.00
Pied shag	1	2	[0–6]	1.00
Little black shag	0	1	[0–3]	1.00

Table 5: Continued

Species	Observed	Posterior Median	Posterior 95% CI	$\hat{R}$
New Zealand king shag	0	0	[0–1]	1.00
Otago shag	2	2	[0–5]	1.00
Foveaux shag	0	0	[0–2]	1.00
Chatham Island shag	0	0	[0–0]	1.00
Bounty Island shag	0	0	[0–0]	1.00
Auckland Island shag	0	0	[0–1]	1.00
Campbell Island shag	0	0	[0–0]	–
Spotted shag	40	39	[26–55]	1.00
Pitt Island shag	0	0	[0–0]	1.00
Subantarctic skua	0	0	[0–0]	1.00
Southern blackbacked gull	10	12	[5–21]	1.00
Caspian tern	0	0	[0–1]	1.00
White tern	0	0	[0–0]	1.00

Table 6: Model fit to observed dead captures per species $C_s^{\text{DEAD}\prime}$, summed from 2006/07 to 2019/20: empirical value, posterior and $\hat{R}$ for each species (continued on next page).

		Posterior		
Species	Observed	Median	95% CI	$\hat{R}$
Gibsons albatross	29	22	[13–34]	1.00
Antipodean albatross	28	28	[18–41]	1.00
Southern royal albatross	18	23	[14–34]	1.00
Northern royal albatross	4	4	[1–8]	1.00
Campbell blackbrowed albatross	40	35	[23–49]	1.00
New Zealand whitecapped albatross	1013	984	[915–1057]	1.00
Salvins albatross	361	368	[327–411]	1.00
Chatham Island albatross	27	24	[14–36]	1.00
Greyheaded albatross	1	3	[0–8]	1.00
Southern Bullers albatross	537	547	[496–599]	1.00
Northern Bullers albatross	50	46	[32–61]	1.00
Lightmantled sooty albatross	0	4	[1–9]	1.00
Northern giant petrel	7	4	[1–9]	1.00
Grey petrel	108	106	[85–131]	1.00
Black petrel	91	98	[77–121]	1.00
Westland petrel	80	82	[63–104]	1.00
Whitechinned petrel	1702	1689	[1595–1784]	1.00
Fleshfooted shearwater	122	135	[110–163]	1.00
Wedgetailed shearwater	0	0	[0–0]	1.00
Bullers shearwater	10	8	[3–16]	1.00
Sooty shearwater	973	958	[889–1033]	1.00
Fluttering shearwater	3	4	[1–10]	1.00
Huttons shearwater	0	1	[0–4]	1.00
Little shearwater	0	0	[0–3]	1.00
Snares Cape petrel	5	3	[0–7]	1.00
Fairy prion	5	6	[2–13]	1.00
Antarctic prion	3	3	[0–7]	1.00
Broadbilled prion	2	2	[0–5]	1.00
Pycrofts petrel	0	0	[0–1]	1.00
Cooks petrel	0	1	[0–3]	1.00
Chatham petrel	0	0	[0–0]	1.00
Mottled petrel	2	2	[0–5]	1.00
Whitenaped petrel	0	0	[0–1]	1.00
Kermadec petrel	0	0	[0–1]	1.00
Greyfaced petrel	13	14	[7–23]	1.00
Chatham Island taiko	0	0	[0–0]	1.00
Whiteheaded petrel	0	2	[0–5]	1.00
Softplumaged petrel	0	0	[0–1]	1.00
Common diving petrel	12	12	[6–21]	1.00
Whenua Hou diving petrel	0	0	[0–0]	1.00
New Zealand whitefaced storm petrel	3	5	[1–10]	1.00
Whitebellied storm petrel	0	0	[0–0]	1.00
Blackbellied storm petrel	2	1	[0–4]	1.00
Kermadec storm petrel	0	0	[0–0]	1.00
New Zealand storm petrel	0	0	[0–0]	1.00
Yelloweyed penguin	17	13	[6–23]	1.00
Northern little penguin	0	1	[0–4]	1.00
Whiteflippered little penguin	0	0	[0–2]	1.00
Southern little penguin	0	1	[0–4]	1.00
Chatham Island little penguin	0	0	[0–2]	1.00
Eastern rockhopper penguin	0	0	[0–3]	1.00
Fiordland crested penguin	5	3	[0–9]	1.00
Snares crested penguin	0	0	[0–3]	1.00
Erectcrested penguin	0	1	[0–3]	1.00
Australasian gannet	0	0	[0–3]	1.00
Masked booby	0	0	[0–0]	1.00
Pied shag	1	2	[0–6]	1.00
Little black shag	0	1	[0–3]	1.00

Table 6: Continued

		Posterior		
Species	Observed	Median	95% CI	$\hat{R}$
New Zealand king shag	0	0	[0–1]	1.00
Otago shag	2	1	[0–5]	1.00
Foveaux shag	0	0	[0–2]	1.00
Chatham Island shag	0	0	[0–0]	1.00
Bounty Island shag	0	0	[0–0]	1.00
Auckland Island shag	0	0	[0–1]	1.00
Campbell Island shag	0	0	[0–0]	–
Spotted shag	38	34	[22–48]	1.00
Pitt Island shag	0	0	[0–0]	1.00
Subantarctic skua	0	0	[0–0]	1.00
Southern blackbacked gull	6	6	[2–13]	1.00
Caspian tern	0	0	[0–0]	1.00
White tern	0	0	[0–0]	1.00

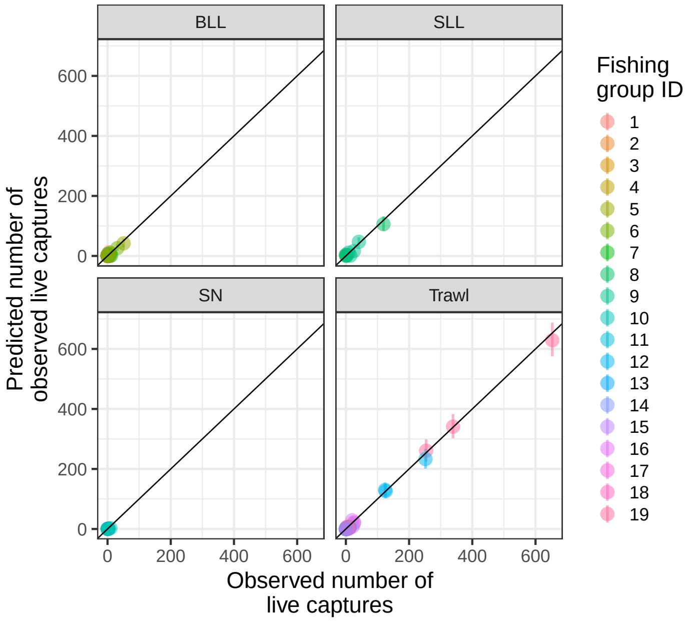

Figure 6: Model fit to observed number of live captures $C_{sg}^{LIVE\prime}$ for each fishing method. Captures are summed across species within each species group, between 2006/07 and 2019/20, and each point represents a unique combination of species group and fishery group. Fishery group IDs are defined in Table 2.

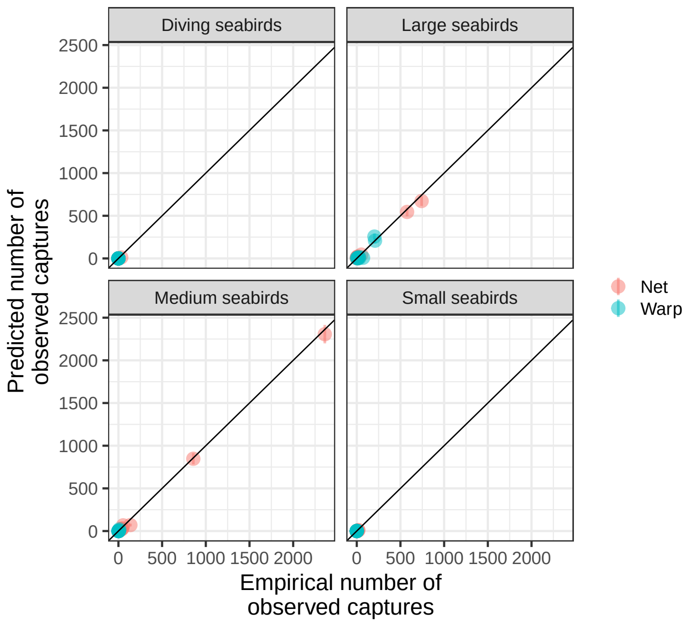

Figure 7: Model fit to number of observed net and warp trawl captures for each net capture group. Captures are summed across species within each group, between 2006/07 and 2019/20, and each point represents a unique combination of net capture group and fishery group.

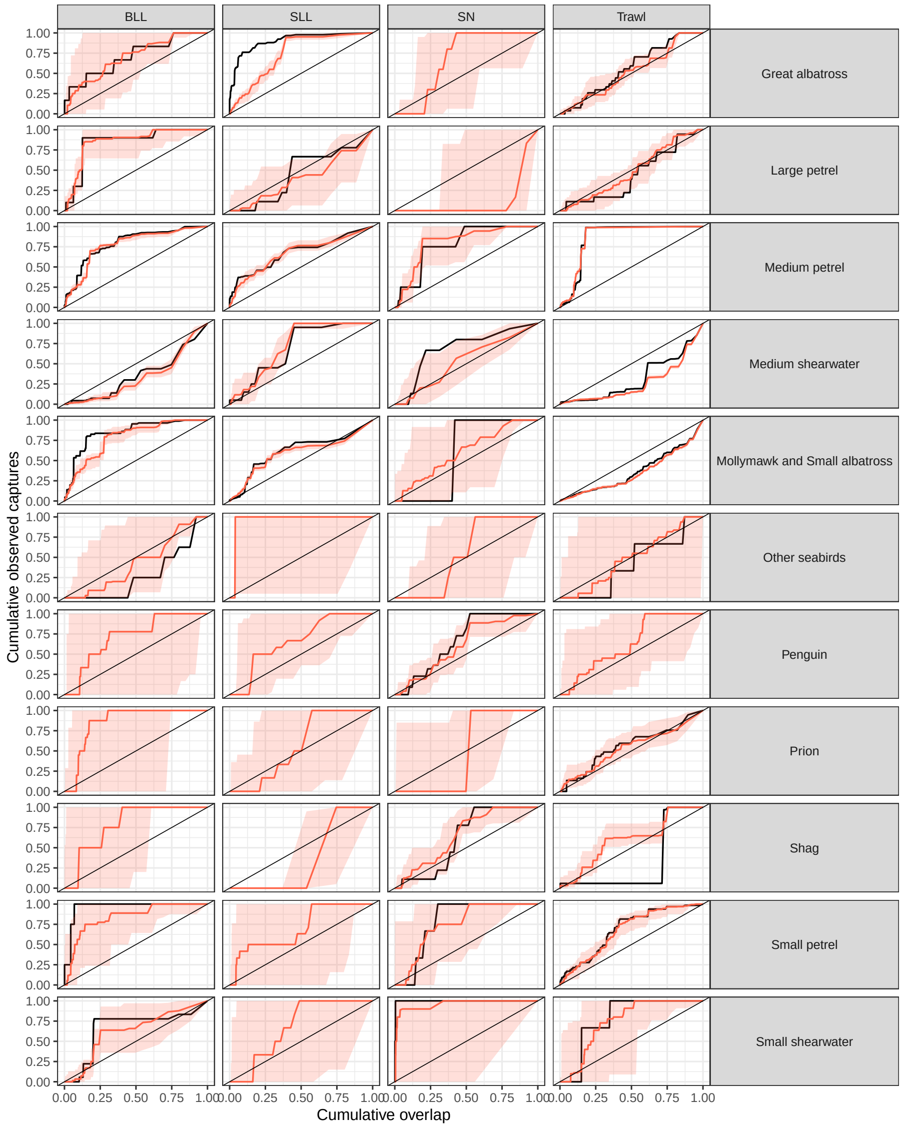

Figure 8: Cumulative sum of the observed captures (C'_{fs}) against cumulative sum of the observed overlap ($\mathbb{O}'_{fs}$) per species group and method. The cumulative sum of predicted values is shown in red, with 95% credibility intervals shaded. Each cumulative sum is re-scaled to one. A close match between observed (black) and predicted (red) relationships indicates that overlap provides a good description of the spatial distribution of captures.

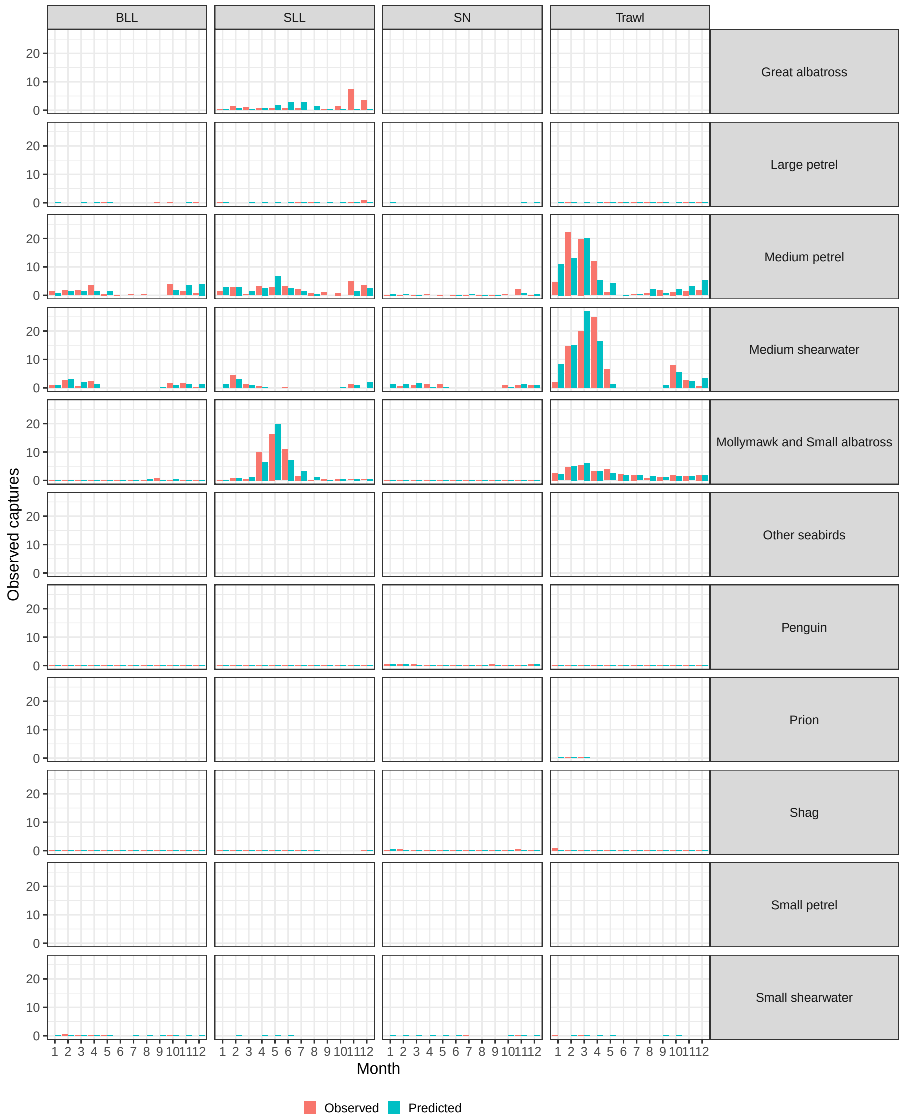

Figure 9: Observed and model predicted captures (C'_{fs}) aggregated by month, species group and method (with month 1 equal to January). Mean posterior predicted values are shown.

5.3 Estimated catchabilities and vulnerabilities

Catchability is the rate of observable capture per unit of overlap. The vulnerability is the catchability multiplied by a rate of cryptic capture:

$$\upsilon_{f,s} = q_{f,s} \cdot K_{f,z}$$

Catchability $q_{f,s}$ is estimated from the fit of the model to observed captures, and provides an indication of the relative capture risk per species and fishery group. Per fishery group, catchabilities can only be compared between methods that share the same effort metric. Because set nets (SN) have a unique effort metric, they cannot be compared with the other fishery groups. The vulnerabilties provide an indication of the overall rate of interaction, but are statistically less robust, since they are based on assumptions concerning the rates of cryptic capture (Edwards et al. 2023).

Catchabilities per species and fishery group combination are shown in Figure 10. For the BLL, SN and trawl fishery groups, catchabilities are highest for the medium petrels. For the SLL groups, catchabilities are high for the medium petrels, but also for the mollymawk, small albatross and great albatross species groups.

Taking the geometric mean across species group, we calculated the catchability per fishery group. These are shown alongside the geometric means of the vulnerabilities per group in Figures 11 and 12. The differences between catchability and vulnerability are an indication of the proportion of the fishery 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 fishery groups. In particular, the Small SLL (tuna and swordfish) fishery group has the highest capture rate per unit overlap. The large SLL vessels have a high catchability, but these vessels are not present in the recent period of effort used to predict risk, because they are joint venture vessels that have left the New Zealand fishery. In the trawl fishery groups, the scampi, southern blue whiting and squid fishing vessels have the highest catchabilties, as well as the large freezer vessels. There is notably a much higher discrepancy between the vulnerabilities and the catchabilities for trawl groups, compared with longlines. This indicates the higher importance of cryptic capture for prediction of captures and deaths by the trawl fleets.

Catchabilities and vulnerabilities per species group and fishery group combination are shown in Tables 7 to 12, with the different fishing methods distinguished. From these, we can identify the species groups that are most likely to be caught by the different fleet components. It is notable that medium petrels have the highest catchabilities and vulnerabilties within each of the fishing methods.

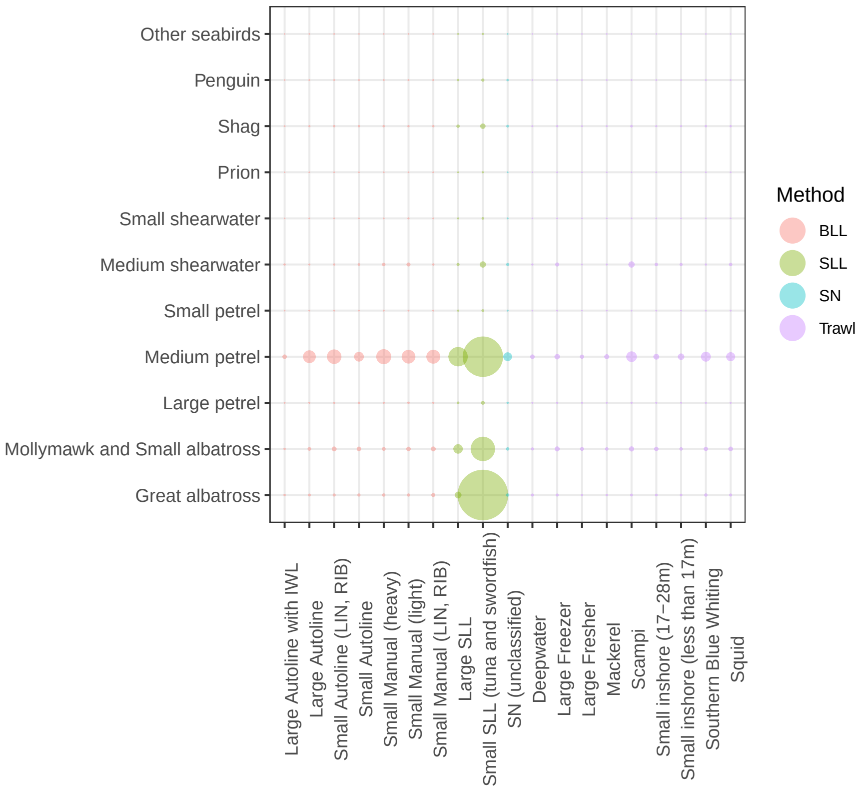

Figure 10: Catchability ($q_{f,z}$) per species group and fishery group combination. Catchabilities are only comparable between methods and groups that share the same effort units.

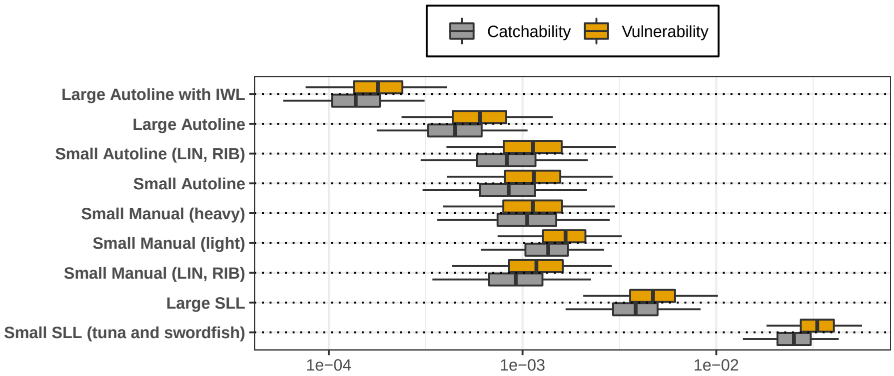

Figure 11: Marginal catchability (q_f) and vulnerability (υ_f) per longline fishing group assuming a geometric mean across species. Values are given on a log10-scale. Boxplots show the median, and 75% and 95% posterior quantiles.

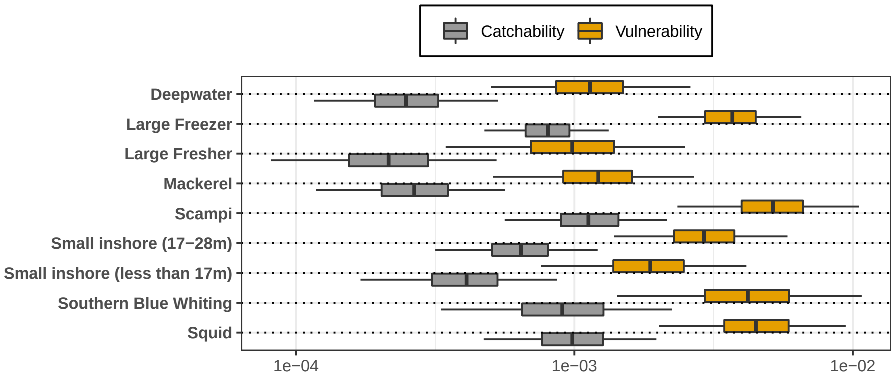

Figure 12: Marginal catchability (q_f) and vulnerability (υ_f) per trawl fishing group assuming a geometric mean across species. Values are given on a log10-scale. Boxplots show the median, and 75% and 95% posterior quantiles.

Table 7: Catchability per species group and fishery group ($q_{f,z}$) for the BLL fleet (log10-scale). Cells values are shaded from the lowest (white) to the highest (dark grey).

	Large Autoline with IWL		Large Autoline		Small Autoline (LIN, RIB)		Small Autoline		Small Manual (heavy)		Small Manual (light)		Small Manual (LIN, RIB)	
Species Group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Great albatross	-2.91	[-3.60,-2.30]	-2.48	[-3.19,-1.86]	-2.34	[-3.17,-1.62]	-2.30	[-3.12,-1.52]	-2.19	[-3.07,-1.37]	-2.23	[-3.01,-1.53]	-1.91	[-2.62,-1.24]
Mollymawk and Small albatross	-2.91	[-3.30,-2.57]	-2.03	[-2.37,-1.73]	-1.63	[-2.06,-1.28]	-1.71	[-2.21,-1.29]	-1.98	[-2.58,-1.43]	-1.74	[-2.26,-1.25]	-1.62	[-2.09,-1.23]
Large petrel	-3.82	[-4.53,-3.18]	-3.54	[-4.28,-2.83]	-3.25	[-4.01,-2.53]	-2.89	[-3.60,-2.24]	-3.23	[-3.98,-2.48]	-2.86	[-3.47,-2.29]	-3.22	[-3.99,-2.50]
Medium petrel	-1.74	[-2.31,-1.23]	-0.56	[-1.02,-0.12]	-0.43	[-0.93,-0.01]	-0.83	[-1.37,-0.36]	-0.40	[-0.82,-0.06]	-0.49	[-0.99,-0.07]	-0.47	[-0.85,-0.17]
Small petrel	-4.59	[-5.13,-4.08]	-4.07	[-4.66,-3.53]	-3.80	[-4.42,-3.23]	-3.87	[-4.47,-3.31]	-3.67	[-4.23,-3.11]	-3.79	[-4.30,-3.32]	-3.82	[-4.40,-3.26]
Medium shearwater	-3.01	[-3.80,-2.15]	-3.38	[-4.33,-2.54]	-3.01	[-4.02,-2.17]	-2.70	[-3.56,-1.95]	-2.14	[-2.77,-1.67]	-1.91	[-2.19,-1.69]	-2.93	[-3.75,-2.28]
Small shearwater	-4.69	[-5.50,-3.95]	-4.20	[-4.98,-3.45]	-3.89	[-4.73,-3.12]	-3.90	[-4.76,-3.10]	-3.87	[-4.69,-3.09]	-3.33	[-3.89,-2.81]	-3.96	[-4.75,-3.24]
Prion	-5.11	[-5.96,-4.39]	-4.58	[-5.45,-3.85]	-4.27	[-5.16,-3.43]	-4.32	[-5.20,-3.52]	-4.13	[-5.10,-3.23]	-4.19	[-5.09,-3.41]	-4.19	[-5.13,-3.33]
Shag	-3.72	[-4.42,-3.09]	-3.18	[-3.89,-2.52]	-2.91	[-3.64,-2.26]	-2.95	[-3.63,-2.29]	-2.90	[-3.61,-2.26]	-3.01	[-3.60,-2.45]	-2.95	[-3.64,-2.28]
Penguin	-4.50	[-5.15,-3.90]	-3.92	[-4.63,-3.30]	-3.66	[-4.38,-2.97]	-3.68	[-4.40,-3.01]	-3.63	[-4.35,-2.92]	-3.58	[-4.24,-2.91]	-3.65	[-4.35,-3.00]
Other seabirds	-5.39	[-6.24,-4.57]	-4.80	[-5.71,-3.97]	-4.56	[-5.47,-3.73]	-4.59	[-5.48,-3.76]	-4.53	[-5.40,-3.72]	-4.41	[-5.16,-3.71]	-4.58	[-5.48,-3.74]

Table 8: Vulnerability per species group and fishery group ($\upsilon_{f,z}$) for the BLL fleet (log10-scale). Cells values are shaded from the lowest (white) to the highest (dark grey).

	Large Autoline with IWL		Large Autoline		Small Autoline (LIN, RIB)		Small Autoline		Small Manual (heavy)		Small Manual (light)		Small Manual (LIN, RIB)	
Species Group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Great albatross	-2.81	[-3.50,-2.19]	-2.37	[-3.07,-1.74]	-2.21	[-3.03,-1.48]	-2.18	[-3.01,-1.40]	-2.18	[-3.06,-1.36]	-2.17	[-2.95,-1.47]	-1.83	[-2.54,-1.15]
Mollymawk and Small albatross	-2.79	[-3.18,-2.44]	-1.90	[-2.25,-1.60]	-1.49	[-1.92,-1.13]	-1.58	[-2.07,-1.16]	-1.96	[-2.56,-1.42]	-1.64	[-2.16,-1.14]	-1.51	[-1.97,-1.11]
Large petrel	-3.72	[-4.43,-3.08]	-3.42	[-4.17,-2.71]	-3.11	[-3.87,-2.39]	-2.77	[-3.48,-2.11]	-3.22	[-3.97,-2.47]	-2.80	[-3.41,-2.22]	-3.14	[-3.90,-2.41]
Medium petrel	-1.61	[-2.19,-1.09]	-0.42	[-0.89,0.01]	-0.29	[-0.80,0.14]	-0.69	[-1.23,-0.22]	-0.37	[-0.79,-0.04]	-0.38	[-0.88,0.04]	-0.35	[-0.73,-0.04]
Small petrel	-4.51	[-5.04,-3.98]	-3.96	[-4.55,-3.42]	-3.68	[-4.29,-3.10]	-3.76	[-4.35,-3.20]	-3.66	[-4.23,-3.10]	-3.74	[-4.24,-3.27]	-3.74	[-4.33,-3.18]
Medium shearwater	-2.88	[-3.67,-2.02]	-3.24	[-4.18,-2.40]	-2.87	[-3.87,-2.02]	-2.55	[-3.42,-1.81]	-2.11	[-2.74,-1.63]	-1.80	[-2.09,-1.57]	-2.81	[-3.64,-2.15]
Small shearwater	-4.57	[-5.38,-3.83]	-4.07	[-4.86,-3.31]	-3.76	[-4.61,-2.99]	-3.77	[-4.62,-2.97]	-3.86	[-4.68,-3.07]	-3.24	[-3.80,-2.72]	-3.85	[-4.64,-3.12]
Prion	-5.03	[-5.89,-4.31]	-4.48	[-5.37,-3.75]	-4.15	[-5.05,-3.31]	-4.21	[-5.11,-3.41]	-4.12	[-5.09,-3.22]	-4.14	[-5.05,-3.36]	-4.13	[-5.06,-3.27]
Shag	-3.58	[-4.28,-2.95]	-3.03	[-3.75,-2.37]	-2.77	[-3.51,-2.12]	-2.80	[-3.49,-2.14]	-2.81	[-3.54,-2.17]	-2.87	[-3.46,-2.31]	-2.81	[-3.51,-2.15]
Penguin	-4.36	[-5.02,-3.75]	-3.78	[-4.48,-3.15]	-3.52	[-4.24,-2.83]	-3.54	[-4.25,-2.86]	-3.55	[-4.28,-2.83]	-3.44	[-4.10,-2.77]	-3.51	[-4.21,-2.86]
Other seabirds	-5.27	[-6.13,-4.44]	-4.67	[-5.58,-3.84]	-4.42	[-5.34,-3.60]	-4.46	[-5.35,-3.62]	-4.52	[-5.38,-3.70]	-4.32	[-5.08,-3.62]	-4.48	[-5.38,-3.63]

Table 9: Catchability per species group and fishery group ($q_{f,z}$) for the SLL fleet (log10-scale). Cells values are shaded from the lowest (white) to the highest (dark grey).

	Large SLL		Small SLL (tuna and swordfish)	
Species Group	Mean	95% CI	Mean	95% CI
Great albatross	-1.22	[-1.79,-0.76]	0.73	[0.59,0.85]
Mollymawk and Small albatross	-0.86	[-1.24,-0.53]	0.06	[-0.19,0.29]
Large petrel	-2.67	[-3.36,-2.02]	-1.98	[-2.55,-1.45]
Medium petrel	-0.16	[-0.60,0.24]	0.52	[0.42,0.62]
Small petrel	-3.17	[-3.69,-2.65]	-2.58	[-3.05,-2.13]
Medium shearwater	-2.36	[-3.22,-1.50]	-1.32	[-1.69,-1.04]
Small shearwater	-3.35	[-4.10,-2.65]	-2.75	[-3.43,-2.14]
Prion	-3.75	[-4.55,-3.09]	-3.22	[-3.98,-2.64]
Shag	-2.20	[-2.84,-1.53]	-1.49	[-2.13,-0.86]
Penguin	-2.95	[-3.61,-2.31]	-2.31	[-2.94,-1.74]
Other seabirds	-3.84	[-4.73,-2.95]	-3.17	[-3.98,-2.43]

Table 10: Vulnerability per species group and fishery group ($\upsilon_{f,z}$) for the SLL fleet (log10-scale). Cells values are shaded from the lowest (white) to the highest (dark grey).

	Large SLL		Small SLL (tuna and swordfish)	
Species Group	Mean	95% CI	Mean	95% CI
Great albatross	-1.16	[-1.73,-0.69]	0.83	[0.68,0.97]
Mollymawk and Small albatross	-0.76	[-1.14,-0.43]	0.19	[-0.07,0.42]
Large petrel	-2.61	[-3.29,-1.95]	-1.88	[-2.44,-1.34]
Medium petrel	-0.04	[-0.50,0.36]	0.66	[0.54,0.78]
Small petrel	-3.12	[-3.65,-2.60]	-2.48	[-2.95,-2.04]
Medium shearwater	-2.25	[-3.12,-1.39]	-1.19	[-1.55,-0.90]
Small shearwater	-3.26	[-4.01,-2.55]	-2.62	[-3.30,-2.02]
Prion	-3.70	[-4.51,-3.05]	-3.13	[-3.90,-2.55]
Shag	-2.06	[-2.71,-1.39]	-1.35	[-1.99,-0.72]
Penguin	-2.82	[-3.47,-2.17]	-2.17	[-2.79,-1.59]
Other seabirds	-3.75	[-4.64,-2.87]	-3.05	[-3.86,-2.32]

Table 11: Catchability per species group and fishery group ($q_{f,z}$) for the Trawl fleet (log10-scale). Cells values are shaded from the lowest (white) to the highest (dark grey).

	Deepwater		Large Freezer		Large Fresher		Mackerel		Scampi		Small inshore (17-28m)		Small inshore (less than 17m)		Southern Blue Whiting		Squid	
Species Group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Great albatross	-2.37	[-2.96,-1.86]	-2.38	[-2.88,-1.94]	-2.81	[-3.67,-2.05]	-2.83	[-3.61,-2.15]	-2.50	[-3.22,-1.88]	-2.59	[-3.33,-1.89]	-2.65	[-3.46,-1.95]	-2.21	[-2.91,-1.54]	-2.35	[-2.99,-1.82]
Mollymawk and Small albatross	-2.31	[-2.67,-2.00]	-1.59	[-1.79,-1.42]	-1.91	[-2.33,-1.55]	-2.13	[-2.51,-1.80]	-1.55	[-1.84,-1.29]	-1.75	[-2.17,-1.37]	-2.14	[-2.64,-1.70]	-1.79	[-2.18,-1.41]	-1.68	[-1.99,-1.42]
Large petrel	-3.61	[-4.27,-2.98]	-3.16	[-3.72,-2.64]	-3.55	[-4.24,-2.87]	-3.81	[-4.48,-3.12]	-3.11	[-3.75,-2.52]	-3.37	[-3.99,-2.75]	-3.67	[-4.40,-3.00]	-3.25	[-3.98,-2.57]	-3.33	[-3.97,-2.72]
Medium petrel	-1.72	[-2.18,-1.34]	-1.48	[-1.83,-1.22]	-1.82	[-2.38,-1.37]	-1.60	[-2.11,-1.15]	-0.74	[-1.11,-0.45]	-1.40	[-1.77,-1.11]	-1.28	[-1.77,-0.86]	-0.81	[-1.48,-0.19]	-0.91	[-1.46,-0.40]
Small petrel	-4.27	[-4.78,-3.79]	-3.71	[-4.13,-3.32]	-4.38	[-4.93,-3.85]	-4.12	[-4.62,-3.65]	-3.77	[-4.28,-3.28]	-3.83	[-4.31,-3.39]	-4.03	[-4.56,-3.53]	-3.47	[-4.01,-2.94]	-3.51	[-3.97,-3.08]
Medium shearwater	-3.16	[-3.91,-2.57]	-1.88	[-2.17,-1.65]	-3.60	[-4.51,-2.87]	-3.32	[-4.03,-2.78]	-1.31	[-1.46,-1.17]	-2.13	[-2.30,-1.96]	-2.27	[-2.55,-2.03]	-3.05	[-3.99,-2.14]	-2.14	[-2.94,-1.40]
Small shearwater	-4.49	[-5.25,-3.80]	-4.08	[-4.72,-3.52]	-4.46	[-5.31,-3.67]	-4.40	[-5.19,-3.72]	-4.03	[-4.78,-3.35]	-4.07	[-4.70,-3.51]	-4.38	[-5.14,-3.70]	-3.85	[-4.68,-3.08]	-4.01	[-4.75,-3.33]
Prion	-4.91	[-5.74,-4.20]	-3.94	[-4.45,-3.55]	-4.87	[-5.74,-4.08]	-4.69	[-5.41,-4.07]	-4.34	[-5.18,-3.64]	-3.87	[-4.53,-3.31]	-4.65	[-5.54,-3.86]	-3.96	[-4.78,-3.27]	-3.76	[-4.24,-3.36]
Shag	-3.43	[-4.12,-2.77]	-3.07	[-3.70,-2.49]	-3.51	[-4.16,-2.88]	-3.38	[-4.05,-2.76]	-2.70	[-3.31,-2.11]	-3.27	[-3.87,-2.70]	-3.22	[-3.78,-2.69]	-2.87	[-3.59,-2.19]	-2.93	[-3.58,-2.27]
Penguin	-4.19	[-4.84,-3.57]	-3.95	[-4.51,-3.42]	-4.20	[-4.91,-3.53]	-4.15	[-4.81,-3.51]	-3.69	[-4.33,-3.09]	-3.89	[-4.53,-3.27]	-4.03	[-4.69,-3.42]	-3.66	[-4.37,-3.00]	-3.81	[-4.42,-3.25]
Other seabirds	-5.06	[-5.94,-4.23]	-4.73	[-5.54,-3.93]	-5.15	[-5.98,-4.34]	-4.79	[-5.62,-4.01]	-4.58	[-5.41,-3.78]	-4.90	[-5.68,-4.17]	-4.89	[-5.66,-4.18]	-4.50	[-5.40,-3.67]	-4.56	[-5.43,-3.78]

Table 12: Vulnerability per species group and fishery group ($\upsilon_{f,z}$) for the Trawl fleet (log10-scale). Cells values are shaded from the lowest (white) to the highest (dark grey).

	Deepwater		Large Freezer		Large Fresher		Mackerel		Scampi		Small inshore (17-28m)		Small inshore (less than 17m)		Southern Blue Whiting		Squid	
Species Group	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Great albatross	-1.55	[-2.14,-1.03]	-1.55	[-2.05,-1.11]	-1.99	[-2.84,-1.22]	-2.01	[-2.79,-1.33]	-1.68	[-2.40,-1.05]	-1.76	[-2.51,-1.06]	-1.83	[-2.64,-1.12]	-1.38	[-2.09,-0.72]	-1.53	[-2.15,-1.00]
Mollymawk and Small albatross	-1.49	[-1.85,-1.17]	-0.77	[-0.98,-0.58]	-1.09	[-1.52,-0.72]	-1.31	[-1.70,-0.98]	-0.73	[-1.01,-0.46]	-0.93	[-1.35,-0.54]	-1.32	[-1.82,-0.88]	-0.96	[-1.36,-0.58]	-0.85	[-1.17,-0.59]
Large petrel	-3.10	[-3.75,-2.48]	-2.65	[-3.23,-2.12]	-3.03	[-3.74,-2.36]	-3.30	[-4.00,-2.61]	-2.61	[-3.25,-2.01]	-2.86	[-3.49,-2.24]	-3.16	[-3.90,-2.48]	-2.75	[-3.48,-2.05]	-2.83	[-3.46,-2.22]
Medium petrel	-1.28	[-1.76,-0.88]	-1.05	[-1.40,-0.75]	-1.38	[-1.95,-0.91]	-1.16	[-1.68,-0.69]	-0.30	[-0.69,0.01]	-0.96	[-1.35,-0.65]	-0.84	[-1.34,-0.39]	-0.37	[-1.05,0.28]	-0.46	[-1.02,0.05]
Small petrel	-3.12	[-3.75,-2.53]	-2.57	[-3.11,-2.06]	-3.22	[-3.90,-2.61]	-2.96	[-3.59,-2.41]	-2.62	[-3.26,-2.04]	-2.68	[-3.27,-2.15]	-2.88	[-3.55,-2.29]	-2.31	[-2.97,-1.70]	-2.35	[-2.95,-1.82]
Medium shearwater	-2.72	[-3.50,-2.11]	-1.44	[-1.77,-1.16]	-3.16	[-4.08,-2.43]	-2.88	[-3.61,-2.32]	-0.87	[-1.07,-0.66]	-1.69	[-1.91,-1.45]	-1.83	[-2.15,-1.54]	-2.60	[-3.56,-1.68]	-1.70	[-2.51,-0.93]
Small shearwater	-3.35	[-4.21,-2.56]	-2.94	[-3.67,-2.29]	-3.32	[-4.23,-2.42]	-3.26	[-4.13,-2.50]	-2.89	[-3.74,-2.12]	-2.93	[-3.65,-2.27]	-3.24	[-4.09,-2.48]	-2.70	[-3.59,-1.87]	-2.85	[-3.69,-2.10]
Prion	-3.77	[-4.66,-2.94]	-2.79	[-3.42,-2.26]	-3.73	[-4.68,-2.86]	-3.55	[-4.36,-2.82]	-3.19	[-4.10,-2.43]	-2.72	[-3.48,-2.06]	-3.51	[-4.49,-2.64]	-2.80	[-3.73,-2.02]	-2.62	[-3.24,-2.07]
Shag	-3.32	[-4.01,-2.66]	-2.96	[-3.59,-2.37]	-3.40	[-4.06,-2.76]	-3.28	[-3.94,-2.65]	-2.60	[-3.20,-2.00]	-3.16	[-3.77,-2.59]	-3.11	[-3.67,-2.58]	-2.77	[-3.49,-2.08]	-2.82	[-3.47,-2.16]
Penguin	-4.09	[-4.74,-3.46]	-3.84	[-4.40,-3.31]	-4.09	[-4.80,-3.42]	-4.04	[-4.70,-3.40]	-3.58	[-4.22,-2.98]	-3.78	[-4.43,-3.16]	-3.92	[-4.58,-3.31]	-3.56	[-4.27,-2.89]	-3.70	[-4.31,-3.14]
Other seabirds	-4.49	[-5.39,-3.64]	-4.16	[-5.00,-3.36]	-4.59	[-5.45,-3.76]	-4.23	[-5.07,-3.44]	-4.01	[-4.85,-3.20]	-4.33	[-5.13,-3.58]	-4.32	[-5.11,-3.59]	-3.93	[-4.85,-3.08]	-3.99	[-4.88,-3.19]

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. 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 (XWM) and Salvin's albatross (XSA), which are noticeably lower than the priors. If P_s^{B} is less than the prior, this indicates that the model is able to improve the fit to the capture data if there are fewer birds breeding and more non-breeders in the population. Since the model assumes that breeders are less available to be caught, a lower P_s^{B} implies that more birds are available for capture, and the same number of observed captures can be achieved with a lower catchability. This result illustrates the interaction between parameters within the model, which should be explored further before conclusions can be drawn. The posteriors are also listed in Table 13 alongside the age of first breeding (A_s^{curr}) and optimum survivorship (S_s^{opt}).

In Figure 15 we illustrate the different estimators for λ_s. The Euler-Lotka (λ_s^{EL}) and demographic invariant (λ_s^{DI}) methods give different but overlapping estimates of the productivity (see also Table 14). Our approach in the current assessment is to use the intersection of the two methods. Using this value, and the estimated number of adults, we are able to calculate the PST reference point per species (Table 15). All biological values within the model are consistent. Updates to N_s^{BP} for example, will be consistent with estimates of the catchability ($q_{f,s}$), and updates to N_s^{BP}, P_s^{B} and S_s^{opt} will be consistent with estimates of λ_s and the PST.

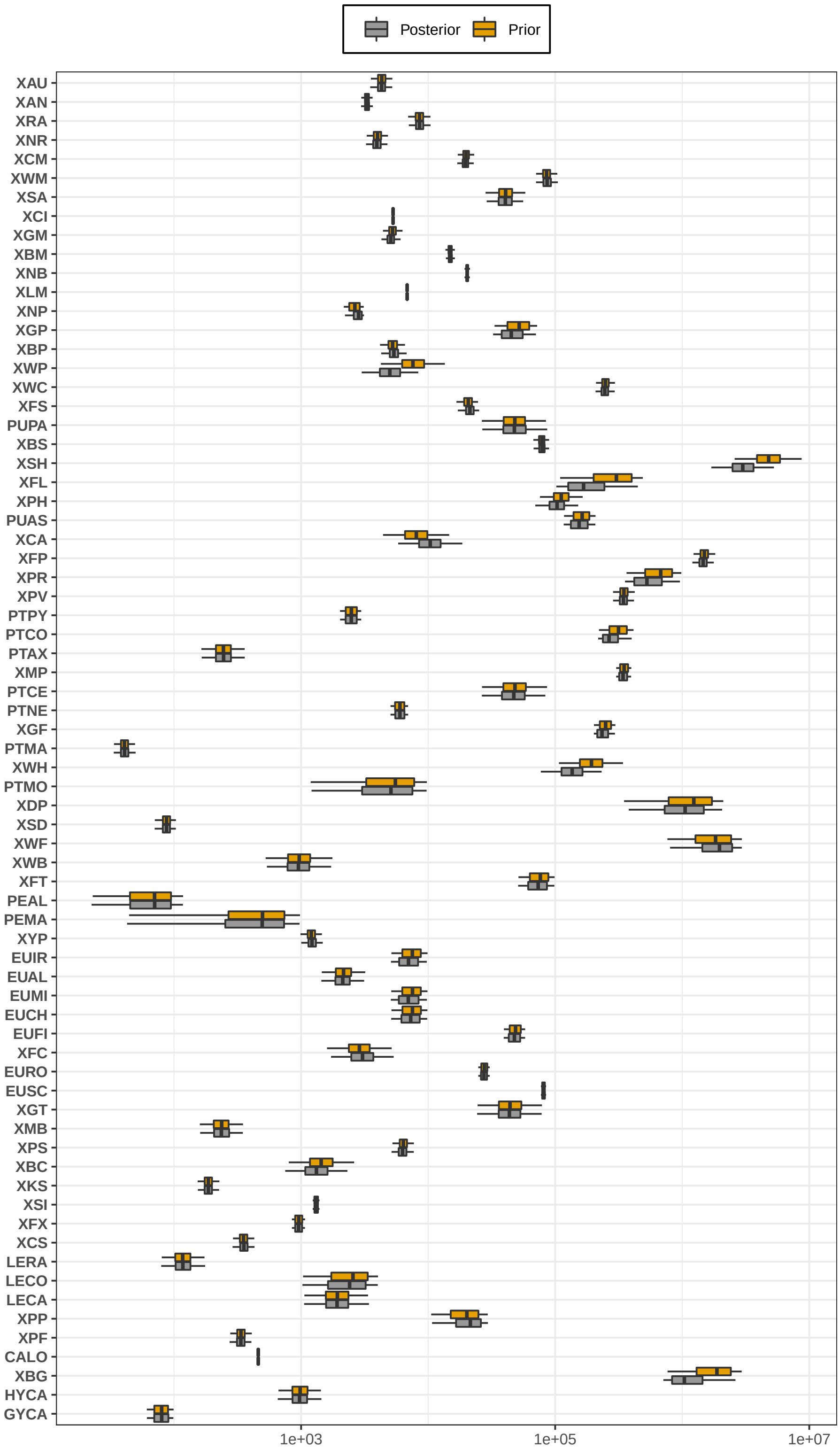

Figure 13: Prior and posterior densities for the number of breeding pairs (N_s^{BP}; log10-scale) for each species (see Table 1). Boxplots show the median, and 75% and 95% posterior quantiles.

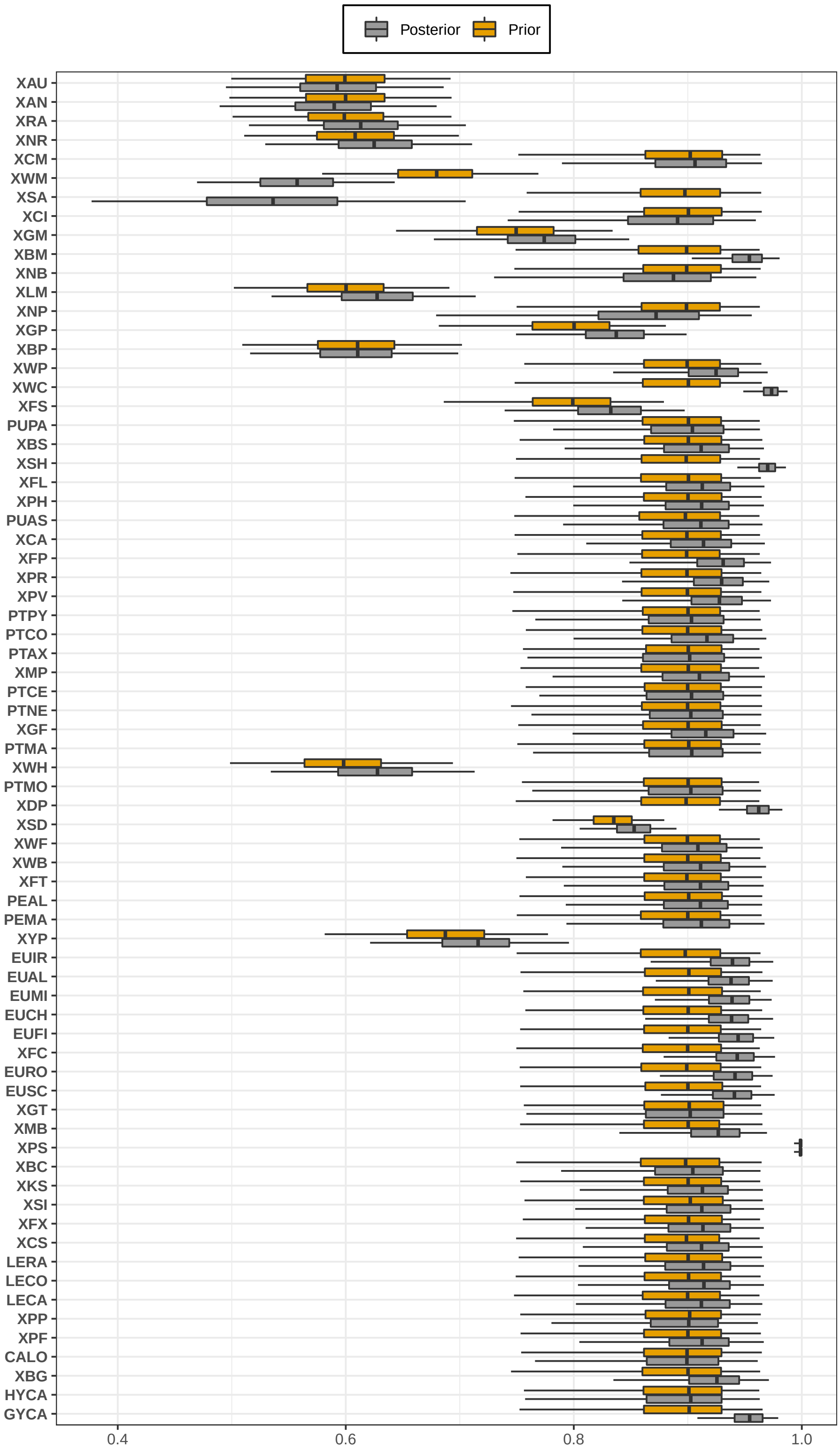

Figure 14: Prior and posterior densities for the proportion breeding (P_s^B) for each species (see Table 1). Boxplots show the median, and 75% and 95% posterior quantiles.

Table 13: 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}) (continued on next page). Prior distributions are listed by Peatman et al. (2023).

	N_s^{BP}		P_s^B		A_s^{curr}		S_s^{opt}	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XAU	4315	[3497-5217]	0.59	[0.49-0.69]	11.0	[10.0-11.9]	0.97	[0.96-0.98]
XAN	3306	[2966-3669]	0.59	[0.49-0.68]	9.4	[7.1-12.7]	0.96	[0.95-0.97]
XRA	8611	[7049-10445]	0.61	[0.52-0.71]	9.5	[8.5-10.5]	0.96	[0.95-0.97]
XNR	3966	[3243-4781]	0.62	[0.53-0.71]	9.5	[8.5-10.5]	0.96	[0.95-0.97]
XCM	19707	[16959-22836]	0.90	[0.79-0.97]	8.4	[6.1-12.5]	0.95	[0.94-0.96]
XWM	86856	[70655-104919]	0.56	[0.47-0.64]	11.5	[9.1-14.8]	0.97	[0.95-0.98]
XSA	41062	[28886-55978]	0.54	[0.38-0.71]	11.7	[9.1-14.8]	0.97	[0.96-0.98]
XCI	5295	[5145-5442]	0.88	[0.74-0.96]	11.8	[9.1-14.8]	0.97	[0.95-0.98]
XGM	5103	[4289-6064]	0.77	[0.68-0.85]	9.4	[7.1-12.7]	0.96	[0.94-0.97]
XBM	14951	[13798-16227]	0.95	[0.90-0.98]	11.7	[9.1-14.8]	0.97	[0.94-0.98]
XNB	20293	[19339-21291]	0.88	[0.73-0.96]	11.7	[9.1-14.8]	0.97	[0.94-0.98]
XLM	6835	[6774-6897]	0.63	[0.53-0.71]	11.7	[9.1-14.8]	0.97	[0.96-0.98]
XNP	2781	[2214-3127]	0.86	[0.68-0.96]	7.7	[6.1-9.9]	0.95	[0.93-0.96]
XGP	47439	[32476-70499]	0.83	[0.75-0.90]	6.8	[5.1-8.9]	0.96	[0.93-0.97]
XBP	5413	[4270-6769]	0.61	[0.52-0.70]	6.6	[6.2-7.0]	0.96	[0.95-0.97]
XWP	5180	[3001-8362]	0.92	[0.83-0.97]	6.4	[4.1-8.8]	0.95	[0.93-0.97]
XWC	247117	[207810-294036]	0.97	[0.95-0.99]	6.4	[4.1-8.8]	0.95	[0.93-0.97]
XFS	21302	[17114-25205]	0.83	[0.74-0.90]	6.5	[4.1-8.8]	0.96	[0.94-0.98]
PUPA	50158	[26699-86519]	0.90	[0.78-0.96]	4.0	[3.1-4.9]	0.94	[0.93-0.96]
XBS	78795	[67624-89529]	0.90	[0.79-0.97]	6.2	[4.1-8.8]	0.95	[0.93-0.97]
XSH	3123462	[1696071-5270288]	0.97	[0.94-0.99]	6.0	[5.0-6.9]	0.95	[0.93-0.98]
XFL	198297	[102102-447085]	0.91	[0.80-0.97]	5.0	[4.0-5.9]	0.95	[0.93-0.96]
XPH	105042	[69719-151766]	0.90	[0.80-0.97]	5.0	[4.1-5.9]	0.95	[0.93-0.96]
PUAS	157261	[116692-207161]	0.90	[0.79-0.97]	5.0	[4.0-5.9]	0.95	[0.93-0.96]
XCA	10814	[5806-18576]	0.91	[0.81-0.97]	4.7	[3.1-7.7]	0.93	[0.92-0.94]
XFP	1465686	[1202255-1772379]	0.93	[0.85-0.97]	4.5	[4.0-5.0]	0.92	[0.91-0.94]
XPR	569939	[354620-959018]	0.92	[0.84-0.97]	5.4	[5.0-6.0]	0.92	[0.91-0.94]
XPV	346081	[285514-417214]	0.92	[0.84-0.97]	4.5	[4.0-5.0]	0.92	[0.91-0.94]
PTPY	2491	[2027-2971]	0.89	[0.77-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTCO	279970	[217888-399754]	0.91	[0.80-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTAX	250	[165-360]	0.89	[0.76-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XMP	344456	[301932-396127]	0.90	[0.78-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTCE	49176	[26484-83643]	0.89	[0.77-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTNE	6004	[5054-6957]	0.89	[0.76-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XGF	238890	[201513-295234]	0.91	[0.80-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTMA	41	[34-50]	0.89	[0.76-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XWH	140918	[77083-231948]	0.63	[0.53-0.71]	5.4	[4.1-6.9]	0.96	[0.95-0.98]
PTMO	5292	[1208-9720]	0.89	[0.76-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XDP	1114330	[379547-2060986]	0.96	[0.93-0.98]	2.9	[2.6-3.0]	0.87	[0.87-0.87]
XSD	87	[70-103]	0.85	[0.81-0.89]	2.6	[2.1-3.0]	0.92	[0.91-0.93]
XWF	1942863	[802859-2944297]	0.90	[0.79-0.97]	4.0	[3.0-4.9]	0.94	[0.92-0.96]
XWB	996	[538-1724]	0.90	[0.79-0.97]	4.5	[4.0-5.0]	0.94	[0.92-0.96]
XFT	73794	[51097-98497]	0.90	[0.79-0.97]	4.5	[4.0-5.0]	0.94	[0.92-0.96]
PEAL	70	[22-117]	0.90	[0.79-0.97]	4.0	[3.0-4.9]	0.94	[0.92-0.96]
PEMA	496	[43-972]	0.90	[0.79-0.97]	4.5	[4.0-5.0]	0.94	[0.92-0.96]
XYP	1226	[1003-1481]	0.71	[0.62-0.80]	3.0	[2.0-3.9]	0.93	[0.91-0.94]
EUIR	7159	[5096-9758]	0.93	[0.87-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.91]
EUAL	2163	[1442-3135]	0.93	[0.87-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.90]
EUMI	7157	[5081-9780]	0.93	[0.87-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.90]
EUCH	7376	[5119-9839]	0.93	[0.86-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.91]
EUFI	48109	[39335-57974]	0.94	[0.88-0.98]	3.6	[3.0-5.2]	0.87	[0.86-0.89]
XFC	3169	[1721-5354]	0.94	[0.88-0.98]	3.6	[3.0-5.1]	0.88	[0.86-0.89]
EURO	27552	[24818-30496]	0.94	[0.88-0.97]	5.4	[5.0-5.9]	0.88	[0.86-0.89]
EUSC	81000	[77183-84843]	0.94	[0.88-0.98]	5.4	[5.0-5.9]	0.88	[0.86-0.89]
XGT	45738	[24286-78228]	0.89	[0.76-0.97]	5.0	[3.1-6.9]	0.95	[0.93-0.97]
XMB	241	[161-348]	0.92	[0.84-0.97]	3.0	[2.1-3.9]	0.93	[0.91-0.94]
XPS	6324	[5150-7704]	1.00	[0.99-1.00]	2.7	[2.0-3.3]	0.88	[0.86-0.89]

Table 13: Continued

Code	N_s^{BP}		P_s^B		A_s^{curr}		S_s^{opt}	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBC	1378	[750-2315]	0.90	[0.79-0.96]	2.1	[1.1-3.0]	0.88	[0.86-0.90]
XKS	187	[154-226]	0.91	[0.81-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XSI	1315	[1234-1396]	0.91	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XFX	957	[847-1073]	0.91	[0.81-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XCS	356	[289-430]	0.91	[0.81-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
LERA	120	[79-176]	0.91	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
LECO	2445	[1025-4014]	0.91	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
LECA	2009	[1056-3419]	0.90	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XPP	21080	[10734-29546]	0.89	[0.78-0.96]	2.1	[1.1-3.0]	0.88	[0.86-0.90]
XPF	337	[274-406]	0.91	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
CALO	460	[450-469]	0.89	[0.77-0.96]	8.0	[7.6-8.4]	0.94	[0.91-0.97]
XBG	1215308	[710470-2623469]	0.92	[0.83-0.97]	3.6	[3.0-4.8]	0.88	[0.85-0.90]
HYCA	995	[655-1444]	0.89	[0.76-0.96]	3.0	[2.1-4.0]	0.89	[0.86-0.92]
GYCA	80	[61-99]	0.95	[0.91-0.98]	3.2	[3.0-3.8]	0.83	[0.82-0.83]

Table 14: Productivity estimates λ_s^{DI} and λ_s^{EL}, with their intersection λ_s used derive the PST reference point (continued on next page).

Code	λ_s^{DI}		λ_s^{EL}		λ_s	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
XAU	1.04	[1.02-1.06]	1.03	[1.01-1.06]	1.04	[1.02-1.05]
XAN	1.05	[1.03-1.08]	1.04	[1.01-1.07]	1.04	[1.02-1.06]
XRA	1.05	[1.03-1.07]	1.03	[1.01-1.06]	1.04	[1.03-1.06]
XNR	1.05	[1.03-1.07]	1.04	[1.01-1.06]	1.04	[1.03-1.06]
XCM	1.06	[1.03-1.09]	1.05	[1.02-1.09]	1.06	[1.03-1.08]
XWM	1.04	[1.02-1.06]	1.03	[1.00-1.06]	1.03	[1.02-1.05]
XSA	1.04	[1.02-1.06]	1.03	[1.00-1.06]	1.03	[1.01-1.05]
XCI	1.04	[1.02-1.06]	1.04	[1.01-1.07]	1.04	[1.02-1.06]
XGM	1.05	[1.03-1.08]	1.04	[1.01-1.08]	1.05	[1.03-1.07]
XBM	1.04	[1.02-1.07]	1.04	[1.01-1.07]	1.04	[1.02-1.06]
XNB	1.04	[1.02-1.07]	1.04	[1.01-1.07]	1.04	[1.02-1.06]
XLM	1.04	[1.02-1.06]	1.03	[1.00-1.06]	1.04	[1.02-1.05]
XNP	1.06	[1.04-1.09]	1.05	[1.02-1.09]	1.06	[1.04-1.08]
XGP	1.07	[1.04-1.10]	1.06	[1.03-1.10]	1.07	[1.04-1.09]
XBP	1.07	[1.04-1.09]	1.05	[1.03-1.08]	1.06	[1.04-1.08]
XWP	1.07	[1.04-1.11]	1.07	[1.03-1.11]	1.07	[1.04-1.11]
XWC	1.08	[1.04-1.11]	1.07	[1.03-1.12]	1.07	[1.04-1.11]
XFS	1.07	[1.04-1.11]	1.07	[1.03-1.11]	1.07	[1.04-1.10]
PUPA	1.11	[1.08-1.15]	1.11	[1.07-1.15]	1.11	[1.08-1.14]
XBS	1.08	[1.04-1.12]	1.07	[1.03-1.12]	1.08	[1.04-1.11]
XSH	1.07	[1.05-1.10]	1.07	[1.04-1.11]	1.07	[1.05-1.10]
XFL	1.09	[1.06-1.12]	1.09	[1.05-1.12]	1.09	[1.07-1.11]
XPH	1.09	[1.07-1.12]	1.09	[1.05-1.12]	1.09	[1.06-1.11]
PUAS	1.09	[1.07-1.12]	1.09	[1.05-1.12]	1.09	[1.07-1.11]
XCA	1.11	[1.07-1.15]	1.09	[1.04-1.14]	1.10	[1.06-1.14]
XFP	1.11	[1.09-1.14]	1.09	[1.06-1.12]	1.10	[1.08-1.12]
XPR	1.10	[1.08-1.12]	1.07	[1.04-1.10]	1.08	[1.07-1.10]
XPV	1.11	[1.09-1.14]	1.09	[1.06-1.12]	1.10	[1.08-1.12]
PTPY	1.07	[1.05-1.09]	1.07	[1.03-1.10]	1.07	[1.05-1.09]
PTCO	1.07	[1.04-1.09]	1.07	[1.04-1.10]	1.07	[1.05-1.09]
PTAX	1.07	[1.04-1.09]	1.07	[1.03-1.10]	1.07	[1.04-1.09]
XMP	1.07	[1.04-1.09]	1.07	[1.04-1.10]	1.07	[1.05-1.09]
PTCE	1.07	[1.04-1.09]	1.07	[1.03-1.10]	1.07	[1.05-1.09]
PTNE	1.07	[1.04-1.09]	1.07	[1.03-1.10]	1.07	[1.05-1.09]
XGF	1.07	[1.04-1.09]	1.07	[1.04-1.10]	1.07	[1.04-1.09]
PTMA	1.07	[1.04-1.09]	1.07	[1.03-1.10]	1.07	[1.05-1.09]
XWH	1.07	[1.04-1.10]	1.07	[1.03-1.10]	1.07	[1.05-1.10]
PTMO	1.07	[1.04-1.09]	1.07	[1.03-1.10]	1.07	[1.04-1.09]

Table 14: Continued

	λ_s^{DI}		λ_s^{EL}		λ_s	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
XDP	1.20	[1.18-1.22]	1.10	[1.07-1.12]	1.15	[1.13-1.17]
XSD	1.17	[1.14-1.21]	1.14	[1.10-1.18]	1.16	[1.13-1.19]
XWF	1.11	[1.08-1.15]	1.11	[1.07-1.15]	1.11	[1.08-1.14]
XWB	1.10	[1.08-1.13]	1.09	[1.06-1.12]	1.10	[1.08-1.12]
XFT	1.10	[1.08-1.13]	1.09	[1.06-1.12]	1.10	[1.08-1.12]
PEAL	1.11	[1.08-1.15]	1.11	[1.07-1.15]	1.11	[1.08-1.14]
PEMA	1.10	[1.08-1.13]	1.09	[1.06-1.12]	1.10	[1.08-1.12]
XYP	1.16	[1.11-1.21]	1.14	[1.09-1.20]	1.15	[1.11-1.20]
EUIR	1.21	[1.17-1.26]	1.19	[1.14-1.24]	1.20	[1.16-1.25]
EUAL	1.21	[1.17-1.26]	1.19	[1.14-1.24]	1.20	[1.16-1.25]
EUMI	1.21	[1.17-1.26]	1.19	[1.14-1.24]	1.20	[1.16-1.24]
EUCH	1.21	[1.17-1.26]	1.19	[1.14-1.24]	1.20	[1.16-1.25]
EUFI	1.16	[1.12-1.20]	1.12	[1.06-1.16]	1.14	[1.09-1.18]
XFC	1.17	[1.12-1.20]	1.12	[1.07-1.16]	1.14	[1.09-1.18]
EURO	1.12	[1.10-1.14]	1.06	[1.03-1.09]	1.09	[1.07-1.11]
EUSC	1.12	[1.10-1.14]	1.06	[1.03-1.09]	1.09	[1.07-1.11]
XGT	1.09	[1.05-1.14]	1.09	[1.05-1.14]	1.09	[1.05-1.13]
XMB	1.15	[1.11-1.21]	1.13	[1.09-1.19]	1.14	[1.11-1.19]
XPS	1.21	[1.16-1.27]	1.21	[1.15-1.28]	1.21	[1.16-1.27]
XBC	1.28	[1.18-1.49]	1.28	[1.17-1.49]	1.28	[1.18-1.49]
XKS	1.15	[1.11-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
XSI	1.15	[1.11-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
XFX	1.15	[1.12-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
XCS	1.15	[1.11-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
LERA	1.15	[1.11-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
LECO	1.15	[1.11-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
LECA	1.15	[1.11-1.19]	1.14	[1.09-1.19]	1.15	[1.11-1.19]
XPP	1.27	[1.18-1.48]	1.27	[1.17-1.48]	1.27	[1.18-1.49]
XPF	1.15	[1.11-1.19]	1.15	[1.10-1.19]	1.15	[1.11-1.19]
CALO	1.07	[1.04-1.09]	1.07	[1.03-1.10]	1.07	[1.05-1.09]
XBG	1.16	[1.12-1.20]	1.15	[1.10-1.20]	1.16	[1.11-1.19]
HYCA	1.18	[1.12-1.26]	1.18	[1.12-1.27]	1.18	[1.13-1.26]
GYCA	1.20	[1.17-1.23]	1.14	[1.10-1.18]	1.17	[1.14-1.20]

Table 15: Productivity estimates and population size used to estimate PST reference points for each species, assuming $\phi = 1$ (continued on next page). Numbers are given in units of a thousand individuals.

	N_s (thousand)		r_s		PST_s	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
XAU	15	[11-19]	0.03	[0.02-0.05]	255.54	[129.69-403.87]
XAN	11	[9-14]	0.04	[0.02-0.06]	241.44	[121.95-368.14]
XRA	28	[22-36]	0.04	[0.03-0.06]	594.93	[350.19-874.22]
XNR	13	[10-16]	0.04	[0.03-0.06]	270.32	[156.08-403.30]
XCM	44	[37-53]	0.06	[0.03-0.08]	1211.30	[615.30-1838.51]
XWM	314	[243-400]	0.03	[0.02-0.05]	5366.94	[2496.99-8555.03]
XSA	157	[101-237]	0.03	[0.01-0.05]	2550.95	[1076.74-4571.32]
XCI	12	[11-14]	0.04	[0.02-0.06]	225.22	[102.44-346.92]
XGM	13	[11-16]	0.05	[0.03-0.07]	311.14	[160.89-473.00]
XBM	31	[29-35]	0.04	[0.02-0.06]	612.71	[297.27-946.87]
XNB	47	[42-56]	0.04	[0.02-0.06]	888.78	[440.82-1365.94]
XLM	22	[19-26]	0.03	[0.02-0.05]	377.75	[173.57-602.67]
XNP	7	[5-9]	0.06	[0.04-0.08]	188.82	[111.90-276.00]
XGP	114	[76-170]	0.06	[0.04-0.09]	3591.54	[1892.89-6184.51]
XBP	18	[14-23]	0.06	[0.04-0.07]	520.67	[344.98-726.48]
XWP	11	[7-18]	0.07	[0.04-0.10]	392.22	[179.77-736.32]
XWC	508	[427-605]	0.07	[0.04-0.10]	18097.67	[10144.22-27935.82]

Table 15: Continued

	N_s (thousand)		r_s		PST_s	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
XFS	51	[41-63]	0.07	[0.04-0.10]	1690.71	[904.98-2666.30]
PUPA	112	[59-197]	0.10	[0.08-0.13]	5736.74	[2846.28-10552.67]
XBS	175	[147-207]	0.07	[0.04-0.11]	6350.24	[3636.71-9496.25]
XSH	6449	[3514-10903]	0.07	[0.05-0.09]	231005.14	[112980.79-419251.79]
XFL	439	[222-989]	0.09	[0.06-0.11]	18733.25	[8460.71-42351.04]
XPH	233	[152-343]	0.09	[0.06-0.11]	9900.51	[5822.34-15445.98]
PUAS	349	[252-470]	0.09	[0.06-0.11]	14885.03	[9402.31-22027.61]
XCA	24	[13-41]	0.10	[0.05-0.13]	1141.74	[482.11-2180.25]
XFP	3170	[2571-3862]	0.10	[0.08-0.11]	152938.08	[113954.44-196879.43]
XPR	1236	[761-2078]	0.08	[0.06-0.10]	49710.66	[28084.71-86623.14]
XPV	752	[610-920]	0.10	[0.08-0.11]	36204.68	[27268.51-47110.72]
PTPY	6	[4-7]	0.07	[0.05-0.08]	182.09	[121.81-253.80]
PTCO	618	[468-889]	0.07	[0.05-0.08]	20307.56	[12501.75-31888.90]
PTAX	1	[0-1]	0.06	[0.04-0.08]	18.15	[10.19-28.77]
XMP	766	[646-927]	0.06	[0.05-0.08]	24848.67	[16636.28-33872.37]
PTCE	111	[59-188]	0.06	[0.04-0.08]	3584.32	[1717.15-6451.58]
PTNE	14	[11-17]	0.06	[0.04-0.08]	436.81	[287.52-601.96]
XGF	527	[429-665]	0.07	[0.04-0.08]	17180.02	[11087.34-24072.76]
PTMA	0	[0-0]	0.07	[0.05-0.08]	3.01	[2.02-4.17]
XWH	452	[244-762]	0.07	[0.04-0.09]	15297.66	[7269.97-27894.68]
PTMO	12	[3-22]	0.06	[0.04-0.08]	385.82	[83.90-788.90]
XDP	2321	[786-4282]	0.14	[0.12-0.16]	160045.00	[55403.46-295755.58]
XSD	0	[0-0]	0.14	[0.12-0.18]	14.80	[11.24-19.05]
XWF	4319	[1797-6661]	0.10	[0.08-0.13]	224534.08	[87476.51-381082.19]
XWB	2	[1-4]	0.09	[0.07-0.11]	103.10	[53.48-180.17]
XFT	164	[112-223]	0.09	[0.07-0.11]	7641.59	[4847.62-11160.03]
PEAL	0	[0-0]	0.10	[0.08-0.13]	8.11	[2.51-15.05]
PEMA	1	[0-2]	0.09	[0.07-0.11]	51.42	[4.32-106.12]
XYP	3	[3-4]	0.14	[0.10-0.18]	239.08	[162.34-339.19]
EUIR	15	[11-21]	0.18	[0.15-0.22]	1410.71	[912.82-2076.30]
EUAL	5	[3-7]	0.18	[0.15-0.22]	423.84	[267.20-640.38]
EUMI	15	[11-21]	0.18	[0.15-0.22]	1405.65	[902.46-2065.27]
EUCH	16	[11-21]	0.18	[0.15-0.22]	1441.23	[925.17-2087.66]
EUFI	102	[83-125]	0.13	[0.09-0.16]	6836.59	[4249.03-9244.10]
XFC	7	[4-12]	0.13	[0.09-0.16]	451.36	[219.63-801.39]
EURO	59	[52-67]	0.09	[0.07-0.10]	2548.08	[1956.47-3184.89]
EUSC	173	[161-188]	0.09	[0.07-0.10]	7466.88	[5891.69-9058.58]
XGT	103	[54-179]	0.08	[0.05-0.12]	4317.45	[1923.72-8367.43]
XMB	1	[0-1]	0.13	[0.10-0.18]	35.22	[20.54-56.55]
XPS	13	[10-15]	0.19	[0.15-0.24]	1201.55	[864.59-1654.33]
XBC	3	[2-5]	0.24	[0.16-0.40]	373.60	[171.51-757.30]
XKS	0	[0-1]	0.14	[0.10-0.17]	28.73	[20.02-38.98]
XSI	3	[3-3]	0.14	[0.10-0.17]	201.90	[147.85-258.21]
XFX	2	[2-2]	0.14	[0.11-0.17]	148.00	[106.19-193.70]
XCS	1	[1-1]	0.14	[0.11-0.17]	54.70	[38.40-74.40]
LERA	0	[0-0]	0.14	[0.10-0.17]	18.45	[11.15-29.08]
LECO	5	[2-9]	0.14	[0.10-0.17]	376.41	[144.67-672.39]
LECA	4	[2-8]	0.14	[0.10-0.17]	306.84	[150.40-541.36]
XPP	47	[24-68]	0.24	[0.16-0.40]	5692.28	[2414.27-10804.74]
XPF	1	[1-1]	0.14	[0.10-0.17]	51.63	[35.83-70.56]
CALO	1	[1-1]	0.06	[0.04-0.08]	33.44	[22.72-44.26]
XBG	2646	[1529-5685]	0.15	[0.11-0.18]	194090.91	[98777.91-429630.35]
HYCA	2	[1-3]	0.17	[0.12-0.23]	186.68	[106.28-307.03]
GYCA	0	[0-0]	0.16	[0.13-0.18]	13.44	[9.59-17.55]

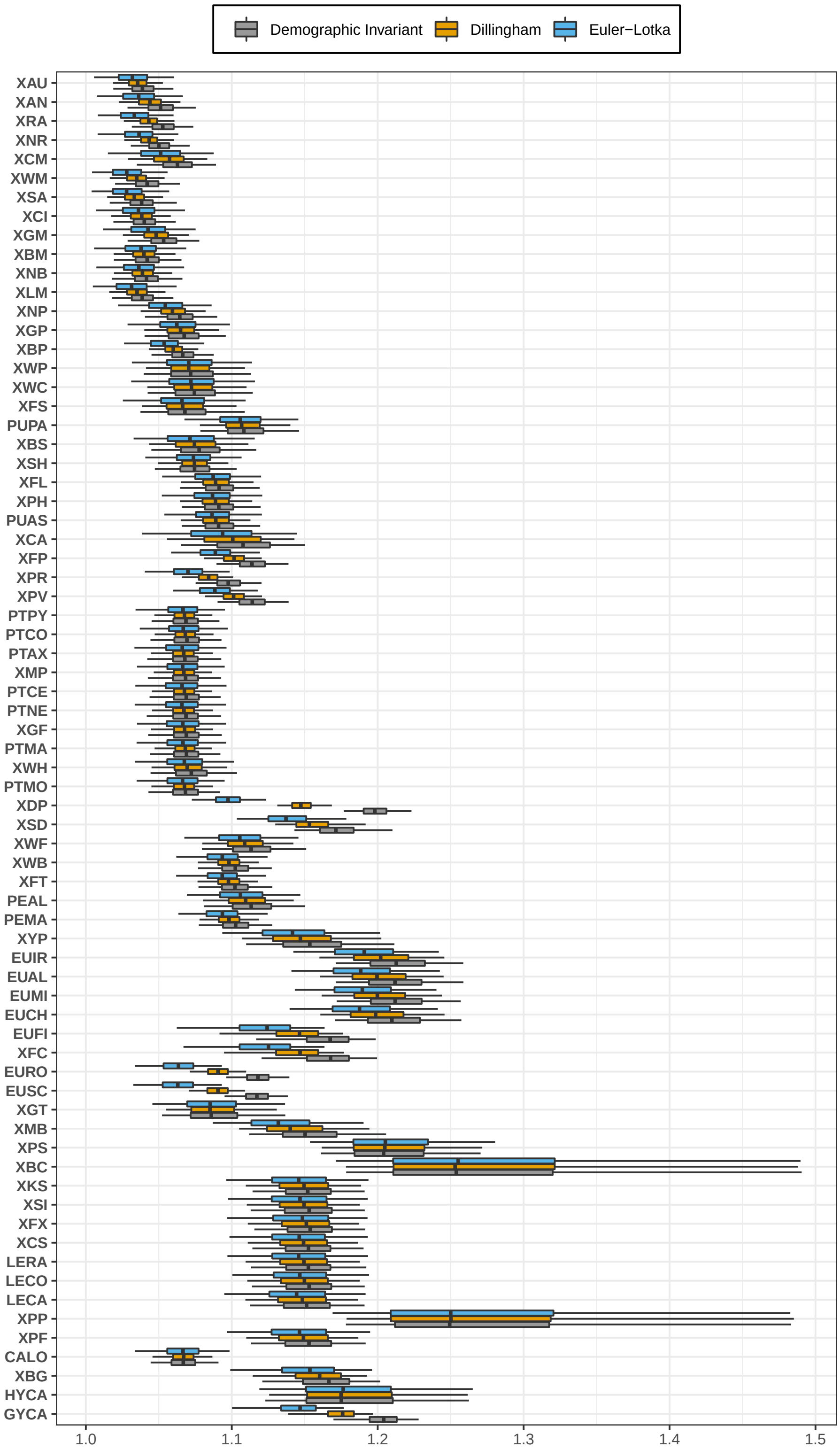

Figure 15: Euler-Lotka (EL) and demographic invariant (DI) methods for estimation of λ_s for each species (Table 1). Each method has a different relationship to S_s^{opt}, which can by used to bound the uncertainty by selecting values for λ_s that are compatible with both. The Dillingham estimate represents the intersection of the EL and DI methods (as recommended by Dillingham et al. 2016), and was used in the current project. Values for each estimate are listed in Table 14.

5.5 Model predictions

Given the estimated catchabilities, the number of adult birds available for capture and total overlap (including both observed and unobserved fishing effort), we can estimate the total annual observable captures (Table 16). These values represent an average across the most recent three years of data (2017/18 to 2019/20 inclusive). Using the cryptic mortality multipliers in Table 4 we can further estimate the average number of deaths and the risk. These are listed per species in Table 16, with the risk also illustrated in Figure 16. Risk values of greater than one indicate that the current deaths exceed the sustainable death rate. According to the model, there is a high probability that this is true for southern Buller's albatross (XBM). Salvin's albatross (XSA), New Zealand white-capped albatross (XWM), black petrel (XBP) and Westland petrel (XWP) are also amongst the highest risk species. However, only southern Buller's albatross has a risk greater than one (Table 16).

Predicted annual deaths per species per method are listed in Table 17. Because these deaths will include cryptic mortalities, the proportion of deaths that are cryptic are listed in Table 18. It is calculated as:

$$\text{Proportion cryptic} = \frac{\sum D_{f,s} - \sum C_{f,s}^{\text{DEAD}}}{\sum D_{f,s}}$$

with the summation taken over fishery groups within a particular method.

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), and the proportion of captures that are live (since live captures will likely suffer some post-release cryptic mortality). The SN fishery, for example, has no unobservable cryptic captures, but live birds will suffer post-release mortality, and the proportion of captures that are live will determine the proportion of mortalities that are cryptic. Overall, this leads to non-zero cryptic mortalities. 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 small and 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.

For the top thirty at-risk species, deaths are disaggregated by fishery group in Tables 19, 20, and 21. 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 16.

Table 16: Annual observable captures, deaths and risk per species, ranked from highest to lowest median risk (continued on next page). Risk is calculated assuming that $\phi = 1$. 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	
Code	Mean	95% CI	Mean	95% CI	Median	95% CI
XBM	242.2	[208.0-280.7]	728.5	[554.5-938.7]	1.19	[0.71-2.65]
XSA	299.5	[256.0-349.0]	1706.3	[1291.0-2258.5]	0.69	[0.35-1.69]
XWM	570.0	[506.3-638.3]	2634.8	[2071.1-3334.1]	0.50	[0.29-1.07]
XBP	221.8	[180.3-279.0]	256.1	[177.6-352.2]	0.49	[0.30-0.82]
XWP	89.9	[65.7-121.3]	143.3	[91.2-220.5]	0.38	[0.17-0.88]
XCI	26.9	[14.7-43.0]	61.5	[33.5-98.7]	0.27	[0.13-0.68]
XFS	253.0	[211.7-296.7]	368.1	[264.3-493.5]	0.22	[0.12-0.44]
XNB	63.2	[43.3-88.7]	173.8	[109.3-262.9]	0.19	[0.10-0.43]
XAU	33.0	[20.7-48.0]	41.9	[22.9-68.4]	0.16	[0.08-0.37]
XAN	31.8	[21.0-44.0]	38.3	[21.8-60.3]	0.16	[0.08-0.35]
XWC	895.8	[820.0-975.0]	1694.3	[1295.3-2319.9]	0.09	[0.06-0.18]
XRA	22.5	[12.7-36.3]	49.6	[25.9-84.6]	0.08	[0.04-0.17]
XNP	6.2	[1.7-14.3]	16.0	[4.1-35.0]	0.08	[0.02-0.22]
XCM	30.9	[18.7-46.7]	68.5	[37.8-117.6]	0.05	[0.03-0.14]
XYP	11.2	[5.3-18.7]	10.6	[5.0-17.9]	0.04	[0.02-0.08]
XPP	188.5	[131.0-257.0]	226.1	[149.3-337.9]	0.04	[0.02-0.10]
XNR	5.9	[1.7-12.3]	13.0	[2.6-35.2]	0.04	[0.01-0.15]
XLM	4.7	[1.0-11.3]	14.8	[2.3-43.8]	0.03	[0.01-0.14]
XGM	4.4	[1.0-10.7]	12.5	[1.6-37.0]	0.03	[0.01-0.14]
XGP	52.3	[35.0-73.0]	78.1	[50.7-113.4]	0.02	[0.01-0.05]
XCA	2.1	[0.3-6.0]	29.8	[0.4-120.4]	0.02	[0.00-0.13]
XSI	2.9	[0.0-10.0]	3.2	[0.0-12.1]	0.01	[0.00-0.06]
XBS	30.2	[15.7-49.0]	79.0	[22.2-240.5]	0.01	[0.00-0.04]
XKS	0.7	[0.0-4.3]	0.8	[0.0-5.0]	0.01	[0.00-0.18]
XBC	3.2	[0.0-12.7]	3.6	[0.0-13.7]	0.01	[0.00-0.04]
XFC	2.7	[0.3-6.7]	2.8	[0.3-7.3]	0.01	[0.00-0.02]
XPS	5.5	[0.7-15.0]	6.0	[0.9-16.4]	0.00	[0.00-0.01]
XPV	12.4	[4.0-26.0]	173.7	[24.5-613.6]	0.00	[0.00-0.02]
XFX	1.0	[0.0-5.0]	1.1	[0.0-6.3]	0.00	[0.00-0.04]
XSH	275.7	[238.7-316.7]	688.7	[469.8-1024.6]	0.00	[0.00-0.01]
XFL	43.7	[14.7-96.7]	51.3	[16.0-117.2]	0.00	[0.00-0.01]
XMP	7.6	[1.3-21.7]	96.6	[7.2-379.2]	0.00	[0.00-0.02]
XPH	4.7	[0.7-14.7]	42.8	[0.7-208.8]	0.00	[0.00-0.02]
XDP	29.4	[15.0-50.3]	388.7	[82.9-1065.4]	0.00	[0.00-0.01]
XGF	23.6	[13.3-36.7]	35.2	[17.3-64.1]	0.00	[0.00-0.00]
XFT	1.9	[0.0-5.0]	16.8	[0.0-66.1]	0.00	[0.00-0.01]
PTPY	0.5	[0.0-2.7]	1.9	[0.0-15.1]	0.00	[0.00-0.09]
EUAL	0.8	[0.0-4.3]	1.0	[0.0-4.9]	0.00	[0.00-0.01]
EUIR	1.7	[0.0-5.7]	2.1	[0.0-6.8]	0.00	[0.00-0.01]
EUMI	1.3	[0.0-5.3]	1.6	[0.0-6.8]	0.00	[0.00-0.01]
XWF	47.0	[11.7-168.7]	186.7	[39.3-574.3]	0.00	[0.00-0.00]
PTCO	5.2	[0.7-18.0]	19.3	[0.8-71.6]	0.00	[0.00-0.00]
XFP	15.6	[4.3-46.7]	139.7	[22.0-473.6]	0.00	[0.00-0.00]
XPR	3.0	[0.7-7.0]	31.5	[2.7-110.4]	0.00	[0.00-0.00]
EUCH	0.8	[0.0-4.3]	1.0	[0.0-5.8]	0.00	[0.00-0.00]
XWH	3.3	[0.7-8.3]	5.0	[0.7-14.2]	0.00	[0.00-0.00]
XBG	30.2	[14.7-50.3]	41.1	[16.1-81.6]	0.00	[0.00-0.00]
XGT	1.1	[0.0-4.7]	1.0	[0.0-4.2]	0.00	[0.00-0.00]
EURO	0.5	[0.0-2.0]	0.6	[0.0-2.7]	0.00	[0.00-0.00]
PUAS	1.3	[0.0-5.0]	5.7	[0.0-30.0]	0.00	[0.00-0.00]
EUFI	0.4	[0.0-1.7]	0.5	[0.0-2.4]	0.00	[0.00-0.00]
PUPA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTAX	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTCE	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTNE	0.1	[0.0-1.0]	0.2	[0.0-1.3]	0.00	[0.00-0.00]

Table 16: Continued

Code	C_s Mean	C_s 95% CI	D_s Mean	D_s 95% CI	Risk Median	Risk 95% CI
PTMA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTMO	0.1	[0.0-1.0]	0.9	[0.0-9.6]	0.00	[0.00-0.03]
XSD	0.0	[0.0-0.0]	0.1	[0.0-0.0]	0.00	[0.00-0.00]
XWB	0.0	[0.0-0.3]	0.0	[0.0-0.3]	0.00	[0.00-0.00]
PEAL	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PEMA	0.1	[0.0-1.0]	0.4	[0.0-4.3]	0.00	[0.00-0.07]
EUSC	0.3	[0.0-1.3]	0.4	[0.0-1.9]	0.00	[0.00-0.00]
XMB	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
XCS	0.4	[0.0-2.7]	0.5	[0.0-3.6]	0.00	[0.00-0.07]
LERA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
LECO	0.1	[0.0-0.7]	0.1	[0.0-0.7]	0.00	[0.00-0.00]
LECA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
XPF	0.4	[0.0-3.0]	0.5	[0.0-4.4]	0.00	[0.00-0.08]
CALO	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
HYCA	0.2	[0.0-1.0]	1.0	[0.0-10.6]	0.00	[0.00-0.06]
GYCA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]

Table 17: Predicted annual deaths per species and method, ranked from highest to lowest median risk (continued on next page). Colours are defined as per Table 16.

Code	BLL Mean	BLL 95% CI	SLL Mean	SLL 95% CI	SN Mean	SN 95% CI	Trawl Mean	Trawl 95% CI
XBM	12	[5–24]	192	[138–268]	0	[0–1]	512	[389–675]
XSA	55	[38–78]	7	[3–16]	0	[0–2]	1618	[1276–2092]
XWM	32	[18–55]	225	[163–311]	1	[0–2]	2339	[1890–2934]
XBP	125	[77–180]	60	[39–89]	2	[0–31]	58	[34–100]
XWP	39	[23–65]	35	[23–52]	2	[0–6]	59	[30–118]
XCI	28	[15–50]	0	[0–1]	0	[0–0]	30	[14–55]
XFS	208	[146–292]	26	[15–43]	4	[1–12]	120	[78–187]
XNB	22	[9–47]	34	[20–55]	0	[0–1]	109	[65–178]
XAU	0	[0–2]	35	[21–55]	0	[0–0]	4	[0–16]
XAN	0	[0–3]	34	[22–52]	0	[0–0]	2	[0–9]
XWC	554	[446–692]	115	[71–185]	6	[3–11]	963	[688–1464]
XRA	6	[2–16]	11	[5–20]	0	[0–1]	28	[13–54]
XNP	3	[0–9]	0	[0–1]	0	[0–0]	11	[2–26]
XCM	11	[3–26]	19	[11–32]	0	[0–1]	33	[14–68]
XYP	0	[0–0]	0	[0–0]	10	[6–16]	0	[0–1]
XPP	2	[0–8]	0	[0–1]	13	[6–25]	205	[144–297]
XNR	1	[0–4]	3	[1–8]	0	[0–1]	6	[0–23]
XLM	2	[0–6]	0	[0–3]	0	[0–1]	9	[0–31]
XGM	1	[0–5]	1	[0–4]	0	[0–1]	6	[0–27]
XGP	37	[22–59]	18	[10–31]	0	[0–2]	19	[10–36]
XCA	0	[0–1]	0	[0–1]	0	[0–0]	20	[2–86]
XSI	0	[0–0]	0	[0–0]	1	[0–3]	1	[0–7]
XBS	26	[13–47]	0	[0–2]	0	[0–1]	34	[4–154]
XKS	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–2]
XBC	1	[0–5]	0	[0–0]	0	[0–6]	0	[0–3]
XFC	0	[0–2]	0	[0–1]	2	[0–4]	0	[0–2]
XPS	1	[0–6]	0	[0–1]	2	[0–8]	1	[0–4]
XPV	1	[0–6]	0	[0–1]	0	[0–1]	122	[29–476]
XFX	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–4]
XSH	26	[14–44]	2	[0–6]	9	[5–15]	629	[458–917]
XFL	17	[6–37]	0	[0–2]	14	[2–48]	8	[0–48]
XMP	1	[0–4]	0	[0–1]	0	[0–1]	61	[9–291]
XPH	1	[0–4]	0	[0–2]	0	[0–2]	21	[0–147]
XDP	3	[0–10]	0	[0–2]	1	[0–3]	317	[97–893]
XGF	8	[3–17]	8	[3–14]	0	[0–3]	15	[6–36]
XFT	0	[0–2]	0	[0–1]	0	[0–1]	11	[0–49]

Table 17: Continued

	BLL		SLL		SN		Trawl	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
PTPY	0	[0–1]	0	[0–0]	0	[0–1]	0	[0–10]
EUAL	0	[0–1]	0	[0–0]	0	[0–1]	0	[0–2]
EUIR	0	[0–3]	0	[0–2]	0	[0–1]	0	[0–2]
EUMI	0	[0–2]	0	[0–1]	0	[0–1]	0	[0–4]
XWF	15	[4–69]	0	[0–1]	0	[0–2]	125	[31–426]
PTCO	1	[0–4]	0	[0–1]	0	[0–7]	10	[0–53]
XFP	2	[0–13]	0	[0–1]	0	[0–3]	95	[25–360]
XPR	0	[0–2]	0	[0–1]	0	[0–1]	22	[4–86]
EUCH	0	[0–3]	0	[0–0]	0	[0–0]	0	[0–1]
XWH	1	[0–4]	0	[0–2]	0	[0–1]	2	[0–9]
XBG	21	[9–40]	0	[0–2]	0	[0–3]	15	[4–44]
XGT	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–1]
EURO	0	[0–1]	0	[0–1]	0	[0–0]	0	[0–1]
PUAS	0	[0–2]	0	[0–1]	0	[0–1]	0	[0–21]
EUFI	0	[0–1]	0	[0–1]	0	[0–0]	0	[0–1]
PUPA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
PTAX	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
PTCE	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
PTNE	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]
PTMA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
PTMO	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–6]
XSD	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XWB	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
PEAL	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
PEMA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
EUSC	0	[0–1]	0	[0–0]	0	[0–0]	0	[0–1]
XMB	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XCS	0	[0–2]	0	[0–0]	0	[0–0]	0	[0–0]
LERA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
LECO	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
LECA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XPF	0	[0–2]	0	[0–0]	0	[0–0]	0	[0–0]
CALO	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
HYCA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–6]
GYCA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]

Table 18: Annual cryptic deaths per species and method, expressed as a proportion of total deaths, ranked from highest to lowest median risk (continued on next page). Colours are defined as per Table 16.

	BLL		SLL		SN		Trawl	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBM	0.36	[0.19–0.51]	0.32	[0.09–0.50]	0.00	[0.00–0.50]	0.89	[0.87–0.91]
XSA	0.32	[0.16–0.45]	0.32	[0.09–0.49]	0.18	[0.00–0.52]	0.89	[0.87–0.91]
XWM	0.37	[0.17–0.53]	0.32	[0.10–0.50]	0.28	[0.00–0.53]	0.90	[0.88–0.91]
XBP	0.54	[0.31–0.67]	0.31	[0.07–0.49]	0.21	[0.00–0.43]	0.76	[0.65–0.85]
XWP	0.38	[0.18–0.54]	0.31	[0.07–0.49]	0.24	[0.02–0.44]	0.74	[0.63–0.84]
XCI	0.31	[0.08–0.48]	0.00	[0.00–0.36]	0.00	[0.00–0.09]	0.89	[0.86–0.91]
XFS	0.38	[0.16–0.53]	0.30	[0.06–0.48]	0.21	[0.02–0.40]	0.73	[0.63–0.81]
XNB	0.33	[0.13–0.48]	0.32	[0.10–0.50]	0.00	[0.00–0.47]	0.89	[0.86–0.91]
XAU	0.35	[0.00–0.88]	0.38	[0.16–0.54]	0.00	[0.00–0.66]	0.91	[0.00–0.94]
XAN	0.34	[0.00–0.72]	0.38	[0.15–0.53]	0.00	[0.00–0.63]	0.87	[0.00–0.94]
XWC	0.32	[0.18–0.43]	0.31	[0.07–0.49]	0.24	[0.03–0.44]	0.74	[0.64–0.83]
XRA	0.44	[0.25–0.60]	0.38	[0.16–0.54]	0.00	[0.00–0.72]	0.92	[0.90–0.94]
XNP	0.53	[0.25–0.72]	0.00	[0.00–0.46]	0.00	[0.00–0.55]	0.91	[0.88–0.94]
XCM	0.33	[0.15–0.49]	0.32	[0.09–0.50]	0.04	[0.00–0.51]	0.89	[0.87–0.91]
XYP	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.05	[0.01–0.16]	0.00	[0.00–0.36]

Table 18: Continued

	BLL		SLL		SN		Trawl	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XPP	0.32	[0.00–0.52]	0.00	[0.00–0.34]	0.04	[0.00–0.14]	0.26	[0.14–0.42]
XNR	0.40	[0.00–0.81]	0.38	[0.15–0.54]	0.00	[0.00–0.70]	0.91	[0.00–0.94]
XLM	0.38	[0.00–0.66]	0.14	[0.00–0.47]	0.00	[0.00–0.49]	0.89	[0.00–0.92]
XGM	0.37	[0.00–0.67]	0.29	[0.00–0.49]	0.00	[0.00–0.49]	0.89	[0.00–0.92]
XGP	0.33	[0.20–0.44]	0.31	[0.08–0.49]	0.14	[0.00–0.42]	0.73	[0.63–0.82]
XCA	0.00	[0.00–0.72]	0.00	[0.00–0.48]	0.00	[0.00–0.68]	0.98	[0.90–0.99]
XSI	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.04	[0.00–0.13]	0.22	[0.00–0.39]
XBS	0.44	[0.20–0.61]	0.00	[0.00–0.46]	0.00	[0.00–0.53]	0.96	[0.87–0.99]
XKS	0.00	[0.00–0.45]	0.00	[0.00–0.00]	0.00	[0.00–0.06]	0.00	[0.00–0.36]
XBC	0.25	[0.00–0.49]	0.00	[0.00–0.00]	0.02	[0.00–0.12]	0.20	[0.00–0.38]
XFC	0.00	[0.00–0.48]	0.00	[0.00–0.33]	0.05	[0.00–0.16]	0.00	[0.00–0.37]
XPS	0.28	[0.00–0.49]	0.00	[0.00–0.35]	0.04	[0.00–0.13]	0.23	[0.00–0.38]
XPV	0.44	[0.00–0.83]	0.00	[0.00–0.58]	0.00	[0.00–0.82]	0.98	[0.94–0.99]
XFX	0.00	[0.00–0.35]	0.00	[0.00–0.00]	0.00	[0.00–0.09]	0.17	[0.00–0.38]
XSH	0.36	[0.23–0.47]	0.29	[0.00–0.48]	0.21	[0.03–0.40]	0.73	[0.64–0.81]
XFL	0.44	[0.21–0.60]	0.00	[0.00–0.47]	0.35	[0.06–0.64]	0.95	[0.00–0.98]
XMP	0.44	[0.00–0.93]	0.00	[0.00–0.52]	0.00	[0.00–0.81]	0.98	[0.93–0.99]
XPH	0.38	[0.00–0.81]	0.00	[0.00–0.46]	0.22	[0.00–0.61]	0.96	[0.00–0.99]
XDP	0.48	[0.23–0.78]	0.00	[0.00–0.55]	0.62	[0.09–0.84]	0.98	[0.94–0.99]
XGF	0.41	[0.20–0.58]	0.39	[0.16–0.55]	0.43	[0.00–0.78]	0.87	[0.75–0.94]
XFT	0.35	[0.00–0.85]	0.00	[0.00–0.52]	0.00	[0.00–0.76]	0.97	[0.00–0.99]
PTPY	0.00	[0.00–0.72]	0.00	[0.00–0.47]	0.00	[0.00–0.72]	0.00	[0.00–0.98]
EUAL	0.00	[0.00–0.41]	0.00	[0.00–0.00]	0.00	[0.00–0.12]	0.00	[0.00–0.38]
EUIR	0.21	[0.00–0.50]	0.00	[0.00–0.42]	0.00	[0.00–0.12]	0.18	[0.00–0.38]
EUMI	0.00	[0.00–0.49]	0.00	[0.00–0.39]	0.00	[0.00–0.10]	0.21	[0.00–0.40]
XWF	0.71	[0.36–0.92]	0.00	[0.00–0.54]	0.17	[0.00–0.81]	0.98	[0.93–0.99]
PTCO	0.56	[0.00–0.88]	0.00	[0.00–0.54]	0.51	[0.00–0.82]	0.97	[0.00–0.99]
XFP	0.61	[0.21–0.95]	0.00	[0.00–0.59]	0.59	[0.00–0.88]	0.98	[0.94–0.99]
XPR	0.44	[0.00–0.92]	0.00	[0.00–0.58]	0.00	[0.00–0.82]	0.98	[0.94–0.99]
EUCH	0.09	[0.00–0.47]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.31]
XWH	0.44	[0.00–0.80]	0.00	[0.00–0.52]	0.00	[0.00–0.74]	0.85	[0.00–0.93]
XBG	0.46	[0.23–0.64]	0.00	[0.00–0.47]	0.27	[0.00–0.68]	0.83	[0.69–0.93]
XGT	0.00	[0.00–0.77]	0.00	[0.00–0.42]	0.00	[0.00–0.58]	0.00	[0.00–0.67]
EURO	0.00	[0.00–0.41]	0.00	[0.00–0.30]	0.00	[0.00–0.07]	0.00	[0.00–0.36]
PUAS	0.26	[0.00–0.63]	0.00	[0.00–0.43]	0.00	[0.00–0.54]	0.00	[0.00–0.98]
EUFI	0.00	[0.00–0.41]	0.00	[0.00–0.30]	0.00	[0.00–0.04]	0.00	[0.00–0.35]
PUPA	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
PTAX	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
PTCE	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
PTNE	0.00	[0.00–0.54]	0.00	[0.00–0.35]	0.00	[0.00–0.00]	0.00	[0.00–0.85]
PTMA	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
PTMO	0.00	[0.00–0.47]	0.00	[0.00–0.36]	0.00	[0.00–0.00]	0.00	[0.00–0.98]
XSD	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
XWB	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
PEAL	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
PEMA	0.00	[0.00–0.54]	0.00	[0.00–0.34]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
EUSC	0.00	[0.00–0.36]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.33]
XMB	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
XCS	0.00	[0.00–0.43]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.20]
LERA	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
LECO	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.24]
LECA	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
XPF	0.00	[0.00–0.42]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
CALO	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]
HYCA	0.00	[0.00–0.47]	0.00	[0.00–0.00]	0.00	[0.00–0.36]	0.00	[0.00–0.97]
GYCA	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]	0.00	[0.00–0.00]

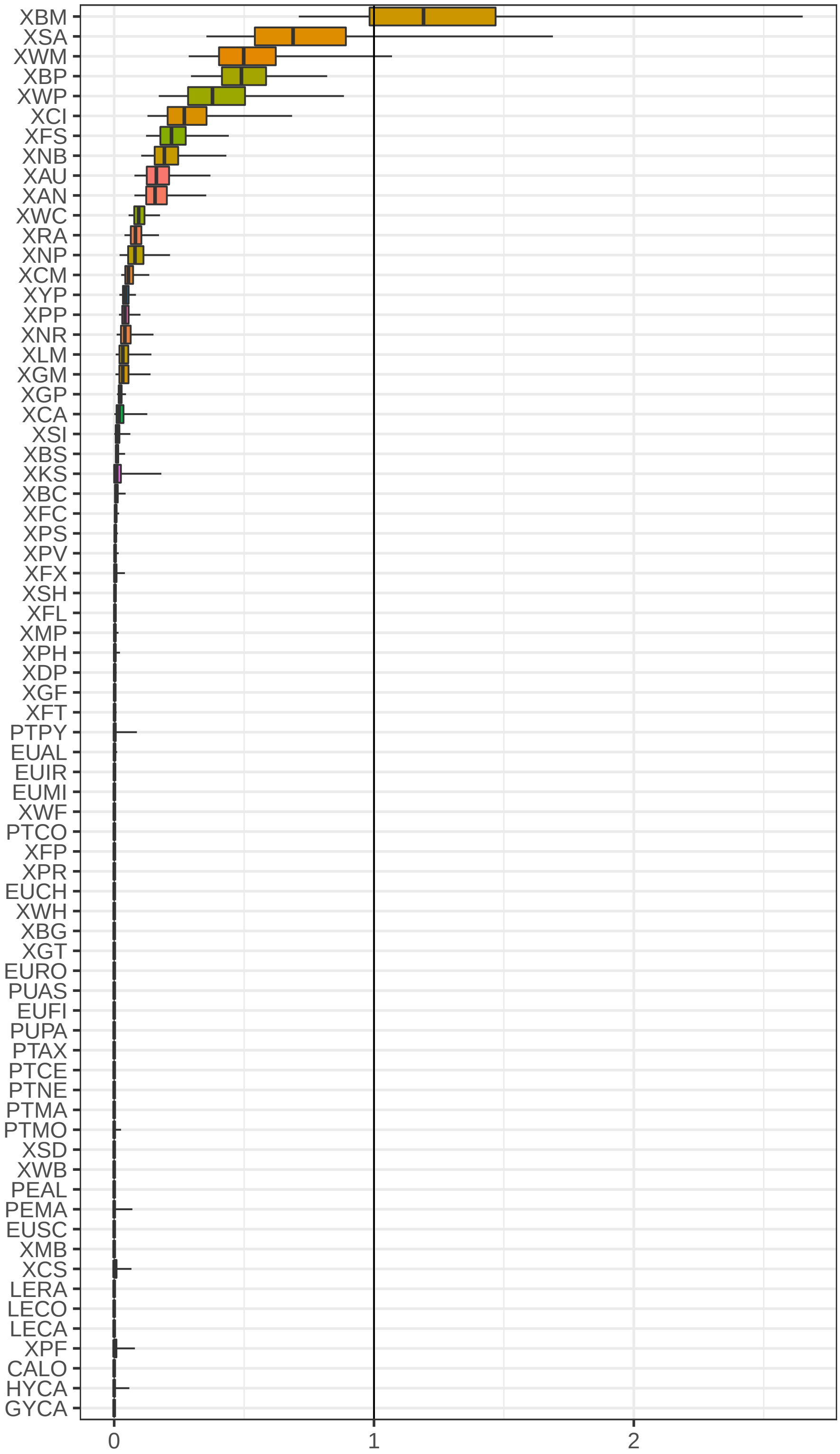

Figure 16: Estimation of the risk per species, ranked from highest to lowest risk. Species codes are given and correspond to the names listed in Table 1. Boxplots show the median, and 75% and 95% posterior quantiles.

Table 19: Annual deaths per fishery group (BLL) for the top thirty at risk species, ranked in order of highest to lowest median risk.

	Large Autoline with IWL		Large Autoline		Small Autoline (LIN, RIB)		Small Autoline		Small Manual (heavy)		Small Manual (light)		Small Manual (LIN, RIB)	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBM	0	[0–0]	3	[1–10]	0	[0–1]	0	[0–1]	0	[0–2]	0	[0–0]	7	[1–18]
XSA	1	[0–3]	9	[4–17]	33	[20–54]	0	[0–3]	0	[0–1]	1	[0–5]	7	[2–17]
XWM	0	[0–1]	1	[0–5]	0	[0–2]	0	[0–4]	0	[0–5]	0	[0–3]	28	[14–49]
XBP	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	54	[21–92]	69	[44–104]	0	[0–4]
XWP	0	[0–0]	0	[0–3]	0	[0–1]	0	[0–2]	3	[0–14]	1	[0–6]	31	[17–55]
XCI	1	[0–2]	0	[0–2]	25	[13–45]	0	[0–4]	0	[0–1]	0	[0–0]	0	[0–3]
XFS	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	5	[1–15]	201	[141–283]	0	[0–3]
XNB	0	[0–1]	2	[0–6]	1	[0–4]	16	[5–41]	0	[0–3]	0	[0–1]	0	[0–3]
XAU	0	[0–0]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–0]	0	[0–1]
XAN	0	[0–0]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–0]	0	[0–1]	0	[0–1]
XWC	19	[11–30]	280	[201–390]	154	[101–227]	4	[1–12]	6	[1–19]	0	[0–1]	82	[52–127]
XRA	1	[0–3]	0	[0–3]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–2]	3	[0–12]
XNP	0	[0–1]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	3	[0–9]	0	[0–0]
XCM	0	[0–2]	0	[0–1]	0	[0–1]	7	[2–22]	0	[0–1]	0	[0–3]	0	[0–3]
XYP	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XPP	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–3]	0	[0–4]	0	[0–2]
XNR	0	[0–0]	0	[0–1]	0	[0–1]	0	[0–2]	0	[0–1]	0	[0–1]	0	[0–1]
XLM	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–2]	0	[0–1]	0	[0–2]	0	[0–3]
XGM	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–2]	0	[0–2]
XGP	0	[0–2]	13	[5–25]	7	[2–16]	0	[0–3]	0	[0–2]	5	[1–16]	7	[1–22]
XCA	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XSI	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XBS	0	[0–0]	0	[0–1]	0	[0–1]	0	[0–1]	0	[0–1]	26	[12–46]	0	[0–1]
XKS	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XBC	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–5]	0	[0–1]
XFC	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]
XPS	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–5]	0	[0–2]
XPV	0	[0–0]	0	[0–1]	0	[0–1]	0	[0–4]	0	[0–1]	0	[0–1]	0	[0–1]
XFX	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]
XSH	8	[4–13]	0	[0–2]	0	[0–4]	4	[0–15]	1	[0–6]	5	[1–15]	3	[0–13]

Table 20: Annual deaths per fishery group (SLL and SN) for the top thirty at risk species, ranked in order of highest to lowest median risk.

	Large SLL		Small SLL (tuna and swordfish)		SN (unclassified)	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBM	0	[0–0]	192	[138–268]	0	[0–1]
XSA	0	[0–0]	7	[3–16]	0	[0–2]
XWM	0	[0–0]	225	[163–311]	1	[0–2]
XBP	0	[0–0]	60	[39–89]	2	[0–31]
XWP	0	[0–0]	35	[23–52]	2	[0–6]
XCI	0	[0–0]	0	[0–1]	0	[0–0]
XFS	0	[0–0]	26	[15–43]	4	[1–12]
XNB	0	[0–0]	34	[20–55]	0	[0–1]
XAU	0	[0–0]	35	[21–55]	0	[0–0]
XAN	0	[0–0]	34	[22–52]	0	[0–0]
XWC	0	[0–0]	115	[71–185]	6	[3–11]
XRA	0	[0–0]	11	[5–20]	0	[0–1]
XNP	0	[0–0]	0	[0–1]	0	[0–0]
XCM	0	[0–0]	19	[11–32]	0	[0–1]
XYP	0	[0–0]	0	[0–0]	10	[6–16]
XPP	0	[0–0]	0	[0–1]	13	[6–25]
XNR	0	[0–0]	3	[1–8]	0	[0–1]
XLM	0	[0–0]	0	[0–3]	0	[0–1]
XGM	0	[0–0]	1	[0–4]	0	[0–1]
XGP	0	[0–0]	18	[10–31]	0	[0–2]
XCA	0	[0–0]	0	[0–1]	0	[0–0]
XSI	0	[0–0]	0	[0–0]	1	[0–3]
XBS	0	[0–0]	0	[0–2]	0	[0–1]
XKS	0	[0–0]	0	[0–0]	0	[0–1]
XBC	0	[0–0]	0	[0–0]	0	[0–6]
XFC	0	[0–0]	0	[0–1]	2	[0–4]
XPS	0	[0–0]	0	[0–1]	2	[0–8]
XPV	0	[0–0]	0	[0–1]	0	[0–1]
XFX	0	[0–0]	0	[0–0]	0	[0–1]
XSH	0	[0–0]	2	[0–6]	9	[5–15]

Table 21: Annual deaths per fishery group (Trawl) for the top thirty at risk species, ranked in order of highest to lowest median risk.

	Deepwater		Large Freezer		Large Fresher		Mackerel		Scampi		Small inshore (17-28m)		Small inshore (less than 17m)		Southern Blue Whiting		Squid	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBM	0	[0–2]	215	[150–315]	0	[0–4]	2	[0–8]	65	[33–114]	50	[9–159]	3	[0–41]	0	[0–2]	150	[101–224]
XSA	21	[8–41]	553	[390–780]	37	[14–80]	2	[0–9]	175	[111–271]	740	[490–1151]	29	[5–93]	2	[0–6]	22	[9–42]
XWM	7	[0–19]	292	[204–429]	33	[13–69]	11	[3–24]	142	[86–222]	968	[632–1459]	259	[130–471]	0	[0–3]	583	[411–815]
XBP	0	[0–3]	0	[0–2]	1	[0–5]	0	[0–0]	1	[0–7]	30	[15–63]	21	[10–45]	0	[0–0]	0	[0–0]
XWP	0	[0–2]	13	[6–27]	0	[0–3]	0	[0–2]	1	[0–4]	37	[14–89]	2	[0–25]	0	[0–0]	0	[0–1]
XCI	17	[6–36]	4	[0–13]	3	[0–15]	0	[0–2]	0	[0–6]	0	[0–6]	0	[0–0]	0	[0–0]	0	[0–3]
XFS	0	[0–1]	2	[0–8]	0	[0–1]	0	[0–0]	46	[25–89]	41	[20–87]	23	[10–52]	0	[0–0]	0	[0–0]
XNB	2	[0–8]	30	[14–55]	3	[0–19]	0	[0–4]	62	[27–120]	2	[0–25]	0	[0–8]	0	[0–0]	0	[0–5]
XAU	0	[0–5]	0	[0–2]	0	[0–2]	0	[0–0]	0	[0–5]	0	[0–7]	0	[0–5]	0	[0–0]	0	[0–3]
XAN	0	[0–2]	0	[0–2]	0	[0–1]	0	[0–0]	0	[0–3]	0	[0–4]	0	[0–2]	0	[0–0]	0	[0–0]
XWC	2	[0–6]	206	[130–372]	1	[0–6]	11	[5–23]	130	[79–235]	8	[1–36]	6	[0–27]	0	[0–0]	558	[352–1001]
XRA	3	[0–11]	6	[0–17]	0	[0–3]	0	[0–2]	0	[0–7]	0	[0–13]	0	[0–15]	0	[0–4]	9	[2–21]
XNP	0	[0–3]	8	[1–19]	0	[0–4]	0	[0–0]	0	[0–8]	0	[0–2]	0	[0–2]	0	[0–0]	0	[0–0]
XCM	0	[0–2]	14	[4–30]	0	[0–4]	0	[0–1]	4	[0–19]	2	[0–22]	2	[0–25]	2	[0–7]	0	[0–3]
XYP	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–0]	0	[0–0]
XPP	0	[0–0]	0	[0–1]	0	[0–0]	0	[0–0]	0	[0–3]	0	[0–4]	202	[142–295]	0	[0–0]	0	[0–0]
XNR	0	[0–2]	0	[0–6]	0	[0–2]	0	[0–0]	0	[0–5]	0	[0–13]	0	[0–10]	0	[0–0]	0	[0–2]
XLM	0	[0–2]	0	[0–3]	0	[0–3]	0	[0–2]	0	[0–6]	2	[0–16]	0	[0–18]	0	[0–2]	0	[0–5]
XGM	0	[0–2]	0	[0–3]	0	[0–3]	0	[0–0]	0	[0–6]	0	[0–14]	0	[0–14]	0	[0–2]	0	[0–3]
XGP	0	[0–2]	1	[0–4]	0	[0–2]	0	[0–1]	2	[0–9]	1	[0–9]	1	[0–9]	9	[4–19]	1	[0–3]
XCA	0	[0–0]	5	[0–31]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–6]	3	[0–51]	3	[0–23]	0	[0–10]
XSI	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–4]	0	[0–5]	0	[0–0]	0	[0–0]
XBS	0	[0–2]	0	[0–14]	0	[0–3]	0	[0–0]	0	[0–8]	25	[0–136]	0	[0–18]	0	[0–0]	0	[0–3]
XKS	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–2]	0	[0–0]	0	[0–0]
XBC	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–3]	0	[0–0]	0	[0–0]
XFC	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–1]	0	[0–0]	0	[0–0]
XPS	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–2]	0	[0–3]	0	[0–0]	0	[0–0]
XPV	0	[0–6]	2	[0–21]	0	[0–6]	0	[0–2]	0	[0–10]	110	[24–457]	0	[0–14]	0	[0–0]	0	[0–3]
XFX	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–0]	0	[0–1]	0	[0–3]	0	[0–0]	0	[0–0]
XSH	3	[0–8]	165	[105–293]	0	[0–4]	2	[0–6]	68	[40–131]	114	[57–234]	31	[9–85]	0	[0–1]	208	[131–387]

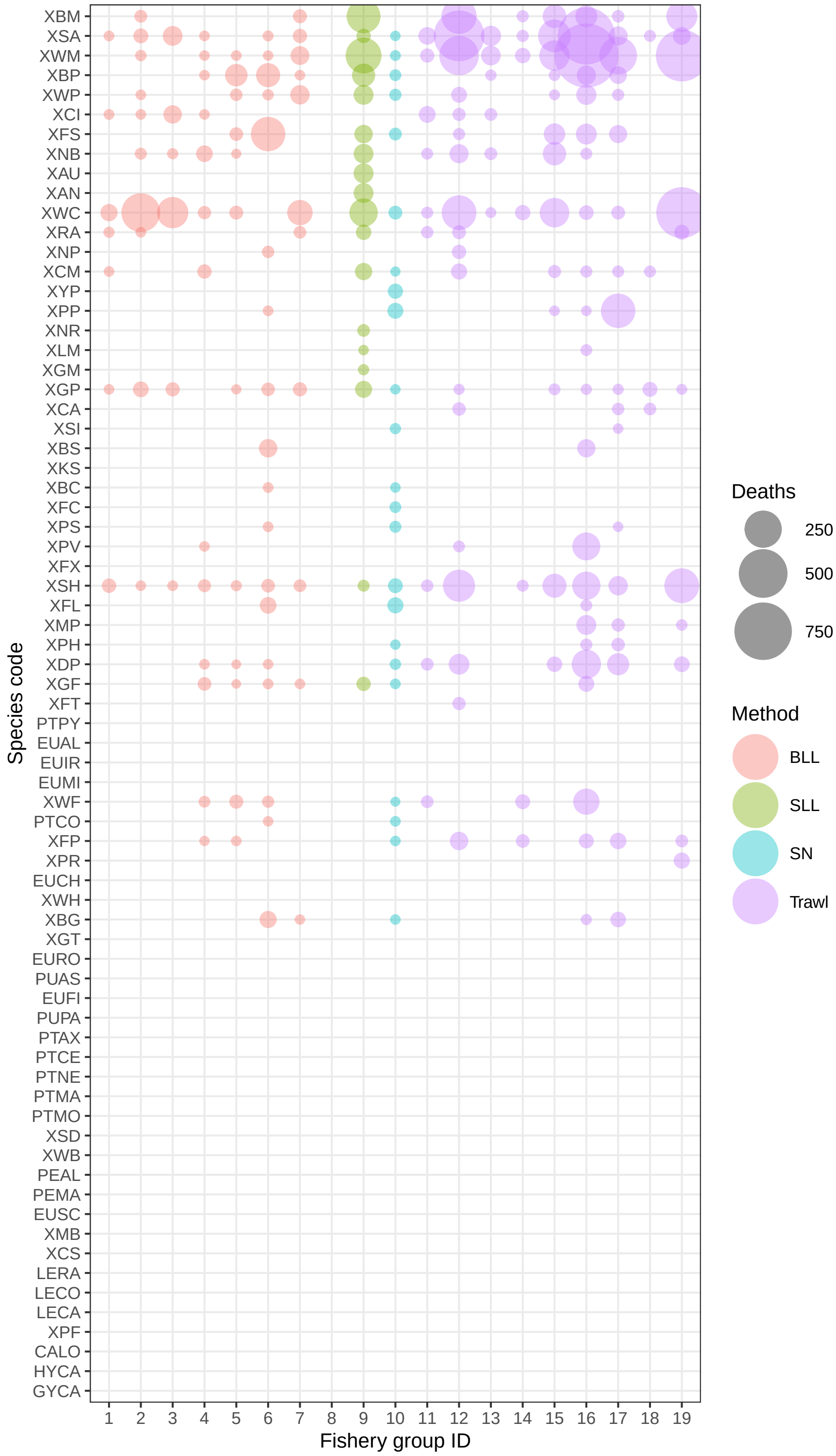

Figure 17: Predicted annual deaths (D) per species and fishery group combination, with speices ranked from highest to lowest risk. Species codes are given and correspond to the names listed in Table 1. Fishery group IDs are listed in Table 2.

6. DISCUSSION

The SEFRA approach utilises the idea that spatial and temporal overlap between a population and fishing effort will, *a priori*, determine the degree of fishing related mortality. This perceived relationship has led to overlap metrics being incorporated into the risk assessments for non-target bycatch species (including protected species; e.g., Cortés et al. 2010, Waugh et al. 2013, Walker et al. 2019). However, although overlap is intuitively important, it cannot be directly used to estimate susceptibility, being limited in two important ways. The first is the unknown strength of the relationship, i.e., the mortality per unit overlap; and the second is the issue of combining overlap from multiple fishing fleets. Both of these issues can be resolved with estimates of the catchability. Specifically, knowledge of the catchability allows anthropogenic mortality per fishery to be quantified. In the current context, mortality is quantified directly in terms of the number of deaths, rather than units of overlap, and allows this impact to be combined across multiple fishing fleets using simple summation. What makes SEFRA different from standard PSA approaches is that it attempts to estimate this catchability from fisheries observer data, rather than relying on qualitative metrics. Although SEFRA is not unique in proposing a more quantitative approach to PSA risk assessment (e.g., Zhou et al. 2011, 2016), it probably requires the least amount of data to do so. The approach has been successfully applied in a wide variety of settings, in both single species (Roberts et al. 2019, Large et al. 2019) and multi-species applications (MacKenzie et al. 2023), and to seabirds domestically (Richard & Abraham 2015, Richard et al. 2017, 2020, Webber 2020) and internationally (Waugh et al. 2008a,b, 2015, 2013, Abraham et al. 2017, 2019). The current project represents the most recent iteration of the approach.

A number of modifications have been progressed, based on first principles. The first was to update the model to a monthly temporal partition. This allowed a higher resolution estimate of the overlap, including representation of the breeding of different species and the availability of birds to fishing at different times of the breeding cycle. The regression equations have also been updated, with the cryptic capture and mortality multipliers now applied directly to the number of captures predicted following the model fit. These two changes allow a more intuitive model structure and easier construction of diagnostic outputs. Two important changes were also made to estimation of the PST reference point. The first was a change to estimation of the PST using adults only. This was justified on the basis that almost all captures observed in New Zealand fisheries are of adults. It is unlikely that this change will have led to a change in the risk estimate for any species, because the same section of the population is used to estimate the number of captures. However it will have led to changes in the catchability estimates, and the influence of this assumption should be examined formally. A second change concerned how the intrinsic rate of growth was estimated, being updated to the approach advocated by Dillingham et al. (2016). This has led to a change in the estimated value for λ_s (Figure 15), and should also reduce uncertainty in the PST estimate. We note that both the median risk and credibility intervals are used in classifying the risk to birds (Richard et al. 2020), but we have not been able to examine the marginal consequence of this change within the current project.

In addition to restructing the model itself, we have reviewed and updated the biological inputs (Peatman et al. 2023), including the species distribution maps. This new information has been provided through a collaborative effort with members of the Aquatic Environment and Biodiversity working group, facilitated by Fisheries New Zealand.

The model is able to provide a good description of the data, with favourable diagnostics. However, the updated risk assessment results differ from the most recent iteration by Richard et al. (2020).

The most notable is an elevation in the estimated risk to southern Buller's albatross from 0.39 (0.22 – 0.66) (table 9 of Richard et al. 2017) and 0.37 (0.21 – 0.60) (table 8 of Richard et al. 2020), to 1.35 (0.72 – 2.59) (Table 16). This is due to a reduction in the PST and an increase in the estimated number of deaths. Another significant change is that the risk to black petrel is reduced in the updated assessment, from 1.15 (0.51 – 2.03) (table 9 of Richard et al. 2017) and 1.23 (0.55 – 2.11) (table 8 of Richard et al. 2020), to 0.51 (0.29-0.82) (Table 16). The PST is similar, but the estimated number of deaths has reduced.

There have also been changes in the list of species considered to be most at risk. The Otago shag, spotted shag and yellow-eyed penguin, for example, have moved down the ranking and would now be considered at negligible risk according to the NPOA, whereas they were previously classified as medium or low risk (Richard et al. 2020). However there are also instances in which the risk has not changed. Antipodean albatross, Westland petrel, Chatham Island albatross and white-chinned petrel, for example, all have similar risk estimates when compared with the previous iteration.

7. POTENTIAL RESEARCH

Implementation of a new model structure, with new data inputs, has led to an update in the assessment of risk to New Zealand seabirds. However, there was little capacity within the current project to address how structural assumptions within the model may have driven the result. Future work could examine a number of features of the approach as it is currently constructed, most importantly including structural assumptions concerning the species, fishery and cryptic capture group partitions. These groupings effectively allow the sharing of information within partitions, and the extent to which this may be influencing the result should be a high priority avenue of research. Concerning the fishery groups, the approach adopted by MacKenzie et al. (2023) of applying multiple structural assumptions would provide a good starting point, with a careful understanding of the different fisheries the most important consideration.

Beyond the structural assumptions of the model, and the need to continuously improve the input data, methodological improvements could be sought to address the representation of the species distribution maps. These are assumed to be known, and, if the consequential estimate of overlap is a poor predictor of captures, the model structure is ill-suited for accomodating this deficiency. The only practical solution currently is to partition the fishery groups spatially so as to improve the model fit. It would be advantageous to develop an approach that is able to address spatial uncertainty directly. We note however that modifications of this type are likely impossible with the current multi-species approach, because the computational requirements are too large. The complexity of even the current model is likely excessive for some of the lowest risk species, and we would support an approach whereby SEFRA is tailored according to the percieved importance of the species or species group. A tiered approach to risk assessment is useful, and an attractive feature of SEFRA is that its complexity can be easily adjusted to the data and to the desired accuracy of the required output.

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APPENDIX

DATA SENSITIVITY

Biological data from Richard et al. (2017) and Webber (2020) was provided by the authors and restructured according to the updated monthly partitions used in the current risk assessment. This included the species distribution maps, which were provided by breeding season for breeders and non-breeders, and which were converted to represent all adults, by month, according to breeding season and the associated probabilities of breeding and attending the nest (see Peatman et al. 2023).

The model was then fitted to the same capture data as were used for the risk assessment, and with identical structural assumptions concerning the species and fishery groups. Estimated biological values and the PST reference points are given in Tables A1 and A2, respectively. The risk estimates are listed in Table A3 and illustrated in Figure A1. Species are listed in the same order as that used in Table 15 and Figure 16, to facilitate comparison. A direct comparison is provided in Figure A2. Given that changes to the model structure have been justified based on first principles, it is instructive to examine how much of the change in the assessment results can be attributed to changes in the data. From Figure A2 we can summarise that new data collected during the current project has led to a slight increase in the risk to black petrel (XBP) and New Zealand white-capped albatross (XWM), but a decrease in the risk to Westland petrel (XWP), flesh-footed shearwater (XFS) and antipodean albatross (XAN). The highest risk species, namely southern Buller's albatross (XBM) and Salvin's albatross (XSA), are not sensitive to the changes in the data. This is despite updates that have led to an increase in the PST for Salvin's albatross, although for southern Buller's albatross the PST reference point is unchanged by the data updates.

We can conclude that updates to the data have led to slight revisions in the risk metrics for each species, to the extent that the risk ranking has changed. However the neither the ranking nor the risk estimate has changed for the two most at risk species, namely southern Buller's albatross and Salvin's albatross. We further note that the top ten species most at-risk are the same. In summary, if the purpose of the risk assessment is to identify the species requiring the most attention, our conclusions are robust to the data updates.

Table A1: 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}), using prior values provided by Richard et al. (2017) and Webber (2020) (continued on next page).

	N_s^{BP}		P_s^B		A_s^{curr}		S_s^{opt}	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBM	14133	[11660-17032]	0.88	[0.73-0.96]	11.7	[9.1-14.8]	0.97	[0.94-0.98]
XSA	41496	[41031-41937]	0.75	[0.55-0.91]	11.7	[9.1-14.8]	0.97	[0.95-0.98]
XWM	87825	[75017-101051]	0.63	[0.52-0.72]	11.5	[9.1-14.7]	0.97	[0.95-0.98]
XBP	7052	[4345-8325]	0.78	[0.66-0.87]	6.6	[6.2-7.0]	0.96	[0.94-0.97]
XWP	4144	[3033-5095]	0.89	[0.76-0.97]	6.5	[4.1-8.9]	0.96	[0.93-0.97]
XCI	5322	[4347-6422]	0.89	[0.75-0.96]	11.8	[9.1-14.8]	0.97	[0.95-0.98]
XFS	13079	[10268-14940]	0.87	[0.70-0.96]	6.4	[4.1-8.9]	0.96	[0.93-0.98]
XNB	16418	[13346-19772]	0.89	[0.77-0.96]	11.7	[9.1-14.8]	0.97	[0.94-0.98]
XAU	4757	[3898-5719]	0.61	[0.51-0.70]	11.0	[10.0-11.9]	0.97	[0.95-0.98]
XAN	3306	[2687-3992]	0.61	[0.52-0.70]	11.3	[10.0-12.9]	0.96	[0.95-0.97]
XWC	262684	[207160-356027]	0.49	[0.36-0.62]	6.3	[4.1-8.8]	0.96	[0.95-0.97]
XRA	8095	[6594-9923]	0.60	[0.51-0.70]	9.5	[8.5-10.5]	0.96	[0.95-0.97]
XNP	2780	[2205-3126]	0.85	[0.66-0.96]	7.8	[6.1-9.9]	0.95	[0.93-0.96]
XCM	18716	[10257-30807]	0.90	[0.78-0.96]	8.5	[6.1-12.5]	0.95	[0.94-0.96]
XYP	1679	[1464-1878]	0.71	[0.63-0.79]	3.0	[2.1-3.9]	0.93	[0.91-0.94]
XPP	21085	[10688-29606]	0.89	[0.78-0.96]	2.1	[1.1-3.0]	0.88	[0.86-0.90]
XNR	4626	[2539-7763]	0.63	[0.54-0.72]	9.5	[8.5-10.5]	0.96	[0.95-0.97]
XLM	6834	[6773-6897]	0.63	[0.54-0.72]	11.7	[9.1-14.8]	0.97	[0.96-0.98]
XGM	4688	[2631-7914]	0.77	[0.67-0.85]	9.4	[7.1-12.7]	0.96	[0.94-0.97]
XGP	49322	[32866-71227]	0.81	[0.71-0.89]	6.8	[5.1-8.8]	0.96	[0.94-0.97]
XCA	10855	[5845-18488]	0.91	[0.80-0.97]	4.7	[3.1-7.6]	0.93	[0.92-0.94]
XSI	1315	[1235-1396]	0.90	[0.80-0.96]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XBS	348675	[302476-396819]	0.90	[0.79-0.96]	6.2	[4.1-8.8]	0.95	[0.93-0.97]
XKS	187	[153-226]	0.91	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XBC	1375	[727-2296]	0.90	[0.79-0.96]	2.0	[1.1-2.9]	0.88	[0.86-0.90]
XFC	3188	[1714-5478]	0.94	[0.88-0.98]	3.6	[3.0-5.1]	0.87	[0.86-0.89]
XPS	6317	[5212-7591]	1.00	[0.99-1.00]	2.7	[2.0-3.3]	0.88	[0.86-0.90]
XPV	346841	[285226-416346]	0.92	[0.84-0.97]	4.5	[4.0-5.0]	0.92	[0.91-0.94]
XFX	958	[847-1073]	0.91	[0.81-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XSH	3232695	[1808760-5447381]	0.97	[0.94-0.99]	6.0	[5.0-6.9]	0.95	[0.93-0.98]
XFL	217737	[102656-454427]	0.90	[0.79-0.97]	5.0	[4.0-5.9]	0.95	[0.93-0.96]
XMP	344669	[301852-396350]	0.90	[0.79-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XPH	106263	[72133-152735]	0.90	[0.80-0.97]	5.0	[4.0-5.9]	0.95	[0.93-0.96]
XDP	1140741	[354899-2072549]	0.96	[0.93-0.98]	2.9	[2.6-3.0]	0.87	[0.87-0.87]
XGF	238603	[201121-295275]	0.91	[0.80-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XFT	73652	[50995-98648]	0.90	[0.79-0.97]	4.5	[4.0-5.0]	0.94	[0.92-0.96]
PTPY	2500	[2028-2974]	0.89	[0.76-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
EUAL	2162	[1422-3147]	0.93	[0.87-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.91]
EUIR	7176	[5098-9813]	0.93	[0.87-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.90]
EUMI	7189	[5079-9839]	0.93	[0.87-0.97]	2.5	[2.0-3.0]	0.89	[0.87-0.91]
XWF	1944838	[825079-2950586]	0.90	[0.79-0.97]	3.9	[3.0-4.9]	0.94	[0.92-0.96]
PTCO	281687	[217837-402324]	0.91	[0.81-0.97]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XFP	1469179	[1204418-1774523]	0.93	[0.85-0.97]	4.5	[4.0-5.0]	0.92	[0.91-0.94]
XPR	566871	[356693-952159]	0.92	[0.84-0.97]	5.5	[5.0-6.0]	0.92	[0.91-0.94]
EUCH	7358	[5113-9856]	0.93	[0.87-0.98]	2.5	[2.0-3.0]	0.89	[0.87-0.90]
XWH	142992	[77368-243878]	0.63	[0.53-0.72]	5.5	[4.1-6.9]	0.96	[0.95-0.98]
XBG	1215736	[710932-2635665]	0.92	[0.83-0.97]	3.7	[3.0-4.9]	0.88	[0.85-0.90]
XGT	45461	[24018-77061]	0.89	[0.76-0.97]	5.0	[3.1-6.9]	0.95	[0.93-0.97]
EURO	27575	[24831-30530]	0.94	[0.88-0.98]	5.4	[5.0-5.9]	0.88	[0.86-0.89]
PUAS	157870	[116880-206872]	0.90	[0.79-0.97]	4.9	[4.0-5.9]	0.95	[0.93-0.96]
EUFI	48090	[39374-57789]	0.94	[0.88-0.98]	3.6	[3.0-5.0]	0.87	[0.86-0.89]
PUPA	49971	[26900-85858]	0.90	[0.78-0.97]	4.0	[3.0-4.9]	0.94	[0.93-0.96]
PTAX	250	[164-362]	0.89	[0.77-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTCE	49643	[26535-86105]	0.89	[0.77-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTNE	5995	[5058-6962]	0.89	[0.77-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
PTMA	17	[14-20]	0.89	[0.76-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]

Table A1: Continued

	N_s^{BP}		P_s^B		A_s^{curr}		S_s^{opt}	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
PTMO	5294	[1167-9820]	0.89	[0.77-0.96]	6.5	[6.0-7.0]	0.96	[0.93-0.98]
XSD	64	[35-108]	0.96	[0.92-0.98]	2.9	[2.6-3.0]	0.87	[0.87-0.87]
XWB	1005	[536-1743]	0.90	[0.79-0.97]	4.5	[4.0-5.0]	0.94	[0.92-0.96]
PEAL	71	[23-118]	0.90	[0.79-0.97]	4.0	[3.0-4.9]	0.94	[0.92-0.96]
PEMA	492	[39-971]	0.90	[0.80-0.97]	4.5	[4.0-5.0]	0.94	[0.92-0.96]
EUSC	80955	[77217-84793]	0.94	[0.88-0.98]	5.4	[5.0-5.9]	0.88	[0.86-0.89]
XMB	240	[158-352]	0.92	[0.83-0.97]	3.0	[2.1-3.9]	0.93	[0.91-0.94]
XCS	355	[289-432]	0.91	[0.81-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
LERA	120	[78-177]	0.90	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
LECO	2433	[1022-4003]	0.91	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
LECA	2006	[1055-3427]	0.90	[0.81-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
XPF	337	[277-408]	0.90	[0.80-0.97]	3.8	[3.0-4.9]	0.89	[0.87-0.90]
CALO	460	[450-470]	0.89	[0.76-0.96]	8.0	[7.6-8.4]	0.94	[0.91-0.97]
HYCA	998	[660-1431]	0.89	[0.76-0.96]	3.0	[2.1-4.0]	0.89	[0.86-0.93]
GYCA	80	[61-99]	0.95	[0.91-0.98]	3.2	[3.0-3.8]	0.83	[0.82-0.83]

Table A2: Productivity estimates and population size used to estimate PST reference points for each species, assuming $\phi = 1$ (continued on next page). Numbers are given in units of a thousand individuals.

	N_s (thousand)		r_s		PST_s	
Code	Mean	95% CI	Mean	95% CI	Mean	95% CI
XBM	32	[26-41]	0.04	[0.02-0.06]	614.86	[281.04-979.32]
XSA	112	[91-152]	0.04	[0.02-0.06]	2017.22	[922.95-3238.81]
XWM	283	[225-352]	0.04	[0.02-0.05]	5023.33	[2448.50-7912.86]
XBP	18	[11-23]	0.06	[0.05-0.08]	577.22	[341.18-804.65]
XWP	9	[7-12]	0.07	[0.04-0.10]	317.62	[169.26-518.59]
XCI	12	[10-15]	0.04	[0.02-0.06]	227.36	[103.92-367.30]
XFS	30	[23-39]	0.07	[0.04-0.10]	1026.69	[564.51-1606.50]
XNB	37	[29-46]	0.04	[0.02-0.06]	708.66	[352.20-1106.08]
XAU	16	[12-20]	0.04	[0.02-0.05]	277.85	[140.82-429.97]
XAN	11	[8-14]	0.04	[0.02-0.05]	190.19	[98.59-293.80]
XWC	1095	[749-1631]	0.06	[0.03-0.08]	31050.97	[16078.35-52112.07]
XRA	27	[21-35]	0.04	[0.03-0.06]	561.61	[323.58-844.39]
XNP	7	[5-9]	0.06	[0.03-0.08]	186.79	[105.54-273.20]
XCM	42	[23-69]	0.05	[0.03-0.08]	1148.77	[467.60-2147.85]
XYP	5	[4-6]	0.14	[0.10-0.18]	327.05	[229.96-448.14]
XPP	47	[24-69]	0.24	[0.16-0.39]	5739.49	[2401.17-11019.60]
XNR	15	[8-25]	0.04	[0.03-0.06]	312.57	[139.28-577.51]
XLM	22	[19-26]	0.03	[0.02-0.05]	377.37	[166.61-594.75]
XGM	12	[7-21]	0.05	[0.03-0.07]	283.90	[118.32-536.57]
XGP	123	[80-181]	0.06	[0.04-0.09]	3833.88	[1963.83-6606.93]
XCA	24	[13-41]	0.09	[0.06-0.13]	1138.20	[477.77-2159.94]
XSI	3	[3-3]	0.14	[0.10-0.17]	201.75	[148.49-258.97]
XBS	778	[649-935]	0.07	[0.04-0.10]	28179.15	[16356.24-42226.45]
XKS	0	[0-1]	0.14	[0.11-0.17]	28.84	[19.90-38.90]
XBC	3	[2-5]	0.25	[0.16-0.40]	378.63	[167.56-781.44]
XFC	7	[4-12]	0.13	[0.09-0.16]	454.19	[225.77-803.63]
XPS	13	[10-15]	0.19	[0.15-0.24]	1203.19	[880.69-1626.00]
XPV	753	[610-918]	0.10	[0.08-0.11]	36300.66	[27342.98-46908.07]
XFX	2	[2-3]	0.14	[0.10-0.17]	146.67	[104.26-193.50]
XSH	6669	[3758-11197]	0.07	[0.05-0.09]	239320.88	[119431.47-432338.05]
XFL	484	[225-1006]	0.09	[0.06-0.11]	20614.08	[8854.06-44109.17]
XMP	766	[646-918]	0.07	[0.05-0.08]	24975.83	[16799.82-33822.58]
XPH	235	[159-341]	0.09	[0.06-0.11]	10082.00	[6096.59-15424.76]
XDP	2376	[739-4305]	0.14	[0.12-0.16]	164339.76	[51619.96-302048.76]
XGF	526	[431-664]	0.07	[0.05-0.08]	17198.09	[11466.82-23940.82]

Table A2: Continued

Code	N_s (thousand) Mean	95% CI	r_s Mean	95% CI	PST_s Mean	95% CI
XFT	164	[110-225]	0.09	[0.07-0.11]	7651.87	[4783.91-11202.76]
PTPY	6	[4-7]	0.06	[0.04-0.08]	182.02	[115.59-255.80]
EUAL	5	[3-7]	0.18	[0.15-0.22]	423.89	[261.74-639.69]
EUIR	15	[11-21]	0.18	[0.15-0.22]	1411.75	[912.93-2093.24]
EUMI	15	[11-21]	0.18	[0.15-0.22]	1396.42	[903.31-2074.99]
XWF	4315	[1824-6646]	0.10	[0.08-0.13]	225771.68	[92539.15-381098.29]
PTCO	621	[468-887]	0.07	[0.05-0.08]	20281.66	[12589.18-31472.40]
XFP	3180	[2578-3922]	0.10	[0.08-0.11]	152739.93	[114512.07-196106.83]
XPR	1229	[767-2059]	0.08	[0.06-0.10]	49321.68	[28290.23-86840.78]
EUCH	16	[11-21]	0.18	[0.15-0.22]	1442.93	[921.59-2102.61]
XWH	460	[244-803]	0.07	[0.04-0.09]	15368.92	[7167.19-28175.89]
XBG	2651	[1523-5797]	0.14	[0.11-0.18]	191724.97	[95639.15-437327.49]
XGT	102	[54-178]	0.08	[0.05-0.12]	4332.10	[1888.28-8181.95]
EURO	59	[52-67]	0.09	[0.07-0.10]	2553.70	[1953.50-3187.01]
PUAS	351	[254-473]	0.09	[0.06-0.11]	15000.69	[9544.37-21972.40]
EUFI	102	[83-124]	0.13	[0.09-0.16]	6895.41	[4495.58-9249.57]
PUPA	112	[59-192]	0.10	[0.08-0.13]	5702.87	[2819.08-10301.15]
PTAX	1	[0-1]	0.07	[0.05-0.08]	18.28	[10.62-28.53]
PTCE	111	[59-196]	0.07	[0.05-0.08]	3658.87	[1793.40-6685.02]
PTNE	13	[11-17]	0.07	[0.05-0.08]	437.79	[286.47-602.56]
PTMA	0	[0-0]	0.07	[0.05-0.08]	1.25	[0.84-1.72]
PTMO	12	[3-23]	0.07	[0.05-0.08]	386.97	[81.96-789.12]
XSD	0	[0-0]	0.14	[0.12-0.16]	9.15	[4.91-15.85]
XWB	2	[1-4]	0.09	[0.07-0.11]	103.89	[52.90-185.61]
PEAL	0	[0-0]	0.10	[0.08-0.13]	8.20	[2.52-15.18]
PEMA	1	[0-2]	0.09	[0.07-0.11]	50.96	[4.10-105.22]
EUSC	173	[161-188]	0.09	[0.07-0.10]	7478.82	[5892.40-9044.97]
XMB	1	[0-1]	0.13	[0.10-0.18]	34.83	[20.49-55.12]
XCS	1	[1-1]	0.14	[0.10-0.17]	54.89	[37.85-74.98]
LERA	0	[0-0]	0.14	[0.10-0.17]	18.43	[10.84-28.79]
LECO	5	[2-9]	0.14	[0.11-0.17]	374.13	[143.76-676.71]
LECA	4	[2-8]	0.14	[0.10-0.17]	308.62	[150.20-551.01]
XPF	1	[1-1]	0.14	[0.10-0.17]	51.99	[35.91-70.38]
CALO	1	[1-1]	0.06	[0.04-0.08]	33.53	[23.00-44.18]
HYCA	2	[1-3]	0.17	[0.12-0.23]	188.50	[108.56-312.27]
GYCA	0	[0-0]	0.16	[0.13-0.18]	13.44	[9.57-17.46]

Table A3: Annual observable captures, deaths and risk per species, ranked from highest to lowest median risk estimated in Table 16 (continued on next page). Risk is calculated assuming that $\phi = 1$.

Code	C_s Mean	95% CI	D_s Mean	95% CI	Risk Median	95% CI
XBM	226.0	[194.0-260.7]	711.0	[548.5-893.7]	1.16	[0.67-2.57]
XSA	269.1	[230.0-312.3]	1438.1	[1102.6-1867.0]	0.72	[0.41-1.62]
XWM	476.1	[426.3-528.0]	2187.8	[1745.9-2691.0]	0.44	[0.26-0.90]
XBP	154.6	[129.0-183.3]	189.5	[129.3-261.7]	0.33	[0.20-0.61]
XWP	104.9	[77.0-137.7]	156.8	[103.1-235.8]	0.50	[0.26-1.04]
XCI	21.4	[12.3-33.7]	56.1	[30.5-89.4]	0.25	[0.12-0.61]
XFS	311.0	[259.0-365.7]	422.1	[300.9-573.1]	0.41	[0.23-0.81]
XNB	50.2	[34.0-70.3]	138.4	[88.1-202.9]	0.20	[0.10-0.43]
XAU	25.2	[15.7-37.0]	34.2	[17.9-59.2]	0.12	[0.06-0.29]
XAN	47.1	[32.7-64.0]	58.0	[33.6-93.0]	0.30	[0.15-0.69]
XWC	753.3	[692.3-820.0]	1457.5	[1082.1-2038.4]	0.05	[0.03-0.10]
XRA	20.7	[11.3-32.3]	45.3	[24.2-72.5]	0.08	[0.04-0.17]
XNP	6.1	[1.7-14.3]	16.1	[4.3-35.4]	0.08	[0.02-0.22]
XCM	29.8	[18.0-46.3]	66.0	[36.9-110.7]	0.06	[0.02-0.15]

Table A3: Continued

	C_s		D_s		Risk	
Code	Mean	95% CI	Mean	95% CI	Median	95% CI
XYP	13.6	[6.7-22.3]	13.0	[6.3-21.6]	0.04	[0.02-0.07]
XPP	187.9	[130.7-256.0]	225.1	[150.6-330.5]	0.04	[0.02-0.10]
XNR	6.7	[2.0-13.7]	15.3	[3.1-42.4]	0.04	[0.01-0.16]
XLM	4.4	[1.0-10.7]	13.9	[2.0-42.1]	0.03	[0.00-0.14]
XGM	4.0	[0.7-10.0]	11.1	[1.3-34.4]	0.03	[0.00-0.15]
XGP	43.3	[29.3-61.0]	65.1	[42.7-95.7]	0.02	[0.01-0.04]
XCA	2.1	[0.3-6.0]	18.2	[0.3-73.4]	0.01	[0.00-0.08]
XSI	2.8	[0.0-9.7]	3.1	[0.0-11.7]	0.01	[0.00-0.06]
XBS	31.9	[16.7-51.0]	66.8	[22.5-184.7]	0.00	[0.00-0.01]
XKS	0.6	[0.0-3.7]	0.7	[0.0-4.4]	0.01	[0.00-0.15]
XBC	3.0	[0.0-12.3]	3.4	[0.0-13.6]	0.01	[0.00-0.04]
XFC	2.6	[0.3-6.7]	2.7	[0.3-7.1]	0.01	[0.00-0.02]
XPS	5.3	[0.7-14.0]	5.9	[0.8-15.7]	0.00	[0.00-0.01]
XPV	12.2	[4.0-24.7]	101.7	[15.1-359.9]	0.00	[0.00-0.01]
XFX	0.9	[0.0-5.0]	1.1	[0.0-6.1]	0.00	[0.00-0.04]
XSH	284.9	[248.3-327.3]	721.7	[489.3-1065.4]	0.00	[0.00-0.01]
XFL	42.3	[14.0-93.3]	44.0	[14.2-97.7]	0.00	[0.00-0.01]
XMP	7.3	[1.3-20.0]	57.7	[4.3-253.3]	0.00	[0.00-0.01]
XPH	4.0	[0.3-12.3]	22.8	[0.4-112.1]	0.00	[0.00-0.01]
XDP	29.2	[15.0-50.0]	239.8	[50.4-715.9]	0.00	[0.00-0.01]
XGF	23.5	[13.3-37.0]	35.2	[17.4-64.2]	0.00	[0.00-0.00]
XFT	1.8	[0.0-5.3]	10.5	[0.0-41.5]	0.00	[0.00-0.01]
PTPY	0.5	[0.0-2.3]	1.3	[0.0-9.9]	0.00	[0.00-0.06]
EUAL	0.8	[0.0-4.0]	0.9	[0.0-4.6]	0.00	[0.00-0.01]
EUIR	1.5	[0.0-5.0]	1.9	[0.0-6.4]	0.00	[0.00-0.00]
EUMI	1.2	[0.0-4.7]	1.4	[0.0-5.8]	0.00	[0.00-0.00]
XWF	48.1	[11.7-164.7]	122.8	[26.8-369.0]	0.00	[0.00-0.00]
PTCO	4.8	[0.7-16.3]	12.4	[0.7-43.6]	0.00	[0.00-0.00]
XFP	15.3	[4.7-47.0]	85.4	[13.7-307.8]	0.00	[0.00-0.00]
XPR	2.9	[0.7-6.7]	19.3	[1.7-68.4]	0.00	[0.00-0.00]
EUCH	0.7	[0.0-3.3]	0.9	[0.0-4.7]	0.00	[0.00-0.00]
XWH	3.2	[0.3-8.7]	4.9	[0.6-14.0]	0.00	[0.00-0.00]
XBG	30.3	[15.0-51.3]	41.0	[16.6-82.7]	0.00	[0.00-0.00]
XGT	1.2	[0.0-5.0]	1.1	[0.0-4.5]	0.00	[0.00-0.00]
EURO	0.5	[0.0-2.0]	0.6	[0.0-2.5]	0.00	[0.00-0.00]
PUAS	1.0	[0.0-4.0]	3.1	[0.0-16.5]	0.00	[0.00-0.00]
EUFI	0.4	[0.0-1.7]	0.5	[0.0-2.1]	0.00	[0.00-0.00]
PUPA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTAX	0.0	[0.0-0.3]	0.1	[0.0-0.4]	0.00	[0.00-0.02]
PTCE	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTNE	0.1	[0.0-1.0]	0.2	[0.0-1.2]	0.00	[0.00-0.00]
PTMA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PTMO	0.1	[0.0-1.0]	0.6	[0.0-5.8]	0.00	[0.00-0.01]
XSD	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
XWB	0.0	[0.0-0.3]	0.0	[0.0-0.3]	0.00	[0.00-0.00]
PEAL	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
PEMA	0.1	[0.0-0.7]	0.2	[0.0-2.6]	0.00	[0.00-0.05]
EUSC	0.3	[0.0-1.3]	0.3	[0.0-1.7]	0.00	[0.00-0.00]
XMB	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
XCS	0.4	[0.0-2.7]	0.5	[0.0-4.0]	0.00	[0.00-0.08]
LERA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
LECO	0.1	[0.0-0.7]	0.1	[0.0-0.8]	0.00	[0.00-0.00]
LECA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
XPF	0.4	[0.0-3.0]	0.5	[0.0-4.0]	0.00	[0.00-0.08]
CALO	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]
HYCA	0.2	[0.0-1.0]	0.6	[0.0-6.4]	0.00	[0.00-0.04]
GYCA	0.0	[0.0-0.0]	0.0	[0.0-0.0]	0.00	[0.00-0.00]

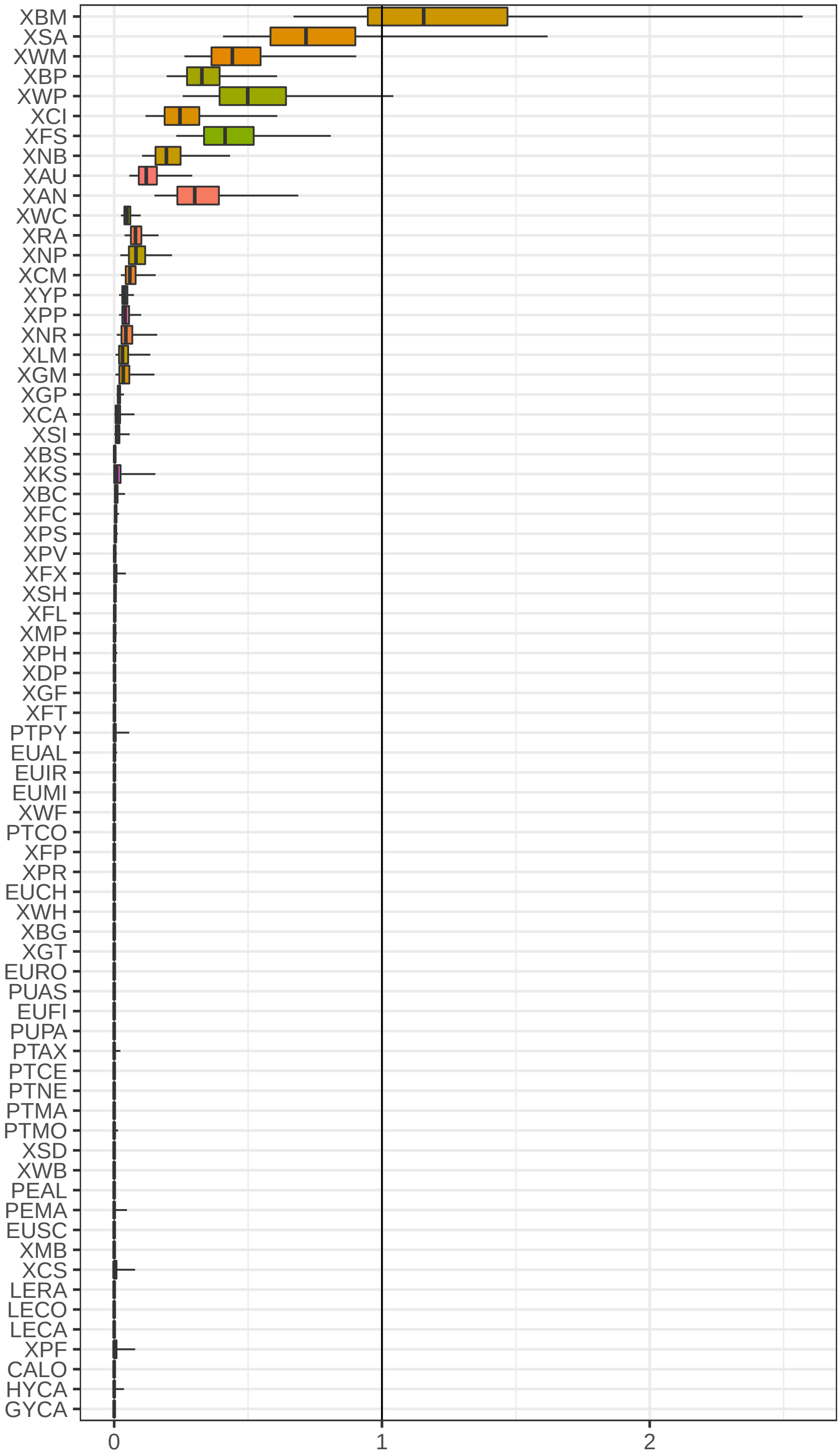

Figure A1: Estimation of the risk per species, ranked from highest to lowest median risk in Table 16. Species codes are given, and correspond to the names listed in Table A1. Boxplots show the median, and 75% and 95% posterior quantiles.

Figure A2: Posterior estimates of the risk for the current risk assessment, and using prior data values from Richard et al. (2017) and Webber (2020) as a sensitivity. Boxplots show the median, and 75% and 95% posterior quantiles.