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Population indicators for porbeagle sharks in the Chilean swordfish fishery

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Executive summary

This collaborative study of the Chilean swordfish fishery was carried out by NIWA and the Instituto de Fomento Pesquero (IFOP) as part of the southern hemisphere porbeagle stock status assessment. Objectives were, to explore the information available for all shark species, and potentially provide porbeagle population indicators and biological information for the eastern Pacific region. The Chilean swordfish fishery comprises industrial and artisanal longlining, and artisanal gillnetting. The longline fishery operates mainly between 22°S and 35°S, while the gillnet fishery operates closer to shore and slightly further north and south. IFOP collects effort and catch information for all species including bycatch, along with some biological data, via an observer program that has operated since 2006.

We prepared, cleaned, and characterised the datasets, and plotted the spatial distributions of effort, catch, and bycatch by fleet, year, and season. We used cluster analysis to identify potentially different fishery components. Characteristics of artisanal and industrial longlining were similar and they were combined for further analysis. We analysed catch rate, size, and sex ratio data for porbeagle sharks using random forest analyses and generalised additive models.

Porbeagle catch rates were generally low, but much higher south of 35 °S. Spatial effects along with moon phase (lunar illumination) were important for catch rates, with more porbeagles caught further south and in brighter moonlight. Standardized CPUE indices were generated based on generalised linear modelling, but were variable and uncertain. Continued data collection is recommended to improve the estimates.

Biological analyses found variable sizes by year, with gillnet fisheries taking fewer small porbeagles. Patterns by both size and sex were complex. Larger sharks were found further north, which contrasts with results from elsewhere including Japanese, Argentinian, and New Zealand fisheries. Differentiation by sex was both spatial and seasonal. Both catch rates and sizes were associated with lunar illumination, which may be due to shark behaviour or to setting patterns in the swordfish longline fishery.

This analysis has characterised the catches of porbeagle sharks and other shark species in the Chilean swordfish fishery, and provided the first estimates of standardized catch rates for porbeagles in this fishery. It has also analysed biological data associated with porbeagle sharks, and identified spatial and temporal patterns, and operational effects, on the sizes and sexes of the sharks captured.

1 Introduction

The Western and Central Pacific Fisheries Commission (WCPFC) is leading the development of a Southern Hemisphere porbeagle shark (*Lamna nasus*) stock status assessment. The study involves working with many WCPFC member countries to locate, analyse and assess sources of data from Southern Hemisphere fisheries that catch porbeagle sharks. The goal is to generate suitable ‘indicators’ of stock abundance, and combine them with data on stock distribution, catches and biological productivity to estimate stock status. In the Eastern Pacific region, the Chilean swordfish fishery is the only fishery for which we have obtained a time series of porbeagle shark bycatch records.

The Chilean swordfish fishery has used several fishing modes through its history. Until 1985, harpoons were used and annual landings were less than 600 tonnes (Yañez *et al.* 2003). With increased development from the mid-1980s, the fishery began to use gillnets and longlines, and the total catch increased to an average of 3-5000 tonnes per year. The current fishery has three main components, artisanal gillnet, artisanal longline, and industrial longline. Industrial vessels are over 28m in length, and must operate at least 120 nm from shore. For these vessels, gillnet area must not exceed 125,574 m^2, and longline sets must have no more than 2000 hooks. Artisanal vessels have no spatial restrictions, but are limited to 83,722 m^2 of gillnet, or 1200 hooks per set. The longline fishery operates mainly between 22°S and 35°S and between 120 and 800 nautical miles of the coast (Silva et al. 2015). The artisanal gillnet fleet operates closer to shore and extends slightly further to the north and south (Figure 1).

The Instituto de Fomento Pesquero (IFOP) collects effort and catch information for all species including bycatch via an observer program (Barría et al. 2016). Scientific observers collect operational information. Data collection has been carried out by observers since 2006. Data include catch and effort data, information on the characteristics of captured individuals, such as length, weight, and sex. The swordfish fisheries take large numbers of bycatch species, particularly sharks. Along with small numbers of porbeagles, the fishery takes larger numbers of blue sharks (*Prionace glauca*) and shortfin mako sharks (*Isurus oxyrinchus*).

The analyses documented in this report were carried during a collaboration between NIWA and IFOP, funded by the WCPFC under the ABNJ Tuna Project. The objectives were to explore the information collected by the swordfish observer program, to investigate its utility for shark stock assessment, and if possible to develop CPUE indices for porbeagle sharks suitable for use in assessing the stock status.

2 Methods

Observer data for the Chilean swordfish fishery from 2006-2015 were compiled by the Chilean Instituto de Fomento Pesquero (IFOP). Data were collected by the Highly Migratory Resources Project. Data were available from 2006 for the industrial longline fleet, from 2007 for the artisanal longline fleet, and from 2010 for the artisanal gillnet fleet (Table 1). Observer coverage differed substantially between fleets, estimated at 85% for the industrial fleet, but only 2% for each of the artisanal fleets (Barría et al. 2016).

For all datasets, the set by set data include information on catch numbers and total weight by species for tunas, billfish, sharks, and pelagic fish species (Table 2); and operational data including vessel identity, fleet, trip start date, trip end date, set date (and time in some cases), and set location. Set locations are recorded in degrees, minutes and seconds. For the longline fleets, the dataset includes the number of hooks set and the hook type. For the gillnet data, the dataset includes the net length, the mesh size, and the net depth, but these fields are often empty and may not be reliable. Days out of port were used to indicate gillnet effort.

Biological data on individual sampled fish were also collected by scientific observers. The available fields identified the fleet, vessel, trip, and set, which could be linked to the effort dataset for information on location, date, and other effort characteristics. Biological information included species id, curve fork length, inter-dorsal length, processed weight, whole weight, sex code (male, female, indeterminate), and fate (retained on board, finned and discarded, discarded, released alive, fate unknown, escaped, used by crew, eaten on board, used for bait). Curved fork lengths were measured using a tape.

2.1 Data preparation

Data were checked for errors and for outliers. Catch and effort data were prepared by converting spatial variables into decimal latitude and longitude, assigning set dates to year-quarters, and converting species codes to names. Relative lunar illumination and moon phase were determined from the set date, using the functions lunar.illumination() and lunar.phase() in the R package lunar (Lazaridis 2014). Values 0 to 1 for illumination indicate the range from the dark new moon to full brightness at full moon. This approach does not take account of cloud cover. Biological data were prepared by linking to catch effort records via the vessel and set identifiers, to obtain sample date, location, and effort characteristics. Curved fork lengths were converted to standard fork lengths using the relationship reported by Francis and Duffy (2005).

2.1.1 Characterise datasets

For each fleet, we plotted frequency distributions of the number of sets per trip, set dates, sets per vessel, hooks per set, hook type (1, 2, and 3 were J hooks with 10° offset, respectively 9/0, 17/0, and 18/0; 4 and 5 were 18/0 circle hooks offset 0° and 10°respectively; 6 was other hook types); catch per set in numbers for swordfish, porbeagles, blue shark and shortfin mako; sets per year, sets per month, and sets by level of lunar illumination.

Set locations were plotted by year and by month for longline and gillnet fisheries. Due to their similar distributions, artisanal and industrial longlines were plotted together.

Distributions of catch per set were explored by plotting the mean CPUE across the whole dataset by 2-degree square, species, and fishing method.

We further explored patterns of species distribution by determining the proportions of each species per set, and the distribution of zero-catch sets by species, i.e. sets in which there was no catch of the species.

We explored the possibility that, at certain times and locations, parts of the swordfish fishery may target sharks exclusively, using different fishing methods. To do this we ran a cluster analysis based on species composition, following similar methods to Hoyle et al. (2017). Clustering was based on species composition in the catch. Due to sparse catches for some species, not all were included in the cluster analysis. We included all species for which catches were non-zero in at least 20% of sets. These were swordfish, blue shark, mako shark, porbeagle shark, escolar, oilfish, and opah. Data were clustered using the Ward clustering method, implemented with the function hclust(data, method=”ward.D”) from the stats package (R Core Team 2016). Clustering was applied separately at both the trip and the set level.

Random forest analyses were used to explore the catch rate data and generate hypotheses about parameters likely to affect catch rates. Analyses were carried out using the function randomForest from the R package of the same name (Liaw and Wiener 2002). Analyses were carried out per set, separately for longline and gillnet sets. Catch per set in numbers was used as the response variable, and variables year, month, latitude, longitude, lunar illumination, hook type, number of hooks, and vessel id were provided as explanatory variables. Results were plotted by variable importance.

We analysed catch rates of porbeagle sharks and other species with generalized additive models using the function *gam* from the R package (Wood 2011). We plotted residuals to check their distribution. Models were compared using Wald-like tests (Wood 2013) and the Akaike Information criterion (AIC) (Akaike 1973). Model differences were reported as delta AIC, which is the absolute difference in the AIC values.

Modelling used a two-part hurdle approach. The first part used a gam with a binomial distribution to model the probability of a set having non-zero catch of porbeagle sharks.

$$gam(por > 0 \sim parlist, family = binomial)$$

The model parameters, *parlist*, had the form: $yq + te(lon, lat) + vessel + s(moon) + s(hooks)$, where *yq* was year-quarter, *moon* was lunar illumination, *te(lat, lon)* was a two dimensional tensor spline fitted to latitude and longitude, and *s()* was a smoothing spline.

The second part of the model fitted the data from non-zero sets only. It used a gam with a Normal distribution to model the number of porbeagles caught per non-zero set. To normalize the residuals, we applied a transformation to the number of porbeagles caught. Transformations considered included natural logarithm and various power transformations $y^{(1/n)}$, with values of *n* from 2 to 8.

$$gam(trans(por) \sim parlist, family = gaussian)$$

Combined year-quarter effects were estimated by multiplying the predicted probabilities of occurrence by the expected catch rates for positive sets. Probabilities of occurrence were predicted for the base vessel fishing at 35 °S and at longitude 80 °W, with 0.5 lunar illumination. Probabilities of occurrence were adjusted so that the mean occurrence across year-quarters was the same as observed in the data, i.e. the mean of all the year-quarter means.

2.2 Biological data analysis

The biological data were explored to identify spatial, temporal, and other patterns associated with porbeagle shark sex and size distributions. Both fork length and dorsal length were available for most samples, with similar patterns for both. There were more data points for fork length (n=1927) than for inter-dorsal length (n=1835) so we conducted all analyses using fork length. Samples with inter-dorsal length but not fork length could be converted to fork length, but this was of limited value for only 21 sharks.

We plotted the length distributions by fishery, and the numbers above and below 145 cm (approximate age of male maturity (Francis and Duffy 2005)) by year and fishery.

Length and sex data were analysed with generalized additive models, using the R package mgcv (Wood 2011). Length analyses assumed a Normal distribution, and transformations were not required to normalize the residuals. Sex data analyses assumed a binomial response.

Spatial separation of sexes and seasonality associated with breeding and movement are common in sharks, so we explored models for sex and length that included interactions between latitude, longitude, and month. We also explored potential effects of lunar illumination, number of hooks, and year as a categorical variable. Statistical tests used the same approaches as for the catch rate analyses.

Results were plotted by predicting results from the gam across the range of values for statistically significant variables. Parameters not in a plot were fixed at the following values: longitude 80W, latitude 31S, month 6, lunar illumination of 0.5, year 2014, and median hooks of 1320.

3 Results

Exploratory plots by fleet (Figures 2 to 4) showed relatively few sets for most trips. Data for the artisanal longline fleet represented only 3 vessels, and their fishing characteristics were similar to the industrial fleet. For later analyses all longline data were combined into a single fishery. Median hooks per set was 1320. Most sets employed hook type 1, representing 9/0 J hook with 10° offset. Swordfish was, as expected, the most important and consistent catch component, but blue and mako shark catches were also significant. Longline fisheries operated at all moon phases, with somewhat lower effort at the new moon. Gillnet fisheries in contrast peaked at the new moon. Only 4.1% of sets were at full moon, while 20.8% were at new moon.

For longline fisheries, fishing locations were relatively stable from 2007-2015 (Figure 5). Gillnet fisheries were more variable, reflecting the relatively low number of observer samples available (Figure 6). Monthly distributions suggested that longline effort progressively moved north during the year (Figure 7), while gillnet spatial patterns were more variable (Figure 8).

Simple catch rates in longline data indicated that swordfish (SWO) catch per set was quite evenly distributed across the area, but shark catch rates were more variable (Figure 9). For porbeagles (POR), the otherwise low catch per set was much higher south of 35°S, while shortfin mako shark (SMA) catch rates were higher south of 30°S and east of 80°W. Blue shark catch rates (BSH) were low north of 25°S and south of about 34°S. Other species were less common in the catch, with dolphinfish (DOL), bigeye tuna (BET) and escolar (LEC) mainly caught in the northwest, oilfish (OIL) at mid-latitudes, and opah (LAG) becoming more common further south.

Patterns in the more sparse and patchy gillnet data were less clear for blue and shortfin mako sharks (Figure 10). Porbeagles again showed a peak in catch rates south of 35°S, particularly in the east, and swordfish catch rates did not vary substantially, apart from low catch rates in the north-eastern coastal section of the gillnet fishery. No further analyses of porbeagle gillnet catch rates were carried out.

Similarly, zero catches of swordfish were very low south of 24°S, while the proportions of zero catches of porbeagle sharks increased progressively to the north (Figure 11). Most sets caught shortfin mako sharks, peaking at 35°S, but still around 50% at both 40°S and 20°S. Blue sharks were also caught in most sets, but zero catches increased considerably south of 35°S and north of 23°S.

Cluster analysis of species composition in the longline catch did not show substantial differentiation. Groups in the clusters mostly represented variation in species composition by area. This result is consistent with a relatively homogeneous fishery that consistently targets swordfish. We did not consider clusters further.

Random forest analyses indicated that latitude, longitude, and lunar illumination (*moon*) were the most important variables for porbeagle sharks, with less importance for hooks, month, vessel, and year (Figure 12). Hook type was unimportant. For gillnets, the most important variable was latitude, with longitude, vessel, lunar illumination and month also important (Figure 13).

Porbeagle shark catch rates were modelled with a two-part hurdle approach. Anova-style tables of the terms in the models are reported in Tables 3 and 4.

The preferred model for the binomial component included year-quarter, vessel, location, and lunar illumination. The number of hooks was omitted because it did not improve the model (delta AIC = -1.96). Year-quarter fitted the data better than using year and quarter effects separately (delta AIC = 77.2).

The modelled spatial patterns of porbeagle shark occurrence in the longline catch were like those in the raw data. Occurrence was higher south of 33S and east of 80W, although the sets closest to the coast, east of 76W, had very low occurrence of porbeagle sharks (Figure 14). Porbeagle occurrence increased with brighter moonlight. The year-quarter effects were highly variable and uncertain. Vessel effects were also very uncertain.

For the positive component of the model, residual distributions were reasonable when transformed to the power ¼. The preferred model for the positive (lognormally distributed) component included year-quarter, vessel, and location, but not lunar illumination since removing this term improved the AIC by 1.6. The number of hooks was also omitted (delta AIC = 1.65). Year-quarter fitted the data better than using year and quarter effects separately (delta AIC = 39.8).

Porbeagle catch rates in positive sets increased to the southeast. Time variation was quite low apart from higher levels in the third quarter of 2006, the last quarter of 2007, and (notably) the last quarter of 2013. Variation among vessels was not substantial.

Predicted probabilities of occurrence (non-zero catch) and predicted catch rates for each year-quarter were generated using the *predict.gam* function with the values of other parameters fixed at their medians. Combined year-quarter effects were estimated by multiplying the predicted probabilities of occurrence by the predicted catch rates for positive sets, to give the expected catch rate per set. Results are reported in Table 7 and Figure 16.

3.1 Biological data

Length distributions differed between the longline and gillnet fisheries (Figure 17). Sizes varied considerably by year (Figure 18). The gillnet fishery captured a high proportion of large porbeagles, with modal length classes from 160-180 cm curve fork length, and median length of 143 cm. Lengths at maturity are 140-150 for males, and 170-180 for females (Francis and Duffy 2005). The longline fishery in contrast had two modes, with the first and largest at 70-90 cm, and the second from 140-190 cm. Median length in the longline fishery was 122 cm.

Analyses of patterns in size distribution showed strong interaction between latitude, longitude, and month, and significant effects of lunar illumination and hooks (Tables 5 and 6).

$$length \sim te(lon, lat, month) + s(moon) + s(hooks) + year$$

Observed patterns were complex both spatially and temporally (Figure 19). Larger sharks were generally found further north, but there was also seasonality, with the largest sharks caught mid-year. During the mid-year period, larger sharks were caught further west. Larger sharks tended to be caught with more moonlight and more hooks set. There was considerable inter-annual size variation.

The best model for the sex ratio included a three-way interaction between latitude, longitude, and month, with a categorical year effect (Tables 5 and 6).

$$sex \sim te(lon, lat, month) + year$$

There was strong spatial and seasonal differentiation by sex, but the patterns were quite complex (Figure 20). The population was more male-biased to the east and north, particularly early in the year. There was some evidence that the sex ratio may vary among years.

4 Discussion

This analysis has characterised the catches of porbeagle sharks and other shark species in the Chilean swordfish fishery, and provided the first estimates of standardized catch rates for porbeagles in this fishery. It has also analysed biological data associated with porbeagle sharks, and identified spatial and temporal patterns, and operational effects, on the sizes and sexes of the sharks captured.

Catch rates of porbeagle sharks were found to be highly variable among years. This suggests that the short available time series of 10 years' data may yet be too sparse to provide useful indices of abundance. Continued data collection is recommended to improve the estimates.

Catch rates varied spatially and seasonally, with patterns that were similar in most respects to those observed in other regions. In the New Zealand region porbeagles move north and south with the seasons (Francis et al. 2015), and similar patterns were observed here. Supporting this point, along Chilean coast a north-south movement in a tagged female porbeagle between Spring (November) and Summer time (February) was observed (Patricia Zárate personal communication).

However, sizes of porbeagles were found to increase further north (Figure 19), which differs from the patterns observed in the Tasman Sea and Indian Ocean fisheries, where sizes increase to the south (Francis et al. 2014; Hoyle et al. 2017). Spatial size patterns varied seasonally, as did the sex distributions. Sharks often separate spatially according to size and sex, with breeding, feeding and pupping areas. The differences from other regions may be associated with features of the local environment or habitat, such as seamounts. However, further exploration of these data would be useful, and these analyses should be revisited once more data have been collected.

There are anecdotal reports of high catch rates of large porbeagles on the Nazca seamount from 1995-2000 (Jorge Azócar Rangel, personal communication). The Nazca ridge runs from 23S to 19S, 80 to 83W, at the northern end of the swordfish fishery, suggesting the possibility of a breeding or pupping area here.

In the Indian Ocean Japanese longline fishery, size distributions are associated with sea surface temperature, with larger sharks mainly observed at temperatures below about 12 degrees C. It would be useful to explore temperature patterns in the Chilean fishery.

Catch rates and sizes were associated with lunar illumination, which may be due to shark behaviour or to setting patterns in the swordfish longline fishery. The nocturnal depth of the deep scattering layer, which contains prey items, can change with light intensity, and swimming depths (Kitagawa et al. 2007; Matsumoto et al. 2013) and catch rates (Poisson et al. 2010) of other species are known to change with lunar illumination. Regarding the later possibility, datasets do not report the number of hooks between floats, but a swordfish targeting fishery may change its set depth with light intensity. There is also evidence that lunar illumination affects shortfin mako and blue shark catch rates in this fishery (unpublished data).

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Tables

Table 1: Observed sets per year, by fishery.

	Artisanal longline	Industrial longline	Gillnet
2006	0	120	0
2007	52	987	0
2008	35	620	0
2009	50	545	0
2010	78	766	102
2011	185	510	75
2012	266	508	56
2013	143	272	113
2014	225	213	122
2015	129	109	186

Table 2: Species reported in observer data.

Common name	Chilean common name	Scientific name	FAO Code
Swordfish	Albacora; espada	*Xiphias gladius*	SWO
Blue shark	Tiburon azulejo	*Prionacea glauca*	BSH
Shortfin mako shark	Tiburon marrajo	*Isurus oxyrinchus*	SMA
Porbeagle shark	Tiburon sardinero	*Lamna nasus*	POR
Common thresher	Tiburon pejezorro	*Alopias vulpinus*	ALV
Dolphinfish	Dorado; dorado de alta mar; palometa	*Coryphaena hippurus*	DOL
Albacore tuna	Atun aleta larga	*Thunnus alalunga*	ALB
Bigeye thresher	Tiburon pejezorro	*Alopias superciliosus*	BTH
Yellowfin tuna	Atun aleta amarilla	*Thunnus albacares*	YFT
Butterfly mackerel	Atun chauchera	*Gasterochisma melampus*	BUK
Skipjack tuna	Atun listado	*Katsuwonus pelamis*	SKJ
Escolar	Atun negro	*Lepidocybium flavobrunneum*	LEC
Oilfish	Atun negro escofina;konso;pez aceitoso	*Ruvettus pretiosus*	OIL
Bigeye tuna	Atun ojo grande	*Thunnus obesus*	BET
Snake mackerel	Barracuda chica	*Gempylus serpens*	GES
Longnose lancetfish	Barracuda grande	*Alepisaurus ferox*	ADW
Black marlin	Marlin negro	*Makaira indica*	BLM
Striped marlin	Marlin rayado	*Tetrapturus audax*	MLS
Shortbill spearfish	Marlin trompa corta	*Tetrapturus angustirostris*	SSP
Ocean sunfish	Pez luna	*Mola mola*	MOX
Opah	Pez sol	*Lampris guttatus*	LAG
Pelagic stingray	Pastinaca;raya violeta	*Pteroplatytrygon violacea*	PLS
Wahoo	Atun peto;sierra altamar	*Acanthocybium solandri*	WAH
Crocodile shark	Tiburon cocodrilo	*Pseudocarcharias kamoharai*	PSK
Cookie-cutter shark	Tiburon galletero	*Isistius brasiliensis*	ISB
Galapagos shark	Tiburon jaqueton	*Carcharhinus galapagensis*	CCG
Smooth hammerhead	Tiburon martillo	*Sphyrna zygaena*	SPL

Table 3: Parametric terms in gams of porbeagle catch rate.

Model	Term	DF	Chi sq	p-value
Delta	Year-qtr	35	421	< 2e-16
	Vessel	12	58.5	4.2E-08
Lognormal	Year-qtr	35	6.11	< 2e-16
	Vessel	12	3.55	3.4E-05

Table 4: Smooth terms in gams of porbeagle catch rate.

Model	Term	Estimated DF	Chi.sq	p-value
Delta	te(lat, lon)	42.8	234.6	< 2e-16
	s(moon)	1	53.0	3.5E-13
Model	**Term**	**Estimated DF**	**F**	**p-value**
Lognormal	te(lon ,lat)	12.5	3.24	9.6E-06

Table 5: Parametric terms in gams of porbeagle length and sex ratio.

Model	Term	DF	Chi sq	p-value
Size	Year	9	4.54	6.67E-06
Sex	Year	9	14.89	0.0941

Table 6: Smooth terms in gams of porbeagle length and sex ratio.

Model	Term	Estimated DF	Chi.sq	p-value
Size	te(lon, lat, month)	84.248	3.118	< 2e-16
	s(moon)	1	9.381	0.00224
	s(hooks)	3.942	2.299	0.04294
Sex	te(lon, lat, month)	9.847	63.58	5.01E-09

Table 7: Indices of abundance for porbeagle shark based on standardizing catch and effort from the Chilean swordfish longline fishery. Confidence intervals are twice the standard error of the binomial component of the model. Indices are normalized to average 1.

Year-quarter	Indices	Lower CI	Upper CI
2006.625	2.84	2.84	2.84
2006.875	-	-	-
2007.125	0.22	0.04	0.84
2007.375	0.23	0.06	0.76
2007.625	1.56	0.59	2.50
2007.875	2.33	0.83	3.80
2008.125	-	-	-
2008.375	0.19	0.04	0.66
2008.625	0.68	0.19	1.59
2008.875	0.16	0.03	0.65
2009.125	0.18	0.02	1.14
2009.375	0.16	0.04	0.61
2009.625	0.86	0.26	1.83
2009.875	1.19	0.39	2.24
2010.125	0.53	0.12	1.66
2010.375	0.20	0.05	0.67
2010.625	0.86	0.24	2.01
2010.875	1.31	0.42	2.46
2011.125	1.01	0.25	2.30
2011.375	0.64	0.17	1.57
2011.625	1.53	0.56	2.52
2011.875	1.03	0.31	2.15
2012.125	0.23	0.05	0.84
2012.375	0.24	0.06	0.77
2012.625	0.43	0.11	1.25
2012.875	0.31	0.07	1.06
2013.125	0.22	0.04	0.92
2013.375	0.33	0.08	1.05
2013.625	0.85	0.24	1.91
2013.875	7.55	4.33	8.77
2014.125	1.92	0.56	3.51
2014.375	0.92	0.26	2.09
2014.625	1.75	0.69	2.67
2014.875	1.46	0.44	2.89
2015.125	1.30	0.11	2.39
2015.375	0.25	0.05	0.92
2015.625	0.31	0.07	1.00
2015.875	0.24	0.05	0.92

Figures

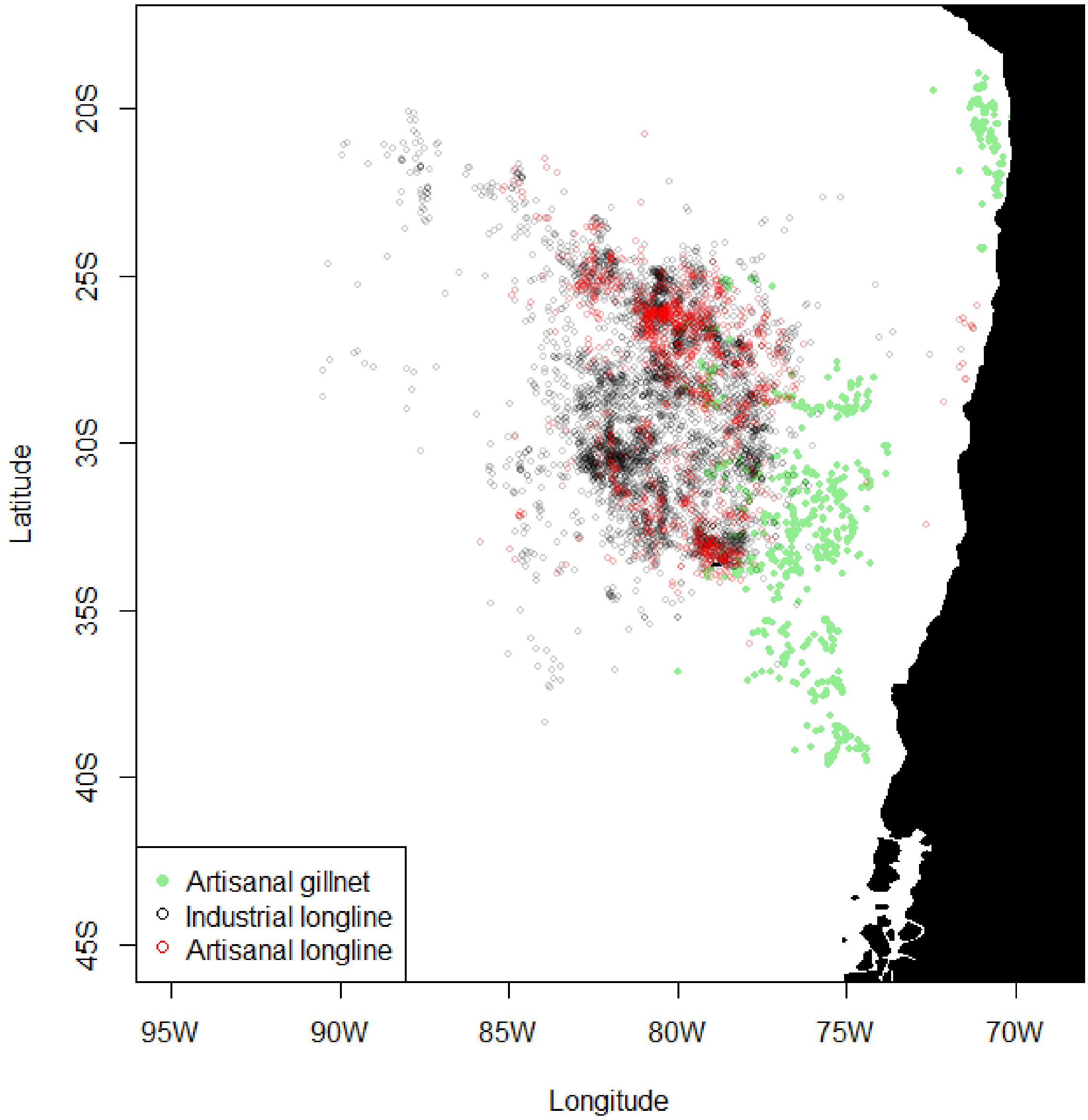

Figure 1: Locations of observed sets in the Chilean swordfish fishery 2006-2015.

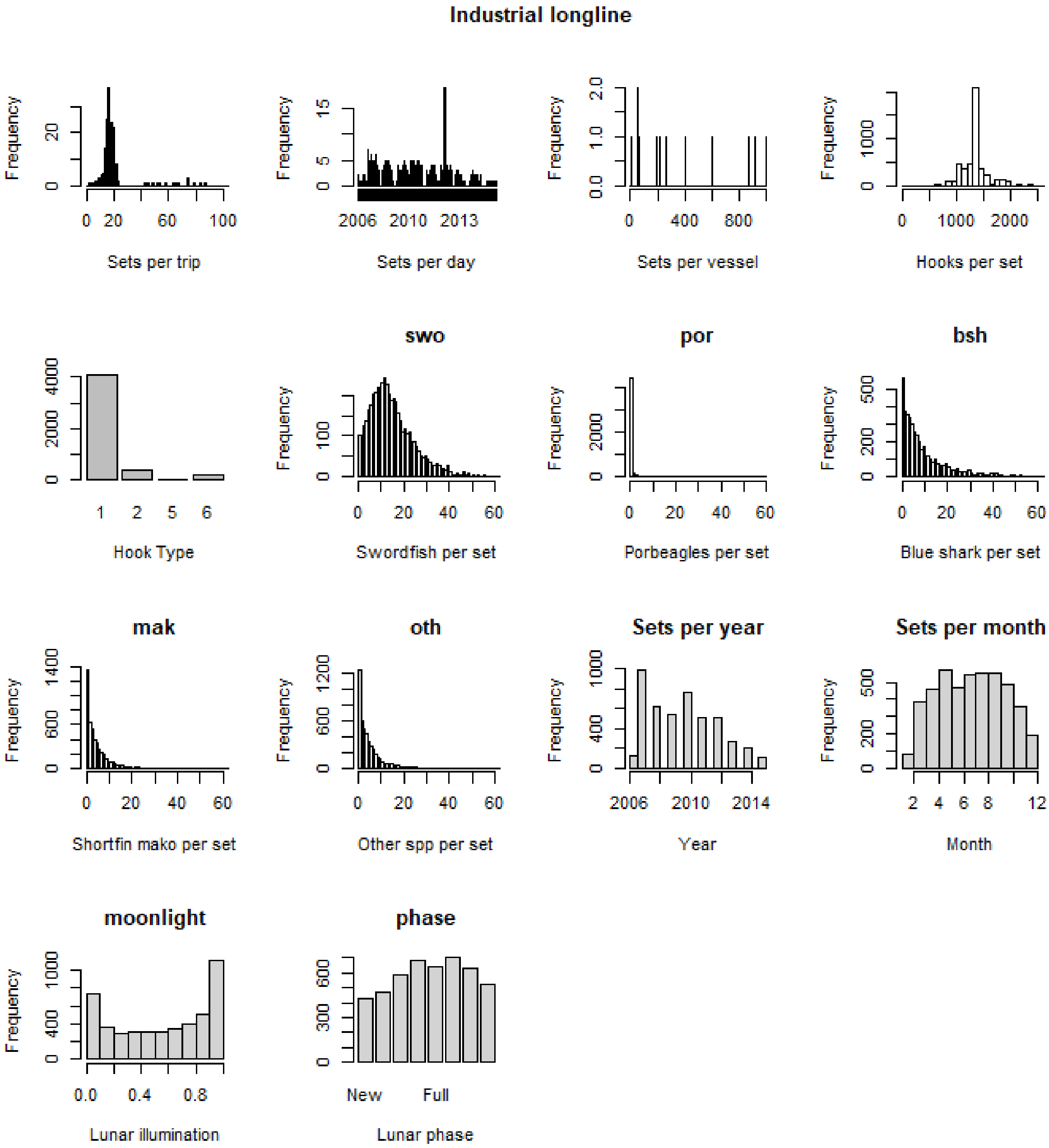

Figure 2: Summaries of parameter values for industrial longline fisheries.

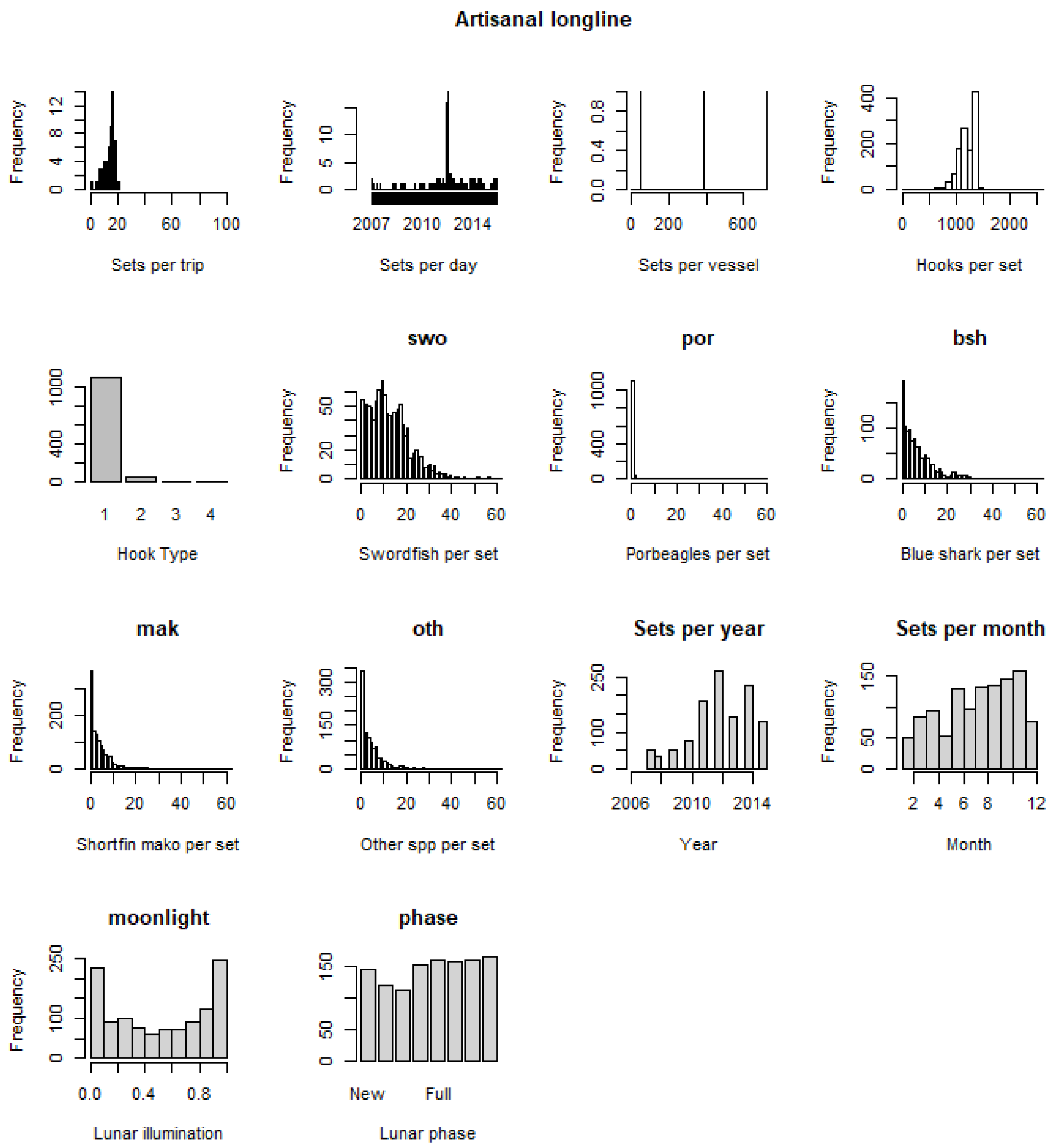

Figure 3: Summaries of parameter values for artisanal longline fisheries.

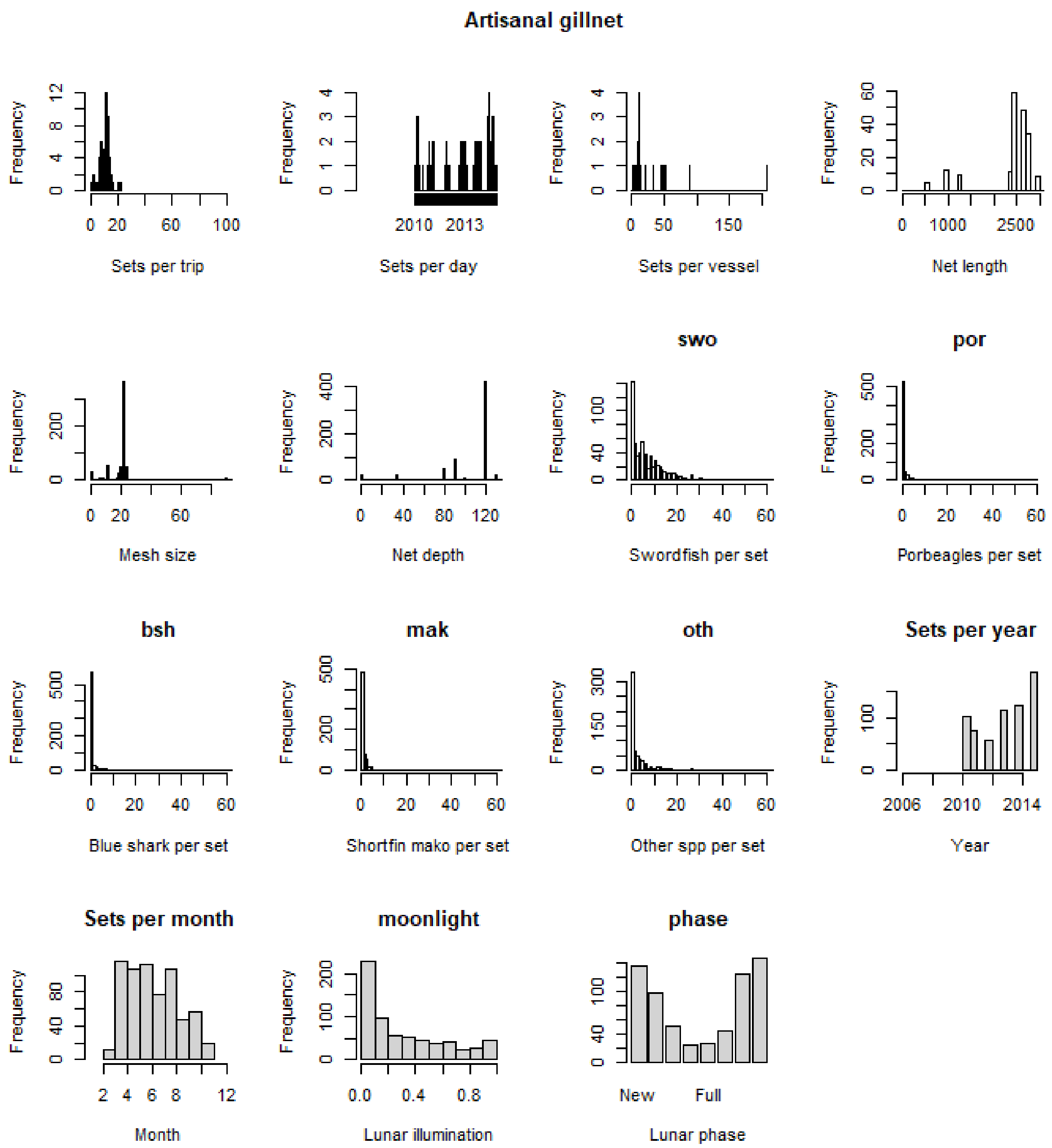

Figure 4: Summaries of parameter values for artisanal gillnet fisheries.

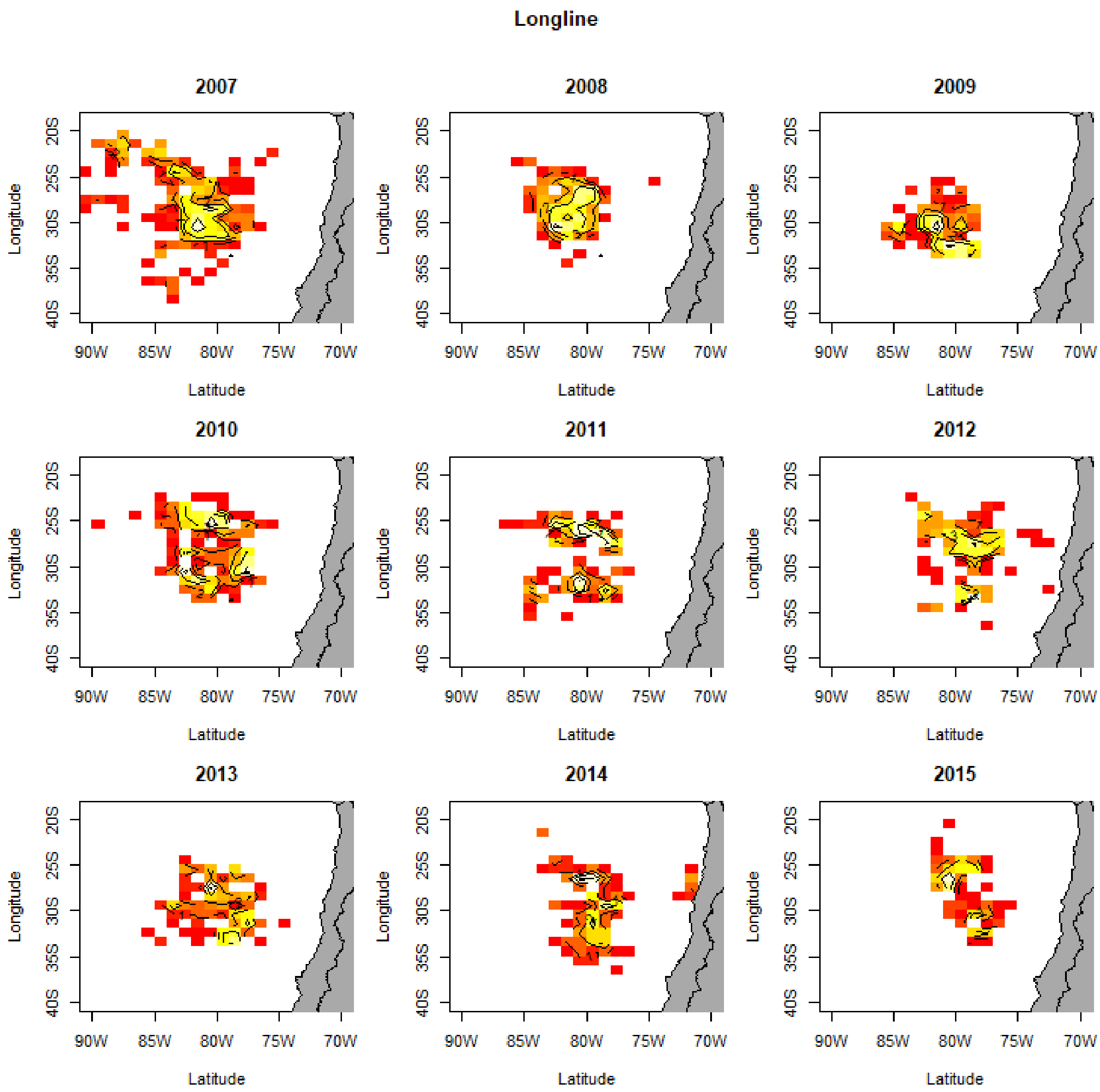

Figure 5: Spatial distributions by year of observed effort in the longline fishery. Yellow colour indicates higher catch.

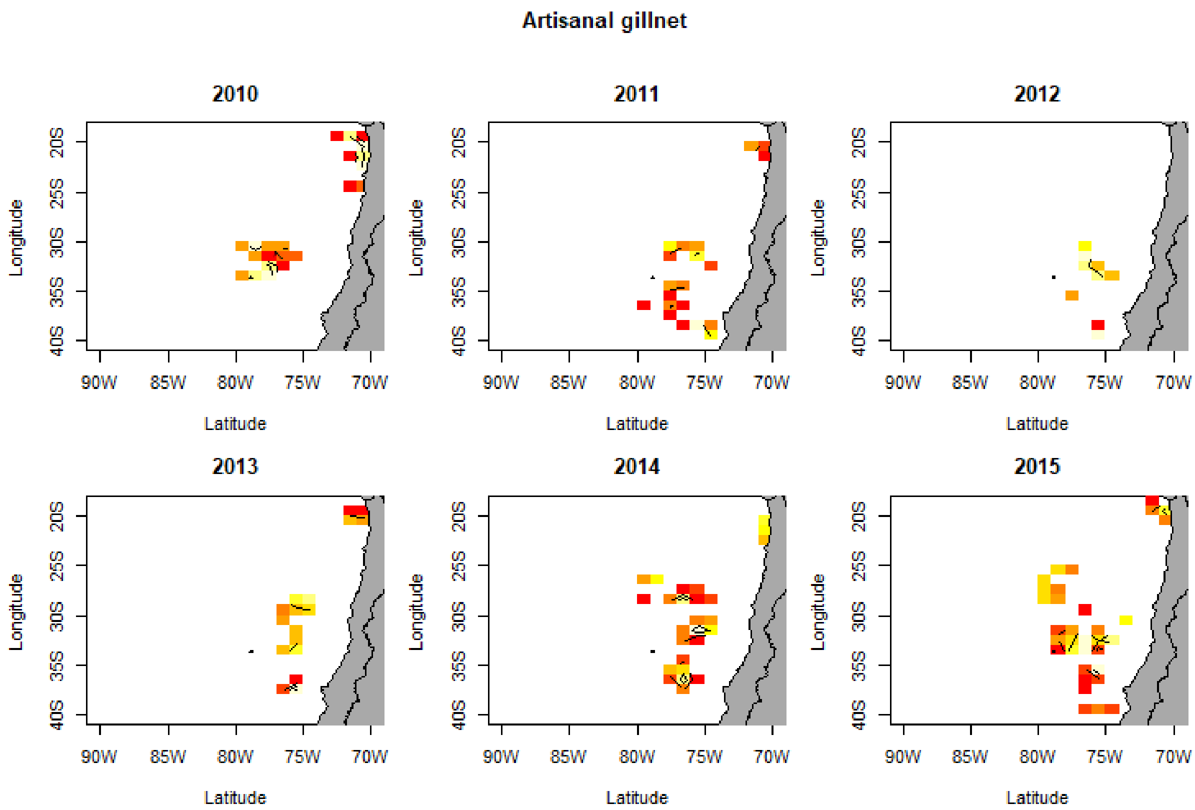

Figure 6: Spatial distributions by year of observed effort in the artisanal gillnet fishery. Yellow colour indicates higher catch.

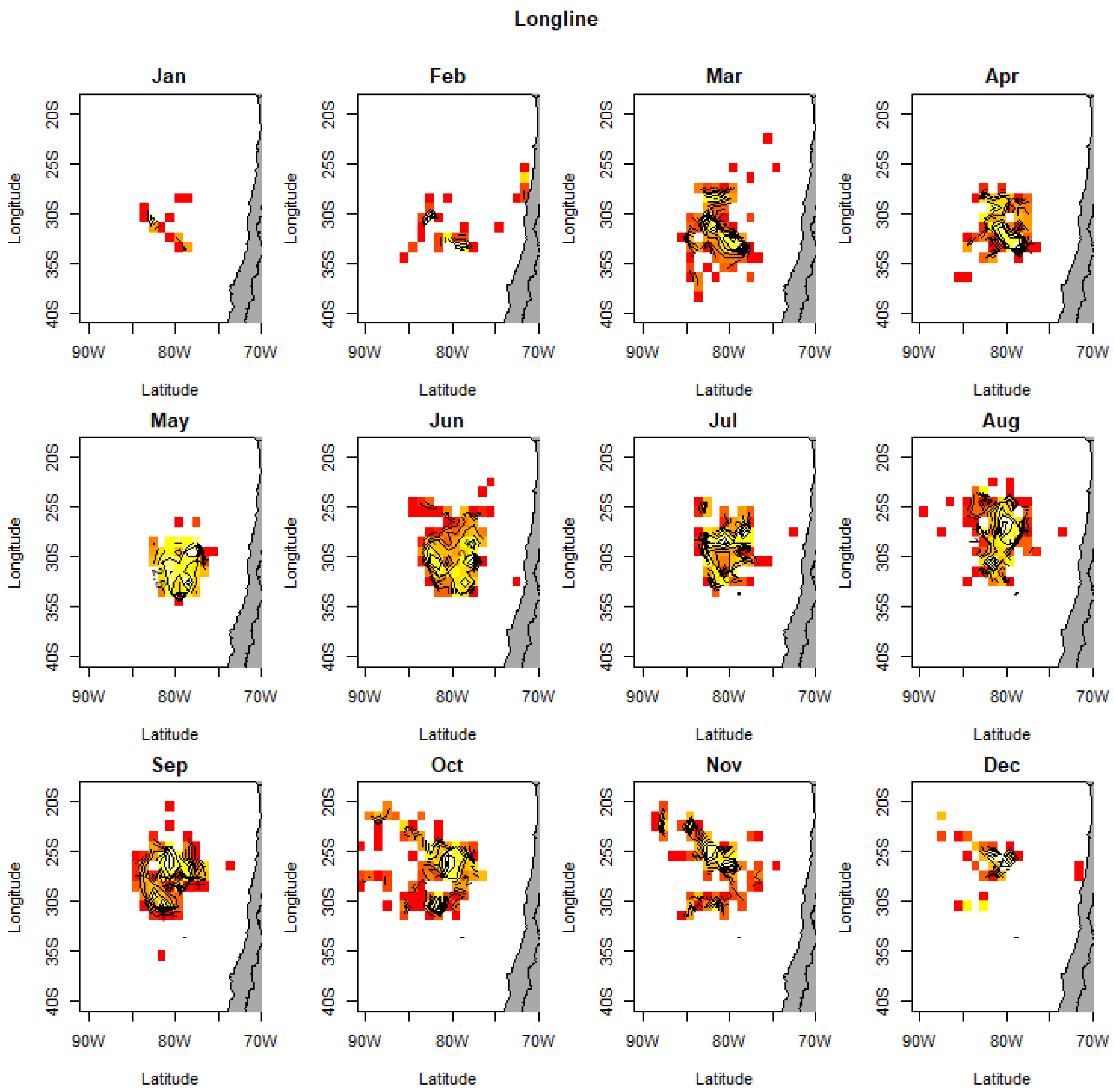

Figure 7: Spatial distributions by month of observed effort in the longline fishery, aggregated from 2006-2015. Yellow colour indicates higher catch.

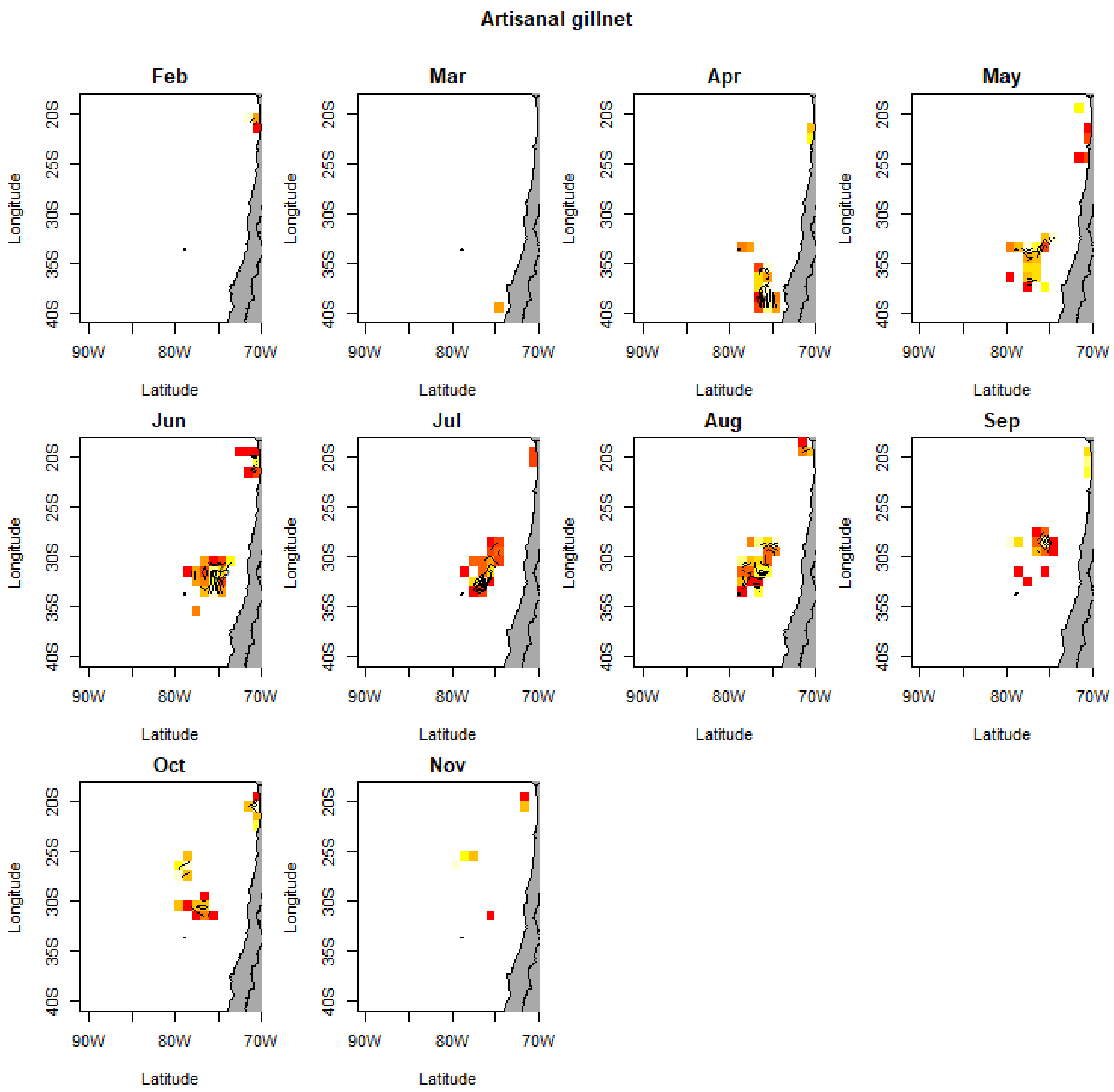

Figure 8: Spatial distributions by month of observed effort in the artisanal gillnet fishery, aggregated from 2006-2015. Yellow colour indicates higher catch.

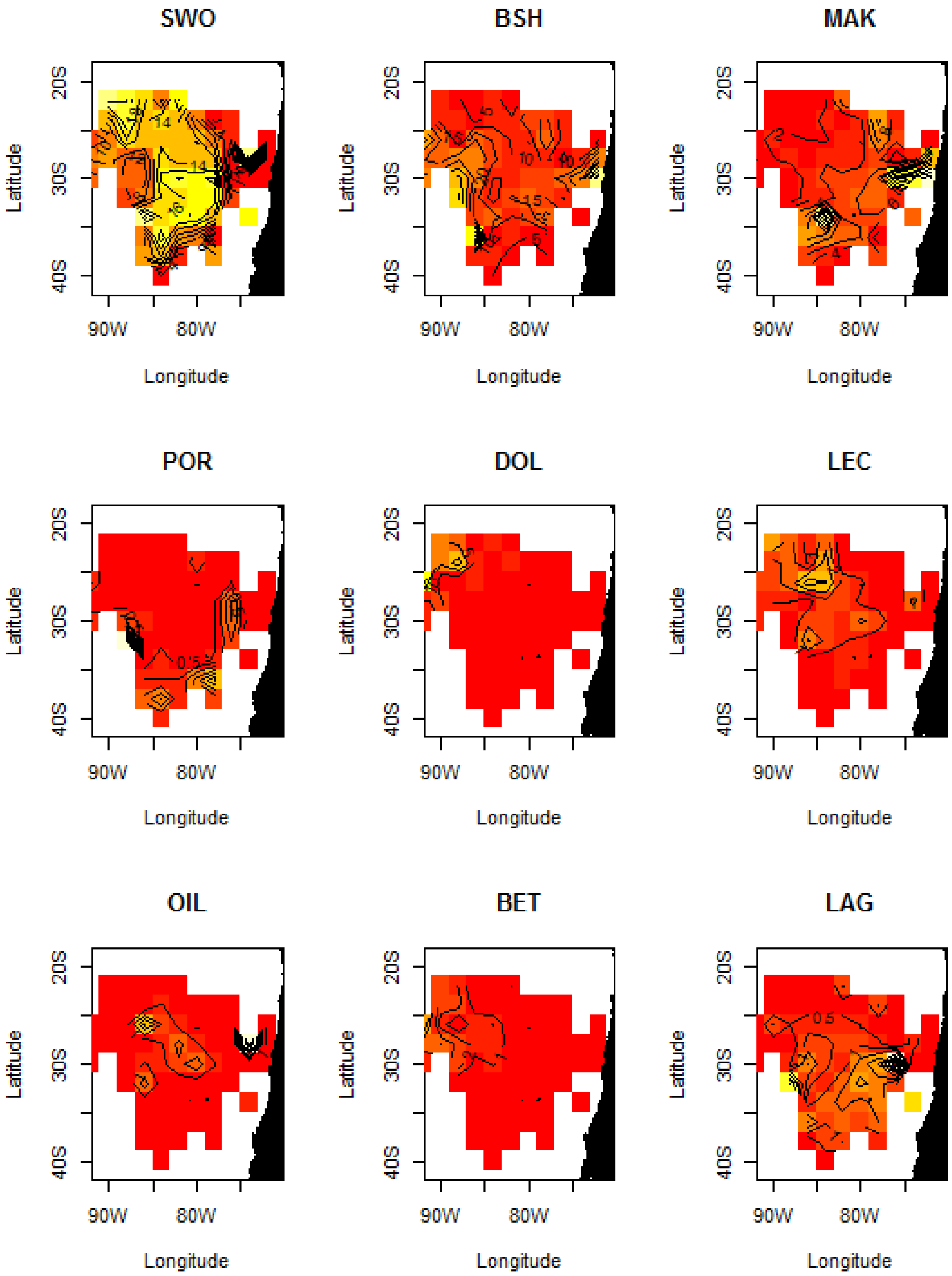

Figure 9: Mean CPUE of observed longline sets by 2 degree square, with red indicating no catch and yellow indicating the highest observed CPUE for the species. White indicates areas with no effort.

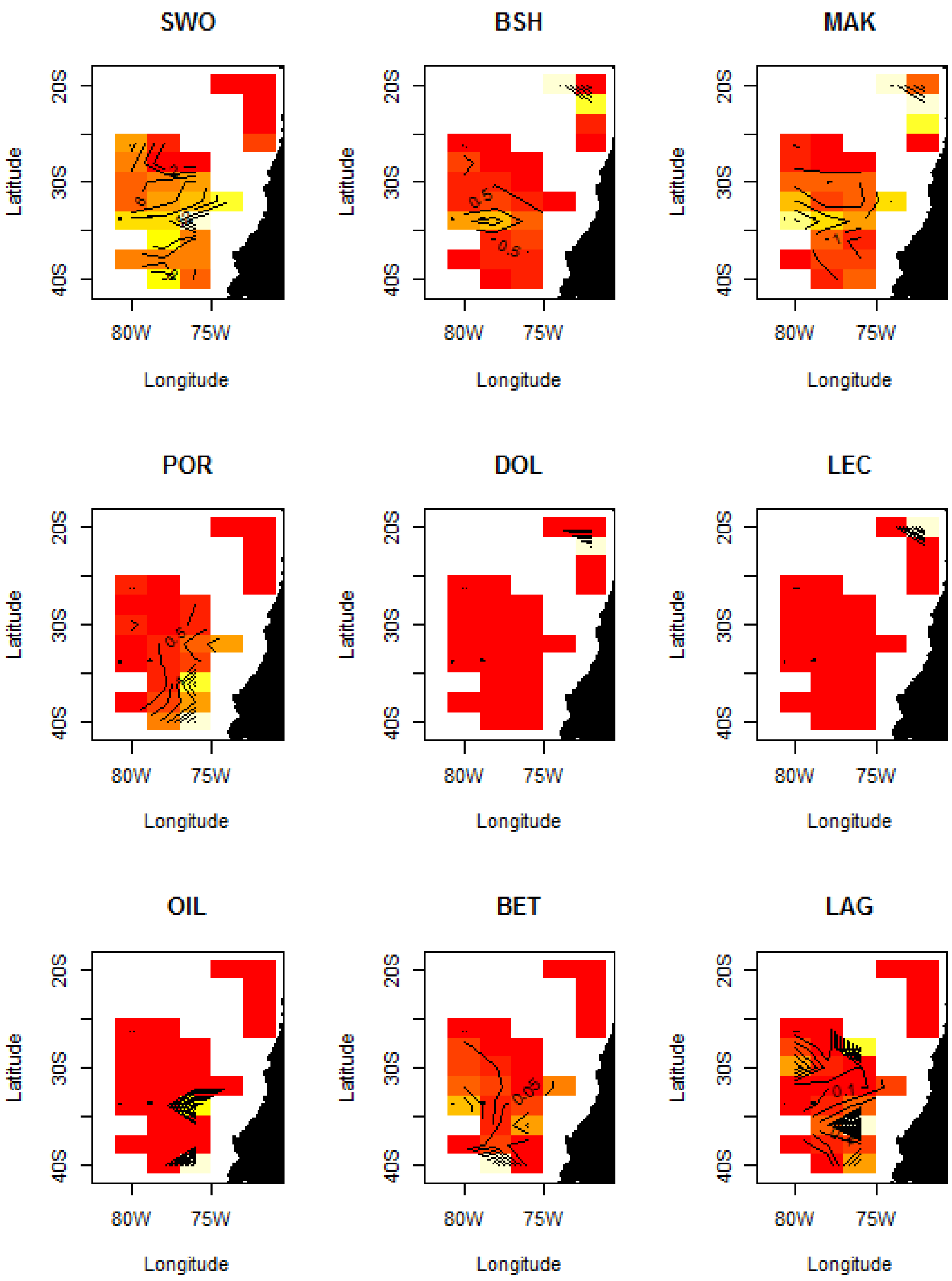

Figure 10: Mean CPUE of observed artisanal gillnet sets by 2 degree square, with red indicating no catch and yellow indicating the highest observed CPUE for the species. White indicates areas with no effort.

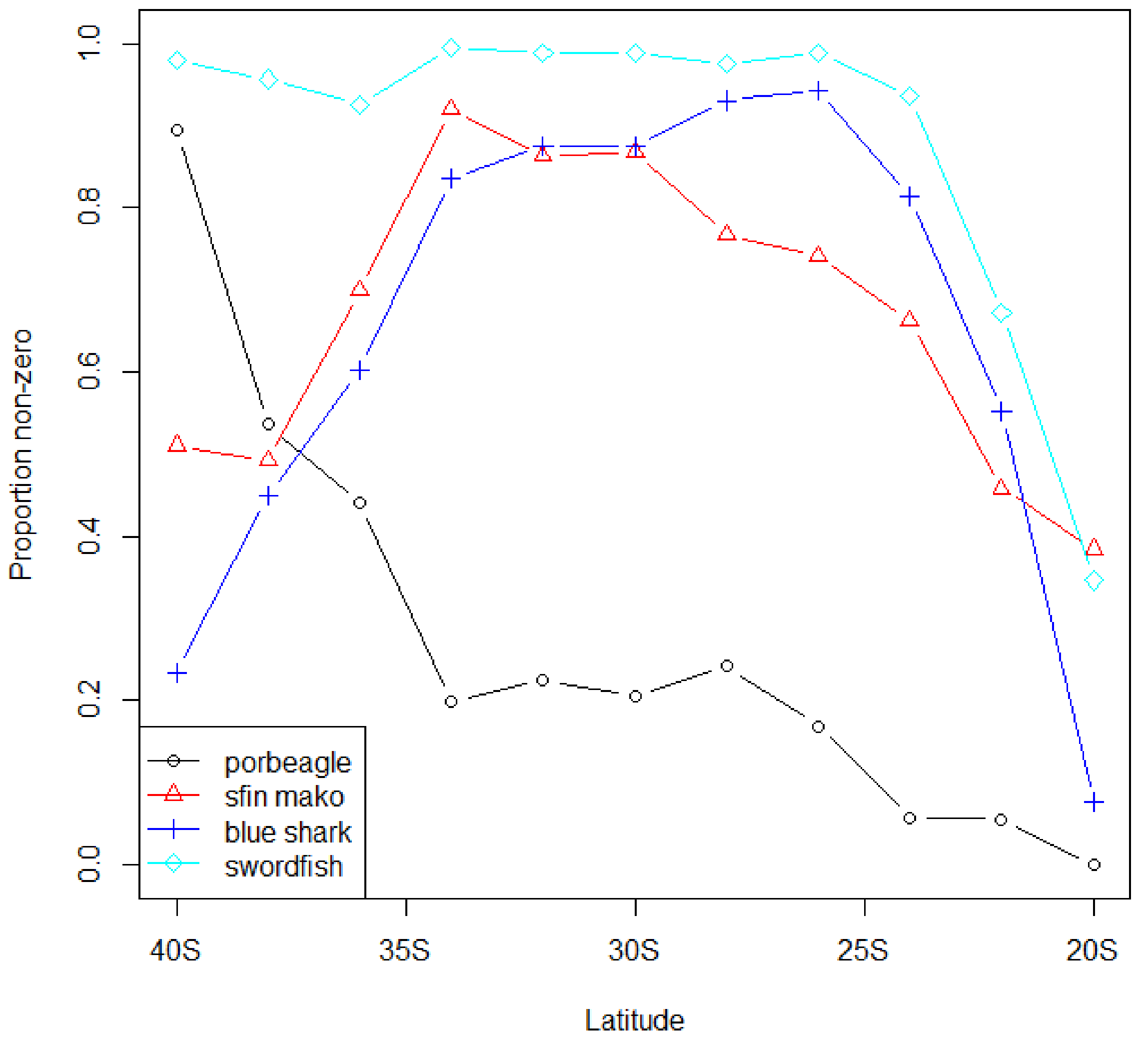

Figure 11: Proportions by latitude of non-zero catch per longline set for swordfish, shortfin mako, blue shark, and porbeagle shark.

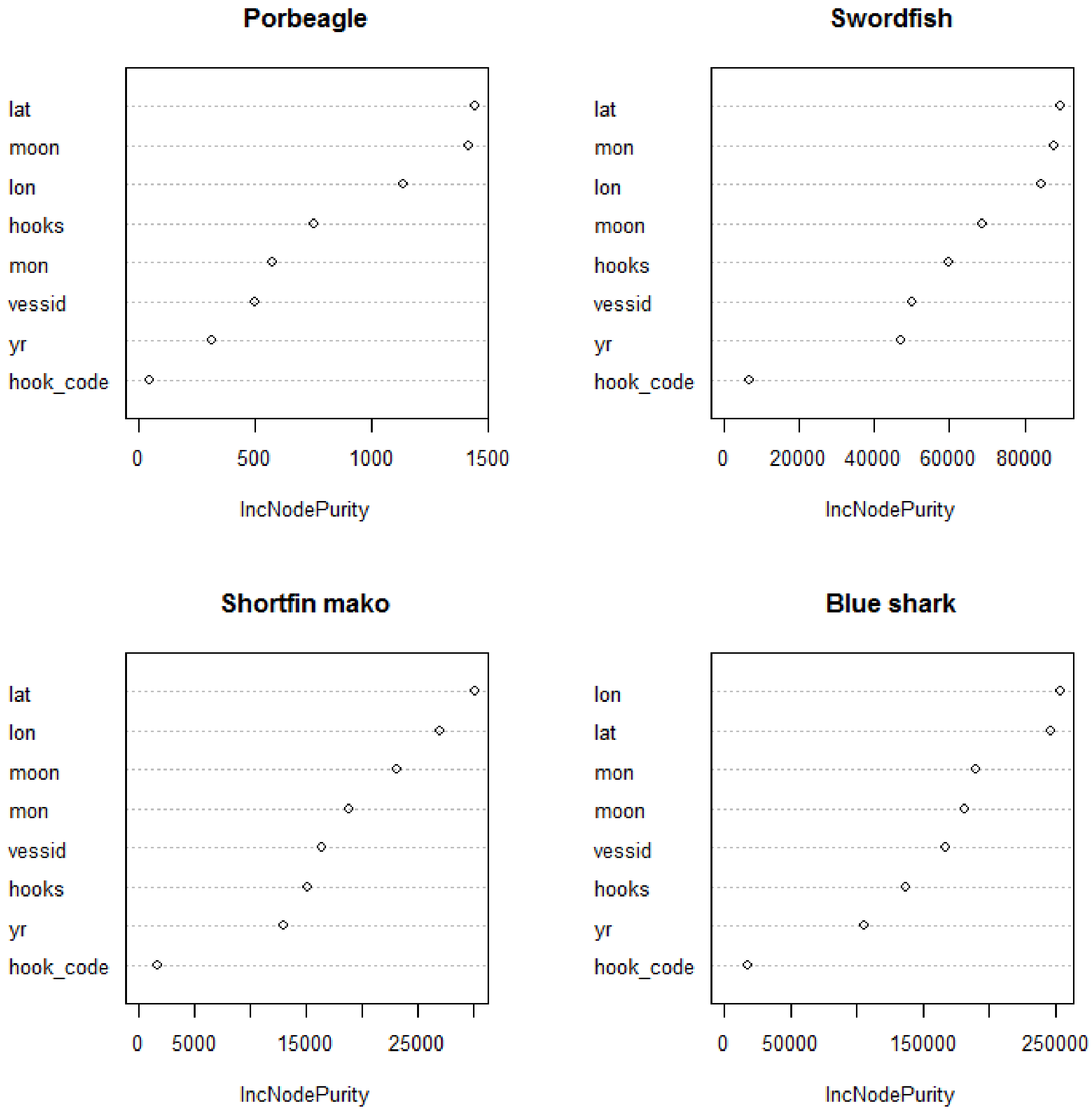

Figure 12: Variable importance plots from a random forest analysis including 500 regression trees, for porbeagle sharks and the four main species caught in the longline fishery.

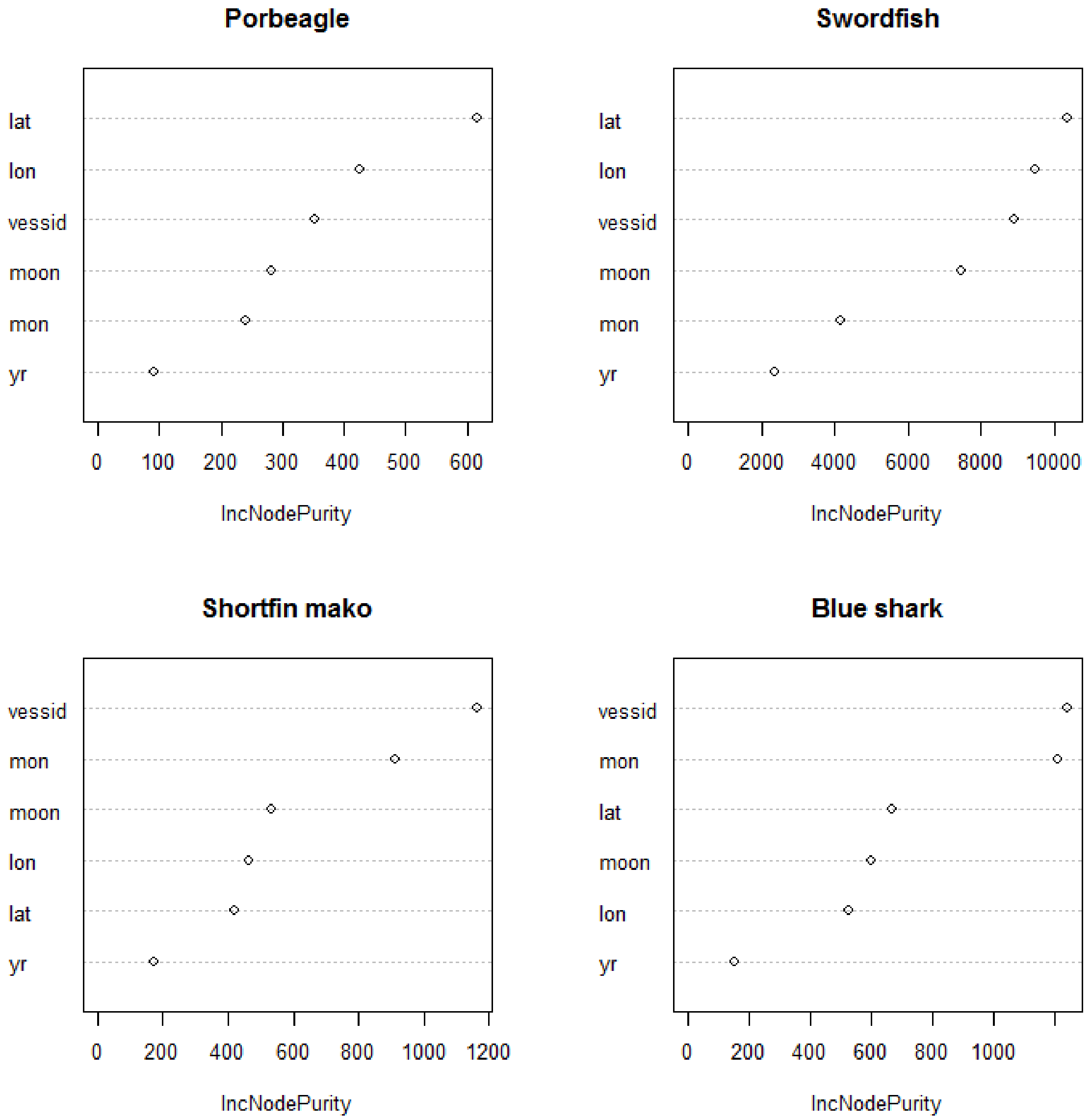

Figure 13: Variable importance plots from a random forest analysis including 500 regression trees, for porbeagle sharks and the four main species caught in the artisanal gillnet fishery.

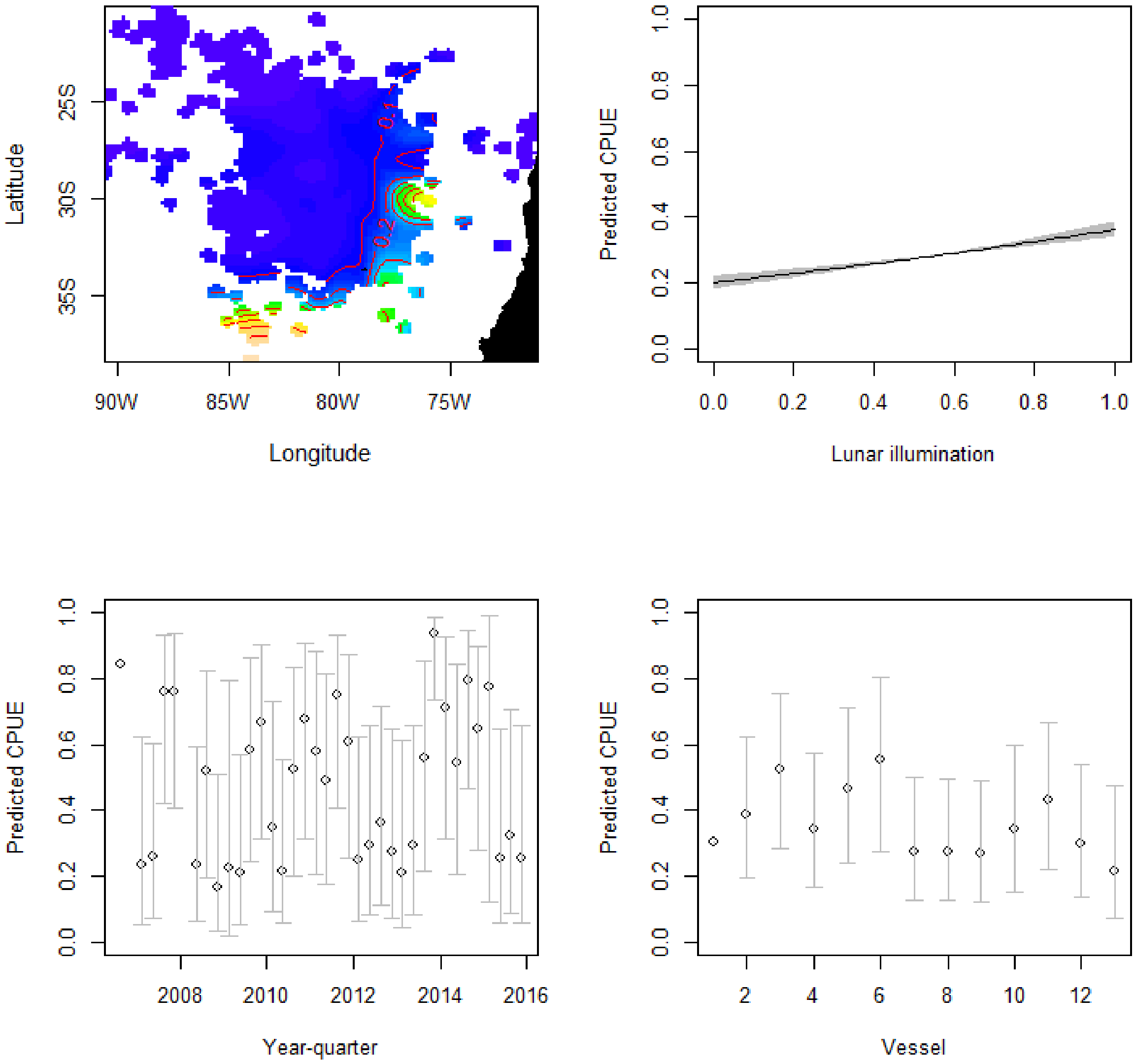

Figure 14: Plots for predicted probability of non-zero sets by location (top-left), lunar illumination (top right), year-quarter (bottom left) and vessel (bottom right). Probabilities are predicted for the modal vessel in the

4th quarter of 2012, with lunar illumination of 0.5, at location 84°W, 35°S. Confidence intervals are twice the standard error associated with the parameter. There are no confidence intervals for the base values.

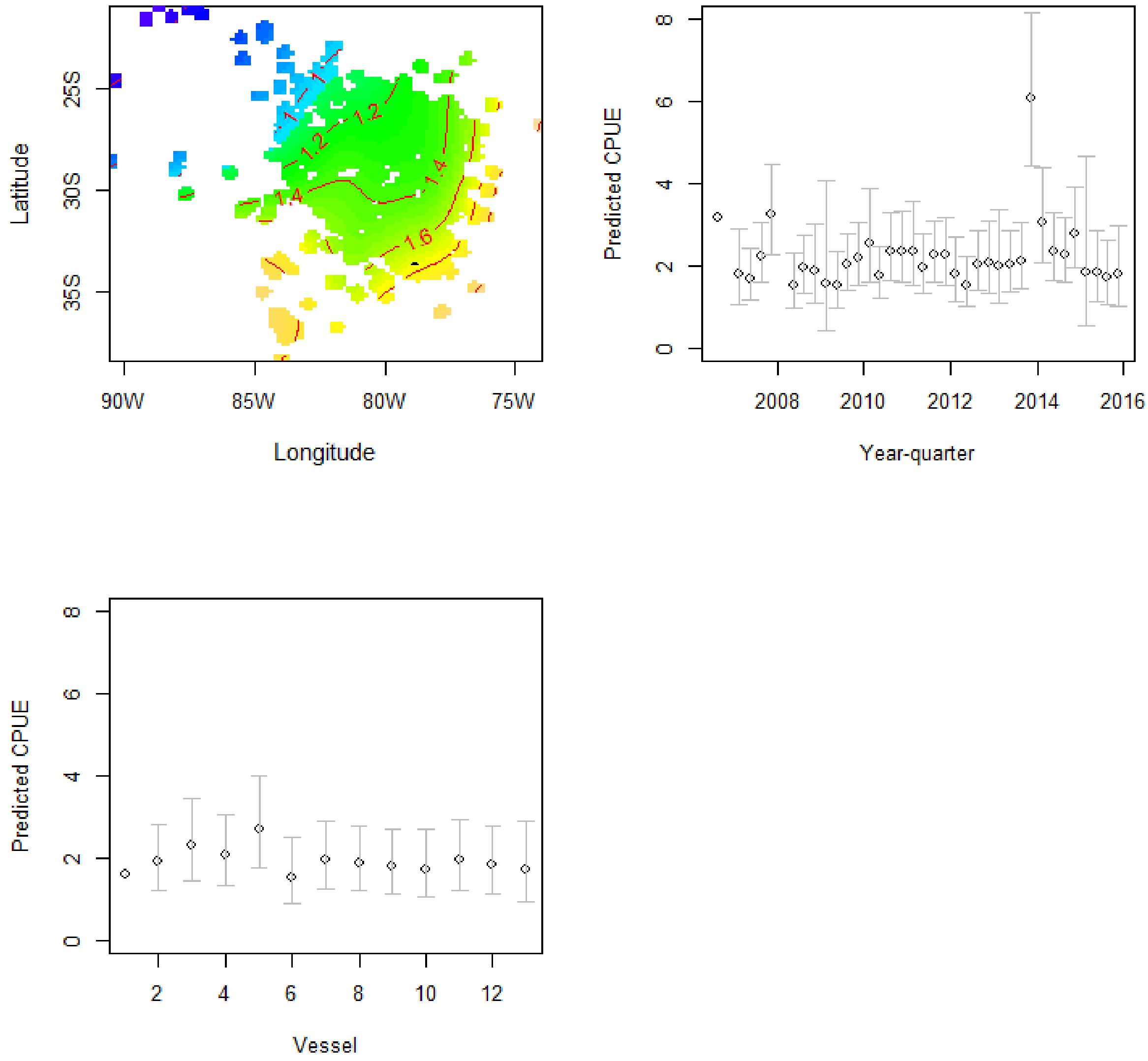

Figure 15: Plots for predicted catch rates in non-zero sets by location (top-left), year-quarter (top right) and vessel (bottom left). Catch rates are predicted for the modal vessel in the 4th quarter of 2012, at location

84°W, 35°S. Confidence intervals are twice the standard error associated with the parameter. There are no confidence intervals for the base values.

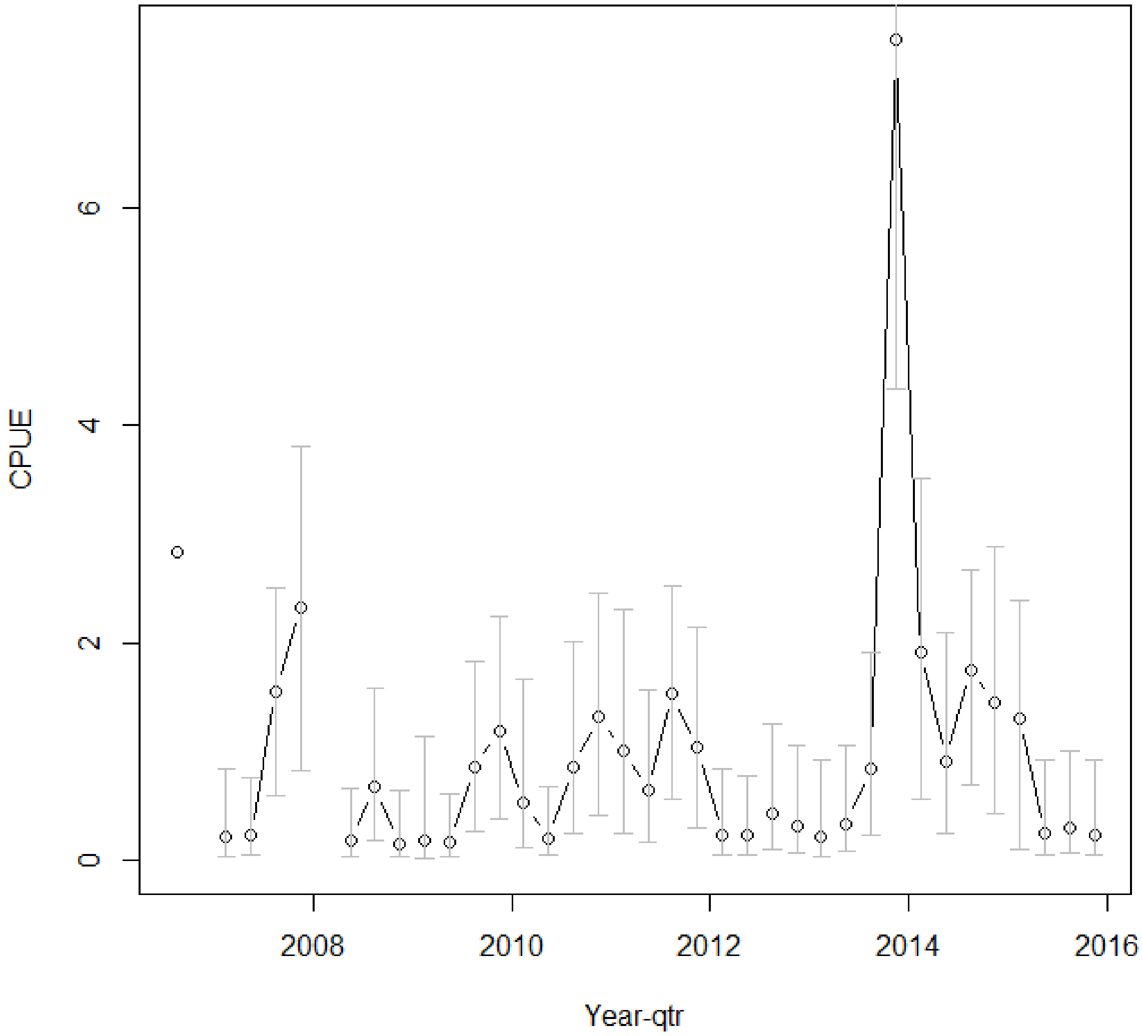

Figure 16: Quarterly indices of abundance for porbeagle shark derived from standardizing swordfish longline data. Confidence intervals are twice the standard error of the binomial component of the model. Indices are normalized to average 1. There is no confidence interval for the base value.

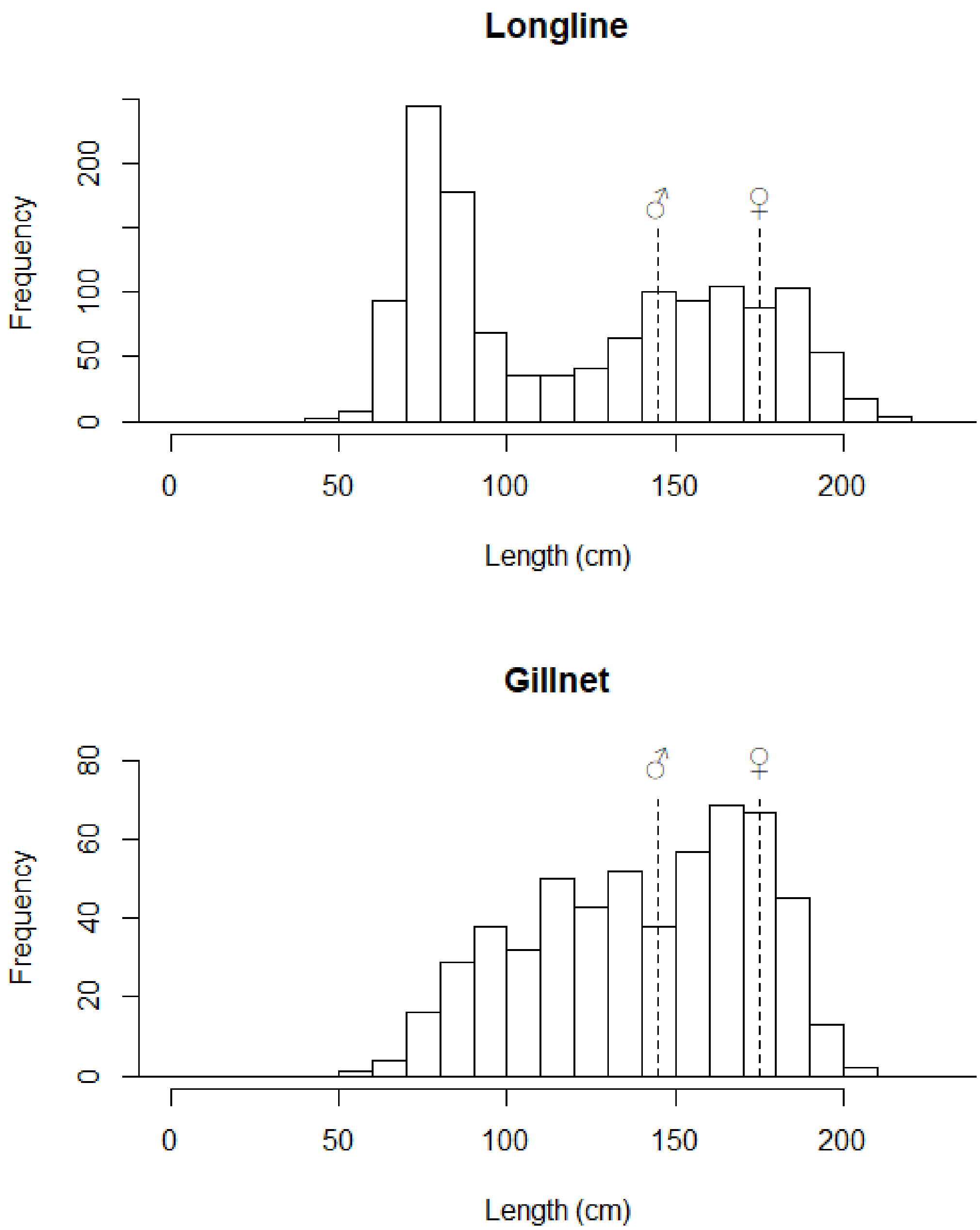

Figure 17: Frequency distributions of numbers at fork length for the longline (above) and gillnet (below) fisheries. Male and female approximate lengths at maturity are indicated on each figure.

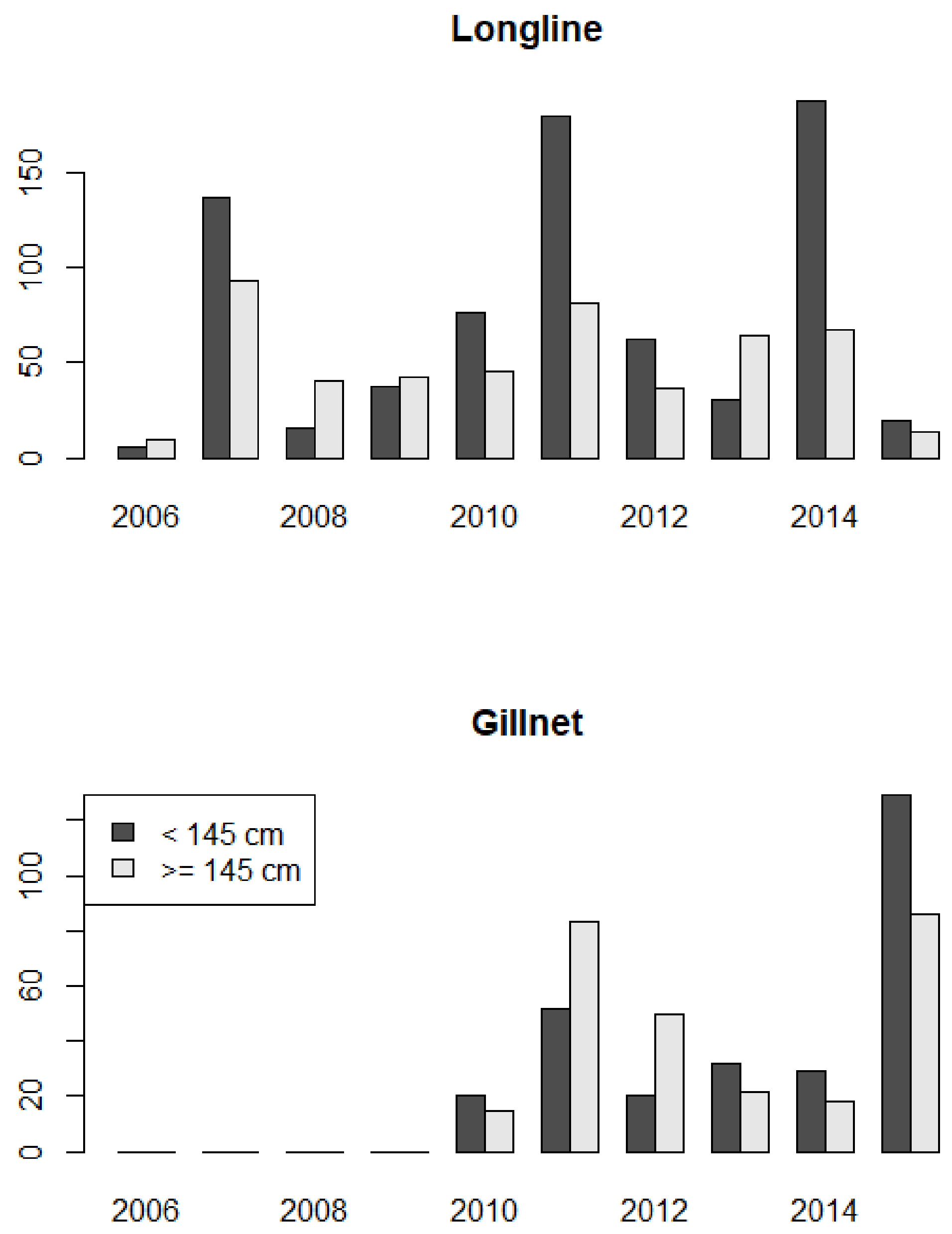

Figure 18: Numbers of measured porbeagle sharks less than or greater than 145 cm, the approximate length of male maturity, by year and fishery.

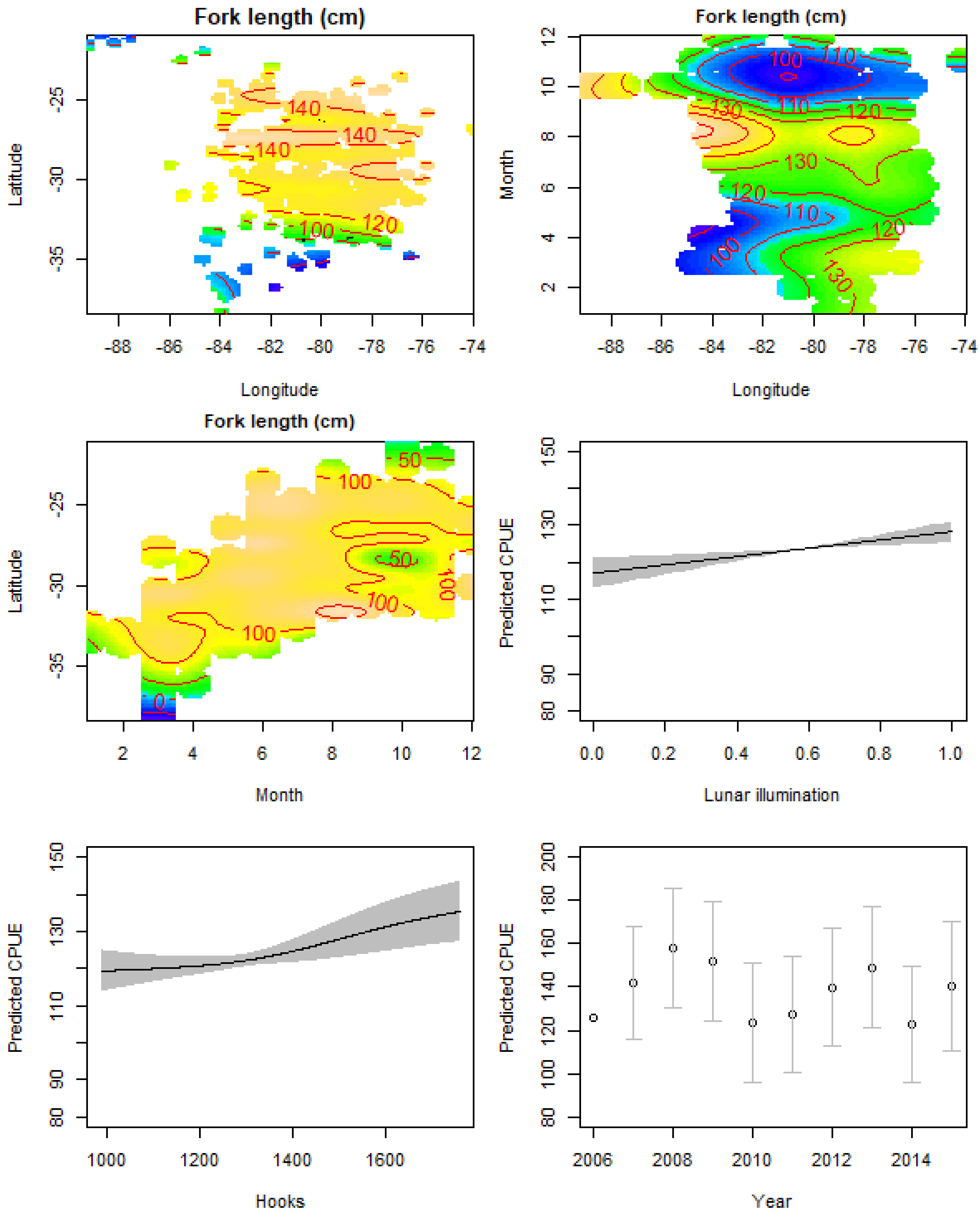

Figure 19: Predicted lengths in the longline fishery, based on standardization. Confidence intervals are twice the standard error associated with the parameter.

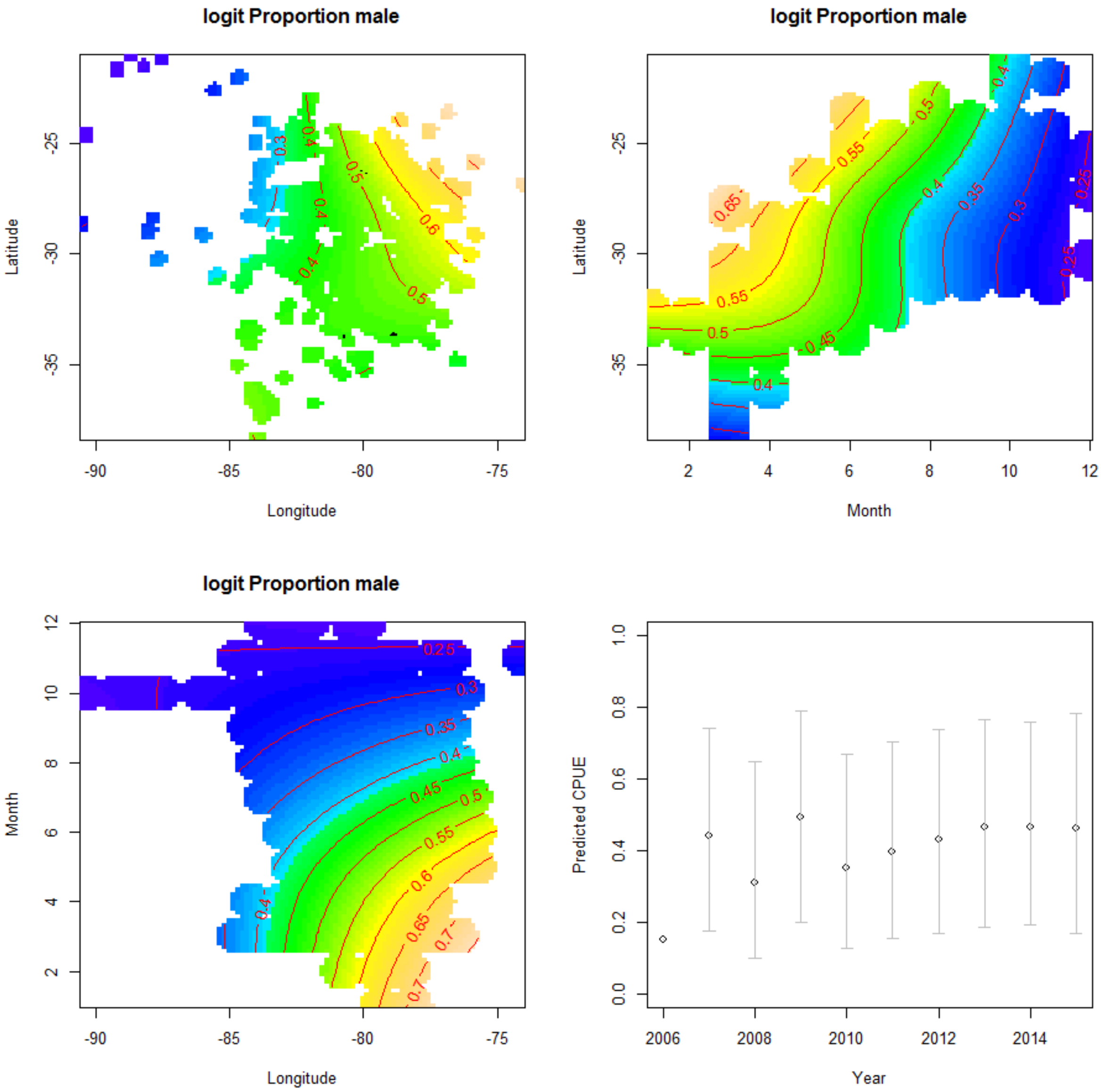

Figure 20: Plots for predicted sex as a function of month, location, and year. Significant effects were observed due to the location (top-left), the interaction of month and latitude (top right), interaction of month and longitude (bottom left), and year (bottom right). Sex is predicted for the location 80°W, 30°S, month 6, and year 2011. Confidence intervals are twice the standard error associated with the parameter.