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Tini a Tangaroa

Risk assessment framework for seabirds in the southern hemisphere

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EXECUTIVE SUMMARY

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This report provides a description of the seabird Spatially Explicit Fisheries Risk Assessment (SEFRA) framework that is currently being used in New Zealand, and how it can be extended to the Southern Hemisphere. Including the full spatial distribution of the seabirds, and all the fishing effort to which they are exposed, is necessary for a more comprehensive understanding of the fisheries dependent risk.

The work is currently in development, and only the methods and a broad description of the data are provided here, with the expectation that the model willl be applied once observer capture data are secured.

1. INTRODUCTION

New Zealand have 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 (MPI 2017). The approach is designed to accommodate multiple species and fisheries simultaneously. Application has been primarily within the New Zealand Exclusive Economic Zone (EEZ; e.g. Richard & Abraham 2015, Richard et al. 2017, 2020), but since seabirds migrate widely across the southern hemisphere, a comprehensive assessment of the fisheries risk needs to account for all the fishing effort that may be encountered as they move through international waters This has motivated application of the method in this wider context, and in so doing it has included other species not resident in New Zealand (e.g. Abraham et al. 2017, 2019).

This paper presents an update to the approach of Abraham et al. (2019), extending the New Zealand risk assessment beyond the EEZ and into international waters, and has been generated as part of Fisheries New Zealand project PSB2020-09.

2. METHODOLOGY

The SEFRA approach implements a type of Productivity-Susceptibility Analyses (PSA; Hobday et al. 2011). Seabird deaths are estimated and 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). The 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. The model in turn predicts the interaction rate and subsequent captures. Paramaterisation of the interaction rate per unit of overlap occurs via a fit to fisheries observer captures data, and total interactions are calculated by multiplication of the total overlap (including the un-observed component) with this estimated rate (referred to as the "catchability"). Deaths are calculated from the predicted interactions 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_s (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 (MPI 2017). The Potential Biological Removals (PBR) of Wade (1998) 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 parameters. The PST further excludes the "recovery factor" f, replacing it with a more generic term: ϕ.

With reference to the terms listed in Table 1, the key SEFRA data inputs can be summarised as:

- Biological demographic parameters: "optimum" adult survivorship (S_s^{opt}), age at first breeding (A_s^{opt}), and the probability that an adult breeds in any given year (P_s^B), are used to estimate r_s from demographic theory;
- Population size: the number of breeding pairs (N_s^{BP}), summed across all colonies in the southern hemisphere, is used to estimate the adult population size, which is combined with r_s to calculate the PST;
- Population distribution: the density of birds, in numbers per km^2, at grid location x for each month m of the year, and re-normalised to sum to one ($d_{s,m,x}$);
- Fishing effort: fisheries are split into discrete groups,a nd for each fishing group k, the cumulative fishing effort ($a_{k,m,x}$) is multiplied by $d_{s,m,x}$ and summed across x to calculate the density overlap ($\mathbb{O}_{k,s,m}$), 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 ($C'_{k,s,m}$), summed over space, are used to fit the model, allowing it to predict captures as a function of the catchability $q_{k,z,m}$ and total overlap $\mathbb{O}_{k,s,m}$;
- Cryptic capture: a multiplier $\kappa_{k,z}$ is used to convert model predicted captures into actual captures 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; we refer to this as the vulnerability $\upsilon_{k,z,m} = q_{k,z,m} \cdot \kappa_{k,z}$.

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 little data are available; and will become more reliable as more or better data are added.

In addition to the data inputs above, 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 $q_{k,z}$, which is specific to the fishery and species group. Birds are grouped according to their biological behavior 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. Fishery groups are defined according to their perceived risk to birds, usually based on the fishing method and gear type.

3. DATA

3.1. Biological data inputs

Biological data were compiled and reviewed by earlier projects, specifically Peatman et al. (In prep.) for New Zealand species, and Abraham et al. (2017) for non-New Zealand species. These were supplemented by additional data in the current work: the biological inputs for non-New Zealand species were reviewed and updated where necessary, and new maps of the biological species distributions were generated (see accompanying document by Devine et al. 2022). The list of species assessed, along with their catchability grouping, is given in Table 2.

Table 1: Summary of model terms

	Description
Subscripts	
k	Fishing group
t	Capture type
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
β_k, $\beta_{z\|k}$	Catchability coefficients
γ_k, γ_z	Survivorship coefficients
π_z^{net}	Probability of net capture
Derived parameters	
N_s^{adults}	Total number of adults
$\mathbb{N}_{s,m}$	Number of adults available to fishing
$q_{k,z}$	Catchabilty
$\upsilon_{k,z}$	Vulnerability
$\Psi_{k,z}$	Probability alive given capture
$I_{k,s,m}$	Number of interactions
Input covariates	
$P_{s,m}^{\mathrm{SH}}$	Probability of an adult being in the southern hemisphere
$P_{s,m}^{\mathrm{nest}}$	Probability of a breeding adult being on the nest
$d_{s,m,x}$	Normalised number of adults per km^2
$a_{k,m,x}$	Fishing effort (number of events)
$\kappa_{k,z}$	Cryptic capture multiplier
ω	Probability of post-release death
Derived covariates	
$\mathbb{O}_{k,s,m}$	Density overlap
Observational data	
$C'_{k,s,m}$	Number of captures
$C^{l\prime}_{k,s,m}$	Number of live captures
$C^{net\prime}_{k,s,m}$	Number of net captures

Biological data 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 no 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 ($d_{s,m,x}$) but also the probabilities of being on the nest when breeding breeding (P_s^{nest}), and being in the southern hemisphere (P_s^{SH}). We deal with each of these biological input data types (i.e. with and without uncertainty) in the sections below.

Table 2: Species and vulnerability groups used in the southern hemisphere risk assessment model. Species codes are from the FAO-ASFIS species list (https://www.fao.org/fishery/en/species/search).

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

3.1.1. Number and rate parameters

Biological prior inputs to the model are defined according to four, two parameter probability distributions. The input parameters for these distributions are referred to as Parameter a and Parameter b, and specified as follows:

uniform:

$$x \sim \mathcal{U}\left(a, b\right)$$

normal:

$$x \sim \mathcal{N}\left(a, (b)^2\right)$$

log-normal:

$$log(x) \sim \mathcal{N}\left(log(a) - 0.5 \cdot (b)^2, (b)^2\right)$$

logit-normal:

$$logit(x) \sim \mathcal{N}\left(logit(a), \frac{b}{a \cdot (1-a)}\right)$$

Prior specifications by parameter are given in Tables A3 to A9, with the mean and quantile intervals listed in Tables 3 and 4.

Uniform, normal and log-normal prior distributions are assumed for the number of annual breeding pairs (N_s^{BP}). In Table A3 parameters a and b are listed per species. Logit-normal prior distributions constrain $0 < x < 1$ and are assumed for the proportion of adults breeding annually (P_s^B), with parameters listed in Table A4. Uniform prior distributions are assumed for the current age at first breeding (A_s^{curr}; Table A6). Either a uniform or logit-normal distribution is assumed for the current and optimum adult survival rates (S_s^{curr} and S_s^{opt} respectively; Tables A8 and A9). Log-normal priors are parameterised so that the mean of the distribution on the natural scale is equal to a, and the standard deviation on the log scale is equal to b.

Priors of N_s^{BP} were derived from a review of the latest available values of annual breeding pairs for each species. For species breeding only within the New Zealand EEZ, we used the priors developed by Peatman et al. (In prep.). For all other species, we summed the point estimates across all colonies, using Peatman et al. (In prep.) for New Zealand colonies and the ACAP colony database (ACAP 2022) for all colonies outside of the New Zealand EEZ. This value was then used as the mean of the log-normal prior. The single exception to this was spectacled petrel (*Procellaria conspicillata*), for which a uniform prior with wide bounds was used, reflecting uncertainty in the most recent published estimate for this species (Ryan et al. 2019).

Noting that r_s is needed for estimation of the PST, it is derived from S_s^{opt} and A_s^{opt} (Section 4.3). It is highly sensitive to these values (Dillingham & Fletcher 2008), and prior distributions of each parameter were required that were likely to include the "true" optimal rates. The approach taken was consistent with that of Dillingham & Fletcher (2011), who determined that the optimal demographic rates of albatross and petrel species were relatively consistent within taxonomic/biological groups. Although we had data for S_s^{curr} and A_s^{curr}, these were retained for reference purposes only.

The scientific literature was first reviewed to obtain the most optimistic rates of survivorship and ages of first breeding for each species. From this review, we summarised the three modal ages of first reproduction (or the nearest three ages to the mean, if the distribution was not reported) and the mean estimate of annual survival. For some species, no estimates could be found in the literature, or no estimates were available for growing populations, and these were left blank (Table A2 and Table A5).

We then combined these values to produce uniform priors of S^{opt} and A^{opt} for each of four taxonomic/biological groups: Great albatross, Small albatross, Large petrel, Medium petrel (Table 2). For A^{opt}, uniform prior bounds were defined by the range across all species within each respective group (Table A7). For all groups except the medium-sized petrels, the prior bounds of S_s^{opt} were defined by the range of point estimates across all species within each respective group. For medium-sized petrels, estimates of adult survival were sparse for growing populations, and so prior bounds consistent with A^{opt} specified by Dillingham & Fletcher (2011) were used (Table A9).

3.1.2. Fixed data inputs

The breeding and non-breeding months per species are listed in Table A10. The probability of a breeding adult being on the nest during breeding (P_s^{nest}), is relevant to the proportion of the population that is vulnerable to fishing. It is considered fixed on input and listed in Table A11. In the absence of any information on these values, we assumed that birds breed throughout the year with a probability P_s^{B}, with one of each breeding pair on the nest (i.e. $P_s^{\text{nest}} = 0.5$).

For the purposes of estimating the captures of each species, we also require estimates of the proportions of the global adult populations that are within the Southern Hemisphere (P_s^{SH}). Of the study species, only black petrel (*Procellaria parkinsoni*) are known to regularly venture into the Northern Hemisphere, foraging off the coast of Central America during the non-breeding period. For this species, we assumed that $P^{\text{SH}} = 0.8$ during the non-breeding period. For all other species, we assumed $P_s^{\text{SH}} = 1$ in all months (Table A12).

Finally, the density of birds in numbers per km^2 is renormalised to sum to one across the southern hemisphere, and given the notation $d_{s,m,x}$. This is a key input in characterising the exposure of a species to fishing effort, and it's calculation is detailed further by Devine et al. (2022).

Table 3: Annual number of breeding pairs (N_s^{BP}), proportion of adults breeding (P_s^B) and age at first reproduction (A_s^{curr} and A_s^{opt}), simulated from distributions listed in Table A3, A4, A6, and A7.

	N_s^{BP}		P_s^B		A_s^{curr}		A_s^{opt}	
Common name	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Gibson's albatross	4320	3520-5230	0.598	0.501-0.694	11	10.1-11.9	8.48	7.06-9.92
Antipodean albatross	3060	2510-3730	0.6	0.501-0.692	11.5	10.1-12.9	8.5	7.07-9.93
Wandering albatross	9400	7680-11400	0.743	0.638-0.832	10	7.15-12.8	8.51	7.07-9.92
Tristan albatross	1460	1190-1770	0.745	0.639-0.833	9.99	7.14-12.8	8.5	7.08-9.93
Amsterdam albatross	50	41-60.4	0.599	0.501-0.691	11.5	10.1-12.9	8.51	7.07-9.93
Southern royal albatross	8550	7000-10300	0.599	0.498-0.696	10	9.05-11	8.49	7.08-9.92
Northern royal albatross	4440	3630-5390	0.609	0.51-0.703	10	9.05-10.9	8.5	7.08-9.93
Atlantic yellow-nosed albatross	33700	27500-40700	0.743	0.637-0.832	8.99	6.15-11.9	9.99	7.15-12.9
Indian yellow-nosed albatross	34000	27800-41100	0.744	0.637-0.832	8.96	6.15-11.8	10	7.15-12.9
Black-browed albatross	692000	566000-843000	0.743	0.637-0.833	9	7.1-10.9	9.97	7.15-12.8
Campbell black-browed albatross	19900	17100-23200	0.889	0.755-0.964	9.5	6.18-12.8	10	7.14-12.9
Shy albatross	9580	7810-11600	0.744	0.637-0.832	12	9.15-14.9	10	7.16-12.9
New Zealand white-capped albatross	85900	70400-104000	0.679	0.577-0.768	12	9.15-14.9	10	7.16-12.9
Salvin's albatross	41200	33600-49700	0.889	0.749-0.964	12	9.14-14.9	10	7.14-12.9
Chatham Island albatross	5290	5140-5450	0.89	0.754-0.964	12	9.15-14.8	10	7.15-12.8
Grey-headed albatross	79600	65200-96300	0.747	0.64-0.836	10	7.14-12.9	9.98	7.14-12.9
Southern Buller's albatross	14900	13700-16200	0.889	0.753-0.965	12	9.16-14.9	9.98	7.14-12.8
Northern Buller's albatross	20300	19300-21300	0.89	0.753-0.964	12	9.16-14.9	9.99	7.14-12.8
Sooty albatross	12500	10200-15100	0.747	0.64-0.833	12	9.14-14.9	9.97	7.12-12.9
Light-mantled sooty albatross	21500	17500-26000	0.599	0.501-0.693	12	9.14-14.8	10	7.15-12.8
Southern giant petrel	44100	36000-53500	0.742	0.634-0.828	7.5	7.02-7.98	10.5	9.07-11.9
Northern giant petrel	11800	9660-14300	0.889	0.756-0.964	7.99	6.11-9.9	10.5	9.07-11.9
Grey petrel	79200	64600-95500	0.795	0.687-0.882	6.97	5.11-8.89	6.49	5.07-7.92
Black petrel	5280	4180-6560	0.609	0.51-0.703	6.6	6.23-6.97	6.5	5.08-7.93
Westland petrel	7960	4260-13700	0.889	0.753-0.965	6.48	4.12-8.88	6.5	5.08-7.92
White-chinned petrel	1150000	935000-1390000	0.889	0.748-0.964	6.5	4.13-8.86	6.5	5.08-7.93
Spectacled petrel	42000	34400-49600	0.743	0.637-0.831	6.5	4.13-8.88	6.48	5.07-7.91

3.2. Fisheries data inputs

Fisheries data are still being collected. Spatial maps for the fishing effort have been provided by Devine et al. (2022).

Table 4: Current and optimal survival rates (S_s^{curr}, S_s^{opt} and S_s^{juv}) simulated from distributions listed in Table A8 and A9, with an assumption that juvenile (0-1 year old) survivorship is 0.75-0.95 of S_s^{opt}.

	S_s^{curr}		S_s^{opt}		S_s^{juv}	
Common name	Mean	95% CI	Mean	95% CI	Mean	95% CI
Gibson's albatross	0.962	0.939-0.984	0.954	0.949-0.96	0.788	0.719-0.855
Antipodean albatross	0.956	0.941-0.969	0.955	0.949-0.96	0.787	0.719-0.856
Wandering albatross	0.951	0.941-0.962	0.955	0.949-0.96	0.787	0.719-0.856
Tristan albatross	0.892	0.834-0.95	0.954	0.949-0.96	0.787	0.719-0.856
Amsterdam albatross	0.943	0.906-0.979	0.955	0.949-0.96	0.788	0.719-0.856
Southern royal albatross	0.948	0.93-0.962	0.955	0.949-0.96	0.788	0.719-0.855
Northern royal albatross	0.939	0.909-0.967	0.954	0.949-0.96	0.787	0.72-0.855
Atlantic yellow-nosed albatross	0.919	0.9-0.937	0.951	0.931-0.972	0.784	0.712-0.859
Indian yellow-nosed albatross	0.906	0.844-0.968	0.951	0.931-0.972	0.785	0.712-0.859
Black-browed albatross	0.943	0.931-0.956	0.952	0.931-0.972	0.786	0.713-0.859
Campbell black-browed albatross	0.945	0.929-0.957	0.952	0.931-0.972	0.784	0.713-0.859
Shy albatross	0.954	0.935-0.974	0.951	0.931-0.972	0.786	0.713-0.859
New Zealand white-capped albatross	0.959	0.934-0.975	0.952	0.931-0.972	0.784	0.713-0.859
Salvin's albatross	0.965	0.941-0.982	0.951	0.931-0.972	0.785	0.713-0.859
Chatham Island albatross	0.965	0.941-0.982	0.952	0.931-0.972	0.785	0.713-0.859
Grey-headed albatross	0.952	0.932-0.968	0.951	0.931-0.972	0.784	0.713-0.858
Southern Buller's albatross	0.955	0.931-0.979	0.951	0.931-0.972	0.785	0.713-0.859
Northern Buller's albatross	0.955	0.931-0.979	0.951	0.931-0.972	0.785	0.713-0.858
Sooty albatross	0.97	0.961-0.979	0.951	0.931-0.972	0.785	0.713-0.859
Light-mantled sooty albatross	0.97	0.96-0.98	0.952	0.931-0.972	0.786	0.713-0.859
Southern giant petrel	0.898	0.84-0.957	0.945	0.931-0.959	0.78	0.71-0.85
Northern giant petrel	0.887	0.812-0.961	0.945	0.931-0.959	0.779	0.71-0.85
Grey petrel	0.935	0.902-0.968	0.935	0.921-0.949	0.771	0.703-0.84
Black petrel	0.926	0.9-0.947	0.935	0.921-0.949	0.772	0.703-0.84
Westland petrel	0.947	0.919-0.974	0.935	0.921-0.949	0.771	0.703-0.841
White-chinned petrel	0.935	0.902-0.968	0.935	0.921-0.949	0.771	0.702-0.84
Spectacled petrel	0.947	0.92-0.973	0.935	0.921-0.949	0.771	0.703-0.841

4. STATISTICAL METHODS

4.1. Estimation of captures

Equations needed to represent the SEFRA framework (MPI 2017), are described. A list of model terms is given in Table 1.

4.1.1. 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 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. Since we are considering birds in the southern hemisphere, the number of available adults per species and month (m) is:

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

noting that $P_{s,m}^{\text{SH}} = 1$ for all species with the exception of the Black Petrel (Table A12), which spends part of the year in the north Pacific hemisphere. Outside of the breeding season $P_{s,m}^{\text{nest}} = 0$, and all adults are available to fishing (see Tables A11).

4.1.2. Spatial distribution and overlap

The spatial distribution of the species is described using a density term $d_{s,m,x}$, which is derived from the number of individuals of species s, per km^2, within grid location x (Devine et al. 2022). Each grid has an assumed uniform density within it. The density is treated as a fixed data input, assumed constant across years and normalised to sum to one across the southern hemisphere.

The value $d_{s,m,x}$ can be thought of as the binomial sampling probability of an individual being in grid x. The expected number of individuals at that location is therefore:

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

If fishing effort for each fishery group k 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:

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

and the density overlap is:

$$\underbrace{\text{density overlap}_{k,s,m}}_{\mathbb{O}_{k,s,m}} = \sum_x a_{k,m,x} \cdot d_{s,m,x} \cdot N_{s,m}$$

for which we introduce the notation $\mathbb{O}_{k,s,m}$ and $a_{k,m,x}$ (MPI 2017). The density overlap is proportional to the opportunity for interaction between birds of species s and fishing group k in month m, when considered across their full spatial distributions.

4.1.3. Expected captures and deaths

The rate of interaction per unit of density overlap is described by the vulnerability $\upsilon_{k,z}$, which is defined at the level of the fishing group k and species group z (see vulnerability groups in Table 2). The total number of interactions per group, species and month is expected to be:

$$\underbrace{\text{interaction}_{k,s,m}}_{I_{k,s,m}} = \upsilon_{k,z} \cdot \mathbb{O}_{k,s,m}$$

The observable interactions are referred to as "captures," for which we need $p^{obs}_{k,z}$, which is the probability of observing a capture given that an observer is present and the interaction has occurred. The product of $\upsilon_{k,z}$ and $p^{obs}_{k,z}$ gives the catchability ($q_{k,z}$) and the number of captures is therefore expected to be:

$$\begin{aligned} \text{captures}_{k,s,m} &= \upsilon_{k,z} \cdot \mathbb{O}_{k,s,m} \cdot p^{obs}_{k,z} \\ &= q_{k,z} \cdot \mathbb{O}_{k,s,m} \end{aligned}$$

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

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

The number of live captures is $C^l_{k,s,m}$.

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

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

Similarly the number of observed dead and live captures are $C^{d\prime}_{k,s,m}$ and $C^{l,\prime}_{k,s,m}$ respectively.

4.1.4. Regression equations

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

$$\lambda_{k,s,m} = q_{k,z} \cdot \mathbb{O}'_{k,s,m}$$

and the likelihood is:

$$C'_{k,s,m} \sim Poisson(\lambda_{k,s,m})$$

This regression can be disaggregated according to the spatial limit of the fishing effort data. For the New Zealand fisheries for example, the density overlap is calculated as the sum of effort and population density within the New Zealand EEZ (with notation $x \in \mathrm{NZ}$):

$$\underbrace{\mathbb{O}^{\mathrm{NZ}}_{k,s,m}}_{\mathrm{NZ}} = \sum_{x \in \mathrm{NZ}} a_{k,m,x} \cdot d_{s,m,x} \cdot N_{s,m}$$

and similarly for other fisheries where observer data are available.

Where data are available, we can further refine the description of captures. For example, the probability of live capture is included as a separate likelihood, using the number of live captures $C^{l\prime}_{k,s,m} \leq C'_{k,s,m}$:

$$C^{l\prime}_{k,s,m} \sim Binomial(C'_{k,s,m}, \Psi_{k,z})$$

For the trawl fishery, we can also distinguish between net and warp captures, using for example:

$$C^{net\prime}_{k,s,m} \sim Binomial(C'_{k,s,m}, \pi^{net}_{z})$$

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

$$\log(q_{k,z}) = \mu + \beta_k + \beta_{z|k}$$

where the species group specific coefficient ($\beta_{z|k}$) is nested within the fishery group (i.e. a vector of coefficients is estimated for each k). Coefficients β_k and $\beta_{z|k}$ are constrained to sum to zero. The probability of live captures is:

$$\mathrm{logit}(\Psi_{k,z}) = \gamma_k + \gamma_z$$

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

4.2. Prediction of total interactions and deaths

During the fitting process we estimate the catchability $q_{k,z}$, but to estimate the total interactions and subsequent deaths, we need to calculate the vulnerability $\upsilon_{k,s} = q_{k,z} \cdot \kappa_{k,z}$. To do this we include a cryptic capture multiplier $\kappa_{k,z}$ (equal to $1/p^{obs}_{k,z}$) and write the interaction equation:

$$\begin{aligned} I_{k,s,m} &= \upsilon_{k,z} \cdot \mathbb{O}_{k,s,m} \\ &= q_{k,z} \cdot \mathbb{O}_{k,s,m} \cdot \kappa_{k,z} \end{aligned}$$

The derivation of $\kappa_{k,z}$ involves the specification of cryptic multipliers for different fishery groups and capture types, which we summarise here.

For the longline fishery, we assume that captures at haul-back are typically alive, and we use available information on the cryptic captures that take place during setting to calculate the total interactions as:

$$I_{k,s,m} = q_{k,z} \cdot \mathbb{O}_{k,s,m} \cdot \underbrace{(\Psi_{k,z} + (1 - \Psi_{k,z}) \cdot k^{\text{longline}})}_{\kappa_{k,z}}$$

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 cryptic capture multiplier for all net captures, both alive and dead.

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

For warps, similar to the longline captures, all alive captures are assume to be seen and the cryptic multiplier is applied to dead captures only. In this case however, the multipliers are species group specific:

$$I_{k,s,m} = q_{k,z} \cdot \mathbb{O}_{k,s,m} \cdot (1 - \pi^{\text{net}}) \cdot (\Psi_{k,z} + (1 - \Psi_{k,z}) \cdot k_z^{\text{warp}})$$

For the trawl fishery overall, this simplifies to:

$$I_{k,s,m} = q_{k,z} \cdot \mathbb{O}_{k,s,m} \cdot \underbrace{(\Psi_{k,z} + (1 - \Psi_{k,z}) \cdot (\pi^{\text{net}_z} \cdot k^{\text{net}} + (1 - \pi^{\text{net}}) \cdot k_z^{\text{warp}}))}_{\kappa_{k,z}}$$

The total deaths is a summation of the interactions that lead to death, including deaths that occur at capture and after capture and live release. We include an ω term to represent post-capture death of live captures.

$$\underbrace{\text{deaths}_{k,s,m}}_{D_{k,s,m}} = I_{k,s,m} \cdot (\Psi_{k,z} \cdot \omega + (1 - \Psi_{k,z}))$$

Deaths ($D_{k,s,m}$) summed across k and m and compared to the PST to calculate the species specific risk.

4.3. Derivation of PST reference points

Given the adult population size, which is specified as a prior distribution for each species (Table 5), we are required to estimate an accompanying distribution for $r_s = \ln(\lambda_{[max]})$. This is achieved using two competing methods, following the approach of Dillingham et al. (2016), which proposes to use the region of overlap as the most likely value.

The first method, the Euler-Lotka (EL) (Euler 1760, Lotka 1907) equation provides the following definition for $\lambda_{[max]}$:

$$1 = \sum_{i=1}^{\infty} l_i \cdot f_i \cdot \lambda_{[max]}^{-i}$$

For the current study we use a simpler derivation (Skalski et al. 2008) that assumes constant survivorship and fecundity for all ages following the age at first reproduction:

$$0 = \lambda_{[max]}^{\alpha-1} \cdot (s - \lambda_{[max]}) + l_\alpha \cdot f$$

where f is the fecundity (average number of females born per female), α is the average age of sexual maturity and l_α is the survivorship to age α. The age at first reproduction is equal to $\alpha + 1$.

This approach is frequently used in the ecological literature (reviewed by Cortes & Travis 2016). An alternative method is provided by allometric theory as follows. Mean generation time is first defined as:

$$\bar{T} = \sum_{i=1}^{\infty} i \cdot l_i \cdot f_i \cdot \lambda^{-i}$$

which can be approximated by a constant-fecundity model as:

$$\bar{T} = \alpha + \frac{s}{\lambda - s}$$

Allometric theory defines the "optimal" generation time such that:

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

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

$$\frac{k}{\ln(\lambda_{[max]})} = \alpha + \frac{s}{\lambda_{[max]} - s}$$

$$\implies \lambda_{[max]} = \exp\left(k \cdot \left(\alpha + \frac{s}{\lambda_{[max]} - s}\right)^{-1}\right)$$

which must be solved numerically. This provides the so-called "demographic-invariant" (DI) solution for $\lambda_{[max]}$ (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 adopt the approach of Dillingham et al. (2016), who combined the EL and DI methods, limiting the uncertainty by selecting values for $\lambda_{[max]}$ that are compatible with both estimators.

Using Monte-Carlo sampling from the prior distributions listed in Tables A4, A7, and A9, we can estimate $\lambda_{[max]}$ using the EL and DI methods for each sample. When plotted against survivorship, these intersect (Figure 1), and we can select values that fall within this point of intersection. Specifically, values for $\lambda_{[max]}$ that are within ± 0.01 of each other are retained, giving the results per species in Table 5. Using the number of adults we can calculate the PST.

5. FURTHER WORK

This document has described the SEFRA methodolgy as applied to seabirds in the southern hemisphere, and based on the previous work by Abraham et al. (2017, 2019). Fisheries effort data, as well as distributional maps for each species are described in an accompanying document by Devine et al. (2022). Fisheries observer capture data are currently being collected and will be used to implement the modelling approach and estimate the fisheries risk to each species.

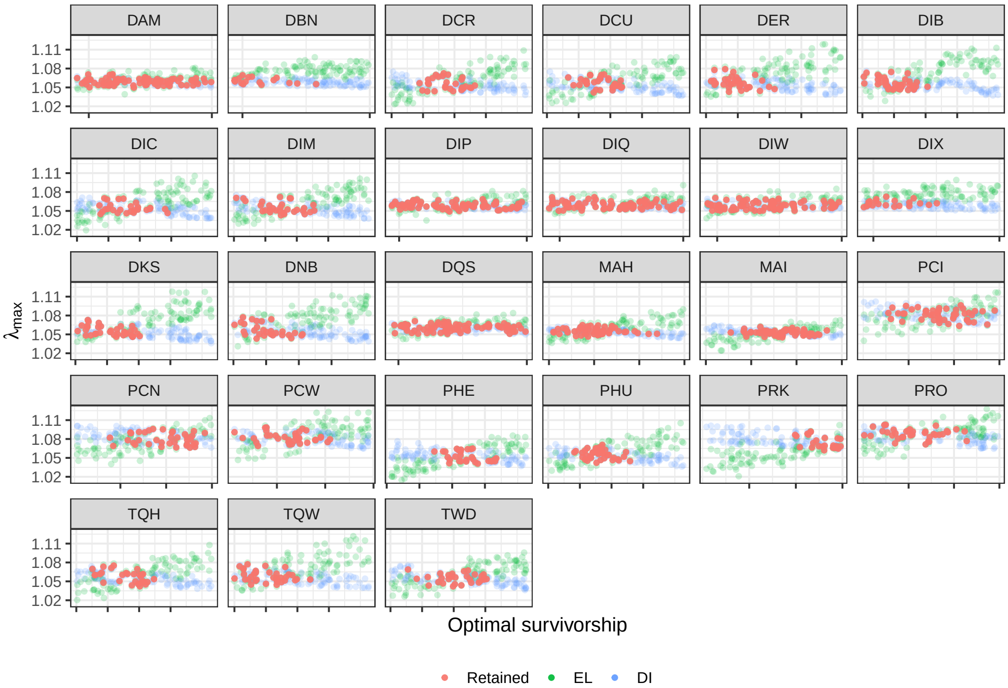

Figure 1: Intersection of Euler-Lotka (EL) and demographic invariant (DI) methods for estimation of $\lambda_{[max]}$ for each species (Table 2). Each method has a different relationship to S_s^{opt}, which can by used to bound the uncertainty by selecting values for $\lambda_{[max]}$ that are compatible with both. In this case values from each method that are within ± 0.01 of each other are retained. Only a subset of Monte-Carlo samples are shown.

Table 5: Productivity estimates and population size used to estimate PST reference points for each species, assuming $\phi = 1$.

	$\lambda_{[max],s}$		r_s		N_s		PST_s	
Common name	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Gibson's albatross	1.06	1.05-1.07	0.0572	0.049-0.0667	14500	11200-18700	419	316-547
Antipodean albatross	1.06	1.05-1.07	0.0572	0.0491-0.0666	10300	7960-13200	296	225-383
Wandering albatross	1.06	1.05-1.07	0.059	0.0523-0.0683	25400	20000-32200	790	608-1050
Tristan albatross	1.06	1.05-1.07	0.0594	0.0526-0.0685	3920	3080-5010	123	93.6-162
Amsterdam albatross	1.06	1.05-1.07	0.0572	0.049-0.0664	168	130-216	4.84	3.68-6.3
Southern royal albatross	1.06	1.05-1.07	0.0572	0.0491-0.0665	28800	22200-37100	829	636-1090
Northern royal albatross	1.06	1.05-1.07	0.0574	0.0493-0.0667	14700	11400-19000	426	324-554
Atlantic yellow-nosed albatross	1.06	1.04-1.07	0.0544	0.0424-0.0698	91000	71900-115000	2480	1740-3460
Indian yellow-nosed albatross	1.06	1.04-1.07	0.0539	0.0423-0.0696	91900	72000-117000	2470	1730-3500
Black-browed albatross	1.06	1.04-1.07	0.0541	0.0425-0.0697	1870000	1470000-2380000	50600	35500-70700
Campbell black-browed albatross	1.06	1.04-1.08	0.0561	0.0436-0.0732	45000	37500-55700	1260	904-1780
Shy albatross	1.06	1.04-1.07	0.0542	0.0425-0.0696	25900	20300-32800	701	489-974
New Zealand white-capped albatross	1.05	1.04-1.07	0.0529	0.0412-0.0684	254000	199000-324000	6720	4740-9370
Salvin's albatross	1.06	1.04-1.08	0.0555	0.0437-0.0729	93200	74000-118000	2600	1840-3670
Chatham Island albatross	1.06	1.04-1.08	0.0557	0.0439-0.0728	11900	10900-14100	333	256-451
Grey-headed albatross	1.06	1.04-1.07	0.0546	0.0421-0.0701	214000	169000-272000	5840	4030-8160
Southern Buller's albatross	1.06	1.04-1.08	0.0558	0.0439-0.0732	33700	29700-40200	944	709-1280
Northern Buller's albatross	1.06	1.04-1.08	0.0559	0.0439-0.0728	45900	41300-54300	1280	979-1720
Sooty albatross	1.06	1.04-1.07	0.0543	0.0426-0.0703	33500	26400-42300	908	632-1280
Light-mantled sooty albatross	1.05	1.04-1.07	0.0512	0.0405-0.0654	72200	55700-93200	1850	1310-2610
Southern giant petrel	1.05	1.05-1.06	0.0516	0.0447-0.0589	119000	94200-152000	3070	2360-3990
Northern giant petrel	1.06	1.05-1.06	0.0536	0.0463-0.0617	26700	21200-33900	713	546-927
Grey petrel	1.08	1.07-1.1	0.077	0.0641-0.0929	2e+05	158000-252000	7660	5690-10200
Black petrel	1.07	1.06-1.09	0.0718	0.0599-0.0864	17500	13100-23000	600	434-807
Westland petrel	1.08	1.07-1.1	0.079	0.066-0.0955	18000	9410-31300	713	362-1290
White-chinned petrel	1.08	1.07-1.1	0.0792	0.0662-0.096	2600000	2060000-3300000	103000	75600-138000
Spectacled petrel	1.08	1.07-1.09	0.0757	0.0632-0.0906	113000	88300-143000	4260	3080-5620

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6. APPENDIX

6.1. References for biological data

Table A1: Sources of species' values of annual breeding pairs (N_s^{BP}), current annual survival probability (S_s^{curr}), current age at first breeding (A_s^{curr}), and annual proportion of adults breeding (P_s^B).

Common name	N_s^{BP}	S_s^{curr}, A_s^{curr} and P_s^B
Gibson's albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Antipodean albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Wandering albatross	ACAP (2022)	Abraham et al. (2017)
Tristan albatross	ACAP (2022)	Abraham et al. (2017)
Amsterdam albatross	ACAP (2022)	Abraham et al. (2017)
Southern royal albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Northern royal albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Atlantic yellow-nosed albatross	ACAP (2022)	Abraham et al. (2017)
Indian yellow-nosed albatross	ACAP (2022)	Abraham et al. (2017)
Black-browed albatross	ACAP (2022)	Abraham et al. (2017)
Campbell black-browed albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Shy albatross	ACAP (2022)	Abraham et al. (2017)
New Zealand white-capped albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Salvin's albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Chatham Island albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Grey-headed albatross	ACAP (2022), Peatman et al. (In prep.)	Peatman et al. (In prep.)
Southern Buller's albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Northern Buller's albatross	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Sooty albatross	ACAP (2022)	Abraham et al. (2017)
Light-mantled sooty albatross	ACAP (2022), Peatman et al. (In prep.)	Peatman et al. (In prep.)
Southern giant petrel	ACAP (2022)	Abraham et al. (2017)
Northern giant petrel	ACAP (2022), Peatman et al. (In prep.)	Peatman et al. (In prep.)
Grey petrel	ACAP (2022), Peatman et al. (In prep.)	Peatman et al. (In prep.)
Black petrel	Peatman et al. (In prep.)	Peatman et al. (In prep.)
Westland petrel	Peatman et al. (In prep.)	Peatman et al. (In prep.)
White-chinned petrel	ACAP (2022), Peatman et al. (In prep.)	Peatman et al. (In prep.)
Spectacled petrel	Ryan et al. (2019)	Abraham et al. (2017)

Table A2: Sources of species' values of optimal annual survival probability (S_s^{opt}) and optimal age at first breeding (A_s^{opt}), used to derive priors for each across taxonomic groups and, ultimately, to estimate the maximum population growth rate of each species (r_s). "ACAP assessment" indicates that the greatest value was extracted from the latest version of the respective ACAP species assessment report; "None growing" indicates that no information was available for periods of population growth; "No data" indicates that no rates could be found in the literature.

Common name	S_s^{opt}	A_s^{opt}
Gibson's albatross	ACAP assessment	None growing
Antipodean albatross	ACAP assessment	Edwards et al. (2017)
Wandering albatross	ACAP assessment	Weimerskirch et al. (1997)
Tristan albatross	ACAP assessment	Ryan et al. (2001)
Amsterdam albatross	Weimerskirch et al. (1997)	Weimerskirch et al. (1997)
Southern royal albatross	ACAP assessment	No data
Northern royal albatross	ACAP assessment	Richard et al. (2015)
Atlantic yellow-nosed albatross	None growing	Cuthbert et al. (2003)
Indian yellow-nosed albatross	None growing	No data
Black-browed albatross	ACAP assessment	Nevoux et al. (2010)
Campbell black-browed albatross	ACAP assessment	None growing
Shy albatross	Baylis et al. (2018)	No data
New Zealand white-capped albatross	Francis (2012)	No data
Salvin's albatross	Sagar et al. (2014)	No data
Chatham Island albatross	None growing	None growing
Grey-headed albatross	ACAP assessment	None growing
Southern Buller's albatross	ACAP assessment	Francis & Sagar (2012)
Northern Buller's albatross	ACAP assessment	No data
Sooty albatross	None growing	Weimerskirch et al. (1987)
Light-mantled sooty albatross	ACAP assessment	Weimerskirch et al. (1987)
Southern giant petrel	ACAP assessment	Woehler & Johnstone (1988)
Northern giant petrel	Baylis et al. (2018)	Woehler & Johnstone (1988)
Grey petrel	No data	No data
Black petrel	None growing	Zhang et al. (2020)
Westland petrel	Waugh et al. (2015)	Waugh et al. (2015)
White-chinned petrel	None growing	Barbraud et al. (2008)
Spectacled petrel	No data	No data

6.2. Prior distribution parameters

Table A3: Prior distributions for numbers of breeding pairs (N_s^{BP}).

Common name	Distribution	Parameter a	Parameter b
Gibson's albatross	log-normal	4313.0	0.100
Antipodean albatross	log-normal	3061.0	0.100
Wandering albatross	log-normal	9399.5	0.100
Tristan albatross	log-normal	1455.5	0.100
Amsterdam albatross	log-normal	50.0	0.100
Southern royal albatross	log-normal	8564.0	0.100
Northern royal albatross	log-normal	4442.0	0.100
Atlantic yellow-nosed albatross	log-normal	33650.0	0.100
Indian yellow-nosed albatross	log-normal	33974.0	0.100
Black-browed albatross	log-normal	691500.0	0.100
Campbell black-browed albatross	log-normal	19950.0	0.076
Shy albatross	log-normal	9569.5	0.100
New Zealand white-capped albatross	log-normal	85944.0	0.100
Salvin's albatross	log-normal	41208.0	0.100
Chatham Island albatross	log-normal	5294.0	0.015
Grey-headed albatross	log-normal	79704.0	0.100
Southern Buller's albatross	log-normal	14903.0	0.043
Northern Buller's albatross	log-normal	20305.0	0.025
Sooty albatross	log-normal	12443.0	0.100
Light-mantled sooty albatross	log-normal	21498.0	0.100
Southern giant petrel	log-normal	44066.0	0.100
Northern giant petrel	log-normal	11813.0	0.100
Grey petrel	log-normal	79222.0	0.100
Black petrel	log-normal	5286.0	0.114
Westland petrel	log-normal	7965.0	0.300
White-chinned petrel	log-normal	1147870.0	0.100
Spectacled petrel	uniform	34000.0	50000

Table A4: Prior distributions for proportion of adults breeding (P_s^B).

Common name	Distribution	Parameter a	Parameter b
Gibson's albatross	logit-normal	0.600	0.05
Antipodean albatross	logit-normal	0.600	0.05
Wandering albatross	logit-normal	0.747	0.05
Tristan albatross	logit-normal	0.748	0.05
Amsterdam albatross	logit-normal	0.600	0.05
Southern royal albatross	logit-normal	0.600	0.05
Northern royal albatross	logit-normal	0.610	0.05
Atlantic yellow-nosed albatross	logit-normal	0.746	0.05
Indian yellow-nosed albatross	logit-normal	0.747	0.05
Black-browed albatross	logit-normal	0.747	0.05
Campbell black-browed albatross	logit-normal	0.900	0.05
Shy albatross	logit-normal	0.747	0.05
New Zealand white-capped albatross	logit-normal	0.680	0.05
Salvin's albatross	logit-normal	0.900	0.05
Chatham Island albatross	logit-normal	0.900	0.05
Grey-headed albatross	logit-normal	0.750	0.05
Southern Buller's albatross	logit-normal	0.900	0.05
Northern Buller's albatross	logit-normal	0.900	0.05
Sooty albatross	logit-normal	0.749	0.05
Light-mantled sooty albatross	logit-normal	0.600	0.05
Southern giant petrel	logit-normal	0.745	0.05
Northern giant petrel	logit-normal	0.900	0.05
Grey petrel	logit-normal	0.800	0.05
Black petrel	logit-normal	0.610	0.05
Westland petrel	logit-normal	0.900	0.05
White-chinned petrel	logit-normal	0.900	0.05
Spectacled petrel	logit-normal	0.747	0.05

Table A5: Greatest estimates of species annual survival and observed "optimal" breeding ages, used to estimate priors of S_s^{opt} and A_s^{opt}. These values were obtained from a review of the literature (Table A2). "None growing" indicates that no information was available for periods of population growth; "No data" indicates that no rates could be found in the literature.

Common name	Mean estimate of annual adult survival	Modal breeding ages during "optimal" breeding
Gibson's albatross	0.960	None growing
Antipodean albatross	0.959	7–9
Wandering albatross	0.953	8–10
Tristan albatross	None growing	8–10
Amsterdam albatross	0.957	7–9
Southern royal albatross	0.949	No data
Northern royal albatross	0.952	7–9
Atlantic yellow-nosed albatross	None growing	9–11
Indian yellow-nosed albatross	None growing	No data
Black-browed albatross	0.957	7–9
Campbell black-browed albatross	0.945	None growing
Shy albatross	0.961	No data
New Zealand white-capped albatross	0.960	No data
Salvin's albatross	0.967	No data
Chatham Island albatross	None growing	None growing
Grey-headed albatross	0.973	None growing
Southern Buller's albatross	0.930	11–13
Northern Buller's albatross	0.930	No data
Sooty albatross	None growing	11–13
Light-mantled sooty albatross	0.973	11–13
Southern giant petrel	0.917	10–12
Northern giant petrel	0.932	9–11
Grey petrel	No data	No data
Black petrel	None growing	5–7
Westland petrel	0.94	6–8
White-chinned petrel	None growing	5–7
Spectacled petrel	No data	No data

Table A6: Prior distributions for current age at first reproduction (A_s^{curr}).

Common name	Distribution	Parameter a	Parameter b
Gibson's albatross	uniform	10.00	12.00
Antipodean albatross	uniform	10.00	13.00
Wandering albatross	uniform	7.00	13.00
Tristan albatross	uniform	7.00	13.00
Amsterdam albatross	uniform	10.00	13.00
Southern royal albatross	uniform	9.00	11.00
Northern royal albatross	uniform	9.00	11.00
Atlantic yellow-nosed albatross	uniform	6.00	12.00
Indian yellow-nosed albatross	uniform	6.00	12.00
Black-browed albatross	uniform	7.00	11.00
Campbell black-browed albatross	uniform	6.00	13.00
Shy albatross	uniform	9.00	15.00
New Zealand white-capped albatross	uniform	9.00	15.00
Salvin's albatross	uniform	9.00	15.00
Chatham Island albatross	uniform	9.00	15.00
Grey-headed albatross	uniform	7.00	13.00
Southern Buller's albatross	uniform	9.00	15.00
Northern Buller's albatross	uniform	9.00	15.00
Sooty albatross	uniform	9.00	15.00
Light-mantled sooty albatross	uniform	9.00	15.00
Southern giant petrel	uniform	7.00	8.00
Northern giant petrel	uniform	6.00	10.00
Grey petrel	uniform	5.00	9.00
Black petrel	uniform	6.21	6.99
Westland petrel	uniform	4.00	9.00
White-chinned petrel	uniform	4.00	9.00
Spectacled petrel	uniform	4.00	9.00

Table A7: Prior distributions for optimum age at first reproduction (A_s^{opt}).

Common name	Distribution	Parameter a	Parameter b
Gibson's albatross	uniform	7	10
Antipodean albatross	uniform	7	10
Wandering albatross	uniform	7	10
Tristan albatross	uniform	7	10
Amsterdam albatross	uniform	7	10
Southern royal albatross	uniform	7	10
Northern royal albatross	uniform	7	10
Atlantic yellow-nosed albatross	uniform	7	13
Indian yellow-nosed albatross	uniform	7	13
Black-browed albatross	uniform	7	13
Campbell black-browed albatross	uniform	7	13
Shy albatross	uniform	7	13
New Zealand white-capped albatross	uniform	7	13
Salvin's albatross	uniform	7	13
Chatham Island albatross	uniform	7	13
Grey-headed albatross	uniform	7	13
Southern Buller's albatross	uniform	7	13
Northern Buller's albatross	uniform	7	13
Sooty albatross	uniform	7	13
Light-mantled sooty albatross	uniform	7	13
Southern giant petrel	uniform	9	12
Northern giant petrel	uniform	9	12
Grey petrel	uniform	5	8
Black petrel	uniform	5	8
Westland petrel	uniform	5	8
White-chinned petrel	uniform	5	8
Spectacled petrel	uniform	5	8

Table A8: Prior distributions for current adult survival rate (S_s^{curr}).

Common name	Distribution	Parameter a	Parameter b
Gibson's albatross	uniform	0.938	0.985
Antipodean albatross	logit-normal	0.957	0.007
Wandering albatross	uniform	0.940	0.963
Tristan albatross	uniform	0.831	0.953
Amsterdam albatross	uniform	0.904	0.981
Southern royal albatross	logit-normal	0.949	0.008
Northern royal albatross	uniform	0.908	0.969
Atlantic yellow-nosed albatross	uniform	0.899	0.938
Indian yellow-nosed albatross	uniform	0.841	0.971
Black-browed albatross	uniform	0.930	0.957
Campbell black-browed albatross	logit-normal	0.945	0.007
Shy albatross	uniform	0.934	0.975
New Zealand white-capped albatross	logit-normal	0.960	0.010
Salvin's albatross	logit-normal	0.967	0.010
Chatham Island albatross	logit-normal	0.967	0.010
Grey-headed albatross	logit-normal	0.953	0.009
Southern Buller's albatross	uniform	0.930	0.980
Northern Buller's albatross	uniform	0.930	0.980
Sooty albatross	uniform	0.961	0.979
Light-mantled sooty albatross	uniform	0.960	0.980
Southern giant petrel	uniform	0.837	0.960
Northern giant petrel	uniform	0.808	0.965
Grey petrel	uniform	0.900	0.970
Black petrel	logit-normal	0.927	0.012
Westland petrel	uniform	0.918	0.975
White-chinned petrel	uniform	0.900	0.970
Spectacled petrel	uniform	0.919	0.974

Table A9: Prior distributions for optimum adult survival rate (S_s^{opt}).

Common name	Distribution	Parameter a	Parameter b
Gibson's albatross	uniform	0.949	0.960
Antipodean albatross	uniform	0.949	0.960
Wandering albatross	uniform	0.949	0.960
Tristan albatross	uniform	0.949	0.960
Amsterdam albatross	uniform	0.949	0.960
Southern royal albatross	uniform	0.949	0.960
Northern royal albatross	uniform	0.949	0.960
Atlantic yellow-nosed albatross	uniform	0.930	0.973
Indian yellow-nosed albatross	uniform	0.930	0.973
Black-browed albatross	uniform	0.930	0.973
Campbell black-browed albatross	uniform	0.930	0.973
Shy albatross	uniform	0.930	0.973
New Zealand white-capped albatross	uniform	0.930	0.973
Salvin's albatross	uniform	0.930	0.973
Chatham Island albatross	uniform	0.930	0.973
Grey-headed albatross	uniform	0.930	0.973
Southern Buller's albatross	uniform	0.930	0.973
Northern Buller's albatross	uniform	0.930	0.973
Sooty albatross	uniform	0.930	0.973
Light-mantled sooty albatross	uniform	0.930	0.973
Southern giant petrel	uniform	0.930	0.960
Northern giant petrel	uniform	0.930	0.960
Grey petrel	uniform	0.920	0.950
Black petrel	uniform	0.920	0.950
Westland petrel	uniform	0.920	0.950
White-chinned petrel	uniform	0.920	0.950
Spectacled petrel	uniform	0.920	0.950

6.3. Fixed data inputs

Table A10: Breeding / non-breeding months per species

Common name	Breeding	Non-breeding
Gibson's albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Antipodean albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Wandering albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Tristan albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Amsterdam albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Southern royal albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Northern royal albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Atlantic yellow-nosed albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Indian yellow-nosed albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Black-browed albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Campbell black-browed albatross	Aug,Sep,Oct,Nov,Dec,Jan,Feb,Mar,Apr,May	Jun,Jul
Shy albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
New Zealand white-capped albatross	Nov,Dec,Jan,Feb,Mar,Apr,May,Jun,Jul,Aug	Sep,Oct
Salvin's albatross	Sep,Oct,Nov,Dec,Jan,Feb,Mar,Apr	May,Jun,Jul,Aug
Chatham Island albatross	Aug,Sep,Oct,Nov,Dec,Jan,Feb,Mar,Apr,May	Jun,Jul
Grey-headed albatross	Sep,Oct,Nov,Dec,Jan,Feb,Mar,Apr,May	Jun,Jul,Aug
Southern Buller's albatross	Dec,Jan,Feb,Mar,Apr,May,Jun,Jul,Aug	Sep,Oct,Nov
Northern Buller's albatross	Oct,Nov,Dec,Jan,Feb,Mar,Apr,May,Jun	Jul,Aug,Sep
Sooty albatross	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Light-mantled sooty albatross	Sep,Oct,Nov,Dec,Jan,Feb,Mar,Apr,May,Jun	Jul,Aug
Southern giant petrel	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–
Northern giant petrel	Aug,Sep,Oct,Nov,Dec,Jan,Feb	Mar,Apr,May,Jun,Jul
Grey petrel	Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov	Jan,Dec
Black petrel	Oct,Nov,Dec,Jan,Feb,Mar,Apr,May	Jun,Jul,Aug,Sep
Westland petrel	Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	Jan,Feb
White-chinned petrel	Nov,Dec,Jan,Feb,Mar,Apr,May	Jun,Jul,Aug,Sep,Oct
Spectacled petrel	Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec	–

Table A11: Proportion of adults on nest by month (P_s^{nest}). Shaded cells are breeding months.

Common name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gibson's albatross	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Antipodean albatross	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Wandering albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Tristan albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Amsterdam albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Southern royal albatross	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50
Northern royal albatross	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50	0.50
Atlantic yellow-nosed albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Indian yellow-nosed albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Black-browed albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Campbell black-browed albatross	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50
Shy albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
New Zealand white-capped albatross	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50
Salvin's albatross	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50	0.50	0.50	0.50
Chatham Island albatross	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
Grey-headed albatross	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50
Southern Buller's albatross	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Northern Buller's albatross	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50
Sooty albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Light-mantled sooty albatross	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.50	0.50	0.50	0.50
Southern giant petrel	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Northern giant petrel	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50
Grey petrel	0.00	1.00	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00
Black petrel	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50
Westland petrel	0.00	0.00	0.00	0.00	0.25	0.50	0.50	0.00	0.00	0.00	0.00	0.00
White-chinned petrel	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50
Spectacled petrel	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Table A12: Proportion of adults in the southern hemisphere by month (P_s^{SH}). Shaded cells are breeding months.

Common name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gibson's albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Antipodean albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wandering albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tristan albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Amsterdam albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Southern royal albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Northern royal albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Atlantic yellow-nosed albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Indian yellow-nosed albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Black-browed albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Campbell black-browed albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Shy albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
New Zealand white-capped albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Salvin's albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Chatham Island albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Grey-headed albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Southern Buller's albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Northern Buller's albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sooty albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Light-mantled sooty albatross	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Southern giant petrel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Northern giant petrel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Grey petrel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Black petrel	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80	0.80	0.80	1.00	1.00
Westland petrel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
White-chinned petrel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Spectacled petrel	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00