

Optimal setting time and season increase the target and reduce the incidental catch in longline fisheries: a Bayesian beta mixed regression approach

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Sustainable fisheries' managers increasingly seek to implement measures that reduce the mortality of threatened species while maintaining or increasing catch of target species. Our study proposed a simple management option for optimizing fishing over daily and seasonal scales to maximize catch success while protecting non-target species in pelagic longline fisheries. We used Bayesian beta mixed regression models to describe the effects of setting times and seasonality on catches in a pelagic longline fishery in the southwest South Atlantic Ocean (SWAO). Targeted species (swordfish, blue shark, and albacore tuna) are typically captured in fully nocturnal sets (started between 16 and 00 h), whereas shortfin mako shark and loggerhead turtles are typically captured during partially nocturnal sets (started between 00 and 04 h); probably a response to hook depth and circadian behaviours. The results suggest that it is feasible to use only fully nocturnal sets to target preferred species while reducing incidental catch of non-target species. The catch of target species was higher in austral winter, explained by the northward displacement of the subtropical convergence in the SWAO during this season. These results provide a baseline for bycatch mitigation strategies in pelagic longline fisheries at regional and global scales.

Keywords: bycatch, circadian rhythm, diel vertical migration, GLMMs, modelling, sustainable fishery.

Introduction

Pelagic longline fishing is common in all ocean basins worldwide, primarily targeting swordfish (*Xiphias gladius* Linnaeus, 1758; Xiphiidae) and tunas (*Thunnus* spp.; Kerstetter and Graves, 2006). These target species comprise a valuable portion of fishery resources landed around the globe, and the exploitation status of most stocks can be considered enduring, with biomass above the maximum sustainable yield (MSY; Collette *et al.*, 2011, 2021a, b, c, d). On regional scales, species such as blue shark (*Prionace glauca*; Linnaeus, 1758), Carcharhinidae, and escolar (*Lepidocybium flavobrunneum*; Smith, 1843; Gempylidae) are byproducts and can complement the profitability of these fisheries (Amorim *et al.*, 1998; Milessi and Defeo, 2002; FURG/SEMA, 2020).

Pelagic longline fishing practices result in negative bycatch interactions with sharks, sea turtles, seabirds, and marine mammals, which has emerged as an international priority (Hall *et al.*, 2000; Lewison *et al.*, 2004; Gilman *et al.*, 2008; Petersen *et al.*, 2009; Clarke *et al.*, 2014; Sacchi, 2021). The impacts of these bycatch interactions may include economic loss of fishing resources and equipment (Secchi and Vaske Jr, 1998; Dalla-Rosa and Secchi, 2007; Passadore *et al.*, 2015a; Richardson *et al.*, 2019), as well as ecological impacts given the increased mortality of k-strategy species, which are long-lived, show late sexual maturity, and have low reproductive rates (Lewison and Crowder, 2007; Bugoni *et al.*, 2008, 2009; Gallagher *et al.*, 2014; Passadore *et al.*, 2015b).

Interest in using mitigation measures to reduce this bycatch (also referred to as incidental catch) is increasing. Some mul-

tidisciplinary (Squires *et al.*, 2021) and necessary (Guerra, 2019) actions have been highlighted as good practices, as suggested by Gilman (2011) including: circular instead of J-shaped hooks to avoid capturing sea turtles and marine mammals (Reinhardt *et al.*, 2018), deep sets (> 100 m) for avoiding sea turtles and sharks (Gilman *et al.*, 2006), “tori lines” (Mancini *et al.*, 2009; Jiménez *et al.*, 2014), and line weighting for deterring seabirds (Santos *et al.*, 2019), among other methods as well (Gilman *et al.*, 2016). These actions often encounter resistance from the fishing industry and fishers due to alleged operational difficulties and high costs (Solís *et al.*, 2021). There are distinct levels of adherence to bycatch mitigation between fleets due to socio-political characteristics specific to each country. Alternatives that soften these implementation difficulties are continuously pursued (Løkkeborg and Pina, 1997; Carruthers *et al.*, 2011; Jordan *et al.*, 2013; Auger *et al.*, 2015; Bielli *et al.*, 2020). For this reason, ideal mitigating actions would alter fishing activities minimally, have low cost, and maintain the efficient catch of target species. These factors are especially critical in countries where fisheries management is precarious and inefficient. Optimal timing for fishing, both on a daily or seasonal scale, is one of these alternatives, as it may be considered an easy-to-apply rule for fishing fleets.

The behaviour of most species is driven by light and dark cycling of circadian rhythms, which make it the most predictable pattern in nature (Hammerschlag *et al.*, 2017; Bandara *et al.*, 2021). Species will be most active in periods that maximize their feeding for growth and development, breeding opportunities, and predator avoidance (Hammerschlag *et al.*,

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2017). In the marine environment, diel vertical migration is a widely known behavioural strategy. It allows herbivorous zooplankton to feed at night on abundant phytoplankton close to the surface with low risk of visual predation by zooplanktonic organisms, and, during the day, allows zooplankton to seek the safety of deeper water (Bandara *et al.*, 2021). This such a strategy by zooplankton provides a strong signal for species of higher trophic levels to follow them (Frederiksen *et al.*, 2006). Importantly, this general pattern of diel vertical migration is not identical among large pelagics such as swordfish, tuna, and sea turtles (Andrzejczek *et al.*, 2019; Madigan *et al.*, 2021). The occupied depth in relation to the thermocline (Madigan *et al.*, 2021), the presence and frequency of thermoregulatory migrations (Thygesen *et al.*, 2016), and other diel foraging patterns (Driggers *et al.*, 2012) are examples of discordant behaviours between pelagic species over daily, 24-h cycle.

Routinely longline fleet fishers conduct nocturnal sets to capture swordfish, and fish during day for yellowfin tuna (Gallagher *et al.*, 2014). However, in many countries the pelagic longline fishing is restricted by law to occur only during the night, specifically to reduce the incidental bycatch of seabirds (e.g. in Brazil; IN-MPA/MAPA, 2014). Despite the nocturnal exclusivity, the setting time (ST; start time for setting the longline) is quite variable and can start at any time between dusk and dawn of the following day. Therefore, given these characteristics of pelagic longline fishing and the different behaviours of diel vertical migration among species, it is plausible that the ST has the potential to directly influence the catch (Auger *et al.*, 2015).

Furthermore, environmental conditions such as low temperatures, nutrients, and upwellings drive the primary production levels and, in turn, their associated food web (e.g. 3rd and 4th order consumers; Perez *et al.*, 2015). Seasonal movements of oceanographic currents strongly alter the intensity and frequency of these conditions in medium latitudes such as the southwest South Atlantic Ocean (SWAO), becoming a determining factor for the local abundance of swordfish, tuna, sea turtles, and other species (Kot *et al.*, 2010). The SWAO is an important physical (Mendonça *et al.*, 2017), biogeochemical (Liutti *et al.*, 2021), feeding (Troina *et al.*, 2021), and fishery (Haimovici, 1997; Perez *et al.*, 2015) oceanographic region. It extends from latitude 22°S in Rio de Janeiro (Brazil) to 55°S in Tierra del Fuego (Argentina) with the sub-region between 29°S and 38°S, characterized by the seasonal confluence between the Brazil Current and the Falklands Current (Mendonça *et al.*, 2017). The Brazil Current transports warm ($T > 20^{\circ}\text{C}$) salt water southward, while the Falkland Current transports cold ($T: 4\text{--}15^{\circ}\text{C}$) nutrient-rich water northward over the continental slope and shelf (Franco *et al.*, 2017). During austral winter, the confluence ascends to the Brazilian coast, generates deep water upwelling events on the continental slope (Hubold, 1980a, b; García, 1997), increases nutrient availability, fertilizes the base of the trophic web (Niencheski and Fillmann, 1997; Braga *et al.*, 2008), and sustains significant fishery biomass (Haimovici, 1997) especially including individuals of swordfish and tuna that migrate to this region to feed.

Understanding when (at both daily and seasonal scales) each species is most likely to be caught by surface longline fisheries could provide a baseline for a fishery exhibiting maximum yield and minimum environmental impact. Thus, the aim of this research was to compare the catch of the main target

and bycatch species because of different STs and seasons in pelagic longline fisheries in the SWAO. We hypothesized that (1) the ST would directly influence the amount of catch; (2) sets with most of their catch time occurring at night (fully nocturnal) would capture with greater success target species than sets operating during periods of partial sunlight (partially nocturnal); and (3) the catch is larger during the austral fall and winter due to the oceanographic features that supply the region with nutrients. The verification of these hypotheses is essential to support mitigation strategies regarding the impacts of the surface longline fishery on a regional and global scale, and additionally has the potential to further elucidate species behaviour and seasonality.

Material and methods

Fleet and catch

The Brazilian surface longline is the main fleet exploring the northern portion of the SWAO, restricted to the limits of the Brazilian Exclusive Economic Zone (EEZ; Figure 1). It comprises approximately 38 vessels, of which 23 landed at the port of Rio Grande between 2017 and 2021, and are included in this study. These vessels vary in total length, engine power, storage capacity, and crew number. The main target species are swordfish, bigeye tuna (*Thunnus obesus*; Lowe, 1839; Scombridae), yellowfin tuna (*Thunnus albacares*; Bonnaterre, 1788; Scombridae), and albacore tuna (*Thunnus alalunga*; Bonnaterre, 1788; Scombridae). Blue shark and escolar (in summer months) supplement profitability as byproducts (FURG/SEMA, 2020). Shortfin mako shark (*Isurus oxyrinchus*; Rafinesque, 1810; Lamnidae) and loggerhead turtles (*Caretta caretta*; Linnaeus, 1758; Cheloniidae) are an important part of incidental catch, and are considered threatened and vulnerable by the IUCN Red List of Threatened Species, respectively (Casale and Tucker, 2017; Rigby *et al.*, 2019). There is a high rate of interaction between these species and longline fisheries (Lewison and Crowder, 2007).

Data acquisition and filtering

Logbooks were completed by the vessel captains within the scope of the Tubarão Azul Project (FURG/SEMA, 2020). In these logbooks, the vessel captain documented each fishing set with information such as the number of hooks, the type of hook, the type of bait, the geographic positions, the ST, and haul back time (HT) of the longline, as well as the numbers caught per species. For in three and a half years (2018–2021), this information was compiled into a single monitoring matrix, totalling, 2639 observations/sets and adding up to more than 100 000 animals reported among the aforementioned species (loggerhead turtle reported alive, passed out, or dead were combined). In 557 sets, essential information was either missing or explicitly wrong and were removed. Because certain information was not typically recorded by fishers, additional information by onboard scientific observers (OSO) was combined with the logbook data.

We classified each set according to two covariates: ST and season (Table 1). ST was categorized to facilitate its operationalization in possible public policy. Furthermore, we know that the ST is not the time over which resources will be captured. Based on studies by Wendling *et al.* (2003), Poisson *et al.* (2010), and Peterson *et al.* (2017), who used hook timers, we speculate that most of the effective catch takes place between

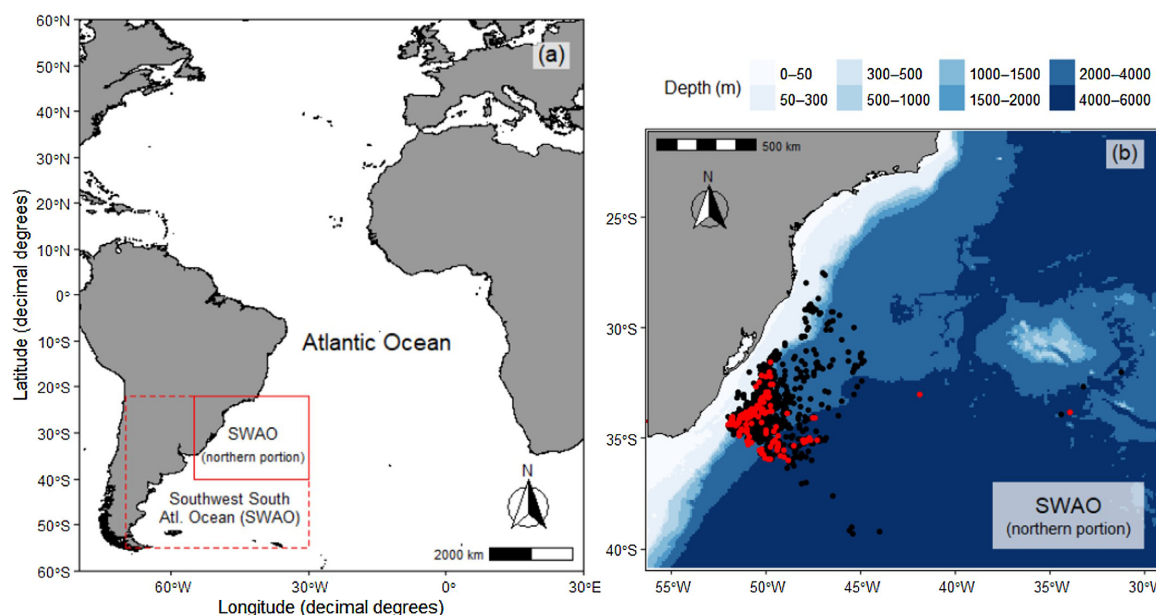


Figure 1. (a) Atlantic Ocean with emphasis on the SWAO and its northern portion; (b) northern portion of SWAO highlighting the initial positions of the sets (2082 reported by logbooks in black, 156 by onboard observers in red) between 2018 and 2021. The shades of blue indicate the bathymetry.

Table 1. Levels of fixed (and number of observations) and random variables of Bayesian beta mixed regression models.

Variable	Fixed					Random				
	Setting time (h) (6)	N	Season (4)	N	Year (4)	Vessel (22) †	Hook (7)	Bait (6)	Moon (4)	Trip (181)
Levels	16–18	748	Spring	322	2018	1	C13	Skipjack tuna	New	1
	20–22	931	Summer	473	2019	2	C14	Chub mackerel	Waxing	2
	22–00	182	Fall	657	2020	3	C15	Brazilian sardinella	Full	3
	00–02	37	Winter	630	2021	4	C16	Squid	Waning	4
	02–04	111				5	C18	Combined baits		5
	04–06	73				6	J	Others		6
						...	C13 + J			...

†Names purposely omitted.

1 and 5 h after the ST. Knowing this, we assumed that the first four ST intervals (16–18 h, 18–20 h, 20–22 h, and 22–00 h) possibly had a majority of the catch and were called fully nocturnal (17–23 h, 19–01 h, 21–03 h, and 23–05 h, respectively), while the last two levels of ST (00–02 h and 02–04 h) had most of the catch under partial incidence of sunlight, that is, partially nocturnal (01–07 h and 03–09 h, respectively). We highlight that the terms “fully (or, partially) nocturnal sets” refer to the possible larger captures occurring fully (or, partially) at night, which do not prevent unusual captures out of the expected period. The seasons were classified as austral spring (October, November, and December), summer (January, February, and March), fall (April, May, and June), and winter (July, August, and September).

In addition to the two covariates of interest, six random effects were considered: year of fishing (hereafter year), vessel, hook type (hereafter hook), bait type (hereafter bait), moon phase (hereafter moon), and trip. These variables are known to influence species catches (Poisson *et al.*, 2010; Campana *et al.*, 2011; Løkkeborg *et al.*, 2014; Gilman and Huang, 2017; Gilman *et al.*, 2020). It is noteworthy that although interesting, these variables were included as random effects to account for eventual overdispersion in the reported response variable, and not to make inferences. More details on the fixed and

random effects levels are given in Table 1. Each vessel fished with approximately the same total primary line length among the trips, so the effect of line length should be interpreted as having a similar randomness effect as that of the vessel. Additionally, we calculated the soak time as the difference between the ST and the HT. HT was not reported by logbooks, so we calculated its value as the ST plus the median difference between ST and HT reported by OSOs (9 h 09 min). We provide more details about fixed effects, random effects, and soak time in the next section.

Bayesian beta mixed regression models

In this study, the response variable of interest is the catch ratio (referred to hereinafter as catch), given by the number of hooks with a given species over the total number of hooks used in the set. A total of two main characteristics of this variable make it comparable to other abundance-like indices (e.g. CPUE) considering strengths/limitations: (1) each hook captures a single specimen by exclusion, and (2) the maximum catch (number of hooks with a caught specimen) per set never reaches the total number of hooks on the longline. Both requirements were met, the first due to the nature of the pelagic longline fishery and the second because the set with the

highest catch never exceeded 40% of the total number of hooks, gear saturation never occurred.

Generalized linear models containing exclusively fixed effects (GLM) or a mix of fixed and random effects (GLMM) require the response variable to be from the exponential family of distributions. The models explored in this paper, denoted by beta regression (Cibbari-Neto and Zeileis, 2010), use a beta distribution to describe the response variable that is restricted to the continuous range between 0 and 1. Although the beta distribution does not belong to the exponential family, it uses the same general structure as GLMs and GLMMs to model the effects of covariates on their mean. Furthermore, fitting these models within a Bayesian framework explains the classification as Bayesian beta mixed regression models (BMRM). Other probability distributions, such as Poisson and Negative Binomial distributions, are commonly used in surface long-line fisheries studies, based directly on the count of individuals (e.g. Orbesen *et al.*, 2017); however, we found better diagnostic qualities for the beta distribution.

A Bayesian decision analysis can combine data uncertainty (likelihood) with extra data information from experts or other sources (expressed as a prior distribution) and, finally, result in the construction of a posterior probability distribution *via* Bayes' Theorem, which contains all the information necessary for the inference (Korner-Nievergelt *et al.*, 2015). The exclusive use of posterior probability is based on the understanding that it is the only consistent metric for quantifying uncertainties (Kinas and Andrade, 2021). Additionally, incorporating random effects (year, vessel, hook, bait, moon, and trip), allows the fixed effects to vary among them, and thus part of the residual variance of the models is absorbed by them. Hence, fixed effects estimate slopes while variances are estimated by random effects. Soak time varied between 8.9 and 23.9 h, with median of 20.8 h (± 1.31 h *SD*). It was considered a measure of effort and used as an offset in the models after log transformation (Ward *et al.*, 2004). The model is described by the following components:

$$\begin{aligned} y_{[i]} &\sim \text{Beta}(\alpha_{[i]}, \beta_{[i]}), \\ \alpha_{[i]} &= \mu_{[i]} * \Phi, \\ \beta_{[i]} &= (1 - \mu_{[i]}) * \Phi, \end{aligned}$$

where $y_{[i]}$ is the catch ratio, $\alpha_{[i]}$ and $\beta_{[i]}$ are the parameters of the beta distribution at set i , $\mu_{[i]}$ is the mean of the catch ratio at set i , and Φ is a parameter of precision. A total of four nested models were proposed:

[non-informative prior]

- (i) $\text{logit}(\mu_{[i]}) = 1 + \text{offset}(\text{soaktime}_{[i]}) + \text{settingtime}_{[i]} + \text{season}_{[i]},$
- (ii) $\text{logit}(\mu_{[i]}) = 1 + \text{offset}(\text{soaktime}_{[i]}) + \text{settingtime}_{[i]} + \text{season}_{[i]} + \sum_{[j=1, \dots, 6]} \text{random effects}_{[i, j]},$

[informative prior]

- (iii) $\text{logit}(\mu_{[i]}) = 1 + \text{offset}(\text{soaktime}_{[i]}) + \text{settingtime}_{[i]} + \text{season}_{[i]},$
- (iv) $\text{logit}(\mu_{[i]}) = 1 + \text{offset}(\text{soaktime}_{[i]}) + \text{settingtime}_{[i]} + \text{season}_{[i]} + \sum_{[j=1, \dots, 6]} \text{random effects}_{[i, j]},$

where $\text{logit}(\mu_{[i]})$ is the link function, transformation needed for the catch ratio to cover all real values, $\text{offset}(\text{soaktime}_{[i]})$ is the necessary component to incorporate soak time as

effort at set i , $\text{settingtime}_{[i]}$ is the ST component at set i , $\text{season}_{[i]}$ is the season component at set i , and $\sum_{[j=1, \dots, 6]} \text{random effects}_{[i, j]}$ is the sum of components for

each of the six random effects. Thus, the parameter vector θ is composed of the intercept, ST effects, season effect, six variance components for the random effects, and Φ the precision parameter for the beta distribution.

Posterior distribution simulations were generated using the stochastic Markov chain Monte Carlo (MCMC) method. The samples were generated through three chains of 15 000 values each, of which the first 1000 values were discarded in order to eliminate the dependence on θ_0 (burn-in). Only the simulated tenth values were retained to avoid autocorrelation between them, resulting in posterior distributions of $3_{[\text{chains}]} \times [(15\,000_{[\text{initial}]} - 1000_{[\text{burn-in}]}] / 10_{[\text{autocorrelation}]}] = 4200$ values each.

The standardized coefficients of covariates in models (i) and (ii) received weakly informative priors with normal distribution Normal (0, $\sqrt{1000}$). In models (iii) and (iv), informative prior means were obtained from the OSOs, an independent dataset with 156 observations/sets that provides more reliable information on set-specific covariates than logbook. These priors were defined with a normal distribution Normal ($\text{logit}(\text{OSO_settingtime}_i)$, $\sqrt{1000}$) for ST and Normal ($\text{logit}(\text{OSO_season}_i)$, $\sqrt{1000}$) for season, where OSO_settingtime_i is the mean catch ratio per ST at set i by OSO, and OSO_season_i is the mean catch ratio per season at set i by OSO. Random components in models (ii) and (iv) have noninformative priors as follows:

$$\begin{aligned} z_{[i_{(j)} = 1, \dots, 6]} &\sim \text{Normal}(0, \tau_{[j = 1, \dots, 6]}) \\ \tau_{[j = 1, \dots, 6]} &= \sigma_{[j = 1, \dots, 6]}^{-2} \\ \sigma_{[j = 1, \dots, 6]} &\sim \text{Gamma}(0.1, \mu_{[j = 1, \dots, 6]}), \end{aligned}$$

where, $z_{[i_{(j)}]}$ is the component that indicates the random effect j , τ_j is the precision of the random effect j , σ_j is the standard deviation of the random effect j and, $\mu_{[j]}$ is the observed mean of the standard deviation of the random effect j . Gamma distributions were parameterized by the coefficient of variation (CV = 10%) and mean ($\mu_{[j]}$). These relate to the conventional parameterization $\text{Gamma}(\alpha, \beta_j)$ as follows:

$$\begin{aligned} \alpha &= 1/(cv)^2 \\ \beta_j &= \alpha/\mu_{[j]}. \end{aligned}$$

To determine whether the model accurately described the data, three distinct aspects were assessed with the use of informative and vague priors: residual analysis, posterior prediction model verification (Korner-Nievergelt *et al.*, 2015), and empirical cumulative distribution function (ECDF) plots. The first was assessed by visually comparing the residuals to theoretical normal distribution QQ plots. The second was evaluated by simulating a set of data using the fitted model and then comparing the simulated data to observed data. The third was by comparing the ECDFs of simulated predictions from the models to the ECDF of the observed data. The diagnostic tools were considered satisfactory (Supplementary Material 1) and, when necessary, are highlighted in the results. The choice of models was given by the lowest value of Deviance Information Criteria (DIC; Spiegelhalter *et al.*, 2002), followed by the DIC weight formula used to facilitate the interpretation of

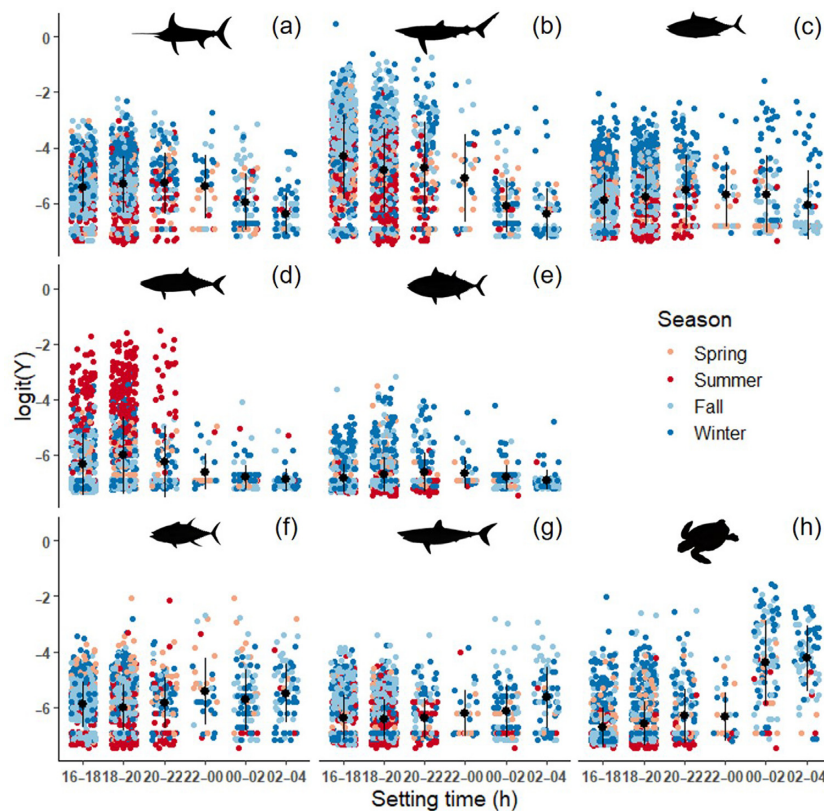


Figure 2. Scatterplot and mean (\pm standard deviation) of observed catch (expressed as $\text{logit}(Y)$) by ST and season for (a) swordfish, (b) blue shark, (c) albacore tuna, (d) escolar, (e) bigeye tuna, (f) yellowfin tuna, (g) shortfin mako shark, and (h) loggerhead turtle.

distances between DICs

$$DIC_{weight} = e^{\frac{-(DIC - DIC_{lowest})}{2}},$$

whose result can be interpreted as proportional to the probability that the model minimizes the loss of information (Burnham and Anderson, 2002). Pairwise comparisons among estimates were made due to the overlap between the 95% Highest Density Intervals (HDIs) of their respective posterior marginal distributions (Kruschke, 2011). All plots, and exploratory and inferential analyses were conducted using the R language, using *ggOceanMaps* v1.1.25 (Vihtakari, 2021), *jagsUI* v1.5.1 (Kellner, 2021) and *HDInterval* v0.2.2 packages (Meredith and Kruschke, 2021).

Results

Catch composition

Data used in these analyses were collected from 2082 fishing sets that included ST and season (Table 1). A total of 111 937 individual animals were captured, including swordfish (15%), blue sharks (48%), albacore tuna (10%), escolar (10%), bigeye tuna (2%), yellowfin tuna (5%), shortfin mako sharks (7%), and loggerhead turtles (3%). These eight species represented 90% of all species reported between January 2018 and June 2021.

Overall, the observed data showed that sets starting in the first three ST intervals (16–18 h, 18–20 h, and 20–22 h) captured more individuals of swordfish, blue shark, bigeye tuna, and escolar (Figure 2a, b, d, and e), whereas sets that started in the last two ST intervals (00–02 h and 02–04 h) captured more

shortfin mako shark and loggerhead turtle (Figure 2g and h). In terms of seasonality, the observed data point to greater captures in the cold seasons of fall and winter (Figure 2a–c and e–h), except for escolar individuals, which were captured more during summer (Figure 2d).

Bayesian BMRM: predictive power and chosen models

In general, the diagnostics evaluated in this study were considered satisfactory so that we could continue to observe the main results (Supplementary Material 1). Swordfish and blue shark models, the two species with the highest number of reported individuals, showed greater predictive power and goodness-of-fit (Supplementary Material 1a). Additional information provided by OSOs (integrated into the model by informative prior distributions) increased the goodness-of-fit in six of the eight models (Table 2). For all species, mixed models that included the six random effects also considerably increased the predictive power of the models, as confirmed by the reduction in DIC values (Table 2). Vessel, year, and hook contributed similarly to the explained variance between random effects: between 15.1 and 17.5%. Bait contributed proportionately more to blue shark (22.6%) and less to loggerhead turtle (10.1%) models. Moon contributed proportionately less to blue shark (8.5%) and to escolar (11.1%). Finally, Trip contributed proportionately more to the models of blue shark (23.2%), albacore tuna (19.6%), escolar (25.2%), and loggerhead turtle (24.9%) (Supplementary Material 2).

Table 2. DIC of proposed Bayesian beta fixed or mixed regression models. Chosen models in bold and %DIC_{weight} in parentheses.

Prior		Non-informative		Informative	
Code		(i)	(ii)	(iii)	(iv)
Model		Fixed	Mixed	Fixed	Mixed
		setting time + season	setting time + season	setting time + season	setting time + season
Species	Swordfish	−16 606 (0.00)	−17 395 (0.01)	−16 606 (0.00)	−17 404 (0.99)
	Blue shark	−11 894 (0.00)	−12 313 (0.00)	−11 895 (0.00)	−12 326 (1.00)
	Albacore tuna	−17 895 (0.00)	−18 486 (0.03)	−17 895 (0.00)	−18 493 (0.97)
	Escolar	−17 787 (0.00)	−18 663 (0.08)	−17 787 (0.00)	−18 668 (0.92)
	Bigeye tuna	−23 190 (0.00)	−23 861 (0.88)	−23 190 (0.00)	−23 857 (0.12)
	Yellowfin tuna	−19 153 (0.00)	−19 720 (0.73)	−19 154 (0.00)	−19 718 (0.27)
	Shortfin mako shark	−18 817 (0.00)	−19 031 (0.27)	−18 818 (0.00)	−19 033 (0.73)
	Loggerhead turtle	−20 725 (0.00)	−21 146 (0.00)	−20 725 (0.00)	−21 167 (1.00)

Bayesian BMRM: ST

There is an indication in the data that the capture probability of species is not completely by chance but that it is influenced by the ST (Figure 3; Table 3). Fully nocturnal sets were more likely to capture more swordfish and blue shark individuals than partially nocturnal sets (Figure 3a and b). In these fully nocturnal sets, the catches were 29–88%, and 58–276% larger, respectively (Table 3). Additionally, sets that started between 18 and 00 h captured more albacore tuna than those started between 02 and 04 h (Figure 3c). On the other hand, partially nocturnal sets captured more yellowfin tuna, shortfin mako shark, and loggerhead turtle than most fully nocturnal sets (Figure 3f–h). For these species, the catches were approximately 157–338%, 44–84%, and 60–90% larger in partially nocturnal sets, respectively (Table 3). Therefore, three catch patterns per ST can be identified given the posterior distributions. The first pattern was observed for the species swordfish, blue shark and albacore tuna, with a greater probability of capture in STs between 18 and 00 h, (fully nocturnal sets; Figure 3a–c). The second pattern is of yellowfin tuna, shortfin mako shark, and loggerhead turtle, with greater chances of capture in the last two intervals, starting between 00 and 04 h (partially nocturnal sets; Figure 3f–h). The last pattern is for the escolar and bigeye tuna species, whose models did not demonstrate a specific ST for greater catches (Figure 3d and e). Furthermore, the highest capture probabilities do not occur in sets started in 16–18 h, except for blue shark (Figure 3; t be extrapolated without first conducting out a Table 3).

Bayesian BMRM: season

Seasonality influenced the catch ratio throughout the year (Figure 4; Table 3). Overall, the austral fall and winter provided higher catches for seven species (Figure 4a–c and e–h), except for escolar, which was more likely to be captured in the summer (Figure 4d). Of these cold season species, blue shark and loggerhead turtle were mostly captured during fall months (Figure 4b, h), and the others were captured during winter months (Figure 4a, c, and e–g).

Discussion

Bycatch mitigation strategies have emerged as a critical issue in the ecosystem-based management of fisheries. Studies conducted worldwide have proposed multiple methods to reduce incidental catch, resulting in benefits to both fisheries and ecosystem objectives (Sacchi, 2021). However, the use of op-

timizing STs to improve the efficiency of fisheries is still underexplored (but see Løkkeborg and Pina, 1997; Auger *et al.*, 2015), despite suggestions by researchers and specialists including the Food and Agriculture Organization (FAO; Løkkeborg and Pina, 1997; Clarke *et al.*, 2014; Sacchi, 2021). The proposal of optimal STs has the potential of minimizing additional costs to fishers while reducing the bycatch of vulnerable species, such as sharks and turtles.

Catch by ST: fisher and animal behaviour

It was evident in our models that the ST significantly influences the amount and composition of resources caught. The probability of capturing swordfish, blue shark, and albacore tuna is larger in fully nocturnal sets, in contrast to what is expected in partially nocturnal sets, when there are larger probabilities for captures of yellowfin tuna, shortfin mako shark, and loggerhead turtle. This evidence is supported by the combination of two factors: the depth of the hooks and the depth occupied by the species. The first factor is easy to understand since the depth at which the hooks are placed in the water column by the Brazilian fleet in SWAO can vary from 15 to 80 m below the surface (Amorim *et al.*, 1998), reaching a maximum of 100 m (personal communication by vessel captains). Thus, it is possible that the capturability of fishery resources by surface longlines that operated in SWAO is strongly related to the specific resources that are present at depths equal to or less than 100 m during fishing activities.

The second factor is the depth occupied by the species, which increases the complexity of this topic: the vertical migration given by circadian behaviour is species specific, which implies a good understanding of the behaviour of each species within the range of 24 h. The study conducted by Madigan *et al.* (2021) in the South Atlantic provides clues for better understanding these results. These researchers used electronic tagging data to assess the depths and temperatures selected by 12 pelagic predators and classified them according to the characteristics of the water column they occupied. In general, all species occupied surface waters close to the mixing layer during the night (~50 m), which differed from the depth they occupied during the daytime. The named “clade 4,” composed of swordfish and blue shark, made extensive use of deep sub-thermocline waters during the daytime (> 500 m, > 300 m, respectively). This deep diving feature is reported in all ocean basins for swordfish (Carey and Robinson, 1981; Takahashi *et al.*, 2003; Dewar *et al.*, 2011) and for blue shark (Carey *et al.*, 1990; Campana *et al.*, 2011). Regarding albacore tuna, our models point to a similar pattern, allowing us to consider

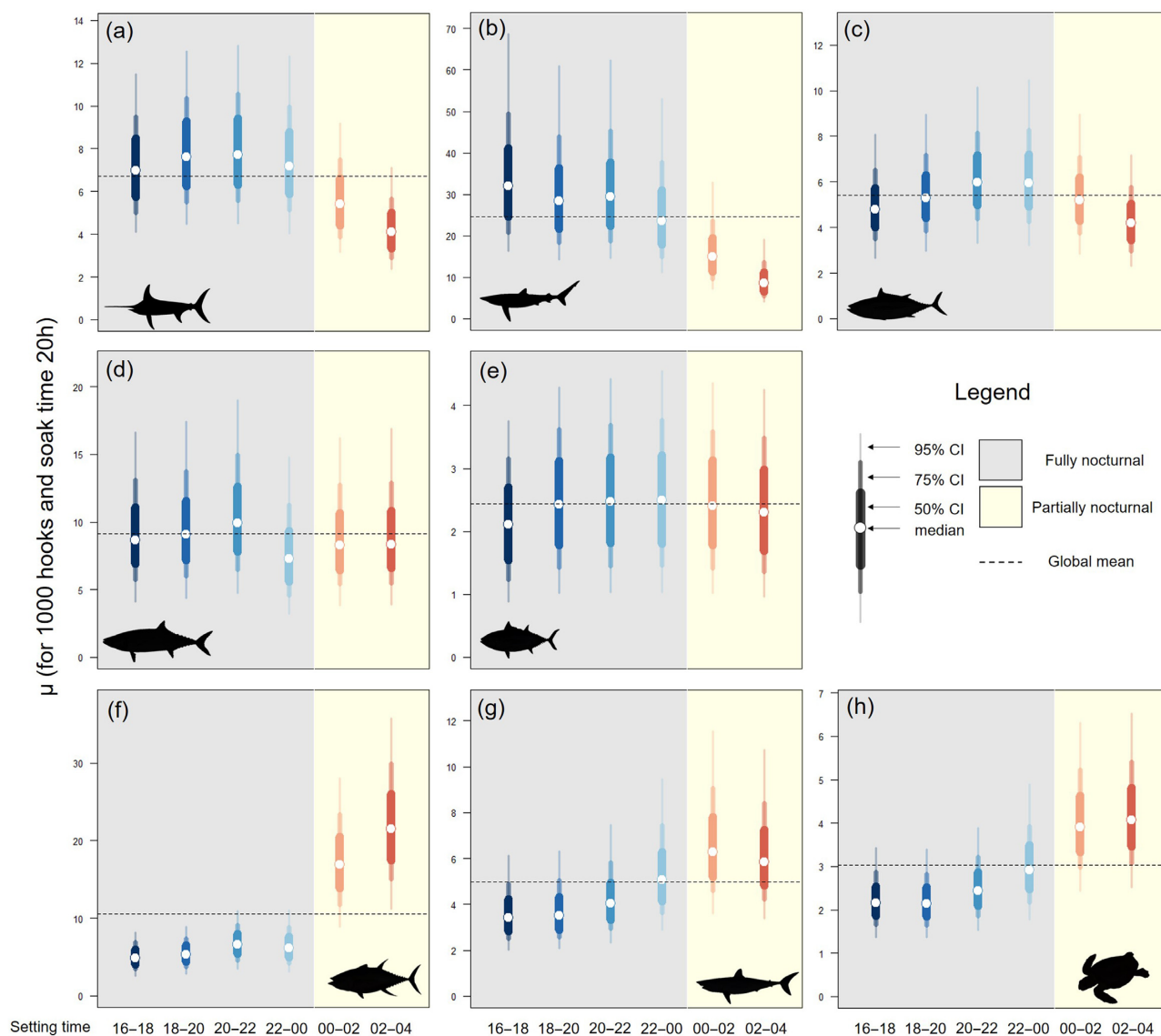


Figure 3. Posterior distributions by MCMC simulation of BMRMs for each ST. The values of μ are the number of individuals caught considering a set with 1000 hooks and a soak time of 20 h for (a) swordfish, (b) blue shark, (c) albacore tuna, (d) escolar, (e) bigeye tuna, (f) yellowfin tuna, (g) shortfin mako shark, and (h) loggerhead turtle. The coloured bars are the 50, 75, and 95% credibility intervals. These data are the result of the proposed models ii (e) and (f) and iv (a)–(d), (g), and (h) chosen by DIC. Background colours indicate possible fully nocturnal set (grey) or possible partially nocturnal set (yellow). The dashed horizontal line indicates the global mean.

that it also occupies deeper subthermocline waters during daytime in SWAO; although there is some conflicting evidence regarding the specific depth utilized by this species at latitudes similar to the northern portion of SWAO ($\sim 35^\circ$; Cosgrove *et al.*, 2014; Williams *et al.*, 2015). Such behaviour of these three species is commonly followed by thermoregulatory vertical migrations during the day, which can indicate a level of vulnerability to longline fleets during this period. During this daytime period, the need to maintain a high body temperature guides these animals to ascend to surface waters, while the greater probability of finding prey in deep/cold waters offsets the disadvantageous metabolic cost of remaining near the deep (Stephens and Krebs, 2019). However, it is plausible that even when rising to the epipelagic zone during the day for body warming, the chances of foraging during the ascent are smaller; even more so knowing that swordfish, blue shark, and albacore tuna feed largely on mesopelagic cephalopods,

fish, and crustaceans (Young *et al.*, 2006; Consoli *et al.*, 2008; Vaske-Jr *et al.*, 2009). Additionally, the study by Vedor *et al.* (2021) seems to conflict with the abovementioned pattern, in that tagging results indicated that vertical migrations of blue sharks are more related to optimizing foraging than to thermoregulation. Despite this, there is evidence that predation behaviour in mature female blue sharks (> 171.2 cm fork length Montealegre-Quijano *et al.*, 2014; > 171.9 cm fork length Fujinami *et al.*, 2017) are more likely to occur during descent than ascent movements (Watanabe *et al.*, 2021), pointing to the necessity of more information about depth of feeding activities. Vedor *et al.* (2021) also demonstrated that, at low latitudes in the North Atlantic ($20\text{--}25^\circ\text{N}$), blue sharks perform depth-oriented normal diel vertical migration (nDVM), remaining for approximately 50% of the daytime at depths greater than 250 m, which leads to the hypothesis that, in those latitudes, sets that started between 00 and 04 h will

Table 3. Pairwise comparisons between posterior distributions for ST and season. Values indicate the percentage gain (+) or loss (–) of catch between categories in rows relative to columns. n.s.: same probability.

	Setting time						Season			
	Swordfish						Swordfish			
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	(+) 9%	-					Summer	n.s.	-	
20–22 h	(+) 11%	n.s.	-				Fall	(+) 39%	(+) 48%	-
22–00 h	n.s.	n.s.	n.s.	-			Winter	(+) 58%	(+) 68%	n.s.
00–02 h	(-) 29%	(-) 41%	(-) 43%	(-) 33%	-					-
02–04 h	(-) 79%	(-) 86%	(-) 88%	(-) 75%	(-) 31%	-				
Blue shark										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	(-) 14%	-					Summer	n.s.	-	
20–22 h	n.s.	n.s.	-				Fall	(+) 121%	(+) 81%	-
22–00 h	n.s.	n.s.	n.s.	-			Winter	(+) 61%	(+) 32%	(-) 37%
00–02 h	(-) 115%	(-) 89%	(-) 95%	(-) 58%	-					-
02–04 h	(-) 276%	(-) 231%	(-) 241%	(-) 176%	(-) 75%	-				
Albacore tuna										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	(+) 10%	-					Summer	(-) 29%	-	
20–22 h	(+) 25%	(+) 13%	-				Fall	n.s.	(+) 50%	-
22–00 h	n.s.	n.s.	n.s.	-			Winter	(+) 121%	(+) 185%	(+) 90%
00–02 h	n.s.	n.s.	n.s.	n.s.	-					-
02–04 h	n.s.	(-) 27%	(-) 43%	(-) 42%	n.s.	-				
Escolar										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	n.s.	-					Summer	(+) 201%	-	
20–22 h	n.s.	n.s.	-				Fall	n.s.	(-) 223%	-
22–00 h	n.s.	n.s.	(-) 37%	-			Winter	n.s.	(-) 197%	n.s.
00–02 h	n.s.	n.s.	n.s.	n.s.	-					-
02–04 h	n.s.	n.s.	n.s.	n.s.	n.s.	-				
Bigeye tuna										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	(+) 15%	-					Summer	n.s.	-	
20–22 h	(+) 17%	n.s.	-				Fall	(+) 29%	(+) 34%	-
22–00 h	n.s.	n.s.	n.s.	-			Winter	(+) 35%	(+) 40%	n.s.
00–02 h	n.s.	n.s.	n.s.	n.s.	-					-
02–04 h	n.s.	n.s.	n.s.	n.s.	n.s.	-				
Yellowfin tuna										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	n.s.	-					Summer	n.s.	-	
20–22 h	(+) 34%	(+) 23%	-				Fall	n.s.	(+) 30%	-
22–00 h	n.s.	n.s.	n.s.	-			Winter	(+) 33%	(+) 64%	(+) 26%
00–02 h	(+) 245%	(+) 216%	(+) 157%	(+) 174%	-					-
02–04 h	(+) 338%	(+) 301%	(+) 226%	(+) 248%	(+) 27%	-				
Shortfin mako shark										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	n.s.	-					Summer	(+) 76%	-	
20–22 h	(+) 18%	(+) 15%	-				Fall	(-) 22%	(+) 44%	-
22–00 h	(+) 48%	(+) 45%	(+) 25%	-			Winter	n.s.	(+) 75%	(+) 22%
00–02 h	(+) 84%	(+) 80%	(+) 56%	n.s.	-					-
02–04 h	(+) 70%	(+) 67%	(+) 44%	n.s.	n.s.	-				
Loggerhead turtle										
	16–18 h	18–20 h	20–22 h	22–00 h	00–02 h	02–04 h	Spring	Summer	Fall	Winter
16–18 h	-						Spring	-		
18–20 h	n.s.	-					Summer	n.s.	-	
20–22 h	n.s.	(+) 14%	-				Fall	(+) 49%	(+) 37%	-
22–00 h	(+) 35%	(+) 37%	n.s.	-			Winter	(+) 29%	(+) 19%	(-) 16%
00–02 h	(+) 80%	(+) 83%	(+) 60%	(+) 34%	-					-
02–04 h	(+) 88%	(+) 90%	(+) 67%	(+) 39%	n.s.	-				

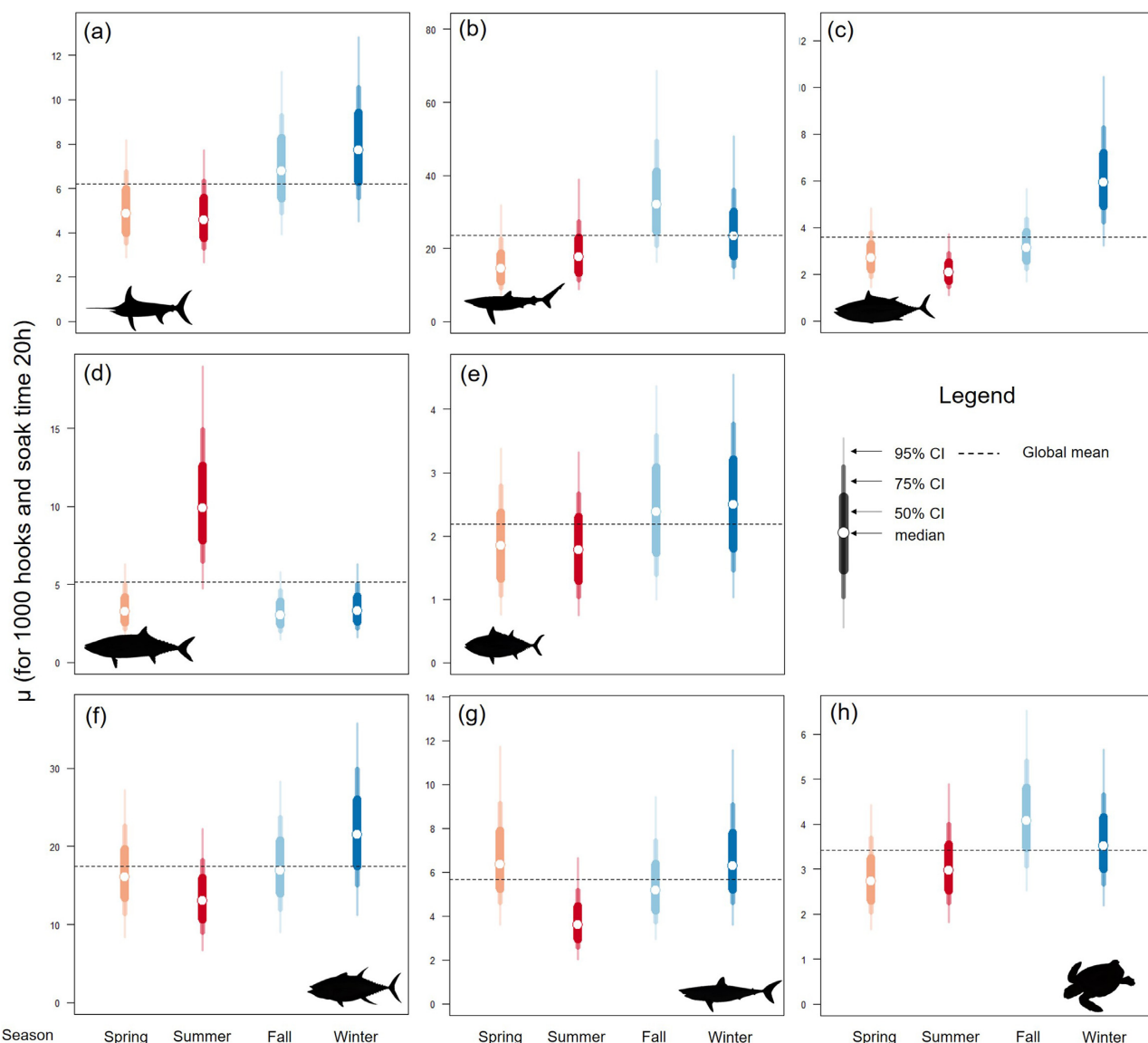


Figure 4. Posterior distributions by MCMC simulation of BMRMs for each season. The values of μ are the number of individuals caught considering a set with 1000 hooks and a soak time of 20 h for (a) swordfish, (b) blue shark, (c) albacore tuna, (d) escolar, (e) bigeye tuna, (f) yellowfin tuna, (g) shortfin mako shark, and (h) loggerhead turtle. The coloured bars are the 50, 75, and 95% credibility intervals. These data are the result of the proposed models ii (e), (f) and iv (a)–(d), (g), and (h) chosen by DIC. The dashed horizontal line indicates the global mean.

catch even fewer blue sharks than in SWAO. In summary, the results we found reinforce the understanding that swordfish, blue shark, and albacore tuna do migrate to depths inaccessible by surface longline fishery during day, significantly reducing the vertical overlap with the fishing gear and, consequently, the catch in sets conducted under solar incidence.

On the other hand, Madigan *et al.* (2021) classified yellowfin tuna in “clade 2,” which is a species restricted to the top of the thermocline (85 m) during the daytime, with few dives into the thermocline (85–150 m), and rare dives to greater depths (> 150 m). In fact, yellowfin tuna is a species that spends a significant part of its time in the epipelagic zone (Weng *et al.*, 2013; Schaefer *et al.*, 2014). Evidence indicates that within the daily, 24-h period, 6 a.m. is a critical time for this species when, surprisingly, they engage in more frequent dives (Schaefer *et al.*, 2014) and fast starts (sudden accelerations during the encounter between predators and prey;

Wright *et al.*, 2021). The apex of these behaviours at approximately 6 a.m. explains the highest catches recorded in the Indian Ocean (Wendling and Bargain, 2002) and in partially nocturnal sets in the SWAO. Like yellowfin tuna, the shortfin mako shark spends up to 99% of its time near the surface of the open ocean (< 75 m; Vetter *et al.*, 2008), and the time spent in shallow areas in SWAO is the same between both day and night (Santos *et al.*, 2021). Other evidence, such as greater day-than night-time predation activities, reinforces understanding that shortfin mako sharks reside at depths above 200 m (Vetter *et al.*, 2008). Despite intraspecific variations, it is commonly accepted that loggerhead turtles spend most of their time at depths less than 40 m, and even when diving, they do not exceed 100 m (Polovina *et al.*, 2003); especially in SWAO, where they are captured almost exclusively in shallow sets above the thermocline (Pinedo and Polacheck, 2004). The evolution of loggerhead turtles demonstrates that these animals descend

from a terrestrial ancestor, and for this reason they carry typical phenotypes of this environment (Duchene *et al.*, 2012). One of the main characteristics of its evolutionary past is the need to breathe atmospheric air, like marine mammals, which becomes a strong limitation in reaching greater depths. In addition, the photoreceptors (cones) in the eyes of sea turtles contain oil droplets that function as filters that change the sensitivity of the cones towards longer wavelengths, such as red (Southwood *et al.*, 2008). Therefore, knowing that wavelengths in the red spectrum penetrate just a few metres into the water column, the ability to see prey in these colours reinforces understanding of their epipelagic habits. Last, foraging events in loggerhead turtles are more common during day than at night, and the few nocturnal feeding events may be associated with bioluminescent gelatinous prey (Narazaki *et al.*, 2013), which is not the case for pelagic longline baits. Thus, more frequent foraging habits during the day may explain why line sets under daylight (partially nocturnal) capture more yellowfin tuna, shortfin mako shark, and loggerhead turtles.

Our results do not indicate a clear influence of ST on the capture of bigeye tuna and escolar. Despite this, there is evidence that these animals have remarkably similar behaviours to swordfish, blue shark, and albacore tuna (Kerstetter *et al.*, 2008; Thygesen *et al.*, 2016; Lin *et al.*, 2021; Madigan *et al.*, 2021), in addition to the observed data (Figure 3d and e). We attribute this result to the relatively low number of bigeye tuna reported (only 2% of individuals among all species caught). Regarding the escolar, very few observations were made in the STs 00–02 h and 02–04 h during the summer, when they were captured almost exclusively (Figure 2). However, more data are needed to elucidate the optimal STs for both bigeye tuna and escolar.

In none of our models for the target species (swordfish, albacore tuna, escolar, and bigeye tuna) did the ST 16–18 h have the highest catch probability. Knowing that during this period catch occurs in the transitional time from day to night (Figure 3), the most plausible explanation is that not all individuals have completed their circadian migration towards the surface, preventing maximum catch.

Catch by season: environmental oscillation

The influence of seasonality on the catch of fishery resources is a widely known phenomenon in ecological studies. Particularly in the mid-latitudes, the oscillation between warm and cold periods alters the environment in such a way that it generates changes from the individual to community level (Martins and Haimovici, 2017). The strengthening of the Falkland Current during the austral winter allows the subtropical convergence to ascend to the northern portion of the SWAO (off the Brazilian coast), generating a marked thermal front, which increases nutrient-rich cold waters, and primary productivity and, finally resulting in a larger abundance of prey to maintain apex predators. In total, seven of the eight species in this study seem to respond to this pattern, which was expected given past evidence (e.g. Carvalho *et al.*, 2011), and the strong effect of parameters such as surface temperature (negative) and chl *a* concentration (positive) on these animals (Mourato *et al.*, 2008).

Escolar was the only exception to abovementioned pattern, being mostly caught in the warm summer months, when the northern portion of SWAO is under almost exclusive influence of the Brazil Current (warm and oligotrophic). This result is

different from what was found in SWAO at the Uruguayan coast (Milessi and Defeo, 2002). By using logbooks, these records show higher catches of escolar during the winter and spring months, relating them to the rise in subtropical convergence towards the north of SWAO, which is in line with what we suggest for the other species. The authors note that in warm months, escolar can migrate to lower latitudes to reproduce, which contradicts our results. More studies on the reproductive biology of escolar in SWAO are needed to elucidate whether this region is also important for the reproduction of these animals.

The highest catch of loggerhead turtles during the austral fall and winter coincides with the lowest incidence of strandings on the adjacent coast of SWAO (Monteiro *et al.*, 2016). It is suggested that during these months the turtles seek out more oceanic areas, which would decrease the probability of being stranded on the beach (Monteiro *et al.*, 2016) and increase the probability of being caught by longlines at a long distance from the coast. In addition, more frequent anticyclonic eddies during the austral winter (Garzoli and Garraffo, 1989) in the northern portion of the SWAO (Mason *et al.*, 2017) can function as access channels for loggerhead turtles and blue sharks. This can facilitate access to mesopelagic prey as they push isolines from warmer temperatures to greater depths (e.g. Gaube *et al.*, 2017; Braun *et al.*, 2019), thus favouring the presence of these predators during the winter.

Modelling, priors, and random effects

All model diagnostics were considered satisfactory. Compared to the most used probability distributions in pelagic longline fisheries studies (e.g. Poisson and Negative Binomial), the beta distribution showed better diagnostic results and satisfactory performance regarding its predictive power for the Brazilian SWAO fleet (results not shown). Therefore, we strongly suggest that this probability distribution be considered a candidate among other distributions in future studies.

Models with informative priors (given by the dataset of OSOs) and the addition of random effects increased the quality of fit in BMRMs. Among these findings it is noteworthy that: (1) Bayesian statistics allowed the advantageous use of observed data updated by prior knowledge of the various phenomena studied; (2) this approach allowed us to integrate in this approach the use of dual sources of information (onboard scientific observations and logbooks), which presented complementary characteristics of data quality and volume, respectively, and; (3) the six integrated random effects contributed to at least ~10% of residual variance to all models: contribution indicates that the chosen random effects had some influence on the catch variation within each species, mainly the trip-effect. We suggest evaluating and discussing the fixed effects of bait, hook, and moon in the future as it was not the focus of this paper.

Previous studies indicate a possible interaction between the depth occupied by fishery resources and seasonality; that is, specific depths are likely to be occupied by individuals in a population depending on the season (e.g. Wright *et al.*, 2021), most likely linked to mixing layer depth and seasonal thermocline. Therefore, we recommend continuous data collection modelled by the Tubarão Azul Project (FURG/SEMA, 2020). With an increased number of observed trips and sets, it will be possible to evaluate interactions between ST and season with greater precision.

Management implication

The information produced here can be used by fishers, researchers, decision-makers, and regulators to improve the efficiency and sustainability of surface longline fisheries. Fishing activities that start exclusively between 18 and 00 h (resulting in fully nocturnal sets) are more beneficial and ecologically wise. On the one hand, they reduce the probability of capturing aquatic species that forage under sunlight by avoiding partially nocturnal sets (in this case, shortfin mako shark and loggerhead turtle). On the other hand, during dusk (ST 16–18 h), seabirds engage in dangerous and often deadly flights when near longlines (Bugoni *et al.*, 2008). By avoiding this ST, it is likely that incidental catches of seabirds can be reduced (Jiménez *et al.*, 2009) without decreasing the maximum catch of target species (which do not occur in sets started at these periods; Figure 3). Due to the spatial limitation of data used in this study, the composition of species caught as a function of the ST may vary in fishing zones other than SWAO. This implies that these results must be interpreted with care and should not be extrapolated without first conducting out analyses with a more widely distributed dataset.

In surface longline fisheries, mitigation measures are often thought to be modifications to the equipment used by fleets, through which endangered or depleted species will have their catch and mortality reduced. Such measures are fundamental and are effective in countries committed to good fishery management. However, implementing these measures in fleets operating in countries with less efficient management is a major obstacle. In these cases, alternatives that are supported not only by law but also by the willingness of those interested in maintaining a productive and sustainable fishery have greater chances of being efficient. A strong motivation for a fishery of this type is the increase in the catch of target species (and consequent income), which makes the fishery more efficient by reducing the pressure from the incidental catches. Thus, selecting optimal timing for specific fishing activities can be a good strategy to increase the catch of target species and reduce bycatch. However, future studies are needed to calculate the benefits of maintaining a surface longline fishery only using fully nocturnal sets and carefully considering the reduction in catch of yellowfin tuna, a fish with high commercial value and particularly important to the Brazilian fleet.

Final remarks

The results presented in this article point to an alternative technical measure that would provide greater efficiency in the catch of the main target species of the longline pelagic fishery of the Brazilian fleet in SWAO by using fully nocturnal sets. At the same time, this measure has the potential to reduce the catch of species with greater vulnerability to overfishing and extinction. Favourable environmental conditions increase the catch of most species during the austral winter. Considering random effects ensured better fit quality and predictive power of the models. Bayesian statistics allowed accurate information from OSOs to be updated by the large data set obtained from logbooks, giving us the best possible knowledge about the phenomena being studied. Finally, we hope that the easy-to-apply results presented here support public policies to mitigate the impacts of the surface longline fishery on a regional and global scale.

Supplementary data

Supplementary material is available at the ICESJMS online.

Data availability statement

The data that support this study are property of the *Secretaria do Meio Ambiente e Infraestrutura do Estado do Rio Grande do Sul* (SEMA) and the summary of these, allowed for sharing, are available at the address <https://demersais.furg.br/>.

Authors' contribution

LSR: conceptualization, methodology, formal analysis, investigations, data curation, visualization, writing original draft, and writing—review and editing; PGK: methodology, formal analysis, investigation, visualization, and writing—review and editing and supervision; LGC: writing—review and editing, resources, project administration, and supervision.

Competing interest statement

The authors declares no conflict of interest.

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