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Characterisation of striped marlin bycatch in New Zealand surface-longline fisheries

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EXECUTIVE SUMMARY

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Striped marlin (*Kajikia audax*) supports a popular and valuable recreational fishery in New Zealand. They are occasionally caught by the surface-longline fleet, but retention of commercial catches has been prohibited since 1987. Striped marlin prefer warm waters between 20 °C and 24 °C and primarily occupy the mixed layer near the surface. They are found in New Zealand during austral summer months especially, with large, mature individuals moving from spawning grounds in the Coral Sea to feed in New Zealand and neighbouring waters.

This study assessed bycatch of striped marlin by commercial surface longliners in New Zealand waters. The characterisation focused on data for fishing years from 2003–04 to 2018–19, with striped marlin bycatch records prior to this period considered to be less reliable. In addition to the characterisation, a bycatch prediction model was also developed to assess the influence of environmental and operational covariates on striped marlin bycatch rates.

Overall, striped marlin bycatch levels were stable from 2003–04 to 2018–19, with some year-to-year variability. Both striped marlin captures and catch-per-unit-effort declined in the last three years of the assessment period (2016–17 to 2018–19), following a peak in 2015–16. The three key surface-longline target species with striped marlin bycatch were bigeye tuna (*Thunnus obesus*), swordfish (*Xiphias gladius*), and southern bluefin tuna (*Thunnus maccoyii*). Striped marlin bycatch was common in sets targeting bigeye tuna and swordfish, with occasional bycatch in sets targeting southern bluefin tuna.

Trends in striped marlin bycatch have mirrored changes in the surface-longline fishery over time. Early in the reporting period, striped marlin bycatch mostly occurred in surface-longline sets targeting bigeye tuna. However, fishing effort targeting swordfish has increased since 2003–04 and striped marlin bycatch rates for those sets are high compared with other target species. As such, about half of the recent striped marlin bycatch was in sets targeting swordfish. In contrast, although fishing effort targeting southern bluefin tuna has also steadily increased since 2003–04, this increase did not result in increased striped marlin bycatch levels; striped marlin captures rates for this fleet were consistently low.

There were distinct spatial patterns in the distribution of striped marlin bycatch in New Zealand: most capture events occurred in North Island waters, from Bay of Plenty to Northland, and there were few captures (and low catch-per-unit-effort, CPUE) on the east coast south of Hawke Bay. This pattern appeared to correspond with patterns of spatial occupancy and not catchability given similar fishing fleets were active in both of these areas and over the same seasons. In parallel, increases in sea surface temperatures may have impacted the distribution of striped marlin in New Zealand waters as the boundary of striped marlin bycatch has expanded southward along the South Island west coast.

Striped marlin's preference for warm waters was reflected in seasonal trends in the bycatch records. Capture rates were particularly high in warm months between January and March. This period coincided with the fishing season for swordfish, as well as bigeye tuna to some extent. For these two target species, striped marlin captures were highest in February and March. In contrast, for southern bluefin tuna, striped marlin bycatch was highest in the winter months between June and August, when effort targeting this species shifted from the North Island southern east coast towards Bay of Plenty and Northland.

The bycatch prediction model confirmed a distinct signal in striped marlin capture rates across target species, with the probability of striped marlin bycatch highest in swordfish-targeted sets. However, the operational covariates considered in this analysis did not explain a high proportion of variation in the capture rates across sets. Instead, oceanographic covariates, mostly sea surface temperature (SST) and also surface water chorophyll-*a*, had the strongest predicted influence on bycatch rates. Moon illumination was also predicted to impact capture rates, with a predicted increase in the probability of bycatch for sets during periods approaching the full moon. Overall the proportion of bycatch explained

by covariates was low (about 20%), which may indicate high variability in striped marlin capture rates that is due to chance, or the importance of other significant covariates that were not considered in this analysis.

When the dataset for the prediction model was extended to examine the effect of the El Niño Southern Oscillation (ENSO) on striped marlin bycatch and CPUE, two prominent trends were identified. First, there was a distinct increase in bycatch and CPUE during or immediately following the two strong El Niño events of 1998 and 2015; however, there was no consistent pattern in catch or CPUE in the period in-between these two years when weaker El Niño or La Niña events occurred. Second, there was a gradual decline in CPUE over three years following the peaks associated with the two strong El Niño events in 1998 and 2015. It is unclear whether these patterns were due to changes in local abundance, catchability, or recruitment of striped marlin, or a combination of these factors. Given the main covariatne explaining striped marlin bycatch in New Zealand waters was SST, both ENSO and long-term climate change are expected to influence bycatch rates and the distribution of captures of this species in the medium- to long-term.

1. INTRODUCTION

Striped marlin (*Kajikia audax*) is one of five billfish species that occur in New Zealand, where it supports a popular and valuable recreational fishery (Fisheries New Zealand 2019). Striped marlin is a mobile species that primarily utilises the mixed layer, with different studies indicating temperature preferences between 20 and 25 °C based on tagging data (Sippel et al. 2007, Lam et al. 2015), and a restricted depth range based on a temperature difference from the surface (8 °C, Lam et al. 2015). In New Zealand, striped marlin occurs seasonally, typically (but not exclusively) during the warmer months between December and May (Holdsworth & Kopf 2011).

Although its distribution is circumglobal, striped marlin tagged across locations in the Pacific Ocean showed regional fidelity (Domeier 2006). Most individuals tagged in New Zealand have been recaptured or tracked in the southwest Pacific Ocean, in areas spanning New Caledonia to French Polynesia. This finding corroborates updated genetic analyses of the stock structure of striped marlin, which have identified five stocks in the Pacific Ocean, including a southwestern Pacific Ocean stock with individuals in eastern Australia and New Zealand (Mamoozadeh et al. 2020). Although the occupancy of striped marlin in New Zealand waters is relatively low, this region is considered to be important for the population in providing feeding grounds for large, mature individuals that travel from spawning grounds in the Coral Sea (Kopf et al. 2005). There is no evidence of striped marlin spawning activity in New Zealand to date (Kopf et al. 2012).

Striped marlin in the southwest Pacific Ocean is targeted opportunistically by commercial fleets of tuna longliners. Early catches have been mainly by the Japanese fleet, but are currently by Pacific Island nations and other distant-water fishing nations, although overall catch levels have declined (Ducharme-Barth et al. 2019). In New Zealand, retention of striped marlin catches has been prohibited since 1987 following the Billfish Moratorium (in 1988 for domestic vessels; Fisheries New Zealand 2019). The moratorium was enacted as a response to commercial catches in the 1980s that were considered to negatively impact the recreational fishing sector. Since the adoption of the moratorium, there has been an increase in the availability of striped marlin to recreational anglers (Holdsworth & Kopf 2011). Although striped marlin is still being caught by surface longliners, any bycatch individuals have to be released. The post-release mortality of bycatch striped marlin in New Zealand is unknown. In the Central Pacific Ocean, it has been estimated at 14.5% for catches on circle hooks (Musyl et al. 2015).

A recent stock assessment of striped marlin in the southwest Pacific Ocean by the Western and Central Pacific Fisheries Commission (WCPFC) found that the stock was likely overfished and approaching levels of overfishing (Ducharme-Barth et al. 2019). The scenarios showed high uncertainty in stock status, but all scenarios included an ongoing decline in spawning biomass.

The recreational fisheries for striped marlin in New Zealand have been well-described, with studies characterising catch and catch-per-unit-effort (CPUE) (e.g., see Holdsworth & Saul 2013, 2017, 2019); analysing changes in size and condition of caught individuals over time (Kopf et al. 2005); and describing the spatial dynamics of individuals with satellite tags following capture by anglers (Sippel et al. 2011). In comparison, striped marlin bycatch in commercial surface-longline fisheries has received limited attention other than the reporting of captures in official statistics (Holdsworth et al. 2018, Fisheries New Zealand 2019, but see Holdsworth & Kopf 2011).

The objective of the current study was to characterise the commercial fisheries that capture striped marlin in New Zealand. It includes an assessment of the impact of operational and environmental factors on striped marlin bycatch rates, using descriptive statistics and as well as within a modelling framework.

2. METHODS

2.1 Data preparation

An extract from the *warehou* database was obtained from Fisheries New Zealand (replog 13507), comprising of all effort records for the primary method surface longline (SLL), for the period 1989–90 to 2018–19. Also included were the corresponding estimated and processed catch in numbers and weight. Only records from form types Catch Effort Landing Return (CELR), Tuna Longlining Catch Effort Return (TUN) and Electronic Reporting System—Tuna lining (ERS) were retained for the final analyses. The fishing year for surface-longline fisheries extends from 1 October to 30 September the next year. References to single fishing years correspond with the latter year in the time period.

Commercial vessels in New Zealand waters have been prohibited from retaining striped marlin since the Billfish Moratorium of 1987 (extended to domestic vessels in 1988). Nevertheless, there has been no consistent approach for fishers to declare striped marlin captures until the inclusion of a "catch discarded or released" section in the TUN form in April 2003. Therefore, catch records from 2003–04 onwards were considered more reliable than earlier records, so that all statistics aggregating catch and effort records over multiple years here use records from this fishing year onwards. For some descriptive analyses, years prior to 2003–04 were included to provide further context or increase the time period available for examination. In thoses instances the time period started in 1994–95 because very few striped marlin captures were recorded before then.

Sets were discarded if the hook number was missing or outside of a likely range per set of 250 to 10 000 hooks, or if the number of floats was missing following the inclusion of this field in the TUN form (2003–04). Many captures prior to 2003–04 did not include a conversion factor, green weight and/or processed weight; these records were retained in the analysis because catch statistics were based on the number of individuals captured. Two records with exceedingly high CPUE (>99.9th quantile) and improbable individual weight (<10 kg) were discarded because they indicated likely recording errors; this omission included a total of 122 individuals. Following the advice of the Highly Migratory Species working group, striped marlin individuals caught in waters with sea surface temperatures less than 16 °C and weighing less than 60 kg were assumed to be species identification errors and discarded (11 individuals, all from fishing events prior to 2003–04).

Given individual weight is estimated by vessel crew upon capture, all reported statistics focused on catch of individuals. When weight was included, unlikely values were discarded where the number of individuals caught exceeded the recorded green weight. When weight was used, only measures of central tendencies were shown (median and inter-quartile range).

The surface-longline fleet in New Zealand used to include foreign vessels, but is currently an exclusively domestic fleet. Vessel nationality can be obtained from the *vessel_history* database maintained by Fisheries New Zealand, but this field is missing for a high proportion of vessels up to 2000–01. Where possible, vessel nationality was imputed from records for the same *vessel_id* that included a nationality when a single nationality was recorded for all records with that same *vessel_id*. A significant amount of effort could not be attributed to a nationality following this step, so vessel nationality was not used as a filter for long-term analyses spanning years prior to 2003–04; all metrics and analyses from 2003–04 onwards included vessels from the domestic (New Zealand) fleet only.

Records were assigned to "North Island" and "South Island" regions according to a defined geographical boundary (see Figure 1). When relevant, spatial summaries were constrained to key months when striped marlin is caught (January to May, 93.2% of captures overall from 2003–04 to 2018–19) to exclude fishing effort that is unlikely to catch striped marlin given its low occupancy at other times.

The influence of operational and oceanographical covariates on the occurrence of striped marlin captures was first assessed with data characterisation. The operational covariates consisted of total hook number, number of hooks-between-floats (the ratio of hook number to floats), the time and month of setting, the number of light sticks, and the percentage of hooks by bait type (fish or squid) in the set.

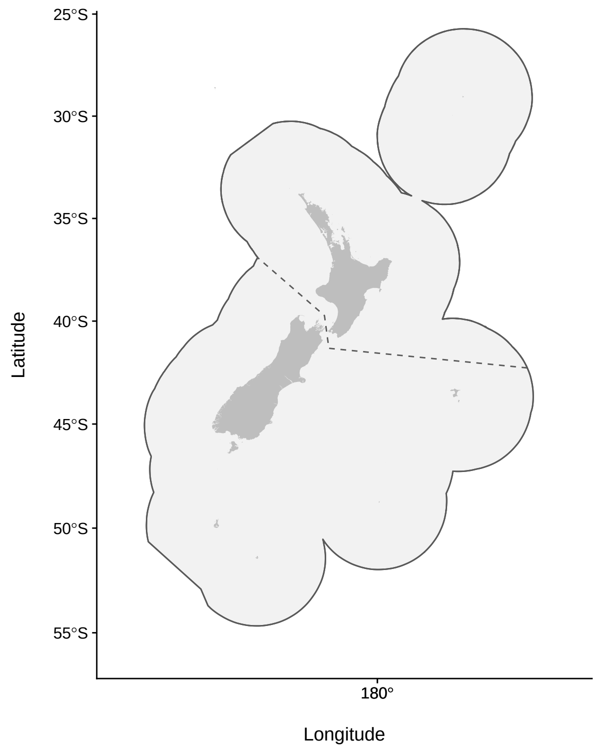

Figure 1: Geographical boundary (dashed line) used to assign sets to fishing in North Island or South Island waters.

Bait data were obtained *via* a separate extract from Fisheries New Zealand (replog 13160). Bait data was consistently available from 2003–04 onwards, recorded as the percentage of hooks using the specified bait. Bait types recorded were artificial, fish, squid or unspecified. When the total hook percentage recorded per set across bait types exceeded 100%, percentage across bait types was standardised to equal 100%. Lure information was available but only for a short time period (1990–91), so this covariate was not considered in the analysis.

Key oceanographic covariates were selected following a review of studies of striped marlin biology. The covariates were sea surface temperature (SST), chlorophyll-*a*, bathymetry, and moon illumination. Data on SST at set time were consistently available (i.e., less than 10% of records were missing this information) in fishing effort records from 1999–00 onwards. A second dataset of SST for New Zealand was also obtained from the National Centers for Environmental Prediction Climate Modelling Branch (Reynolds et al. 2002), at a coarser resolution of weekly predicted SST by 1° cell. This dataset was used to capture broader trends in the spatial distribution of SST as opposed to fine-scale trends from fishers *in situ* measurements. Near-surface chlorophyll-*a* (mg m^{-3}) at the 1/4° resolution was obtained from the MODIS Aqua data product (NASA 2014). Moon illumination by set date was obtained *via* the R package *suncalc* (Thieurmel & Elmarhraoui 2019), which computes the illuminated fraction of the moon based on date (0.0 for new moon to 1.0 for full moon). Bathymetry at the 1/6° resolution was obtained from the ETOPO1 Global Relief Model *via* the R package *marmap* (Pante & Simon-Bouhet 2013). Finally, the Oceanic Niño Index was used as a metric for the El Niño Southern Oscillation; monthly time series were obtained from the National Oceanic and Atmospheric Administration *via* the R package *rsoi* (Albers 2020).

All analyses were conducted in the R software package (R Core Team 2021).

2.2 Modelling framework

A modelling framework was used to quantify the impact of covariates on striped marlin captures. Because most capture events were of a single individual and there was a high proportion of zero-capture fishing events, occurrence was modelled assuming a binomial error distribution, whereby the response variable was the presence of at least one striped marlin on the longline set.

Given the collinearity across operational, environmental, and oceanographic covariates, two modelling frameworks were used: a General Additive Model (GAM) and a random forest model. The GAM framework allows a range of shapes (linear and non-linear, including splines) to be specified by the analyst for the expected relationship between covariates and the response variable; however, inference on optimal model structure can be biased when covariates are collinear. In comparison, random forest models are more robust to collinearity and can rank the importance of covariates in predicting the response variable. Nevertheless, the predictions are more difficult to interpret, because they result from a combination of decision trees.

Both GAM and random forest models were applied to the surface-longline dataset using striped marlin occurrence in the set as a response variable and the covariates described in Table 1. The predicted relationship between probability of occurrence of striped marlin and covariates was examined using the GAM. Model selection was implemented by including all available covariates in a single model with an extra penalty that allowed for the model estimation procedure to shrink covariate terms to zero when they did not provide useful information for the prediction. All continuous covariates were specified using a thin-plate spline with the additional penalty allowing shrinking and a maximum basis dimension of 4 (to only allow simple non-linear relationships). Alternative models excluding target species or set longitude were also developed to assess the impact of collinearity between covariates on model output; a basic model with SST, longitude, and target species as covariates was also used as a baseline. The GAM gamma parameter was set to 1.4 as recommended by Wood (2017) to further penalise wiggly splines.

Table 1: Description of the covariates used in the bycatch prediction model, including the range for the retained continuous covariates.

Variable	Description	Type	Min	Max
Target species	Target species for the fishing event recorded in the effort return form TUN.	Categorical	—	—
Total hook number	Total number of hooks used on the fishing set.	Spline	250	1600
Hooks-between-floats	The ratio of the total number of hooks to the number of floats used in the set.	Spline	4	25
Percentage squid bait	Percentage of hooks in the set using squid bait.	Spline	25	100
Hour	Hour at which the longline set started.	Spline	0	24
Haul hour	The hour at which the longline set started being hauled.	Spline	6	18
Lightsticks-per-hook	The ratio of lightsticks in the set to total number of hooks.	Spline	0	1
Sea surface temperature	Sea surface temperature in $^{\circ}$C from a 1°-resolution climatology for New Zealand.	Spline	13.5	23
Chlorophyll-*a*	Surface water chlorophyll-*a* concentration at the 1/4°-resolution in $mg\ m^{-3}$.	Spline	0	1
Moon illumination	Proportion of the moon that is illuminated (from 0 to 1 for the full moon).	Spline	0	1
Bottom depth	Sea floor depth (in m) at the 1/6 $^{\circ}$-resolution at the location of the start of the set.	Spline	0	4000
Oceanic Niño Index	Metric of ENSO with negative and positive values scaling with El Niño and La Niña conditions respectively.	Spline	-3	3
Longitude	Longitude coordinate at the start of the set.	Spline	168	181

The relative importance of covariates in predicting the probability of striped marlin occurrence was examined using the random forest model by providing all covariates except for longitude. The latter covariate was omitted given a number of collinear operational and oceanographic covariates. Covariate importance was assessed with the mean decrease in node impurity, a measure of the change in the random forest's ability to successfully classify a prediction when a specific covariate is included.

For both the GAM and the random forest models the dataset was prepared to exclude extreme values poorly represented in the covariates (see Table 1), because these can lead to unstable spline predictions at the edges of the distribution. Only months from January to May were included to focus on the time period where striped marlin occupancy in New Zealand is higher. The SST dataset included was the modelled climatology because it explained a higher proportion of the deviance in bycatch rates during initial model exploration.

GAMs were implemented using the *mgcv* package in R (Wood 2017); random forest models were implemented using the *randomForest* package (Liaw & Wiener 2002). Model assumptions for the binomial error distribution were assessed using quantile residuals (Dunn & Smyth 1996).

2.3 Observer records

Observer records for striped marlin were obtained from the Fisheries New Zealand Centralised Observer Database (COD) (replog 13410). Life status at release was summarised by fleet type based on the 'specimen_life' field up to 2014–15 and the 'fate' from 2015–16 onwards. For the fate field, injured individuals and individuals with unknown condition were classified as alive; moribund individuals were classified as dead.

3. RESULTS

3.1 Characterisation of surface-longline fisheries that catch striped marlin

Most effort records for surface longline from 1989–90 to 2018–19 were submitted using the Tuna Longlining Catch Effort Return (TLCER) form; the exception was a small number of records in 1990 that were submitted on the Catch Effort Landing Return (CELR) forms (Figure 2). In the final year of this study (2018–19), submissions shifted towards the use of the Electronic Reporting System (ERS), with about 20% of records submitted using the ERS—Tuna Lining form.

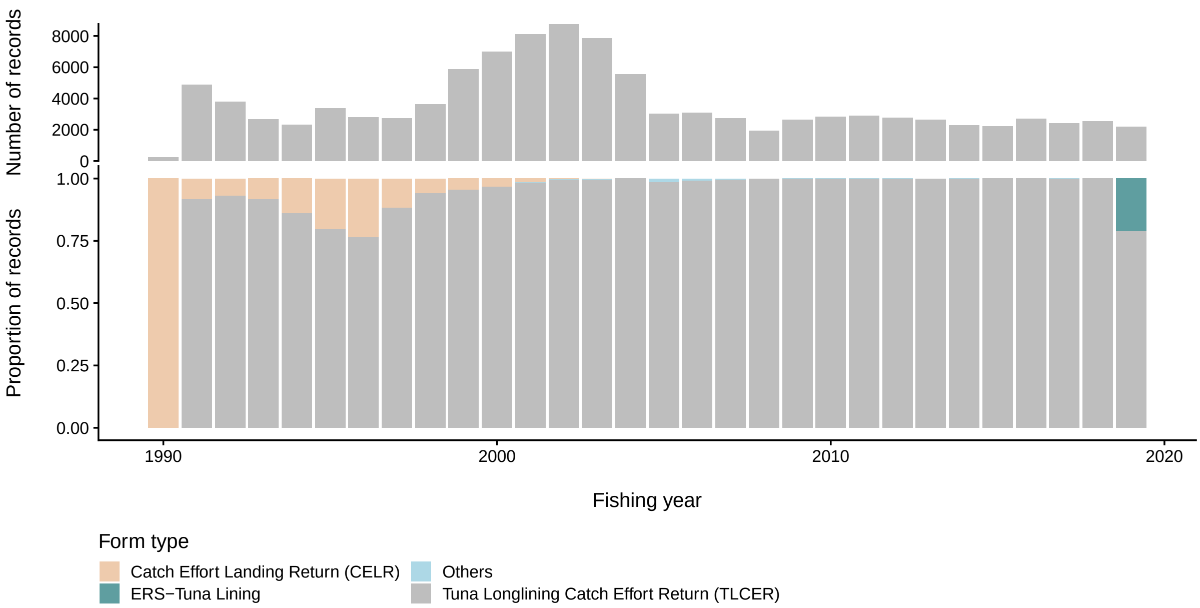

Figure 2: Fishing effort in surface-longline fisheries in New Zealand waters between 1989–90 and 2018–19. Number of fishing effort records reported on fishing event forms by fishing year (top), and proportion of records by form type used (bottom). ERS, Electronic Reporting System.

Surface-longline effort in New Zealand (including all vessel nationalities) increased from the early 1990s to a peak in the 2001–02 fishing year, before declining below 1990s levels in recent years (Figure 3). For most years, surface-longline effort was higher in North Island waters, with some recent exceptions.

Striped marlin was almost exclusively caught in North Island waters, but a few catches occurred in South Island waters every year (Figure 3). Catches previous to the 2003–04 fishing year were considered unreliable, because there was no consistent approach for fishers to report discarded individuals; subsequent catches were reported on a modified version of the form including a section for discarded catch. The two years with the highest total number of catches (1998–99 and 2015–16) occurred during the El Niño phase of ENSO (El Niño-Southern Oscillation) events. In the same years, comparatively high numbers of catches were also reported from South Island waters. Some captures occurred when a fisheries observer was present. For those observed captures an average of 61.4% were released alive (Table 2). This number fluctuated between 52.9% and 85.7% over the last five years (2014–15 to 2018–19).

In North Island waters, CPUE has generally increased since the early 2000s, with a peak in 2015–16, and a decrease since then (Figure 3). There were no clear trends in CPUE in South Island waters given the low number of captures overall, but CPUE was relatively high in 2015–16, when it was comparable with average capture rates from North Island waters.

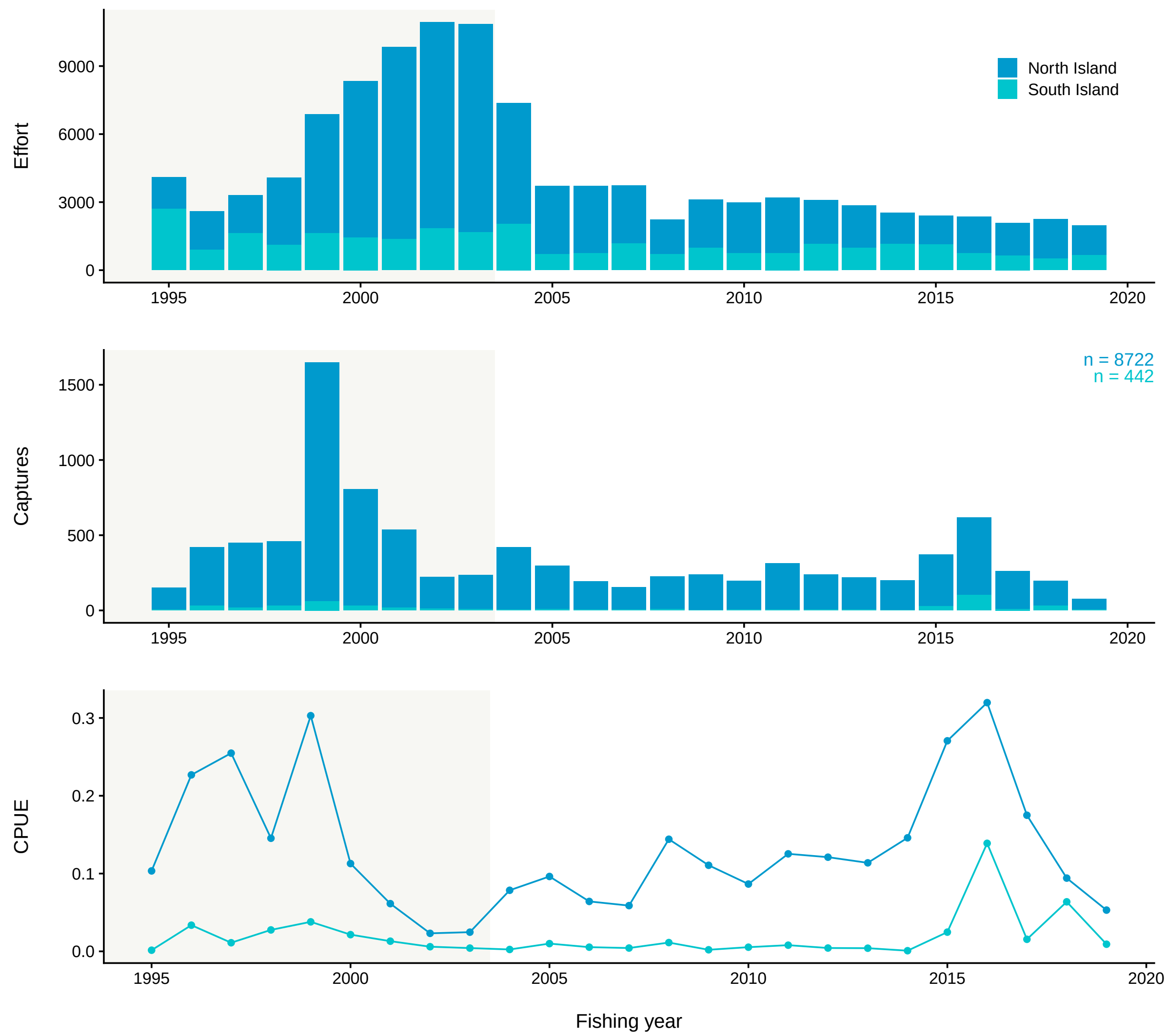

Figure 3: Surface-longline effort (in thousand hooks; top), striped marlin bycatch (in individuals; centre) and catch-per-unit effort (CPUE, individuals per thousand hooks; bottom) in New Zealand waters over time. Centre panel includes the total number of individuals recorded as caught in North Island and South Island waters (top right corner). Beige rectangle indicates time period when catch statistics were considered less reliable (prior to 2003–04).

Table 2: Observed captures of striped marlin by fishing year and proportion captured alive from 2003–04 to 2018–19. Fishing years where observations included vessels not within the New Zealand domestic fleet also include the summary statistics aggregated over all observed vessels ('All'). The total sums observations across all vessels.

Fishing year	Fleet	No.	Live (%)
2003–04	Domestic	6	66.7
2004–05	All	25	12.0
	Domestic	4	75.0
2005–06	All	4	100.0
	Domestic	2	100.0
2006–07	All	20	65.0
	Domestic	12	58.3
2007–08	Domestic	6	100.0
2008–09	Domestic	8	50.0
2009–10	Domestic	22	72.7
2010–11	Domestic	8	62.5
2011–12	Domestic	6	83.3
2012–13	All	9	44.4
	Domestic	8	50.0
2013–14	Domestic	5	80.0
2014–15	Domestic	9	55.6
2015–16	Domestic	40	65.0
2016–17	Domestic	24	70.8
2017–18	Domestic	17	52.9
2018–19	Domestic	14	85.7
Total	All	223	61.4

The two main target species declared on effort records submitted by surface-longline fishers were bigeye tuna (*Thunnus obesus*) and southern bluefin tuna (*Tunnus maccoyii*) (Figure 4). The relative prevalence of bigeye tuna as a target species has decreased since the early 2000s, with most of the current surface-longline effort targeting southern bluefin tuna. Concomitant with this shift in target species was an overall decline in surface-longline effort. Furthermore, there was an increase in the targeting of swordfish (*Xiphias gladius*) since the 2004–05 fishing year. Before this fishing year, fishers did not record this species as a target. In contrast, albacore tuna (*Thunnus alalunga*) was previously recorded as a target species, but has been rarely recorded in the past 15 years. During the three most recent years of this study (2016–17 to 2018–19), 61.2%, 23.4%, and 13.9% of the surface-longline effort was recorded as targeting southern bluefin tuna, bigeye tuna, and swordfish, respectively.

Most striped marlin captures were recorded in sets targeting bigeye tuna (71.1% of all captures from 2003–04 onwards), followed by swordfish targets (25.3%) (Figure 5 and Table A-1). Earlier captures of striped marlin in sets targeting swordfish were low, but have increased in the recent period to match the scale of captures in bigeye-target sets: from 2016–17 to 2018–19, 44.3% of striped marlin individuals were caught in sets targeting swordfish. In comparison, there were considerably fewer striped marlin captures in sets targeting southern bluefin tuna (2.2%), even though this target fishery was characterised by high fishing effort. Corresponding with these patterns, CPUE was highest overall for sets targeting swordfish, followed by bigeye sets; the CPUE for southern bluefin tuna was markedly lower in comparison.

Trends in average estimated striped marlin weight differed slightly for the key target species bigeye tuna, swordfish, and southern bluefin tuna (Figure 6). Striped marlin median weight caught in sets targeting bigeye tuna or swordfish was 100 kg per individual, with weight of individuals caught in the swordfish target fisheries showing greater variability overall and across time. In sets targeting southern bluefin tuna, median individual striped marlin weight was slightly higher (110 kg) than in the other two key target fisheries. There was no consistent temporal trend in average striped marlin weight for any of the three target species.

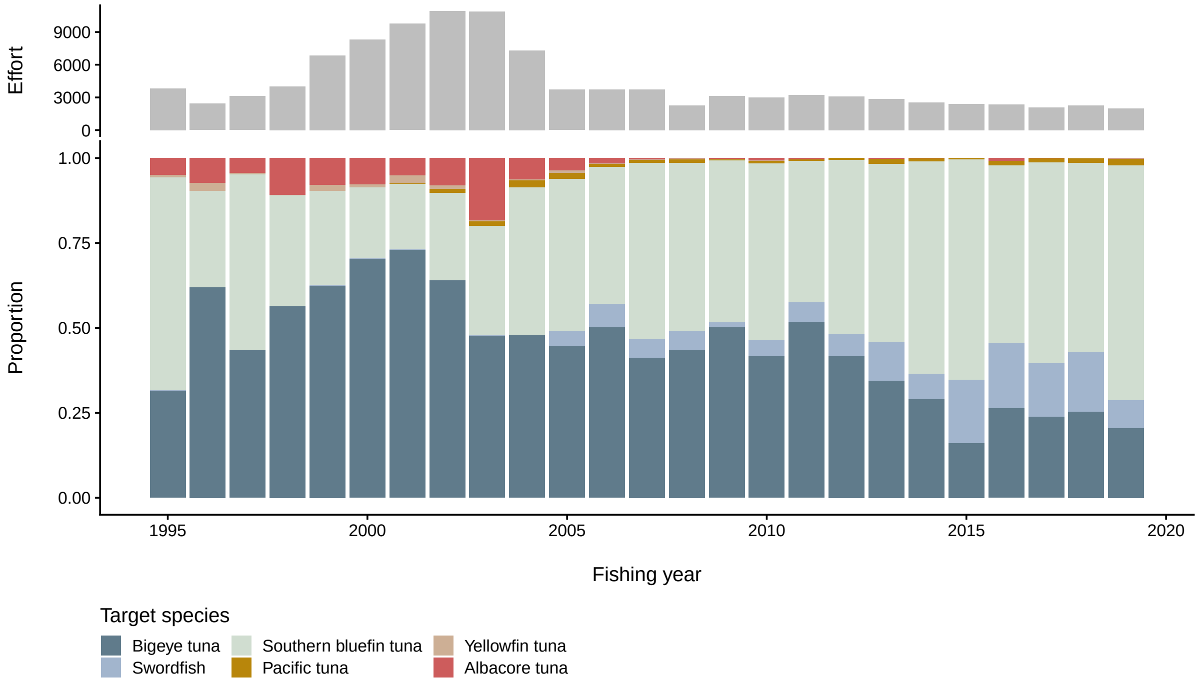

Figure 4: Surface-longline effort (in thousand hooks; top) and proportion of longline effort by target species recorded by fishers on catch effort return forms (bottom).

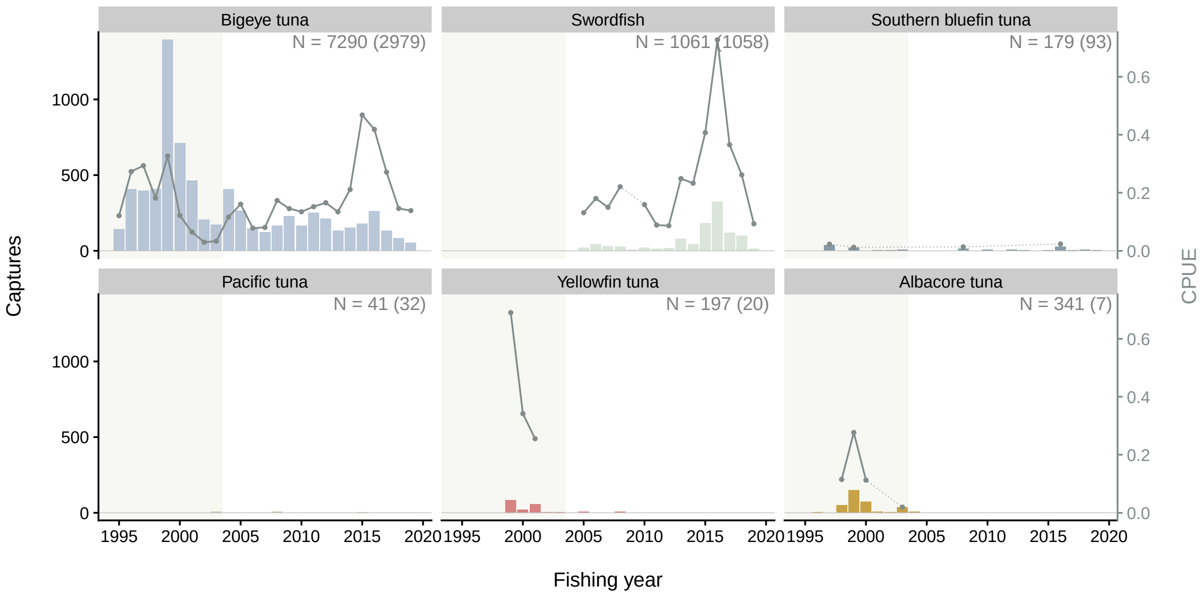

Figure 5: Number of captures of striped marlin (in individuals) in commercial surface-longline fisheries, by target species, including the corresponding catch-per-unit-effort (CPUE, individuals per thousand hooks; points and line). CPUE is only shown for years with at least 10 individual captures and 5000 hooks of effort. The total number of striped marlin captures per target species is noted in the top-right corner for the period 1989–90 to 2018–19, and in parentheses for the period 2003–04 to 2018–19, when records were considered reliable compared with the earlier period. The earlier period (pre-2003) corresponds with the grey background shading. Graphs are arranged by descending total captures over the high-reliability period (left to right and top to bottom). Observations separated by more than a single year are connected by a dotted line.

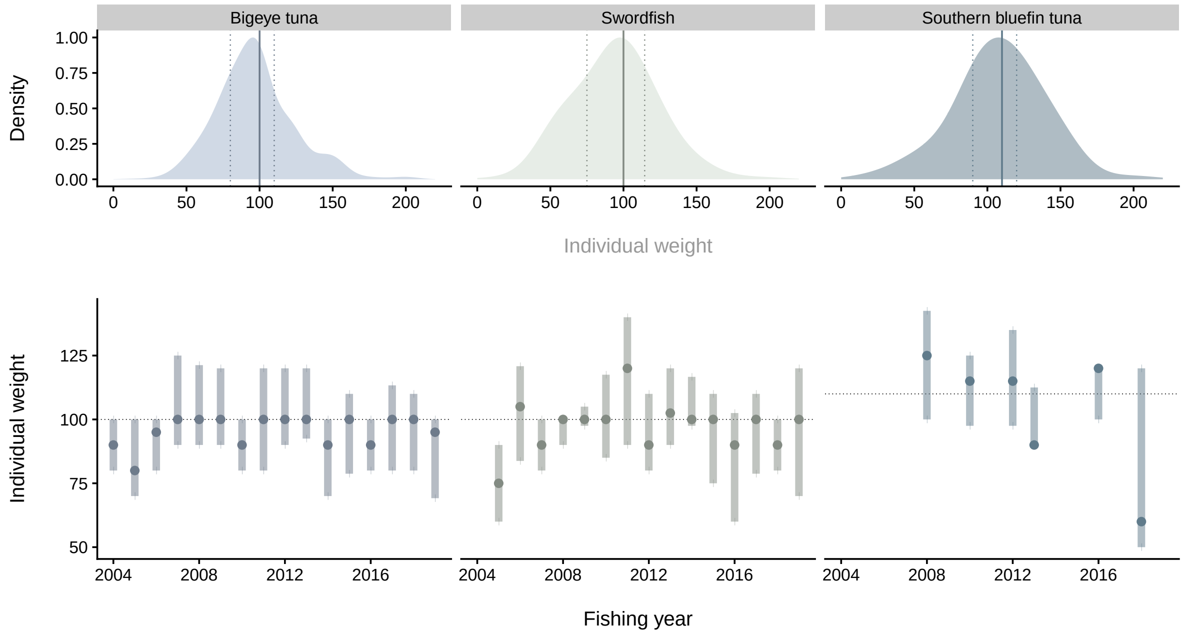

Figure 6: Overall distribution of average estimated individual weight (in kg) of striped marlin per set with a positive catch event, by key target species. Bold and dotted lines (top) show the median and interquartile range (25th to 75th), respectively. Temporal distribution of average individual weight by fishing year (bottom), with the dot showing the median, and the band spanning the interquartile range. Fishing years are only included when at least five striped marlin individuals were caught in one of these target fisheries.

Trends of striped marlin captures by region were partially determined by the distribution of targeted effort and CPUE by target species: surface-longline effort in North Island waters was spread across multiple species, primarily southern bluefin tuna, bigeye tuna, and swordfish (Figure 7). In contrast, effort in South Island waters was mainly aimed at southern bluefin tuna, with some effort aimed at swordfish. Striped marlin captures in North Island mostly occurred in bigeye- and swordfish-target sets, whereas recent captures in South Island were mostly in swordfish-target sets, despite their lower prevalence. The South Island CPUE for striped marlin in swordfish-target sets was 0.293 individuals per thousand hooks compared with 0.004 individuals per thousand hooks for southern bluefin tuna sets.

Differences in striped marlin CPUE by target species were more pronounced when CPUE was disaggregated by month (Figure 8 and Table A-2). The North Island CPUE was highest in the summer month of February followed by March and January, and it was particularly high for sets targeting swordfish in February and March. Striped marlin CPUE for North Island swordfish targets in the two latter months was on average 0.567 individuals per thousand hooks. There were rare instances of high CPUE (annual and monthly) for sets targeting yellowfin tuna (*Thunnus albacares*), but these sets made up only a small proportion of the overall effort.

Monthly CPUE for striped marlin caught in South Island waters followed a similar seasonal trend (Figure 8); it was highest in March followed by February and January, but was markedly lower overall than North Island CPUE in most months. For all target species, striped marlin CPUE was low between June and December, with an average of 0.014 individuals per thousand hooks, compared with 0.186 individuals per thousand hooks between January and May. Since 2003–04, 93.2% of captured individuals were caught between these two latter months. Average January-to-June CPUE for North Island waters was 0.217 individuals per thousand hooks, and 0.055 individuals per thousand hooks for South Island waters, reflecting an almost 10-fold difference between the two regions. This pattern was less pronounced when focusing on swordfish targets—the target species with the highest number of striped marlin catches in South Island—with a North Island CPUE of 0.335 compared with a South Island CPUE of 0.19.

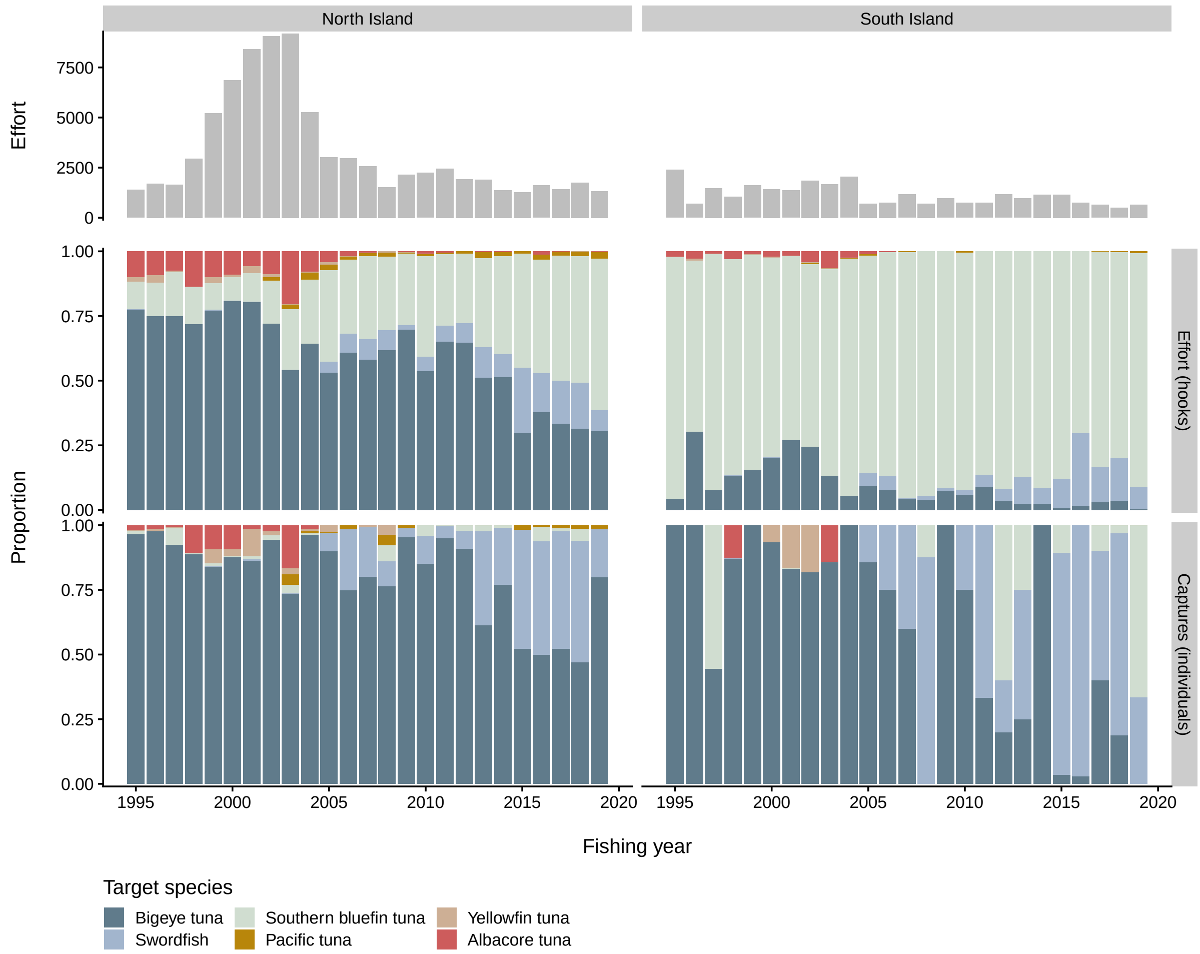

Figure 7: Surface-longline effort (in thousand hooks; top), proportion of longline effort by target species recorded by fishers on catch effort return forms (centre), and proportion of striped marlin captures by target species (bottom) by region.

The length of the fishing season and overlap with the main striped marlin capture period (January to May) varied by target species (Figure 9). Bigeye tuna had the longest fishing season, with effort extending over most of the year. Overlap with the striped marlin capture period increased over time with the fishing season mid-point gradually shifting from early April (in 2003–04) to late January (in 2018–19). Southern bluefin tuna had the smallest overlap with the main striped marlin capture period; most of the fishing effort targeted at this tuna species overall occurred outside of January to May. The fishing season mid-point was typically in June or early July. The swordfish-target fishery had the most overlap with the main striped marlin capture period, with most of the effort occurring between January and May, except in earlier years. The mid-point of its fishing season gradually shifted over time, from mid-April in the earlier years of the fishery to mid-March in 2018–19.

Analyses of spatial trends in striped marlin bycatch focused on the main striped marlin capture period between January and May. Most captures of striped marlin occurred in North Island waters around Bay of Plenty, Northland and north of the Taranaki Bight (Figure 10). Captures were frequently in offshore areas, in waters exceeding 1000 metres depth. Of the few captures that occurred in South Island waters, most captures were in offshore areas off the northern half of the west coast; there were no captures off the South Island east coast. Striped marlin CPUE tended to be higher off the North Island west coast, although there were fewer captures overall; it was markedly lower off the North Island east coast in waters surrounding East Cape and areas offshore of Hawke's Bay.

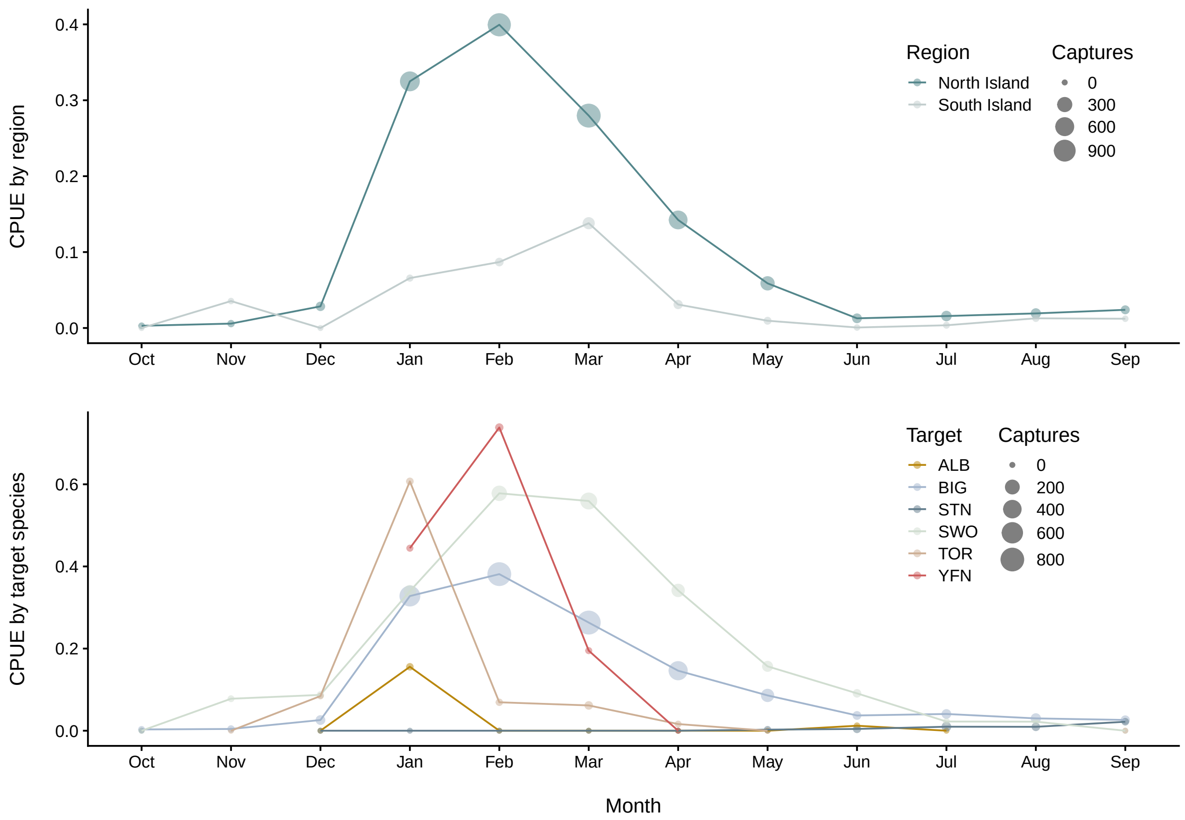

Figure 8: Nominal catch-per-unit-effort (CPUE) per month for striped marlin in surface-longline fisheries by region. CPUE aggregated for the period from 2003–04 to 2018–19 (top), and by month and key target species, for the North Island only (bottom). Circle size scales with the total number of captures for the month over the time period; records are only included if there were at least 5000 hooks of effort for a target species during the month. Target species were: ALB, albacore tuna; BIG, bigeye tuna; STN, southern bluefin tuna; SWO, swordfish; TOR, Pacific bluefin tuna; YFN, yellowfin tuna. Months are ordered from October to September, following the definition for the fishing year.

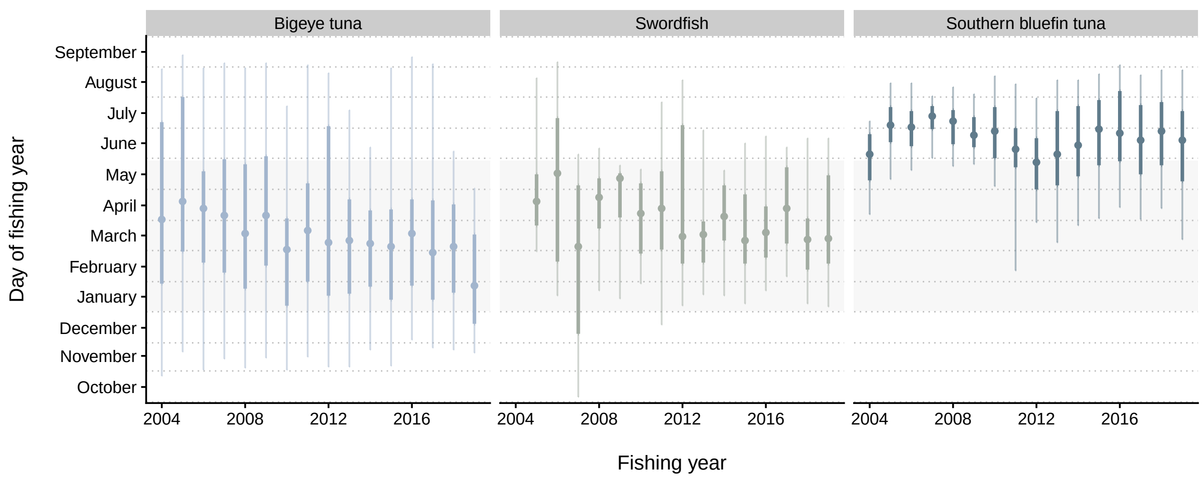

Figure 9: Distribution of surface-longline fishing effort by target species throughout the fishing year, starting October 1st. Dots indicate the mid-point of the fishing season (when 50% of the effort was applied), whiskers the period of 90% of the effort (in hooks), and coloured band the period of 50% of the effort. The grey rectangle outlines the period from January to May. Ticks for month labels show the 15th day of each month.

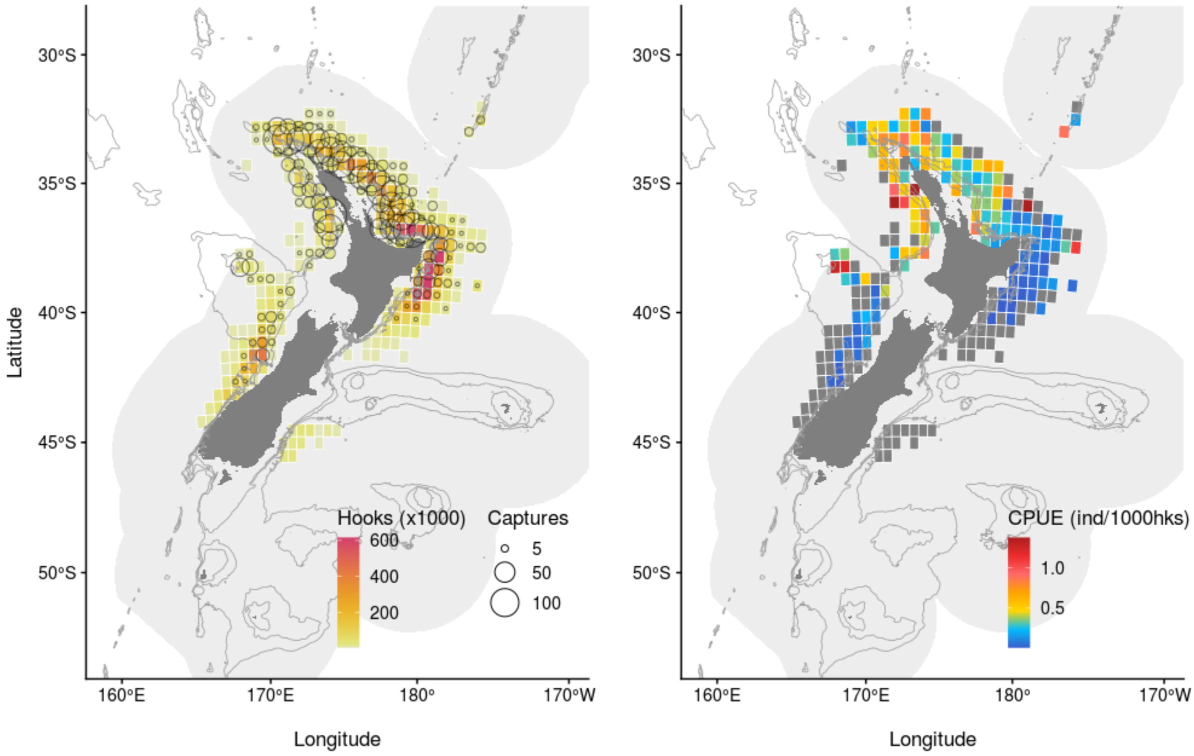

Figure 10: Surface-longline effort (in thousand hooks) and striped marlin captures (overlaid circles; left), and striped marlin catch-per-unit-effort (CPUE; right). Data are for the five main months (January to May) when striped marlin is bycaught in New Zealand's Exclusive Economic Zone, aggregated across all target species at the 0.5° resolution from 2003–04 to 2018–19. CPUE for cells with no captures are shown in dark grey, and effort and CPUE values higher than the 99th quantile are shown in dark red. Cells are only included if records are from at least three vessels.

There were distinct fishing grounds for surface-longline effort for the three key species, bigeye tuna, southern bluefin tuna, and swordfish, targeted between January and May in the period between 2003–04 and 2018–2019 (Figure 11). Most of the effort recorded as targeting bigeye tuna occurred in North Island, particularly in Bay of Plenty and off the east coast, with some effort in waters west of the North Island, south to the Taranaki Bight. For southern bluefin tuna, the effort was split between the North Island east coast and the South Island west coast, with some effort in Bay of Plenty and areas off the southern end of the South Island east coast. For swordfish, effort was spread throughout North Island waters, with some targeted effort also off the northern end of the South Island west coast.

Striped marlin was caught throughout the fishing grounds of bigeye tuna and swordfish; for these two target species in particular, locations with no striped marlin captures tended to also have low fishing effort overall (Figure 11). In contrast, there were few locations within the fishing grounds for southern bluefin tuna where striped marlin was caught, and CPUE overall was low in most of those locations (Figure 11). Within the fishing grounds for southern bluefin tuna, striped marlin CPUE tended to be higher in South Island than in North Island waters (Figure 11, CPUE quantiles). For effort targeting both bigeye tuna and swordfish, there was a distinct east-to-west gradient in CPUE, with east coast locations usually having lower capture rates, whereas most CPUE "hotspots" occurred off the North Island west coast or in westward offshore areas (Figure 11). For effort targeting swordfish, capture rates in South Island were generally lower than in North Island, except for the North Island east coast where CPUE rates were the lowest.

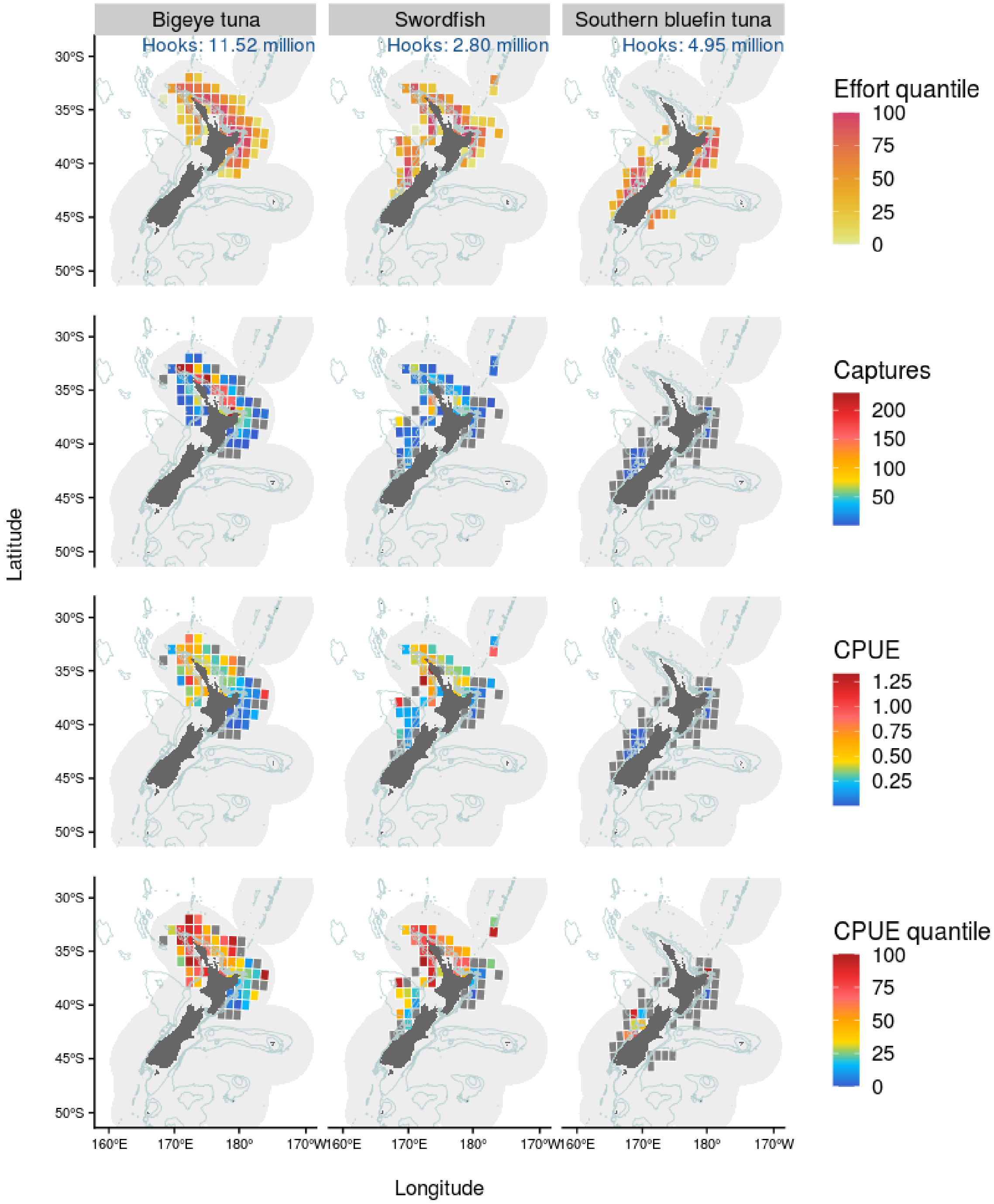

Figure 11: Effort quantile, striped marlin captures, striped marlin catch-per-unit-effort (CPUE) and CPUE quantile by key target species over the five main months when striped marlin was caught in New Zealand's Exclusive Economic Zone (January to May), aggregated at the 1° resolution from 2003–04 to 2018–19. Effort and CPUE quantiles show the relative quantile position of each cell compared with the overall effort and CPUE for the target species. Cells with no captures are shown in dark grey. Total effort and striped marlin captures are noted in the top right corner. Catch and CPUE values higher than the 99th quantile across target species are shown in dark red. Cells are only included if records span at least three vessels. Bathymetry contours for 200, 500, and 1000 metres depth are included.

The spatial trends seen in the most recent five years (2014–15 to 2018–19) largely reflected those in the full data set, except for a contraction of the spatial extent of surface-longline effort towards the coast for all target species (Figure 12). In addition, effort targeting bigeye tuna off the west coast of the North Island was considerably reduced. For both bigeye tuna and swordfish, the east-to-west gradient in CPUE was retained with few captures off the North Island east coast.

Seasonal patterns in the spatial distribution of striped marlin bycatch appear when CPUE is disaggregated by month (Figure 13). Captures span the broadest area in the summer months, especially in March, but the east-to-west gradient in CPUE is retained throughout the year, even during winter months. Catch rates within months are always highest around Northland and lowest off the east coast south of Hawke's Bay; South Island captures mostly occur from February to April. In addition, there are shifts in the distribution of fishing fleets during the year that can be seen when monthly CPUE is further disaggregated by target species (Figure B-1 to B-3). The bigeye tuna- and swordfish-targeting fleets are mostly centered around the area betwen the Bay of Plenty to Northland, but the swordfish-targeting fleet expands to waters off the west coast of South Island from February to May. In contrast, effort by the southern bluefine tuna-target fleet only occurs in the Bay of Plenty to Northland area during the months of June to September, which is also when they catch the most striped marlin (Table A-2). For all of these fleets, the spatial pattern of higher CPUE approaching and around Northland is maintained in all months where they are active.

3.2 Influence of operational and environmental variables on striped marlin bycatch

Operational features and environmental characteristics were compared between longline sets that had striped marlin bycatch, and longline sets overall, distinguishing the three key target species. Operational features of longline sets included the distribution of hooks per set, the number of hooks-between-floats, the use of lightsticks, and also the month and time of the day. Environmental characteristics associated with longline sets included sea surface temperature, chlorophyll-*a* concentration, water depth, and moon illumination (fraction). In addition, striped marlin captures were also examined in relation to different phases of the El Niño Southern Oscillation (ENSO).

3.2.1 Operational features of surface-longline sets

Considering operational features, the distribution of hooks per set with a positive capture was similar for bigeye tuna and swordfish, whereas southern bluefin tuna had a slightly higher number of hooks per set (Figure 14). Nevertheless, striped marlin captures tended to occur on sets with slightly fewer hooks than the overall median.

The number of hooks-between-floats is often used as a proxy for hook depth. There was a wide range in the number of hooks-between-floats used on sets with striped marlin bycatch, with 90% of captures occurring on sets with 4 to 18 hooks-between-floats. There was no clear difference in this feature between overall sets and sets with positive captures. In contrast, there were some differences in the distribution of number of hooks-between-floats amongst target species; e.g., swordfish tended to have a lower number of hooks-between-floats than bigeye tuna and southern bluefin tuna, corresponding with shallower sets.

The use of lightsticks differed on sets with striped marlin bycatch compared with overall sets: the distribution of this operational feature shifted towards a higher number of lightsticks per hook for all target species, and particularly for swordfish.

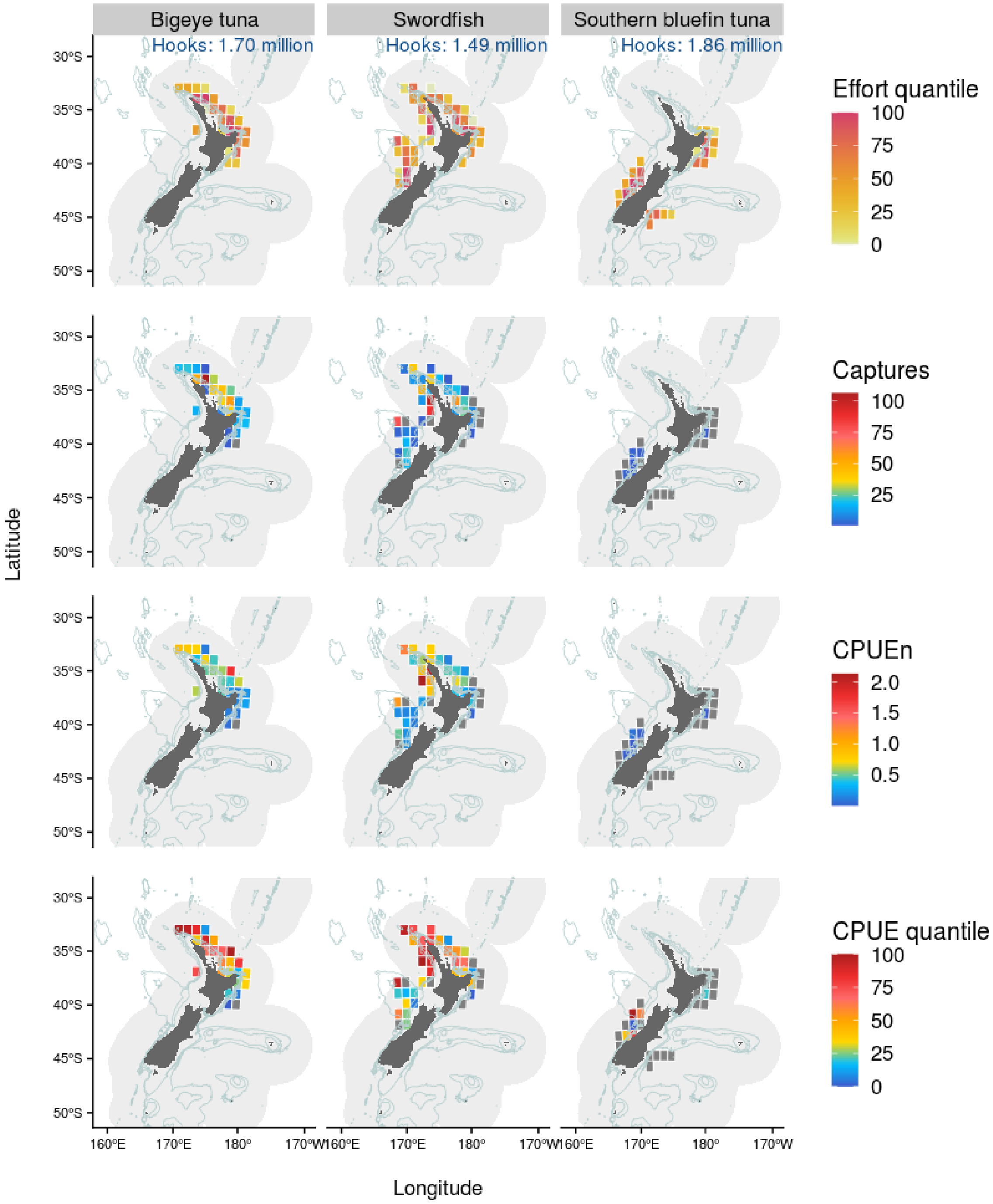

Figure 12: Effort quantile, striped marlin captures, striped marlin catch-per-unit-effort (CPUE) and CPUE quantile by key target species over the five main months when striped marlin was caught in New Zealand's Exclusive Economic Zone (January to May), aggregated at the 1° resolution from 2014–15 to 2018–19. Effort and CPUE quantiles show the relative quantile position of each cell compared with the overall effort and CPUE for the target species. Cells with no captures are shown in dark grey. Total effort and striped marlin captures are noted in the top right corner. Catch and CPUE values higher than the 99th quantile across target species are shown in dark red. Cells are only included if records span at least three vessels. Bathymetry contours for 200, 500, and 1000 metres depth are included.

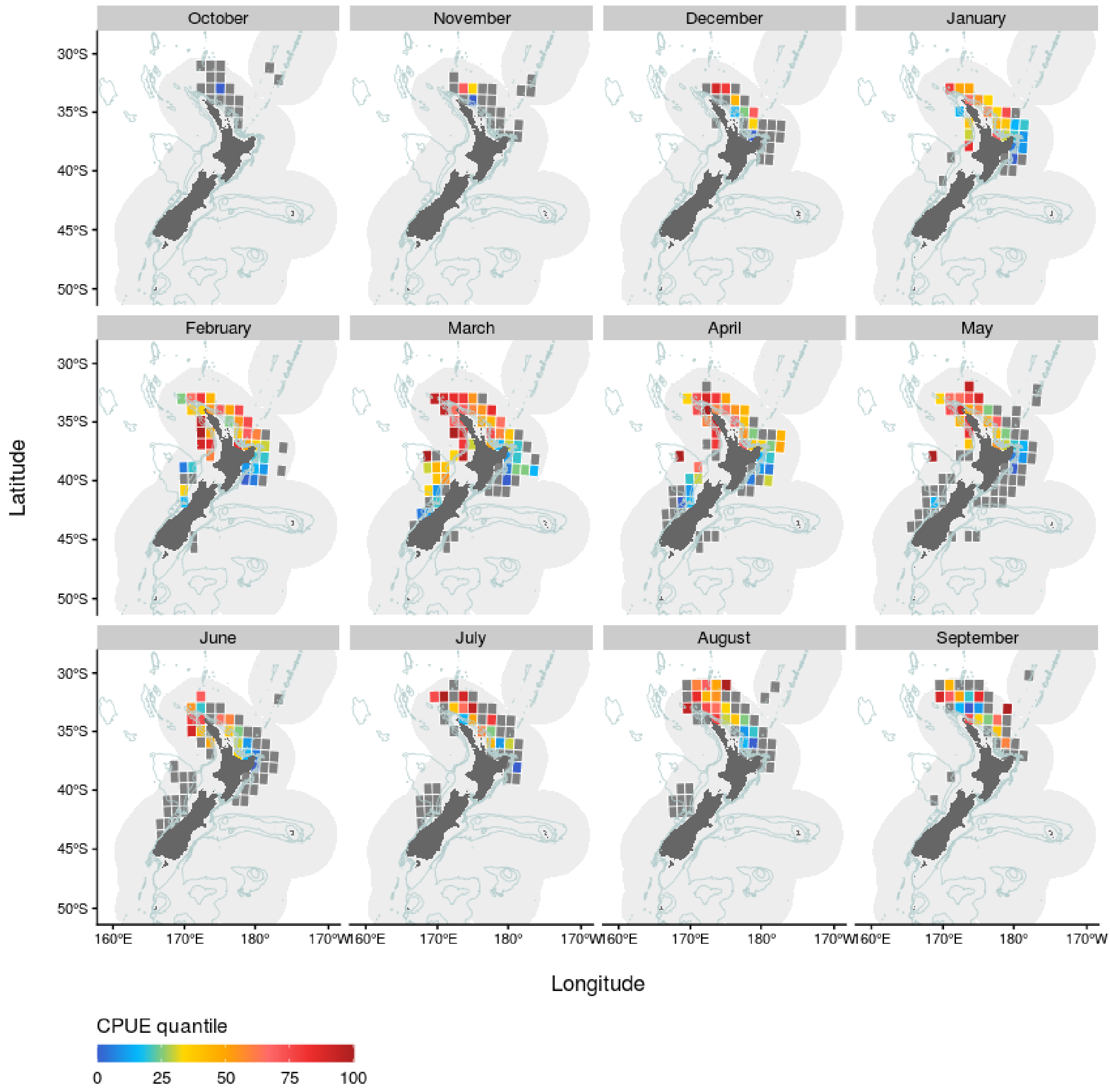

Figure 13: CPUE quantile by month over the New Zealand's Exclusive Economic Zone, aggregated at the 1° resolution from 2003–04 to 2018–19. CPUE quantiles show the relative quantile position of each cell compared with the overall CPUE for month. Cells with no captures are shown in dark grey. Cells are only included if records span at least three vessels. Bathymetry contours for 200, 500, and 1000 metres depth are included. Months are ordered from October to September, following the definition for the fishing year.

Regarding temporal features, the seasonal distribution of effort varied amongst target species during the year (Figure 14). Effort targeting bigeye tuna was spread throughout the year with a peak in summer, whereas effort targeting swordfish mostly occurred between January and June; sets targeting southern bluefin tuna peaked in the winter months between May and August. For target species, there was also a seasonal difference between the distribution of overall sets and sets with striped marlin captures. Striped marlin captures on bigeye tuna sets mostly occurred between January and July (90% quantile range; median: March), whereas sets targeting swordfish mostly captured striped marlin between January and May (median: March). In contrast, striped marlin bycatch in sets targeting southern bluefin tuna mostly occurred in the later part of the year, between March and September (median: July). In addition, there were small differences in the timing of sets throughout the day across target species, but most sets occurred after dusk and overnight. There was no clear pattern in the timing of sets in relation to striped marlin bycatch.

3.2.2 Temporal trends in bait type and light stick usage

Bait type and the use of lightsticks are two operational characteristics that are often associated with specific target species in longline fisheries (e.g., Ward et al. 2000). Since bait type was first recorded in 2003–04, squid bait has become increasingly prevalent over time on longline sets for all three key target species (Figure 15). Throughout the time series, the use of squid bait was particularly prevalent on sets targeting swordfish, but the use of fish bait has declined in all target species over time. There was a concomitant increase in the proportion of sets using at least 95% squid bait. In the second half of the time series this proportion of sets exceeded 75% for sets targeting swordfish and southern bluefin tuna, with some variability.

Nominal striped marlin CPUE for sets using mostly squid bait tended to be higher than the CPUE for sets using mostly fish bait for all target species; however, the reduced use of fish bait also implied that there were considerably fewer sets for which to calculate this statistic, so there is little statistical power to confirm this pattern.

The use of lightsticks also increased over time for all three main target species (Figure 16). For swordfish targets, sets frequently used lightsticks on at least 50% of hooks. Lightsticks were less prevalent on sets targeting southern bluefin tuna, with most sets having less than 1 in 4 lightsticks per hook throughout the time series. The influence of the use of lightsticks on nominal striped marlin catch rates was variable; for swordfish and bigeye tuna targets, the number of lightsticks-per-hook spanned a wider range than for sets targeting southern bluefin tuna. For these two target fisheries, sets with high lightstick usage (>75%) tended to have a similar or higher striped marlin CPUE than sets with low lightstick usage (<25%).

3.2.3 Environmental characteristics associated with surface-longline sets

There were some clear differences in the distribution of oceanographic variables associated with longline effort that caught striped marlin compared with overall effort (Figure 17). For all target species, striped marlin was caught in sets associated with comparatively higher sea surface temperature and lower chlorophyll-*a* concentration. For bigeye tuna, striped marlin tended to be caught on sets with bottom depths slightly shallower than overall effort. In comparison, for southern bluefin tuna, striped marlin captures were more constrained towards the mean of the depth distribution (noting different depth distributions of North Island fishing grounds for this target species compared with the South Island region). There was no depth effect for swordfish targets. For sets targeting bigeye tuna or swordfish, the rate of striped marlin captures was higher for those sets when approaching the full moon, but there was no apparent effect of moon illumination for southern bluefin tuna target sets.

Operational covariates:

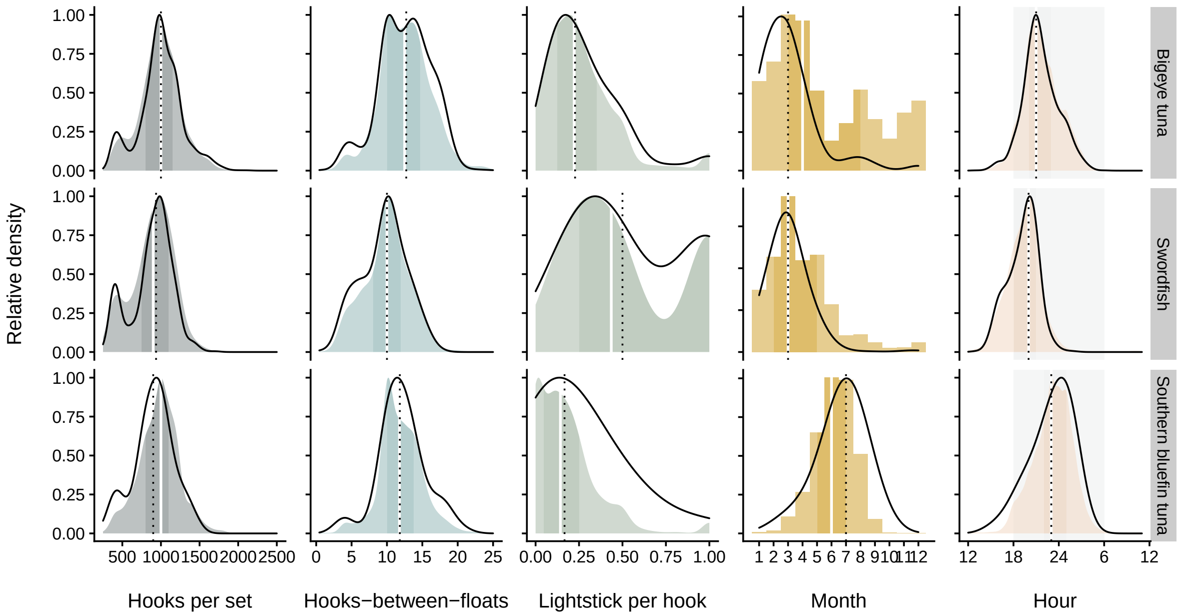

Figure 14: Distribution of key operational variables for the three main target species with striped marlin bycatch, aggregated from 2003–04 to 2018–19. The corresponding distribution for sets with at least one striped marlin capture is overlaid in black. The median values for the distributions for all sets (white) and sets with a striped marlin capture (dotted black) are shown with the vertical lines, and the inter-quartile range for the overall distribution is highlighted in a darker colour. For clarity, effort as number of hooks per set was constrained to a maximum of 2500 hooks, and number of hooks-between-floats to values between 0 and 25.

The oceanographic variable with the greatest influence on striped marlin captures was sea surface temperature (SST; Figure 17). Surface-longline effort was distributed across a range of SST values, varying seasonally throughout the year (Figure 18). Striped marlin captures occurred on sets that were fished at the upper end of the SST range in most years. Striped marlin CPUE also tended to be higher in the uppermost SST range of the effort. For bigeye tuna and swordfish targets, striped marlin was caught across a wider range of SST than for southern bluefin tuna.

The highest striped marlin CPUE across fishing effort was in the 2015–16 fishing year and associated with SST in the upper range (>20 °C); it also coincided with a strong El Niño phase of the El Niño Southern Oscillation (ENSO). This pattern was less evident when extending the striped marlin time series to include years with less reliable catch records prior to 2003–04: years with high striped marlin CPUE occurred in both ENSO phases throughout the time series (Figure 19). When focusing on strong ENSO events only, the year immediately following the 1998 El Niño event showed the highest number of striped marlin captures and CPUE, with CPUE gradually declining to long-term monthly averages in the two subsequent years. This gradual three-year decline in high CPUE also occurred to a lesser extent in the three years following the strong El Niño event in 2015.

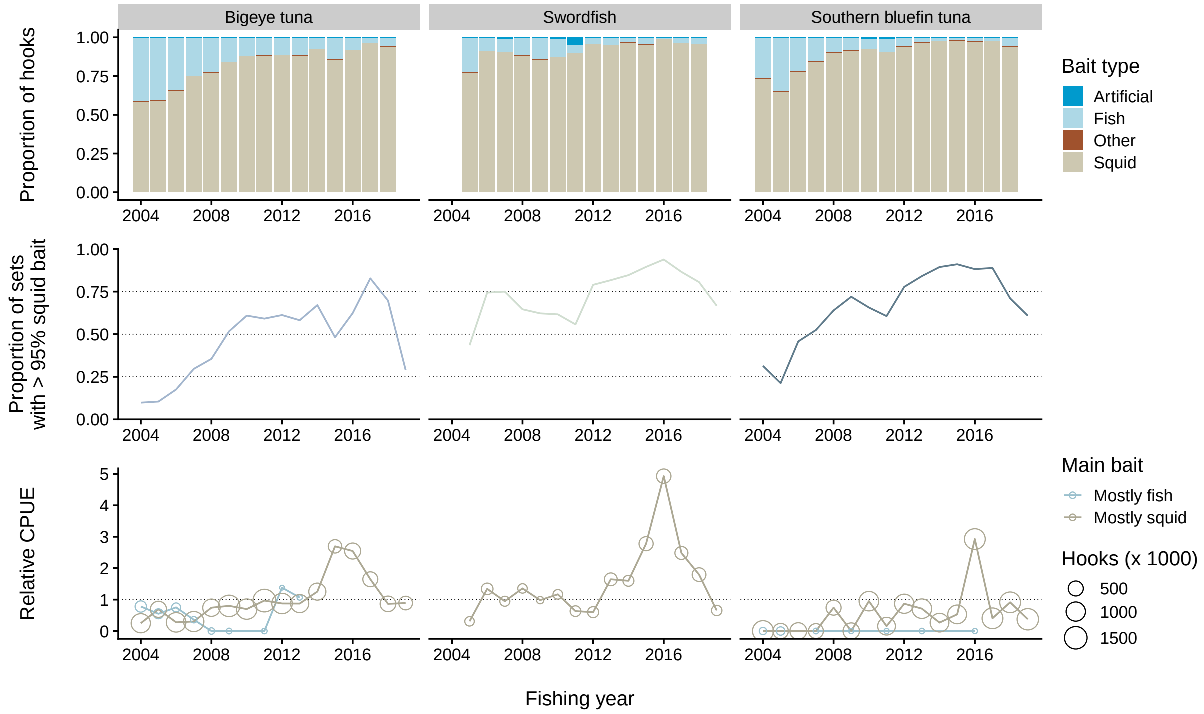

Figure 15: Summary of trends in bait use by fishing year and key target species catching striped marlin, for the period between 2004 and 2019. Proportion of effort (in hooks) by bait type (top), proportion of sets using primarily (>95%) squid bait (centre), and nominal catch-per-unit-effort (CPUE mean-centered) of striped marlin, aggregated over sets using mostly squid bait (> 50%; beige) or mostly fish bait (> 50%; blue) (bottom). Size of the circles shows the fishing effort in thousand hooks.

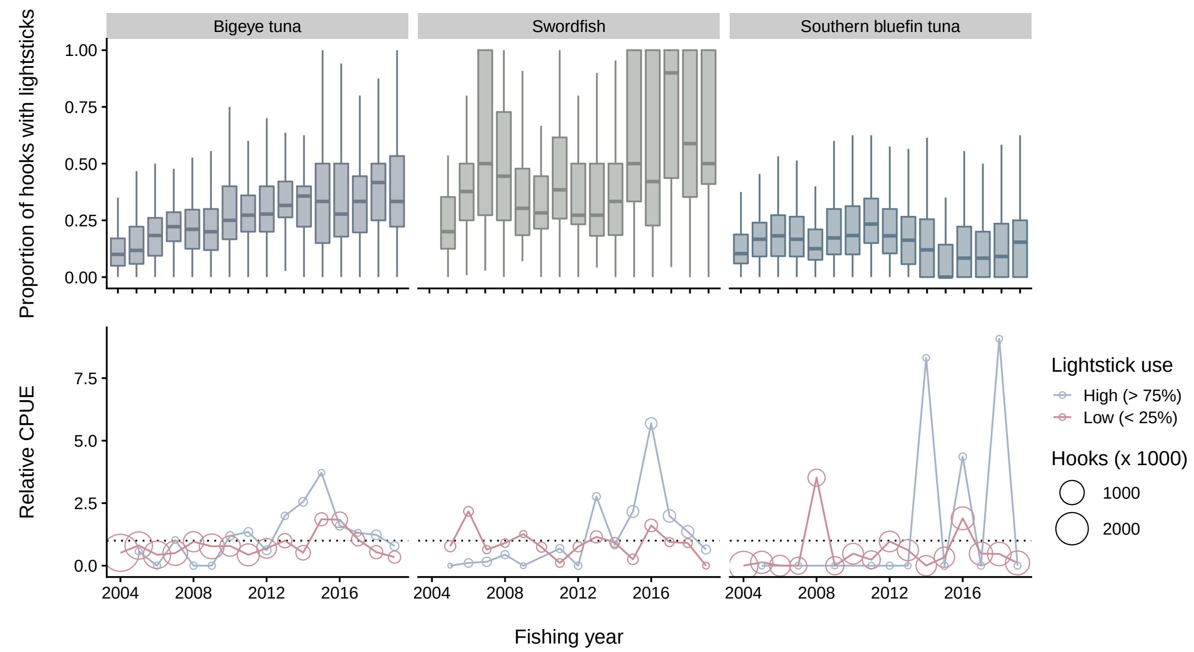

Figure 16: Summary of trends in lightstick use by fishing year for the key target species catching striped marlin, for the period between 2004 and 2019. Boxplot of the proportion of hooks on sets using lightsticks, with the median indicated by bold horizontal line (top). Nominal catch-per-unit-effort (CPUE, mean-centered) of striped marlin, aggregated over sets with high (>75% of hooks) and low (<25% of hooks) lightstick usage (bottom). Size of the circles shows the fishing effort in thousand hooks.

Environmental covariates:

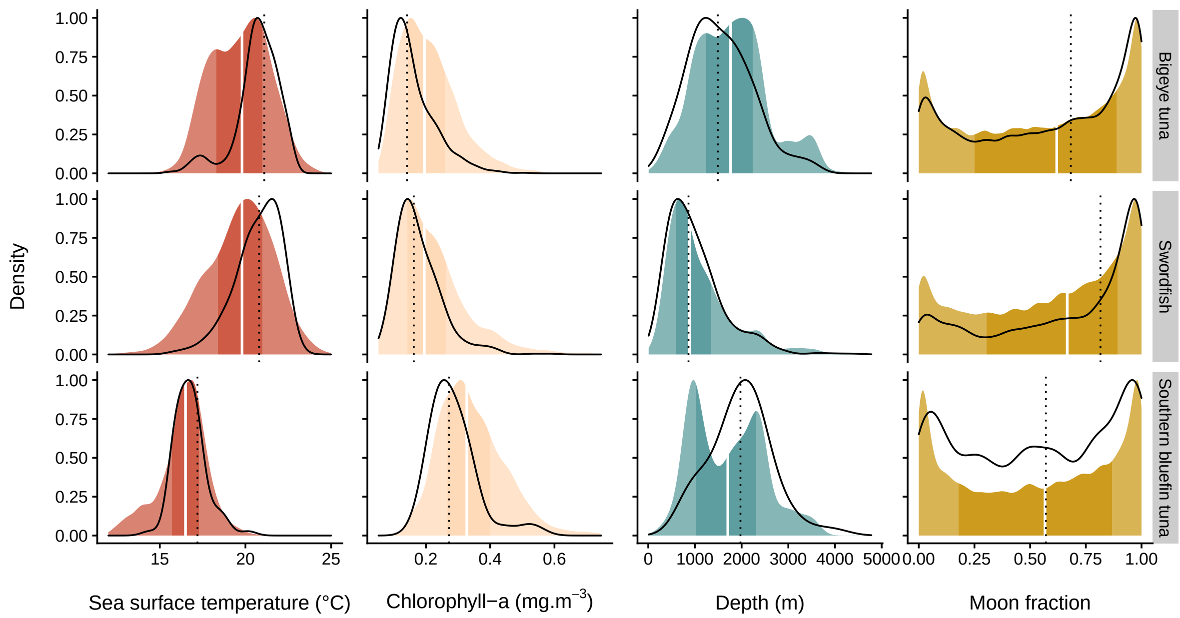

Figure 17: Distribution of key oceanographic variables for the three main target species with striped marlin bycatch, aggregated from 2003–04 to 2018–19. The corresponding distribution for sets with at least one striped marlin capture is overlaid in black. The median values for the distributions for all sets (white) and sets with a striped marlin capture (dotted black) are shown with the vertical lines, and the inter-quartile range for the overall distribution is highlighted in a darker colour. SST is based on *in situ* measurements by fishers recorded on the effort return forms.

Monthly CPUEs were grouped by month and ranked in descending order from high to low to compare the distribution of CPUEs within the same month across years. The highest December, January, February, March, and April CPUEs consistently occurred in years with moderate or strong El Niño events (Figure 20). High monthly CPUE outlier events in the months of March, August, and December also occurred during El Niño events.

At the same time, the latitudinal extent of sea surface temperatures that are optimal for striped marlin (>20°C) has increased within New Zealand's Exclusive Economic Zone since 1990, with the southern bound of the 20°C isotherm extending south over time (Figure 21). This aspect was evident in most months, except for March, August, and September. The rate of this southward extension of warm SST was especially high during the months of January, April, and December. There was no clear link between the southern extent of the 20 °C isotherm and ENSO, although outliers for some months (e.g., January, February, and December) can be associated with La Niña or El Niño phases of ENSO.

The distribution of striped marlin captures also extended southward, with an overall decrease in the median latitude of striped marlin captures over time (Figure 22). For longline sets targeting swordfish, the southward expansion was also evident when considering the southern boundary of fishing sets with striped marlin bycatch (97.5th quantile of latitudes). The southward expansion was reflected to a lesser extent in the distribution of overall longline effort for the main three target species, particularly for swordfish and southern bluefin tuna.

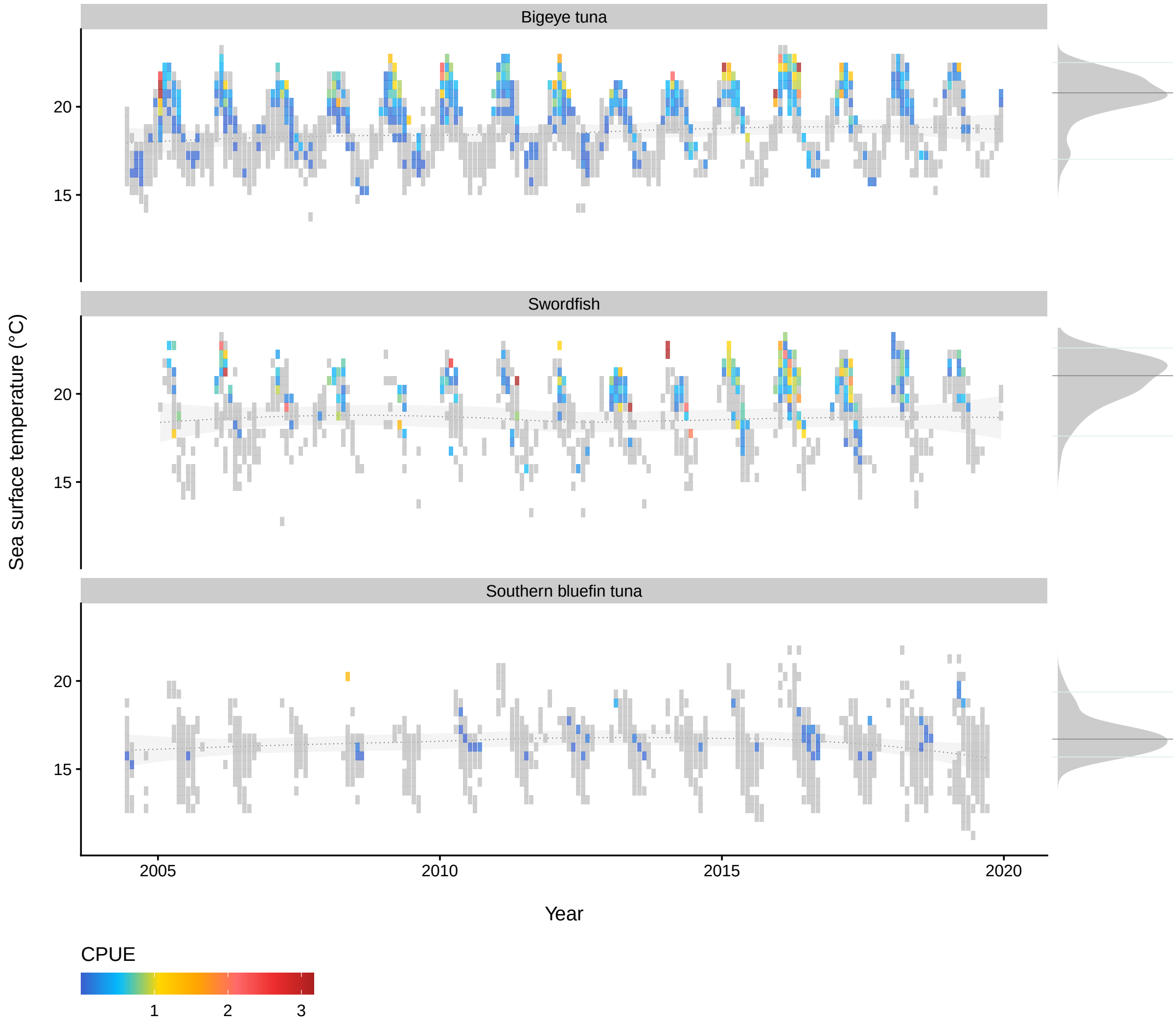

Figure 18: Striped marlin catch-per-unit-effort (CPUE; individuals per 1000 hooks) by main surface-longline target species, aggregated by month-year and by sea surface temperature (SST) associated with a set, grouped by 0.5 °C. Cells with no striped marlin bycatch are shown in grey, CPUE values in excess of the 99th quantile are shown in dark red. Smoothed trend of overall SST distribution of effort for each target species is overlaid. Marginal density plots (right-hand side) show the overall distribution of striped marlin bycatch by SST, with the median and 95% quantile range highlighted.

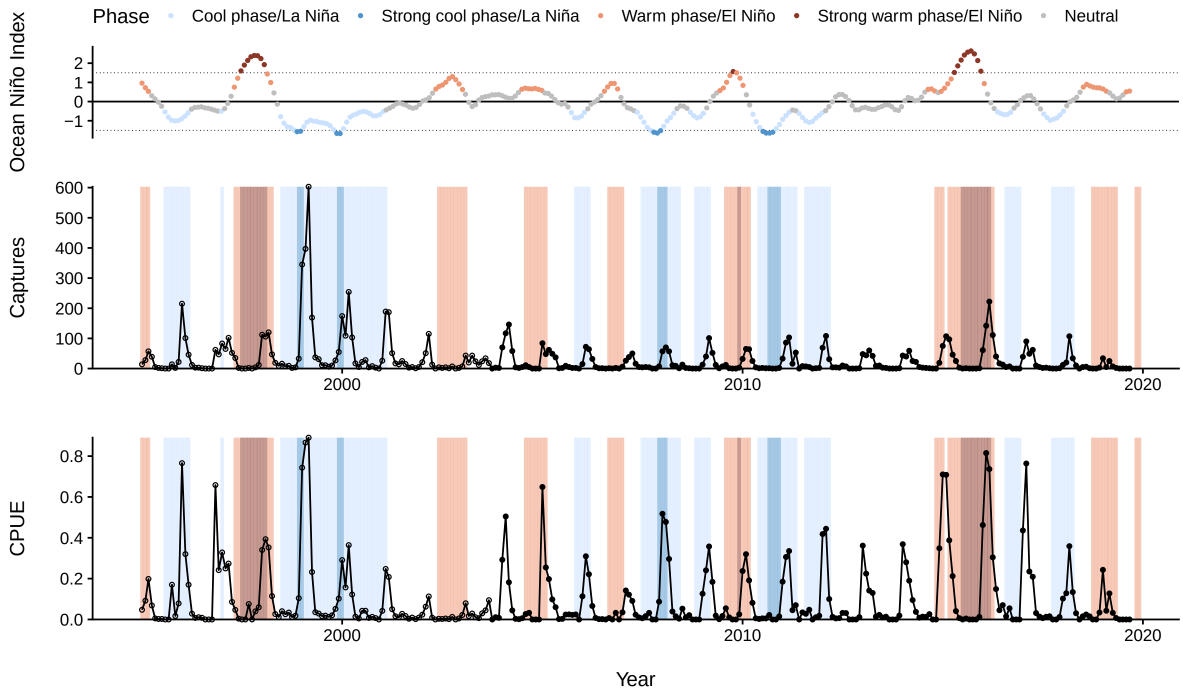

Figure 19: Summary of temporal trends in bycatch of striped marlin in surface longlines and catch-per-unit-effort (CPUE) by month in relation to the El Niño Southern Oscillation (ENSO). Top: Ocean Niño Index (ONI) over time, with El Niño and La Niña phases shown in red and blue, respectively; horizontal dotted lines highlight the threshold for defining "strong" events. Centre and bottom: Striped marlin captures (in individuals) and CPUE (individuals per thousand hooks) over time, with ENSO phases shown in the background when not in neutral phase. Less reliable catch records from the period prior to 2003–04 are shown by empty circles.

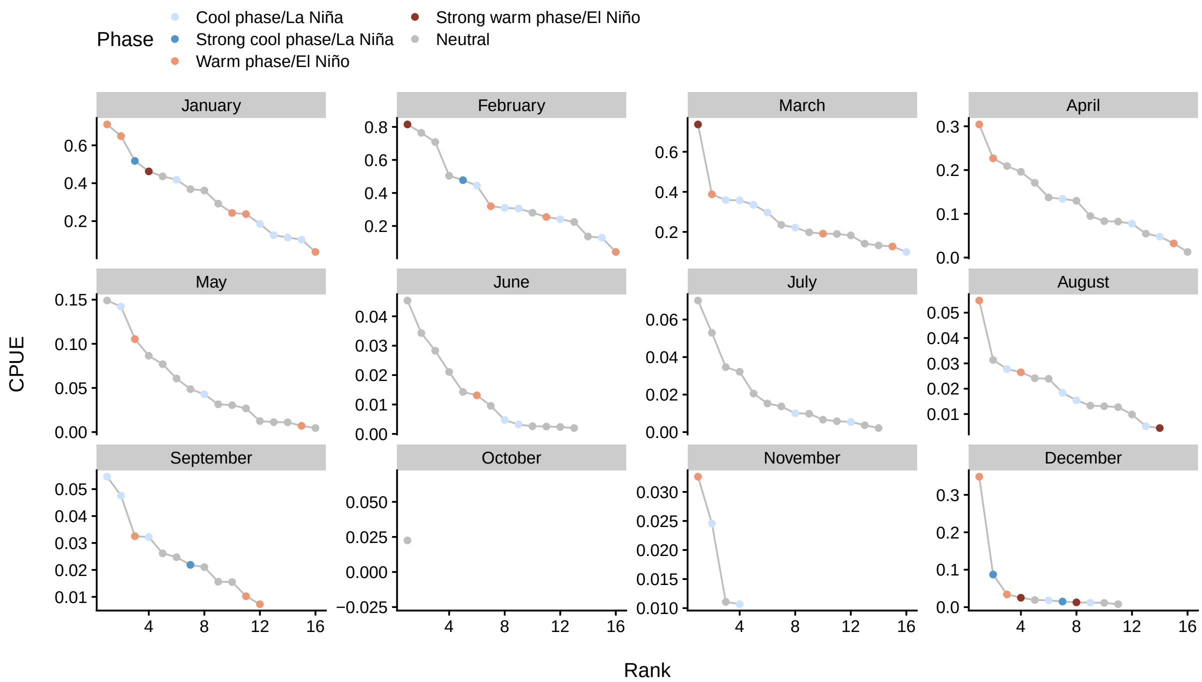

Figure 20: Striped marlin catch-per-unit-effort (CPUE; individuals per thousand hooks) by year-month for the period of reliable records (2003–04 onwards), ranked within months by descending CPUE, i.e., the year with the highest CPUE for a given month receives a rank of 1. Points are coloured as a function of the different phases of the El Niño Southern Oscillation (ENSO).

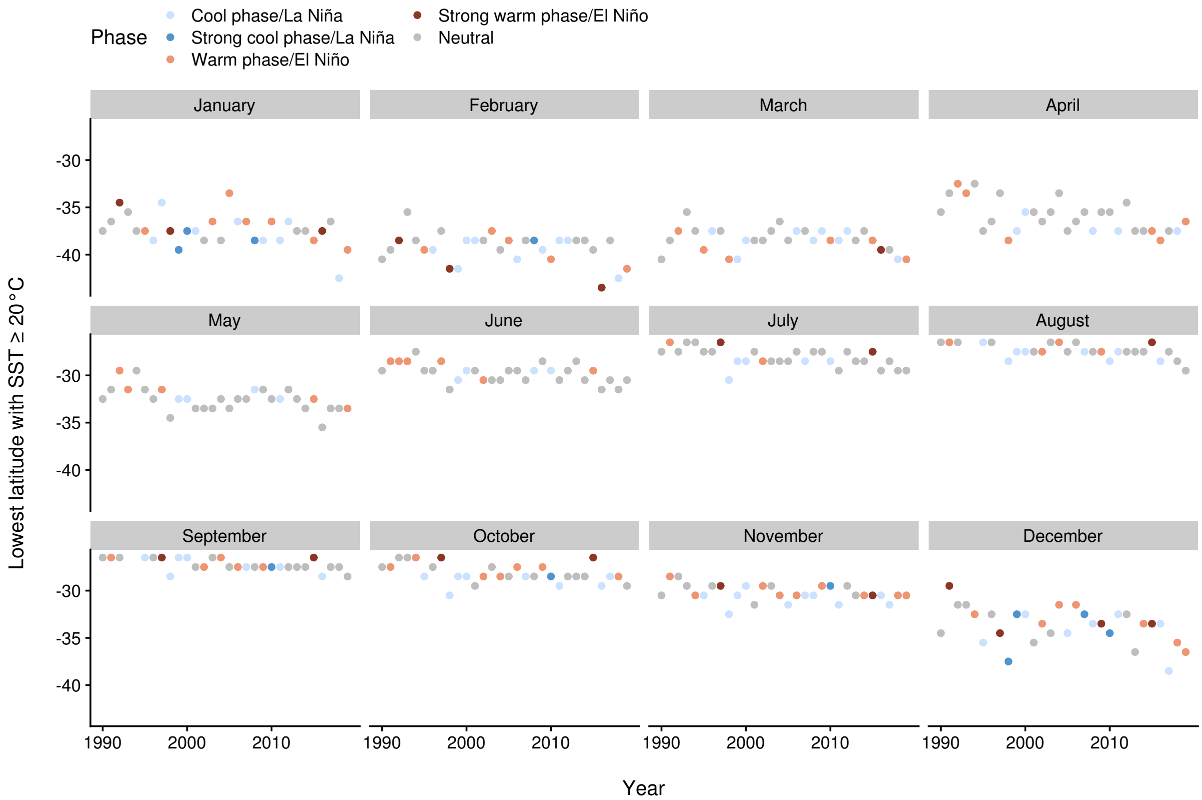

Figure 21: Southernmost latitude of the 20 °C isotherm by month from 1990 to 2019 based on the 1° resolution SST climatology for New Zealand, with points showing the different phases of the El Niño Southern Oscillation (ENSO).

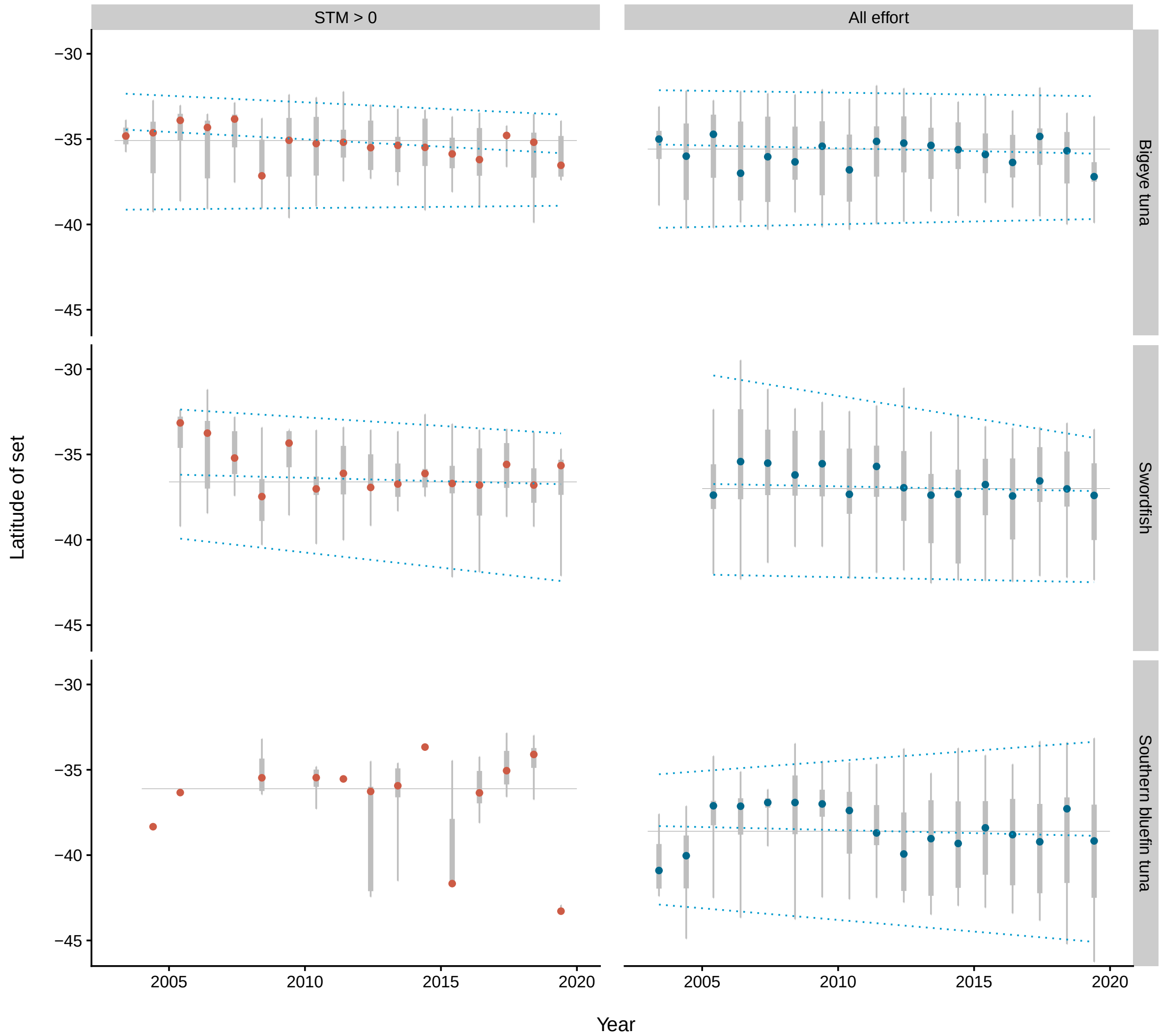

Figure 22: Distribution of the latitude of surface-longline sets with striped marlin bycatch (left) and all effort (right), by key target fishery. Coloured points show the median, grey bar the inter-quartile range, and whiskers extend to the 95% quantile range. Dotted lines are the predicted trend for a quantile regression of the 2.5th, 50th, and 97.5th quantiles for each category, and were only included when there were at least ten years of observations with at least three records. The horizontal grey line shows the overall median latitude for each effort and target species category.

3.2.4 Modelling the impacts of oceanography and environmental variables

The probability of striped marlin bycatch in a set was modelled as a function of oceanographic and environmental variables using a Generalised Additive Model (GAM). A set of different model structures was explored to assess the effect of collinearity between covariates on the predicted effect on striped marlin bycatch (Figure 23). The full model including all covariates explained a limited proportion, 22.1%, of the data; a simpler model including SST, target species, and longitude explained 18.2% of the data (Table C-3). Model diagnostics are shown in Figure C-1.

Model interpretation was complex owing to the non-linear interactions between covariates. The most influential covariates across models were SST and chlorophyll-*a*, with increases in SST consistently predicted to increase the probability of capture (reaching a plateau at 21 °C, with uncertainty in the effect below 17.5 °C). In contrast, increasing concentrations of chlorophyll-*a* decreased the probability of capture. Moon illumination was less influential, but consistently predicted higher probability of capture at both new and full moons, with full moon having the highest probability of capture overall. The Ocean Niño index also scaled with higher probability of bycatch, i.e., striped marlin bycatch was predicted to increase during El Niño phases of the cycle. The impact of most operational covariates varied as a function of model structure, especially whether target species was included as a categorical covariate (e.g., see "Full model, no target species" in Figure 23). The probability of bycatch increased slightly with an increase in the number of hooks; there were no clear effects for other operational covariates.

The predicted relationship for lightstick usage and number of hooks-between-floats varied across models depending on whether longitude was included as a covariate, indicating that the distribution of these variables varied with longitude. Set haul time was not retained as a covariate in any of the models, whereas depth was retained only in the model without longitude.When included, longitude was predicted to decrease the probability of bycatch from 172° E eastward.

The relative effect of target species, when included as a categorical covariate, was consistent across models: sets targeting swordfish were estimated to increase the probability of striped marlin bycatch to a small extent compared with bigeye tuna target sets (the intercept), whereas southern bluefin tuna target sets had a markedly lower probability of bycatch overall (Figure 24). The coefficient for swordfish targets was only significantly different from the bigeye tuna target coefficient in models that did not include longitude as a covariate, indicating that the target species effect was confounded with longitude within the model.

A random forest model was used as an alternative modelling approach to rank the covariates in terms of their importance in predicting bycatch probability (Figure 25). This approach is robust to collinearity, and the results were consistent with the findings under the GAM-based multi-model approach: the most influential covariates were SST and longitude, followed by moon illumination and chlorophyll-*a*, then bathymetry, hooks-between-floats, and the Oceanic Niño Index.

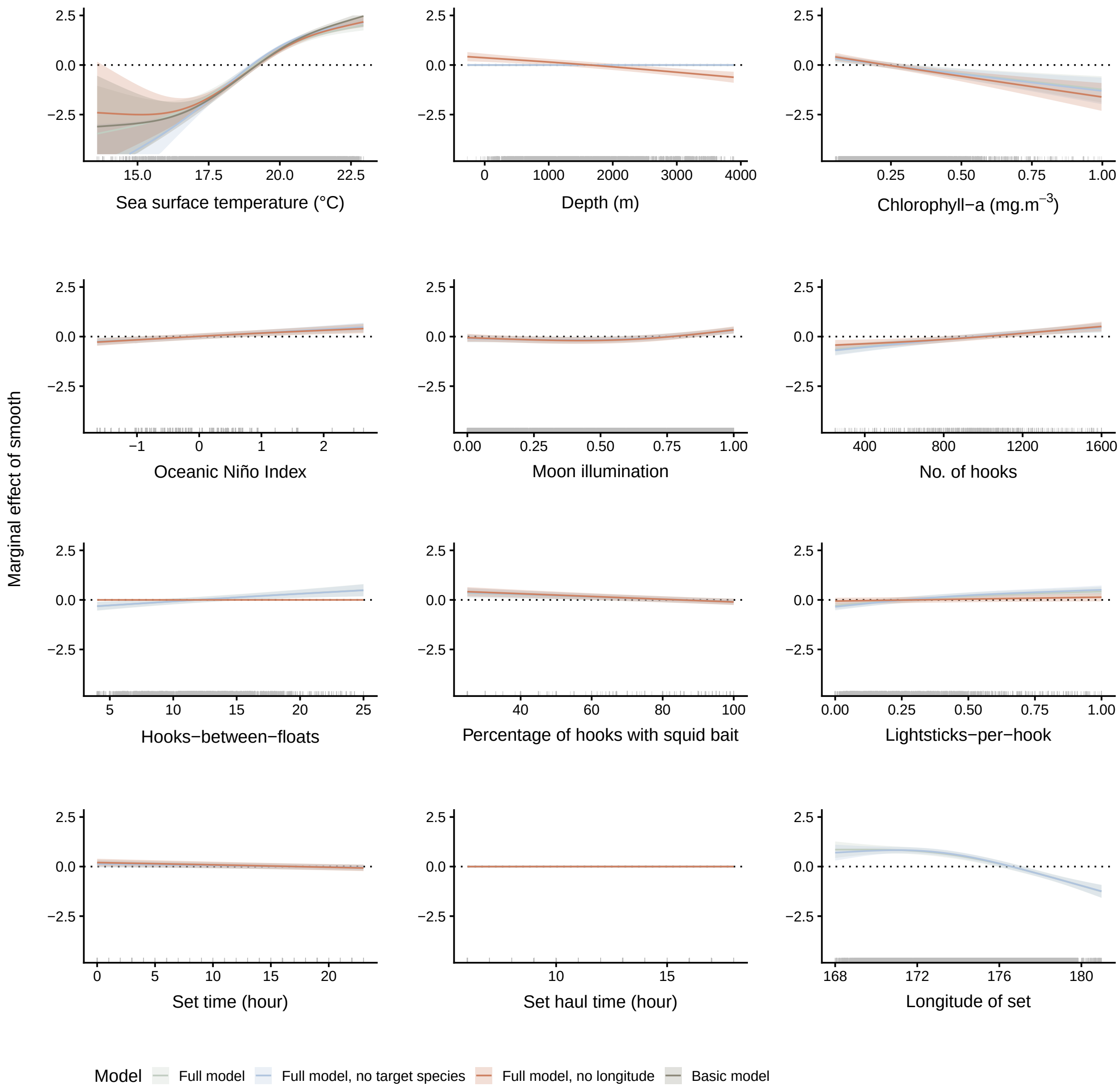

Figure 23: Marginal effect for the estimated smooth for each covariate used to predict the probability of striped marlin bycatch in surface-longline fisheries. The estimated relationship is shown for different model structures, with the band showing the 95% confidence interval. Covariates discarded by the model are shown as a straight line; dotted line shows a baseline relationship of no effect.

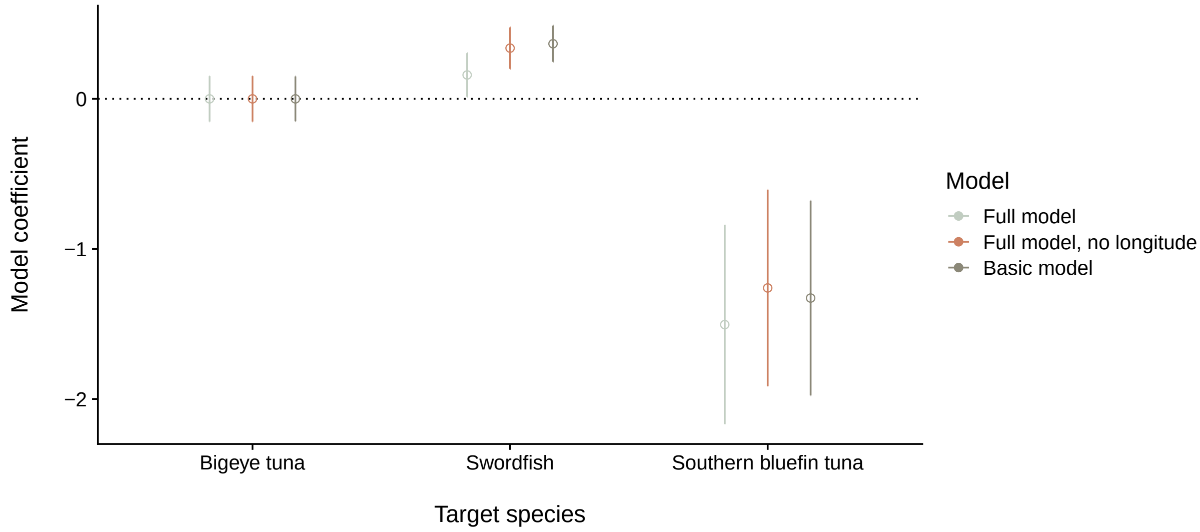

Figure 24: Estimated coefficient for target species under alternative model structures including target species as a categorical variable. All coefficients are relative to the intercept for bigeye tuna target sets. Whiskers span the 95% confidence interval.

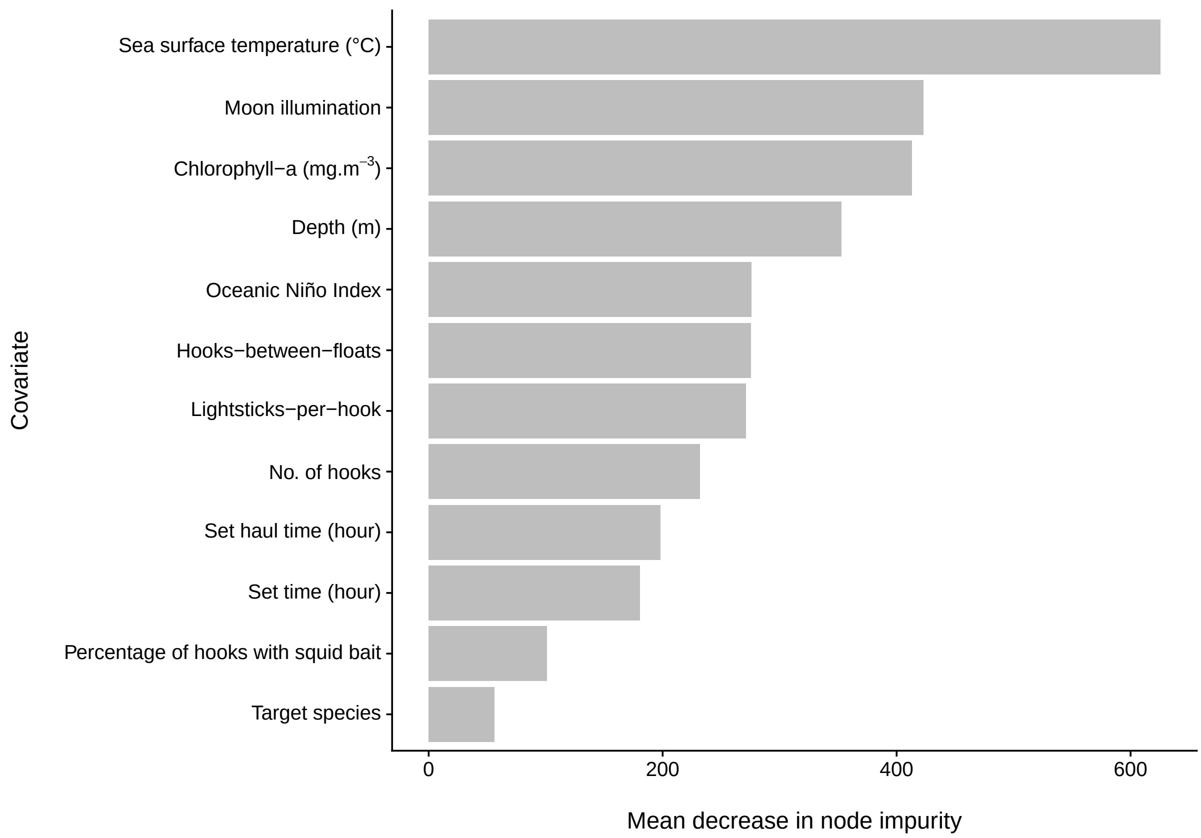

Figure 25: Relative importance of covariates in the prediction of striped marlin bycatch in surface-longline fisheries in a random forest model, as quantified by the mean decrease in the Gini index. SST, sea surface temperature; chl-*a*, surface water chlorophyll-*a* concentration.

4. DISCUSSION

This study reviewed bycatch of striped marlin by commercial surface longliners in New Zealand waters. Overall bycatch levels were stable over the time period that had reliable catch records (2003–04 to 2018–19), with some year-to-year variability. Both striped marlin captures and catch-per-unit-effort have declined over the last three years (2016–17 to 2018–19) following a peak in 2015–16. The three key target species in the surface-longline fleet were bigeye tuna, swordfish and southern bluefin tuna; striped marlin bycatch was common in sets targeting bigeye tuna and swordfish, with occasional bycatch in southern bluefin tuna target sets.

Changes in the surface-longline fishing fleet over time led to changes in striped marlin bycatch. Initially, most bycatch occurred in surface-longline sets targeting bigeye tuna, but about half of recent striped marlin bycatch occurred in swordfish-targeted sets. Swordfish-targeted sets became more common in the early 2000s when swordfish became a legal target species, and fishing effort directed at this species has increased over time. At the same time, fishing effort targeting southern bluefin tuna has steadily increased and makes up most of the current surface-longline fishing effort. Nevertheless, striped marlin captures rates in this target fishery have been low, so that the increased effort in the southern bluefin tuna target fishery did not result in increased striped marlin bycatch levels for this fleet.

There were distinct spatial patterns in the distribution of striped marlin bycatch, with most capture events occurring in North Island waters, from Bay of Plenty to Northland. In contrast, there were few captures (and low CPUE) off the east coast south of Hawke Bay. This pattern appeared to correspond with patterns of spatial occupancy and not catchability, because effort targeting bigeye tuna and swordfish spanned both of these regions during summer, and capture rates by these two fleets were considerably higher north of Hawke Bay. Also, none of the striped marlin individuals tagged with archival or satellite tagss in New Zealand have been recorded south of Hawke Bay, although it is worth noting that all individuals were tagged in Bay of Plenty or Northland (Sippel et al. 2007, Sippel et al. 2011).

There was occasional striped marlin bycatch in South Island waters, but only off the west coast during the warmer months of summer. Increasing sea surface temperatures may have impacted the distribution of striped marlin captures, with the boundary of striped marlin bycatch extending southward. This aspect was particularly evident in the swordfish target fishery. Fishing effort for this species extends along a north-to-south axis off the west coast, which could enhance the chance of detecting a shift in the distribution of striped marlin in the future.

Striped marlin's preference for warmer waters between 20 and 24 °C was reflected in distinct seasonal trends in the bycatch records. Capture rates were particularly high in warmer months between January and March, coinciding with the fishing season for swordfish and also bigeye tuna to some extent. For these two target species, the number of striped marlin captures were highest in February and March. In contrast, for southern bluefin tuna, striped marlin bycatch was highest in the winter months between June and August, when effort targeting this species shifted from off North Island east coast towards Bay of Plenty and Northland.

Striped marlin CPUE was highest in swordfish target sets. This finding is in part explained by the seasonal and spatial distribution of this target fishery, which has the greatest overlap with striped marlin occupancy in New Zealand waters. In addition, the operational features of sets targeting swordfish should increase the catchability of striped marlin, because they tend to be shallower (indicated by the number of hooks-between-floats), which should increase the probability of striped marlin bycatch given its preference for epipelagic waters (Sippel et al. 2007). This expectation, however, was not confirmed by this analysis: striped marlin captures occurred across a range of hooks-between-floats setups, and this operational feature had little influence on the bycatch prediction model. It is possible that striped marlin were captured on shallow hooks close to a float, but the hook position of captures is not recorded on TUN forms. Alternatively, there have been reports of striped marlin captures occurring as the line is being hauled (Holdsworth & Kopf 2011); in this situation, the number of hooks-between-floats would not necessarily be representative of hook depth at the time of striped marlin captures.

Although there was a distinct signal in striped marlin capture rates by target species, the operational covariates included in this analysis, including hooks-between-floats, did not explain a high proportion of variation in the capture rates across sets. Instead, oceanographic covariates, mostly SST but also chorophyll-*a*, had the strongest predicted influence. Moon illumination was also selected as influential, with higher predicted capture rates when sets were fished in periods approaching the full moon. Overall the proportion of bycatch explained by covariates was low (about 20%), which might mean that there is high variability in striped marlin capture rates due to chance; it may also indicate that there are other significant covariates that were not considered here.

A previous study by Holdsworth & Kopf (2011) standardised CPUE from the commercial observer data for the surface longlining fleet and explained a higher proportion of the deviance (34.5%) than the present models. Their model included year as an explanatory variable, which explained on its own about 13% of the deviance. Year was not considered as a covariate in the current analysis as the aim was to identify operational or environmental conditions likely to increase striped marlin bycatch, and these can be confounded with a year effect if their distribution changes over time. In parallel, other standardisation models of the recreational billfish fishery (e.g., Holdsworth et al. 2018, Holdsworth & Saul 2019) included a recreational fishing zone as a categorical factor and found an increasing gradient in the model coefficients from the Bay of Plenty/Gisborne, East Northland and Far North; the model coefficient for the North Island west coast was also high (but slightly lower than Far North). This spatial pattern matches the relative distribution in commercial striped marlin bycatch rates described here for the commercial surface-longline fleet, as well as the longitude effect estimated by the GAMs that included longitude as a covariate.

The current analysis relied on the species declared by fishers as their target as a basis for classifying and interpreting trends in the surface-longline dataset. The HMS working group noted that this variable might not always be reliable (Highly Migratory Species Working Group 2020), which may explain the lack of contrast observed here in the operational characteristics of sets targeting bigeye tuna, swordfish, and southern bluefin tuna. Nevertheless, the target species covariate remained useful for this analysis because it was still associated to an effect on striped marlin bycatch, and allowed the classification of fishing effort according to distinct spatial and temporal trends.

Two temporal trends in operational covariates that were particularly pronounced over the assessment period were the transition from fish bait to almost exclusively squid bait across target species, and the increased use of lightsticks. The latter aspect was particularly evident on sets targeting bigeye tuna and swordfish. The impact of squid bait on striped marlin bycatch was difficult to formally quantify, because there was limited effort using primarily fish bait at the start of the time series only. There was a small positive effect of lightstick usage on the probability of striped marlin bycatch, determined by the bycatch prediction model, but the distribution of this covariate also appeared to change with longitude. An earlier study by Francis et al. (2000) spanning 1988–89 to 1997–98 found that the probability of striped marlin bycatch was higher when fish bait was used, but the use of squid bait was not widely spread over the years included in the study. No previous study documenting the effect of lightsticks on striped marlin bycatch was found.

A key challenge in this analysis was the restricted time period with reliable catch records (given the lack of a formal process for recording discarded bycatch prior to 2003–04). This aspect complicated the long-term analyses of the effect of climate on catch rates, particularly because one of the two strong El Niño events occurred prior to 2003–04. Although there was a clear signal that this El Niño event influenced striped marlin bycatch and CPUE, this part of the dataset was not included in the bycatch prediction model because the catch records in this time period were considered unreliable. The effect of ENSO on striped marlin bycatch rates might be better characterised in future years, once it is possible to include a second strong ENSO event (or more) in the model data set.

The main covariate explaining striped marlin bycatch in New Zealand was SST, so that both ENSO and long-term climate change were expected to influence bycatch rates. When examining the long-term time series of striped marlin bycatch and CPUE in relation to the Oceanic Niño Index used as a proxy of ENSO phases, there were two prominent trends. First, there was a distinct increase in bycatch and CPUE during or immediately following the two strong El Niño events of 1998 and 2015, but there was no consistent pattern in catch or CPUE in the period in-between these two years when weaker El Niño or La Niña events occurred. From the limited time series it appeared that strong El Niño events increase striped marlin bycatch rates, but the cause of this increase is unclear: it is possible that the increased bycatch rates were due to an increase in catchability (e.g., by a reduction in the availability of vertical habitat) or, alternatively, changes in local striped marlin abundance (e.g., by increasing the southward migration from the northern end of the range). Elucidating the underlying mechanisms of the increase associated with El Niño events was not part of the current analysis.

There was also a gradual decline in CPUE over three years following the peaks associated with the two strong El Niño events that occurred in 1998 and 2015. If the CPUE increase persists beyond El Niño, it might indicate that there was a recruitment effect which strengthened the El Niño cohort. As striped marlin takes on average three to four years to reach maturity, and individuals caught in New Zealand have been shown in a previous studies to be mostly mature (Kopf et al. 2012), this explanation appears unlikely. Instead, it might be that conditions in the years leading to a strong El Niño improved recruitment; this aspect may explain the high CPUE in years following the strong El Niño event, given the time-lag for individuals to reach maturity. Because weight is only roughly estimated in the TUN forms, it is currently not possible to examine whether a recruitment effect might be detected from shifts in the weight distribution of bycatch individuals, or if the proportion of mature individuals in the bycatch changes over time.

In summary, this analysis identified trends in striped marlin bycatch in New Zealand surface-longline fisheries by season, area, and fleet; however, it did not detect distinct patterns in operational features that result in increased capture rates. Instead, spatial and seasonal patterns in the distribution of fishing effort appeared to explain a high proportion of bycatch levels by target species, with bycatch rates highest in Bay of Plenty and Northland in February and March, and the Northland area and surrounding waters remaining a bycatch hotspot throughout the year, even during the winter months. Accordingly, the bycatch prediction model prioritised environmental over operational covariates; SST, chlorophyll-*a*, and moon illumination in particular were identified as having the greatest influence on striped marlin captures. In parallel, short-term effects of climate cycles and long-term effects of climate change were apparent in both catch and catch rate statistics. It is unclear whether these effects result from climate-determined changes in local abundance, catchability, or recruitment of striped marlin, or a combination of these factors.

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6. REFERENCES

Albers, S. (2020). Rsoi: Import various northern and southern hemisphere climate indices. R package version 0.5.4. Retrieved from https://CRAN.R-project.org/package=rsoi.

Domeier, M.L. (2006). An analysis of Pacific striped marlin (*Tetrapturus audax*) horizontal movement patterns using pop-up satellite archival tags. *Bulletin of Marine Science 79 (3)*: 811–825.

Ducharme-Barth, N.; Pilling, G.; Hampton, J. (2019). Stock assessment of SW Pacific striped marlin in the WCPO. WCPFC-SC15-2019/SA-WP-07, Report to the Western and Central Pacific Fisheries Commission Scientific Committee. Fifteenth Regular Session 12–20 August 2019, Pohnpei, Federated States of Micronesia.

Dunn, P.K.; Smyth, G.K. (1996). Randomized quantile residuals. *Journal of Computational and Graphical Statistics 5*: 236–244.

Fisheries New Zealand (2019). Fisheries Assessment Plenary, November 2019: Stock assessments and stock status. Compiled by the Fisheries Science and Information Group. Fisheries Science, Wellington, New Zealand.

Francis, M.P.; Griggs, L.H.; Baird, S.J.; Murray, T.E.; Dean, H.A. (2000). Fish bycatch in New Zealand tuna longline fisheries, 1988–89 to 1997–98. *NIWA Technical Report 76*. 79 p.

Highly Migratory Species Working Group (2020). Highly Migratory Species Working Group—August 4th 2020 meeting. Wellington, New Zealand. (Unpublished document held by Fisheries New Zealand).

Holdsworth, J.C.; Kendrick, T.H.; Domeier, M. (2018). Characterisation and catch per unit effort of striped marlin in New Zealand. *New Zealand Fisheries Assessment Report 2018/30*. 41 p.

Holdsworth, J.C.; Kopf, R.K. (2011). Characterisation of striped marlin fisheries and biology in New Zealand and wider southwest Pacific Ocean. *New Zealand Fisheries Assessment Report 2011/22*. 74 p.

Holdsworth, J.C.; Saul, P.J. (2013). New Zealand striped marlin recreational catch and effort 2011–12 and 2012–13. *New Zealand Fisheries Assessment Report 2013/67*. 29 p.

Holdsworth, J.C.; Saul, P.J. (2017). Striped marlin catch and CPUE in the New Zealand sport fishery 2013–14 to 2015–16. *New Zealand Fisheries Assessment Report 2017/18*. 27 p.

Holdsworth, J.C.; Saul, P.J. (2019). Striped marlin catch and CPUE in the New Zealand sport fishery 2013–14 to 2018–19. *New Zealand Fisheries Assessment Report 2019/74*. 33 p.

Kopf, R.; Davie, P.; Bromhead, D.; Young, J. (2012). Reproductive biology and spatiotemporal patterns of spawning in striped marlin *Kajikia audax*. *Journal of Fish Biology 81 (6)*: 1834–1858.

Kopf, R.; Davie, P.; Holdsworth, J. (2005). Size trends and population characteristics of striped marlin, *Tetrapturus audax* caught in the new zealand recreational fishery. *New Zealand Journal of Marine and Freshwater Research 39 (5)*: 1145–1156.

Lam, C.H.; Kiefer, D.A.; Domeier, M.L. (2015). Habitat characterization for striped marlin in the Pacific Ocean. *Fisheries Research 166*: 80–91.

Liaw, A.; Wiener, M. (2002). Classification and regression by randomforest. *R News 2 (3)*: 18–22. Retrieved from https://CRAN.R-project.org/doc/Rnews/.

Mamoozadeh, N.R.; Graves, J.E.; McDowell, J.R. (2020). Genome-wide SNPs resolve spatiotemporal patterns of connectivity within striped marlin (*Kajikia audax*), a broadly distributed and highly migratory pelagic species. *Evolutionary Applications 13 (4)*: 677–698.

Musyl, M.K.; Moyes, C.D.; Brill, R.W.; Mourato, B.L.; West, A.; McNaughton, L.M.; Chiang, W.-C.; Sun, C.-L. (2015). Postrelease mortality in istiophorid billfish. *Canadian Journal of Fisheries and Aquatic Sciences 72 (4)*: 538–556.

NASA (2014). MODIS-Aqua Ocean Color Data. NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Retrieved from https://modis.gsfc.nasa.gov/data/dataprod/chlor_a.php.

Pante, E.; Simon-Bouhet, B. (2013). marmap: A Package for Importing, Plotting and Analyzing Bathymetric and Topographic Data in R. *PLoS ONE 8 (9)*: e73051. doi:10.1371/journal.pone.0073051.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. Retrieved from https://www.R-project.org/.

Reynolds, R.W.; Rayner, N.A.; Smith, T.M.; Stokes, D.C.; Wang, W. (2002). An improved in situ and satellite SST analysis for climate. *Journal of climate 15 (13)*: 1609–1625. Retrieved from https://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/.

Sippel, T.J.; Davie, P.S.; Holdsworth, J.C.; Block, B.A. (2007). Striped marlin (*Tetrapturus audax*) movements and habitat utilization during a summer and autumn in the Southwest Pacific Ocean. *Fisheries Oceanography 16 (5)*: 459–472.

Sippel, T.; Holdsworth, J.; Dennis, T.; Montgomery, J. (2011). Investigating behaviour and population dynamics of striped marlin (*Kajikia audax*) from the southwest Pacific Ocean with satellite tags. *PLoS One 6 (6)*: e21087.

Thieurmel, B.; Elmarhraoui, A. (2019). Suncalc: Compute sun position, sunlight phases, moon position and lunar phase. R package version 0.5.0. Retrieved from https://CRAN.R-project.org/package=suncalc.

Ward, P.; Porter, J.; Elscot, S. (2000). Broadbill swordfish: Status of established fisheries and lessons for developing fisheries. *Fish and Fisheries 1 (4)*: 317–336.

Wood, S.N. (2017). Generalized additive models: An introduction with r (2nd ed.). Chapman.

APPENDIX A: Striped marlin captures by target species

Table A-1: Annual captures and catch-per-unit effort (CPUE) of striped marlin (number of individuals) by target species over the high-reliability period for records (2003–04 to 2018–19). CPUE is in individuals per thousand hooks. Records include surface-longline effort for New Zealand vessels.

	Bigeye tuna		Swordfish		Southern bluefin tuna		Others		All	
Fishing year	Captures	CPUE	Captures	CPUE	Captures	CPUE	Captures	CPUE	Captures	CPUE
2003–04	407	0.1179	0	—	2	0.0010	13	0.0190	422	0.0681
2004–05	267	0.1606	21	0.1313	1	0.0010	8	0.0349	297	0.0966
2005–06	146	0.0793	46	0.1803	0	0.0000	3	0.0304	195	0.0631
2006–07	124	0.0818	22	0.1487	0	0.0000	1	0.0175	147	0.0643
2007–08	168	0.1734	28	0.2209	14	0.0261	17	0.4822	227	0.1362
2008–09	228	0.1461	9	0.2093	0	0.0000	2	0.0834	239	0.1035
2009–10	168	0.1347	22	0.1592	8	0.0074	0	0.0000	198	0.0789
2010–11	252	0.1527	16	0.0889	1	0.0012	44	1.2713	313	0.1160
2011–12	214	0.1665	17	0.0865	8	0.0076	0	0.0000	239	0.0938
2012–13	132	0.1386	80	0.2488	6	0.0057	0	0.0000	218	0.0915
2013–14	155	0.2114	44	0.2330	2	0.0022	0	0.0000	201	0.1072
2014–15	181	0.4682	182	0.4074	4	0.0042	6	0.5742	373	0.2089
2015–16	261	0.4186	326	0.7276	29	0.0235	3	0.0594	619	0.2628
2016–17	135	0.2712	119	0.3657	4	0.0033	3	0.1154	261	0.1255
2017–18	83	0.1459	102	0.2618	9	0.0072	2	0.0625	196	0.0873
2018–19	56	0.1386	15	0.0931	4	0.0029	1	0.0251	76	0.0385
Total	2977	—	1049	—	92	—	103	—	4221	—

Table A-2: Monthly captures and catch-per-unit effort (CPUE) of striped marlin (number of individuals) by target species aggregated over the high-reliability period for records (2003–04 to 2018–19). CPUE is in individuals per thousand hooks. Records include surface-longline effort for New Zealand vessels.

	Bigeye tuna		Swordfish		Southern bluefin tuna		Others		All	
Month	Captures	CPUE	Captures	CPUE	Captures	CPUE	Captures	CPUE	Captures	CPUE
January	566	0.3249	109	0.3192	0	0.0000	16	0.2382	691	0.3159
February	815	0.3743	243	0.4439	1	0.0119	19	0.1653	1078	0.3687
March	827	0.2566	426	0.4526	6	0.0117	22	0.0555	1281	0.2525
April	453	0.1459	166	0.3144	2	0.0015	2	0.0056	623	0.1162
May	136	0.0838	75	0.1354	7	0.0023	42	0.1388	260	0.0468
June	20	0.0360	18	0.0703	14	0.0030	1	0.0086	53	0.0094
July	37	0.0394	2	0.0219	38	0.0085	0	0.0000	77	0.0139
August	54	0.0317	2	0.0193	17	0.0079	0	0.0000	73	0.0185
September	25	0.0251	1	0.0169	7	0.0198	0	0.0000	33	0.0233
October	2	0.0030	0	0.0000	0	0.0000	0	0.0000	2	0.0028
November	6	0.0050	2	0.0763	0	0.0000	0	0.0000	8	0.0065
December	36	0.0254	5	0.0857	0	0.0000	1	0.0438	42	0.0279

APPENDIX B: Spatial distribution of striped marlin CPUE by target species and month

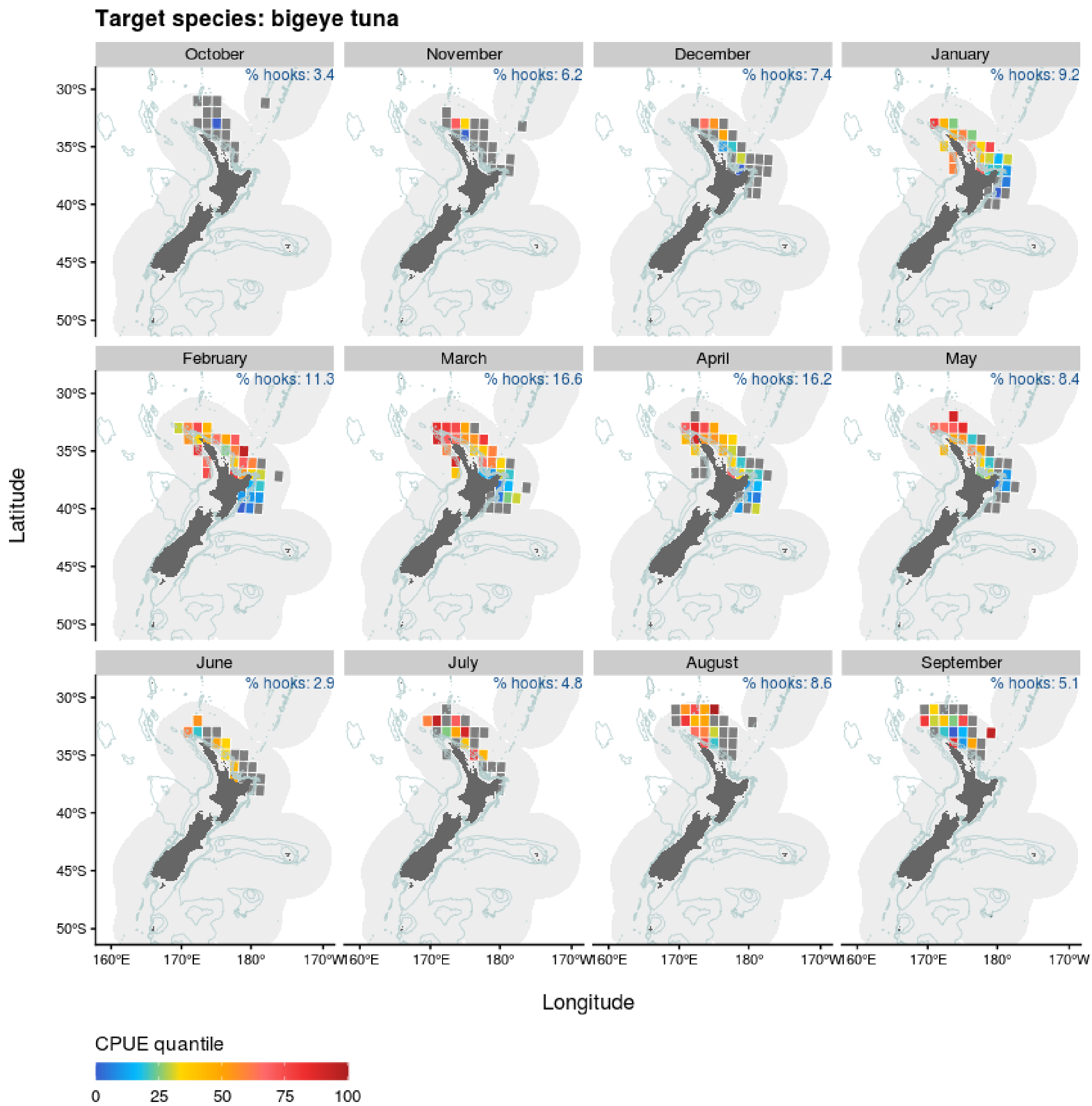

Figure B-1: Striped marlin CPUE quantile by month over the New Zealand's Exclusive Economic Zone for fishing effort targeting bigeye tuna, aggregated at the 1° resolution from 2003–04 to 2018–19. CPUE quantiles show the relative quantile position of each cell compared with the overall CPUE for month. Cells with no captures are shown in dark grey. Cells are only included if records span at least three vessels. Bathymetry contours for 200, 500 and 1000 metres depth are included.

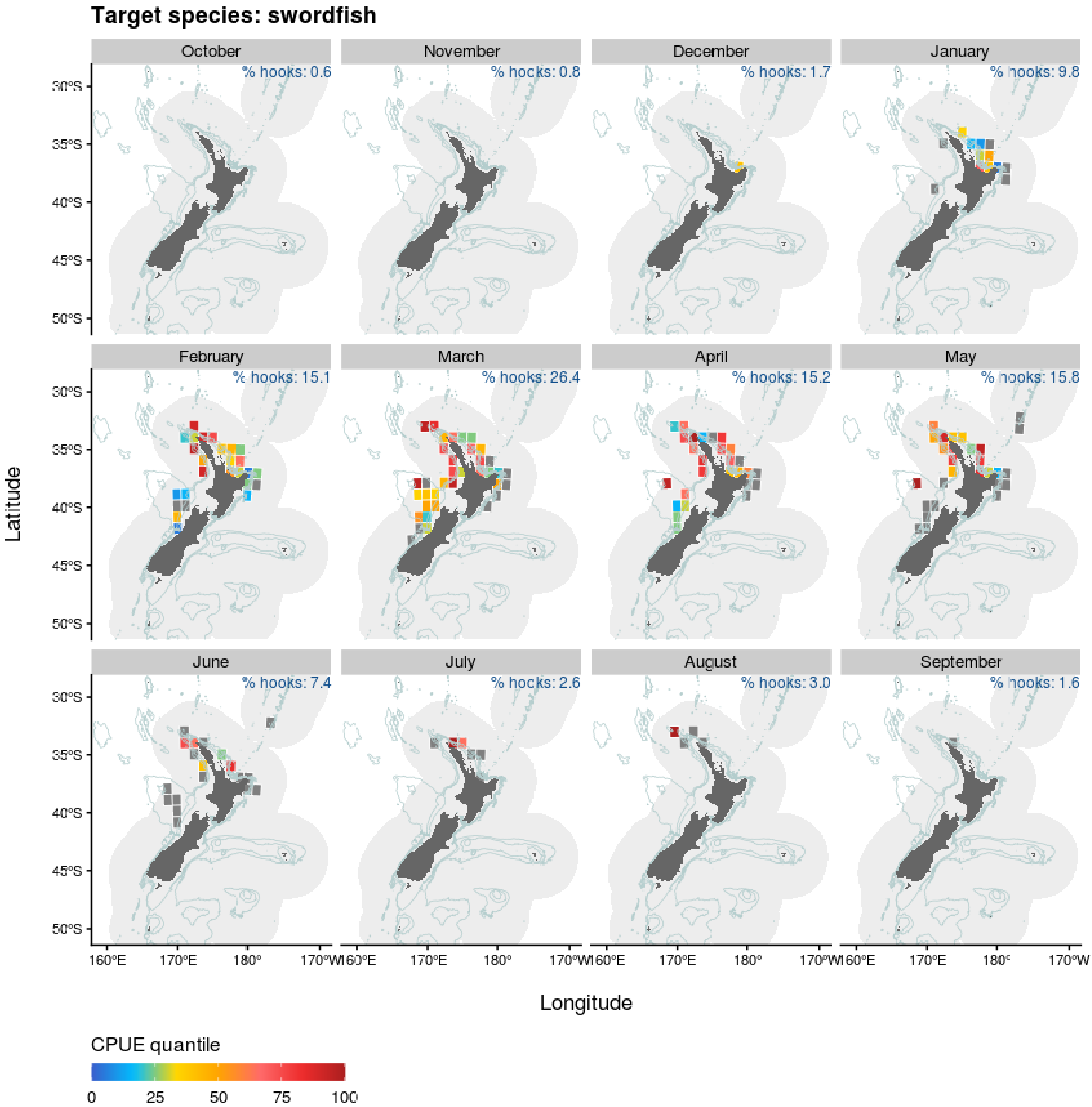

Figure B-2: Striped marlin CPUE quantile by month over the New Zealand's Exclusive Economic Zone for fishing effort targeting swordfish, aggregated at the 1°resolution from 2003–04 to 2018–19. CPUE quantiles show the relative quantile position of each cell compared with the overall CPUE for month. Cells with no captures are shown in dark grey. Cells are only included if records span at least three vessels. Bathymetry contours for 200, 500 and 1000 metres depth are included.

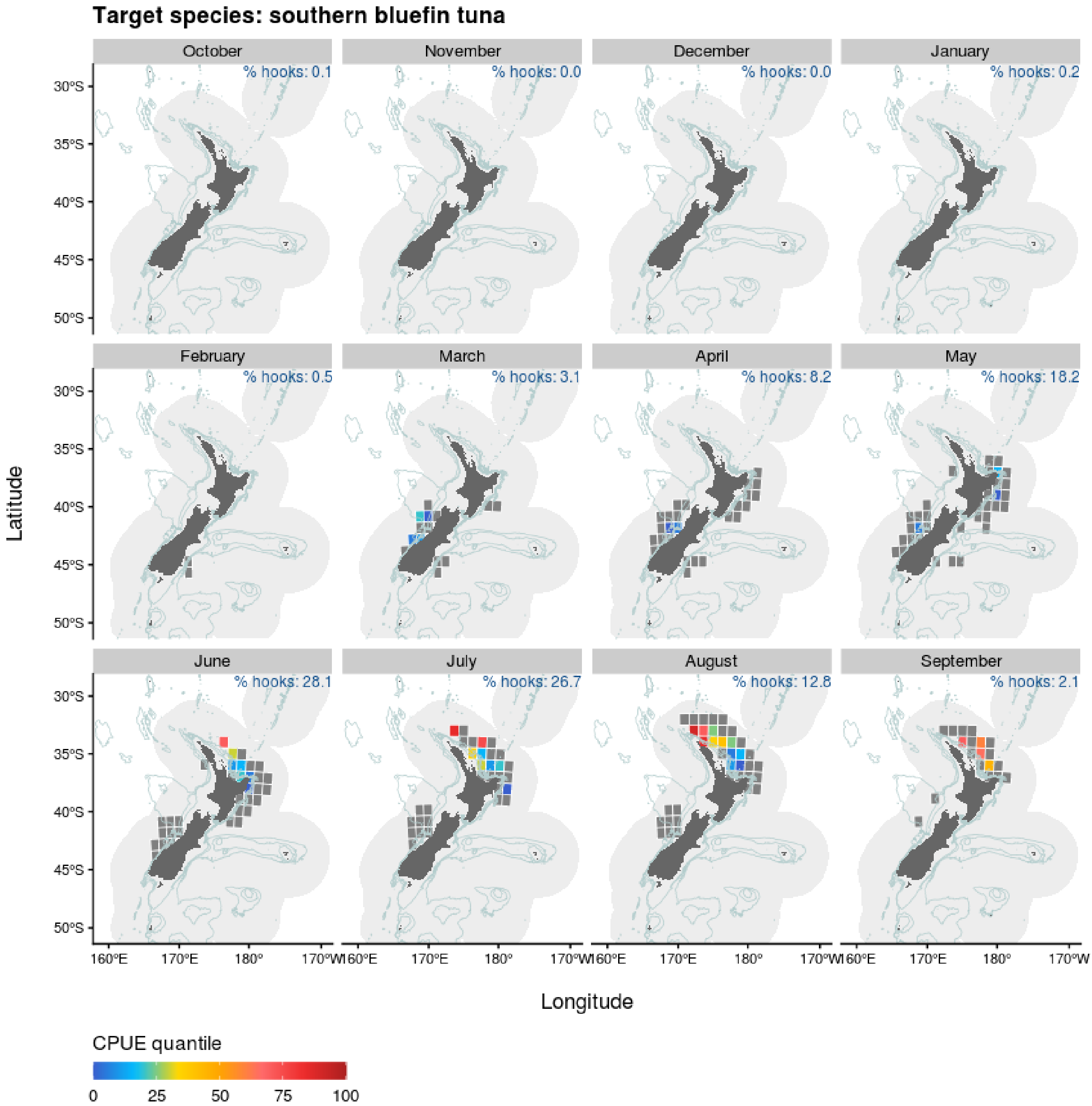

Figure B-3: Striped marlin CPUE quantile by month over the New Zealand's Exclusive Economic Zone for fishing effort targeting southern bluefin tuna, aggregated at the 1° resolution from 2003–04 to 2018–19. CPUE quantiles show the relative quantile position of each cell compared with the overall CPUE for month. Cells with no captures are shown in dark grey. Cells are only included if records span at least three vessels. Bathymetry contours for 200, 500 and 1000 metres depth are included.

APPENDIX C: Generalised Additive Models summary and diagnostics

Table C-3: Summary of main Generalized Additive Models considered, with the Aikake Information Criterion (AIC) and the percentage of the deviance explained.

Model	Structure	AIC	Dev. expl.
Full model	s(sst, k = 4) + s(ONI, k = 4) + target_species + s(hour, k = 4) + s(haul_hour, k = 4) + s(moonfrac, k = 4) + s(lightstick_per_hk, k = 4) + s(bathy, k = 4) + s(chl.25d.mm, k = 4) + s(total_hook_num, k = 4) + s(hk_bt_flt, k = 4) + s(BaitTypePercentSquid, k = 4) + s(start_longitude, k = 4)	9450.70	22.20
Full model + no target species	s(sst, k = 4) + s(ONI, k = 4) + s(hour, k = 4) + s(haul_hour, k = 4) + s(moonfrac, k = 4) + s(lightstick_per_hk, k = 4) + s(bathy, k = 4) + s(chl.25d.mm, k = 4) + s(total_hook_num, k = 4) + s(hk_bt_flt, k = 4) + s(BaitTypePercentSquid, k = 4) + s(start_longitude, k = 4)	9480.60	22.00
Full model + no longitude	s(sst, k = 4) + s(ONI, k = 4) + target_species + s(hour, k = 4) + s(haul_hour, k = 4) + s(moonfrac, k = 4) + s(lightstick_per_hk, k = 4) + s(bathy, k = 4) + s(chl.25d.mm, k = 4) + s(total_hook_num, k = 4) + s(hk_bt_flt, k = 4) + s(BaitTypePercentSquid, k = 4)	9713.00	20.00
Basic model	s(sst, k = 4) + target_species	9927.70	18.10

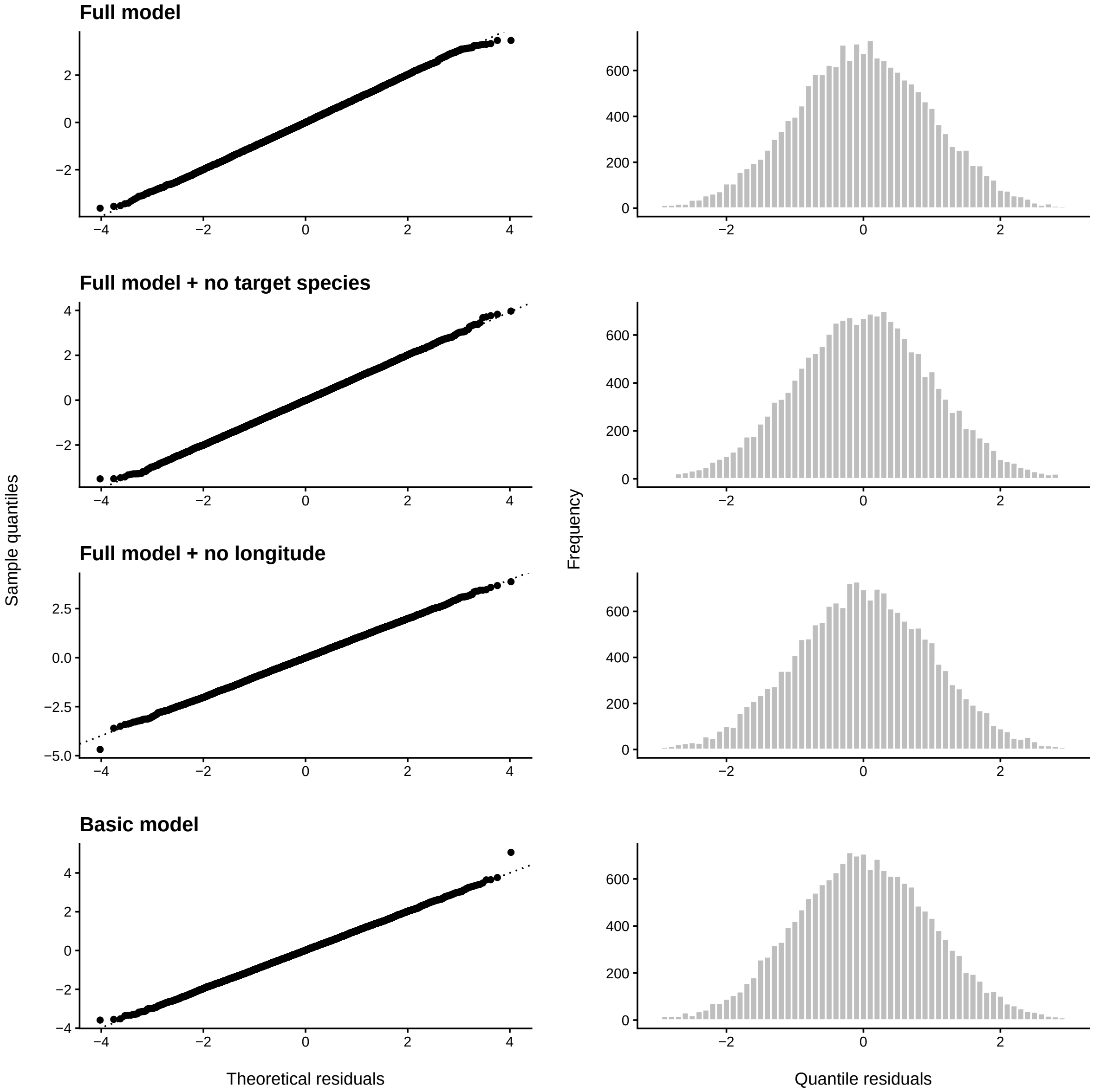

Figure C-1: Residual diagnostics for the four main models considered: quantile-quantile relationship (left) and histogram of quantile residuals (right).