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Updated spatially explicit fisheries risk assessment for New Zealand marine mammal populations

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Darryl I. MacKenzie,
David Fletcher,
Stefan Meyer,
Heloise Pavanato

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Fisheries Science Editor
Fisheries New Zealand
Ministry for Primary Industries
PO Box 2526
Wellington 6140
NEW ZEALAND

Email: Fisheries-Science.Editor@mpi.govt.nz
Telephone: 0800 00 83 33

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EXECUTIVE SUMMARY

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The purpose of this project is to conduct an updated marine mammal risk assessment for using recently developed cetacean species distribution layers, and an alternative implementation of a multi-species spatially explicit fisheries risk assessment (SEFRA) to that used previously. As such, this assessment uses the best available information on the marine mammal species.

Fifty-four marine mammal species were specified by Fisheries New Zealand for inclusion in this assessment. It was found that data on required biological input information (i.e., population size, proportion of population within the NZ EEZ each month, spatial distribution within the New Zealand Exclusive Economic Zone (NZ EEZ), adult survival, age of first reproduction, inter-birth interval, first-year survival) was limited for most species as relatively few marine mammal species have been studied extensively at the relevant spatial and temporal scales, either locally or globally. As such, it was necessary to make assumptions about biological inputs for many species based on those obtained for similar species, or from 'grey literature' sources and expert opinion. The results obtained are conditional upon the (unknown) validity of these assumptions.

The multi-species SEFRA model was used here, in which the density overlap of individual species within the same defined species group is aggregated before fitting the model to the number of observed captures of individuals of that species group (i.e., the model is fitted to species group-level captures rather than species-level captures). An alternate parametrisation of the SEFRA model was applied that estimated species catchability (q) directly. Nine species groups were used: small pinnipeds, large pinnipeds, Cephalorhynchus (*Cephalorhynchus hectori*), common dolphin, other small dolphins, large dolphins, baleen whales, beaked whales, and other whales.

A generalised set of fishing groups were defined based on fishing method, gear type, target species, and mitigation measures. Three additional sets of fishing groups were also defined, that were simplifications of the generalised groupings arising through combination of some groups. Each set of fishing groups represent a different estimating model that was fitted to the observed captures. The simplest set, comprising 16 fishing groups, was selected on the basis of the leave one out information criterion (LOOIC) and used for subsequent inferences.

Assessments of model fit indicated that the model accurately re-predicted the total number of observed captures for each species group; however, cumulative sum plots of captures versus density overlap identified that for most of the pinniped and delphinid species groups and fishing methods with substantive number of captures (e.g., > 5) there was systematic under- and over-prediction of captures for some range of overlap values. There were insufficient observed captures of whales to assess the performance of the model for the three whale species groups. Fishery Management Area (FMA) based goodness-of-fit tests to assess the model's predictive performance at that spatial scale also highlighted poor re-predictive ability for some fishing methods in some FMAs for pinniped and delphinid species groups. A small sensitivity analysis was conducted where the model was re-applied to the data using seasonal occurrence probability for the species distribution layers for 10 cetacean species, but overall there was no notable improvement to the results (although there were some changes in areas where the model was performing poorly). Poor performance of the model could be due to inappropriate structural assumptions (e.g., fishing group definitions) or

inappropriate biological inputs (e.g., species distribution layers); however, it is difficult to resolve which aspects of the models should be adjusted without additional information as there is likely to be spatial confounding. It was not unexpected that the model would not perform well for pinniped species as simplistic species distribution layers had to be used for New Zealand fur seals and New Zealand sea lions. For species in the other small dolphin group, there was also evidence of 'species switching', where observed captures of one species would tend to get assigned to another species, which is a consequence of using aggregated species group density overlap within the SEFRA model framework. Results should be interpreted with caution.

The key demographic parameters required for determination of r_{max} are adult survival, age of first reproduction, inter-birth interval, and first-year survival. No information on any of these parameters could be located for 13 of the 54 species following a thorough literature search, and no information could be located for many of the other species on one or more of the demographic parameters (e.g., information on adult survival could be located for 25 of the 54 species). Demographic parameter values were used from a similar species when species-specific values could not be found.

The five species with the highest predicted annual exploitation rates (predicted fishing-related death per individual in the population) using New Zealand population sizes are (in decreasing order of posterior mean) New Zealand fur seal, Māui dolphin, Hector's dolphin, New Zealand sea lion, and crabeater seal, although the posterior mean is < 0.01 (or $< 1\%$) for all species. Based on the equilibrium status metric of population impact (proportion of carrying capacity K after long-term constant exploitation rate), the three most impacted species are Māui dolphin (90% credible interval: 0.635–0.960), New Zealand fur seal (0.749–0.937), and Hector's dolphin (0.831–0.964), using New Zealand population sizes.

1. INTRODUCTION

Incidental capture of non-target species, including marine mammals, can happen in commercial fishing operations. Captures of relatively large numbers of individuals of non-target species may lead to declines of those populations, hence quantification of the risk posed by fishing is of interest to fishery managers.

Abraham et al. (2017) conducted a risk assessment of 35 marine mammal species identified as being at potential risk of capture by commercial fisheries operating within the New Zealand Exclusive Economic Zone (NZ EEZ). They used a spatially explicit fisheries risk assessment (SEFRA) method, which Fisheries New Zealand have adopted as a preferred framework for determining potential impacts of fishing activities on many protected species populations. Briefly, the method uses spatially resolved species density layers and the location, and amount, of observed fishing effort to quantify the 'overlap' between the protected species and observed fishing activities, which is then used in combination with observed species captures to estimate the 'catchability' of the species in different fisheries. Once catchability has been estimated, the total number of captures can be predicted for the set of commercial effort of interest. Further calculations are used to convert the number of captures to a predicted number of deaths, enabling quantification of a risk metric for the impact of fishing-related deaths on the protected species populations.

The purpose of this project was to conduct an updated marine mammal risk assessment using recently developed cetacean species distribution layers (Stephenson et al. 2020), and an alternative implementation of a multi-species SEFRA to that used by Abraham et al. (2017). Updated information on other demographic parameters was also included, to be used to revise suitable values of r_{max} for each species using the method of Dillingham et al. (2016). Previous SEFRA-based risk assessments have used a risk metric that requires the derivation of a population sustainability threshold (PST) that includes specification of a management-related tuning parameter (recently denoted as ϕ; Ministry for Primary Industries 2018, Roberts et al. 2019) which controls the level of impact which is considered to be 'sustainable' from a management perspective. Fisheries New Zealand requested that alternative risk metrics that do not use PST be used in this assessment, hence the results of this assessment are not directly comparable with those of Abraham et al. (2017).

1.1. Objectives

Overall objective: Deliver a fully spatially explicit marine mammal risk assessment (MMRA) using updated species spatial distribution inputs and updated demographic parameterisation, in a format that facilitates routine future update as new data become available, and management scenario evaluation.

The three original specific objectives were:

1. Produce and fit a preliminary multi-species multi-fishery MMRA model using available spatial distribution layers and default biological parameterisation from the previous MMRA (or as provided by MPI) fitted to protected species captures data, with outputs in a standardised format,

2. Produce updated estimates of r_{max} for all marine mammal species, using the empirical methods of Dillingham et al. (2016), and incorporate updated input parameters for other parameters (and distributions where required), following a workshop or expert elicitation process organised jointly with MPI,

3. Using spatial and statistical model diagnostics, modify the preliminary model produced under Objective 1, reflecting: i) updated estimates of r_{max} and other parameter estimates and spatial layers under Objective 2; and ii) optimised structural assumptions (i.e. definition of fishery groups and species groups) affecting goodness of fit.

2. METHODS

2.1. Species included in assessment and available biological inputs

Fifty-four marine mammal species were specified by Fisheries New Zealand to be considered in this risk assessment (Table 1). The biological input information required either for the SEFRA-based modelling of the capture data, or for the estimation of r_{max} using the method of Dillingham et al. (2016) include:

- Population size,
- Proportion of population within NZ EEZ each month,
- Spatial distribution within NZ EEZ,
- Adult survival,
- Age of first reproduction,
- Inter-birth interval,
- First-year survival.

A thorough literature search was conducted for information on these biological inputs. The search was guided, in part, by information supplied by experts during the workshop sessions (Objective 2). Further details of the biological inputs for r_{max} are given below.

Table 1: Species considered in this project. Species codes in italics have been specifically defined for this project as there is no applicable Fisheries New Zealand code. Conservation status is based on Baker et al. (2016); DD = Data Deficient, TNC = Threatened - Nationally Critical, TNE = Threatened - Nationally Endangered, TNV = Threatened - Nationally Vulnerable, ARR = At Risk - Recovering, ARNU = At Risk - Naturally Uncommon, NT = Not Threatened, NRNM = Non-resident Native - Migrant, NRNV = Non-resident Native - Vagrant. HSL is generally referred to as NZSL, and FUR as NZFS, in this report.

Family	Common name	Scientific name	Species code	Conservation Status
Otariidae	Antarctic fur seal	*Arctocephalus gazella*	*AFS*	NRNV
Otariidae	Subantarctic fur seal	*Arctocephalus tropicalis*	*SFS*	NRNV
Otariidae	New Zealand fur seal	*Arctocephalus forsteri*	FUR	NT
Otariidae	New Zealand sea lion	*Phocarctos hookeri*	HSL	TNV
Phocidae	Ross seal	*Ommatophoca rossi*	*RSS*	NRNV
Phocidae	Crabeater seal	*Lobodon carcinophaga*	*CES*	NRNV
Phocidae	Leopard seal	*Hydrurga leptonyx*	LEO	ARNU
Phocidae	Weddell seal	*Leptonychotes weddellii*	*WES*	NRNV
Phocidae	Southern elephant seal	*Mirounga leonina*	EPH	TNC
Phocoenidae	Spectacled porpoise	*Phocoena dioptrica*	PHD	DD
Delphinidae	Hector's dolphin	*Cephalorhynchus hectori hectori*	HDO	TNV
Delphinidae	Māui dolphin	*Cephalorhynchus hectori maui*	HDM	TNC
Delphinidae	Hourglass dolphin	*Lagenorhynchus cruciger*	*HGD*	DD
Delphinidae	Common dolphin	*Delphinus delphis*	CDD	NT
Delphinidae	Dusky dolphin	*Lagenorhynchus obscurus*	DDO	NT
Delphinidae	Bottlenose dolphin	*Tursiops truncatus*	BDO	TNE
Delphinidae	Pygmy killer whale	*Feresa attenuata*	KPW	NRNV
Delphinidae	Pantropical spotted dolphin	*Stenella attenuata*	DPN	NRNV
Delphinidae	Striped dolphin	*Stenella coeruleoalba*	DST	DD
Delphinidae	Rough-toothed dolphin	*Steno bredanensis*	RTD	DD
Delphinidae	Fraser's dolphin	*Lagenodelphis hosei*	FDR	DD
Delphinidae	Risso's dolphin	*Grampus griseus*	GGR	DD
Delphinidae	Southern right whale dolphin	*Lissodelphis peronii*	*SWD*	DD
Delphinidae	Melon-headed whale	*Peponocephala electra*	MEW	NRNV
Delphinidae	False killer whale	*Pseudorca crassidens*	FAW	ARNU
Delphinidae	Short-finned pilot whale	*Globicephala macrorhynchus*	SHW	DD
Delphinidae	Long-finned pilot whale	*Globicephala melas*	PIW	NT
Delphinidae	Orca	*Orcinus orca*	ORC	TNC/NRNV
Kogiidae	Dwarf sperm whale	*Kogia simus*	DWW	DD
Kogiidae	Pygmy sperm whale	*Kogia breviceps*	PYW	DD
Physeteridae	Sperm whale	*Physeter macrocephalus*	SPW	DD
Neobalaenidae	Pygmy right whale	*Caperea marginata*	PRW	DD
Balaenidae	Southern right whale	*Eubalaena australis*	SRW	ARR
Balaenopteridae	Minke whale	*Balaenoptera acutorostrata*	MIW	DD
Balaenopteridae	Antarctic minke whale	*Balaenoptera bonaerensis*	*AMW*	DD
Balaenopteridae	Bryde's whale	*Balaenoptera edeni*	BRW	TNC
Balaenopteridae	Humpback whale	*Megaptera novaeangliae*	HBW	NRNM
Balaenopteridae	Sei whale	*Balaenoptera borealis*	SEW	DD
Balaenopteridae	Pygmy blue whale	*Balaenoptera musculus brevicauda*	*PBL*	DD
Balaenopteridae	Fin whale	*Balaenoptera physalus*	FIW	DD
Balaenopteridae	Blue whale	*Balaenoptera musculus intermedia*	BLW	DD
Ziphiidae	Pygmy beaked whale	*Mesoplodon peruvianus*	*PBW*	DD
Ziphiidae	Andrew's beaked whale	*Mesoplodon bowdoini*	*ANW*	DD
Ziphiidae	Hector's beaked whale	*Mesoplodon hectori*	*HEW*	DD
Ziphiidae	Strap-toothed whale	*Mesoplodon layardii*	*STW*	DD
Ziphiidae	Blainville's beaked whale	*Mesoplodon densirostris*	BBW	DD
Ziphiidae	Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	TGW	DD
Ziphiidae	Gray's beaked whale	*Mesoplodon grayi*	*GBW*	NT
Ziphiidae	Spade-toothed whale	*Mesoplodon traversii*	*SFW*	DD
Ziphiidae	True's beaked whale	*Mesoplodon mirus*	*TBW*	DD
Ziphiidae	Southern bottlenose whale	*Hyperoodon planifrons*	*BSW*	DD
Ziphiidae	Shepherd's beaked whale	*Tasmacetus shepherdi*	*BPW*	DD
Ziphiidae	Cuvier's beaked whale	*Ziphius cavirostris*	BCW	DD
Ziphiidae	Arnoux's beaked whale	*Berardius arnuxii*	*ABW*	DD

2.1.1. Population size and proportion within NZ EEZ

Prior distributions for the abundance of each species within New Zealand waters were developed based on (in order of preference) values from the published literature, the New Zealand Threat Classification System (Baker et al. 2016), and loosely upon the expert opinion information from Abraham et al. (2017).

A small group of Fisheries New Zealand and Proteus staff reviewed the inputs of population size and proportion of the population within NZ EEZ in October 2021 and produced the distributions used in this research. Published values were used where possible, although it was necessary to use information from other sources for some species. Details on the sources used for each species are provided in the Appendix A. The relevant source or 'stock' population for each is the population of animals from which animals that come within the EEZ are drawn (e.g., southern hemisphere or worldwide). A schematic of the process used to derive these biological input values is given in Figure 1. A CV of 35% was used to define the standard deviation of the prior distribution for any population size for which an associated measure of uncertainty could not be sourced.

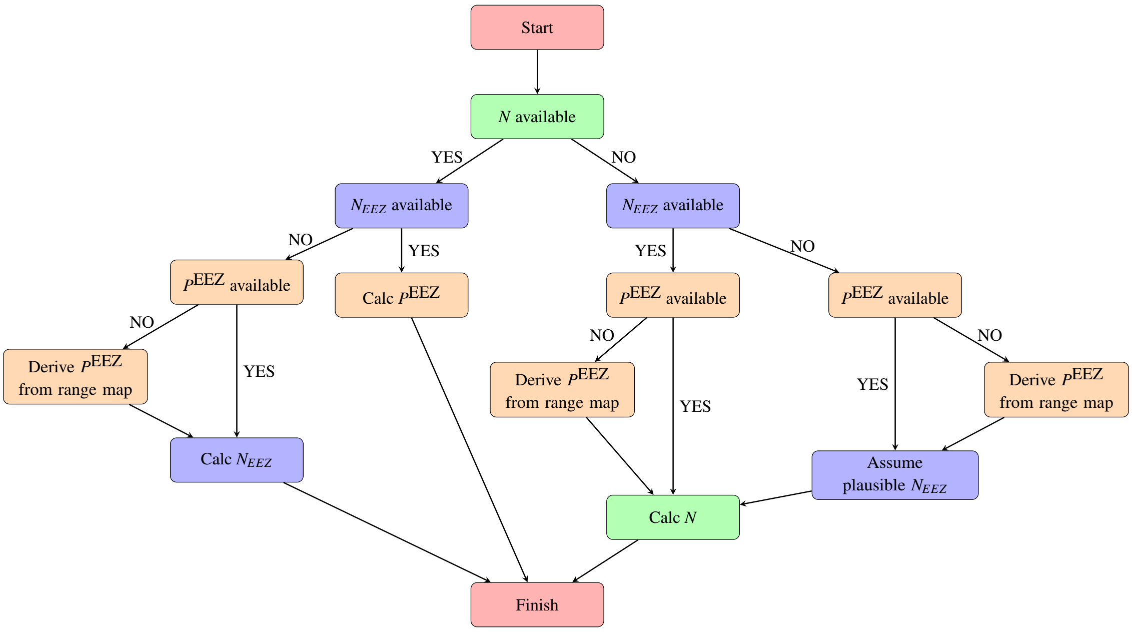


Figure 1: Schematic of process to determine values for stock population size (N), population size in NZ EEZ (N_{EEZ}) and proportion of population in NZ EEZ (p^{EEZ}). A value is 'available' if it could be determined from an attributable source.

2.1.2. Spatial distribution with EEZ

Cetecean spatial distribution raster layers developed by Stephenson et al. (2020) were requested from Fisheries New Zealand. Stephenson et al. (2020) developed three different types of distribution layers, each using a different technique:

1. relative occurrence probability; using relative environmental suitability (RES) models of presence/absence data
2. occurrence probability; using boosted regression trees (BRT) of presence/absence data
3. density; using BRT of count data

These layers are listed in order of increasing data requirements, and a method was only applied if there were sufficient data. Therefore, relative occurrence layers were developed for species that had few recorded sightings, and density surfaces were developed for species with a relatively large number of sightings. Distribution layers were prioritised for use in this project in the order of:

1. density,
2. occurrence probability,
3. relative occurrence probability.

Stephenson et al. (2020) developed seasonal occurrence probability distribution layers for some cetacean species, that have been used for a sensitivity analysis (details below).

Distribution layers for other marine mammal species were sourced as rasters from AquaMaps (`http://www.aquamaps.org`) or as polygon shapefiles from NABIS (`http://www.nabis.govt.nz`). The rasters available from AquaMaps are of relative occurrence probabilities, estimated using RES models similar those used by Stephenson et al. (2020). For NABIS-sourced distribution information, raster layers were developed from the 'full range' polygon where it was assumed that 95% of the population within NZ EEZ was inside the full range and 5% of the population was outside the full range but within the NZ EEZ.

It is noted that developing species spatial distribution layers is outside the scope of this project and all layers were to be supplied by the Ministry for Primary Industries (MPI).

2.2. Fishing group definitions

Fishing groups were defined based on combinations of general method, target species, vessel and gear characteristics (Table 2). The `squ6t` and `sbw6i` variables are derived from the start locations of fishing events, and the remaining variables are available from the `catch_effort_t` table from the Protected Species Captures Database (PSCDB), although to access all variables requires linking records from the `observer_effort_t` or `all_captures_t` tables to `catch_effort_t`. This approach to defining fishing groups was taken such that fishing group effects associated with marine mammal captures are primarily reflecting differences in catchability associated with how the fishing is occurring, rather than the location of the event or the target species. A similar philosophy is being used for the current seabird risk assessment (PSB2019-10; C. Edwards and D. Goad, pers comm).

Fishery group definitions are somewhat arbitrary, although the particular grouping used specifies the set of associated parameters to be estimated, i.e., specifies the estimating model. Therefore, different fishery group definitions specify different estimating models that can be compared to determine which model, or models, has greater support. A statistical comparison allows a formal evaluation of which fishery group definition may be more appropriate to use for inferences about catchability.

Leave-one-out information criterion (LOOIC) (Gelman et al. 2014, Vehtari et al. 2017) has been used as a metric to compare models using Bayesian estimation methods. A generalised fishing group structure was defined, and simpler models were defined by combining some fishing groups (Table 3). A total of four models were considered by combining groups across different combinations of setnet, inshore trawl variables. Models are denoted where the subscript indicates which fishing group variables have not been combined. The variables used to define the generalised fishing group model are given in Table 4.

Table 2: Variables that could be used to define fishing groups.

Defining variable	Description
`method`	Fishing method
`gear`	Trawl gear type (e.g., midwater (MW) or bottom trawl (BT))
`fishery`	Fishery (e.g., squaid trawl (SQUT))
`target`	Target species
`vessel_class`	Vessel size class (small (S) or large (L))
`vessel_size`	Vessel length categories
`squ6t`	Fishing event inside SQU 6T
`sbw6i`	Fishing event inside SBW 6I
`fishing_year`	Fishing year (1 Oct. to 30 Sep.)
`fma_area`	Fishery Management Area of event

Table 3: Generalised fishing groups and group indices that define models fit to the data (same index value within a column indicated groups that have been combined within that model). Models are denoted where the subscript indicates which fishing group variables have not been combined: S = setnet, and I = inshore fisheries (FLAT and INST). Model M_{SI} is the generalised fishing group model, and $M_{\bullet}$ is the model where setnet and inshore fisheries have both been combined.

	Model			
Fishing Group	$M_{\bullet}$	M_S	M_I	M_{SI}
Bottom long line (BLL)	1	1	1	1
Purse seine	2	2	2	2
Surface long line (SLL) - swordfish	3	3	3	3
SLL - other small	4	4	4	4
SLL - other large	5	5	5	5
Setnet - shark	6	6	6	6
Setnet - other	6	7	6	7
Trawl - scampi (SCI)	7	8	7	8
Trawl - deep water (DW)	8	9	8	9
Trawl - small, flatfish (FLAT)	9	10	9	10
Trawl - small, inshore (INST)	9	10	10	11
Trawl - small, other	10	11	11	12
Trawl - JMA 7 pre 2008	11	12	12	13
Trawl - JMA 7 post 2008	12	13	13	14
Trawl - large, sea lion exclusion device (SLED), midwater (MW)	13	14	14	15
Trawl - large, no SLED, MW	14	15	15	16
Trawl - large, SLED, not MW	15	16	16	17
Trawl - large, no SLED, not MW	16	17	17	18

Table 4: Variables and criteria used to define the generalised fishing groups model, i.e., M_{SI}. See Table 3 for acronyms used in fishing group names. Fishery acronyms: SCIT = scampi trawl, DPWT = deep water trawl, FLAT = flatfish trawl, INST = inshore trawl, MACT = mackerel trawl. Target acronyms: SWO = swordfish, SPO = rig, SCH = school shark, JMA = jack mackerel, EMA = blue mackerel, SQU = squid, SBW = southern blue whiting.

group_id	group_name	method	gear	fishery	target	vessel_class	vessel_size (m)	squ6t	sbw6i	fishing_year	fma_area
1	BLL	BLL									
2	Purse seine	PS									
3	SLL - swordfish	SLL			SWO						
4	SLL - other small	SLL			not SWO	S					
5	SLL - other large	SLL			not SWO	not S					
6	Setnet - shark	SN			SPO, SCH						
7	Setnet - other	SN			not SPO, SCH						
8	Trawl - SCI	Trawl		SCIT							
9	Trawl – DW	Trawl		DPWT							
10	Trawl – small, FLAT	Trawl		FLAT			00-06, 06-17, 17-28				
11	Trawl – small, INST	Trawl		INST			00-06, 06-17, 17-28				
12	Trawl – small, other	Trawl		not DPWT, FLAT, INST, SCIT			00-06, 06-17, 17-28				
13	Trawl – JMA 7 pre 2008	Trawl		MACT	JMA, EMA		28-43, 43+			$\leq$ 2007/2008	FMA7,FMA8,FMA9
14	Trawl – JMA 7 post 2008	Trawl		MACT	JMA, EMA		28-43, 43+			$\geq$ 2008/2009	FMA7,FMA8,FMA9
15	Trawl - large, SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	SQU		28-43, 43+	TRUE		$\geq$ 2008/2009	
	Trawl - large, SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	SBW		28-43, 43+		TRUE	$\geq$ 2013/2014	
16	Trawl - large, no SLED, MW	Trawl	MW	MACT			28-43, 43+				not FMA7,FMA8,FMA9
	Trawl - large, no SLED, MW	Trawl	MW	MACT	not JMA, EMA		28-43, 43+				FMA7,FMA8,FMA9
	Trawl - large, no SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	SQU		28-43, 43+	TRUE		$\leq$ 2007/2008	
	Trawl - large, no SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	not SQU		28-43, 43+	TRUE	not TRUE		
	Trawl - large, no SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	SBW		28-43, 43+		TRUE	$\leq$ 2012/2013	
	Trawl - large, no SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	not SBW		28-43, 43+	not TRUE	TRUE		
	Trawl - large, no SLED, MW	Trawl	MW	not DPWT, SCIT, MACT	not SQU, SBW		28-43, 43+	TRUE	TRUE		
	Trawl - large, no SLED, MW	Trawl	MW	not DPWT, SCIT, MACT			28-43, 43+	not TRUE	not TRUE		
17	Trawl - large, SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	SQU		28-43, 43+	TRUE		$\geq$ 2008/2009	
	Trawl - large, SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	SBW		28-43, 43+		TRUE	$\geq$ 2013/2014	
18	Trawl - large, no SLED, not MW	Trawl	not MW	MACT			28-43, 43+				not FMA7,FMA8,FMA9
	Trawl - large, no SLED, not MW	Trawl	not MW	MACT	not JMA, EMA		28-43, 43+				FMA7,FMA8,FMA9
	Trawl - large, no SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	SQU		28-43, 43+	TRUE		$\leq$ 2007/2008	
	Trawl - large, no SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	not SQU		28-43, 43+	TRUE	not TRUE		
	Trawl - large, no SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	SBW		28-43, 43+		TRUE	$\leq$ 2012/2013	
	Trawl - large, no SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	not SBW		28-43, 43+	not TRUE	TRUE		
	Trawl - large, no SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT	not SQU, SBW		28-43, 43+	TRUE	TRUE		
	Trawl - large, no SLED, not MW	Trawl	not MW	not DPWT, SCIT, MACT			28-43, 43+	not TRUE	not TRUE		

2.3. Species group definitions

The 54 species were placed into species groups for the purpose of this multi-species risk assessment (Table 5). The SEFRA model was fitted to the observed captures of individuals at the species group-level rather than at the species level (details below). An advantage of this approach is that it does not require observed captures to be identified to species level, which has been the case for marine mammal captures, particularly for whale captures. Groupings were partially determined by the level of identification of captured animals (presented in Results).

Table 5: Species groups

Species group	Species common name
Small pinniped	Antarctic fur seal, Crabeater seal, New Zealand fur seal, Ross seal, Subantarctic fur seal
Large pinniped	Leopard seal, New Zealand sea lion, Southern elephant seal, Weddell seal
Cephalorhynchus	Hector's dolphin, Māui dolphin
Common dolphin	Common dolphin
Other small dolphin	Bottlenose dolphin, Dusky dolphin, Fraser's dolphin, Hourglass dolphin, Melon-headed whale, Pantropical spotted dolphin, Pygmy killer whale, Risso's dolphin, Rough-toothed dolphin, Southern right whale dolphin, Spectacled porpoise, Striped dolphin
Large dolphin	False killer whale, Long-finned pilot whale, Orca, Short-finned pilot whale
Baleen whale	Antarctic minke whale, Blue whale, Bryde's whale, Fin whale, Humpback whale, Minke whale, Pygmy blue whale, Pygmy right whale, Sei whale, Southern right whale
Beaked whale	Andrew's beaked whale, Arnoux's beaked whale, Blainville's beaked whale, Cuvier's beaked whale, Ginkgo-toothed beaked whale, Gray's beaked whale, Hector's beaked whale, Pygmy beaked whale, Shepherd's beaked whale, Southern bottlenose whale, Spade-toothed whale, Strap-toothed whale, True's beaked whale
Other whale	Dwarf sperm whale, Pygmy sperm whale, Sperm whale

2.4. SEFRA model

The SEFRA model was implemented as described by Ministry for Primary Industries (2018) where models to estimate catchability are fitted to species group-level capture data, and species density overlap is aggregated to species group-level.

2.4.1. Terminology

The following terminology is used with respect to the SEFRA modelling.

Interactions: number of animals that interact with fishing gear that are at risk of being caught, tangled, injured or restrained in the fishing gear, with the possibility of death.

Captures: number of animals that interact with the fishing gear, that would be observable in the fishing gear at the vessel, if an observer was present. A subset of interactions. Denoted C.

Observed captures: captures that are recorded by a government observer. Denoted C'.

Dead captures: animals that are recorded as dead at the time of capture (as defined above). Denoted C'^D.

Deaths: animals that die as a result of interacting with the fishing gear. Denoted D.

2.4.2. Numbers vulnerable to fishing

The number of adults of species s vulnerable to fishing in month m is defined as:

$$\mathbb{N}_{s,m} = P^{\text{EEZ}}_{s,m} \cdot \mathbb{N}_s,$$

where $\mathbb{N}_s$ is the total population size for the biological 'stock' of which animals within the NZ EEZ are a subset, and $P^{\text{EEZ}}_{s,m}$ is the proportion of that population within the NZ EEZ in month m.

2.4.3. Spatial density and overlap

The spatial distribution of the species is described using a density term $d(s,m,x)$, which is the number of individuals of species s, per km^2, within raster grid cell x, during month m. The density is assumed constant across years. The proportion of the species population at the location of fishing event i, that is allocated to grid cell y, can be calculated as:

$$p_{i,s,m} = \frac{d(s,m,y) \cdot g(y)}{\sum_x d(s,m,x) \cdot g(x)},$$

where $g(x)$ is the area (in km^2) of grid cell x. Note that the resolution of $p_{i,s,m}$ is at the same scale as the density raster used, hence rasters may need to be resampled prior to use if they are not at the required resolution.

The overlap for fishing event i with species s in month m ($O_{i,s,m}$) is defined as:

$$O_{i,s,m} = a_{i,m} \cdot p_{i,s,m},$$

and the density overlap is:

$$\mathbb{O}_{i,s,m,} = O_{i,s,m} \cdot \mathbb{N}_{s,m}.$$

Overlap may be aggregated from the scale of fishing event i to fishing group j by summing across the relevant events belonging to fishing group j, i.e.,

$$\mathbb{O}_{j,s,m} = \sum_{i \in j} O_{i,s,m} \mathbb{N}_{s,m}.$$

Furthermore, overlap may also be aggregated from species s to species group z (Ministry for Primary Industries 2018):

$$\mathbb{O}_{j,z,m} = \sum_{s \in z} \mathbb{O}_{j,s.m}.$$

Only a portion of all fishing effort is observed by government observers, so denote $a'_{i,m}$ as the effort of an observed fishing event in month m. Using the same development as above, the following equations define the corresponding overlap metrics for the observed fishing effort:

$$O'_{i,s,m} = a'_{i,m} \cdot p_{i,s,m},$$

$$\mathbb{O}'_{i,s,m,} = O'_{i,s,m} \cdot \mathbb{N}_{s,m},$$

$$\mathbb{O}'_{j,s,m} = \sum_{i \in j} O'_{i,s,m} \mathbb{N}_{s,m},$$

$$\mathbb{O}'_{j,z,m} = \sum_{s \in z} \mathbb{O}'_{j,s.m}.$$

2.4.4. Vulnerability and catchabilty

Let $v_{j,z}$ denote the vulnerability of species group z to fishing group j, with units: individuals captured per unit overlap. Therefore the expected number of total interactions of species s in fishing group j and month m ($T_{j,s,m}$) would be:

$$T_{j,s,m} = v_{j,z} \cdot \mathbb{O}_{j,s,m}.$$

However, not all interactions are observable, so define the expected number of observable captures as:

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

where $q_{j,z} = v_{j,z} \cdot p^{\text{obs}}_{k,z}$ is the catchability of species group z to fishing group j, with units observable individuals capture per unit overlap, and $p^{\text{obs}}_{k,z}$ is the probability of a capture of species group z being observable for a fishing group of fishing method k.

2.4.5. Estimation model

The estimation model was defined as follows, with the variables and parameters used defined in Table 6.

Let $C_{j,s,m}$ be the number of observable captures (i.e., captures that are landed on the deck or would otherwise be observed if an observer was onboard) of species s in fishing method j and month m, and where $C_{j,s,m}$ is a random value from the Poisson distribution with expected value $\lambda_{j,s,m}$. That is:

$$C_{j,s,m} \sim Poisson(\lambda_{j,s,m}).$$

The number of captures from observed fishing events is therefore:

$$C'_{j,s,m} \sim Poisson(\lambda'_{j,s,m}),$$

where $\lambda'_{j,s,m} = q_{j,z} \cdot \mathbb{O}'_{j,s,m}$ is the expected number of observable captures that were observed.

Using the approach outlined by Ministry for Primary Industries (2018), the model is fitted to the number of observed species group captures rather than number of observed captures of individual species, i.e., $C'_{j,z,m} = \sum_{s \in z} C'_{j,s,m}$, and using the properties of the Poisson distribution:

$$C'_{j,z,m} \sim Poisson(\lambda'_{j,z,m}),$$

where

$$\begin{aligned}\lambda'_{j,z,m} &= \sum_{s \in z} \lambda'_{j,s,m} \\ &= \sum_{s \in z} q_{j,z} \cdot \mathbb{O}'_{j,s,m} \\ &= q_{j,z} \sum_{s \in z} O'_{j,s,m} \mathbb{N}_{s,m}.\end{aligned}$$

Catchability was modelled as a function of fishing method (k), fishing group (j) and species group (z) effects:

$$\log(q_{j,z}) = \mu_k + \beta_j + \beta_z + \varepsilon_{j,z},$$

where μ_k is the mean fishing-related effect for fishing groups of method k, and $\varepsilon_{j,z}$ is a normally distributed random effect

$$\varepsilon_{j,z} \sim \mathcal{N}(0, \tau_\varepsilon).$$

Constraints were placed upon the β_j parameters. Let J_k be the total number of fishing groups associated with fishing method k, and for convenience assume that the fishing groups are indexed consecutively for each fishing method. If $J_k = 1$, the corresponding $\beta_j = 0$. If $J_k > 1$, a constraint was applied such that the β_j parameters for the corresponding fishing method summed to zero,

Table 6: Definitions of variables and parameters used in the multi-species SEFRA estimation model.

Notation	Description
Subscripts	
i	Fishing event
j	Fishing group
k	Fishing method
s	Species
z	Species group
m	Month
x or y	Raster grid cell
Variable	
a_{i_m}	amount of fishing effort in event i (of the respective fishing method) in month m
a'_{i_m}	amount of fishing effort in event i observed by a government observer
$p_{i,s,m}$	relative density of species s at the location of fishing event i in month m
$O_{i,s,m}$	overlap for fishing event i with species s in month m
$O'_{i,s,m}$	observed overlap for fishing event i with species s in month m
$\mathbb{N}_{s,m}$	number of adults of species s within the NZ EEZ in month m
$\mathbb{O}_{i,s,m}$	density overlap for fishing event i with species s in month m
$\mathbb{O}'_{i,s,m}$	observed density overlap for fishing event i with species s in month m
Parameter	
$\lambda_{j,s,m}$	expected number of observable captures of species s in fishing group j and month m
$\lambda'_{j,s,m}$	expected number of observed captures of species s in fishing group j and month m
$\lambda'_{j,z,m}$	expected number of observed captures of species group z in fishing group j and month m
$q_{j,z}$	catchability of individuals of species group z per unit of overlap with fishing group j
μ_k	catchability intercept term for fishing method k
β_j	fishing group level effect on catchability, with constraint $\sum \beta_g = 0$ for each k
β_z	species group level effect on catchability, with constraint $\sum \beta_z = 0$
$\varepsilon_{j,z}$	random effect for species group z and fishing group j
τ_ε	standard deviation of catchability random effects (ε)
$\Psi_{j,z}$	probability of live capture for species group z and fishing group j
γ_j	fishing group level effect for probability of live capture
γ_z	species group level effect for probability of live capture

i.e.,

$$\beta_{J_k} = - \sum_{j=J_{k-1}+1}^{J_k - 1} \beta_j.$$

Under these constraints, the effect for fishing group j (in method k) would be $\mu_k + \beta_j$, and μ_k is the mean of the fishing-related effects for method k. Table 7 demonstrates how these constraints were applied. The number of unconstrained β_j parameters is equal to $J - K$, where J is the total number of fishing groups and K is the number of fishing methods.

Table 7: Hypothetical example to demonstrate constraints applied to the β_j parameters.

Fishing method	Fishing group	μ_k	β_j
1	1	μ_1	0
2	2	μ_2	β_2
2	3	μ_2	$-\beta_2$
3	4	μ_3	β_4
3	5	μ_3	β_5
3	6	μ_3	β_6
3	7	μ_3	$-(\beta_4 + \beta_5 + \beta_6)$
4	8	μ_4	β_8
4	9	μ_4	β_9
4	10	μ_4	β_{10}
4	11	μ_4	β_{11}
4	12	μ_4	β_{12}
4	13	μ_4	β_{13}
4	14	μ_4	$-(\beta_8 + \beta_9 + \cdots + \beta_{13})$

The β_z parameters for the Z species groups were also constrained to sum to 0, with:

$$\beta_Z = - \sum_{z=1}^{z-1} \beta_z$$

A $\mathcal{N}(0, 10)$ prior distribution was assumed for all μ_k, and all unconstrained β_j and β_z parameters. A $Cauchy(0, 1)$ prior distribution was assumed for τ_ε.

The number of observed live-captured animals ($C'^L = C' - C'^D$), conditional upon the number of observed captures, may be modelled as a binomial random variable, where $\Psi_{j,z}$ is the probability of live capture in fishing group j of an individual in species group z.

$$C'^L_{j,z,m} | C'_{j,z,m} \sim Binomial(C'_{j,z}, \Psi_{j,z})$$

$$\text{logit}(\Psi_{j,z}) = \gamma_j + \gamma_z.$$

A $logistic(0, 1)$ prior distribution was used for each of the γ_j and γ_z parameters. The $logistic(0, 1)$ distribution is a bell-shaped distribution that has support on the real number line, centred on 0, and after applying the inverse-logit transformation approximates a $uniform(0, 1)$ distribution.

2.4.6. Model fitting considerations

The SEFRA model is fitted to the data using the Bayesian analysis software `STAN`, and input data are aggregated to the level of relevant factors (e.g., event month, species group, fishery group) to reduce run times. However, to enable LOOIC to be used for model comparisons, the input data must have the same dimensions for each model run. Therefore, the data were aggregated to the level of the generalised fishery group definition (i.e., M_{SI}) for all model runs.

In some circumstances there can be underflow problems when the $\lambda'_{j,z}$ or $\Psi_{j,z}$ are very close to zero, therefore it was necessary to ensure that these values were not too small by constraining them to be:

$$\lambda'_{j,z} = max(1.0e^{-8}, \lambda'_{j,z})$$

and

$$\Psi_{j,z} = max(1.0e^{-8}, \Psi_{j,z}).$$

2.5. Model fit assessments

Assessments of model fit to the observed data may be made using a range of diagnostics, based on re-predicting the number of observed captures using the posterior distributions of the SEFRA-based model parameters. The actual and predicted observed captures should be "similar" if the model provides an adequate representation of the real data. Similarity may be assessed using a range of approaches that may reflect different aspects of the data of interest, and here two approaches have been considered:

1. plots of cumulative observed captures vs. overlap
2. FMA-based goodness-of-fit test

An important point relevant to the use of the re-predicted values for assessing model fit is that they represent the range of values that would be expected from observed capture data if the model is adequate, as the model in question has been used to generate those values.

2.5.1. Re-predicting observed captures

For sampled value b from the posterior distributions of the model parameters, the number of observed captures for fishing event i may be predicted as:

$$C'^{(b)}_{i,s,m} \sim Poisson(\lambda'^{(b)}_{i,s,m}),$$

where

$$\lambda'^{(b)}_{i,s,m} = q^{(b)} O'_{i,s,m} \mathbb{N}^{(b)}_{s,m}.$$

The expected number of observed captures for event i could be approximated from the B samples from the posterior distributions as:

$$\begin{aligned} E(C'_{i,s,m}) &= \frac{\sum_b C'^{(b)}_{i,s,m}}{B} \\ &\approx \frac{\sum_b \lambda'(b)_{i,s,m}}{B} \\ &= O'_{i,s,m} \frac{\sum_b q^{(b)} \mathbb{N}^{(b)}_{s,m}}{B}, \end{aligned}$$

or other relevant summaries of the distribution of $C'^{(b)}_{i,s,m}$ could be used (e.g., credible intervals).

2.5.2. Cumulative captures vs. overlap plots

The SEFRA model assumes that observed species captures increase proportionally with observed overlap. Therefore, a plot of the cumulative sum (CUSUM) of the number of observed captures vs. the CUSUM of the observed overlap should result in a linear relationship if the fitted model is adequate for the observed data, while a non-linear relationship would result if the model is a poor fit to the data. The re-predicted observed captures can be used to provide a visual guide for assessing whether an observed relationship appears non-linear. Such plots were created using the following steps:

1. Subset the observations into desired groups (e.g., fishing methods)
    - 1 plot per group
2. Order the observations in a meaningful manner (e.g., by observed overlap value)
3. Calculate the CUSUM of the overlap for the ordered observations for each group
4. Calculate the CUSUM of the number of captures for the ordered observations for each group
5. Calculate the CUSUM of the predicted number of captures for random subset of Markov chain Monte Carlo (MCMC) iterations
6. Summarise the distribution of predicted value CUSUMs
    - e.g., the mean and 90% credible interval for each ordered observation
7. Plot CUSUM lines, with overlap on the x-axis

Note that the chosen order of the observations is important to identify lack of fit, and overlap value has been used here given that captures should increase with overlap. Other orderings could be used to evaluate other aspects of the data and model that may be considered relevant (e.g., by latitude, longitude, or distance offshore), but alternative orderings have not been explored here. Similarly, only fishing method has been used to define groups for different plots and other grouping variables could be used.

2.5.3. FMA-based goodness-of-fit test

Theoretically, the similarity between the actual and expected (from the model) number of observed captures could be compared for every observed fishing event. However, such a comparison will be computationally intensive and it is practical to apply some level of aggregation of the observations. One option explored here is to aggregate observed captures to the FMA level, for each fishing method, to provide a coarse spatially-oriented numerical summary of model fit. Alternative aggregations could be applied, but have not been explored here as FMA was considered a reasonable scale for this multi-species risk assessment.

Similarity between the actual and expected number of observed captures for species s within FMA f by fishing method k can be measured using a Pearson chi-square statistic:

$$\chi^2_{f,s,k} = \frac{\left(C'_{f,s,k} - E_{f,s,k}\right)^2}{E_{f,s,k}},$$

where $E_{f,s,k}$ = average number of observed captures in FMA f and fishing method k, as predicted from the MCMC output of the SEFRA captures model. The overall measure for species s can be calculated as:

$$\chi_s^2 = \sum_f \sum_f \chi_{f,s,k}^2.$$

Small values for χ_s^2 would indicate the number of observed captures ($C'_{f,s,k}$) are relatively close to the number expected by the model, while larger values indicate a divergence between the values in some FMAs and/or fishing methods.

A Bayesian p-value can be calculated from the MCMC output by substituting the re-predicted number of observed captures for $C'_{f,s,k}$, and calculate the chi-square statistic with the re-predicted values for the bth MCMC iteration ($\chi_{s,(b)}^2$). The p-value can be determined as the proportion of the $\chi_{s,(b)}^2$ values that exceed the actual χ_s^2, with a small p-value indicating the model is a poor fit to the data, while a large p-value may indicate the model is overfitting the data. The contributing $\chi_{f,s,m}^2$ values can be used to identify problematic FMAs and fishing methods.

2.6. Sensitivity analysis

The sensitivity of the results to alternative species distribution layers was briefly evaluated by incorporating seasonal occupancy probability layers for some cetacean species. These layers were supplied by Fisheries New Zealand near the end of the project, and in some instances replaced annual density layers that are arguably more appropriate, hence were only used for a sensitivity analysis.

2.7. Estimation of fishing-related deaths, and population impact

Subsequent to the model fitting stage, to estimate posterior distributions for model parameters from the observed capture and effort data using `STAN` (Stan Development Team 2021), total fishing-related deaths and overall population impacts were calculated within `R` (R Core Team 2021). The method used here is consistent with Abraham et al. (2017), Roberts et al. (2019) and Large et al. (2019), but differs from that detailed by Ministry for Primary Industries (2018)

Let $C_{j,s,m}$ be the number of observable captures with expected value:

$$\lambda_{j,s,m} = q_{j,z} \cdot \mathbb{O}_{j,s,m}.$$

Therefore, the expected total number of interactions (i.e., observable captures and unobservable hook-ups, entaglements, etc.) in fishing group j, of species s in month m would be

$$\frac{q_{j,z} \cdot \mathbb{O}_{j,s,m}}{p_{j,s}^{obs}},$$

where $p_{j,s}^{obs}$ is the probability of an interaction event being an observable capture. Note that $p_{j,s}^{obs}$ is assumed to be the same for both live and dead captures.

Fishing-related deaths (associated with captures) may occur when animals that are released subsequently die post-release, or are dead at capture. That is, all captured animals die except for those that are captured alive and deemed to survive post-release. The expected number of fishing-related deaths is therefore:

$$\lambda_{j,s,m}^D = \frac{q_{j,z} \cdot \mathbb{O}_{j,s,m}}{p_{j,s}^{obs}} \left(1 - \Psi_{j,z}\omega\right),$$

where ω is the post-release survival probability.

The data used in the analysis contains no information on $p^{obs}_{j,s}$ or ω, therefore assumed distributions were used. Four species groups were defined for use with for p^{obs}, and specific distributions were assigned to each fishing group defined under Model $M_{\bullet}$ (Table 8). The distributions assumed for p^{obs} are specified in Table 9. Large et al. (2019) assumed that $p^{obs} = 1$ for New Zealand sea lion (NZSL) in trawl fishing events not targeting squid, and those targeting squid without a SLED, whereas Abraham et al. (2017) assumed a uniform distribution, with bounds of 0.5 and 1.0 ($U(0.5, 1.0)$) for NZSL (and all other marine mammals) in the same fisheries. The approach taken here is to assume p^{obs} is higher in those fisheries for larger marine mammals than for smaller animals, but not perfect, therefore a $U(0.8, 1.0)$ distribution has been used (index distribution 4). A $U(0.5, 1.0)$ distribution was assumed for post-release survival (ω) for all species, which is slight wider than the distribution used by Roberts et al. (2019) for Hector's and Māui dolphins ($U(0.5, 0.9)$), which was also used by Large et al. (2019) for NZSL, but narrower than the distribution used by Abraham et al. (2017) ($U(0.0, 1.0)$).

Table 8: Distribution index table defining which p^{obs} distributions were assigned to each fishing group used in Model $M_{\bullet}$ and p^{obs} species group.

		p^{obs} species group			
ID	Fishing group	Small dolphin	Small pinniped	Large pinniped	Other
1	BLL	1	1	1	1
2	Purse seine	1	1	1	1
3	SLL - swordfish	1	1	1	1
4	SLL - other small	1	1	1	1
5	SLL - other large	1	1	1	1
6	Setnet	2	3	3	1
7	Trawl - SCI	1	1	4	4
8	Trawl – DW	1	1	4	4
9	Trawl – small, inshore	1	1	4	4
10	Trawl – small, other	1	1	4	4
11	Trawl – JMA7 pre 2008	1	1	4	4
12	Trawl – JMA7 post 2008	1	1	4	4
13	Trawl - large, SLED, MW	1	1	5	4
14	Trawl - large, no SLED, MW	1	1	4	4
15	Trawl - large, SLED, not MW	1	1	6	4
16	Trawl - large, no SLED, not MW	1	1	4	4

Table 9: Assumed distributions for each p^{obs} index distribution. Sources: † = Abraham et al. (2017); ‡ = Roberts et al. (2019); ⋄ = Large et al. (2019), Meyer (2019).

Index	Distribution	par1	par2	Mean	SD	Source
1	uniform	0.500	1.000	0.750	0.144	†
2	beta	6.916	6.916	0.500	0.130	‡
3	uniform	0.333	1.000	0.667	0.192	†
4	uniform	0.800	1.000	0.900	0.058	
5	beta	10.617	5.670	0.652	0.115	⋄
6	beta	39.225	5.885	0.870	0.050	⋄

In predicting the number of deaths in fishing group j, of species s in month m ($D_{j,s,m}$), the average overlap from the 2016/17 to 2018/19 fishing years was used for $\mathbb{O}_{j,s,m}$, and following Abraham et al. (2017) and Roberts et al. (2019), the average number of deaths over Y years was predicted as:

$$D_{j,s,m} \sim Poisson\left(Y\lambda^{D}_{j,s,m}\right)/Y,$$

and the number of deaths for species s is

$$D_s = \sum_m \sum_j D_{j,s,m}.$$

Following Abraham et al. (2017), the value $Y = 20$ was used and note that alternative values will affect the variation in the posterior distribution of D_s (e.g., a smaller Y value will increase the variation), although the level of change will depend on the overall contributions of the different sources of uncertainty to the posterior variation of D_s.

The population-level impact could be quantified in terms of the risk ratio

$$R_S = \frac{D_s}{PST_s}$$

where PST_s is the population sustainability threshold for the species (Abraham et al. 2017, Ministry for Primary Industries 2018, Roberts et al. 2019), which is a management-specified threshold. In this assessment alternative metrics (U_s) and (I'_s) are presented that do not involve management decisions. U_s is the exploitation rate (Ministry for Primary Industries 2018) for the species ($= D_s/N_s$) and I_s can be interpreted as the 'equilibrium status' of the population, i.e., the proportion of K that the population will converge towards over time with constant U_s (i.e., N/K; B. Sharp, Fisheries New Zealand, pers comm). This interpretation of I'_s assumes a logistic growth population model and that fishing is the only additional source of mortality.

$$\begin{aligned} I'_s &= 1 - \frac{D_s}{r_{max} N_s} \\ &= 1 - \frac{D_s/N_s}{r_{max}} \\ &= 1 - \frac{U_s}{r_{max}} \end{aligned}$$

These metrics were calculated using both the stock population size and New Zealand population size.

2.8. Estimation of r_{max}

A series of online workshop sessions were held with invited marine mammal experts on 3–5 May 2021 to elicit information from them regarding biological parameters relevant to r_{max} and the SEFRA modelling, along with a thorough literature search for demographic information on the species included in the risk assessment.

The intrinsic rate of increase (r_{max}) for each species was estimated using the method developed by Dillingham et al. (2016). This is based on integrating an analysis based on a deterministic matrix population model with one based on allometric relationships for r_{max} and generation time (T_{opt}). The matrix model uses estimates of adult survival rate, first-year survival rate, age at first reproduction (AFR), and inter-birth interval (IBI). Ideally, we need to use estimates of these parameters obtained under optimal conditions, i.e., for a population that has a stable age distribution, little human-induced mortality and few resource-limitations. In practice, not all estimates will match this ideal, even with extensive knowledge of the studies from which the estimates were derived. In the absence of an estimate of a parameter for a species, we make use of information from similar species.

2.8.1. Matrix population model

We used a deterministic population model, with all parameters being constant over time and the same for all individuals. As AFR and IBI will typically vary across individuals, for these two parameters we have used an estimate of the mean for the population. In the literature, estimates of adult survival are sometimes given separately for the two sexes, and we have chosen to use the estimate for females. Likewise, it is sometimes given separately for different age groups, and we have combined these into a single estimate, using an estimate of the stable age distribution. We also assumed that the annual survival rate from age 1 to adulthood increased linearly on the logistic scale. The value of $\lambda_{max} = exp(r_{max})$ is the solution of the equation $\lambda_{max}^{(a-1)}(\lambda_{max} - S) = fl_a$, where S = adult survival, a = AFR, $f = 0.5/$IBI (female young per year, assuming a 1:1 sex ratio), and l_a = survival from birth to AFR (a linear-logistic function of adult survival, first-year survival, and AFR).

2.8.2. Allometric relationship

Allometric theory suggests that $a_{rT} = r_{max}T_{opt}$ will be approximately constant for a wide range of long-lived species, where T_{opt} is the mean generation time under optimal conditions. Dillingham et al. (2016) showed that the value of a_{rT} for a range of mammal species could be well approximated by a normal distribution, i.e., $a_{rT} \sim \mathcal{N}(\mu_{rT}, \sigma^2_{rT})$, where $\mu_{rT} = 1$ and $\sigma^2_{rT} = 0.09$. We followed Moore (2015) in assuming that approximately half of the estimate of the variance term is sampling error, and therefore set $\sigma^2_{rT} = 0.045$. In the absence of more precise information on the amount of sampling error, this value for σ^2_{rT} has been recommended by Peter Dillingham (pers. comm.), and was used by Edwards et al. (2018) when estimating r_{max} for Hector's dolphin.

2.8.3. Integration of the two analyses

Following the method of Dillingham et al. (2016) we used the matrix model to convert the distributions representing uncertainty in the demographic parameters into a 'prior' distribution for r_{max}. For the matrix model we are using, the corresponding prior distribution for T_{opt} is obtained by calculating:

$$T_{opt} = \alpha + \frac{s}{\lambda_{max} - S}.$$

The prior distribution for a_{rT} based on the matrix model was then obtained by calculating:

$$a^M_{rT} = r^M_{max}T^M_{opt},$$

where the superscript M refers to these values being based on the matrix model. The prior for a_{rT} based on allometric theory was given by $a^A_{rT} \sim \mathcal{N}(1, 0.045)$, the superscript A referring to the fact that this value is based on allometry.

Integration of the two analyses was achieved by retaining those values of r^M_{max} for which $|a^M_{rT} - a^M_{rT}|$ was less than a tolerance level of 0.05, as recommended by Dillingham et al. (2016). The values of a^M_{rT} that were retained in this way are denoted a^I_{rT}, the superscript I referring to this value being based on integration of the two approaches (matrix model and allometry). The distributions of the 'integrated' values of r_{max}, T_{opt}, and the demographic parameters (i.e., those that correspond to the a^I_{rT}) are referred to as the 'posteriors' for these quantities.

2.8.4. Prior distributions for the parameters

Where more than one estimate for a species demographic parameter was provided in the literature, we used the most optimistic estimate, i.e., the highest estimate for adult survival and first-year survival, and the lowest estimate for age at first reproduction and inter-birth interval. When we were unable to obtain a value from the literature, information was used from species in the same species group (Table 10) using the steps described below for each parameter. In the descriptions, 'Est' refers to an estimate of a parameter and 'SE' to its standard error. We also make use of the relative standard error (RSE) for each parameter. For adult and first-year survival this is defined as $\mathrm{RSE} = \mathrm{SE}/\sqrt{(\mathrm{Est}(1-\mathrm{Est}))}$, since the amount of uncertainty in a proportion naturally decreases as we approach the boundary of 0 or 1; for age at first reproduction and inter-birth interval it is defined as RSE = SE/Est (often called the coefficient of variation).

The prior distributions for the demographic parameters were determined as follows.

Adult survival

- Truncated beta distribution with minimum=0.7, mean = Est, standard deviation = SE.
- Where an estimate was not available, we used a truncated beta distribution with minimum as in Step 1, mean selected from a uniform distribution between the lowest and highest estimates for species from the same species group (Table 10), and standard deviation = $0.24 \times \sqrt{\mathrm{Est}(1-\mathrm{Est})}$, as 0.24 was the maximum RSE value for adult survival across all species.

First-year survival

- Beta distribution with mean = Est, standard deviation = SE of the estimate.
- Where an SE was not provided or not easily calculated from details given in the relevant literature, we set standard deviation = $0.41 \times \sqrt{\mathrm{Est}(1-\mathrm{Est})}$, as 0.41 was the maximum value of RSE for first-year survival across all species.
- Where an estimate was not available, we set first-year survival $S_1 = c_0 x S$, where c_0 was chosen from a uniform distribution between 0.6 and 1.0 (pinnipeds) or between 0.7 and 1.0 (cetaceans), the bounds on these distributions being based on the observed values of S_1/S.

Age at first reproduction:

1. Truncated normal distribution, with mean = Est, standard deviation = SE, and minimum = 2.
2. Where an SE was not provided or not easily calculated from details given in the relevant literature, we set standard deviation = $0.20 \times$ Est, as 0.20 was the maximum value of RSE for age at first reproduction across all species.
3. Where an estimate was not available, we used a truncated normal distribution with minimum as in Step 1, mean selected from a uniform distribution between the lowest and highest estimates for species from the same species group (Table 10), and standard deviation as in Step 2.

Inter-birth interval:

1. Truncated normal distribution with mean = Est, and standard deviation = SE. The minimum was set to 1 for pinnipeds and 2 for cetaceans, except for those cetaceans which had Est ≤ 2 years, for which we set the minimum to 1. For cetaceans where a minimum of 3 years was

also plausible, and for which we had an SE, the SE was small enough that the distribution changed by a negligible amount if we used a minimum of 3 years, rather than 2 years. We therefore left these minima at 2 years.

2. Where an SE was not provided or not easily calculated from details given in the relevant literature, we set standard deviation = $0.28 \times$ Est, as 0.28 was the maximum value of RSE for inter-birth interval across all species.

3. Where an estimate was not available, we used a truncated normal distribution with minimum as in Step 1, mean selected from a uniform distribution between the lowest and highest estimates for species from the same species group (Table 10), and standard deviation as in Step 2.

The `R` code used to calculate r_{max} is provided in Appendix B.

Table 10: Species groups used to obtain bounds for the uniform prior distribution for adult survival, age at first reproduction and inter-birth interval, when no estimate for that species was available.

Group	Species	Groups used if no estimate available
Small pinnipeds	Antarctic fur seal, Crabeater seal, New Zealand fur seal, Ross seal, Subantarctic fur seal	Small pinnipeds
Large pinnipeds	Leopard seal, New Zealand sea lion, Southern elephant seal, Weddell seal	Large pinnipeds
Cephalorhynchus	Hector’s dolphin, Māui dolphin	Not applicable (estimates available)
Common dolphins	Common dolphin	Cephalorhynchus, Common dolphins, Other small dolphins
Other small dolphins	Bottlenose dolphin, Dusky dolphin, Fraser’s dolphin, Hourglass dolphin, Melon-headed whale, Pantropical spotted dolphin, Pygmy killer whale, Risso’s dolphin, Rough-toothed dolphin, Southern right whale dolphin, Spectacled porpoise, Striped dolphin	Cephalorhynchus, Common dolphins, Other small dolphins
Large dolphins	False killer whale, Long-finned pilot whale, Orca, Short-finned pilot whale	Not applicable (estimates available)
Baleen whales	Antarctic blue whale, Antarctic minke whale, Bryde’s whale, Dwarf minke whale, Fin whale, Humpback whale, Pygmy blue whale, Pygmy right whale, Sei whale, Southern right whale	Baleen whales, Beaked whales, Other whales
Beaked whales	Andrews beaked whale, Arnoux’s beaked whale, Dense-beaked whale, Ginkgo-toothed beaked whale, Goose-beaked whale, Gray’s beaked whale, Hector’s beaked whale, Pygmy beaked whale, Shepherd’s beaked whale, Southern bottlenose whale, Spade-toothed whale, Strap-toothed whale, True’s beaked whale	Beaked whales
Other whales	Dwarf sperm whale, Pygmy sperm whale, Sperm whale	Baleen whales, Beaked whales, Other whales

3. RESULTS

3.1. Biological inputs for SEFRA modelling

Assumed prior distributions for the stock population size, type of species spatial distribution layer used, and proportion of the stock population within the NZ EEZ (P^{EEZ}) are given in Table 11. Species distribution maps are included in Appendix A. No distribution layer could be sourced for True's beaked whale, hence the distribution was assumed to be uniform throughout the NZ EEZ. The supplied rasters for Hector's and Māui dolphins had to be edited prior to use because it was noted that the rasters included non-zero density values for regions that are well outside the known range of each species (e.g., well beyond 20 nmi offshore), which resulted in relatively large numbers of dolphins being assigned to biologically unrealistic regions. Raster values were set to 0 for cells that corresponded to regions with water depths greater than 100 m for these subspecies.

3.2. Species captures

A total of 4560 observed marine mammal captures in commercial fisheries from the 1995/96 to 2018/19 fishing years (inclusive) were extracted from the PSCDB v5.0 (Table 12). Although based on observer remarks, two of the 'captures' appear to be of body parts recovered during fishing rather than captures of animal during fishing. These remains have been excluded from analyses. Cetacean species account for 7% of the observed captures, with New Zealand fur seals being the predominantly captured species (86% of total). Captures of whale species have seldomly been recorded to the individual species level; however, captures have been assigned to species groups based on observer remarks, and in consultation with Fisheries New Zealand staff. Figure 2 presents a summary of the number of captures by species group and generalised fishing groups. The proportion of live captures tended to be high in SLL fisheries, and low in fisheries using other methods.

Table 11: Species distribution layer type and summary of assumed prior distribution for stock population size ($\mathbb{N}_s$). The density (Den), occurrence probability (OP) and relative occurrence probability (ROP) layer types were developed by Stephenson et al. (2020), AqM indicates distribution layers sourced from the AquaMaps website, NABIS for distribution polygons from NABIS website, and unif indicates a uniform spatial distribution was used. The median and CV of the lognormal prior distributions for $\mathbb{N}_s$ are given, along with the assumed proportion of the stock within the NZ EEZ. For humpback whale, PI= Pacific Islands

Common name	Species group	Layer type	Popn. stock	Median	CV	p^{EEZ}
Antarctic fur seal	Small pinniped	AqM	Antarctic	2 775 689	0.124	0.000
Subantarctic fur seal	Small pinniped	AqM	Worldwide	315 852	0.064	0.000
New Zealand fur seal	Small pinniped	NABIS	NZ and Aus	192 632	0.274	0.634
New Zealand sea lion	Large pinniped	NABIS	NZ	11 743	0.046	1.000
Ross seal	Small pinniped	AqM	Antarctic	73 836	0.350	0.000
Crabeater seal	Small pinniped	AqM	Antarctic	8 872 943	0.350	0.000
Leopard seal	Large pinniped	AqM	Antarctic	32 921	0.350	0.007
Weddell seal	Large pinniped	AqM	Antarctic	595 392	0.350	0.000
Southern elephant seal	Large pinniped	NABIS	NZ and MI.	71 728	0.350	0.003
Spectacled porpoise	Other small dolphin	ROP	Worldwide	2 002	0.350	0.047
Hector’s dolphin	Cephalorhynchus	Den	NZ	14 756	0.112	1.000
Māui dolphin	Cephalorhynchus	Den	NZ	54	0.082	1.000
Hourglass dolphin	Other small dolphin	ROP	Antarctic	142 230	0.170	0.020
Common dolphin	Common dolphin	Den	Worldwide	5 596 800	0.373	0.023
Dusky dolphin	Other small dolphin	Den	NZ	28 442	0.350	1.000
Bottlenose dolphin	Other small dolphin	Den	NZ	1 892	0.350	1.000
Pygmy killer whale	Other small dolphin	AqM	Worldwide	36 899	0.325	0.012
Pantropical spotted dolphin	Other small dolphin	AqM	Worldwide	2 956 962	0.170	0.014
Striped dolphin	Other small dolphin	ROP	Worldwide	1 881 176	0.350	0.015
Rough-toothed dolphin	Other small dolphin	AqM	Worldwide	208 045	0.350	0.010
Fraser’s dolphin	Other small dolphin	AqM	Worldwide	294 445	0.350	0.008
Risso’s dolphin	Other small dolphin	ROP	Worldwide	329 206	0.350	0.009
Southern right whale dolphin	Other small dolphin	ROP	Worldwide	20 013	0.350	0.047
Melon-headed whale	Other small dolphin	AqM	Worldwide	94 059	0.350	0.009
False killer whale	Large dolphin	ROP	Worldwide	54 966	0.350	0.018
Short-finned pilot whale	Large dolphin	OP	Worldwide	649 347	0.350	0.013
Long-finned pilot whale	Large dolphin	OP	Worldwide	188 118	0.350	0.040
Orca	Large dolphin	Den	Worldwide	48 750	0.225	0.021
Dwarf sperm whale	Other whale	AqM	Worldwide	7 694	0.350	0.017
Pygmy sperm whale	Other whale	ROP	Worldwide	9 406	0.350	0.021
Sperm whale	Other whale	Den	Worldwide	338 612	0.350	0.016
Pygmy right whale	Baleen whale	AqM	Worldwide	941	0.350	0.062
Southern right whale	Baleen whale	Den	NZ	2 161	0.085	1.000
Dwarf minke whale	Baleen whale	ROP	Worldwide	9 406	0.350	0.018
Antarctic minke whale	Baleen whale	OP	Worldwide	506 541	0.182	0.002
Bryde’s whale	Baleen whale	Den	W Sth Pac	15 600	0.350	0.030
Humpback whale	Baleen whale	OP	E Aus and PI	18 769	0.080	0.226
Sei whale	Baleen whale	OP	Worldwide	47 029	0.350	0.010
Pygmy blue whale	Baleen whale	AqM	Worldwide	3 292	0.350	0.205
Fin whale	Baleen whale	OP	Worldwide	23 515	0.350	0.020
Antarctic blue whale	Baleen whale	OP	Worldwide	2 145	0.350	0.044
Pygmy beaked whale	Beaked whale	AqM	Worldwide	4 703	0.350	0.002
Andrews’ beaked whale	Beaked whale	ROP	Worldwide	1 384	0.350	0.068
Hector’s beaked whale	Beaked whale	AqM	Worldwide	18 443	0.350	0.051
Strap-toothed whale	Beaked whale	AqM	Worldwide	209 019	0.350	0.045
Dense-beaked whale	Beaked whale	ROP	Worldwide	31 855	0.350	0.015
Ginkgo-toothed beaked whale	Beaked whale	AqM	Worldwide	2 939	0.350	0.032
Gray’s beaked whale	Beaked whale	ROP	Worldwide	204 475	0.350	0.046
Spade-toothed whale	Beaked whale	AqM	Worldwide	484	0.350	0.194
True’s beaked whale	Beaked whale	unif	Worldwide	9 406	0.350	0.010
Southern bottlenose whale	Beaked whale	ROP	Worldwide	50 792	0.350	0.028
Shepherd’s beaked whale	Beaked whale	ROP	Worldwide	18 443	0.350	0.051
Goose-beaked whale (aka Cuvier’s)	Beaked whale	ROP	Worldwide	94 059	0.350	0.016
Arnoux’s beaked whale	Beaked whale	ROP	Worldwide	2 822	0.350	0.031

Table 12: Observed captures of marine mammal species in commercial fisheries, from the 1995/96 to 2018/19 fishing years.

			BLL		Purse seine		Setnet		SLL		Trawl		
Species group	Common name	Species code	All	Live (%)	All	Live (%)	All	Live (%)	All	Live (%)	All	Live (%)	Total
Small pinniped	New Zealand fur seal	FUR	5	20	1	0	63	5	781	94	3057	11	3907
Large pinniped	New Zealand sea lion	HSL							1	0	337	8	338
	Southern elephant seal	EPH									1	0	1
	Leopard seal	LEO									3	0	3
Cephalorhynchus	Hector's dolphin	HDO					16	19			1	0	17
Common dolphin	Common dolphin	CDD					6	0	4	75	215	1	225
	Long-beaked common dolphin	DCZ									3	0	3
Other small dolphin	Dusky dolphin	DDO					7	0	2	100	11	0	20
	Bottlenose dolphin	BDO							4	100	3	0	7
	Porpise	POE							1	100			1
Large dolphin	Pilot whale	PIW	3	33			1	100	3	100	17	0	24
	Orca	ORC							1	100	1	0	2
	Dolphins and toothed whales (generic)	WHT							1	100			1
	Whales (generic)	WHU							2	100			2
Baleen whale	Humpback whale	HBW							1	100			1
Beaked whale	Beaked whales (generic)	MES							5	100			5
	Whales (generic)	WHU							1	100			1
Remains	Seal (generic)	SEA									1	0	1
	Whales (generic)	WHU									1	0	1
Total			8		1		93		807		3651		4560

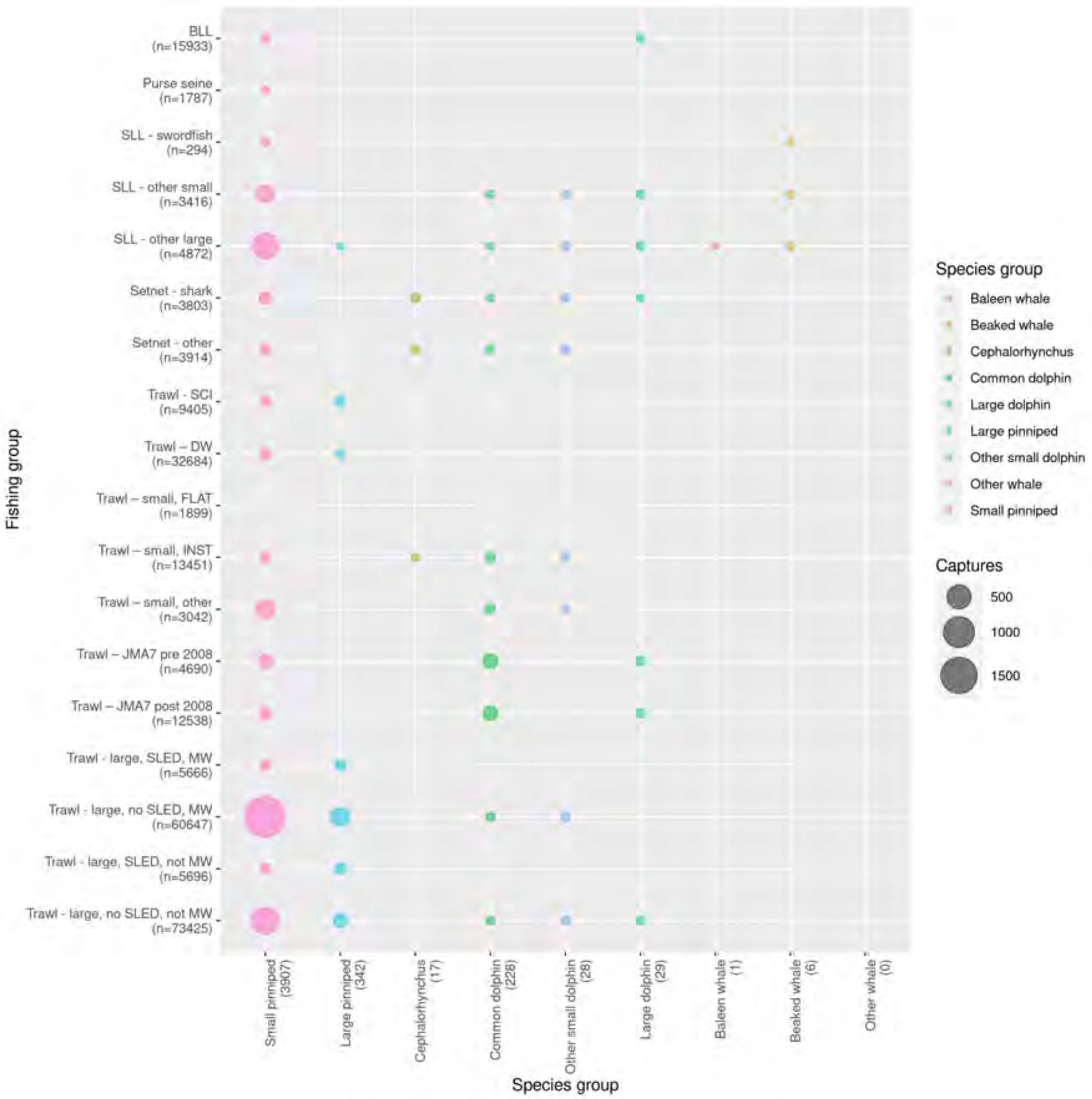


Figure 2: Number of observed marine mammal captures in commercial fisheries from 1995/96 to 2018/19 fishing years, by species group and generalised fishing group. Numbers in parentheses indicate the observed number of captures or fishing events of species groups and fishing groups, respectively.

3.3. SEFRA modelling

The most general fishing group model is highest-ranked on the basis of LOOIC (Table 13), although the standard error is relatively large indicating there is substantial uncertainty in the LOOIC rankings and the performance of the models is similar. This is illustrated in Table 14, which presents the posterior mean of the estimated total number of annual observable captures (i.e., captures that could have been observed had an observer been on board), estimated from each model using the mean annual commercial effort from 2016/17 to 2018/19 fishing years. The estimated captures tend to be very similar for all models, therefore model $M_{\bullet}$ has been used for inference and inclusion in the SEFRA model on the basis of parsimony.

Traceplots for each model parameter suggest convergence of the MCMC chains, and all R-hat values were close to 1 (indicating convergence). The posterior distributions for the model parameters differ from their prior distributions indicating that the parameter values are informed by the data and model structure. See Appendix C for these details.

Table 13: Estimated relative difference in LOOIC values for each model fit to the species-group capture data, where models are specified in terms of different fishing group definitions.

Model	ΔLOOIC	SE
M_{SI}	0.00	0.00
M_S	1.25	6.30
$M_{\bullet}$	3.83	9.42
M_I	6.38	8.02

Table 14: Posterior means of the estimated number of annual observable captures for each species group, using mean annual commercial effort from 2016/17 to 2018/19, for each model. Model $M_{\bullet}$ was selected for inferences.

Species group	M_{SI}	M_S	M_I	$M_{\bullet}$
Small pinniped	1,023.2	1,026.2	1,021.2	**1,024.6**
Large pinniped	34.0	34.4	33.6	**33.9**
Cephalorhynchus	31.7	32.8	29.9	**31.1**
Common dolphin	60.4	60.9	58.4	**59.2**
Other small dolphin	22.2	22.9	19.9	**20.4**
Large dolphin	6.4	6.3	6.3	**6.4**
Baleen whale	0.6	0.6	0.5	**0.5**
Beaked whale	2.4	2.4	2.4	**2.3**
Other whale	0.1	0.1	0.1	**0.1**

3.3.1. Catchability

Posterior distributions for the estimated catchability coefficients for each species and fishing group ($q_{j,z}$) are given in Figures 3–11. Note that the x-axis is on the log-scale, and that the unit of effort is different for different fishing methods so the posterior distributions for $q_{j,z}$ are not directly comparable between fishing methods.

There is some similarity in the relative catchability of different fishing methods across species groups. This is a result of the underlying structure of the model that involves underlying additive effects of fishing method, fishing group and species group on $\log(q_{j,z})$, which effectively shares information about catchability across fishing groups and species groups. The random effect for fishing and species group (i.e., $\varepsilon_{j,z}$) allows some deviation from that consistent pattern in those cases when there is a sufficient amount of information, although assuming a normal distribution with mean = 0 dampens the amount of deviation away from the underlying additive model (i.e., induces 'shrinkage' of the values towards the overall mean).

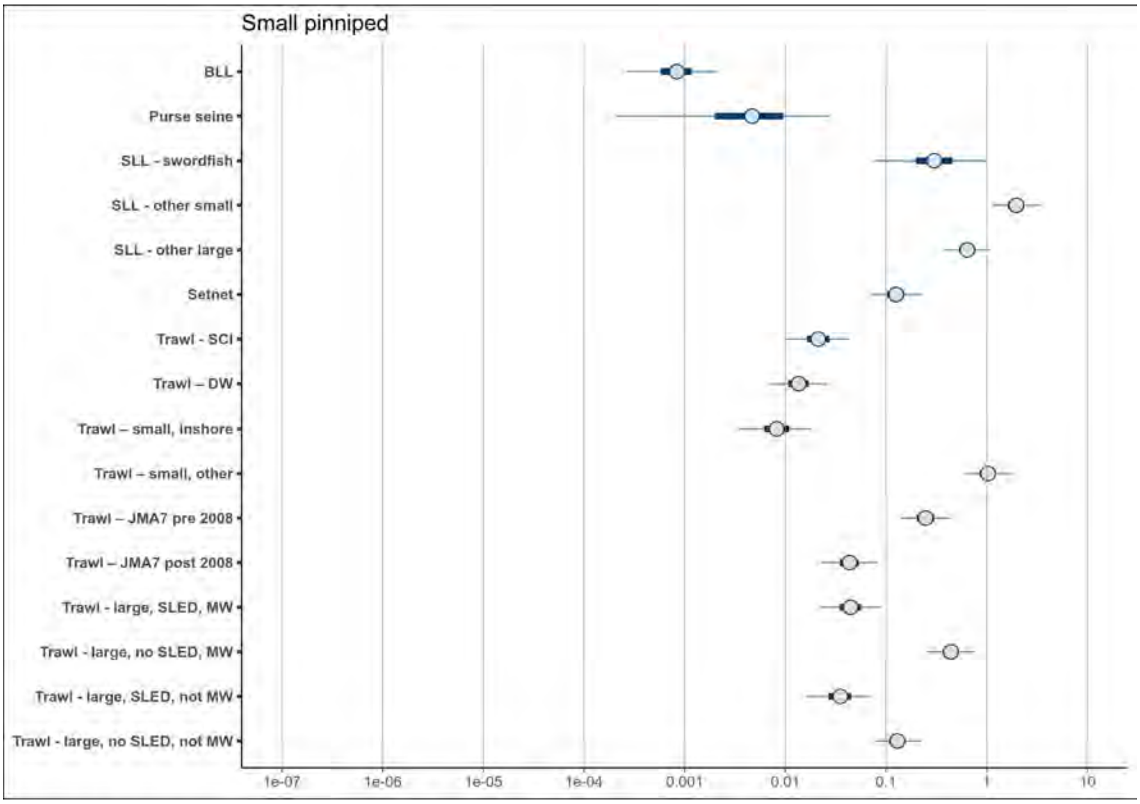


Figure 3: Posterior distribution of catchability ($q_{j,z}$) of small pinnipeds in each fishing group as defined in $M_\bullet$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

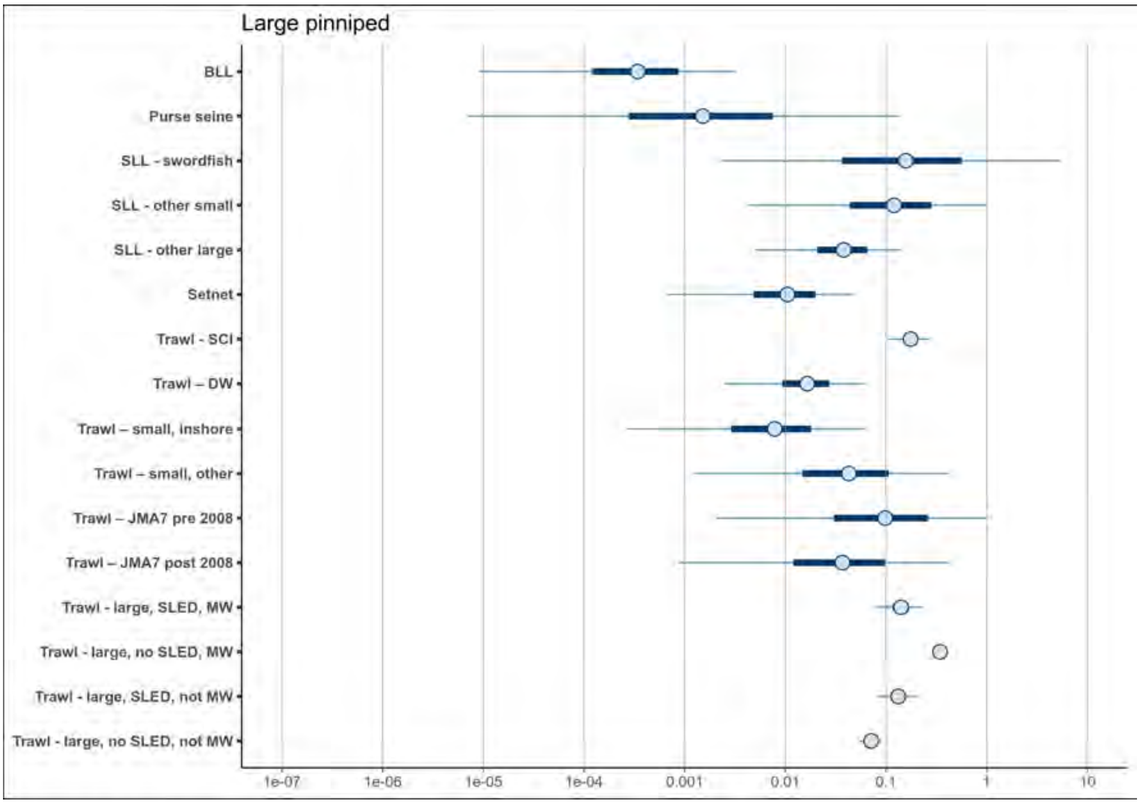


Figure 4: Posterior distribution of catchability ($q_{j,z}$) of large pinnipeds in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

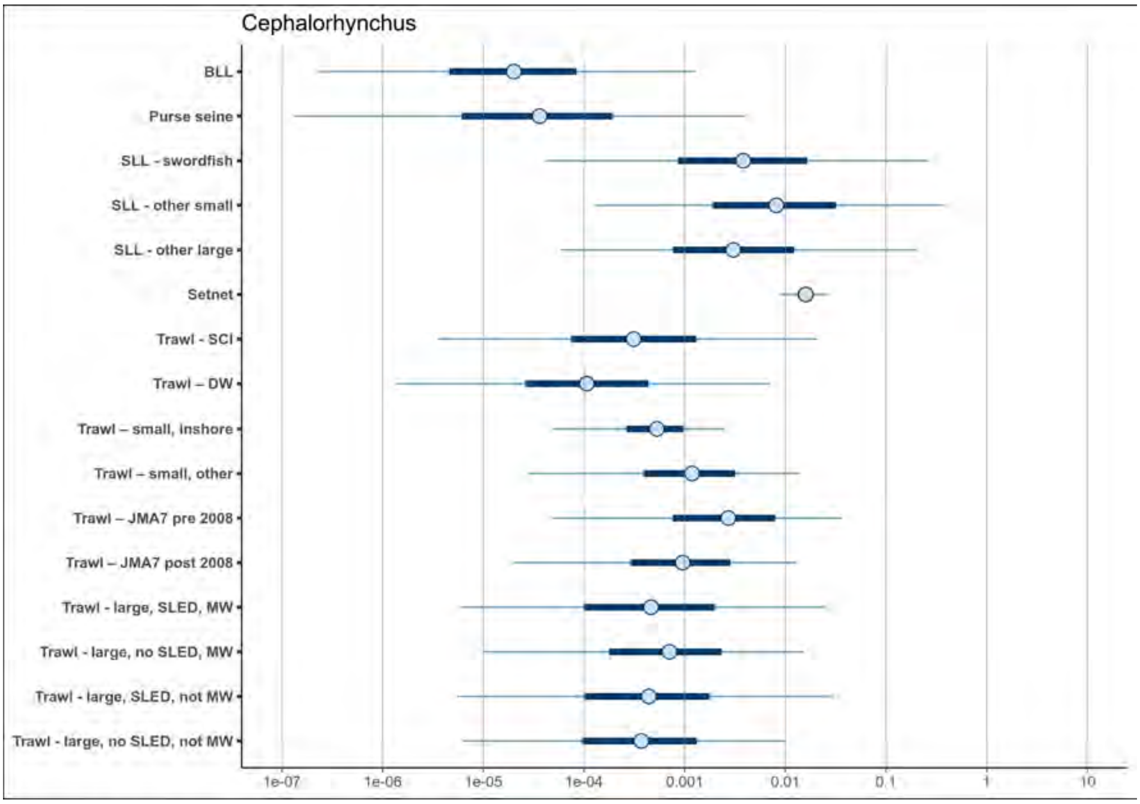


Figure 5: Posterior distribution of catchability ($q_{j,z}$) of Cephalorhynchus in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

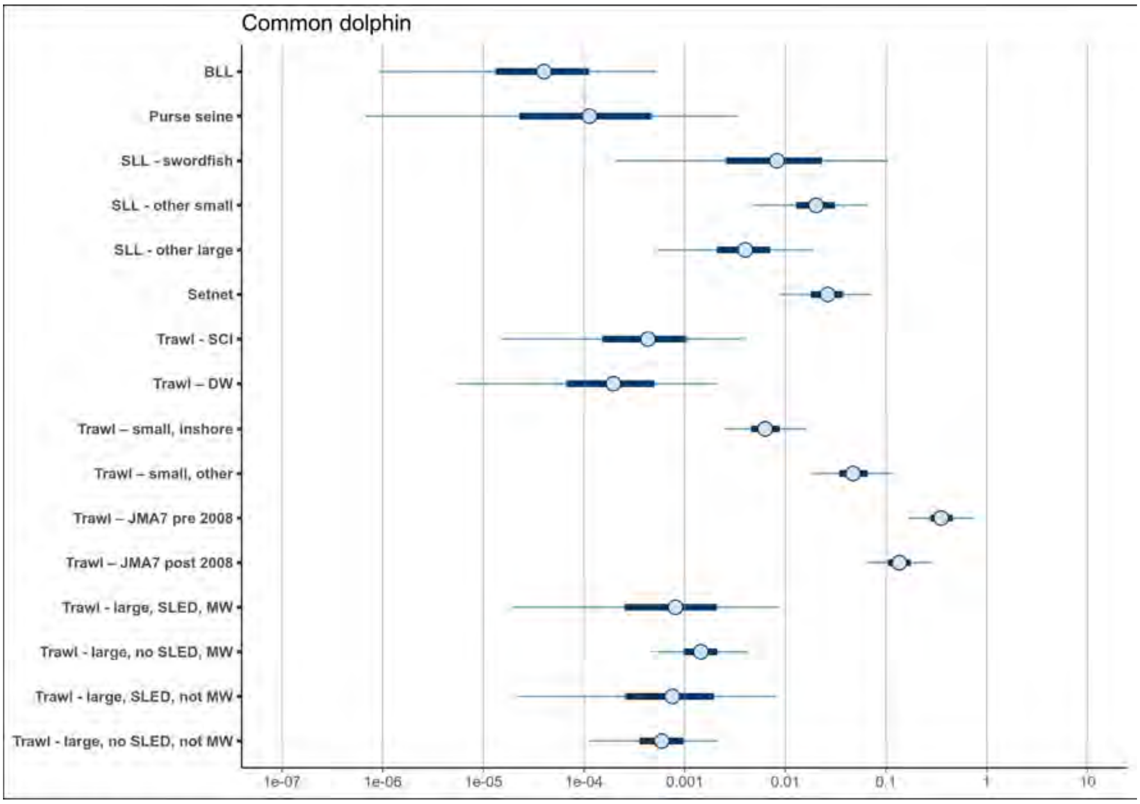


Figure 6: Posterior distribution of catchability ($q_{j,z}$) of common dolphin in each fishing group as defined in $M_\bullet$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

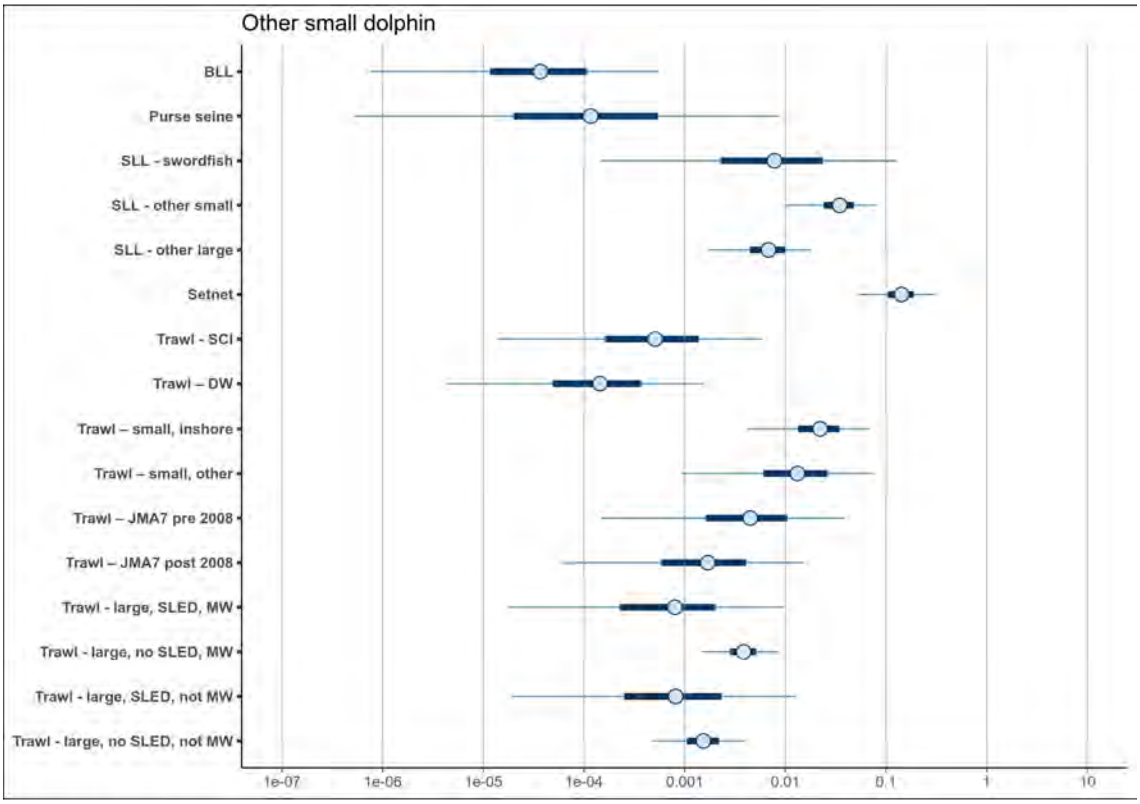


Figure 7: Posterior distribution of catchability ($q_{j,z}$) of other small dolphins in each fishing group as defined in $M_\bullet$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

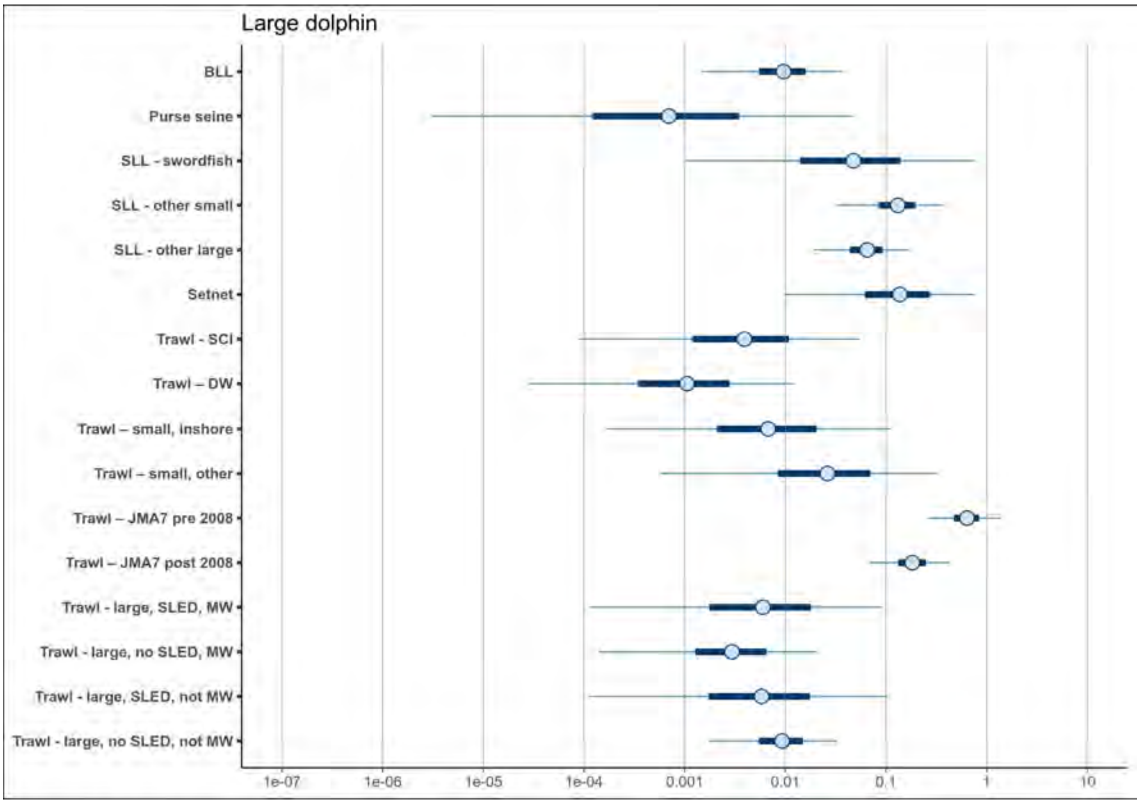


Figure 8: Posterior distribution of catchability ($q_{j,z}$) of large dolphins in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

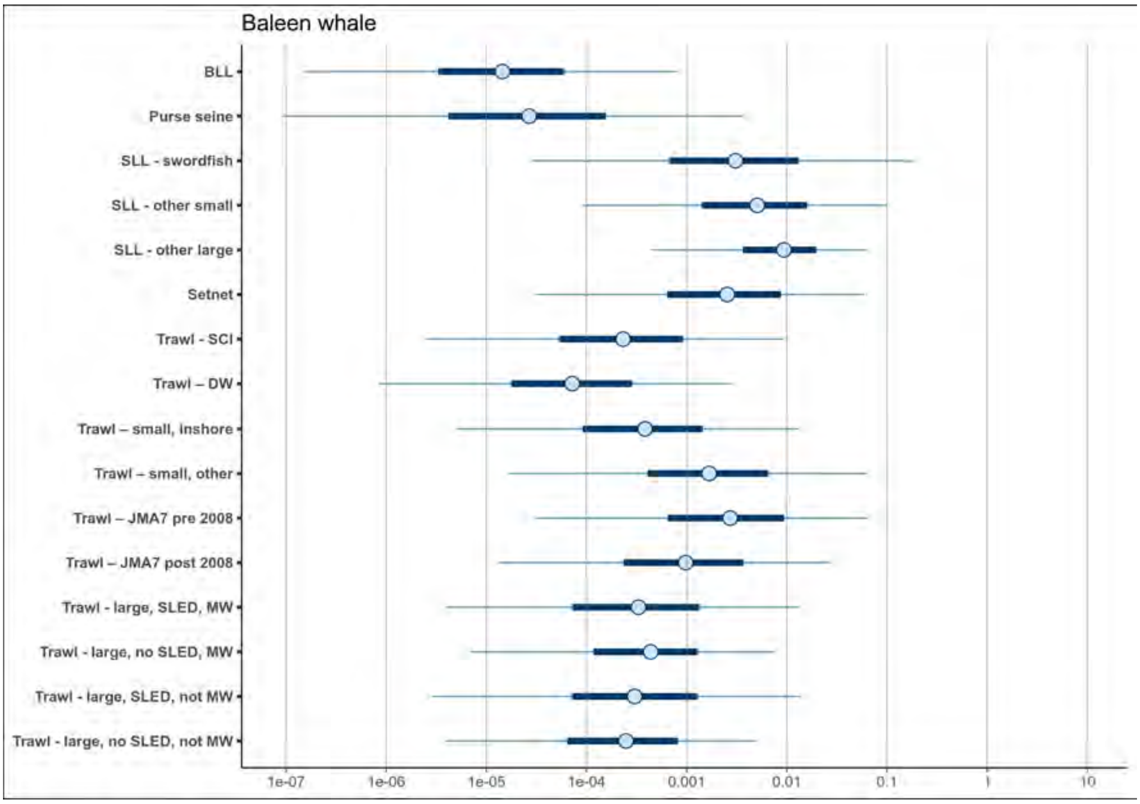


Figure 9: Posterior distribution of catchability ($q_{j,z}$) of baleen whales in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

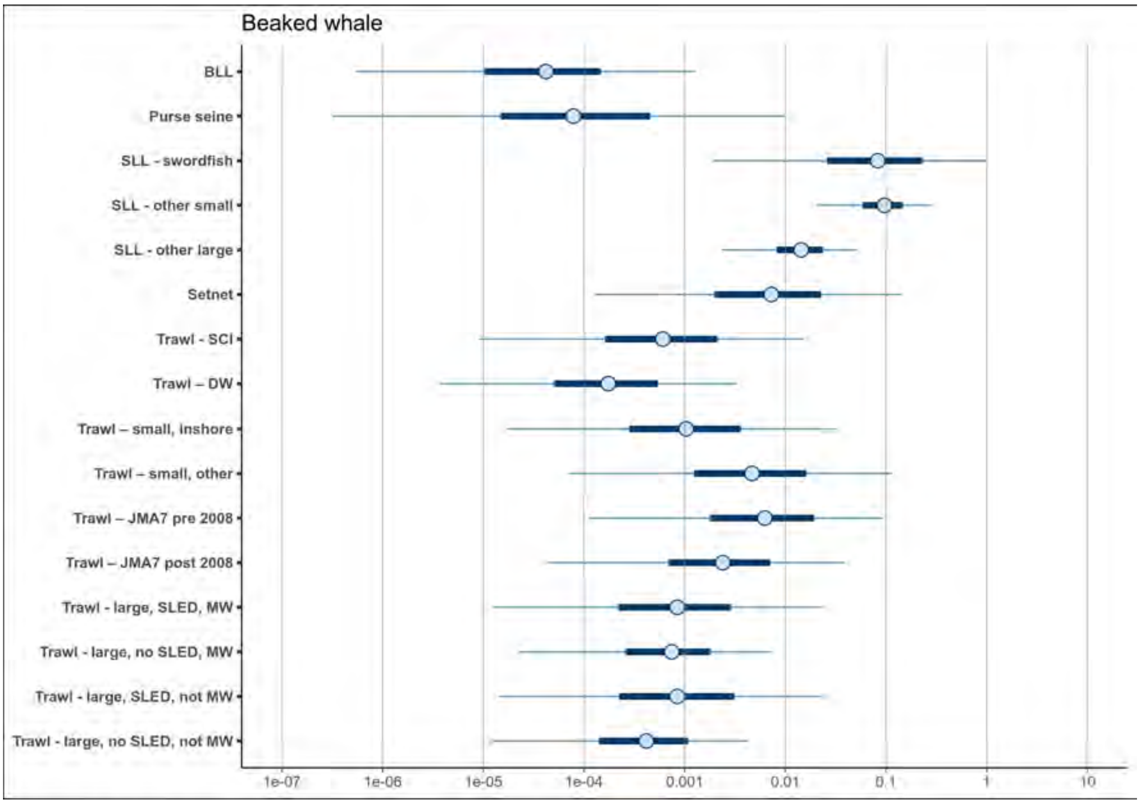


Figure 10: Posterior distribution of catchability ($q_{j,z}$) of beaked whales in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

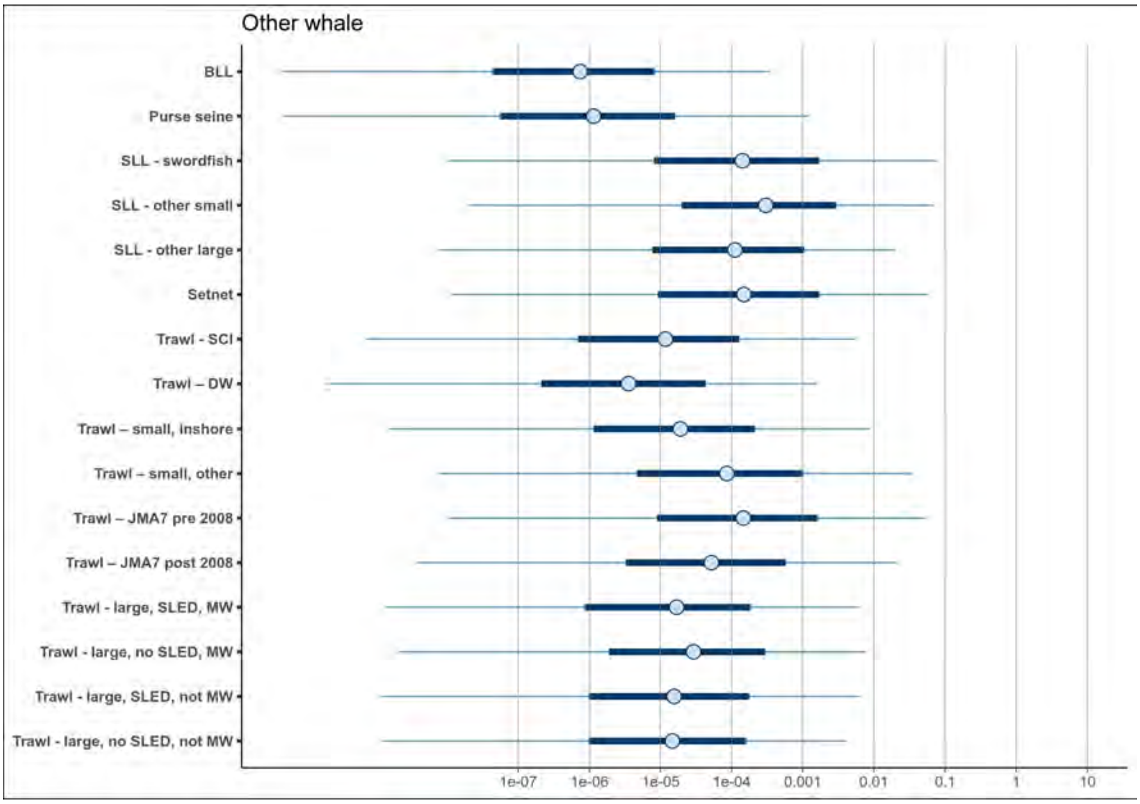


Figure 11: Posterior distribution of catchability ($q_{j,z}$) of other whales in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

3.3.2. Probability of live capture

Figures 12 – 20 present summaries of the posterior distributions for the estimated probability of live capture for each species group and fishing group ($\Psi_{j,z}$). Posterior distributions are presented for all $\Psi_{j,z}$ parameters, including for those combinations of species and fishing groups where there were no observed captures. The posterior distributions for this subset of parameters are characterised with greater levels of variation.

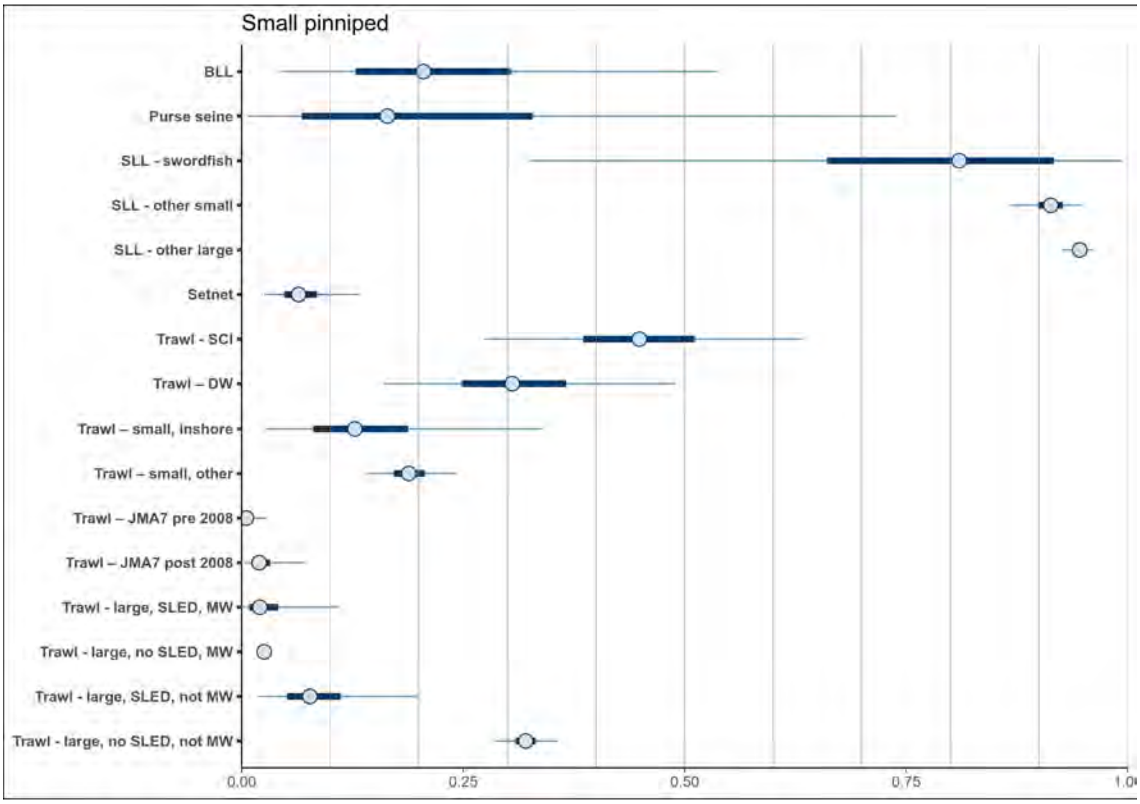


Figure 12: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of small pinnipeds in each fishing group as defined in $M_\bullet$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

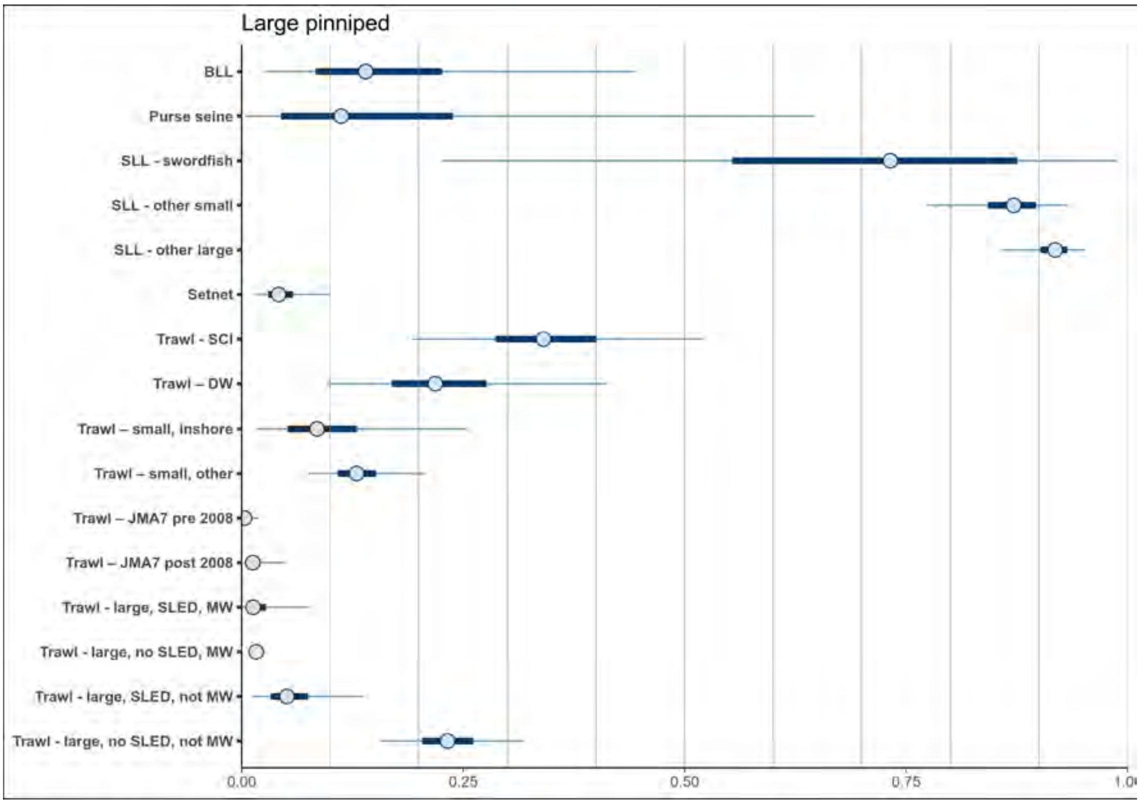


Figure 13: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of large pinnipeds in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

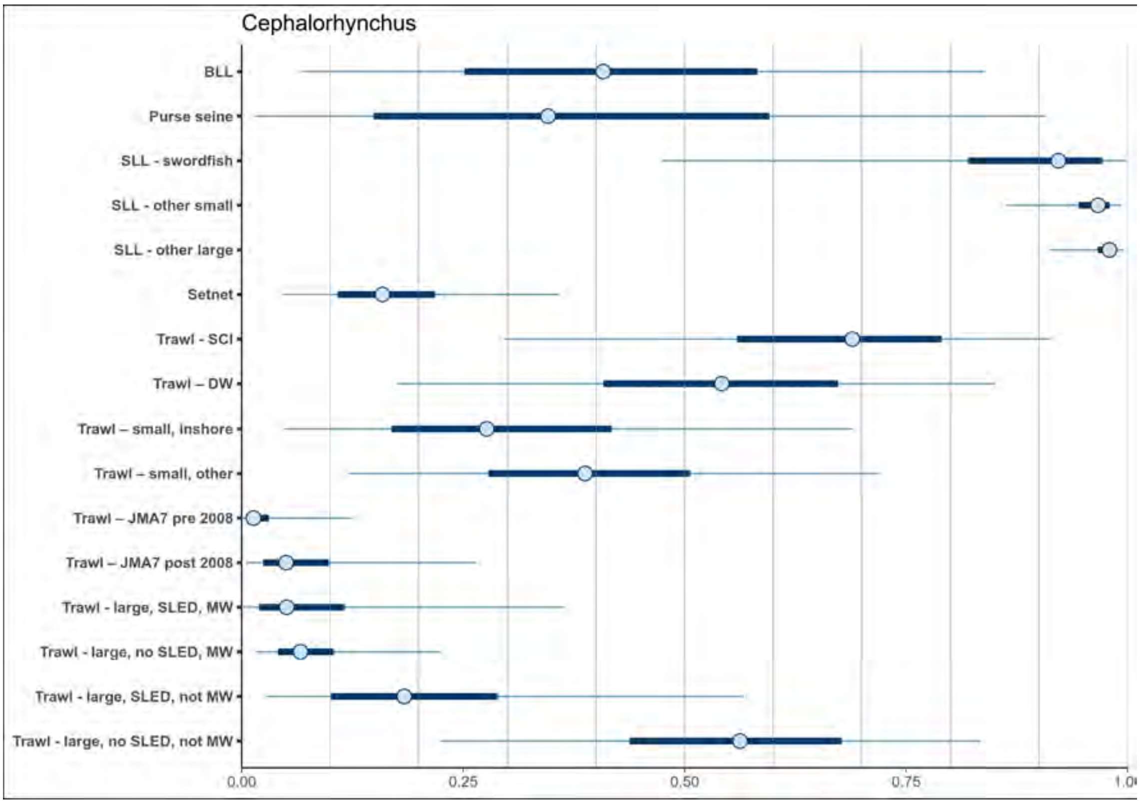


Figure 14: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of Cephalorhynchus in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

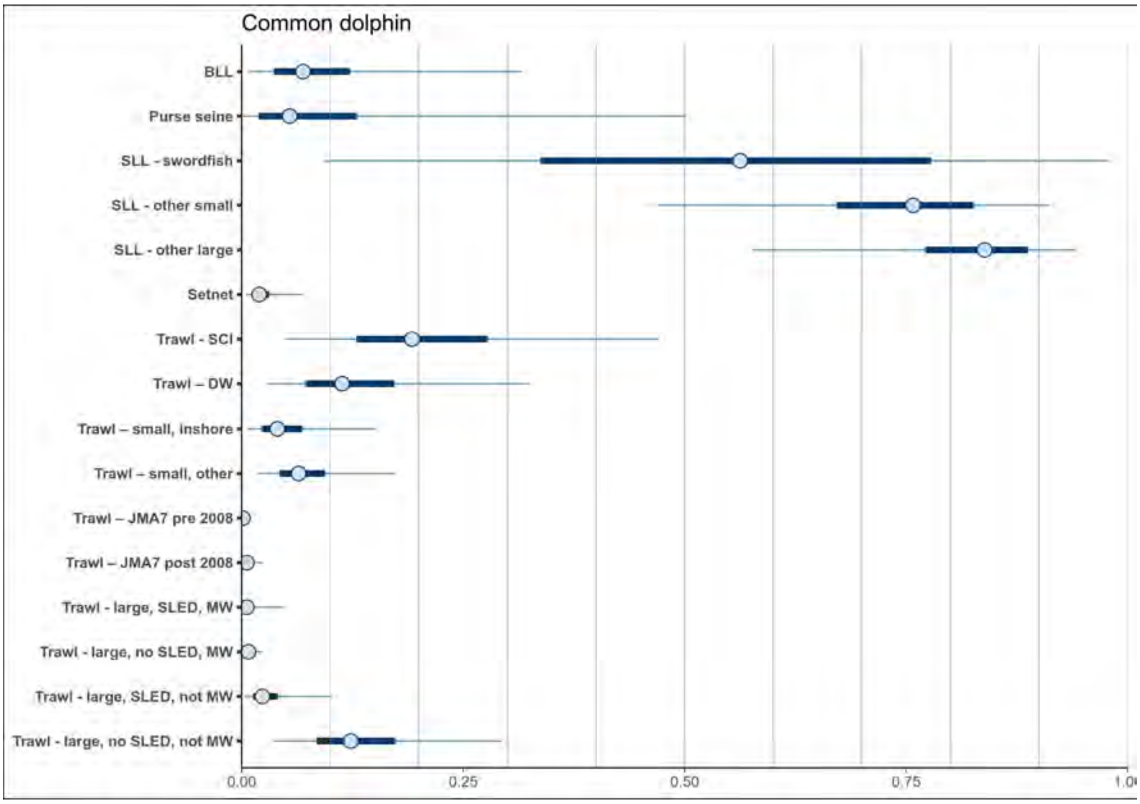


Figure 15: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of common dolphin in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

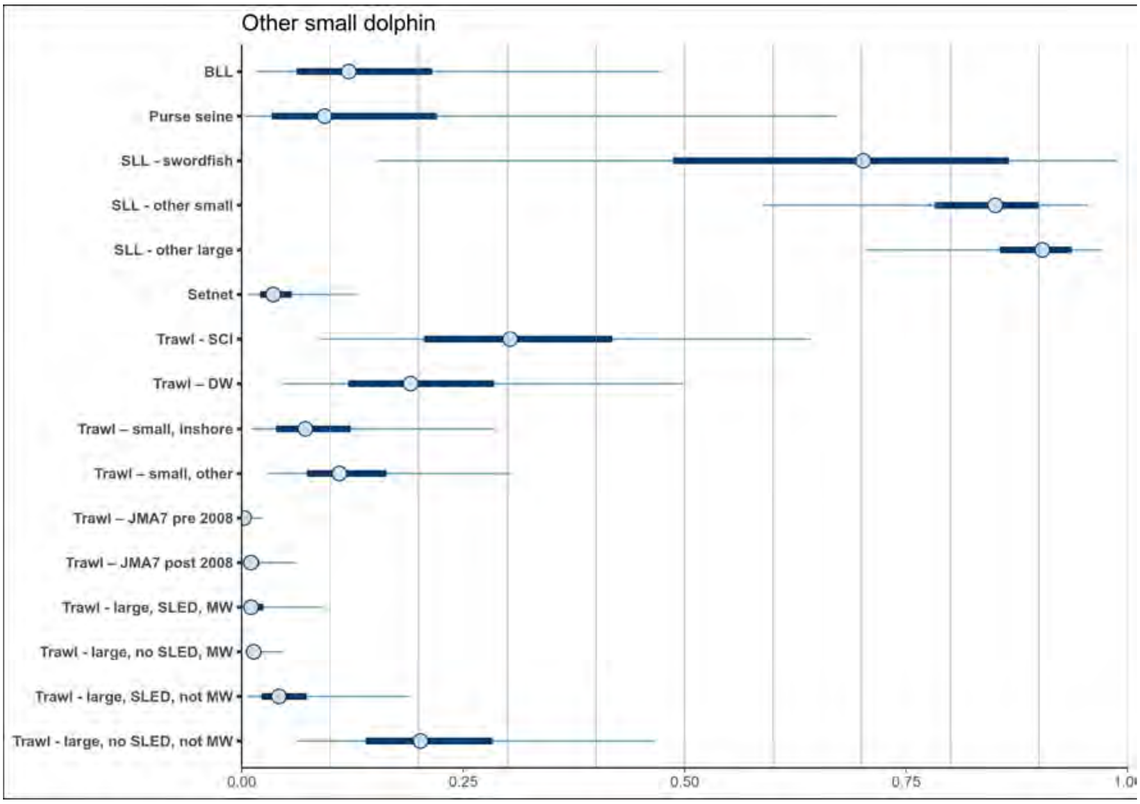


Figure 16: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of other small dolphins in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

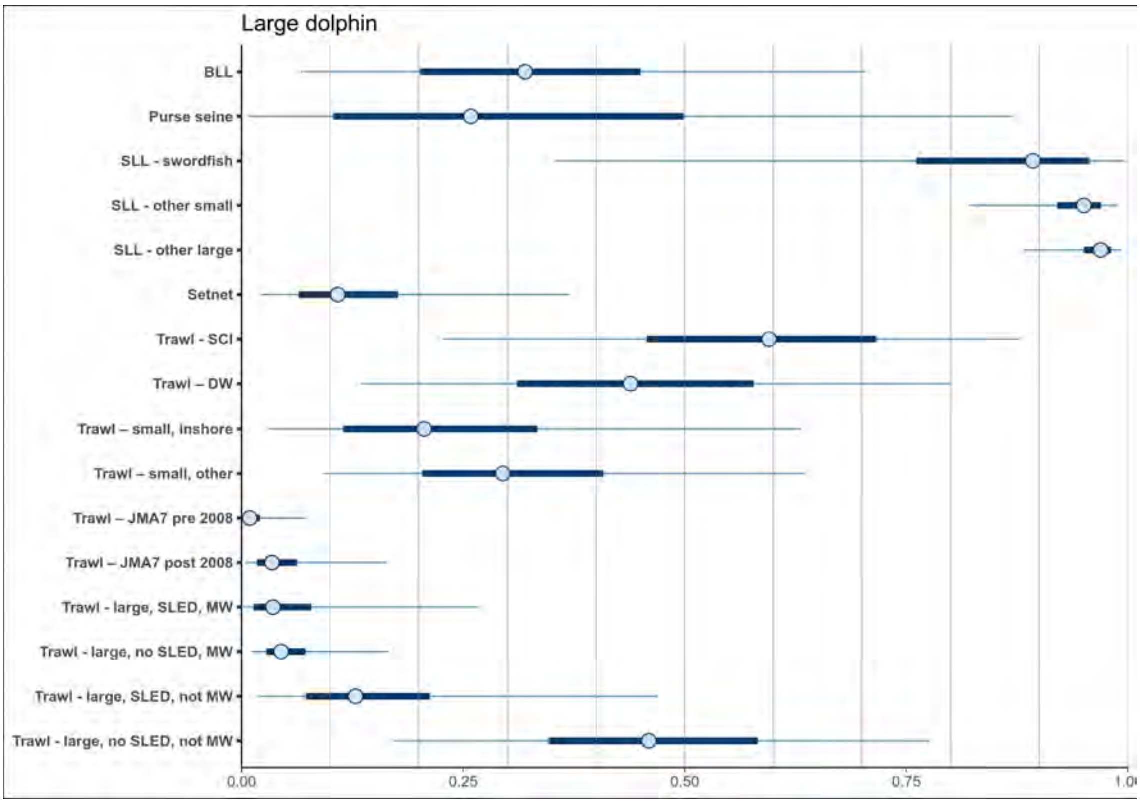


Figure 17: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of large dolphins in each fishing group as defined in $M_\bullet$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

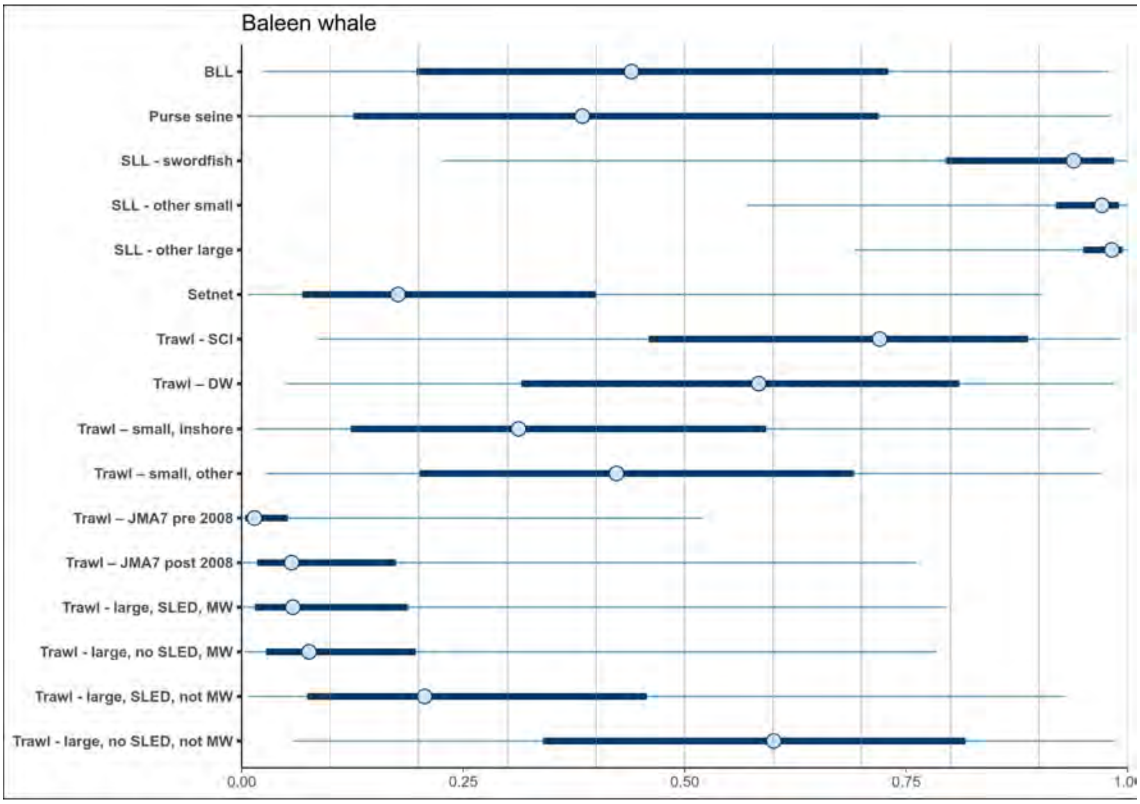


Figure 18: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of baleen whales in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

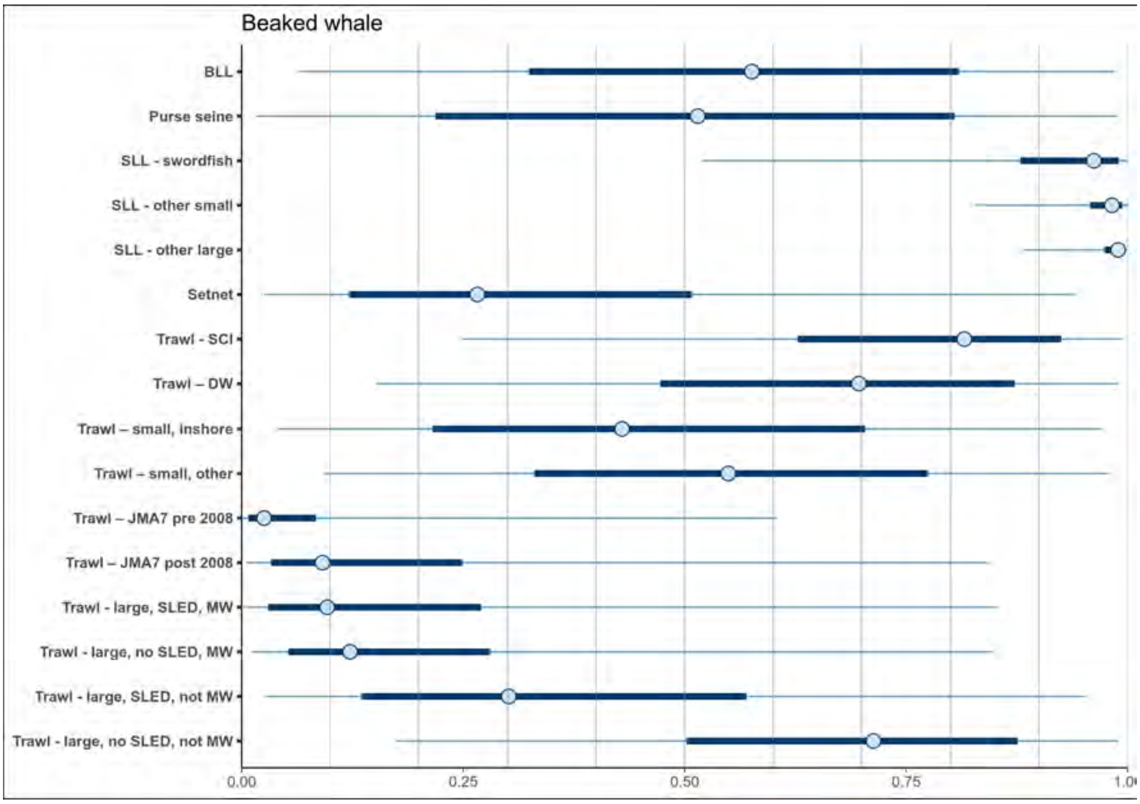


Figure 19: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of beaked whales in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

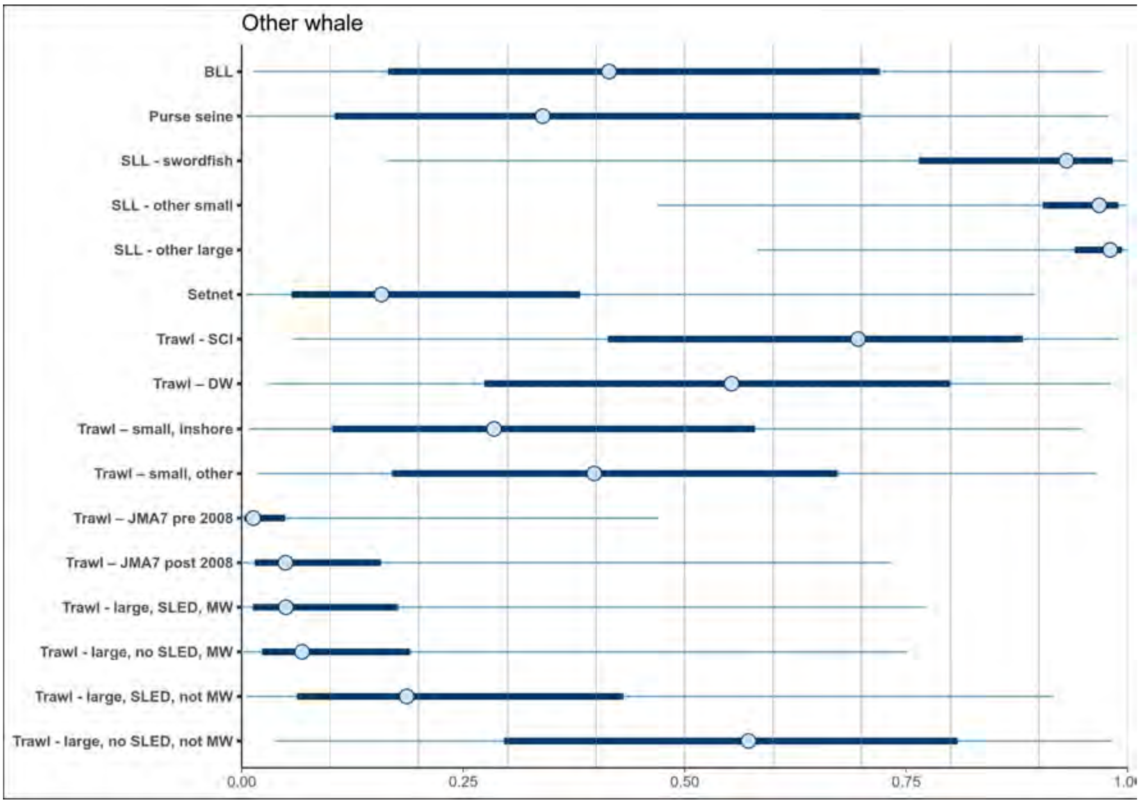


Figure 20: Posterior distribution of probability of live capture ($\Psi_{j,z}$) of other whales in each fishing group as defined in $M_{\bullet}$. The posterior median, central 50th and central 95th quantiles of the distributions are presented.

3.4. Assessments of fit for model $M_\bullet$

3.4.1. Fit to aggregated observations

Model $M_\bullet$ reproduces accurate predictions of the overall number of observable captures of each species group during observed fishing effort (Table 15), and plots of the predicted and observed number of observable captures on an input record basis (i.e., aggregated to generalised fishing group, species group and month) do not indicate cause for concern (Figures 21 – 26).

Table 15: Observed number of marine mammals captures in each species group, and summary of the predicted number from the observed commercial fishing effort from 1995/96 to 2018/19 fishing years.

Species group	Observed	Mean	Median	SD	CV	2.5^{th}	97.5^{th}
Small pinniped	3907	3907	3907	88	2	3739	4081
Large pinniped	342	341	340.5	26	8	292	394
Cephalorhynchus	17	17	17	6	34	7	30
Common dolphin	228	229	228	22	9	188	272
Other small dolphin	28	28	28	8	27	15	45
Large dolphin	29	29	28	8	26	15	45
Baleen whale	1	2	1	2	109	0	6
Beaked whale	6	6	6	3	55	1	14
Other whale	0	0	0	1	336	0	2

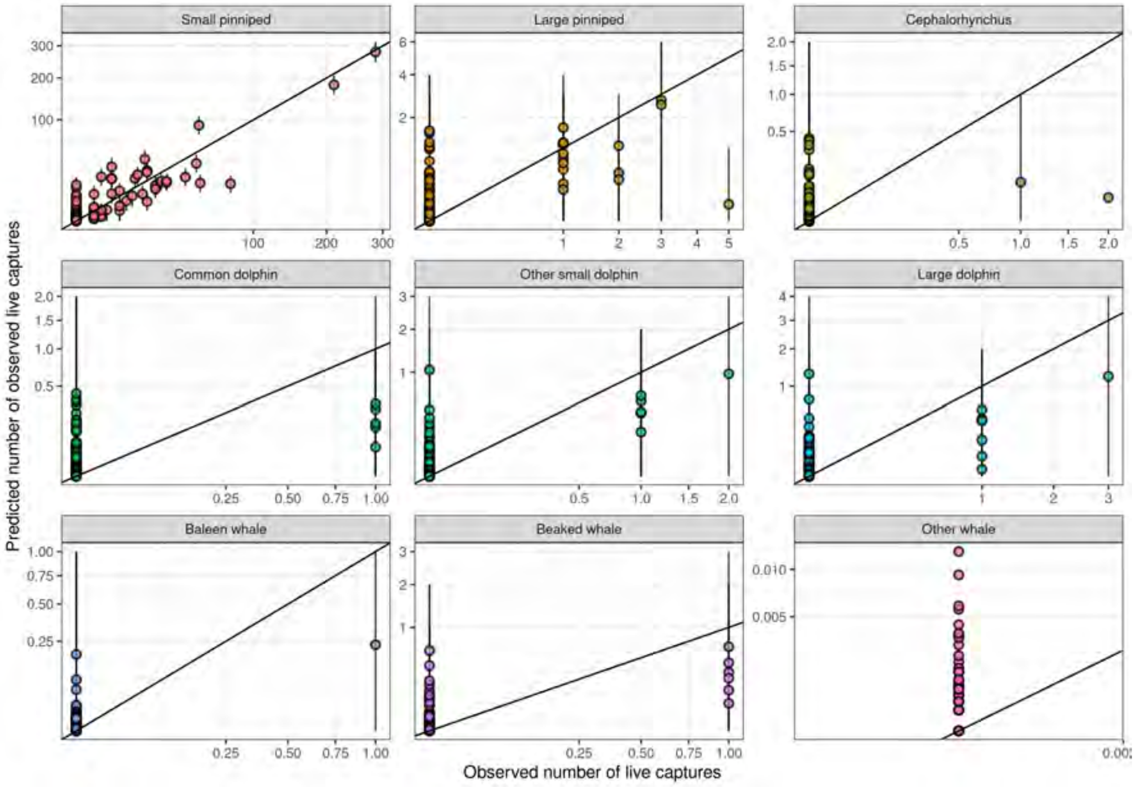


Figure 21: Actual vs. predicted number of observed live captures from $M_{\bullet}$, for each unique summarised data input record (i.e., species group $\times$ fishing group $\times$ fishing month). Axes are on square-root scale.

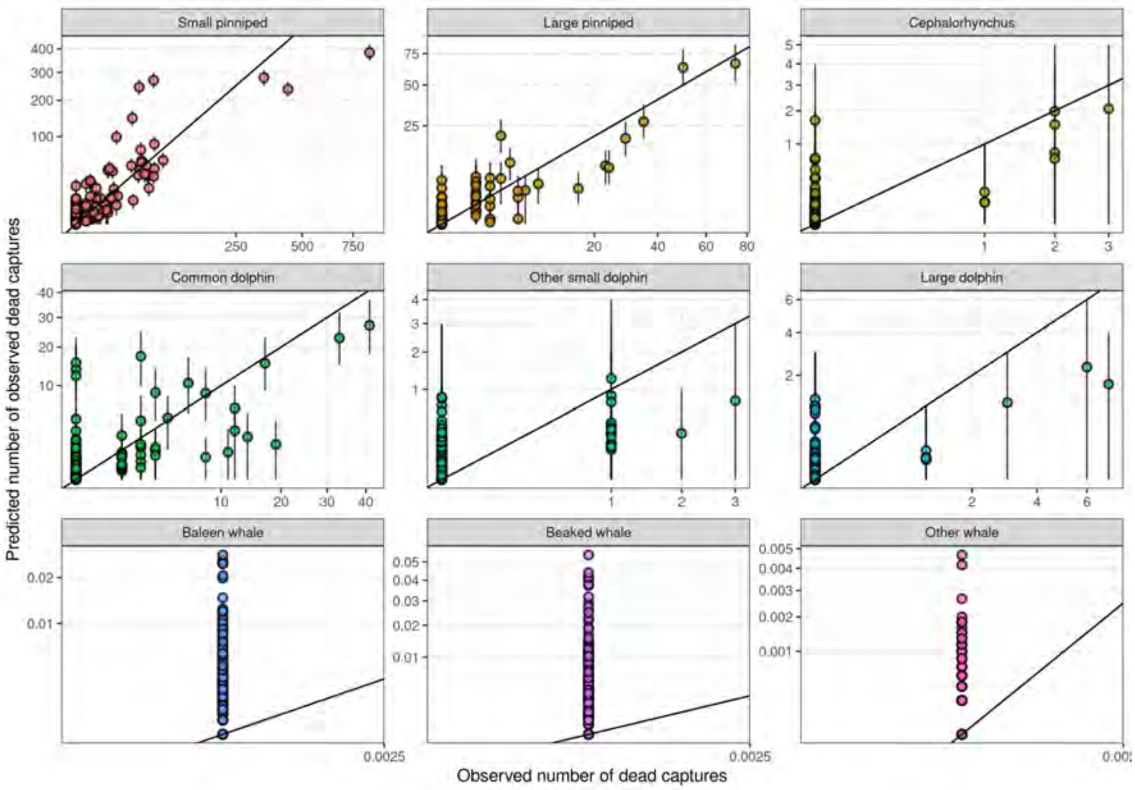


Figure 22: Actual vs. predicted number of observed dead captures from $M_{\bullet}$, for each unique summarised data input record (i.e., species group × fishing group × fishing month). Axes are on square-root scale.

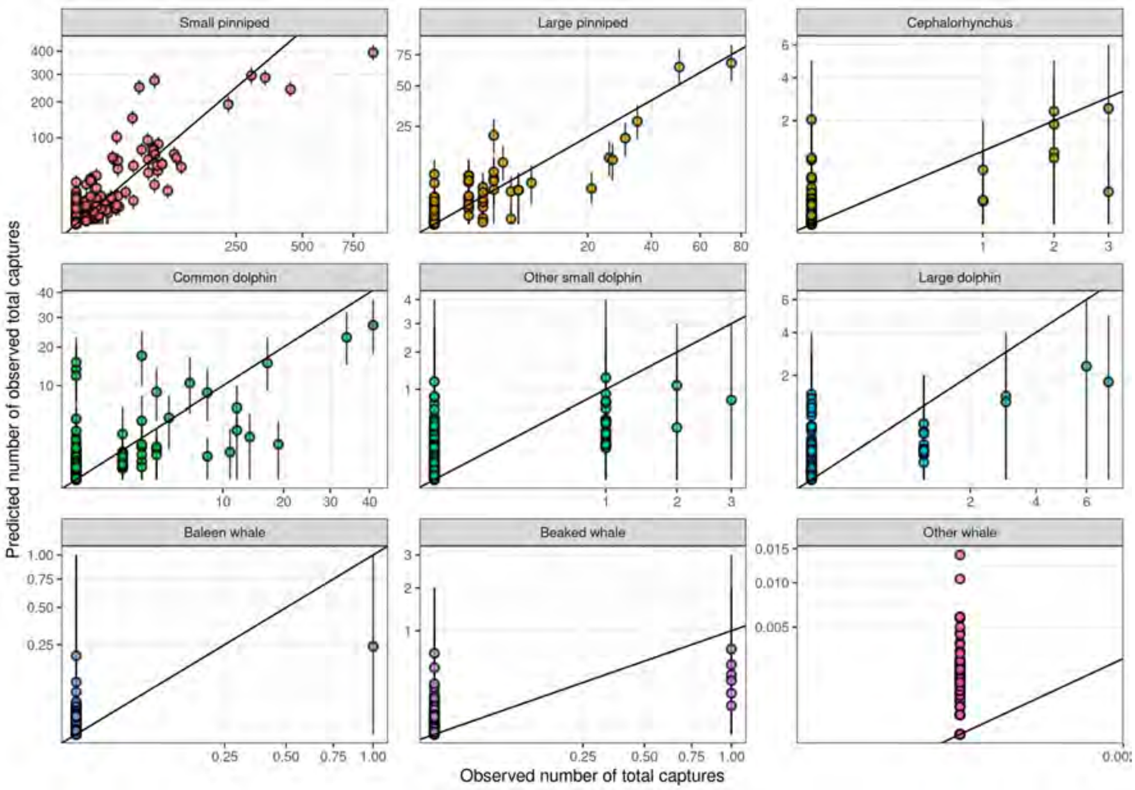


Figure 23: Actual vs. predicted number of total observed captures from $M_{\bullet}$, for each unique summarised data input record (i.e., species group × fishing group × fishing month). Axes are on square-root scale.

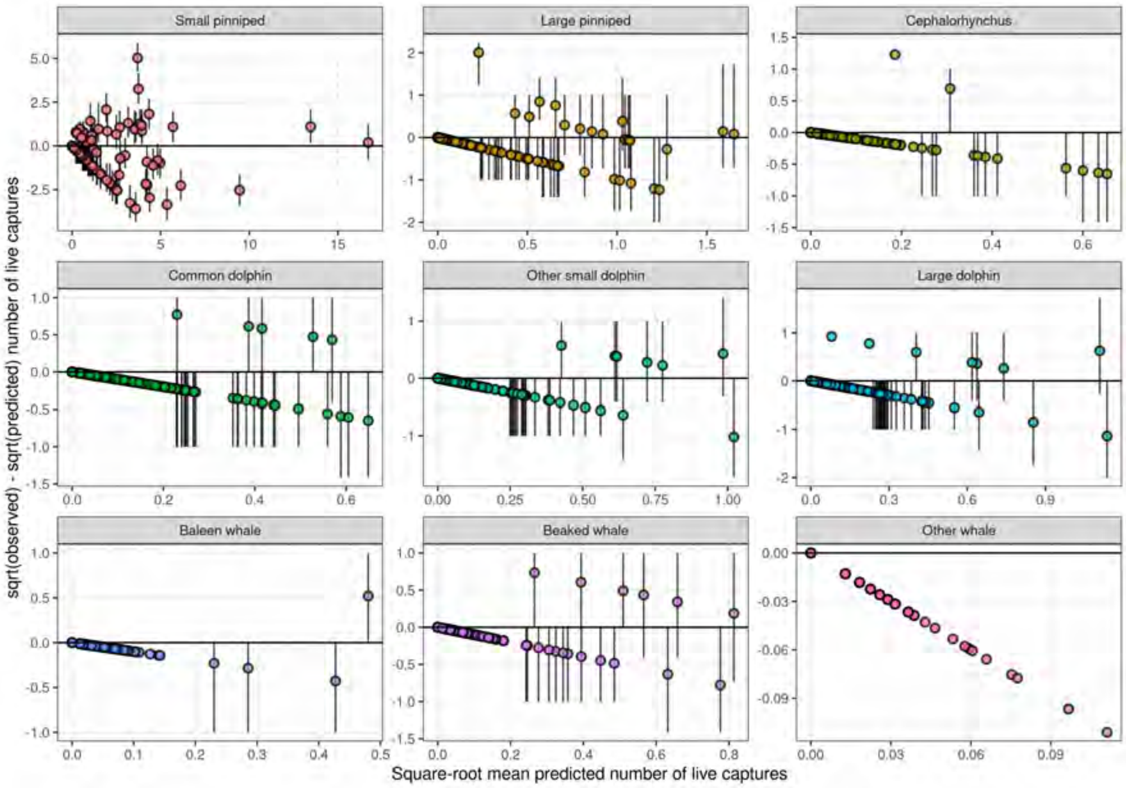


Figure 24: Difference between actual and predicted number of observed live captures from $M_\bullet$ (i.e., residuals), for each unique summarised data input (i.e., species group $\times$ fishing group $\times$ fishing month). The square root of the number of captures has been calculated prior to taking the difference.

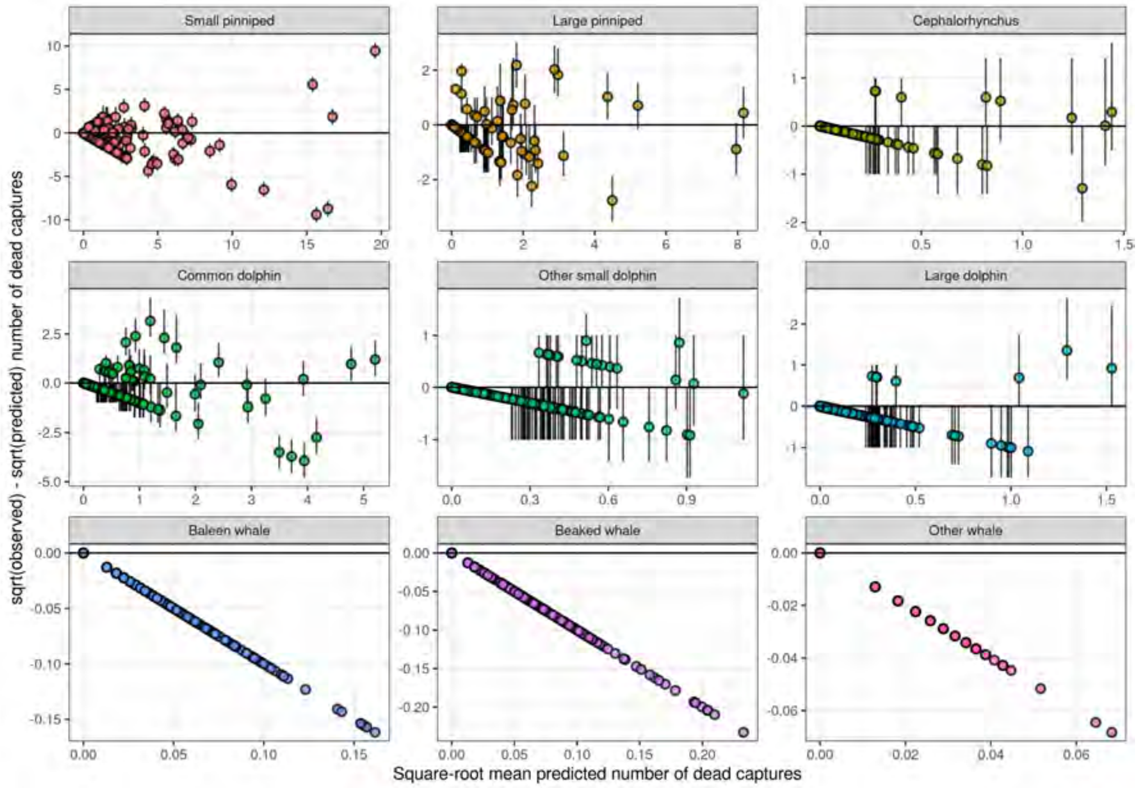


Figure 25: Difference between actual and predicted number of observed dead captures from $M_\bullet$ (i.e., residuals), for each unique summarised data input (i.e., species group × fishing group × fishing month). The square root of the number of captures has been calculated prior to taking the difference.

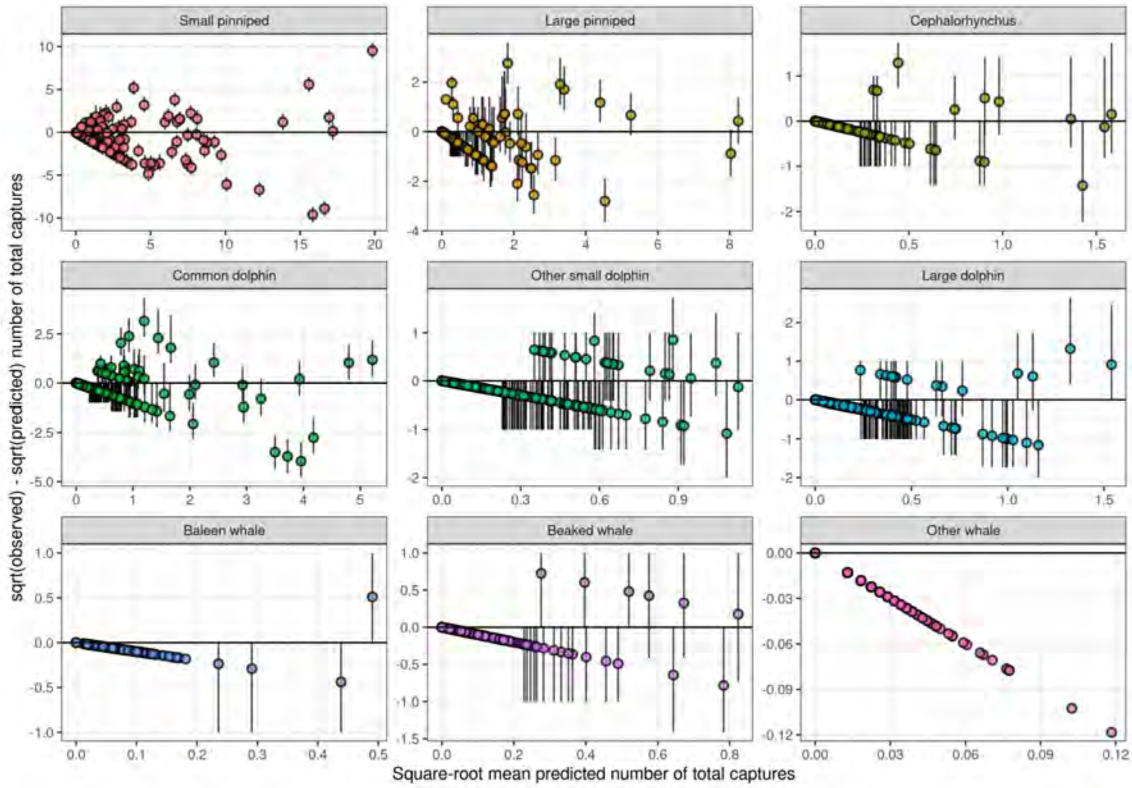


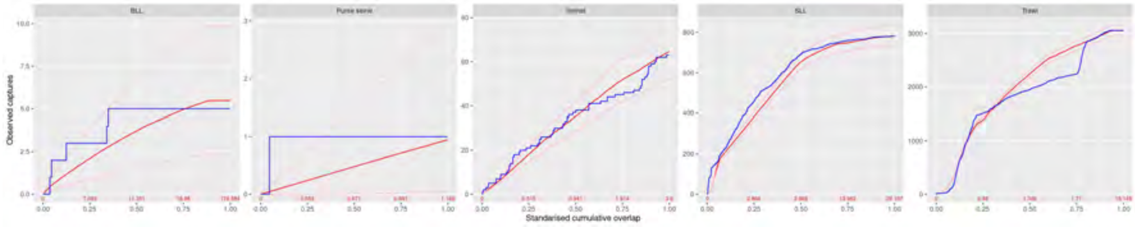
Figure 26: Difference between actual and predicted number of total observed captures from $M_\bullet$ (i.e., residuals), for each unique summarised data input (i.e., species group $\times$ fishing group $\times$ fishing month). The square root of the number of captures has been calculated prior to taking the difference.

3.4.2. Cumulative sum plots

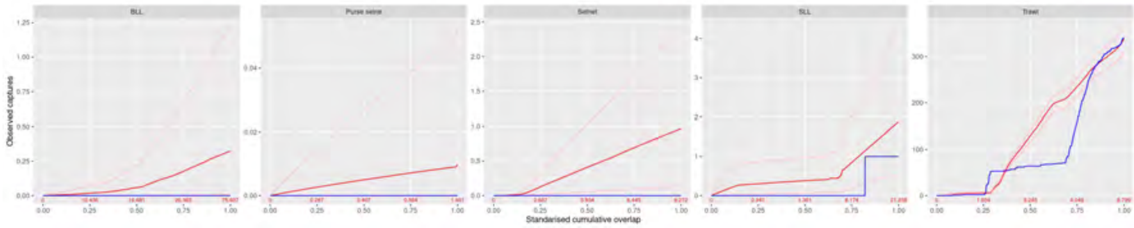
CUSUM plots of the number of captures vs. overlap are presented for species groups in Figures 27 and 28. The low number of observed captures in each fishing method for most species groups makes it difficult to access model fit. However, for those species with an adequate number of observed captures, the blue observed CUSUM line often displays a pattern that is different from the expected relationship (thick red line) and will often be more extreme than the limits of the 90% credible intervals (thin red lines). This behaviour suggests an inadequacy in the model for fitting the observed species-group capture data, and is particularly evident for:

- small pinnipeds in SLL and trawl fisheries,
- large pinnipeds in trawl fisheries,
- common dolphins in trawl fisheries,
- other small dolphins in trawl fisheries.

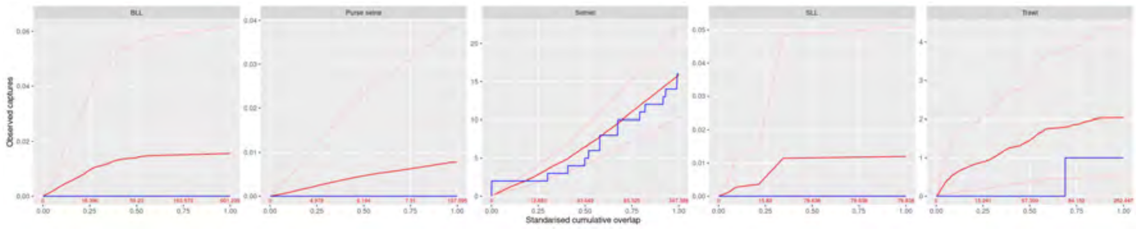
(**a**) Small pinnipeds



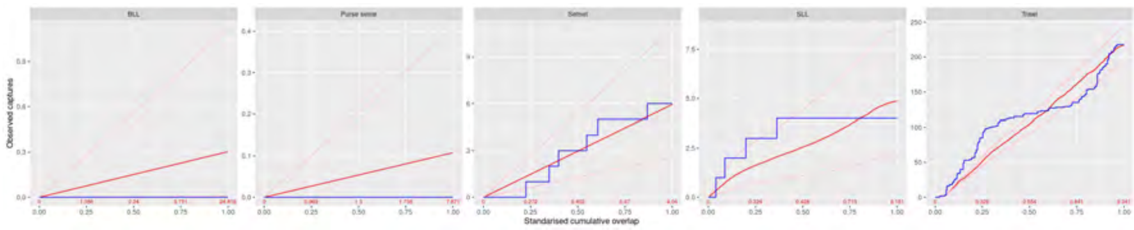
(**b**) Large pinnipeds



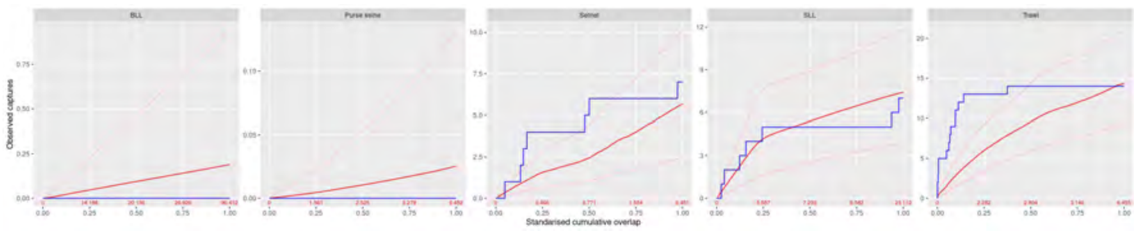
(**c**) Cephalorhynchus



(**d**) Common dolphins



(**e**) Other small dolphins



(**f**) Large dolphins

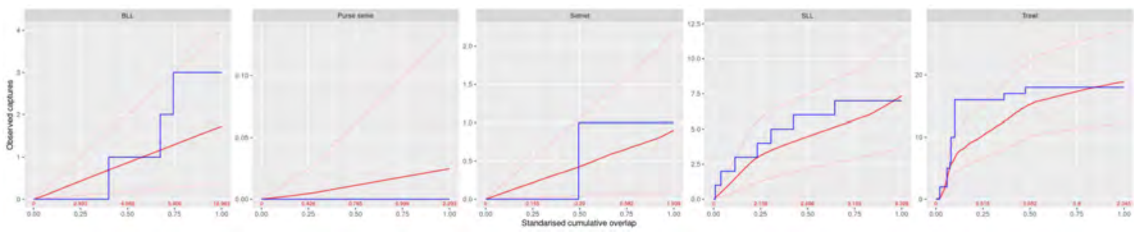
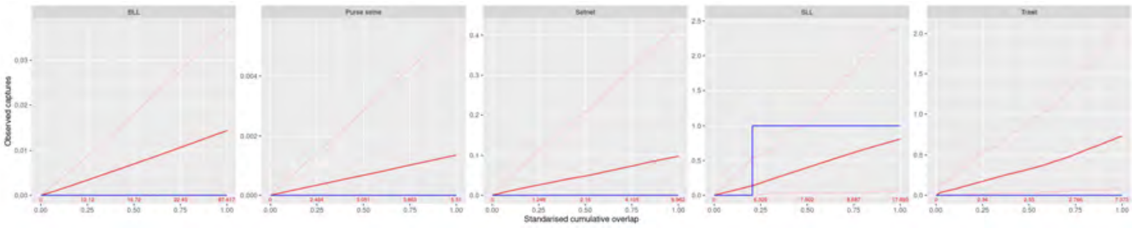
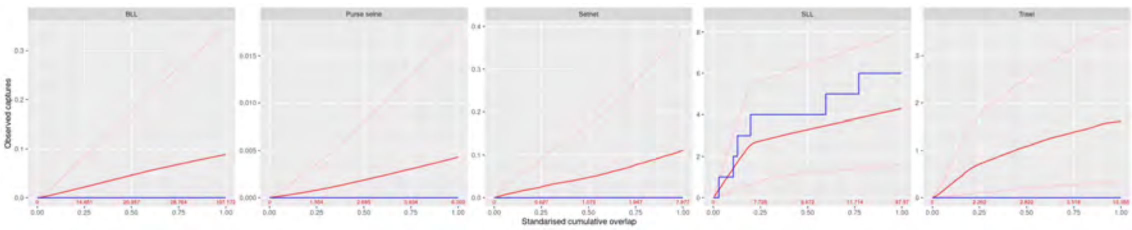


Figure 27: Cumulative number of observed captures vs. species group overlap (blue), for each pinniped and delphinid species group and fishing method. The expected values predicted from the model (thick red line) and 90% credible interval (thin red lines) are also presented for reference.

(**a**) Baleen whales



(**b**) Beaked whales



(**c**) Other whales

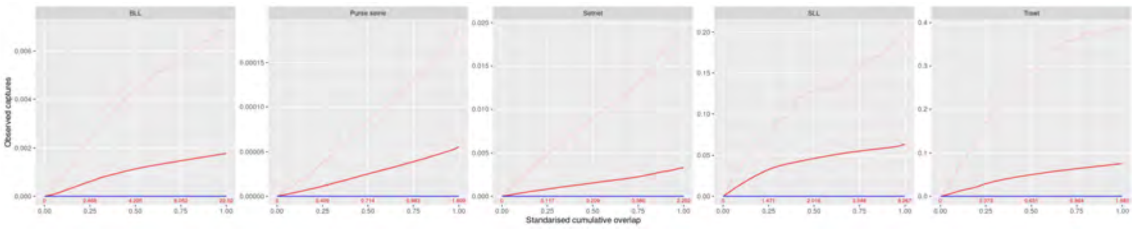


Figure 28: Cumulative number of observed captures vs. species group overlap, for each whale species group and fishing method. The expected values predicted from the model (thick red line) and 90% credible interval (thin red lines) are also presented for reference.

Recalling that the model is fitted to species group-level captures, and species group density overlap is the sum of the density overlaps of the individual species within the group, examination of the CUSUM plots for observed captures of individual species (where identified) can provide further insight to model performance, in those cases where a sufficient number of captures were observed. While the model is not fitted to individual species-level capture data and the intended use of the model is to evaluate the risk to individual species, it is appropriate to evaluate the model at this level. CUSUM plots for species with more than 5 observed captures are presented in Figures 29–34.

The blue CUSUM lines for the actual capture data for New Zealand fur seal (NZFS) (Figure 29) and NZSL (Figure 30) lie well outside the envelope of expected values predicted from the fitted model, with a greater number of observed captures in areas of low density overlap in setnet, SLL and trawl fisheries for NZFS, and for trawl fisheries for NZSL. The poor fit for these species is not unexpected given that generic species distribution layers were used for them, as more detailed distribution layers at the scale of the EEZ were not available.

(a) New Zealand fur seal

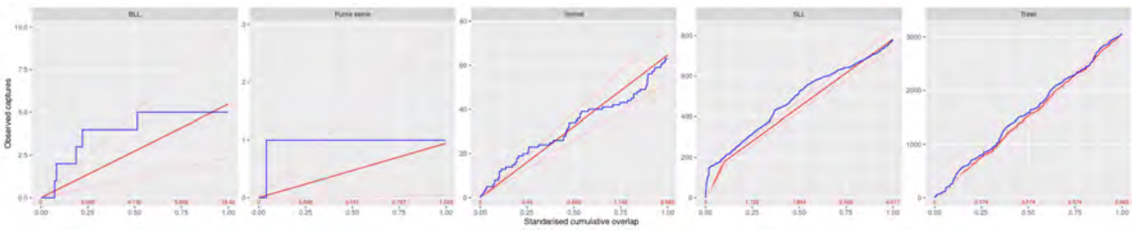


Figure 29: Cumulative number of observed captures vs. species density overlap for New Zealand fur seal, the only small pinniped species with more than 5 observed captures.

(a) New Zealand sea lion

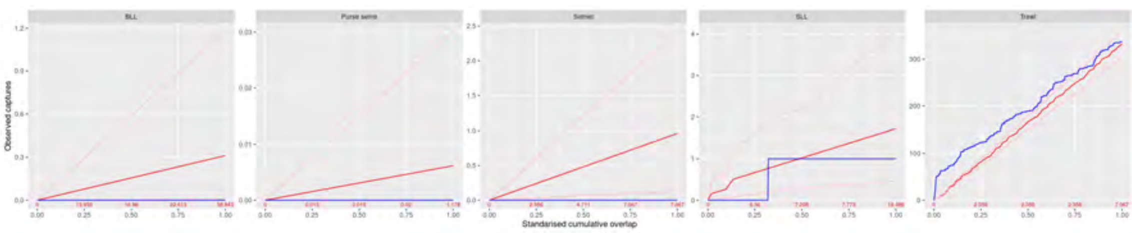


Figure 30: Cumulative number of observed captures vs. species density overlap for New Zealand sea lion, the only large pinniped species with more than 5 observed captures.

CUSUM plots for Hector's dolphin (Figure 31) do not indicate any systematic areas of concern; the blue CUSUM line for setnet fisheries that is briefly outside the 90% credible interval obtained from the model is primarily driven by 1 observed capture occurring at grid cell with very low density overlap.

(**a**) Hector's dolphin

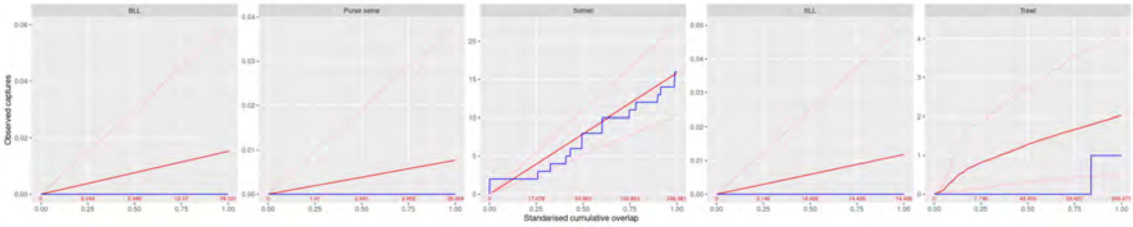


Figure 31: Cumulative number of observed captures vs. species density overlap for Hector's dolphin, the only Cephalorhynchus species with more than 5 observed captures.

For common dolphins (Figure 32), the number of observed captures was low in setnet and SLL fisheries making it difficult to identify meaningful patterns, although having the 4 SLL observed captures in areas of relatively low density overlap does appear slightly unusual. The CUSUM plot for trawl fisheries clearly indicates an unusual systematic pattern, with more observed captures than expected in areas of low density overlap, less captures than expected in areas of moderate density overlap (between the values of 0.326–0.841) and more observed captures than expected in areas of high density overlap. This suggests there is likely a problem with the structural aspects of the model (e.g., defined fishing or species groups), or the inputs used for the modelling (e.g., the species distribution layer).

(**a**) Common dolphin

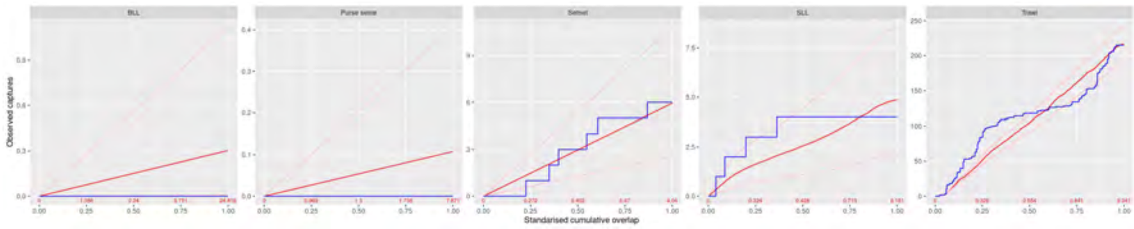
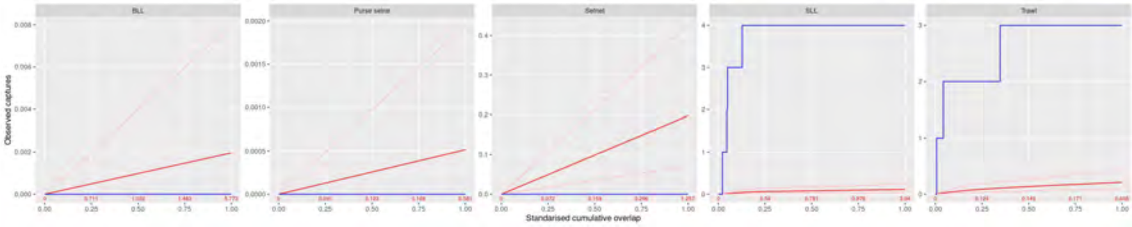


Figure 32: Cumulative number of observed captures vs. species density overlap for common dolphins.

The CUSUM plots for bottlenose and dusky dolphins (Figure 33) are notable as the predicted number of observed captures for these species are substantially lower than the number in the data. Given the predicted number of captures for the respective species group overall is similar to the values in the data (other small dolphins; Figure 27), this would suggest there has been some 'species switching', where captures for one species are being assigned to a different species within the same species group due to the aggregated nature of the species group density overlap calculation. This may be due to the structural assumptions of the modelling, or inappropriate model inputs.

(a) Bottlenose dolphin



(b) Dusky dolphin

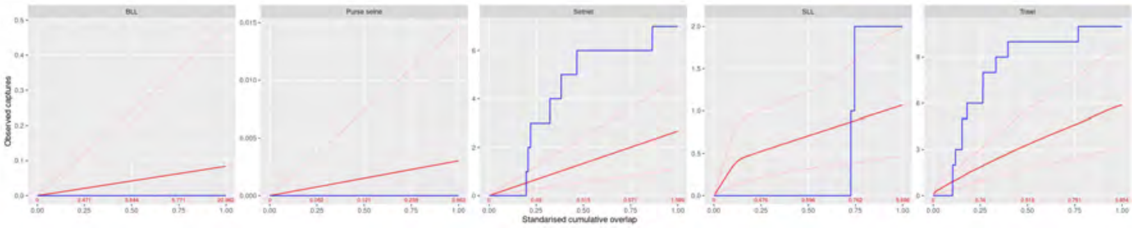


Figure 33: Cumulative number of observed captures vs. species density overlap for bottlenose and dusky dolphins, the only other small dolphin species with more than 5 observed captures.

The number of observed captures of pilot whales in non-trawl fisheries is too low to make reliable conclusions about model fit (Figure 34), and in trawl fisheries there appears to be more observed captures than the model predicts in areas with middling density overlap values. There is also some indication of 'species switching' for the large dolphin species group.

(a) Pilot whale

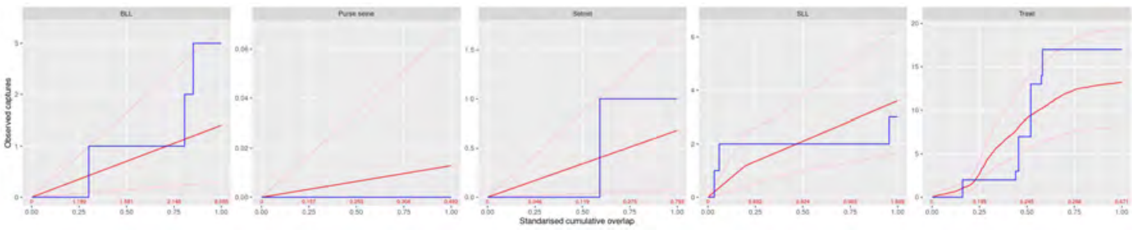


Figure 34: Cumulative number of observed captures vs. species density overlap for long-finned pilot whales, the only large dolphin species with more than 5 observed captures.

3.4.3. FMA-based goodness-of-fit test

Applied at the species group level, the results of the FMA-based goodness-of-fit test suggest there is strong evidence of lack of fit of the model to the observed capture data for small pinnipeds, large pinnipeds, common dolphins, other small dolphins and large dolphins. There is also some evidence of lack of fit of the model for Cephalorhynchus species (Table 16). As there have been very few observed captures of whale species, the assessment is likely to have low power for these species groups, hence the results should not be regarded as indicating that the model is a good fit of the data for these species groups. Overall, these results are in agreement with the inferences drawn from the CUSUM plots regarding model fit.

Tables 17 – 22 present the fishing methods and FMAs that contributed a relatively large value to the overall test (i.e., $\chi^2_{sfm} > 2$) for the pinniped and delphinid species groups. The model does a poor job of predicting the spatial pattern of observed captures for the pinniped groups (at the FMA-scale;

Table 16: Goodness-of-fit tests comparing the actual and predicted number of observed captures for each species group in each FMA, by fishing method.

Species group	χ^2	p-value
Small pinniped	1050.22	0.000
Large pinniped	425.41	0.000
Cephalorhynchus	7.96	0.055
Common dolphin	38.46	0.005
Other small dolphin	45.63	0.005
Large dolphin	59.41	0.000
Baleen whale	3.75	0.160
Beaked whale	5.23	0.170
Other whale	0.14	0.210

Tables 17 and 18) that is likely due to the simplistic nature of the species distribution layers used for NZFS and NZSL (in particular). For Cephalorhynchus species, there is some indication of slight under-prediction of observed captures in setnet fisheries in FMA 3 and over-prediction in FMA 8 (Table 19), while for common dolphins there is clear under-prediction in trawl fisheries in FMA 9 and over-prediction in FMA 7 (Table 20). The number of observed captures is small for the other small dolphin and large dolphin species groups, making it difficult to draw definitive conclusions, although there is an indication of under-prediction in trawl and setnet fisheries in FMA 3 for the former species group (Table 21), and under-prediction in trawl fisheries in FMA 8 for the latter group (Table 22).

Table 17: Fishing methods and FMAs where $\chi^2_{sfm} > 2$ for small pinnipeds. C'_{sfm} is the number of observed captures for the species group in FMA f and fishing method m, and E_{sfm} is the corresponding mean predicted number.

Fishing method	FMA	C'_{sfm}	E_{sfm}	χ^2_{sfm}
Trawl	FMA 6	943	513.98	358.10
Trawl	FMA 5	358	710.03	174.53
Setnet	FMA 2	1	0.01	130.02
Trawl	FMA 4	38	172.69	105.05
Trawl	FMA 7	1183	957.33	53.20
Trawl	FMA 3	272	391.05	36.24
Trawl	FMA 9	9	47.85	31.54
Trawl	FMA 1	5	38.03	28.68
Trawl	FMA 8	22	58.79	23.02
Trawl	FMA 2	227	167.42	21.20
BLL	FMA 2	2	0.21	15.06
SLL	FMA 3	9	28.10	12.98
Setnet	FMA 5	34	18.98	11.89
Purse seine	FMA 8	1	0.09	9.05
SLL	FMA 5	233	281.12	8.24
SLL	FMA 2	61	42.74	7.81
SLL	FMA 7	438	383.32	7.80
Setnet	FMA 3	10	23.37	7.65
BLL	FMA 4	0	2.13	2.13

Table 18: Fishing methods and FMAs where $\chi^2_{sfm} > 2$ for large pinnipeds. C'_{sfm} is the number of observed captures for the species group in FMA f and fishing method m, and E_{sfm} is the corresponding mean predicted number.

Fishing method	FMA	C'_{sfm}	E_{sfm}	χ^2_{sfm}
Trawl	FMA 6	321	134.68	257.76
Trawl	FMA 5	18	191.19	156.89
Trawl	FMA 3	1	8.13	6.25

Table 19: Fishing methods and FMAs where $\chi^2_{sfm} > 2$ for Cephalorhynchus. C'_{sfm} is the number of observed captures for the species group in FMA f and fishing method m, and E_{sfm} is the corresponding mean predicted number.

Fishing method	FMA	C'_{sfm}	E_{sfm}	χ^2_{sfm}
Setnet	FMA 3	16	11.09	2.17
Setnet	FMA 8	0	2.06	2.06

Table 20: Fishing methods and FMAs where $\chi^2_{sfm} > 2$ for common dolphins. C'_{sfm} is the number of observed captures for the species group in FMA f and fishing method m, and E_{sfm} is the corresponding mean predicted number.

Fishing method	FMA	C'_{sfm}	E_{sfm}	χ^2_{sfm}
Trawl	FMA 9	96	63.80	16.26
Trawl	FMA 7	48	67.31	5.54
Setnet	FMA 8	6	2.79	3.69
Trawl	FMA 5	0	2.16	2.16

Table 21: Fishing methods and FMAs where $\chi^2_{sfm} > 2$ for other small dolphins. C'_{sfm} is the number of observed captures for the species group in FMA f and fishing method m, and E_{sfm} is the corresponding mean predicted number.

Fishing method	FMA	C'_{sfm}	E_{sfm}	χ^2_{sfm}
Trawl	FMA 3	7	1.77	15.50
Trawl	FMA 1	3	0.89	5.05
Setnet	FMA 3	6	2.79	3.68
Trawl	FMA 7	0	3.34	3.34
Setnet	FMA 7	1	0.20	3.28
Trawl	FMA 5	0	2.84	2.84
SLL	FMA 7	0	2.11	2.11

Table 22: Fishing methods and FMAs where $\chi^2_{sfm} > 2$ for other large dolphins. C'_{sfm} is the number of observed captures for the species group in FMA f and fishing method m, and E_{sfm} is the corresponding mean predicted number.

Fishing method	FMA	C'_{sfm}	E_{sfm}	χ^2_{sfm}
Setnet	FMA 9	1	0.02	40.49
Trawl	FMA 8	14	7.68	5.20
Trawl	FMA 9	0	2.84	2.84
BLL	FMA 4	2	0.65	2.77
Trawl	FMA 7	2	5.52	2.25

3.5. Conclusion

While the fitted SEFRA model accurately re-predicts the total number of observed captures for each species group, finer-scale evaluations reveal some deficiencies in the modelling; particularly with respect to the spatial prediction of the captures for some species groups, and assignment of captures to the correct species within species groups. Inferences from these models should be made with caution, especially for pinniped species, because NZFS and NZSL constitute the majority of the observed marine mammal captures, but only simplistic distribution layers were available for these species.

3.6. Annual observable captures

The number of annual observable captures for each species group was estimated from Model $M_\bullet$ using the average annual commercial effort from 2016/17 to 2018/19, for both total captures and live captures. Summaries of the posterior distribution are given in Tables 23 & 24 for all fishing groups combined. Estimated captures and live captures for each fishing group are given in Figures 35 & 36 and Tables 25–30.

Table 23: Summary of the posterior distribution for the number of observable total captures estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_\bullet$.

Species group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Small pinniped	1,025	1,024	47	5	935	949	1,104	1,119
Large pinniped	34	33	7	21	21	23	46	50
Cephalorhynchus	31	30	10	31	15	17	48	52
Common dolphin	59	59	12	20	38	41	80	84
Other small dolphin	20	20	7	35	8	10	33	37
Large dolphin	6	6	3	53	1	2	13	14
Baleen whale	1	0	1	181	0	0	2	3
Beaked whale	2	2	2	84	0	0	6	7
Other whale	0	0	0	494	0	0	0	1

Table 24: Summary of the posterior distribution for the number of observable live captures estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_\bullet$.

Species group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Small pinniped	264	264	23	9	220	227	303	310
Large pinniped	6	5	3	48	1	2	10	12
Cephalorhynchus	6	5	4	68	0	1	14	16
Common dolphin	4	4	3	68	0	1	9	11
Other small dolphin	3	3	2	71	0	0	7	9
Large dolphin	3	2	2	74	0	0	6	7
Baleen whale	0	0	1	254	0	0	1	2
Beaked whale	2	2	2	92	0	0	5	6
Other whale	0	0	0	605	0	0	0	1

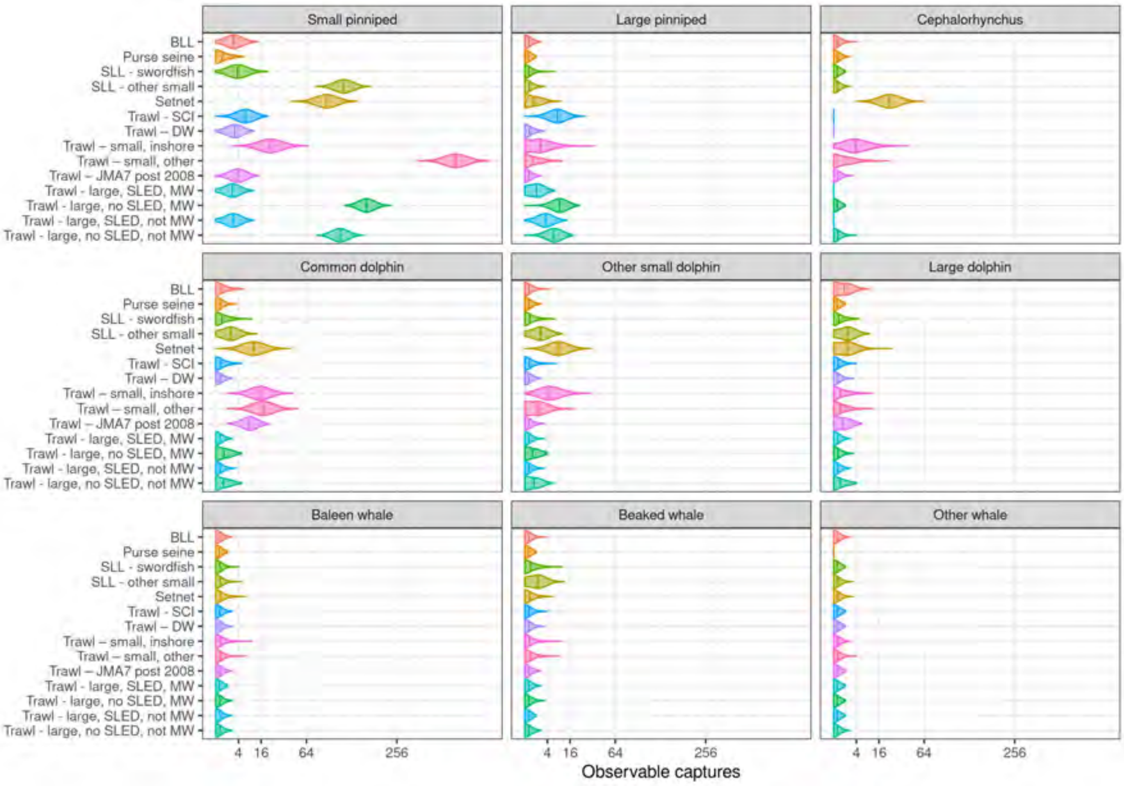


Figure 35: Posterior distribution for the number of annual observable total captures estimated using mean annual commercial effort from 2016/17 to 2018/19 by fishing group (as defined for $M_{\bullet}$).

Table 25: Summary of the posterior distribution for the number of observable captures of pinnipeds estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_{\bullet}$, by fishing group.

Species group	Fishing group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Small pinniped	BLL	3	2	2	74	0	0	6	7
Small pinniped	Purse seine	0	0	1	201	0	0	2	2
Small pinniped	SLL - swordfish	4	4	3	74	0	0	10	12
Small pinniped	SLL - other small	128	128	15	12	101	104	153	158
Small pinniped	Setnet	96	96	15	16	69	73	123	128
Small pinniped	Trawl - SCI	7	7	3	45	2	2	13	15
Small pinniped	Trawl - DW	3	3	2	62	0	0	6	7
Small pinniped	Trawl - small, inshore	24	23	9	38	9	11	41	45
Small pinniped	Trawl - small, other	451	450	37	8	382	392	512	525
Small pinniped	Trawl - JMA7 post 2008	4	4	2	53	0	1	8	9
Small pinniped	Trawl - large, SLED, MW	2	2	2	71	0	0	5	6
Small pinniped	Trawl - large, no SLED, MW	178	178	14	8	151	155	202	206
Small pinniped	Trawl - large, SLED, not MW	2	2	2	70	0	0	6	7
Small pinniped	Trawl - large, no SLED, not MW	121	121	12	10	98	102	141	144
Large pinniped	BLL	0	0	0	529	0	0	0	1
Large pinniped	Purse seine	0	0	0	2 146	0	0	0	0
Large pinniped	SLL - swordfish	0	0	0	514	0	0	0	1
Large pinniped	SLL - other small	0	0	0	325	0	0	1	1
Large pinniped	Setnet	1	0	1	152	0	0	3	3
Large pinniped	Trawl - SCI	9	8	4	42	3	3	15	16
Large pinniped	Trawl - DW	0	0	0	288	0	0	1	1
Large pinniped	Trawl - small, inshore	2	1	3	143	0	0	9	12
Large pinniped	Trawl - small, other	1	0	1	187	0	0	3	4
Large pinniped	Trawl - JMA7 post 2008	0	0	0	624	0	0	0	1
Large pinniped	Trawl - large, SLED, MW	1	1	1	101	0	0	3	4
Large pinniped	Trawl - large, no SLED, MW	10	10	3	33	4	5	15	17
Large pinniped	Trawl - large, SLED, not MW	3	3	2	57	0	1	7	8
Large pinniped	Trawl - large, no SLED, not MW	7	7	3	40	2	3	12	13

Table 26: Summary of the posterior distribution for the number of observable captures of small dolphins estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_{\bullet}$, by fishing group.

Species group	Fishing group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Cephalorhynchus	BLL	0	0	0	628	0	0	0	1
Cephalorhynchus	Purse seine	0	0	0	1 304	0	0	0	0
Cephalorhynchus	SLL - swordfish	0	0	0	3 872	0	0	0	0
Cephalorhynchus	SLL - other small	0	0	0	1 031	0	0	0	0
Cephalorhynchus	Setnet	25	24	8	32	11	13	39	42
Cephalorhynchus	Trawl - SCI	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - DW	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - small, inshore	5	3	5	99	0	0	14	17
Cephalorhynchus	Trawl - small, other	1	0	2	180	0	0	5	7
Cephalorhynchus	Trawl - JMA7 post 2008	0	0	0	792	0	0	0	0
Cephalorhynchus	Trawl - large, SLED, MW	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - large, no SLED, MW	0	0	0	1 366	0	0	0	0
Cephalorhynchus	Trawl - large, SLED, not MW	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - large, no SLED, not MW	0	0	0	483	0	0	0	1
Common dolphin	BLL	0	0	1	245	0	0	2	2
Common dolphin	Purse seine	0	0	0	502	0	0	0	1
Common dolphin	SLL - swordfish	0	0	1	224	0	0	2	3
Common dolphin	SLL - other small	2	1	2	92	0	0	5	6
Common dolphin	Setnet	12	11	6	50	3	4	23	26
Common dolphin	Trawl - SCI	0	0	1	260	0	0	1	2
Common dolphin	Trawl - DW	0	0	0	495	0	0	0	1
Common dolphin	Trawl - small, inshore	16	15	6	39	6	7	27	30
Common dolphin	Trawl - small, other	18	18	7	39	7	8	31	35
Common dolphin	Trawl - JMA7 post 2008	9	9	3	34	4	4	15	16
Common dolphin	Trawl - large, SLED, MW	0	0	0	568	0	0	0	1
Common dolphin	Trawl - large, no SLED, MW	1	0	1	147	0	0	2	2
Common dolphin	Trawl - large, SLED, not MW	0	0	0	460	0	0	0	1
Common dolphin	Trawl - large, no SLED, not MW	0	0	1	158	0	0	2	2
Other small dolphin	BLL	0	0	0	387	0	0	1	1
Other small dolphin	Purse seine	0	0	0	1 432	0	0	0	0
Other small dolphin	SLL - swordfish	0	0	1	292	0	0	1	2
Other small dolphin	SLL - other small	2	2	2	84	0	0	5	6
Other small dolphin	Setnet	9	9	5	51	2	3	18	20
Other small dolphin	Trawl - SCI	0	0	0	326	0	0	1	1
Other small dolphin	Trawl - DW	0	0	0	559	0	0	0	1
Other small dolphin	Trawl - small, inshore	6	5	4	77	0	0	14	17
Other small dolphin	Trawl - small, other	1	1	2	132	0	0	5	7
Other small dolphin	Trawl - JMA7 post 2008	0	0	0	533	0	0	0	1
Other small dolphin	Trawl - large, SLED, MW	0	0	0	648	0	0	0	0
Other small dolphin	Trawl - large, no SLED, MW	0	0	1	149	0	0	2	2
Other small dolphin	Trawl - large, SLED, not MW	0	0	0	574	0	0	0	1
Other small dolphin	Trawl - large, no SLED, not MW	1	0	1	133	0	0	2	3

Table 27: **Summary of the posterior distribution for the number of observable captures or large dolphins and whales estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_{\bullet}$, by fishing group.**

Species group	Fishing group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Large dolphin	BLL	1	1	1	128	0	0	3	4
Large dolphin	Purse seine	0	0	0	1 253	0	0	0	0
Large dolphin	SLL - swordfish	0	0	1	280	0	0	1	2
Large dolphin	SLL - other small	2	1	1	96	0	0	4	5
Large dolphin	Setnet	2	1	2	124	0	0	5	7
Large dolphin	Trawl - SCI	0	0	0	362	0	0	1	1
Large dolphin	Trawl - DW	0	0	0	551	0	0	0	1
Large dolphin	Trawl - small, inshore	0	0	1	225	0	0	2	4
Large dolphin	Trawl - small, other	0	0	1	221	0	0	2	3
Large dolphin	Trawl - JMA7 post 2008	1	0	1	127	0	0	2	3
Large dolphin	Trawl - large, SLED, MW	0	0	0	654	0	0	0	0
Large dolphin	Trawl - large, no SLED, MW	0	0	0	445	0	0	1	1
Large dolphin	Trawl - large, SLED, not MW	0	0	0	668	0	0	0	0
Large dolphin	Trawl - large, no SLED, not MW	0	0	1	184	0	0	2	2
Baleen whale	BLL	0	0	0	1 173	0	0	0	0
Baleen whale	Purse seine	0	0	0	4 471	0	0	0	0
Baleen whale	SLL - swordfish	0	0	0	953	0	0	0	0
Baleen whale	SLL - other small	0	0	0	456	0	0	1	1
Baleen whale	Setnet	0	0	0	329	0	0	1	1
Baleen whale	Trawl - SCI	0	0	0	851	0	0	0	0
Baleen whale	Trawl - DW	0	0	0	1 722	0	0	0	0
Baleen whale	Trawl - small, inshore	0	0	0	397	0	0	1	1
Baleen whale	Trawl - small, other	0	0	0	428	0	0	1	1
Baleen whale	Trawl - JMA7 post 2008	0	0	0	1 049	0	0	0	0
Baleen whale	Trawl - large, SLED, MW	0	0	0	1 435	0	0	0	0
Baleen whale	Trawl - large, no SLED, MW	0	0	0	894	0	0	0	0
Baleen whale	Trawl - large, SLED, not MW	0	0	0	1 573	0	0	0	0
Baleen whale	Trawl - large, no SLED, not MW	0	0	0	667	0	0	0	0
Beaked whale	BLL	0	0	0	666	0	0	0	0
Beaked whale	Purse seine	0	0	0	3 872	0	0	0	0
Beaked whale	SLL - swordfish	0	0	1	238	0	0	2	2
Beaked whale	SLL - other small	1	1	1	106	0	0	4	5
Beaked whale	Setnet	0	0	1	303	0	0	1	2
Beaked whale	Trawl - SCI	0	0	0	532	0	0	0	1
Beaked whale	Trawl - DW	0	0	0	860	0	0	0	0
Beaked whale	Trawl - small, inshore	0	0	1	371	0	0	1	2
Beaked whale	Trawl - small, other	0	0	1	311	0	0	1	2
Beaked whale	Trawl - JMA7 post 2008	0	0	0	767	0	0	0	0
Beaked whale	Trawl - large, SLED, MW	0	0	0	1 110	0	0	0	0
Beaked whale	Trawl - large, no SLED, MW	0	0	0	632	0	0	0	1
Beaked whale	Trawl - large, SLED, not MW	0	0	0	1 030	0	0	0	0
Beaked whale	Trawl - large, no SLED, not MW	0	0	0	440	0	0	1	1
Other whale	BLL	0	0	0	4 743	0	0	0	0
Other whale	Purse seine	0	0	0	0	0	0	0	0
Other whale	SLL - swordfish	0	0	0	1 774	0	0	0	0
Other whale	SLL - other small	0	0	0	842	0	0	0	0
Other whale	Setnet	0	0	0	1 219	0	0	0	0
Other whale	Trawl - SCI	0	0	0	2 737	0	0	0	0
Other whale	Trawl - DW	0	0	0	3 161	0	0	0	0
Other whale	Trawl - small, inshore	0	0	0	1 594	0	0	0	0
Other whale	Trawl - small, other	0	0	0	1 207	0	0	0	0
Other whale	Trawl - JMA7 post 2008	0	0	0	3 463	0	0	0	0
Other whale	Trawl - large, SLED, MW	0	0	0	7 746	0	0	0	0
Other whale	Trawl - large, no SLED, MW	0	0	0	1 876	0	0	0	0
Other whale	Trawl - large, SLED, not MW	0	0	0	4 471	0	0	0	0
Other whale	Trawl - large, no SLED, not MW	0	0	0	1 722	0	0	0	0

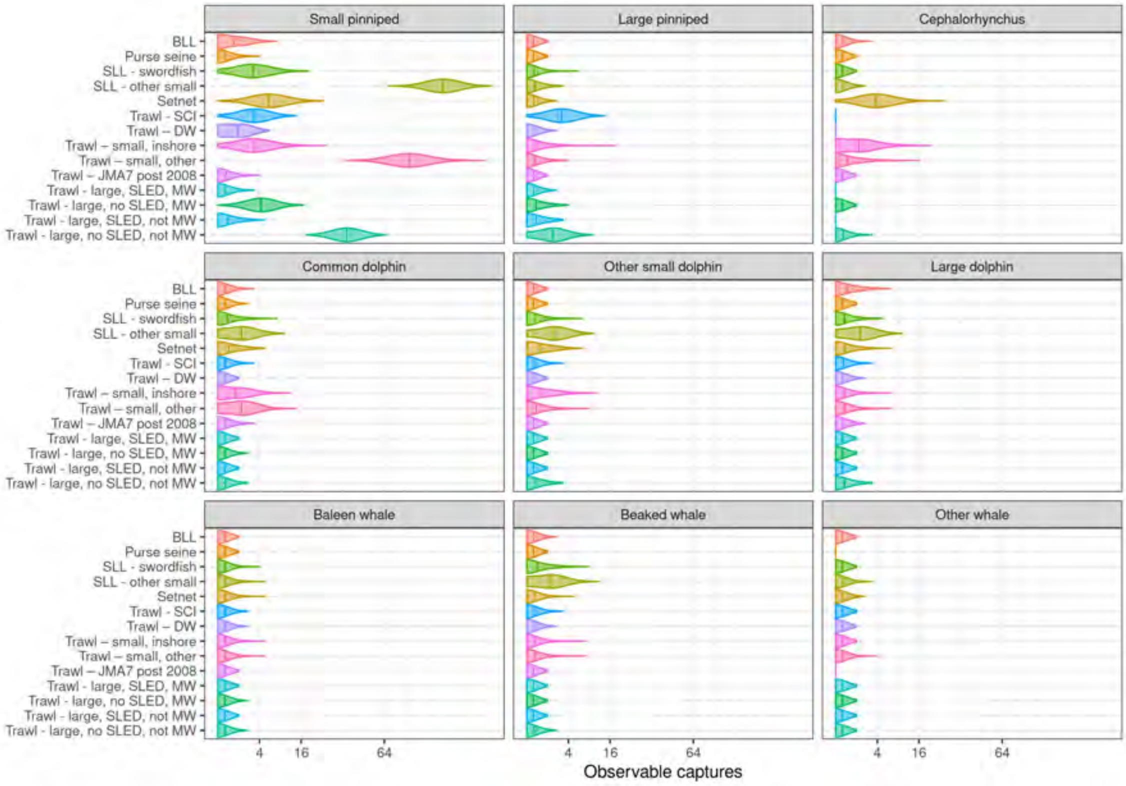


Figure 36: Posterior distribution for the number of observable live captures estimated using mean annual commercial effort from 2016/17 to 2018/19 by fishing group (as defined for $M_{\bullet}$).

Table 28: Summary of the posterior distribution for the number of observable live captures of pinnipeds estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_{\bullet}$, by fishing group.

Species group	Fishing group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Small pinniped	BLL	1	0	1	148	0	0	2	3
Small pinniped	Purse seine	0	0	0	390	0	0	1	1
Small pinniped	SLL - swordfish	3	3	3	84	0	0	8	10
Small pinniped	SLL - other small	117	117	14	12	90	94	141	146
Small pinniped	Setnet	7	6	4	57	1	1	14	15
Small pinniped	Trawl - SCI	3	3	2	64	0	0	7	8
Small pinniped	Trawl - DW	1	1	1	110	0	0	3	3
Small pinniped	Trawl - small, inshore	3	3	3	87	0	0	9	11
Small pinniped	Trawl - small, other	85	84	16	19	56	61	113	119
Small pinniped	Trawl - JMA7 post 2008	0	0	0	339	0	0	1	1
Small pinniped	Trawl - large, SLED, MW	0	0	0	402	0	0	1	1
Small pinniped	Trawl - large, no SLED, MW	5	4	2	49	1	1	9	9
Small pinniped	Trawl - large, SLED, not MW	0	0	0	228	0	0	1	2
Small pinniped	Trawl - large, no SLED, not MW	39	39	7	17	26	28	50	53
Large pinniped	BLL	0	0	0	1 435	0	0	0	0
Large pinniped	Purse seine	0	0	0	3 872	0	0	0	0
Large pinniped	SLL - swordfish	0	0	0	585	0	0	0	1
Large pinniped	SLL - other small	0	0	0	346	0	0	1	1
Large pinniped	Setnet	0	0	0	587	0	0	0	1
Large pinniped	Trawl - SCI	3	3	2	67	0	0	7	8
Large pinniped	Trawl - DW	0	0	0	618	0	0	0	1
Large pinniped	Trawl - small, inshore	0	0	1	270	0	0	1	2
Large pinniped	Trawl - small, other	0	0	0	375	0	0	1	1
Large pinniped	Trawl - JMA7 post 2008	0	0	0	7 746	0	0	0	0
Large pinniped	Trawl - large, SLED, MW	0	0	0	708	0	0	0	0
Large pinniped	Trawl - large, no SLED, MW	0	0	0	246	0	0	1	1
Large pinniped	Trawl - large, SLED, not MW	0	0	0	228	0	0	1	1
Large pinniped	Trawl - large, no SLED, not MW	2	1	1	82	0	0	4	5

Table 29: Summary of the posterior distribution for the number of observable live captures of small dolphins estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_{\bullet}$, by fishing group.

Species group	Fishing group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Cephalorhynchus	BLL	0	0	0	951	0	0	0	0
Cephalorhynchus	Purse seine	0	0	0	2 334	0	0	0	0
Cephalorhynchus	SLL - swordfish	0	0	0	4 471	0	0	0	0
Cephalorhynchus	SLL - other small	0	0	0	1 031	0	0	0	0
Cephalorhynchus	Setnet	4	4	3	74	0	0	10	12
Cephalorhynchus	Trawl - SCI	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - DW	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - small, inshore	1	1	2	140	0	0	5	7
Cephalorhynchus	Trawl - small, other	0	0	1	232	0	0	2	3
Cephalorhynchus	Trawl - JMA7 post 2008	0	0	0	3 161	0	0	0	0
Cephalorhynchus	Trawl - large, SLED, MW	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - large, no SLED, MW	0	0	0	3 161	0	0	0	0
Cephalorhynchus	Trawl - large, SLED, not MW	0	0	0	0	0	0	0	0
Cephalorhynchus	Trawl - large, no SLED, not MW	0	0	0	594	0	0	0	1
Common dolphin	BLL	0	0	0	705	0	0	0	0
Common dolphin	Purse seine	0	0	0	1 484	0	0	0	0
Common dolphin	SLL - swordfish	0	0	1	284	0	0	1	2
Common dolphin	SLL - other small	1	1	1	105	0	0	4	5
Common dolphin	Setnet	0	0	1	209	0	0	1	2
Common dolphin	Trawl - SCI	0	0	0	544	0	0	0	1
Common dolphin	Trawl - DW	0	0	0	1 366	0	0	0	0
Common dolphin	Trawl - small, inshore	1	0	1	142	0	0	3	4
Common dolphin	Trawl - small, other	1	1	1	110	0	0	4	5
Common dolphin	Trawl - JMA7 post 2008	0	0	0	371	0	0	1	1
Common dolphin	Trawl - large, SLED, MW	0	0	0	7 746	0	0	0	0
Common dolphin	Trawl - large, no SLED, MW	0	0	0	1 573	0	0	0	0
Common dolphin	Trawl - large, SLED, not MW	0	0	0	2 926	0	0	0	0
Common dolphin	Trawl - large, no SLED, not MW	0	0	0	412	0	0	1	1
Other small dolphin	BLL	0	0	0	866	0	0	0	0
Other small dolphin	Purse seine	0	0	0	3 161	0	0	0	0
Other small dolphin	SLL - swordfish	0	0	0	345	0	0	1	1
Other small dolphin	SLL - other small	2	1	2	90	0	0	5	5
Other small dolphin	Setnet	0	0	1	177	0	0	2	2
Other small dolphin	Trawl - SCI	0	0	0	546	0	0	0	1
Other small dolphin	Trawl - DW	0	0	0	1 345	0	0	0	0
Other small dolphin	Trawl - small, inshore	1	0	1	180	0	0	2	3
Other small dolphin	Trawl - small, other	0	0	1	266	0	0	1	2
Other small dolphin	Trawl - JMA7 post 2008	0	0	0	3 872	0	0	0	0
Other small dolphin	Trawl - large, SLED, MW	0	0	0	5 477	0	0	0	0
Other small dolphin	Trawl - large, no SLED, MW	0	0	0	1 191	0	0	0	0
Other small dolphin	Trawl - large, SLED, not MW	0	0	0	1 934	0	0	0	0
Other small dolphin	Trawl - large, no SLED, not MW	0	0	0	267	0	0	1	1

Table 30: **Summary of the posterior distribution for the number of observable live captures of large dolphins and whales estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_{\bullet}$, by fishing group.**

Species group	Fishing group	Mean	Median	SD	CV	$2.5^{th}\%$	$5.0^{th}\%$	$95.0^{th}\%$	$97.5^{th}\%$
Large dolphin	BLL	0	0	1	209	0	0	2	2
Large dolphin	Purse seine	0	0	0	1 998	0	0	0	0
Large dolphin	SLL - swordfish	0	0	0	304	0	0	1	2
Large dolphin	SLL - other small	1	1	1	98	0	0	4	5
Large dolphin	Setnet	0	0	1	256	0	0	1	2
Large dolphin	Trawl - SCI	0	0	0	453	0	0	1	1
Large dolphin	Trawl - DW	0	0	0	894	0	0	0	0
Large dolphin	Trawl - small, inshore	0	0	0	367	0	0	1	1
Large dolphin	Trawl - small, other	0	0	0	330	0	0	1	2
Large dolphin	Trawl - JMA7 post 2008	0	0	0	531	0	0	0	1
Large dolphin	Trawl - large, SLED, MW	0	0	0	2 234	0	0	0	0
Large dolphin	Trawl - large, no SLED, MW	0	0	0	1 687	0	0	0	0
Large dolphin	Trawl - large, SLED, not MW	0	0	0	1 774	0	0	0	0
Large dolphin	Trawl - large, no SLED, not MW	0	0	0	262	0	0	1	1
Baleen whale	BLL	0	0	0	1 687	0	0	0	0
Baleen whale	Purse seine	0	0	0	5 477	0	0	0	0
Baleen whale	SLL - swordfish	0	0	0	1 028	0	0	0	0
Baleen whale	SLL - other small	0	0	0	472	0	0	1	1
Baleen whale	Setnet	0	0	0	607	0	0	0	1
Baleen whale	Trawl - SCI	0	0	0	1 008	0	0	0	0
Baleen whale	Trawl - DW	0	0	0	2 127	0	0	0	0
Baleen whale	Trawl - small, inshore	0	0	0	598	0	0	0	1
Baleen whale	Trawl - small, other	0	0	0	584	0	0	0	1
Baleen whale	Trawl - JMA7 post 2008	0	0	0	2 926	0	0	0	0
Baleen whale	Trawl - large, SLED, MW	0	0	0	5 477	0	0	0	0
Baleen whale	Trawl - large, no SLED, MW	0	0	0	2 052	0	0	0	0
Baleen whale	Trawl - large, SLED, not MW	0	0	0	2 926	0	0	0	0
Baleen whale	Trawl - large, no SLED, not MW	0	0	0	855	0	0	0	0
Beaked whale	BLL	0	0	0	886	0	0	0	0
Beaked whale	Purse seine	0	0	0	5 477	0	0	0	0
Beaked whale	SLL - swordfish	0	0	1	245	0	0	2	2
Beaked whale	SLL - other small	1	1	1	107	0	0	4	5
Beaked whale	Setnet	0	0	0	496	0	0	0	1
Beaked whale	Trawl - SCI	0	0	0	615	0	0	0	1
Beaked whale	Trawl - DW	0	0	0	1 079	0	0	0	0
Beaked whale	Trawl - small, inshore	0	0	0	501	0	0	1	1
Beaked whale	Trawl - small, other	0	0	0	391	0	0	1	1
Beaked whale	Trawl - JMA7 post 2008	0	0	0	2 068	0	0	0	0
Beaked whale	Trawl - large, SLED, MW	0	0	0	2 448	0	0	0	0
Beaked whale	Trawl - large, no SLED, MW	0	0	0	1 177	0	0	0	0
Beaked whale	Trawl - large, SLED, not MW	0	0	0	1 612	0	0	0	0
Beaked whale	Trawl - large, no SLED, not MW	0	0	0	539	0	0	0	1
Other whale	BLL	0	0	0	5 477	0	0	0	0
Other whale	Purse seine	0	0	0	0	0	0	0	0
Other whale	SLL - swordfish	0	0	0	1 823	0	0	0	0
Other whale	SLL - other small	0	0	0	853	0	0	0	0
Other whale	Setnet	0	0	0	1 793	0	0	0	0
Other whale	Trawl - SCI	0	0	0	3 463	0	0	0	0
Other whale	Trawl - DW	0	0	0	3 463	0	0	0	0
Other whale	Trawl - small, inshore	0	0	0	2 737	0	0	0	0
Other whale	Trawl - small, other	0	0	0	1 636	0	0	0	0
Other whale	Trawl - JMA7 post 2008	0	0	0	0	0	0	0	0
Other whale	Trawl - large, SLED, MW	0	0	0	7 746	0	0	0	0
Other whale	Trawl - large, no SLED, MW	0	0	0	5 477	0	0	0	0
Other whale	Trawl - large, SLED, not MW	0	0	0	7 746	0	0	0	0
Other whale	Trawl - large, no SLED, not MW	0	0	0	2 580	0	0	0	0

3.7. Sensitivity analysis

The sensitivity analysis was conducted by replacing the distribution layers given in Table 1 with seasonal occupancy probability layers developed by Stephenson et al. (2020) for bottlenose dolphin, Bryde's whale, common dolphin, dusky dolphin, Hector's dolphin, humpback whale, killer whale, Māui dolphin, pilot whale and sperm whale, and refitting model $M_\bullet$.

The FMA-based goodness-of-fit tests suggest that using the season occupancy probability layer may lead to a slight improvement for Cephalorhynchus (i.e., p-value is slightly larger; Table 31), but give similar results for other species groups. The predicted number of annual observable captures in this sensitivity analysis is also similar to those from the main analysis for most species groups, except for Cephalorhynchus for which lower observable captures are predicted (Table 32).

Table 31: Goodness-of-fit tests comparing the actual and predicted number of observed captures for each species group in each FMA, by fishing method, from the main and sensitivity analyses.

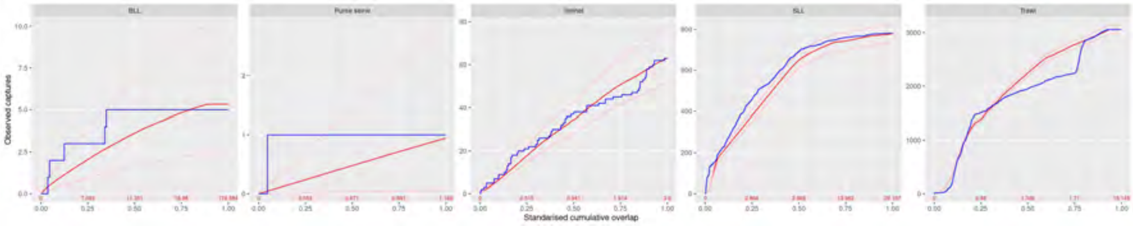
	Main analysis		Sensitivity analysis	
Species group	χ^2	p-value	χ^2	p-value
Small pinniped	1 050.22	0.000	1 050.67	0.000
Large pinniped	425.41	0.000	427.56	0.000
Cephalorhynchus	7.96	0.055	9.64	0.090
Common dolphin	38.46	0.005	81.41	0.000
Other small dolphin	45.63	0.005	39.81	0.000
Large dolphin	59.41	0.000	74.13	0.005
Baleen whale	3.75	0.160	4.87	0.110
Beaked whale	5.23	0.170	5.11	0.195
Other whale	0.14	0.210	0.20	0.210

Table 32: Summary of the posterior distribution for the number of observable total captures estimated using average annual commercial effort from 2016/17 to 2018/19 fishing years from Model $M_\bullet$ in the sensitivity analysis.

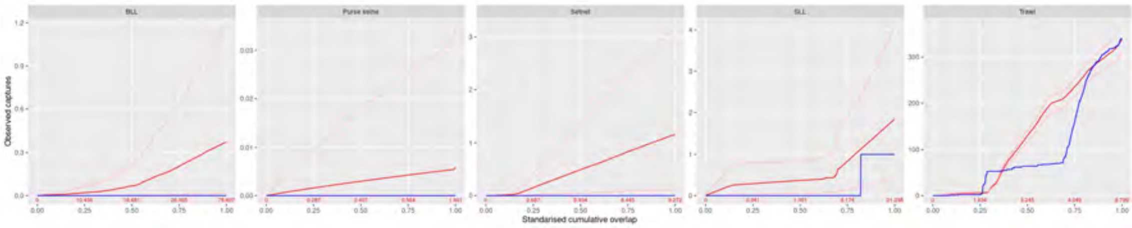
	Main analysis			Sensitivity analysis		
Species group	Mean	SD	90% CI	Mean	SD	90% CI
Small pinniped	1 025	47	(949, 1 104)	1 024	47	(947, 1 104)
Large pinniped	34	7	(23, 46)	34	7	(23, 47)
Cephalorhynchus	31	10	(17, 48)	24	8	(13, 38)
Common dolphin	59	12	(41, 80)	59	12	(41, 79)
Other small dolphin	20	7	(10, 33)	20	7	(9, 33)
Large dolphin	6	3	(2, 13)	6	3	(2, 12)
Baleen whale	1	1	(0, 2)	1	1	(0, 2)
Beaked whale	2	2	(0, 6)	2	2	(0, 6)
Other whale	0	0	(0, 0)	0	0	(0, 1)

CUSUM plots of observed captures against species group overlap when using the alternative distribution layers also indicate poor performance of the models for most species groups, except for Cephalorhynchus, with the blue line for the actual data lying outside of envelope of values expected by the model.

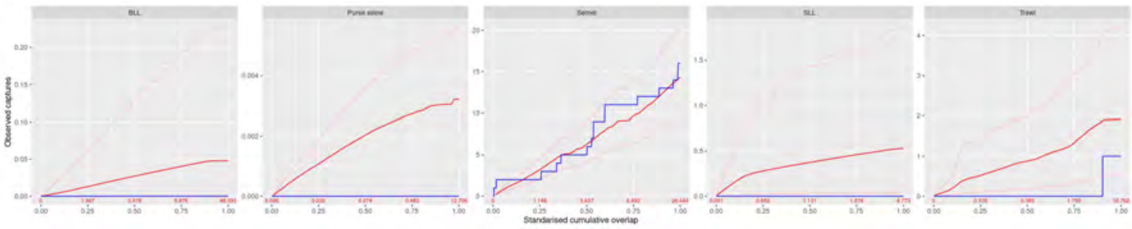
(**a**) Small pinnipeds



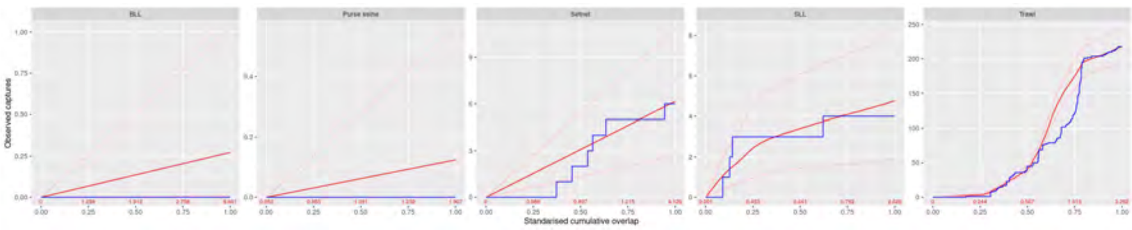
(**b**) Large pinnipeds



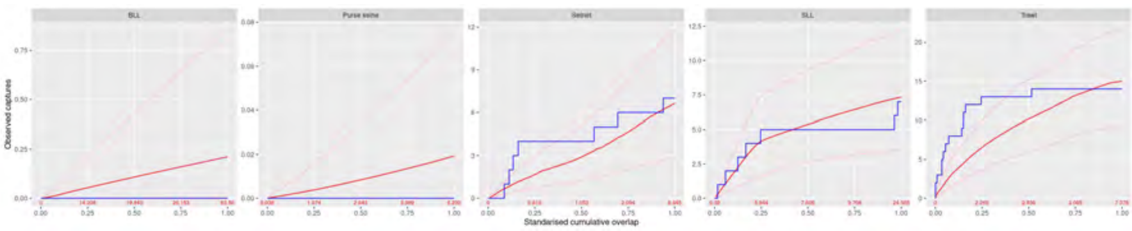
(**c**) Cephalorhynchus



(**d**) Common dolphins



(**e**) Other small dolphins



(**f**) Large dolphins

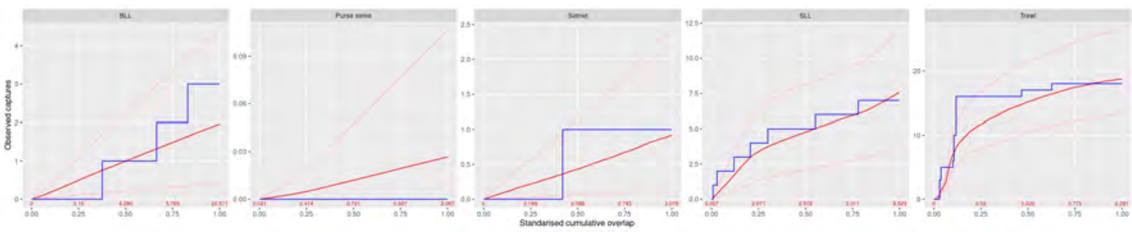
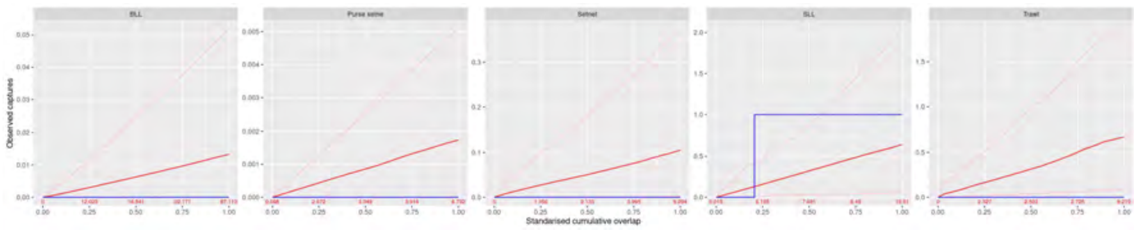
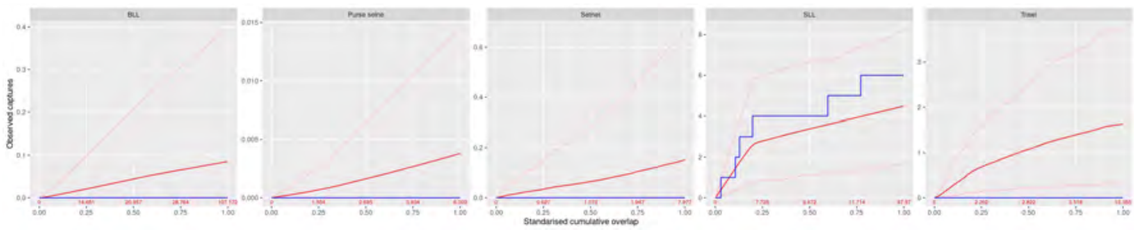


Figure 37: Cumulative number of observed captures vs. species group overlap (blue), for each pinniped and delphinid species group and fishing method using seasonal occurrence probability distribution layers for some species. The expected values predicted from the model (thick red line) and 90% credible interval (thin red lines) are also presented for reference.

(a) Baleen whales



(b) Beaked whales



(c) Other whales

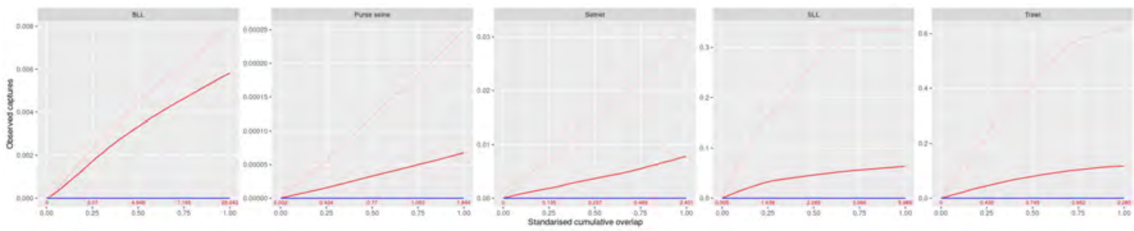


Figure 38: Cumulative number of observed captures vs. species group overlap, for each whale species group and fishing method using seasonal occurrence probability distribution layers for some species. The expected values predicted from the model (thick red line) and 90% credible interval (thin red lines) are also presented for reference.

Overall, there is no definitive improvement in model performance in using the season occurrence probability layers for bottlenose dolphin, Bryde's whale, common dolphin, dusky dolphin, Hector's dolphin, humpback whale, killer whale, Māui dolphin, pilot whale and sperm whale. Therefore, results from the main analysis have been retained.

3.8. Estimation of r_{max}

Tables 33 and 34 summarise the results of the literature search for demographic parameters for the 54 species included in this risk assessment, with a list of sources provided in Table 35. This information was used to define the 'prior' distributions for the demographic parameters to estimate r_{max} using the method of Dillingham et al. (2016). The results of the analysis are presented in Figure 39, which summarise the 'prior' and 'posterior' distributions for r_{max} for each species. Pink/red distributions indicate species for which no demographic information was obtained, and grey/black distributions for the species where some demographic information was obtained to contribute to the estimation of r_{max}. Figures 40–43 show similar information for the demographic parameters, i.e., the 'prior' and 'posterior' distributions where the latter represent the range of values for the demographic parameters that correspond to those used in the calculation of the retained r_{max} values using the Dillingham et al. (2016) method. Table 36 gives the posterior median, 50th and 95th credible intervals for r_{max} calculated in this analysis, and the values elicited from marine mammal experts by Abraham et al. (2017) for the species they considered, as a comparison. All but five of the estimates presented by Abraham et al. (2017) lie within the corresponding 95% credible interval from this analysis.

Table 33: Estimates and standard errors for adult and first-year survival used to define the 'prior' distributions. Sources are listed in Table 35. A blank entry indicates absence of an estimate or SE, which led to assumed values being used for these entries (see methods).

	Adult survival			First-year survival		
	Estimate	SE	Source	Estimate	SE	Source
Antarctic fur seal	0.890	0.025	S2013	0.560	0.190	S2013
Crabeater seal						
New Zealand fur seal						
Ross seal						
Subantarctic fur seal	0.910	0.043	B2006			
Leopard seal						
New Zealand sea lion	0.950	0.010	C2010a	0.830	0.060	R2016
Southern elephant seal	0.860	0.023	P2004	0.860	0.010	C1962
Weddell seal	0.940	0.010	H2006	0.620	0.180	H2008
Hector's dolphin	0.917	0.045	G2012			
Māui dolphin	0.917	0.045	G2012			
Common dolphin						
Bottlenose dolphin	0.970	0.005	C2019c	0.930	0.040	C2019b
Dusky dolphin						
Fraser's dolphin						
Hourglass dolphin						
Melon-headed whale	0.940	0.007	V2017			
Pantropical spotted dolphin						
Pygmy killer whale						
Risso's dolphin						
Rough-toothed dolphin	0.990	0.010	C2019a			
Southern right whale dolphin						
Spectacled porpoise						
Striped dolphin						
False killer whale	0.950	0.043	Z2014			
Long-finned pilot whale	0.982	0.008	V2009	0.938	0.008	B2019
Orca, killer whale	0.996	0.010	M2013	0.910		T2007
Short-finned pilot whale	0.960	0.035	A2015			
Antarctic blue whale	0.963	0.020	B2008a	0.840	0.150	B2008a
Antarctic minke whale	0.950	0.018	M2015			
Bryde's whale	0.925	0.050	T2007	0.840		T2007
Dwarf minke whale						
Fin whale	0.955	0.008	R2014			
Humpback whale	0.992	0.010	R2010	0.811	0.120	Z2010
Pygmy blue whale	0.940	0.005	B2008b			
Pygmy right whale						
Sei whale	0.930	0.020	M2015			
Southern right whale	0.990	0.005	B2005	0.914	0.050	B2012
Andrews beaked whale						
Arnoux's beaked whale						
Dense-beaked whale	0.960	0.048	S2018			
Ginkgo-toothed beaked whale						
Goose-beaked whale	0.950	0.010	C2020			
Gray's beaked whale						
Hector's beaked whale						
Pygmy beaked whale						
Shepherd's beaked whale						
Southern bottlenose whale						
Spade-toothed whale						
Strap-toothed whale						
True's beaked whale						
Dwarf sperm whale						
Pygmy sperm whale						
Sperm whale	0.967	0.010	W2015	0.706	0.120	W2015

[1]Estimate borrowed from Northern right whale dolphin
[2]Estimate borrowed from Baird's beaked whale
[3]Estimate borrowed from Northern bottlenose whale

Table 34: **Estimates and standard errors for age of first reproduction (AFR) and inter-birth interval (IBI) used to define the 'prior' distributions. Sources are listed in Table 35. A blank entry indicates absence of an estimate or SE, which led to assumed values being used for these entries (see methods). Footnotes indicate where an estimate has been borrowed from a closely-related northern-hemisphere species.**

	AFR			IBI		
	Estimate	SE	Source	Estimate	SE	Source
Antarctic fur seal	4.20		T2013	1.00		T2013
Crabeater seal	4.31	0.20	H1995	1.00		E2003
New Zealand fur seal	5.50	0.30	D2003	1.45	0.20	D2003
Ross seal	3.50		P2013	1.00		E2003
Subantarctic fur seal	5.40	0.20	B1995	1.00		E2003
Leopard seal	3.70		T2013	1.00		J2009
New Zealand sea lion	4.20	0.10	A2010	1.40	0.10	R2016
Southern elephant seal	4.20	0.10	O2019	1.00		J2009
Weddell seal	4.10	0.30	C1983	1.62	0.10	S1977
Hector's dolphin	7.80	0.45	E2018b	2.38	0.60	G2012
Māui dolphin	7.80	0.45	J2009	2.38	0.60	G2012
Common dolphin	8.30	0.80	P2022	2.13	0.10	D2007
Bottlenose dolphin	8.20	1.10	R2017	2.50	0.30	C2019c
Dusky dolphin	6.00		C2010b	2.40	0.10	V1994
Fraser's dolphin	7.10	0.90	A1996	2.00	0.40	A1996
Hourglass dolphin						
Melon-headed whale	8.00		E2018a	3.50		E2018a
Pantropical spotted dolphin	9.50	0.20	K1974	3.00		W1993
Pygmy killer whale						
Risso's dolphin	8.70	0.70	P2018	2.40		A2004
Rough-toothed dolphin	10.00		E2018a			
Southern right whale dolphin	11.40	0.50	F1993[1]			
Spectacled porpoise						
Striped dolphin	9.30	0.30	M1977	4.00	1.10	C1996
False killer whale	10.40		F2014	4.50		O2010
Long-finned pilot whale	7.70	0.40	B2019	2.70	0.30	K1988
Orca, killer whale	14.10	0.23	O2005	4.57	0.78	E2016
Short-finned pilot whale	9.75		B2019	6.10		B2019
Antarctic blue whale	9.90	2.00	B2008a	2.50	0.25	B2008a
Antarctic minke whale	8.50		E2018a	1.20		T2007
Bryde's whale	9.50	0.40	B2021	2.00		T2013
Dwarf minke whale	8.40		E2018a	1.00		T2013
Fin whale	7.60	0.60	L1972	2.22	0.10	A1993
Humpback whale	5.90	0.20	Z2010	1.70	0.30	B1987
Pygmy blue whale	10.80	0.50	B2008b	2.20		J2009
Pygmy right whale						
Sei whale	10.70	0.30	L1983	2.00		M1984
Southern right whale	7.40	0.50	B2012	3.12	0.03	B2001
Andrews beaked whale						
Arnoux's beaked whale	10.80		E2018a	3.00		J2009[2]
Dense-beaked whale	10.00		T2013			
Ginkgo-toothed beaked whale						
Goose-beaked whale						
Gray's beaked whale						
Hector's beaked whale						
Pygmy beaked whale						
Shepherd's beaked whale						
Southern bottlenose whale	11.50		E2018a[3]	2.00		E2018a[3]
Spade-toothed whale						
Strap-toothed whale						
True's beaked whale						
Dwarf sperm whale	4.70		E2018a	2.00		T2007
Pygmy sperm whale	5.90		E2018a	1.00		T2013
Sperm whale	9.30		T2013	4.00	0.50	D2006

Table 35: Literature sources used to derive 'prior' distributions of demographic parameters in Tables 33 and 34.

Source	Reference	Source	Reference	Source	Reference
A1993	Agler et al. (1993)	C2020	Curtis et al. (2021)	O2005	Olesiuk et al. (2005)
A1996	Amano et al. (1996)	D2003	Dickie & Dawson (2003)	O2010	Oleson et al. (2010)
A2004	Amano & Miyazaki (2004)	D2006	Doak et al. (2007)	O2019	Oosthuizen et al. (2019)
A2010	Augé (2011)	D2007	Danil & Chivers (2007)	P2004	Pistorius et al. (2004)
A2015	Alves et al. (2015)	E2003	Ernest (2003)	P2013	Pacifici et al. (2013)
B1987	Baker et al. (1987)	E2016	Esteban et al. (2016)	P2018	Plön et al. (2020)
B1995	Bester (1995)	E2018a	Wursig et al. (2018)	P2022	Palmer (In Prep)
B2001	Best et al. (2020)	E2018b	Edwards et al. (2018)	R2010	Ramp et al. (2010)
B2005	Best et al. (2005)	F1993	Ferrero & Walker (1993)	R2014	Ramp et al. (2014)
B2006	Bester et al. (2006)	F2014	Ferreira et al. (2014)	R2016	Roberts & Doonan (2016)
B2008a	Branch (2008b)	G2012	Gormley et al. (2012)	R2017	Robinson et al. (2017)
B2008b	Branch (2008a)	H1995	Hårding & Härkönen (1995)	S1977	Siniff et al. (1977)
B2012	Brandão et al. (2012)	H2006	Hadley et al. (2006)	S2013	Schwarz et al. (2013)
B2019	Betty (2019)	H2008	Hadley et al. (2008)	S2018	Reyes (2017)
B2021	Bando (2021)	J2009	Jones et al. (2009)	T2007	Taylor et al. (2007)
C1962	Carrick & Ingham (1962)	K1974	Kasuya et al. (1974)	T2013	Tacutu et al. (2012)
C1983	Croxall & Hiby (1983)	K1988	Kasuya et al. (1988)	V1994	Van Waerebeek & Read (1994)
C1996	Calzada et al. (1996)	L1972	Lockyer (1972)	V2009	Verborgh et al. (2009)
C2010a	Chilvers & MacKenzie (2010)	L1983	Lockyer & Martin (1983)	V2017	Vieira (2017)
C2010b	Cipriano & Webber (2010)	M1977	Miyazaki (1977)	W1993	Wade (1993)
C2019a	Carvalho et al. (2021)	M1984	Mizroch et al. (1984)	W2015	Whitehead & Gero (2015)
C2019b	Cheney et al. (2019)	M2013	Matkin et al. (2014)	Z2010	Zerbini et al. (2010)
C2019c	Couet et al. (2019)	M2015	Moore (2015)	Z2014	Zaeschmar (2014)

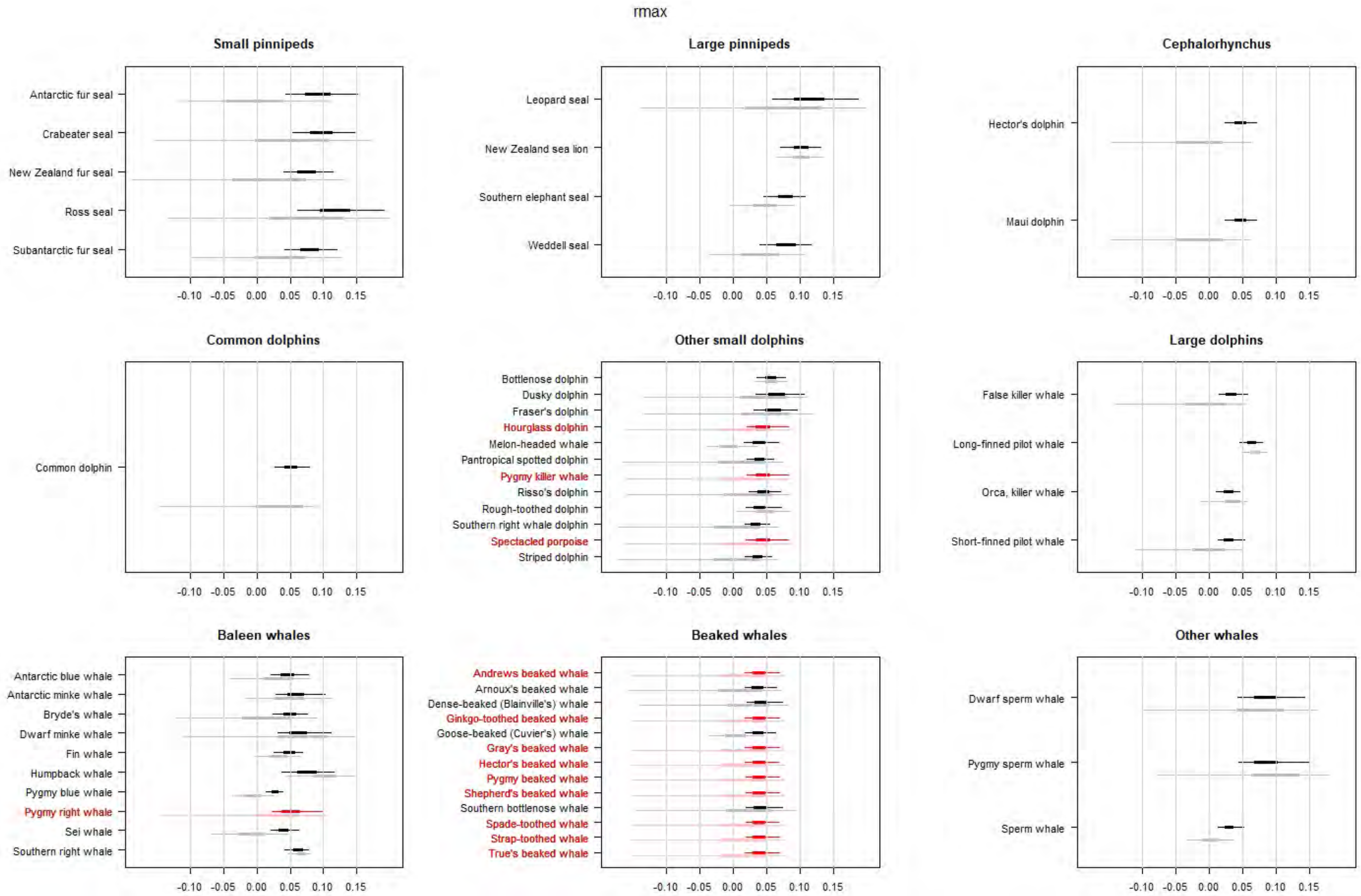


Figure 39: 50% and 95% credible intervals of prior (grey or pink) and posterior (black or red) distributions for r_{max}. Species for which no direct estimates were available for any of the demographic parameters are shown in pink (prior) and red (posterior).

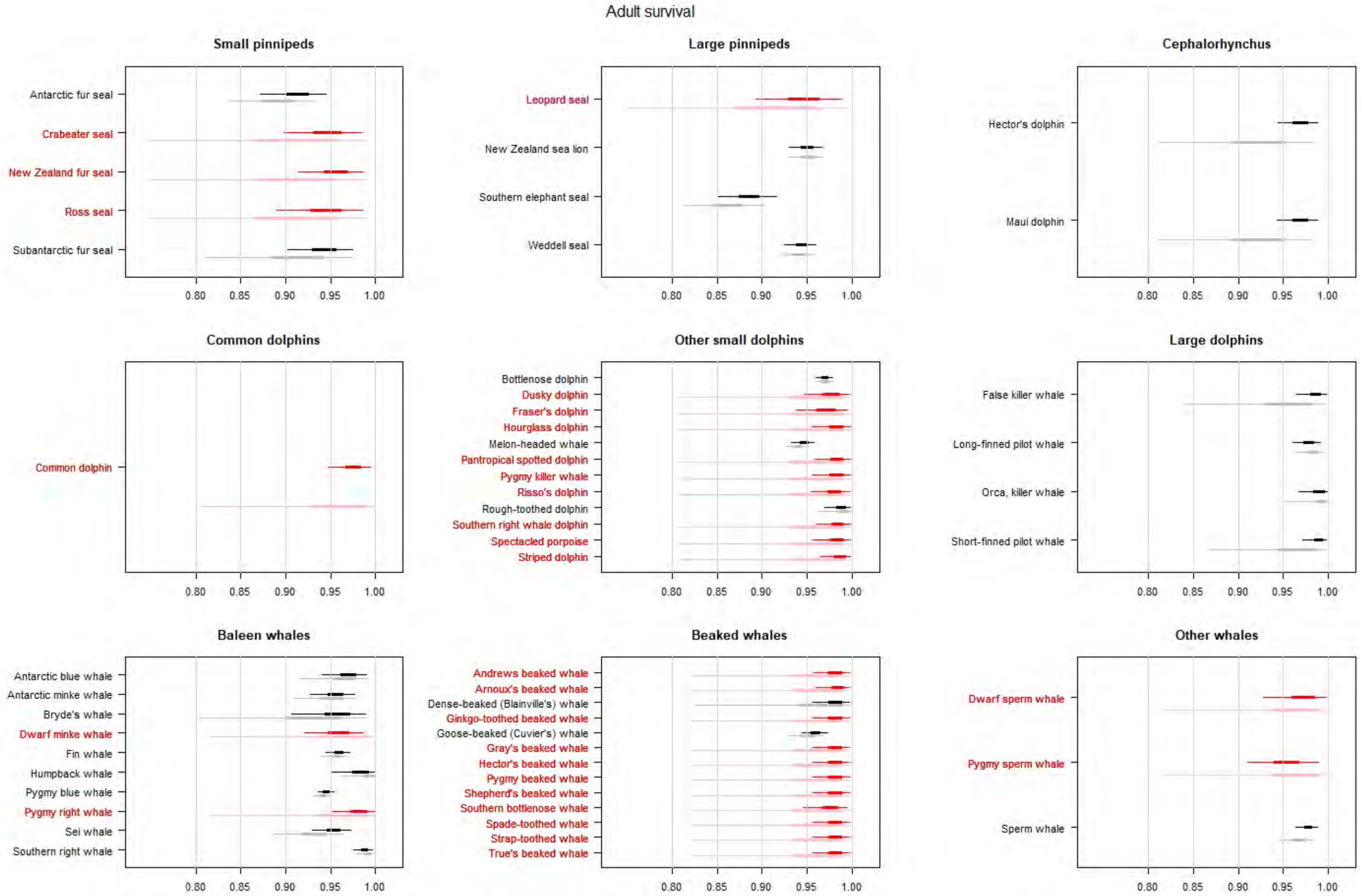


Figure 40: 50% and 95% credible intervals of prior (grey or pink) and posterior (black or red) distributions for adult survival. Species for which no direct estimate was available are shown in pink (prior) and red (posterior).

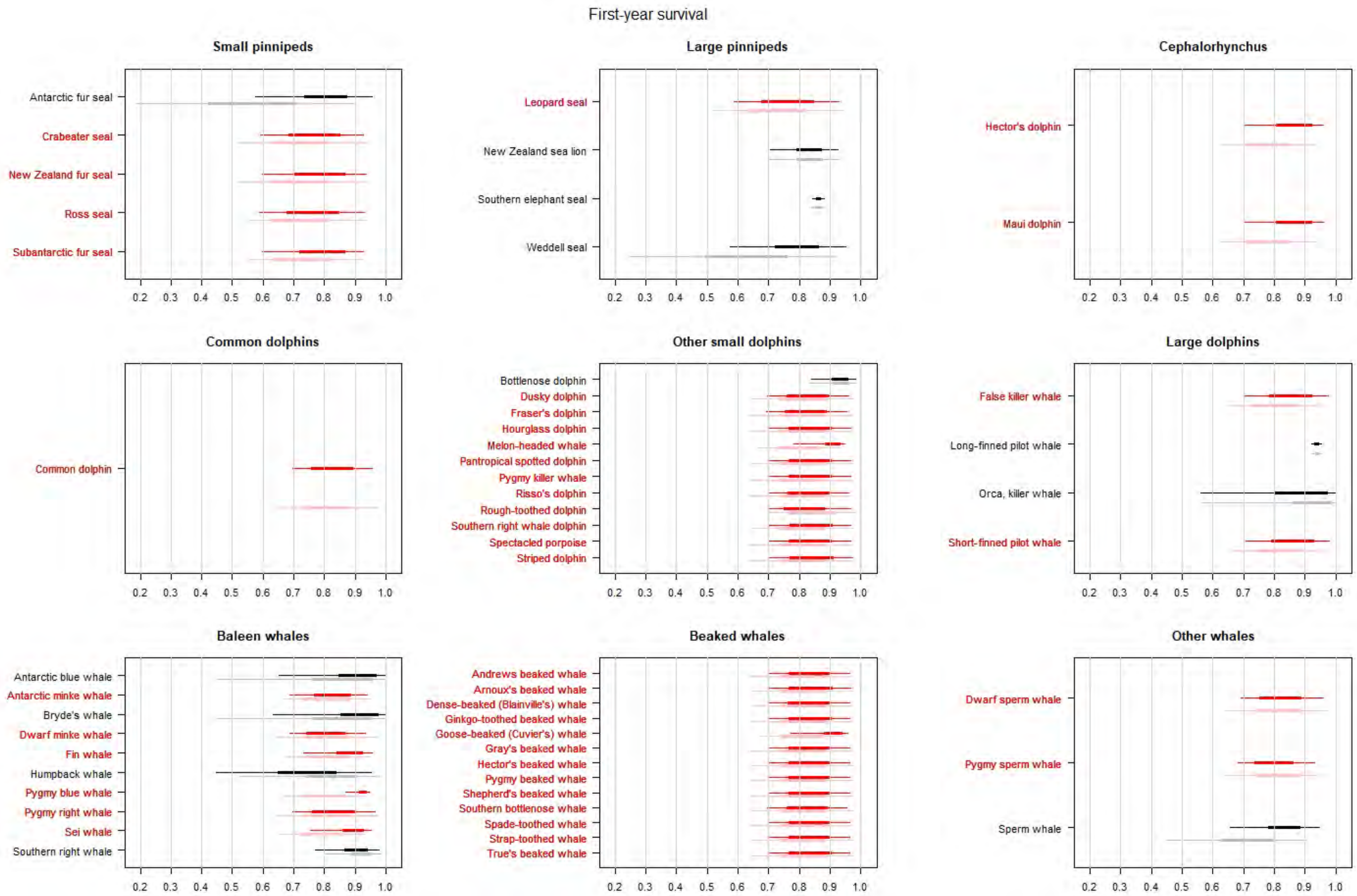


Figure 41: 50% and 95% credible intervals of prior (grey or pink) and posterior (black or red) distributions for first-year survival. Species for which no direct estimate was available are shown in pink (prior) and red (posterior).

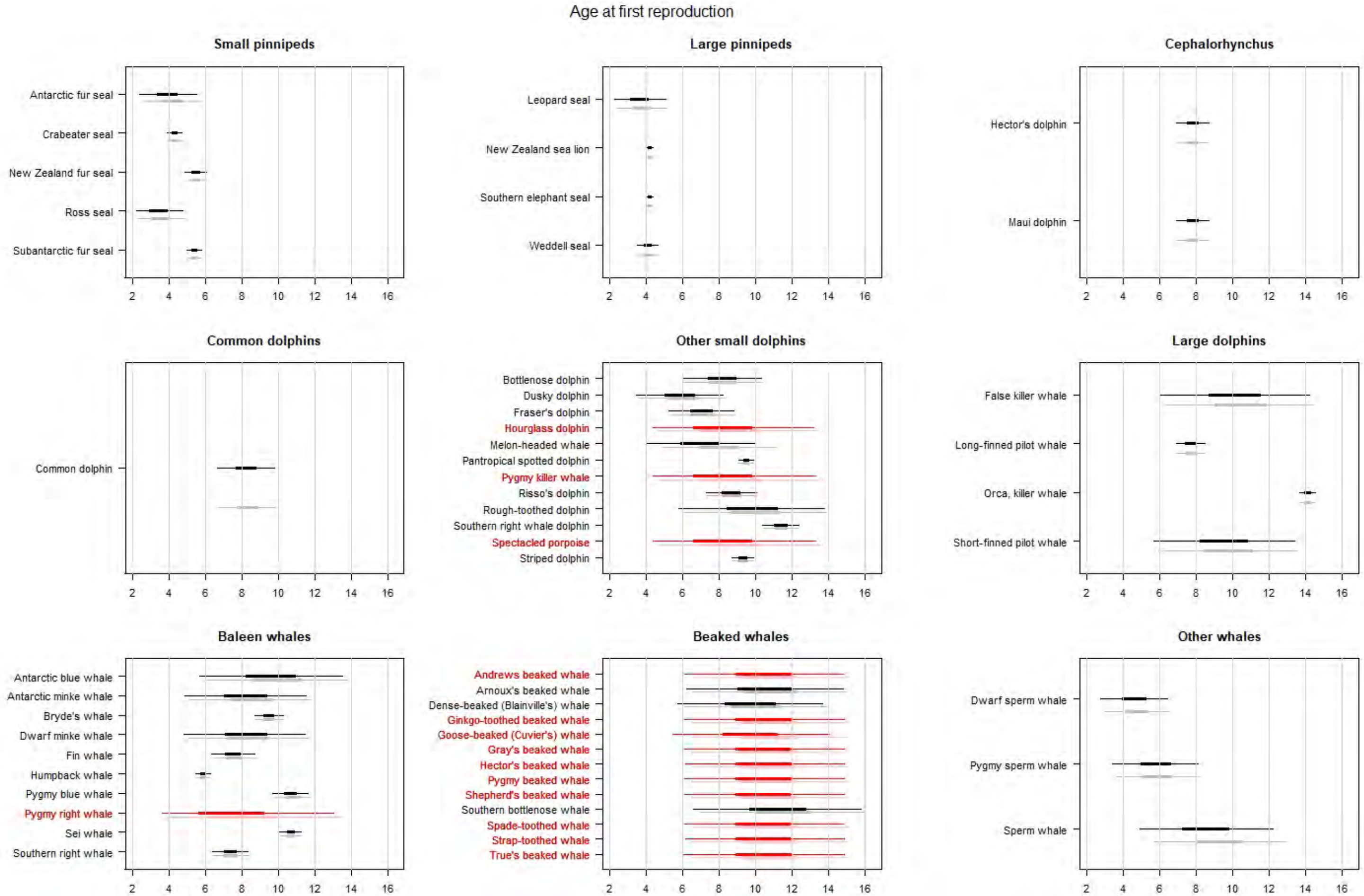


Figure 42: 50% and 95% credible intervals of prior (grey or pink) and posterior (black or red) distributions for age at first reproduction. Species for which no direct estimate was available are shown in pink (prior) and red (posterior).

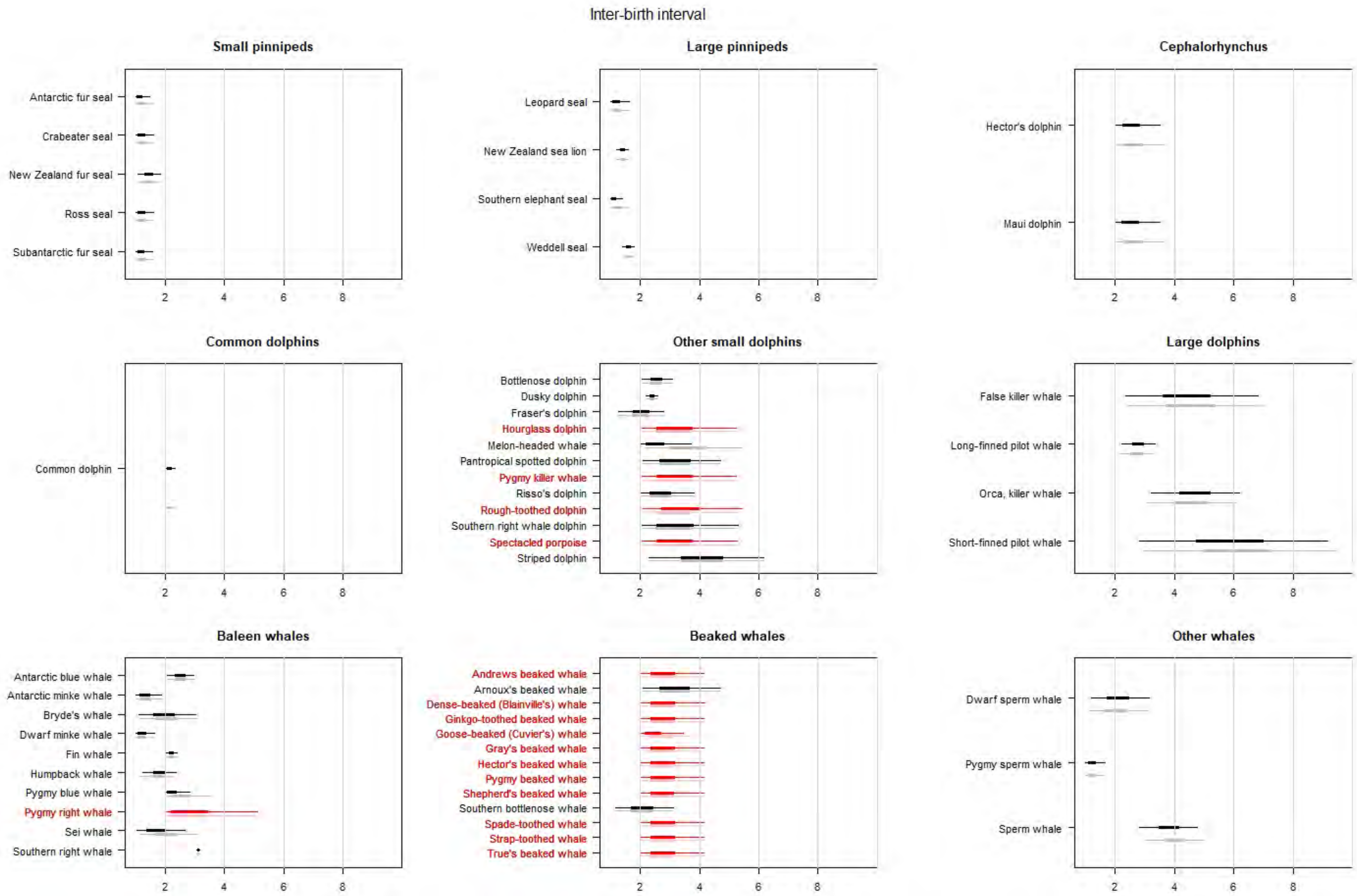


Figure 43: 50% and 95% credible intervals of prior (grey or pink) and posterior (black or red) distributions for inter-birth interval. Species for which no direct estimate was available are shown in pink (prior) and red (posterior).

Table 36: Posterior median and 95% credible interval for r_{max} obtained in this analysis and estimate and 95% credible interval elicited in the second round by Abraham et al. (2017). A gap indicates that no information was elicited for that species. Species in bold are those for which the Abraham et al. (2017) estimate is not within the 95% credible of this analysis.

	This analysis			Abraham et al. (2017)		
Common name	Median	Lower	Upper	Estimate	Lower	Upper
Antarctic fur seal	0.090	0.043	0.151			
Crabeater seal	0.096	0.053	0.146			
New Zealand fur seal	0.074	0.040	0.115	0.107	0.072	0.148
Ross seal	0.116	0.061	0.191			
Subantarctic fur seal	0.078	0.042	0.119			
Leopard seal	0.112	0.059	0.188			
New Zealand sea lion	0.102	0.070	0.131	0.092	0.065	0.125
Southern elephant seal	**0.078**	**0.046**	**0.107**	**0.126**	**0.090**	**0.168**
Weddell seal	0.079	0.040	0.117			
Hector’s dolphin	0.045	0.024	0.070	0.026	0.018	0.036
Māui dolphin	**0.045**	**0.024**	**0.070**	**0.023**	**0.015**	**0.034**
Common dolphin	0.050	0.027	0.079	0.040	0.019	0.072
Bottlenose dolphin	0.056	0.036	0.078	0.052	0.023	0.100
Dusky dolphin	0.064	0.034	0.107	0.048	0.025	0.082
Fraser’s dolphin	0.059	0.032	0.096			
Hourglass dolphin	0.044	0.020	0.083	0.041	0.016	0.086
Melon-headed whale	0.038	0.017	0.068			
Pantropical spotted dolphin	0.039	0.020	0.061			
Pygmy killer whale	0.044	0.020	0.083			
Risso’s dolphin	0.044	0.024	0.070			
Rough-toothed dolphin	0.038	0.019	0.072			
Southern right whale dolphin	0.033	0.017	0.054	0.041	0.016	0.085
Spectacled porpoise	0.044	0.020	0.083			
Striped dolphin	0.035	0.018	0.058			
False killer whale	0.031	0.015	0.057	0.041	0.016	0.083
Long-finned pilot whale	**0.063**	**0.046**	**0.079**	**0.041**	**0.016**	**0.086**
Orca, killer whale	0.028	0.010	0.045	0.026	0.012	0.049
Short-finned pilot whale	0.028	0.013	0.053	0.042	0.016	0.086
Antarctic blue whale	0.045	0.021	0.077	0.040	0.020	0.071
Antarctic minke whale	0.057	0.029	0.103	0.041	0.016	0.085
Bryde’s whale	0.049	0.024	0.076	0.044	0.024	0.073
Dwarf minke whale	0.060	0.031	0.111	0.041	0.016	0.085
Fin whale	0.048	0.025	0.069	0.038	0.020	0.065
Humpback whale	0.075	0.038	0.115	0.088	0.051	0.128
Pygmy blue whale	0.027	0.014	0.040	0.041	0.022	0.070
Pygmy right whale	0.049	0.022	0.099	0.041	0.016	0.089
Sei whale	0.040	0.021	0.062	0.030	0.016	0.052
Southern right whale	0.062	0.042	0.077	0.068	0.046	0.094
Andrews beaked whale	0.038	0.018	0.069	0.041	0.016	0.085
Arnoux’s beaked whale	0.036	0.017	0.065			
Dense-beaked whale	0.040	0.020	0.073	0.041	0.016	0.085
Ginkgo-toothed beaked whale	0.038	0.018	0.069			
Goose-beaked whale	0.036	0.018	0.064	0.041	0.016	0.087
Gray’s beaked whale	0.038	0.019	0.069	0.041	0.016	0.085
Hector’s beaked whale	0.037	0.018	0.069	0.041	0.016	0.086
Pygmy beaked whale	0.038	0.019	0.069			
Shepherd’s beaked whale	0.038	0.019	0.069	0.041	0.016	0.083
Southern bottlenose whale	0.039	0.019	0.073	0.041	0.016	0.086
Spade-toothed whale	0.038	0.019	0.068	0.041	0.016	0.086
Strap-toothed whale	0.038	0.019	0.069	0.041	0.016	0.084
True’s beaked whale	0.038	0.018	0.069			
Dwarf sperm whale	0.082	0.043	0.143			
Pygmy sperm whale	**0.083**	**0.044**	**0.150**	**0.039**	**0.020**	**0.068**
Sperm whale	0.029	0.013	0.051	0.018	0.005	0.048

The National Oceanic and Atmospheric Administration (NOAA) in the USA currently use a default r_{max} of 0.04 for cetaceans, apart from those species shown in Table 37. Also shown are the values used for five species of pinnipeds. The posterior medians and 95% credible intervals for r_{max} that were obtained in this analysis for orca, humpback whale, and (southern) elephant seal are given as a comparison.

Table 37: r_{max} values used by NOAA for specific species rather than a default value. The posterior median and limits of the 95% credible interval obtained in this analysis for comparable species are also given (e.g., southern elephant seal for northern elephant seal).

Family	Common name	NOAA	Median	Lower	Upper
Delphinidae	Orca	0.035	0.028	0.01	0.045
Phocoenidae	Harbor porpoise	0.046			
Mysticeti	Humpback whale (South Pacific)	0.106	0.075	0.038	0.115
Otariidae	Northern fur seal	0.086			
Otariidae	Guadalupe fur seal	0.137			
Phocidae	Hawaiian monk seal	0.070			
Phocidae	Harbour seal	0.120			
Phocidae	Northern elephant seal	0.120	0.078	0.046	0.107

3.9. Predicted fishing-related deaths and population impact

Posterior distributions for the predicted number of expected annual fishing-related deaths, and population impact, were determined from the predicted number of annual observable captures (using average annual commercial effort during the 2016/17 to 2018/19 fishing years) using the assumed distributions for $p^{obs}_{j,s}$, $\Psi_{j,z}$ and ω described in Section 2.7.

3.9.1. Annual fishing related observable captures and deaths

Figures 44 and 45 present summaries of the posterior distributions for the expected number of observable captures and expected number of deaths, using model $M_{\bullet}$. A comparison of the two metrics provides an indication of the cumulative effect of the assumed distributions for $p^{obs}_{j,s}$, $\Psi_{j,z}$ and ω for each species. Values for C_s and D_s are predicted to be very small for most species, although a substantial portion of the posterior distribution is > 5 for NZFS, NZSL, Hector's dolphin and common dolphin. 'Bumpiness' in the posterior distributions arise from the smoothing of integer values. Numerical summaries of the posterior distributions are given in Table 38.

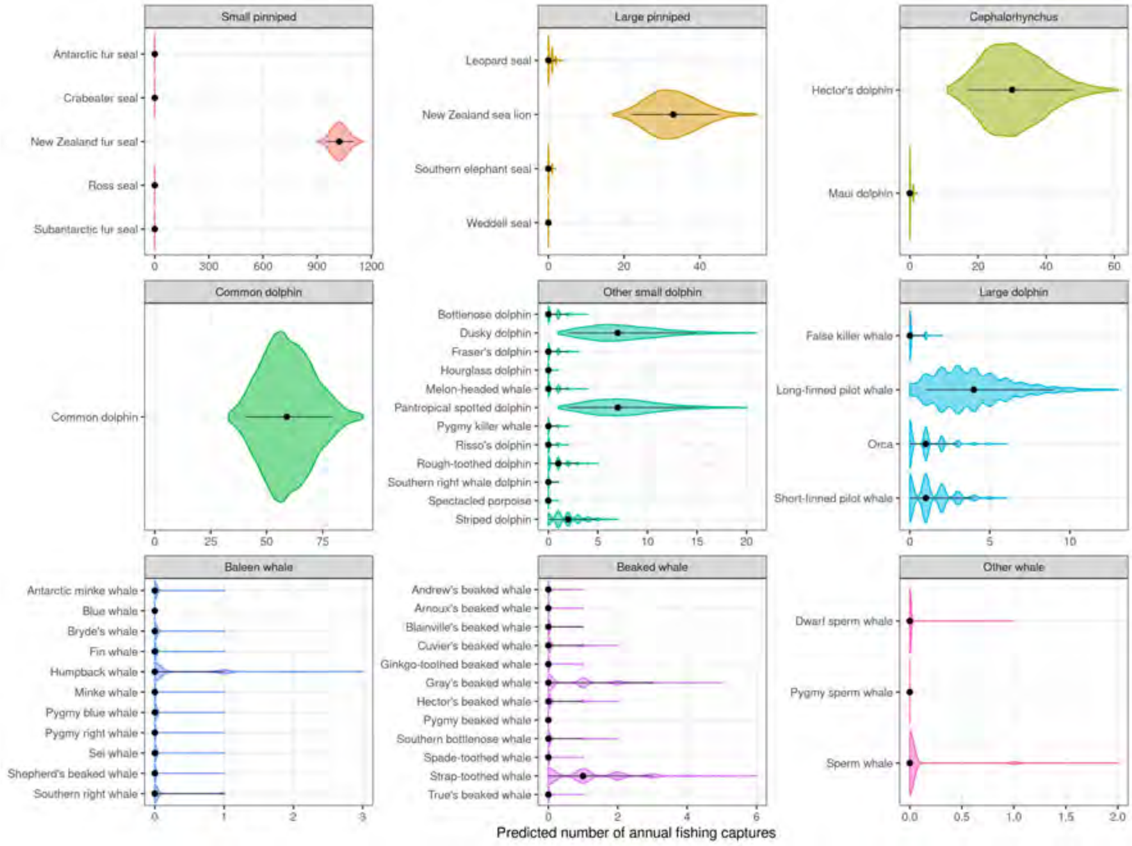


Figure 44: Predicted number of expected annual observable captures of each species (C_s) using Model $M_{\bullet}$, mean annual commercial effort from 2016/17 to 2018/19, and other defined input parameters. Violin plots represent the central 99% of the approximated posterior distribution, and black dots and error bars are the posterior median and central 90% credible interval. Separate panels are presented for each species group.

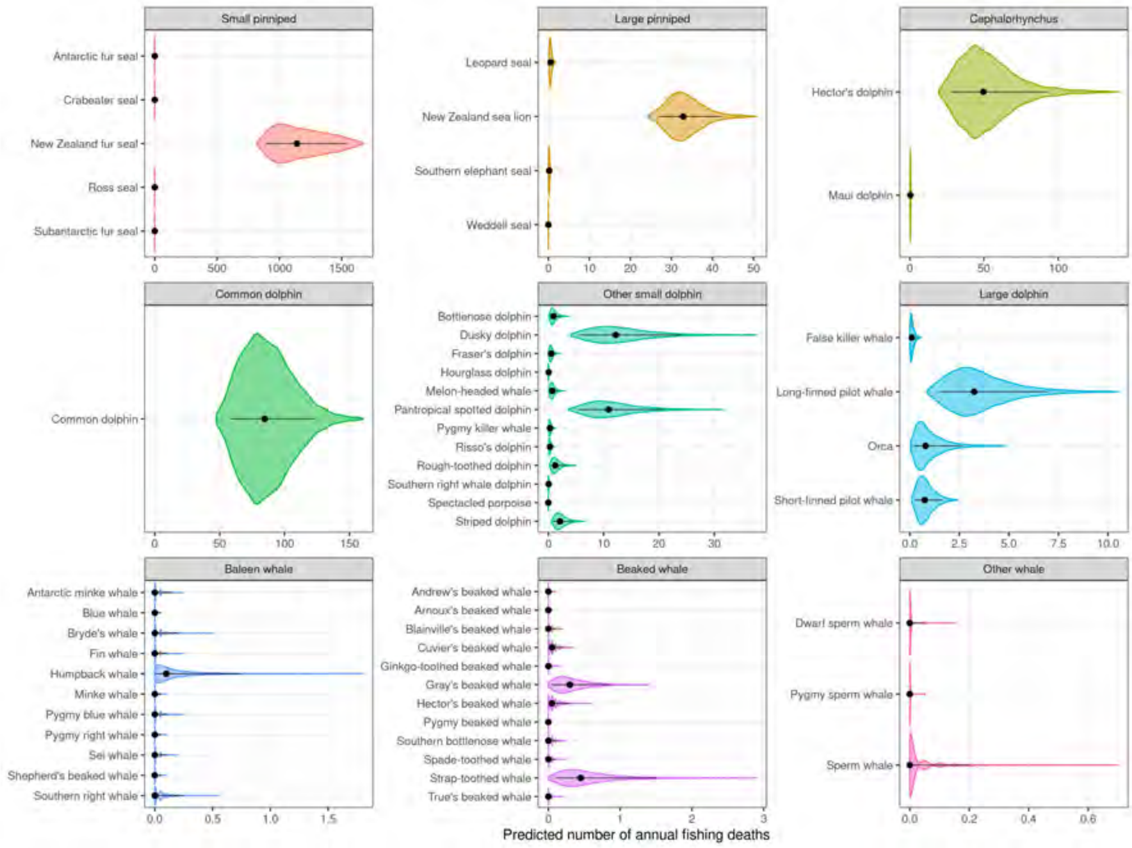


Figure 45: Predicted number of expect annual deaths of each species (D_s) using Model $M_\bullet$, mean annual commercial effort from 2016/17 to 2018/19, and other defined input parameters. Violin plots represent the central 99% of the approximated posterior distribution, and black dots and error bars are the posterior median and central 90% credible interval. Separate panels are presented for each species group.

Table 38: Predicted number of total annual observable captures from model $M_{\bullet}$, and derived number of deaths using the assumed distributions for $p^{obs}_{j,s}$, $\Psi_{j,z}$ and ω. Given are the mean, standard deviation (SD) and 5^{th}, 50^{th} and 95^{th} percentiles of the posterior distributions.

	Total observable captures					Total deaths				
Species	Mean	SD	5^{th}%	50^{th}%	95^{th}%	Mean	SD	5^{th}%	50^{th}%	95^{th}%
Antarctic fur seal	0.00	0.04	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Crabeater seal	0.00	0.04	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
New Zealand fur seal	1,024.29	47.52	949.0	1,023.0	1,105.0	1,172.35	203.93	893.3	1,141.1	1,541.5
Ross seal	0.00	0.05	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Subantarctic fur seal	0.00	0.03	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Leopard seal	0.59	0.83	0.0	0.0	2.0	0.58	0.31	0.2	0.6	1.2
New Zealand sea lion	33.05	7.08	22.0	33.0	45.0	33.46	4.81	26.9	32.9	42.1
Southern elephant seal	0.21	0.48	0.0	0.0	1.0	0.21	0.14	0.1	0.2	0.5
Weddell seal	0.00	0.04	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Hector's dolphin	30.89	9.69	17.0	30.0	48.0	53.48	21.18	27.8	49.5	92.9
Māui dolphin	0.20	0.46	0.0	0.0	1.0	0.38	0.22	0.1	0.4	0.8
Common dolphin	59.43	11.81	41.0	59.0	80.0	87.17	20.87	58.2	84.8	123.8
Bottlenose dolphin	0.58	0.81	0.0	0.0	2.0	1.05	0.66	0.3	0.9	2.3
Dusky dolphin	7.67	3.89	2.0	7.0	15.0	13.24	5.95	5.8	12.2	24.1
Fraser's dolphin	0.38	0.66	0.0	0.0	2.0	0.57	0.35	0.2	0.5	1.2
Hourglass dolphin	0.04	0.19	0.0	0.0	0.0	0.06	0.06	0.0	0.1	0.2
Melon-headed whale	0.51	0.76	0.0	0.0	2.0	0.82	0.51	0.2	0.7	1.8
Pantropical spotted dolphin	7.72	3.69	2.0	7.0	14.0	11.75	4.93	5.5	10.9	20.9
Pygmy killer whale	0.21	0.47	0.0	0.0	1.0	0.34	0.23	0.1	0.3	0.8
Risso's dolphin	0.24	0.51	0.0	0.0	1.0	0.32	0.20	0.1	0.3	0.7
Rough-toothed dolphin	0.91	1.07	0.0	1.0	3.0	1.45	0.86	0.5	1.3	3.1
Southern right whale dolphin	0.07	0.26	0.0	0.0	1.0	0.08	0.07	0.0	0.1	0.2
Spectacled porpoise	0.01	0.07	0.0	0.0	0.0	0.01	0.02	0.0	0.0	0.1
Striped dolphin	1.86	1.56	0.0	2.0	5.0	2.31	1.14	0.9	2.1	4.5
False killer whale	0.16	0.41	0.0	0.0	1.0	0.13	0.11	0.0	0.1	0.4
Long-finned pilot whale	3.93	2.54	1.0	4.0	9.0	3.63	1.75	1.5	3.3	7.0
Orca	0.96	1.18	0.0	1.0	3.0	1.04	0.85	0.2	0.8	2.7
Short-finned pilot whale	1.27	1.27	0.0	1.0	4.0	0.82	0.44	0.3	0.8	1.7
Antarctic minke whale	0.04	0.20	0.0	0.0	0.0	0.03	0.05	0.0	0.0	0.2
Blue whale	0.00	0.06	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.1
Bryde's whale	0.05	0.23	0.0	0.0	0.0	0.04	0.08	0.0	0.0	0.2
Fin whale	0.02	0.15	0.0	0.0	0.0	0.02	0.05	0.0	0.0	0.1
Humpback whale	0.26	0.60	0.0	0.0	1.0	0.21	0.32	0.0	0.1	0.8
Minke whale	0.01	0.09	0.0	0.0	0.0	0.01	0.02	0.0	0.0	0.1
Pygmy blue whale	0.03	0.19	0.0	0.0	0.0	0.02	0.05	0.0	0.0	0.1
Pygmy right whale	0.01	0.08	0.0	0.0	0.0	0.00	0.02	0.0	0.0	0.1
Sei whale	0.02	0.15	0.0	0.0	0.0	0.02	0.04	0.0	0.0	0.1
Shepherd's beaked whale	0.01	0.11	0.0	0.0	0.0	0.01	0.02	0.0	0.0	0.1
Southern right whale	0.07	0.27	0.0	0.0	1.0	0.06	0.10	0.0	0.1	0.3
Andrew's beaked whale	0.01	0.09	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.1
Arnoux's beaked whale	0.01	0.09	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.1
Blainville's beaked whale	0.06	0.25	0.0	0.0	1.0	0.03	0.04	0.0	0.0	0.1
Cuvier's beaked whale	0.13	0.37	0.0	0.0	1.0	0.06	0.07	0.0	0.1	0.2
Ginkgo-toothed beaked whale	0.02	0.15	0.0	0.0	0.0	0.01	0.03	0.0	0.0	0.1
Gray's beaked whale	0.73	0.97	0.0	0.0	3.0	0.34	0.26	0.1	0.3	0.8
Hector's beaked whale	0.14	0.40	0.0	0.0	1.0	0.09	0.11	0.0	0.1	0.3
Pygmy beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Southern bottlenose whale	0.09	0.30	0.0	0.0	1.0	0.04	0.05	0.0	0.0	0.2
Spade-toothed whale	0.03	0.17	0.0	0.0	0.0	0.02	0.04	0.0	0.0	0.1
Strap-toothed whale	1.12	1.24	0.0	1.0	3.0	0.59	0.48	0.1	0.5	1.5
True's beaked whale	0.02	0.13	0.0	0.0	0.0	0.01	0.03	0.0	0.0	0.1
Dwarf sperm whale	0.01	0.08	0.0	0.0	0.0	0.00	0.03	0.0	0.0	0.0
Pygmy sperm whale	0.00	0.04	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Sperm whale	0.05	0.28	0.0	0.0	0.0	0.03	0.12	0.0	0.0	0.2

3.9.2. Exploitation rate

Posterior distributions of the predicted exploitation rate ($U_s = D_s/N_s$) of New Zealand fishing activities on marine mammals suggest a very low removal rate, based on the inputs used in the analysis and assumed distributions for $p^{obs}_{j,s}$, $\Psi_{j,z}$ and ω (Figures 46 and 47). The exploitation rate is greater when using New Zealand population size for those species whose stock ise not fully contained within the NZ EEZ. The upper tail of the posterior distribution is very long for some species which is a consequence of the level of uncertainty in the predicted number of deaths and population size. Numerical summaries of the distributions are presented in Table 39, these are expressed as a percentage of population size to reduce the number of leading zeros. The five species with the highest predicted exploitation rates using New Zealand population sizes (in decreasing order of posterior mean) are NZFS, Māui dolphin, Hector's dolphin, NZSL and crabeater seal, where the posterior mean is < 0.01 (or $< 1\%$) for all species.

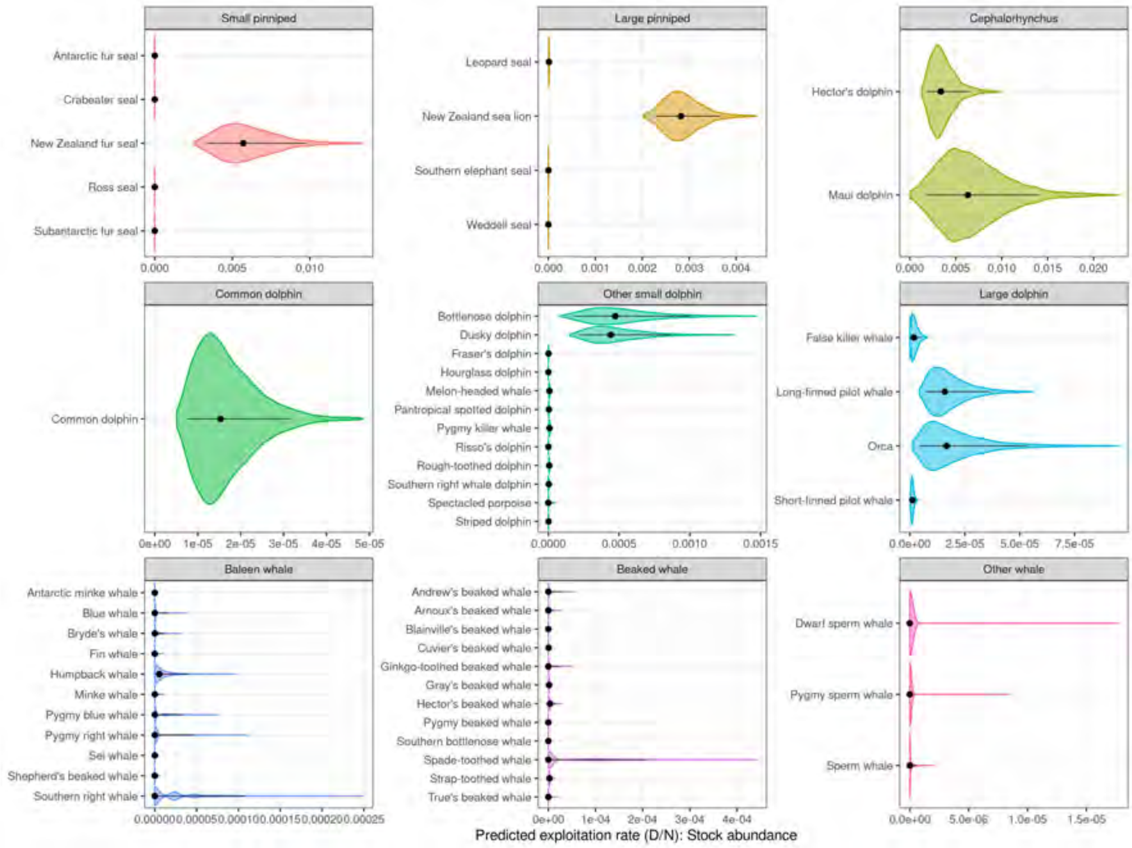


Figure 46: Predicted exploitation rate for each species ($U_s = D_s/N_s$) using stock population size, Model $M_{\bullet}$, mean annual commercial effort from 2016/17 to 2018/19, and other defined input parameters. Violin plots represent the central 99% of the approximated posterior distribution, and black dots and error bars are the posterior median and central 90% credible interval. Separate panels are presented for each species group.

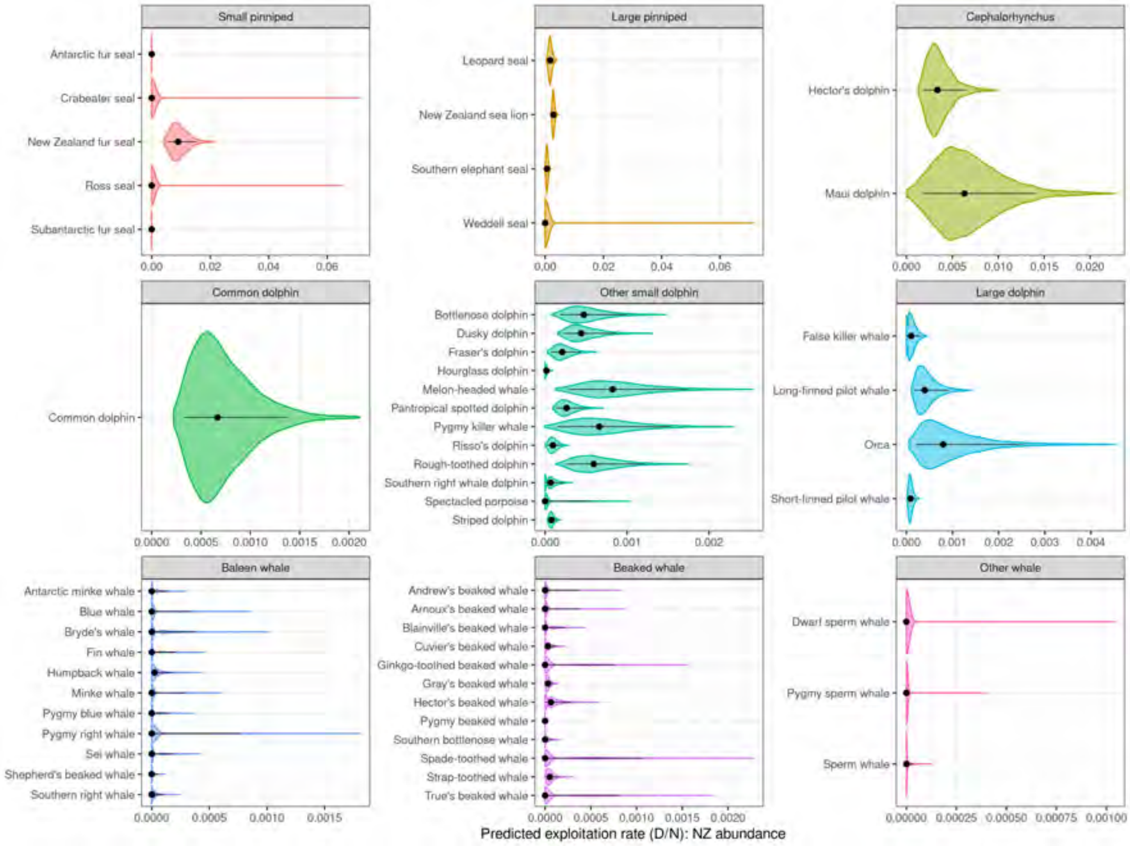


Figure 47: Predicted exploitation rate for each species ($U_s = D_s/N_s$) using NZ population size, Model $M_\bullet$, mean annual commercial effort from 2016/17 to 2018/19, and other defined input parameters. Violin plots represent the central 99% of the approximated posterior distribution, and black dots and error bars are the posterior median and central 90% credible interval. Separate panels are presented for each species group.

Table 39: Predicted exploitation rate ($U_s = D_s/N_s$; expressed as a percentage) using the stock and New Zealand population size (N_s). Given are the mean, standard deviation (SD) and 5th, 50th and 95th percentiles of the posterior distributions.

	Stock population size					NZ population size				
Species	Mean	SD	$5^{th}\%$	$50^{th}\%$	$95^{th}\%$	Mean	SD	$5^{th}\%$	$50^{th}\%$	$95^{th}\%$
Antarctic fur seal	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Crabeater seal	0.00	0.00	0.0	0.0	0.0	0.19	1.06	0.0	0.0	0.0
New Zealand fur seal	0.60	0.20	0.3	0.6	1.0	0.95	0.32	0.5	0.9	1.5
Ross seal	0.00	0.00	0.0	0.0	0.0	0.15	0.89	0.0	0.0	0.0
Subantarctic fur seal	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Leopard seal	0.00	0.00	0.0	0.0	0.0	0.18	0.07	0.1	0.2	0.3
New Zealand sea lion	0.29	0.04	0.2	0.3	0.4	0.29	0.04	0.2	0.3	0.4
Southern elephant seal	0.00	0.00	0.0	0.0	0.0	0.07	0.04	0.0	0.1	0.1
Weddell seal	0.00	0.00	0.0	0.0	0.0	0.16	1.00	0.0	0.0	0.0
Hector's dolphin	0.37	0.15	0.2	0.3	0.7	0.37	0.15	0.2	0.3	0.7
Māui dolphin	0.70	0.40	0.2	0.6	1.4	0.70	0.40	0.2	0.6	1.4
Common dolphin	0.00	0.00	0.0	0.0	0.0	0.07	0.03	0.0	0.1	0.1
Bottlenose dolphin	0.05	0.03	0.0	0.0	0.1	0.05	0.03	0.0	0.0	0.1
Dusky dolphin	0.05	0.02	0.0	0.0	0.1	0.05	0.02	0.0	0.0	0.1
Fraser's dolphin	0.00	0.00	0.0	0.0	0.0	0.02	0.01	0.0	0.0	0.0
Hourglass dolphin	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Melon-headed whale	0.00	0.00	0.0	0.0	0.0	0.09	0.05	0.0	0.1	0.2
Pantropical spotted dolphin	0.00	0.00	0.0	0.0	0.0	0.03	0.01	0.0	0.0	0.0
Pygmy killer whale	0.00	0.00	0.0	0.0	0.0	0.07	0.04	0.0	0.1	0.2
Risso's dolphin	0.00	0.00	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0
Rough-toothed dolphin	0.00	0.00	0.0	0.0	0.0	0.06	0.03	0.0	0.1	0.1
Southern right whale dolphin	0.00	0.00	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0
Spectacled porpoise	0.00	0.00	0.0	0.0	0.0	0.01	0.02	0.0	0.0	0.1
Striped dolphin	0.00	0.00	0.0	0.0	0.0	0.01	0.00	0.0	0.0	0.0
False killer whale	0.00	0.00	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0
Long-finned pilot whale	0.00	0.00	0.0	0.0	0.0	0.05	0.02	0.0	0.0	0.1
Orca	0.00	0.00	0.0	0.0	0.0	0.10	0.08	0.0	0.1	0.3
Short-finned pilot whale	0.00	0.00	0.0	0.0	0.0	0.01	0.00	0.0	0.0	0.0
Antarctic minke whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Blue whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Bryde's whale	0.00	0.00	0.0	0.0	0.0	0.01	0.02	0.0	0.0	0.0
Fin whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Humpback whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Minke whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Pygmy blue whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Pygmy right whale	0.00	0.00	0.0	0.0	0.0	0.01	0.03	0.0	0.0	0.1
Sei whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Shepherd's beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Southern right whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Andrew's beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Arnoux's beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Blainville's beaked whale	0.00	0.00	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0
Cuvier's beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Ginkgo-toothed beaked whale	0.00	0.00	0.0	0.0	0.0	0.01	0.03	0.0	0.0	0.1
Gray's beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Hector's beaked whale	0.00	0.00	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0
Pygmy beaked whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Southern bottlenose whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0
Spade-toothed whale	0.00	0.01	0.0	0.0	0.0	0.02	0.04	0.0	0.0	0.1
Strap-toothed whale	0.00	0.00	0.0	0.0	0.0	0.01	0.01	0.0	0.0	0.0
True's beaked whale	0.00	0.00	0.0	0.0	0.0	0.01	0.03	0.0	0.0	0.1
Dwarf sperm whale	0.00	0.00	0.0	0.0	0.0	0.00	0.03	0.0	0.0	0.0
Pygmy sperm whale	0.00	0.00	0.0	0.0	0.0	0.00	0.01	0.0	0.0	0.0
Sperm whale	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.0	0.0	0.0

3.9.3. Equilibrium status

Figures 48 and 49 present the equilibrium status (I'_s) posterior distributions that are derived from the predicted fishing-related exploitation rates, and revised r_{max} distributions presented above for each species. Stock population size is used in Figure 48 and New Zealand population size in Figure 49, and note that the x-axes are scaled with 1.0 (indicating no impact) on the far left of the axis. Based on these results, it would appear that there is very little commercial fishing-related impact on most marine mammal species included in this assessment, given the methods used. The three most impacted species are Māui dolphin, NZFS and Hector's dolphin, in increasing order of the posterior mean, using New Zealand population size. Table 40 contains a numerical summary of the posterior distributions of equilibrium status, expressed as a percentage.

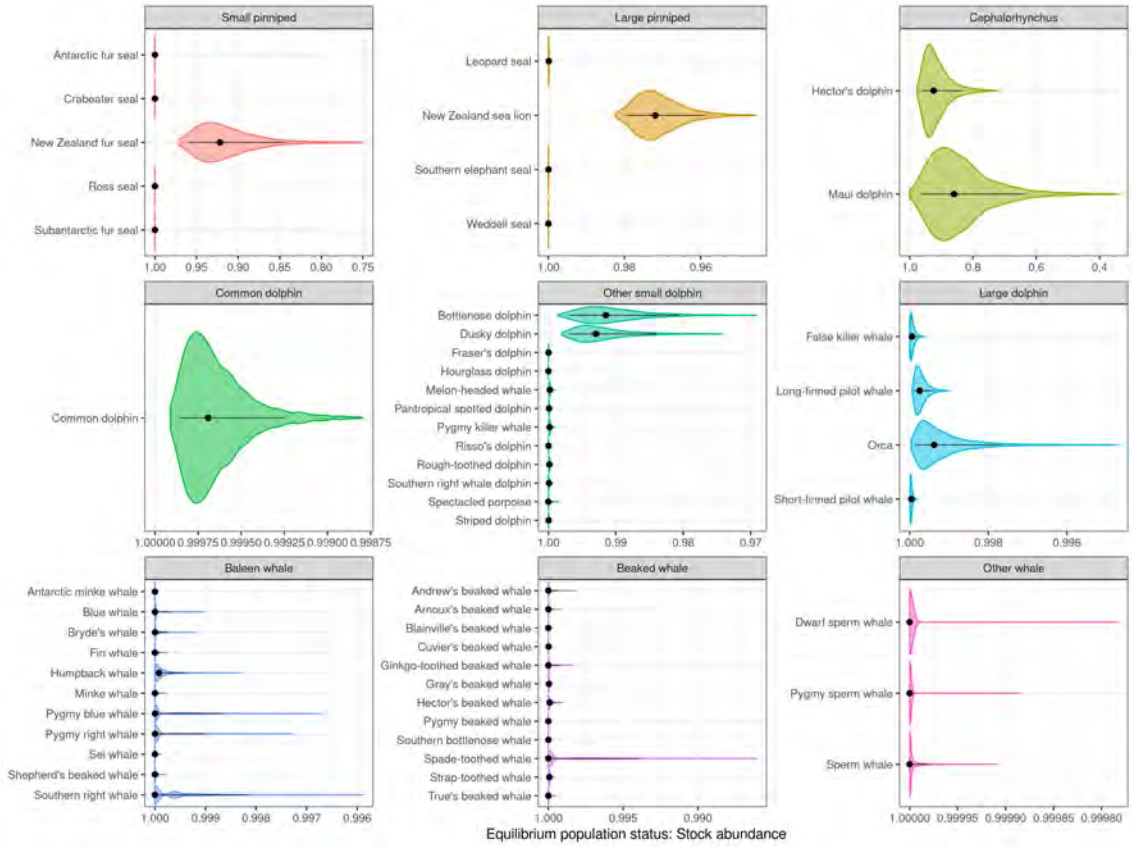


Figure 48: Predicted equilibrium status (I'_s) using stock population size, Model $M_\bullet$, mean annual commercial effort from 2016/17 to 2018/19, and other defined input parameters. Violin plots represent the central 99% of the approximated posterior distribution, and black dots and error bars are the posterior median and central 90% credible interval. Separate panels are presented for each species group.

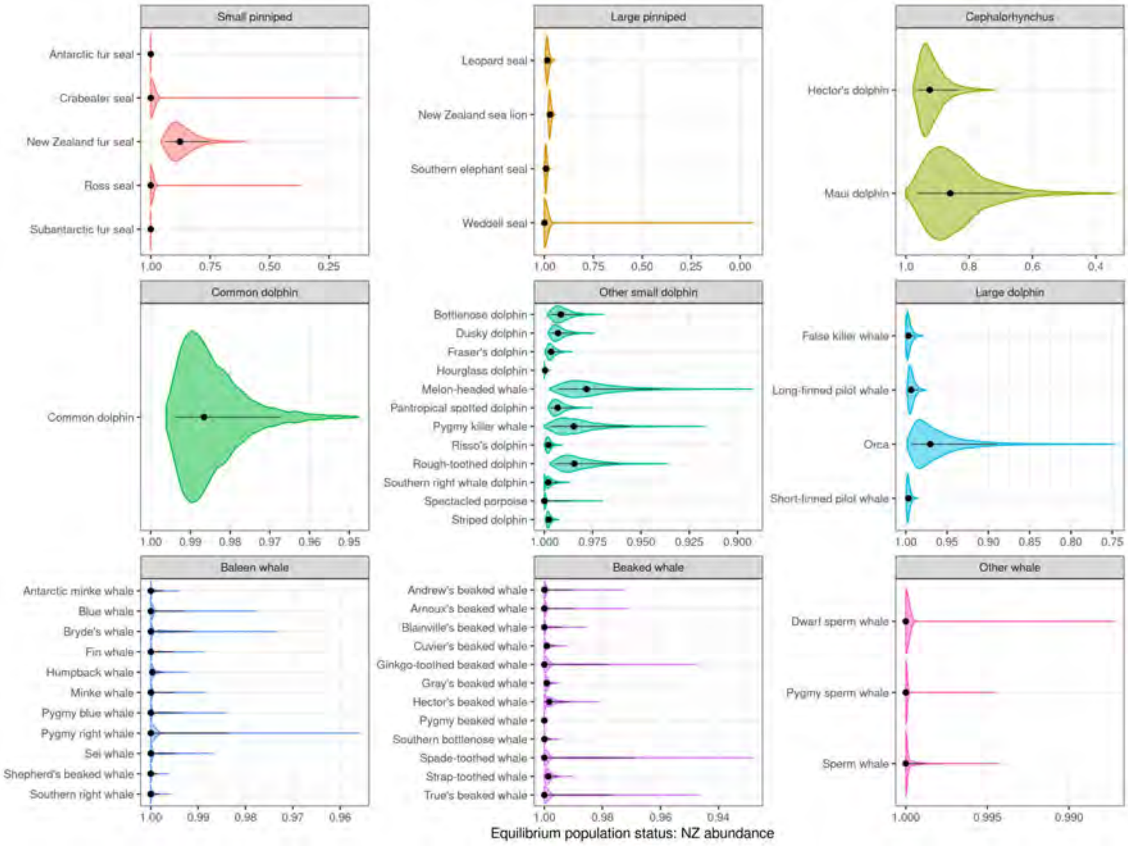


Figure 49: Predicted equilibrium status (I'_s) using New Zealand population size, Model $M_{\bullet}$, mean annual commercial effort from 2016/17 to 2018/19, and other defined input parameters. Violin plots represent the central 99% of the approximated posterior distribution, and black dots and error bars are the posterior median and central 90% credible interval. Separate panels are presented for each species group.

Table 40: Predicted equilibrium status (I'_s; expressed as a percentage) using the stock and New Zealand population size (N_s). Given are the mean, standard deviation (SD) and 5^{th}, 50^{th} and 95^{th} percentiles of the posterior distributions.

	Stock population size					NZ population size				
Species	Mean	SD	5^{th}%	50^{th}%	95^{th}%	Mean	SD	5^{th}%	50^{th}%	95^{th}%
Antarctic fur seal	100.00	0.00	100.0	100.0	100.0	99.99	0.08	100.0	100.0	100.0
Crabeater seal	100.00	0.00	100.0	100.0	100.0	97.73	13.43	100.0	100.0	100.0
New Zealand fur seal	91.38	3.98	84.1	92.2	96.0	86.40	6.27	74.9	87.7	93.7
Ross seal	100.00	0.00	100.0	100.0	100.0	98.66	8.38	100.0	100.0	100.0
Subantarctic fur seal	100.00	0.00	100.0	100.0	100.0	99.99	0.08	100.0	100.0	100.0
Leopard seal	99.99	0.01	100.0	100.0	100.0	98.28	0.88	96.7	98.5	99.3
New Zealand sea lion	97.09	0.66	95.9	97.2	97.9	97.09	0.66	95.9	97.2	97.9
Southern elephant seal	100.00	0.00	100.0	100.0	100.0	99.10	0.55	98.1	99.2	99.8
Weddell seal	100.00	0.00	100.0	100.0	100.0	97.72	14.98	100.0	100.0	100.0
Hector's dolphin	91.41	4.52	83.1	92.4	96.4	91.41	4.52	83.1	92.4	96.4
Māui dolphin	83.57	11.01	63.5	85.9	96.0	83.57	11.01	63.5	85.9	96.0
Common dolphin	99.96	0.02	99.9	100.0	100.0	98.44	0.87	96.8	98.7	99.4
Bottlenose dolphin	99.04	0.52	98.1	99.1	99.7	99.04	0.52	98.1	99.1	99.7
Dusky dolphin	99.20	0.43	98.4	99.3	99.7	99.20	0.43	98.4	99.3	99.7
Fraser's dolphin	100.00	0.00	100.0	100.0	100.0	99.59	0.25	99.1	99.6	99.9
Hourglass dolphin	100.00	0.00	100.0	100.0	100.0	99.95	0.06	99.8	100.0	100.0
Melon-headed whale	99.98	0.02	99.9	100.0	100.0	97.38	1.85	94.0	97.8	99.3
Pantropical spotted dolphin	99.99	0.01	100.0	100.0	100.0	99.22	0.42	98.5	99.3	99.7
Pygmy killer whale	99.98	0.02	99.9	100.0	100.0	98.16	1.43	95.5	98.5	99.7
Risso's dolphin	100.00	0.00	100.0	100.0	100.0	99.76	0.16	99.5	99.8	99.9
Rough-toothed dolphin	99.98	0.01	100.0	100.0	100.0	98.20	1.10	96.2	98.5	99.4
Southern right whale dolphin	99.99	0.01	100.0	100.0	100.0	99.75	0.25	99.3	99.8	100.0
Spectacled porpoise	99.99	0.03	99.9	100.0	100.0	99.81	0.55	98.6	100.0	100.0
Striped dolphin	100.00	0.00	100.0	100.0	100.0	99.75	0.13	99.5	99.8	99.9
False killer whale	99.99	0.01	100.0	100.0	100.0	99.58	0.39	98.9	99.7	100.0
Long-finned pilot whale	99.97	0.02	99.9	100.0	100.0	99.26	0.42	98.5	99.4	99.7
Orca	99.91	0.13	99.8	99.9	100.0	95.83	6.03	88.9	97.0	99.3
Short-finned pilot whale	100.00	0.00	100.0	100.0	100.0	99.63	0.25	99.2	99.7	99.9
Antarctic minke whale	100.00	0.00	100.0	100.0	100.0	99.94	0.11	99.8	100.0	100.0
Blue whale	100.00	0.02	100.0	100.0	100.0	99.92	0.38	99.3	100.0	100.0
Bryde's whale	99.99	0.01	100.0	100.0	100.0	99.81	0.40	99.1	100.0	100.0
Fin whale	100.00	0.00	100.0	100.0	100.0	99.91	0.21	99.5	100.0	100.0
Humpback whale	99.98	0.03	99.9	100.0	100.0	99.93	0.13	99.7	100.0	100.0
Minke whale	100.00	0.00	100.0	100.0	100.0	99.94	0.20	99.5	100.0	100.0
Pygmy blue whale	99.97	0.06	99.9	100.0	100.0	99.87	0.28	99.3	100.0	100.0
Pygmy right whale	99.99	0.05	99.9	100.0	100.0	99.81	0.76	98.4	100.0	100.0
Sei whale	100.00	0.00	100.0	100.0	100.0	99.90	0.22	99.5	100.0	100.0
Shepherd's beaked whale	100.00	0.00	100.0	100.0	100.0	99.98	0.06	99.8	100.0	100.0
Southern right whale	99.95	0.08	99.8	100.0	100.0	99.95	0.08	99.8	100.0	100.0
Andrew's beaked whale	99.99	0.03	99.9	100.0	100.0	99.90	0.43	99.0	100.0	100.0
Arnoux's beaked whale	100.00	0.01	100.0	100.0	100.0	99.90	0.46	99.0	100.0	100.0
Blainville's beaked whale	100.00	0.00	100.0	100.0	100.0	99.86	0.25	99.4	100.0	100.0
Cuvier's beaked whale	100.00	0.00	100.0	100.0	100.0	99.88	0.15	99.6	99.9	100.0
Ginkgo-toothed beaked whale	99.99	0.03	99.9	100.0	100.0	99.61	0.93	97.8	100.0	100.0
Gray's beaked whale	100.00	0.00	100.0	100.0	100.0	99.90	0.09	99.7	99.9	100.0
Hector's beaked whale	99.99	0.02	100.0	100.0	100.0	99.75	0.33	99.1	99.8	100.0
Pygmy beaked whale	100.00	0.00	100.0	100.0	100.0	99.99	0.46	100.0	100.0	100.0
Southern bottlenose whale	100.00	0.00	100.0	100.0	100.0	99.93	0.10	99.7	100.0	100.0
Spade-toothed whale	99.87	0.27	99.4	100.0	100.0	99.34	1.37	96.9	100.0	100.0
Strap-toothed whale	99.99	0.01	100.0	100.0	100.0	99.82	0.17	99.5	99.9	100.0
True's beaked whale	100.00	0.01	100.0	100.0	100.0	99.59	0.99	97.7	100.0	100.0
Dwarf sperm whale	100.00	0.00	100.0	100.0	100.0	99.96	0.28	100.0	100.0	100.0
Pygmy sperm whale	100.00	0.00	100.0	100.0	100.0	99.99	0.07	100.0	100.0	100.0
Sperm whale	100.00	0.00	100.0	100.0	100.0	99.98	0.14	99.9	100.0	100.0

4. DISCUSSION

This risk assessment has attempted to use the best available information on the demographics of the 54 marine mammal species of interest. As such, it represents our assessment of the fishing-related risk to these populations under the assumption that the input information on stock population size, proportion within the NZ EEZ, relative density of individuals within the EEZ (possibly by season), and life-history parameters used in the derivation of r_{max}, is sufficiently accurate. However, the reality of the situation is that few of these species have been studied extensively enough within the NZ EEZ, or even extensively studied anywhere around the globe, and the input information used in this assessment is not derived from systematically collected data sources, collected at appropriate spatial scales. This is an element of uncertainty that is not reflected directly in the result, which should be acknowledged, and considered, in any application of the results. The level of this uncertainty could be evaluated by further sensitivity analyses, and reduced through the implementation of well-designed field studies (noting the challenges of doing so at the spatial scale of species ranges within the EEZ).

A counter-point to the above, is that risk is always going to be difficult to assess for species that are inherently rare within New Zealand waters, or that are observed infrequently as captured by fishing activities. Extensive field studies for such species are unlikely to be an effective use of resources for such species, so the relative benefits of quantitative vs. qualitative risk assessments should be considered.

Diagnostics used to assess the performance of the capture estimation model identified some deficiencies in the model's ability to re-predict the spatial location of observed captures for most species groups, although the model could adequately predict the total number of observed captures. The sub-optimal spatial performance of the model is not unexpected for pinniped species as simplistic species distribution layers were used for NZFS and NZSL. Poor spatial performance of the modelling will be caused by at least one of:

- inappropriate grouping of spatially-distinct fishing effort, with different catchabilities, into the same fishing group;
- inappropriate grouping of different species into the same species group;
- inaccurate overlap metrics.

It is difficult to determine which structural element of the modelling, or which input, requires adjustment as some of the effects are spatially confounded and there are limited available data that could be used to reliably disentangle effects.

Accurate species overlap metrics are key to the successful application of the SEFRA method. The species distribution layers used in this project represent the best pre-existing layers that were able to be sourced, and none of them arise from well-designed surveys across the main extent of the species range within the NZ EEZ, except for the layers for Hector's dolphin. Therefore, it is difficult to assess the accuracy of these layers for most species which largely rely on estimated, or hypothesised, relationships with environmental variables for large portions of the NZ EEZ. Fishing effort data may also be prone to some spatial uncertainty that is not encapsulated in the modelling approaches. For example, the location of the effort is assigned to grid cells based on the start position of the fishing only, and when 1 km^2 grid cells are used (as they were here), the actual fishing activity should be allocated across multiple cells rather than only one (at least for some fishing methods).

The multi-species SEFRA method used in this assessment aggregates the density overlap of all species within the same species group. The species group density overlap and observed captures of individuals of that species group provide information on the associated catchability parameters that are estimated through the modelling procedure. A strength of this approach is that observed captures only have to be identified to species group level, not to species level, which is more likely for some captures (particularly beaked whales). Species misidentification is also likely to be less problematic to the estimation approach, provided the species group of the captured individual is correct. However, a weakness of the approach is that by aggregating density overlaps, information on the relative density of individual species within a species group is lost. This leads to the 'species switching' of predicted captures that occurred that may lead to biased predictions of captures when the results are applied to individual species from a species group. Alternative model structures could be explored to retain the strengths of this approach, but reduce the potential for 'species switching'.

One alternative is that, rather than aggregating density overlaps to the species group-level to enable use of observed captures that are not identified to species level, the SEFRA model is constructed at the species level (incorporating potential parameter constraints such as all species within the same species group may have the same catchability) with the true species of an observed capture considered as a (partially) latent variable. A simple model could be defined for the species identification process, and when there is uncertainty in the species of the captured individual, the modelling integrates across the allowable values for the species during the estimation of model parameters.

Overall, it is our opinion that the SEFRA method used here is a sound approach for conducting a multi-species risk assessment, in general, but could benefit from some methodological refinements. Confidence in the results of the risk assessment would also be increased for species whose biological inputs are derived from appropriate field studies or monitoring programmes.

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Appendix A Species-specific inputs

A.1 Antarctic fur seal

Demographic parameters

Table A.1: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.89	0.025	0.7	0.999
AFR	norm	4.2	0.84	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv					

Table A.2: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	2775689	0.124	Antarctic	5.36e-05

References contributing to stock abundance information: Forcada (2021)

References contributing to NZ abundance information: Lancaster et al. (2006)

Other notes: NZ abundance assumed to be vagrants from Macquarie Is. p^{EEZ} derived from NZ abundance.

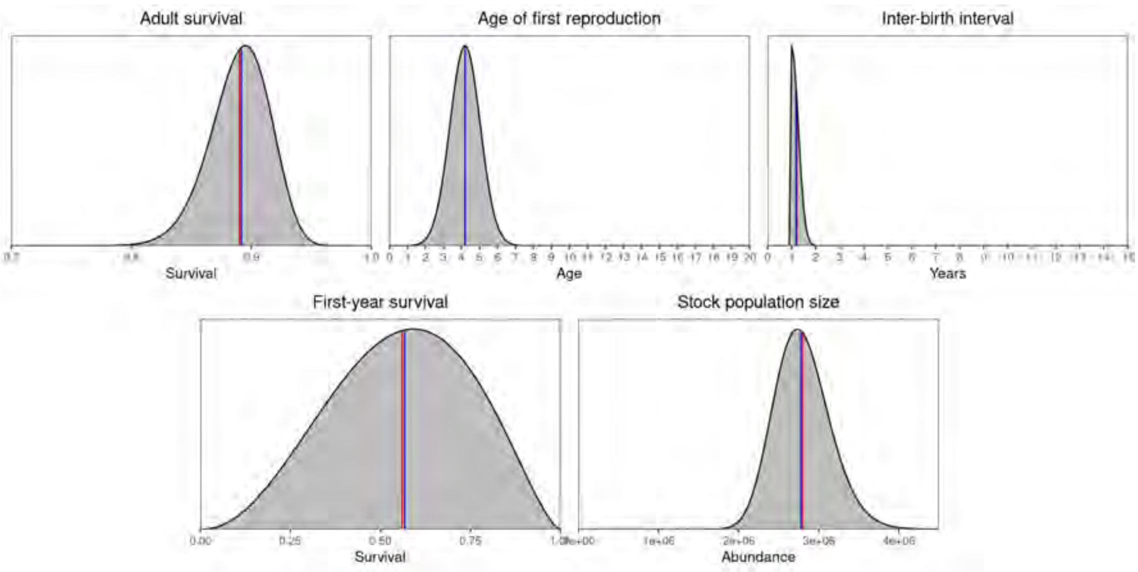

Figure A.1: Prior distributions of demographic input parameters.

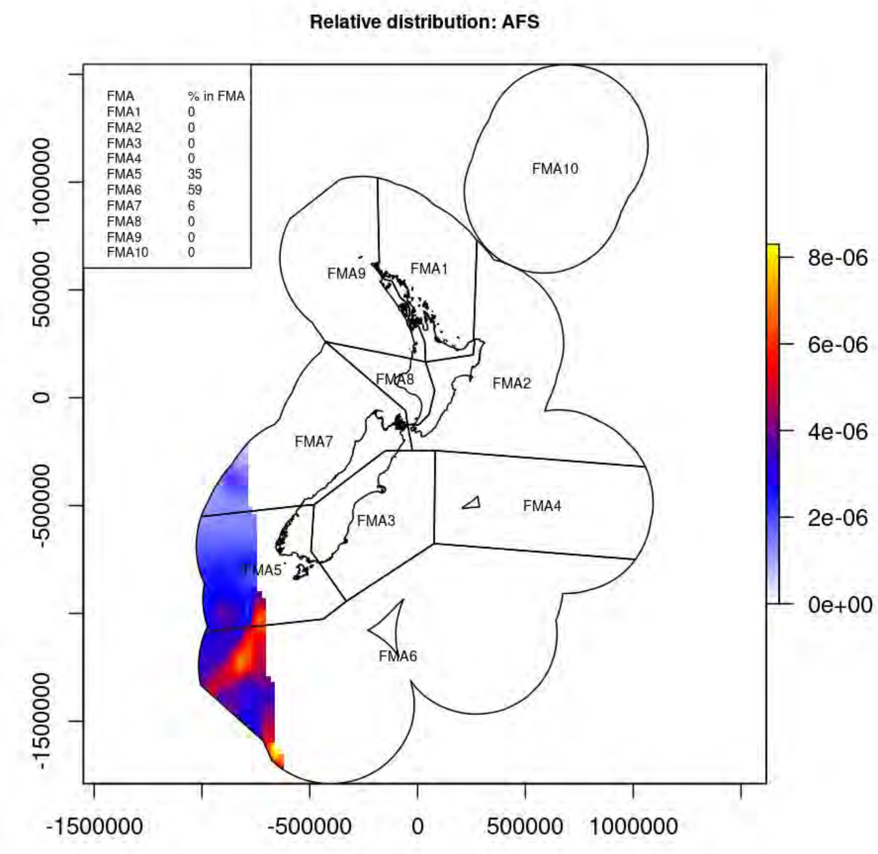

Figure A.2: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.2 Subantarctic fur seal

Demographic parameters

Table A.3: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.91	0.043	0.7	0.999
AFR	norm	5.4	0.2	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.4: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	315852	0.064	Worldwide	0.000474

References contributing to stock abundance information: Lancaster et al. (2006)

References contributing to NZ abundance information: Lancaster et al. (2006)

Other notes: NZ abundance assumed to be vagrants from Macquarie Is. P^{EEZ} derived from NZ abundance.

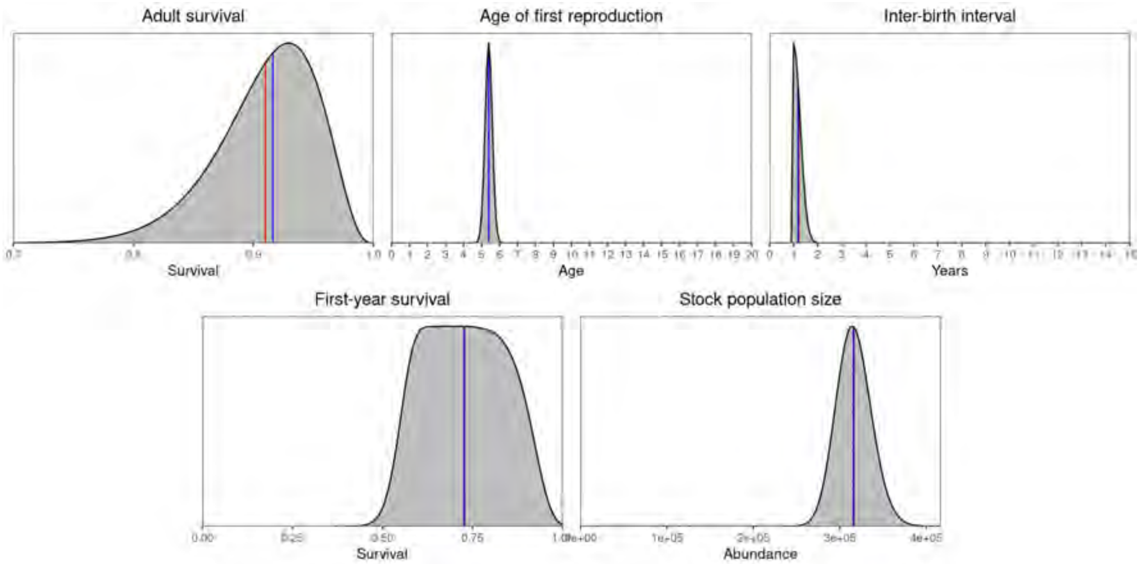

Figure A.3: Prior distributions of demographic input parameters.

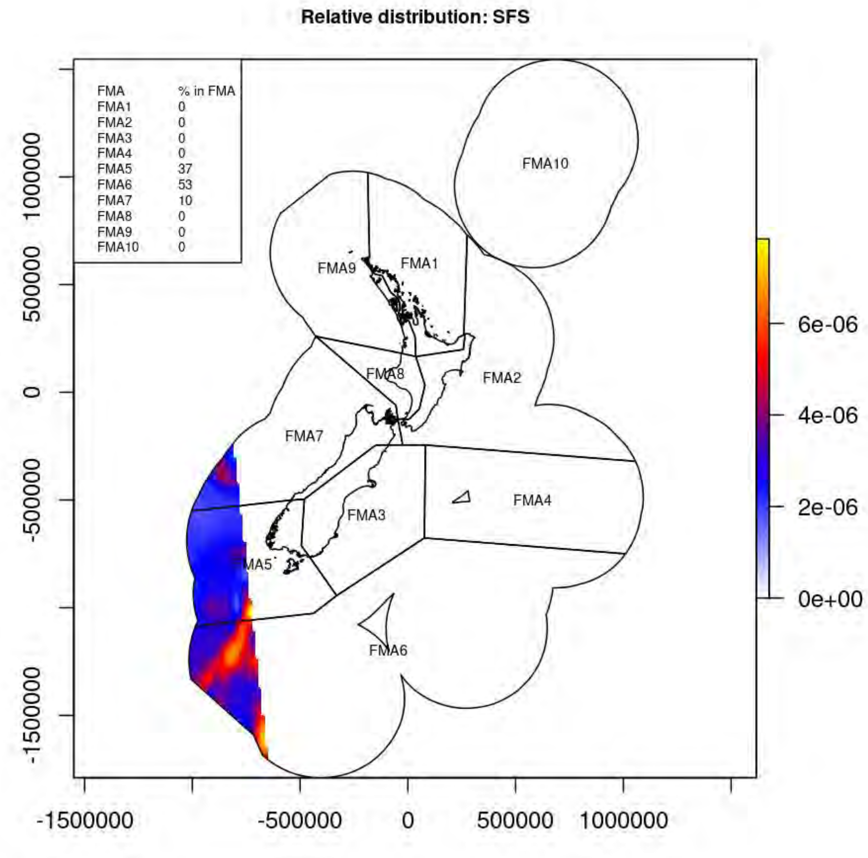

Figure A.4: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.3 Ross seal

Demographic parameters

Table A.5: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.9	0.012	0.88	0.92
AFR	norm	3.5	0.71	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.92

Table A.6: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	73836	0.35	Antarctic	1.27e-05

References contributing to stock abundance information: Southwell et al. (2012)

References contributing to NZ abundance information:

Other notes: NZ population is assumed and represents a very rare vagrant species. Stock abundance CV is assumed value.

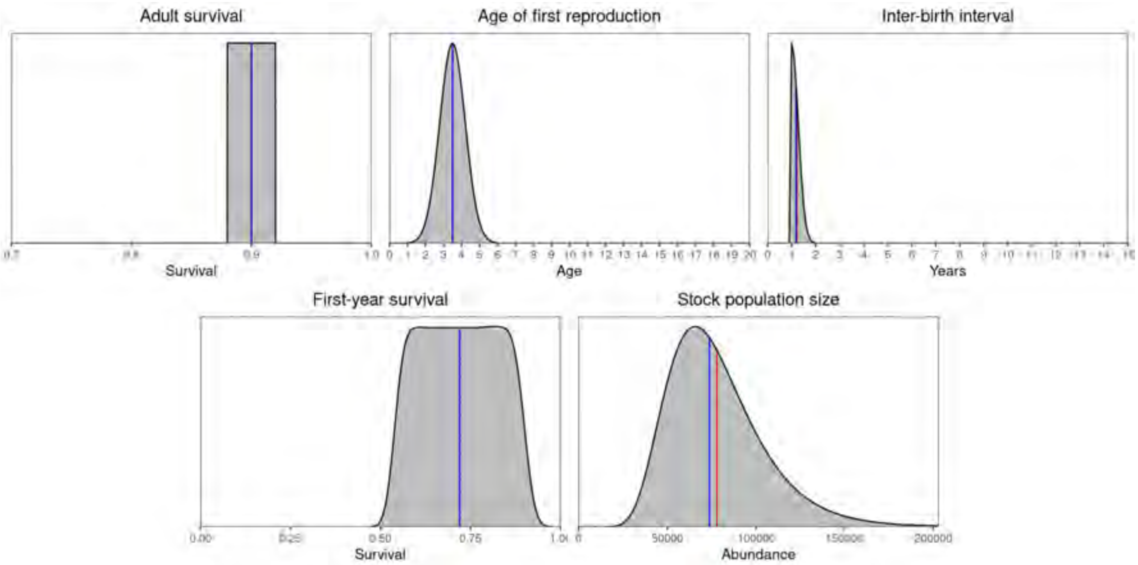

Figure A.5: Prior distributions of demographic input parameters.

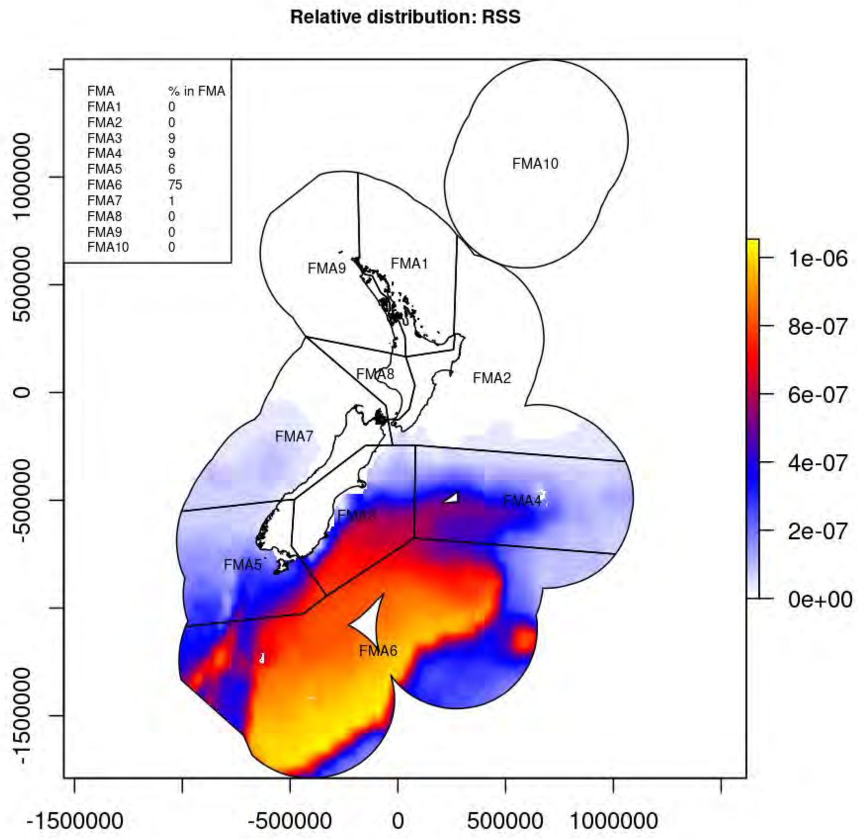

Figure A.6: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.4 Crabeater seal

Demographic parameters

Table A.7: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.9	0.012	0.88	0.92
AFR	norm	4.31	0.2	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.92

Table A.8: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	8872943	0.35	Antarctic	1.06e-07

References contributing to stock abundance information: Southwell et al. (2012)

References contributing to NZ abundance information:

Other notes: NZ population is assumed and represents a very rare vagrant species. Stock abundance CV is assumed value.

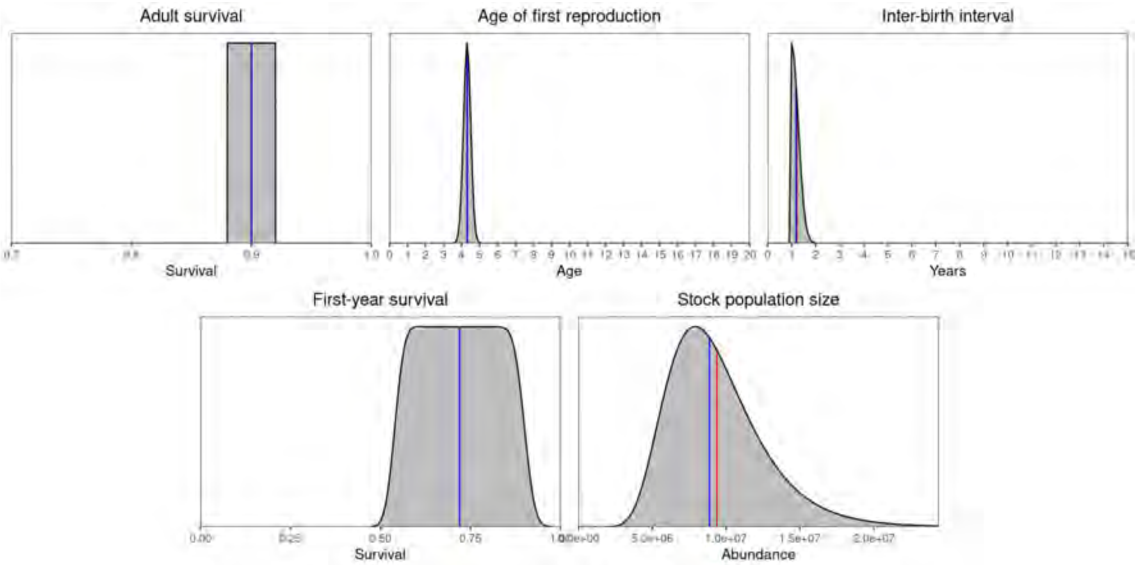

Figure A.7: Prior distributions of demographic input parameters.

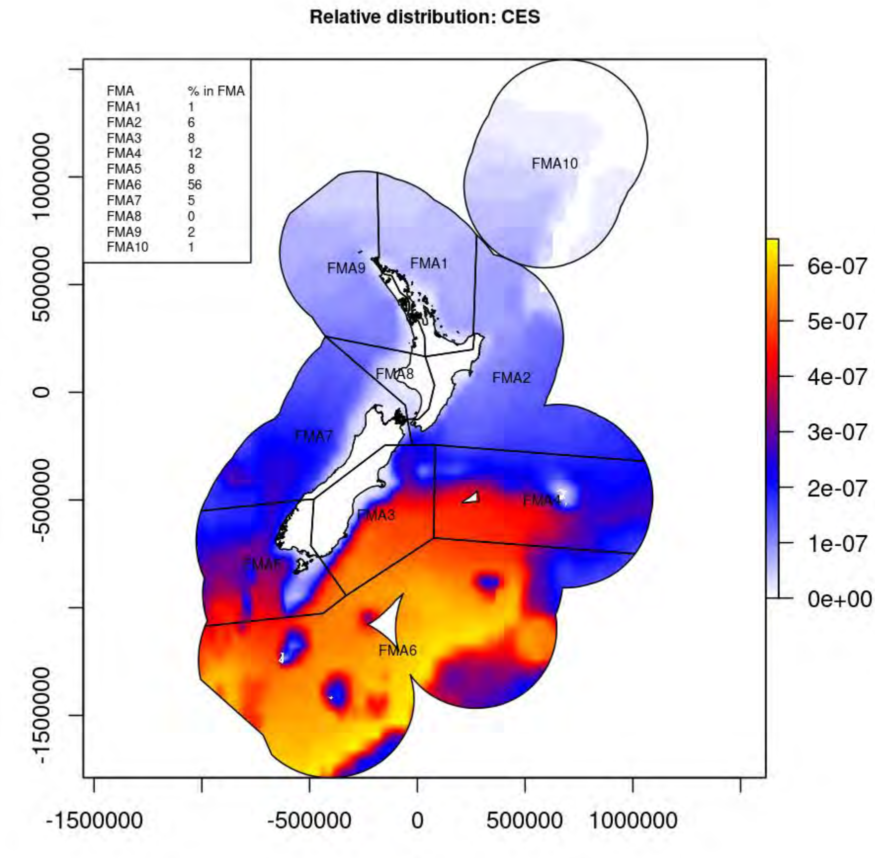

Figure A.8: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.5 New Zealand fur seal

Demographic parameters

Table A.9: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.9	0.012	0.88	0.92
AFR	norm	5.5	0.3	1	Inf
IBI	norm	1.45	0.2	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.92

Table A.10: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	192632	0.274	NZ and Aus	0.634

References contributing to stock abundance information: Berkenbusch et al. (2013)

References contributing to NZ abundance information: Berkenbusch et al. (2013)

Other notes:

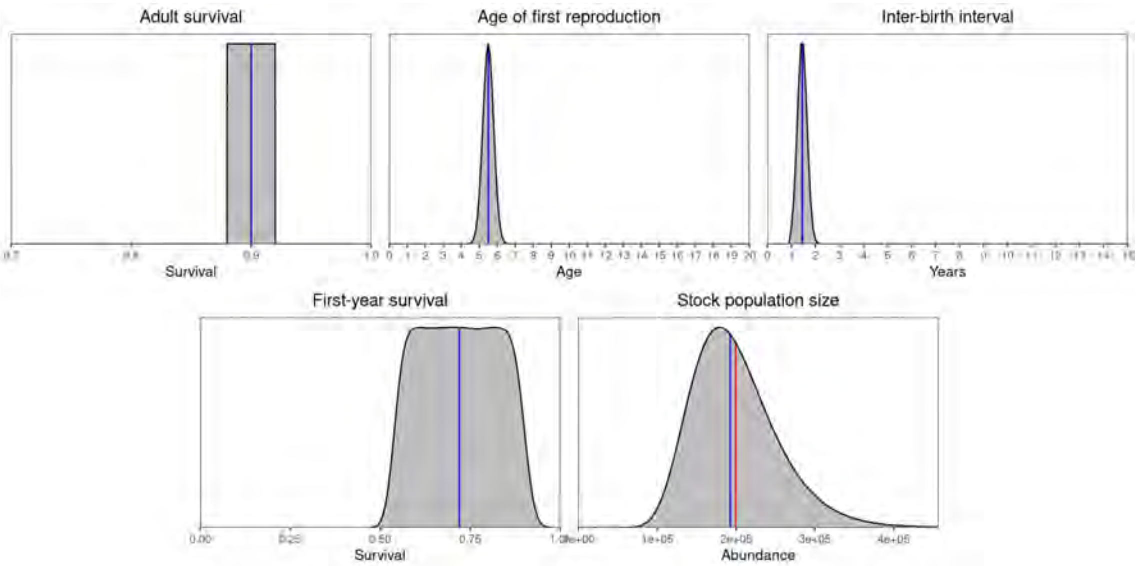

Figure A.9: Prior distributions of demographic input parameters.

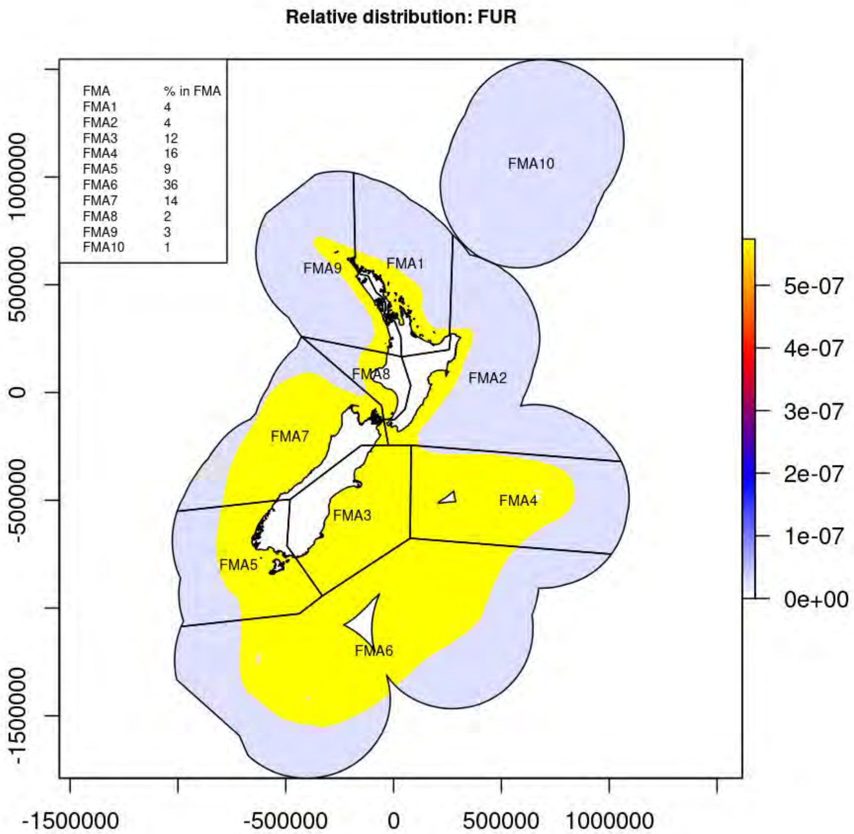

Figure A.10: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.6 Leopard seal

Demographic parameters

Table A.11: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.905	0.026	0.86	0.95
AFR	norm	3.7	0.75	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.95

Table A.12: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	32921	0.35	Antarctic	0.00714

References contributing to stock abundance information: Southwell et al. (2012)

References contributing to NZ abundance information:

Other notes: NZ population is assumed and represents a rare vagrant species. Stock abundance CV is assumed value.

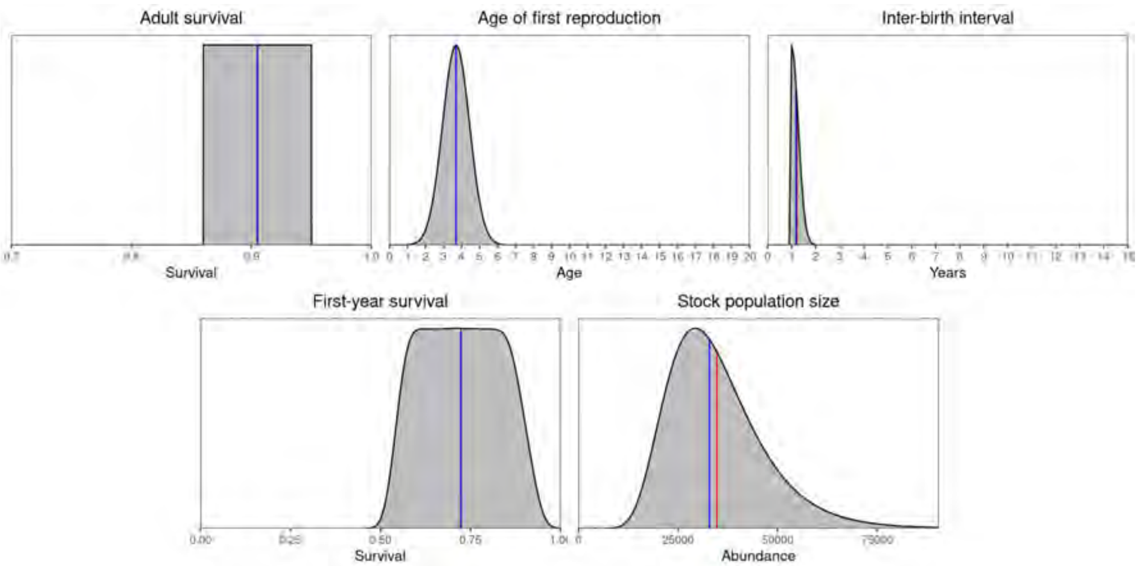

Figure A.11: Prior distributions of demographic input parameters.

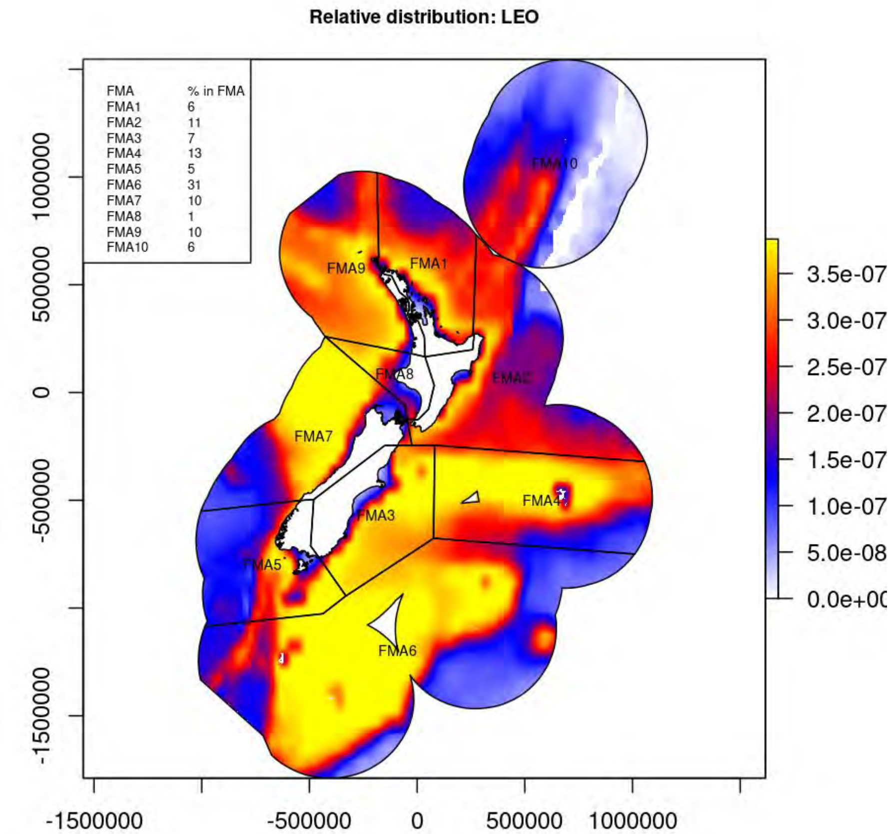

Figure A.12: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.7 Weddell seal

Demographic parameters

Table A.13: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.94	0.01	0.7	0.999
AFR	norm	4.1	0.3	1	Inf
IBI	norm	1.62	0.1	1	Inf
First Yr Surv					

Table A.14: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	595392	0.35	Antarctic	1.58e-06

References contributing to stock abundance information: Southwell et al. (2012)

References contributing to NZ abundance information:

Other notes: NZ population is assumed and represents a very rare vagrant species. Stock abundance CV is assumed value.

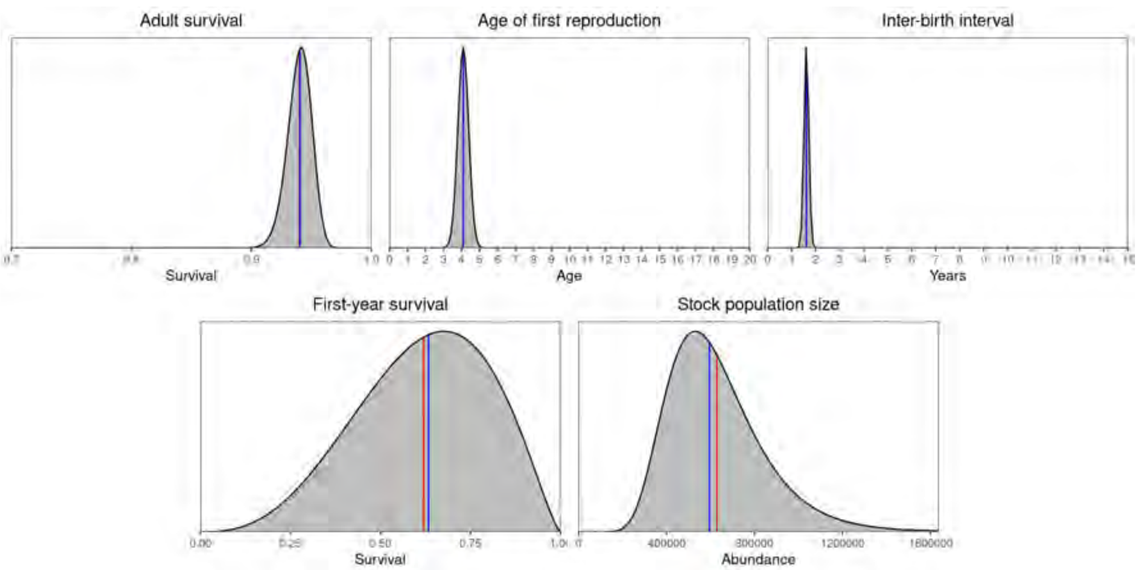

Figure A.13: Prior distributions of demographic input parameters.

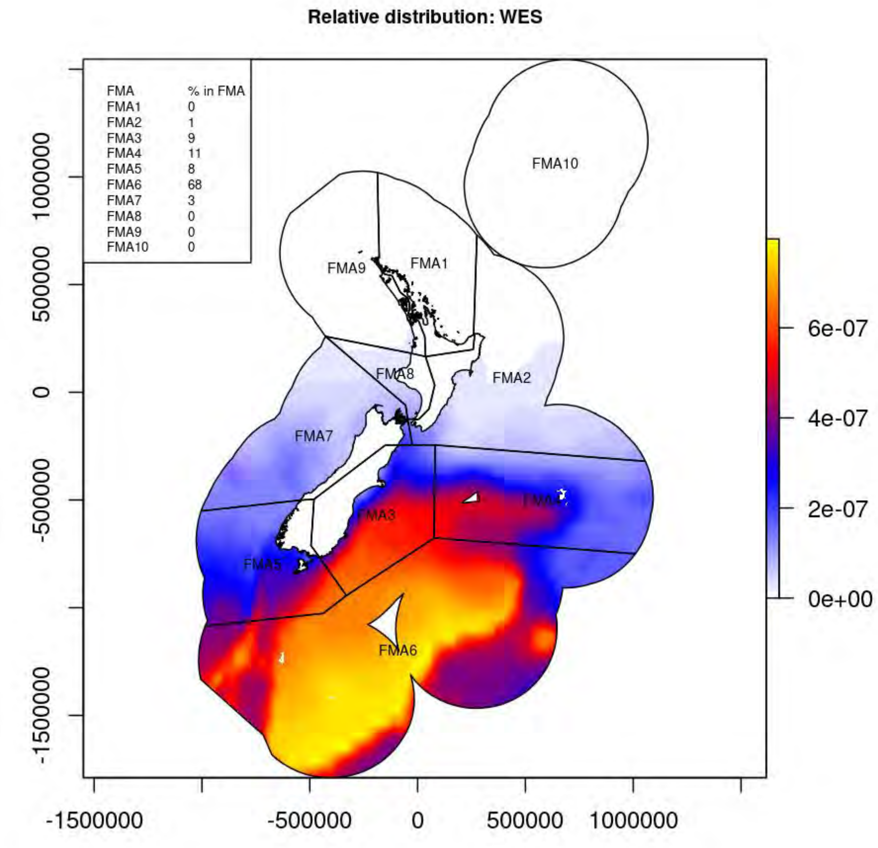

Figure A.14: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.8 New Zealand sea lion

Demographic parameters

Table A.15: Summary of prior distributions used for demographic parameters in determination of r_{max}. Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.95	0.01	0.7	0.999
AFR	norm	4.2	0.1	1	Inf
IBI	norm	1.4	0.1	1	Inf
First Yr Surv					

Table A.16: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	11743	0.046	NZ	1

References contributing to stock abundance information: Chilvers & Meyer (2017)

References contributing to NZ abundance information: Chilvers & Meyer (2017)

Other notes:

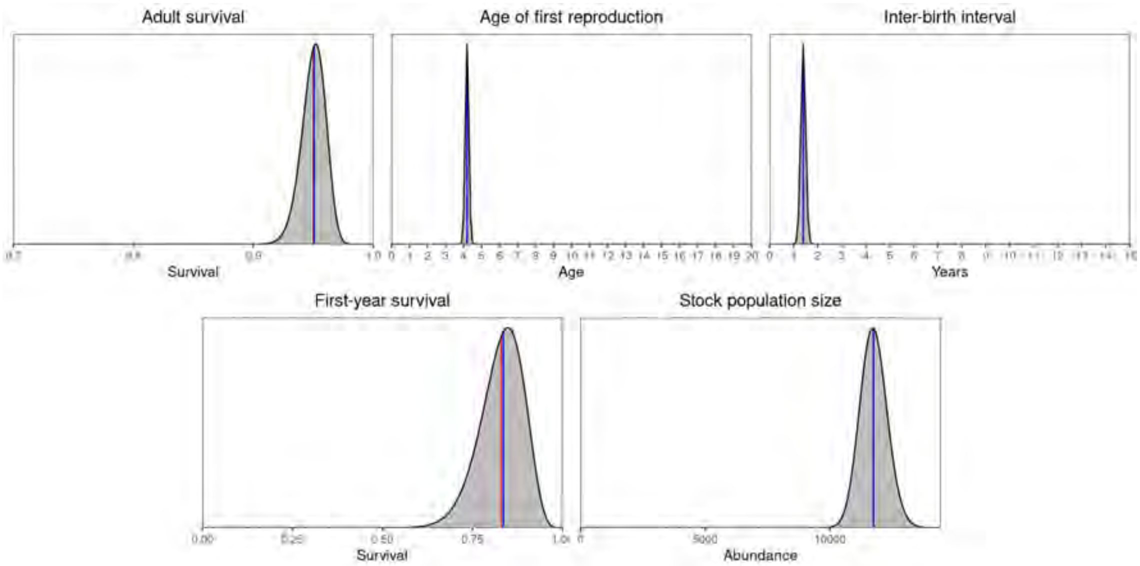

Figure A.15: Prior distributions of demographic input parameters.

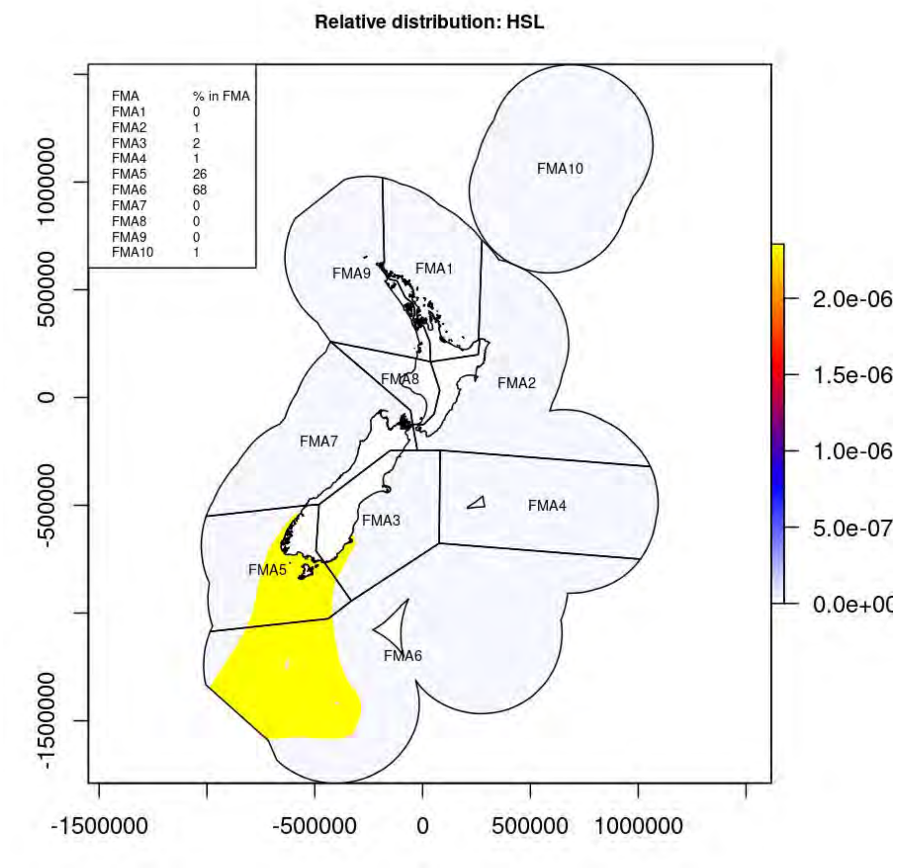

Figure A.16: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.9 Southern elephant seal

Demographic parameters

Table A.17: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.86	0.022	0.7	0.999
AFR	norm	4.2	0.1	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv					

Table A.18: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	71728	0.35	NZ and Macquarie Is.	0.00334

References contributing to stock abundance information: McMahon et al. (2005)

References contributing to NZ abundance information: McMahon et al. (2005)

Other notes: Stock abundance CV is assumed value.

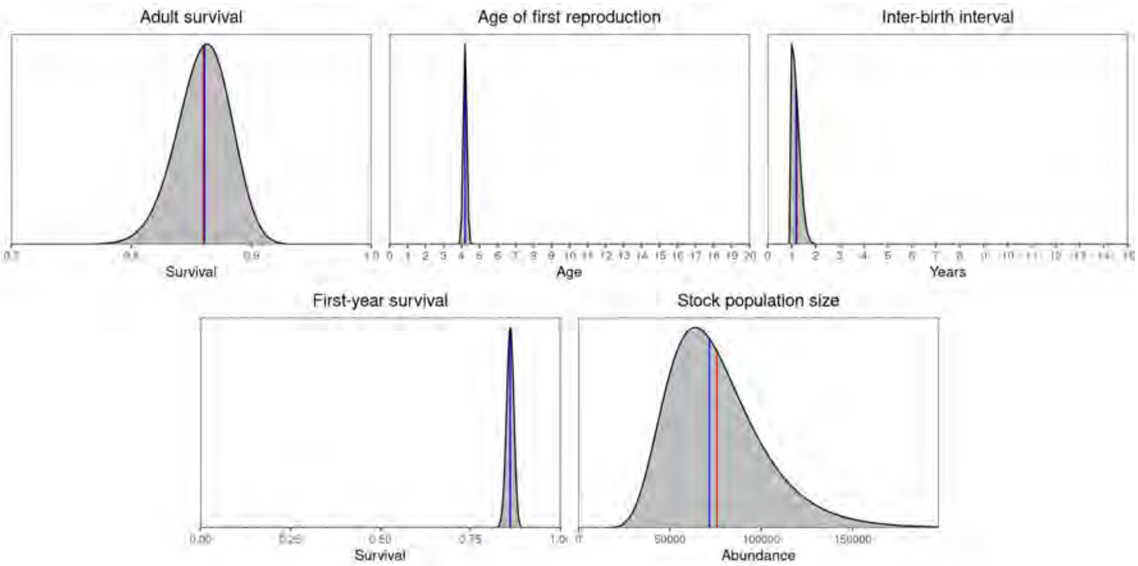

Figure A.17: Prior distributions of demographic input parameters.

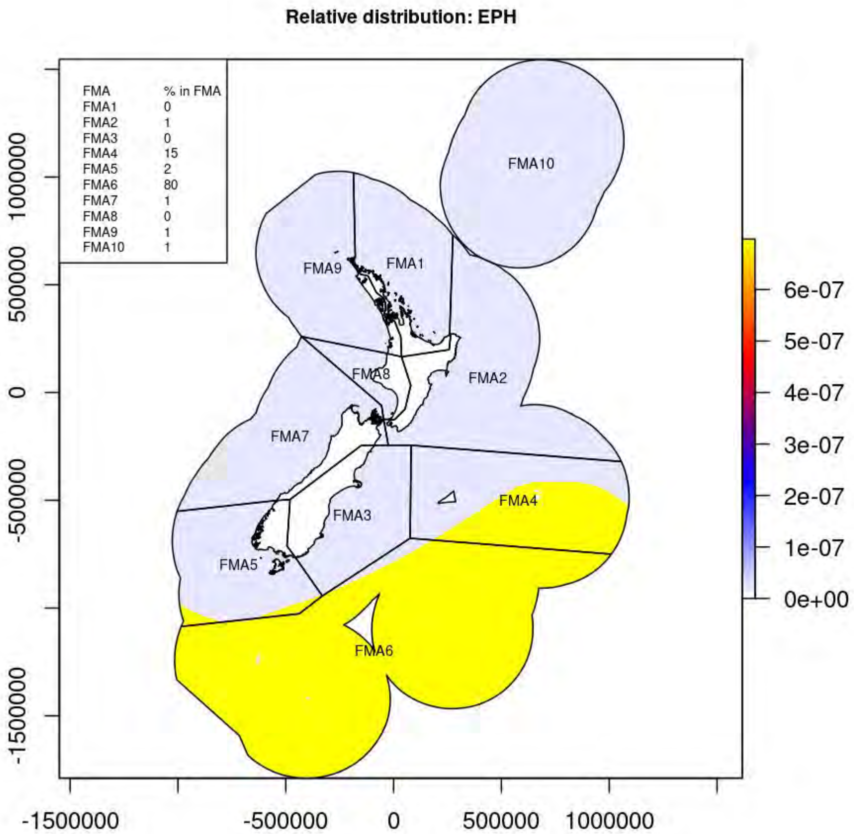

Figure A.18: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.10 Hector's dolphin

Demographic parameters

Table A.19: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.917	0.045	0.7	0.999
AFR	norm	7.8	0.45	1	Inf
IBI	norm	2.38	0.6	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.20: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	14756	0.112	NZ	1

References contributing to stock abundance information: MacKenzie & Clement (2016, 2019)

References contributing to NZ abundance information: MacKenzie & Clement (2016, 2019)

Other notes:

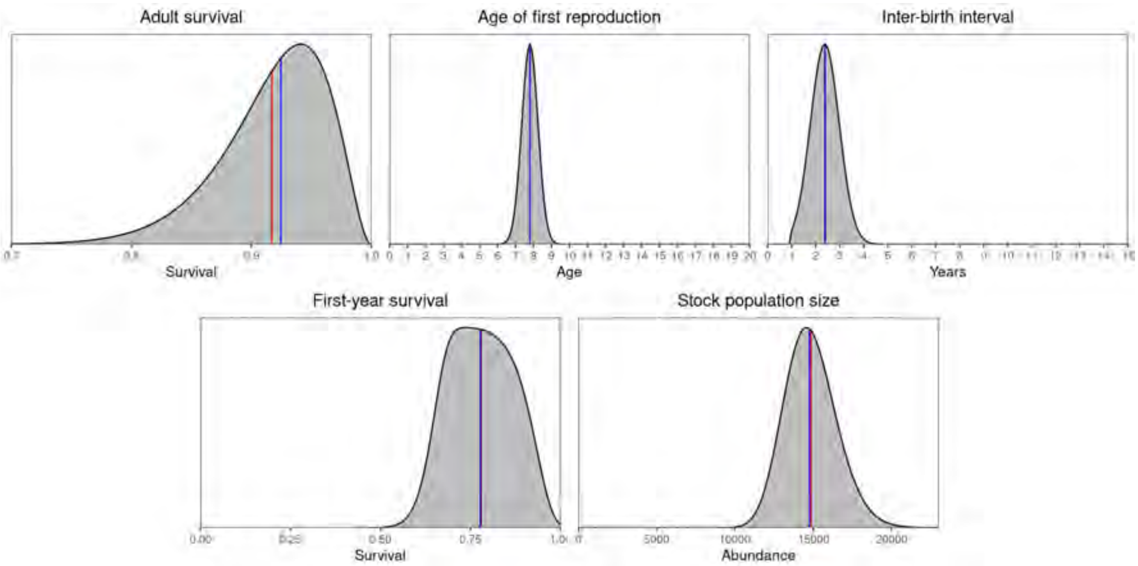

Figure A.19: Prior distributions of demographic input parameters.

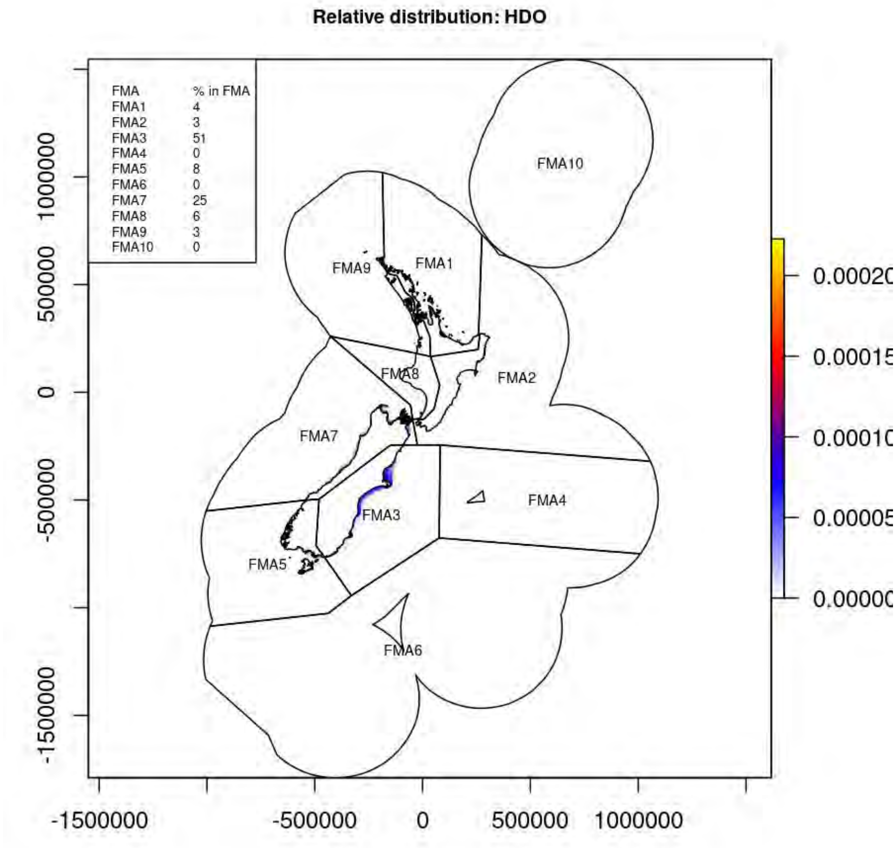

Figure A.20: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.11 Māui dolphin

Demographic parameters

Table A.21: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.917	0.045	0.7	0.999
AFR	norm	7.8	0.45	1	Inf
IBI	norm	2.38	0.6	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.22: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	54	0.082	NZ	1

References contributing to stock abundance information: Constantine et al. (2021)

References contributing to NZ abundance information: Constantine et al. (2021)

Other notes:

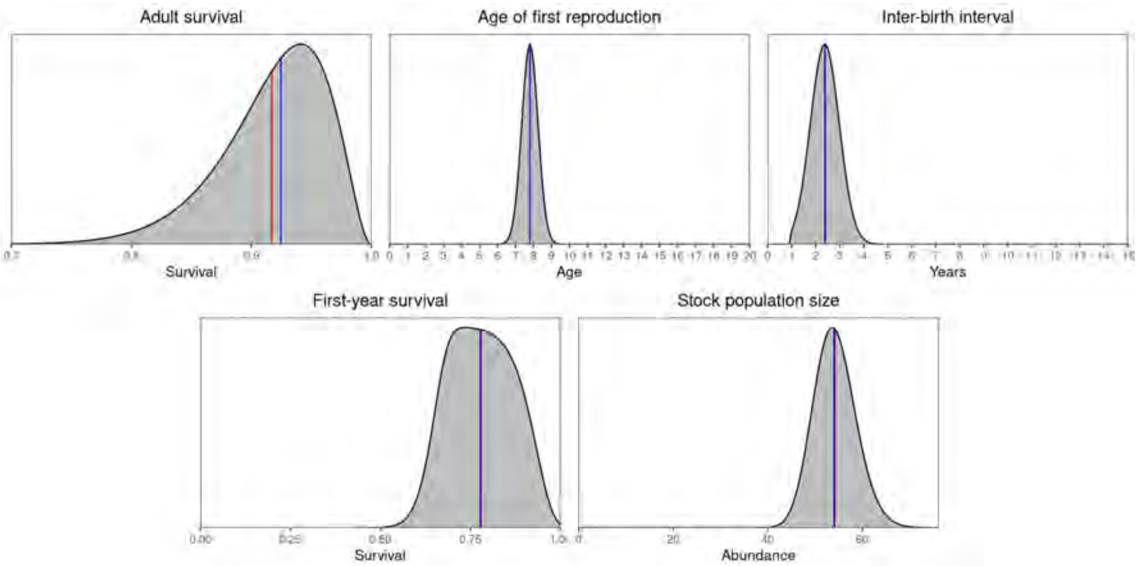

Figure A.21: Prior distributions of demographic input parameters.

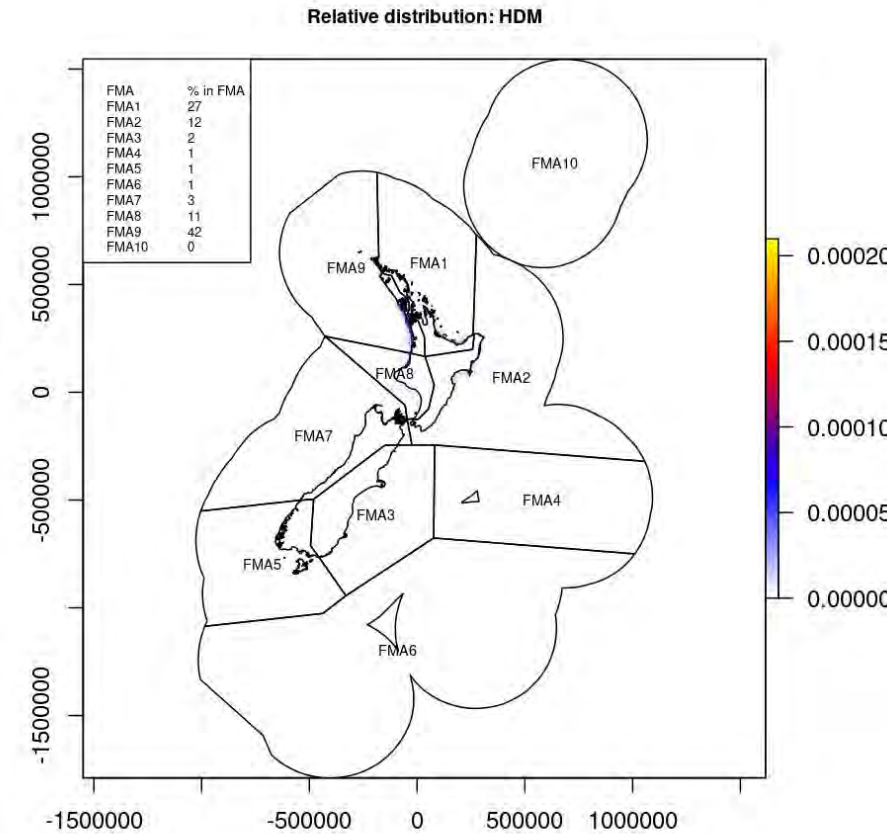

Figure A.22: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.12 Hourglass dolphin

Demographic parameters

Table A.23: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	unif	8.7	1.56	6	11.4
IBI	unif	3	0.58	2	11.4
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.24: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	142230	0.17	Antarctic	0.02

References contributing to stock abundance information: Kasamatsu & Joyce (1995)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}.

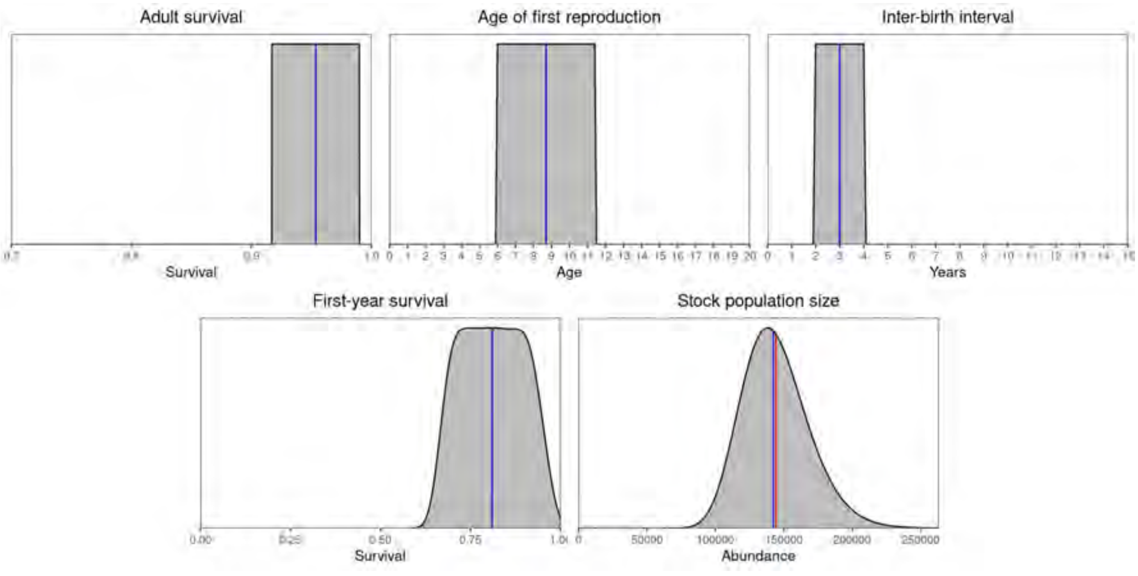

Figure A.23: Prior distributions of demographic input parameters.

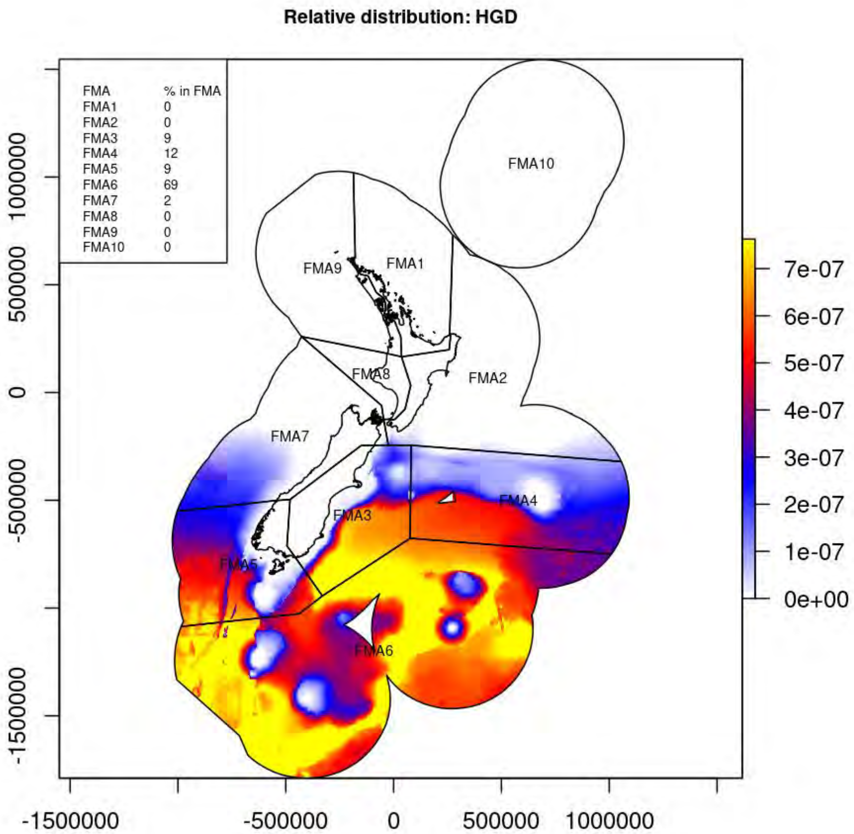

Figure A.24: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.13 Common dolphin

Demographic parameters

Table A.25: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	8.3	0.8	1	Inf
IBI	norm	2.13	0.1	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.26: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	5596800	0.373	Worldwide	0.023

References contributing to stock abundance information: Braulik et al. (2021)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}.

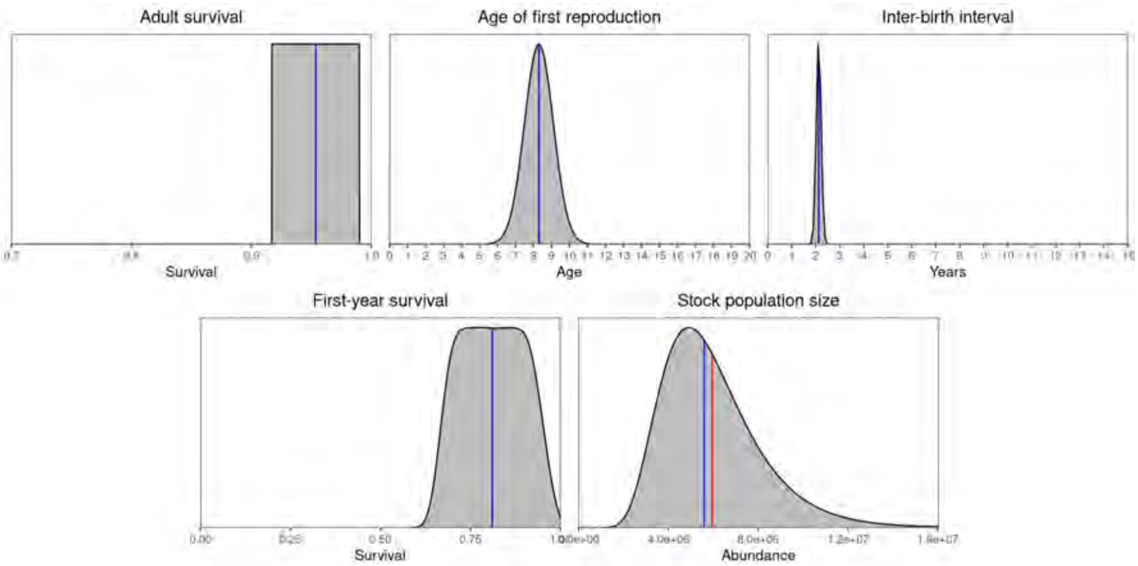

Figure A.25: Prior distributions of demographic input parameters.

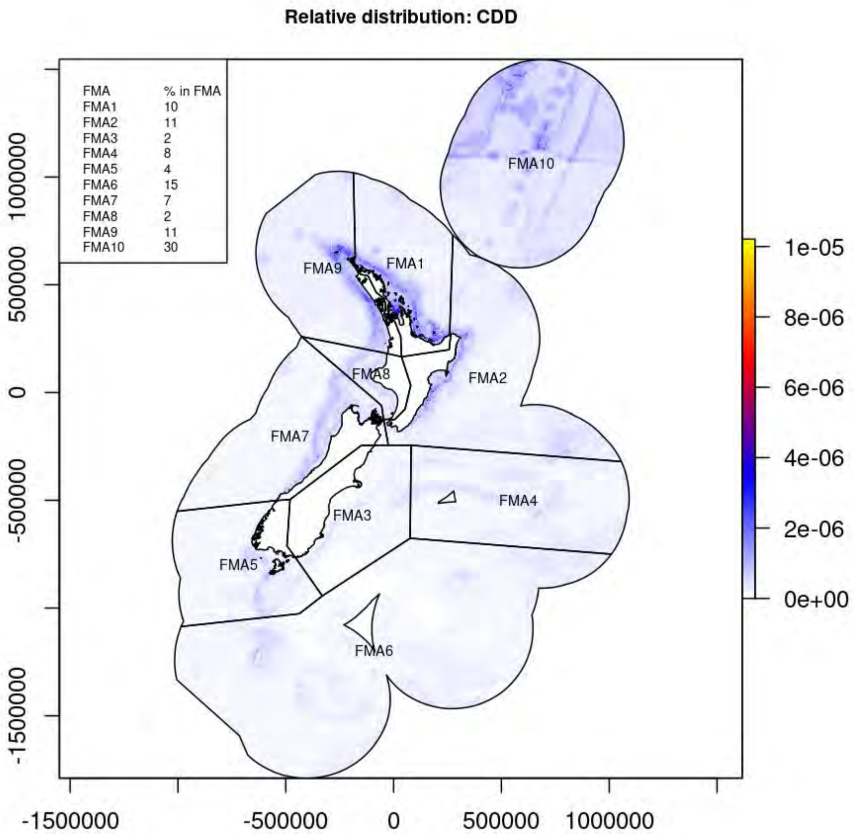

Figure A.26: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.14 Dusky dolphin

Demographic parameters

Table A.27: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	6	1.21	1	Inf
IBI	norm	2.4	0.1	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.28: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	28442	0.35	NZ	1

References contributing to stock abundance information: Harlin et al. (2003), Markowitz et al. (2004), Markowitz (2004)

References contributing to NZ abundance information: Harlin et al. (2003), Markowitz et al. (2004), Markowitz (2004)

Other notes:

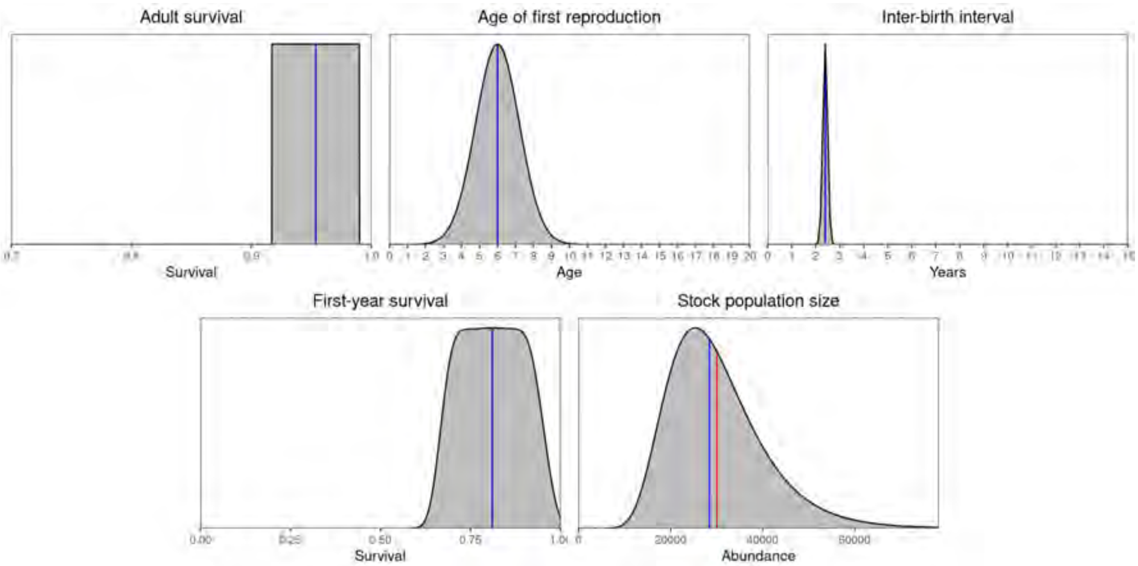

Figure A.27: Prior distributions of demographic input parameters.

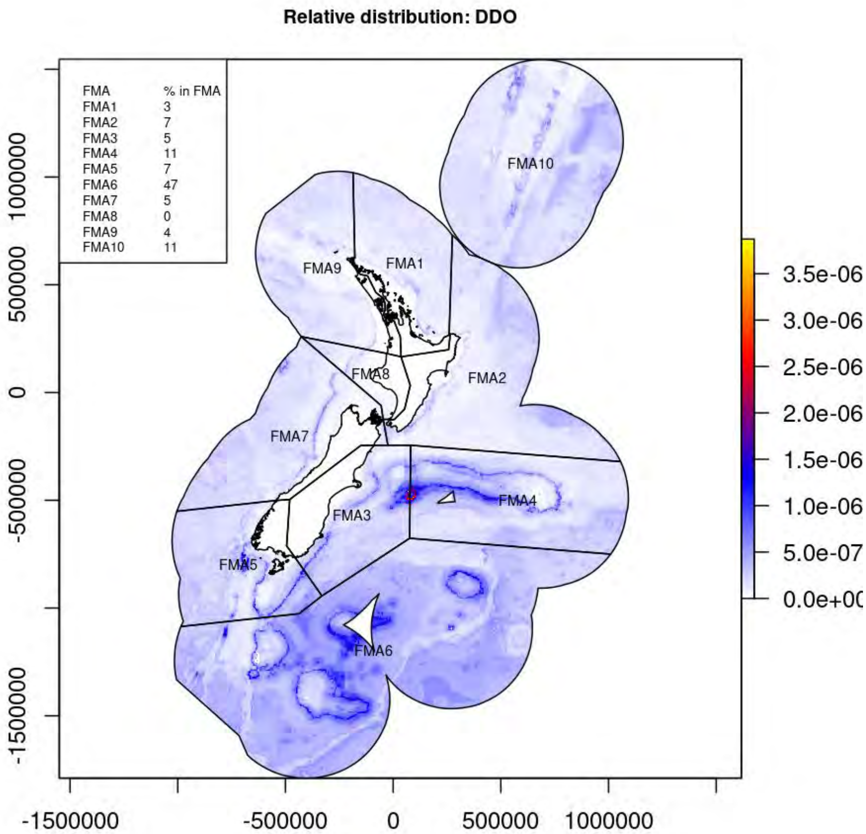

Figure A.28: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.15 Spectacled porpoise

Demographic parameters

Table A.29: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	unif	8.7	1.56	6	11.4
IBI	unif	3	0.58	2	11.4
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.30: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	2002	0.35	Worldwide	0.047

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: Within New Zealand this species is listed under the domestic Threat Classification System as Data Deficient and noted as uncertain whether the taxon is secure overseas (Baker et al. 2019). Total stock is derived from an assumed NZ population and proportion in EEZ. NZ population is assummed value. Stock abundance CV is assumed value.

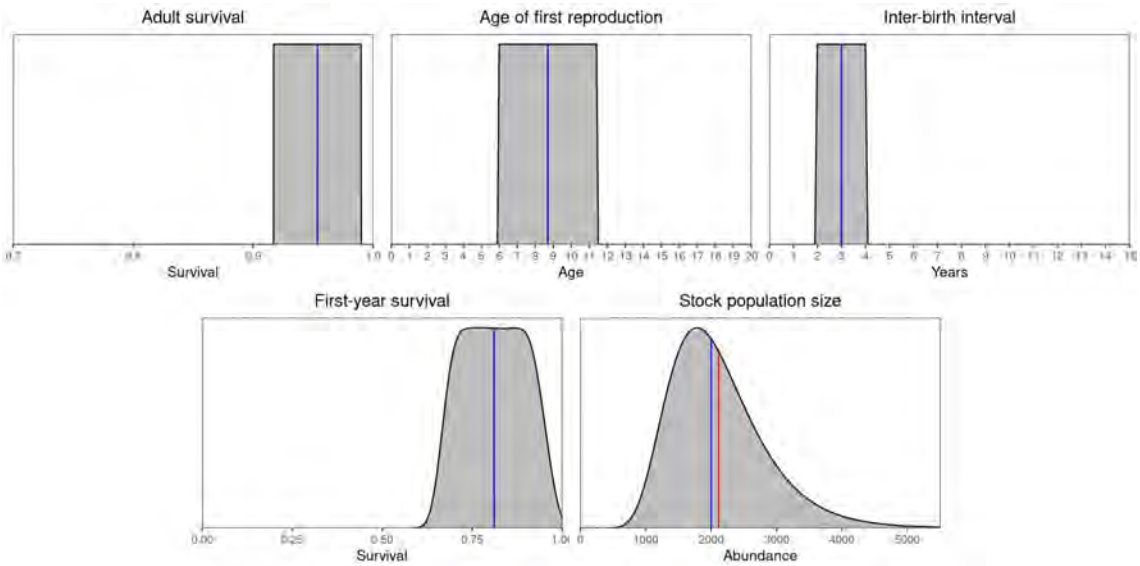

Figure A.29: Prior distributions of demographic input parameters.

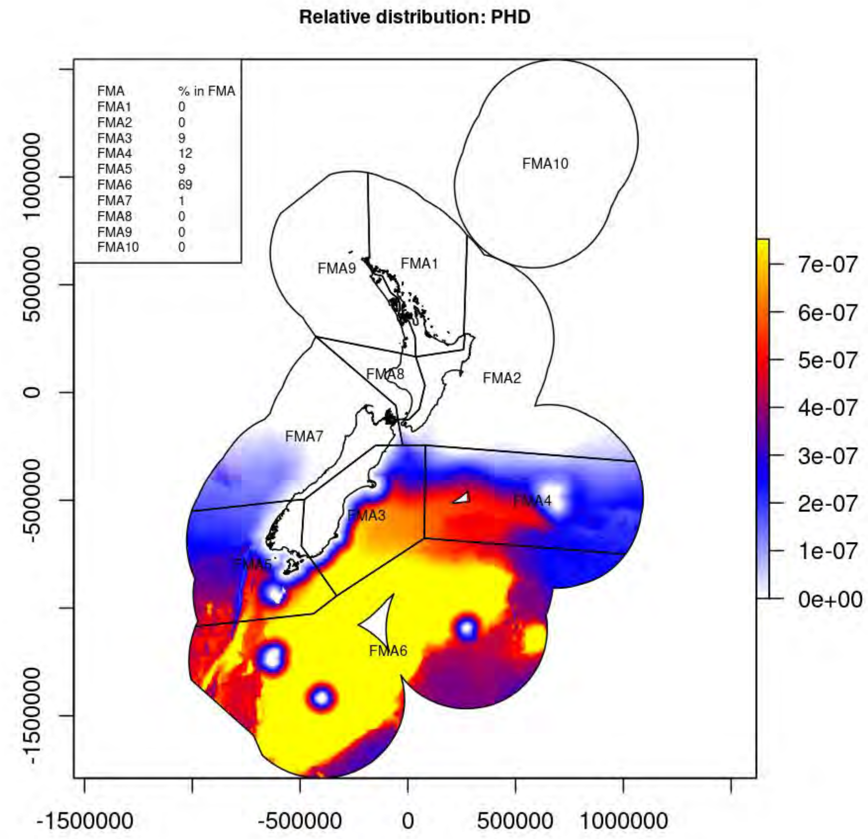

Figure A.30: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.16 Bottlenose dolphin

Demographic parameters

Table A.31: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.97	0.005	0.7	0.999
AFR	norm	8.2	1.1	1	Inf
IBI	norm	2.5	0.3	1	Inf
First Yr Surv					

Table A.32: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	1892	0.35	NZ	1

References contributing to stock abundance information: Baker et al. (2019), Currey et al. (2009), Merriman et al. (2009), Tezanos-Pinto et al. (2009), Zaeschmar et al. (2013)

References contributing to NZ abundance information: Baker et al. (2019), Currey et al. (2009), Merriman et al. (2009), Tezanos-Pinto et al. (2009), Zaeschmar et al. (2013)

Other notes: Stock abundance CV is assumed value.

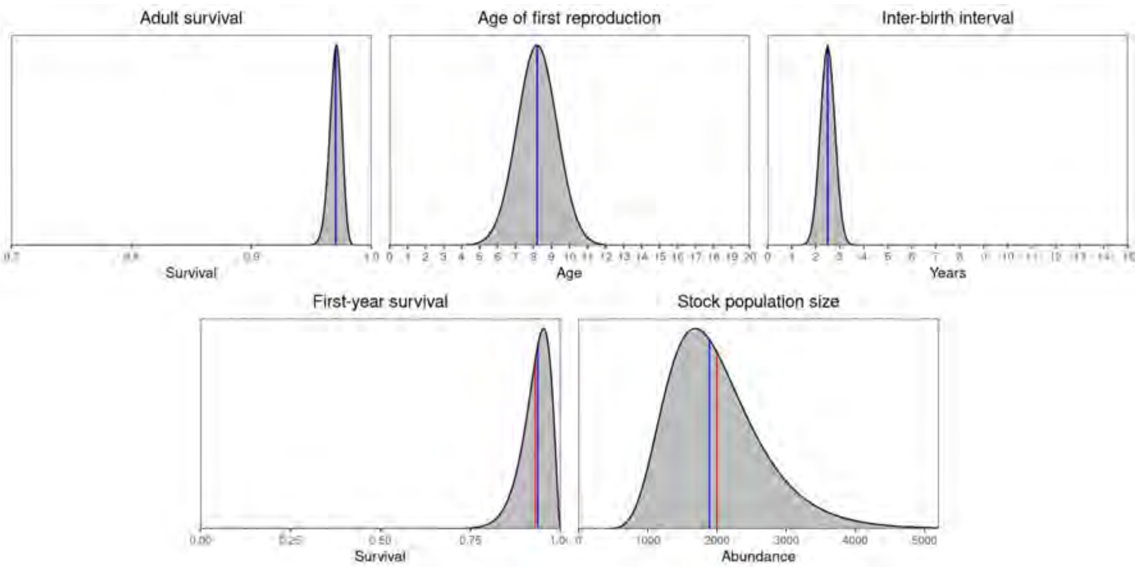

Figure A.31: Prior distributions of demographic input parameters.

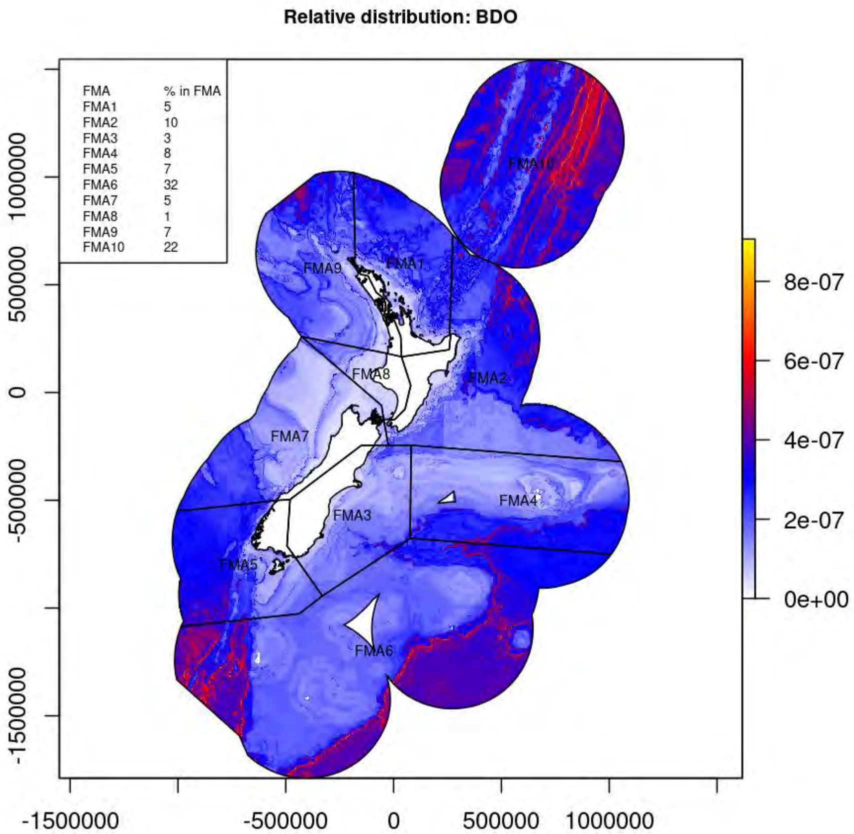

Figure A.32: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.17 Pygmy killer whale

Demographic parameters

Table A.33: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	unif	8.7	1.56	6	11.4
IBI	unif	3	0.58	2	11.4
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.34: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	36899	0.325	Worldwide	0.012

References contributing to stock abundance information: Wade & Gerrodette (1993)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}.

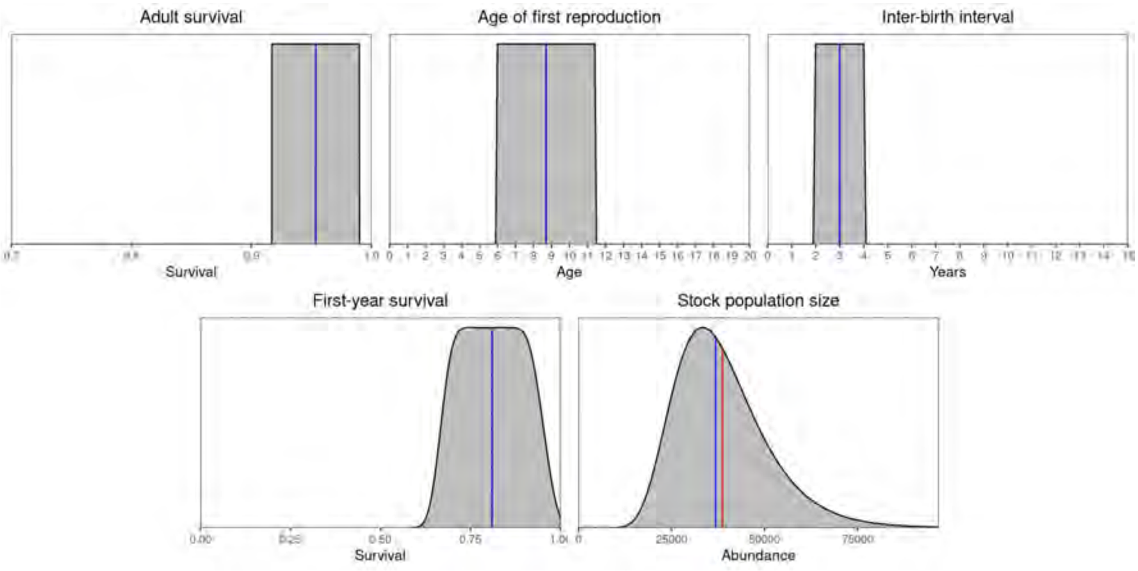

Figure A.33: Prior distributions of demographic input parameters.

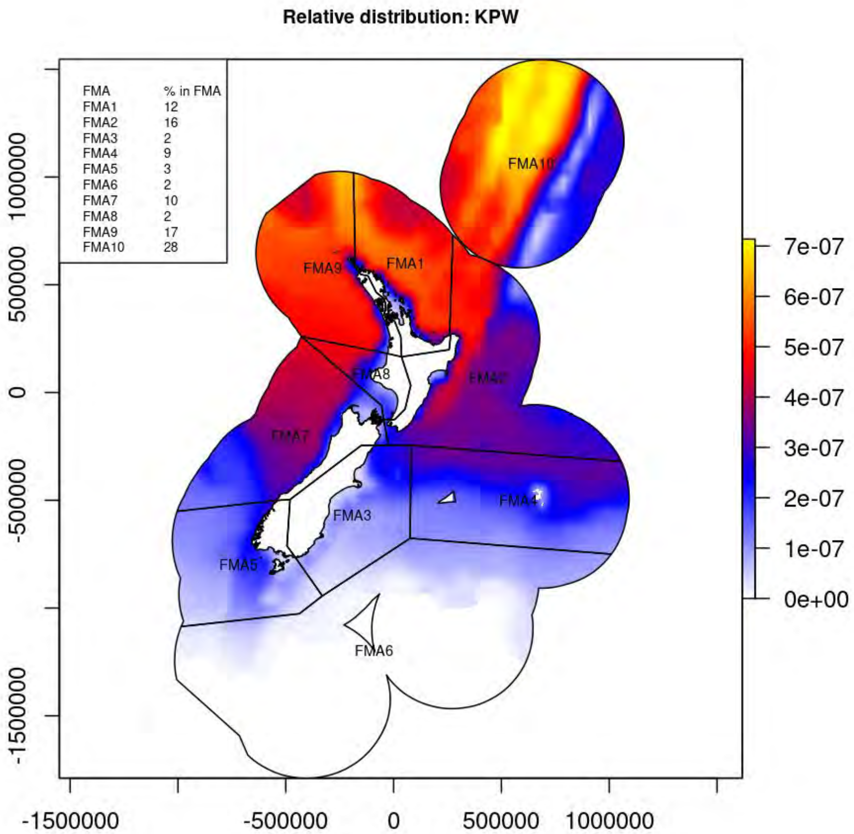

Figure A.34: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.18 Pantropical spotted dolphin

Demographic parameters

Table A.35: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	9.5	0.2	1	Inf
IBI	norm	3	0.82	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.36: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	2956962	0.17	Worldwide	0.014

References contributing to stock abundance information: Wikipedia contributors (2021a)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}.

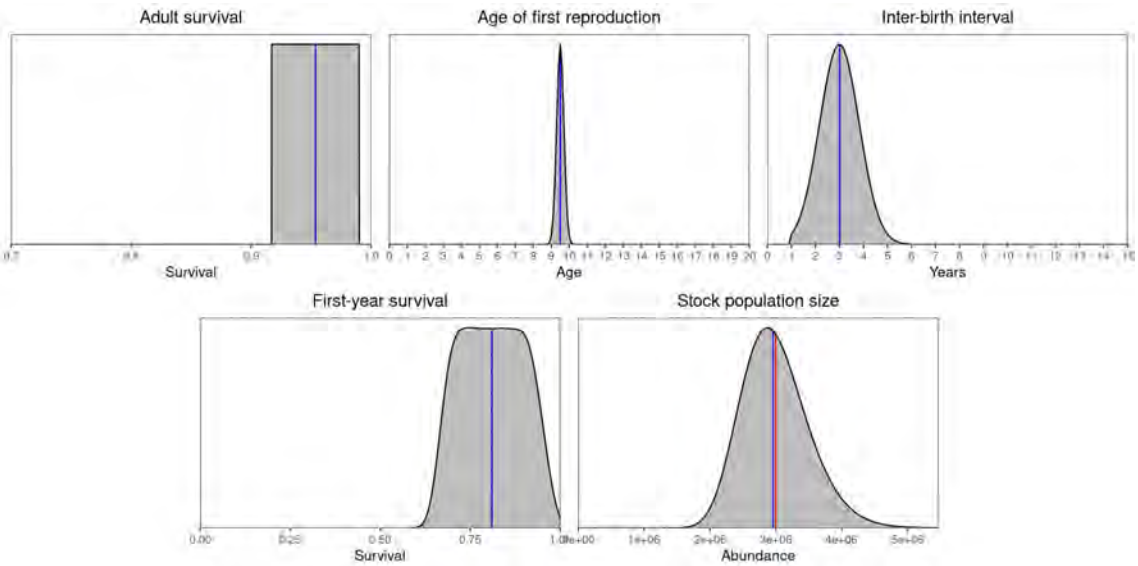

Figure A.35: Prior distributions of demographic input parameters.

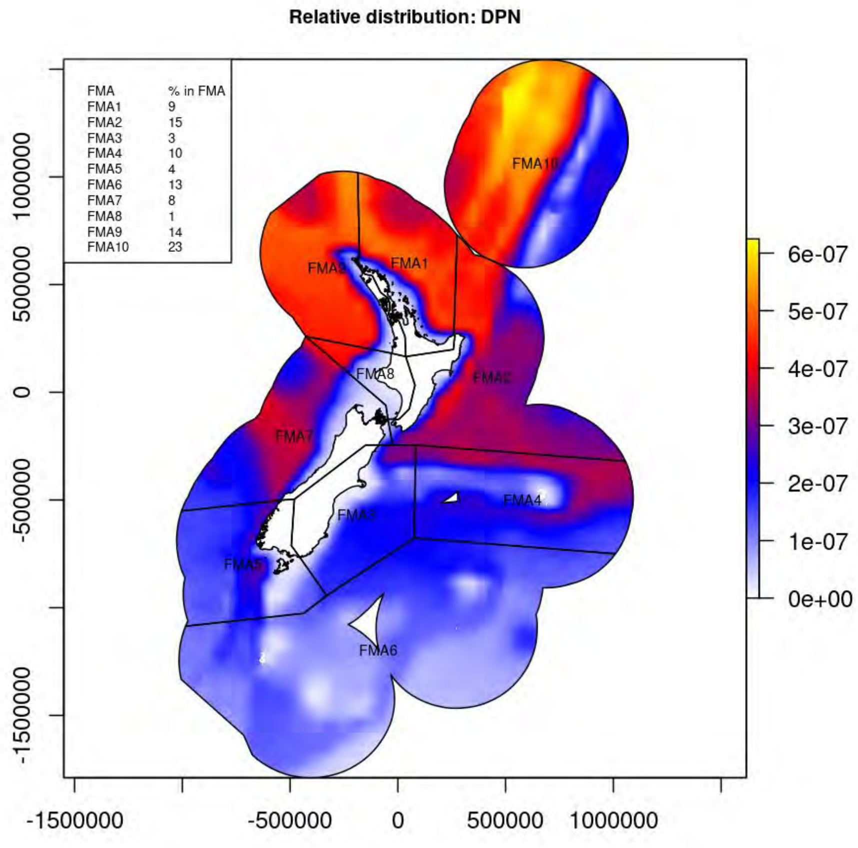

Figure A.36: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.19 Striped dolphin

Demographic parameters

Table A.37: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	9.3	0.3	1	Inf
IBI	norm	4	1.1	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.38: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	1881176	0.35	Worldwide	0.015

References contributing to stock abundance information: Wikipedia contributors (2021b)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

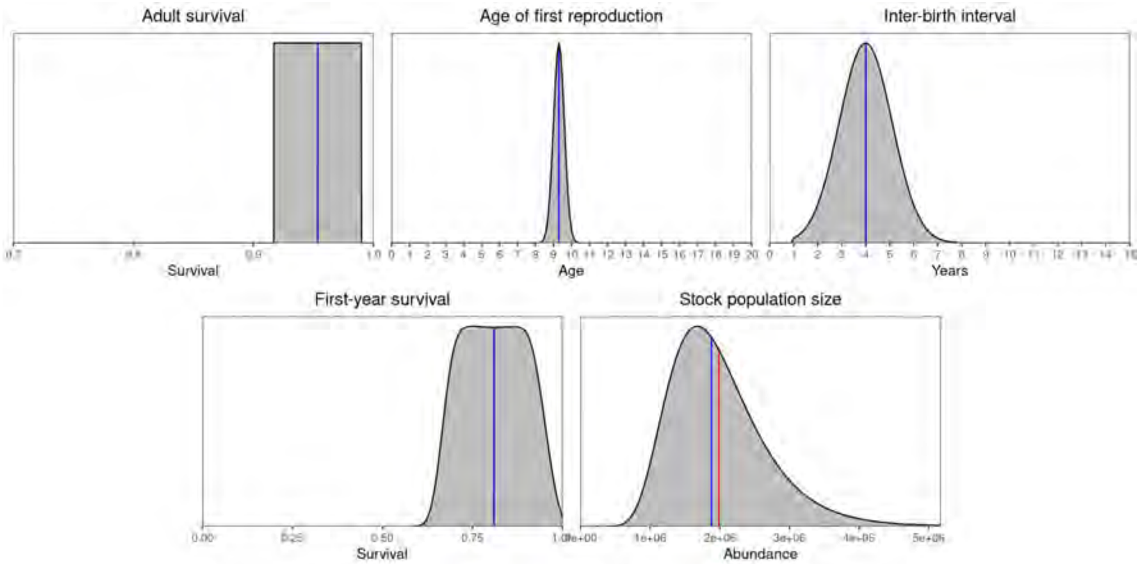

Figure A.37: Prior distributions of demographic input parameters.

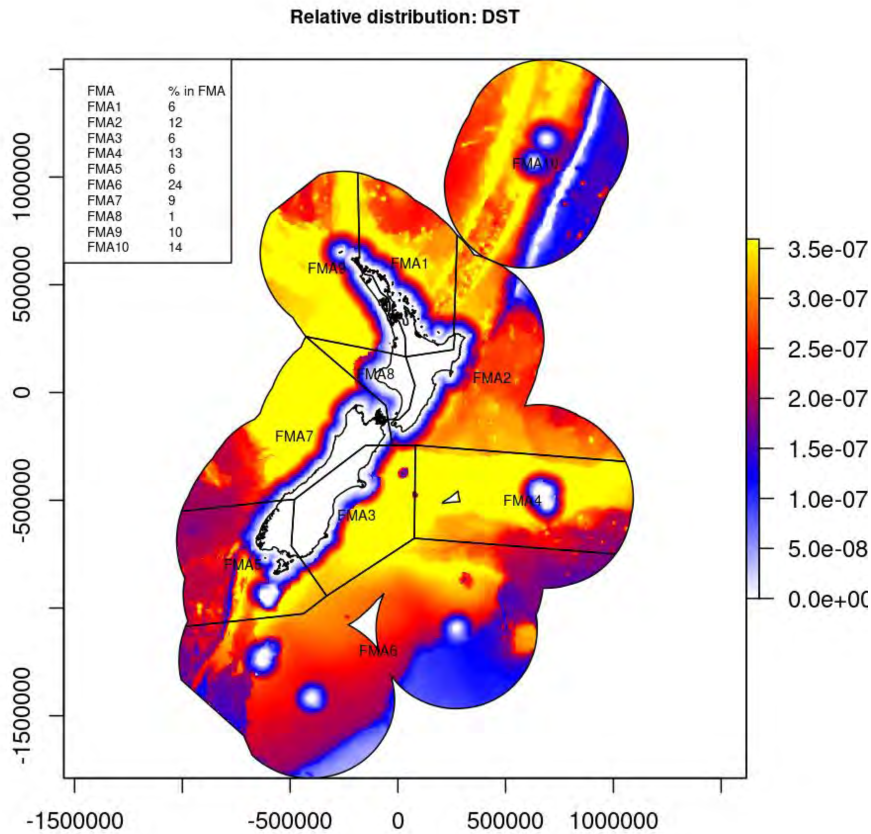

Figure A.38: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.20 Rough-toothed dolphin

Demographic parameters

Table A.39: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.99	0.01	0.7	0.999
AFR	norm	10	2.02	1	Inf
IBI	unif	3	0.58	2	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.40: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	208045	0.35	Worldwide	0.01

References contributing to stock abundance information: Kiszka et al. (2019)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

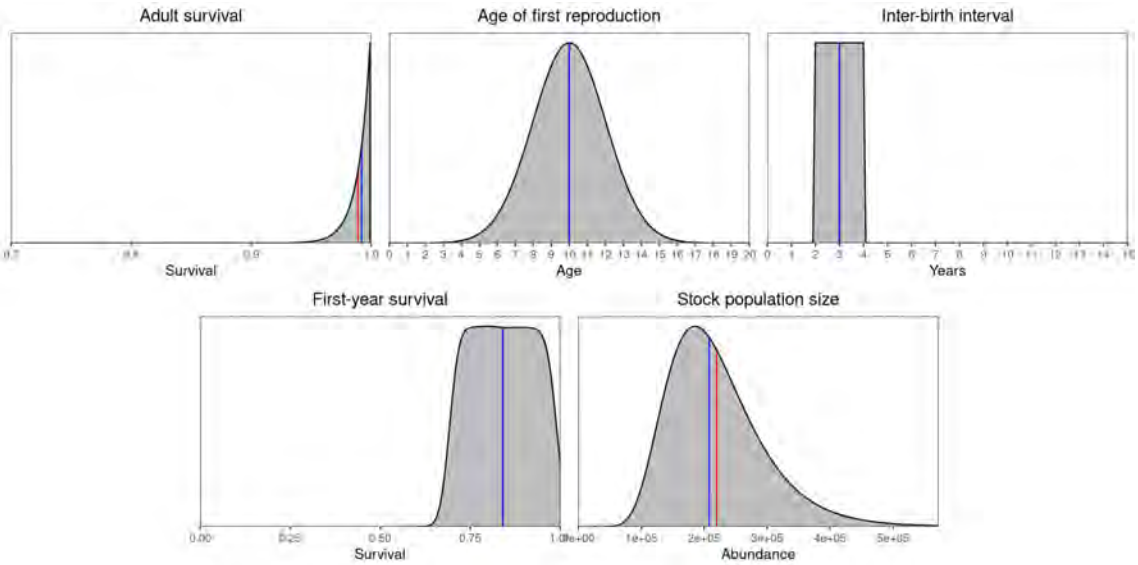

Figure A.39: Prior distributions of demographic input parameters.

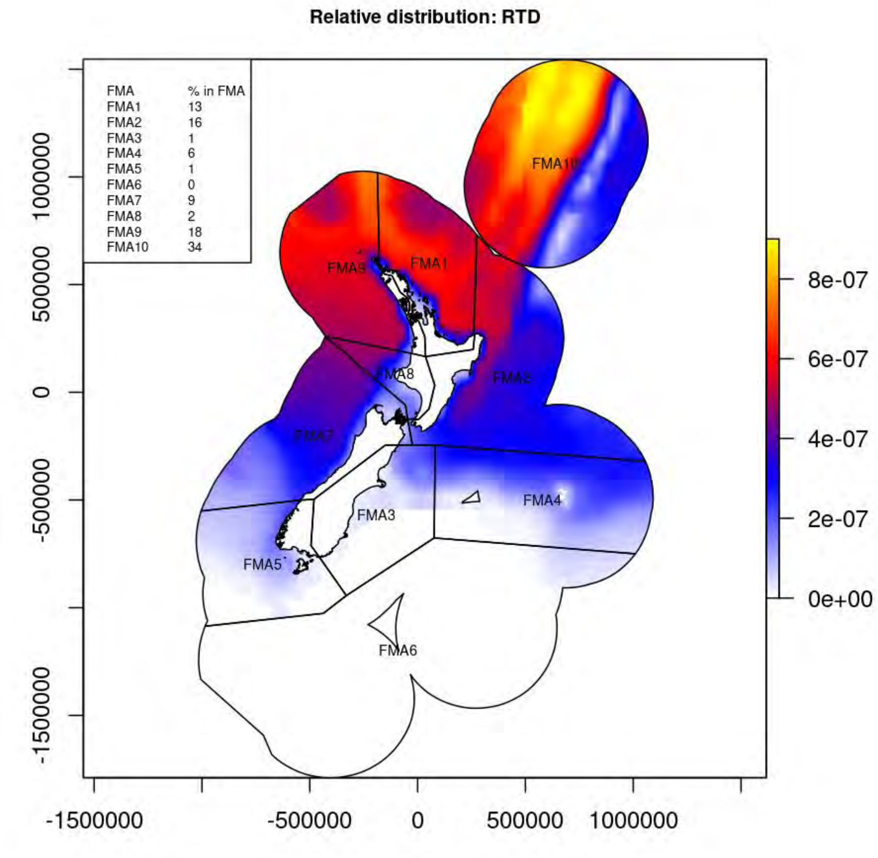

Figure A.40: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.21 Fraser's dolphin

Demographic parameters

Table A.41: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	7.1	0.9	1	Inf
IBI	norm	2	0.4	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.42: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	294445	0.35	Worldwide	0.008

References contributing to stock abundance information: Wade & Gerrodette (1993), Dolar et al. (2006), Barlow (2006)

References contributing to NZ abundance information:

Other notes: Global estimate consists of Eastern Tropical Pacific (289,300, CV = 0.34), eastern Sulu Sea (13,518, CV = 0.26), Hawaii (10,226, CV = 1.16). From Baker et al. (2019): "Moved from Vagrant to Data Deficient. Possibly resident in northern subtropical waters of New Zealand. No data on abundance or trends in New Zealand waters are available." NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

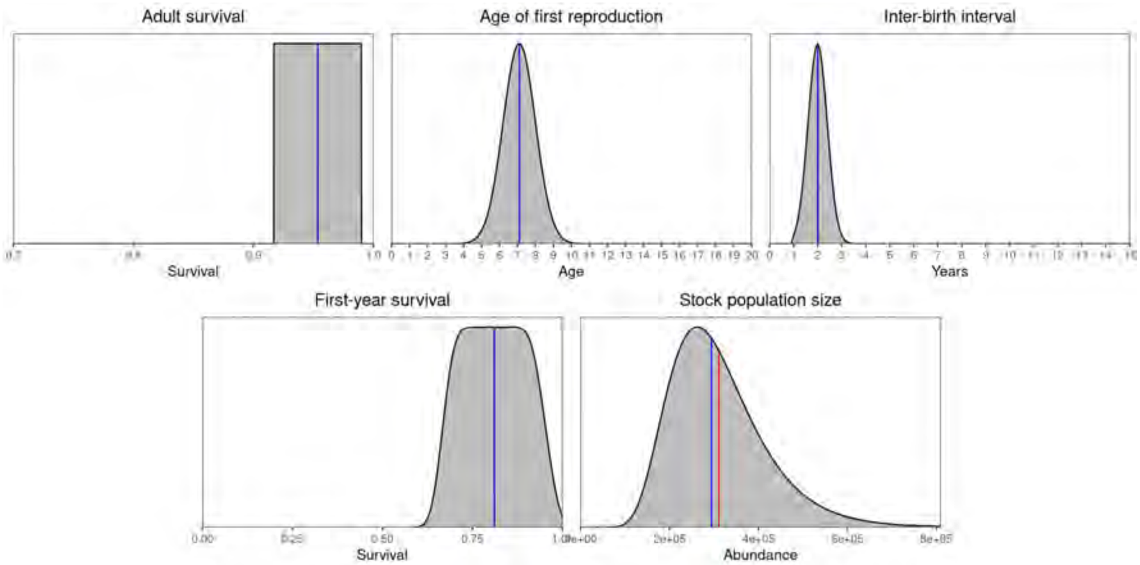

Figure A.41: Prior distributions of demographic input parameters.

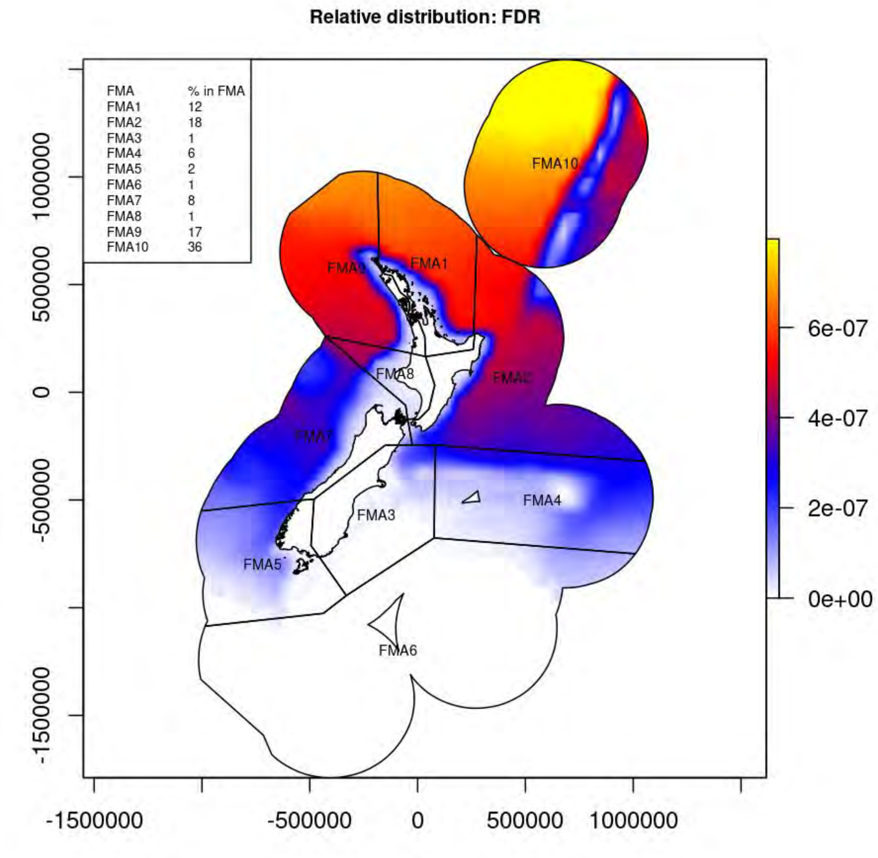

Figure A.42: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.22 Risso's dolphin

Demographic parameters

Table A.43: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	8.7	0.7	1	Inf
IBI	norm	2.4	0.66	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.44: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	329206	0.35	Worldwide	0.009

References contributing to stock abundance information: Kiszka et al. (2019)

References contributing to NZ abundance information:

Other notes: Global estimate only a proportion of possible range (Europe, Japan, Hawaii, Eastern Tropical Pacific, North and West Indian Ocean, NW Atlantic). In NZ, only 6 at-sea sightings and 14 strandings of 20 individuals since 1867 (Peters & Stockin 2021). NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

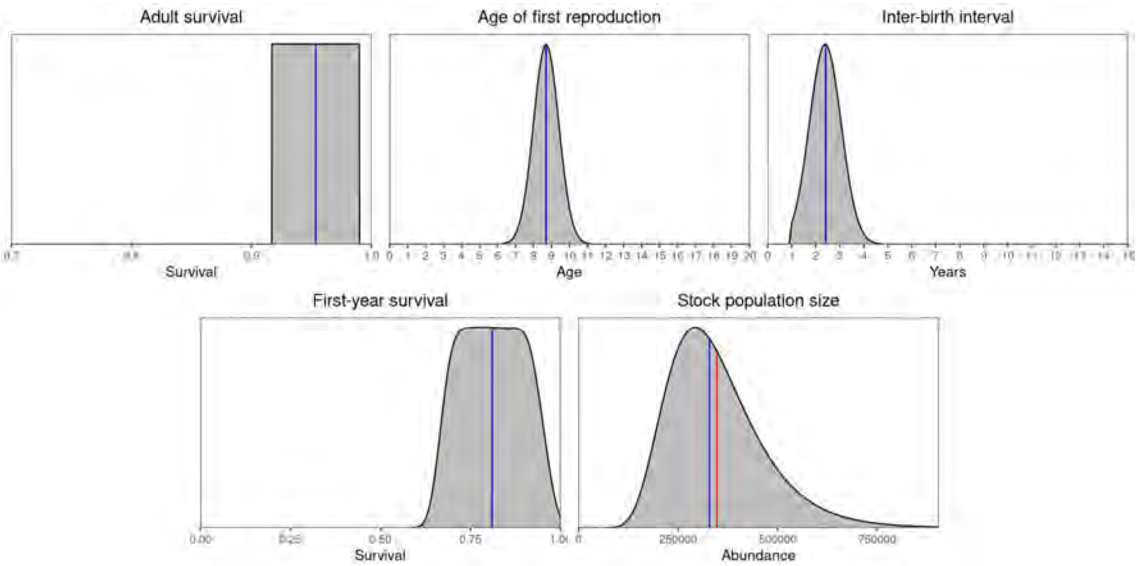

Figure A.43: Prior distributions of demographic input parameters.

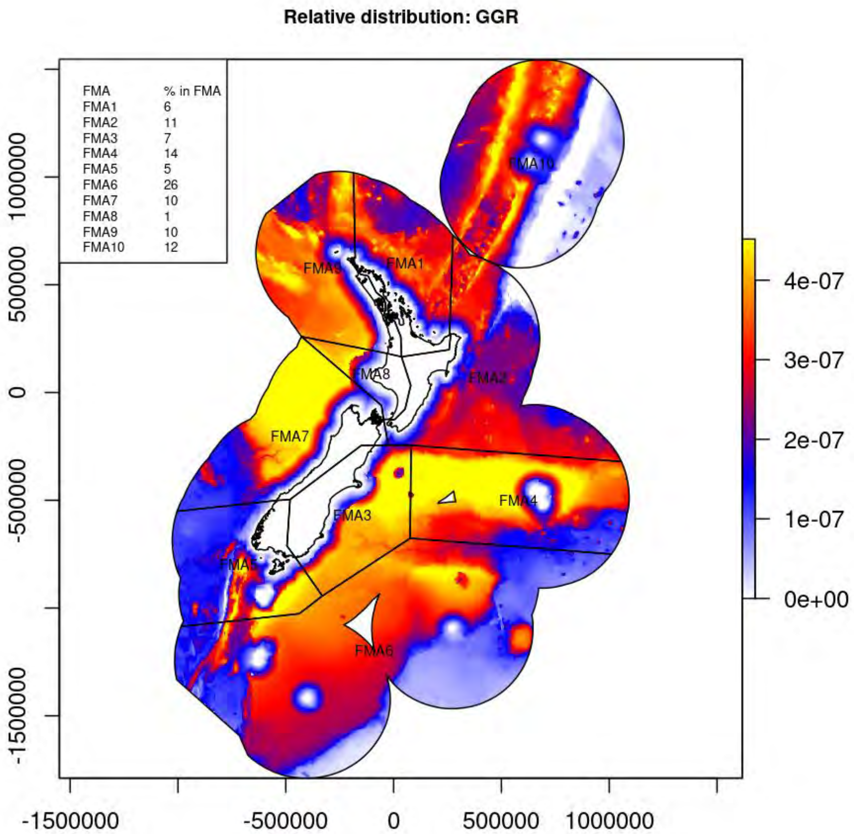

Figure A.44: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.23 Southern right whale dolphin

Demographic parameters

Table A.45: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.954	0.021	0.917	0.99
AFR	norm	11.4	0.5	1	Inf
IBI	norm	2	0.55	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.99

Table A.46: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	20013	0.35	Worldwide	0.047

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: Worldwide population estimate is derived from an order of magnitude assumed value for NZ population size, and assumed proportion in NZ EEZ. Stock abundance CV is assumed value.

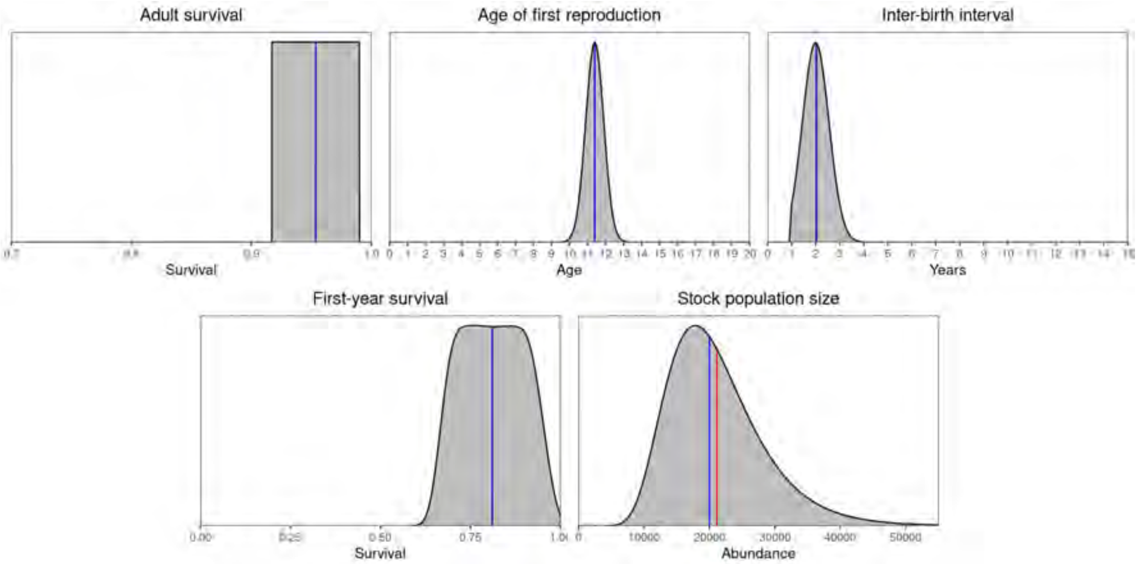

Figure A.45: Prior distributions of demographic input parameters.

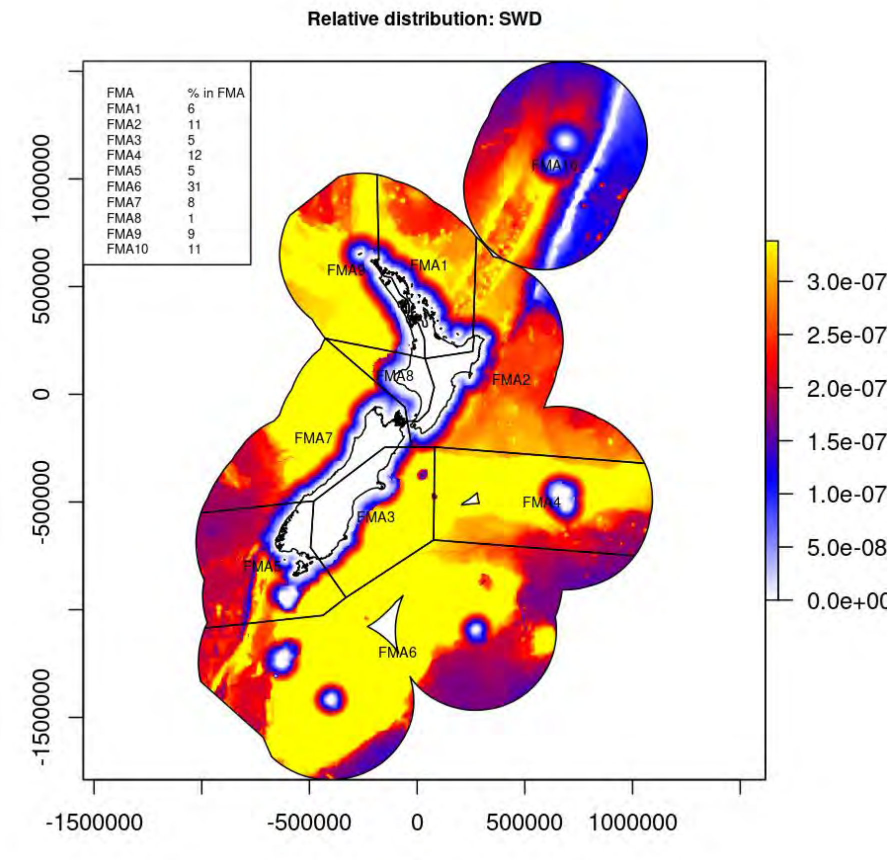

Figure A.46: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.24 Melon-headed whale

Demographic parameters

Table A.47: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.94	0.007	0.7	0.999
AFR	norm	8	1.62	1	Inf
IBI	norm	3.5	0.98	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.48: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	94059	0.35	Worldwide	0.009

References contributing to stock abundance information: Dolar et al. (2006), Bradford et al. (2017), Wade & Gerrodette (1993), Waring et al. (2013), Kiszka & Brownell Jr. (2019)

References contributing to NZ abundance information:

Other notes: Worldwide population estimate is derived from an order of magnitude assumed value for NZ population size, and assumed proportion in NZ EEZ. Stock abundance CV is assumed value.

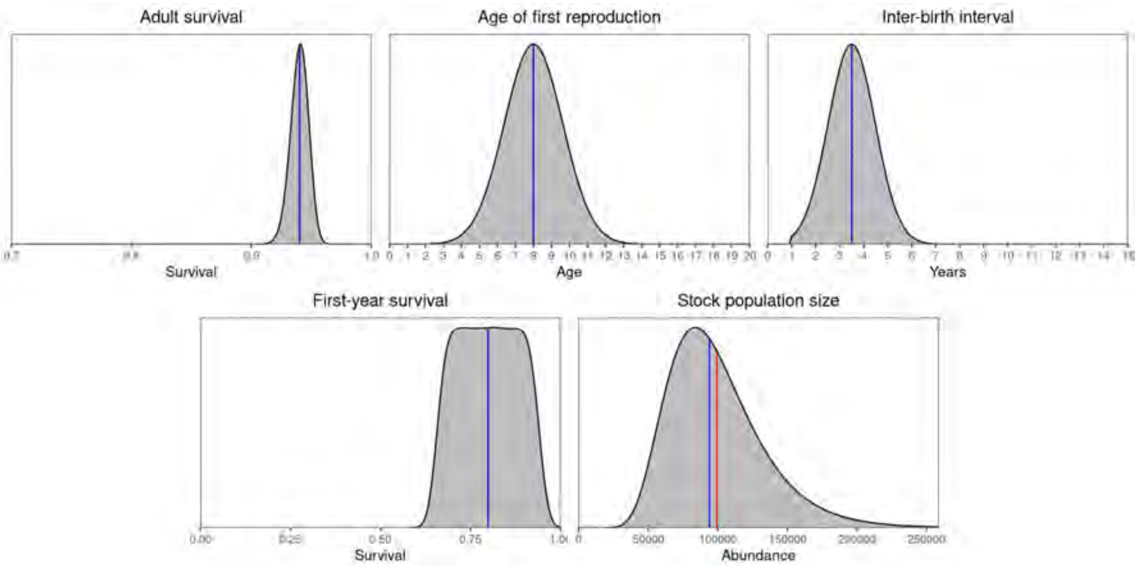

Figure A.47: Prior distributions of demographic input parameters.

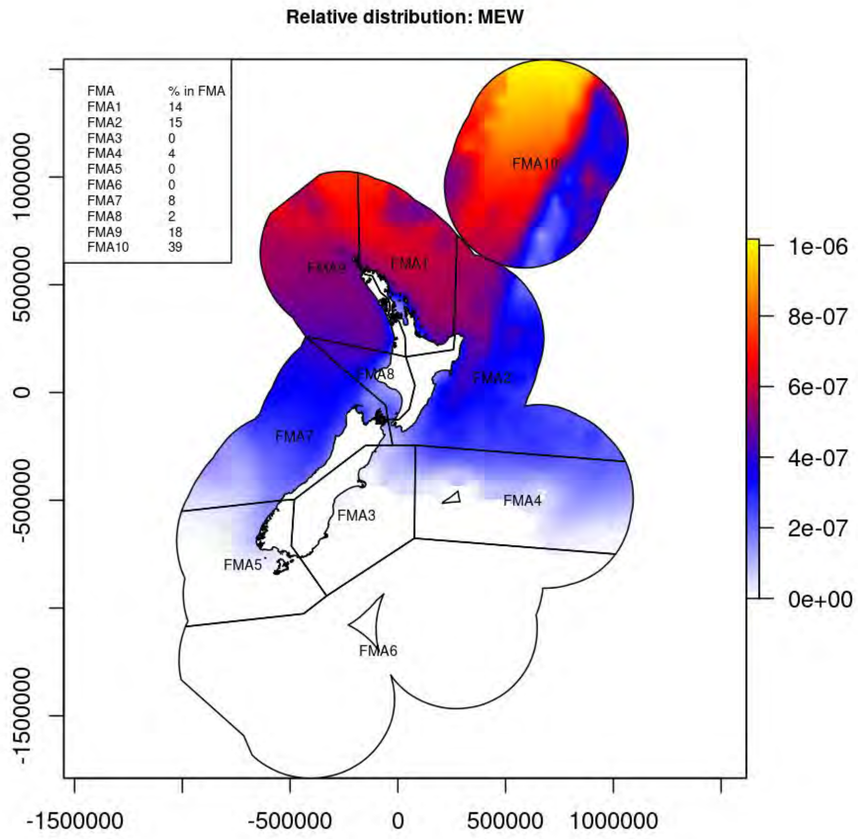

Figure A.48: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.25 False killer whale

Demographic parameters

Table A.49: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.95	0.043	0.7	0.999
AFR	norm	10.4	2.1	1	Inf
IBI	norm	4.5	1.26	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.50: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	54966	0.35	Worldwide	0.018

References contributing to stock abundance information:

References contributing to NZ abundance information: Baker et al. (2019), Zaeschmar (2014)

Other notes: Total stock abundance derived from NZ stock and P^{EEZ}. Stock abundance CV is assumed value.

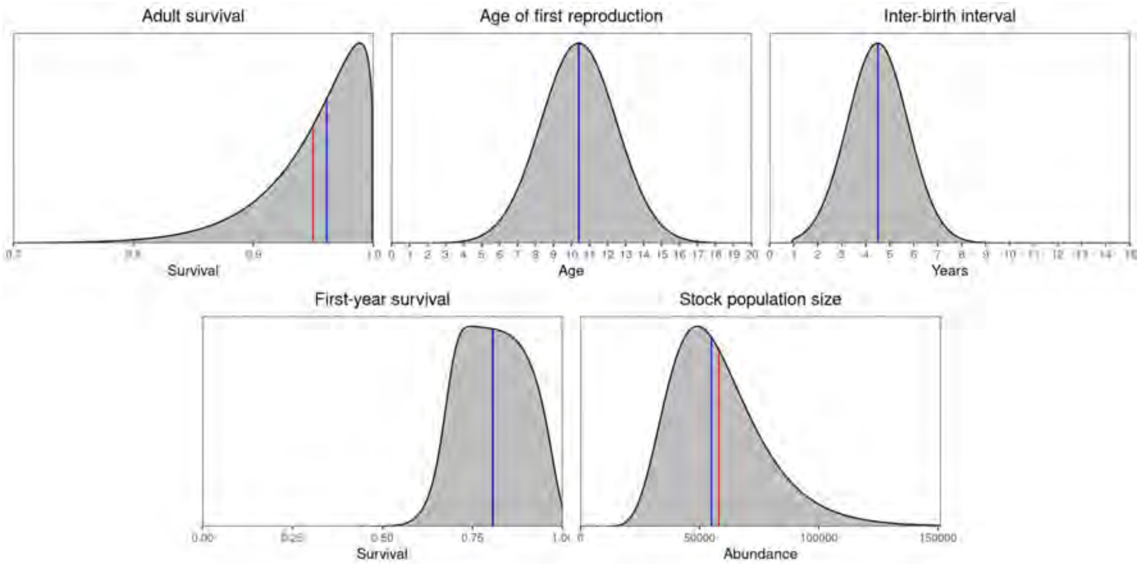

Figure A.49: Prior distributions of demographic input parameters.

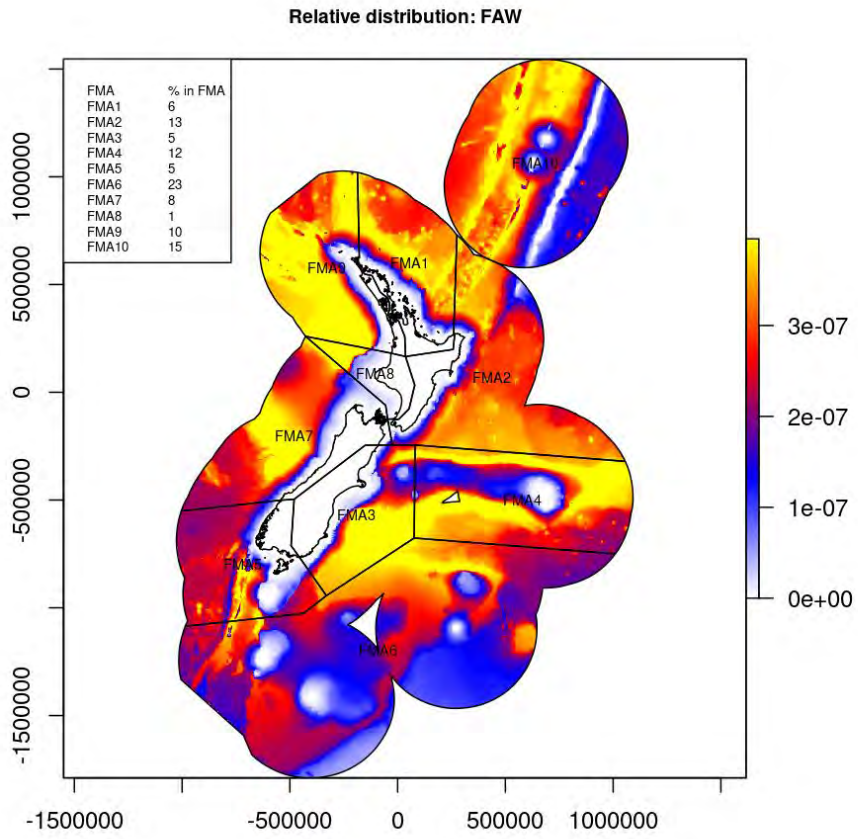

Figure A.50: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.26 Short-finned pilot whale

Demographic parameters

Table A.51: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.96	0.035	0.7	0.999
AFR	norm	9.75	1.97	1	Inf
IBI	norm	6.1	1.68	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.52: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	649347	0.35	Worldwide	0.013

References contributing to stock abundance information: IWC (1992), Miyashita (1993), Gerrodette & Forcada (2002), Bradford et al. (2017), Waring et al. (2013)

References contributing to NZ abundance information: Baker et al. (2019)

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

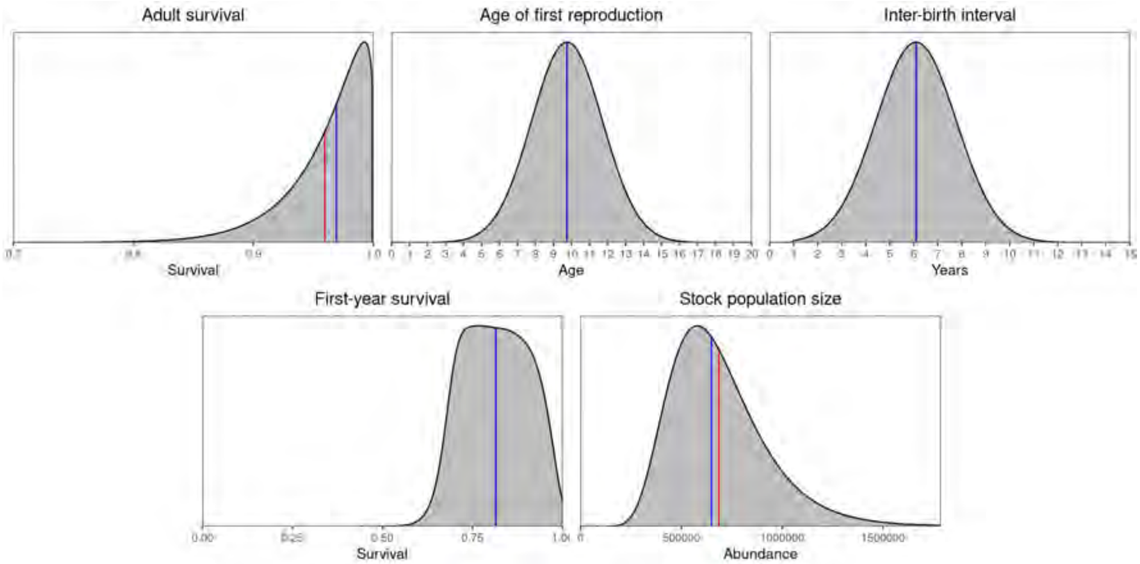

Figure A.51: Prior distributions of demographic input parameters.

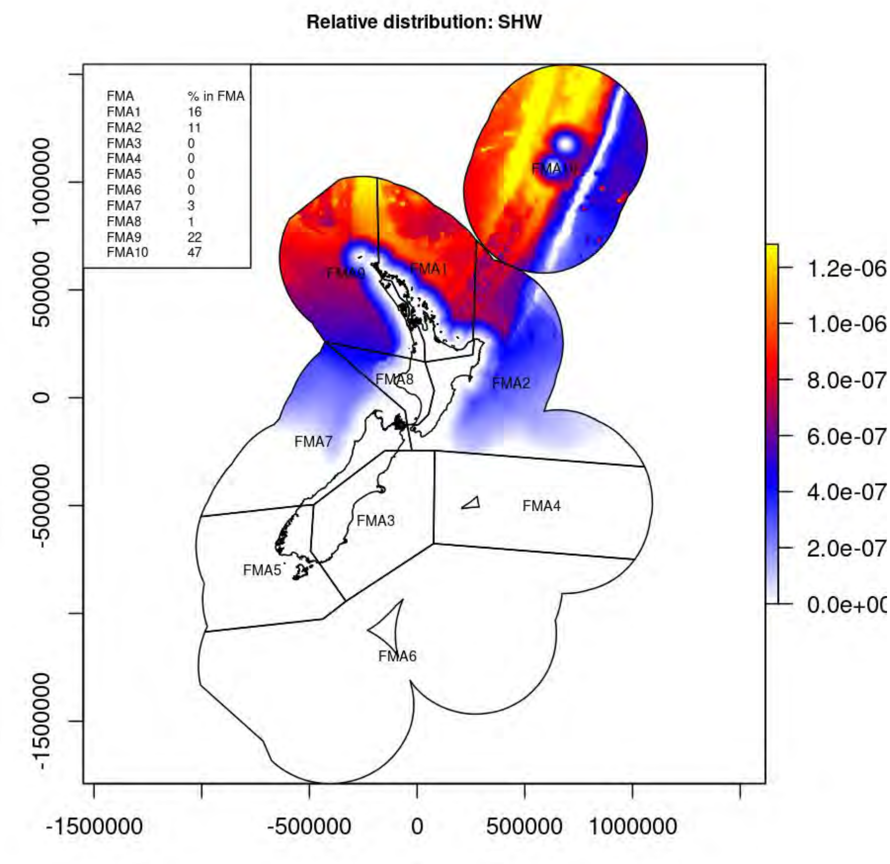

Figure A.52: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.27 Long-finned pilot whale

Demographic parameters

Table A.53: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.982	0.007	0.7	0.999
AFR	norm	7.7	0.4	1	Inf
IBI	norm	2.7	0.3	1	Inf
First Yr Surv					

Table A.54: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	188118	0.35	Worldwide	0.04

References contributing to stock abundance information: Hansen et al. (2018), Kasamatsu & Joyce (1995), Betty et al. (2020)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

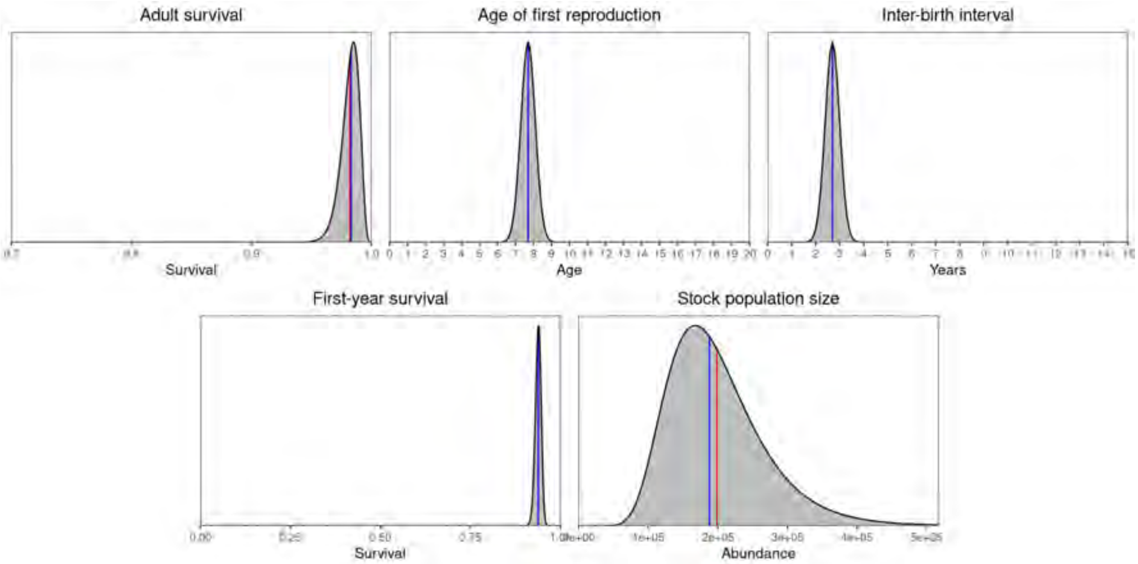

Figure A.53: Prior distributions of demographic input parameters.

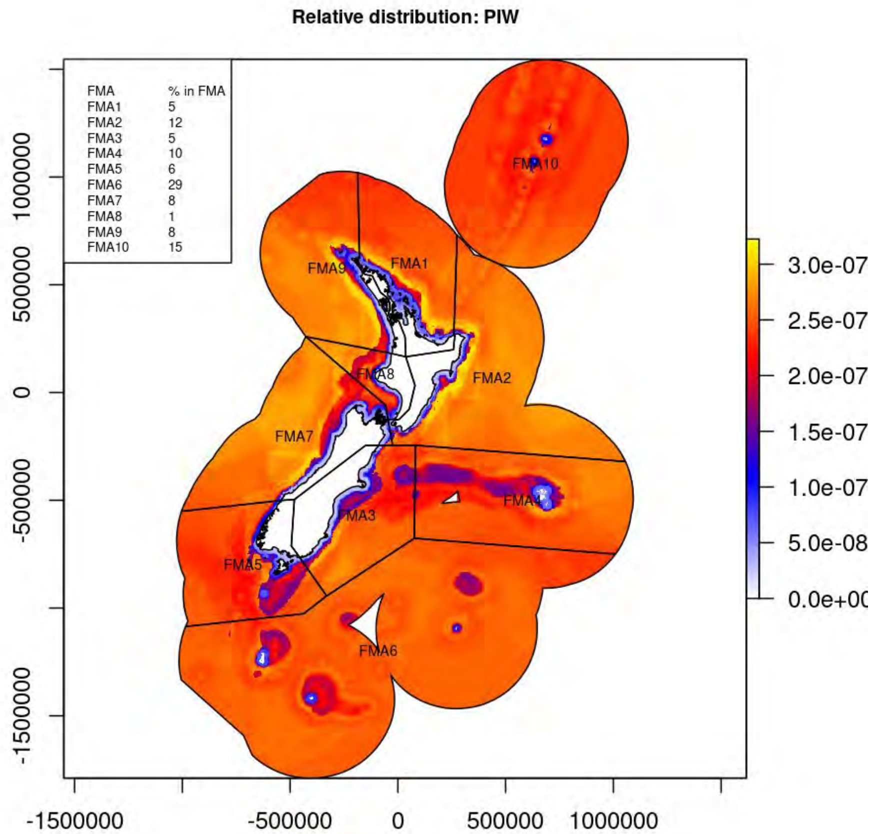

Figure A.54: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.28 Orca

Demographic parameters

Table A.55: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.996	0.01	0.7	0.999
AFR	norm	14.1	0.23	1	Inf
IBI	norm	4.57	0.78	1	Inf
First Yr Surv					

Table A.56: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	48750	0.225	Worldwide	0.021

References contributing to stock abundance information: Forney et al. (2006)

References contributing to NZ abundance information:

Other notes: Within New Zealand this species is listed under the domestic Threat Classification System as Threatened – Nationally Critical and noted as data poor and uncertain whether the taxon is secure overseas. The variation in Orcinus orca by ecotype, subspecies or species is unresolved. Without further research we treat them all as forms of Orcinus orca. For the orca regularly sighted in New Zealand coastal waters, there are suggestions of a decline rate of at least 10

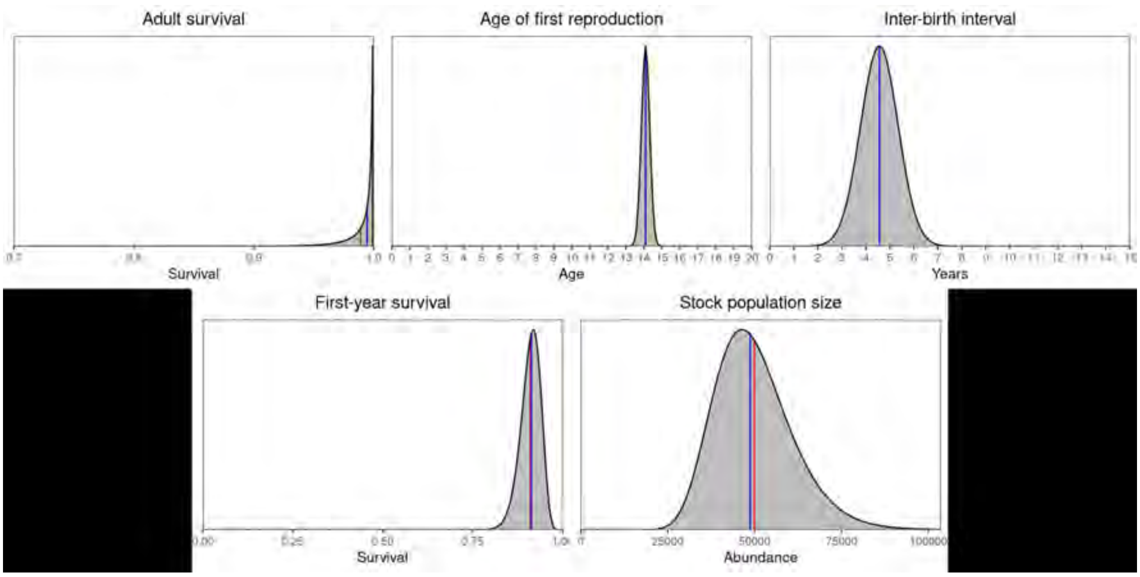

Figure A.55: Prior distributions of demographic input parameters.

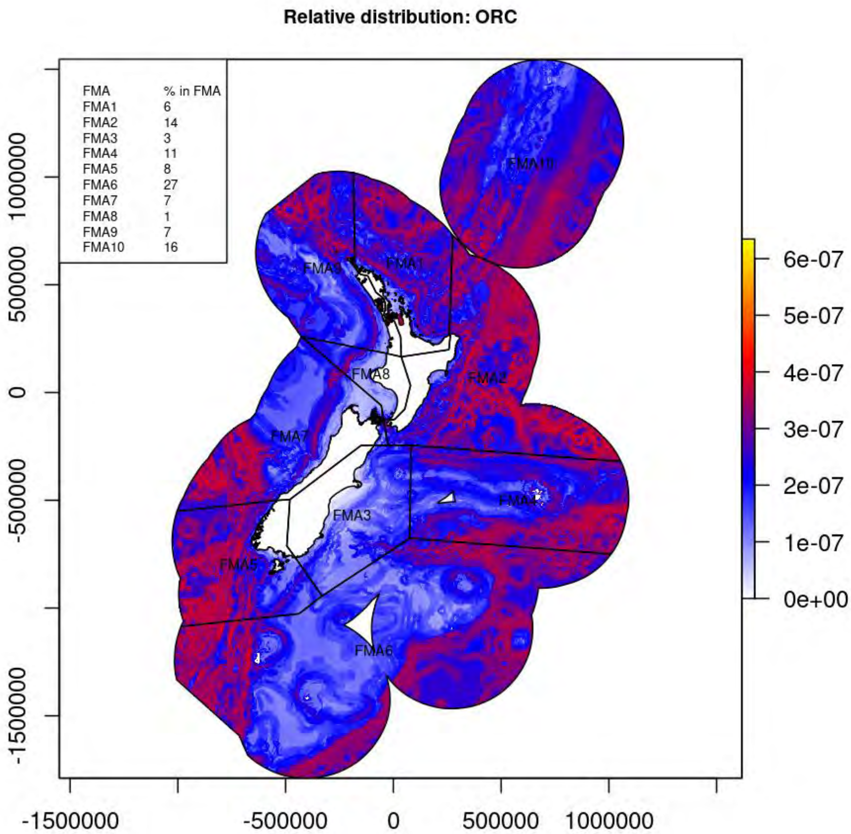

Figure A.56: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.29 Dwarf sperm whale

Demographic parameters

Table A.57: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.959	0.019	0.925	0.992
AFR	norm	4.7	0.95	1	Inf
IBI	norm	2	0.55	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.992

Table A.58: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	7694	0.35	Worldwide	0.017

References contributing to stock abundance information: Palka (2012), Barlow (2006)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

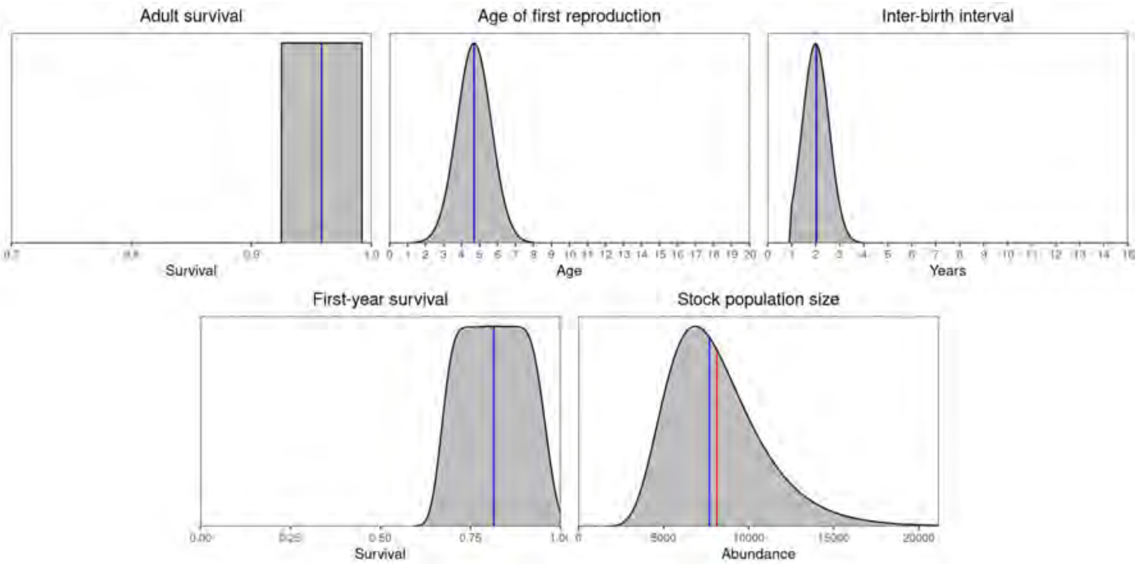

Figure A.57: Prior distributions of demographic input parameters.

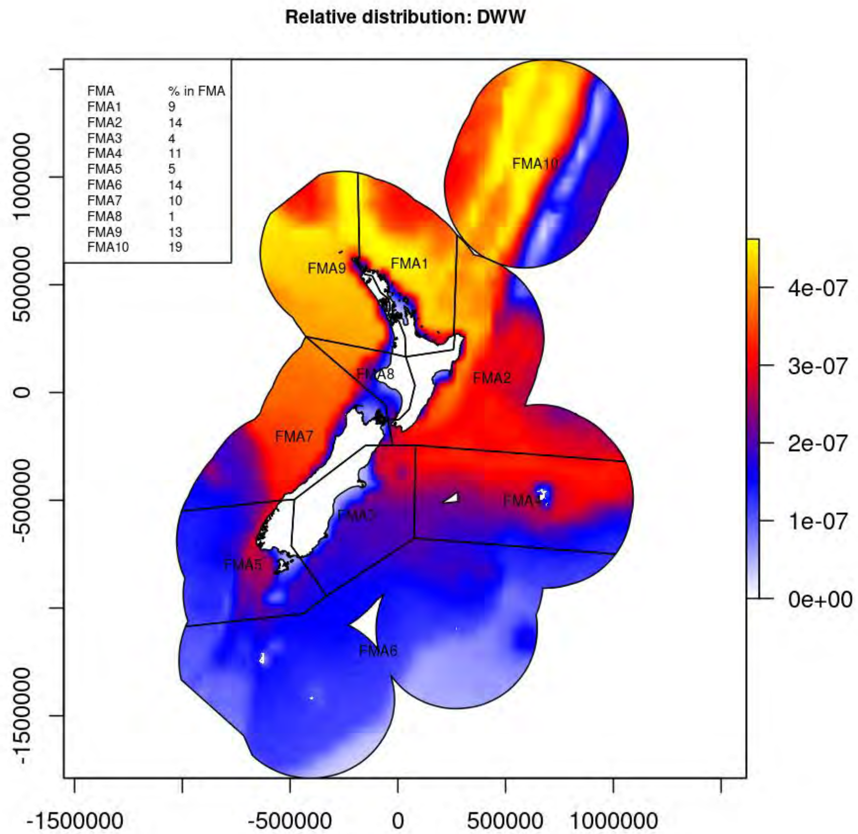

Figure A.58: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.30 Pygmy sperm whale

Demographic parameters

Table A.59: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.959	0.019	0.925	0.992
AFR	norm	5.9	1.19	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.992

Table A.60: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	9406	0.35	Worldwide	0.021

References contributing to stock abundance information: Palka (2012), Garrison et al. (2020), Barlow (2006, 2016)

References contributing to NZ abundance information:

Other notes: Within New Zealand this species is listed under the domestic Threat Classification System as Data Deficient and noted as data poor and uncertain whether the taxon is secure overseas (Baker et al. 2019). There are 10–20 strandings per year in New Zealand waters and good genetic diversity. Global estimate is Western North Atlantic (3785 CV = 0.47), Hawaii (7138 CV = 1.12), US West coast (4111, CV = 0.12). NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

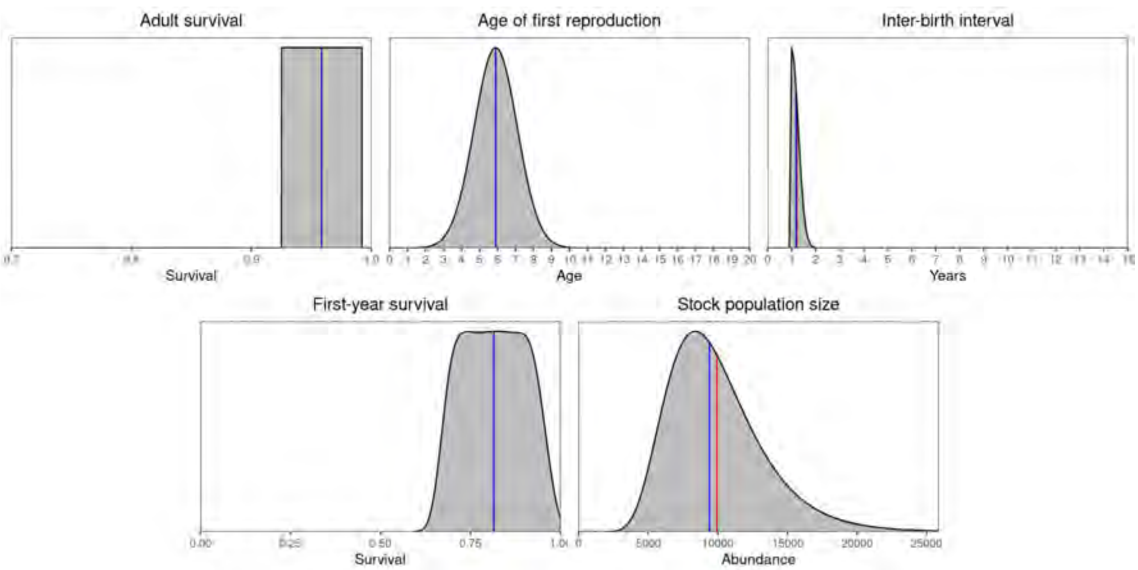

Figure A.59: Prior distributions of demographic input parameters.

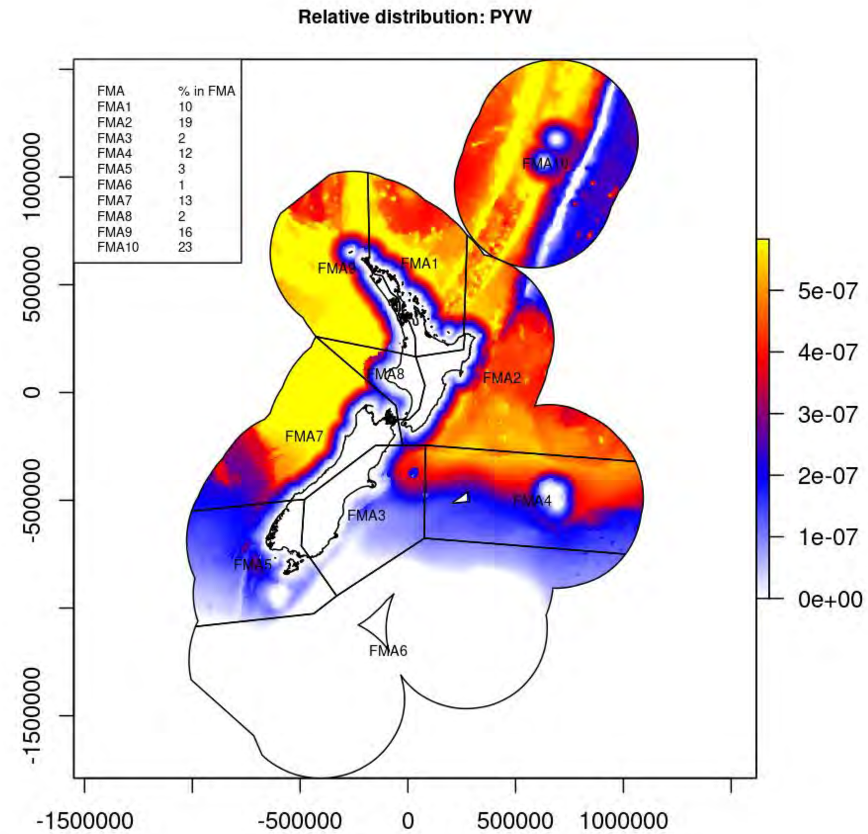

Figure A.60: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.31 Dwarf minke whale

Demographic parameters

Table A.61: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.959	0.019	0.925	0.992
AFR	norm	8.4	1.7	1	Inf
IBI	norm	1	0.28	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.992

Table A.62: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	9406	0.35	Worldwide	0.018

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: Stock abundance is assumed order of magnitude. NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

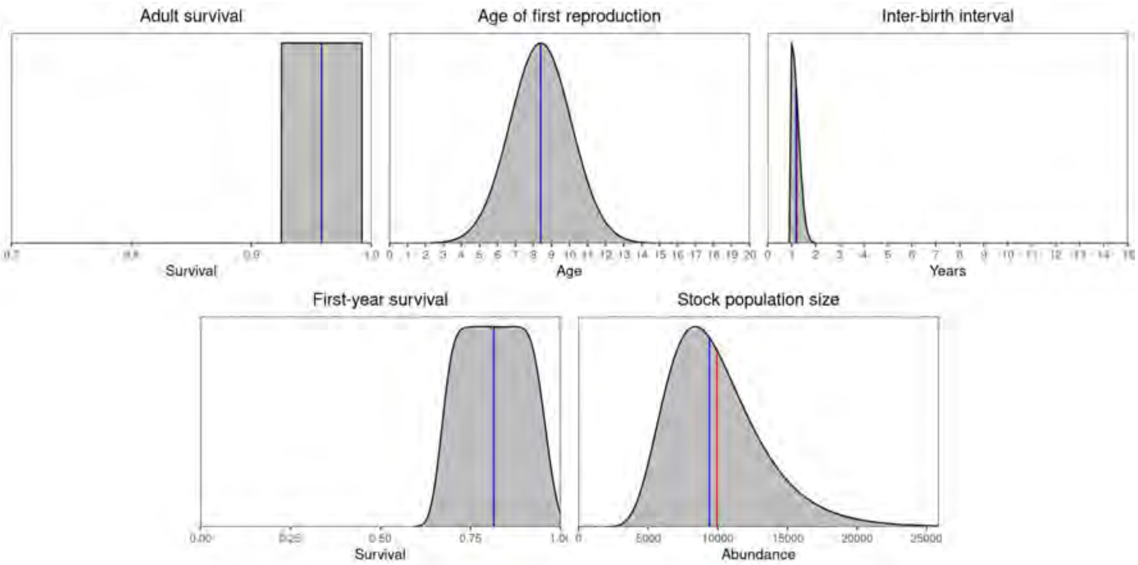

Figure A.61: Prior distributions of demographic input parameters.

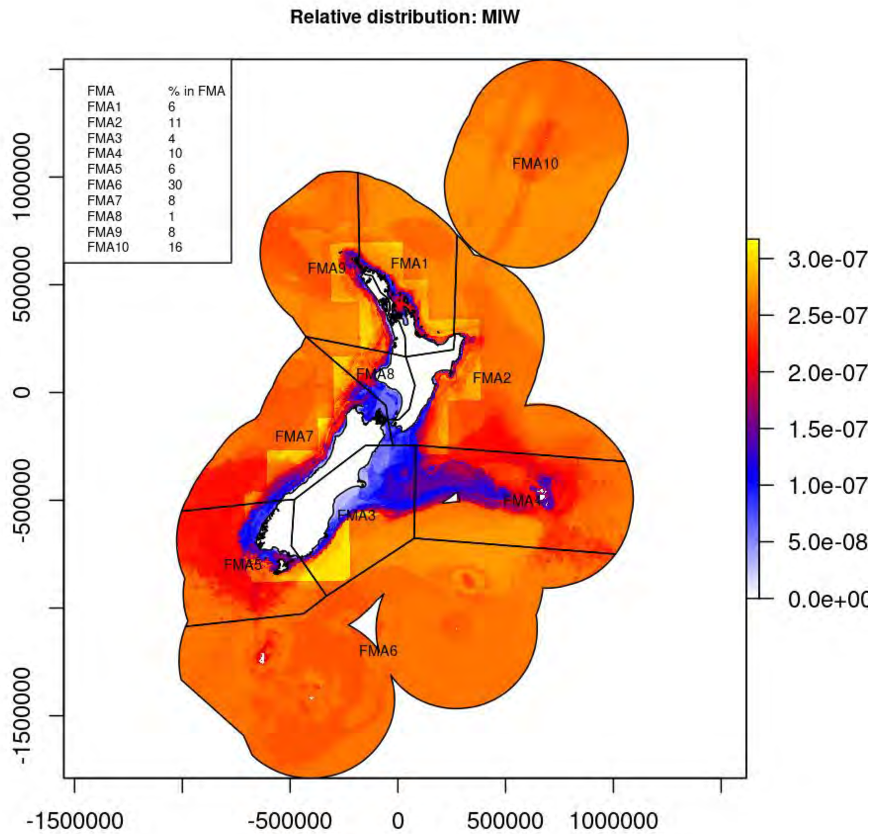

Figure A.62: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.32 Pygmy right whale

Demographic parameters

Table A.63: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.959	0.019	0.925	0.992
AFR	unif	7.75	1.76	4.7	10.8
IBI	unif	2.5	0.87	1	10.8
First Yr Surv.	unif	NA	NA	NA	0.992

Table A.64: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	941	0.35	Worldwide	0.062

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: Stock abundance is assumed order of magnitude. NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

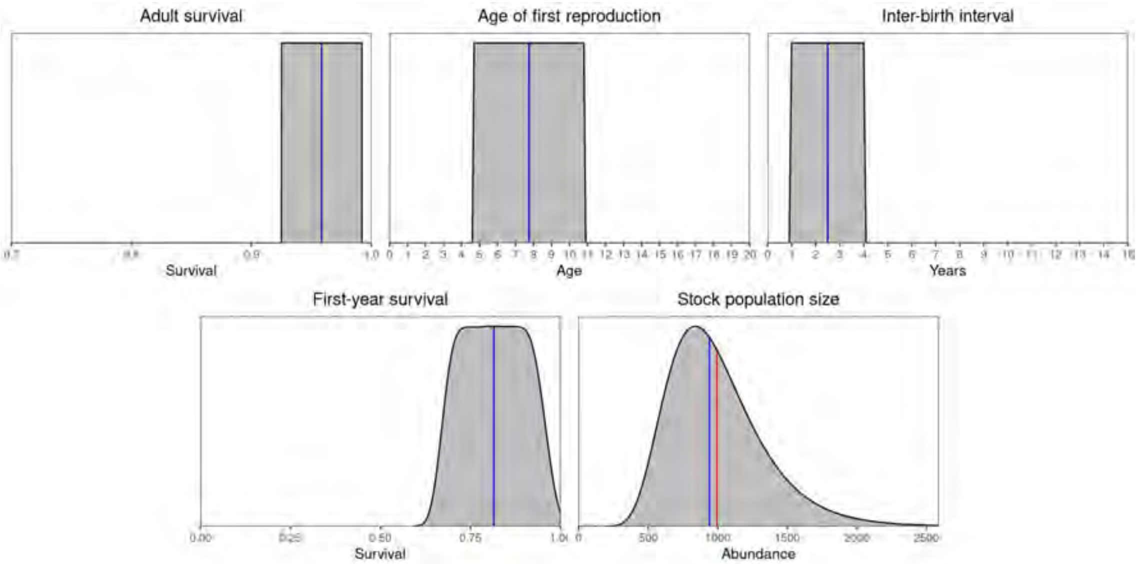

Figure A.63: Prior distributions of demographic input parameters.

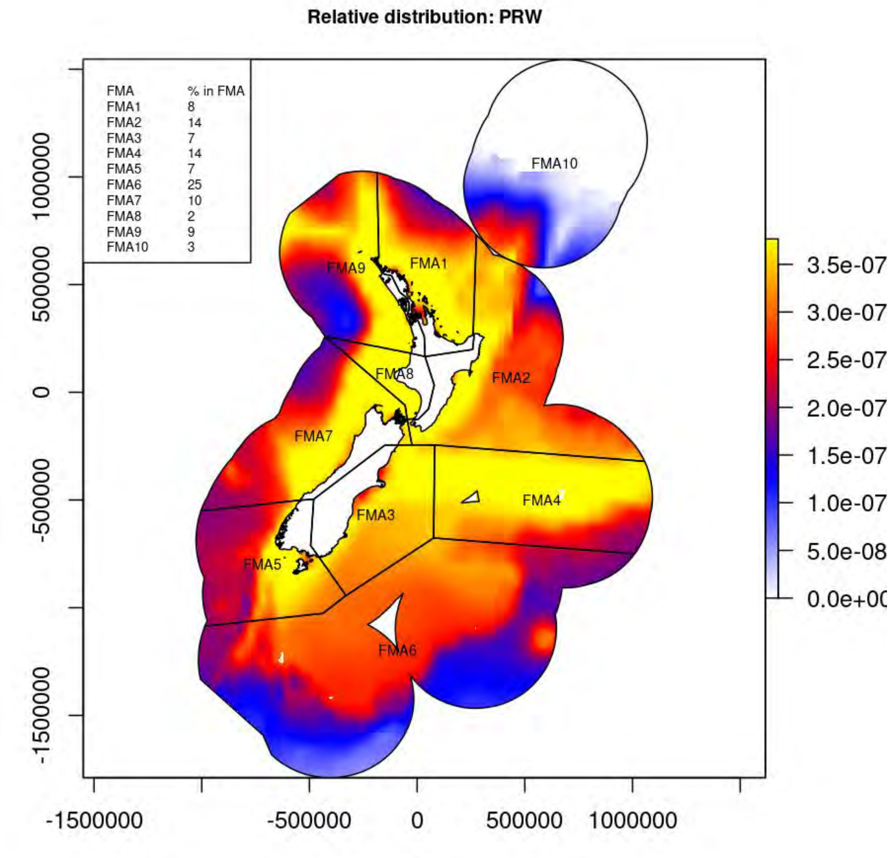

Figure A.64: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.33 Antarctic minke whale

Demographic parameters

Table A.65: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.95	0.018	0.7	0.999
AFR	norm	8.5	1.72	1	Inf
IBI	norm	1.2	0.33	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.66: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	506541	0.182	Worldwide	0.00194

References contributing to stock abundance information: IWC (2013)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}.

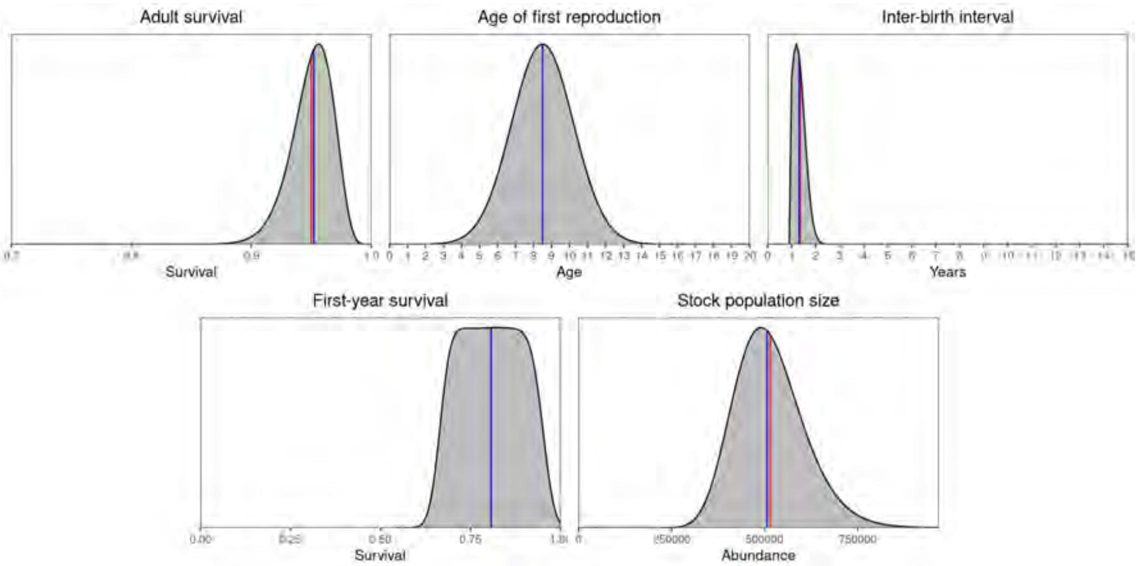

Figure A.65: Prior distributions of demographic input parameters.

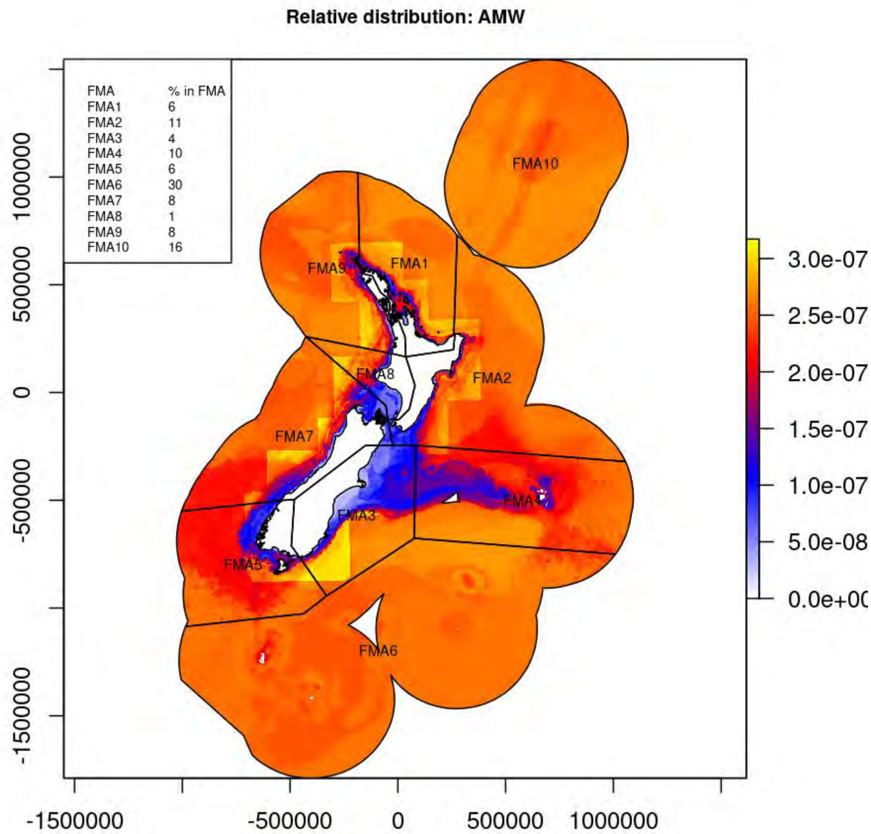

Figure A.66: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.34 Bryde’s whale

Demographic parameters

Table A.67: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.925	0.05	0.7	0.999
AFR	norm	9.5	0.4	1	Inf
IBI	norm	2	0.55	1	Inf
First Yr Surv					

Table A.68: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	15600	0.35	Western South Pacific	0.0301

References contributing to stock abundance information: IWC (1981)

References contributing to NZ abundance information:

Other notes: NZ abundance assumed (R. Constantine, *pers.comm.* Stock abudance CV is assumed value.

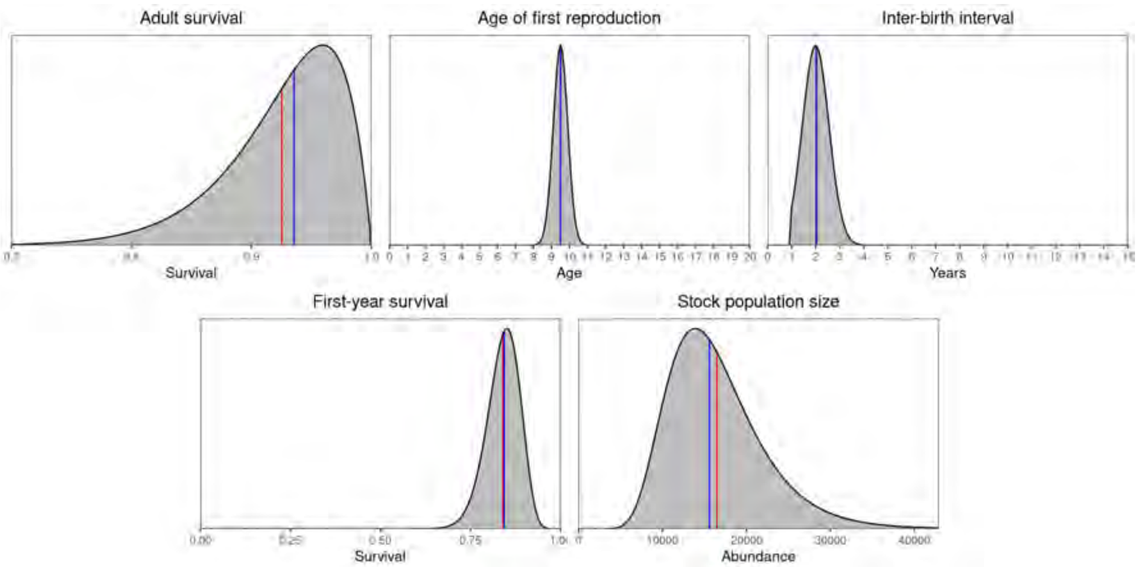

Figure A.67: Prior distributions of demographic input parameters.

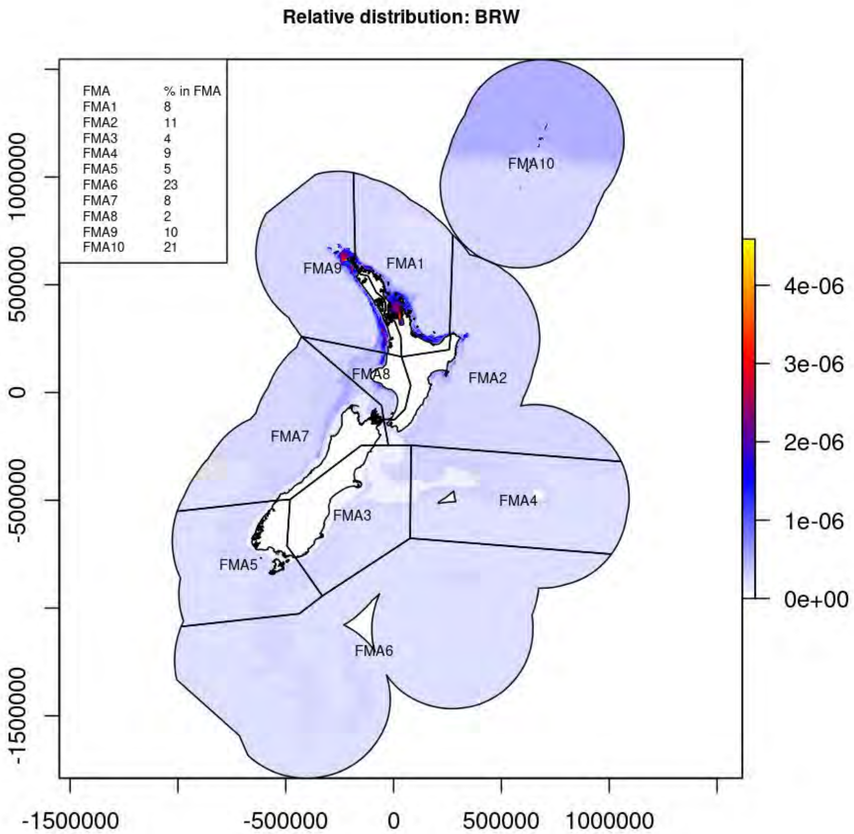

Figure A.68: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.35 Sperm whale

Demographic parameters

Table A.69: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.967	0.01	0.7	0.999
AFR	norm	9.3	1.88	1	Inf
IBI	norm	4	0.5	1	Inf
First Yr Surv					

Table A.70: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	338612	0.35	Worldwide	0.016

References contributing to stock abundance information: Whitehead (2002)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

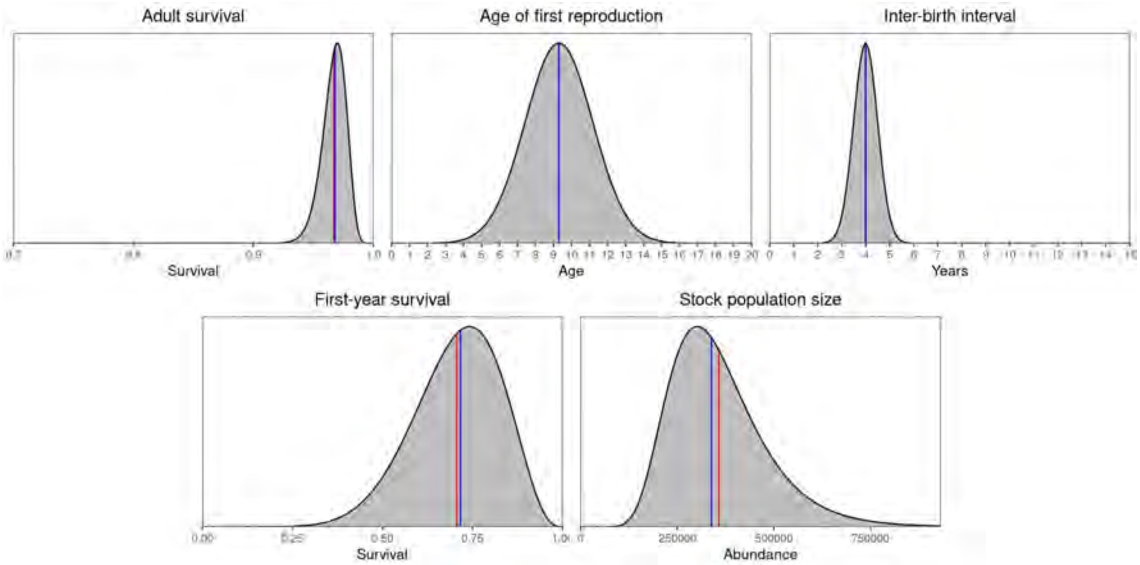

Figure A.69: Prior distributions of demographic input parameters.

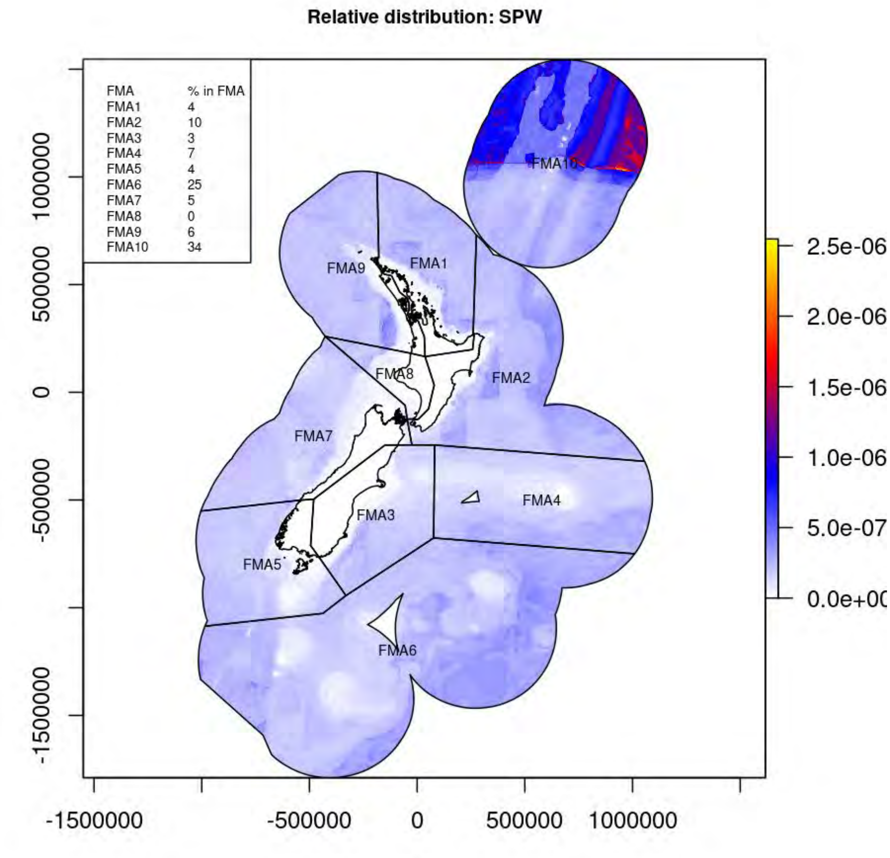

Figure A.70: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.36 Southern right whale

Demographic parameters

Table A.71: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.99	0.005	0.7	0.999
AFR	norm	7.4	0.5	1	Inf
IBI	norm	3.12	0.03	1	Inf
First Yr Surv					

Table A.72: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	2161	0.085	NZ	1

References contributing to stock abundance information: Carroll et al. (2013), Jackson et al. (2016)

References contributing to NZ abundance information: Carroll et al. (2013), Jackson et al. (2016)

Other notes: Within New Zealand this species is listed under the domestic Threat Classification System as at risk – Recovering and noted as secure overseas (Baker et al. 2016). This is supported by multiple estimates of abundance exceeding 1000 animals (Carroll et al. 2013, Jackson et al. 2016) and strong rates of growth (7% per annum Carroll et al. 2013).

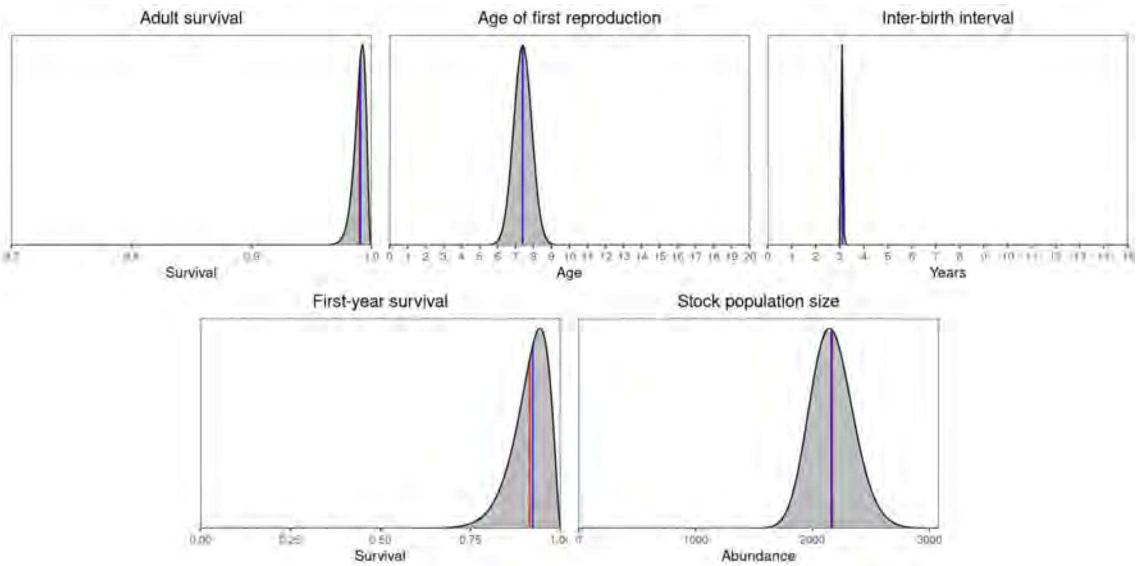

Figure A.71: Prior distributions of demographic input parameters.

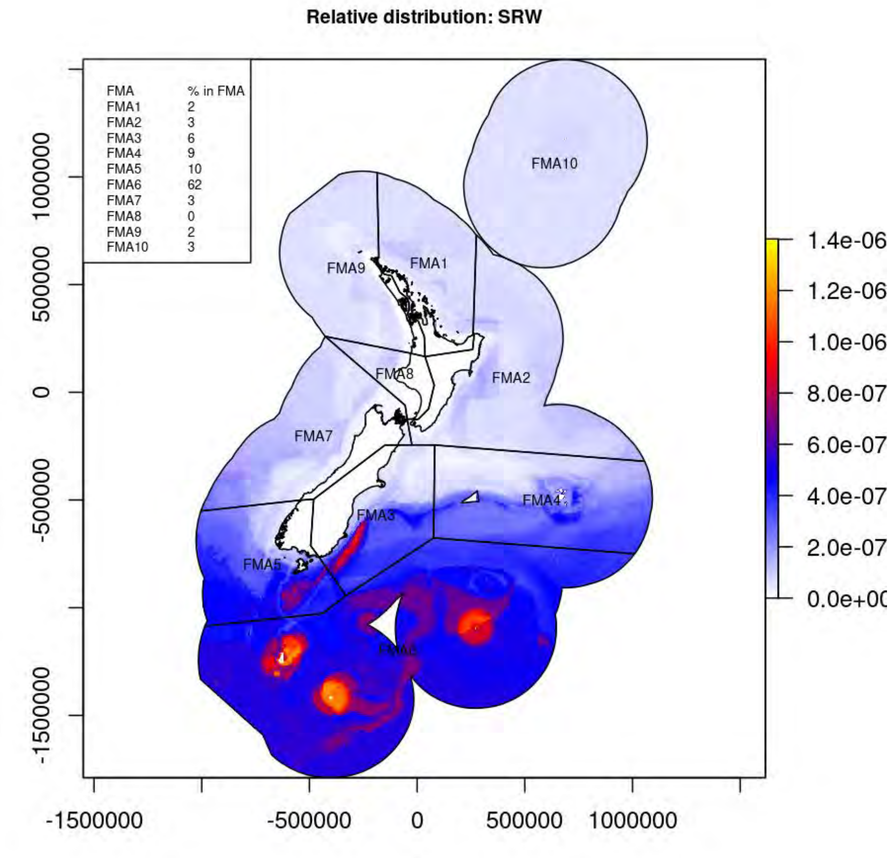

Figure A.72: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.37 Humpback whale

Demographic parameters

Table A.73: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.992	0.01	0.7	0.999
AFR	norm	5.9	0.2	1	Inf
IBI	norm	1.7	0.3	1	Inf
First Yr Surv					

Table A.74: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (p^{EEZ}).

Distribution	Median	CV	Stock	p^{EEZ}
log-normal	18769	0.08	East-coast Aus and Oceania islands.	0.226

References contributing to stock abundance information: IWC (2016)

References contributing to NZ abundance information: Constantine et al. (2012)

Other notes:

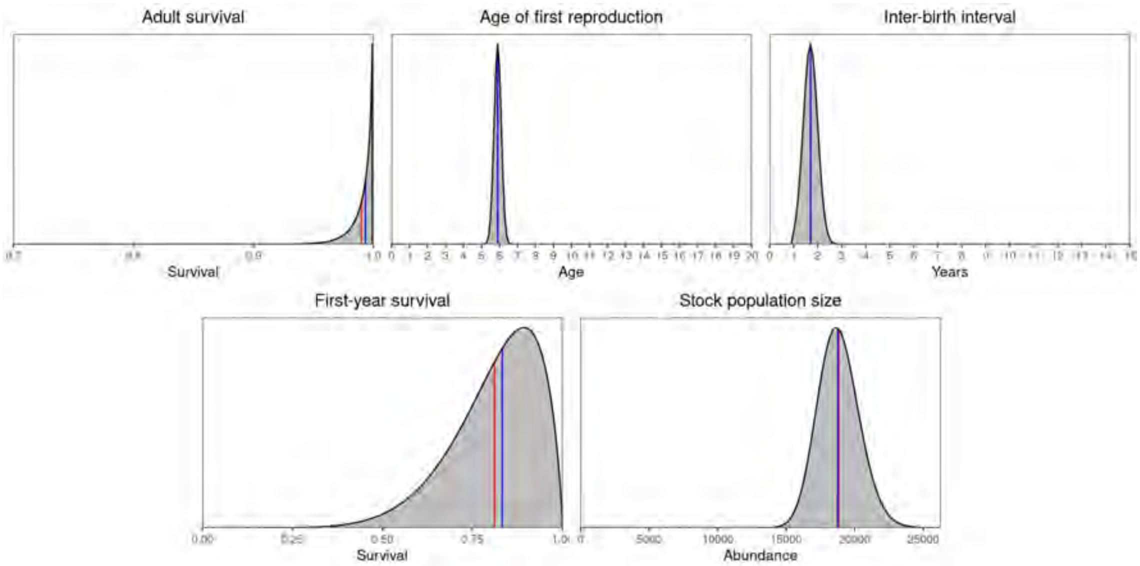

Figure A.73: Prior distributions of demographic input parameters.

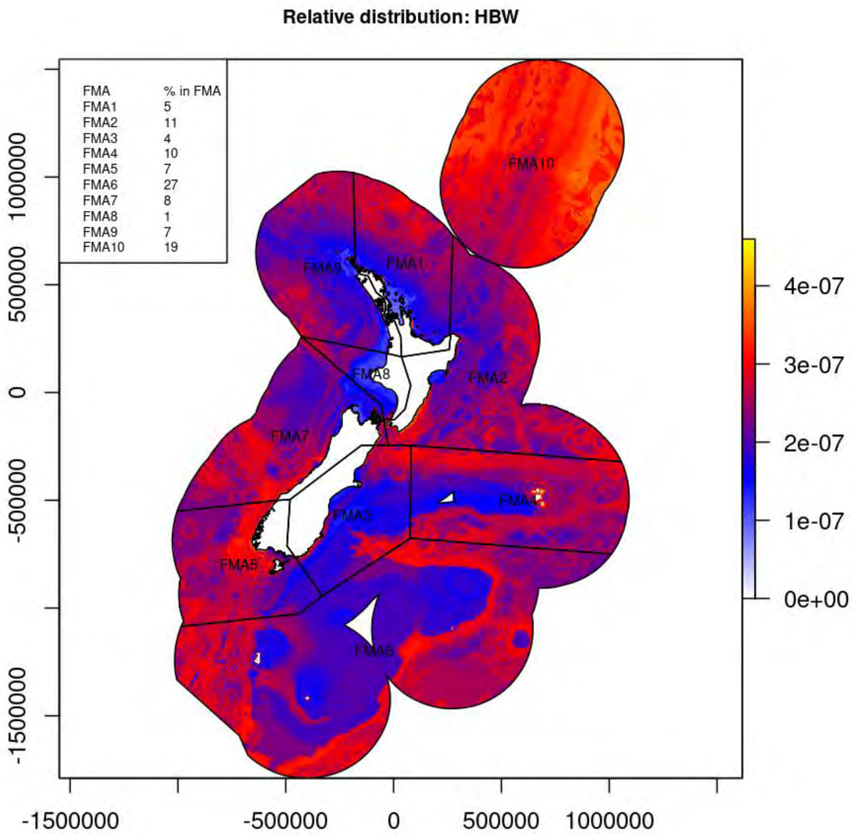

Figure A.74: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.38 Sei whale

Demographic parameters

Table A.75: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.93	0.02	0.7	0.999
AFR	norm	10.7	0.3	1	Inf
IBI	norm	2	0.55	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.76: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	47029	0.35	Worldwide	0.01

References contributing to stock abundance information: Cooke (2018a)

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance CV is assumed value.

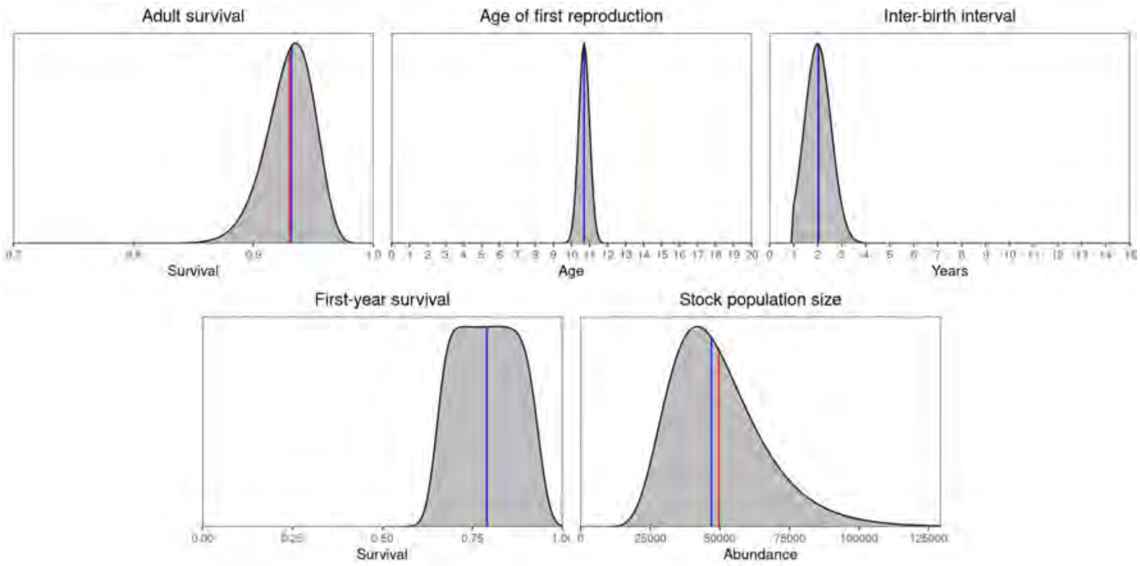

Figure A.75: Prior distributions of demographic input parameters.

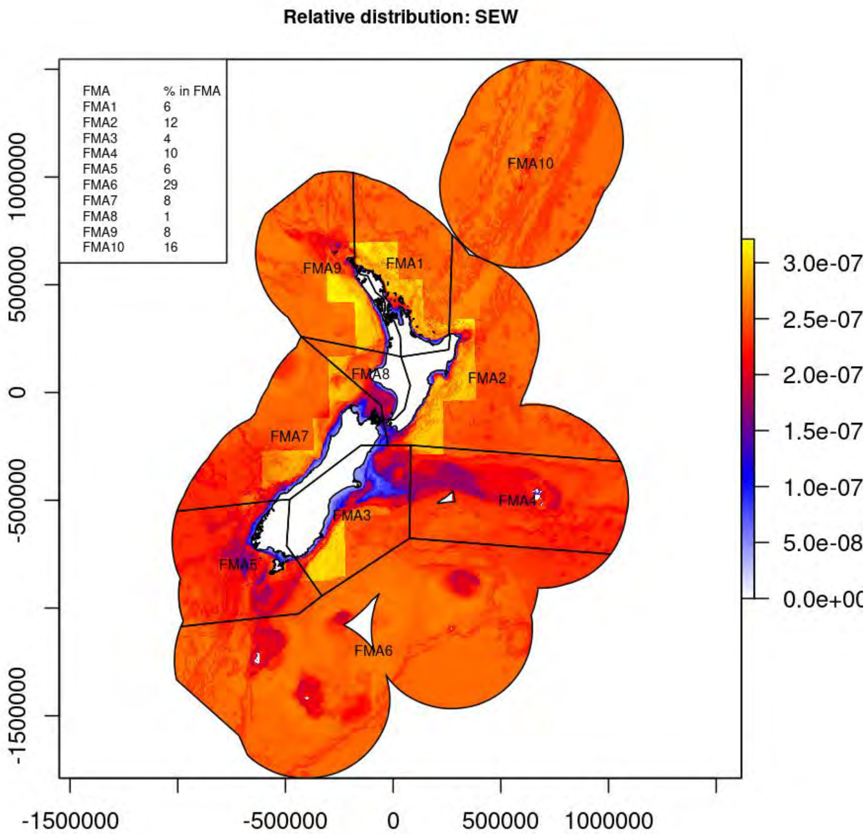

Figure A.76: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.39 Pygmy blue whale

Demographic parameters

Table A.77: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.94	0.005	0.7	0.999
AFR	norm	10.8	0.5	1	Inf
IBI	norm	2.2	0.6	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.78: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	3292	0.35	Worldwide	0.205

References contributing to stock abundance information: Cooke (2018b)

References contributing to NZ abundance information: Barlow et al. (2018)

Other notes: Stock abundance CV is assumed value. Now recognised as present in New Zealand waters year-round with signs of breeding activity. Preliminary abundance estimates for New Zealand are based primarily on photos from the South Taranaki Bight region, but it is not known if this is representative of the entire New Zealand population.

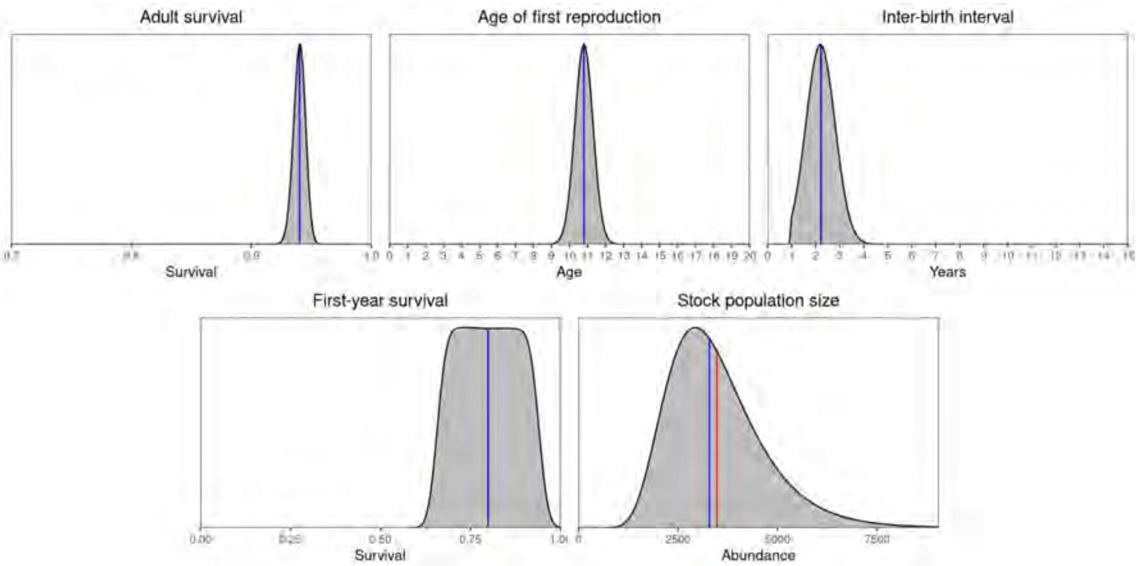

Figure A.77: Prior distributions of demographic input parameters.

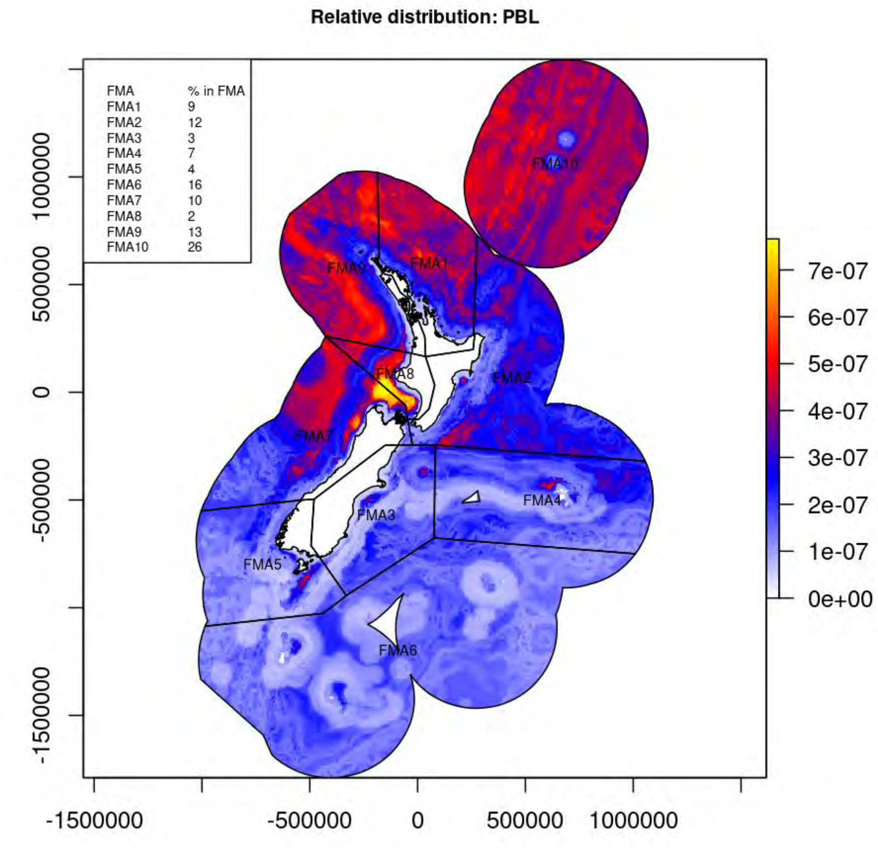

Figure A.78: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.40 Fin whale

Demographic parameters

Table A.79: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.955	0.007	0.7	0.999
AFR	norm	7.6	0.6	1	Inf
IBI	norm	2.22	0.1	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.80: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	23515	0.35	Worldwide	0.02

References contributing to stock abundance information: Cooke (2018c)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

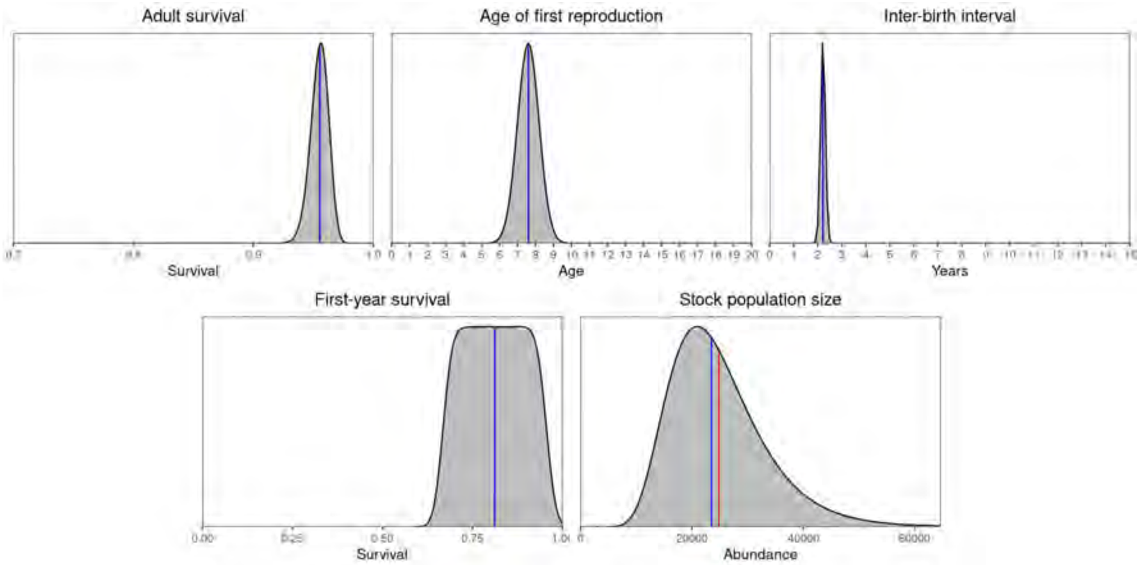

Figure A.79: Prior distributions of demographic input parameters.

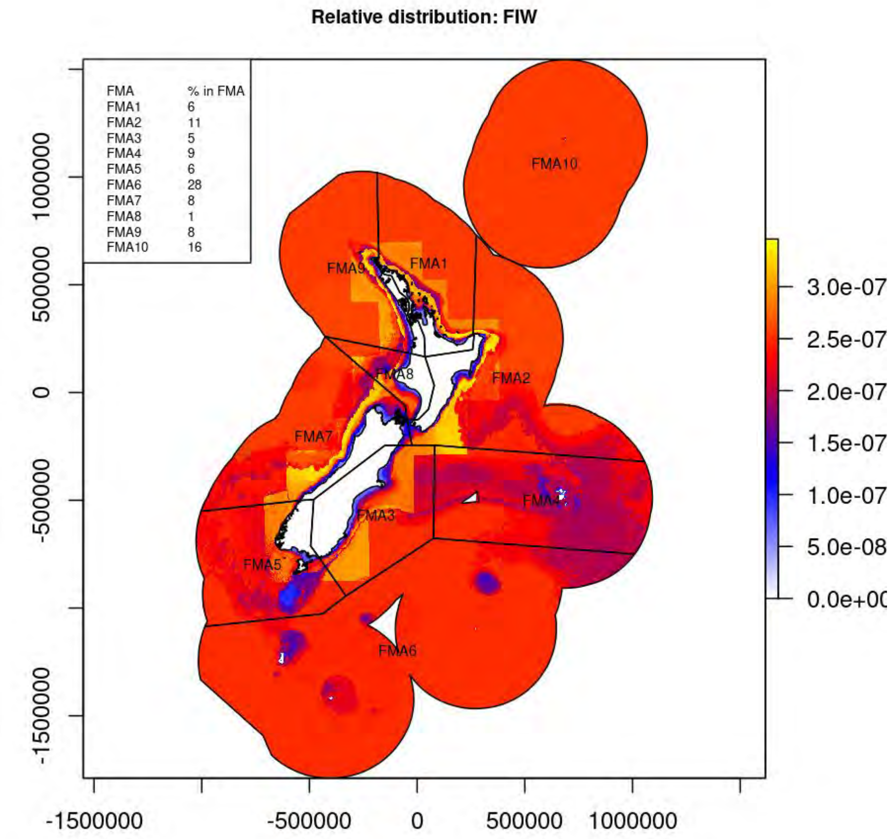

Figure A.80: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.41 Antarctic blue whale

Demographic parameters

Table A.81: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.963	0.02	0.7	0.999
AFR	norm	9.9	2	1	Inf
IBI	norm	2.5	0.25	1	Inf
First Yr Surv					

Table A.82: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	2145	0.35	Worldwide	0.0439

References contributing to stock abundance information: Branch (2007)

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance CV is assumed value.

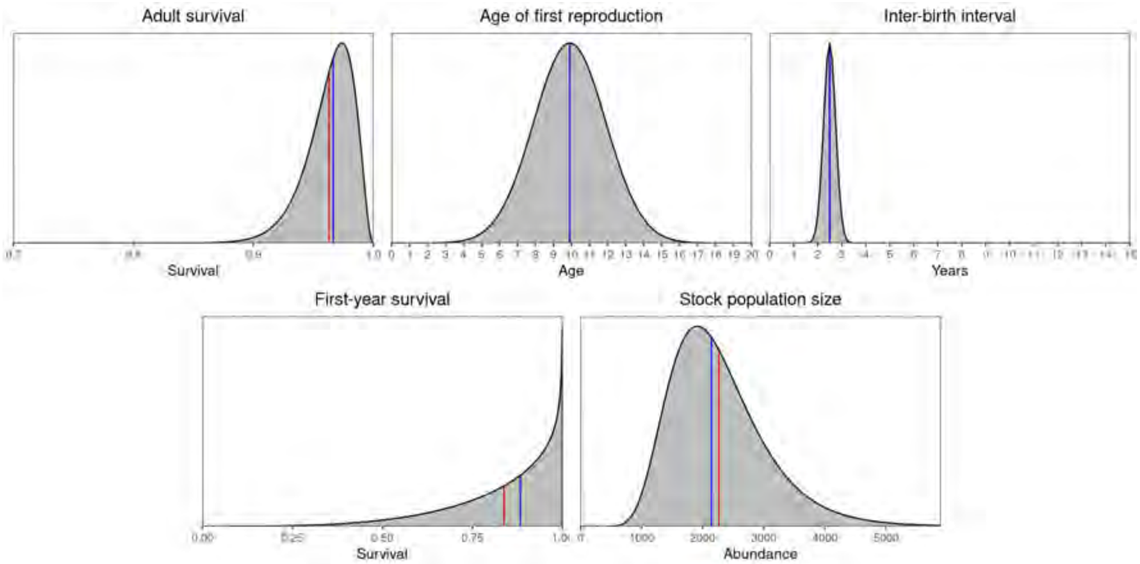

Figure A.81: Prior distributions of demographic input parameters.

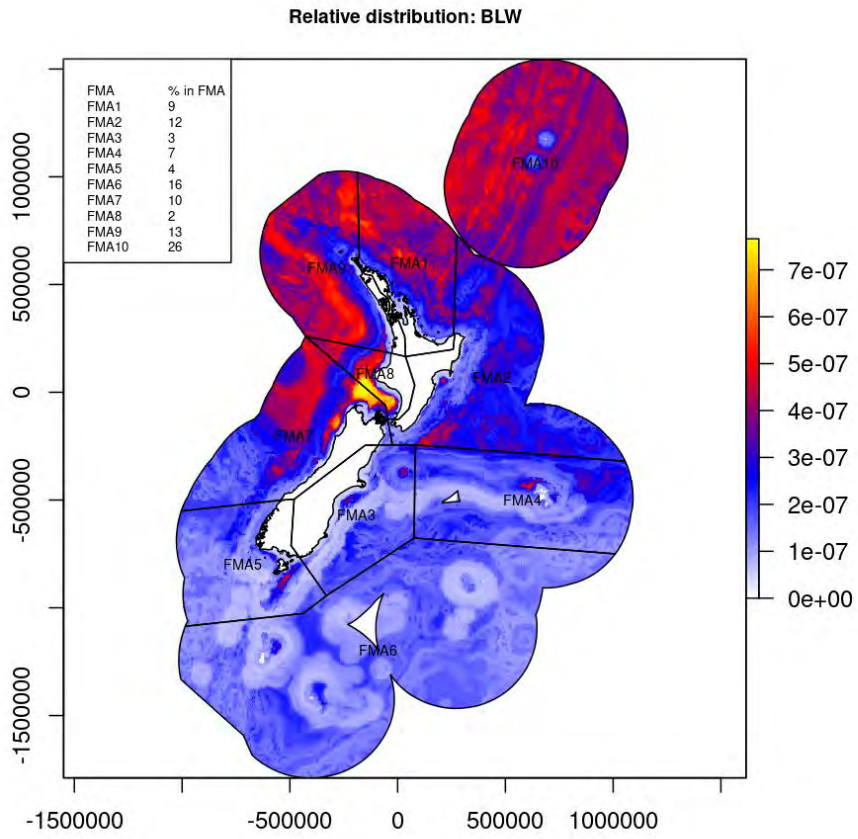

Figure A.82: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.42 Pygmy beaked whale

Demographic parameters

Table A.83: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.84: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	4703	0.35	Worldwide	0.002

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

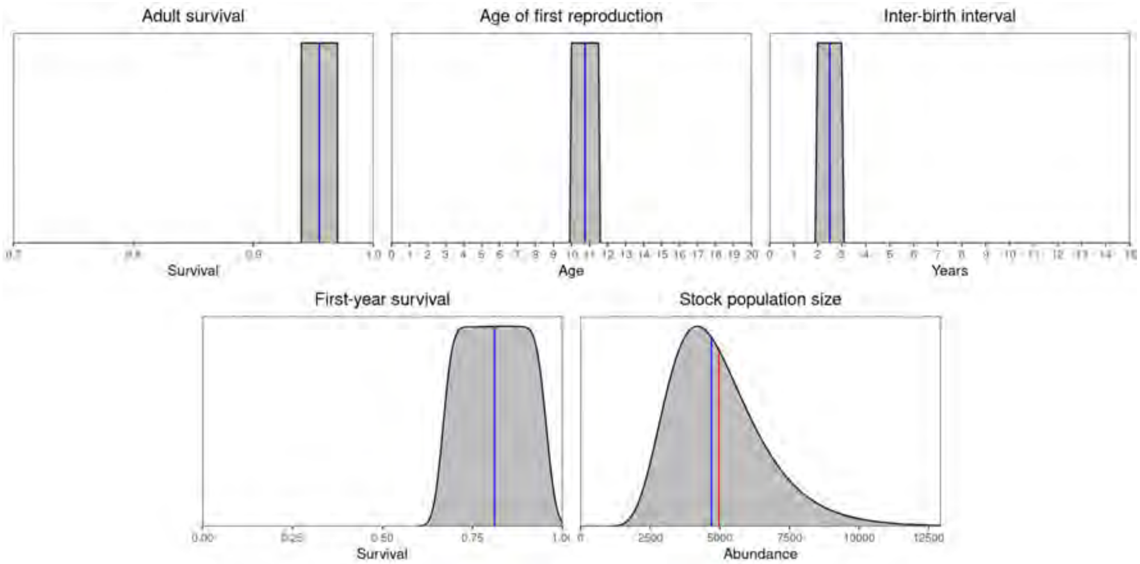

Figure A.83: Prior distributions of demographic input parameters.

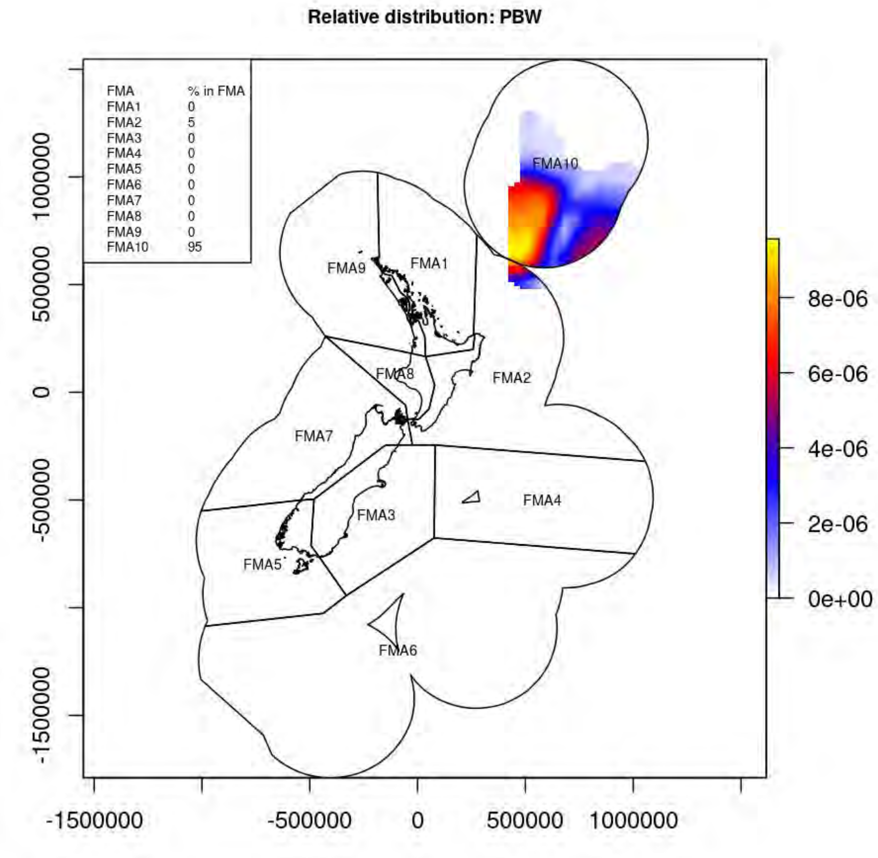

Figure A.84: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.43 Andrews' beaked whale

Demographic parameters

Table A.85: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.86: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	1384	0.35	Worldwide	0.068

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

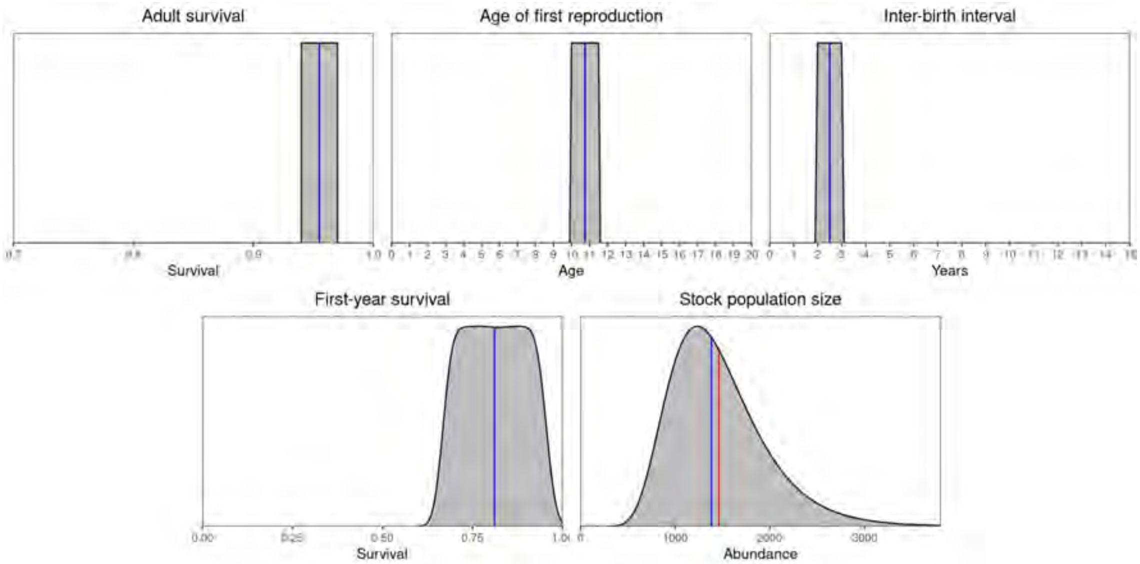

Figure A.85: Prior distributions of demographic input parameters.

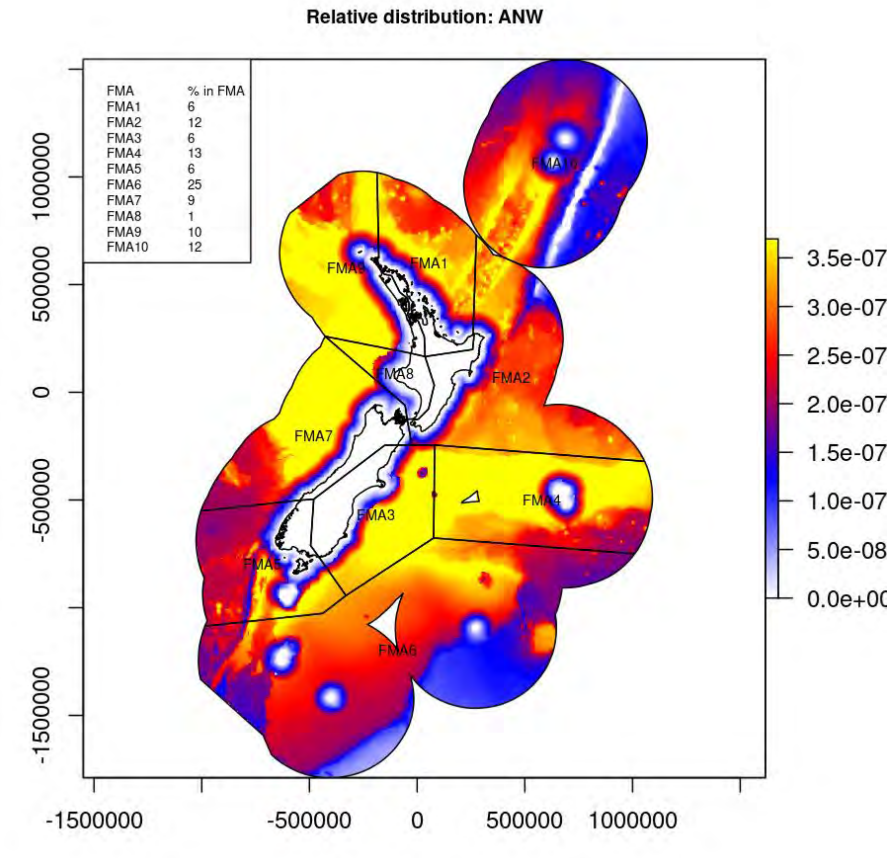

Figure A.86: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.44 Hector's beaked whale

Demographic parameters

Table A.87: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.88: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	18443	0.35	Worldwide	0.051

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

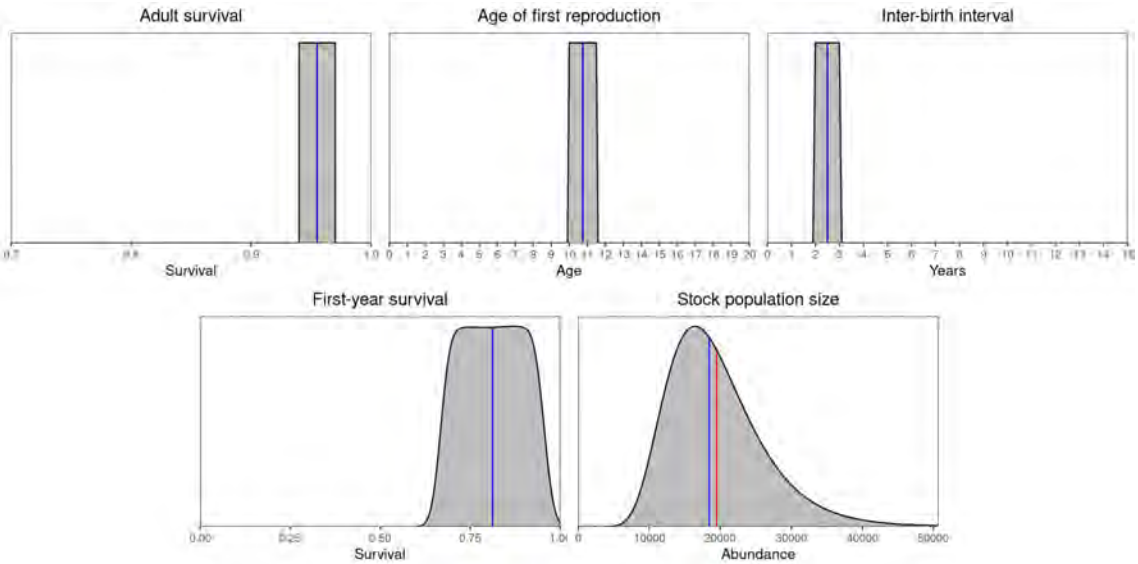

Figure A.87: Prior distributions of demographic input parameters.

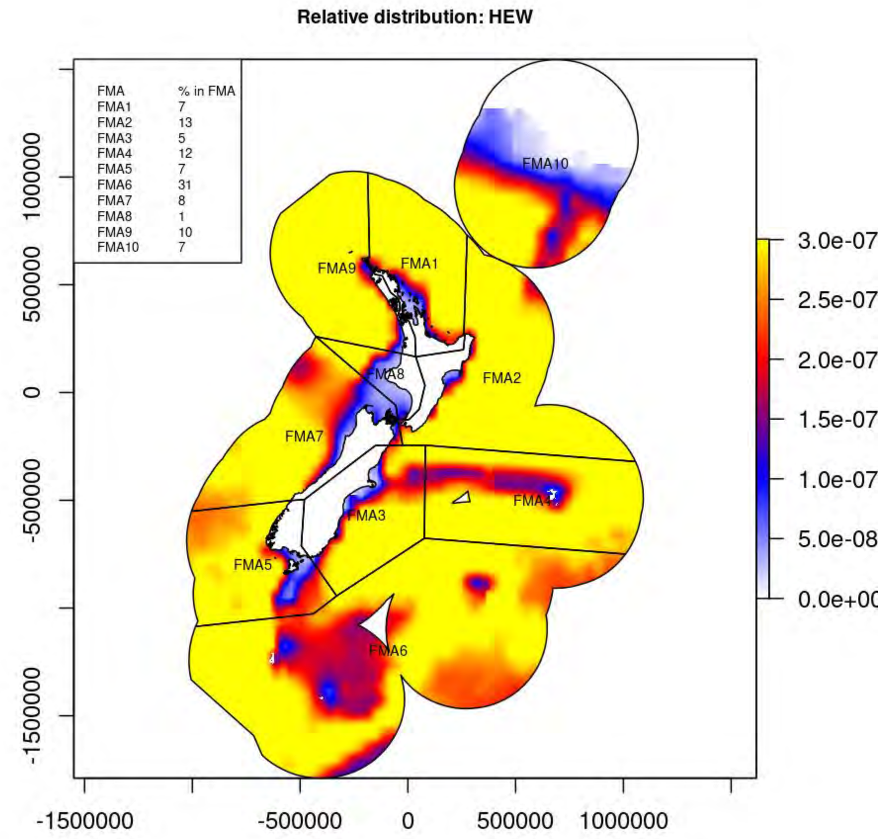

Figure A.88: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.45 Strap-toothed whale

Demographic parameters

Table A.89: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.90: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	209019	0.35	Worldwide	0.045

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

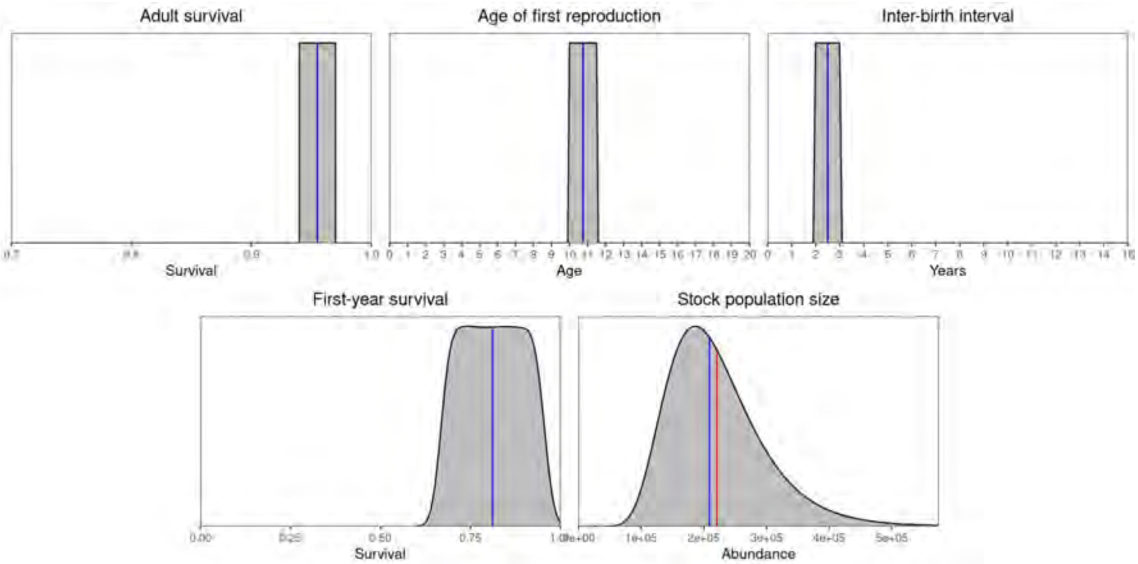

Figure A.89: Prior distributions of demographic input parameters.

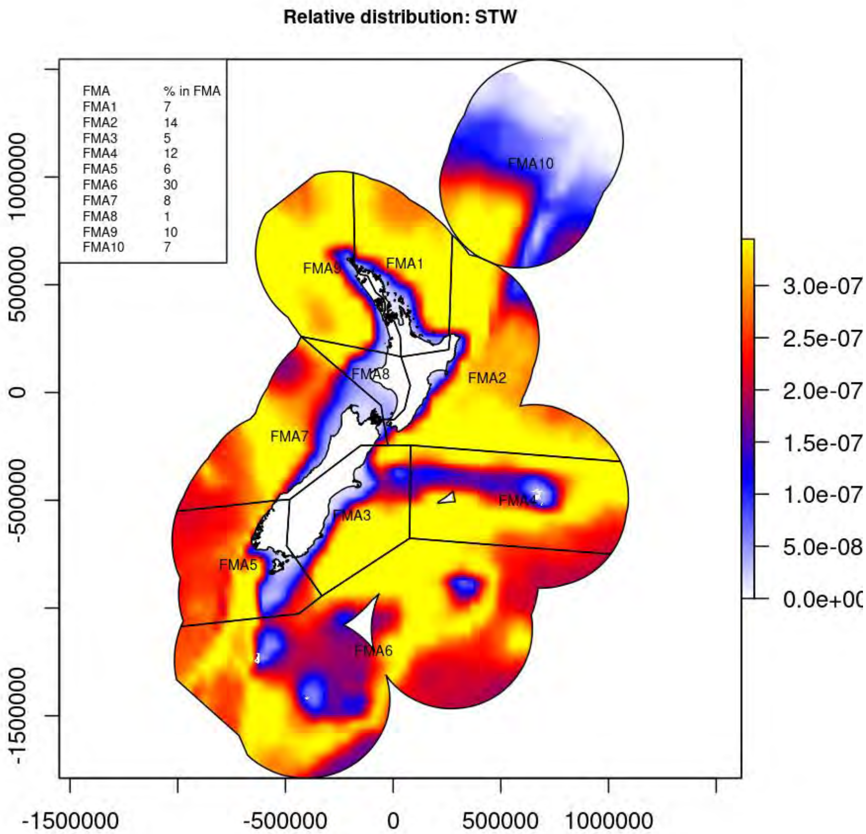

Figure A.90: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.46 Dense-beaked whale

Demographic parameters

Table A.91: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.96	0.048	0.7	0.999
AFR	norm	10	2.02	1	Inf
IBI	unif	2.5	0.29	2	Inf
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.92: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	31855	0.35	Worldwide	0.015

References contributing to stock abundance information: Pitman & Brownell Jr. (2020)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

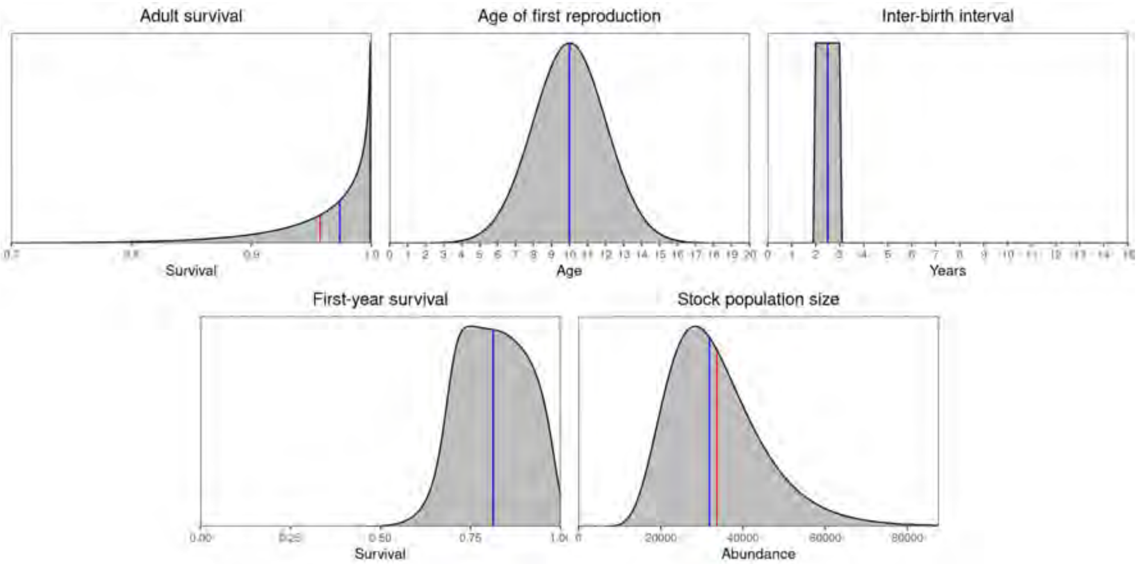

Figure A.91: Prior distributions of demographic input parameters.

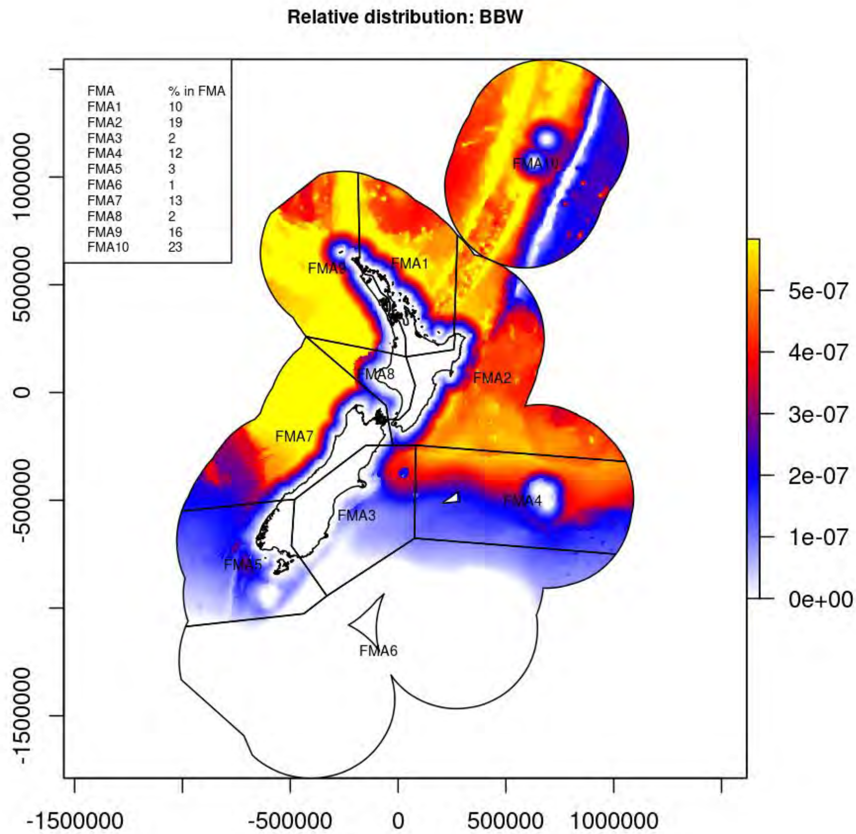

Figure A.92: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.47 Ginkgo-toothed beaked whale

Demographic parameters

Table A.93: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.94: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	2939	0.35	Worldwide	0.032

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

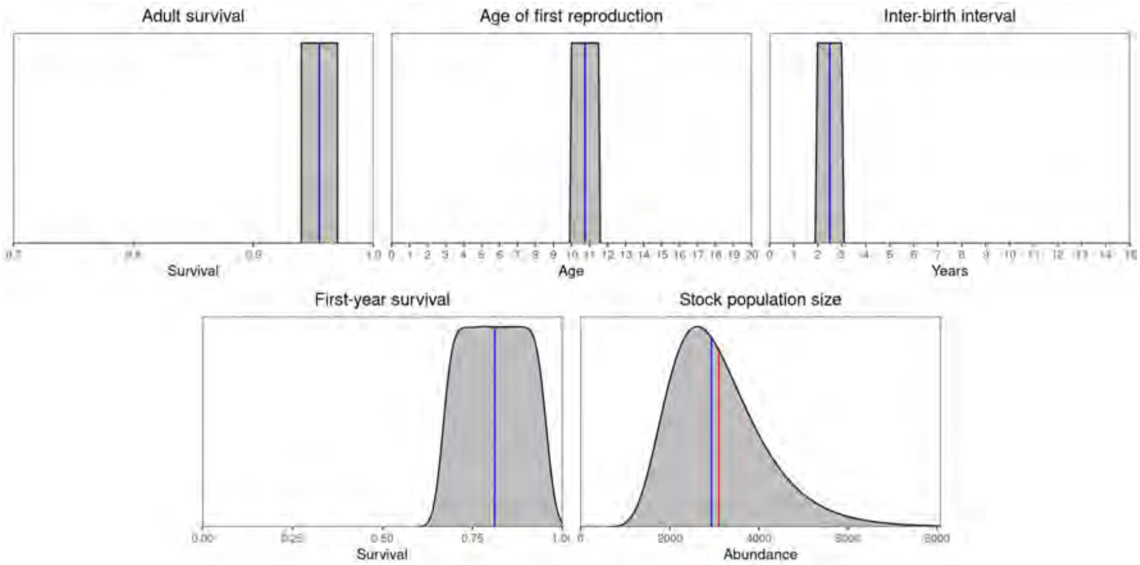

Figure A.93: Prior distributions of demographic input parameters.

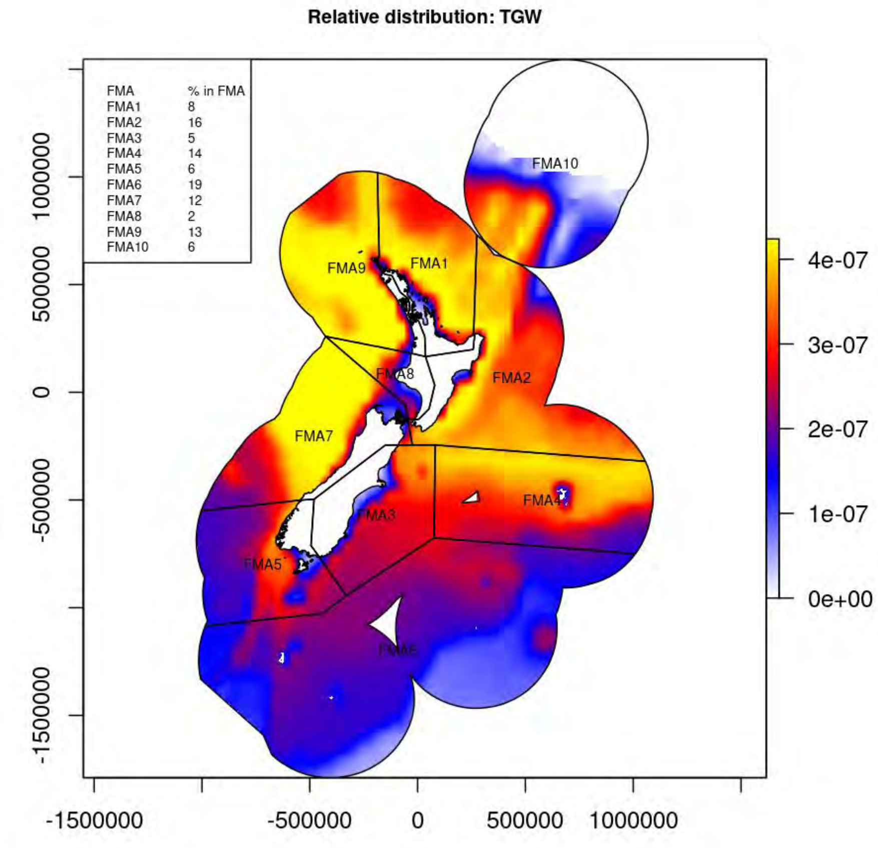

Figure A.94: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.48 Gray's beaked whale

Demographic parameters

Table A.95: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.96: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	204475	0.35	Worldwide	0.046

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

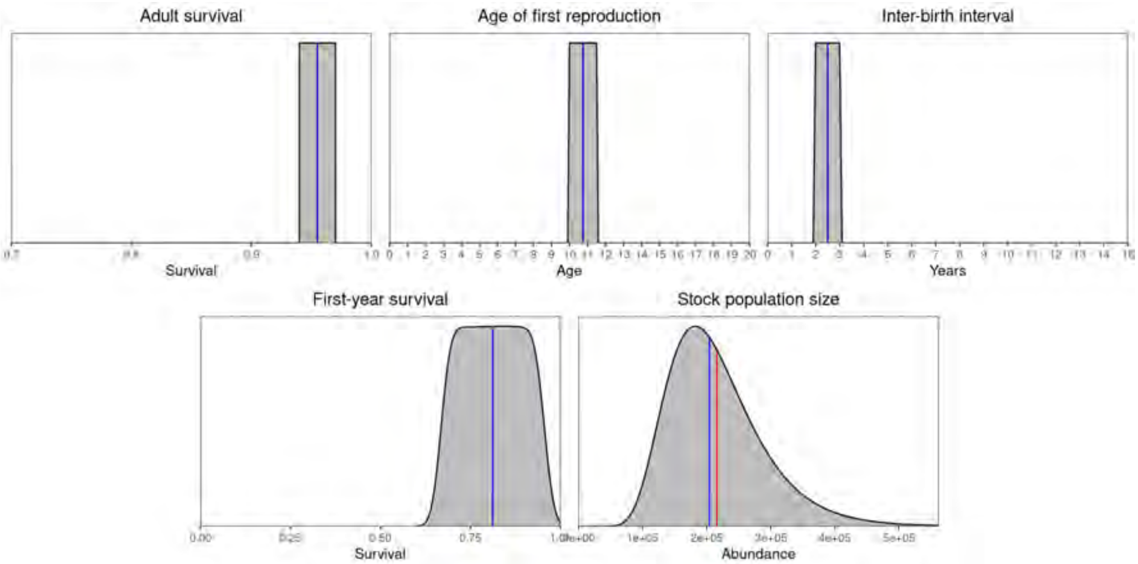

Figure A.95: Prior distributions of demographic input parameters.

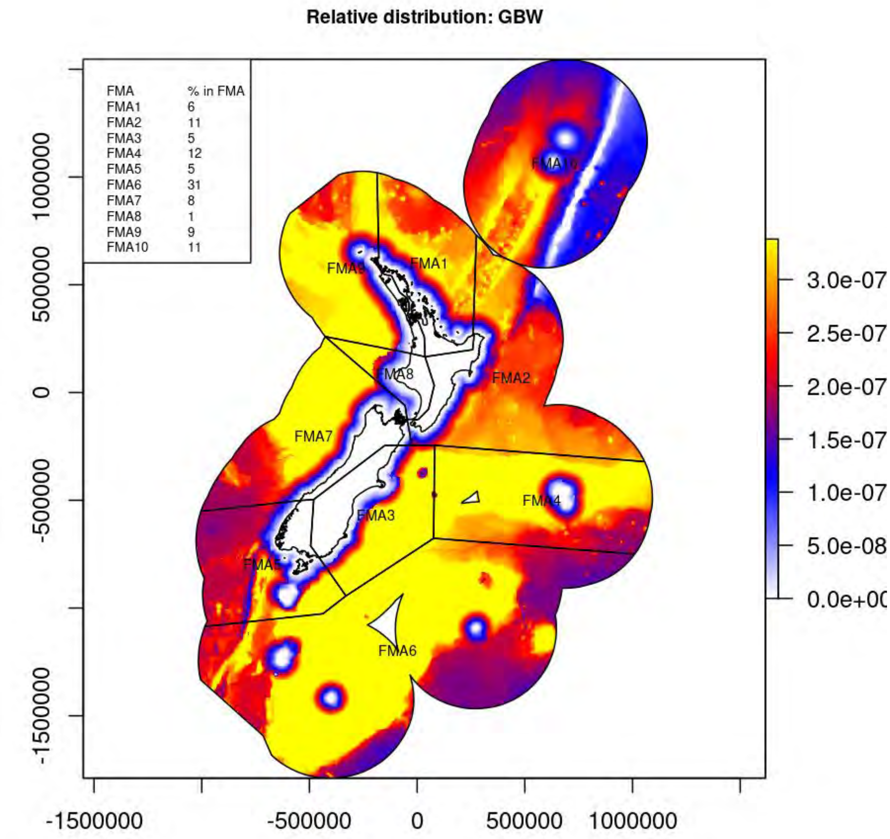

Figure A.96: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.49 Spade-toothed whale

Demographic parameters

Table A.97: Summary of prior distributions used for demographic parameters in determination of r_{max}. Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.98: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	484	0.35	Worldwide	0.194

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

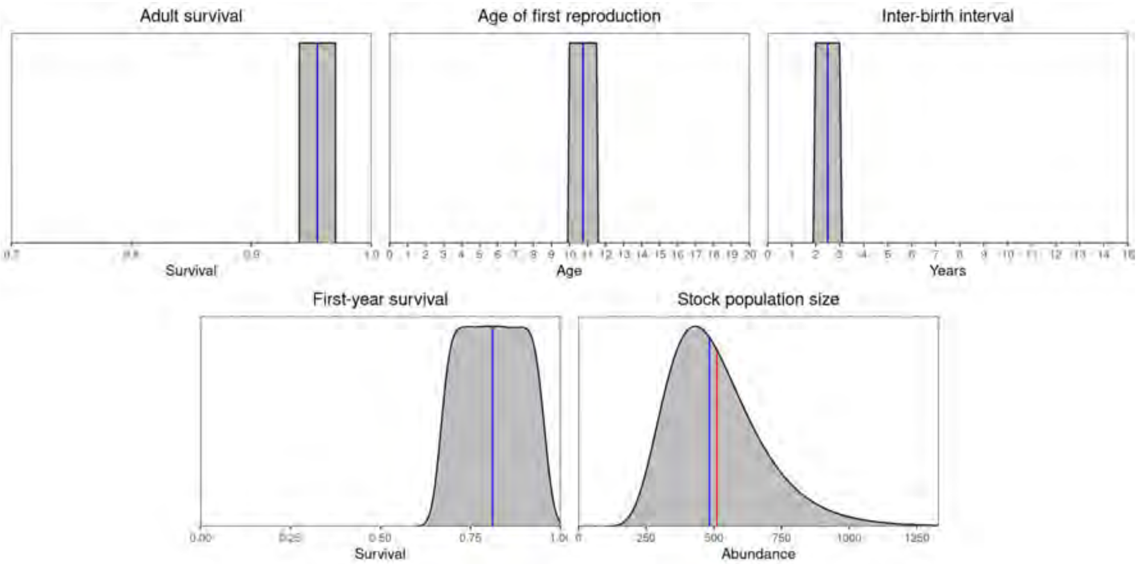

Figure A.97: Prior distributions of demographic input parameters.

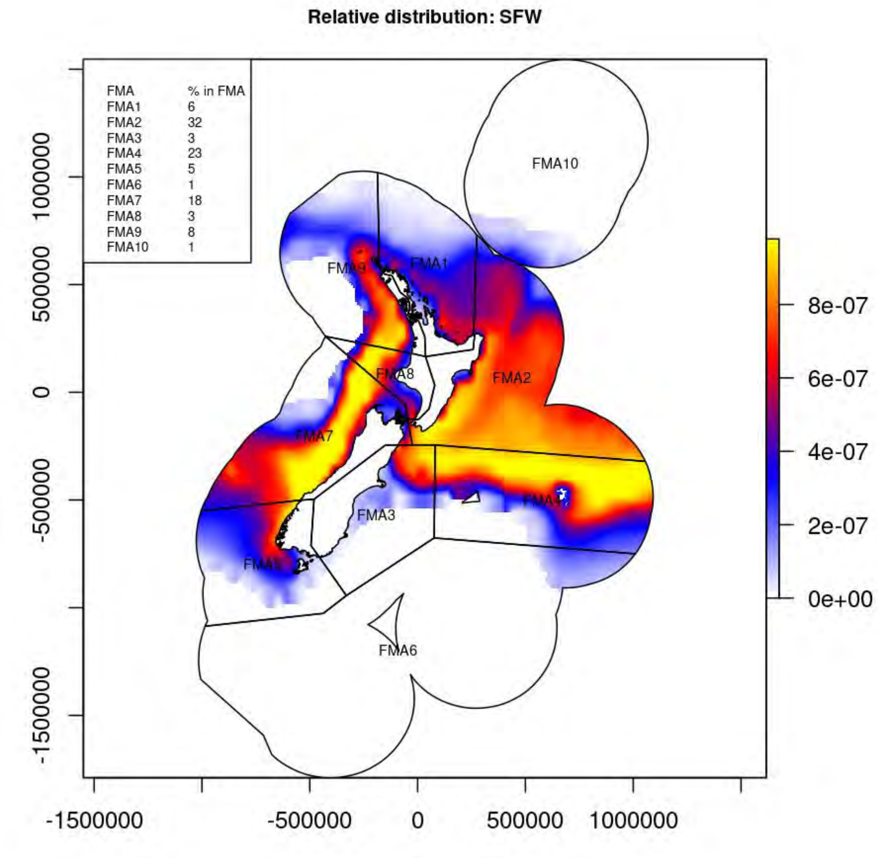

Figure A.98: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.50 True's beaked whale

Demographic parameters

Table A.99: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.100: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	9406	0.35	Worldwide	0.01

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

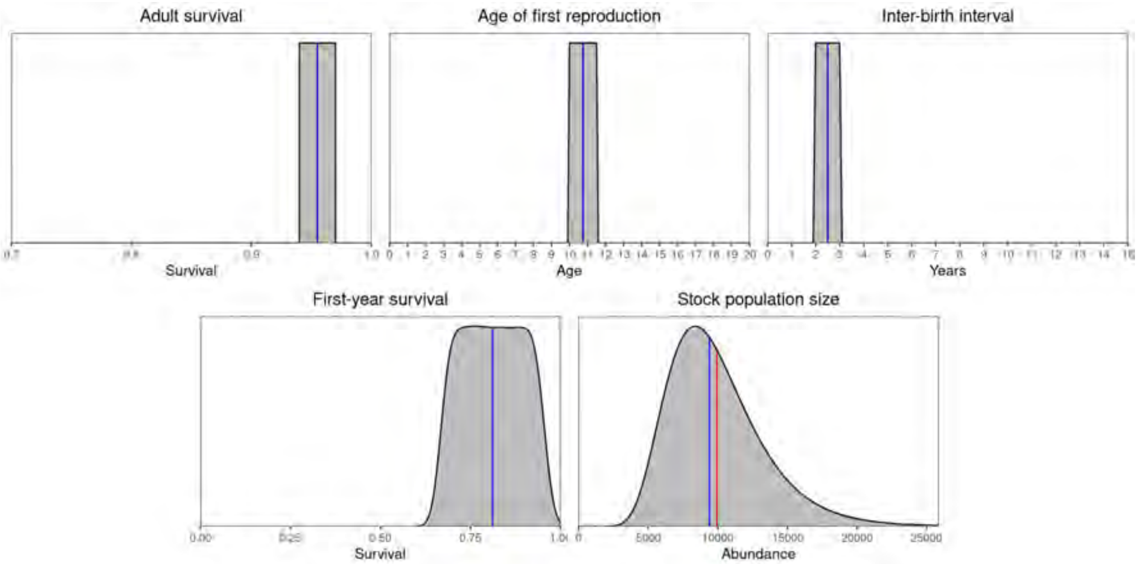

Figure A.99: Prior distributions of demographic input parameters.

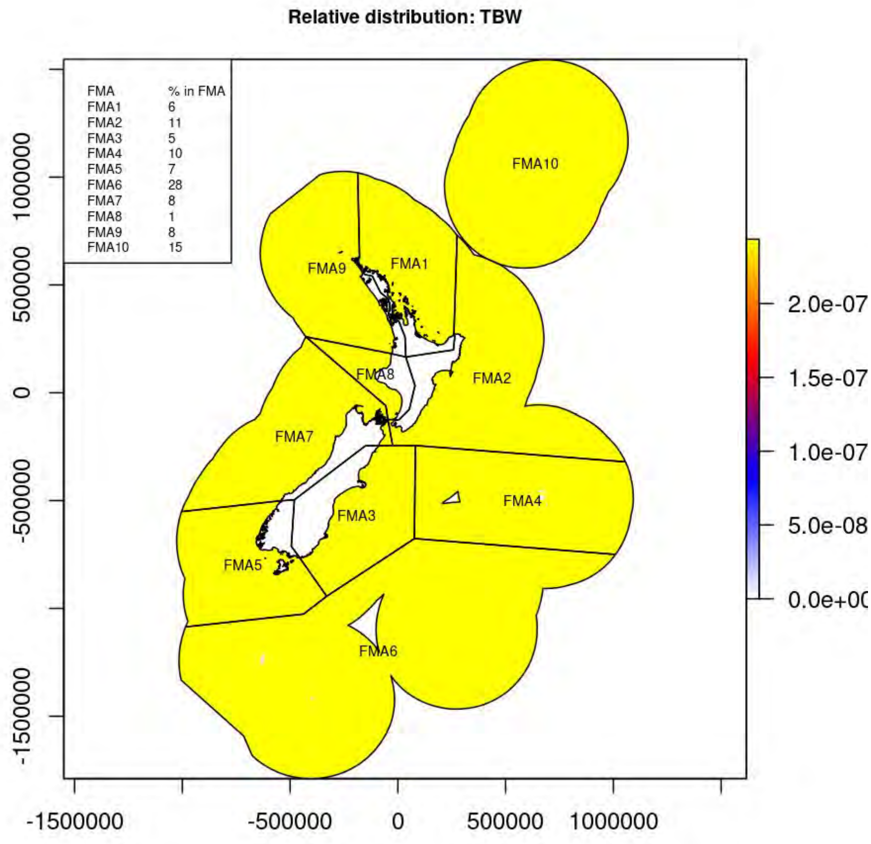

Figure A.100: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.51 Southern bottlenose whale

Demographic parameters

Table A.101: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	norm	11.5	2.32	1	Inf
IBI	norm	2	0.55	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.102: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	50792	0.35	Worldwide	0.028

References contributing to stock abundance information: Branch & Butterworth (2001)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

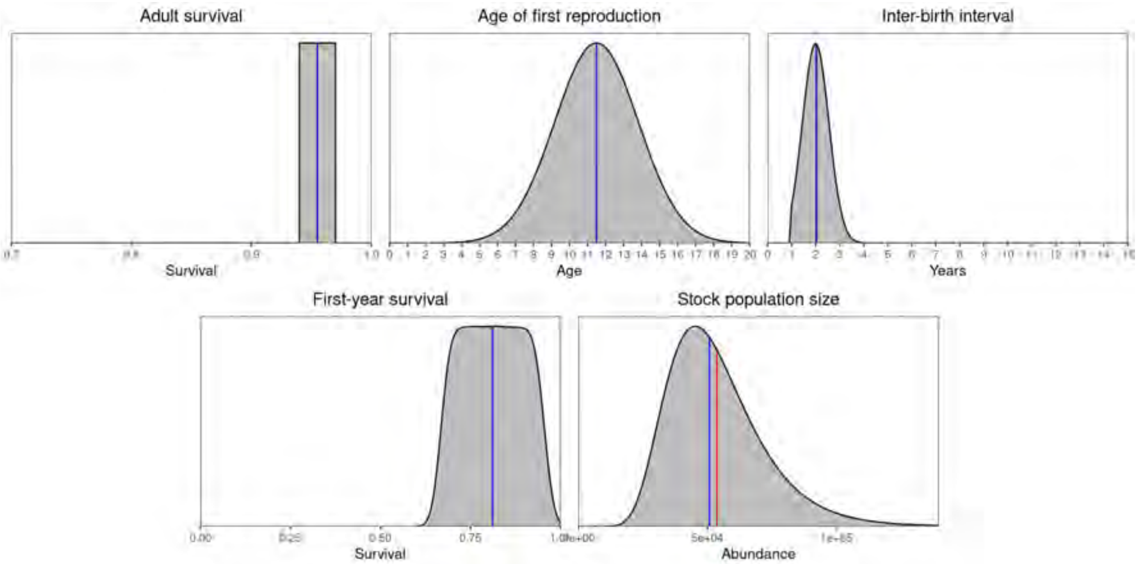

Figure A.101: Prior distributions of demographic input parameters.

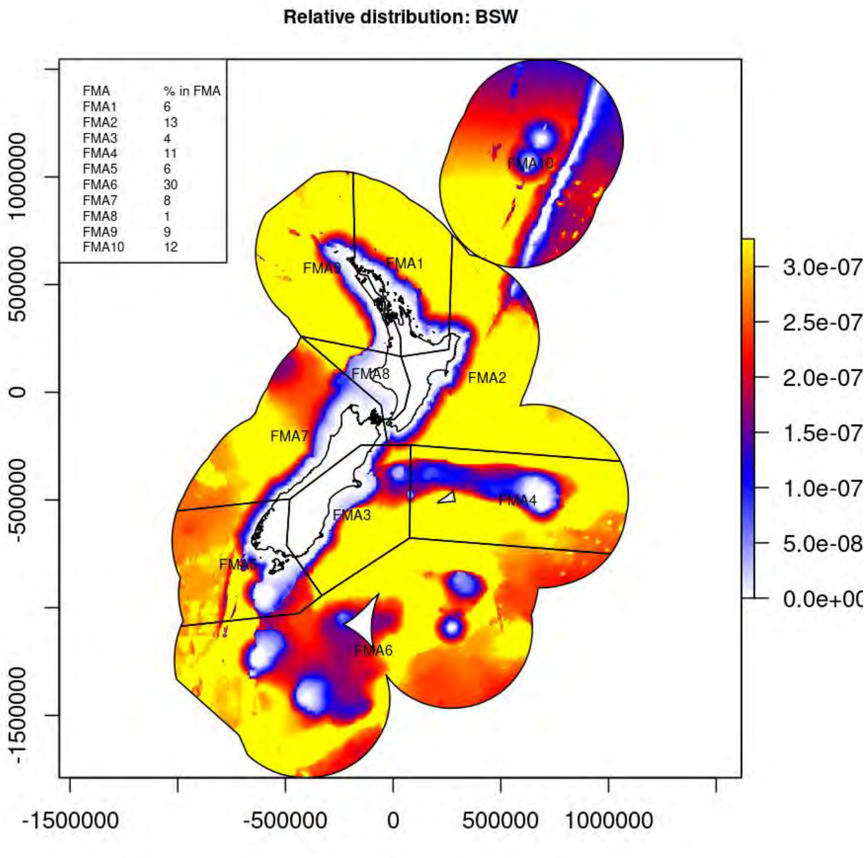

Figure A.102: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.52 Shepherd's beaked whale

Demographic parameters

Table A.103: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.104: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	18443	0.35	Worldwide	0.051

References contributing to stock abundance information:

References contributing to NZ abundance information:

Other notes: NZ abundance is assumed order of magnitude. Stock abundance derived from NZ abundance and P^{EEZ}. Stock abundance CV is assumed value.

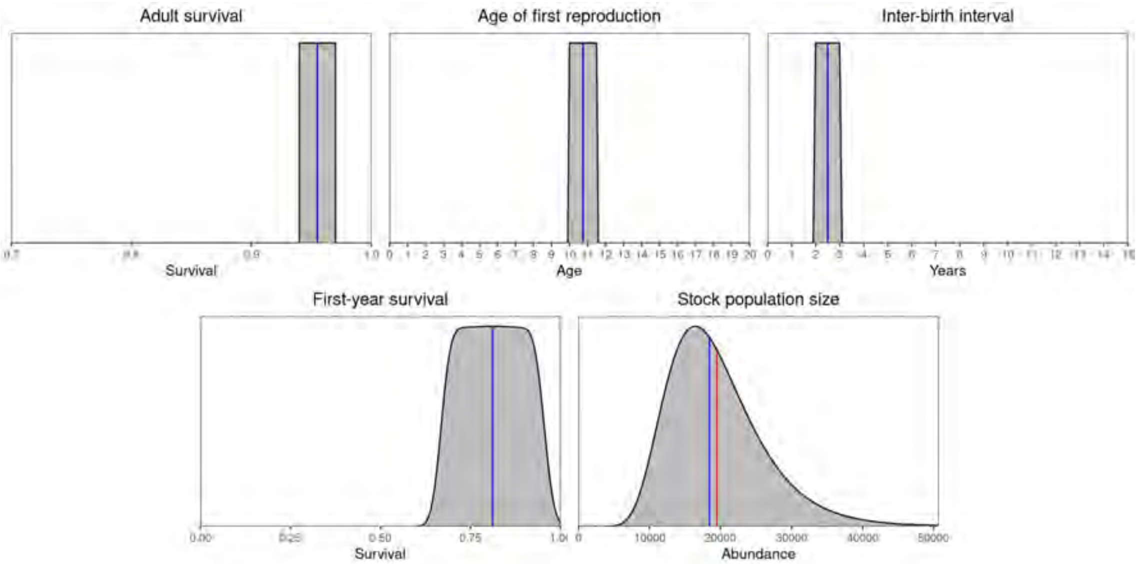

Figure A.103: Prior distributions of demographic input parameters.

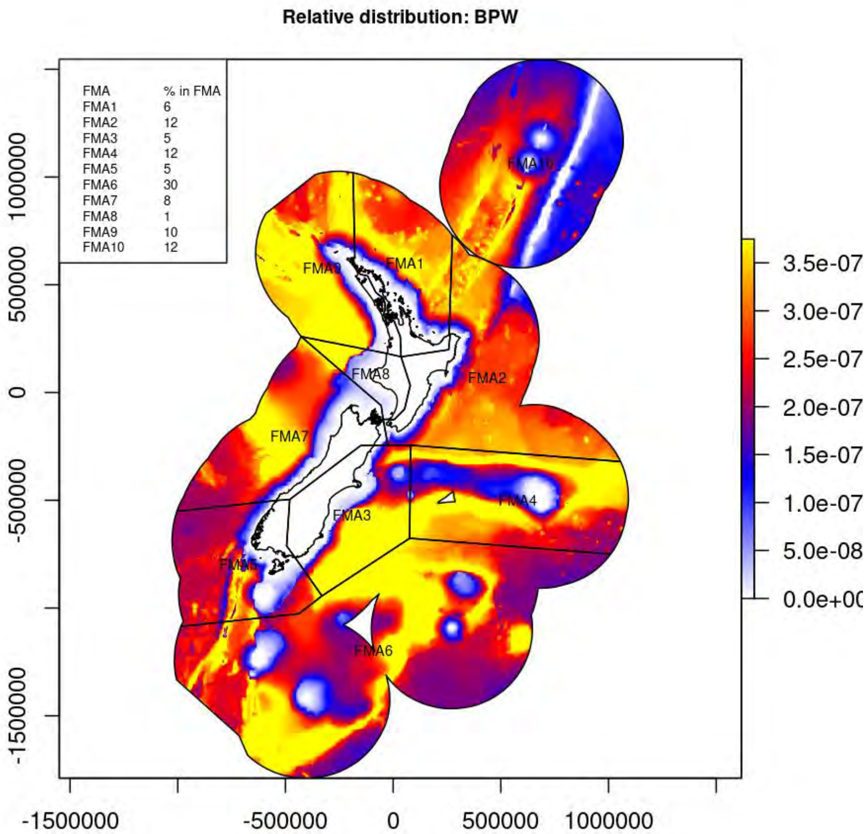

Figure A.104: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.53 Goose-beaked whale (aka Cuvier's)

Demographic parameters

Table A.105: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	beta	0.95	0.01	0.7	0.999
AFR	unif	10.75	0.43	10	11.5
IBI	unif	2.5	0.29	2	11.5
First Yr Surv.	unif	NA	NA	NA	0.999

Table A.106: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	94059	0.35	Worldwide	0.016

References contributing to stock abundance information: Allen et al. (2012)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

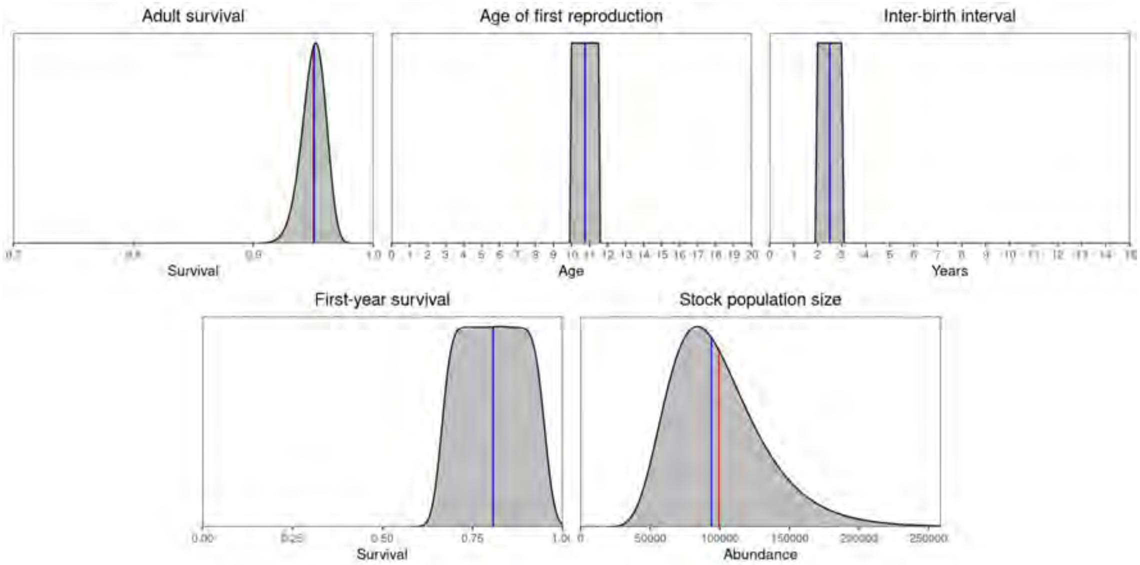

Figure A.105: Prior distributions of demographic input parameters.

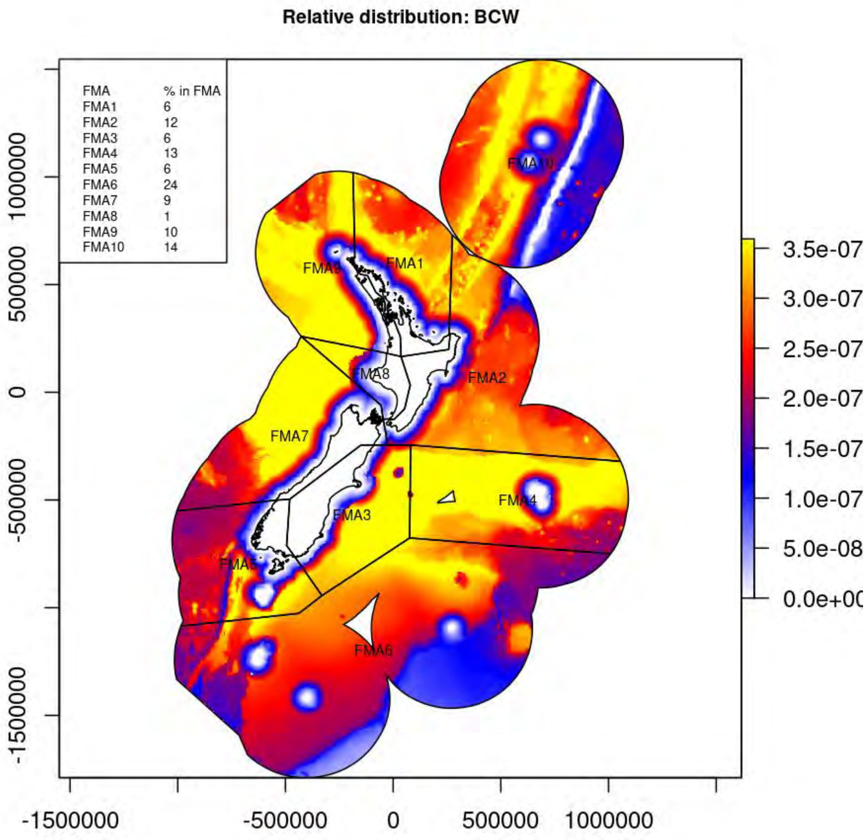

Figure A.106: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

A.54 Arnoux's beaked whale

Demographic parameters

Table A.107: Summary of prior distributions used for demographic parameters in determination of r_{max}.Where no information was obtained for first year survival, values were generated using the ratio method.

Parameter	Distribution	Mean	SD	Min	Max
Ad Surv.	unif	0.955	0.009	0.94	0.97
AFR	norm	10.8	2.18	1	Inf
IBI	norm	3	0.82	1	Inf
First Yr Surv.	unif	NA	NA	NA	0.97

Table A.108: Summary of prior distribution used for stock population size, the applicable stock, and proportion in NZ EEZ (P^{EEZ}).

Distribution	Median	CV	Stock	P^{EEZ}
log-normal	2822	0.35	Worldwide	0.031

References contributing to stock abundance information: Brownell Jr. & Taylor (2021)

References contributing to NZ abundance information:

Other notes: NZ abundance derived from total stock and P^{EEZ}. Stock abundance CV is assumed value.

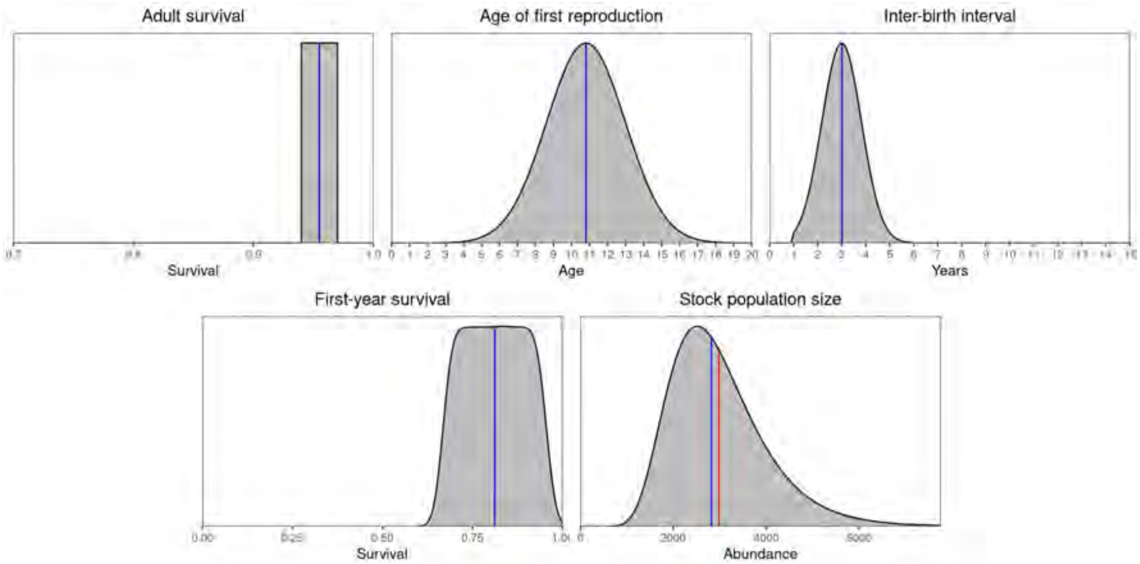

Figure A.107: Prior distributions of demographic input parameters.

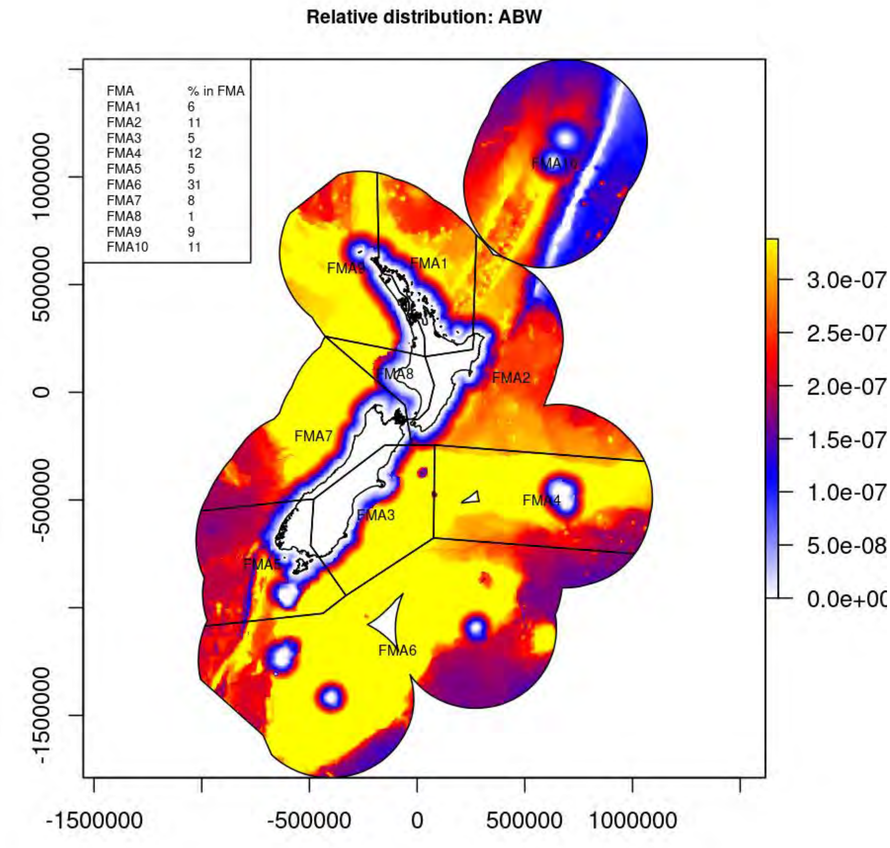

Figure A.108: Species spatial distribution within EEZ. The approximate proportion of the population within each FMA based on the supplied layers is given as a guide.

Appendix B R-code used to estimate r_{max}

```
library(truncdist)  # package for sampling from truncated distributions
nsim<-10^6          # number of simulations from the priors and the
                    #       allometric rT distribution
steps<-nsim/10      # for printing the progress of the simulation loop
mrT<-1              # assumed mean of the allometric rT distribution
srT<-sqrt(0.045)    # assumed sd of the allometric rT distribution
                    #       (cf Moore 2015 and Roberts 2016)
delta<-0.05         # defines the intersection of the prior for rT and
                    #       its allometric distribution

logit<-function(x){ log(x/(1-x)) }
expit<-function(x){ 1/(1+exp(-x)) }
euler<-function(lam,afr,sa,ibi,la){     # used to determine the prior
                                        #       for rmax and Topt
  fec<-0.5/ibi
  lam^(afr-1)*(lam-sa)-fec*la
}
frT<-function(afr,sa,ibi,la){           # determines the prior for rmax
                                        #       and Topt
  lam<-uniroot(euler,interval=c(0,5),tol=10^-6,
               afr=afr,sa=sa,ibi=ibi,la=la)$root
  rmax<-log(lam)
  Topt<-afr+sa/(lam-sa)
  list(rmax=rmax,Topt=Topt)
}
summ<-function(x){                     # summarises results
  summary<-c(quantile(x,probs=c(0.5,0.025,0.975,0.25,0.75)))
  names(summary)<-c("median","lower","upper","lowQ","uppQ")
  return(t(summary))
}

d<-read.table("parameters.txt",T)
attach(d)
nsp<-dim(d)[1]                             # number of species
asa<-sa.mean*(sa.mean*(1-sa.mean)/sa.se^2-1)  # beta shape parameters
                                           #    for adult survival
bsa<-(1-sa.mean)*asa/sa.mean
as0<-s0.mean*(s0.mean*(1-s0.mean)/s0.se^2-1)  # beta shape parameters
                                           #    for first-year survival
bs0<-(1-s0.mean)*as0/s0.mean
saM<-s0M<-afrM<-ibiM<-rmaxM<-ToptM<-rTM<-array(NA,c(nsp,nsim))
saI<-s0I<-afrI<-ibiI<-rmaxI<-ToptI<-rTI<-array(NA,c(nsp,nsim))
rTA<-array(NA,c(nsp,nsim))
prior.rmax<-prior.Topt<-prior.sa<-prior.s0<-prior.a<-prior.ibi<-array(NA,c(nsp,5))
posterior.rmax<-posterior.Topt<-posterior.sa<-posterior.s0<-posterior.a<-
               posterior.ibi<-array(NA,c(nsp,5))
priors<- posteriors<-array(NA,c(nsp,30))
pns<-array(NA,c(nsp,7))
nind<- pind<-vector()
for (i in 1:nsp){
  # sample from the prior for adult survival
  if(is.na(sa.mean[i]))
        { saM[i,]<-runif(nsim,sa.min[i],sa.max[i]) }
  if(!is.na(sa.mean[i]))
        { saM[i,]<-rtrunc(nsim,"beta",sa.min[i],sa.max[i],asa[i],bsa[i]) }
  # sample from the prior for age at first reproduction
  if(is.na(a.mean[i]))
```

```
      { afrM[i,]<-runif(nsim,a.min[i],a.max[i]) }
if(!is.na(a.mean[i]))
      { afrM[i,]<-rtrunc(nsim,"norm",a.min[i],a.max[i],a.mean[i],a.se[i]) }
# sample from the prior for inter-birth interval
if(is.na(ibi.mean[i]))
      { ibiM[i,]<-runif(nsim,ibi.min[i],ibi.max[i]) }
if(!is.na(ibi.mean[i]))
      { ibiM[i,]<-rtrunc(nsim,"norm",ibi.min[i],ibi.max[i],ibi.mean[i],ibi.se[i]) }
# sample from the prior for first-year survival
if(is.na(s0.mean[i]))
      { s0M[i,]<-runif(nsim,c0.min[i],c0.max[i])*saM[i,] }
if(!is.na(s0.mean[i]))
      { s0M[i,]<-rtrunc(nsim,"beta",s0.min[i],s0.max[i],as0[i],bs0[i]) }
lsaM<-logit(saM[i,])        # used to determine survival from age 1 to adulthood
ls0M<-logit(s0M[i,])

for(j in 1:nsim){
  if(j%%steps==0){          # prints the progress of the simulation loop
    time1<-Sys.time()
    dt<-difftime(time1,time0,units=c("secs"))
    print(c(i,j));print(dt)
    time0<-time1
  }
  intaM<-floor(afrM[i,j])                             # determine survival rates
                                                      #   from age 1 to adulthood
  lsjM<-ls0M[j]+(lsaM[j]-ls0M[j])*seq(0,intaM-1)/intaM  # default is linear on a
                                                      #   logistic scale
  sjM<-1/(1+exp(-lsjM))
  laM<-prod(sjM)*saM[i,j]^(afrM[i,j]-intaM)
  find.rT<-frT(afrM[i,j],saM[i,j],ibiM[i,j],laM)      # finds the priors for rmax
                                                      #   and generation time
  rmaxM[i,j]<-find.rT$rmax
  ToptM[i,j]<-find.rT$Topt
}

prior.rmax<-summ(rmaxM[i,])         # stores summaries of the priors
prior.Topt<-summ(ToptM[i,])
prior.sa<-summ(saM[i,])
prior.s0<-summ(s0M[i,])
prior.a<-summ(afrM[i,])
prior.ibi<-summ(ibiM[i,])
priors[i,]<-cbind(prior.rmax,prior.Topt,prior.sa,prior.s0,prior.a,prior.ibi)
rTM[i,]<-rmaxM[i,]*ToptM[i,]                 # finds the intersection of
                                             #     the prior and the
rTA[i,]<-rtrunc(nsim,"norm",0,Inf,mrT,srT)   #     allometric distribution
                                             #     (for rmax x generation time)
ind<-which(abs(rTM[i,]-rTA[i,])<delta)
nind[i]<-length(ind)                         # sizes of the intersections
pind[i]<-nind[i]/nsim
if(nind[i]>0){                               # checks that the intersection
                                             #     is not empty
  rmaxI[i,1:nind[i]]<-rmaxM[i,ind]           # stores the intersections
                                             #     (i.e., the posteriors)
  ToptI[i,1:nind[i]]<-ToptM[i,ind]
  rTI[i,1:nind[i]]<-rTM[i,ind]
  saI[i,1:nind[i]]<-saM[i,ind]
  s0I[i,1:nind[i]]<-s0M[i,ind]
  afrI[i,1:nind[i]]<-afrM[i,ind]
  ibiI[i,1:nind[i]]<-ibiM[i,ind]
```

```
    posterior.rmax<-summ(rmaxI[i,1:nind[i]])      # stores summaries of the posteriors
    posterior.Topt<-summ(ToptI[i,1:nind[i]])
    posterior.sa<-summ(saI[i,1:nind[i]])
    posterior.s0<-summ(s0I[i,1:nind[i]])
    posterior.a<-summ(afrI[i,1:nind[i]])
    posterior.ibi<-summ(ibiI[i,1:nind[i]])
    posteriors[i,]<-cbind(posterior.rmax,posterior.Topt,posterior.sa,
                          posterior.s0,posterior.a,posterior.ibi)
  }
  pns[i,]<-c(summ(pnorm(rTM[i,],mrT,srT)),nind[i],pind[i])      # stores the sizes of
                                                                 #   the intersections
}
colnames(priors)<-colnames(posteriors)<-c("rmax.med","rmax.low","rmax.upp","rmax.lowQ",
"rmax.uppQ","Topt.med","Topt.low","Topt.upp","Topt.lowQ","Topt.uppQ","sa.med","sa.low",
"sa.upp","sa.lowQ","sa.uppQ","s0.med","s0.low","s0.upp","s0.lowQ","s0.uppQ","afr.med",
"afr.low","afr.upp","afr.lowQ","afr.uppQ","ibi.med","ibi.low","ibi.upp","ibi.lowQ",
"ibi.uppQ")

colnames(pns)<-c("p.med","p.low","p.upp","p.lowQ","p.uppQ","nind","pind")
```

Appendix C Diagnostics for model $M_\bullet$

C.1 Model parameter traceplots

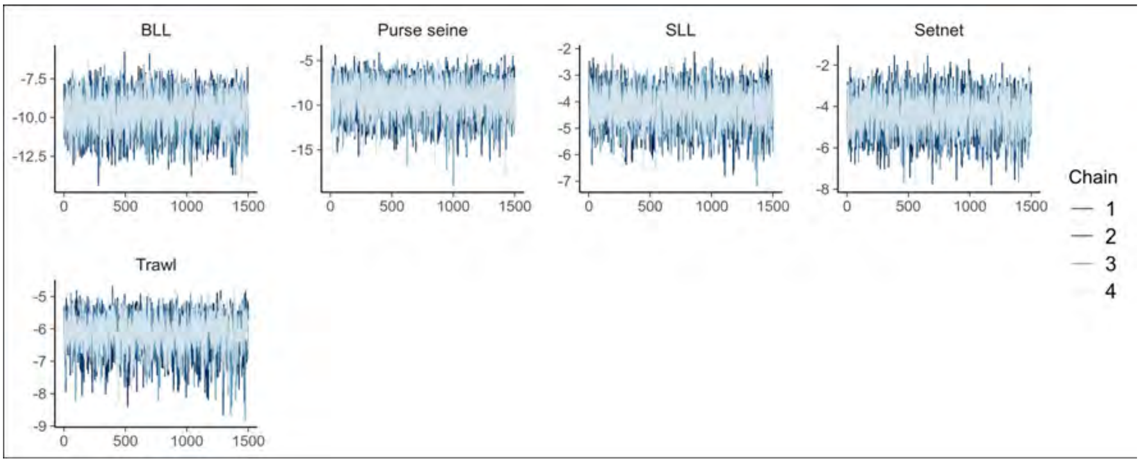

Figure C.1: Traceplot of fishing method catchability intercept terms

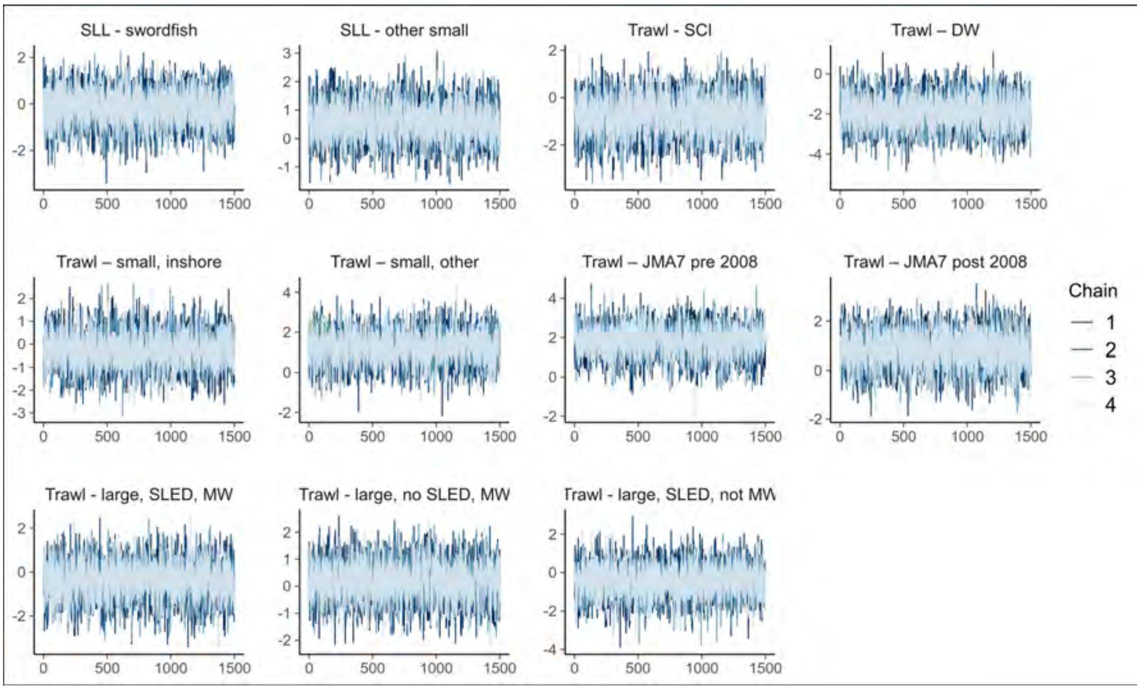

Figure C.2: Traceplot of fishing group catchability terms

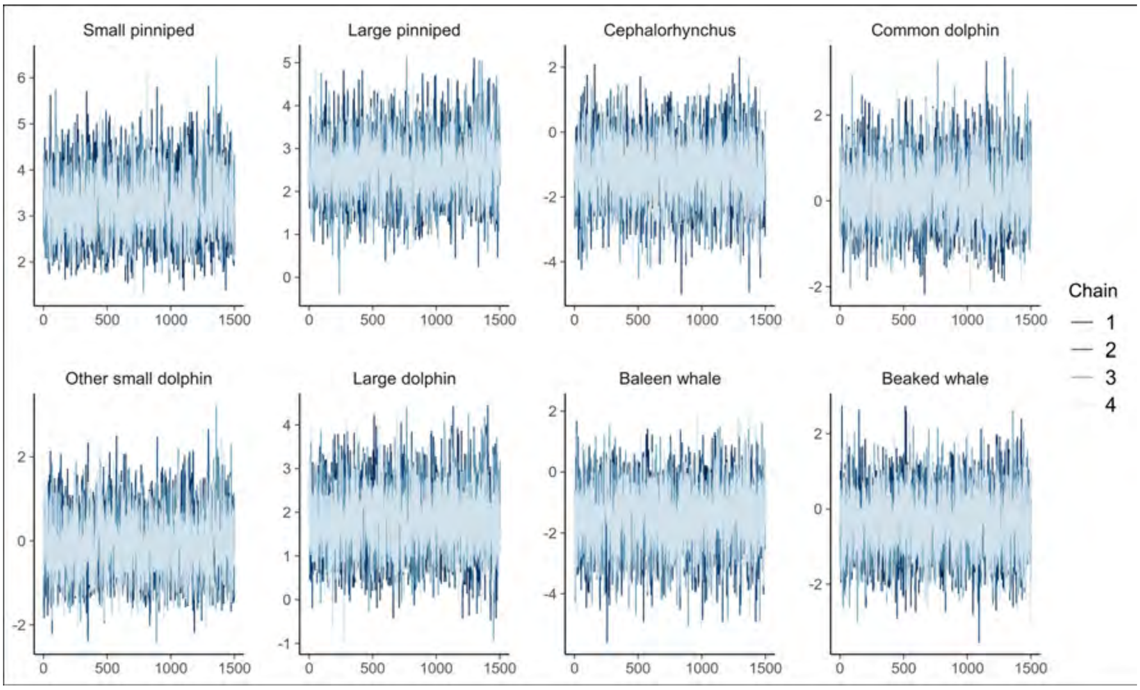

Figure C.3: Traceplot of species group catchability terms

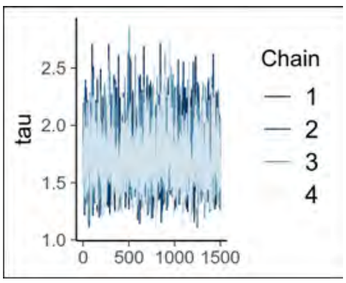

Figure C.4: Traceplot of τ

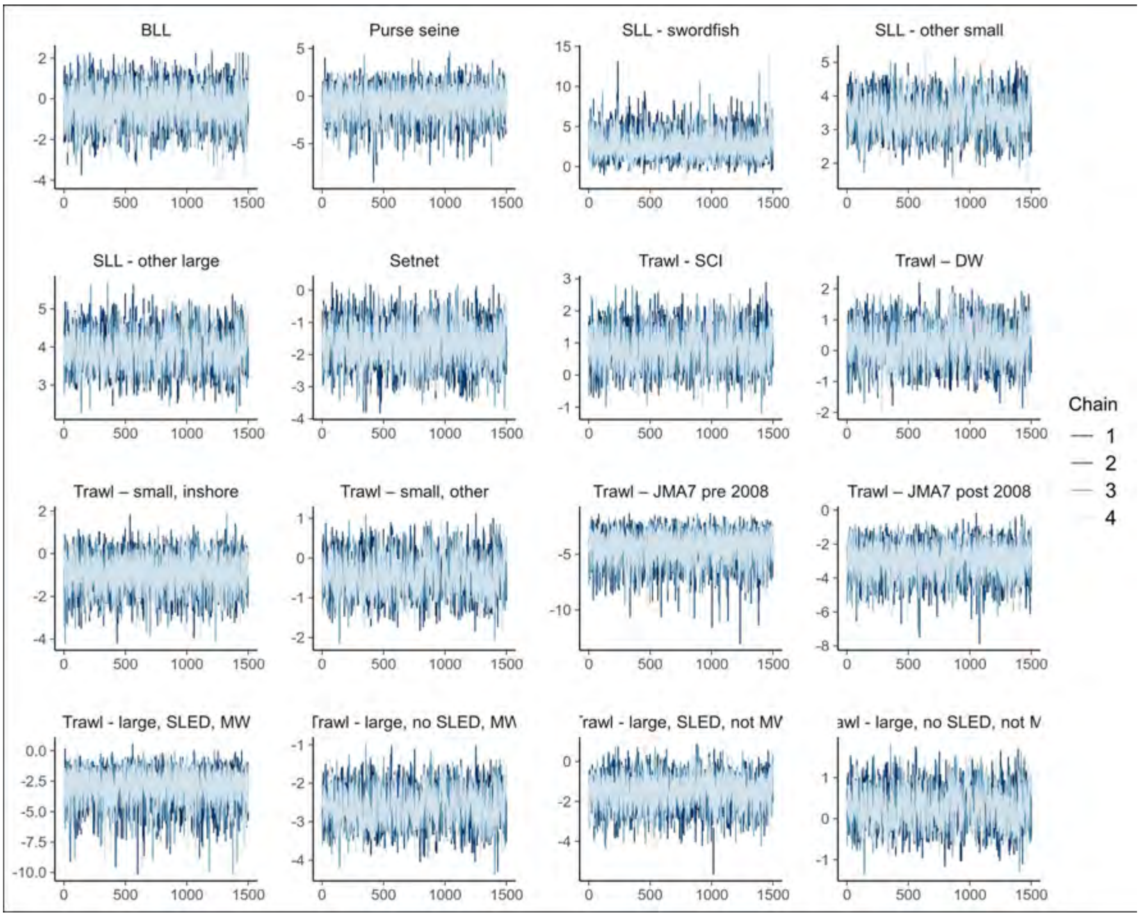

Figure C.5: Traceplot of fishing group live capture terms

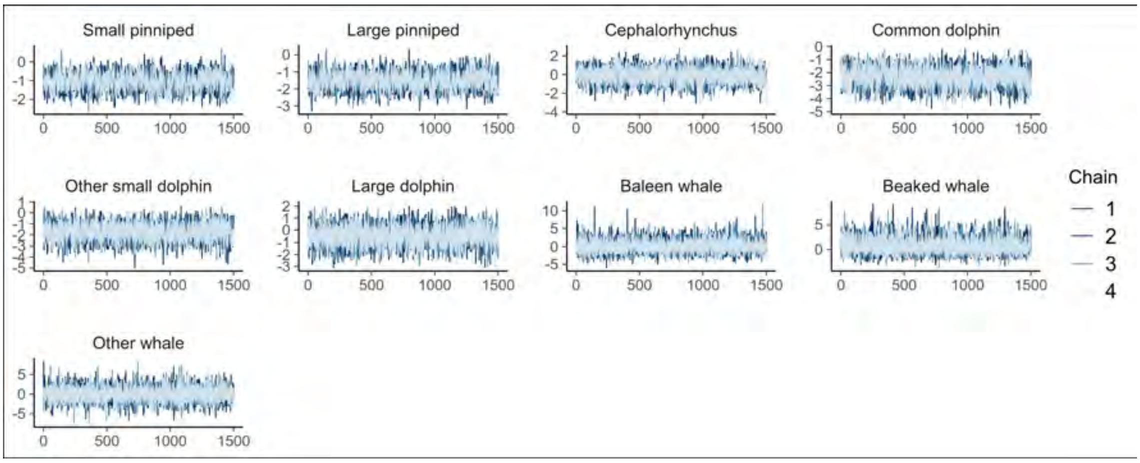

Figure C.6: Traceplot of species group live capture terms