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Research Article**Surveying while fishing in the slope areas off Brazil: direct assessment of fish stock abundance from data recorded during commercial trawl fishing operations****Rodrigo Sant'Ana & José Angel Alvarez Perez**

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ABSTRACT. Estimating the total biomass of fish stocks available for fishing at any one time can highly improve the process of deciding upon sustainable fishing management measures. However, countries where fishing resources are not abundant or valuable can hardly justify a regular investment in costly direct stock assessment programs. One way of overcoming such difficulties is to use catch rate data recorded from monitored commercial fishing operations, usually made available through the implementation of less expensive Observers programs. However, this data is prone to overestimate biomass of targeted stocks, because fishermen tend to operate in high-density areas. This study addresses this issue by exploring the use of geostatistical models to estimate biomass of three slope fish stocks of the Brazilian EEZ: codling (*Urophycis mystacea*), hake (*Merluccius hubbsi*) and monkfish (*Lophius gastrophysus*). The analysis included 25,824 commercial trawls conducted off Brazil between 2000 and 2009. Global biomass tonnage estimations were: codling 16,402 ton in 2001 and 23,816 ton in 2002; hake 267,712 ton in 2001 and 233,107 ton in 2002; monkfish 51,947 ton in 2001 and 16,998 ton in 2002. Values exceeded those obtained by scientific surveys conducted in the same period and area, but an in-depth analysis of methods employed demonstrated that such overestimation was only significant in the case of hake, the main target of the trawl fleet during the study period. The study showed that geostatistical models are most effective in reducing bias introduced by fishermen behavior when some catches away from high density areas are available. Those tend to be rare in the case of major target-species.

Keywords: geostatistical approach, swept-area, biomass assessment, slope fisheries.

Investigando las zonas de talud frente a Brasil mientras se pesca: evaluación directa de la abundancia poblacional de peces a partir de datos registrados en faenas de pesca de arrastre comercial

RESUMEN. Estimar la biomasa total de stocks pesqueros viene siendo una premisa cada vez más importante para mejorar las medidas de manejo pesquero. Sin embargo, en países donde estos stocks son menos abundantes o menos rentables es difícil justificar continuas inversiones en programas científicos para evaluar su biomasa. Una alternativa es el uso de datos colectados a bordo de embarcaciones comerciales por medio de programas de observadores, que son relativamente menos costosos. No obstante, estos datos tienden a reflejar el direccionamiento de la flota sobre regiones con altas densidades del recurso objetivo, resultando en sobreestimaciones de la biomasa de estos recursos. El presente estudio aborda este problema explorando la implementación de modelos geoestadísticos para estimar la biomasa de tres stocks demersales de talud: brótola (*Urophycis mystacea*), merluza (*Merluccius hubbsi*) y rape (*Lophius gastrophysus*). Los datos procedieron de 25.824 lances de arrastre realizados en el sureste y sur de Brasil entre los años 2000 y 2009. Las estimaciones globales para las tres especies fueron: brótola 16.402 ton en 2001 y 23.816 ton en 2002; merluza 267.712 ton en 2001 y 233.107 ton en 2002; rape 51.947 ton en 2001 y 16.998 ton en 2002. Estos valores excedieron aquellos obtenidos por campañas científicas realizadas en la misma época y área, aunque un análisis de los métodos utilizados demostró que esa sobrestimación fue únicamente significativa en el caso de la merluza, el principal

recurso objetivo de la flota durante el período de estudio. Los resultados demostraron que modelos geostatísticos son más efectivos en la reducción del sesgo introducido por el direccionamiento pesquero cuando se dispone de un cierto número de capturas obtenidas fuera de las áreas de alta densidad. Estas son raras en el caso de las especies objetivo.

Palabras clave: enfoque geoestadístico, área barrida, evaluación de biomasa, pesquerías del talud.

INTRODUCTION

In the past 15 years, demersal fishing off the Brazilian coast has expanded to deep areas of the continental margin gradually impacting untouched ecosystems and establishing harvesting regimes over previously unexploited resources (see Perez *et al.*, 2009a for review). This process was motivated by a fishing development policy that allowed a foreign fleet to operate in slope areas off Brazil, with the goals of identifying valuable resources, productive areas and international markets that could be ultimately absorbed by the national industry. Between 1998 and 2007, these vessels produced unprecedented catches of slope finfish and shellfish, driving most stocks to biologically unsafe levels. After 2007, as foreign vessels left Brazilian waters, exploitation of slope areas off southeastern and southern Brazil continued principally through the development of an ongoing trawl fishery directed at three main stocks (monkfish *Lophius gastrophysus*, hake *Merluccius hubbsi* and codling *Urophycis mystacea*). Because this fishery has been virtually unmanaged ever since, its impacts on these stocks as well as on the slope benthic ecosystem have become of critical concern in the context of sustainable use of resources and conservation of the deep areas of the Brazilian Exclusive Economic Zone (EEZ) (Perez *et al.*, 2009a; Visintin, 2015; Dias & Perez, 2016, Port *et al.*, 2016).

Initiatives for managing slope trawling in Brazil date back to 2006, and were focused on the implementation of measures aiming to control the impacts of the growing national fleet and preserve productivity of the new exploited stocks. These measures were based on three components: a) stock biomass estimations obtained in 2001/2002 at the main fishing grounds (Haimovici *et al.*, 2009), b) Maximum Sustainable Yield (MSY) calculations based on life-history parameters (Perez, 2006), and c) the establishment of effort limitations for the national slope trawl fishery (Perez & Pezzuto, 2006; Perez *et al.*, 2009b). The former resulted from a 10-year Government-funded fishing survey REVIZEE Program that ended in 2006, not to be resumed ever since (MMA, 2006). Likewise most stocks exploited in the country, abundance of slope stocks was no longer assessed after this period, and their subsequent management was

based on the availability of few biological data and fishery-derived abundance indices.

Elevated costs of fishing surveys have generally been the root of their discontinued nature in Brazil (see Haimovici, 2007). An alternative and less expensive source of slope stocks information, has been derived from fishing observers set to monitor operations of foreign trawlers, as part of the obligations established by their fishing permits in Brazilian waters (Perez *et al.*, 2009b). These observers reported catch rates of more than 25 thousand commercial tows, which were essential to produce comprehensive descriptions of the fisheries and the distribution of the main resources in the Brazilian slope (Perez *et al.*, 2009c). Yet their potential use to produce abundance estimations, *i.e.*, by using the 'swept-area' method, was *a priori* not attempted because it was expected that sample densities, as calculated from such dynamic and efficient operations of the foreign fleet, could be biased towards maximum levels and potentially generate important biomass overestimations.

These statistical limitations were recently addressed by Sant'Ana (2013), who applied simulated survey designs on theoretical fish populations of known abundance, and demonstrated that such biases could be minimized when geostatistical model-based methods were used to expand sample densities into biomass estimations. The implication of this finding was that fishery-generated catch rate data could produce reliable biomass estimates, at lower costs and on a regular basis, supporting the demand for determining total biomass of exploited stocks periodically available for fishing. In this study, we apply the solution proposed by Sant'Ana (2013) to expand densities calculated from catch rate data, obtained by foreign trawlers to estimate the abundances of monkfish, hake and codling stocks, of southeastern and southern Brazil in 2000-2002. We hypothesize that the resulting biomass estimations will be comparable to those obtained by the REVIZEE fishing surveys, demonstrating that a sustained observers program can be a low cost-benefit alternative for providing regular abundance estimates and improve the slope fisheries management process.

MATERIALS AND METHODS

Data sources

Analyzed data originated from a fishery observers program (PROA - Chartered Fleet Onboard Observers

Program) operated by University of Vale do Itajaí (UNIVALI) in cooperation with Brazilian fisheries authorities. This program was developed from 2000 onwards to support the governmental international fleet chartering policy, which demanded all licensed foreign vessels to carry observers in 100% of their operations in Brazilian waters (Perez *et al.*, 2009b). Between 2000 and 2009 these observers monitored 136 fishing trips, conducted by foreign trawlers off southeastern and southern Brazil, reporting information of over 25,000 tows during this period (Table 1). Data collected for all tows included fishing area (*e.g.*, geographic coordinates), depth, trawl duration and speed, and catch of each retained species. Additionally, for each vessel, fishing gear configuration was recorded and monitored for changes during the study period.

Because the international fleet adopted different targets while operating in Brazilian waters (Perez *et al.*, 2009b), the whole data base was selected for tows directed at concentrations of at least one of the species: hake, codling and monkfish. To that end, only trawls conducted in 2000, 2001 and 2002 were included for biomass estimation analysis, which corresponded to the period when the foreign trawl fleet was fully focused in fishing slope finfish species (Perez *et al.*, 2009b). Selecting that period was also crucial because it also matched the area and period covered by bottom trawl surveys of the Program REVIZEE (Haimovici *et al.*, 2009) (Fig. 1). This selection resulted in a subset of the whole time series that included data produced by nine distinct vessels, 50 fishing trips and approximately 7,000 tows.

Evaluating densities using the swept area method

Estimation of densities of slope fish stocks in the fishing area required a previous consideration of the

trawl nets used by each vessel, particularly regarding the head rope length and mesh size in the cod end. An analysis on a vessel-by-vessel basis revealed that these dimensions were fairly regular, enabling all tows to be pooled in a single data matrix.

The area trawled ('swept') by each *i*-th fishing tow (Sw_i) was calculated in km² by:

$$Sw_i = L_i * \bar{h} * X_2 \quad (1)$$

where L_i is the trawled distance (in km) calculated as the product of trawling speed by the trawling time; \bar{h} is the mean length of the head rope, and X_2 is the fraction of \bar{h} that corresponds to the width of the path swept by the net, that is the 'wing spread' (Sparre & Venema, 1997). In this study that fraction was considered constant and equal to 0.56 (Alverson & Pereyra, 1969; Haimovici, 2007). Densities (d) of the *i*-th species in the *j*-th fishing tow were calculated by:

$$d_{ij} = \frac{C_{ij}}{Sw_i} \quad (2)$$

where C_{ij} is the catch of each species (in kg) in the *j*-th fishing tow. We assumed that C_{ij} could be substantially affected by external factors, including vessel individualities, latitudes, depths, seasons, and years. As an attempt to remove such effects, before densities were calculated, C_{ij} was standardized using Generalized Linear Models (GLM) (see below).

Lastly, it was assumed that the fishing nets efficiency for each studied species was below maximum and, in that sense, estimated densities (d_i) required correction by an efficiency factor (X_1 , Sparre & Venema, 1997).

$$d_{ij} = \left(\frac{C_{ij}}{Sw_i} \right) / X_{1j} \quad (3)$$

Table 1. Summary of the annual effort of the bottom trawl chartered fleet that operated in Brazil during the period of 2000 to 2009.

Year	Number of vessels	Number of fishing operations	Number of fishing tows	Latitudinal range distribution of fishing tows (min-max)
2000	1	2	223	34.036°S - 25.070°S
2001	6	13	1,959	34.602°S - 23.000°S
2002	11	35	4,329	33.322°S - 8.230°N
2003	3	13	2,863	33.485°S - 2.189°S
2004	4	8	1,682	25.967°S - 9.083°S
2005	6	31	6,735	28.720°S - 8.062°S
2006	3	16	3,671	34.478°S - 0.145°S
2007	2	11	2,490	29.083°S - 0.174°S
2008	2	5	1,412	27.955°S - 19.060°S
2009	2	2	460	27.663°S - 2.266°S
Total	17	136	25,824	

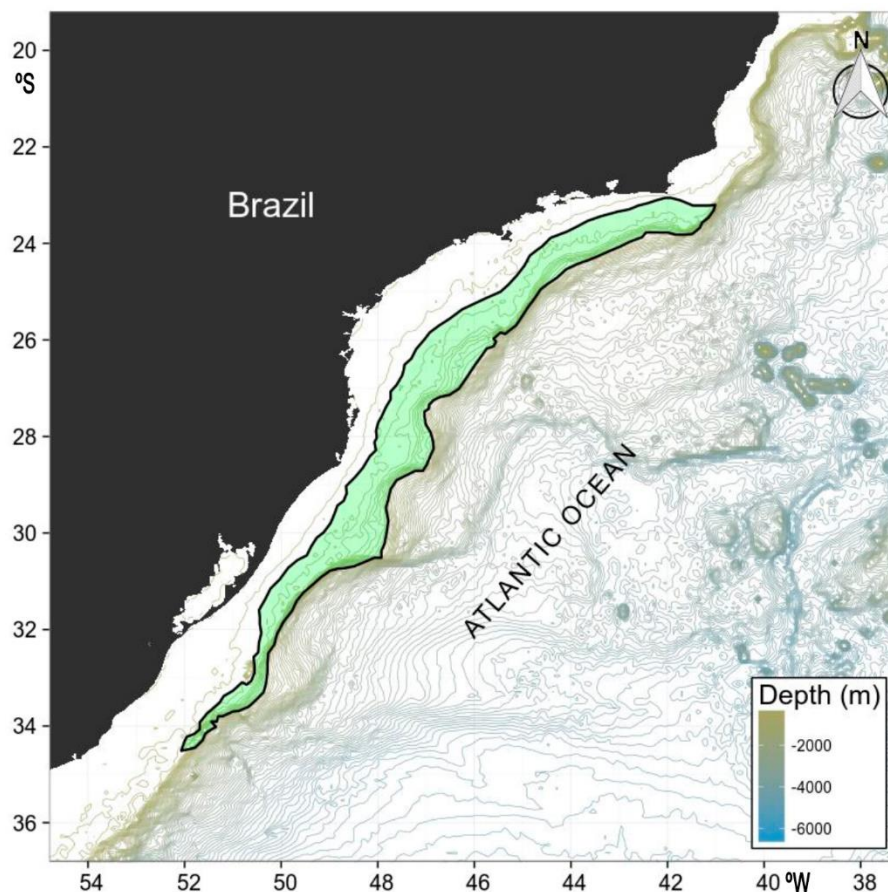


Figure 1. Total area considered as a proxy to comprehend the global biomass estimates for each species analyzed in the present study.

This factor was estimated by using ‘depletion methods’ which assume that in a limited area all biomass losses of a stock during a period of intense fishing are caused by captures, with no entry effects from recruitment or exit effects from natural mortality (‘closed stock’ assumption). In a future hypothetical scenario where the initial abundance had been totally depleted by fishing, the total accumulated capture would correspond to an estimation of the initial abundance (Hilborn & Walters, 1992; Gunderson, 1993). The Leslie’s Depletion Model (Leslie & Davis, 1939) was applied where standardized CPUE was the response variable expected to describe abundance reductions due to sequential catches in ‘depletion scenarios’. These scenarios were defined by groups of trawls concentrated in limited space where catch rates of a series of trawls conducted in a limited period of time showed a decreasing trend. They were considered temporary approximations of a ‘closed stock’ where net efficiency of the nets can be determined by the quotient between the biomass retained by all trawls in a depletion scenario and the initial biomass available

(i.e., existent in front of the path of the nets) (Pezzuto *et al.*, 2008). Following the Leslie model, in this study CPUE decline during a depletion scenario was modeled by a linear regression:

$$\frac{c_t}{f_t} = qP_1 - q(K_t) \quad (4)$$

where $\frac{c_t}{f_t}$ is the capture per unit effort in given t time, q is the catchability coefficient, P_1 is the initial population abundance and K_t is the cumulative catch buildup previous to t . Thus, the simple quotient of the regression intercept ($q P_1$) by the slope coefficient (q) allows the dimensioning of the initial abundance P_1 . From the quotients between catches accumulated by all trawls within a depletion scenario and P_1 , it was possible to determine the net efficiency for each target-species i.e., \bar{X}_1 for each scenario. By analyzing a series of depletion scenarios (see below) the central tendency (\bar{X}_1) of the efficiency of fishing nets for each studied species was calculated and used in the swept area density calculations.

The identification of depletion scenarios was preceded by dividing the study area into subareas of 0.5 latitude degrees. Each year these scenarios were visually identified within each subarea, and confirmed by considering the presence of decreasing trends in daily catches and CPUE. These trends had the linear slope coefficient calculated and submitted to a significance test opposing to 0 value. All regressions that showed a P -value below 0.1 were considered as valid scenarios and incorporated in the net efficiency estimates.

CPUE standardization

Standardizing CPUE was necessary in two methodological procedures of this study: (a) to use as response variable in the Leslie's depletion models and (b) to calculate trawled area densities (see below). In both cases CPUE were calculated based on the catch predictions given by the best adjustment resulted from standardization by the generalized linear models. Distinctly from the common models applied to CPUE standardization, the model structured in this article was rearranged in a way to admit catch as response-variable conditioned on the observed values of effort in each haul, assuming the equality below:

$$\frac{C_i}{f_i} = qB \leftrightarrow C_i = qf_iB \quad (5)$$

Thus, the distribution modeled was not a ratio of two random variables, but a simple and unique random variable conditioned to the fishing effort observed. This approach can reduce difficulties intrinsic to modelling two random variables in a single ratio (Candy, 2004). Free from the previously mentioned effects, catch was then employed as a response variable to both calculate area density and net efficiency using adjusted depletion models (see above).

Two generalized linear models (Nelder & Wedderburn, 1972; McCullagh & Nelder, 1981) were adjusted assuming a Tweedie distribution (Tweedie, 1984) to the response-variable, one considering the fishing effort as a directly predictor of catches and other assuming the same fishing effort as weights of catches. In both cases, the log-link ($g(\cdot)$) function was used to relate the expected value of the response-variable to the linear predictor (Lo *et al.*, 1992; Candy, 2004; Shono, 2008; Maunder & Punt, 2004).

$$Y_i = C_i = \eta_i \quad \eta_i = g(\mu_i) = \alpha + \sum_{j=1}^p \beta_j x_{ij} + \varepsilon_i \quad (6)$$

where y_i is the observed value of response-variable, η_i is the linear predictor and ε_i is an independently and identically distributed random error. Thus, the expected value of the response-variable is $E(y|\eta) = \mu$ and the variance can be given by $Var(y|\eta) = \phi\mu^p$, where μ is the mean, ϕ is the dispersion and p is the power

parameter of Tweedie distribution (Candy, 2004; Shono, 2008).

The models for each of the target species were then fitted using the GLM methodology. Comparisons between competing models were made through the Q-Akaike Information Criteria (quasi-AIC) as proposed by Burnham and Anderson (1998).

Expansions procedures to estimate biomass - Geostatistical models

The method used to estimate the biomass for the three target-species in this study, by means of the geostatistical models, were based on the simulation study performed by Sant'Ana (2013). Nonetheless, because database for each species and year were considerably large and model adjustments were time-consuming, sub-sampling data of each species was necessary in order to facilitate the computing process and estimating spatial correlation matrices. 500 trawls from the entire study area were randomly selected for each species and year, without replacement. A geostatistical model with approximation to the Matern spatial correlation was applied to each data set, and abundance values for the entire area were predicted, based on the kriging procedure.

By definition, a geostatistical model may be specified by: $[S, Y] = [S][Y/S]$. $Y(x)$: $x \in A$ is the measuring process, and Y is the abundance measure according to x points located within the area $A \subset \mathcal{R}^2$. In a stochastic method process, expressed by $S(x)$, we may assume that $S = S(x)$: $x \in \mathcal{R}^2$ is a Gaussian distribution with μ as mean, variance σ^2 and correlation function $\phi(u)$, being u the distance between observation pairs (Diggle & Ribeiro Jr., 2007; Gaetan & Guyon, 2010). As consequence, the observations of Y_i may be considered as noise from $S(x_i)$ for a set of locations x_i . Therefore, the function that describes the random Gaussian field model parameters is specified by:

$$Y(x) = \mu(x) + S(x) + \varepsilon \quad (7)$$

where, Y has a Gaussian distribution, x defines the spatial location belonging to the \mathcal{R}^2 , $\mu(x)$ is the mean component of the model, which may be fixed or not, according to the spatial tendency observed on data, $S(x)$ is the stationary Gaussian process with variance σ^2 ("Sill") and parameterized correlation function in form of ϕ ("Range"). Additionally, the correlation function may be assigned from extra parameters, such as, a smoothing parameter κ ("kappa") and anisotropy parameters. Moreover, ε is the error term with variance parameter τ^2 ("Nugget effect") (Diggle & Ribeiro Jr., 2007). Assuming a stationary covariance condition of $C(h) = C(0) - \gamma(h)$, the Matern spatial correlation model may be presented in the form of variograms as described below:

$$\gamma(h; \emptyset, \sigma^2, v) = \sigma^2 \left(1 - \frac{2^{1-v}}{\Gamma(v)} \left(\frac{\|h\|}{\phi} \right)^v \kappa \left(\frac{\|h\|}{\phi} \right) \right), \text{ if } h \geq 0 \quad (8)$$

In order to incorporate all the existent uncertainties within the database into the total and punctual biomass estimations (to each x_i point from $S(x)$ space), the previous process was repeated a total of 50 times for each of the three analyzed species each year, generating 50 different estimations for total biomass, punctual densities and prediction uncertainties. As a result, it became possible to estimate a more accurate global biomass based on the mean of the 50 processes, as well as the variances around these estimations.

RESULTS

Exploratory data analysis

Data related to the fishing strategies adopted by the trawl fleet (depth, trawl speed, trawl duration, etc.) were explored for vessel variability that could interfere in the density estimations of the three target-species. The analysis of trawl depth variability confirmed previously observed patterns (Perez *et al.*, 2009c), where the fleet operations were shown to concentrate between the isobaths of 200 and 400 m (Fig. 2a). Trawl speeds, used for calculating trawled distances, essentially showed a uniform distribution over the years with a central tendency close to three knots; some extreme values of occurrences, such as 10 knots during trawling, were disregarded from the trawled distance estimations (Fig. 2b). The trawls lasted around four hours on average, reaching exceptionally over eight hours (Fig. 2c). Distances covered by each trawl, estimated through the product of trawl speed and duration, varied little in the three years, with a central tendency between 15 and 20 km (Fig. 2d).

Head rope length and mesh size in the codend also varied little except for two vessels, one with head rope shorter than 50 m (≈ 45.83 m) and another with mean codend mesh size of 50 mm (Table 2). However, these differences did not result in perceptible changes in trawled area estimations (km^2), or any that could affect considerably these estimations. The swept area (km^2) distribution was very similar among the years with a central tendency varying between 0.5 and 0.7 km^2 (Fig. 3).

Estimating fishing efficiencies

Among the GLMs fitted to the catches of each analyzed species, those that presented the best fits, considering the Q-Akaike Information Criteria (Q-AIC), were the models that included "effort" as predictive of the catch response-variable (Tables 4, 5). Catches of the three

species predicted by the GLM with effort as response variable were employed on the depletion experiments to estimate net efficiency. Altogether, 142 depletion scenarios were identified, 42 being significant for codling, 48 for hake and 52 for monkfish (Fig. 4).

In general, the calculated net efficiencies for each species showed a very similar behavior. The central tendencies (medians) in all three species were very close between one another (codling = 0.5077; hake = 0.4193; monkfish = 0.6059), as well as their dispersion measures (codling: 1st Q = 0.344 - 3rd Q = 0.745; hake: 1st Q = 0.285 - 3rd Q = 0.619; monkfish: 1st Q = 0.365 - 3rd Q = 0.695) (Table 3).

Densities distributions and biomass estimations

Sample densities were estimated considering the median estimated efficiency for each species in this study, a wing spread coefficient equal to 0.56 and the standardized catches. Estimated densities (in kg km^{-2}) for each species displayed rather asymmetrical behaviors (Fig. 5). For the codling, the sample densities ranged, on average, from 0 to 200 kg km^{-2} (variation considering all three years), with the presence of very high values, although less frequent, in the years 2001 and 2002. On the other hand, hake showed relatively higher densities, from 0 to 2900 kg km^{-2} in general for the three years, also showing less frequent high concentrations on the sampled tows. Additionally, for the monkfish, variations in the sampled densities ranged from 0 to 400 kg km^{-2} , with some cases showing concentrations higher than these limits (Fig. 5).

Annual biomass estimations of codling, hake and monkfish required an examination of the spatial data distribution for each year. Trawls conducted in the 2000 were discarded from the database due to their insufficient spatial coverage level of the study area (Fig. 6). Spatial gaps were also observed in 2001 and 2002 but these did not affect geostatistical procedures significantly (Fig. 6). Trawls conducted in 2001 and 2002 were re-sampled 50 times each year, which lead to a selection of 600 of them, originating 100 geostatistical models with Matern spatial correlation structure. The variations in the estimated parameters for each re-sampling process are shown in Figure 7.

According to each previously adjusted model, it became possible to estimate 50 values of total biomass and densities distribution for each species and year. Hence, based on the re-sampling processes and its respective estimated global biomasses, as well as using the principle of the Central Limit Theorem, it was possible to estimate more accurate biomass values and their respective dispersion and credibility measures for each species and year analyzed (Table 6). Hake was by

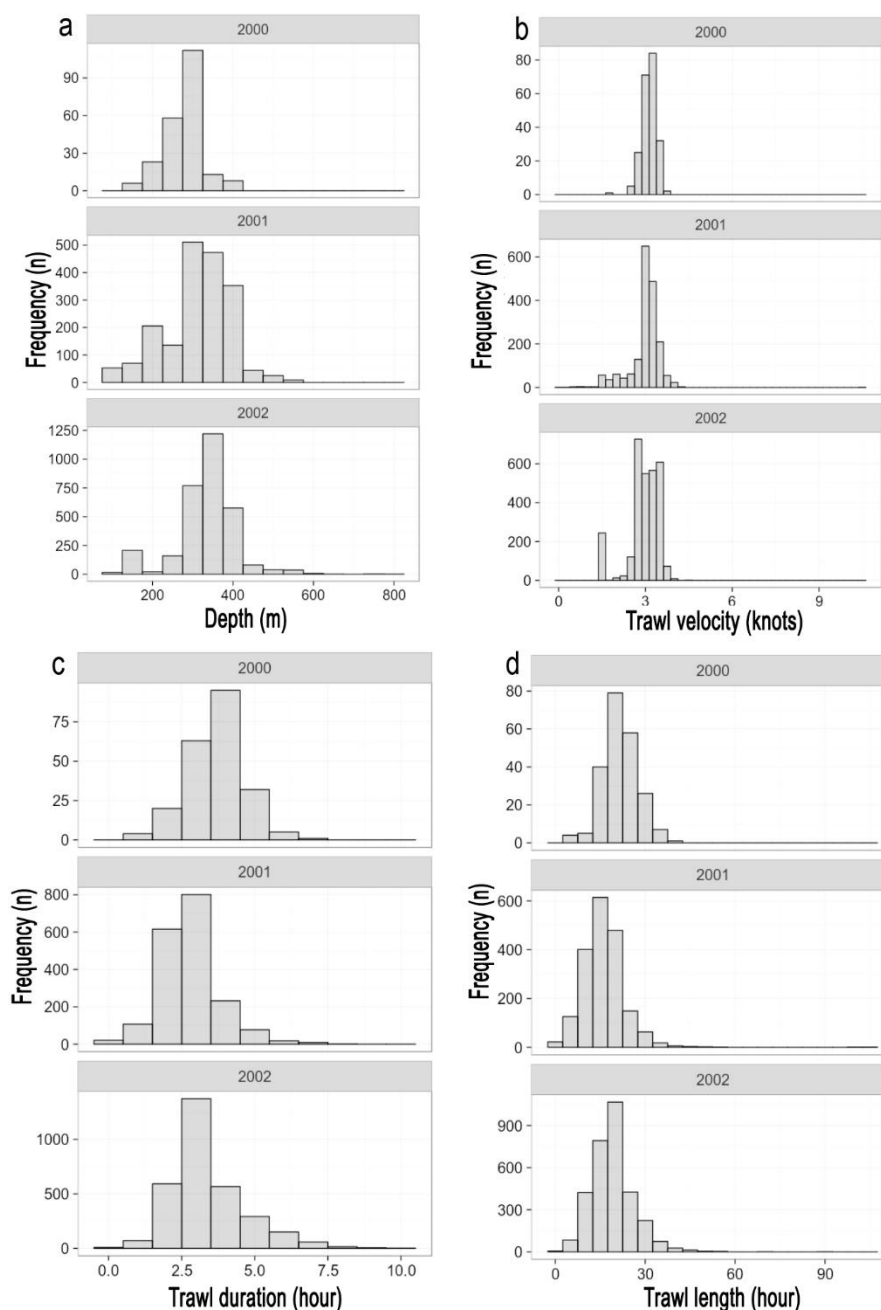


Figure 2. Fishing strategies adopted by the chartered bottom trawling fishing fleet during the period aimed to explore demersal fishes in the southern and southeastern off Brazil, between the years 2000 and 2002. Frequency distribution of a) hauls per depth, b) trawl velocity, c) trawl duration and d) trawl length.

far the most abundant stock (267.7-233.1 thousand ton) surpassing 5-20x the estimated biomass of codling (16.4-23.8 thousand ton) and 8x the biomass of monkfish (51.9-17.0 thousand ton). Codling showed a biomass increment of about 7 thousand ton from 2000 to 2001. Contrastingly, hake and monkfish showed a decrease in the estimated biomass for each year, reducing about 34 thousand tons in the first and 35 thousand tons in the latter species (Table 6). In the least

accurate biomass estimations the confidence interval was 11% of the total estimation, and in the most accurate, it was 2% of the total (Table 6).

Spatial distribution of the density predictions revealed that in 2001 and 2002 codling aggregated in two areas, one of great densities located between the parallels of 24° and 27°S and another south of 34°S. The densities per km² ranged from 0 to 600 kg km⁻² in 2001 (Fig. 8) and from 0 to 1000 kg km⁻² in 2002 (Fig.

Table 2. Statistical summary of the net trawls dimensions (in meters) and mesh dimensions (in millimeters) present in the mesh cod-end of the nets for each of the nine chartered vessels of bottom trawl that operated in the superior slope between the years 2000 and 2002.

Vessel code	Min	1 st Q	Median	Mean	3 rd Q	Max
Net trawls dimensions (m)						
A	92.00	92.00	92.00	92.00	92.00	92.00
B	58.50	67.00	66.25	66.25	67.00	67.20
C	45.00	70.00	72.02	72.02	80.00	101.50
D	38.00	80.00	63.56	63.56	80.00	80.00
E	65.40	65.40	65.60	65.60	65.40	67.00
F	55.00	62.00	63.44	63.44	62.00	76.00
G	37.00	41.00	45.83	45.83	56.00	70.00
H	33.00	70.00	66.29	66.29	85.00	85.00
I	58.00	58.00	59.40	59.40	58.00	65.00
Mesh dimensions (mm)						
A	100.00	100.00	100.00	100.00	100.00	100.00
B	60.00	60.00	75.00	72.73	82.50	85.00
C	50.00	60.00	75.00	77.67	80.00	120.00
D	70.00	70.00	100.00	97.78	120.00	120.00
E	70.00	70.00	70.00	80.25	70.00	152.00
F	40.00	40.00	50.00	50.00	50.00	70.00
G	135.00	135.00	135.00	135.00	135.00	135.00
H	50.00	60.00	90.00	74.39	90.00	90.00
I	65.00	70.00	70.00	69.00	70.00	70.00

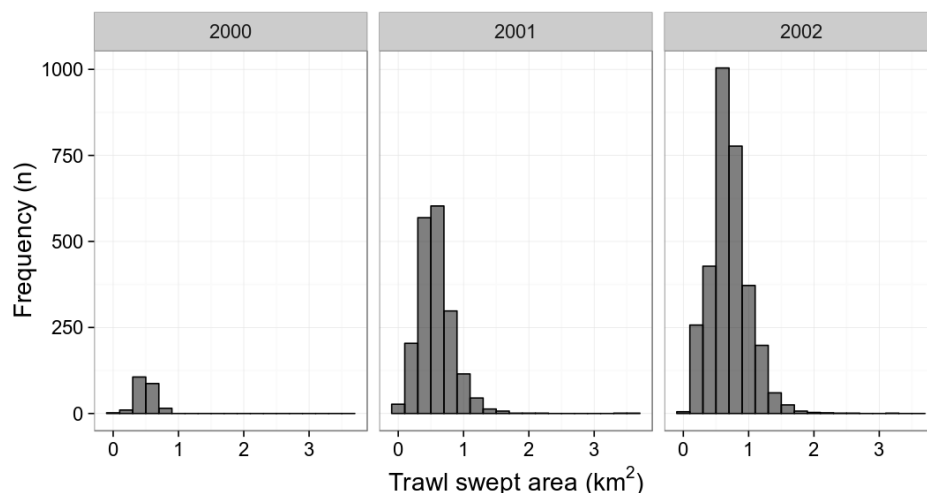


Figure 3. Frequency distribution of the estimated swept area (km²) for each fishing tow performed by the chartered bottom trawling fishing fleet during the years 2000, 2001 and 2002.

8). Hake concentrations were observed in the northern section of the study area between the northern limit of the area and the parallel of 28°S. Predicted densities per km² for 2001 and 2002 oscillated from 0 and 650 kg km⁻² and 0 and 1400 kg km⁻², respectively (Fig. 9). Monkfish highest densities were observed during both years in the northern section of the study area, more

precisely north of the 28.5°S parallel. However, it was in the upper portion of the slope that the greatest concentrations of this species were found. Annual densities variations per km² ranged from 0 to 1400 kg km⁻² in 2001 (Fig. 10) and from 0 to 300 kg km⁻² in 2002 (Fig. 10).

Table 3. Efficiency coefficient statistical summary, as estimated by the depletion method for each of the three target species of this study. SD: standard deviation. SE: standard error.

Species	Min	1 st Q	Median	Mean	3 rd Q	Max	SD	SE
Codling	0.087	0.344	0.508	0.524	0.745	0.868	0.213	0.033
Hake	0.077	0.285	0.420	0.449	0.619	0.860	0.207	0.030
Monkfish	0.097	0.3654	0.606	0.539	0.695	0.944	0.226	0.031

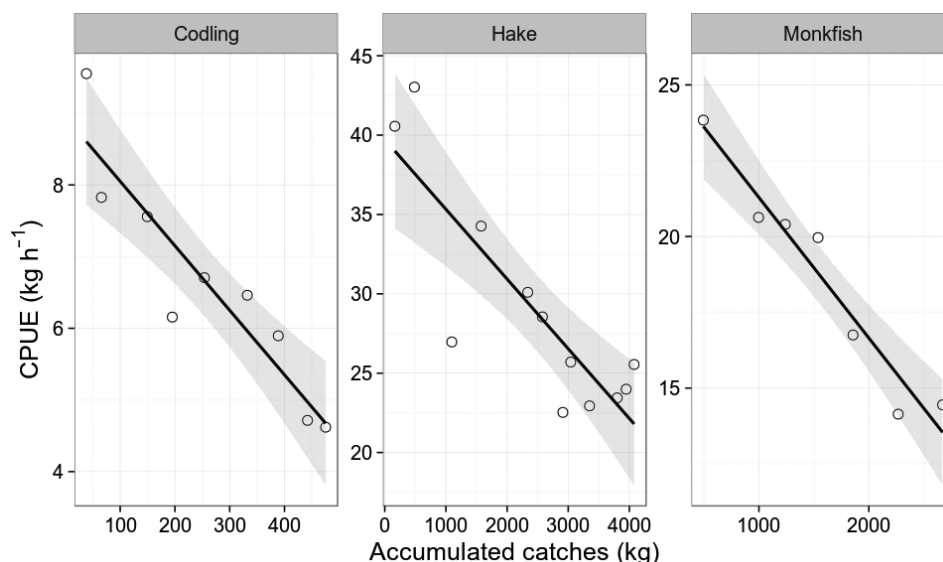


Figure 4. Exemplification of depletion scenarios identified for each of the three target species in this study. Solid line represents the fitted linear regression model. The grey area represents the fitted standard errors and the white dots represent the observed values.

Table 4. Summary of the Generalized Linear Models settings applied to the capture data for each of the three target species of this study, considering the Q-Akaike Information Criteria (Q-AIC) and the explanation proportion of each model.

Species	Model structure	Q-AIC	R ²
Codling	Effort as linear predictor	31,831	0.30
	Effort as weight	126,685	0.28
Hake	Effort as linear predictor	62,699	0.33
	Effort as weight	225,467	0.31
Monkfish	Effort as linear predictor	45,065	0.19
	Effort as weight	164,484	0.18

DISCUSSION

Biomass estimates obtained in this study for the three stocks exceeded those obtained in the same area and years by scientific trawl surveys under REVIZEE Program (Haimovici *et al.*, 2009). Such difference was 14–18 times larger in the case of the hake stock (Table 6). Additionally present estimates showed an increase

of similar proportions (30–45%) in the estimated biomass of codling between 2001 and 2002, a decrease nearly twice as important in the biomass of monkfish, and an inverse pattern in the biomass of hake, *i.e.*, REVIZEE estimations showed a 11% increase, whereas this study showed a 13% decrease. Whereas these patterns in principle refute the proposed hypothesis, an in-depth analysis of basic differences in the data analyzed and methods employed may address at more complex conclusions.

Firstly, this study did not assume that trawl nets operated with full efficiency ($X_1 = 1$) as opposed to the previous fishing survey estimates (Haimovici *et al.*, 2009). Instead efficiency coefficients were estimated for each species and employed during sample density calculation, as generally recommended in bottom trawl surveys, to account for the differential vulnerability of the studied organisms to the ‘sampling’ procedure (Gunderson, 1993). This methodological difference might alone have accounted for most differences observed between biomass estimates obtained for codling and monkfish in 2001 and 2002, when compa-

Table 5. Deviance analysis table of the Generalized Linear Model fitted to the capture data of each of the three target species of this study, considering models with best adjusts concerning the Q-Akaike Information Criteria (Q-AIC).

Model	df	Residual deviance	Chance in deviance	% of total deviance	F	Pr(>F)
<u>Codling</u>						
NULL		136,246				
vessel	8	109,966	26,280	63.64	135.14	<2.2E-16
vessel + lat	29	97,663	12,303	29.79	24.10	<2.2E-16
vessel + lat + season	32	97,430	233	0.56	3.20	0.0222
vessel + lat + season + year	34	96,296	1134	2.75	23.31	8.32E-11
vessel + lat + season + year + depth	35	95,928	368	0.89	15.15	0.0001
vessel + lat + season + year + depth + effort	36	94,948	980	2.37	40.29	2.37E-10
<u>Hake</u>						
NULL		158,028				
vessel	8	145,638	12,390	23.43	63.08	<2.2E-16
vessel + lat	30	118,412	27,226	51.49	50.40	<2.2E-16
vessel + lat + season	33	111,266	7146	13.51	97.02	<2.2E-16
vessel + lat + season + year	35	105,708	5558	10.51	113.20	<2.2E-16
vessel + lat + season + year + depth	36	105,619	89	0.17	3.64	5.64E-02
vessel + lat + season + year + depth + effort	37	105,147	472	0.89	19.20	1.20E-05
<u>Monkfish</u>						
NULL		67,205				
vessel	8	61,924	5281	41.54	61.56	<2.2E-16
vessel + lat	29	59,531	2393	18.82	10.63	<2.2E-16
vessel + lat + season	32	57,455	2076	16.33	64.54	<2.2E-16
vessel + lat + season + year	34	55,870	1585	12.47	73.90	<2.2E-16
vessel + lat + season + year + depth	35	55,638	232	1.83	21.64	3.37E-06
vessel + lat + season + year + depth + effort	36	54,493	1145	9.01	106.85	<2.2E-16

red to those generated by fishing surveys (Table 7). The ratio between both biomass estimates approximate efficiency coefficients used for both species ($B_{REVIZEE}/B_{STUDY} = 0.47-0.52$ for codling and $0.3-0.6$ for monkfish); if applied to REVIZEE estimates, codling and monkfish biomass would be modified to 16,829-21,969 ton and 26,657-18,258 ton respectively, which approximate estimates produced in this study (except for monkfish in 2001 see below).

Net efficiency is a caveat for direct fish stock assessments. The simple adoption of an efficiency coefficient equal to 1 implies assuming that all organisms in the path of a trawl net will be captured. Whereas rarely a realistic choice, this assumption may be sometimes favored as a conservative measure that will result in more precautionary management choices. On the other hand, adopting any estimated value below 1 will result in higher (and potentially more realistic) biomass estimates of the targeted stocks (Harden-Jones *et al.*, 1977; Dickson, 1993a, 1993b; Gunderson, 1993; Hoffman *et al.*, 2009; Doray *et al.*, 2010). REVIZEE trawl surveys have been an example of the former case where biomass tended to be 'underestimated' by using the trawl full efficiency assumption, as a conservative

option that could compensate for other sources of error. As a consequence, for instance, REVIZEE's codling biomass estimates would imply harvesting rates as large as 46% considering the annual landings reported for the species in 2000 and 2003 (around 4,000 ton per year; Anon, 2005; Perez *et al.*, 2009c) (Table 7). Such harvesting rates seem unlikely, particularly considering that maximum sustainable levels, calculated from life-history parameters, may not exceed 9% of the stock virginal biomass (Perez, 2006) and would imply in a stock collapse in the following years. By incorporating an estimated efficiency coefficient of 0.5, biomass estimates obtained in this study produced harvesting rates still considerably high (2001 - 24%; 2002 - 17%), yet probably more realistic.

The scenario described above may parallel that observed for monkfish in 2002, but not in 2001 when biomass estimates obtained in this study was nearly twice that estimated by the 2002 fishing survey. This estimate and those obtained for hake in both years imply that effects, other than those attributed to the net efficiency, may significantly affect biomass estimation from sample densities calculated by commercial catch rate data. A plausible hypothesis is that in these particu-

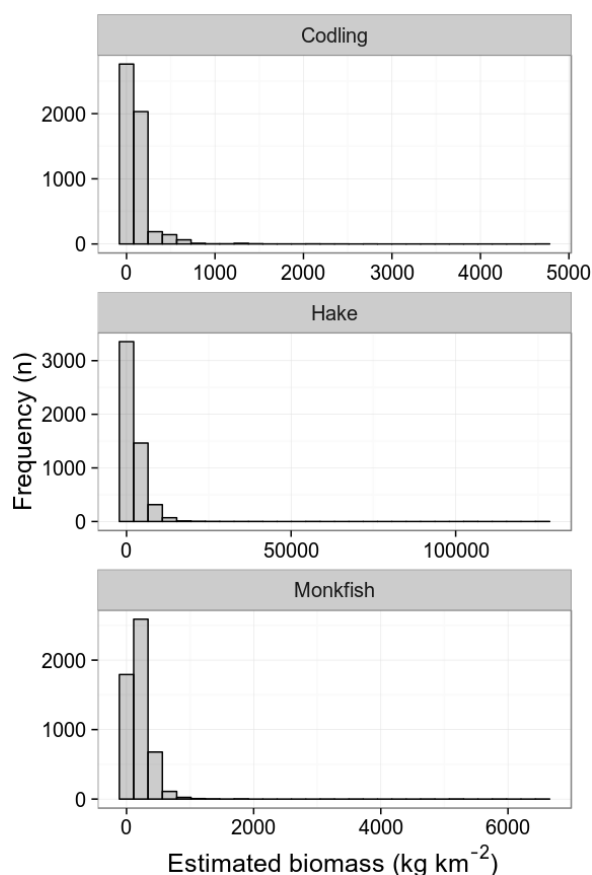


Figure 5. Density distributions (kg km⁻²) estimated for each fishing tow and each of the three target species of this study, during the total period the chartered trawling fleet was directed to demersal fish exploitation.

lar cases the geostatistical approach used for biomass expansion, as developed by Sant'Ana (2013) using

theoretical populations, was not able to compensate for the predominance of data originated from high density areas, as expected in observed commercial operations. In his simulations such 'compensation effect' was conditioned to the availability of a number of catch rate data originated from areas outside the high-density nuclei, where most available data normally would come from (Sant'Ana, 2013). This hypothesis would imply that a) codling in both years and monkfish in 2001 were bycatch species to foreign trawlers which obtained catches from areas of both high and low densities and therefore data from fishing surveys and commercial trawlers would produce similar estimates; b) hake and monkfish in 2001 were important targets to foreign trawlers, which rarely conducted trawls outside high-density areas leading to overestimation of median densities and consequently of global biomass.

Perez *et al.* (2009b) described the dynamics of the foreign trawl fleet using the bulk of data analyzed in the present study and demonstrated that in 2001 the slope trawl fishery went through a transition from an 'exploratory' to a hake 'directed' phase. In 2001 catch rate data recorded in the first 2/3 of the year originated from operations with different targets, including monkfish, but not codling which was a major bycatch component. In the end of this year and throughout 2002, hake appeared as a 'massive target' (*sensu* Biseau, 1988), whereas catches of the remaining species became incidental. This fleet dynamics description generally supports the above mentioned hypothesis since hake biomass estimates would tend to be affected by an almost exclusive availability of catch rate data originated from high density areas in both years, monkfish was potentially submitted to such effect in 2001 but not in 2002, and codling was not affected at

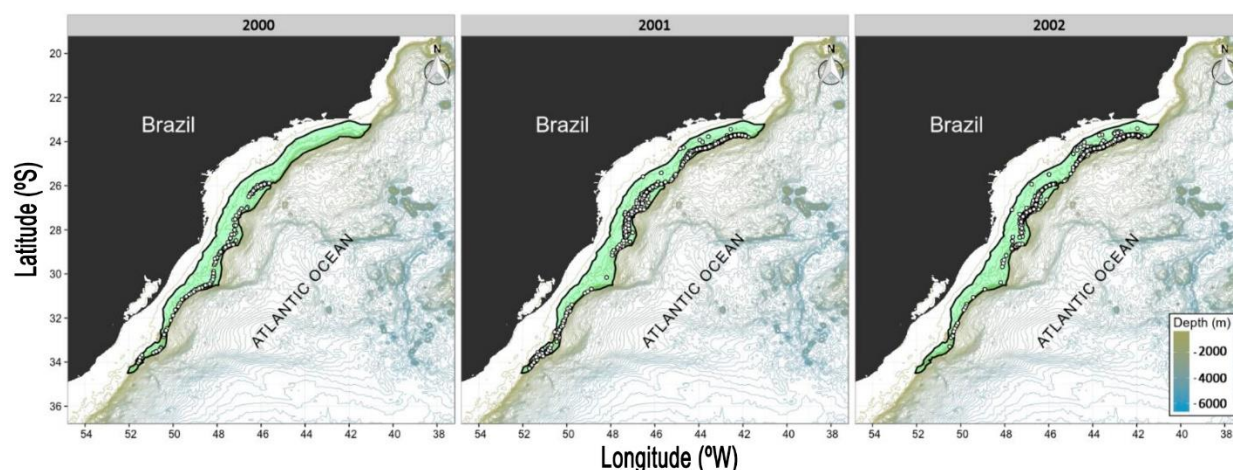


Figure 6. Fishing tows spatial distributions, with capture of the three target species of this study, executed by the bottom trawl chartered fleet during the years 2000, 2001 and 2002.

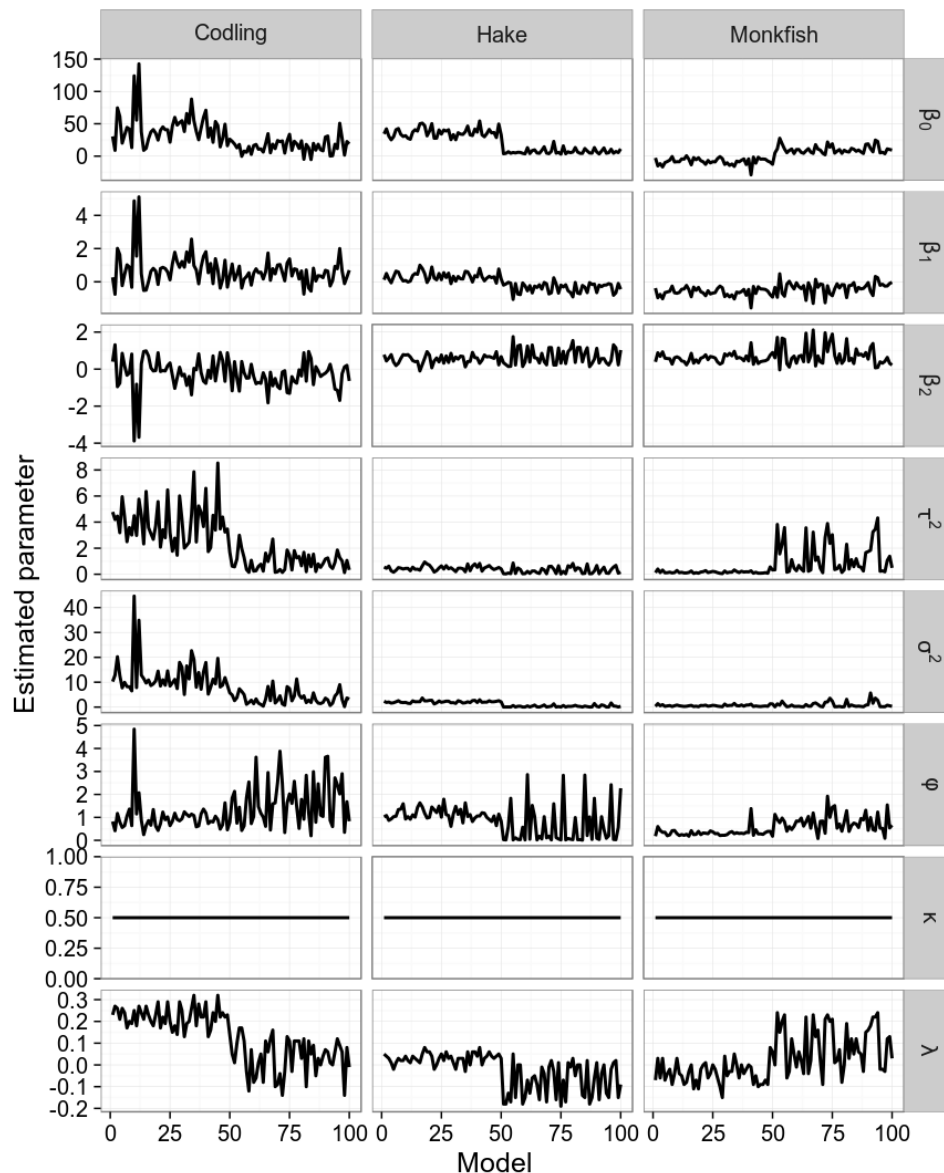


Figure 7. Estimation of the geostatistical model parameters variation with Matern spatial correlation structure fitted for each of the three target species of this study, considering each model of the resampling processes for the two years, 2001 and 2002. Models from 1 to 50 represent models fits to 2001, and models from 51 to 100 for 2002.

Table 6. Summary for the total biomass estimations (in ton), standard deviation (SD) and 95% confidence interval (C.I.) for each of the three target species of this study, discriminated by year.

Species	Year	Biomass	SD	Lower C.I. 95%	Upper C.I. 95%
Codling	2001	16,401.96	249.37	15,900.84	16,903.08
Codling	2002	23,816.21	1,277.01	21,249.96	26,382.47
Hake	2001	267,712.49	4,761.26	258,144.37	277,280.60
Hake	2002	233,107.45	12,663.87	207,658.44	258,556.45
Monkfish	2001	51,947.39	1,246.34	49,442.77	54,452.01
Monkfish	2002	16,998.15	135.55	16,725.76	17,270.55

all. A word of caution, however, is required in regard to monkfish estimates in 2001, since an age-structured assessment method applied to length composition of catches in 2001 produced an estimate of 62,776 ton (Perez *et al.*, 2005). That could indicate that regardless the spatial distribution of sample densities, the high biomass estimated in this study may not be unrealistic.

Validation of fish stock assessments through comparisons with independent experiments is not a rigorous procedure because all assessments incorporate their own amount of error. Yet a biomass estimate can be regarded as robust if it coincides to some extent with

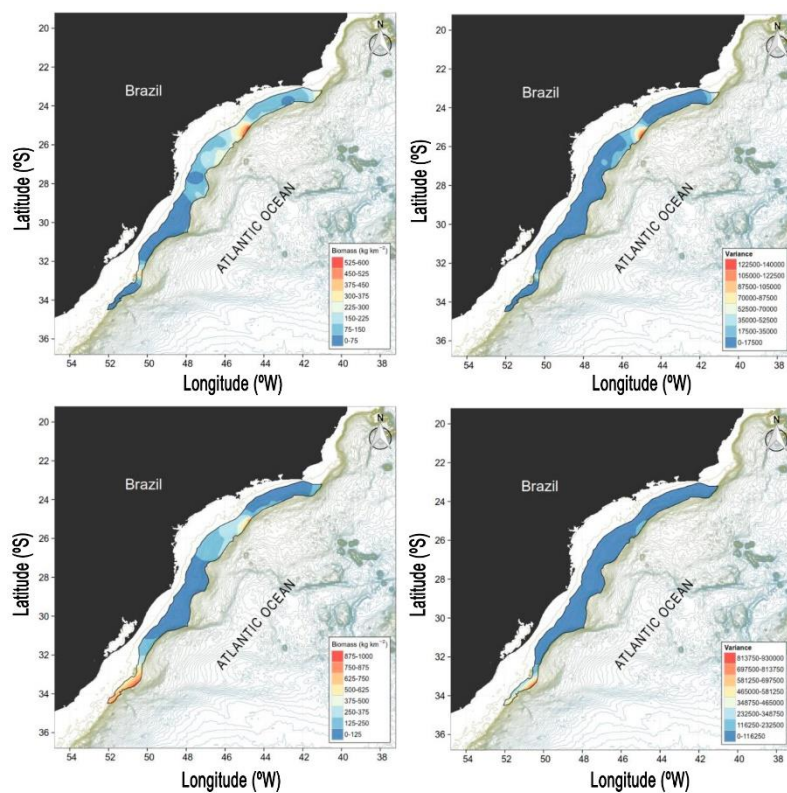


Figure 8. Codling, *Urophycis mystacea*, spatial distribution of the densities (kg km⁻²) predicted for the study area (left side), and respective uncertainties of the prediction (variance) (right side). Year 2001 (top), and year 2002 (bottom).

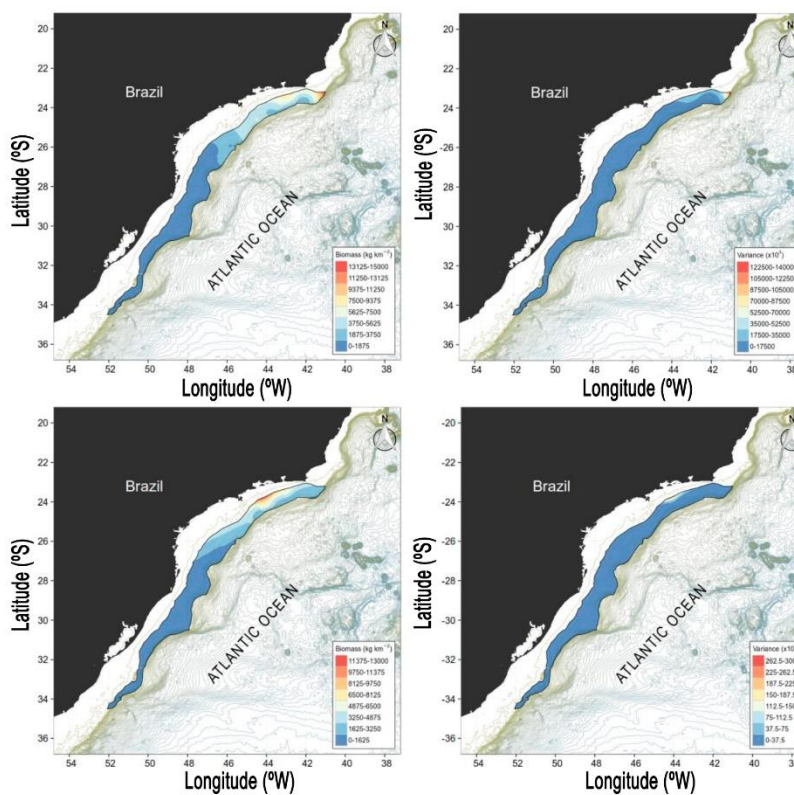


Figure 9. Hake, *Merluccius hubsi*, spatial distribution of the densities (kg km⁻²) predicted for the study area (left side), and respective uncertainties of the prediction (variance) (right side). Year 2001 (top), and year 2002 (bottom).

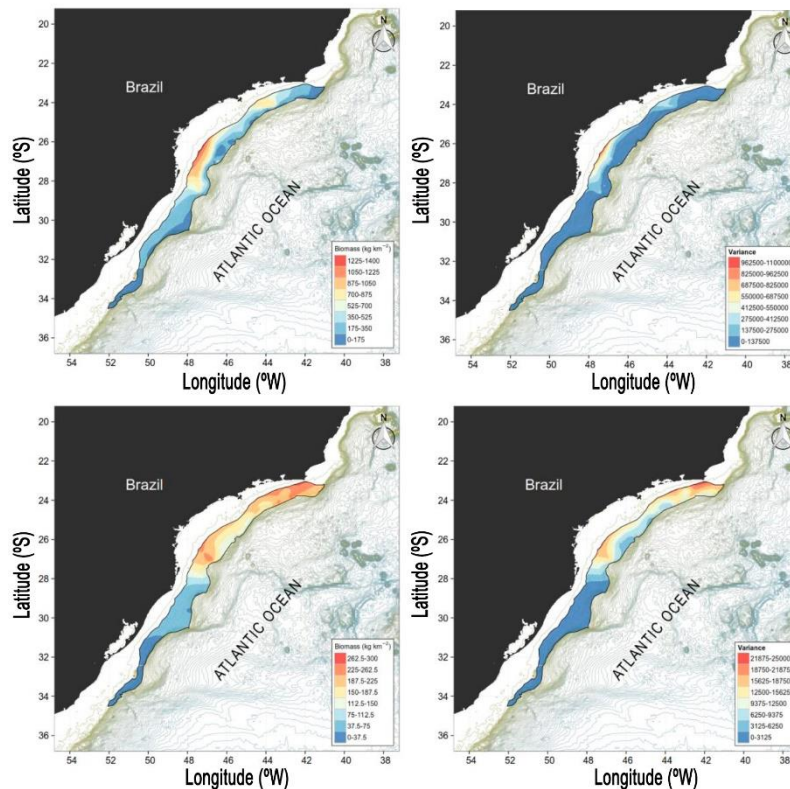


Figure 10. Monkfish, *Lophius gastrophysus*, spatial distributions of the densities (kg km^{-2}) predicted for the study area (left side), and respective uncertainties of the prediction (variance) (right side). Year 2001 (top), and year 2002 (bottom).

Table 7. Comparison between the biomass estimation of the species assessed in this study (Bstudy), the estimated values in the coverage of the REVIZEE (Brevizee) (Haimovici *et al.*, 2009) and others abundance estimations (Bother) held for these species in the Southeast portion of the Atlantic Ocean (in ton). Also, the respective REVIZEE and this study estimated harvesting rates (Erevizee, Estudy) based in each of the specie's landed catch, and the Maximum Sustainable Yield (Erms) for each resource. ¹Harvesting rate in relation to the Maximum Sustainable Yield (MSY) sourced from Perez (2006). ²Annual average capture of *Urophycis mystacea* estimated for the period of 2000 and 2003 sourced from Anon (2005). ³Biomass for the Argentine-Uruguay portion of the *Merluccius hubbsi* stock, estimated by Bezzi & Ibañez (2009). ⁴Total capture for hake according to Anon (2005). ⁵Biomass and total capture of *Lophius gastrophysus* sourced from Perez *et al.* (2005). ⁶Total capture of monkfish sourced from IBAMA (2004).

Species	Year	B _{REVIZEE}	B _{OTHER}	B _{STUDY}	Catches	E _{REVIZEE}	E _{STUDY}	E _{RMS} ¹
Codling	2001	8,583	-	16,402	4,000 ²	0.46	0.24	0.095
	2002	11,204	-	23,816		0.32	0.17	
Hake	2001	14,455	150,001 ³	267,712	2,600 ⁴	0.13	0.01	0.10
	2002	16,078	-	233,107	4,500 ⁴	0.21	0.02	
Monkfish	2001	15,994	62,776 ⁵	51,947	10,000 ⁵	0.63	0.19	0.06
	2002	10,971	-	16,998	5,142 ⁶	0.44	0.31	

estimates obtained by independent and conceptually different methods (Gunderson, 1993). In that sense, the present results confirm that catch rate data originated from commercial trawlers, if adequately modelled by geostatistical concepts, can produce robust biomass estimates of non-target slope species such as codling

and probably monkfish, but not of highly targeted ones such as hake. In that sense we can partially accept the overarching hypothesis that commercial trawl fishing operations can be a reliable source of information for biomass assessments, provided that, as adverted by Sant'Ana (2013), these operations include a certain

amount of data obtained outside the main (high density) fishing areas. It further suggests that observed operations of 'generalist slope trawlers' (as defined by Dias & Perez, 2016) could provide more informative data for biomass assessments than 'specialized' trawlers, but even these could contribute to assessments if collaborative trawls outside main fishing areas could be included in their regular fishing trips.

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