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Aspects of porbeagle shark bycatch in the Argentinean surimi fleet operating in the Southwestern Atlantic Ocean (50-57°S) during 2006-2014

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Summary

In the southern Southwestern Atlantic Ocean (SAO) off Argentina, the porbeagle shark, *Lamna nasus,* is incidentally caught by trawl fleets operating south of 44°S. The surimi fleet has the most frequent and abundant bycatch. After the implementation of the National Plan of Action for the Conservation and Management of Sharks, porbeagle shark data gathering and research were proposed as priority actions. The wide spatial distribution of the porbeagle shark and the unbalanced fishery-dependent data produce high variability in the bycatch trend, creating the need for analyses that include spatio-temporal, environmental and operational variables not considered in previous studies. Therefore, the aims of the present study were 1) to quantify the historical *L. nasus* bycatch in the Argentinean surimi fleet, 2) to determine the bycatch trend using spatio-temporal, environmental and operational variables and 3) to analyze the length and sex structure of the porbeagle shark bycatch.

Bycatch data were recorded by scientific observers on the Argentinean surimi fleet operating at the southern limits of the Southwestern Atlantic between 2006 and 2014.The annual *L. nasus* bycatch was estimated, taking into account the on-board observed coverage. We used a Delta model to standardize the bycatch of porbeagle shark considering spatio-temporal, environmental and operative variables. Generalized additive modeling was applied to explore the variation in the length, sex and proportion mature of the bycatch.

A total of 9965 fishing hauls were analyzed of which 11% had a positive *L. nasus* bycatch. Estimated annual *L. nasus* bycatch by the Argentinean surimi fleet ranged from 10 to 117 tons. The standardized catch rate was stable with some variability until 2011, and increased between 2012 and 2014. The length structure, sex ratio and proportion mature varied by month and latitude. Catch rates were higher during summer and autumn. During this period, mature females with fork length between 180 and 200 cm predominated.

The levels of porbeagle bycatch by the Argentinean surimi fleet demonstrate the need to maintain continuous observer monitoring of the fleets operating in the Southwestern Atlantic Ocean and to adopt further precautionary management measures to mitigate the bycatch.

The variability in the porbeagle bycatch trend may reflect effects associated with unbalanced datasets, the wide distributional range of this species, or changes in the targeting strategies of the fleet that are not apparent in the available data, impeding its use as a population indicator. Further work, such as the investigation of potential changes in fishing strategy, could substantially improve results. Additionally, regional and collaborative studies are needed to understand the spatial distribution and population trend of porbeagle shark in the Southern Hemisphere.

Introduction

The porbeagle shark, *Lamna nasus*, inhabits the epipelagic domain in the cold waters of the Atlantic, Indian and South Pacific Oceans (Compagno, 2001). In the southern Southwestern Atlantic Ocean (SAO) off Argentina, *L. nasus* is incidentally caught by trawl fleets operating south of 44°S, including the surimi fleet which has the most frequent and abundant bycatch (90% of total *L. nasus* bycatch; Waessle, 2007; Waessle and Cortés, 2011). The surimi fleet mainly targets southern blue whiting (*Micromesistius australis australis*) and Patagonian grenadier (*Macruronus magellanicus*), and in smaller quantities Patagonian hake (*Merluccius patagonicus*) and Patagonian toothfish / merluza negra (*Dissostichus eleginoides*). Considering the unknown status of *L. nasus* in the southern SAO and the increasing international concern about porbeagle conservation and trade (Stevens, 2006; Francis et al., 2008), porbeagle shark data gathering and research were proposed as a priority action of the National Plan of Action for the Conservation and Management (PAN-tiburón; CFP, 2009).

After the implementation of the PAN-tiburón, advances in order to improve porbeagle data availability and to reduce the bycatch mortality have been made (Massa *et al*., 2015; Puliafito & Massa, 2016). Hotspots for bycatch and the bycatch trend were identified in the surimi fleet operating in the southern SAO (Waessle & Cortés 2011; Cortés & Waessle, 2017). Although the bycatch trend seems to be stable, there is high variability, which may be due to operational changes in the fleet, or with the wide distributional range of this species in the South Hemisphere relative to the spatial distribution of fishing (Cortés & Waessle, 2017). Therefore, the use of the unstandardized bycatch trend as a population indicator may not be appropriate.

The impacts of exploitation detected by stock assessments in the North Atlantic and the lack of data from the Southern Hemisphere stocks are some of the main reasons for the inclusion of porbeagle into Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora since 2013 (CITES, 2013). In this context, the Western and Central Pacific Fisheries Commission (WCPFC) developed the “Southern Hemisphere Porbeagle Shark Stock Status Assessment” project to assess the conservation status of porbeagle shark in the South Hemisphere and to improve the understanding of porbeagle shark population dynamics at a regional scale.

The limited information and the regional interest about the porbeagle conservation status create the need to update the analysis of the Argentinean surimi fleet data. Therefore, the aims of the present study were 1) to quantify the historical *L. nasus* bycatch in the Argentinean surimi fleet, 2) to determine the bycatch trend using spatio-temporal, environmental and operational variables and 3) to analyze the length and sex structure of the porbeagle shark bycatch.

Methods

Catch and environmental data

Bycatch data was recorded by scientific observers on the Argentinean surimi fleet operating at the southern limits of the Southwestern Atlantic between 2006 and 2014. Between 2006 and 2009 the data come from the three ships in the fleet, which reduced to 2 ships for 2010 – 2012, and 1 ship for 2013 – 2014 (Table 1). The surimi fleet uses either bottom or semi pelagic trawl nets (Martini, 2001). The headline height of the bottom trawl nets was less than 15 m, while in the semi-pelagic trawl nets the headline height was more than 15 m. The frequency of each gear changed between ships and years, showing an increase in the proportion of bottom trawls (Figure 1). All ships operate almost throughout the year (Figure 2), and the areas in which hauls were concentrated did not show major changes between years (Figure 3).

For each trawl, date, geographic coordinates, gear type (bottom or semi-pelagic trawl), trawl speed, trawl duration, gear depth, gear temperature and the estimated catch weight (in kg) of porbeagle shark (*L. nasus*) were registered. The catch weight (kg) of porbeagle shark per haul was estimated from individual fork lengths (measured to the nearest cm), using the fork length-weight relationships presented by Francis & Stevens (2000) for Australian porbeagles. Additionally, in 66% of the trawls with *L. nasus* catches the fork length and sex of each individual were registered.

Bycatch quantification

Considering that on-board observers covered ~93% of the Argentinean surimi fleet operations between 2006 and 2014 (Table 1), the annual *L. nasus* bycatch ($LNBest_t$) was estimated by the seasonally weighting the observed *L. nasus* bycatch according to the observed proportion of the total catch, as follows:

$$LNBest_t = \sum_{i=1}^{4} \frac{Lrep_{ti}}{Lobs_{ti}} \times LNBobs_{ti}$$

where $LNBobs_{ti}$ is the observed *L. nasus* bycatch for season i and year t in the Argentinean surimi fleet and $Lobs_{ti}$ is the landing of all species observed for the same season, year and fleet. $Lrep_{ti}$ is the landing of all species reported for the Argentinean surimi fleet in the season i and year t according to the National Fisheries Statistics (http://www.minagri.gob.ar).

Bycatch standardization

To standardize the *L. nasus* bycatch we used a Delta Model. These models have been widely used to deal with zero catches obtained when sampling low abundance or rare species that aggregate (Maunder & Punt, 2004; Candy, 2004; Shono, 2008; Carvalho *et al*., 2011; Campbell, 2015), such as *L. nasus*. A Delta model consists of two components, one model to estimate the probability of obtaining non-zero captures ($\hat{p}$) and the other to fit the size of positive values ($\hat{catch}$). Estimates of the bycatch rate ($\hat{Bc}$) from a Delta model are obtained by multiplying these two components (Maunder and Punt, 2004; Shono, 2008):

$$\hat{Bc} = \hat{p} \times \hat{catch}$$

Here we used a Delta model that combines two generalized additive models (Delta-GAM) allowing us to model nonlinear relationships through fitting smooth functions to the predictor variables. In the first step, the probability of non-zero catches was estimated assuming a binomial error distribution and a Logit link function, while in the second step the catch size was estimated assuming a Log-normal error distribution and an Identity link function.

The bycatch rate (kg per hour of trawl) of *L. nasus* was the response variable. In each step of the Delta-GAM we used 9 explanatory variables: four spatio-temporal (year, month, latitude and longitude), four operational (ship, gear type, trawl speed and gear depth) and one environmental (gear temperature). Only year, ship and gear type was treated as categorical variables with nine (annual between 2006 and 2014), three (ships A, B and C) and two (bottom or semi-pelagic trawl) levels respectively. The continuous variables were fitted using smooth terms. The geographic position and monthly variation were fitted with a two dimensional tensor spline using the *te()* function of the *mgcv* package (Wood, 2006). The Binomial and Log-normal model took the following forms, respectively:

$g(P_{OCCUR})$ ~ year + ship + gear type + te(longitude, latitude, k=c (8,10)) + s(trawl speed, k=10) + te(month, latitude) + s(gear depth, k=10) + s(gear temperature, k=10)

Log(*LNcatch*) ~ year + ship + gear type + te(longitude, latitude, k=c (8,10)) + s(trawl speed, k=10) + te(month, latitude) + s(gear depth, k=10) + s(gear temperature, k=10)

where P_{OCCUR} is the probability of non-zero catches, *g* was the logit function, *LNcatch* is the *L. nasus* catch in kg/h, and *k* sets the upper limit to the degrees of freedom for an *mgcv* smooth.

Model selection was based on minimization of both the Generalized Cross-Validation statistic (GCV) and the Akaike Information Criterion (AIC). Within a model the significance of each model term was assessed using Wald-like tests, conditional on the smoothing parameter estimates, using the function *anova.gam()* from the mgcv package in R version 2.15.1 (R Development Core Team, 2012).

Length and sex proportion analyses

Fork length and sex data of *L. nasus* were used to estimate the annual length structure, sex ratio and the proportion of mature individuals by sex. The proportion of mature individuals was calculated using a maturity fork length of 145 cm for males and 175 cm for females (Francis & Duffy, 2005). Additionally, to explore the length and sex dataset and to identify variables affecting the length structure, sex ratio and mature proportion of the porbeagle bycatch in the Argentinean surimi fleet we fitted Generalized Additive Models (GAM) using the *mgcv* package in the R statistical software version 2.15.1 (R Development Core Team, 2012). To explore the fork length structure we used a GAM assuming Normal distribution in the response variable and to explore the variation in the sex ratio and proportion of mature females and males we fitted binomially distributed GAMs. These models took the following form:

a) Gaussian model:

LH ~ te(month,latitude) + year + gear type + s(trawl speed) + s(gear depth) + s(gear temperature) + s(fset, bs = "re")

b) Binomial models:

-*Sex ratio model*
$g(P_H)$ ~ te(month,latitude) + year + gear type + s(trawl speed) + s(gear depth) + s(gear temperature) + s(fset, bs = "re")

-*Model for the proportion of mature females*
$g(P_{HM})$ ~ te(month,latitude) + year + gear type + s(trawl speed) + s(gear depth) + s(gear temperature) + s(fset, bs = "re")

- *Model for the proportion of mature males*
$g(P_{MM})$ ~ te(month,latitude) + year + gear type + s(trawl speed) + s(gear depth) + s(gear temperature) + s(fset, bs = "re")

where FL is the fork length, P_H is the proportion of females, P_{HM} and P_{MM} are the proportions of adult males or females respectively; and g is the *logit* link function. The *s(fset, bs="re")* term is the normal distributed random effect associated with the trawl. This term was introduced in order to address overdispersion in case the length, sex or maturity stage of the porbeagles is correlated among individuals on the same trawl.

Model selection was based on minimization of both the Generalized Cross-Validation statistic (GCV) and the Akaike Information Criterion (AIC). Within a model the significance of each model term was assessed using Wald-like tests, conditional on the smoothing parameter estimates, using the function anova.gam() from the mgcv package in R version 2.15.1 (R Development Core Team, 2012). We plotted the partial effects of each explanatory variable. The latitudinal variation by month were plotted by predicting fork lengths, sex ratio or mature proportions across the range of observed values of the parameter of interest, while fixing all other parameters. Numeric variables were fixed at their medians. The categorical variables year and gear type were set to 2008 and semi-pelagic trawls respectively. Confidence intervals were predicted at the 95% confidence level for the parameter of interest.

Results

A total of 9965 fishing hauls were analyzed, of which 11% had a positive *L. nasus* bycatch (Table 1, Figure 4 and 5). Estimated annual *L. nasus* bycatch by the Argentinean surimi fleet ranged from 10 to 117 tons (Table 1).

To standardize the *L. nasus* bycatch we removed hauls with operational failures (e.g. gear damage) and those in which the vertical opening and trawl speed were not registered. The hauls south of 56º S were not included due to this area's separation from the core operational fleet area (Figure 6). Therefore, the number of hauls included in the standardization procedure was 8223 (Table 2).

Standardized *L. nasus* bycatch showed a high variability. The trend was relatively stable until 2011, showing an increase between 2012 and 2014 (Figure 7).

The Delta-GAM analysis showed that the occurrence of *L. nasus* increased with the trawl speed and showed a peak at 500 m depth (Table 3 and Figure 8). The occurrence was higher East of 64º W and South of 54º S; and had a strong seasonality peaked between March and June (Table 3 and Figure 8). The occurrence decreased west of 63°30'W and attained a minimum north of 53°30'S. The occurrence of *L. nasus* was higher in semi-pelagic trawls and showed variations associated with the year and ship (Table 3 and Figure 8).

The bycatch size of *L. nasus* increased to the Southeast and showed a strong seasonality peaked between March and June (Table 4 and Figure 9). The bycatch decreased with trawl depth, was higher in semi-pelagic trawls and showed variations between years and ships (Table 4 and Figure 9). The residuals analysis of the Log-normal model showed a reasonable fit (Figure 10).

The fork length of the porbeagles caught in the Argentinean surimi fleet had a median value of 182 cm and 167 cm for females and males respectively (Figure 11). These values show an annual variation between 163 and 200 cm in females and between 130 and 183 cm in males (Figure 12). The female proportion was between 66 and 79%, with a mean value of 70% (Figure 13). The proportion of adults was 62% for females and 82% for males (Figure 13).

For the length structure, the GAM analysis indicates that smaller sharks were caught between April and August, and south to the 54º S (Table 5 and Figure 14). Additionally, semi-pelagic trawls caught larger porbeagles than bottom trawls, and the fork length varied between years (Table 5 and Figure 15).

The sex ratio analysis showed a smooth latitudinal gradient and a predominance of females during the first semester (Table 6 and Figures 16 and 17).

For females, the bivariate smooth term showed the lower proportions of adults south of 54º S between March and June, whereas between July and December the lower proportions of adults are distributed north of 53º S (Table 7 and Figure 18). The proportion of mature females was higher in semi-pelagic trawls and peaked at 500 m of gear depth (Table 7 and Figure 19).

The proportion of adult males had a maximum value between May and August at latitudes between 53º30` and 54º30` S, however this gradient is very weak (Table 8 and Figure 20). Additionally, the proportion of mature males showed annual variations and was higher in semi-pelagic trawls (Table 8 and Figure 21).

In all models, the random effect term was significant, indicating some degree of aggregation by length, sex and maturity stage (Tables 5, 6, 7 and 8).

Discussion

The present study demonstrates that *L. nasus* is regularly caught as bycatch by the Argentinean surimi fleet operating in the southern Southwestern Atlantic. This bycatch has a relatively stable trend and is associated with spatio-temporal and operational variables.

Recorded bycatch values over the period 2006-2014 were higher than the annual mean catches reported for the Uruguayan longline fleet operating in the North of the Southwestern Atlantic (ICCAT, 2014; Pons & Domingo, 2010). Although after 2009 the Argentinean surimi fleet was reduced, and Argentina has adopted management measures in order to discourage the catch and trade of large sharks and prohibited shark finning (CFP, 2013), the levels of porbeagle bycatch recorded in the present study combined with the low productivity life history traits of the porbeagle (Campana, 2016), demonstrate the need to maintain continuous observer monitoring of the fleets operating in the Southwestern Atlantic Ocean, and to adopt further precautionary management measures to mitigate the bycatch.

Analyses of biological data provided new information about porbeagle population structure in the south Atlantic. The seasonal spatial distribution of *L. nasus* is characterized by latitudinal migration, with high latitude aggregations during summer and autumn, and low latitude (north of 30°S) aggregations during winter (Yatsu, 1995 & Francis and Stevens, 2000). In the Southwestern Atlantic, analyses of longline fleets operating between 20°S and 45°S demonstrate the occurrence of juveniles and adults during winter and spring (Forselledo, 2012; Mas, 2012; Soto and Montealegre-Quijano, 2012). Waessle and Cortés (2011) studied the length structure of *L. nasus* in the southern Southwestern Atlantic (between 51°S and 56°48'S) and observed a wide fork length range (between 70 and 290 cm), but a predominance of adult individuals. In this study we have found that *L. nasus* were more abundant during summer and autumn, coinciding with the prevalence of mature females with fork lengths between 180 and 200 cm. The *L. nasus* seasonality and length structure observed by Forselledo (2012) coupled with the results of our study indicate that its distribution pattern in the Southwestern Atlantic is in line with that observed in the North Atlantic (Campana *et al*., 2010) and South Pacific (Semba *et al*., 2013). This also coincides with the distribution pattern described for *L. ditropis* in the North Pacific (Weng et al., 2008). For both species, nursery areas seem to be located in temperate regions, and adult feeding grounds in cooler regions.

Variability in commercial data and the amount of zero-catch data can affect population trend estimates (Semba *et al*., 2013). In this study, the higher bycatch values since 2012 may reflect effects not included in the data modeling (e.g. fishing strategies) or effects associated with unbalanced datasets (such as the lack of hauls of ship A between September and December of 2012, see Figure 2) rather than changes in *L. nasus* abundance. Dynamic environmental changes in the southwest Atlantic may also have affected local populations. Tagging studies demonstrate that porbeagles may move over thousands of kilometers (Francis *et al.*, 2015; Campana, 2016), so the relatively short-term catch rate trend observed in this study, with a limited spatial extent, may reflect local changes rather than population-level trends. Nevertheless, the standardized bycatch trend we have estimated at the southern limit of the Southwestern Atlantic gives no indication of decline, and is not dissimilar from trends observed in New Zealand and the South Pacific Ocean (Griggs & Baird, 2013; Semba *et al*., 2013; Francis *et al*., 2014).

This study has contributed to the regional and collaborative studies needed to understand the spatial distribution and population trend of porbeagle shark in the Southern Hemisphere.

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Tables

Table 1. Annual numbers of operative ships, percentage of onboard observer coverage, numbers of trawls and bycatch in the Argentinean surimi fleet.

Year	Operating ships	Onboard observer coverage (%)	Trawls	Trawls with L. nasus	Bycatch (t)	Estimated bycatch (t)
2006	3	100	1337	192	71	78
2007	3	100	1182	122	32	37
2008	3	100	1357	232	101	105
2009	3	66	1538	151	64	73
2010	2	86	1161	126	46	67
2011	2	100	745	34	8	12
2012	2	90	996	171	104	117
2013	1	100	771	34	8	10
2014	1	100	878	49	12	14
Total	-	93	9965	1111	426	513

Table 2. Number of trawls used for the porbeagle bycatch standardization in the Argentinean surimi fleet.

Year	Bottom trawls	Semi-pelagic trawls	Total
2006	117	1057	1174
2007	154	637	791
2008	206	682	888
2009	534	876	1410
2010	407	605	1012
2011	385	278	663
2012	499	345	844
2013	378	335	713
2014	440	288	728
Total	3120	5103	8223

Table 3. Significance tests for categorical variables and smoother parameters in Binomial step of the Delta-GAM model of porbeagle bycatch in the southern Southwestern Atlantic Ocean.

Variable	df	χ^2	p-value
Year	8	137.57	< 0.001
Ship	2	183.37	< 0.001
Gear type	1	22.44	< 0.001
	edf	χ^2	**p-value**
te(longitude,latitude)	9.82	126.09	< 0.001
s(trawl speed)	1.00	6.519	0.011
te(month,latitude)	15.23	221.48	< 0.001
s(Gear depth)	3.30	59.58	< 0.001

Table 4. Significance tests for categorical variables and smoother parameters in Log-normal step of the Delta-GAM model of porbeagle bycatch in the southern Southwestern Atlantic Ocean.

Variable	df	F	p-value
Year	8	137.57	< 0.001
Ship	2	183.37	< 0.001
Gear type	1	22.44	< 0.094
	edf	**F**	**p-value**
te(longitude,latitude)	9.82	126.09	< 0.001
te(month,latitude)	15.23	221.48	< 0.001
s(Gear depth)	3.30	59.58	< 0.011

Table 5. Significance tests for categorical variables and smoother parameters for the porbeagle length model in the southern Southwestern Atlantic Ocean.

Variable	df	F	p-value
Year	8	2.968	0.003
Gear type	1	6.018	0.014
	edf	**F**	**p-value**
te(month,latitude)	6.900	24.551	< 0.001
s(Trawl speed)	0.002	0.000	0.687
s(Gear depth)	1.400	1.924	0.081
s(Gear temperature)	0.388	0.289	0.193
s(fset)	250.900	1.085	< 0.001

Table 6. Significance tests for categorical variables and smoother parameters for the porbeagle sex ratio model in the southern Southwestern Atlantic Ocean.

Variable	df	χ^2	p-value
Year	8	10.279	0.246
Gear type	1	0.446	0.504
	edf	χ^2	**p-value**
te(month,latitude)	3.0174	80.846	< 0.001
s(Trawl speed)	0.5359	1.529	0.150
s(Gear depth)	0.6644	2.651	0.085
s(Gear temperature)	0.8718	2.811	0.101
s(fset)	62.9997	84.215	< 0.001

Table 7. Significance tests for categorical variables and smoother parameters for the porbeagle mature female model in the southern Southwestern Atlantic Ocean.

Variable	df	χ^2	p-value
Year	8	13.240	0.104
Gear type	1	5.403	0.020
	edf	χ^2	**p-value**
te(month,latitude)	5.8280	116.150	< 0.001
s(Trawl speed)	0.0001	0.000	1
s(Gear depth)	2.3240	31.162	0.002
s(Gear temperature)	0.5874	3.085	0.130
s(fset)	119.3000	180.580	< 0.001

Table 8. Significance tests for categorical variables and smoother parameters for the porbeagle mature male model in the southern Southwestern Atlantic Ocean.

Variable	df	χ^2	p-value
Year	6	19.910	0.003
Gear type	1	4.464	0.035
	edf	χ^2	**p-value**
te(month,latitude)	4.95300	38.660	< 0.001
s(Trawl speed)	0.97270	4.855	0.121
s(Gear depth)	0.56890	1.850	0.187
s(Gear temperature)	0.00001	0	0.865
s(fset)	75.9100	116.597	< 0.001

Figures

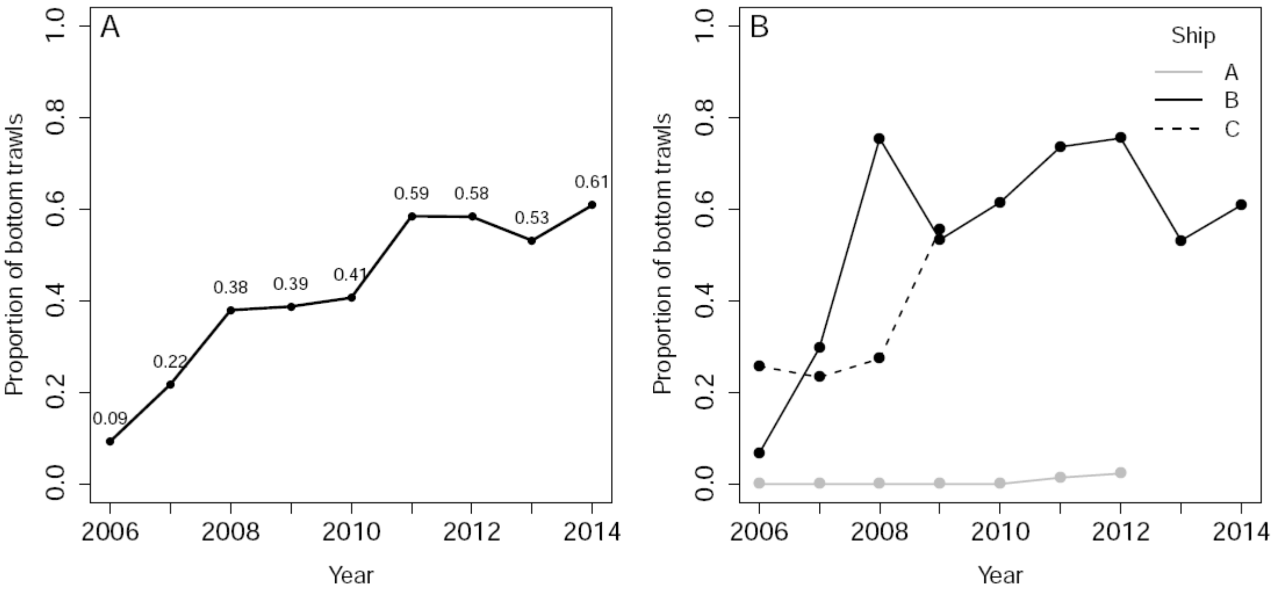

Figure 1. Annual variation in the proportion of bottom trawls for the Argentinean surimi fleet. Results are shown for the whole data (A) and by ship (B).

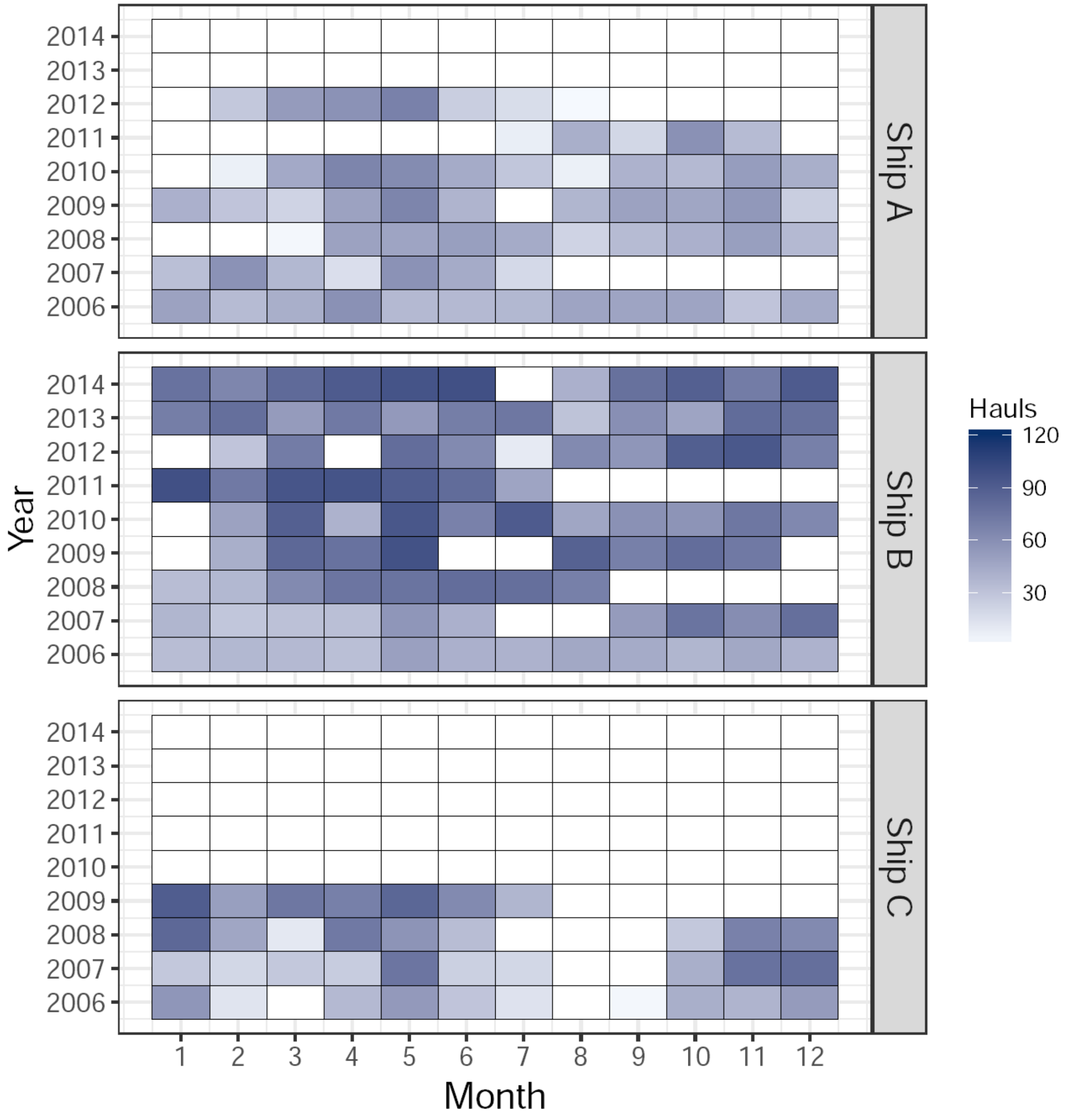

Figure 2. Temporal distribution of fishing effort for each ship of the Argentinean surimi fleet. White squares indicate months without fishing hauls.

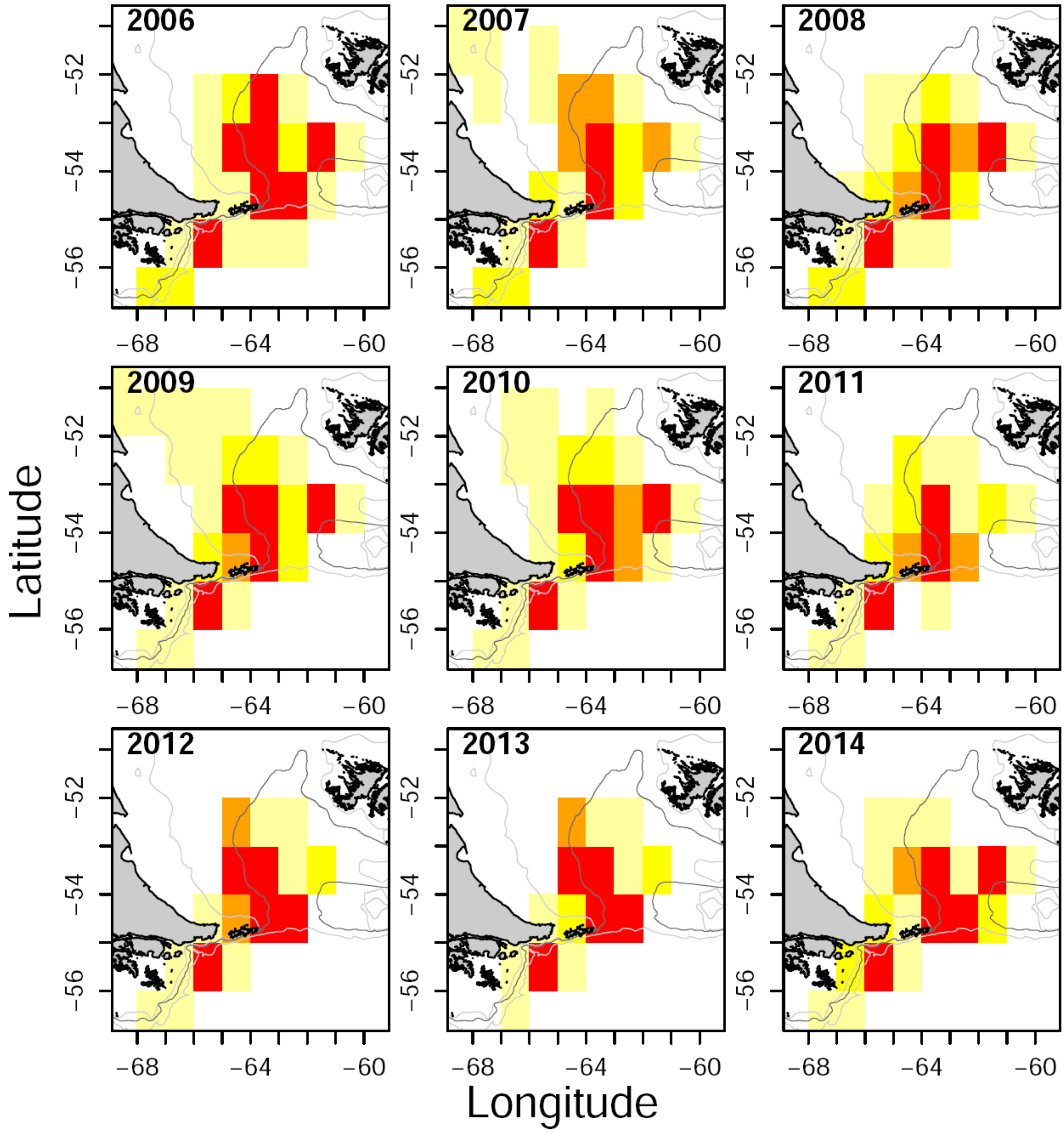

Figure 3. Annual spatial distribution of fishing hauls by the Argentinean surimi fleet in the Southwestern Atlantic from 2006 to 2014. The fishing haul numbers are calculated in a 1-degree resolution grid. The thin grey lines are the 100, 200, and 1000 m isobaths extracted from the General Bathymetric Chart of the Ocean (GEBCO, 2008).Shorelines were extracted from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel & Smith, 1996). Light yellow: Less than 26 hauls; Yellow: between 26 and 50 hauls; Orange: between 51 and 75 hauls; Red: more than 75 hauls.

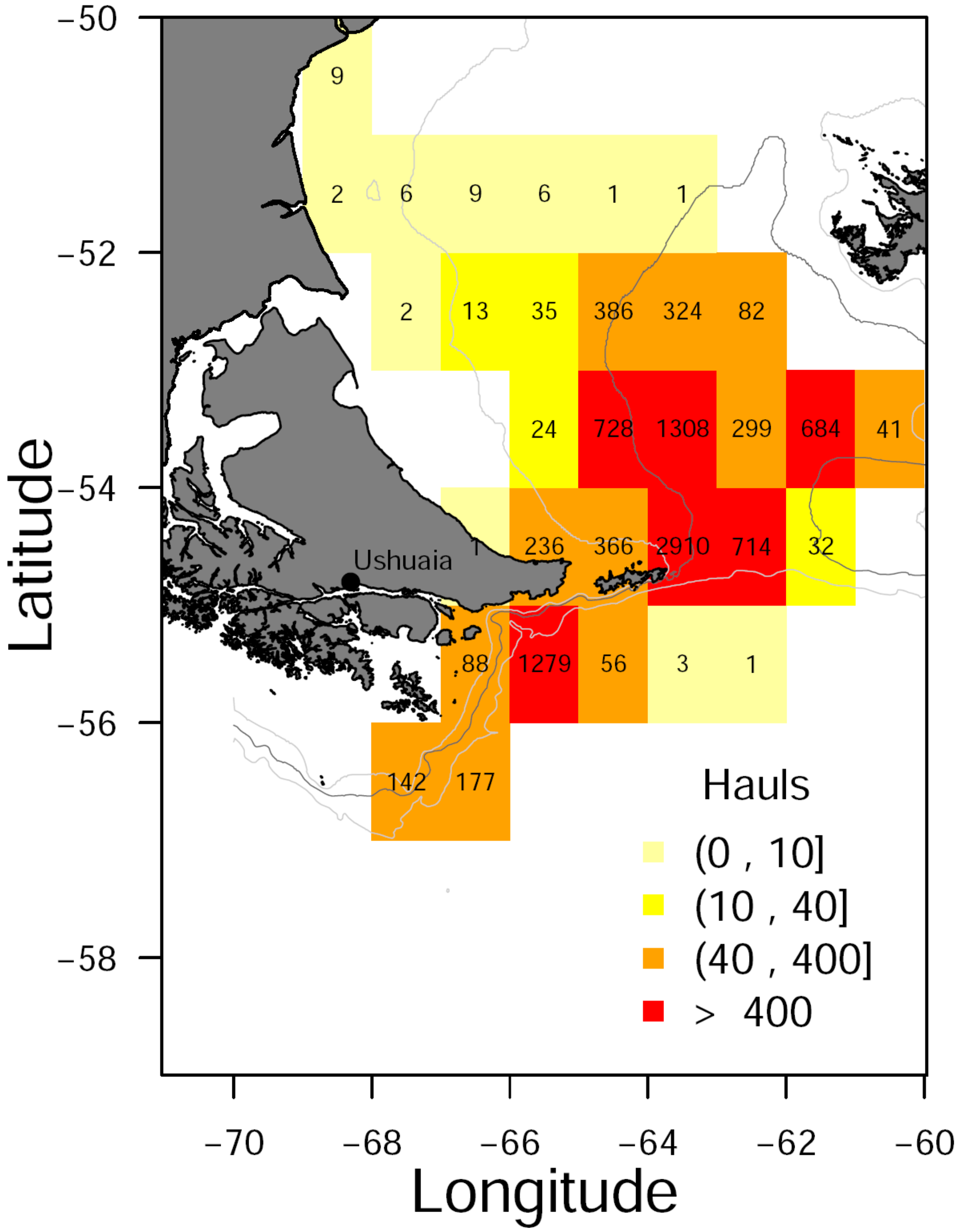

Figure 4. Spatial distribution of fishing hauls of the Argentinean surimi fleet in the Southwestern Atlantic from 2006 to 2014. The fishing haul numbers were calculated in a 1-degree resolution grid. The thin grey lines are the 100, 200, and 1000 m isobaths extracted from the General Bathymetric Chart of the Ocean (GEBCO, 2008). Shorelines were extracted from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel & Smith, 1996).

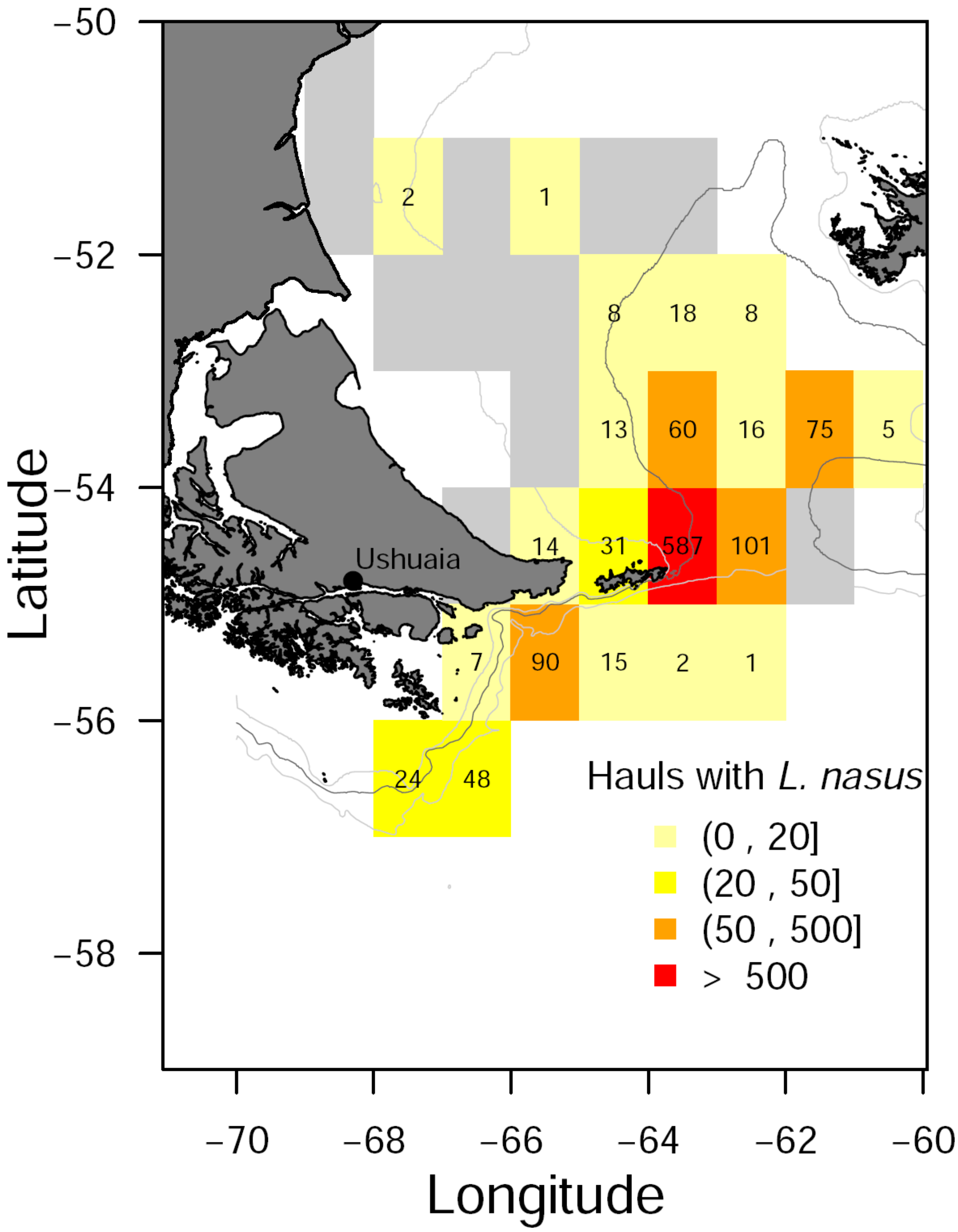

Figure 5. Spatial distribution of fishing hauls with porbeagle shark (*L. nasus*) bycatch in the Argentinean surimi fleet in the Southwestern Atlantic from 2006 to 2014. The fishing haul numbers were calculated in a 1-degree resolution grid. The thin grey lines are the 100, 200, and 1000 m isobaths extracted from the General Bathymetric Chart of the Ocean (GEBCO, 2008). Shorelines were extracted from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel & Smith, 1996).

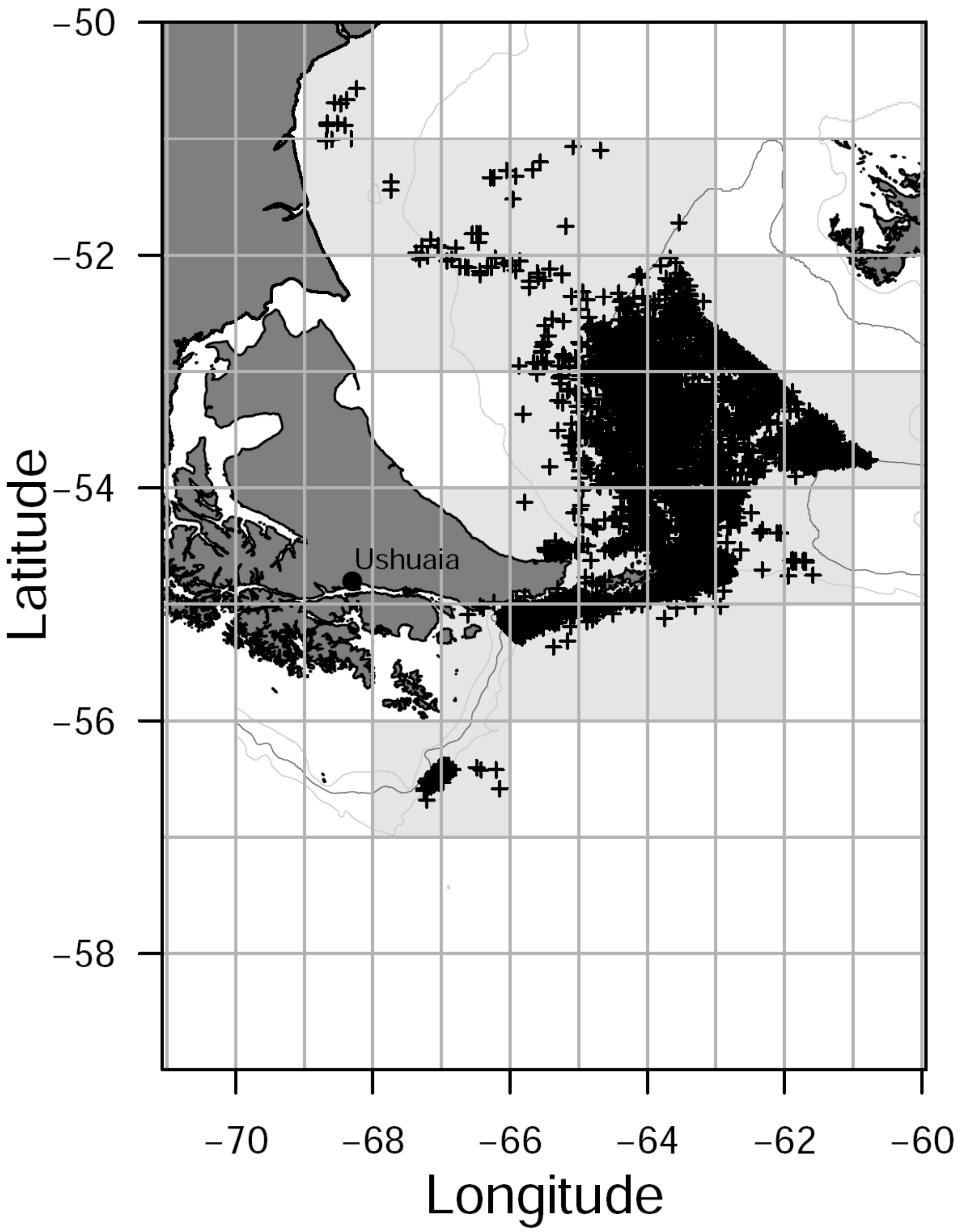

Figure 6. Spatial distribution of fishing hauls of the Argentinean surimi fleet in the Southwestern Atlantic from 2006 to 2014. The thin grey lines are the 100, 200, and 1000 m isobaths extracted from the General Bathymetric Chart of the Ocean (GEBCO, 2008). Shorelines were extracted from the Global, Self-consistent, Hierarchical, High-resolution Shoreline Database (Wessel & Smith, 1996).

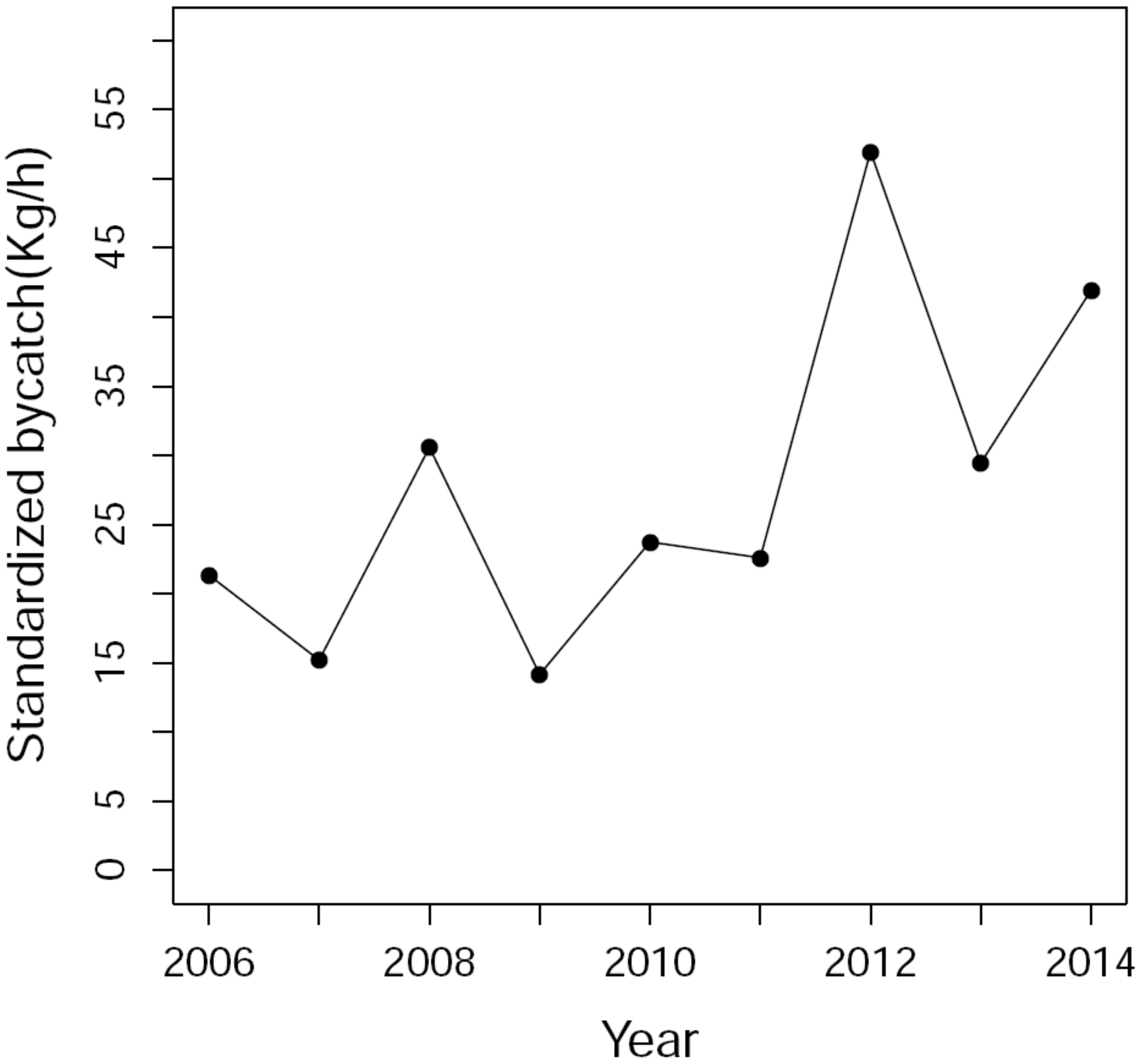

Figure 7. Trend of the porbeagle shark (*L. nasus*) standardized bycatch in the Argentinean surimi fleet operating in Southwestern Atlantic during 2006 and 2014.

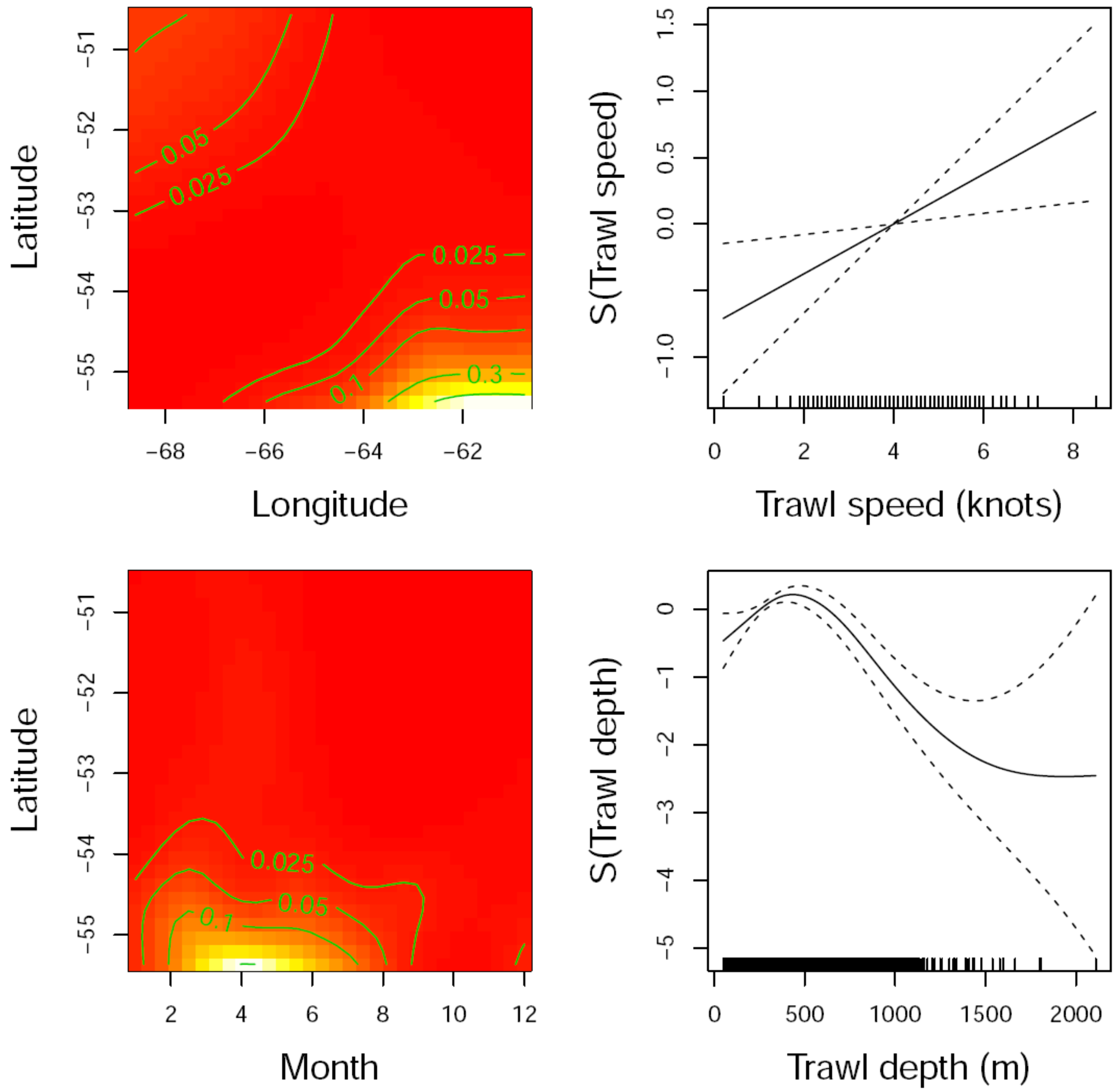

Figure 8. Estimated smooth terms and partial effects for the Binomial step of the Delta-GAM model applied to porbeagle shark (*L. nasus*) bycatch data of the Argentinean surimi fleet. The y-axis shows the contribution of the smoother to the fitted values. Dashed lines indicate 95% confidence bands.

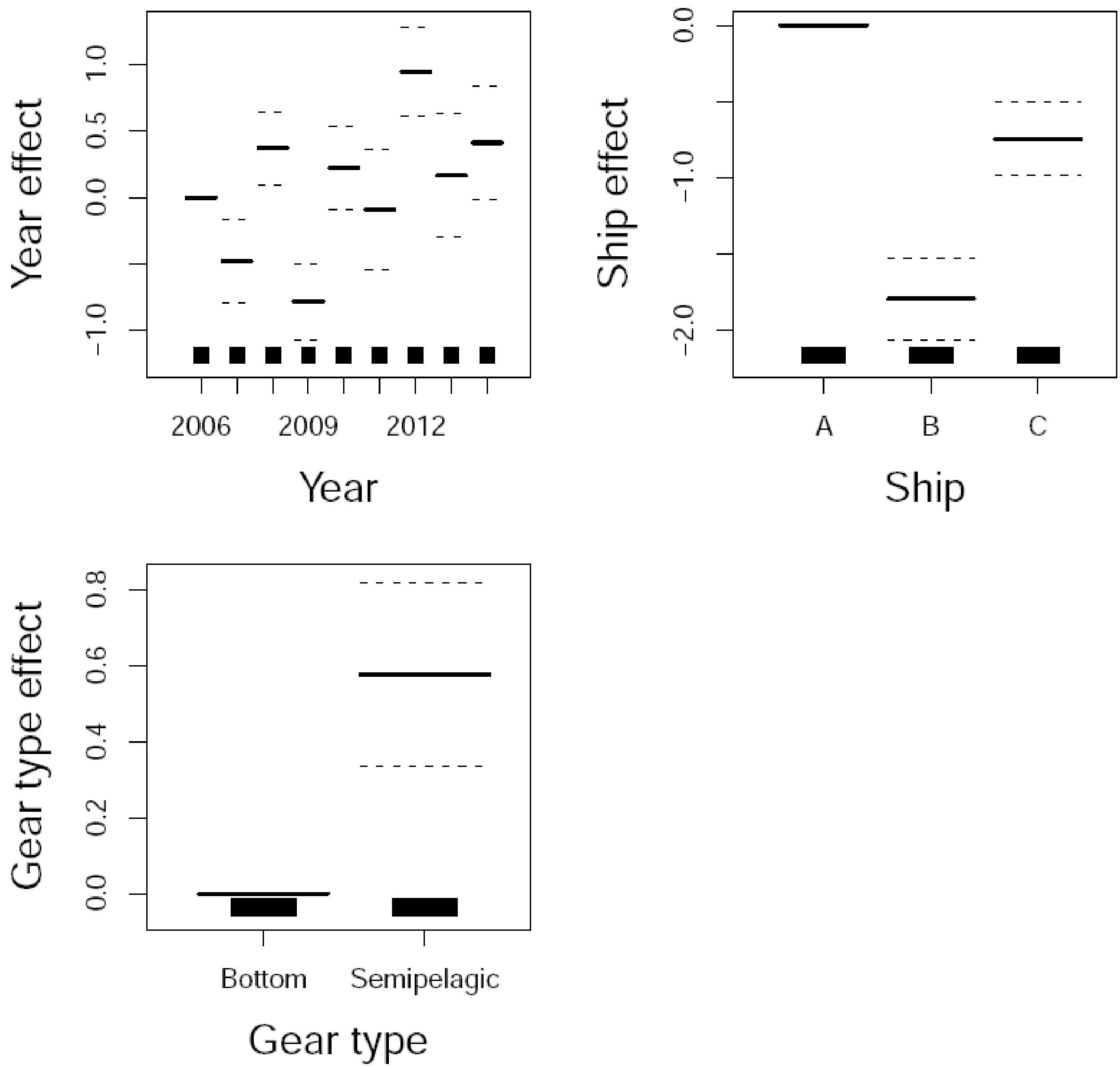

Figure 8 (continued). Estimated smooth terms and partial effects for the Binomial step of the Delta-GAM model applied to porbeagle shark (*L. nasus*) bycatch data of the Argentinean surimi fleet. The y-axis shows the contribution of the smoother to the fitted values. Dashed lines indicate 95% confidence bands.

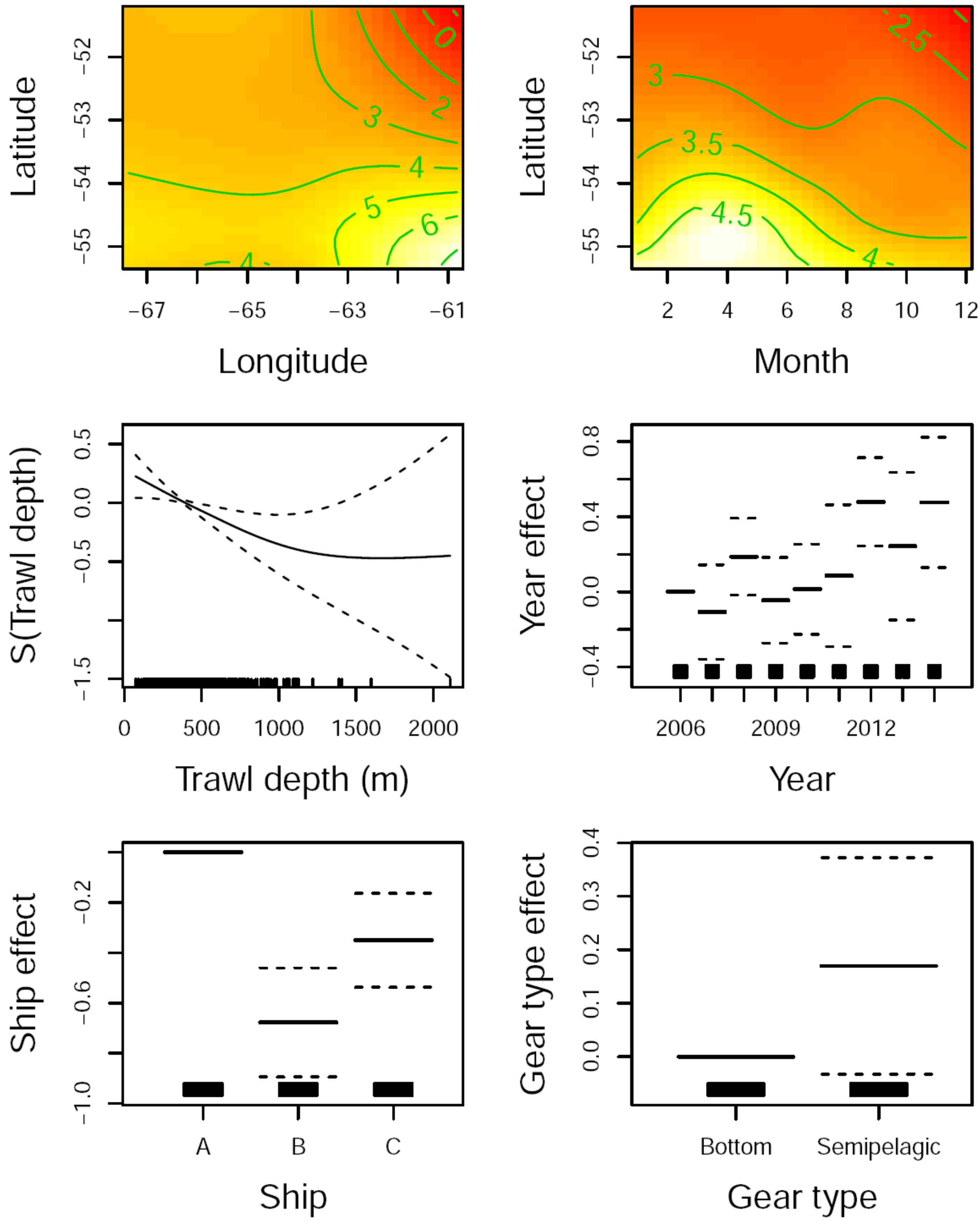

Figure 9. Estimated smooth terms for the Log-normal step of the Delta-GAM model applied to porbeagle shark (*L. nasus*) bycatch data of the Argentinean surimi fleet. The y-axis shows the contribution of the smoother to the fitted values. Dashed lines indicate 95% confidence bands.

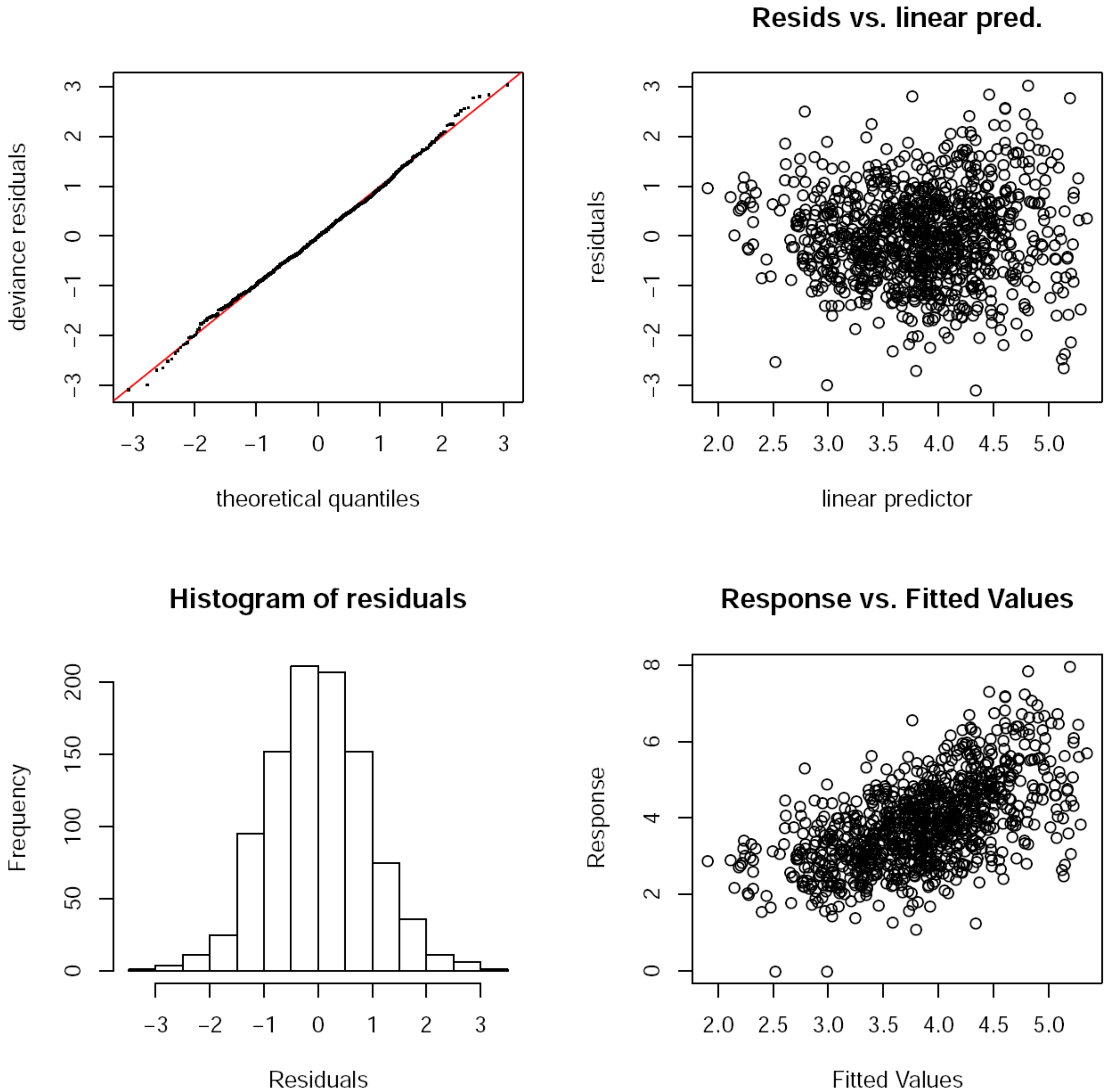

Figure 10. Diagnostic plots for Log-normal model step of the delta-GAM fitted to *L. nasus* bycatch rate in the surimi fleet.

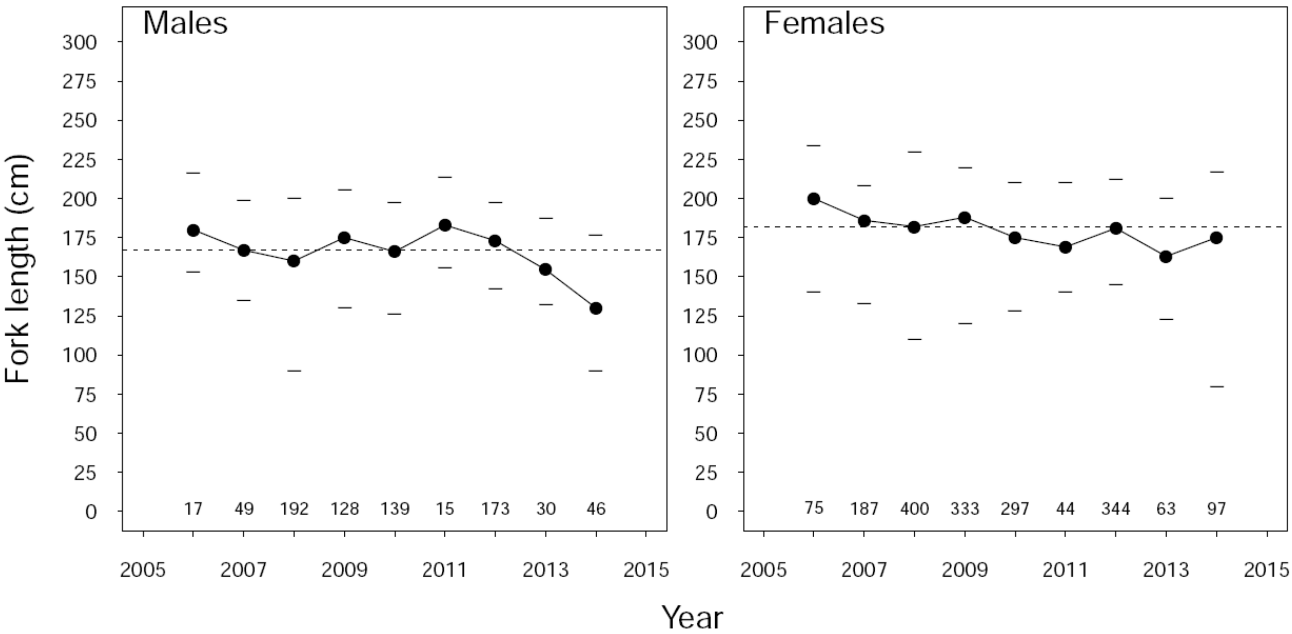

Figure 11. Median fork length of male and female porbeagle shark by year observed on surimi fleet between 2006 and 2014.The horizontal dashed lines indicate the median fork length for the whole time series. The dashes show the 5th and 95th percentiles of the fork length ranges. Sample sizes by year are shown in the bottom margin.

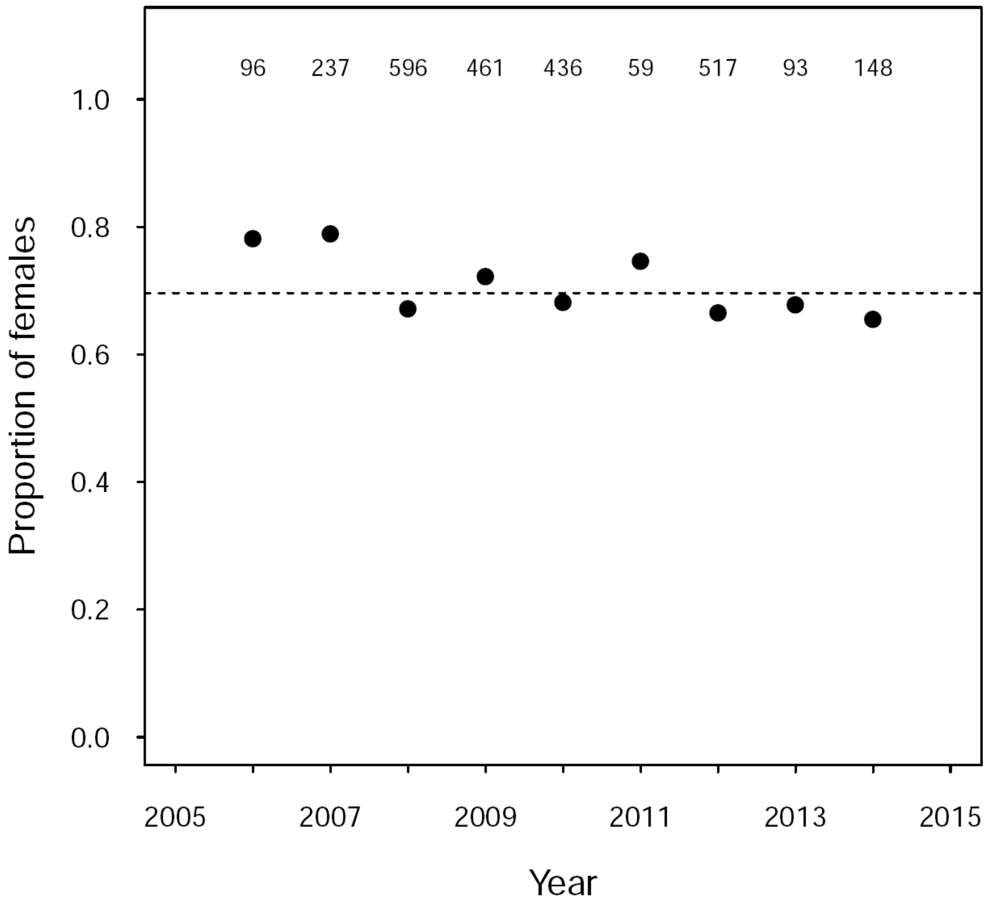

Figure 12. Proportion of porbeagle sharks female by year observed on surimi fleet between 2006 and 2014. The horizontal dashed line indicates the proportion of females for the whole time series. Sample sizes by year are shown in the top margin.

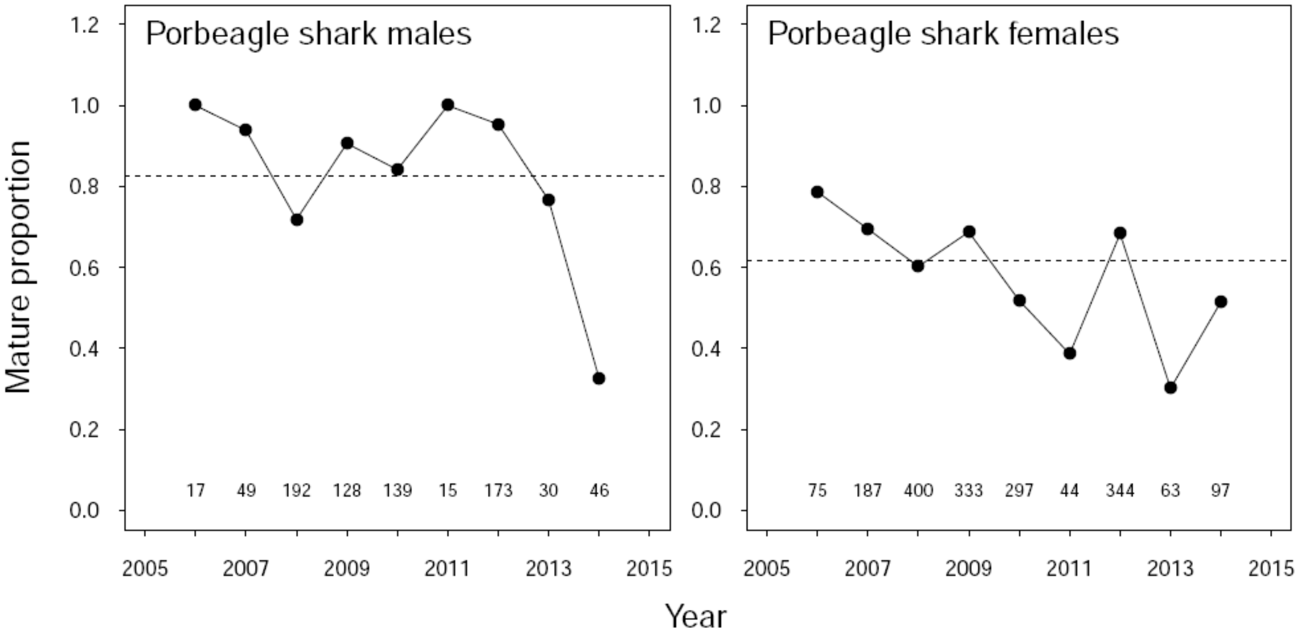

Figure 13. Proportions of male and female porbeagle shark mature by year observed on surimi fleet between 2006 and 2014. The horizontal dashed lines indicate the proportions of matures for the whole time series. Sample sizes by year are shown in the bottom margin.

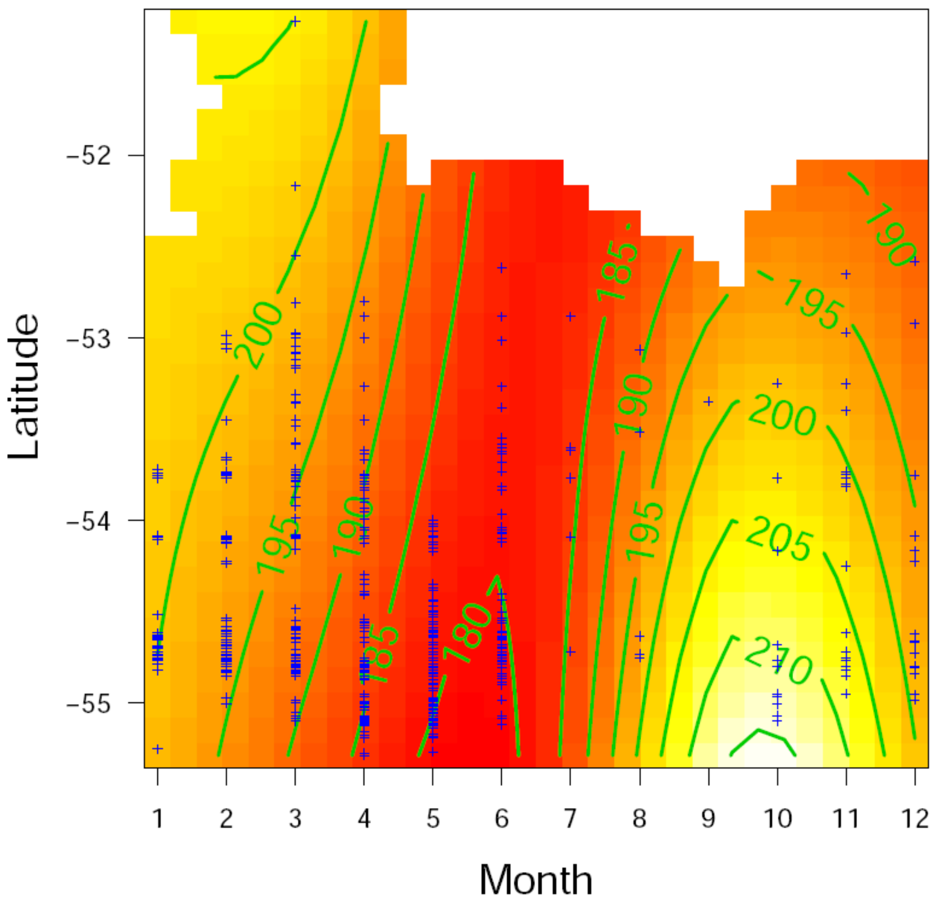

Figure 14. Predicted porbeagle sharks fork lengths by latitude and month in the Southern Southwestern Atlantic Ocean. Yellow colour indicates greater length. Blue crosses indicate sampled locations.

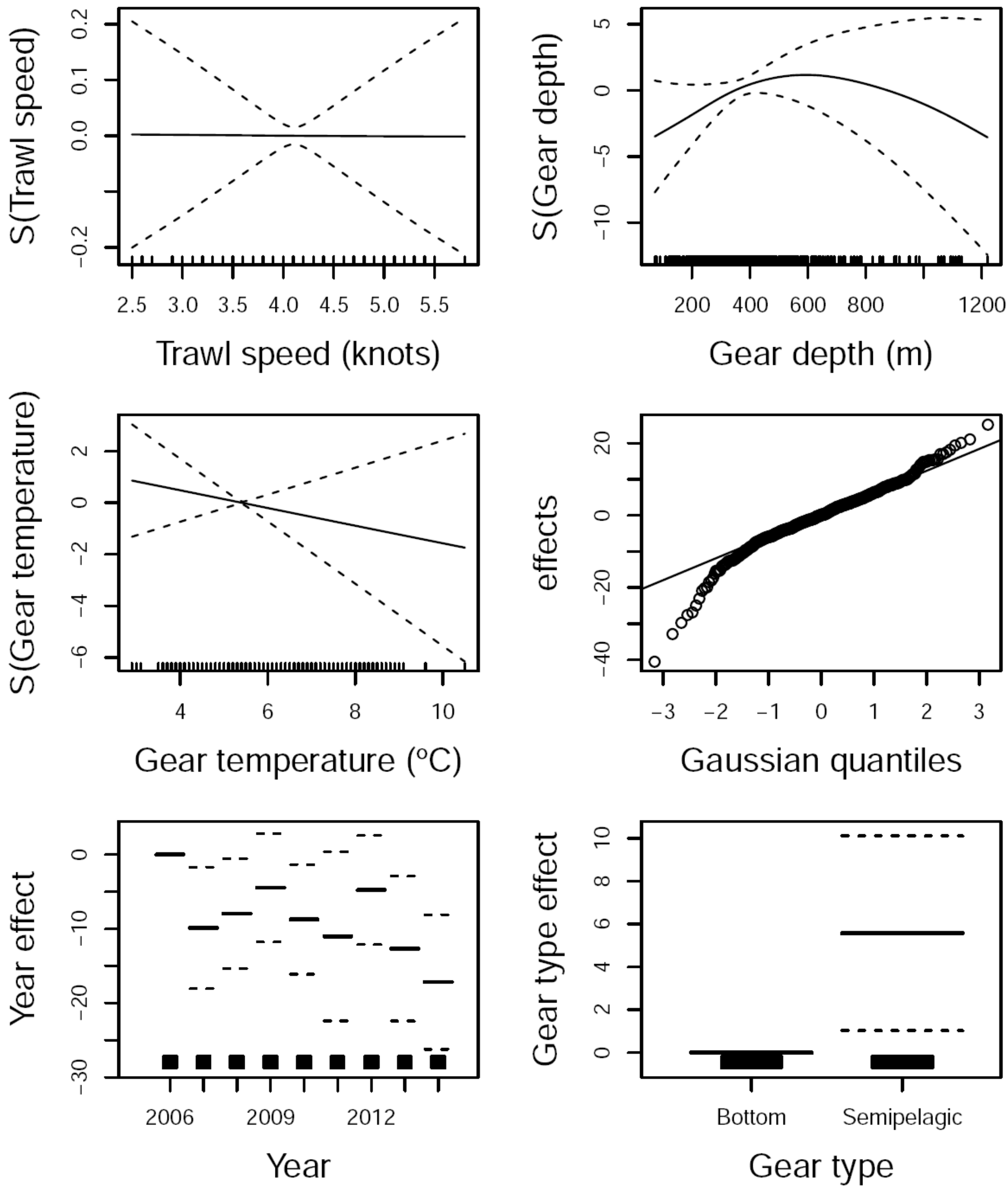

Figure 15. Smooth terms and partial effects for the porbeagle shark lengths analysis in the Southern Southwestern Atlantic Ocean.

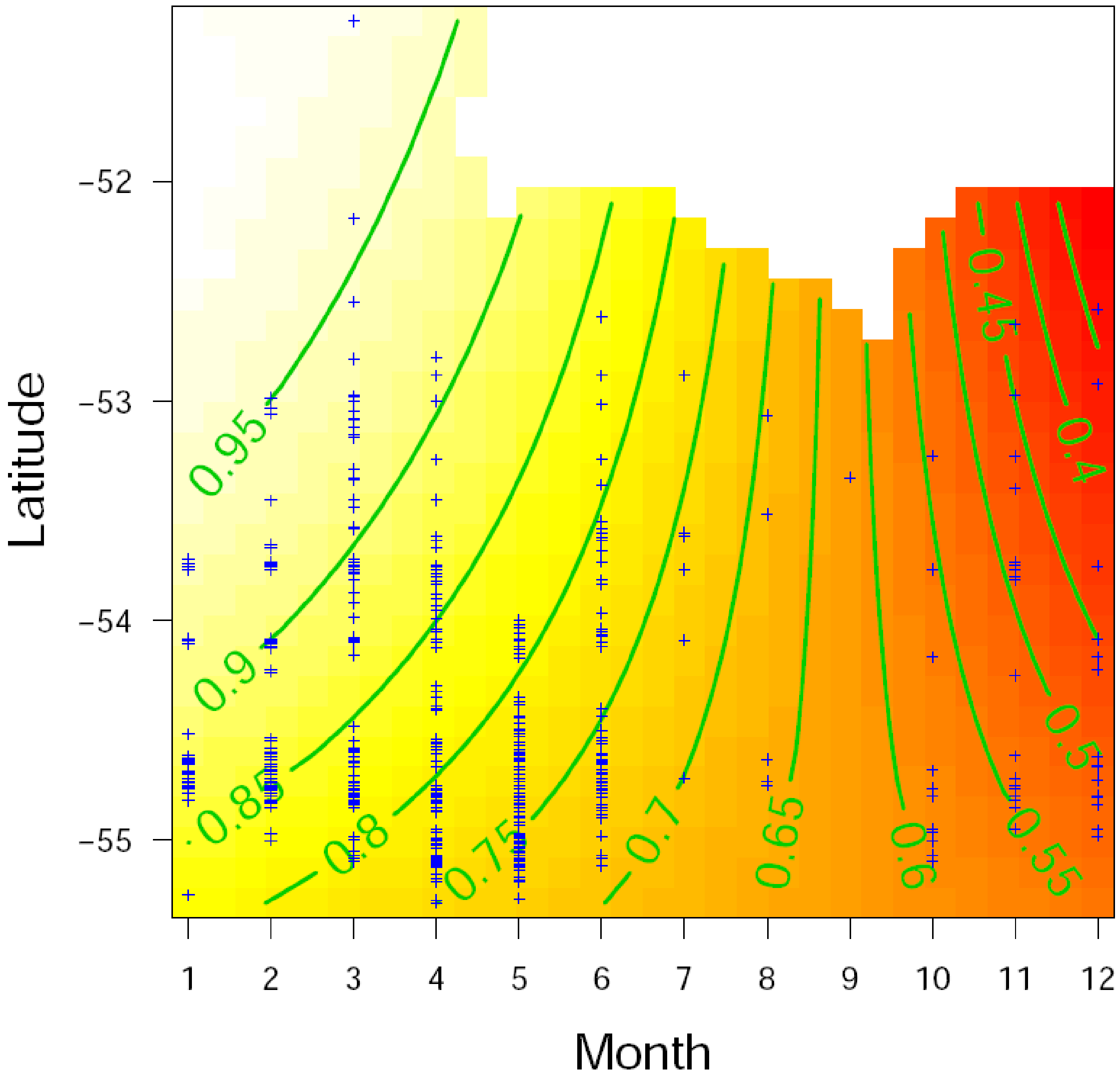

Figure 16. Predicted porbeagle sharks sex ratio by latitude and month for the Southern Southwestern Atlantic Ocean. Yellow colour indicates greater proportion of females. Blue crosses indicate sampled locations. Green lines indicate the proportion of females.

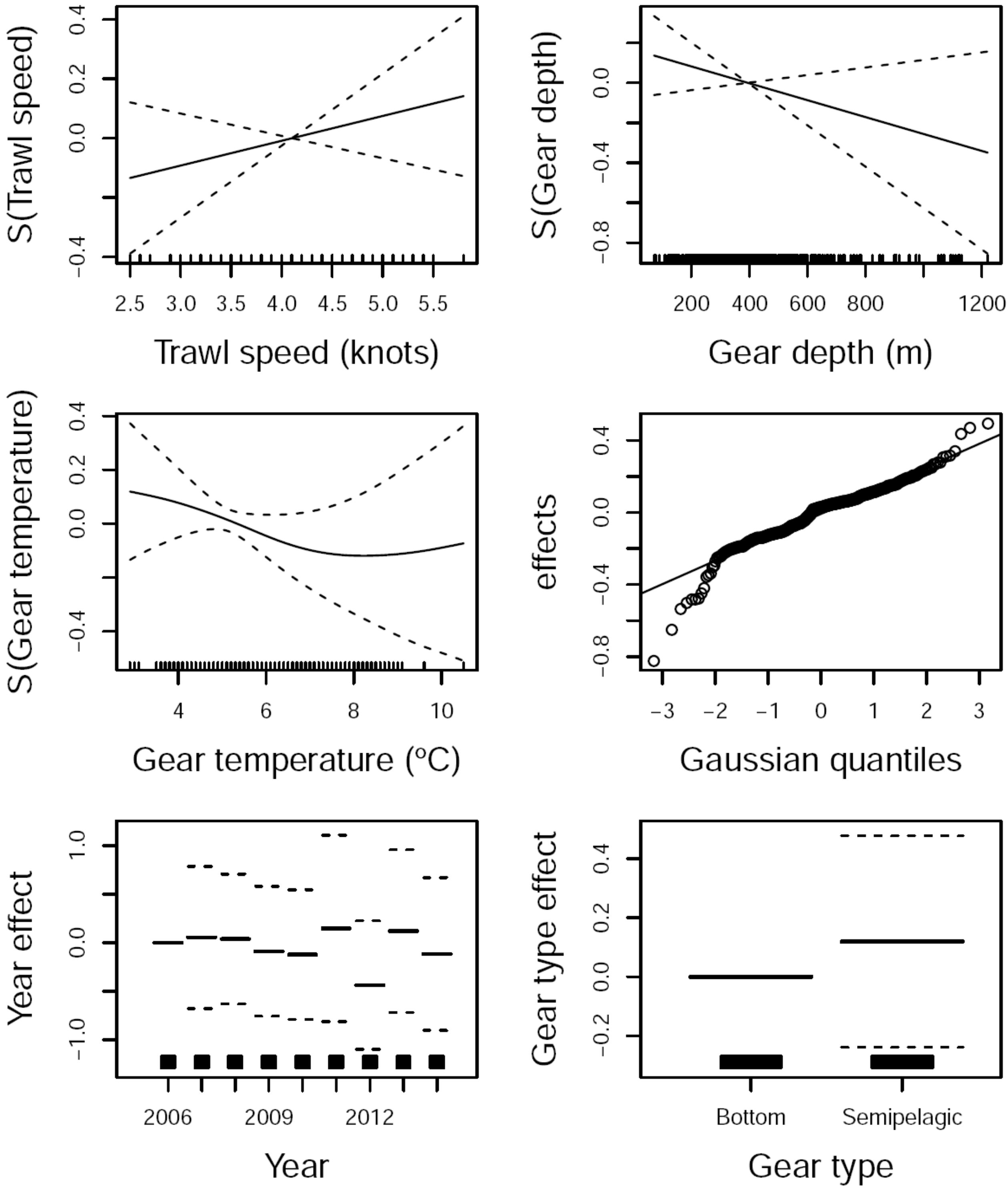

Figure 17. Smooth terms and partial effects for the porbeagle sex ratio analysis in the Southern Southwestern Atlantic Ocean.

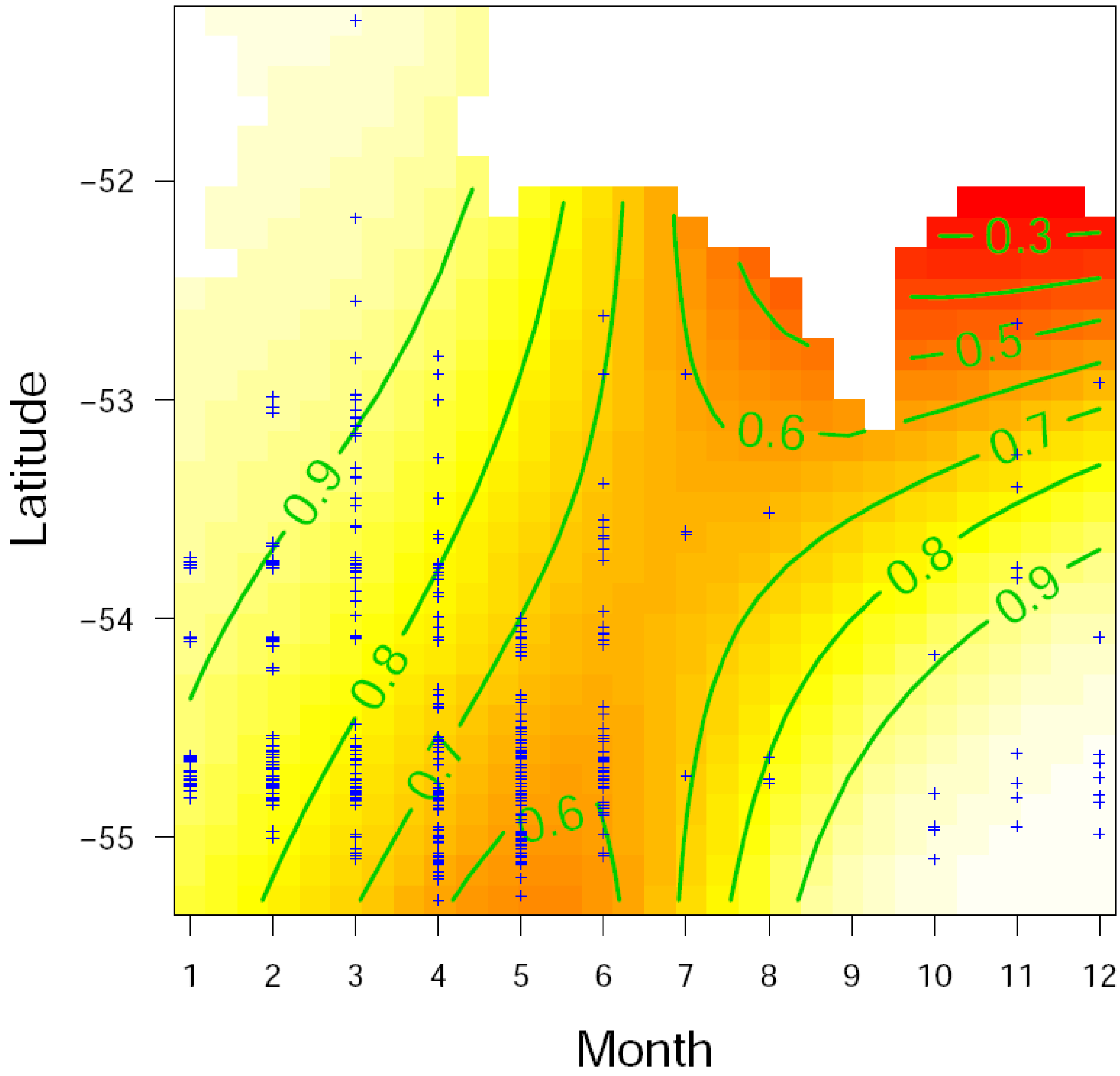

Figure 18. Predicted mature females proportion of porbeagle shark by latitude and month for the Southern Southwestern Atlantic Ocean. Yellow colour indicates higher female mature proportions. Blue crosses indicate sampled locations.

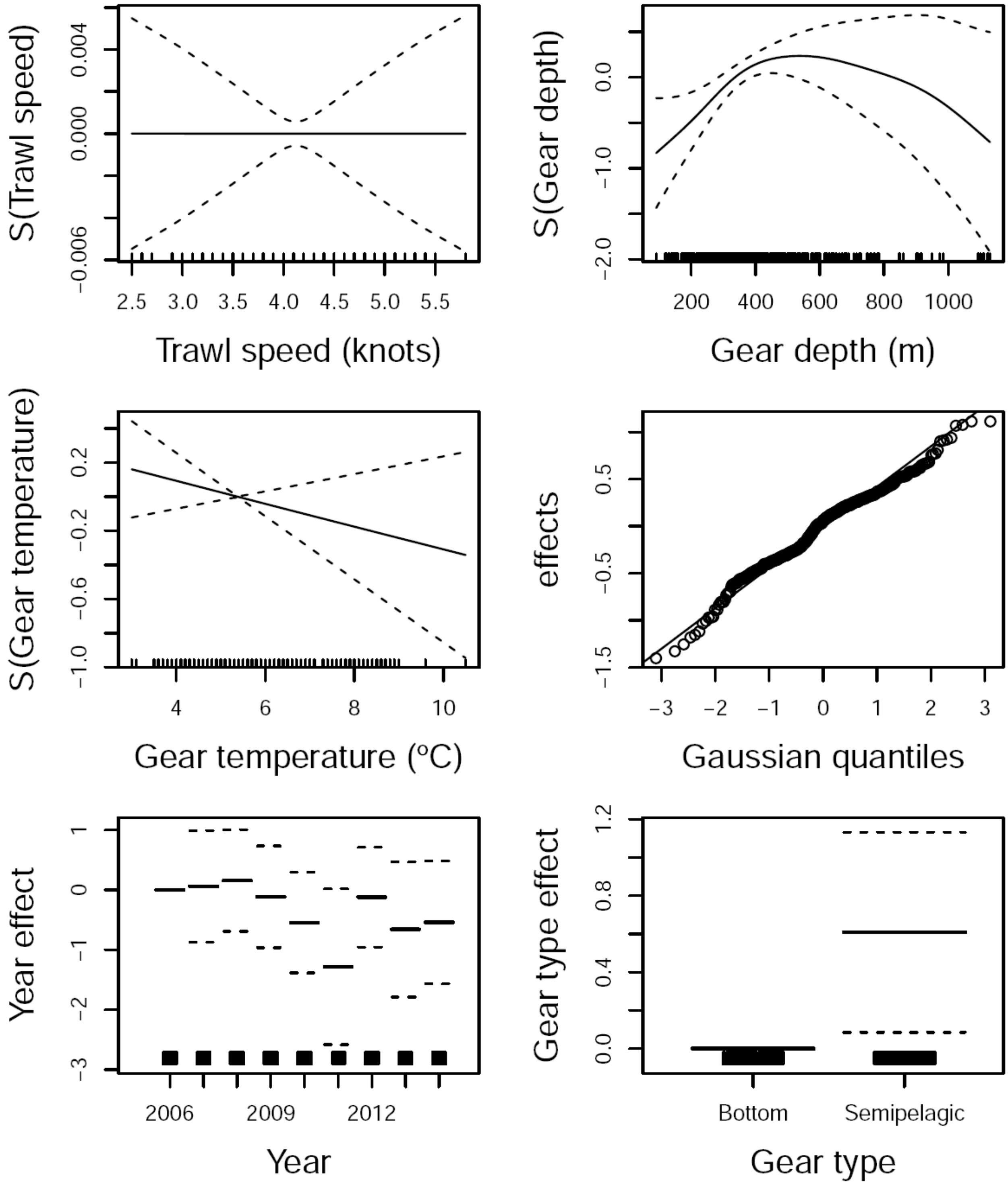

Figure 19. Smooth terms and partial effects for the porbeagle shark mature females analysis in the Southern Southwestern Atlantic Ocean.

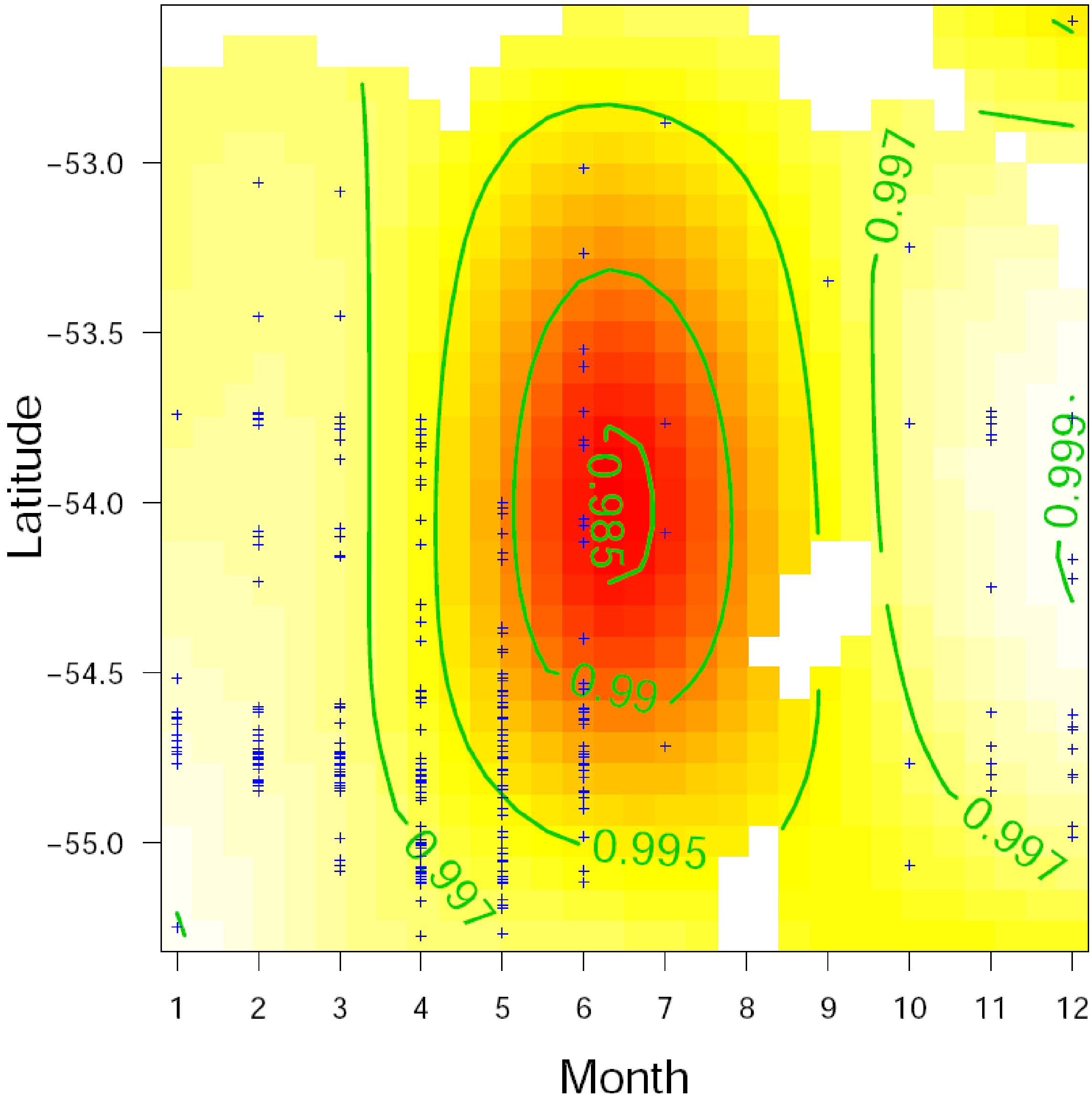

Figure 20. Predicted mature females proportion of porbeagle shark by latitude and month for the Southern end of the Southwestern Atlantic Ocean. Yellow colour indicates higher male mature proportions. Blue crosses indicate sampled locations.

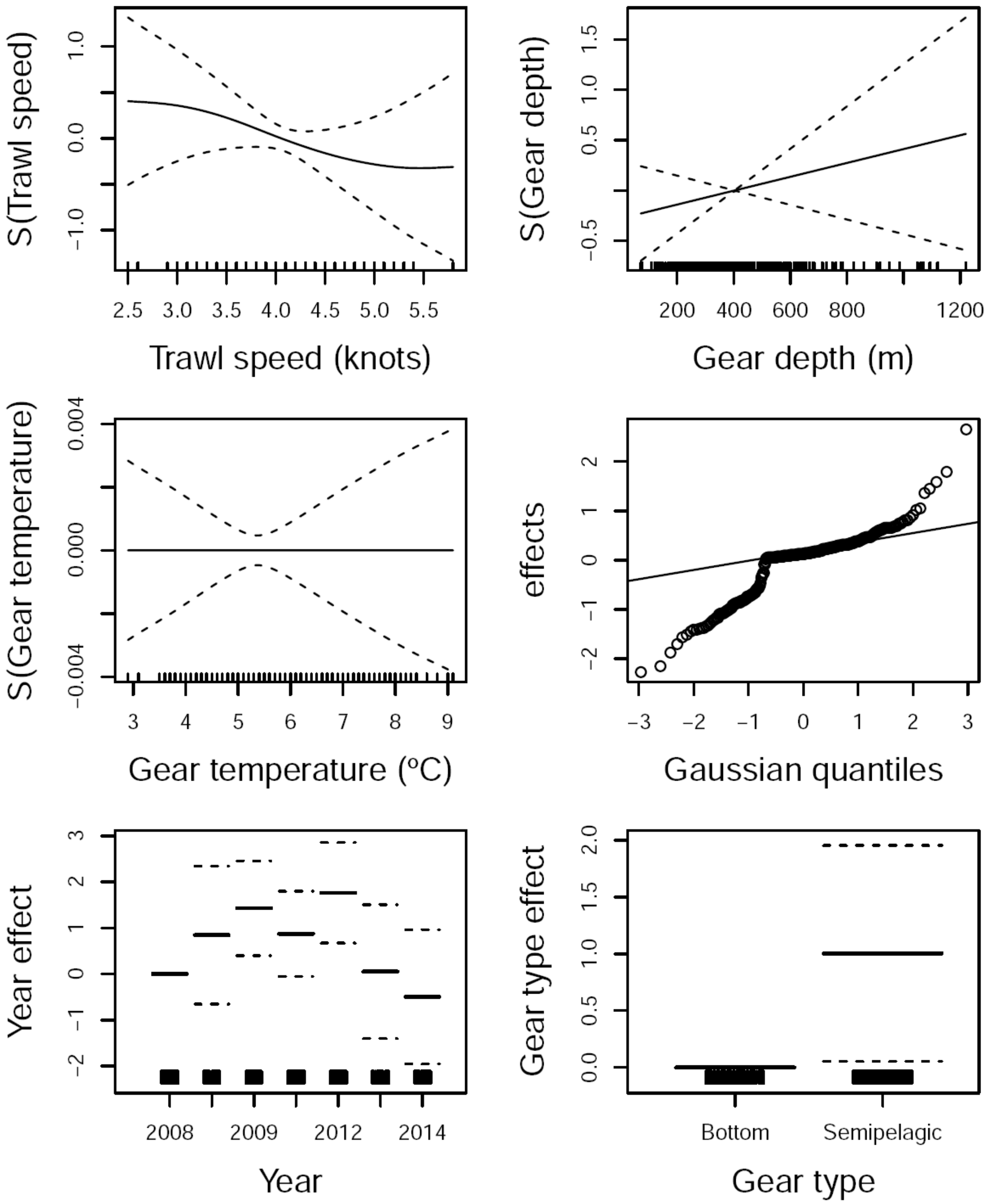

Figure 21. Smooth terms and partial effects for the porbeagle shark mature females analysis in the Southern Southwestern Atlantic Ocean.