A Grüss, D Yemane and TP Fairweather
Exploring the spatial distribution patterns of South African Cape hakes using generalised additive models

Appendix S1: Overview of current knowledge on South African hakes

Spatial distributions and movement patterns
Both *Merluccius capensis* and *M. paradoxus* are demersal species that inhabit the waters of South Africa and Namibia, but it has been common practice to consider South African Cape hake populations separate from Namibian populations, with the boundary between South Africa's and Namibia's exclusive economic zones (EEZs) providing the dividing line (Rademeyer et al. 2008).

Merluccius paradoxus is generally distributed in deeper waters than *M. capensis* (Botha 1973, 1985; Payne 1989; Durholtz et al. 2014). *Merluccius capensis* commonly occurs in water depths between 150 m and 450 m and can be found as deep as 900–1 000 m (Botha 1985; Payne and Punt 1995). *Merluccius paradoxus* is found commonly at depths greater than 350 m, to a maximum of 1 000 m (Botha 1985; Payne 1986; Payne and Punt 1995). Based on fisheries catch and survey data, *M. paradoxus* is believed to be more abundant than *M. capensis* on the west coast of South Africa (i.e. the region located west of Cape Agulhas; see Figure 1b) (Payne 1989; Sumaila et al. 2003; Le Clus et al. 2005a, 2005b). Conversely, *M. capensis* is thought to be more abundant than *M. paradoxus* on the south coast of South Africa (i.e. the region located east of Cape Agulhas) (Payne 1986; Sumaila et al. 2003; Le Clus et al. 2005a, 2005b). However, fisheries catch data suggest that *M. capensis* is more numerous on the west coast than on the south coast (Payne and Punt 1995). Only a few Cape hakes live east of 25° E (Payne 1989).

Based on current evidence, *M. capensis* and *M. paradoxus* have relatively different recruitment areas both on the west and south coasts of South Africa (Crawford et al. 1987; Hutchings et al. 2002; Stenevik et al. 2008). The main recruitment areas of *M. capensis* are thought to be located in shallow waters (<100 m) on the West Coast, between St Helena Bay and Hondeklip Bay, and north of Port Nolloth, and on the South Coast, between Hermanus and Plettenberg Bay. The main recruitment areas of *M. paradoxus* are thought to be located in deeper waters, north-west of Cape Town as far as Doring Bay and off Oranjemund (Crawford et al. 1987; Hutchings et al. 2002; Field et al. 2008; Stenevik et al. 2008).

On reaching a length of 15–20 cm, Cape hakes migrate offshore and into deeper waters (Botha 1971; Payne 1986; Crawford et al. 1987). Both *M. paradoxus* and *M. capensis* undergo several other ontogenetic migrations during their early life (Crawford et al. 1987; Payne and Punt 1995; Le Clus et al. 2005a, 2005b). Small *M. capensis* are abundant at depths <150 m (Botha 1985; Payne 1986). There is considerable spatial overlap between large *M. capensis* and small *M. paradoxus* between 150 m and 400 m water depth (Botha 1973, 1985; Pillar and Barange 1993). Evidence suggests that Cape hake adults do not undertake large-scale migrations at the time of spawning (Van Eck 1969; Botha 1973, 1980; Payne 1989), and that the home ranges of Cape hakes are small compared to that of other hake species (Botha 1973; Payne and Punt 1995).

Definition of size classes and their spatial distribution
Research demersal trawl surveys have been conducted on the west coast of South Africa since 1983, and on the South Coast since 1986, from which the relative abundance and biomass of successive life stages of *M. capensis* and *M. paradoxus* have been estimated (Millar 2000; Sampson 2002; Le Clus et al. 2005a, 2005b; Fairweather and Leslie 2009). West Coast surveys extend from Oranjemund to Cape Agulhas, and South Coast surveys from Cape Agulhas to Port Alfred, from the coast to depths of 500–600 m (Figure 1a). Demersal surveys are designed around 5' × 5' (minutes of latitude and longitude) grid blocks.

Le Clus et al. (2005a, 2005b) employed available data and knowledge on hake ecology to determine size classes with distinct geographical distributions for *M. capensis* and *M. paradoxus* (Payne 1986; Payne et al. 1987; Pillar and Barange 1995; Punt and Leslie 1995): juveniles (<20 cm), small individuals (20–35 cm), medium-small individuals (35–45 cm), medium-large individuals (45–55 cm) and large individuals (>55 cm). Le Clus et al. (2005a, 2005b) then used trawl survey data from 1990 to 2003 to map the root-root transformed biomass per 30-minute trawl, averaged per grid-block, of these five size classes of Cape hakes. The authors also modelled the density of these size classes of Cape hakes by 100-m depth zones, using suitable generalised polynomials (summarised in Table S1).

Environmental factors influencing hake spatial distributions
As emphasised above, the spatial distribution of the different size classes of Cape hakes is strongly related to bottom depth (Payne 1989; Millar 2000; Sampson 2002; Le Clus et al. 2005a, 2005b; Fairweather et al. 2006). Fairweather et al. (2006) suggested that the ontogenetic spatial distributions of Cape hakes may be related to bottom temperature, given that hake physiology is influenced by temperature and that depth and temperature are highly correlated. Inada (1990) reported that *M. capensis* has a lower tolerance for cold water than *M. paradoxus*.

Bottom dissolved oxygen (DO) may also affect Cape hake ontogenetic spatial distributions, due to its influence on hake physiology (Roel and Bailey 1987; Payne 1989). Roel and Bailey (1987) found that small *M. capensis* are in general less sensitive to low DO levels than their larger conspecifics, and that *M. capensis* has developed a physiological tolerance to low DO levels that *M. paradoxus* has not.

Finally, Cape hake spatial distributions are influenced by sediment type. Fairweather et al. (2006) reported that both *M. capensis* and *M. paradoxus* prefer sand over mud, and that Cape hake abundance is generally low in muddy areas.

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Table S1: Summary of the main results of Le Clus et al. (2005a, 2005b)

Species	Size class	Main results
Merluccius capensis	Juvenile (<20 cm)	– Bulk of them found on the west coast of South Africa, especially north of 34° S – Highest concentrations clustered inshore of the 200 m depth contour, especially at depths <100 m
	Small (20–35 cm)	– Bulk of them found on the west coast of South Africa, especially north of 34° S – Distribution shifted further offshore, but also southwards to Cape Agulhas, compared to juveniles – Highest concentrations clustered inshore of the 200 m depth contour
	Medium-small (35–45 cm)	– Bulk of them found on the south coast of South Africa – Highest concentrations found towards the 200 m depth contour
	Medium-large (45–55 cm)	– Bulk of them found on the south coast of South Africa – Distribution shifted eastward, compared to medium-small individuals – Highest concentrations found deeper than 200 m
	Large (>55 cm)	– Bulk of them found on the south coast of South Africa – Distribution shifted further offshore, but also westwards towards Cape Agulhas, compared to medium-large individuals – Highest concentrations found deeper than 200 m
Merluccius paradoxus	Juvenile (<20 cm)	– Main concentrations clustered within the 100–300 m depth contours on the west coast of South Africa north of St Helena Bay – Density on the west coast of South Africa greater than on the South Coast at depths of 100–300 m; similar on the two coasts at depths >300 m
	Small (20–35 cm)	– Distribution shifted further offshore, but also southwards to Cape Agulhas, compared to juveniles – Density greater at depths >200 m than at shallower depths – Highest densities at 200–300 m depths on the west coast of South Africa, and 300–400 m depth on the south coast – Density on the west coast of South Africa greater than on the South Coast at depths of 0–300 m; similar on the two coasts at depths >300 m
	Medium-small (35–45 cm)	– High density south of St. Helena Bay and on the south coast of South Africa – Density on the south coast of South Africa higher than on the West Coast at depths >200 m – High density also close to the Namibian border
	Medium-large (45–55 cm)	– Density on the west and south coasts of South Africa similar at depths >200 m – High density close to the Namibian border
	Large (>55 cm)	– Density on the west and south coasts of South Africa similar at depths >200 m – High density also close to the Namibian border

Appendix S2: Details of the demersal survey data used in the present study

All the demersal survey data used in the present study were collected by the Department of Agriculture, Forestry and Fisheries (DAFF) of South Africa, using a dedicated research vessel (RS *Africana*) operating within the South African EEZ.

Surveys conducted on the RS *Africana* between 1985 and September 2003 used a 2-panel German 180-foot trawl net with a rope-wrapped chain footrope, 150 kg lift and 1 500 kg WV doors. In 2003, a 'new' type of gear was introduced on the RS *Africana* consisting of a 4-panel German 180-foot trawl net with a modified rockhopper footrope, 150 kg lift and 1 500 kg Morgere multi-purpose doors. The new gear has been used as standard on the RS *Africana* since 2003, with the exception of the surveys completed in 2006 and 2010. The gear is usually towed at 3.5 knots for 30 minutes. The entire catch is sorted into species, and where possible sex, before being measured or counted (invertebrates). Biological data are derived from dissections of 10 or 20 of the primary commercial species (*Merluccius capensis, M. paradoxus, Austroglossus pectoralis, Genypterus capensis, Lophius vomerinus* and *Loligo vulgaris*), which are already dead (see below) and include: total length (cm), wet weight (g), gutted weight (g), sex, maturity, gonad weight (g), stomach state, stomach weight (g), liver weight (g), caecum colour, and fertilised (yes/no). The otoliths of dissected animals are retained for aging.

The majority of the catch realised during demersal surveys consists of teleosts, which are generally already dead before reaching the surface due to barotrauma or interaction with the net. On occasions when large sharks or rays are caught, they are weighed and measured and released as a priority. If killed, large shark and ray specimens are retained for scientists specialising in the study of these species. Demersal surveys do not take place in protected locations. No interventions/experiments are performed on captured live marine animals outside of measuring and recording during demersal surveys.

The total area swept by each demersal survey trawl *j* within a stratum *i* ($a_{i,j}$, in nm²) is calculated according to Fairweather and Leslie (2009):

$$a_{i,j} = s_{i,j} \times \frac{t_{i,j}}{60} \times \frac{w_{i,j}}{1852} \tag{S2.1}$$

where $s_{i,j}$ is the towing speed, in knots (nm h^{-1}), $t_{i,j}$ is the duration (in minutes), and $w_{i,j}$ is the horizontal mouth width (in m), i.e. the width of the trawl track in the *j*-th trawl of the *i*-th stratum.

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Appendix S3: Data used to produce spatial estimates of environmental parameters, and manipulations required on these data to attain a contiguous surface with which to make predictions with generalised additive models (GAMs)

Spatial estimates of depth
We accessed the GEBCO 1-minute global bathymetry dataset (http://www.gebco.net – accessed 5 August 2014), from which a continuous raster of bathymetry with a resolution of 0.11° was generated.

Spatial estimates of bottom temperature and bottom DO
During demersal surveys, at each trawl station, a CTD is deployed either before or after the trawl to collect hydrographic variables, including bottom temperature, salinity, turbidity and bottom DO (Fairweather and Leslie 2009). Hydrographic variables are captured as the average value measured over every second and binned into defined depths. On occasion, time constraints or bad weather preclude the completion of a CTD dip (Fairweather and Leslie 2009). Annual maps of bottom temperature and bottom DO were produced for the present study from the CTD data collected during the demersal surveys conducted between 2003 and 2011. Annual spatial estimates of bottom temperature and bottom DO were then interpolated using ordinary kriging (Cressie 1988). Finally, kriged annual bottom temperature and bottom DO estimates were averaged to obtain continuous rasters of bottom temperature and bottom DO for the period 2003-2011 from which to fit GAMs and make predictions with these GAMs.

Spatial estimates of sediment type
The sediment type data used in the present study (Geological Survey 1986) were provided by the Council for Geoscience, South Africa. A continuous raster of sediment type with a resolution of 0.11° was generated from these data.

Analysis of collinearity
We evaluated the degree of collinearity between all continuous predictors (i.e. depth, bottom temperature, bottom DO, longitude and latitude), since regression methods may be sensitive to correlated variables (Guisan et al. 2002; Dormann et al. 2013). The variance inflation factor (VIF) between continuous predictors was analysed using the 'usdm' package in the R environment (Naimi et al. 2014). The VIF analysis did not suggest discarding any continuous predictor.

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Table S2: Contingency table of the binomial distribution's sediment type for juvenile *Merluccius capensis* as well as the percentage of stations in each sediment type with juvenile *Merluccius capensis* present. Due to lack of significance (α = 0.05), sediment type was discarded from the binomial generalised additive models fitted for small, medium-small, medium-large and large *M. capensis* and all size classes of *M. paradoxus*

| Size class	Sediment type	Absent	Present	% stations with size class present
Juvenile *M. capensis*	Mud	216	202	30.8
	Sand	709	454	69.2
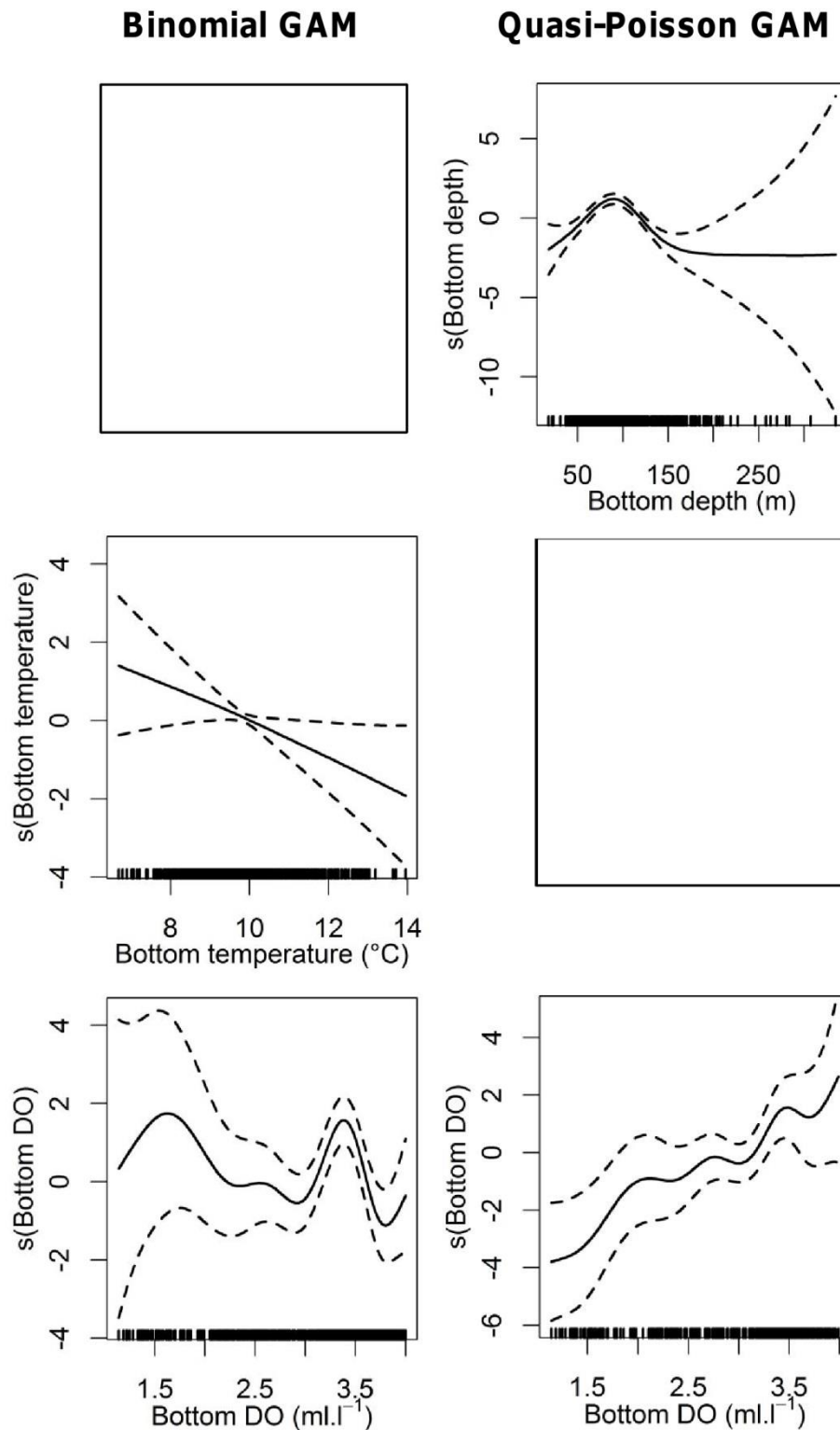
Figure S1: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of juvenile *Merluccius capensis* (<20 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of juvenile *M. capensis* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen
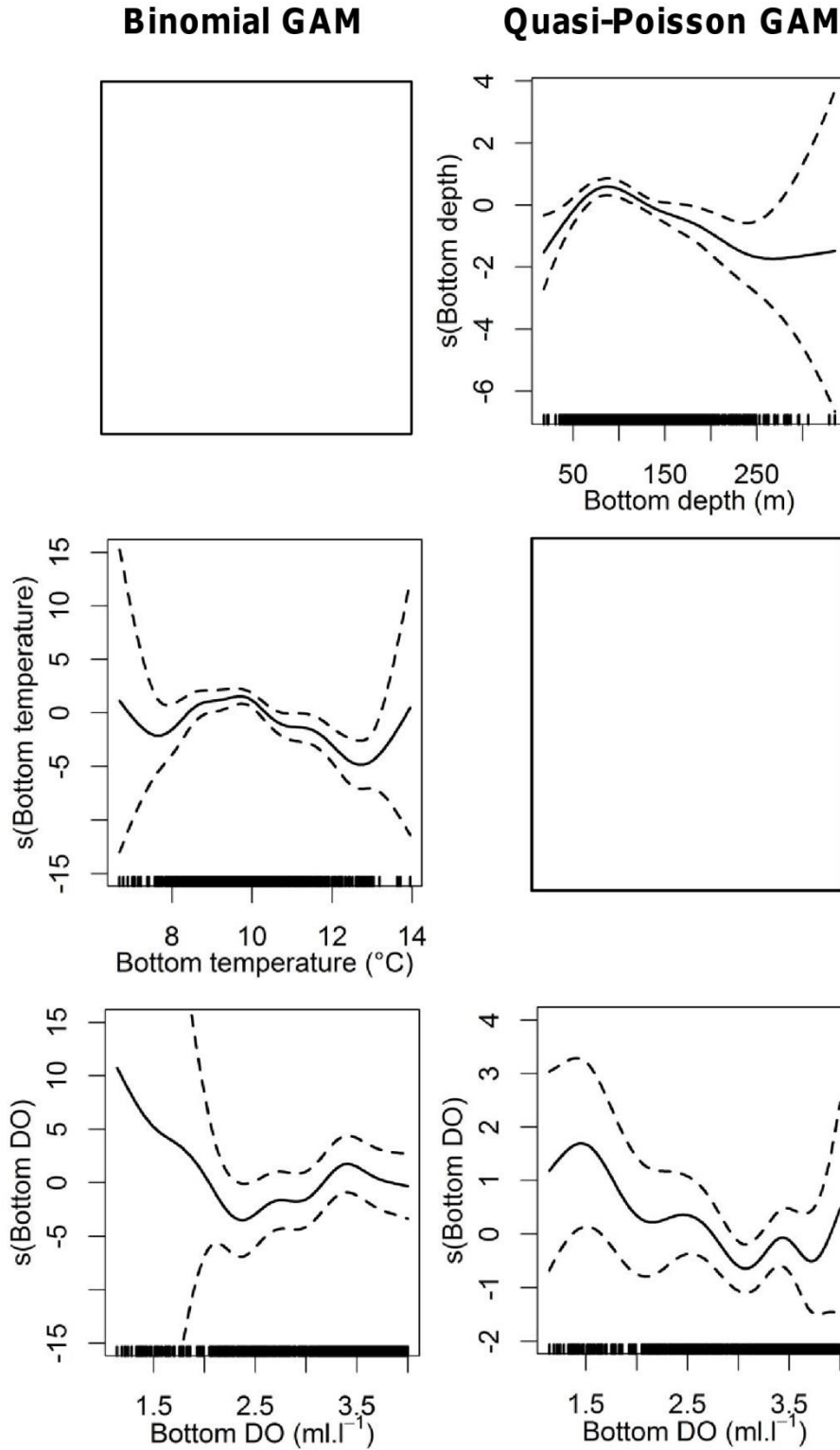
Figure S2: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of small *Merluccius capensis* (20–35 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of small *M. capensis* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen
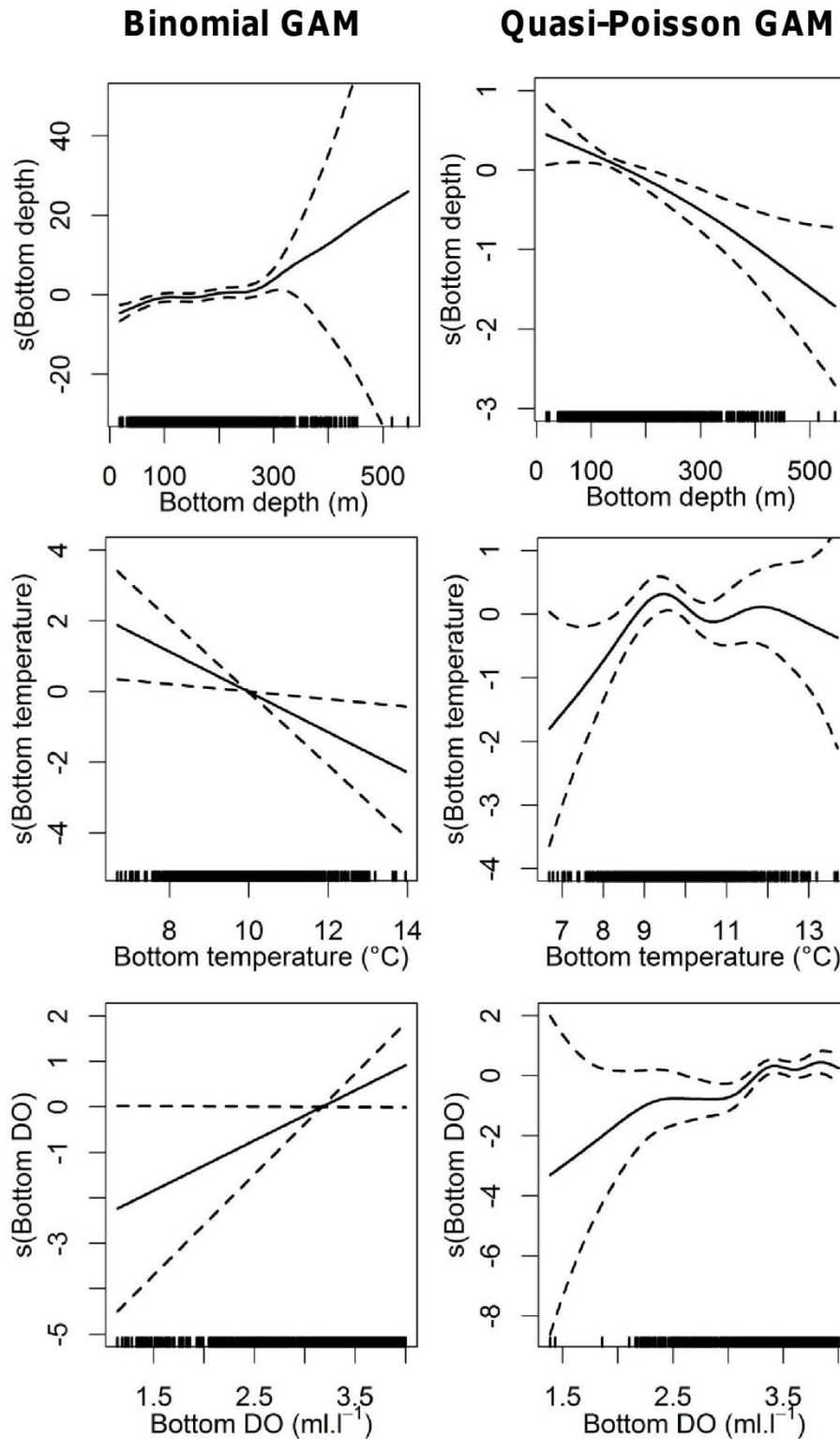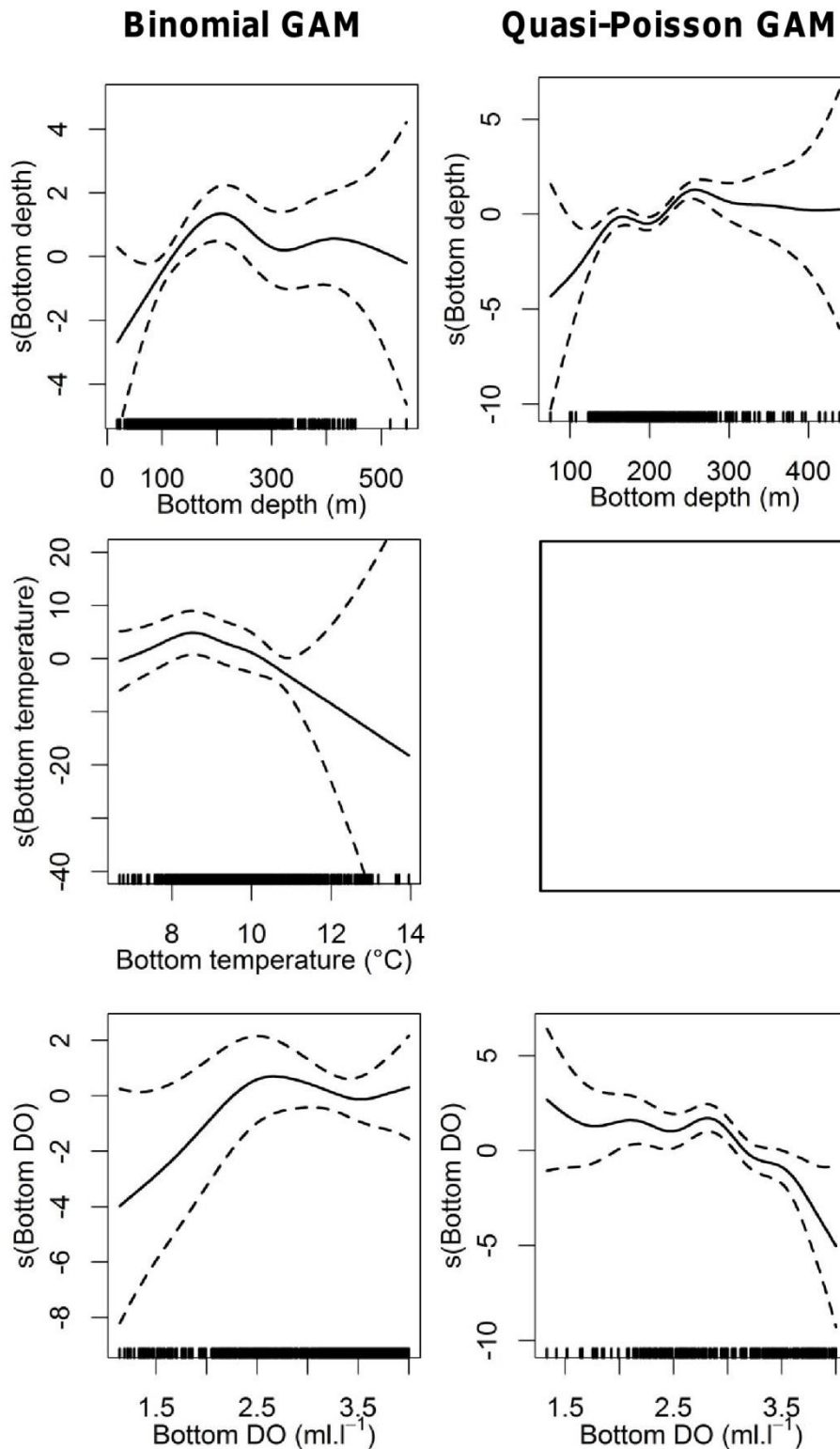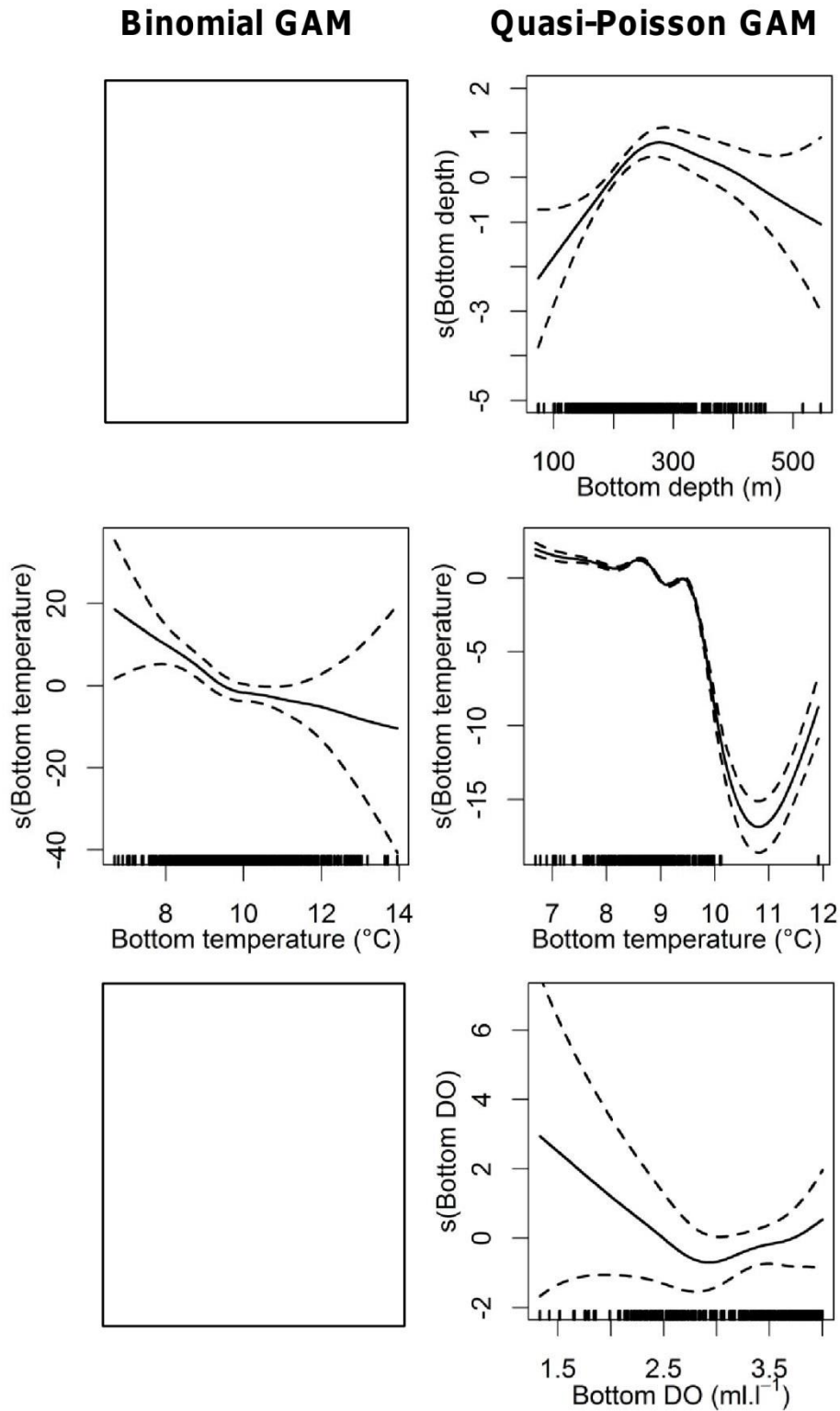
Binomial GAM
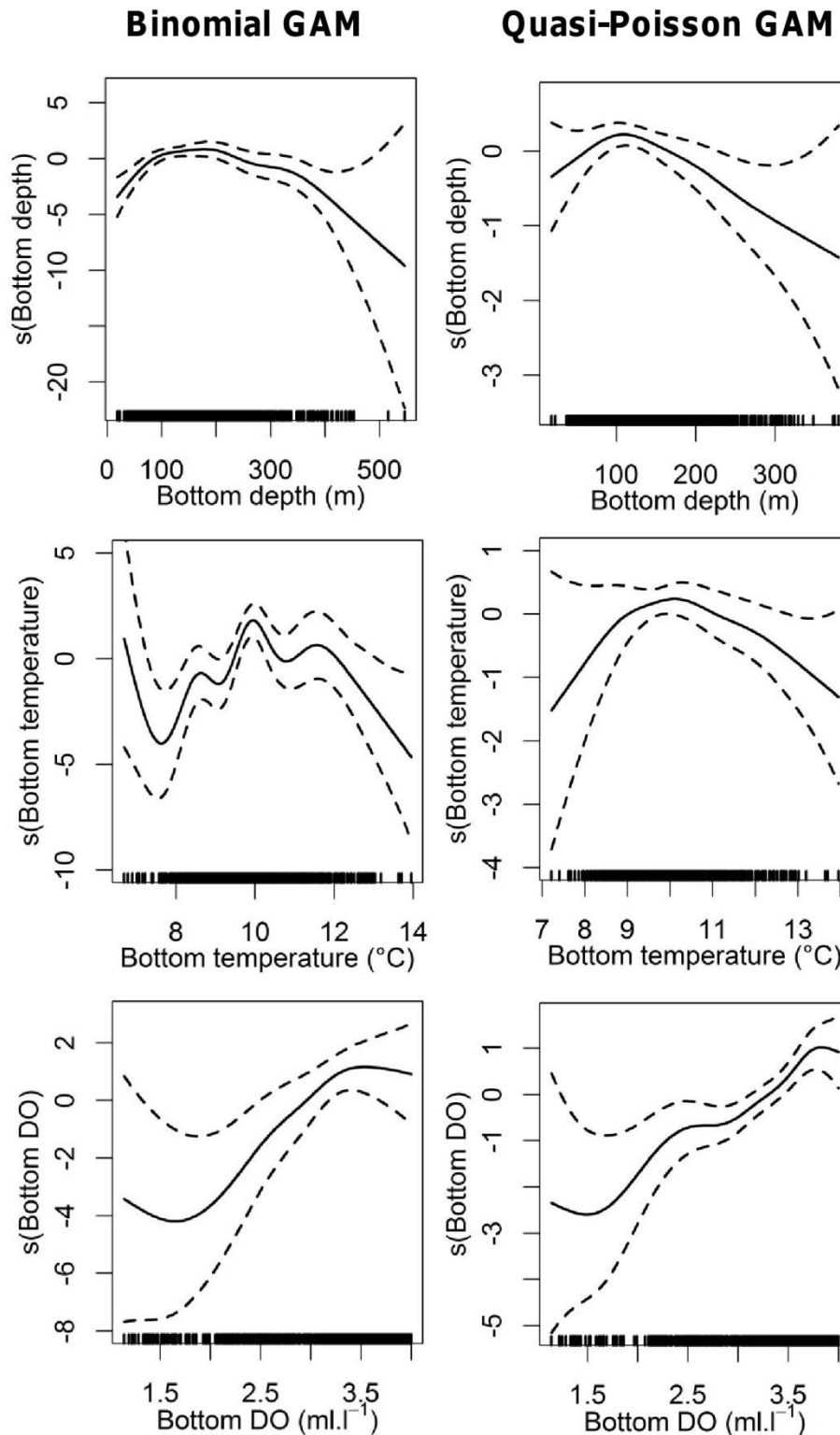
Quasi-Poisson GAM

Figure S3: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of medium-small *Merluccius capensis* (35–45 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of medium-small *M. capensis* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. DO = dissolved oxygen

Binomial GAM
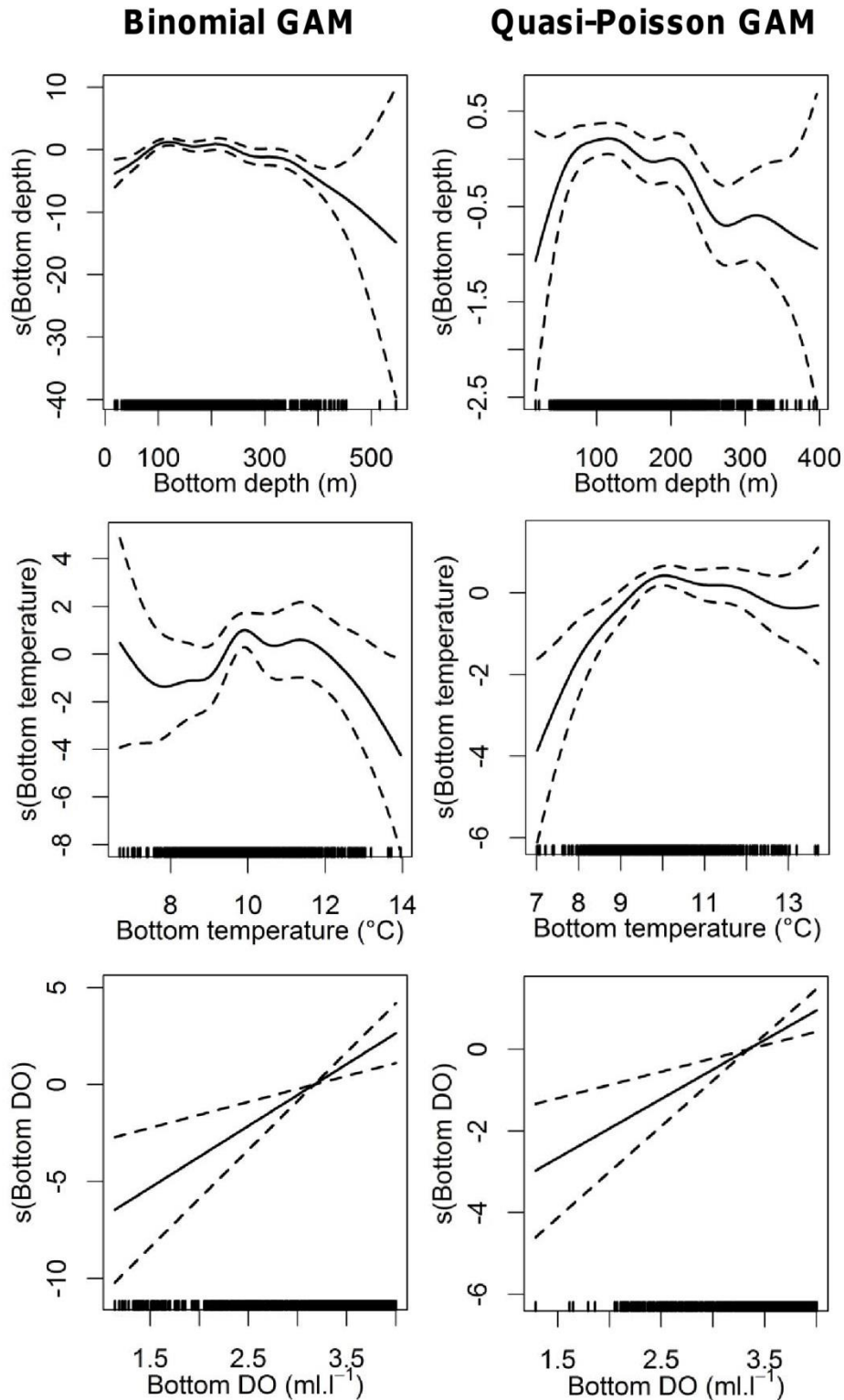
Quasi-Poisson GAM

Figure S4: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of medium-large *Merluccius capensis* (45–55 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of medium-large *M. capensis* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. DO = dissolved oxygen

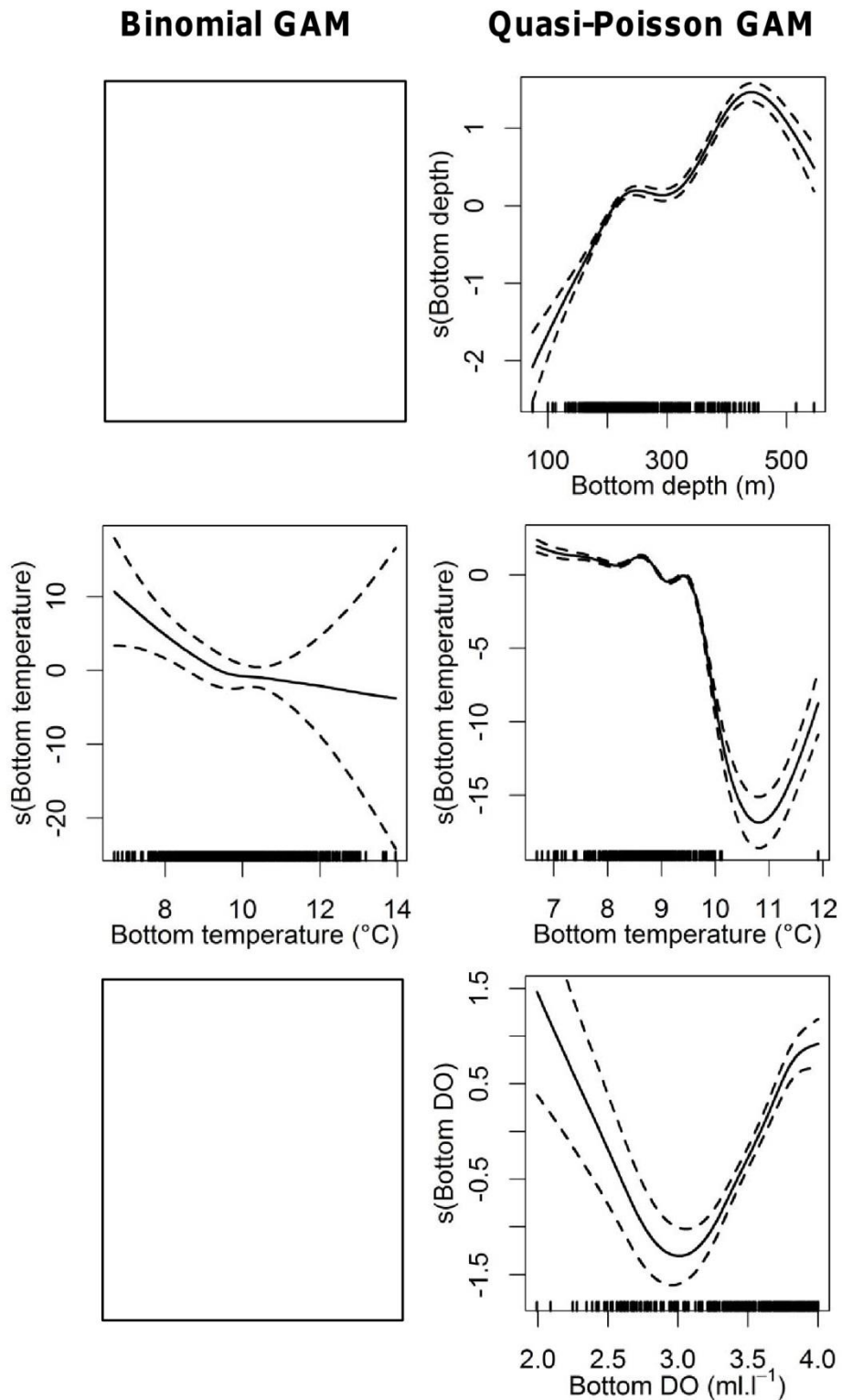**Binomial GAM**   **Quasi-Poisson GAM**

Figure S5: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of large *Merluccius capensis* (>55 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of large *M. capensis* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. DO = dissolved oxygen
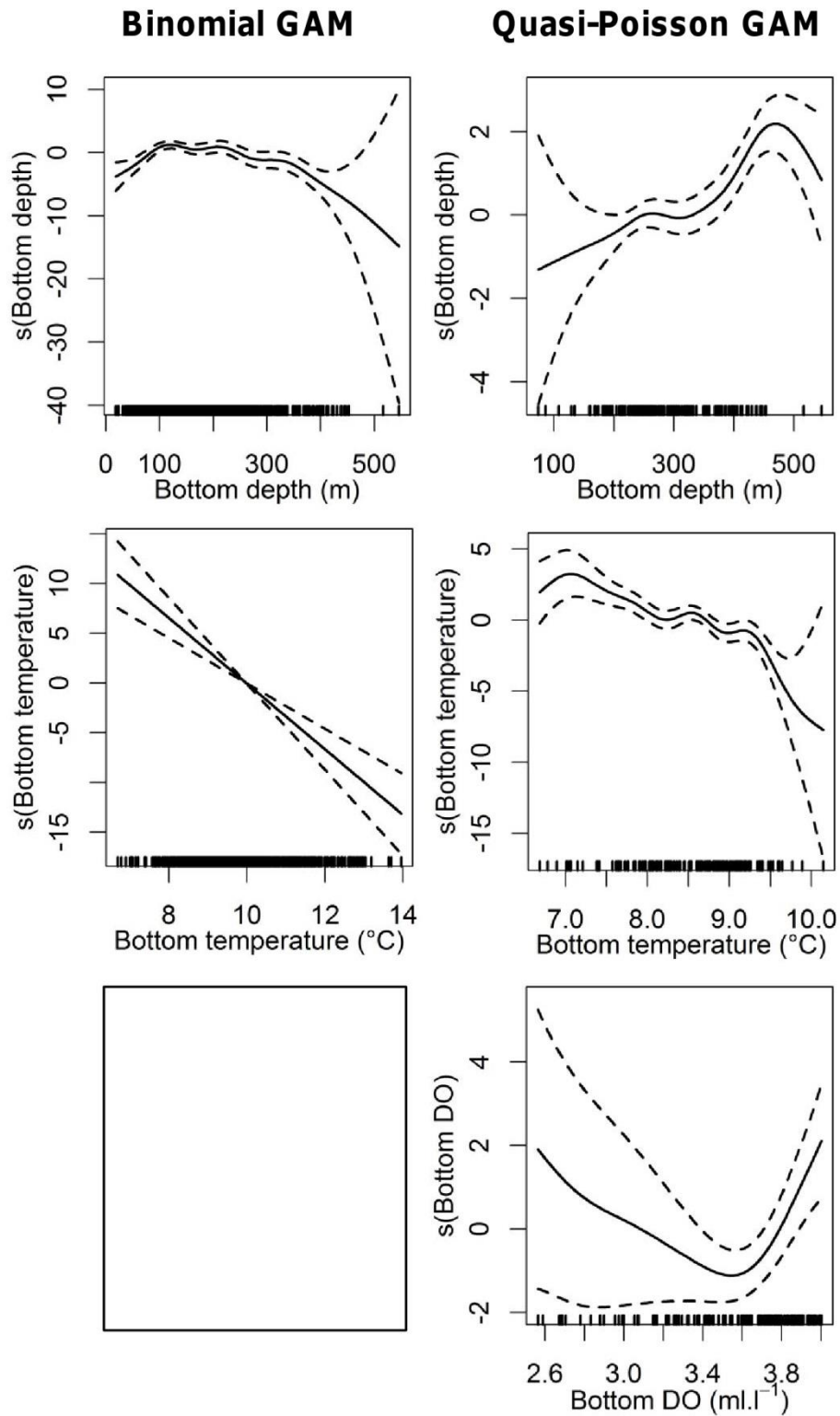
Binomial GAM **Quasi-Poisson GAM**

Figure S6: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of juvenile *Merluccius paradoxus* (<20 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of juvenile *M. paradoxus* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen
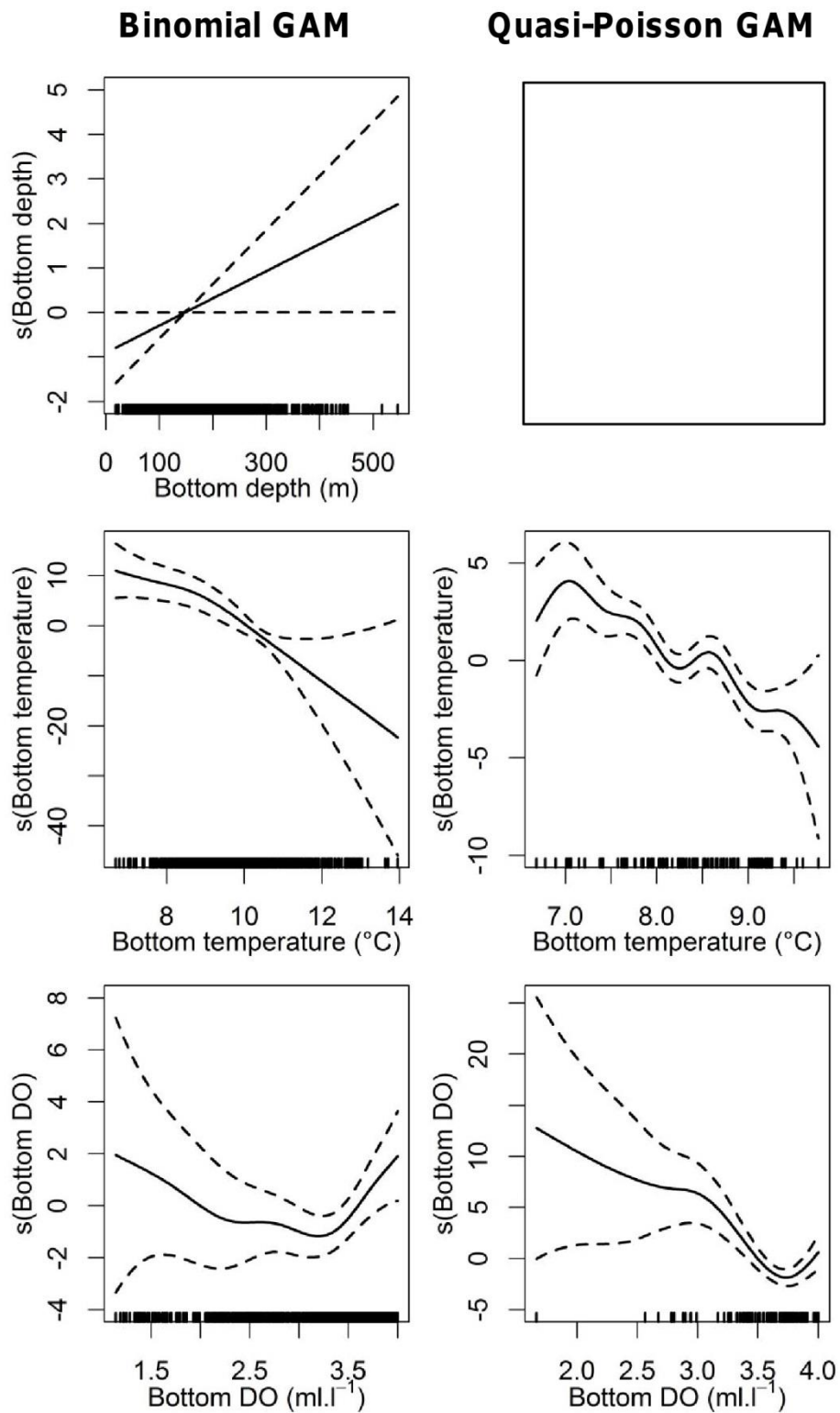
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Figure S7: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of small *Merluccius paradoxus* (20–35 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of small *M. paradoxus* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen

Binomial GAM

Quasi-Poisson GAM

Figure S8: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of medium-small *Merluccius paradoxus* (35–45 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of medium-small *M. paradoxus* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen

Binomial GAM   ## Quasi-Poisson GAM

Figure S9: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of medium-large *Merluccius paradoxus* (45–55 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of medium-large *M. paradoxus* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen
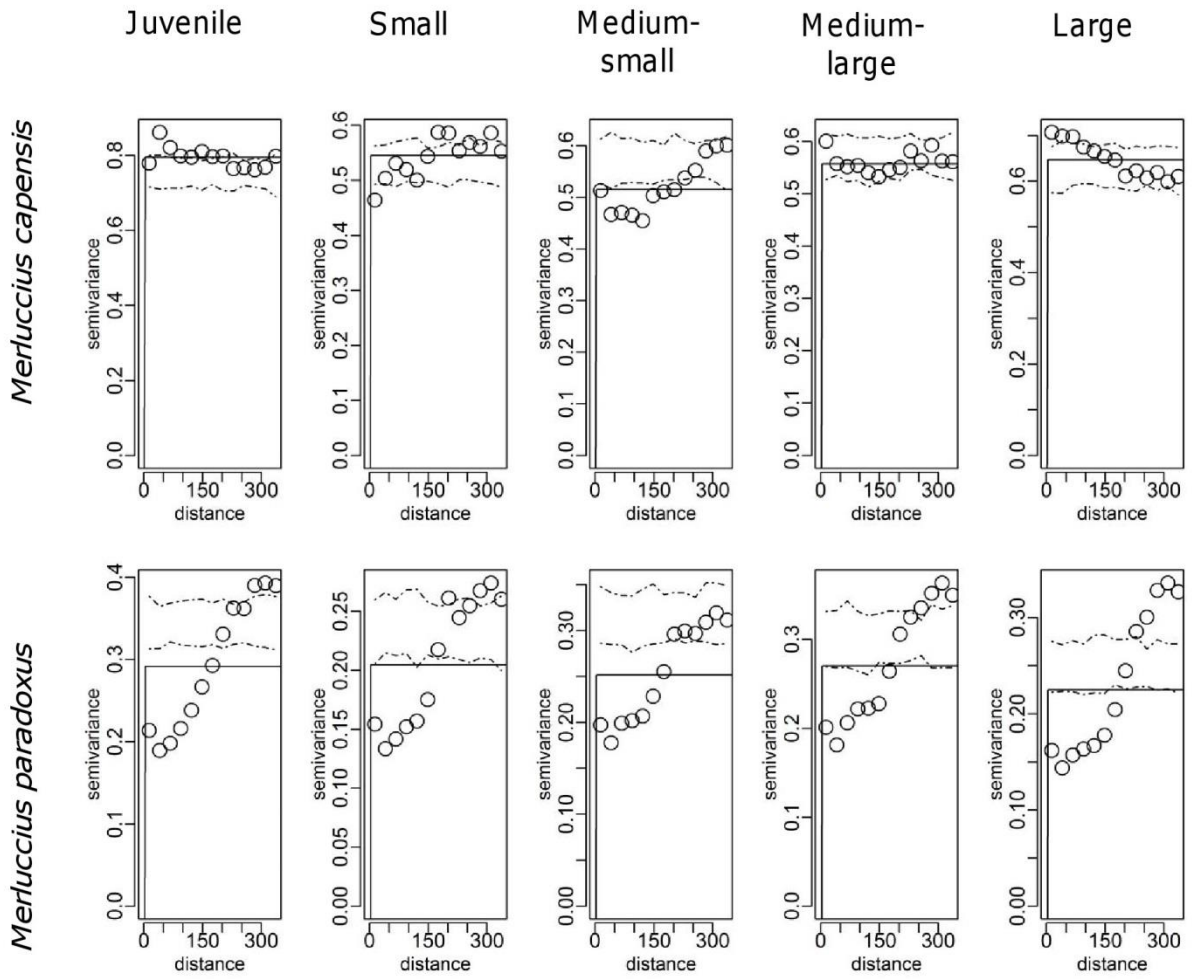
Binomial GAM

Quasi-Poisson GAM

Figure S10: Fits for the binomial and quasi-Poisson generalised additive models (GAMs) developed for predicting the spatial distribution of large *Merluccius paradoxus* (>55 cm). Smoothed curve of the additive effect to the estimated probability of presence/abundance of large *M. paradoxus* for the individual environmental parameters considered in the GAMs. Dotted lines represent 95% confidence intervals, and each mark along the *x*-axis is a single observation. Note that the scale of the *y*-axis differs from one panel to the next for display purposes. Empty box indicates the exclusion of a variable when its smoothing parameter is close to zero or lack of significance (α = 0.05). DO = dissolved oxygen
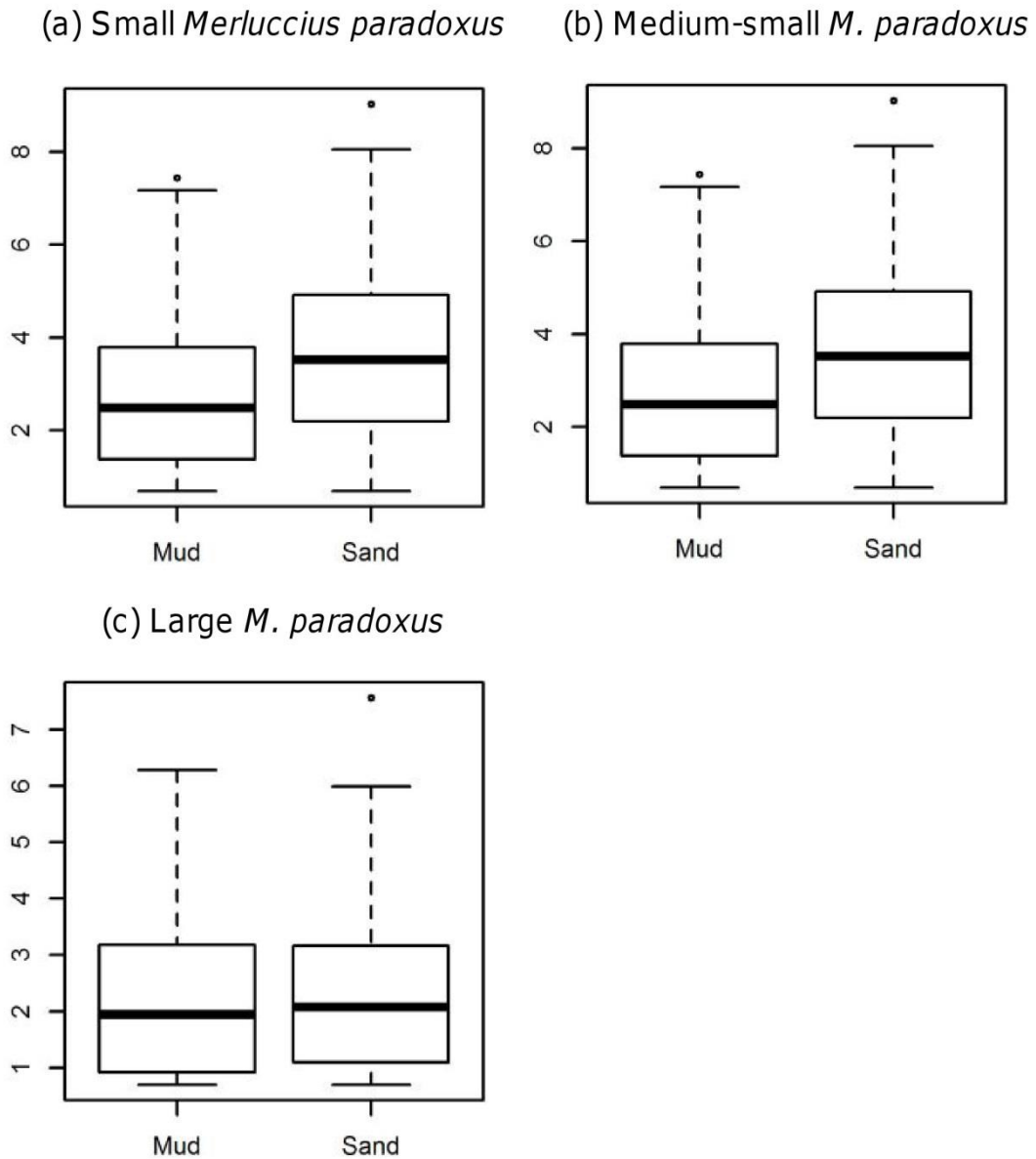
Figure S11: Distribution of the abundance of (a) small, (b) medium-small and (c) large *M. paradoxus* for each sediment type predicted by quasi-Poisson generalised additive models (GAMS). Abundance is expressed here as ln(individuals + 1). Because we are primarily interested in which sediment type is suitable for hake size classes, the zeros have been removed for display purpose. Due to lack of significance (α = 0.05), sediment type was discarded from the quasi-Poisson GAMs fitted for all size classes of *M. capensis* and juvenile and medium-large *M. paradoxus*.

Figure S12: Empirical variograms of the residuals from the binomial generalised additive models fitted for different size classes of South African hakes *Merluccius capensis* and *M. paradoxus*. The dashed lines represent the 95% envelope of the variograms under the null hypothesis of no spatial structure, and the solid lines represent pure nugget variograms. Juvenile hakes are <20 cm long, small 20–35 cm, medium-small 35–45 cm, medium-large 45–55 cm, and large >55 cm
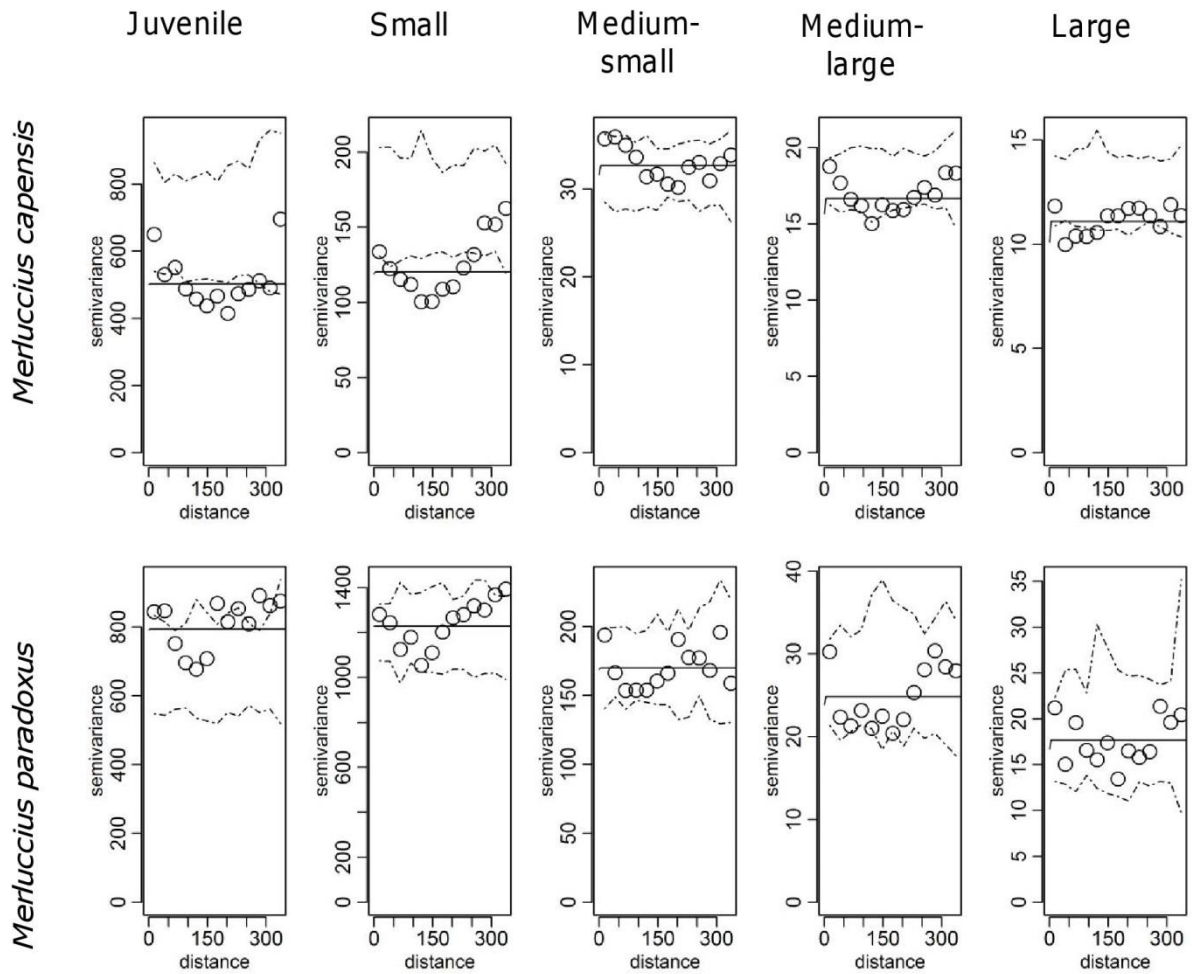
Figure S13: Empirical variograms of the residuals from the quasi-Poisson generalised additive models fitted for different size classes of South African hakes *Merluccius capensis* and *M. paradoxus*. The dashed lines represent the 95% envelope of the variograms under the null hypothesis of no spatial structure, and the solid lines represent pure nugget variograms. Juvenile hakes are <20 cm long, small 20–35 cm, medium-small 35–45 cm, medium-large 45–55 cm, and large >55 cm