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Spatial-temporal distribution of inshore fish and cephalopod species of interest to selected top predators

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The estimated spatial distributions of top predator species are increasingly used by fisheries managers; for example, to develop spatially explicit fisheries risk assessments. An important predictor in predator distribution models can be the distributions of prey. The work presented here investigated the diet of several top predators in New Zealand and estimated the spatial and temporal distribution of some of their prey species.

The diet of bottlenose dolphin, common dolphin, flesh-footed shearwater, Hector's and Māui dolphin, juvenile great white shark, New Zealand fur seal, New Zealand sea lion, orca, black petrel, Salvin's albatross, Stewart Island shag, and yellow-eyed penguin in New Zealand were summarised based on available literature. A subset of the prey of most importance to these predators and which also occur in inshore fisheries data in sufficient numbers to allow modelling were selected. The distribution of these prey species in space and time in the New Zealand Exclusive Economic Zone was estimated using vector autoregressive spatial-temporal models fitted to inshore commercial, observer, and survey data using fishing and environmental covariates as well as spatial covariates.

The spatial distributions developed were consistent with previous estimates of distributions where such distributions were available. The general spatial distribution and temporal trend in biomass of all species was generally consistent with the information contained within the 2021 Fisheries New Zealand plenary report. Both spatial and temporal trends were also robust to changes in model parametrisation in most instances. Care should however be taken when interpreting the expected distribution of species such as squid or hoki where only the shallow part of their range was included in the modelling and species group such as jack mackerel or rattail which cover multiple species with potentially different ecological niches.

Spatial models were also attempted for species in length classes such as sea perch smaller than 10 cm in length, reflecting the size selectivity of some predators. However, results were not as robust due to the paucity of length data available.

The biomass density distributions developed for many species could be used as inputs in other processes such as spatial risk assessment models of top predators. However, the use of species groups should be carefully considered because these are likely to represent a range of species and niches.

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1. INTRODUCTION

The estimated spatial distributions of species are increasingly used by fisheries managers; for example, as inputs to spatial management processes (e.g., Sharp & Watters 2011, Fisheries New Zealand 2020 chapter 3). In the case of the development of spatially explicit fisheries risk assessments (SEFRA), prey species can be used as an input to the expected spatial distribution of predator species (Roberts et al. 2019). A range of methodologies are available to develop spatial distributions of species, some of which are mentioned below.

Similar work (Roberts et al. 2019) was carried out to estimate the probability of occurrence of the prey of Hector's dolphin (*Cephalorhynchus hectori*) using generalised additive models (GAM), which in turn were used as inputs in a GAM model of the spatial distribution of Hector's dolphin. The prey species analysed were red cod (*Pseudophycis bachus*), arrow squid (*Nototodarus* spp.), sole (*Peltorhamphus* spp.), āhuru (*Auchenoceros punctatus*), sprat (*Sprattus* spp.), and stargazer (*Crapatalus* sp.). The prey data used were survey data from the research vessels *Tangaroa* and *Kaharoa*, with coordinates (eastings and northings), gear depth, trawled area, method, and cod end mesh size as proposed explanatory variables. In that work, only coordinates and sometimes depth were used in the prey species distribution models. The distribution model selected for predicting Hector's dolphin abundance in space was a GAM with turbidity (split for summer or winter conditions) and the probability of presence of āhuru as explanatory variables (Roberts et al. 2019).

Research into key ecological areas for the New Zealand marine environment used an ensemble method (combining estimates from boosted regression trees (BRT) and Random Forest (RF) models) with environmental covariates, but no catchability covariates, to estimate the probability of occurrence of over 600 taxa from demersal fish, benthic invertebrates, macroalgae, and reef fish in the New Zealand Exclusive Economic Zone (EEZ) (Lundquist et al. 2020). Data used were survey data and scuba data for reef species.

The calculation of estimates of over 20 bycatch species or species groups in five deepwater fisheries used a spatial model with fishing year, area, net type, and vessel class as covariates in addition to environmental covariates (Anderson et al. 2019). Research survey catch and effort data were used to develop the model and to predict on the commercial effort data to calculate the expected bycatch for the selected New Zealand deepwater fisheries. This model was developed further to estimate the spatial distribution of selected deepwater fish species in multiple fisheries (Edwards 2021). The species of interest were elephantfish (*Callorhinchus milii*), red gurnard (*Chelidonichthys kumu*), hake (*Merluccius australis*), ling (*Genypterus blacodes*), rough skate (*Zearaja nasuta*), snapper (*Chrysophrys auratus*), sea perch (*Helicolenus* spp.), giant stargazer (*Kathetostoma* spp.), and tarakihi (*Nemadactylus macropterus*, *N.* sp. A).

These studies presented limitations including the use of a subset of the data available (e.g., only survey data by Roberts et al. 2019 and Lundquist et al. 2020), spatial effects proxied through splines (Roberts et al. 2019), modelling the probability of presence rather than abundance of species (Roberts et al. 2019, Lundquist et al. 2020), assuming that the abundance / probability of presence of these species do not change over time (Roberts et al. 2019, Lundquist et al. 2020, Edwards 2021), or not predicting over the entire EEZ (Edwards 2021). These points were addressed in the present project, with survey, commercial, and observer data used within a single model, full spatial effects including spatial correlations accounted for, both probability of presence and abundance estimated within the models, and spatial-temporal trends of biomass estimated for the inshore fisheries over the entire EEZ.

The aim of the present project was to develop spatial distribution layers of inshore fish and cephalopod species which appear in the diet of top predators. These layers, if deemed suitable, could then be used in SEFRA models of said top predators. Specifically, the overall objective of the project was to:

Apply spatial statistical modelling approaches to estimate spatial distributions for inshore finfish and cephalopods of particular importance as prey for key protected species, including seasonal variation, and distinguishing between prey size classes, where relevant.

The specific objectives were:

1. *Utilise available data to identify key prey species (and prey size-class preferences) for up to ten top predator species that forage in the inshore environment. Predator species will include fur seals, sea lions, yellow-eyed penguins, Hector's / Māui dolphins, and 3–6 additional species chosen in consultation with Fisheries New Zealand.*
2. *Applying statistical spatial modelling techniques, estimate spatially resolved densities of up to 30 inshore fish and cephalopod species, including seasonal variation, with a focus on prey species and size classes identified under Objective 1. Where top predators exhibit size-selective foraging (e.g., eating only small fish), estimate separate spatial distributions for the relevant prey size classes.*

2. METHODS

2.1 Fisheries data

Inshore fisheries were defined as all fishing activity, in all areas, for all form types and by any fishing method, where the target species was not one of the following deepwater species codes: ASQ, BOE, CAR, CDL, CDO, HAK, HOK, HOR, JMA, JMD, JMM, JMN, LDO, LIN, NOG, NOS, OEO, ORH, PRA, PTO, RIB, SBO, SBW, SCI, SOR, SQU, SSO, SWA, WOE, WWA. The species codes are defined in Table B.1 in Appendix B.

All bottom trawl survey data regardless of their target (from 1990 to 2019), as well as inshore fisheries data from the observer programme and inshore fisheries commercial data (from 2001 to 2020) were extracted by Fisheries New Zealand on 29 March 2021 under replog 13541. This included length frequency data collected during the trawl surveys and observer sampling programme.

Commercial catch and effort data as well as data from the observer programme were checked for errors using simple checking and imputation algorithms and implemented in the software package 'R' (R Core Team 2019). Individual tows were investigated, and missing values or outliers beyond the 99 percentile for start/finish latitude or longitude, fishing method, target species, tow speed, net depth, bottom depth, wingspread, duration, and headline height were replaced with the median imputation on larger ranges of data such as the combination of vessel, target species, and fishing method for a day, month or year. Where possible, distance was calculated based on speed and duration rather than latitude and longitude information to account for when fishing paths are not straight. Data from daily reporting forms such as catch effort landing reporting forms (CELR) and high sea forms, and any data missing latitude or longitude information, were removed. Only bottom trawl, bottom longline, and set net events were retained.

The commercial and observer data were selected based on the target species not being a deepwater species. The trawl survey data required an equivalent selection as multiple targets are the subject of any one survey. Three methods were investigated: based on a maximum depth (90th percentile of the commercial data is 154 m, 95th percentile is 210 m, and 99th percentile is 355 m), based on the target species of the trawl survey, or a combination. The depth distribution of the various datasets is depicted in Figure 1, and the spatial distribution of the data available is shown in Figure 2 and Figure 3.

For this analysis, all survey tows where the trip was not targeting deepwater species and survey tows where the trip was targeting deepwater species with tows in 350 m depth or shallower were used.

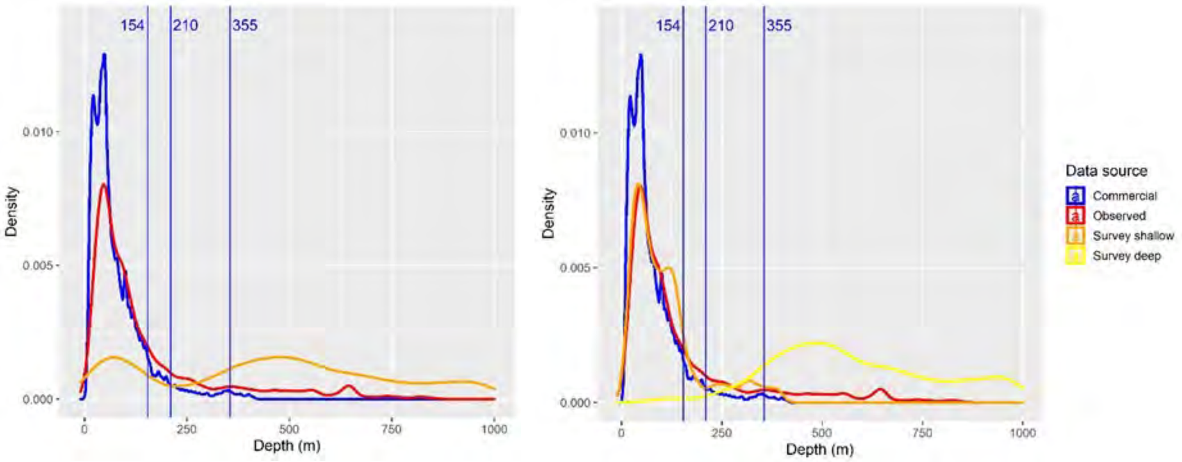
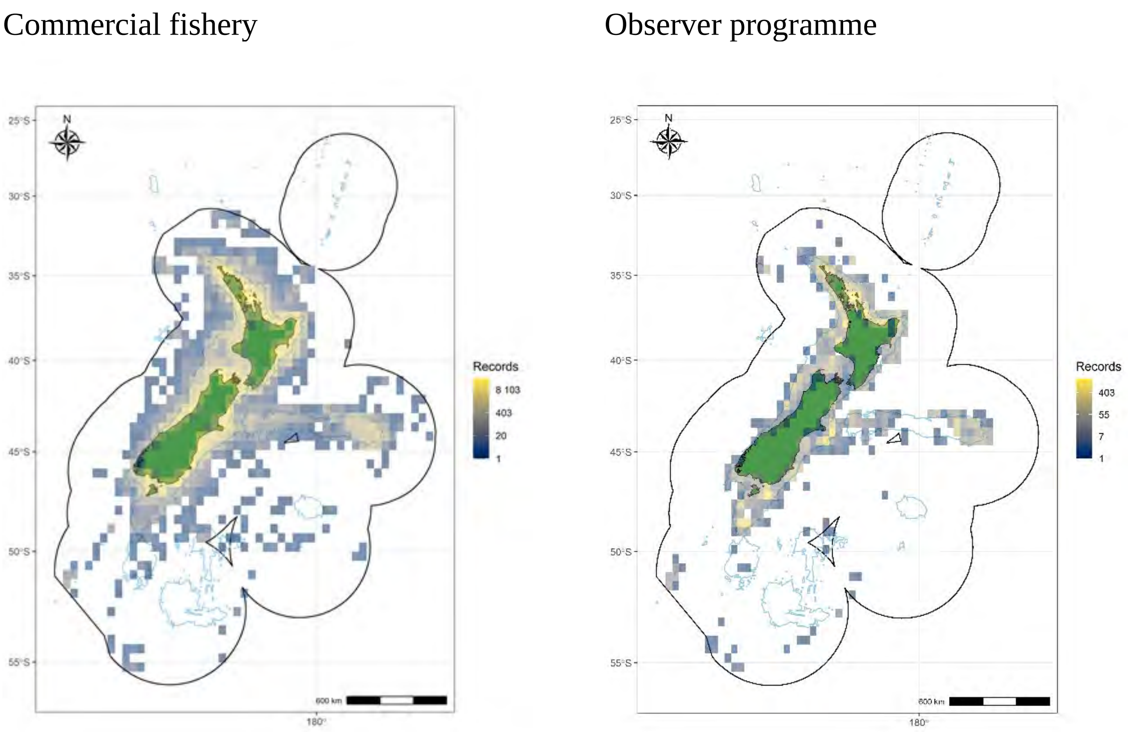


Figure 1: Depth by data type. The plot on the right splits the survey data depending on if the target species included deepwater species as defined above (survey deep) or not (survey shallow). Also shown the 90th percentile, 95th percentile, and 99th percentile of depth for the commercial data in vertical blue lines.

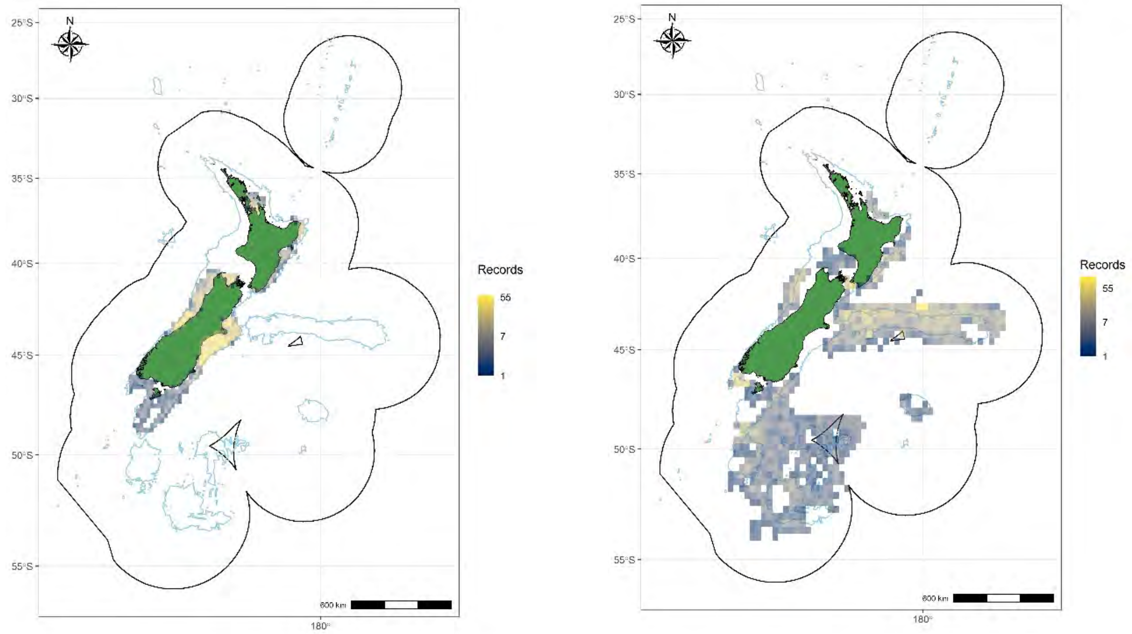

Commercial fishery

Observer programme

Figure 2: Spatial distribution of the commercial and observer mid-point fishing events available for the analysis in the New Zealand EEZ outer boundary (black line). The 500 m depth contour is also shown in light blue.

Survey – non-deepwater species

Survey – deepwater species



Survey – shallower than 350 m

Survey – shallow or deepwater tows shallower than 350 m

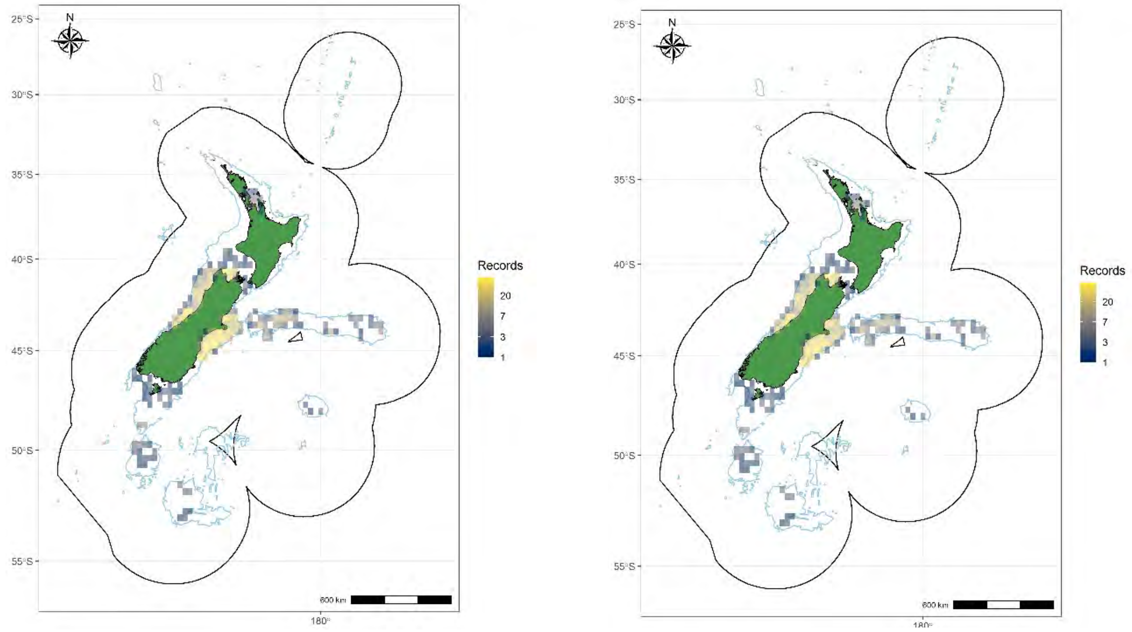


Figure 3: Spatial distribution of the survey mid-tow position available for the analysis. The survey data are presented separately for non-deepwater and deepwater surveys (as defined above) or shallower than 350 m depth (see below for rationale). The 500 m depth contour is also shown in light blue and the New Zealand EEZ outer boundary in black.

Because both the diet of top predators and fisheries data were not necessarily recorded to species level, groups of species were defined for this analysis:

- BUL: includes all bullies and generic code
- FLO: includes all flounder species and generic flounder code
- JMA: includes all jack mackerel species and generic code
- KAH: includes KAH and ATT codes
- MOR: includes all morid species (including red cod) and generic code

- SOL: includes all sole species and generic sole code, witch, and unspecified flatfish
- SQU: includes all squid and generic code
- STA: includes all stargazer species and generic code
- TAR: includes TAR and NMP codes
- WAR: includes common, silver and white warehou
- WRA: includes all wrasses and generic code
- RAT: includes all rattail species and generic codes

2.2 Modelling

Methods such as vector autoregressive spatial-temporal (VAST, Thorson & Barnett 2017) models apply a smoother to catch data (expressed in catch per area) in both time and space. Maunder et al. (2020) showed that spatial-temporal models were useful to derive indices of abundance and composition data when sampling intensity varies across the spatial domain — better accounting for variability in sampling over space and time that otherwise would violate the assumptions of time-invariant catchability and selectivity in stock assessment models. Similar results were reported elsewhere; for example, comparing GAM and VAST performance (Grüss et al. 2019, Mormede et al. 2020). The performance of VAST has also been tested using simulations (e.g., Brodie et al. 2020). VAST was used in this study to fully account for the spatial and spatial-temporal relationship in the data.

Model specifications: species distributions

For models of the distribution of individual species, the model build and selection followed recommendations by Thorson and others (Thorson 2019, Thorson et al. 2021):

- The model distribution chosen was a delta-lognormal (the recommended delta-gamma distribution provided less stable models and minimisation issues). The first component of a delta model (here log-link function) estimates the probability of encountering a species at a given location and time, and the second component (here a lognormal function) of the model estimates positive catch rates on condition that the species is encountered (VAST parameter Obsmodel = c(4,1)). The predicted biomass accounts for both the probability of presence and the catch rate given the species is encountered.
- Bias correction was implemented for the probability of presence and abundance indices, whereby these derived quantities are corrected for retransformation bias (Thorson 2019).
- Spatial, spatial-temporal, and temporal variation were assumed present and estimated as random effects (VAST parameter FieldConfig = “IDD” for all).
- The method used was ‘*Barrier*’ to ensure no correlation was carried across land, either on a longitude or latitude basis (VAST parameter Method). Because the models allow for spatial correlation, any land area must be accounted for to ensure no such spatial correlation is carried over across land (Bakka et al. 2019).
- Intercepts and spatial-temporal variation were assumed as fixed annual effects (VAST parameter RhoConfig = c(0,0,0,0)).
- Overdispersion was turned off for both encounter probability and for positive catch rates (VAST parameter OverdispersionConfig =c(0,0)).
- The number of knots used was 150 with fine-scale extrapolation smoothing. This was the maximum number of knots where the model still converged and provided marginal improvement in precision compared with 50 or 100 knots. Smoothing allows for the extrapolation of the abundance from the scale of the mesh to a finer scale defined by the user, in this case the equal area grid.

The effective area occupied is calculated as the area required to contain the population at its biomass-weighted average density. This estimator can then be used to monitor range expansion or contraction or density-dependent range expansion. Similarly, the centre of gravity as the biomass-weighted mean latitude and longitude are calculated and can be monitored over time (Thorson et al. 2016).

Model specifications: length-class species distributions

For models of the distribution of species split by length class, the model selection was limited by data availability, leading to minimisation issues. The model selected was the most complex model which minimised (ran to completion) and with acceptable convergence diagnostics:

- The model distribution was a delta-Poisson at coarse scale with no bias-correction.
- The method used was '*Barrier*' to ensure no correlation was carried across land, either on a longitude or latitude basis.
- The number of knots used was 50 with no fine-scale extrapolation smoothing. This was the maximum number of knots where the model still converged.

Model selection

Because of long model run times, model runs investigating various potential structures were carried out on a subset of the full dataset (including commercial, observer, and survey data): retaining only data from 2018 to 2020 from the full dataset and run on snapper as an exemplar species. No bias-correction or fine-scale calculations were carried out during model selection, and 50 knots were used to speed up model run time. The model structure was then applied to all further model runs for all species to ensure comparability, with the acknowledgement that not all variables will be relevant for all species.

During model selection, potential explanatory variables and environmental variables were added to the models in a stepwise manner. Vessel identification, a random effect parameter in VAST, was either ignored, set at a combination of data source (commercial, observer, or survey) and method (bottom longline, bottom trawl, or set net), or as a combination of data source and unique vessel identifier.

The model structure selected was a combination of lower AIC, no convergence or dispersion issues, and an acceptable run time (hours rather than days for the models run with 2018–2020 data). A model was deemed to have no obvious convergence issues if no parameters hit a bound, the gradient of the marginal log-likelihood was less than 0.0001 for all fixed effects, and the hessian matrix of the second derivative of the negative log-likelihood was positive-definite. Partial effect plots were also investigated to check for a significant effect although these were not removed because the effects are likely to differ between species.

Model grid

The model predictions were run to an equal area grid. The functions used to create such grids are provided by Mormede et al. (2022). All environmental variables were re-projected to the equal area projection before being extracted for the purposes of this work.

The choice of grid size is a balance between very small grids with hardly any data in each cell and very large grids which smooth over the information available. Furthermore, a small grid size might 'hide' the actual resolution of the data, and the smaller the grid size the more computationally intensive the analysis will be. For example, a grid size of 250 m will present the most precise depth data available (albeit in a different projection) but will have many cells with no fishing information, where the model will need to extrapolate outcomes. Where fishing information is available, the model will assume that each fishing event is at the resolution of the cell, 250 m in this case.

The mean trawl length in the data selected was 18 km, so even a grid of 16 km will assume that the entirety of the fishing event happens in this grid size. This grid size was chosen as a natural balance between an overly optimistic precision of the model and an overly coarse result reducing the usefulness of the outputs. To avoid spurious distributions at the margins of the area fished and remove any residual errors in location recorded, only cells in which over 10 events were recorded over the 20 years of the dataset and where the mean depth was shallower than 500 m were kept (Figure 4). This dataset is further referred to as the ‘full dataset’. The data were further aggregated by vessel / method / month / grid combination (see below) and this dataset is further referred to as the ‘aggregated dataset’. Each fishing event is assigned to a grid based on its mid position when start and end positions are available.

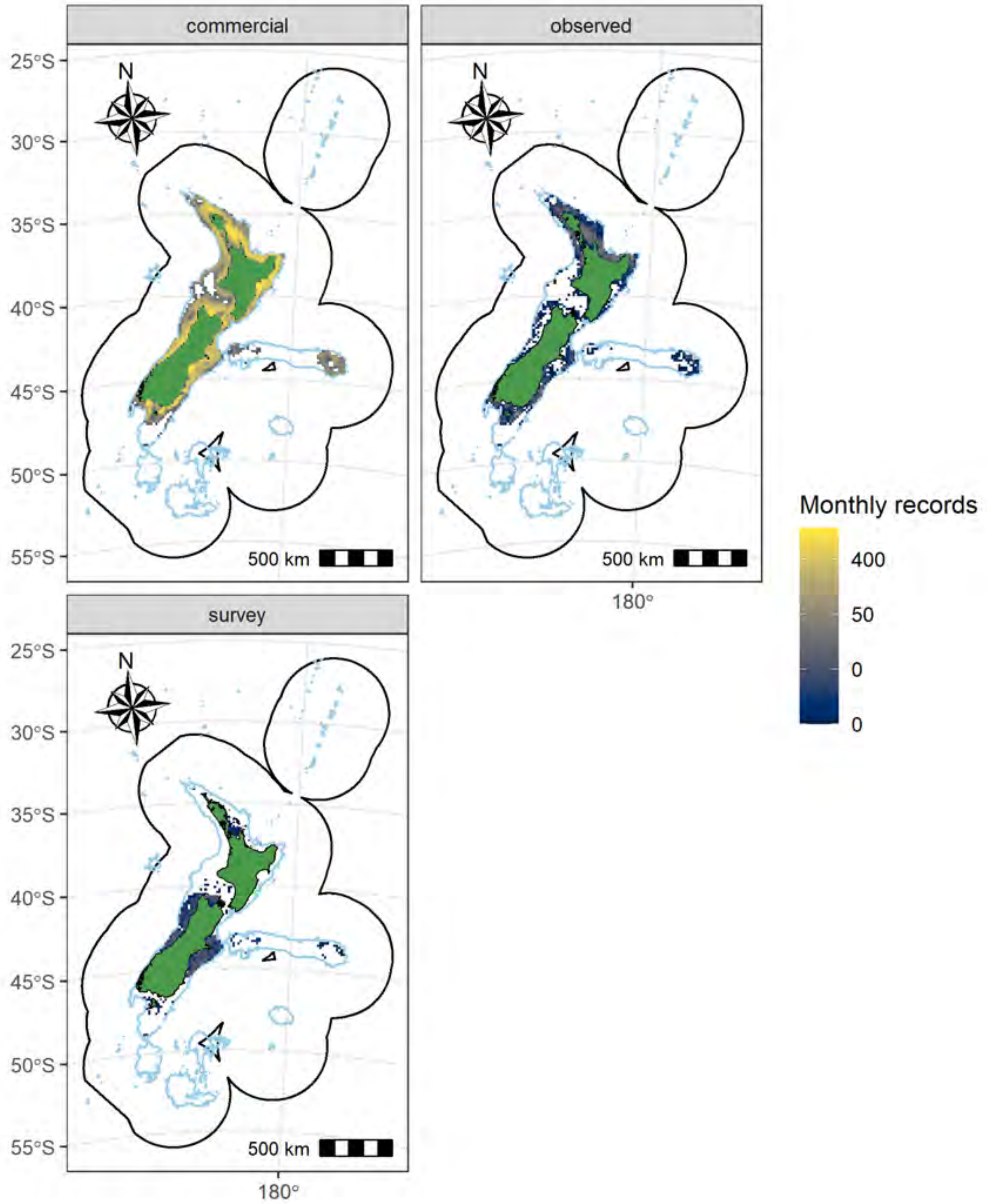


Figure 4: Spatial distribution of the aggregated dataset (see details below) records used in the VAST models by data source. The 500 m depth contour is shown in light blue and the New Zealand EEZ outer boundary in black.

Potential explanatory variables

Year was used in all models. Potential fishing covariates tested in the model were:

- data source (observer, commercial, or survey),
- month,
- method (bottom trawl, bottom longline, or set net),
- vessel length (m), and
- vessel identification (as a random effect variable).

In VAST, catches are provided along the surface area of the fishing effort in order to calculate biomass. The surface area in square kilometres was calculated as follows for commercial data:

- For bottom trawls: distance × wingspread, with distances of 0 assumed as 100 m. These represent short tows where distance could not be calculated using duration and speed and the recorded latitude and longitude did not change between the start and end positions.
- For bottom longlines: spacing between hooks (parameter width) × number of hooks, assuming a 1-km wide attraction.
- For set nets: total net length, assuming width of effort will be included in the selectivity parameter.

The surface area in square kilometres was calculated as follows for observer data:

- For bottom trawls: distance × doorspread, with distances of 0 assumed as 100 m.
- For bottom longlines: number of hooks ×2 m (the median distance between hooks in the commercial data), assuming a 1-km wide attraction (longline length is hardly ever recorded).
- For set nets: total net length, assuming width of effort will be included in the selectivity parameter.

The observer data were missing many bottom trawl doorspread and set net total net length data despite missing values having already been replaced with the median imputation by vessel, method, and month combined as part of the initial data analysis (detailed in the methods section). The remaining missing values were replaced by the median value by method and year and, where still missing, by the median value by method.

Potential environmental covariates used in the model were: depth, turbidity, slope, sea surface temperature, tidal current, chlA, and mixed layer depth. These environmental variables were the same as those used by Stephenson et al. (2020) with details therein; they were assumed constant over time. Because these were not in the equal area projection, the grid was re-projected to that of each environmental variable, and their mean value in each of the grid polygons extracted using the R package *raster* and function *extract*. This difference in projection leads to unavoidable smoothing or approximation of the environmental values in each grid cell; however, these are expected to be small at the 16 km resolution. The values of the environmental variables used at the 16 km grid size resolution are shown in Appendix A, Figure A.1 to Figure A.4.

The environmental variables at the level of grid size were tested for collinearity using the variance influence factor calculation in the R package *usdm*; they presented no collinearity problems. All numerical covariates were offered to the model as third-degree polynomials. The suitability of such a shape for the environmental variables and, in particular, its suitability at the extremes of the environment captured can be inferred based on the credible intervals of the partial effects plots and the rug of the distribution of the data.

3. RESULTS

3.1 Selection of top predators of interest

Up to ten predator species that forage in the inshore environment were chosen in consultation with Fisheries New Zealand and the Department of Conservation. Criteria used included:

- The risk status of the predator based on the New Zealand Threat Classification System (Robertson et al. 2017, Baker et al. 2019) which classifies species from not threatened to nationally critical and includes data deficient, migrant, and vagrant categories.
- The fisheries risk ratio of the species where it has been calculated (Fisheries New Zealand 2020), which estimates the risk to protected marine species posed by fishing.

- Whether diet information is available for the species, and whether that diet includes species caught in the New Zealand inshore fisheries.
- Any future scientific or spatial management project which might benefit from the distribution of prey species of top predators.

A long list of species considered is summarised in Table 1, including the risk status of the species based on the New Zealand Threat Classification System and the fisheries risk ratio where available. Species names in bold were initially selected for the analysis. Common dolphin (*Delphinus delphi delphi*) was also added to the list of species of interest when the diet information for bottlenose dolphin (*Tursiops truncates*) was found to be sparse.

3.2 Diet of selected top predators

A summary of the diet of each of the selected top predators is given below. These summaries are not aimed at being exhaustive or detailed, but to represent the main prey species consumed, and if any size-specificity of the prey or seasonality of the diet is known. Where little information was available, diet was extrapolated from similar species or diet information from Australia. Furthermore, prey species excluded marine mammals, seabirds, and other species not regularly caught in inshore fisheries.

Black petrel

The diet of black petrel is not well documented (Imber 1976, Bell 2013). The main prey species likely to appear in the inshore fisheries catches include arrow squid (*Nototodarus sloanii*, *N. gouldi*), lighthouse fish (*Photichthys argenteus*), cephalopod *Ommastrephes* spp., rattail (*Macrouridae* family), and violet squid (*Histioteuthis* spp.). There is no seasonal, location, or prey size information available.

Bottlenose dolphin

There are few studies of what bottlenose dolphin might consume in Aotearoa New Zealand. Bottlenose dolphins have a flexible and generalist diet.

In Fiordland, Schneider (1999) reported five dead and injured fish in the vicinity of bottlenose dolphin (two spotties – *Notolabrus celidotus*, two rattails, and one hoki – *Macruronus novaezelandiae*). Stable isotope work has also been carried out but is not precise enough to provide prey items to the species level (Lusseau & Wing 2006). A study of bottlenose dolphin in Fiordland as a function of species distribution found a positive correlation with girdled wrasse (*Notolabrus cinctus*, Bennington et al. 2020). A population of bottlenose dolphin at Stewart Island was also repeatedly observed foraging around salmon farms and surfacing with salmon (*Salmo salar*, Brough 2013).

Inshore bottlenose dolphins have been studied in the Bay of Islands (Hartel 2010), and possible prey include morays (*Muraenidae* family), conger eel (*Conger* spp.), pilchard (*Sardinops sagax*), lizardfish (*Synodus* spp.), flying fish (Exocoetidae), piper (*Hyporhamphus ihi*), golden snapper (*Centroberyx affinis*), John dory (*Zeus faber*), hāpuku (*Polyprion oxygeneios*), perch (*Perca fluviatilis*), maomao (*Caprodon longimanus*, *Scorpis violacea*), trevally (*Pseudocaranx georgianus*), kōheru (*Decapterus koheru*), jack mackerel (*Trachurus declivis, T. murphyi, T. novaezelandiae*), kingfish (*Seriola lalandi*), kahawai (*Arripis trutta, A. xylabion*), snapper (*Chrysophrys auratus*), goat fish / red mullet (*Upeneichthys lineatus*), bluefish (*Girella cyanea*), parore (*Girella tricuspidate*), knifefish (*Labracoglossa nitida*), grey mullet (*Mugil cephalus*), yellow-eyed mullet (*Aldrichetta forsteri*), pigfish (*Congiopodus leucopaecilus*), spotty, wrasse species (*Labridae*), goby (*Gobiidae*), tuna (*Thunnus* spp.), flounder (multiple species), and leatherjacket (*Meuschenia scaber*). Offshore bottlenose dolphins are considered a different ecotype or different population (Hartel 2010) and are likely to have a different diet and are not considered here.

Table 1: Long list of predator species considered for the analysis with their risk status based on the New Zealand Threat Classification System and fisheries risk ratio from the New Zealand spatially explicit fisheries risk assessment (SEFRA) where available (Fisheries New Zealand 2020), ordered by group and decreasing risk ratio. Risk status is highlighted red for nationally critical, dark yellow for nationally vulnerable, and light yellow for nationally endangered. Risk ratio is highlighted red for above 1, dark yellow for 0.3 to 1, and light yellow 0.1 to 0.3. The species retained for this study are in bold.

Species	Risk status	Risk ratio
Marine mammals in the SEFRA model		
Common dolphin (*Delphinus delphi delphi*)	not threatened	0.80
Orca (*Orcinus orca*)	threatened - nationally critical	0.50
Hector's dolphin (*Cephalorhynchus hectori hectori*)	threatened - nationally vulnerable	0.40
Māui dolpin (*Cehphalorhynchus hectori maui*)	threatened - nationally critical	0.40
Bottlenose dolphin (*Tursiops truncates*)	threatened - nationally endangered	0.30
Short-finned pilot whale (*Globicephala macrorhynchus*)	data deficient	0.30
New Zealand fur seal (*Arctocephalus forsteri*)	not threatened	0.30
False killer whale (*Pseudorca crassidens*)	at risk - naturally uncommon	0.28
Long-finned pilot whale (*Globicephala melas*)	not threatened	0.25
Dusky dolphin (*Lagenorhynchus obscurus*)	not threatened	0.12
Southern elephant seal (*Mirounga leonina*)	threatened - nationally critical	0.10
New Zealand sea lion (*Phocarctos hookeri*)	threatened - nationally vulnerable	0.09
Other marine mammals considered		
Bryde's whales (*Balaenoptera edeni*)	threatened - nationally critical	
Seabirds in the SEFRA model		
Black petrel (*Procellaria parkinsoni*)	threatened - nationally vulnerable	1.23
Salvin's albatross (*Thalassarche salvini*)	threatened - nationally critical	0.65
Westland petrel (*Procellaria westlandica*)	at risk - naturally uncommon	0.54
Flesh-footed shearwater (*Puffinus carneipes*)	threatened - nationally vulnerable	0.49
Southern Buller's albatross (*Thalassarche bulleri bulleri*)	at risk - naturally uncommon	0.37
Gibson's albatross (*Diomedea antipodensis gibsoni*)	threatened - nationally critical	0.31
New Zealand white-capped albatross (*Thalassarche steadi*)	at risk - declining	0.28
Chatham Island albatross (*Thalassarche eremita*)	at risk - naturally uncommon	0.28
Northern Buller's albatross (*Thalassarche bulleri platei*)	at risk - naturally uncommon	0.26
Yellow-eyed penguin (*Megadyptes antipodes*)	threatened - nationally endangered	0.17
Antopodean albatross (*Diomedea antipodensis antipodensis*)	threatened - nationally critical	0.17
Northern giant petrel (*Macronectes halli*)	at risk - recovering	0.15
Stewart Island shag (*Phalacrocorax chalconotus*)	at risk - recovering	0.13
Spotted shag (*Phalacrocorax punctatus*)	not threatened	0.09
White-chinned petrel (*Procellaria aequinoctialis*)	not threatened	0.07
Campbell black-browed albatross (*Thalassarche impavida*)	threatened - nationally vulnerable	0.06
Northern royal albatross (*Diomedea sanfordi*)	at risk - naturally uncommon	0.03
Other seabirds considered		
Little penguin (*Eudyptula minor*)	declining	
Red-billed gull (*Larus scopulinus*)	declining	
Sharks		
Basking shark (*Cetorhinus maximus*)	threatened - nationally vulnerable	
Great white shark (*Carcharodon carcharias*)	threatened - nationally endangered	
Whale shark (*Rhincodon typus*)	migrant	
Oceanic whitetip shark (*Carcharhinus longimanus*)	migrant	
Deepwater nurse shark (*Odontaspis ferox*)	naturally uncommon	
Spine-tailed devil ray (*Mobula japanica*)	data deficient	
Broadnose sevengill shark (*Notorynchus cepedianus*)	not threatened	
Blue shark (*Prionace glauca*)	not threatened	

Common dolphin

The diet of common dolphin has been studied through the analysis of stomach contents of incidentally-caught dolphins and through observations of foraging behaviour (e.g., Meynier et al. 2008, Stockin & Orams 2009, Fisheries New Zealand 2020 and references therein).

Main prey included anchovy (*Engraulis australis*), arrow squid, and jack mackerel. Other prey of importance included cardinalfish (*Epigonus* spp.), conger eel, dwarf cod (*Notophycis marginata*), flying fish (Exocoetidae), garfish (*Hyporhamphus ihi*), grey mullet, hagfish (*Eptatretus cirrhatus*), hāpuku, kahawai, pilchard, and yellow-eyed mullet.

Common dolphins seemed to favour prey less than 10 cm long, although the mean length of arrow squid was 13.8 cm and jack mackerel 18.3 cm (Meynier et al. 2008). The diet of common dolphins varied spatially, but the studies did not note seasonal variations.

Flesh-footed shearwater

Very little information is available on flesh-footed shearwater diet in New Zealand. Taylor (2013) reports that “flesh-footed shearwaters specialise on small fish caught by shallow dives into shoals, or occasional deeper dives reaching 30 m in depth. They sometimes eat small squid”.

International studies have looked at stable isotopes and plastic content (e.g., Thalmann et al. 2010). Initial diet composition based on stomach contents from Australian flesh-footed shearwaters is currently being analysed and includes mostly heavily digested contents, some squid mantles and beaks, and very large euphausiids (Jennifer Lavers, UTAS, pers. comm.).

Great white shark – juvenile

No diet information was found for juvenile great white sharks in New Zealand. Juvenile great white sharks were tracked in the Kaipara Harbour, where they were believed to feed on schools of snapper (W. Lyon, pers. comm.).

Grainger et al. (2020) studied the stomachs of 40 juvenile great white sharks caught incidentally off New South Wales. The most important fish species was kahawai followed by jack mackerel and stargazer (*Ichthyscopus barbatus*). Elasmobranchs contributed to a small portion of juvenile great white shark diet, with eagle ray (*Myliobatis* spp.) and stingray (*Trygonoptera testacea*) the most common elasmobranchs found. Cephalopods and marine mammals had low importance in the diet of those sharks studied.

Hector’s and Māui dolphin

The diet of Hector’s and Māui dolphins is based on stomach analysis of beach-cast and incidentally captured Hector’s dolphin (Fisheries New Zealand 2020 and references therein). It is dominated by red cod (*Pseudophycis bachus*), arrow squid, āhuru (*Auchenoceros punctatus*), and sprat (*Sprattus antipodum, S. muelleri*), with flounder, javelinfish (*Lepidorhynchus denticulatus*), sole (group of species), and stargazer also important parts of their diet. Hector’s dolphins have also been seen to occasionally forage on pilchard and yellow-eyed mullet. Sprat, yellow-eyed mullet, and pilchard were found to be important drivers of the distribution of Hector’s dolphins at Banks Peninsula (Brough et al. 2019).

Hector’s dolphin diet varied by sex and area. The majority of the prey was less than 10 cm in length, although red cod up to 44 cm in length, sole up to 50 cm in length, and squid up to 60 cm in length were also obtained (Miller 2014).

New Zealand fur seal

The diet of New Zealand fur seal has been summarised in a number of studies (e.g., Boren 2010, Khoyi 2015, Fisheries New Zealand 2020). Diet was derived through a combination of methods, including regurgitates and DNA analysis of scat which provides a long list of species without an indication of prevalence (Khoyi 2015).

The main prey species in winter and spring included āhuru, barracouta (*Thyrsites atun*), jack mackerel, octopus (*Pinnoctopus cordiformis*), and pilchard. The main prey species in summer and autumn was arrow squid. Other prey species not linked to a specific season included anchovy, red gurnard (*Chelidonichthys kumu*), hoki, lanternfish (family *Myctophidae*), pilchard, silverside (*Argentina elongate*), smelt (*Retropinna retropinna*), and sprat.

Other prey species based on the DNA analysis included bluenose (*Hyperoglyphe antarctica*), butterfish (*Odax pullus*), perch (*Perca fluviatilis*), cardinalfish, warehou (*Seriolella* spp.), rattail, kahawai, porae (*Nemadactylus douglasii*), Ray's bream (*Brama brama*), redbait (*Emmelichthys nitidus*), rubyfish (*Plagiogeneion rubiginosum*), rudderfish (*Centrolophus niger*), southern bream (*Brama australis*), and tarakihi (*Nemadactylus macropterus, Nemadactylus* sp. A).

New Zealand sea lion

The diet and distribution of prey species of New Zealand sea lion in the Sub-Antarctic islands has been well documented (summarised in Fisheries New Zealand 2020). This section reports on the diet of the Stewart Island and mainland populations of New Zealand sea lion (Meynier et al. 2010, Augé et al. 2012, Fisheries New Zealand 2020).

Main prey species around Stewart Island were barracouta and jack mackerel. Other prey species included arrow squid, blue cod (*Parapercis colias*), butterfish, crustaceans, flounder, hoki, javelinfish, spiny dogfish (*Squalus acanthias*), squat lobster (*Gastroptychus* spp.), ling (*Genypterus blacodes*), octopus, opalfish (*Hemerocoetes* spp.), red cod (*Pseudophycis bachus*), rough skate (*Zearaja nasuta*), salp (*Salpida* sp.), southern blue whiting (*Micromesistius australis*), and wrasses. These studies noted location differences and a large variability in prey size which varied by prey species.

Orca

The diet of orca in New Zealand is mostly derived from at-sea observations, with a few stomach samples of dead animals (Visser 2000, 2005, 2007). They are known to preferentially feed on eagle rays and stingrays as well as skate in New Zealand. Other prey species included a variety of sharks such as mako (*Isurus oxyrinchus*), school (*Galeorhinus galeus*), hammerhead (*Sphyrna zygaena*), and thresher shark (*Alopias vulpinus*), dusky dolphin (*Lagenorhynchus obscurus*), and blue penguin. Orca in New Zealand have also been reported to feed on finfish species such as kahawai and to depredate longlines for bluenose and yellowfin tuna (*Thunnus albacares*). Orca were also observed foraging off the Northland coast at a known spawning aggregation of bluenose when no fishing vessels were in the area, indicating bluenose might not only be taken as depredation events (Tom Brough, pers. comm.). Other likely fish species targeted included flounder and sole, leatherjacket, and other reef fish, and salmon in Kaikōura (R. Constantine, pers. comm.).

Salvin's albatross

Very little information is available on Salvin's albatross diet in New Zealand (McInnes et al. 2016). Their diet could be similar to white-capped albatross (*Thalassarche cauta*) and include fish, squid, krill (*Euphausia crystallorophias*), salp, and offal from fishing vessels (Sagar 2013).

The diet of white-capped albatross was studied in Tasmania based on chicks that had died of natural causes and also fresh food delivered to chicks (Hedd & Gales 2001). The diet was dominated by jack mackerel and redbait, with also squid, salp and krill present although in smaller quantities.

Stewart Island shag

Diet knowledge of Stewart Island shag is limited to the study of 144 regurgitate pellets in the Otago Harbour in 1979 and 1980 (Lalas 1983). Main prey species included bully (family *Eleotridae*), cancer crab (*Metacarcinus novaezelandiae*), flounder, octopus, red cod, and sole. Other species included pigfish, stargazer, and wrasses. This study recorded location differences as well as seasonal differences with more fish in spring and fewer in winter.

Yellow-eyed penguin – hoiho

The diet of yellow-eyed penguin has been summarised (Mattern & Ellenberg 2016, Mattern et al. 2018). The diet has shown some seasonal and regional patterns, as well as prey size preference. Studies indicate a shift from red cod in the 1980s to predominantly blue cod and opalfish in the 2010s, potentially attributed to a decline in red cod population.

Main prey species included the juveniles of blue cod, opalfish, red cod, perch (*Hypoplectrodes* sp.), and tarakihi, as well as all sizes of arrow squid. Other prey species included āhuru, common roughy (*Paratrachichthys trailli*), Capro dory (*Capromimus abbreviatus*), lamprey (*Geotria australis*), silverside, and sprat. Studies carried out in 1990 reported sprat, followed by red cod, opalfish, and squid in that order, with most prey items less than 200 mm long (van Heezik 1990a, 1990b). A 2020 DNA study of scat reported, in this order, blue cod, opalfish, silverside, pigfish, blue warehou, baitfish, red cod, sprat, and āhuru (Young et al. 2020).

3.3 Selection of prey species of interest

Prey species/species groups

Prey species names, codes, and number of records are summarised in Table B.1 of Appendix B. Prey species selection was attempted through various data criteria (Table 2, Figure 5).

The species which are prey to at least two of the predators identified and with over 500 records were barracouta, blue cod, bluenose, butterfish, cardinalfish, conger eel, eagle ray, flounder, grey mullet, hoki, jack mackerel, kahawai, leatherjacket, morid cod, octopus, pigfish, rattail, redbait, rough skate, snapper, sole, squid, silverside, stargazer, tarakihi, warehou, wrasse, and yellow-eyed mullet. These were chosen as species of interest for the analysis. Note that some of these species are deepwater species/species groups (e.g., hoki, jack mackerel, squid, warehou) and therefore their entire spatial distribution will not be captured within this dataset. This will be addressed in the discussion. Species where no catch was recorded for multiple years were further removed from the selection; these were butterfish, cardinalfish, grey mullet, stingray, and yellow-eyed mullet.

The final species/species groups modelled were barracouta, blue cod, bluenose, butterfish, conger eel, eagle ray, flounder, hoki, jack mackerel, kahawai, leatherjacket, morid cod, octopus, pigfish, rattail, redbait, rough skate, snapper, sole, squid, silverside, stargazer, tarakihi, warehou, and wrasse.

The species/species groups which are prey to at least two of the predators identified (number in brackets) and with between 100 and 500 records are: opalfish (2), pilchard (4), sprat (3), and spotty (2). These species were not added to the species/species groups of interest for the analysis.

Table 2: Number of species/species groups retained depending on various data criteria. The species codes are in Table B.1 in Appendix B.

Criterion	Number of species
Over 1000 records (commercial, observer or survey)	42
2 or more predators	37
Over 1000 records (observer or survey only)	27
Over 5000 records (commercial, observer or survey)	29
Over 5000 records (observer or survey only)	11
2+ predators and over 500 records (commercial, observer or survey)	29
2+ predators and over 1000 records (commercial, observer or survey)	29
2+ predators and over 500 records (observer or survey only)	24
2+ predators and over 1000 records (observer or survey only)	21

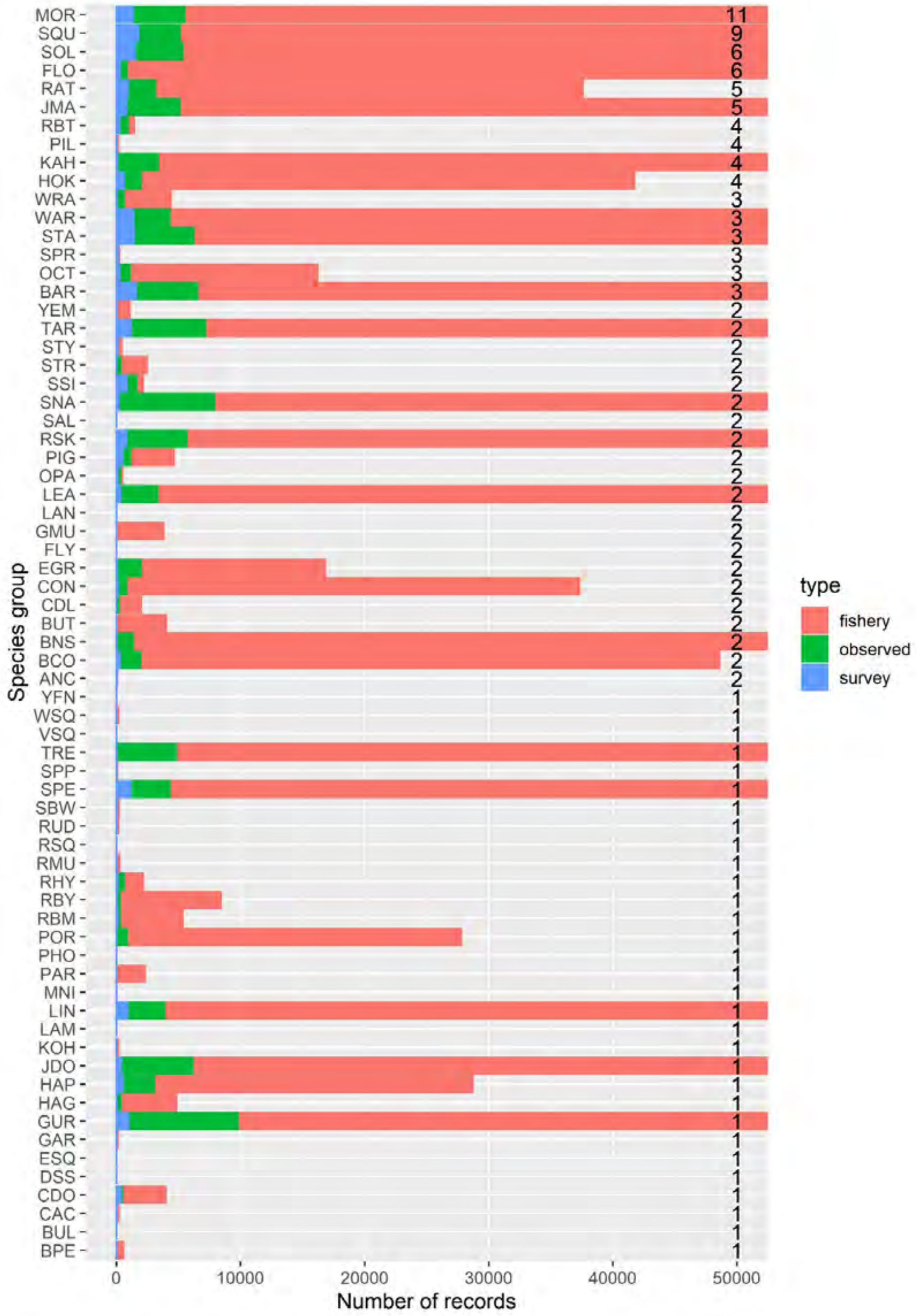


Figure 5: Number of records per species/species group and per data type, ordered by the number of predators identified in this study (number on the right) and total number of data records available. The species codes are in Table B.1. The x-axis was truncated at 50 000 records.

Size-specific prey species

Of the predators investigated, Hector’s dolphins and yellow-eyed penguins exhibited a preference for anchovy, blue cod, opalfish, red cod, sea perch, and tarakihi less than 10 cm in length. Hector’s dolphins also exhibited a preference for squid and jack mackerel less than 20 cm in length.

Of these prey species, only four had over 100 records in the smaller size class, all within the survey dataset:

- Less than 10 cm: sea perch
- Less than 20 cm: squid and jack mackerel

Size-specific models were run on these size classes. All other prey species had fewer than 100 records of the smaller class size. Selectivity of the gear is likely one of the reasons why so few records of smaller fish were available in the data.

3.4 VAST species/species groups distribution model optimisation

Data preparation

Using the full dataset, the models became too large to run. A number of alternatives were tested:

- Using year as a covariate rather than a fully spatial-temporal parameter did not improve performance time.
- Using a subset of the data (observer and survey data only) led to a loss of too much information (Appendix C, Figure C.1). The dataset was reduced from approximately 840 000 events to approximately 14 400 events. Using this subset of data, the model could not reliably estimate the biomass in many years, resulting in very wide confidence intervals in the biomass estimate in some years and biomass estimates of zero for other years.
- Using data from 2018 to 2020 fishing years allowed for test models to run (Appendix C, Figure C.2). This option was deemed to omit too much information, particularly on surveys in early years and biomass trajectory over time. The dataset was reduced from approximately 840 000 events to approximately 140 000 events.
- Aggregating the commercial and observer data by summing catch and surface area covered for each vessel / month / method / grid cell combination also allowed for test models to run whilst retaining the spatial distribution of the data and potential covariates (Appendix C, Figure C.3). The survey data were kept at the tow-by-tow resolution. The spatial distribution of biomass was visually similar to that of test models run with the full dataset and only a few years of data (Figure C.4). The dataset was reduced from approximately 840 000 events to approximately 305 000 events.

The dataset was therefore aggregated by data source, vessel, month, method, and grid cell for the full analysis (retaining the survey data at the tow-by-tow resolution). The grid size used was 16 × 16 km. The surface area covered and catch of each species/species groups was summed over these events for each data source, vessel, month, method, and grid cell combination. Cells with over 10 events per cell over the aggregated dataset were retained for the analysis. This dataset is further referred to as the aggregated dataset.

GAM / GLM alternatives using *speedglm* or *mgcv* were also investigated. The unique identifier for each grid cell was used as the spatial covariate in all test model runs. Only *speedglm* could deal with the size of the full dataset but it did not provide satisfactory results; it required a 32 km grid size and a small number of covariates, yet many cells still had no estimate of biomass.

VAST model selection

A summary of some of the models run during the model selection are detailed in Table C.1 in Appendix C.

Vessel identification was either ignored, set at a combination of data source (commercial, observer, or survey) and method (bottom longline, bottom trawl, or set net), or as a combination of data source and unique vessel identifier. Including source and method as covariates rather than a vessel random effect resulted in a model with a lower AIC (model runs 2 and 3). Adding source and vessel as a random vessel effect on a model with source and method as covariates did not improve the AIC (model runs 3 and 4). Further models were run without a vessel effect.

Catchability variables were added incrementally, and the model with all of them (vessel length, month, data source, method) presented the lowest AIC (models 1 to 4). Adding environmental covariates incrementally and in different combinations led to the optimised model including depth, turbidity, and chlA (models 5 to 9). The model structure put forward had no vessel random effect and included the following covariates: vessel length, month, source, method, depth, turbidity, and chlA.

The number of knots used was also investigated during model selection. Results were similar with knots from 50 to 150, with a small increase in precision as the number of knots increased whilst the model with 200 knots did not minimise (failed to run to completion). The final models were run with 150 knots. The location of the knots and of the extrapolation grid as used by VAST are shown in Figure C.5.

Alternative models for specific species

Data were too sparse for some species to allow such complex models to minimise (run to completion). These were butterfish, cardinalfish, flounder, pigfish, redbait, stingray, grey mullet, and yellow-eyed mullet.

Silverside and wrasse were not reported in the commercial data selected. For these two species, models were run using only observer or survey data at the event level (aggregation was not required because the commercial records were not included and therefore the size of the dataset was much smaller). The final model for silverside was run without method, month, or vessel size as covariates. The final model for wrasse was run by combining all years together and without method, month, or vessel size as covariates. Any more complex model failed to minimise (run to completion) due to the paucity of data.

Sensitivities

Even though they minimised (ran to completion), many models presented uncertain convergence (see Appendix D). The only models with positive convergence were for jack mackerel, morid cod, snapper, stargazer, and squid. Alternative models were run to investigate the stability of the results of those models with uncertain convergence.

Models were run with gamma distribution instead of lognormal distribution. In most instances, the results were almost identical. In some instances, the models using gamma distributions failed to converge to a suitable space with, for example, many annual indices estimated at zero with wide confidence intervals.

Simplified models were also run with only depth and data source as covariates. Most other covariates did not have a significant effect (see Appendix D). In most instances the results were almost identical. In some instances, the simplified models clearly failed to converge to a suitable space (e.g., stargazer and rough skate) with, for example, many annual indices estimated at zero with wide confidence intervals.

Because these sensitivities mostly provided very similar trends in time and space, the results were deemed to be robust to those model changes and therefore reliable for the purposes of this study. However, the partial effects plots were sensitive to model selection and should not be used as diagnostic tools.

3.5 Distribution of prey species/species groups

A total of 22 species/species groups were successfully modelled. For each species/species groups, Appendix D provides plots of the spatial-temporal distribution of biomass, biomass index at the scale of the model over time, effective area occupied over time, partial effects plots for all covariates, location of the centre of gravity of each population over time, and residual diagnostics. In this section, the biomass of a species is defined as the predicted relative biomass of the combination of the predicted probability of presence of a species and its predicted biomass given it was present. The predicted biomass is a relative index because fishery catchability is not known. A short summary of relevant knowledge on distribution and biomass trend is provided for each species.

The biomass trajectory between 2000 and 2020 based on the inshore fisheries data analysed varied between species. Hoki, jack mackerel, morid cod, sole, and tarakihi presented a general decline in biomass between 2000 and 2020. On the other hand, conger eel, eagle ray, octopus, rough skate, and snapper presented a general increase in biomass between 2000 and 2020. Other species presented a variable trend over time (Figure 6, Figure 7, and Appendix D). The entire stock area of some of these species is not fully captured by the data selection (inshore fisheries data only) and therefore these trends might not represent that of the entire stock.

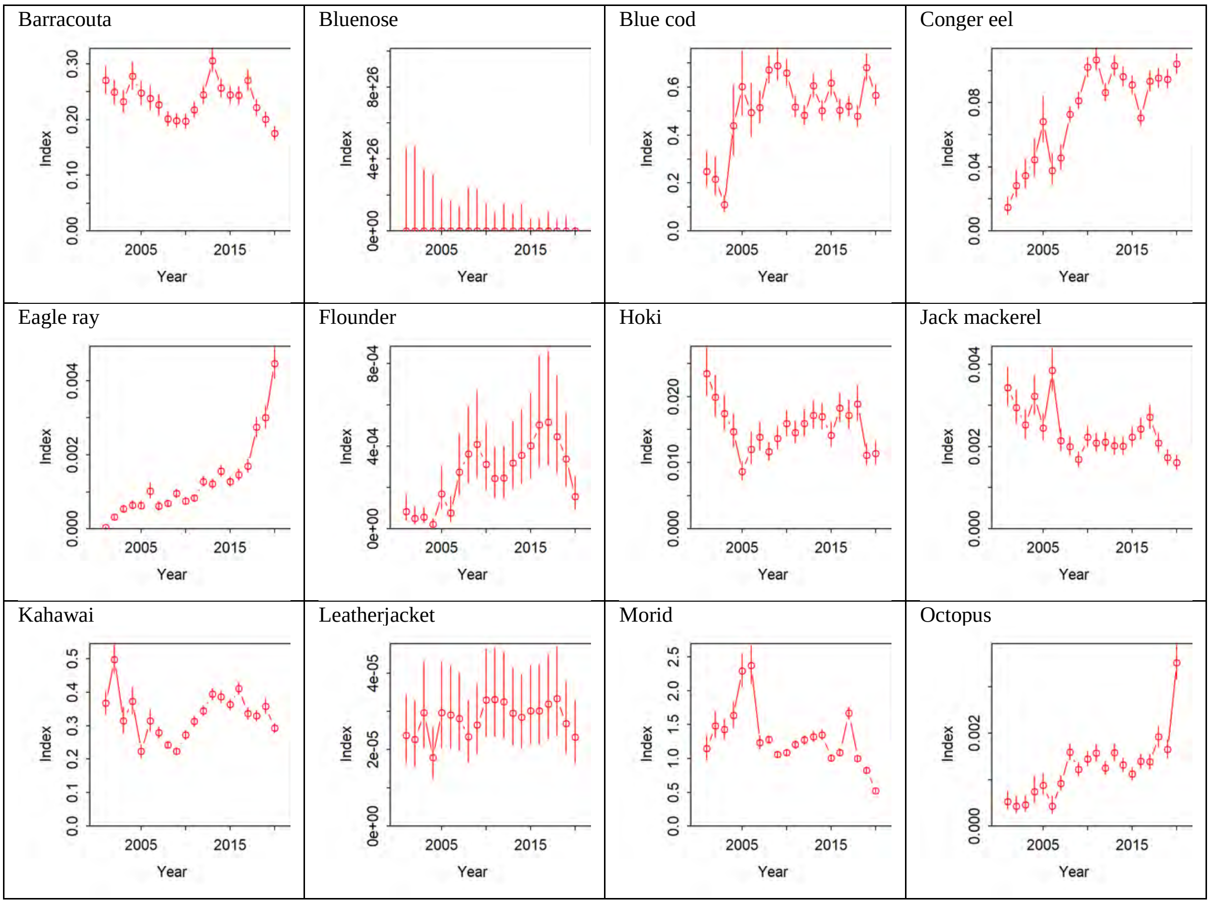


Figure 6: Biomass trajectory between 2000 and 2020 for barracouta, bluenose, blue cod, conger eel, eagle ray, flounder, hoki, jack mackerel, kahawai, leatherjacket, morid cod, and octopus.

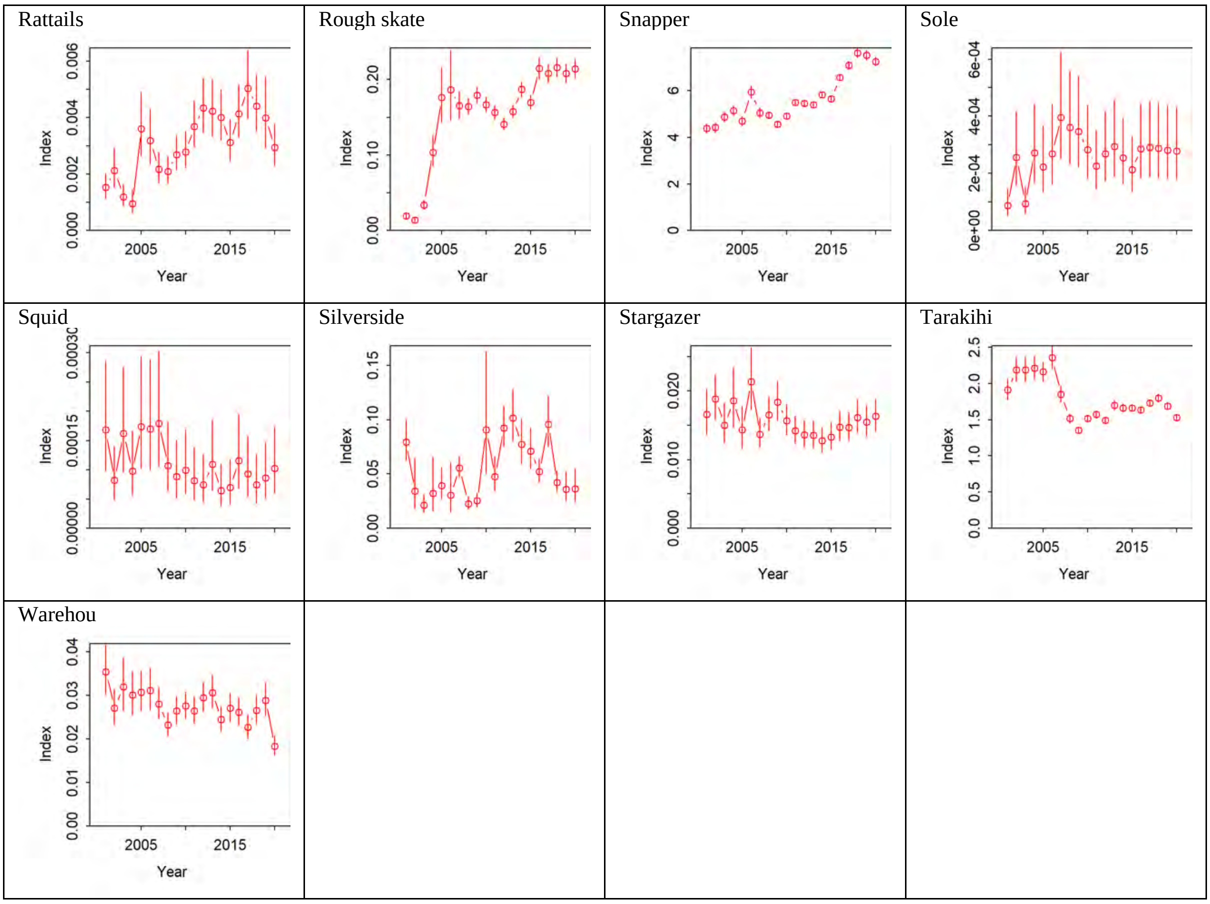


Figure 7: Biomass trajectory between 2000 and 2020 for rattails, rough skate, snapper, sole, squid, silverside, stargazer, tarakihi, and warehou.

Spatial trends were clearly defined for some species: eagle ray, snapper, and wrasse were more frequent around the North Island; blue cod, morid, rough skate, and stargazer were more frequent around the South Island; with the remaining species spread around both islands (albeit not necessarily throughout the range). Based on the depth partial effects plots, barracouta, bluenose, hoki, jack mackerel, morid cod, rattail, squid, and tarakihi were more common in deeper waters.

Spatially, the effective area occupied generally contracted over time for barracouta and leatherjacket but expanded for jack mackerel and snapper, with no clear trend for the other species. The centre of gravity of the distribution of barracouta, jack mackerel, octopus, sole, tarakihi, and warehou moved in a general south-west direction between 2000 and 2020, whereas that of rattail group moved north-east; these movements are generally consistent with moving up or down the coast along a given depth contour. There were no clear trends for the other species.

The covariates vessel length, method, and month presented wide confidence intervals for all species. However, removing those rendered the models unstable in many instances (see above). Other partial effects plots were different between different species.

3.6 VAST length-class species distribution model optimisation

Data preparation

The species for which the top predators of interest presented size selectivity, and where enough data were available for analysis, were red cod and perch smaller than 10 cm or 10 cm in length and above, and squid and jack mackerel smaller than 20 cm or 20 cm in length and above (see section 3.2). Of the inshore data selected for this study, only survey data had over 10 sets where those species length classes were measured.

To keep as much data as possible, all survey data since 1990 were used. Bottom tows, bottom high opening tows, and midwater tows were included in the analysis. Because only a subset of species gets measured on any fishing event, only events where the species of interest was measured were included in the length-class models for that species.

Model selection

Models were run for each species length class using the numbers measured for that length class scaled by the proportion of the catch measured. The model distribution used was delta-Poisson.

The paucity of data drove model selection in this instance. Models had to be run with all years combined. The most complex model to minimise (run to completion) and converge had 50 knots, no fine-scale or bias correction, and no environmental covariates. Models for squid length classes had method and month as covariates, whilst models for the other species did not. Predictions were carried out for the 16 km equal area grid.

Sensitivities

Alternative simplified models were run for the squid length class: removing month as a covariate, or removing month and using bottom trawl only. Although the most complex model had the lowest AIC, all three models presented similar spatial densities, providing some comfort on the stability of the predicted spatial distribution.

3.7 Distribution of prey species in length classes

Only squid size-class models, simple sea perch size-class models, and the red cod simple model for individuals smaller than 10 cm minimised (ran to completion). All of these models successfully converged but some of the residual diagnostics were unsatisfactory. Results are plotted in Appendix E.

Squid smaller than 20 cm in length were in higher densities around the north of the North Island and south Canterbury Bight, and squid 20 cm and longer were in higher densities in these areas and off the west coast of the South Island as well (Figure E.1). There were no data available for the south of the South Island in this dataset. For both size groups, the density of squid generally dropped from February to December, and squid smaller than 20 cm length were generally not caught in May and June (Figure E.2).

Sea perch smaller than 10 cm in length were in higher densities around the north of the North Island and south Canterbury Bight, and sea perch 10 cm and longer were in higher densities around the South Island. The models predicted very low levels of small sea perch off the west coast of the South Island but much larger densities of larger sea perch in the same area (Figure E.3).

High densities of red cod smaller than 10 cm were also found south of the Canterbury Bight, with very low densities elsewhere (Figure E.4).

4. DISCUSSION

4.1 Distribution of prey species

Although not all models converged, most model results were robust to changes in assumptions such as data distribution (gamma or lognormal) or the inclusion of covariates. Where the models differed, the simplified models had clearly minimised to an area of low and highly uncertain biomasses (very low estimated biomass coupled with very high confidence intervals). Yet the spatial distributions were still consistent, providing comfort that the spatial distributions developed in the present study could be useful as inputs to spatial management processes such as developing SEFRA models for those top predators of interest. Prey species for which the inshore fisheries do not represent the full extent such as hoki would need to be considered carefully. Only the inshore fishery was considered here because the prey distribution was designed to capture the inshore distribution of these species, in locations where they are more available to distance-limited predators such as hoiho for example.

The spatial distribution of prey species and the temporal trends in their biomass were compared with information contained in the 2021 plenary report (Fisheries New Zealand 2021) and summarised briefly in Appendix D. These comparisons were strictly qualitative because spatial distributions are described in general terms and temporal trends in biomass tend to be split by stock rather than for the entire New Zealand EEZ or based on full stock assessments rather than standardised CPUEs which the method used here is more akin to. Furthermore, the full distribution of deepwater species such as jack mackerel or hoki is not adequately captured by the inshore fisheries data used in this study.

Despite all these caveats, the general spatial distribution and temporal trend in biomass of all species was generally consistent with the information contained within the 2021 plenary report (Fisheries New Zealand 2021), providing further comfort in the potential usefulness of these distributions. For example, the snapper biomass is mainly restricted to the North Island, and the biomass trend increased between 2000 and 2020, when the various CPUE or stock assessment trends for all stocks show an increase over the same time period. Even blue cod, which is not particularly vulnerable to trawl but more to potting, presented spatial distribution of higher abundances south of Cook Strait and in around the Chatham Islands, in concordance with the information contained within the plenary report (Fisheries New Zealand 2021).

Hoki is assessed as a single stock across the entire New Zealand EEZ and, as such, its biomass trajectory is easier to compare with the results obtained herein, noting that the inshore fisheries used in the present report do not cover the entire hoki distribution but rather its juvenile component. Although the biomass trajectories calculated from the full stock assessment and from this spatial-temporal standardisation were not identical over the overlapping time period, they were mostly within each other’s confidence intervals and showed similar trends, which in itself is quite remarkable (Figure 8). The use of commercial, observer, and survey data within the same spatial-temporal standardisation (in particular in the deepwater fishery) might have helped improve the concordance compared with the traditional fit (or lack of) between traditional standardised CPUE indices within stock assessment trajectories. The low points in the predicted hoki biomass in the last couple of years of the present study might be a combination of the move to the Electronic Reporting System (ERS, from 2017 onwards) and COVID-19 with companies reporting difficulties in finding experienced crew for their vessels with corresponding drops in CPUE.

The snapper population is expected to have been increasing since 2000 (Figure 6), which is in agreement with the assessment of stocks around New Zealand (Fisheries New Zealand 2021). The tarakihi trends found here and in stock assessments also generally corroborate (Fisheries New Zealand 2021). In contrast, the three CPUE indices of jack mackerel species have increased sharply from 2001 to 2020 (Fisheries New Zealand 2021), when the jack mackerel combined biomass was found to decline in this study (Figure 6). Comparison in other species was more difficult because biomass studies were not carried out at the scale of the EEZ, trends are uncertain, or where no biomass information is available.

The introduction of rough skates into the QMS in 2004 is likely to explain the low estimates in the early part of the series. The effect of the move to ERS reporting might also have partly influenced the very large increase in modelled biomass of eagle ray and octopus. Reporting requirements have changed over time: TCEPR forms required the estimated greenweight of the top 5 species , then the top 8 species for TCER forms, and now using ERS forms fishers can report as many species as they want and have to report the top 8 species for vessels over 28 m or top 5 QMS species and 3 non-QMS species otherwise. Species such as eagle ray and octopus might not have been reported in the past but might be reported more often in ERS forms. This effect is fully correlated with the year effect (e.g., most deepwater fishers moved to ERS in 2017, and therefore an increase in 2017 could be either an increase in biomass or a change in form type) but could be investigated in the future by looking at where each species is recorded in terms of importance in the catch.

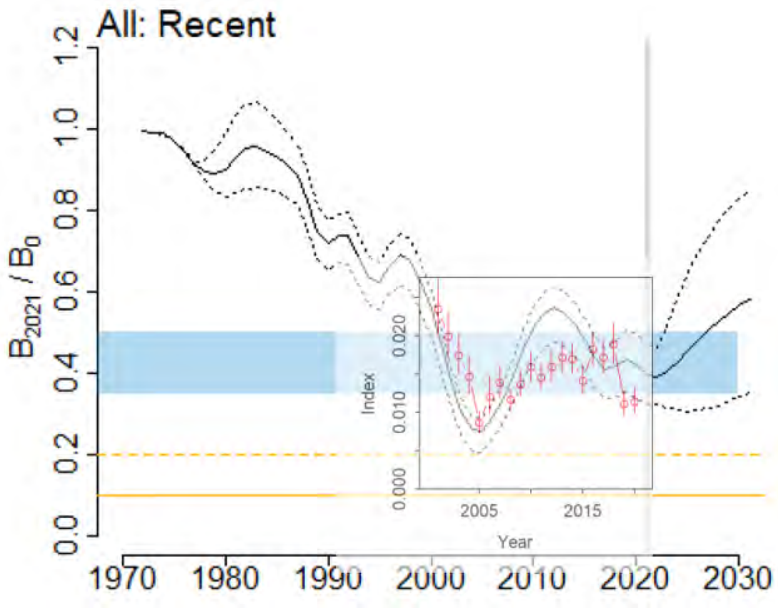


Figure 8: **Comparison of the hoki biomass trajectory from the stock assessment (Fisheries New Zealand 2021) and from the present study (in red) through an overlay of the plots.**

The predicted spatial distributions of species were also compared with that developed in other studies. Roberts et al. (2019) developed spatial models of species prey of Hector's and Māui dolphins as inputs to the SEFRA model for those species. They used GLM to predict the proportion of tows carried out during research surveys by the vessels *Kaharoa* and *Tangaroa* that might capture those species, using smoothers on longitude and latitude as a proxy for spatial patterns in the biomass distribution. Predicted distributions for the two species in common between the two studies followed the same generic trends, with squid distributed throughout the study area and giant stargazer concentrated around South Island.

In another study, Edwards (2021) predicted the spatial density of a number of fish species around specific parts of Aotearoa New Zealand. He used a custom model based on similar principles to VAST and commercial and survey data which caught the species of interest. In areas where the predictions were carried out, the species densities followed similar trends as well. Species in common were rough skate, snapper (limited to SNA 7), and giant stargazer around the South Island and tarakihi.

Arguably the most comprehensive estimate of distribution of fish species carried out recently in New Zealand is that of Lundquist et al. (2020) as part of their project to evaluate key areas of biodiversity in the New Zealand EEZ. As part of this project the probability of presence of over 600 species was estimated using an ensemble approach combining estimates from BRT and Random Forest models. The data used were survey data for demersal species and scuba records for reef species. Although this study predicted the probability of presence assuming no temporal variability, the general trends over the EEZ were not in contradiction in the two studies.

Although the three studies mentioned above had different aims, data sources, methodologies, and areas of interest, the results from all three were in general agreement with each other. This is reassuring for the potential use of these results as inputs in other projects or in management processes. Of interest was the divergence between the probability of presence of the three species of jack mackerel in the study of

Lundquist et al. (2020), highlighting the need to estimate the distribution of species separately where at all possible.

Species such as squid, jack mackerel, and hoki are deepwater species. The data used in this study only covered the shallow part of their distribution so the predicted modelling might not adequately represent the biomass of the entire stock. They might, however, still be adequate to represent the distribution of those species in shallow waters; for example, in SEFRA models of predators foraging the inshore area. The results for these species should be considered with this in mind. Where biomass estimates or distributions across the full range of these species are required, it is recommended this analysis be rerun including all fisheries data, deepwater or not.

The distribution models for species groups which comprise multiple species should also be interpreted with care. For example, the jack mackerel group comprises three different species which exhibit different latitudinal and depth preferences (Hurst et al. 2012), and the model will invariably average these. Likewise, the rattail, stargazer or flounder groups, for example, comprise multiple species and likely different niches. These were aggregated because the data often included generic codes, and predator diets tended to be generic as well. If these species were of interest for other studies, it is recommended their distributions are re-estimated at the species level, if data are available at species level.

The lack of difference in catchability between bottom trawl, midwater trawl, and set nets was surprising. The effects had very wide confidence intervals and might have benefited from the addition of other explanatory parameters such as target species group. They might also represent a wider variability of catchability in space than by target gear.

Finally, this study as well as all the other studies referenced herein were limited to using fisheries data, be it commercial, observer, or sometimes trawl survey data. That the results are consistent is reassuring but not unexpected because they were all derived from the same data sources. Extrapolation from these data present numerous caveats including but not limited to the catchability of species to fisheries gear, the location of fishing and level of recording of catches including species resolution, changes in management and economic incentives, loss of knowledge of scientific surveys over time, etc. There is a need for more independent data collection targeted to specific questions.

4.2 Distribution of prey species by length class

The distribution of prey species by length class relied on far fewer data points than that of species distributions that were not separated into length classes. As a result, the models had to be pared back to their simplest form. Although sensitivity runs seemed to indicate that the spatial distribution patterns were robust to those simplifications and convergence tests showed the models had converged, care should be taken before using these results. For example, how do large sea perch reach the west coast of the South Island when no small sea perch are found there? The lack of small fish for squid, sea perch, and red cod off the west coast of the South Island and large densities in the Canterbury Bight might be real or might be artefacts of the survey designs, timing, and aims.

It is reassuring to see that month has an effect in the squid models given they live for a year only, migrate, spawn, and die, but it is still hard to tell if these results are consistent with current knowledge of squid biology (Hurst et al. 2012, Fisheries New Zealand 2021). If squid length-based distributions were to be used, it is recommended that these be rerun including deepwater data, because it will then include observer data and offshore survey data as well as inshore survey data.

There is a need for more independent data collection targeted to specific questions. For example, small fish are an essential diet of Hector’s and Māui dolphin yet are not sufficiently represented in the fisheries data to allow for the development of size-specific distribution models.

4.3 Summary

As they stand, the biomass density distributions developed for many species could be used as inputs in other processes such as spatial risk assessment models of top predators. The use of species groups should be carefully considered as these are likely to represent a range of species and niches. On the other hand, the confidence in the length-class distributions is low.

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6. REFERENCES

Anderson, O.F.; Edwards, C.T.T.; Ballara, S. (2019). Non-target fish and invertebrate catch and discards in New Zealand hoki, hake, ling, silver warehou, and white warehou trawl fisheries from 1990–91 to 2016–17. *New Zealand Aquatic Environment and Biodiversity Report No. 220*. 121 p.

Augé, A.; Lalas, C.; Davis, L.; Chilvers, B. (2012). Autumn diet of recolonising female New Zealand sea lions based at Otago Peninsula, South Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research 46*: 97–110. https://doi.org/10.1080/00288330.2011.606326

Baker, C.S.; Boren, L.; Childerhouse, S.; Constantine, R.; van Helden, A.; Lundquist, D.; Rayment, W.; Rolfe, J.R. (2019). Conservation status of New Zealand marine mammals, 2019. *New Zealand Threat Classification Series 29*. 22 p.

Bakka, H.; Vanhatalo, J.; Illian, J.; Simpson, D.; Rue, H. (2019). Non-stationary Gaussian models with physical barriers. arXiv:1608.03787 [stat].

Bell, E.A. (2013). Black petrel. *In* Miskelly, C.M. (ed.) New Zealand Birds Online. [WWW Document]. URL www.nzbirdsonline.org.nz

Bennington, S.; Rayment, W.; Dawson, S. (2020). Putting prey into the picture: improvements to species distribution models for bottlenose dolphins in Doubtful Sound, New Zealand. *Marine Ecology Progress Series 653*: 191–204. https://doi.org/10.3354/meps13492

Boren, L. (2010). Diet of New Zealand fur seals (*Arctocephalus forsteri*): a summary. *DOC Research & Development Series 319*. 20 p.

Brodie, S.J.; Thorson, J.T.; Carroll, G.; Hazen, E.L.; Bograd, S.; Haltuch, M.A.; Holsman, K.K.; Kotwicki, S.; Samhouri, J.F.; Willis-Norton, E.; Selden, R.L. (2020). Trade-offs in covariate selection for species distribution models: a methodological comparison. *Ecography 43*: 11–24. https://doi.org/10.1111/ecog.04707

Brough, T.; Rayment, W.; Dawson, S. (2019). Using a recreational grade echosounder to quantify the potential prey field of coastal predators. *PLoS ONE 14*: e0217013. https://doi.org/10.1371/journal.pone.0217013

Brough, T.E. (2013). Using photography to study the conservation biology of bottlenose dolphins in southern New Zealand. Masters Thesis. University of Otago, Dunedin, New Zealand.

Edwards, C.T.T. (2021). Integrated estimation of density and catchability parameters from fisheries catch-effort data. *New Zealand Fisheries Assessment Report 2021/32*. 32 p.

Fisheries New Zealand (2020). Aquatic Environment and Biodiversity Annual Review 2019-20. Compiled by the Aquatic Environment Team, Fisheries Science and Information, Fisheries New Zealand, Wellington New Zealand. 762 p.

Fisheries New Zealand (2021). Fisheries Assessment Plenary, May 2021: stock assessments and stock status. Compiled by the Fisheries Science Team, Fisheries New Zealand, Wellington, New Zealand. 1782 p.

Grainger, R.; Peddemors, V.M.; Raubenheimer, D.; Machovsky-Capuska, G.E. (2020). Diet Composition and Nutritional Niche Breadth Variability in Juvenile White Sharks (*Carcharodon carcharias*). Frontiers in Marine Science 7: 422. https://doi.org/10.3389/fmars.2020.00422

Grüss, A.; Walter, J.F.; Babcock, E.A.; Forrestal, F.C.; Thorson, J.T.; Lauretta, M.V.; Schirripa, M.J. (2019). Evaluation of the impacts of different treatments of spatio-temporal variation in catch-per-unit-effort standardization models. *Fisheries Research 213*: 75–93. https://doi.org/10.1016/j.fishres.2019.01.008

Hartel, E. (2010). Habitat use by bottlenose dolphins (*Tursiops truncatus*) in the Bay of Islands, New Zealand. (MSc thesis, University of Auckland.)

Hedd, A.; Gales, R. (2001). The diet of shy albatrosses (*Thalassarche cauta*) at Albatross Island, Tasmania. *Journal of Zoology 253*: 69–90. https://doi.org/10.1017/S0952836901000073

Hurst, R.J.; Ballara, S.L.; MacGibbon, D.J.; Triantafillos, L. (2012). Fishery characterisation and standardised CPUE analyses for arrow squid (*Nototodarus gouldi* and *N. sloanii*), 1989-90 to 2007-08, and potential management approaches for southern fisheries. *New Zealand Fisheries Assessment Report 2012/47*. 309 p.

Imber, M.J. (1976). Comparison of prey of the black *Procellaria* petrels of New Zealand. *New Zealand Journal of Marine and Freshwater Research 10*: 119–130 https://doi.org/10.1080/00288330.1976.9515603

Khoyi, A.E. (2015). Population and diet of the New Zealand fur seal (*Arctocephalus forsteri*): molecular approaches. (PhD thesis, Lincoln University.)

Lalas, C. (1983). Comparative feeding ecology of New Zealand marine shags (*Phalacrocoracidae*). (PhD thesis, University of Otago, Dunedin.)

Lundquist, C.; Stephenson, F.; McCartain, L.; Watson, S.; Brough, T.; Nelson, W.; Neill, K.; Anderson, T.; Anderson, O.; Bulmer, R.; Gee, E.; Pinkerton, M.; Rowden, A.; Thompson, D. (2020). Evaluating Key Ecological Areas datasets for the New Zealand Marine Environment. (NIWA Client Report 2020109HN prepared for the Department of Conservation.) 131 p. https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-protected-areas/mpa-publications/evaluating-kea-datasets-2020.pdf

Lusseau, S.; Wing, S. (2006). Importance of local production versus pelagic subsidies in the diet of an isolated population of bottlenose dolphins *Tursiops* sp. *Marine Ecology Progress Series 321*: 283–293. https://doi.org/10.3354/meps321283

Mattern, T.; Ellenberg, U. (2016). Yellow-eyed penguin diet and indirect effects affecting prey composition - collation of biological information. CSP16205-1 POP2016-05. https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/marine-conservation-services/reports/pre-2019-annual-plans/pop-2016-05-indirect-effects-on-yellow-eyed-penguin.pdf

Mattern, T.; McPherson, M.D.; Ellenberg, U.; van Heezik, Y.; Seddon, P.J. (2018). High definition video loggers provide new insights into behaviour, physiology, and the oceanic habitat of a marine predator, the yellow-eyed penguin. *PeerJ 6*: e5459. https://doi.org/10.7717/peerj.5459

Maunder, M.N.; Thorson, J.T.; Xu, H.; Oliveros-Ramos, R.; Hoyle, S.D.; Tremblay-Boyer, L.; Lee, H.H.; Kai, M.; Chang, S.-K.; Kitakado, T.; Albertsen, C.M.; Minte-Vera, C.V.; Lennert-Cody, C.E.; Aires-da-Silva, A.M.; Piner, K.R. (2020). The need for spatio-temporal modeling to determine catch-per-unit effort based indices of abundance and associated composition data for inclusion in stock assessment models. *Fisheries Research 229*: 105594. https://doi.org/10.1016/j.fishres.2020.105594

McInnes, J.C.; Raymond, B.; Phillips, R.A.; Jarman, S.N.; Lea, M.-A.; Alderman, R. (2016). A review of methods used to analyse albatross diets—assessing priorities across their range. *ICES Journal of Marine Science 73*: 2125–2137. https://doi.org/10.1093/icesjms/fsw105

Meynier, L.; Morel, P.C.H.; Chilvers, B.L.; Mackenzie, D.D.S.; Duignan, P.J. (2010). Quantitative fatty acid signature analysis on New Zealand sea lions: model sensitivity and diet estimates. *Journal of Mammalogy 91*: 1484–1495. https://doi.org/10.1644/09-MAMM-A-299.1

Meynier, L.; Stockin, K.A.; Bando, M.K.H.; Duignan, P.J. (2008). Stomach contents of common dolphin (*Deiphinus* sp.) from New Zealand waters. *New Zealand Journal of Marine and Freshwater Research 42*: 257–268. https://doi.org/10.1080/00288330809509952

Miller, E.J. (2014). Ecology of Hector’s dolphin (*Cephalorhynchus hectori*): Quantifying diet and investigating habitat selection at Banks Peninsula. (PhD thesis, Univeristy of Otago, Dunedin, New Zealand.)

Ministry of Fisheries (2008). Species under consideration for introduction into the Quota Management System on 1 October 2009 Information briefs and risk analyses 10 June. 78 p.

Mormede, S.; Parker, S.J.; Pinkerton, M.H. (2020). Comparing spatial distribution modelling of fisheries data with single-area or spatially-explicit integrated population models, a case study of toothfish in the Ross Sea region. *Fisheries Research 221*: 105381. https://doi.org/10.1016/j.fishres.2019.105381

Mormede, S.; Webber, D.N.; Edwards, C. (2022). Creating standardised grids for New Zealand marine science outputs. *New Zealand Aquatic Environment and Biodiversity Report No. 283*. 7 p.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/. Vienna, Austria.

Roberts, C.D.; Stewart, A.L.; Struthers, C.D. (Eds.) (2015). *The Fishes of New Zealand*. Te Papa Press, Wellington, New Zealand.

Roberts, J.O.; Webber, D.N.; Roe, W.D.; Edwards, C.T.T.;Doonan, I. (2019). Spatial risk assessment of threats to Hector’s and Māui dolphins (*Cephalorhynchus hectori*). *New Zealand Aquatic Environment and Biodiversity Report No. 214*. 168 p.

Robertson, H.A.; Baird, K.; Dowding, J.E.; Elliott, G.P.; Hitchmough, R.A.; Miskelly, C.M.; McArthur, N.; O’Donnell, C.F.J.; Sagar, P.M.; Scofield, R.P.; Taylor, G.A. (2017). Conservation status of New Zealand birds, 2016. *New Zealand Threat Classification Series 9*. 23 p.

Sagar, P.M. (2013). Salvin’s mollymawk. *In* Miskelly, C.M. (ed.) New Zealand Birds Online. [WWW Document]. URL www.nzbirdsonline.org.nz

Schneider, K. (1999). Behaviour and Ecology of Bottlenose Dolphins in Doubtful Sound, Fiordland, New Zealand. (PhD thesis, University of Otago, Dunedin.)

Sharp, B.R.; Watters, G.M. (2011). Marine protected area planning by New Zealand and the United States in the Ross Sea region. WS-MPA-11/25. CCAMLR, Hobart, 40 p.

Stephenson, F.; Goetz, K.; Mouton, T.; Beets, F.; Hailes, S.; Roberts, J.; Pinkerton, M.; MacDiarmid, A. (2020). Spatial distribution modelling of New Zealand cetacean species. *New Zealand Aquatic Environment and Biodiversity Report No. 240*. 217 p.

Stockin, K.A.; Orams, M.B. (2009). The status of common dolphins (*Delphinus delphis*) within New Zealand waters. Journal of Cetacean Research and Management SC/61/SM20, 13.

Taylor, G.A. (2013). Flesh-footed shearwater. *In* Miskelly, C.M. (ed.) New Zealand Birds Online. [WWW Document]. URL www.nzbirdsonline.org.nz

Thalmann, S.J.; Lea, M.-A.; Hindell, M.; Priddel, D.; Carlile, N. (2010). Provisioning in Flesh-footed Shearwaters (*Puffinus carneipes*): Plastic Foraging Behavior and the Implications for Increased Fishery Interactions. *The Auk 127*: 140–150. https://doi.org/10.1525/auk.2009.09158

Thorson, J.T. (2019). Guidance for decisions using the Vector Autoregressive Spatio-Temporal (VAST) package in stock, ecosystem, habitat and climate assessments. *Fisheries Research 210*: 143–161. https://doi.org/10.1016/j.fishres.2018.10.013

Thorson, J.T.; Barnett, L.A.K. (2017). Comparing estimates of abundance trends and distribution shifts using single- and multispecies models of fishes and biogenic habitat. *ICES Journal of Marine Science 74*: 1311–1321.

Thorson, J.T.; Cunningham, C.J.; Jorgensen, E.; Havron, A.; Hulson, P.-J.F.; Monnahan, C.C.; von Szalay, P. (2021). The surprising sensitivity of index scale to delta-model assumptions: Recommendations for model-based index standardization. *Fisheries Research 233*: 105745. https://doi.org/10.1016/j.fishres.2020.105745

Thorson, J.T.; Pinsky, M.L.; Ward, E.J. (2016). Model-based inference for estimating shifts in species distribution, area occupied and centre of gravity. *Methods in Ecology and Evolution 7 (8)*: 990–1002. https://doi.org/10.1111/2041-210x.12567

van Heezik, Y. (1990a). Seasonal, geographical, and age-related variations in the diet of the yellow-eyed penguin (*Megadyptes antipodes*). *New Zealand Journal of Zoology 17*: 201–212. https://doi.org/10.1080/03014223.1990.10422597

van Heezik, Y. (1990b). Diets of yellow-eyed, Fiordland crested, and little blue penguins breeding sympatrically on Codfish Island, New Zealand. *New Zealand Journal of Zoology 17*: 543–548. https://doi.org/10.1080/03014223.1990.10422952

Visser, I. (2000). Orca (*Orcinus orca*) in New Zealand waters. (PhD thesis, University of Auckland.)

Visser, I.N. (2005). First Observations of Feeding on Thresher (*Alopias vulpinus*) and Hammerhead (*Sphyrna zygaena*) Sharks by Killer Whales (*Orcinus orca*) Specialising on Elasmobranch Prey. *Aquatic Mammals 31*: 83–88. https://doi.org/10.1578/AM.31.1.2005.83

Visser, I.N. (2007). Killer whales in New Zealand waters: Status and distribution with comments on foraging. https://www.orcaresearch.org/wp-content/uploads/2011/08/Visser-2007-Killer-whales-in-NZ-waters-SC-59-SM19.pdf

Young, M.J.; Dutoit, L.; Robertson, F.; van Heezik, Y.; Seddon, P.J.; Robertson, B.C. (2020). Species in the faeces: DNA metabarcoding as a method to determine the diet of the endangered yellow-eyed penguin. *Wildlife Research 47*: 509. https://doi.org/10.1071/WR19246

Appendix A – Environmental variables

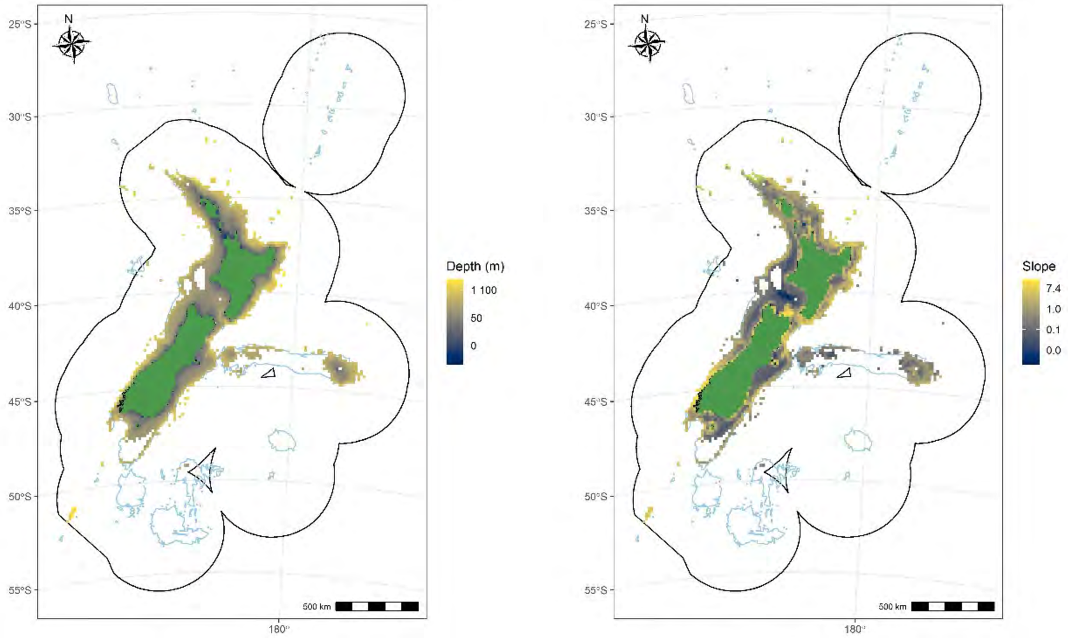

Figure A.1: Depth (m) and slope (°) at the 16 km grid size resolution. Only cells with over 10 events are shown. The 500 m depth contour is shown in light blue and the New Zealand EEZ in black.

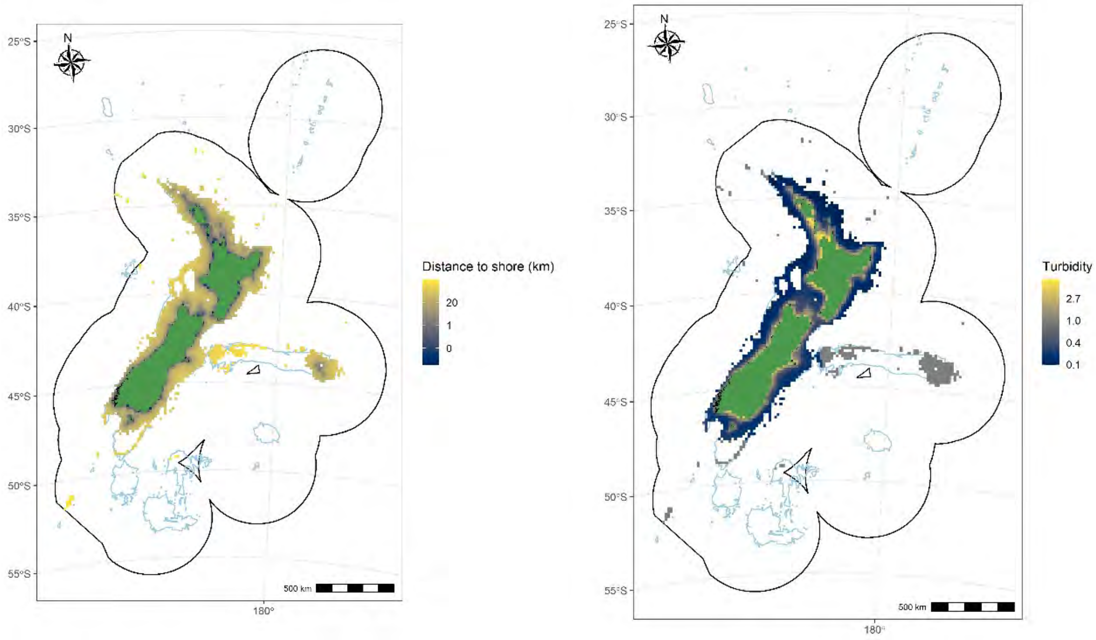

Figure A.2: Distance to shore (km) and turbidity (NTU) at the 16 km grid size resolution. Only cells with over 10 events are shown. The 500 m depth contour is shown in light blue and the New Zealand EEZ in black.

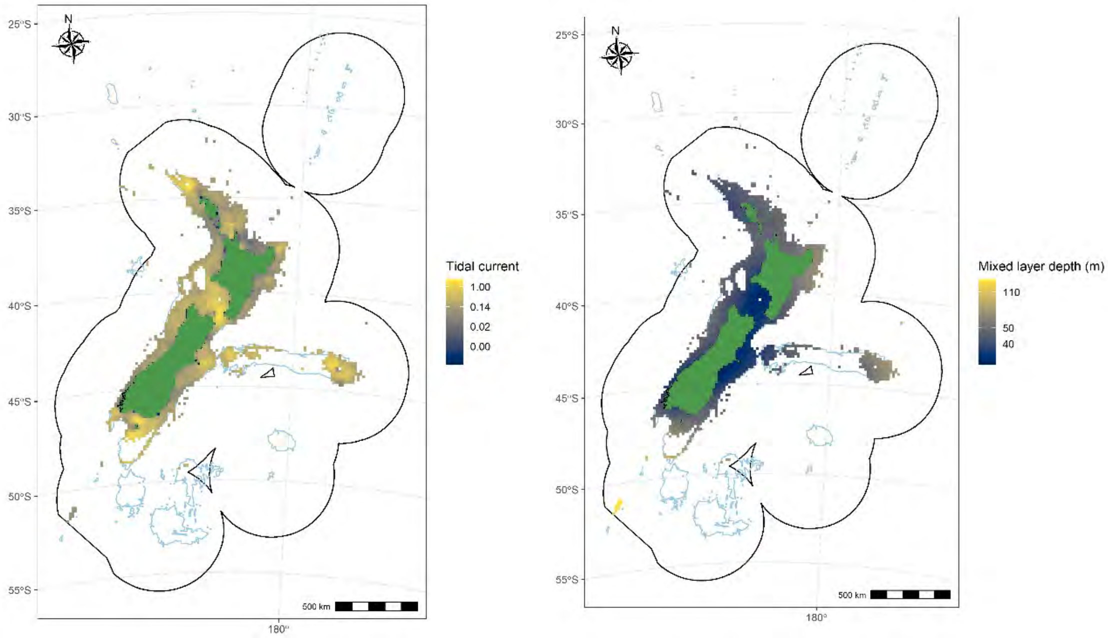

Figure A.3: Tidal current (m s^{-1}) and mixed layer depth (m) at the 16 km grid size resolution. Only cells with over 10 events are shown. The 500m depth contour is shown in light blue and the New Zealand EEZ in black.

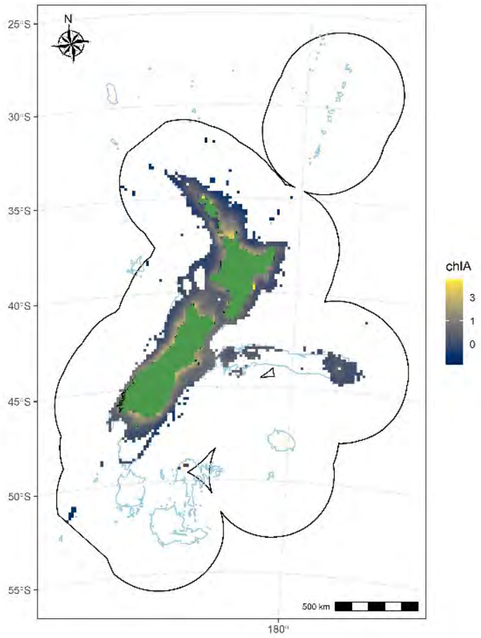

Figure A.4: ChlA (mg m^{-3}) at the 16 km grid size resolution. Only cells with over 10 events are shown. The 500m depth contour is shown in light blue and the New Zealand EEZ in black.

Appendix B – Prey species

Table B.1: Prey species/species group code, common name, and scientific name, as well as number of predators from this study and how often they were caught in observer, fishery, and survey data. Note the species groups of section 3.1 where relevant.

Code	Common name	Scientific name	Predators	Observer	Fishery	Survey	Total
ANC	Anchovy	*Engraulis australis*	2	9	20	54	83
BAR	Barracouta	*Thyrsites atun*	3	5 103	227 698	1 564	234 365
BCO	Blue Cod	*Parapercis colias*	2	1 767	46 550	286	48 603
BNS	Bluenose	*Hyperoglyphe antarctica*	2	1 475	52 495	13	53 983
BPE	Butterfly Perch	*Caesioperca lepidoptera*	1	65	491	4	560
BUL	Bully (group)	Eleotridae (family)	1	0	2	0	2
BUT	Butterfish	*Odax pullus*	2	114	3 903	0	4 017
CAC	Cancer Crab	*Cancer novaezelandiae*	1	1	183	13	197
CDL	Cardinal Fish	*Epigonus telescopus*	2	326	1 683	0	2 009
CDO	Capro Dory	*Capromimus abbreviatus*	1	249	3 316	371	3 936
CON	Conger Eel	*Conger* spp.	2	785	36 387	147	37 319
DSS	Deepsea Smelt	*Bathylagus* spp.	1	0	0	0	0
EGR	Eagle Ray	*Myliobatis tenuicaudatus*	2	2 056	14 719	52	16 827
ESQ	Enoploteuthis Squid	*Enoploteuthis* spp.	1	0	1	0	1
FLO	Flounder (group)		6	693	118 912	276	119 881
FLY	Flying Fish	Exocoetidae (family)	2	1	17	0	18
GAR	Garfish	*Hyporhamphus ihi*	1	2	139	0	141
GMU	Grey Mullet	*Mugil cephalus*	2	43	3 764	0	3 807
GUR	Gurnard	*Chelidonichthys kumu*	1	8 954	557 898	961	567 813
HAG	Hagfish	*Eptatretus cirrhatus*	1	457	4 378	9	4 844
HAP	Hapuku	*Polyprion oxygeneios*	1	2 649	25 567	507	28 723
HOK	Hoki	*Macruronus novaezelandiae*	4	1 526	39 652	585	41 763
JDO	John Dory	*Zeus faber*	1	5 881	226 632	383	232 896
JMA	Jack Mackerel	*Trachurus declivis, T. murphyi, T. novaezelandiae*	5	4 438	76 404	793	81 635
KAH	Kahawai	*Arripis trutta, a. Xylabion*	4	3 404	99 053	87	102 544
KOH	Kōheru	*Decapterus koheru*	1	22	126	0	148
LAM	Lamprey	*Geotria australis*	1	0	0	0	0
LAN	Lanternfish	Myctophidae (family)	2	12	9	5	26
LEA	Leatherjacket	*Meuschenia scaber*	2	3 114	104 871	336	108 321
LIN	Ling	*Genypterus blacodes*	1	3 127	111 378	879	115 384
MNI	Krill, Squat Lobsters	*Munida* spp.	1	17	1	6	24
MOR	Morid (group)		11	4 291	289 659	1 334	295 284
OCT	Octopus	*Pinnoctopus cordiformis*	3	990	14 968	236	16 194
OPA	Opalfish	*Hemerocoetes* spp.	2	333	31	108	472
PAR	Parore	*Girella tricuspidate*	1	14	2 278	1	2 293

Code	Common name	Scientific name	Predators	Observer	Fishery	Survey	Total
PHO	Lighthouse Fish	*Photichthys argenteus*	1	8	0	1	9
PIG	Pigfish	*Congiopodus leucopaecilus*	2	774	3 363	485	4 622
PIL	Pilchard	*Sardinops sagax*	4	19	133	24	176
POR	Porae	*Nemadactylus douglasii*	1	991	26 793	1	27 785
RAT	Rattail (group)		5	2 351	34 297	908	37 556
RBM	Ray's Bream	*Brama brama*	1	320	4 927	97	5 344
RBT	Redbait	*Emmelichthys nitidus*	4	854	356	208	1 418
RBY	Rubyfish	*Plagiogeneion rubiginosum*	1	372	8 010	26	8 408
RHY	Common Roughy	*Paratrachichthys trailli*	1	627	1 421	117	2 165
RMU	Red Mullet	*Upeneichthys lineatus*	1	77	142	22	241
RSK	Rough Skate	*Zearaja nasuta*	2	4 977	226 570	799	232 346
RSQ	Ommastrephes Bartrami	*Ommastrephes bartrami*	1	3	4	0	7
RUD	Rudderfish	*Centrolophus niger*	1	44	98	8	150
SAL	Salps		2	0	0	0	0
SBW	Southern Blue Whiting	*Micromesistius australis*	1	12	117	59	188
SNA	Snapper	*Chrysophrys auratus*	2	7 798	362 164	199	370 161
SOL	Sole (group)		6	3 979	276 250	1 483	281 712
SPE	Sea Perch	*Helicolenus* spp.	1	3 298	71 109	1 144	75 551
SPP	Splendid Perch	*Callanthias allporti*	1	20	56	2	78
SPR	Sprats	*Sprattus antipodum, S. muelleri*	3	6	78	138	222
SQU	Squid (group)	*Nototodarus sloanii, N. gouldi*	9	3 506	71 631	1 755	76 892
SSI	Silverside	*Argentina elongata*	2	945	354	827	2 126
STA	Stargazer (group)	*Kathetostoma* spp. and unspecificed stargazer	3	4 923	206 359	1 420	212 702
STR	Stingray (Unspecified)		2	467	1 984	3	2 454
STY	Spotty	*Notolabrus celidotus*	2	10	311	97	418
TAR	Tarakihi	*Nemadactylus macropterus, Nemadactylus* sp. A (King tarakihi)	2	6 113	355 617	1 172	362 902
TRE	Trevally	*Pseudocaranx georgianus*	1	4 905	174 279	31	179 215
VSQ	Violet Squid	*Histioteuthis* spp.	1	14	1	0	15
WAR	Warehou (group)	*Seriolella* spp.	3	3 085	91 873	1 351	96 309
WRA	Wrasses (group)	Labridae	3	720	3 669	23	4 412
WSQ	Warty Squid	*Onykia* spp.	1	119	42	0	161
YEM	Yellow-Eyed Mullet	*Aldrichetta forsteri*	2	6	1 045	32	1 083
YFN	Yellowfin Tuna	*Thunnus albacares*	1	1	13	0	14

Appendix C – Supporting tables and figures

Table C.1: Models run to investigate model settings. These models were run on the 2018–2020 years of the 'full dataset', using snapper as the exemplar species. The model in bold had the lowest AIC with acceptable dispersion and convergence and was therefore selected. The model number (#) is reported in the text where appropriate. All continuous variables were offered to the model as third-degree polynomials.

#	Vessel	Covariates	Catchability	AIC	Dispersion	Convergence
1	Source + method	-	vessel length	54 685	0.000	No
2	Source + method	-	vessel length + month	52 427	0.192	Ok
3	-	-	vessel length + month + source + method	5 861	0.976	Ok
4	source + vessel		vessel length + month + source + method	5 861	1.000	Ok
5	Source + vessel	Depth	vessel length + month + source + method	-12 854	0.648	Ok
6	Source + vessel	Depth, turbidity, slope	vessel length + month + source + method	-14 082	0.496	Ok
7	-	Depth, turbidity, slope, tidal current, chla, mixed layer depth	vessel length + month + source + method	-15 198	0.606	No
8	-	Depth, turbidity, slope, tidal current, chla, mixed layer depth	vessel length + month + source + method + year	-8 475	0.296	Ok
9	**-**	**Depth, turbidity, chla**	**vessel length + month + source + method**	**-18 402**	**0.896**	**Ok**

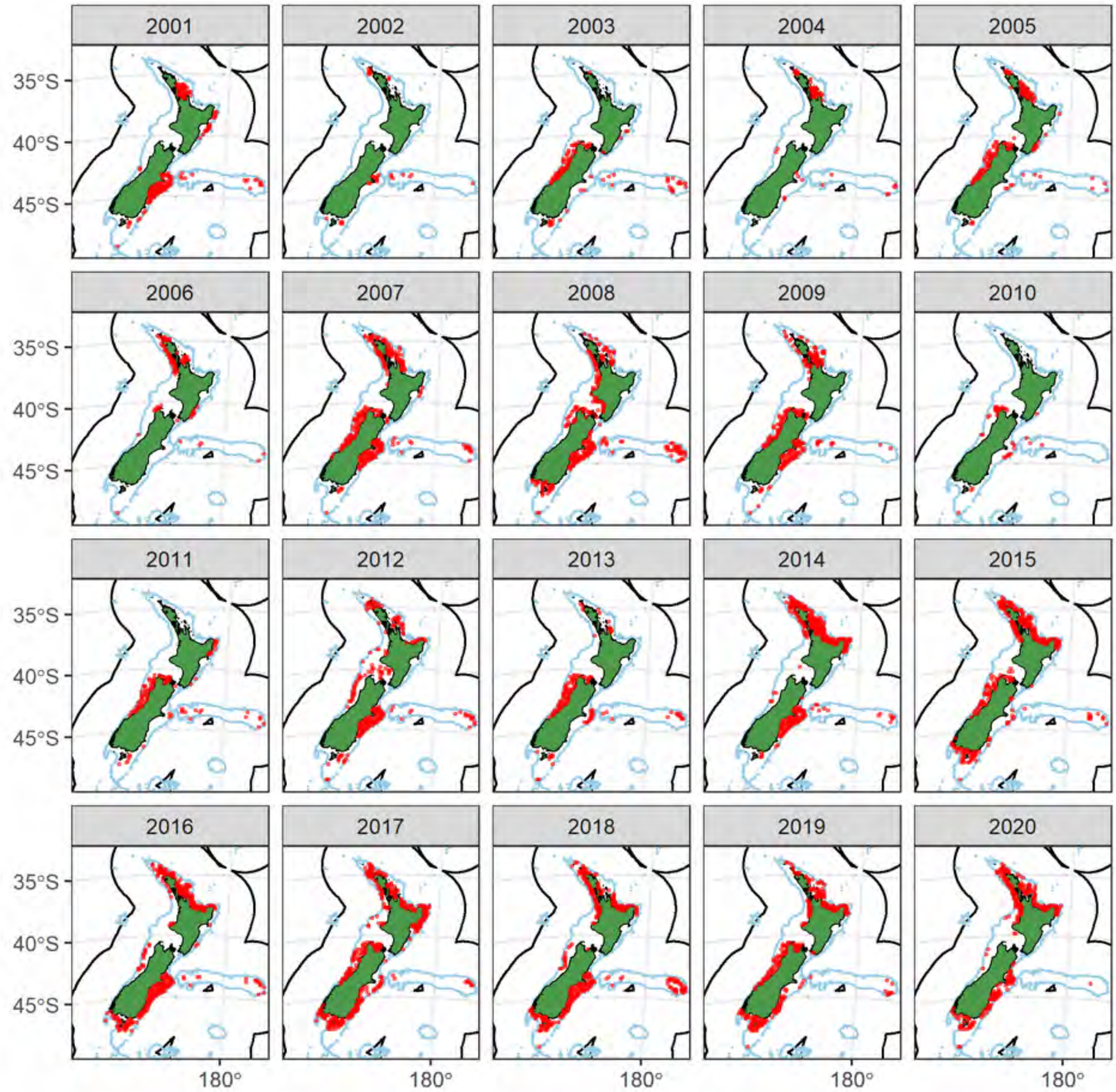

Figure C.1: Location of data by fishing year for the full dataset but with observer and survey events only. The 500 m depth contour is shown in light blue and the New Zealand EEZ in black.

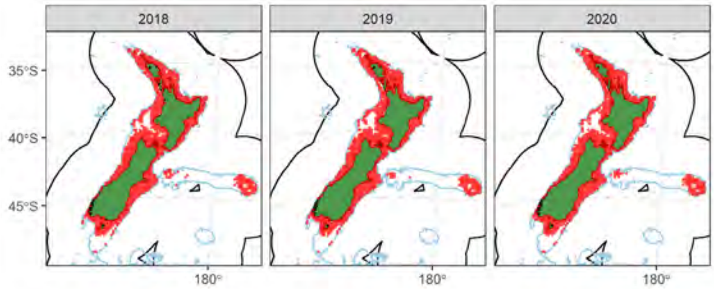

Figure C.2: Location of data by fishing year for the full dataset with all events in the 2018 to 2020 fishing years. The 500 m depth contour is shown in light blue and the New Zealand EEZ in black.

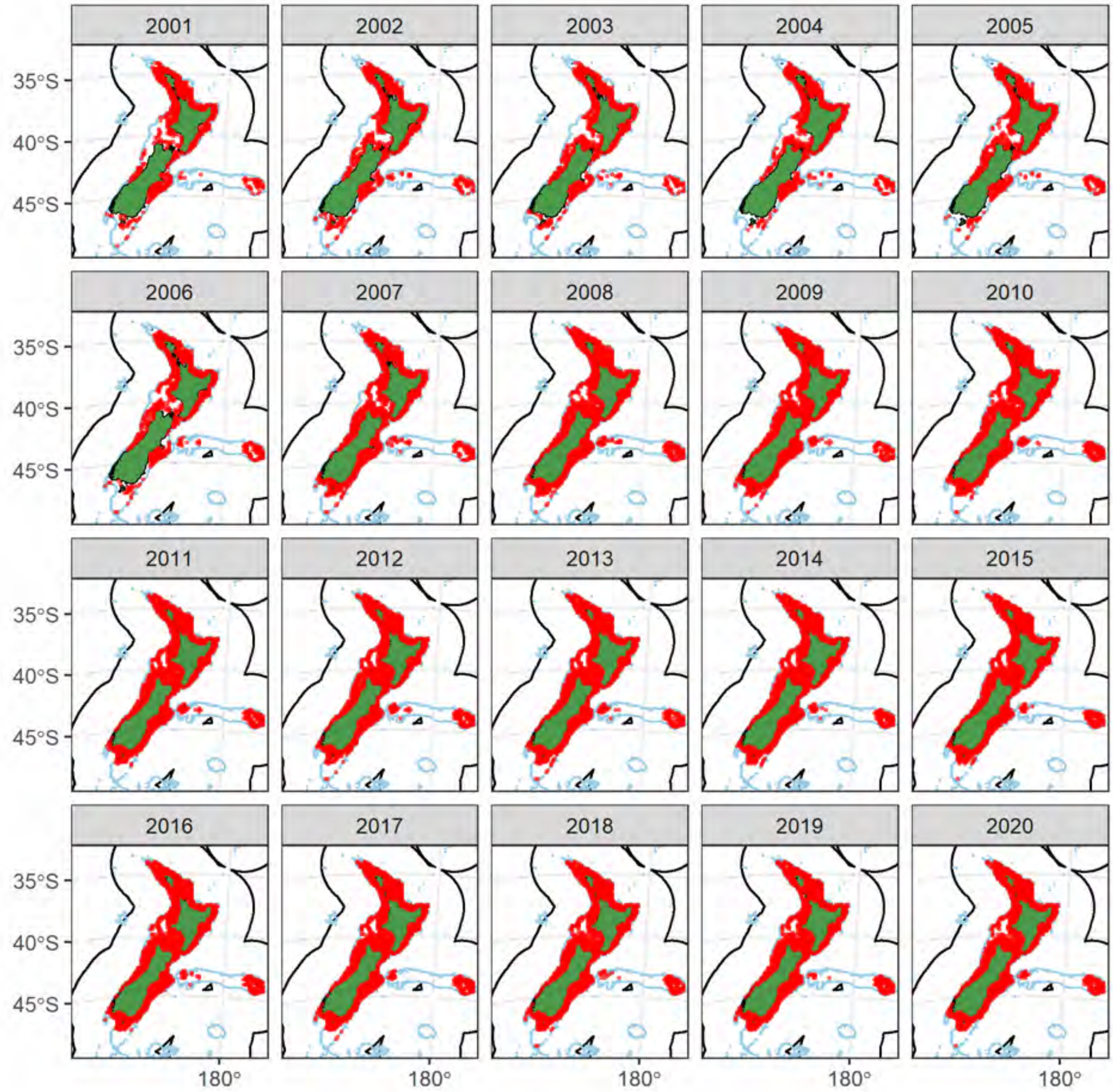

Figure C.3: Location of data by fishing year for the aggregated dataset (aggregated at the level of the vessel / month / method and 16 km grid cell combination), retaining cells with over 10 events. The 500 m depth contour is shown in light blue and the New Zealand EEZ in black.

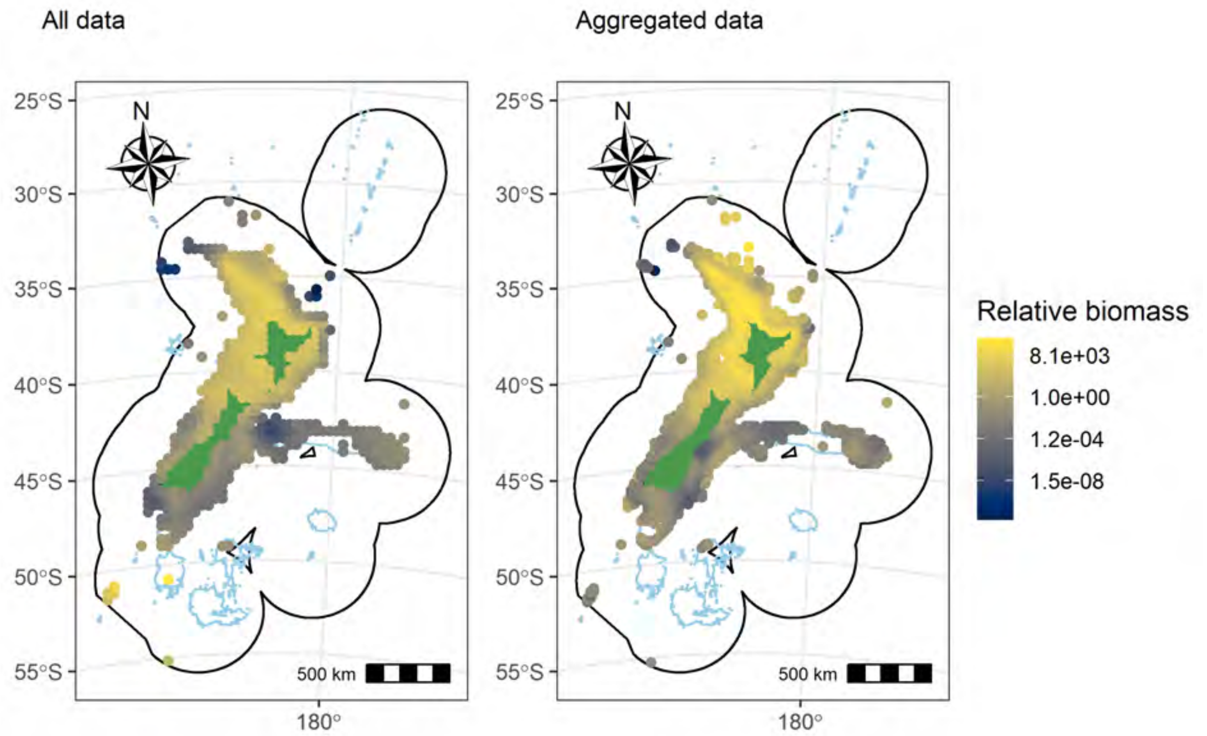

Figure C.4: Estimated relative biomass for the snapper model with all data and 50 knots in the model (left) and aggregated data and 100 knots in the model (right). The 500 m depth contour is shown in light blue and the New Zealand EEZ in black.

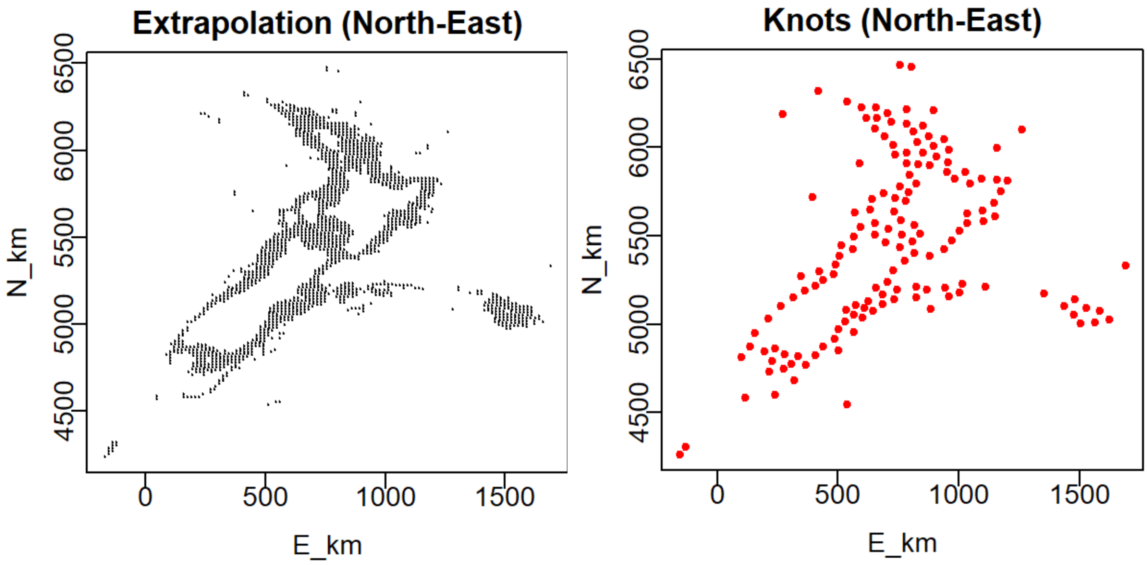

Figure C.5: Location of the 16×16 km extrapolation grid (left) and 150 knots (right) used by the VAST models.

Appendix D – Species distributions and diagnostics

Barracouta

Juvenile barracouta have been recorded from inshore areas (less than 100 m depths) all around New Zealand and the Chatham Islands, although they appear to be less common off the west coast of the South Island. Adult fish are found down to about 400 m depth. The only indices of abundance available are CPUE and survey trends by QMS, mostly going slightly down in recent years (Fisheries New Zealand 2021).

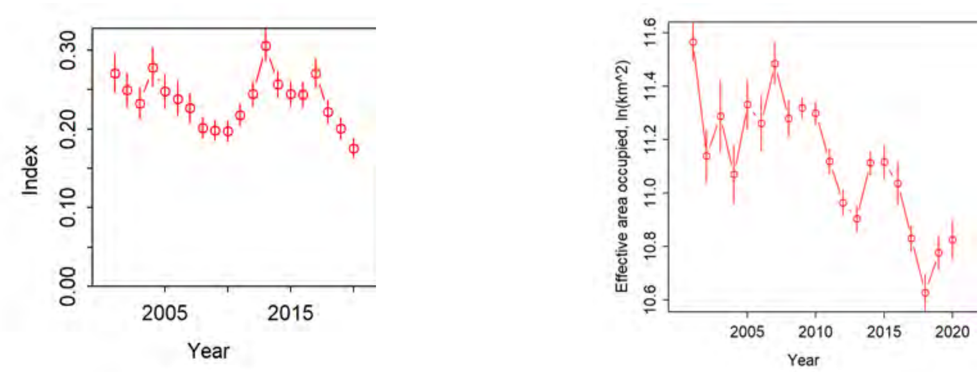

Figure D.1: Temporal index of barracouta biomass (left) and Effective area occupied over time and one standard error (right).

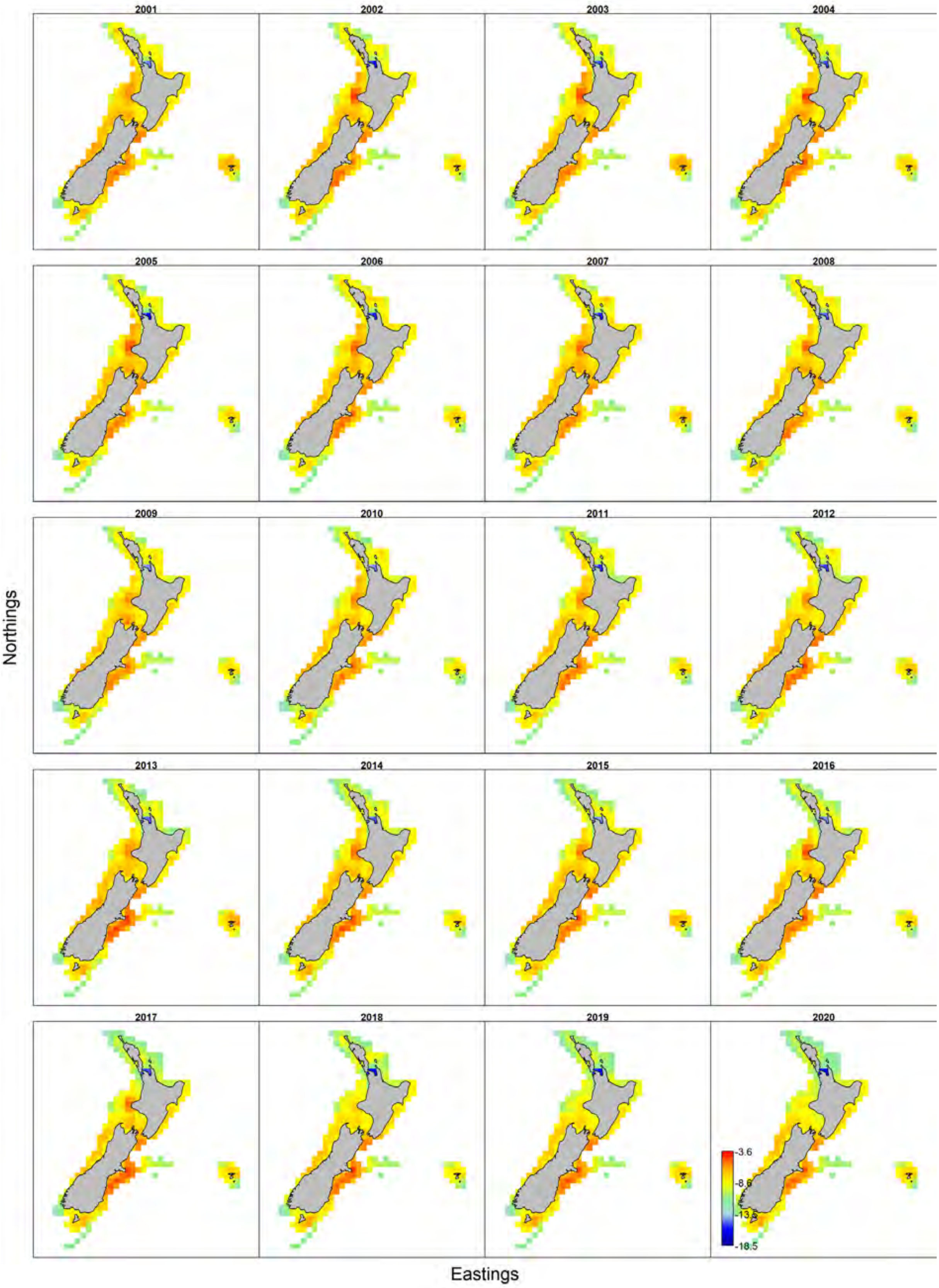

Figure D.2: Spatial-temporal distribution of biomass for barracouta, expressed in lognormal scale.

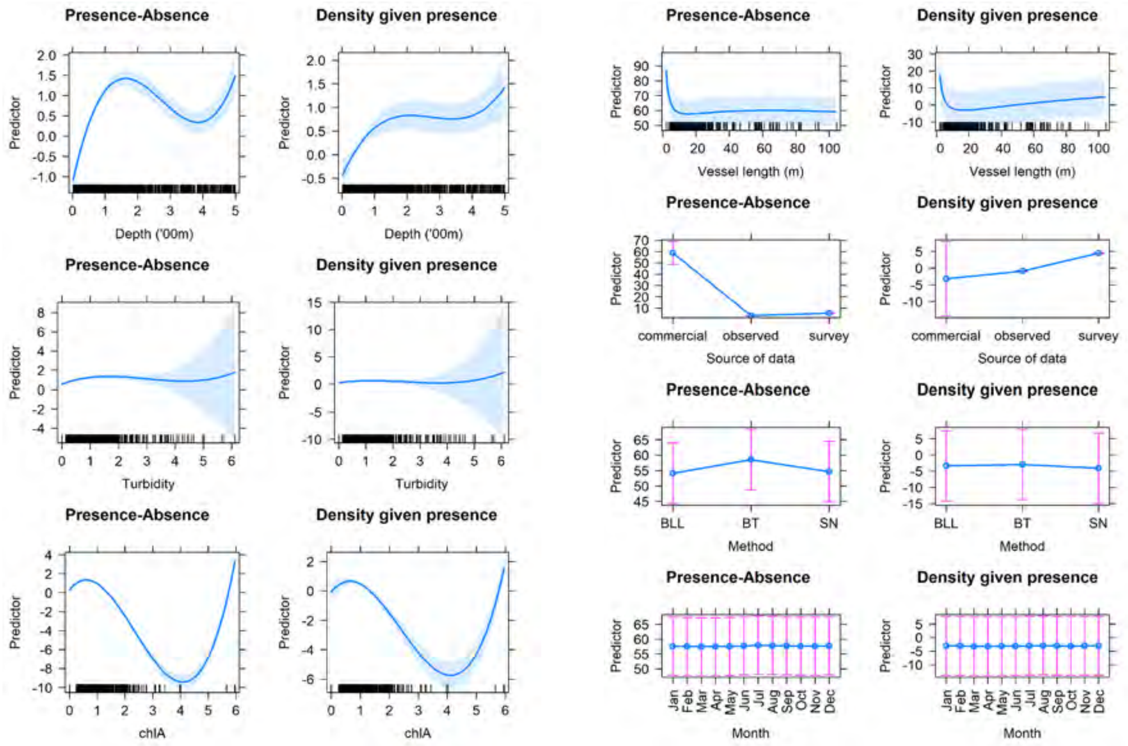

Figure D.3: Barracouta model partial effects plots and one standard error.

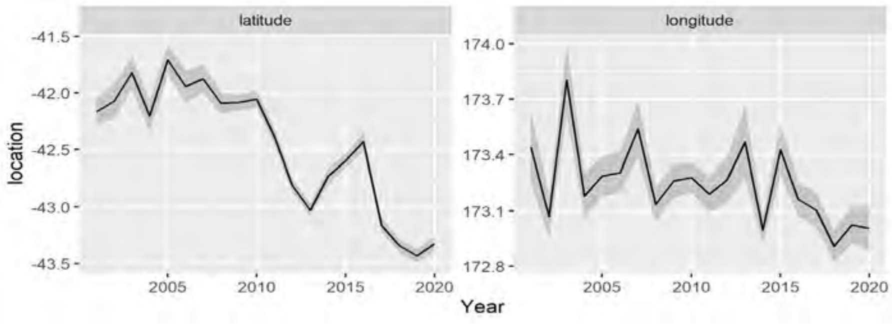

Figure D.4: Location of the centre of gravity over time for barracouta and one standard error.

Bluenose

The depth distribution of bluenose ranges from near-surface to about 1200 m. The main depth range is 250–750m with a peak at 300–400m. A stock assessment is available for the entire EEZ, with the spawning stock biomass (SSB) dropping to 2010 and increasing to 2020 (Fisheries New Zealand 2021).

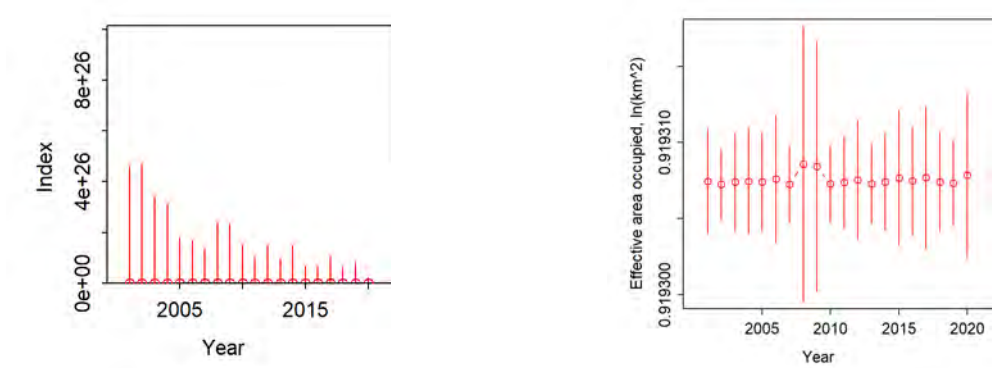

Figure D.5: Temporal index of bluenose biomass and Effective area occupied over time and one standard error.

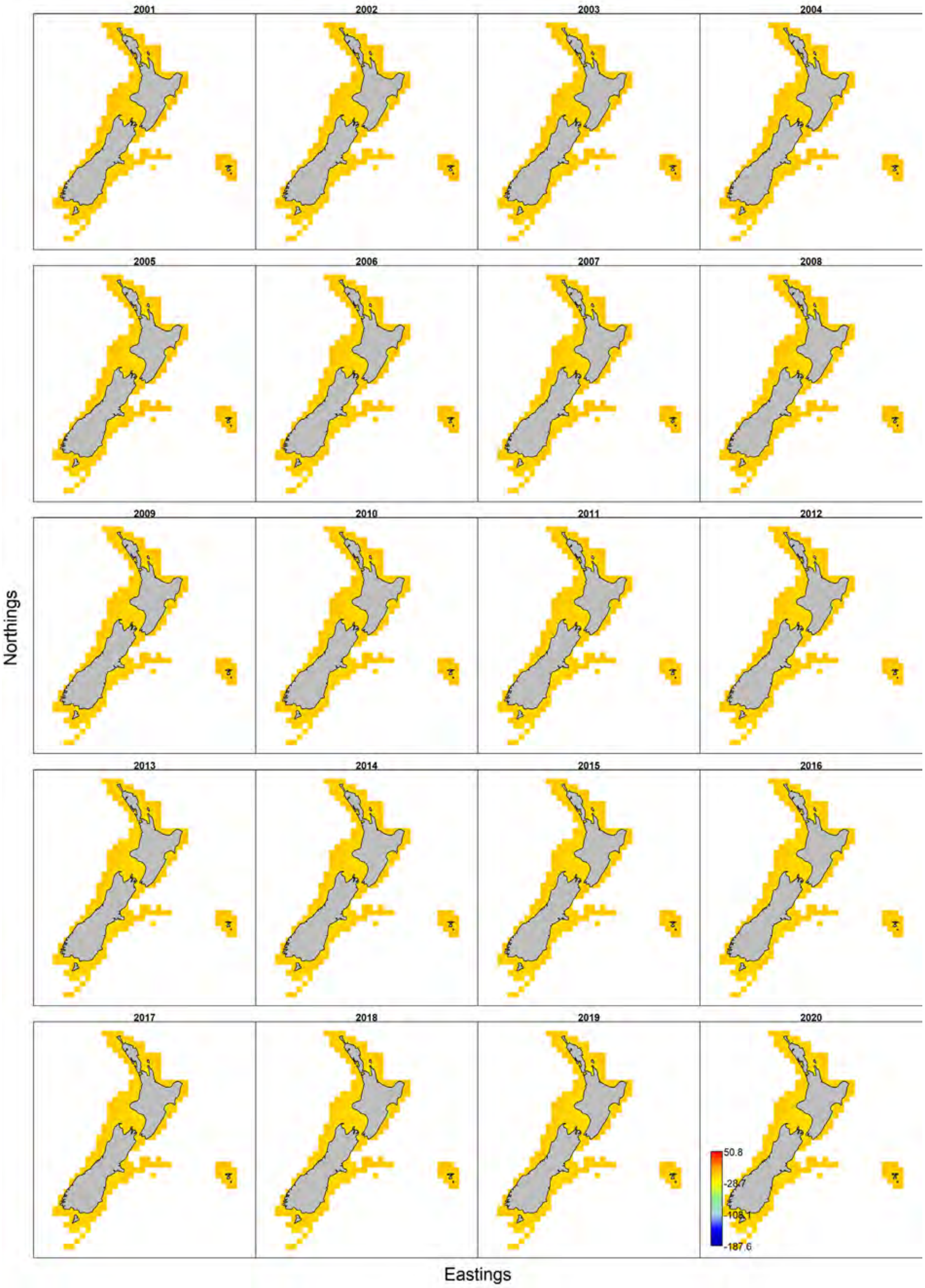

Figure D.6: Spatial-temporal distribution of biomass for bluenose, expressed in lognormal scale.

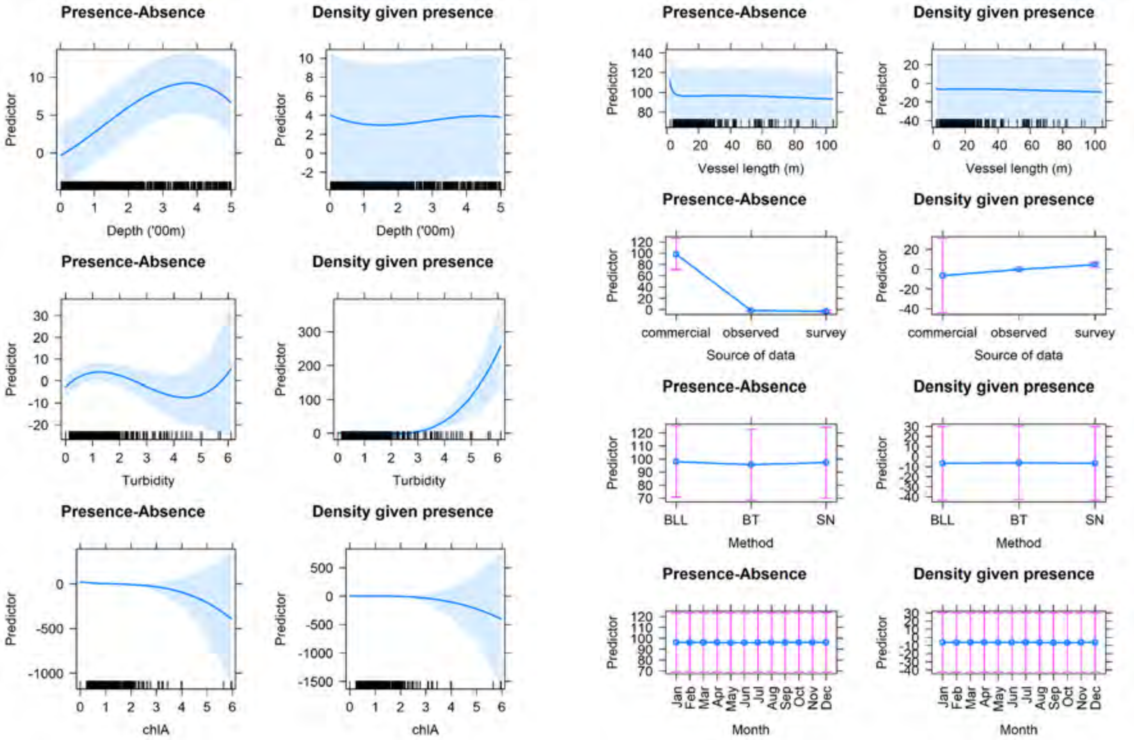

Figure D.7: Bluenose model partial effects plots and one standard error.

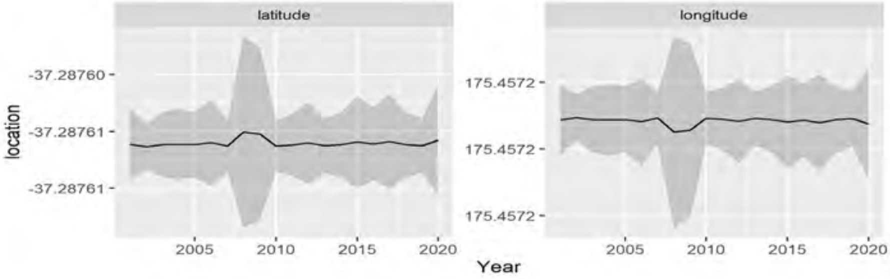

Figure D.8: Location of the centre of gravity over time for bluenose and one standard error.

Blue cod

Although distributed around New Zealand near foul ground to a depth of 150 m, blue cod are more abundant south of Cook Strait and around the Chatham Islands. Blue cod biomass is expected to have dropped since 2000 in parts of the fishery (Fisheries New Zealand 2021).

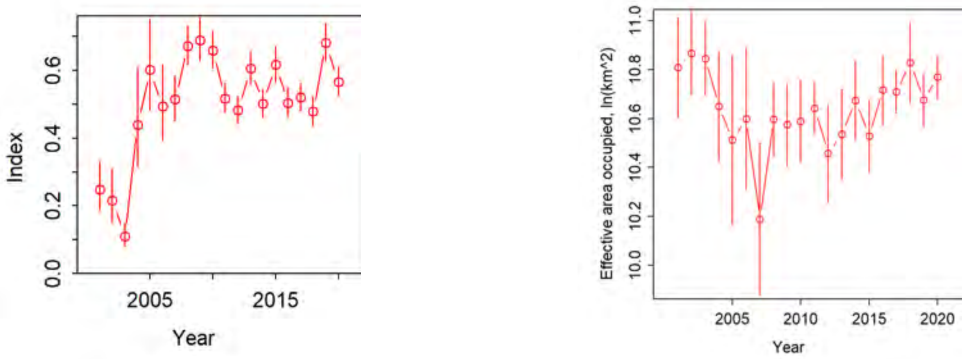

Figure D.9: Temporal index of blue cod biomass and Effective area occupied over time and one standard error.

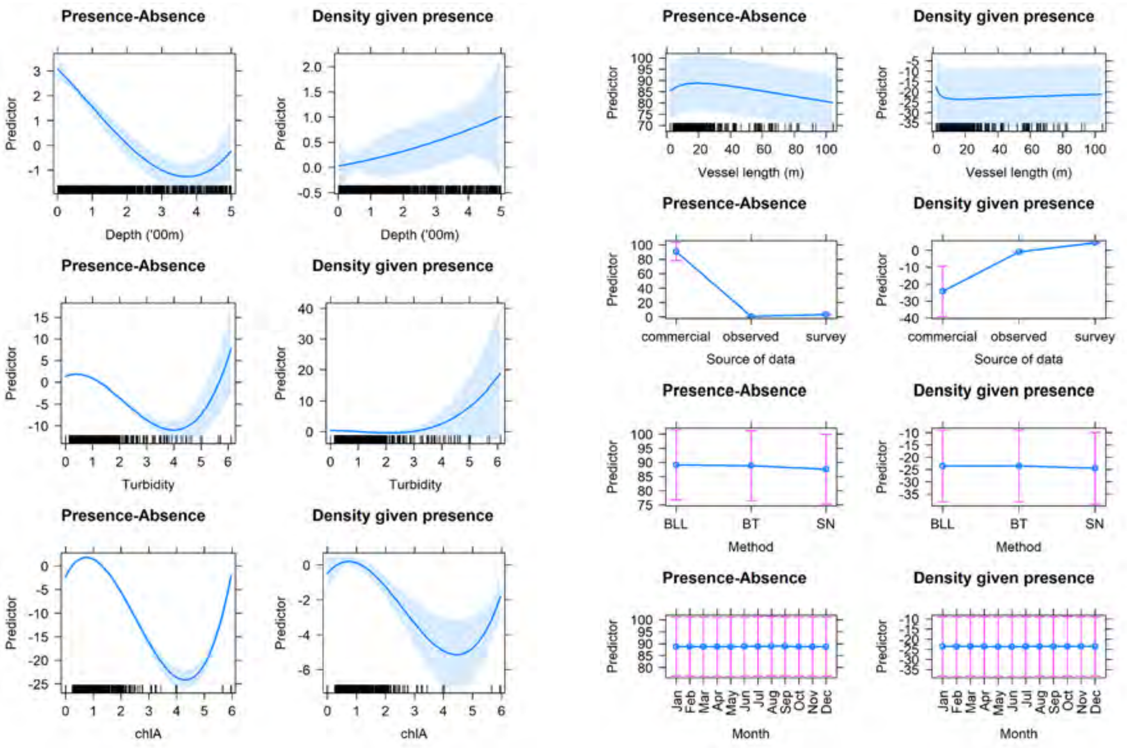

Figure D.10: Blue cod model partial effects plots and one standard error.

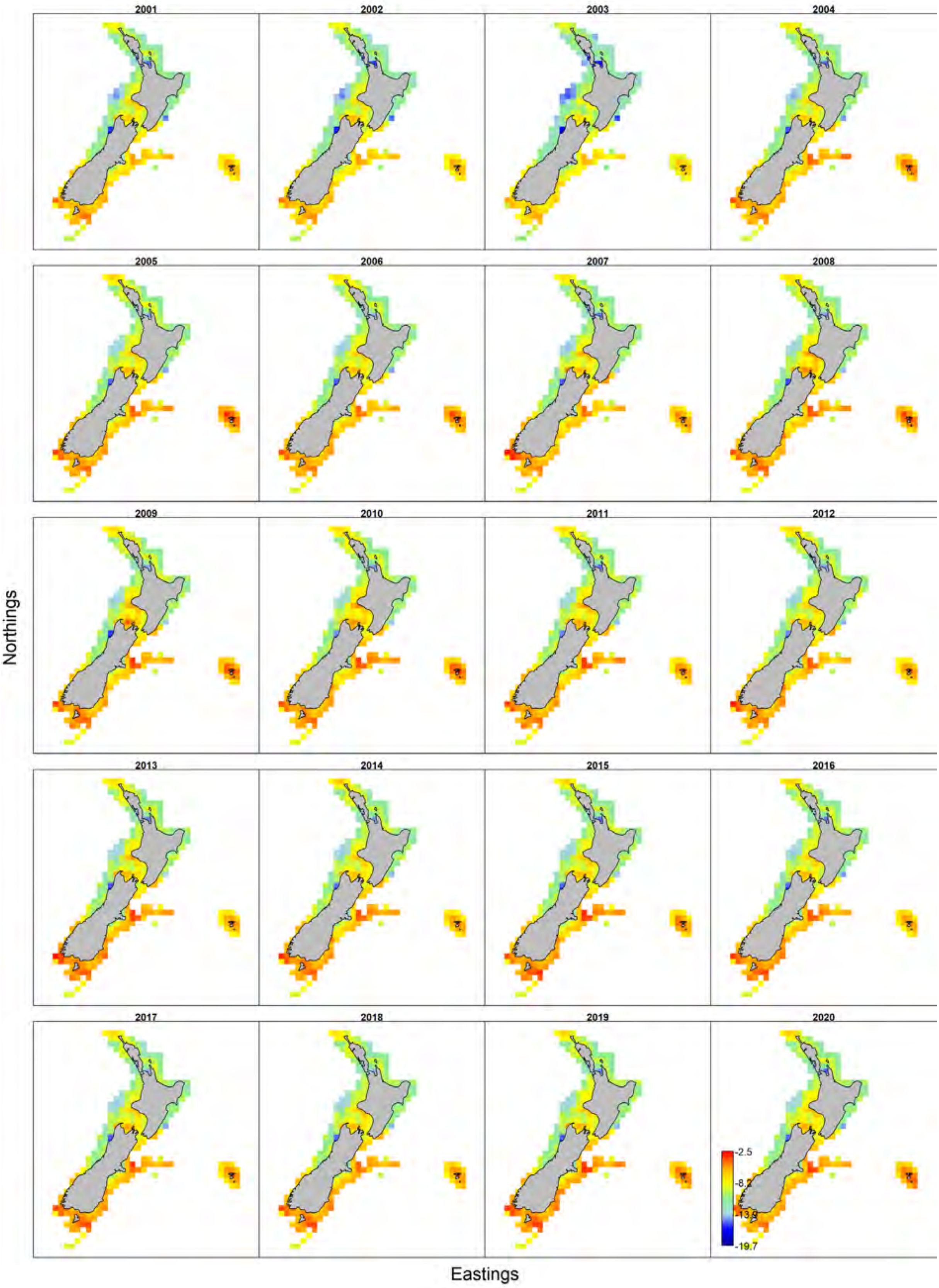

Figure D.11: Spatial-temporal distribution of biomass for blue cod, expressed in lognormal scale.

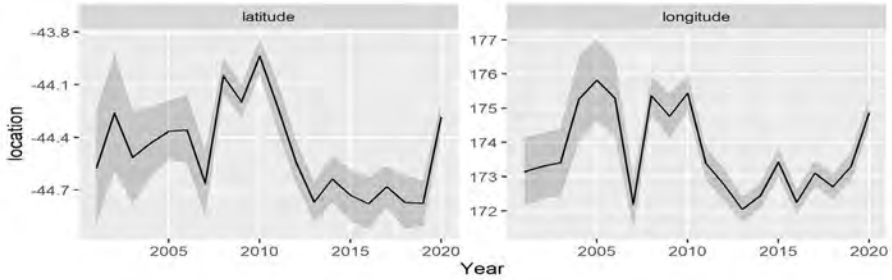

Figure D.12: Location of the centre of gravity over time for blue cod and one standard error.

Conger eel

The Northern conger (*Conger monganius*) is primarily found in association with reefs down to about 100 metres. In New Zealand waters it occurs mainly around the North Island, more abundant along the northern coast. The southern conger (*Conger verreauxi*) occurs in depths of 200 m or less, but some specimens have been caught as deep as 557 m. It is found around New Zealand but more common in the central and southern part (Roberts et al. 2015). Indices of abundance are not available.

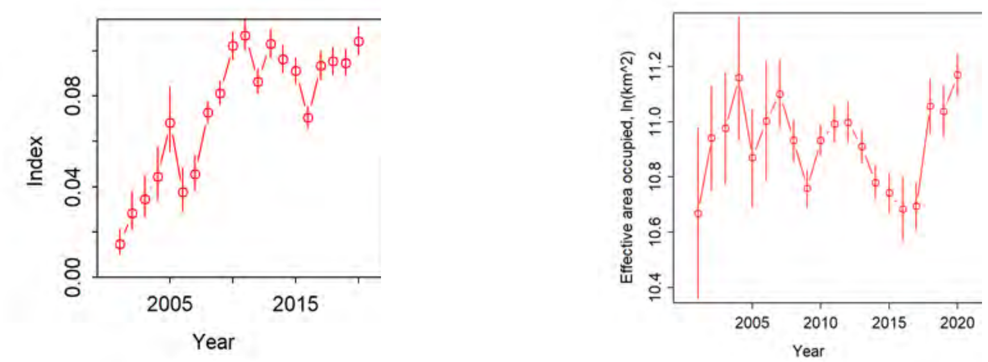

Figure D.13: Temporal index of conger eel biomass and Effective area occupied over time and one standard error.

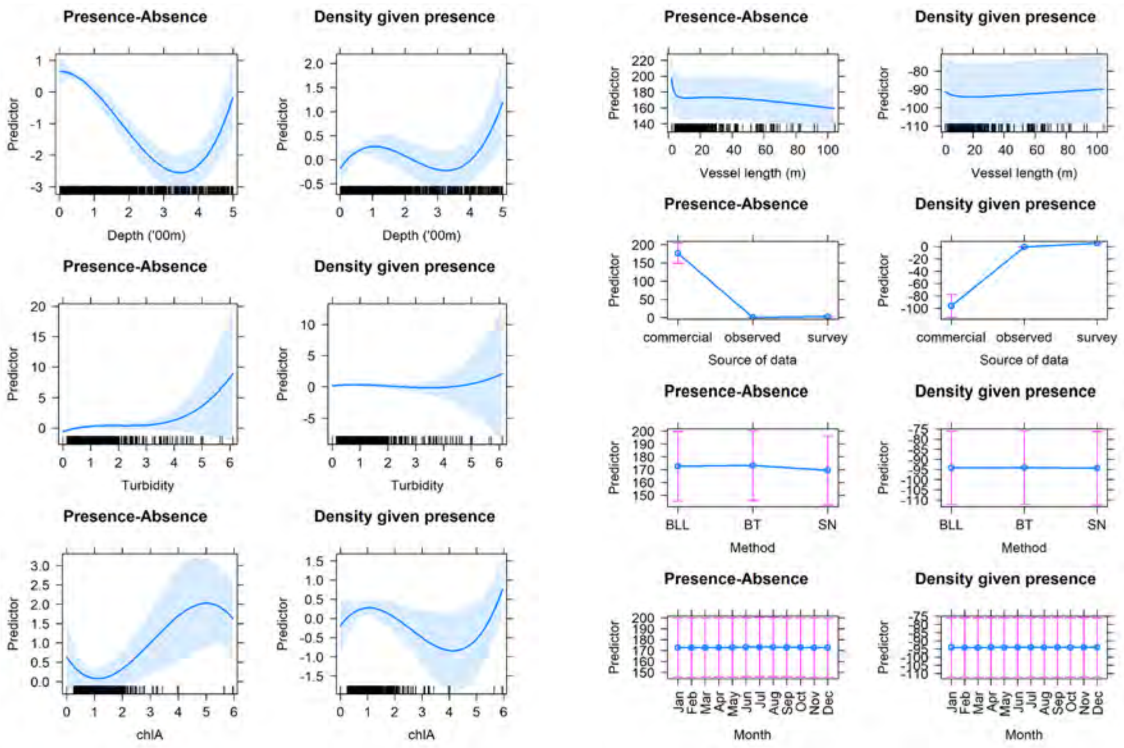

Figure D.14: Conger eel model partial effects plots and one standard error.

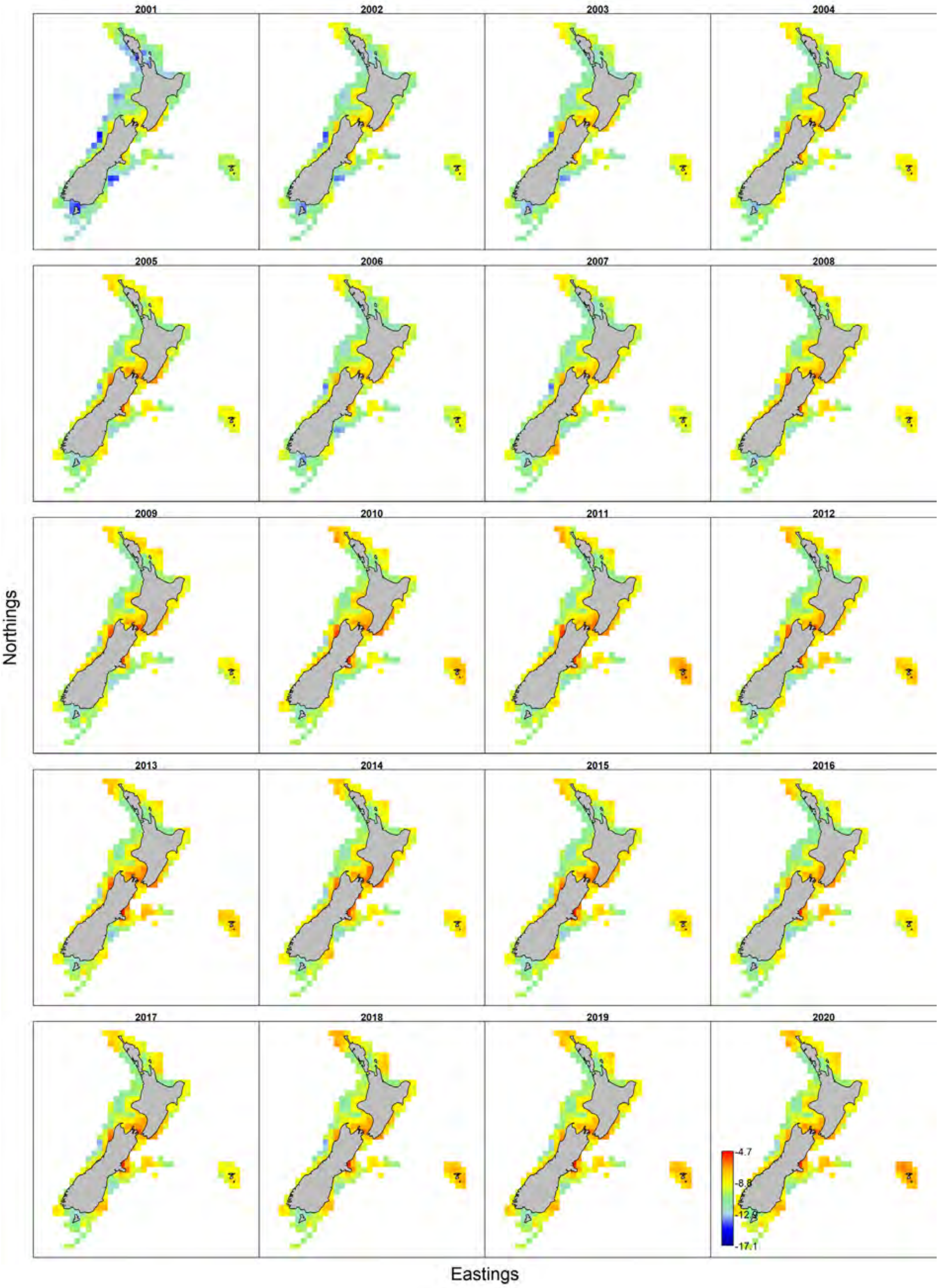

Figure D.15: Spatial-temporal distribution of biomass for conger eel, expressed in lognormal scale.

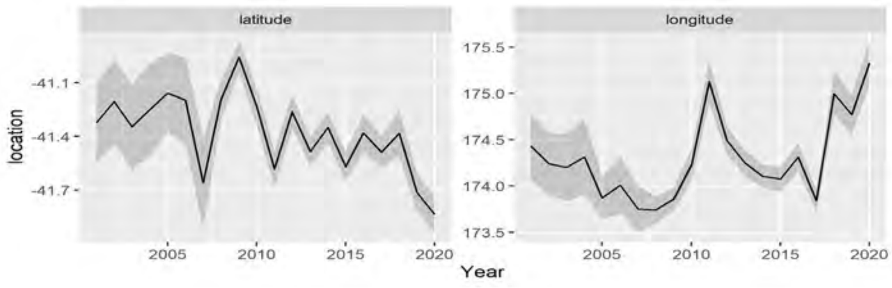

Figure D.16: Location of the centre of gravity over time for conger eel and one standard error.

Eagle ray

Eagle ray occur over soft sediments and rocky reefs down to 422 m depth but are uncommon below 50m. Around New Zealand they are distributed from Northland to the Chatham Rise and Foveaux Strait but are more abundant from Cook Strait north (Roberts et al. 2015). Indices of abundance are not available.

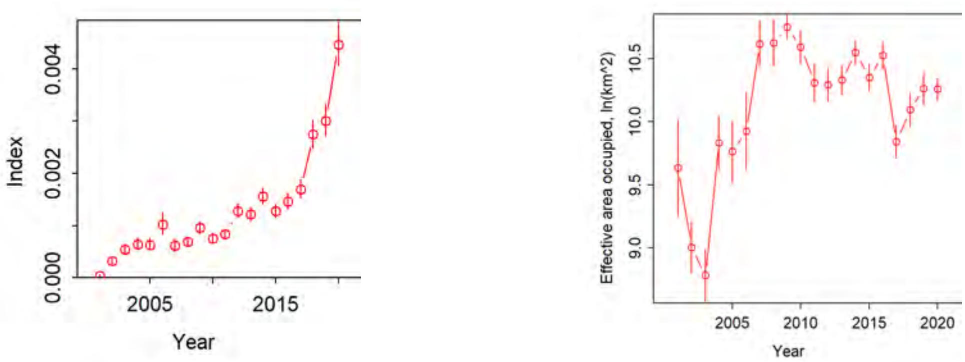

Figure D.17: Temporal index of eagle ray biomass and Effective area occupied over time and one standard error.

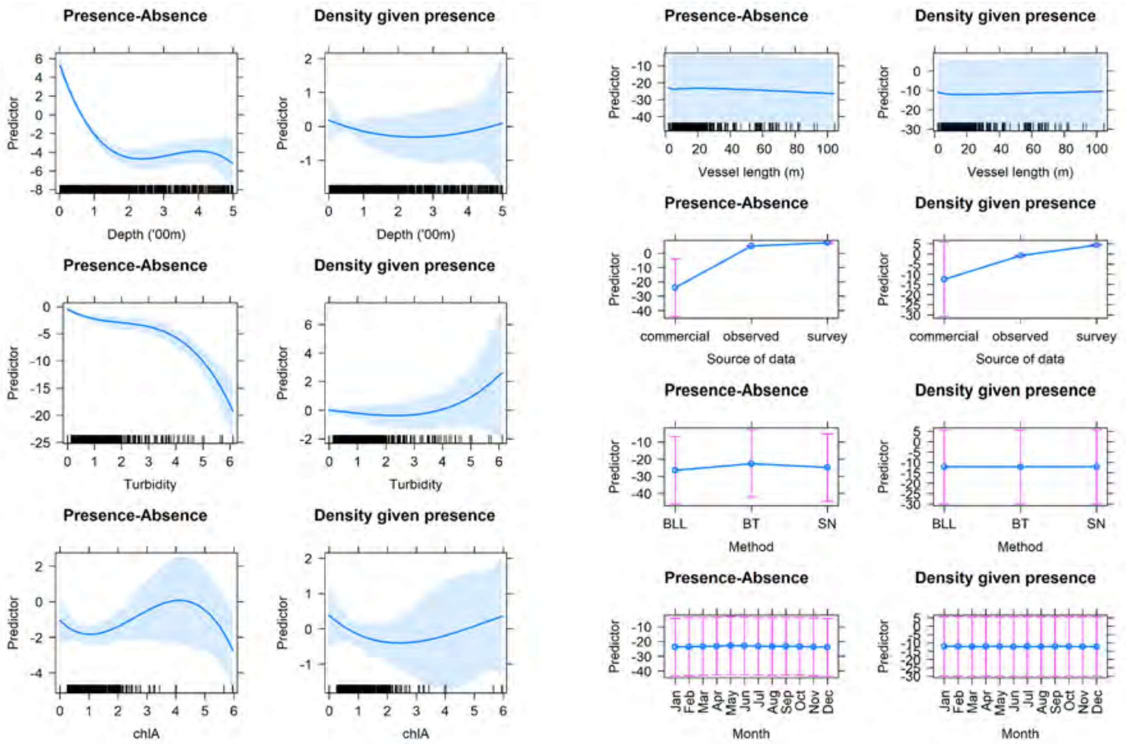

Figure D.18: Eagle ray model partial effects plots and one standard error.

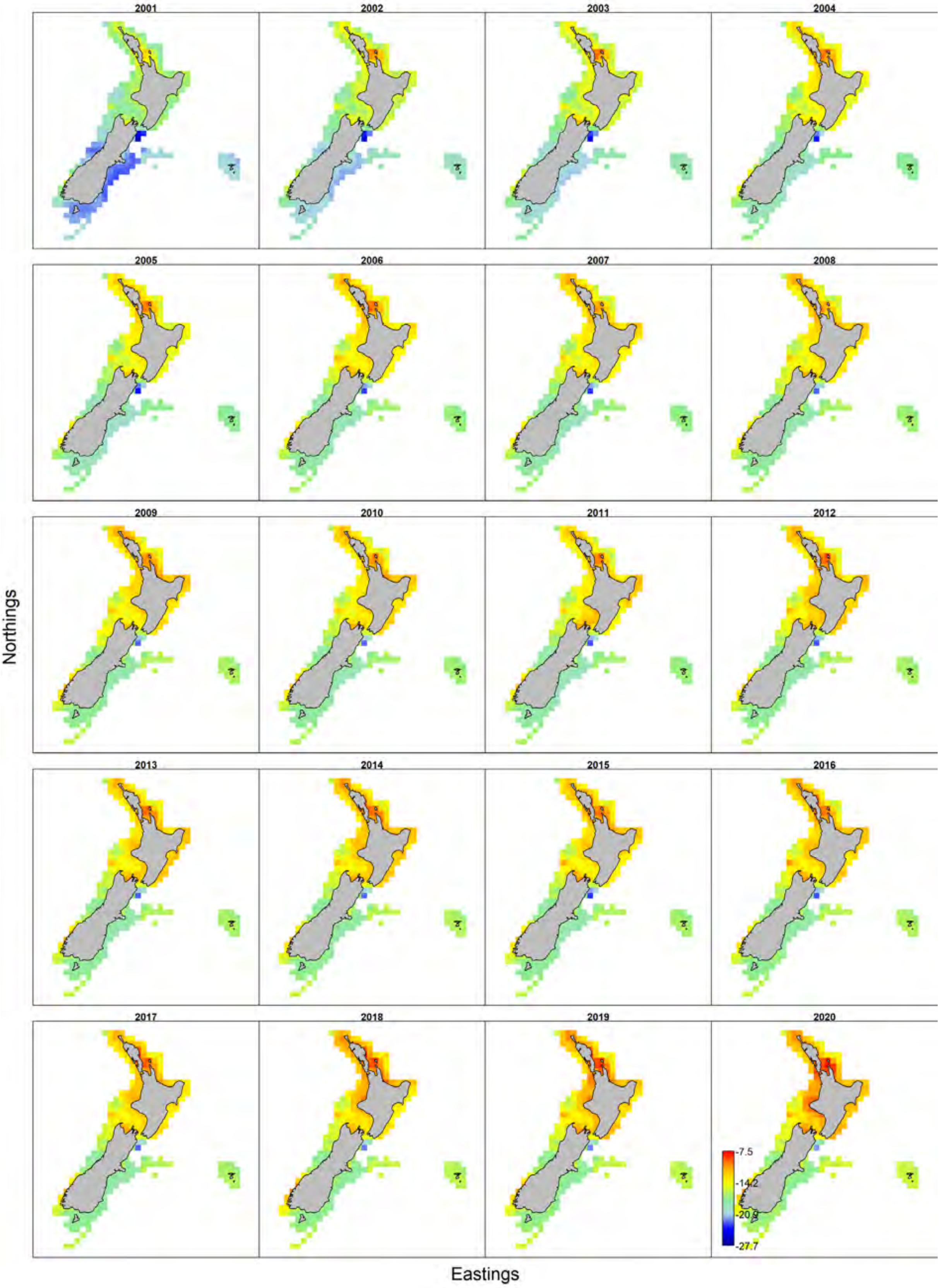

Figure D.19: Spatial-temporal distribution of biomass for eagle ray, expressed in lognormal scale.

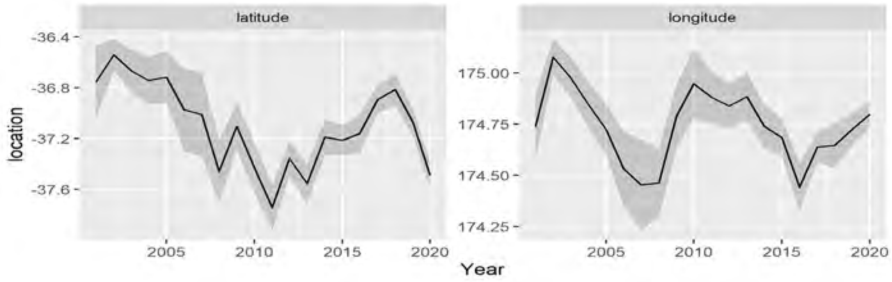

Figure D.20: Location of the centre of gravity over time for eagle ray and one standard error.

Flounder

Flatfish are a large, distinctive and diverse order of benthic fishes found nearly worldwide. Some species occur to depths of around 1500 m although the majority live on the continental shelf at depths less than 200 m (Roberts et al. 2015). Indices of abundance are not available.

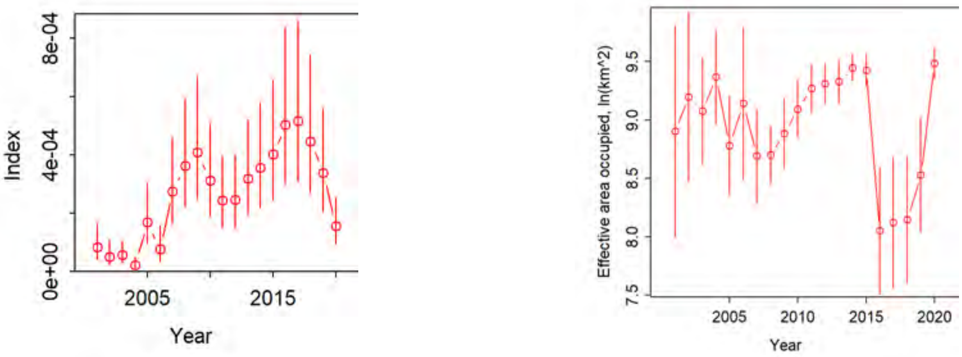

Figure D.21: Temporal index of flounder biomass and Effective area occupied over time and one standard error.

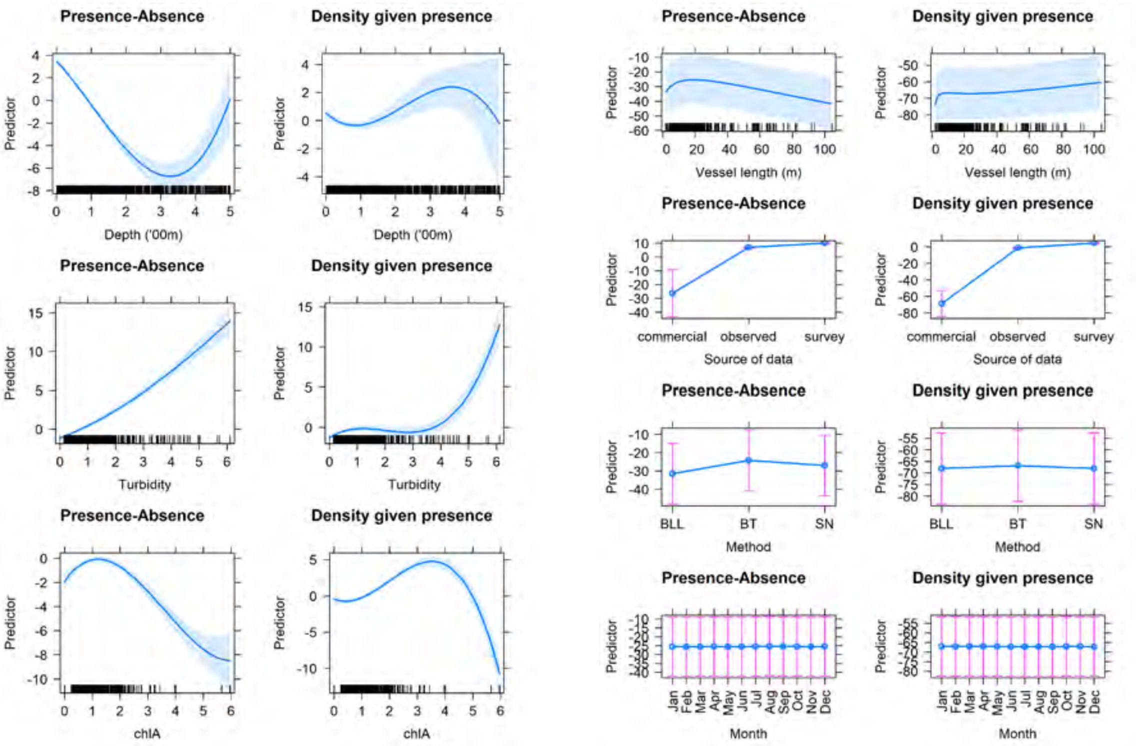

Figure D.22: Flounder model partial effects plots and one standard error.

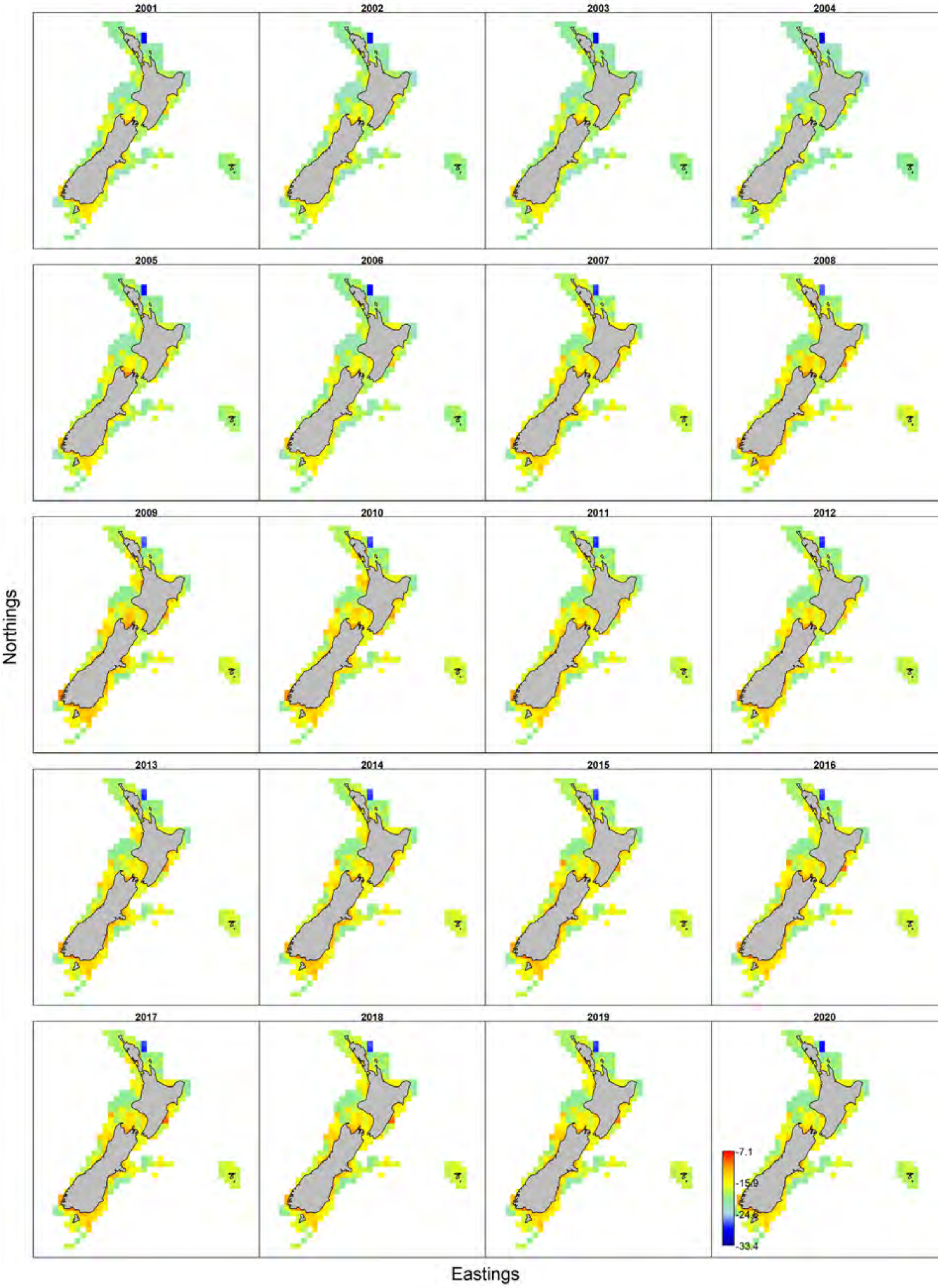

Figure D.23: Spatial-temporal distribution of biomass for flounder, expressed in lognormal scale.

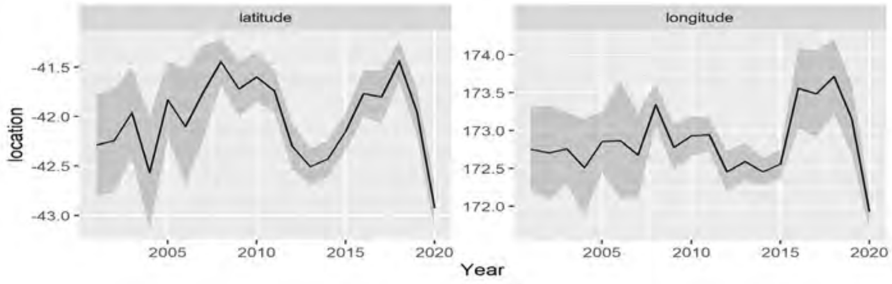

Figure D.24: Location of the centre of gravity over time for flounder and one standard error.

Hoki

Hoki are widely distributed throughout New Zealand waters, from depths of 10 m to over 900 m, with greatest abundance between 200 m and 600 m. The stock assessment for the entire EEZ shows a drop from 1995 to 2005, an increase to 2011, and a drop to 2021 (Fisheries New Zealand 2021).

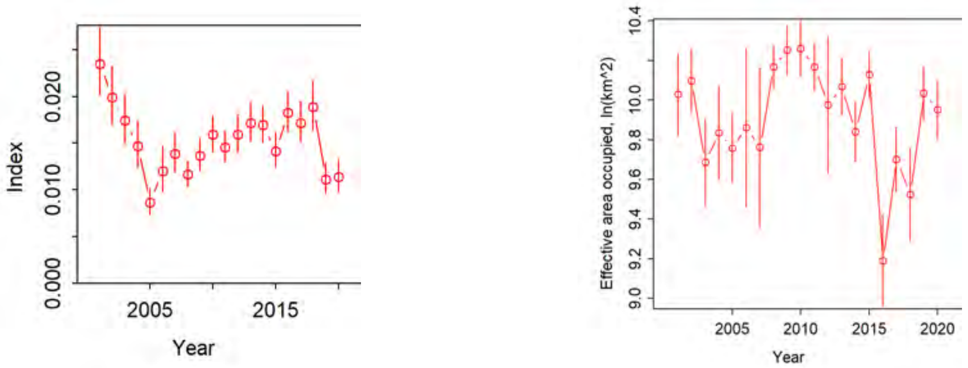

Figure D.25: Temporal index of hoki biomass and Effective area occupied over time and one standard error.

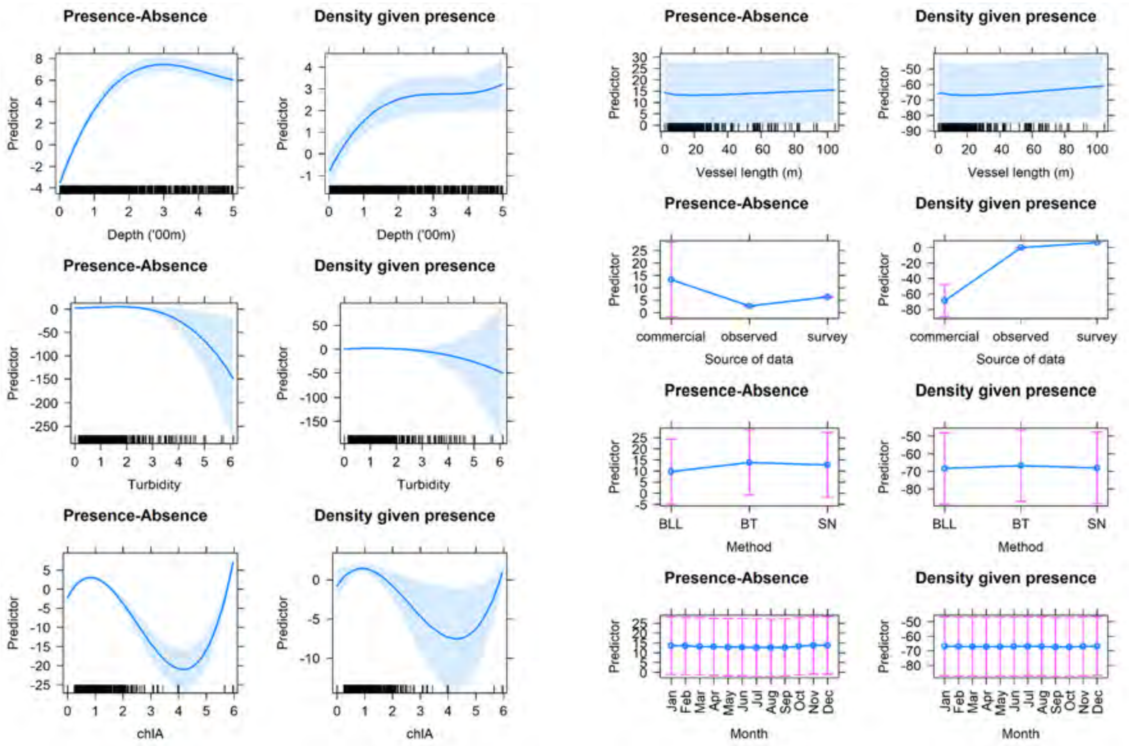

Figure D.26: Hoki model partial effects plots and one standard error.

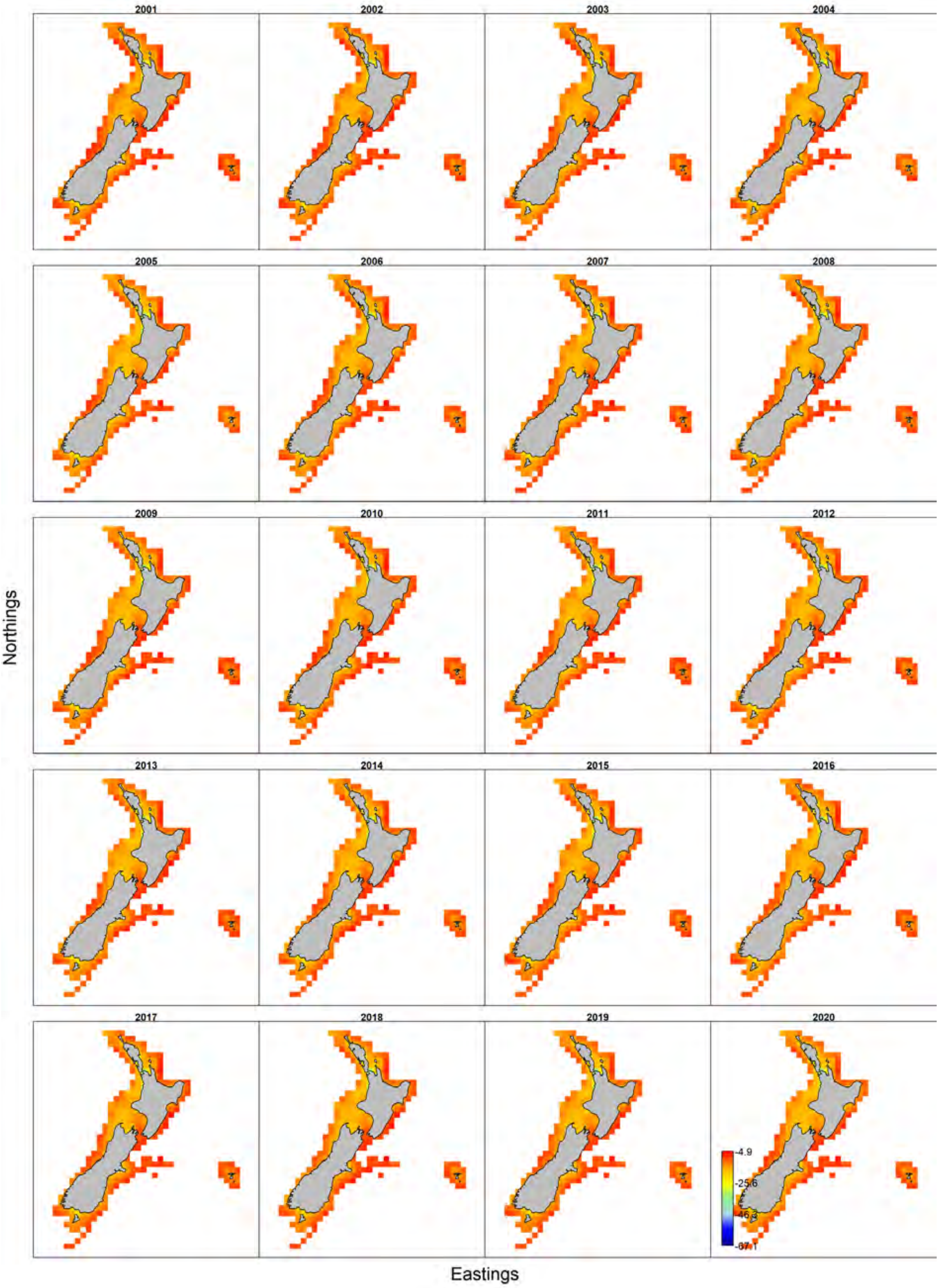

Figure D.27: Spatial-temporal distribution of biomass for hoki, expressed in lognormal scale.

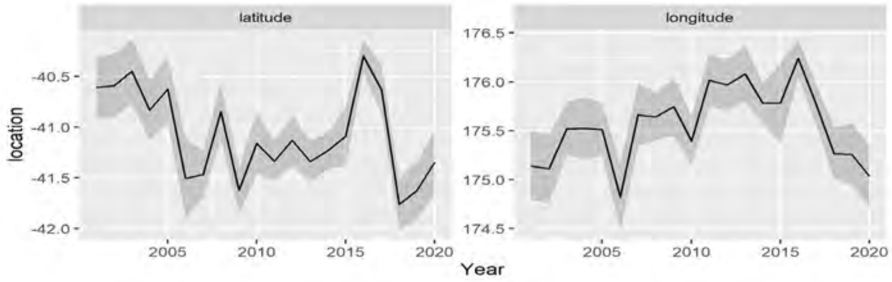

Figure D.28: Location of the centre of gravity over time for hoki and one standard error.

Jack mackerel

The three species of jack mackerel in New Zealand have different geographical distributions, but their ranges partially overlap. *Trachurus novaezelandiae* predominates in waters shallower than 150 m and warmer than 13 °C; it is uncommon south of latitude 42° S. *Trachurus declivis* generally occurs in deeper (but less than 300 m) waters cooler than 16 °C, north of latitude 45° S (Robertson 1978). *T. murphyi* occurs to depths of least 500 m and has a wide latitudinal range (0° at the Galapagos Islands and coastal Ecuador, to south of 40° S off the Chilean coast). Standardised CPUE indices of all three JMA species combined increased sharply from 2001 to 2020 (Fisheries New Zealand 2021).

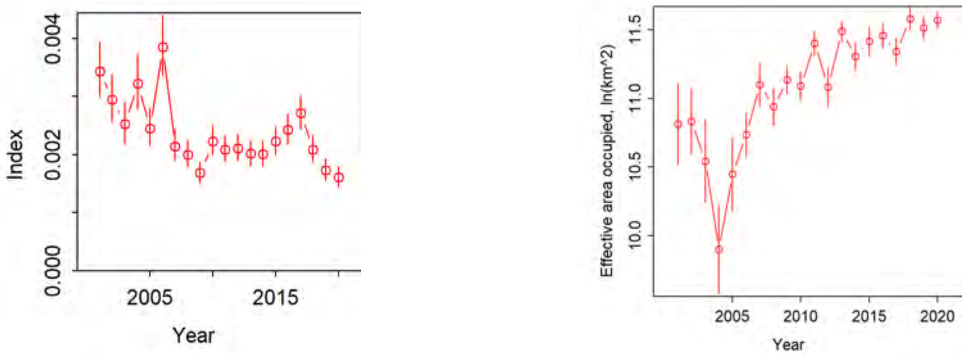

Figure D.29: Temporal index of jack mackerel biomass and Effective area occupied over time and one standard error.

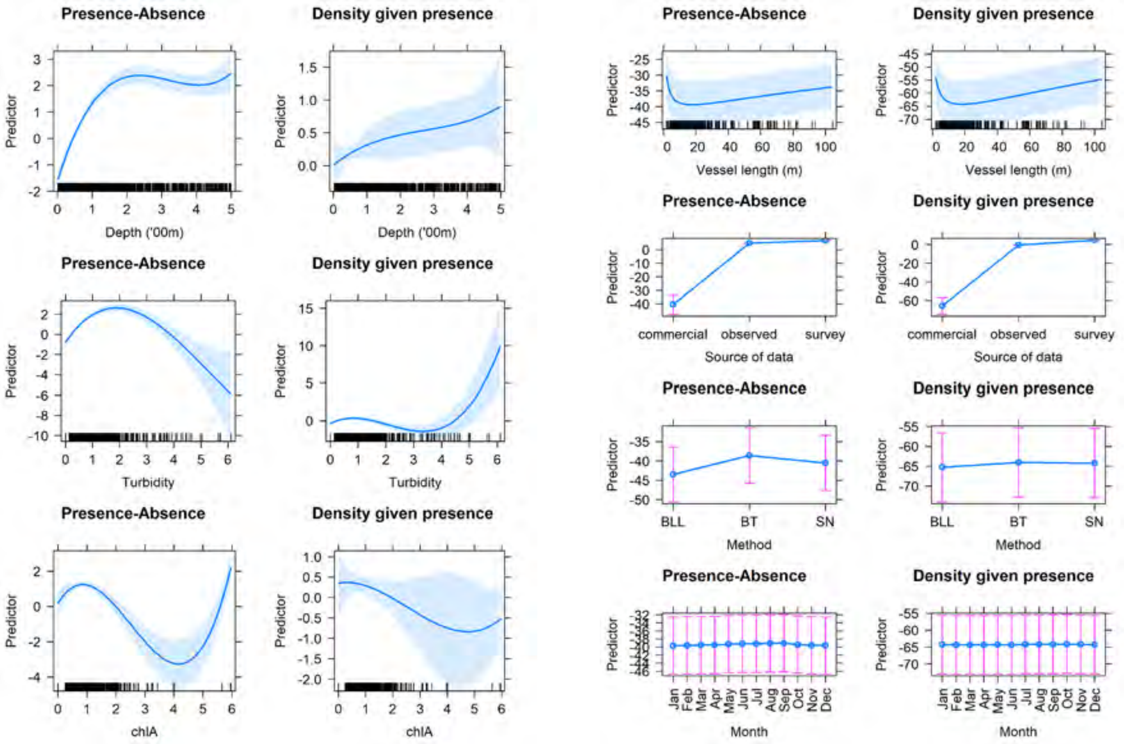

Figure D.30: Jack mackerel model partial effects plots and one standard error.

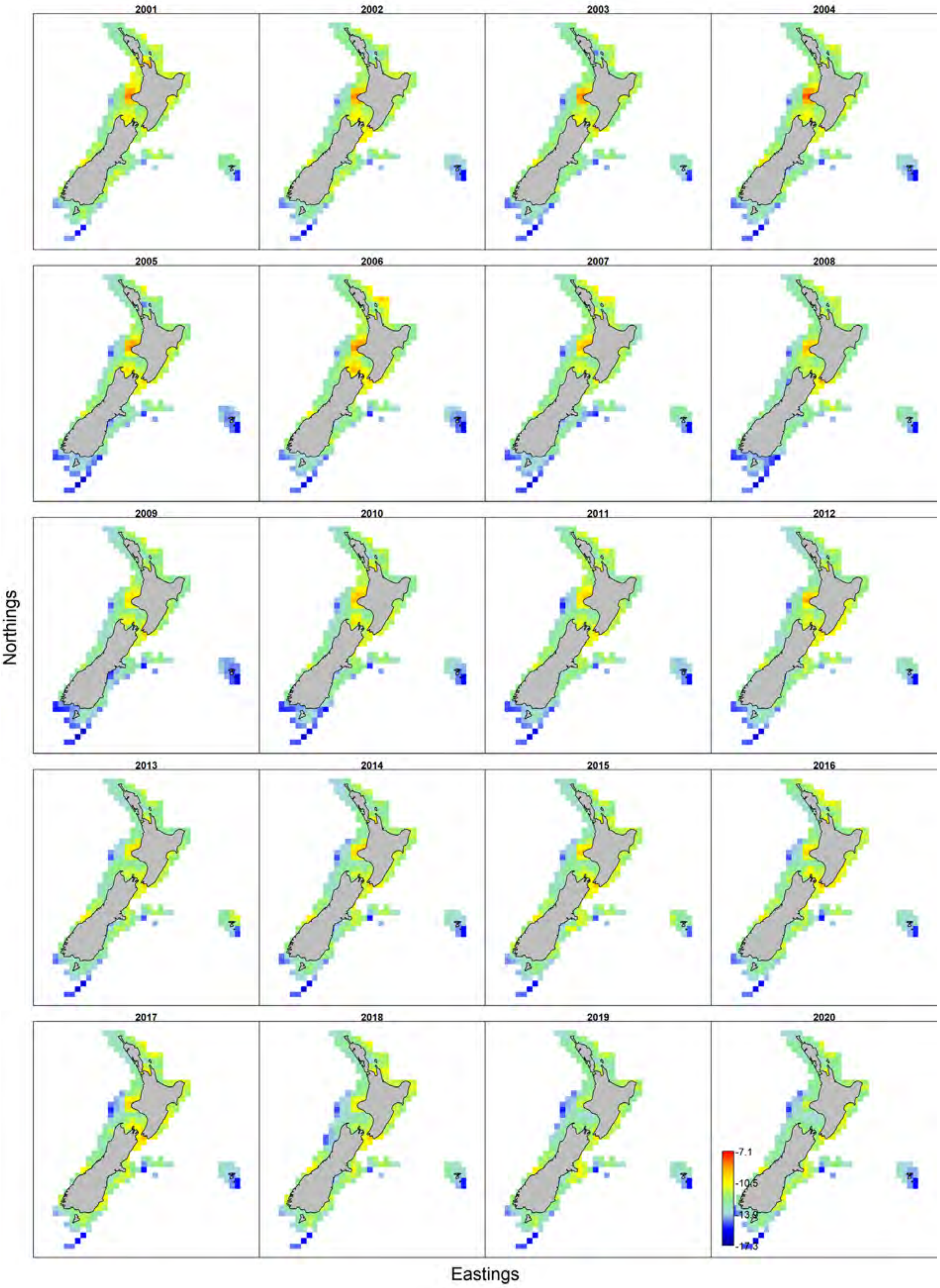

Figure D.31: Spatial-temporal distribution of biomass for jack mackerel, expressed in lognormal scale.

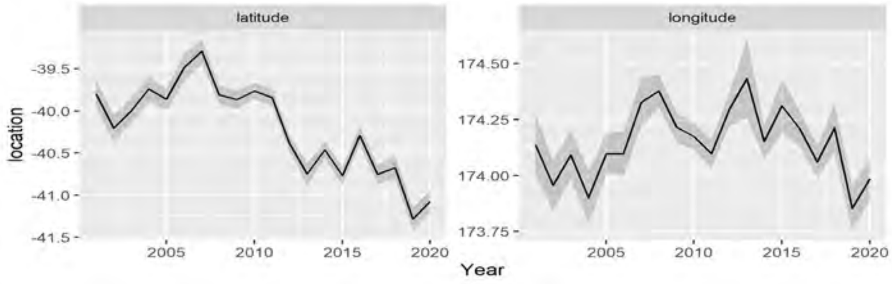

Figure D.32: Location of the centre of gravity over time for jack mackerel and one standard error.

Kahawai

Kahawai are found throughout the New Zealand waters. They occur mainly in coastal seas, harbours, and estuaries and will enter the brackish water sections of rivers. The stock assessment for KAH1 generally increased from 2000, other areas are not assessed (Fisheries New Zealand 2021).

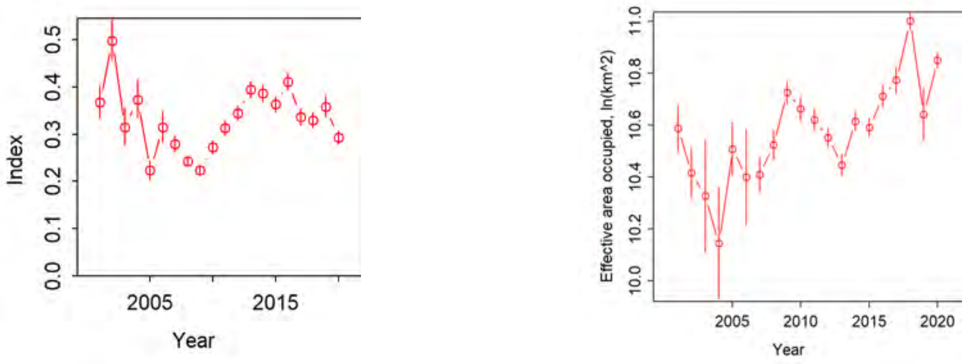

Figure D.33: Temporal index of kahawai biomass and Effective area occupied over time and one standard error.

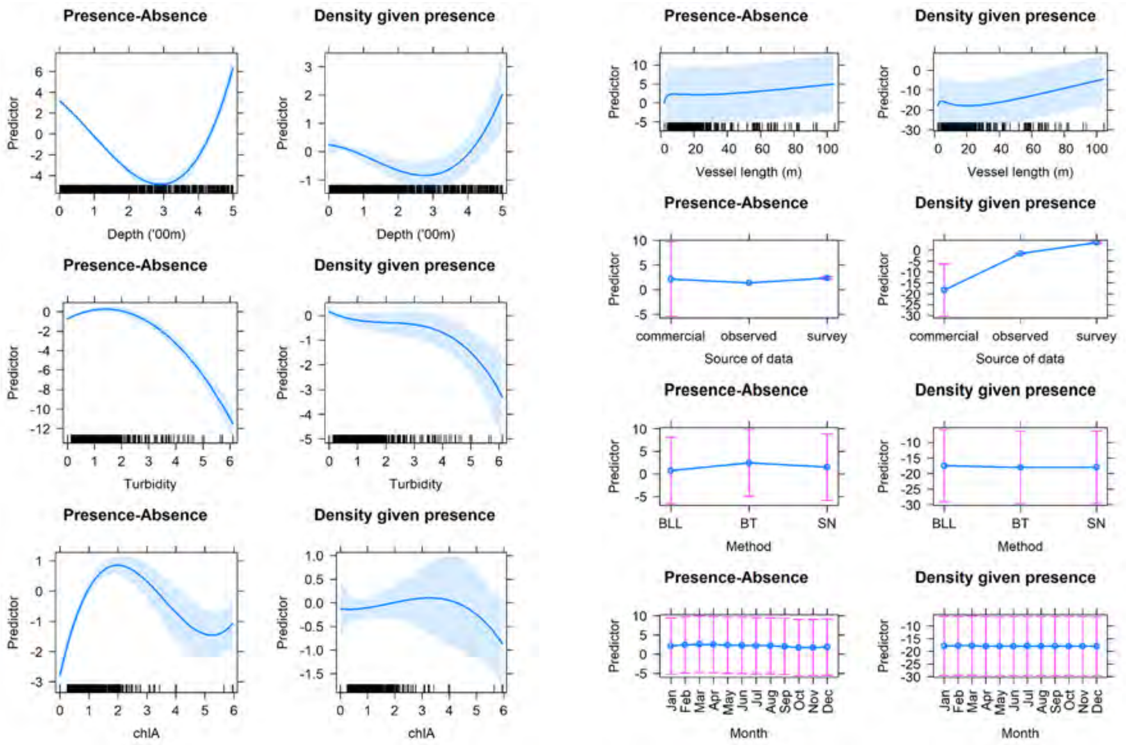

Figure D.34: Kahawai model partial effects plots and one standard error.

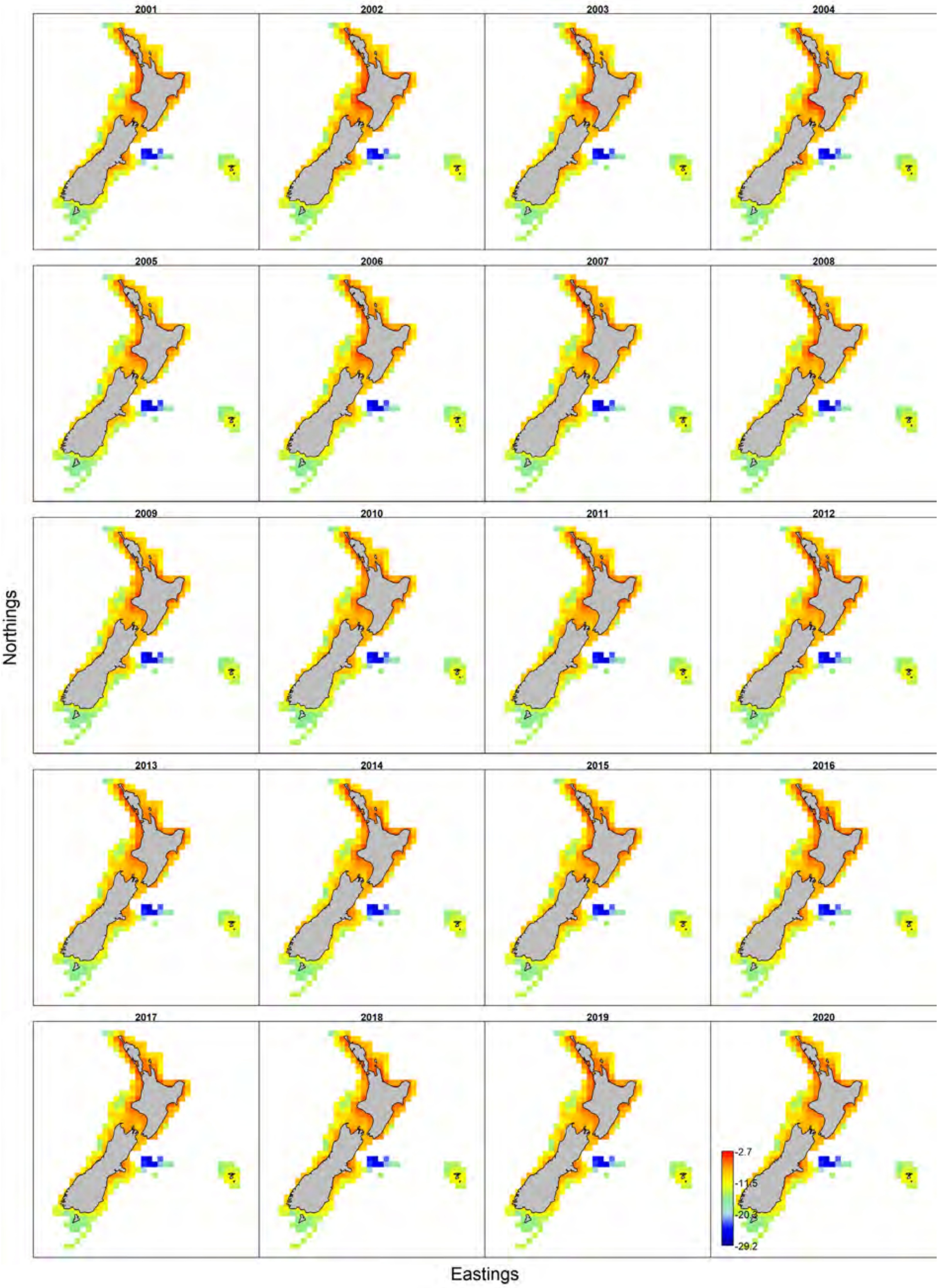

Figure D.35: Spatial-temporal distribution of biomass for kahawai, expressed in lognormal scale.

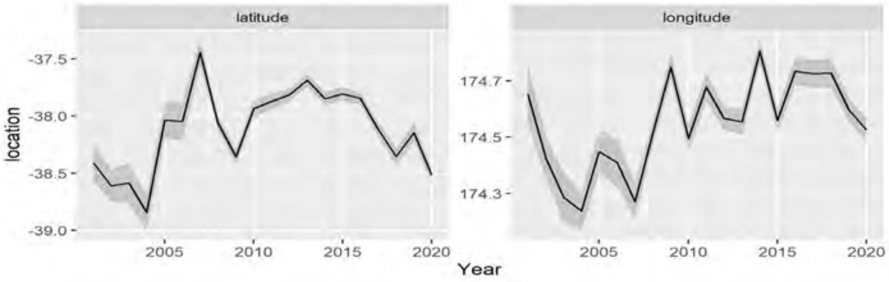

Figure D.36: Location of the centre of gravity over time for kahawai and one standard error.

Leatherjacket

The New Zealand leatherjacket (*Meuschenia scaber*) is present around much of New Zealand, but is most common in the north. Trawl survey records show it to be widespread over the inner shelf north of East Cape and Cape Egmont, in the South Taranaki Bight, in Tasman Bay and Golden Bay, Pegasus Bay, and the South Canterbury Bight, extending to depths below 100 m, but with greatest abundance at 10−60 m. Survey series present high uncertainty and were generally flat, whilst the CPUE for East Coast South Island increased from 2000 (Fisheries New Zealand 2021).

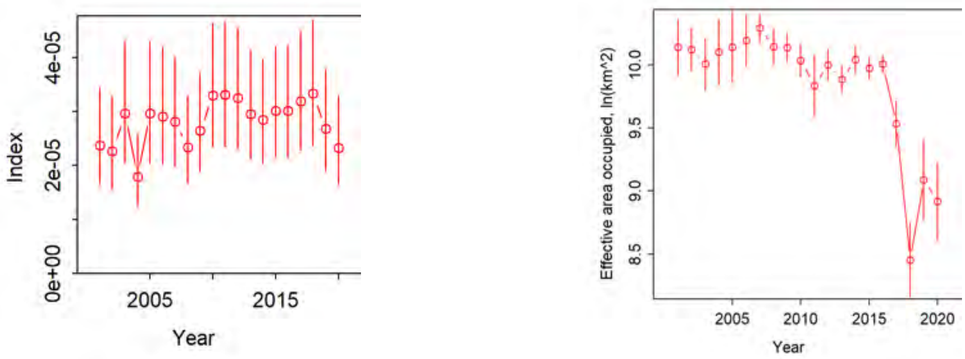

Figure D.37: Temporal index of leatherjacket biomass and Effective area occupied over time and one standard error.

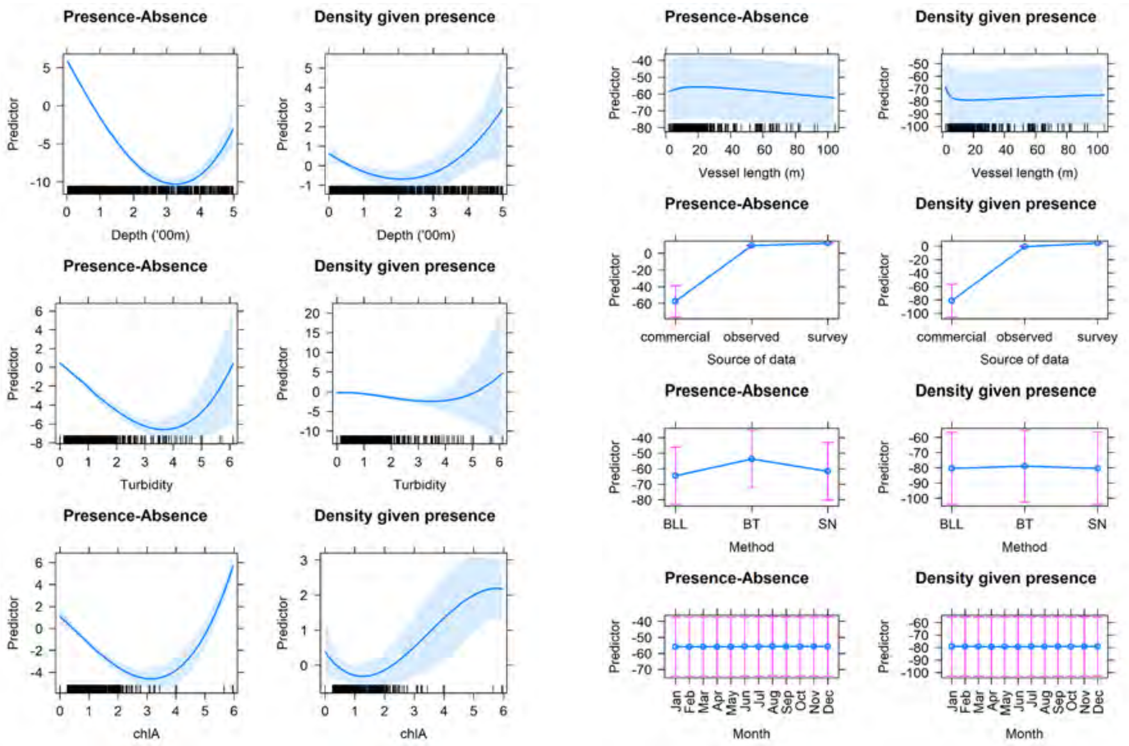

Figure D.38: Leatherjacket model partial effects plots and one standard error.

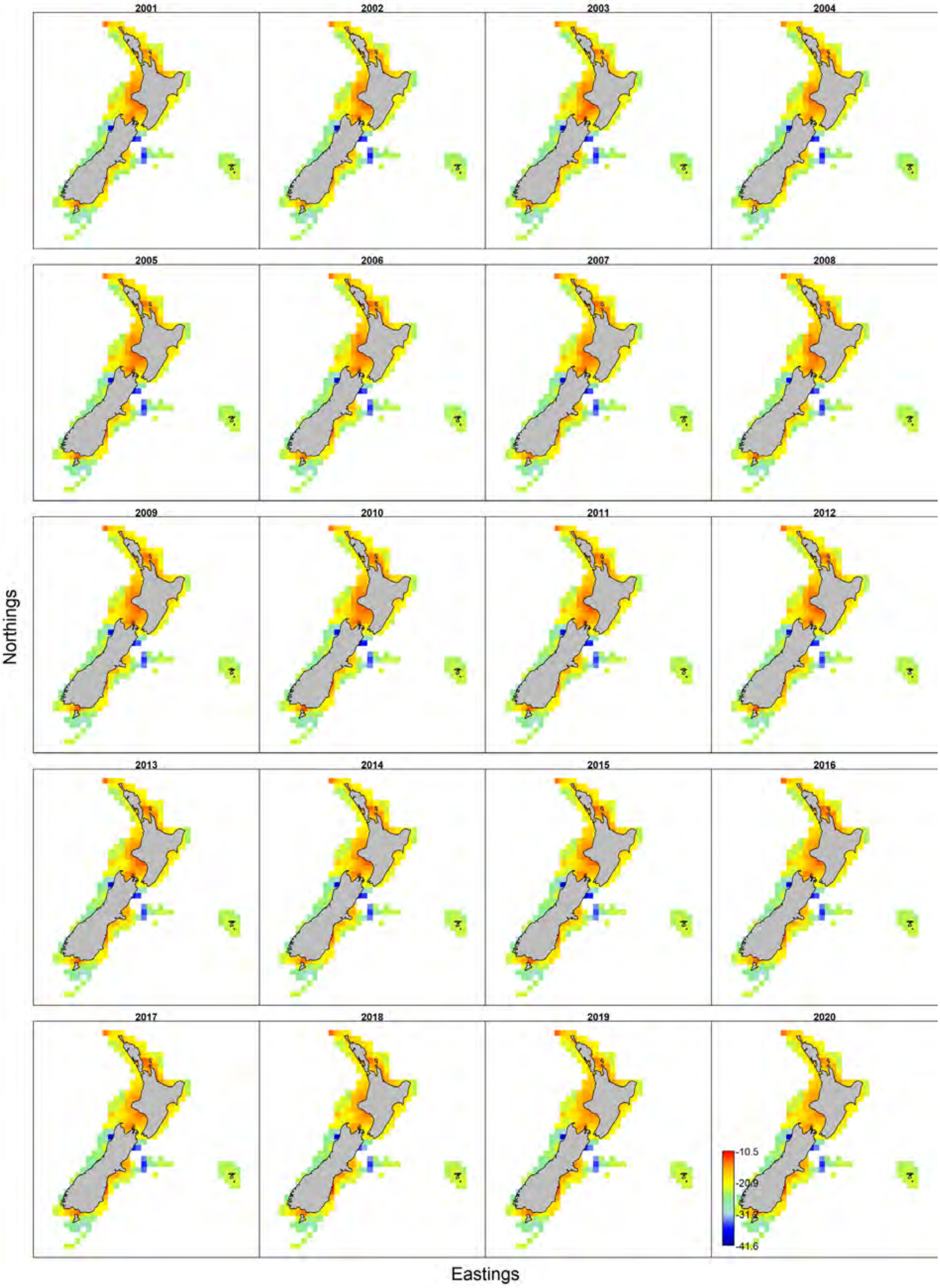

Figure D.39: Spatial-temporal distribution of biomass for leatherjacket, expressed in lognormal scale.

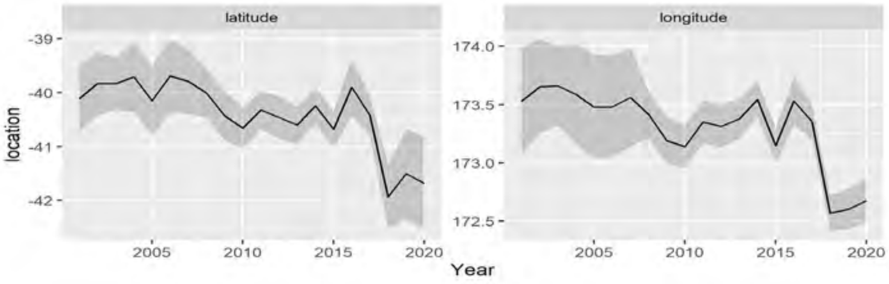

Figure D.40: Location of the centre of gravity over time for leatherjacket and one standard error.

Morid

Moray cods are marine fishes that are restricted to cold-temperate to Antarctic waters. Generally they occur on or near the seabed over a wide depth range from 18 m to below 2000 m (Roberts et al. 2015). Indices of abundance are not available.

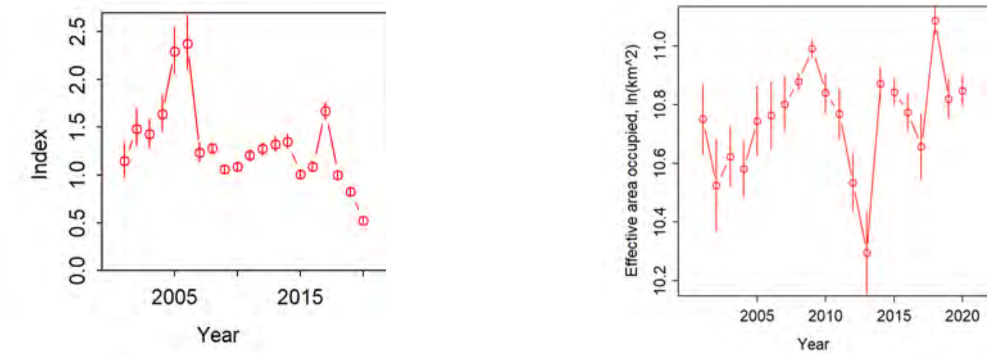

Figure D.41: Temporal index of morid cod biomass and Effective area occupied over time and one standard error.

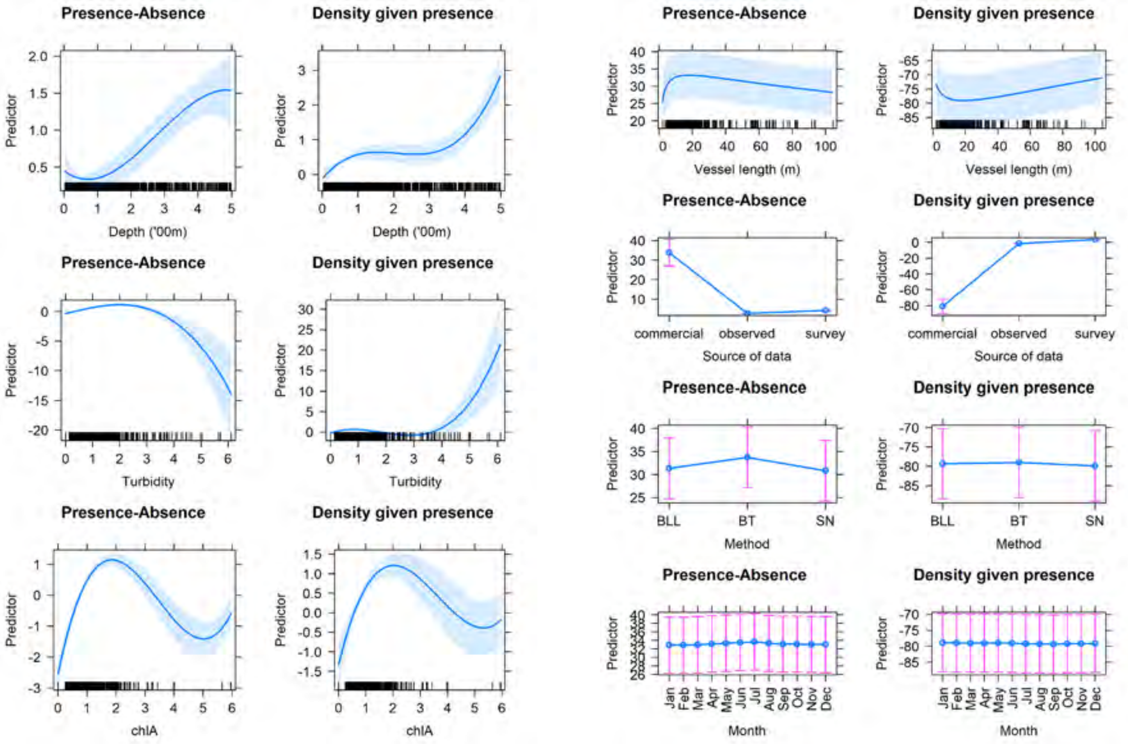

Figure D.42: Morid cod model partial effects plots and one standard error.

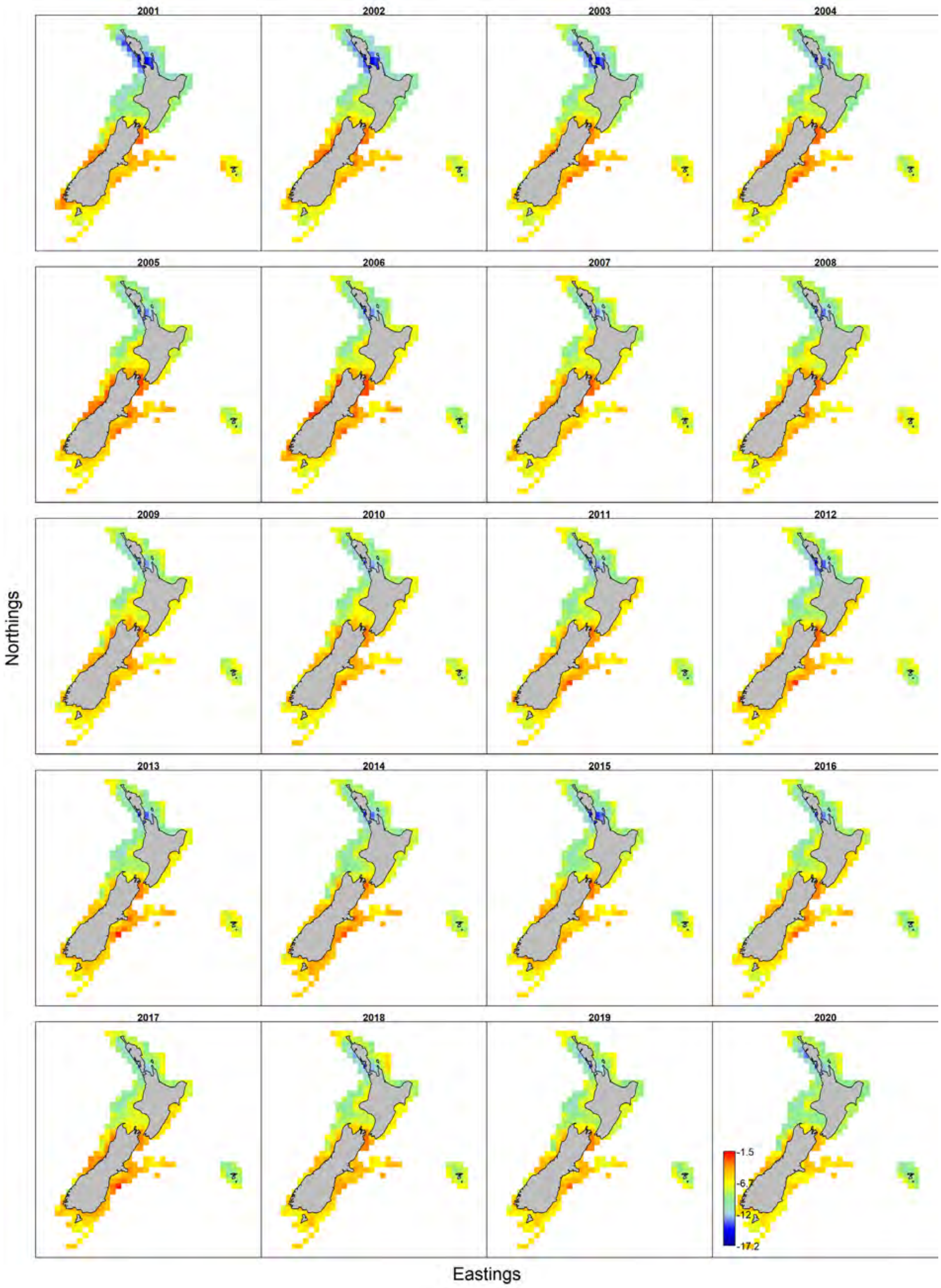

Figure D.43: Spatial-temporal distribution of biomass for morid cod, expressed in lognormal scale.

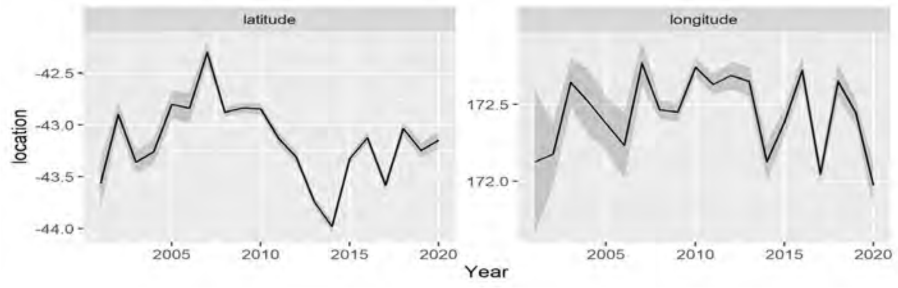

Figure D.44: Location of the centre of gravity over time for morid cod and one standard error.

Octopus

There are forty-one octopus species known in New Zealand but only three generic reporting classifications used to report catch: OCT (octopus, expected to be mostly *Pinnoctopus cordiformis*), DWO (deep water octopus spp.), and OPI (umbrella octopus species). The coastal octopus *Pinnoctopus cordiformis* (also known as *Octopus cordiformis* or *Octopus maorum*) is considered to be the most common near-shore species caught. It is found in shallow coastal areas, often around reefs or harbour entrances. Another species, albeit not as commonly caught, is *Octopus kaharoa*, which is found off the east coast between Kaikōura and North Cape in depths of between 70 and 550 m on sandy bottoms. Indices of abundance are not available (Ministry of Fisheries 2008).

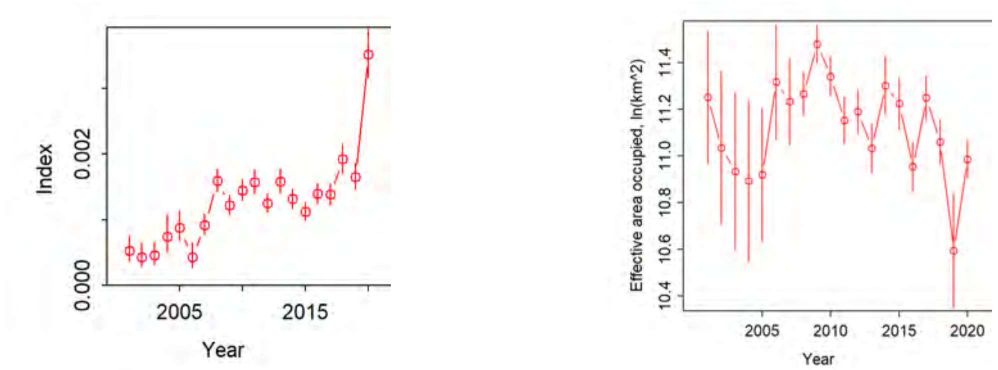

Figure D.45: Temporal index of octopus biomass and Effective area occupied over time and one standard error.

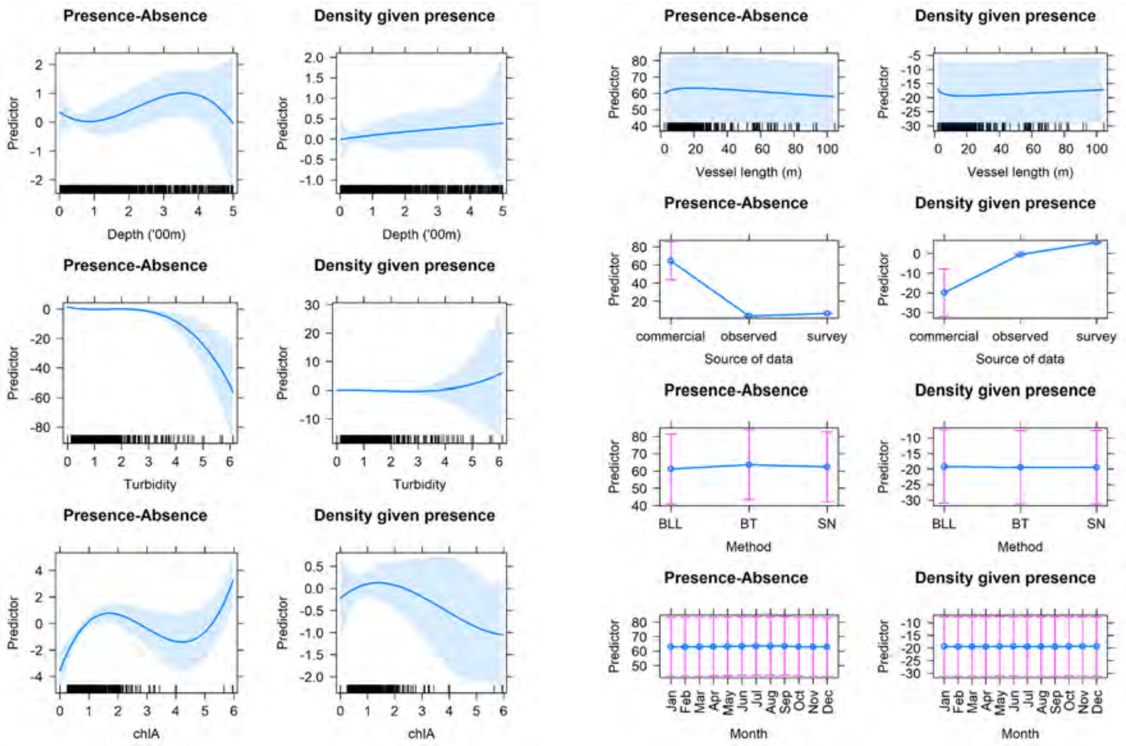

Figure D.46: Octopus model partial effects plots and one standard error.

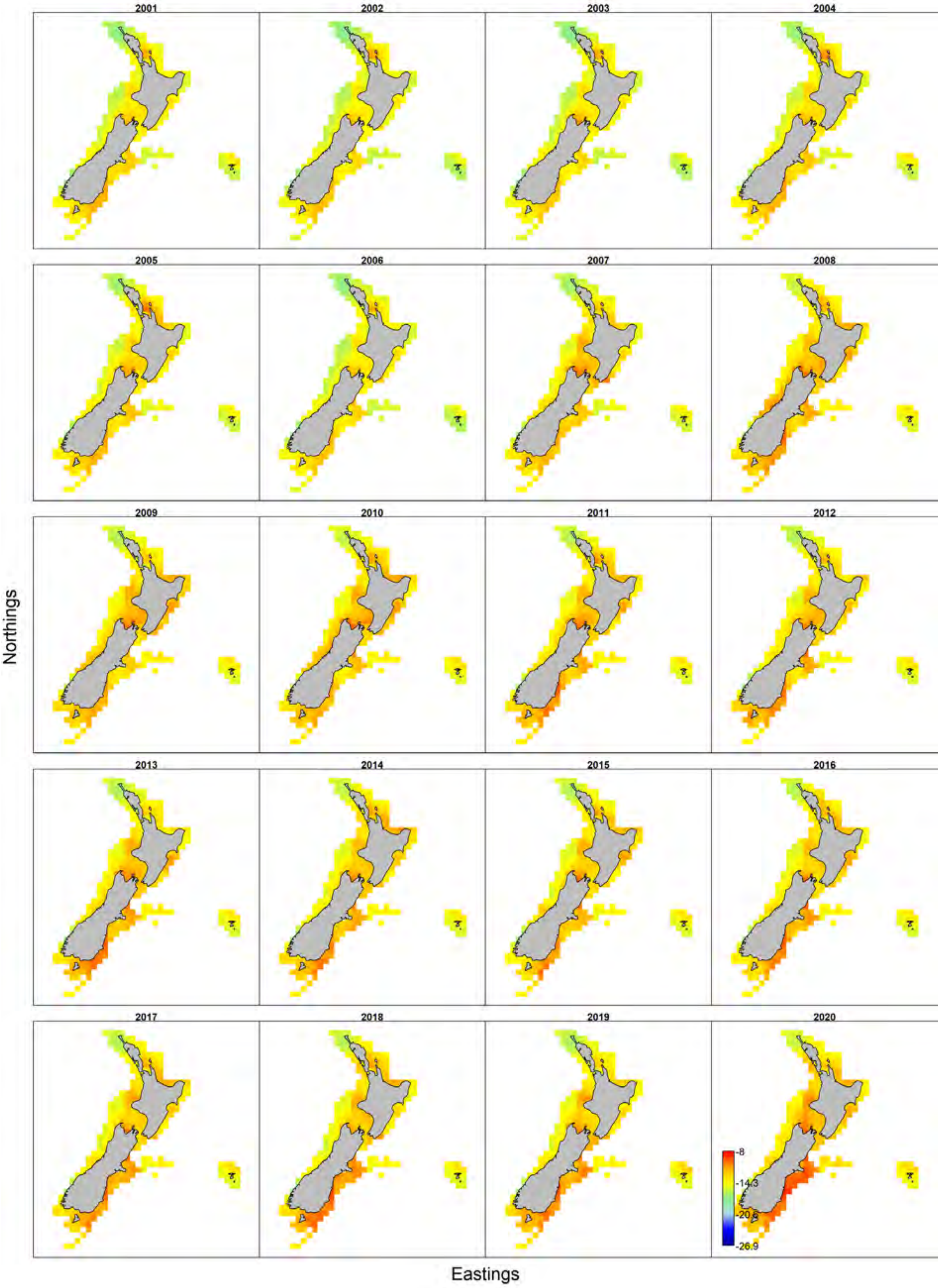

Figure D.47: Spatial-temporal distribution of biomass for octopus, expressed in lognormal scale.

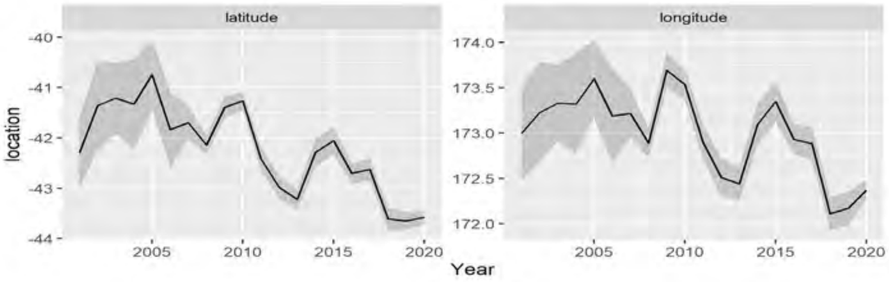

Figure D.48: Location of the centre of gravity over time for octopus and one standard error.

Rattail

Rattails are deepsea fishes with many species commonly taken as incidental catch of deepwater trawlers. In New Zealand waters there are currently 64 species in 19 genera (Roberts et al. 2015). Indices of abundance are not available.

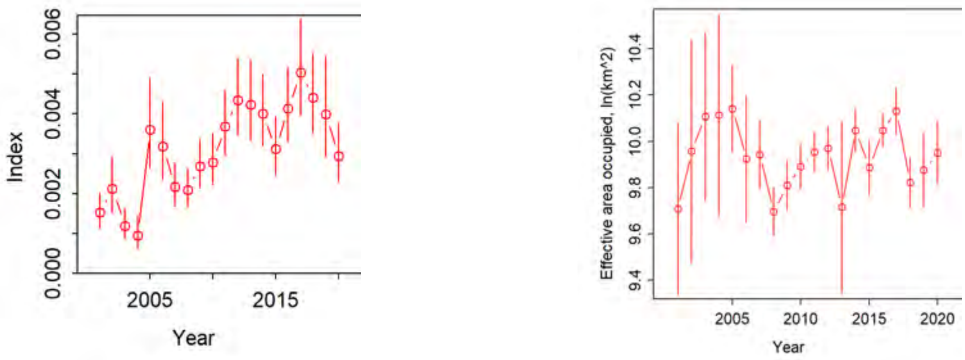

Figure D.49: Temporal index of rattail biomass and Effective area occupied over time and one standard error.

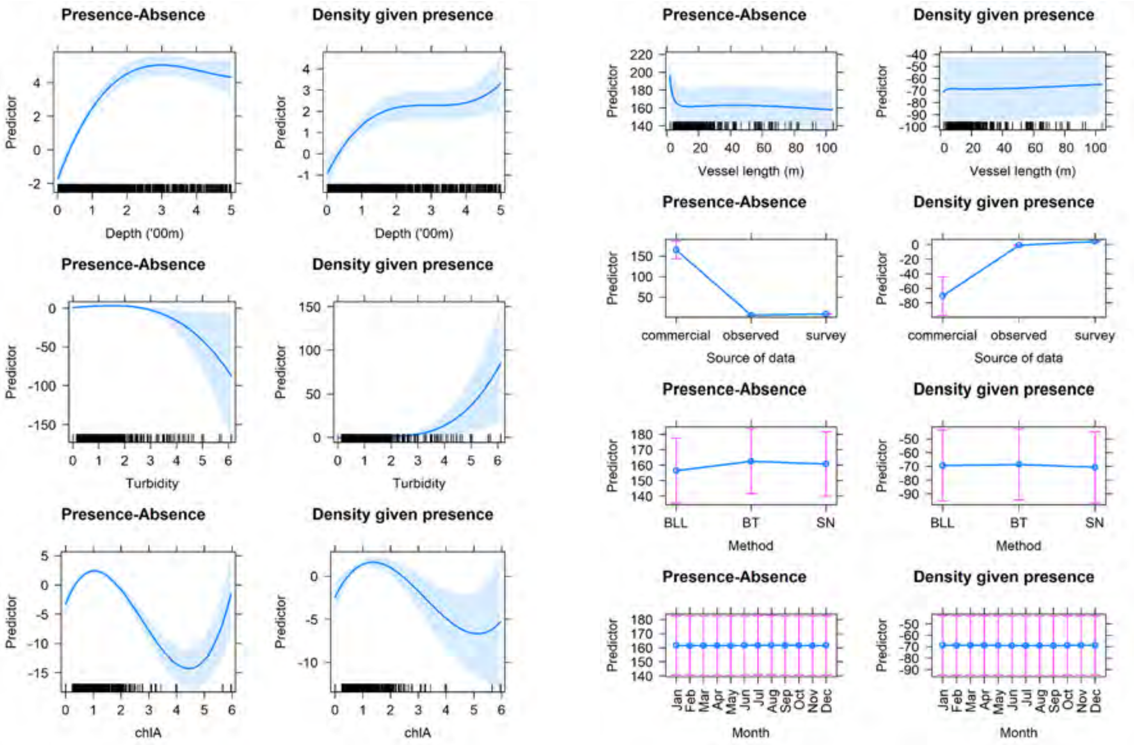

Figure D.50: Rattail model partial effects plots and one standard error.

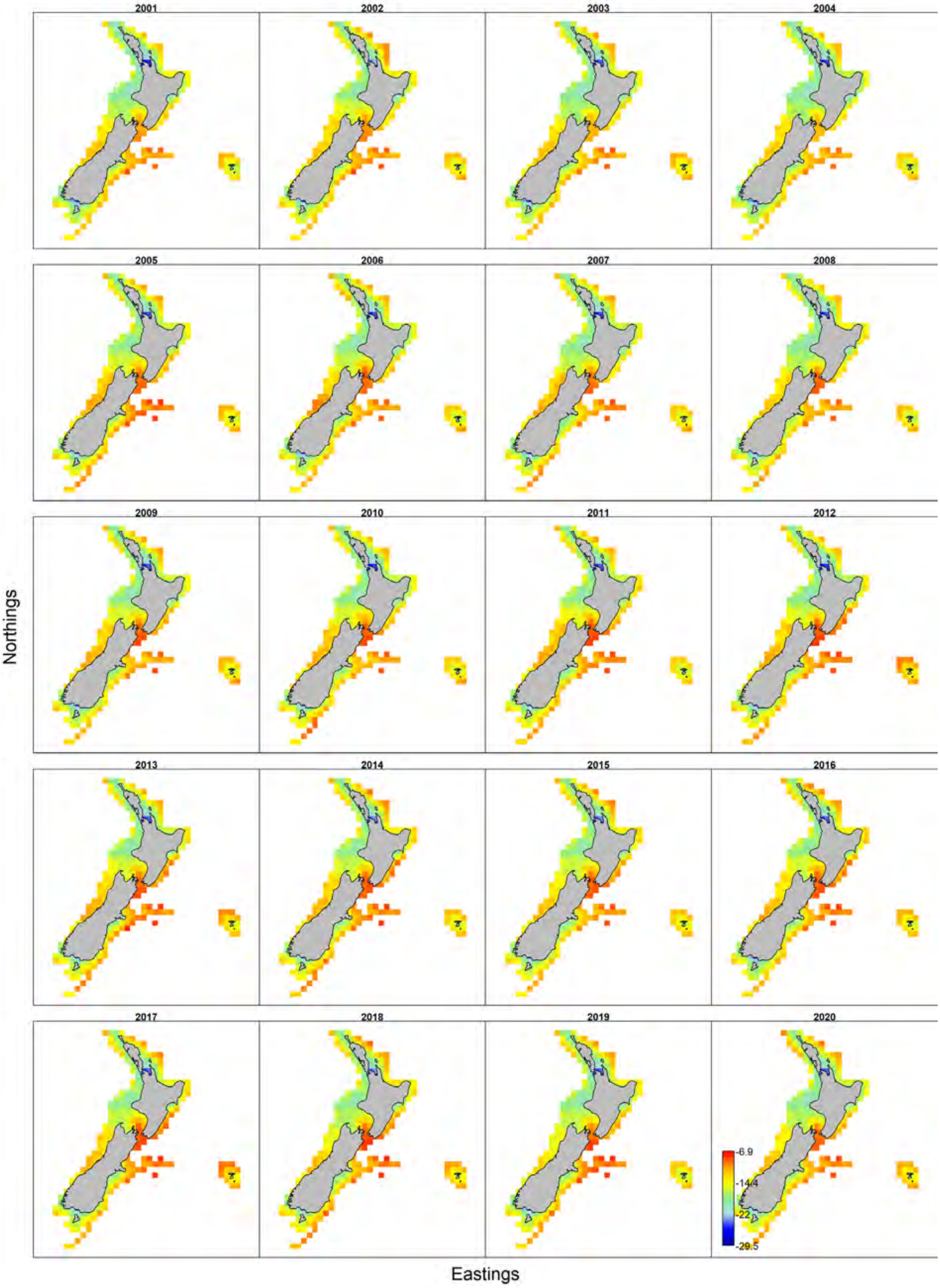

Figure D.51: Spatial-temporal distribution of biomass for rattail, expressed in lognormal scale.

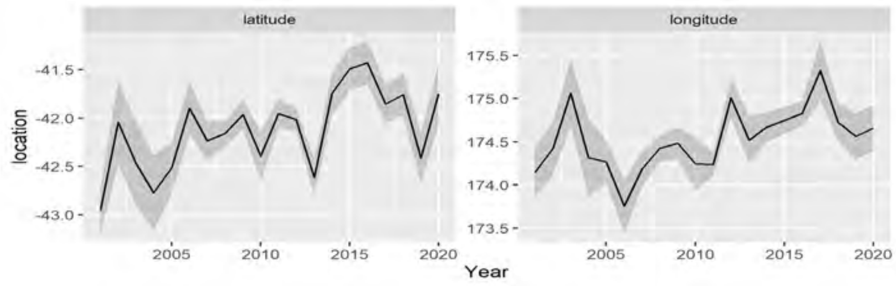

Figure D.52: Location of the centre of gravity over time for rattail and one standard error.

Rough skate

Rough skate are endemic to the New Zealand region. They are widespread in New Zealand waters, and mainly distributed in depths of 17 to 600 m but sometimes straggling to 1500 m (Roberts et al. 2015). Survey indices of rough skate have been highly variable with wide confidence intervals (Fisheries New Zealand 2021).

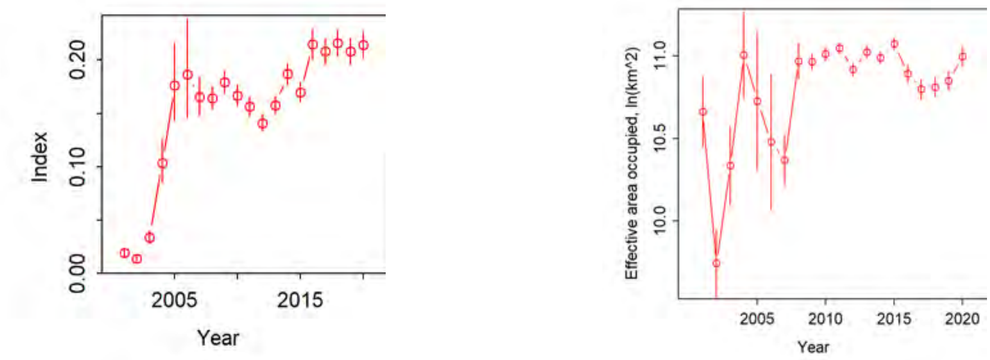

Figure D.53: Temporal index of rough skate biomass and Effective area occupied over time and one standard error.

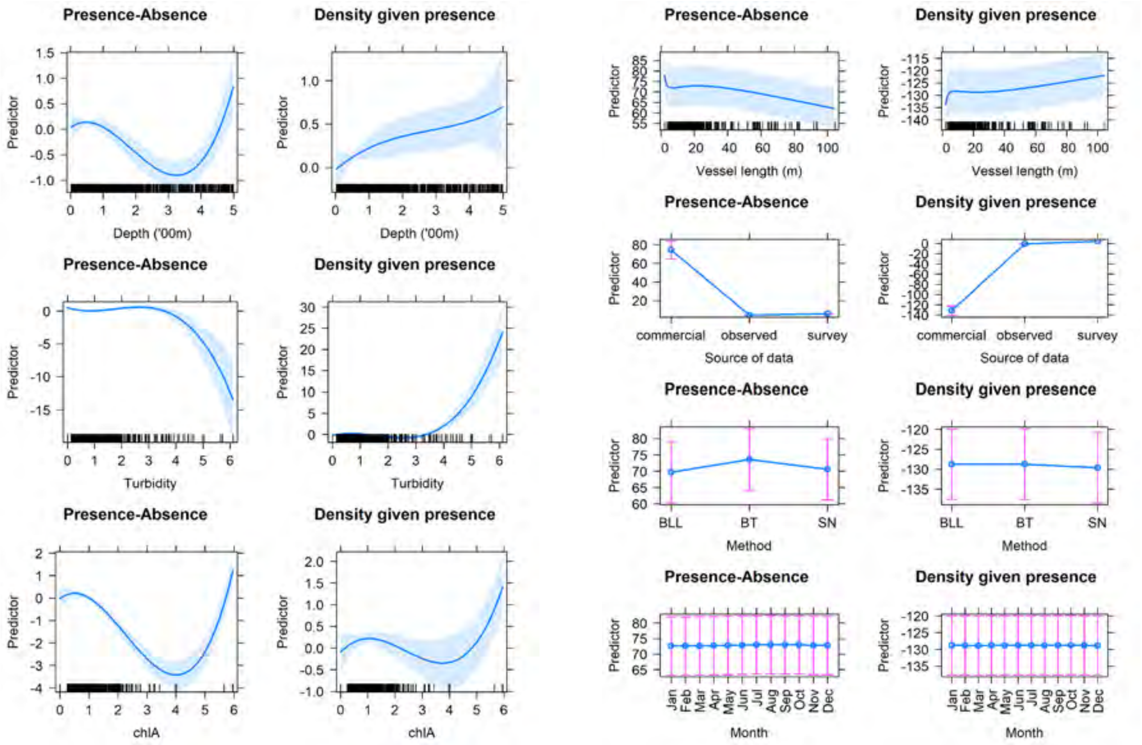

Figure D.54: Rough skate model partial effects plots and one standard error.

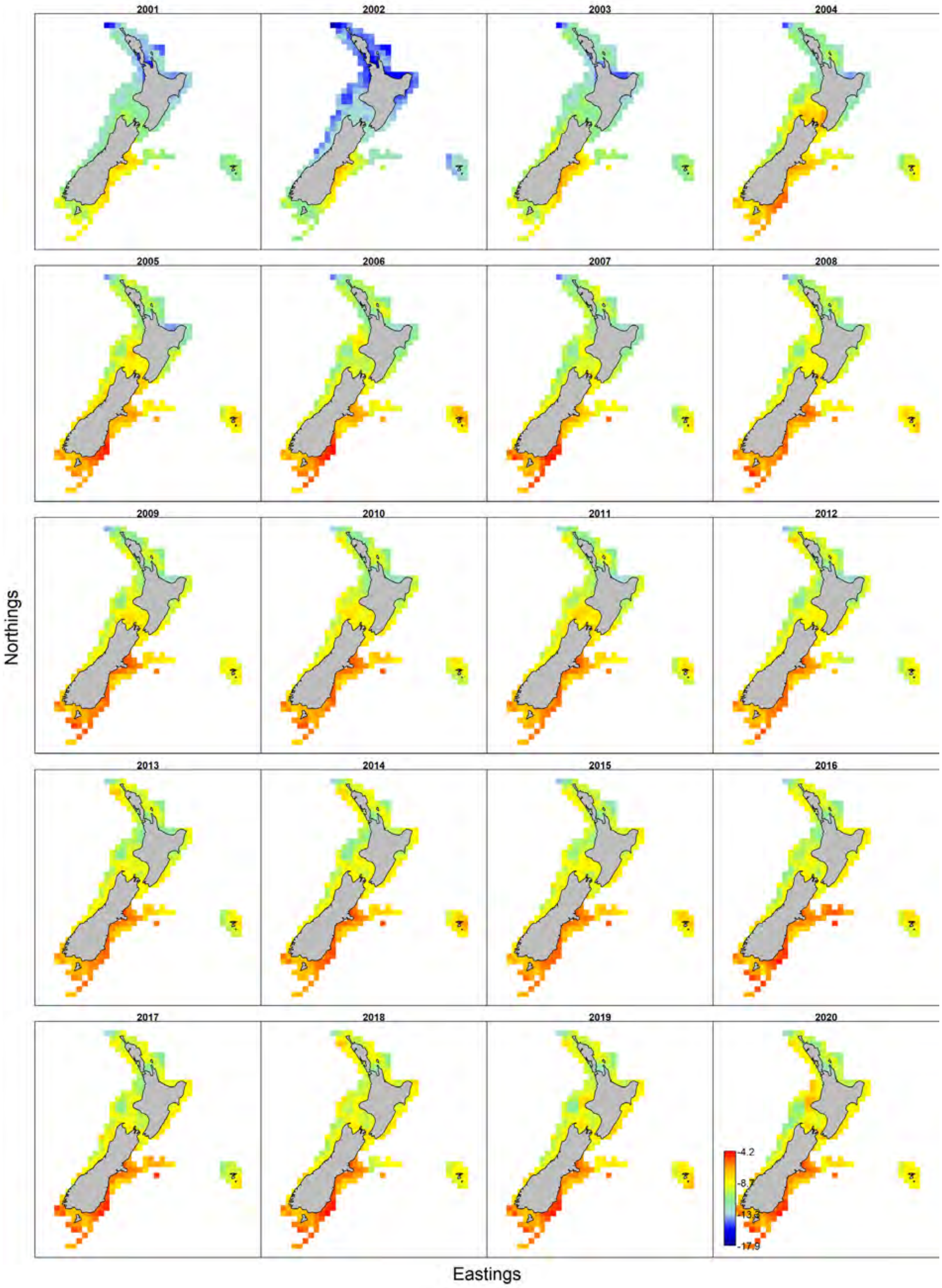

Figure D.55: Spatial-temporal distribution of biomass for rough skate, expressed in lognormal scale.

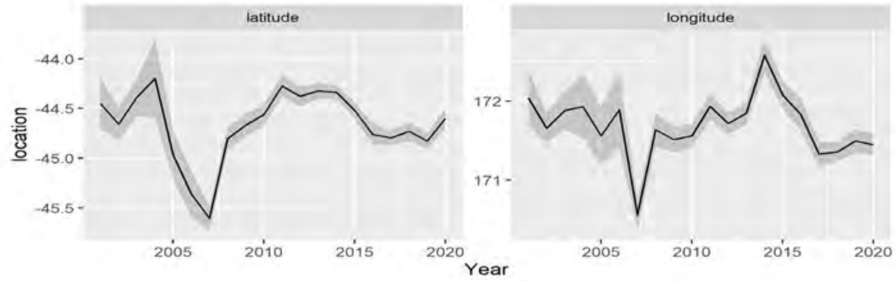

Figure D.56: Location of the centre of gravity over time for rough skate and one standard error.

Snapper

Snapper are demersal fish found down to depths of about 200 m, but are most abundant in 15–60 m. They are the dominant fish in northern inshore communities and occupy a wide range of habitats, including rocky reefs and areas of sand and mud bottom. They are widely distributed in the warmer waters of New Zealand, being most abundant in the Hauraki Gulf. Most stocks present a flat or an increase in spawning stock biomass between 2000 to 2020 (Fisheries New Zealand 2021).

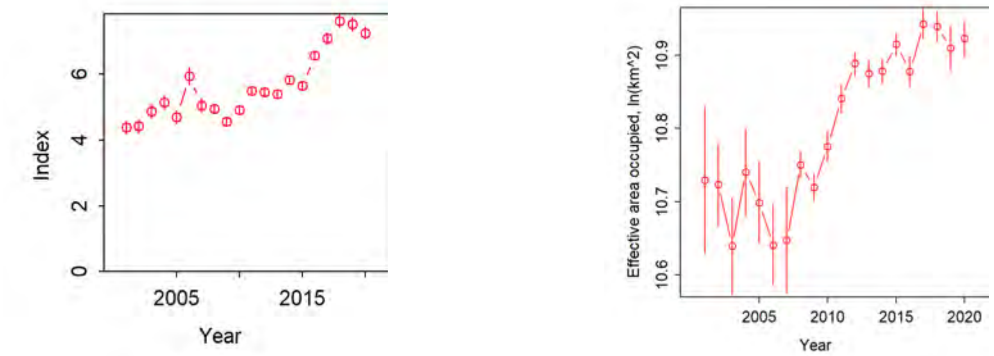

Figure D.57: Temporal index of snapper biomass and Effective area occupied over time and one standard error.

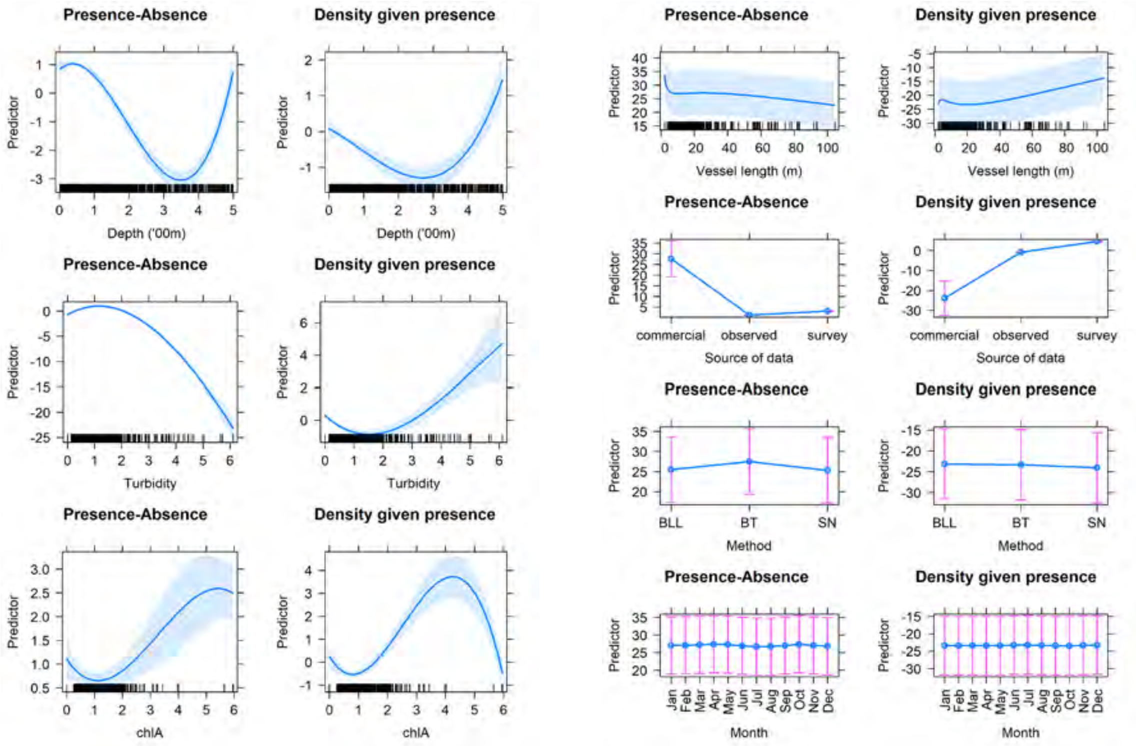

Figure D.58: Snapper model partial effects plots and one standard error.

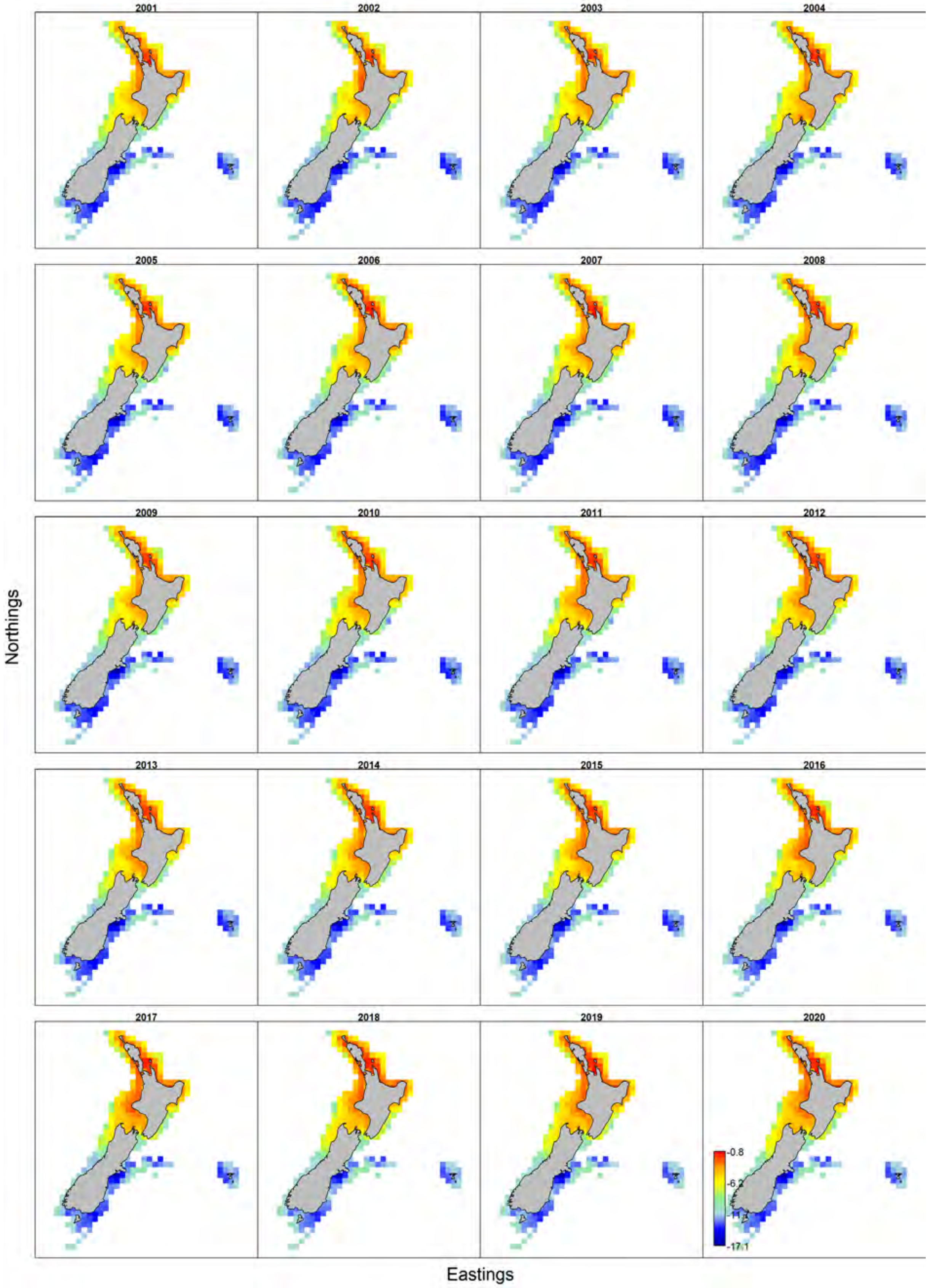

Figure D.59: Spatial-temporal distribution of biomass for snapper, expressed in lognormal scale.

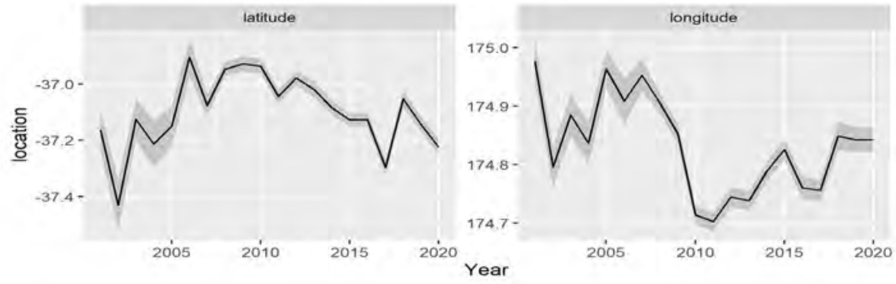

Figure D.60: Location of the centre of gravity over time for snapper and one standard error.

Sole

Flatfish are shallow-water species, generally found in waters less than 50 m depth. Flatfish move offshore for first spawning at 2–3 years of age during winter and spring. CPUE trends are variable by area, generally flat or dropping between 2000 and 2020 (Fisheries New Zealand 2021).

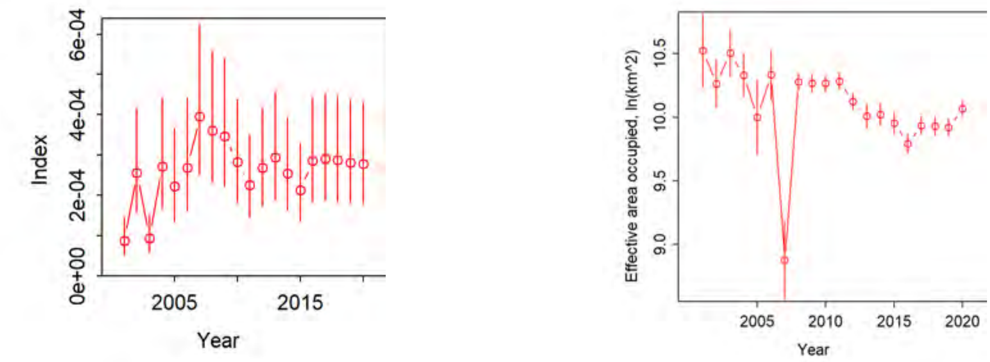

Figure D.61: Temporal index of sole biomass and Effective area occupied over time and one standard error.

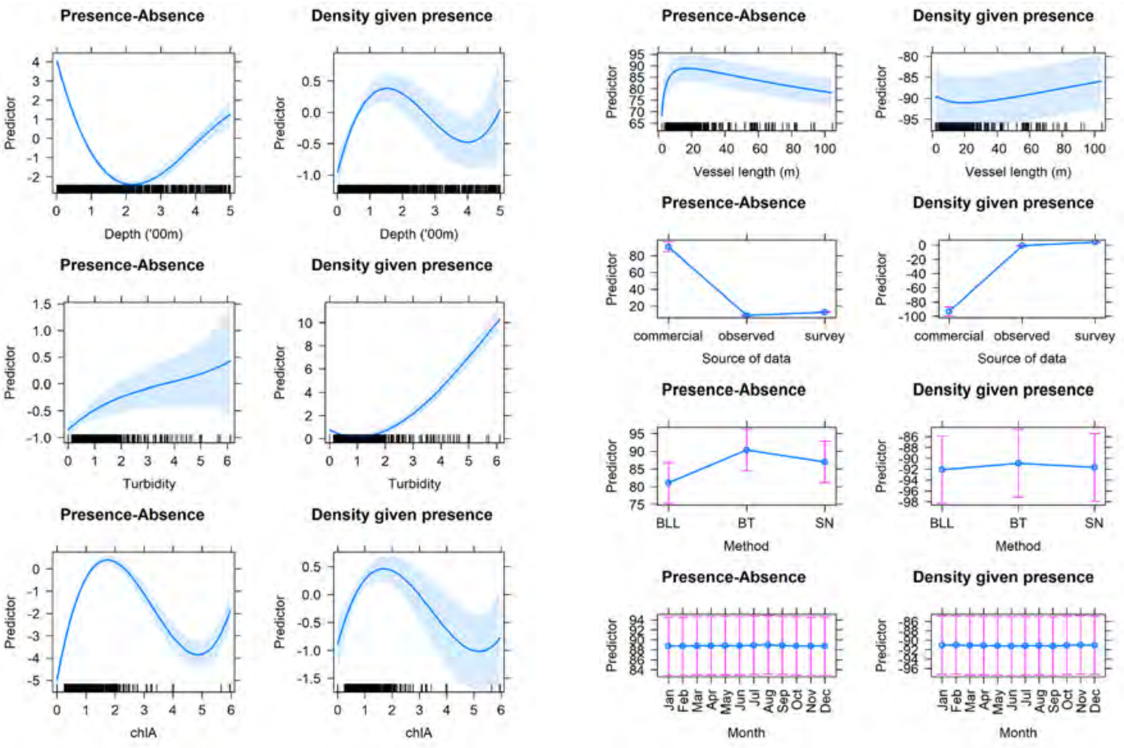

Figure D.62: Sole model partial effects plots and one standard error.

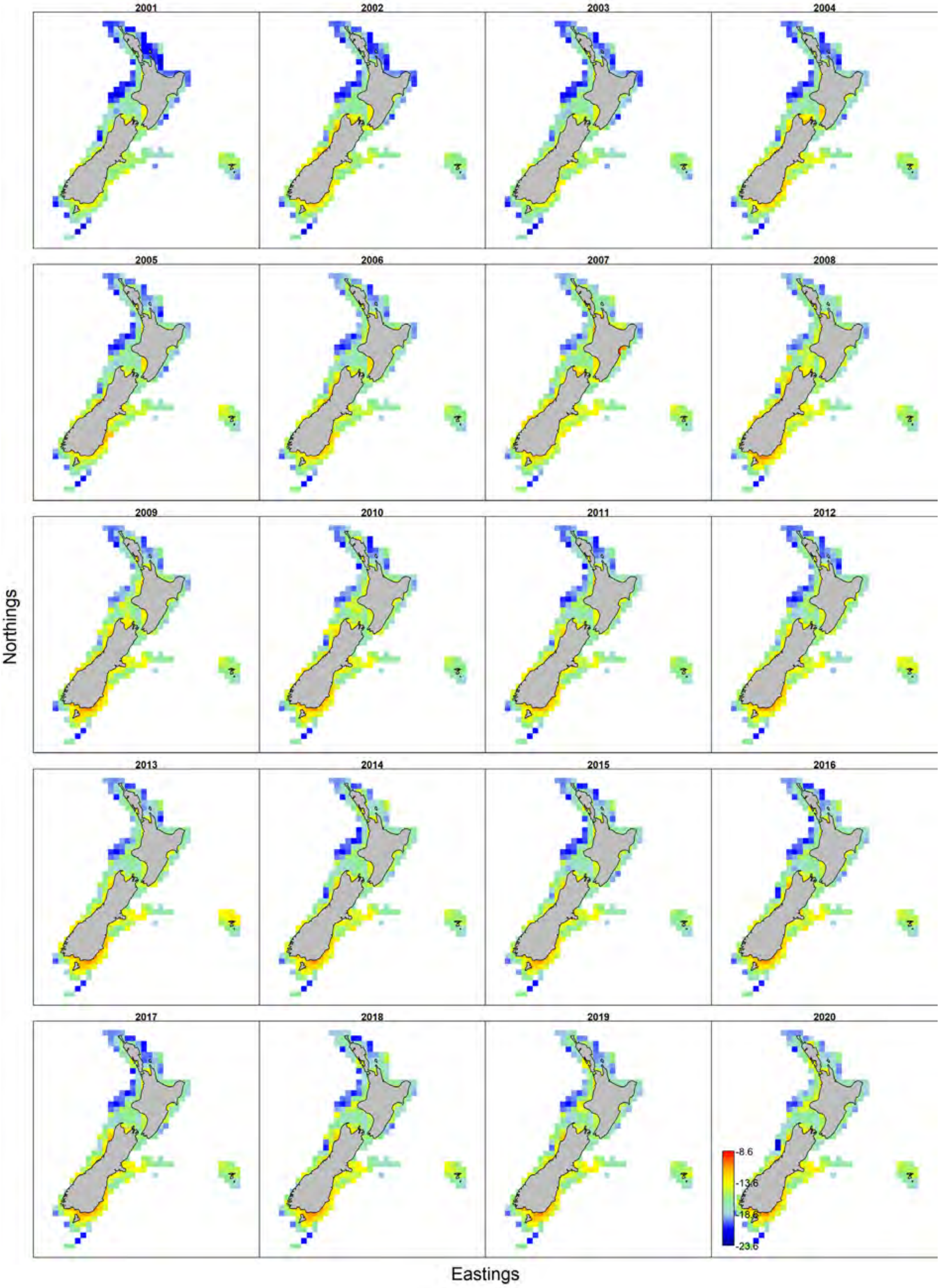

Figure D.63: Spatial-temporal distribution of biomass for sole, expressed in lognormal scale.

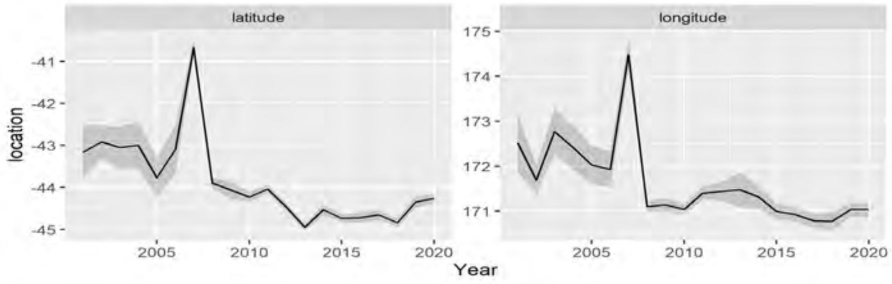

Figure D.64: Location of the centre of gravity over time for sole and one standard error.

Squid

Two species of arrow squid are caught in the New Zealand fishery. Both species are found over the continental shelf in waters to 500 m depth, though they are most prevalent in waters less than 300 m depth. No estimates of abundance are available: squid live for about one year, spawn and then die (Fisheries New Zealand 2021). Indices of abundance are not available.

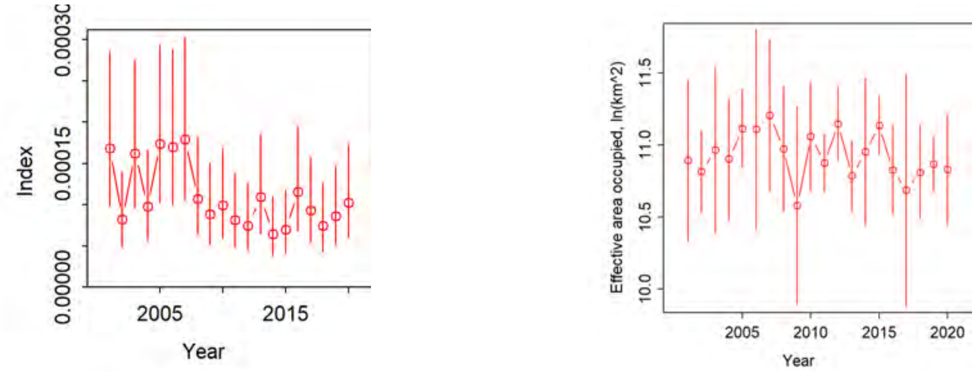

Figure D.65: Temporal index of squid biomass and Effective area occupied over time and one standard error.

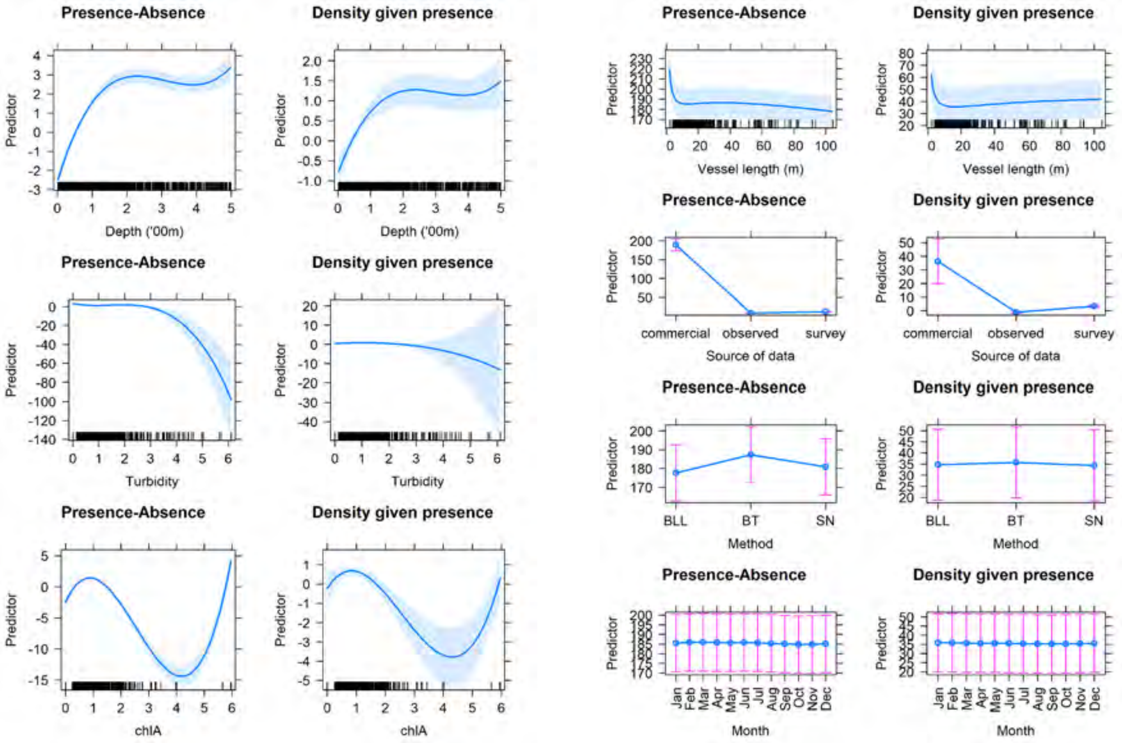

Figure D.66: Squid model partial effects plots and one standard error.

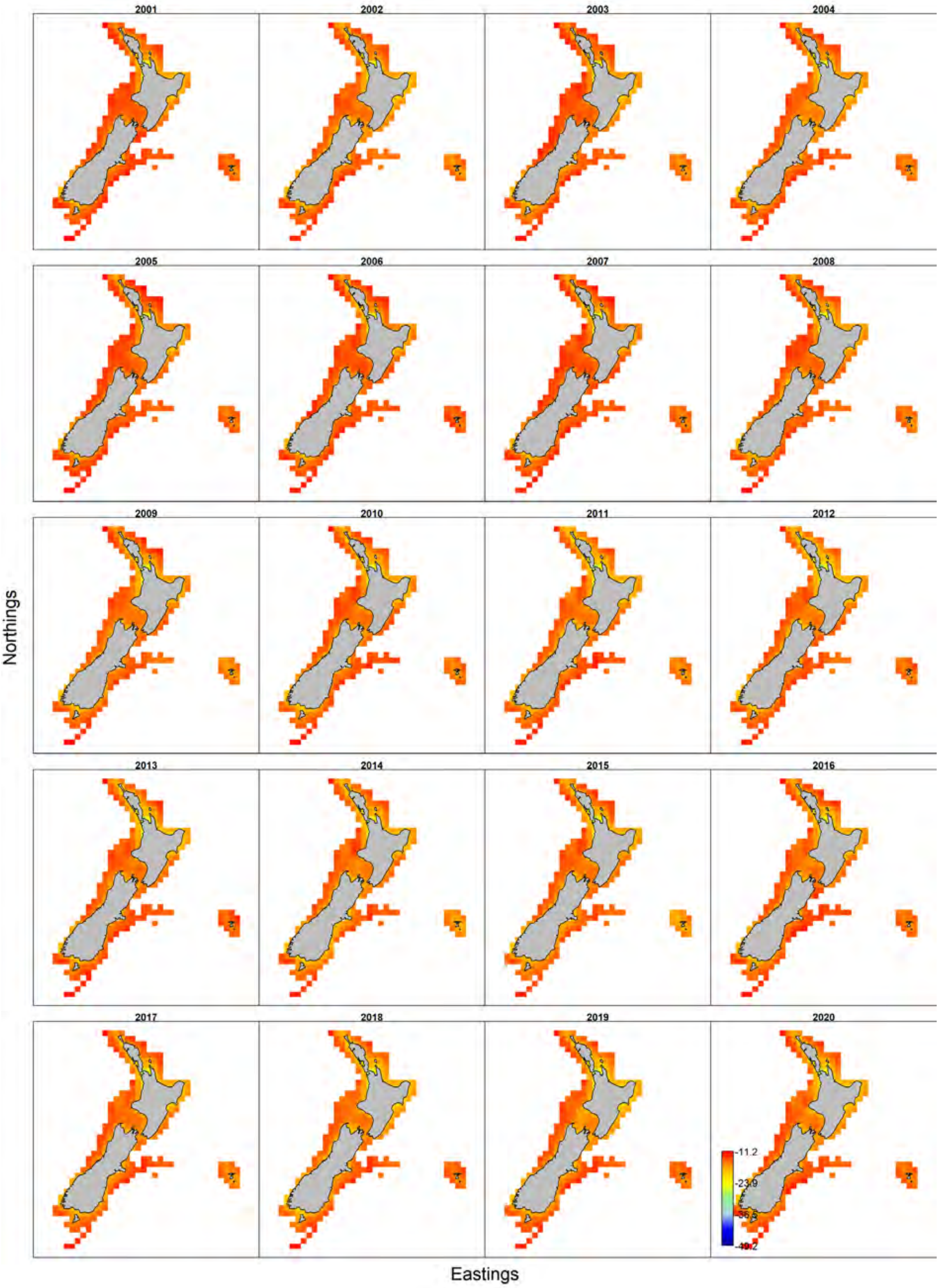

Figure D.67: Spatial-temporal distribution of biomass for squid, expressed in lognormal scale.

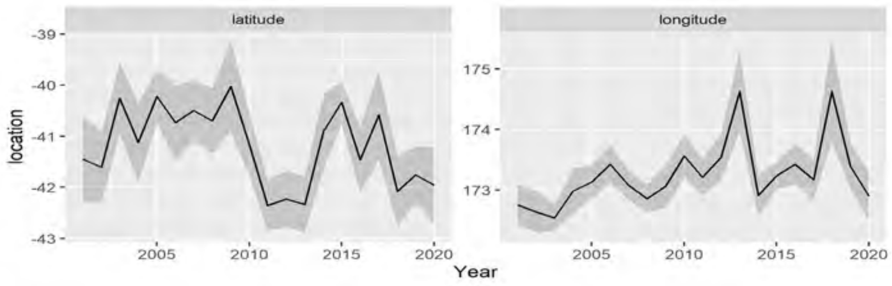

Figure D.68: Location of the centre of gravity over time for squid and one standard error.

Silverside

Silverside are endemic to New Zealand. They occur from North Cape to the Campbell Plateau, east to the Chatham Islands in 30 to 622 m depth, usually below 100 m (Roberts et al. 2015). Indices of abundance are not available.

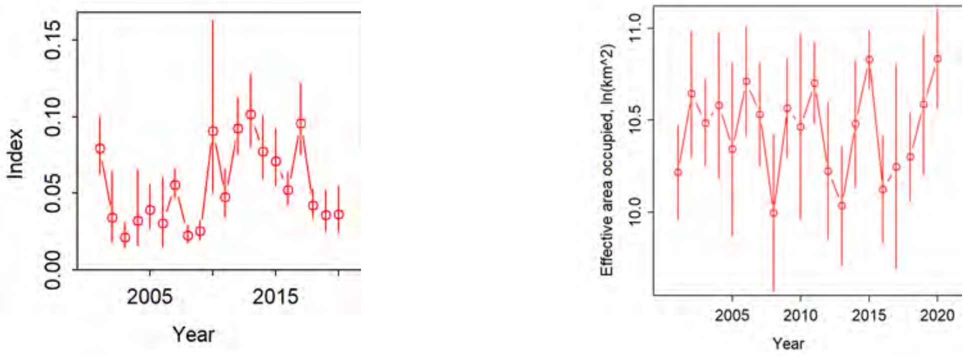

Figure D.69: Temporal index of silverside biomass and Effective area occupied over time and one standard error.

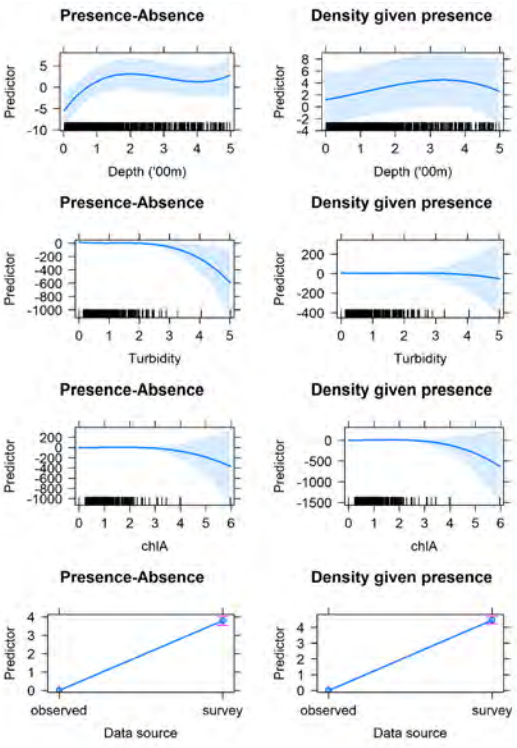

Figure D.70: Silverside model partial effects plots and one standard error.

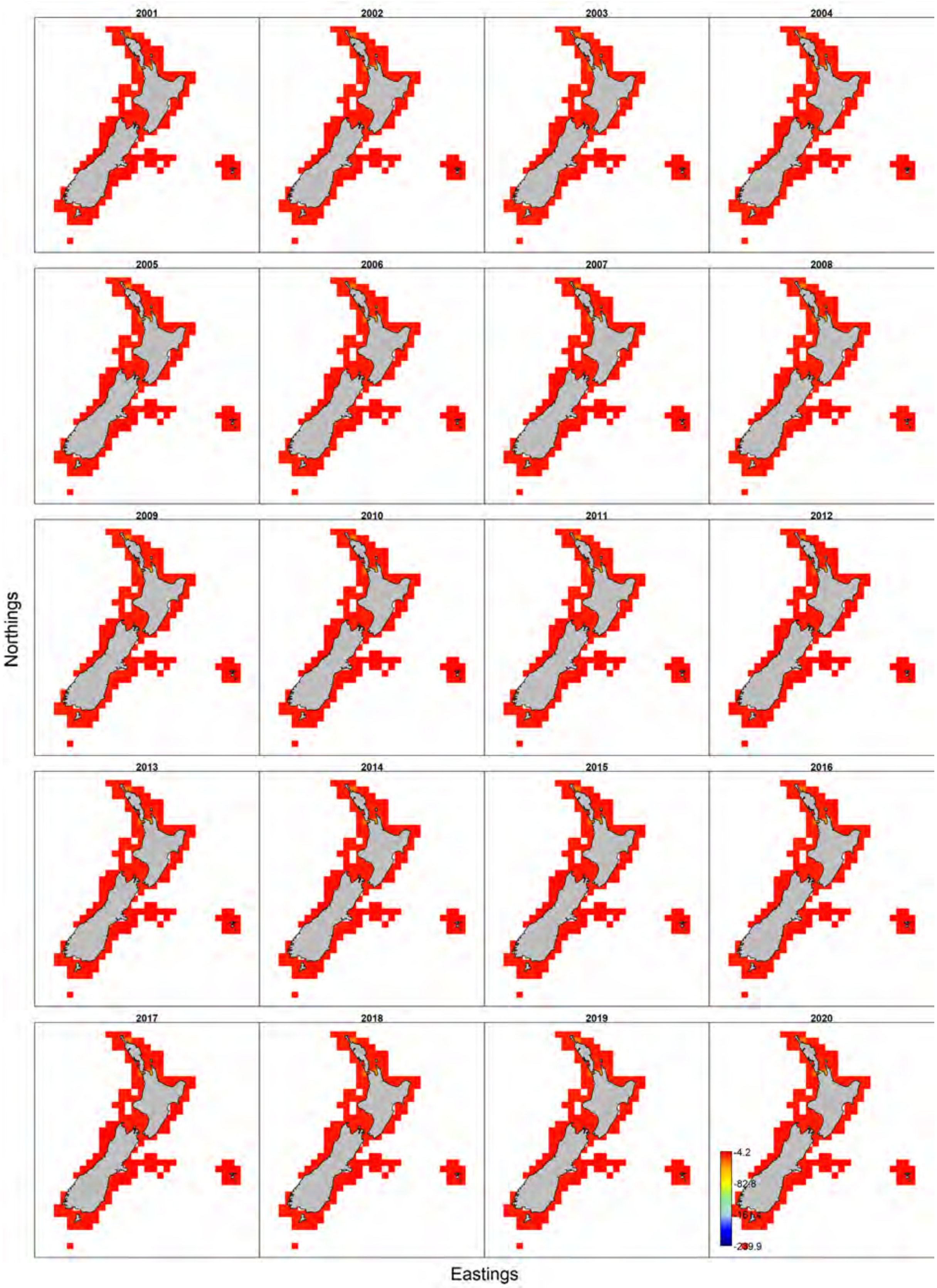

Figure D.71: Spatial-temporal distribution of biomass for silverside, expressed in lognormal scale.

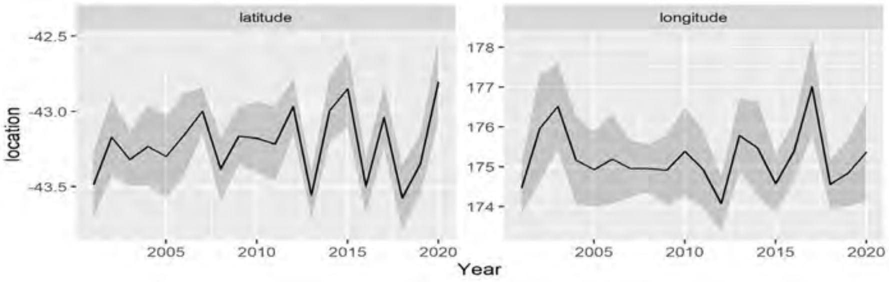

Figure D.72: Location of the centre of gravity over time for silverside and one standard error.

Stargazer

Giant stargazer is found throughout the New Zealand EEZ. It is most plentiful around the South Island (STA 3, 5, & 7) and on the Mernoo Bank on the Chatham Rise (STA 4). Survey and CPUE indices are mostly stable and highly variable, with a slight increase in some instances to 2020 (Fisheries New Zealand 2021).

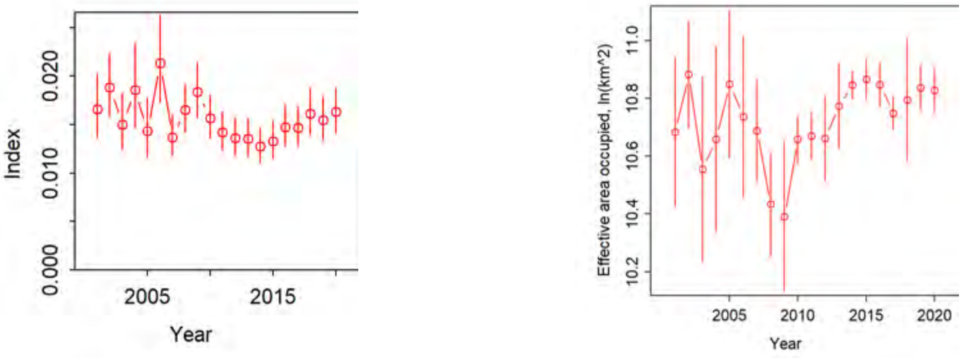

Figure D.73: Temporal index of stargazer biomass and Effective area occupied over time and one standard error.

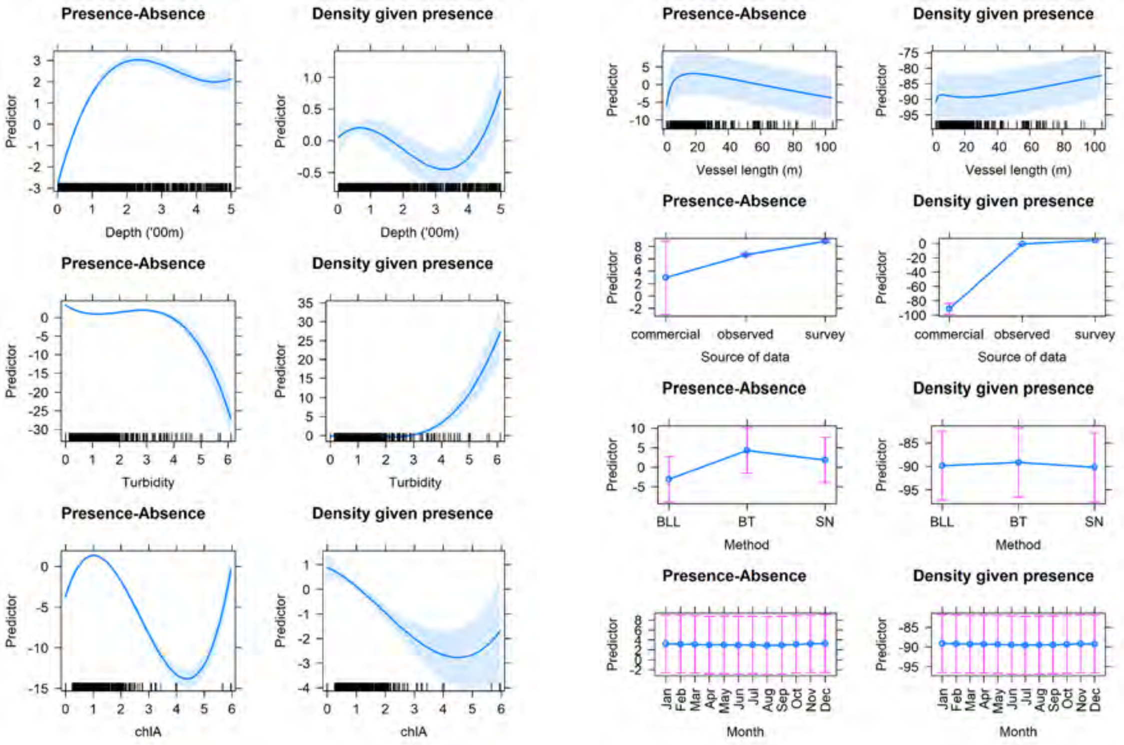

Figure D.74: Stargazer model partial effects plots and one standard error.

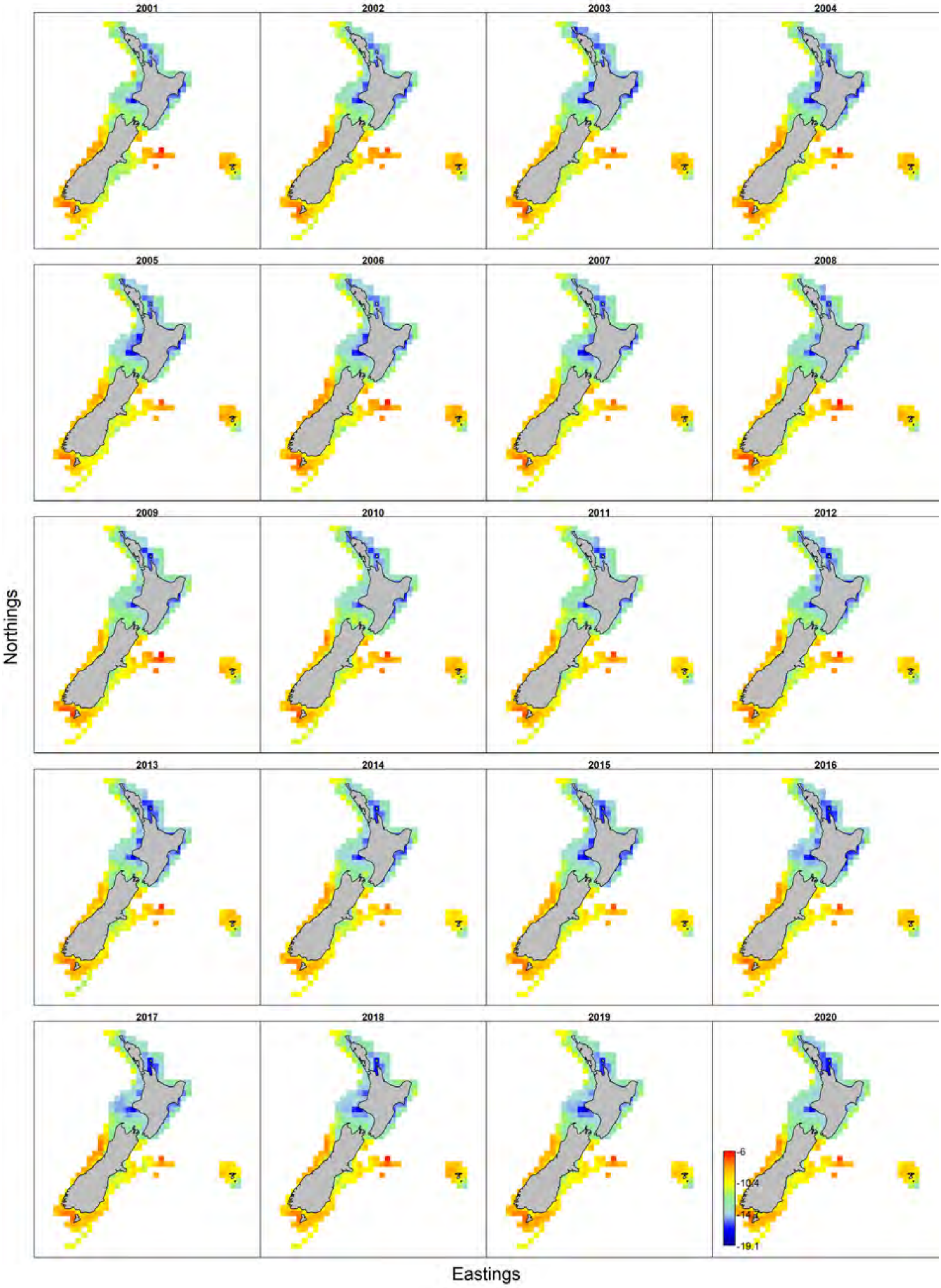

Figure D.75: Spatial-temporal distribution of biomass for stargazer, expressed in lognormal scale.

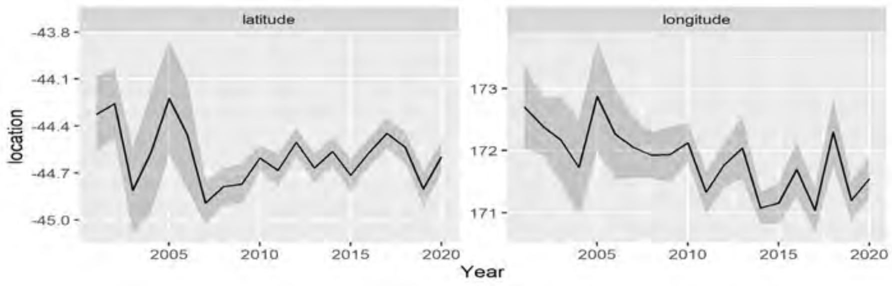

Figure D.76: Location of the centre of gravity over time for stargazer and one standard error.

Tarakihi

Tarakihi are caught in the coastal waters of the North Island and South Island, Stewart Island, and the Chatham Islands, down to depths of about 250 m. The stock assessment shows a general decline in SSB from 2000, with a small increase from 2007 to 2010 (Fisheries New Zealand 2021).

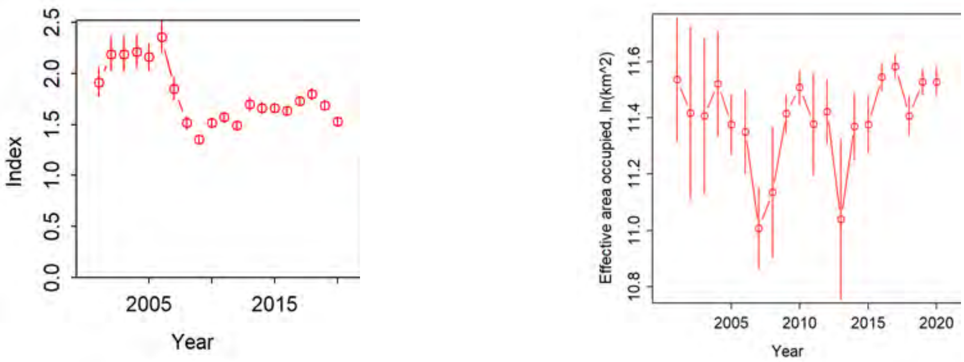

Figure D.77: Temporal index of tarakihi biomass and Effective area occupied over time and one standard error.

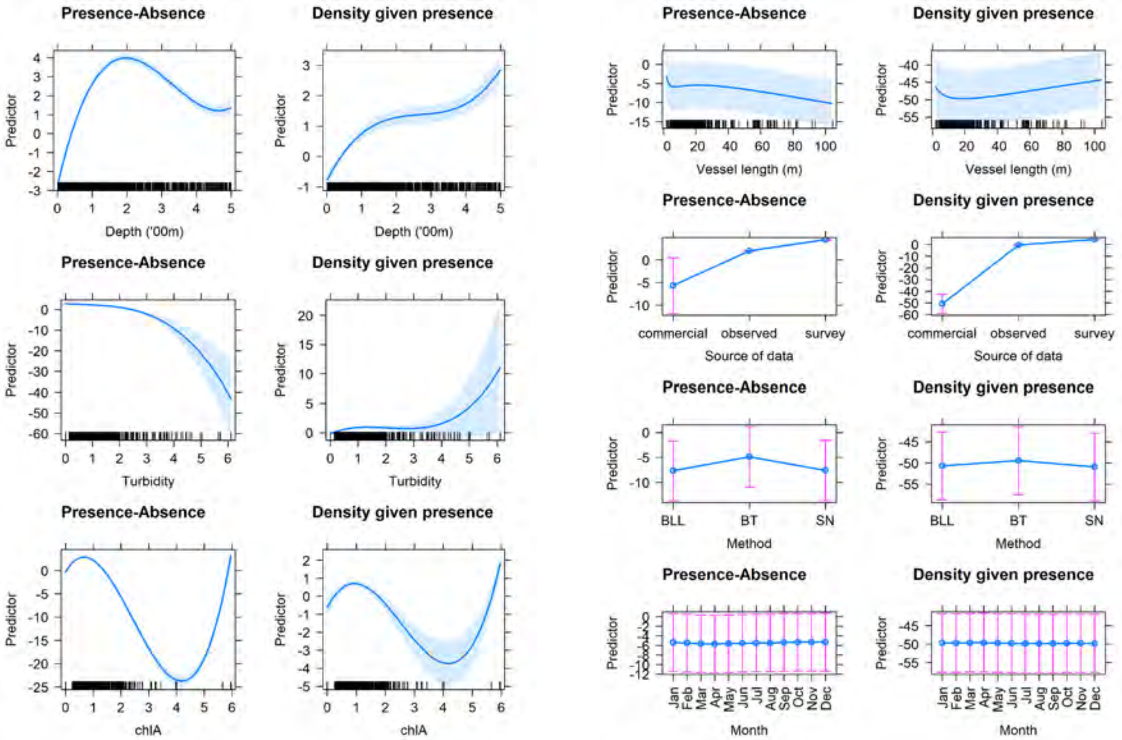

Figure D.78: Tarakihi model partial effects plots and one standard error.

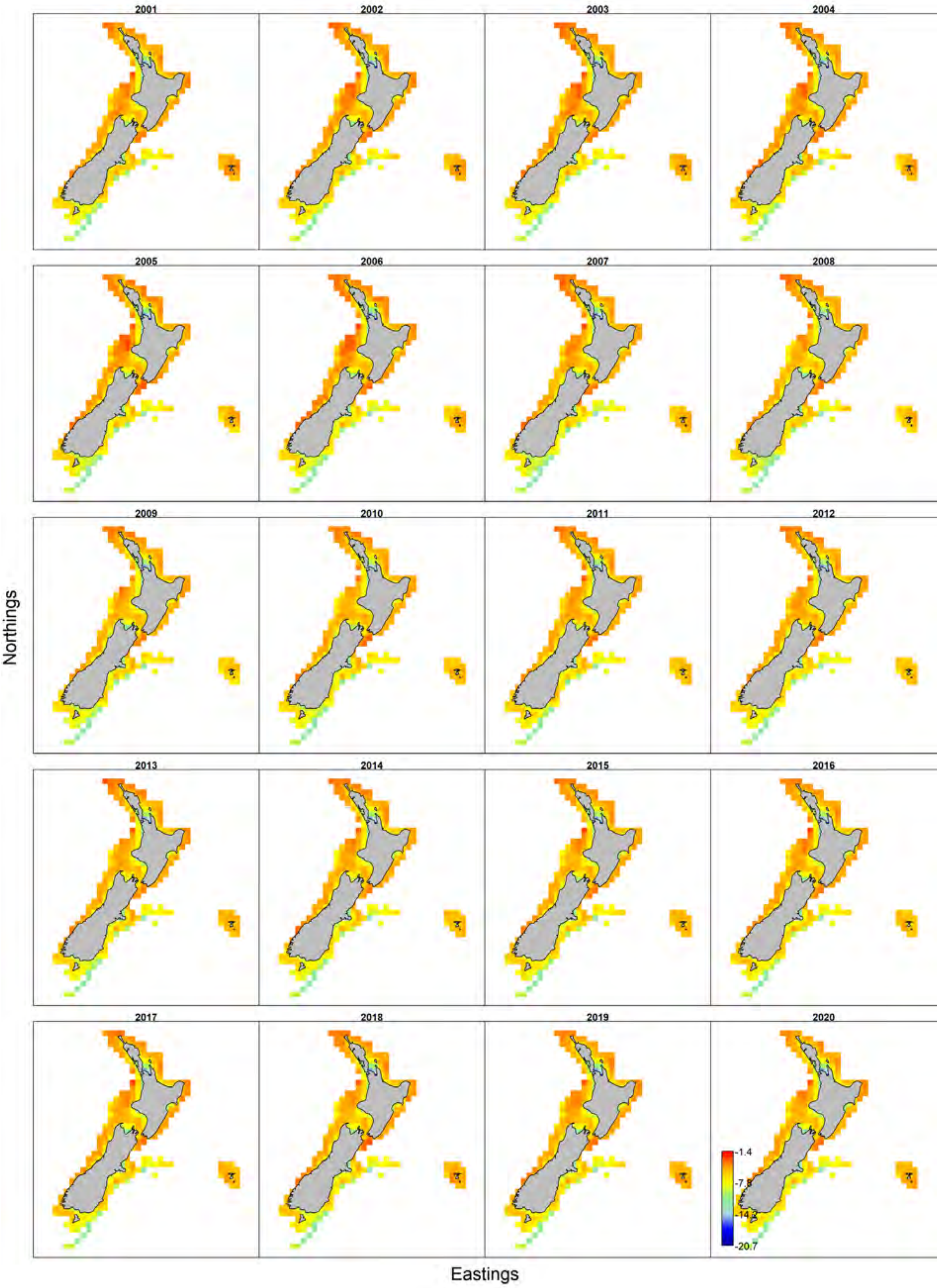

Figure D.79: Spatial-temporal distribution of biomass for tarakihi, expressed in lognormal scale.

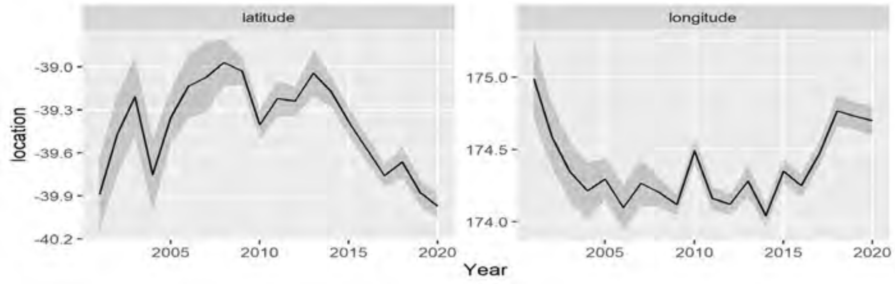

Figure D.80: Location of the centre of gravity over time for tarakihi and one standard error.

Warehou

Silver warehou are common around the South Island and on the Chatham Rise in depths of 200–800 m. The *Tangaroa* trawl survey indicates a substantial decline in biomass from off the west coast South Island between 2000 and 2018 whilst biomass indices from off the east coast South Island have increased (Fisheries New Zealand 2021).

Blue (or common) warehou are caught in coastal waters of the South Island and lower North Island down to depths of about 400 m. Indices of abundance are not available. White warehou are mostly caught in 150 to 800 m depth. Indices of abundance are not reliable (Fisheries New Zealand 2021).

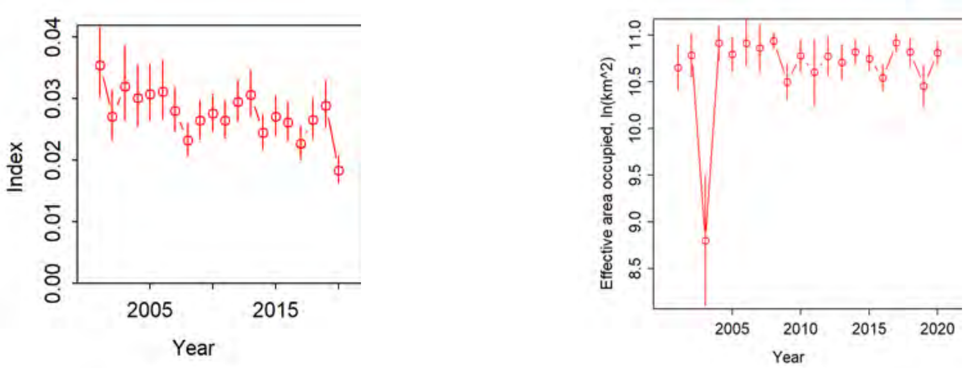

Figure D.81: Temporal index of warehou biomass and Effective area occupied over time and one standard error.

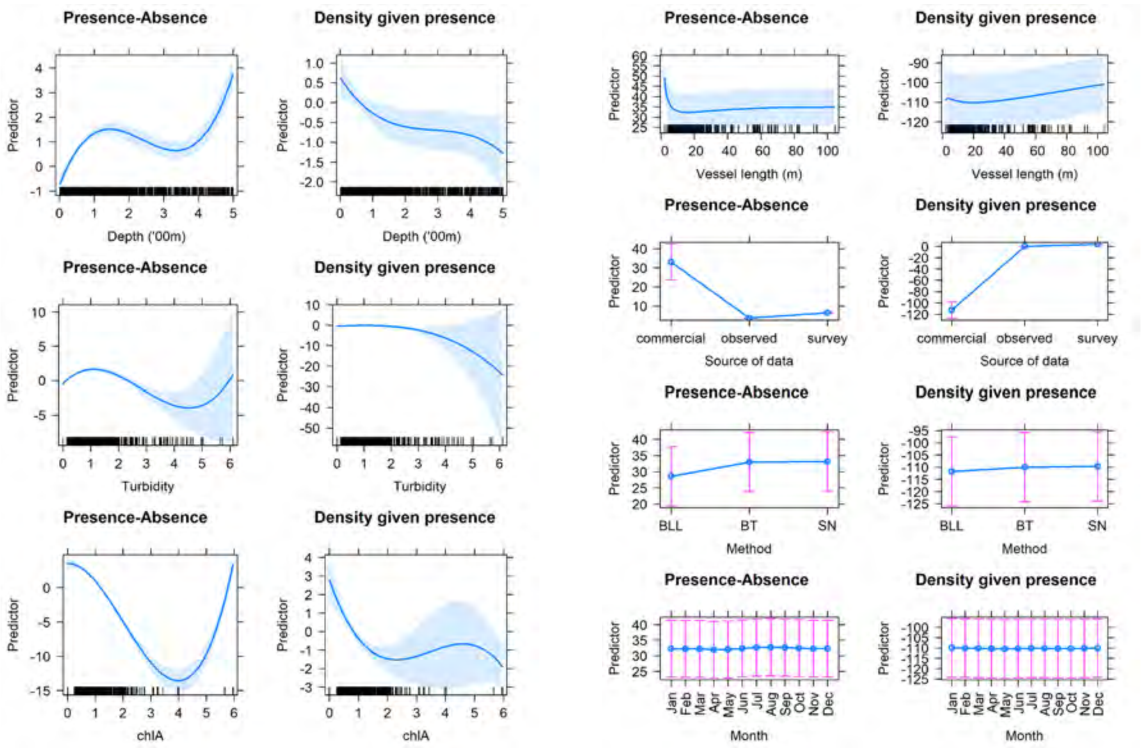

Figure D.82: Warehou model partial effects plots and one standard error.

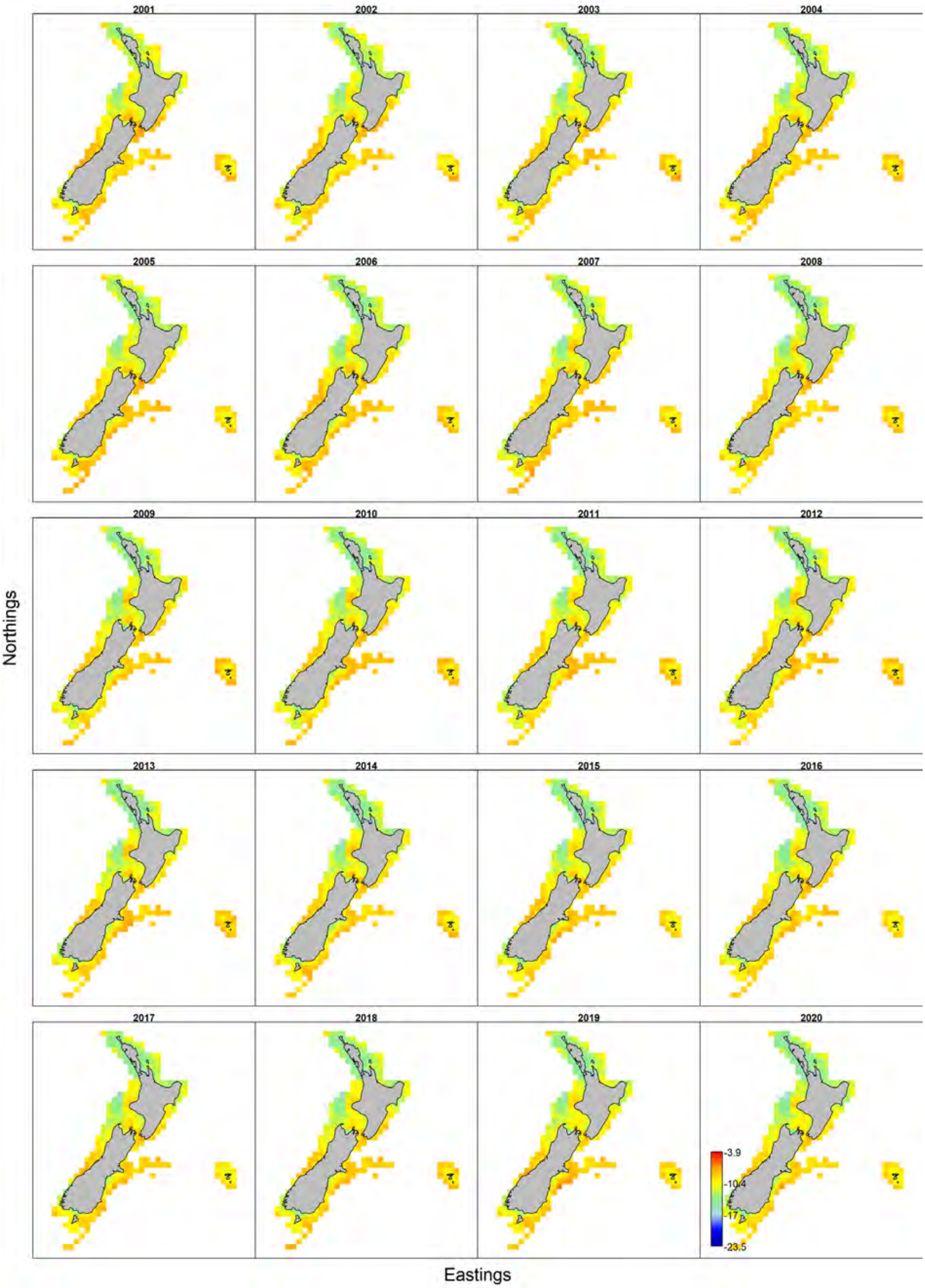

Figure D.83: Spatial-temporal distribution of biomass for warehou, expressed in lognormal scale.

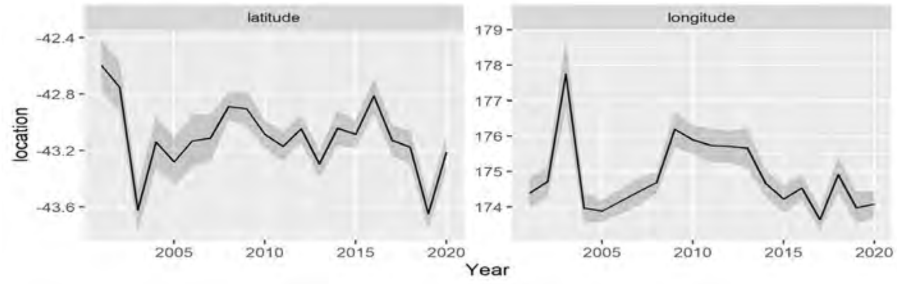

Figure D.84: Location of the centre of gravity over time for warehou and one standard error.

Wrasse

The family Labridae is the second largest family of marine fishes, of which 31 species occur in New Zealand waters. Most species are especially dominant in shallow rocky reefs, down to about 50 m depth (Roberts et al. 2015). Indices of abundance are not available.

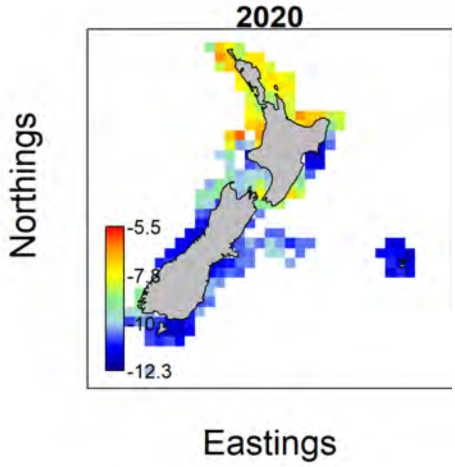

Figure D.85: Spatial distribution of biomass for wrasse, expressed in lognormal scale (all data are assumed from 2020 because of paucity of captures over time).

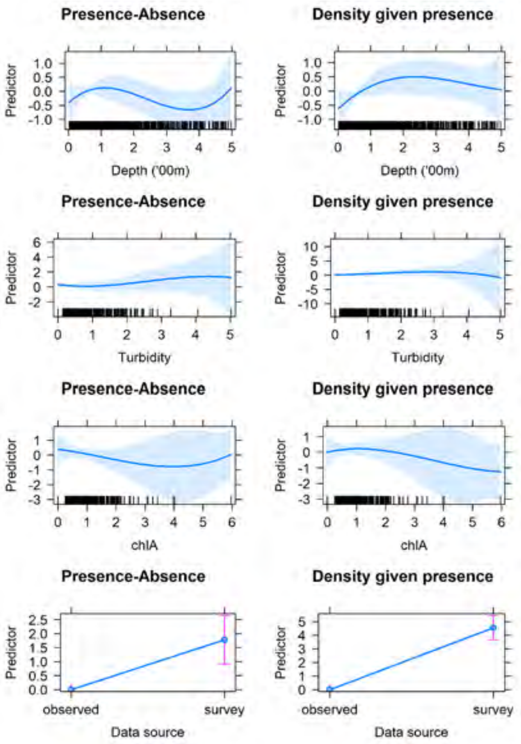

Figure D.86: Wrasse model partial effects plots and one standard error.

Appendix E: Species length-class distributions and diagnostics

Squid

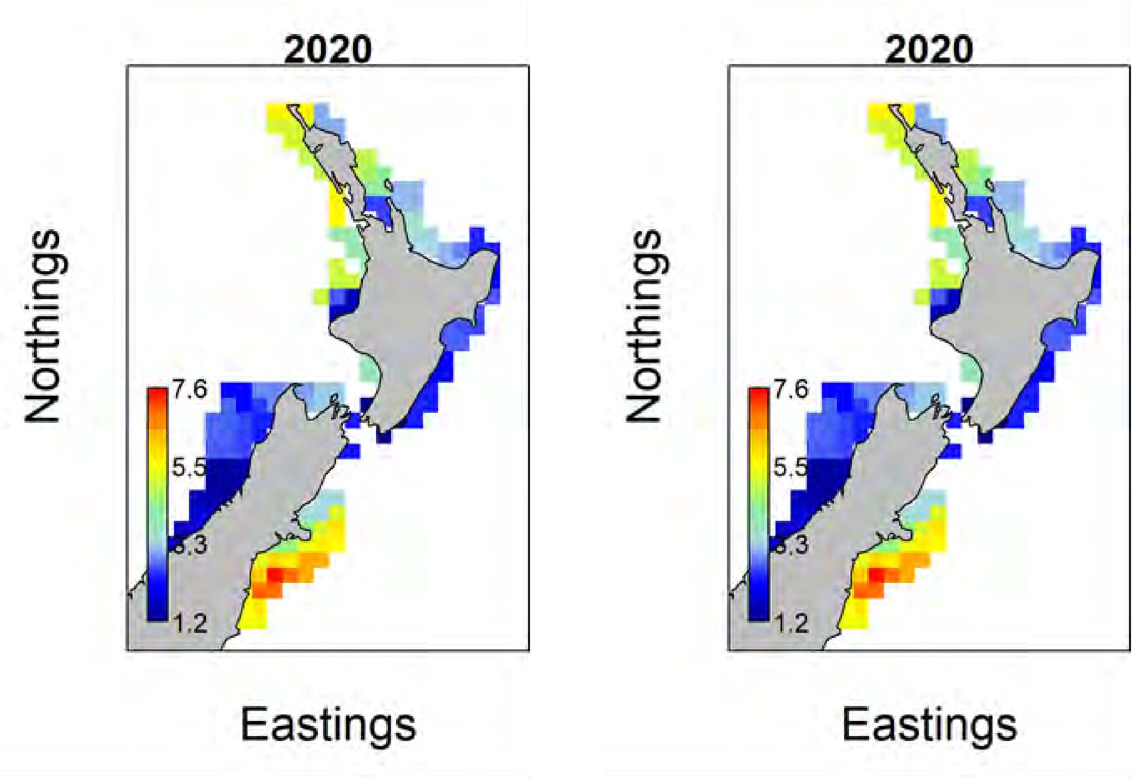

Figure E.1: Spatial distribution of density for squid smaller than 20 cm length (left) or 20 cm and longer (right), expressed in lognormal scale (all data are assumed from 2020 because of paucity of captures over time).

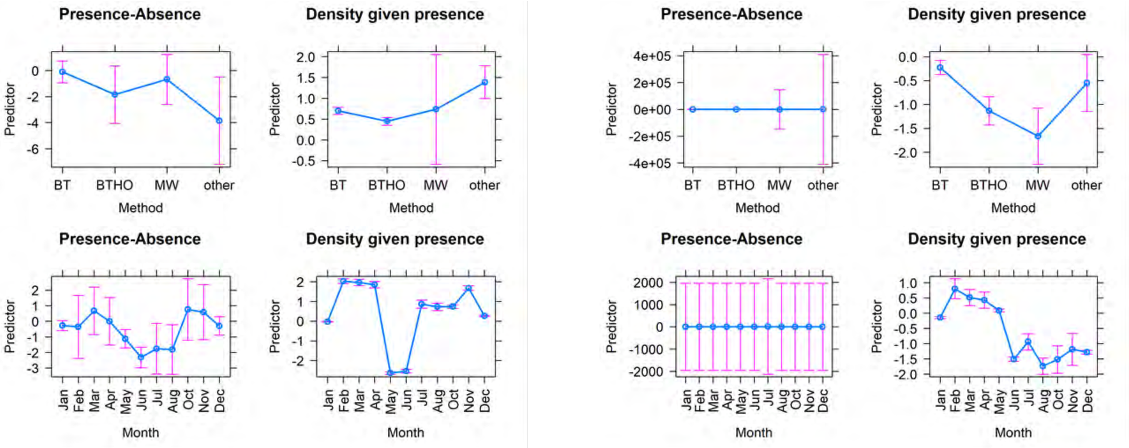

Figure E.2: Squid smaller than 20 cm length (left) or 20 cm and longer (right) model partial effects plots and one standard error.

Sea perch

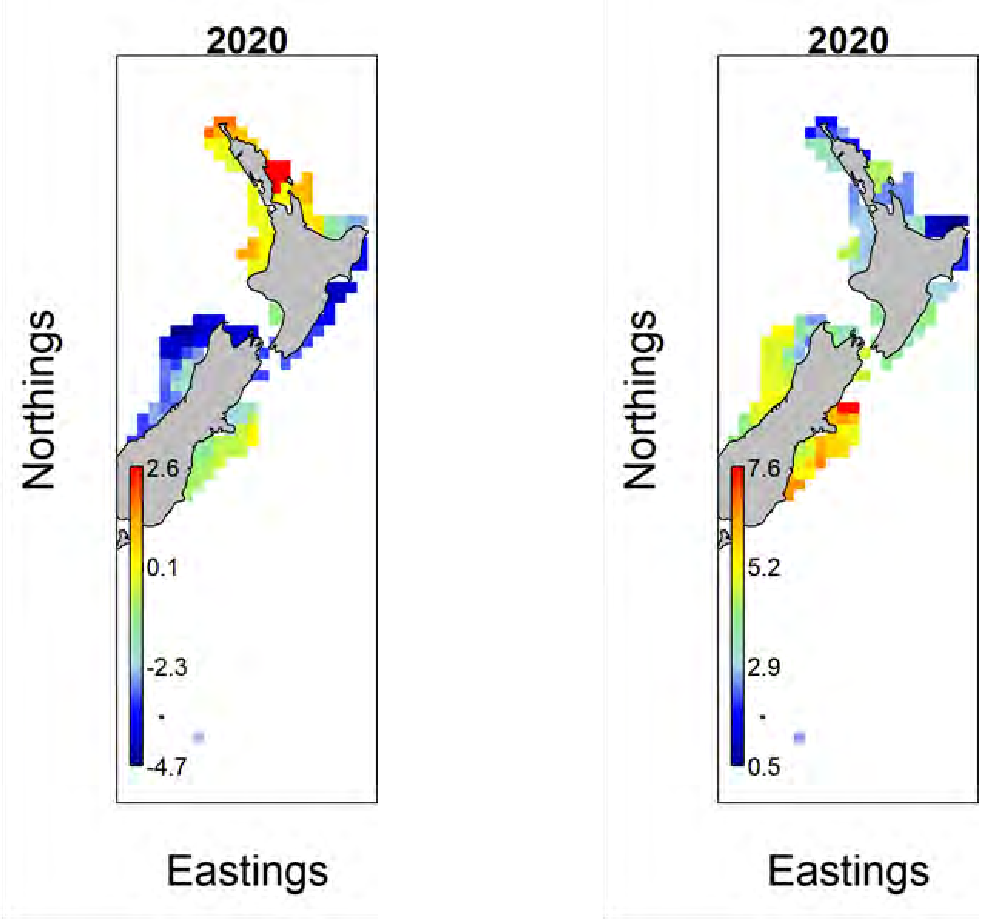

Figure E.3: Spatial distribution of density for sea perch smaller than 10 cm length (left) or 10 cm and longer (right), expressed in lognormal scale (all data are assumed from 2020 because of paucity of captures over time).

Red cod

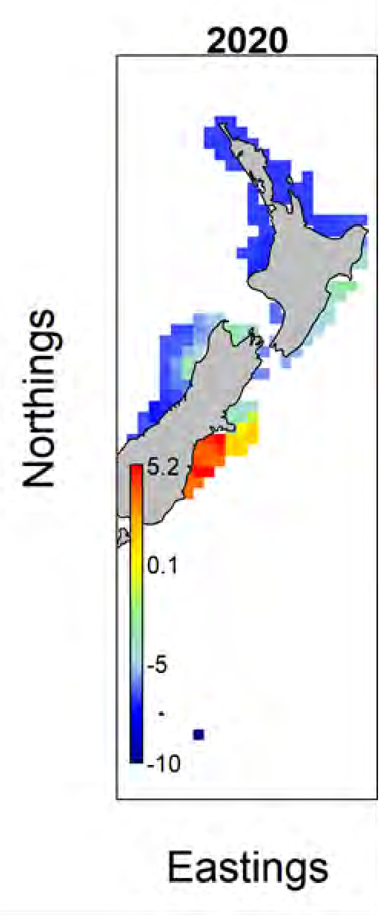

Figure E.4: Spatial distribution of density for red cod smaller than 10 cm length, expressed in lognormal scale (all data are assumed from 2020 because of paucity of captures over time).