Ocean and Coastal Research

ORIGINAL ARTICLES

http://doi.org/10.1590/2675-2824071.20019adfl
ISSN 2675-2824

Spatio-temporal distribution of the swordfish *Xiphias gladius* (Linnaeus, 1758) caught by the Brazilian longline fleet.

Antônia Duciene Feitosa Lima[1], Humberto Gomes Hazin[1, 2], Guelson Batista da Silva[1, 2], Marcelo Augusto Bezerra[2]

[1] Universidade Federal Rural do Semi-Árido, Pós-Graduação em Ecologia e Conservação. (Av. Francisco Mota, 572 Costa e Silva. 59625-900 - Mossoró, RN – Brazil)
[2] Universidade Federal Rural do Semi-Árido, DCAN-Departamento de Ciências Animais.
(Av. Francisco Mota, 572 Costa e Silva. 59625-900 - Mossoró, RN – Brazil)

* Corresponding author: duci_lima78@hotmail.com

ABSTRACT

Studies relating the populational structure of target species to operational and environmental variables contribute directly to the management of the fisheries in these resources. Therefore, this study aimed to provide data on fishing and ecology of the swordfish (*Xiphias gladius*) caught by the Brazilian longline fleet operating in the western Atlantic between 2010 and 2016. Generalized additive mixed models were used to evaluate the relationship between explanatory variables and responses based on Catch Per Unit of Effort (CPUE) data. Results show that the Brazilian longline fleet catches the swordfish mostly between latitudes of 5°N to 30°S and longitudes of 20° to 50°W and that the swordfish prefers temperatures under 25°C at depths below 60 meters. The species showed a tendency toward intermediate light intensity, predominating in the crescent moon phase, and a preference for areas with low chlorophyll concentrations. Our findings on operational and environmental interactions with swordfish CPUE suggest areas and times that can be used by fishing fleets and government institutions as a starting point for swordfish management strategies.

Descriptors: Industrial fishing, Generalized additive mixed models, Migration pattern, Pelagic fisheries, South atlantic.

INTRODUCTION

Climatic conditions and environmental factors of habitats determine the distribution and diversity of species. Thus, knowledge on distribution patterns and diversity measures help establish goals for the management of natural resources, which are directly associated with the health and good functioning of the ecosystem (Ricklefs, 2011).

Submitted: 08/11/2020
Approved: 17/01/2023

Associate Editor: Margit Wilhelm

Researchers such as Bigelow et al. (1999), Maury et al. (2001), and Zagaglia et al. (2004a) conducted studies relating the distribution of pelagic fish species to environmental variables. Bach et al. (2003) investigated *Thunnus obesus*, analyzing depth distribution using two different observation techniques and different environmental variables. The swordfish is one of the most studied pelagic species, which lives as solitary specimens that rarely form schools (Guitart-Manday, 1964) and migrate long distances. Swordfish distribution and abundance have been studied in the Atlantic, Pacific, and Indian Oceans (Hazin, 2006). The management regulations for swordfish were established in the Atlantic Ocean since 1991 by the International Commission for the Conservation of Atlantic Tunas (ICCAT) (Coelho and Muñoz-Lechuga, 2019).

New technologies have been used to improve studies on pelagic fish species (Molina et al., 2004; Cosgrove et al., 2006), producing more detailed information on diversity, horizontal and vertical movements, occupation of the pelagic oceanic habitat, as well as physiological and behavioral aspects of thermoregulation (Dagorn et al., 2000, 2006; Itoh and Tsuji, 2003). Following this line of research, studies have been performed recently to determine the relationship between environmental variables and the distribution of large pelagic fish (Bigelow et al., 1999; Maury et al., 2001; Zagaglia et al., 2004a). Non-linear models including generalized additive models (GAMs) and general linear models (GLMs) combined with geographic information systems (GIS) can help establishing the influence of environmental variables on catch data. These methods have significant potential for use in the conservation of species affected by fishing, such as spatial conservation strategies (e.g., temporary closure of fishing areas) (Zheng, 2002; Hazin, 2006; Hazin and Erzini, 2008).

Although several studies have demonstrated the benefits of spatial management for the conservation of coastal fish stocks (Prates et al., 2012; Castrejón and Charles, 2013), studies using this approach on oceanic ecosystems are scarce, probably due to the greater distance from the coast and the spatial and temporal complexity of this ecosystem (Hyrenbach et al., 2000). Therefore, this study aimed to identify the environmental variables related to spatial and temporal distribution of *X. gladius* targeted by the Brazilian longline fleet operating in the western Atlantic Ocean.

METHODS

Data on launch site, fishing area, effort, and catch were obtained from the logbooks of the Brazilian longline fleet operating in the western Atlantic at latitudes of 05°N to 30°S and longitudes of 20° to 50° W, from 2010 to 2016, targeting the swordfish, yellowfin tuna (*Thunnus albacares*), and bigeye tuna (*Thunnus obesus*). Catch per unit of effort (CPUE) was established as a relative abundance index in number of individuals caught per 1,000 hooks.

The following data on oceanographic variables were obtained by satellite sensors from time series stored in databases available online: (i) Sea surface temperature (SST) and depth of the mixing layer (DML) were obtained from the Physical Oceanography Distributed Active Archive Center of the Jet Propulsion Laboratory of the U.S. National Aeronautics and Space Administration (NASA), the Geophysical Fluid Dynamics Laboratory (ocean data from the IRI/ARCS/Ocean assimilation), and Centre ERS d'Archivage et de Traitement (CERSAT/IFREMER); (ii) images from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) of the NASA's Goddard Space Flight Center provided information on chlorophyll concentration (CHO), which was converted into numerical data that were aggregated from an original resolution of 0.5° × 0.5° to a resolution of 1° × 1° to form an oceanographic database (full data) per day, year, month, latitude (5°N-30°S), and longitude (20°-50°W) and then incorporated into the fishing database; (iii) the lunar illumination index (LI) was extracted from the R LUNAR package (Lazaridis, 2022).

Since commercial fishing activities occur in a pre-defined space and time based on the target species, which eliminates the data independence (randomly collected) (Augustin et al., 2013), generalized additive mixed models (GAMMs) were used to analyze associations between environmental factors related to catches and the abundance (CPUE) of swordfish. Two types of variables can be considered in GAMMs: random effects and fixed effects. Random effects usually include observational blocks or studies that are replicated in space or time; however, they can also encompass variations among individuals, species, and regions. Defining a fixed or random effect can be conceptual. In this study, vessels were used as random variables, since the conceptual variability in swordfish catch rates among vessels depends on the intrinsic characteristics of each fishing fleet, skipper, and crew, whereas other explanatory variables were considered fixed effects.

To choose the covariates used in the final model, the double penalty approach proposed by Marra and Wood (2011) was applied. According to this approach, all covariates with a tendency towards zero, that is, their final smoothing function is a line of zero value, must be removed from the final model. In a double penalty approach, Marra and Wood (2011) decompose the quadratic smoothing spline penalty for GAMs into two terms: the null space, e.g. linear functions, and the penalty range space, e.g. cubic spline deviations from linear functions; shrinking both of them to zero (i.e., if the smoother does not improve the model fit). The restricted maximum likelihood (ReML) method was used to estimate the smoothing functions. Three models were developed, in which different configurations were tested with and without a space-time structure. The final Equation of the GAMM used was expressed as follows:

Models with space-time structure:

$$\mu icatch = f1(Latitude, Longitude, Year) + f1(Latitude, Longitude, Month) + f2(SST) + f3(CHO) + f4(IL) + f5(DML) + \upsilon k(i) + offset(log(effort)),$$

Models with space structure:

$$\mu icatch = f3(Latitude, Longitude) + f6(SST) + f7(Month) + f8(CHO) + f9(IL) + f9(DML) + Year(i) + \upsilon k(i) + offset(log(effort)),$$

Models without space-time structure:

$$\mu icatch = f10(Latitude) + f11(Longitude) + f12(SST) + f13(Month) + f14(CHO) + f15(IL) + f16(DML) + Year(i) + \upsilon k(i) + offset(log(effort))$$

where μi = E (yi) and yi is part of a Tweedie distribution (Tweedie, 1984; Dunn and Smyth, 2005) with $\varnothing\mu^{i^P}$ variance. The Tweedie distribution was chosen due to its ability to handle continuous data with many zeros (45.5%) (Tweedie, 1984). The year variable in both models represents the year factor in i^{th}, f2 to f16 smoothing functions of the covariates latitude, longitude, month, sea surface temperature (SST), depth of the mixing layer (DLM), chlorophyll (CHO), and lunar illumination index (LI). υk(i) is the effect of the random fleet variable. The 3D smoothing tensor is expressed by f1, in which space (latitude and longitude) was modeled with an isotropic smoother (soap films and thin plate regression splines) and time (month and year) was modeled with a cubic regression spline smoother (Wood, 2008). The power parameter analyzed in this distribution, which displays the maximization of likelihood, was estimated at 1.34, indicating a composition between Poisson and Gamma distributions.

The accuracy of the model was assessed using n-fold cross-validation, in which (1) all data were randomly divided into subsets and (2) the predicted values were estimated while concealing observed values for each subset. The correlation coefficient between the observed values and corresponding predicted values was then used for the cross-validation of the candidate model. For the selection of the final model, it was adjusted to a basis different from the mean forecast error (SRAFE), which is essential to select the best performing model among the forecast models in each data. SRAFE was estimated as follows:

$$\text{SRAFE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f_i - o_i)^2}$$

where f_i is the predicted value; o_i is the observed or actual value; and *n* is the total sample size. The smallest SRAFE value indicates the smallest prediction error and thus the best model.

RESULTS

Effort distribution and Model selection

According to the effort data, the swordfish fishery is distributed throughout the western Atlantic between latitudes of 10°N and 40°S, in two main areas: (i) one in tropical waters, close to the Northeast region of Brazil and (ii) the other in temperate waters near the South and Southeast regions of Brazil (Figure 1).

The lowest square root of the average forecast error (SRAFE = 1.69) was found using the model with space-time structuring (Table 1), explaining 49% of the final variation in the model. All variables in the model were significant (F test, $p<0.05$). In order of importance and explanation in the variation of CPUE, “longitude, latitude, year” interaction explained 50% of the total variation in the final model, sea surface temperature explained 38%, and the other variables together added 12%.

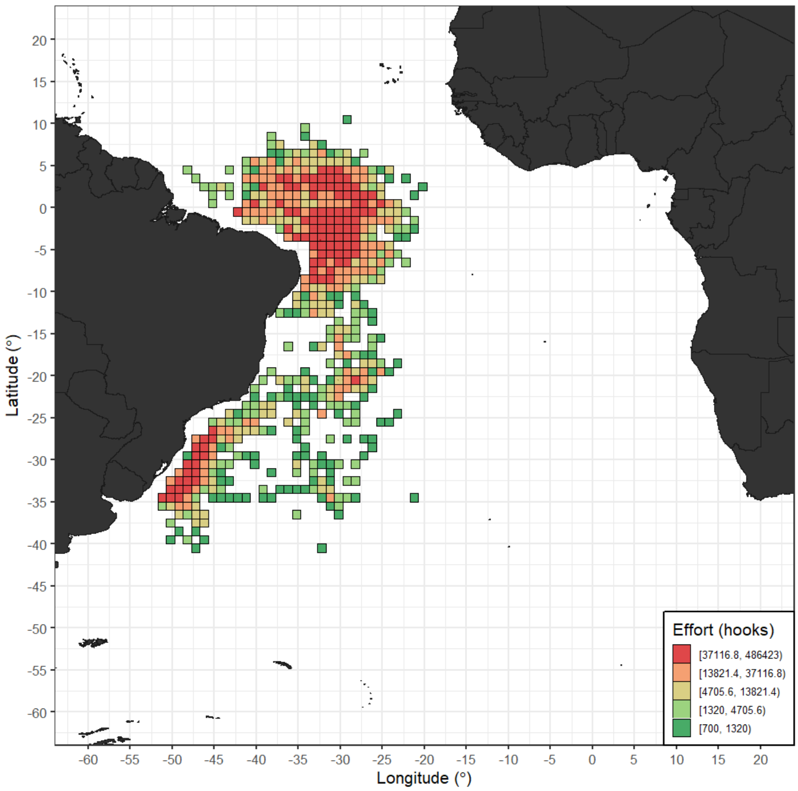

Figure 1. Spatial distribution of the fishing effort carried out by the Brazilian longline fleet from 2010 to 2016.

Table 1. Results of models used to analyze relationship between environmental factors and swordfish catches (CPUE) in the western Atlantic from the period of 2010 to 2016. DE = deviance explained; SRAFE = square root of average forecast error; Border = soap film smoothers.

Structure	Model	DE (%)	SRAFE	Border
Space-time	$f_1(Latitude,Longitude,Year)+f_1(Latitude,Longitude,Mouth)+f_2(SST)+f_3(CHO)+f_4(IL)+f_5(DML)+\upsilon_{k(i)}+offset(log(effort))$	49	1.69	yes
	$f_1(Latitude,Longitude,Year)+f_1(Latitude,Longitude,Mouth)+f_2(SST)+f_3(CHO)+f_4(IL)+f_5(DML)+\upsilon_{k(i)}+offset(log(effort))$	43	1.87	no
Space	$f_3(Latitude,Longitude)+f_6(SST)+f_7(Mouth)+f_8(CHO)+f_9(IL)+f_9(DML)+Year_{(i)}+\upsilon_{k(i)}+offset(log(effort))$	33	3.5	yes
	$f_3(Latitude,Longitude)+f_6(SST)+f_7(Mouth)+f_8(CHO)+f_9(IL)+f_9(DML)+Year_{(i)}+\upsilon_{k(i)}+offset(log(effort))$	27	3.78	no
Without space time structuring	$f_{10}(Latitude)+f_{11}(Longitude)+f_{12}(SST)+f_{13}(Mouths)+f_{14}(CHO)+f_{15}(IL)+f_{16}(DML)+Year_{(i)}+\upsilon_{k(i)}+offset(log(effort))$	32	3.89	yes
	$f_{10}(Latitude)+f_{11}(Longitude)+f_{12}(SST)+f_{13}(Mouth)+f_{14}(CHO)+f_{15}(IL)+f_{16}(DML)+Year_{(i)}+\upsilon_{k(i)}+offset(log(effort))$	24	4.4	no

The analysis of the residuals of the Tweedie model revealed that the values were distributed evenly and mainly around zero, indicating no bias in the adjusted model. However, we found small differences between residual quantiles and normalized residual quantiles, with extreme values appearing only at the positive end (Figure 2), indicating that the assumptions made for the distribution of the response variable (error) and link function were acceptable.

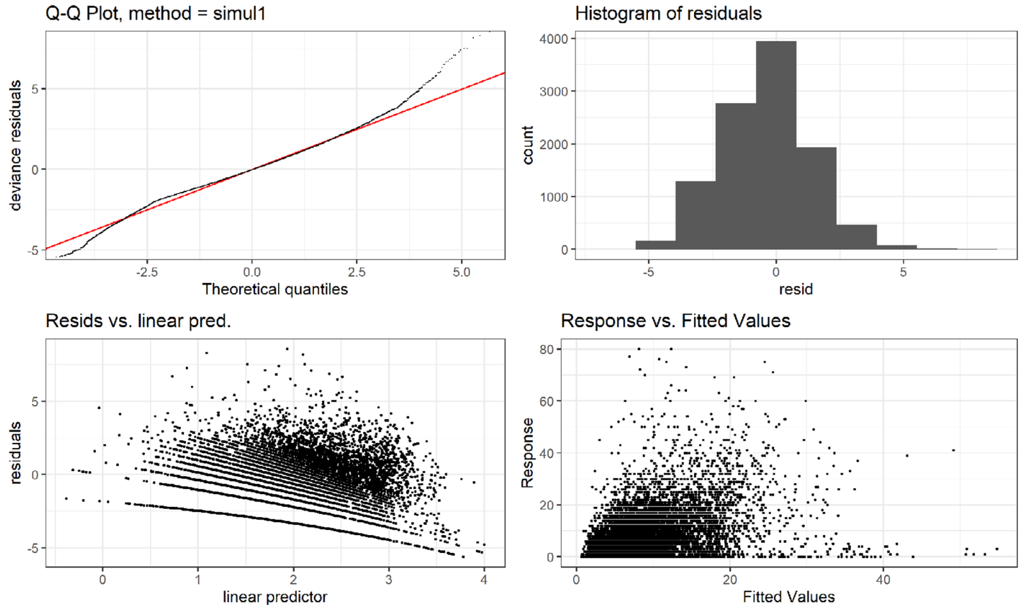

Figure 2. Distribution of residues and QQ plot of final model adjusted to CPUE data of swordfish caught by Brazilian longline fleet in the western Atlantic Ocean using Tweedie distribution.

Effects of operational and environmental variables on CPUE

The analysis of the effect of the sea surface temperature on the swordfish CPUE revealed a significantly negative trend at higher temperatures, with the highest CPUE values between 17° and 22°C, which later decreased (Figure 3-A). Higher CPUE occurred at low chlorophyll concentrations (between 0.1 and 0.5 mg m^{-3}) (Figure 3-B).

The analysis of LI effect on the swordfish CPUE revealed an increasing trend up to approximately 0.8 (80%), decreasing gradually with the approach of the full moon (1.0 or 100%) (Figure 4-A). The depth of the mixing layer (DML) affected the swordfish CPUE, which showed better responses at depths below 60 m, revealing an effect with positive oscillations down to approximately 40 m, where the effect tended to become positive, followed by a negative effect around 60 m (Figure 4-B).

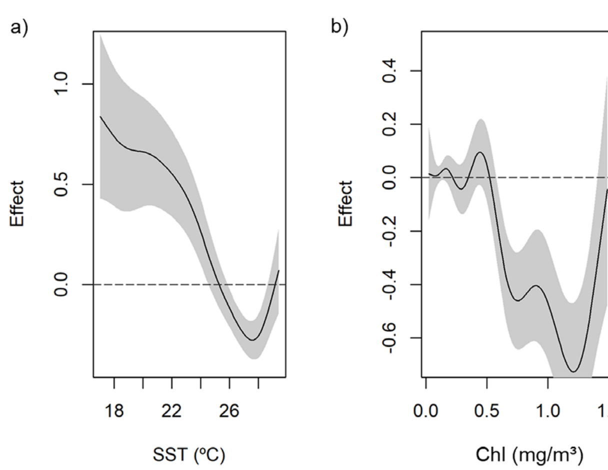

Figure 3. Effects of sea surface temperature (SST) (a) and chlorophyll (CHO) (b) on CPUE of swordfish caught by Brazilian longline fleet in the western Atlantic from 2010 to 2016.

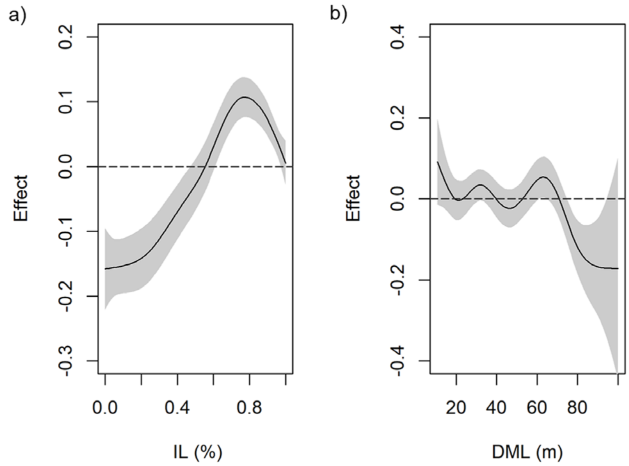

Figure 4. Effects of lunar illumination index (IL) (a) and depth of mixing layer (DML) (b) on CPUE of swordfish caught by Brazilian longline fleet in the western Atlantic from 2010 to 2016.

Effects of temporal and spatial variables on swordfish CPUE

Regarding general distribution, the swordfish had four areas of greater longline CPUE: (1) in the equatorial region at 5°N-0N/30°W-40°W; (2) at 5°N-0N/20°W-25°W; (3) in the Southeast farthest from the coast at 10°S-20°S/25°W-20°W; (4) in the South close to the Brazilian coast at 20°S-30°S/45°W-55°W. However, space-time persistence was observed only in the Areas 1, 2, and 3, except for 2014, 2015, and 2016 (Figure 5).

The effect of the interaction between latitude and longitude on the swordfish CPUE analyzed by month was greater in Areas 2, 3, and 4 in the first months of the year. From the third month onwards, the effect was weak in Areas 3 and 4. The effect gradually increased over months 3 to 12 in Areas 1 and 2. The effect gradually increased in Areas 3 and 4 between months 8 and 9. From the 10th month onwards, the effect decreased in Area 4 and increased in Areas 3, 2, and 1, mainly in the former two (Figure 6).

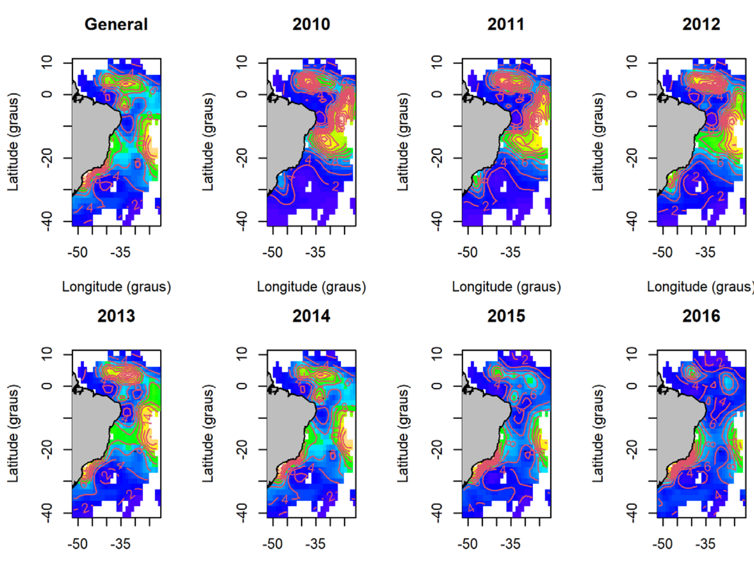

Figure 5. Spatial prediction of the annual CPUE of swordfish caught by Brazilian longline fleet in the western Atlantic from 2010 to 2016.

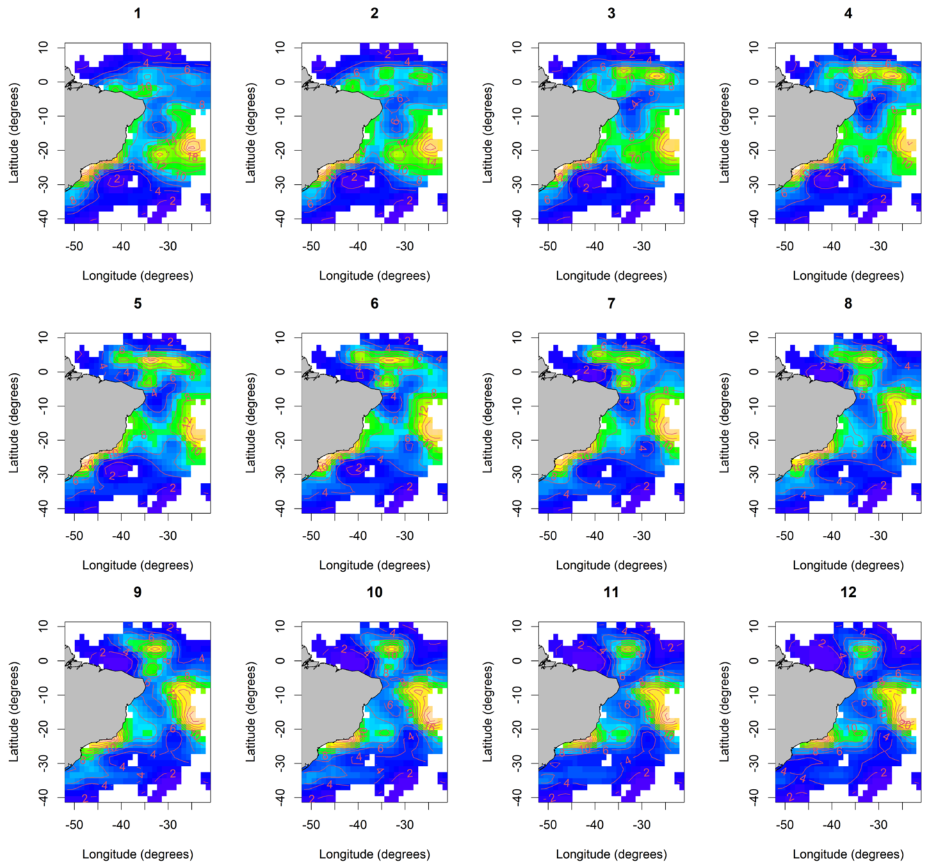

Figure 6. Spatial prediction of the monthly CPUE of swordfish caught by Brazilian longline fleet in the western Atlantic from 2010 to 2016.

DISCUSSION

Identifying significant associations between catches of pelagic species and environmental conditions is essential to interpret the CPUE of highly migratory species (Schick et al., 1994), as the fishing strategies and performance of longline fleets are influenced by the availability and gear vulnerability of fishing resources, which are related to the environment where the target species occur (Ricker, 1975). The CPUE undergoes variations due mainly to the selectivity of the fishing gear, as well as the availability and accessibility of the target species (Swain and Sinclair, 1994; Vignaux, 1996). Such factors vary according to technical/operational characteristics and environmental variables (Brill et al., 1998; Hazin, 2006). Therefore, in models with space-time structuring, it is essential not to assume that catches in geographically neighboring areas are similar due to the intrinsic characteristics of the environment (e.g., upwelling) (Augustin et al., 2013). This concern is especially essential when the analysis aims to assess spatiotemporal interactions.

Models without the specification of boundary limits are inadequate for imposing smoothness across fishing areas and may lead to incorrect conclusions (Wood, 2008). When supposing a rapid change in density, models attempt to accommodate this by increasing the flexibility of space-time smoothers and consequently the probability of the existence of a space-time interaction outside the limits of the fishing area, even if this change is not present. On the other hand, if the model incorrectly interprets the sudden change in random variability, the result will be over-smoothing and, consequently, the probability of detecting an interaction will decrease, even when it is present. Thus, the soap film smoother was used in this study on the interaction to avoid smoothing the limits of these boundaries.

SRAFE analysis revealed that the models performed better with soap film smoothers, which corroborates the results obtained by Augustin et al. (2013). Soap film smoothers have a clear advantage of avoiding the imposition of spatially corresponding areas in the case of the dependent variables used in this model. However, since the results may have limitations of established boundaries, they must be carefully interpreted (Wood, 2008; Augustin et al., 2013).

The swordfish seemed to have a well-defined seasonal CPUE pattern, migrating to warmer waters from Equatorial regions from March to May and to colder waters southward along the Brazilian coast from August to October. These results corroborate previous studies reporting a greater abundance of swordfish in the Southeastern and Southern regions at the end of the second quarter and in the third quarter of the year (Amorim, 1976; Hazin et al., 2001). This would also explain the reduction in catch rates in the southern part of the area between August and October. This hypothesis is supported by the observation of a greater frequency of large specimens from the catches in the Southeastern and Southern regions of the country in the third quarter of the year (Amorim and Arfelli, 1988; Hazin et al., 2002) when the 20° and 25°C isotherms are more displaced to the south (Hazin, 1994), which is within the range considered optimal for the species according to this study.

This southward migration between August and October may be related to food availability, given the increase in squid abundance in the Southeastern and Southern regions during this time of the year (Zavala-Camin, 1982, 1987; Haimovici et al., 2014), as squid is one of the main food items for swordfish (Zavala-Camin, 1982; Vaske Júnior and Lessa, 2005). Regarding reproduction in the southwestern portion of the equatorial region, Hazin et al. (Hazin et al., 2001) analyzed swordfish ovaries, and concluded that the region studied is not for breeding, but for maturing and subsequent spawning.

The swordfish CPUE had a tendency toward an intermediate light intensity, measured as lunar illumination index, occurring in the crescent moon phase. This may be explained by the swordfish being a nocturnal predator with a circadian rhythm (Carey and Robison, 1981). Other authors have also identified the swordfish preference for the crescent moon phase (Gaertner et al., 2001; Hazin, 2006). Furthermore, Hazin (Hazin, 2006) identified differences between moon phases and the depth of the top of the thermocline, indicating that the slightest change in light intensity can affect swordfish vertical distribution. Santos and Garcia (2005) also found that swordfish size in the Atlantic is influenced by moon phase. The moon phases influence not only swordfish fishing, but also other species such as yellowfin tuna (*Thunnus albacares*), which is caught more extensively during more illuminated phases, with catches of larger individuals during the full moon (Lira, 2016).

The swordfish was associated with depths shallower than 60 m, with an increasing trend below 20 m. This finding directly affects the choice of fishing equipment, supporting the use of a surface longline, since the pelagic longline is for depths from 45 to 80 m (Azevedo, 2003). Poisson et al. (2001) and Poisson and Guyomard (2001) found that juvenile swordfish showed distinct movement compared to adults in the Indian Ocean, occurring mainly in the depths between 20 and 60 m. Collette (1995) also found that adult swordfish are mainly present over the slope from 200 to 800 m depth only in oceanic environment.

Although chlorophyll was negatively correlated with the swordfish CPUE, other variables tested were more significant. Zagaglia et al. (2004a) also reported an inverse association between the abundance of this species and chlorophyll concentration, with the highest yields close to 0.12 mg m^{-3}.

CONCLUSION

This study provides insight into some essential environmental features that have driven swordfish distribution in the Atlantic Ocean and the associated variability in fishery catch rates. Swordfish fishery presents a well-defined spatial-seasonal pattern, migrating from warmer waters in the equatorial region between March and May to colder waters in the south along the Brazilian coast between August and October. Furthermore, the results showed four hotspots, which enables to minimize the costs of fishing operations and increase the catches of target species, redirecting the fleet to these areas while reducing the accidental capture of other species, avoiding an ecological impact of fishing. Regarding habitat, swordfish prefer colder waters with a low concentration of chlorophyll. Knowledge about the distribution of this species reduces uncertainties, which can facilitate the assessment, management, and monitoring strategies of stocks aimed at swordfish fisheries in the western Atlantic.

ACKNOWLEDGMENTS

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for awarding a study grant (A. D. F. L Process: 88882.455841/2019-01)

AUTHOR CONTRIBUTIONS

A. D. F. L.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing.

H. G. H.: Conceptualization; Investigation; Methodology; Visualization; Supervision; Writing – original draft; Writing – review & editing.

G. B. S.: Visualization; Supervision; Writing – original draft; Writing – review & editing.

M. A. B.: Visualization; Writing – review & editing.

REFERENCES

Amorim, A. F. 1976. O que teria acontecido às pescarias de atuns?. a pesca do atum no Sudeste e Sul do Brasil. *Pesca Em Revista*, (7), 18–25.

Amorim, A. F. & Arfelli, C. A. 1988. Description of the Brazilian swordfish fishery in Santos. *Collective Volume of Scientific Papers ICCAT*, *27*(1), 315–317.

Augustin, N., Trenkel, V., Wood, S. & Lorance, P. 2013. Space-time modelling of blue ling for fisheries stock management. *Environmetrics (London, Ont.)*, *24*(2), 109–119. DOI: https://doi.org/10.1002/env.2196

Azevedo, V. G. 2003. *Aspectos biológicos e dinâmica das capturas do tubarão-azul (*Prionace glauca*) realizadas pela frota espinheleira de Itajaí - SC, Brasil* (Dissertação de Mestrado). Universidade de São Paulo, São Paulo, 160 pp. https://doi.org/10.11606/d.21.2003.tde-13082004-111652

Bach, P., Dagorn, L., Bertrand, A., Josse, E. & Misselis, C. 2003. Acoustic telemetry versus monitored longline fishing for studying the vertical distribution of pelagic fish. Bigeye tuna (*Thunnus obesus*) in French Polynesia. *Fisheries Research*, *60*(2), 281–292. DOI: https://doi.org/10.1016/s0165-7836(02)00180-7

Bigelow, K. A., Boggs, C. H. & He, X. 1999. Environmental effects on swordfish and blue shark catch rates in the US North Pacific longline fishery. *Fisheries Oceanography*, *8*(3), 178–198. DOI: https://doi.org/10.1046/j.1365-2419.1999.00105.x

Brill, R. W., Lowe, T. E. & Cousins, K. L. 1998. How water temperature really limits the vertical movements of tunas and billfishes. It's the Heart Stupid. *International congress on biology of fish*. Baltimore, MD.

Carey, F. & Robison, B. 1981. Daily patterns in the activities of swordfish, *Xiphias gladius*, observed by acoustic telemetry. *Fishery Bulletin*, *79*, 277–292.

Castrejón, M. & Charles, A. 2013. Improving fisheries co-management through ecosystem-based spatial management. The Galapagos Marine Reserve. *Marine Policy*, *38*, 235–245. DOI: https://doi.org/10.1016/j.marpol.2012.05.040

Coelho, R. & Muñoz-Lechuga, R. 2019. Hooking mortality of swordfish in pelagic longlines. Comments on the efficiency of minimum retention sizes. *Reviews in Fish Biology and Fisheries*, *29*, 453–463. DOI: https://doi.org/10.1007/s11160-018-9543-0

Collette, B. 1995. *Xiphiidae*. Peces espada. *Guia FAO para identificación de especies para los fines de la pesca* (Vol. 3, pp. 1651–1652). Roma: FAO.

Cosgrove, R., Arregi, I. & Arrizabalaga, H. 2006. Archival tagging of albacore tuna (*Thunnus alalunga*) in the North Atlantic. A pilot study. *Collective Volume of Scientific Papers ICCAT*, *59*(3), 923–927.

Dagorn, L., Holland, K., Hallier, J.-P., Taquet, M., Moreno, G., Sancho, G., Itano, D., Aumeeruddy, R., Girard, C., Million, J. & Fonteneau, A. 2006. Deep diving behavior observed in yellowfin tuna (*Thunnus albacares*). *Aquatic Living Resources*, *19*(1), 85–88. DOI: https://doi.org/10.1051/alr:2006008

Dagorn, L., Josse, E. & Bach, P. 2000. Individual differences in horizontal movements of yellowfin tuna (*Thunnus albacares*) in nearshore areas in French Polynesia, determined using ultrasonic telemetry. *Aquatic Living Resources*, *13*(4), 193–202. DOI: https://doi.org/10.1016/s0990-7440(00)01063-9

Dunn, P. & Smyth, G. 2005. Series evaluation of Tweedie exponential dispersion model densities. *Statistics and Computing*, *15*(4), 267–280. DOI: https://doi.org/10.1007/s11222-005-4070-y

Gaertner, J., Poisson, F. & Taquet, M. 2001. Analyse des interactions entre les captures de grands pélagiques de la flottille palangrière réunionnaise et les conditions de pêche (caractéristiques techniques, environnement). *L'espadon: de la recherche à l'exploitation durable* (pp. 106–127). Paris: Ifremer. Accessed: https://archimer.ifremer.fr/doc/2001/rapport-6427.pdf#page=63

Guitart-Manday, G. 1964. Biología pesquera del emperador o pez de espada, *Xiphias gladius* Linnaeus (Teleostomi: *Xiphiidae*) en las aguas de cuba. *Poeyana*, *1*, 3–37.

Haimovici, M., Santos, R., Bainy, M., Fischer, L. & Cardoso, L. 2014. Abundance, distribution and population dynamics of the short fin squid *Illex argentinus* in Southeastern and Southern Brazil. *Fisheries Research*, *152*, 1–12. DOI: https://doi.org/10.1016/j.fishres.2013.09.007

Hazin, F. H. V. 1994. *Fisheries-oceanographical study on tunas, billfishes and sharks in the southwestern equatorial Atlantic ocean* (Tese de doutorado). 東京水産大学 (Universidade de Pesca de Tóquio), Tokyo, 217 pp. https://doi.org/10.11501/3076461

Hazin, F. H. V., Hazin, H. G., Boeckmann, C. & Travassos, P. 2001. La reproduction de l'espadon (*Xiphias gladius*) dans l'atlantique sud-ouest equatorial: la ponte et la fecondité. *Collective Volume of Scientific Papers ICCAT*, *52*(4), 1233–1240.

Hazin, H. G. 2006. *Influência das variáveis oceanográficas na dinâmica populacional e pesca do espadarte,* Xiphias gladius *Linnaeus 1758, capturados pela frota brasileira* (Tese de Doutorado). Universidade do Algarve, Faro, 202 pp.

Hazin, H. G. & Erzini, K. 2008. Assessing swordfish distribution in the South Atlantic from spatial predictions. *Fisheries Research*, *90*(1), 45–55. DOI: https://doi.org/10.1016/j.fishres.2007.09.010

Hazin, H. G., Vieira, F. H. & Travassos, P. 2002. Analyse de la distribution de frequence de taille des espadons (*Xiphias gladius*, Linnaeus 1758) capturés dans l'atlantique sud-ouest equatorial. *Collective Volume of Scientific Papers ICCAT*, *54*(5), 1579–1585.

Hyrenbach, K., Forney, K. & Dayton, P. 2000. Marine protected areas and ocean basin management. *Aquatic Conservation*, *10*(6), 437–458. DOI: https://doi.org/10.1002/1099-0755

Itoh, T. & Tsuji, S. 2003. Migration patterns of Young Pacific bluefin tuna (*Thunnus orientalis*) determined with archival tags. *Fishery Bulletin*, *101*(3), 514–534.

Lazaridis, E. 2022. lunar. Lunar Phase & Distance, Seasons and Other Environmental Factors. Available at: https://cran.r-project.org/package=lunar. Acessed: 20 October 2022.

Lira, M. G. 2016. Pesca de atuns e afins no Oceano Atlântico. interações oceanográficas, implicações socioeconômicas e tecnológicas. Natal: Universidade Federal do Rio Grande do Norte. Available at: https://repositorio.ufrn.br/bitstream/123456789/22112/1/MarceloGomesDeLira_DISSERT.pdf Acessed: 16 June 2019.

Marra, G. & Wood, S. 2011. Practical variable selection for Generalized Additive Models. *Computational Statistics & Data Analysis*, *55*(7), 2372–2387. DOI: https://doi.org/10.1016/j.csda.2011.02.004

Maury, O., Gascuel, D., Marsac, F., Fonteneau, A. & Rosa, A.-L. D. 2001. Hierarchical interpretation of nonlinear relationships linking yellowfin tuna (*Thunnus albacares*) distribution to the environment in the Atlantic Ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, *58*(3), 458–469. DOI: https://doi.org/10.1139/f00-261

Molina, A., Molina, R., Santana, J. & Ariz, J. 2004. Marcado de patudo em las islas Canarias dentro del betyp. *Collective Volume of Scientific Papers ICCAT*, *56*(2), 769–772.

Poisson, F., Bargain, R. M. & Taquet, M. 2001. Premiers essais de marquages d'espadon (*Xiphias gladius*) a l'aide de marques intelligentes archives de type 'pop up'. *IOTC proceedings* (pp. 245–254). Available at: https://archimer.ifremer.fr/doc/00129/24049/22013.pdf. Accessed: 25 February 2022.

Poisson, F. & Guyomard, D. 2001. Description de la technique et des stratégies de pêche de la flottille palangrière réunionnaise. *L'espadon* (pp. 61–78). Paris: Ifremer. Available at: https://archimer.ifremer.fr/doc/2001/rapport-6427.pdf#page=63. Accessed: 25 February 2022.

Prates, A. P. L., Gonçalves, M. A. & Rosa, M. R. 2012. *Panorama da conservação dos ecossistemas costeiros e marinhos no brasil* (2nd ed.). Brasília: MMA. Available at: https://www.terrabrasilis.org.br/ecotecadigital/images/abook/pdf/2016/15-PanoramadaConservao.pdf. Accessed: 11 June 2020.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada*, *191*, 1–382.

Ricklefs, R. 2011. *A economia da natureza* (6th ed.). Rio de Janeiro: Guanabara Koogan.

Santos, M. & Guarcia, A. 2005. The influence of the moon phase on the CPUEs for the Portuguese swordfish (*Xiphias gladius* L. 1758) fishery. *Collective Volume of Scientific Papers ICCAT*, *8*(4), 1466–1469.

Schick, R., Goldstein, J. & Lutcavage, M. 1994. Bluefin tuna (*Thunnus thynnus*) distribution in relation to sea surface temperature fronts in the Gulf of Maine (1994–96). *Fisheries Oceanography*, *13*(4), 225–238. DOI: https://doi.org/10.1111/j.1365-2419.2004.00290.x

Swain, D. & Sinclair, A. 1994. Fish distribution and catchability: What is the appropriate measure of distribution? *Canadian Journal of Fisheries and Aquatic Sciences*, *51*(5), 1046–1054. DOI: https://doi.org/10.1139/f94-104

Tweedie, M. 1984. An index which distinguishes between some important exponential families. Proceedings of the Indian Statistical Institute Golden Jubilee International Conference. *Statistics* (pp. 579–604). Calcutta: Indian Statistical Institute and Statistical Pub. Society.

Vaske Júnior, T. & Lessa, R. 2005. Estratégia alimentar do espadarte (*Xiphias gladius*) no Atlântico Equatorial Sudoeste. *Tropical Oceanography*, *33*(2), 219–227. DOI: https://doi.org/10.5914/tropocean.v33i2.5064

Vignaux, M. 1996. Analysis of spatial structure in fish distribution using commercial catch and effort data from the New Zealand hoki fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, *53*(5), 963–973. DOI: https://doi.org/10.1139/f96-035

Wood, S. N. 2008. Fast stable direct fitting and smoothness selection for generalized additive models. *Journal of the Royal Statistical Society*, *70*(3), 495–518. DOI: https://doi.org/10.1111/j.1467-9868.2007.00646.x

Zagaglia, C. R., Lorenzzetti, J. A. & Stech, J. L. 2004a. Remote sensing data and longline catches of yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic. *Remote Sensing of Environment*, *93*(1–2), 267–281. DOI: https://doi.org/10.1016/j.rse.2004.07.015

Zavala-Camin, L. 1982. Distribucion vertical y estacional de tunideos y otras espécies pelágicas en el suoeste y sur del Brasil, obtenida por médio de analysis de contenido estomacal. *Collective Volume of Scientific Papers ICCAT*, *17*, 439–443.

Zavala-Camin, L. A. 1987. Ocorrência de peixes, cefalópodos e crustáceos em estômagos de atuns e espécies afins, capturadas com espinhel no Brasil (23ºS-34ºS) 1972-1985. *Boletim Do Instituto de Pesca*, *14*, 93–102.

Zheng, X. 2002. Does the North Atlantic current affect spatial distribution of whiting? Testing environmental hypotheses using statistical and GIS techniques. *ICES Journal of Marine Science*, *59*(2), 239–253. DOI: https://doi.org/10.1006/jmsc.2001.1131