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Using an integrative approach to evaluate shrimp bycatch from subtropical data-poor fisheries

L. Jorge Rodrigues-Filho[a,b,*], Marina Dolbeth[c], Jurandir J. Bernardes Jr[d], Igor Ogashawara[e], Joaquim O. Branco[f]

[a] *Universidade Estadual de Santa Catarina, Departamento de Engenharia de Pesca e Ciências Biológicas, Laboratório de Ecologia, Laguna, Brazil*
[b] *Programa de Pós-Graduação em Planejamento Territorial e Desenvolvimento Socioambiental (PPGPLAN)/UDESC/FAED, Florianópolis, Brazil*
[c] *CIIMAR – Interdisciplinary Centre of Marine and Environmental Research of the University of Porto, Novo Edifício do Terminal de Cruzeiros do Porto de Leixões, Matosinhos, Portugal*
[d] *Universidade Federal de Santa Catarina, Laboratório de Biologia e Cultivo de Peixes de Água Doce, Florianópolis, Brazil*
[e] *Department of Experimental Limnology, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Neuglobsow, Germany*
[f] *Universidade do Vale do Itajaí, Escola do mar, Ciência e Tecnologia, Laboratório de Biologia, Itajaí, Brazil*

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ABSTRACT

Tropical and subtropical shrimp fisheries occur mainly nearshore, where numerous non-target species (bycatch) are captured. Bycatch is a serious issue for fishing activity and understanding its impacts through integrative analyses of the bycatch structure is necessary. In Brazil, information on bycatch composition and structure is limited. As such, we conducted a study on the target species and bycatch communities from a fishery area in the southern Brazilian coast, considering a 20-year dataset. The target species abundance was influenced by seasonal conditions, where peaks of abundance occurred from February to May and August to October. The trawl captures comprised 149 species, of which 116 species were discarded and 33 were considered usable by the fishermen. The bycatch composition had few abundant and several rare species, with a high bycatch rate associated with salinity and TSS, mainly in the latter years of study. Bycatch diversity showed association with salinity, and multiyear oscillations, but generally maintained a stable trend over years. Our analysis revealed bycatch patterns and the influence of environmental variables in a single ecosystem. In the context of scarce data and an incipient management structure, these findings are crucial to develop a coherent approach for fisheries management.

1. Introduction

Shrimp fisheries take place in a wide range of marine and estuarine ecosystems, with considerable economic and social importance worldwide (Gillett, 2008). Recently, the global production of shrimp species has reached a new maximum in world capture (3.4 million tons), mainly because of the high commercial value of these resources in the market (FAO, 2018), contributing to intense fishery pressure.

In tropical and subtropical regions, fishing occurs mainly nearshore focusing on the penaeid family (García and Le-Reste, 1986). Among penaeids, *Xiphopenaeus kroyeri* (Heller, 1862) is abundant in shallow depths (< 30 m) with mud-bottom substrates (Dall et al., 1990) along the western Atlantic coast from Virginia (United States) to Rio Grande do Sul (Brazil) (D'Incao et al., 2002). There is a *X. kroyeri* fishery along the Brazilian coastline (Lopes, 2008), with a representative biomass of 15,417.8 t caught by both artisanal and industrial fleets (BRASIL, 2012). In the southern Brazilian coast, the activity is more intense because of a set of conditions that promote high shrimp production levels, including upwelling events of nutrient-enriched waters, the influence of the Río de La Plata plume, and a wide shallow shelf suitable for trawling (Pereira et al., 2009; FAO, 2011).

There has been relatively high fishing effort on *X. kroyeri* stocks, resulting in decreased Brazilian captures since the late 1980s (Vasconcellos et al., 2007). Consequently, the species was categorized as overfished in 2004 (Ministry of the Environment, Normative Instruction 5, 21 May 2004) and, currently, *X. kroyeri* is classified as a data-deficient species (Boos et al., 2016), without a robust evaluation from it stocks. This status has generated concerns about how effective management actions are to protect shrimp populations, such as fishing licenses, marine trawl exclusion, and 3-month closed fishing seasons

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* Corresponding author at: Universidade Estadual de Santa Catarina, Departamento de Engenharia de Pesca e Ciências Biológicas, Laboratório de Ecologia, Laguna, Brazil

E-mail addresses: jorlrf@gmail.com, jorge.rodrigues@udesc.br (L.J. Rodrigues-Filho).

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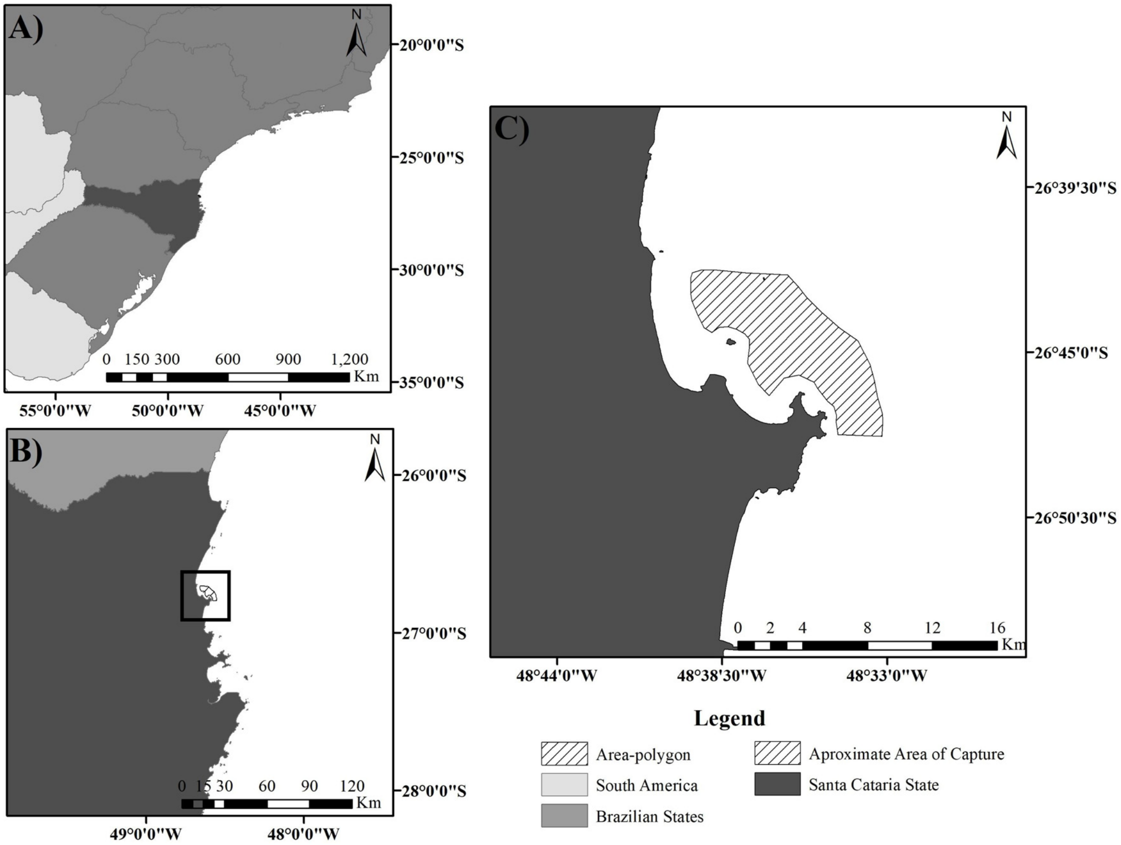

Fig. 1. The Southern Brazilian Coast (A), Santa Catarina State Coast (B) and Armação do Itapocoroy ecosystem (C) where the 20 years of scientific research on shrimp trawling were carried out.

(Simões et al., 2017; Musiello-Fernandes et al., 2017).

Another aspect that has been highly criticized in the shrimp fishery management structure is that it was determined based only on the target species biological parameters (Dias-Neto, 2011), without considering non-target species (bycatch). This corroborates with the potential low efficiency of these management actions to ecosystemic levels, considering that trawl fishing captures a high amount of bycatch, from which several species are discarded back to the sea (Hall et al. 2000). The bycatch is recognized worldwide as “additional unnecessary mortality”, with several potential impacts on the structure and function of marine ecosystems (Bellido et al., 2011). Its composition and ratio to the target species are highly variable, depending on the area, gear selectivity, and seasonality (Stobutzki et al., 2001; Davies et al., 2009).

Although Brazil is a major shrimp producer (FAO, 2018), there is no governmental program to monitor trawl fleet captures and bycatch data from commercial fleets are limited summarized in few efforts (e.g., Ricardo-Pezzuto and Mastella-Beninca, 2015). Therefore, sentinel trawl fisheries conducted by researchers (i.e., research independent trawls) are essential to generate data on incidental catches. Most sentinel trawls carried out on the Brazilian coast have focused on particular groups, such as cnidarians (Schroeder et al., 2014), crustaceans (Pantaleão et al., 2016), and fishes (Rodrigues-Filho et al., 2015). Limited studies have examined the whole community caught in shrimp trawls, and even these only explored the species occurrence (e.g., Graça-Lopes et al., 2002; Branco et al., 2015), without an integrative analysis of the biota structure, or the potential environmental drivers for the patterns observed.

The use of more holistic approaches is imperative to understand the potential impacts of fishing and trawling on the ecosystem (FAO, 2005; Link, 2011). In bycatch studies, an integrative approach, combining different data, such as oceanographic variables, target and bycatch species abundance, and fishermen expertise, could prove the interplay among fishery variables and subsidize more assertive actions to manage marine ecosystems. Furthermore, it is particularly difficult to obtain data for shrimp bycatch because hundreds of species are involved, with a high discard rate (Dell et al., 2009), especially in Brazilian fisheries.

In the present study, we evaluated shrimp fisheries data using an integrative approach, using a 20-year dataset obtained by sentinel trawls from a research program carried out in a traditional ground fishery in the southern coast of Brazil. This analysis is highly relevant in the context of the absence of governmental monitoring, limited data from commercial fleets, and high demands for broader bycatch studies. We started by evaluating the prevailing environmental conditions in the study area over time, and assessing trawl capture composition, including target and bycatch data. Then, trawl captures were evaluated considering their economic importance for the fishermen. Based on this baseline data, we generated relevant information for management, which contributes to a better understanding of (i) how the bycatch is structured, focusing on its abundance and frequency (occasional and core species); (ii) the main bycatch species associated with the target species; (iii) the rate between bycatch/target species biomass and, also, the bycatch diversity in the study area; and (iv) the potential drivers structuring bycatch parameters (i.e., discard rate and diversity) throughout the years in the study area.

2. Materials & methods

2.1. Sampling effort and species classification by fishermen knowledge

The study area is located in the southern coast of Brazil, more specifically in North Santa Catarina State, a subtropical region with marked oceanographic features associated with coastal, tropical, and South Atlantic Central Water mass interaction (Emílsson, 1961; Matsuura, 1986). In the shallow marine ecosystem of this region

(10–30 m), there are several habitats with mud sediments, where shrimp species are the main fisheries resource (Pezzuto et al., 2008; Branco et al., 2015). In this region, Armação do Itapocoroy is recognized as a traditional fishery ground, where a fleet of 115 small artisanal boats operates in an area of approximately 168 km^2 (AI, Fig. 1), fishing 200 tons of shrimp per year (Acauan et al., 2018).

In the present study, trawling sites were established according to traditional fishing areas (Fig. 1). Sentinel trawls occurred from 1997 to 2016, with mostly monthly sampling (sampling frequency detailed in Supplementary Material 1). To faithfully reproduce fishing in the study area, a single boat (double rigged) was used for bottom trawling, using a 3.0-cm mesh in the wings and 2.0-cm mesh at the cod end, towed at an average speed of 2.0 knots. The boat used was from AI local artisanal fleets and operated by a fisherman. At each sampling, three hauls (one hour each) were carried out during daylight. The methodology was the same over 20 years of monitoring, regarding the vessel type, fishery gear, and sampling effort.

On all sampling occasions, a team of 3–4 scientists were on board, responsible for registering the trawl localization, collecting bottom water samples with a Van Dorn bottle and *in situ* measurements, including salinity (with optical refractometer, ITREF-10, Instrutemp) and temperature (manual thermometer, model 9793.16.1.00, Incoterm). All the biological resources caught in the trawls were displayed on the boat deck, where captures were sorted according to local fishermen knowledge. In this step, species were initially classified as landed or discard species (i.e., species that are usually thrown back into the sea). Thereafter, landed species were subcategorized as target species – species with economic importance to the shrimp fishery, or as incidental species – species not important for the fishery activity, but that could be used by fishermen for consumption and/or sale in the local market. All the sampled material, independent of classification, was kept in iced coolers until arriving at the laboratory for taxonomic identification and measurements.

2.2. Biological data processing and environmental data acquisition

In the laboratory, all organisms were identified to the lowest possible taxonomic level using specialized literature (Menezes et al., 2003, and references therein), counted, and weighed. Then, we estimated the catch by species as follows: frequency of occurrence (FO: %), catch per unit effort in weight (CPUEw: kg h^{-1}), species biomass importance from total caught (%), catch per unit effort in abundance (CPUEn: individuals h^{-1}), and species abundance importance from total caught (%). Using the sum of all species caught, we estimated the total catch per unit effort in biomass (Total CPUEw: kg h^{-1}) and abundance (Total CPUEn: n h^{-1}) for the fishing area.

In addition, we acquired remote sensing data from the NASA's Terra and Aqua satellites, available from 2002 to 2016: Chlorophyll-*a* (Chl-a), particulate organic carbon (POC), and total solid suspended (TSS) estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (details in Supplementary Material 2).

2.3. Data analysis

2.3.1. Environmental variables

In South Brazil, weather seasonality is pronounced (Rodrigues-Filho et al., 2015), so data were explored as follows: spring (October–December), summer (January–March), winter (July–September), and fall (April–June). As the remote sensing variables were available from 2002 to 2016, only this period was considered in subsequent analyses.

Abiotic data were analyzed using principal component analysis (PCA) to clarify seasonal patterns. The tested environmental variables were *in situ* salinity and temperature, and Chl-*a*, POC, and TSS from the remote sensing data, which were first analyzed for collinearity using Spearman correlation coefficients (non-parametric analyses), considering a 5% significance level (Zar, 2010). With the exception of POC, the other non-collinear variables were standardized through z-scale transformation to ensure that all variables have equal weight and then used in the PCA analysis (Zuur et al., 2007). PCA was performed using R software (R Core Team 2018) and computed with the vegan package (Oksanen et al., 2019), whereas correlations were tested with the *envfit* function ($p = 0.05$; permutation = 999). Biplots were created using the packages *ggplot* (Wickham, 2016).

2.3.2. Target species

The monthly dynamics of target species (*Xiphopenaeus kroyeri*, *Artemesia longinaris*, and *Pleoticus muelleri*) were modeled using General Additive Models (GAM) (Zuur et al., 2009) in which $CPUE_n$ was the dependent variable and Month the covariate.

GAMs were chosen because monthly shrimp captures were nonlinear during the study period and, in this situation, GAMs allow nonlinearity by incorporating smooth splines terms into the model (Wood, 2017). Since data exploration analysis revealed a high number of zeros, over-dispersed species data, and temporal dependency (Supplementary Material 3), $CPUE_n$ was modeled using a negative binomial function and autoregressive moving average (ARMA) correlation structure (Zuur et al., 2009). For each target species, the best theta parameter was extracted as suggested by Zuur et al. (2009) and used to refit the regression with a specific variance function.

Deviance explained were estimated from models and, also, the predicted value plus the confidence bands (95%), which were plotted against observed $CPUE_n$ to visualize patterns in the study area. Additionally, p-values based on ANOVA F-ratio test statistics were used to evaluate the significance of month on target species variation. All analyses were performed using the mgcv library (Wood, 2017).

2.3.3. Core and occasional species

In general, communities and/or assemblages are comprised of core and occasional species, and there are several methods to split between these two (Magurran, 2004), which differ in how they determine the exact location of the split. Although the position of the spilt is relatively subjective, methods combining species abundance and frequency of occurrence information are usually more accurate, such as the Magurran and Henderson (2003) method, since both components are important for determining the status of a species in the community. Here, we used this method, with the information from all datasets (180 months) to plot the maximum abundance along the 20 years against the frequency of the occurrence of each species, here named as "permanence". When discontinuity is observed on the plot, it can be used to define the split between species groups (Magurran and Henderson, 2003) and they can be classified as mentioned above.

2.3.4. Association between bycatch and target species

We evaluated the temporal relationship between target and selected bycatch species using a monthly continuous 6-year period (August 1997 to July 2003), which was more robust to check for temporal correlation. The species with > 10% occurrence were selected to infer species occurring more often, and potentially more abundant based on the fishing activity. We ran a cross-correlation analysis (Box et al., 2015) with seasonal decomposition (Census I method: ratio-to-moving-average; temporal lag = 0) to remove trend and seasonality, both time components from auto-correlated time series (Makridakis et al., 1998). The residuals were used to compute cross-correlation between target and bycatch species, and coefficients higher than two standard errors were considered significant (Box et al., 2015).

Then, we considered the biomass of the discard species and that of target species plus incidental species (i.e., landings) to estimate the discard rate (DR), which was expressed as the proportion of the total catch that is discarded (Pérez Roda et al., 2019).

The DR monthly values were utilized to calculate the total mean DR to the study area and its confidence interval (95%).

2.3.5. Bycatch diversity

Taxonomic diversity was estimated considering the untransformed biological dataset from each trawl alone (i.e., trawled area as lower levels of sampling) and from the trawls' monthly α-diversity average (within the community). We used the Shannon index (H') transformed into the numeric function exp(H'), based on the 'equivalent communities' concept (Jost, 2006). All steps described were conducted using the *vegan* package R (version 2.5-2) (Oksanen et al., 2019).

2.3.6. Relationship between bycatch parameters and environmental data

To explore the potential environmental drivers of the bycatch rate and diversity, we performed modeling techniques, adopting the bycatch diversity and ratio as dependent variables and the significant environmental variables from the PCA as covariates. Month and Year were additionally considered as covariates to infer the seasonal and yearly dynamics. Data were initially explored following the protocol for data exploration by Zuur et al. (2010), using graphical methods to assess the presence of outliers, homoscedasticity, normality, interactions between covariates, and auto-correlation.

Based on data exploration, the bycatch rate and diversity were modeled with GAM to handle non-linear relationships between response and environmental variables. The GAMs were fitted with the normal Gaussian family and link function identity, and with an autoregressive moving average (ARMA) correlation structure because of the autocorrelation detected for dependent variables (all graphs available on request).

Two groups of models were fitted for each dependent variable: a first with single smooth terms for each explanatory variable to account for non-linear patterns, and a second, where the individual smooth terms of temporal explanatory variables (year and months) were replaced by a factor-smooth interaction between these variables to account for interactions detected in the data exploration step (Supplementary Material 3). Subsequently, a global model considering all variables was generated for each model group, without concern for their order and with interactions among the categorical temporal variables (month and year) for each dependent variable (Table 1).

The effect of dropping terms from the global model was explored by examining the Akaike Information Criterion (AIC) (Akaike, 1974) of each single term, to exclude variables from models and reorder variables based on their AIC value. For each dependent variable, we selected the model with the lowest AIC (Zuur et al., 2009), the best model. GAMs were fitted with the mgcv library (Wood, 2017).

3. Results

3.1. Oceanographic conditions

From the initially tested abiotic variables, only temperature, salinity, TSS, and Chl-*a* were non-colinear and significant (*envfit* model p-values < 0.05, Fig. 2). The first and second axes of the PCA accounted for 33.98% and 28.10% of the data variability, respectively. Summer samples (January – March) were associated with higher temperatures and generally lower TSS and Chl-a values. The opposite trend was observed for the winter samples (July – September), with high concentrations of TSS and Chl-a and low temperature. Spring samples (October– December) were dispersed on the lower central area of the biplot associated with intermediate values of salinity and TSS. The autumn samples (April–June) were associated with higher salinity values, mainly for the May observations.

3.2. Capture composition in the 20-year period

During the 20-year study period, 756,008 organisms were captured, with a biomass of 5.56 tons, a total CPUE_w of 10.55 kg h^{-1}, and a CPUE_n of 1,443.5 individuals h^{-1}. Overall, 72 families and 149 species were identified, including cnidarians, mollusks, crustaceans, echinoderms, and fishes (Supplementary Material 4). Most species were classified by fisherman as discards (i.e., 116 species), 30 species as incidental, and only three as target species.

The crustacean assemblage accounted for 39% of the biomass and 67% of the abundance. Thirty-three species were identified, including the three target species *Xiphopenaeus kroyeri*, *Artemesia longinaris,* and *Pleoticus muelleri*. *X. kroyeri* was a remarkable resource regarding the frequency of occurrence, total biomass, and abundance. Moreover, *A. longinaris, P. muelleri*, and the incidental penaeid shrimp *Litopenaeus schimitti* were also representative of trawls.

Hermit crabs, represented by families Diogenidae, Paguridae, and Anomura are scarce and considered as discards. In contrast, other crab species, such as the discard species *Callinectes ornatus* and *Hepatus pudibundus* were relatively frequent (i.e., occurrence > 80 %), achieving expressive biomass and abundance.

Mollusca was represented by 12 discard species, representing 6% of the biomass and 5% of the abundance. The gastropods *Buccinanops cochlidium* and *Olivaris urceus* occurred in > 70% of the samples, with an important contribution to total biomass and abundance. Bivalve species were occasional and less abundant, whereas Cephalopod species were more frequent and abundant, composed mostly of the squid *Lolliguncula brevis* and *Doryteuthis pleii*.

Echinoderms were represented by nine discard species. The sea stars

Table 1
Backward stepwise selection of the best fitted General Additive Models (GAM) using the Akaike Information Criterion (AIC).

Response variable	Model group	Model	Covariates[1]	AIC
Bycatch diversity	1	GAM0	Year + Month + Temperature + Salinity + Chl-a + TSS	453.53
		GAM1	**Year + Month + Salinity + Chl-a + TSS**	**451.95**
		GAM2	Year + Month + Salinity + Chl-a	455.02
		GAM3	Year + Month + Salinity	725.00
	2	GAM4	Year * Month + Temperature + Salinity + Chl-a + TSS	461.29
		GAM5	Year * Month + Salinity + Chl-a + TSS	460.12
		GAM6	Year * Month + Salinity + TSS	461.82
Discard rate	1	GAM7	Year + Month + Temperature + Salinity + Chl-a + TSS	−84.74
		GAM8	Year + Month + Salinity + Temperature + TSS	−85.86
		GAM9	**Year + Salinity + Temperature + TSS**	**−86.87**
		GAM10	Year + Salinity + TSS	−86.15
	2	GAM11	Year * Month + Temperature + Salinity + Chl-a + TSS	−81.24
		GAM12	Year * Month + Salinity + Chl-a + TSS	−81.69
		GAM13	Year * Month + Salinity + TSS	−80.53

The best-fitted models are highlighted in bold. [1]The representation of the smooth terms [e.g.,s(Temperature)] was omitted in the formulas to provide a clearer view of the table.

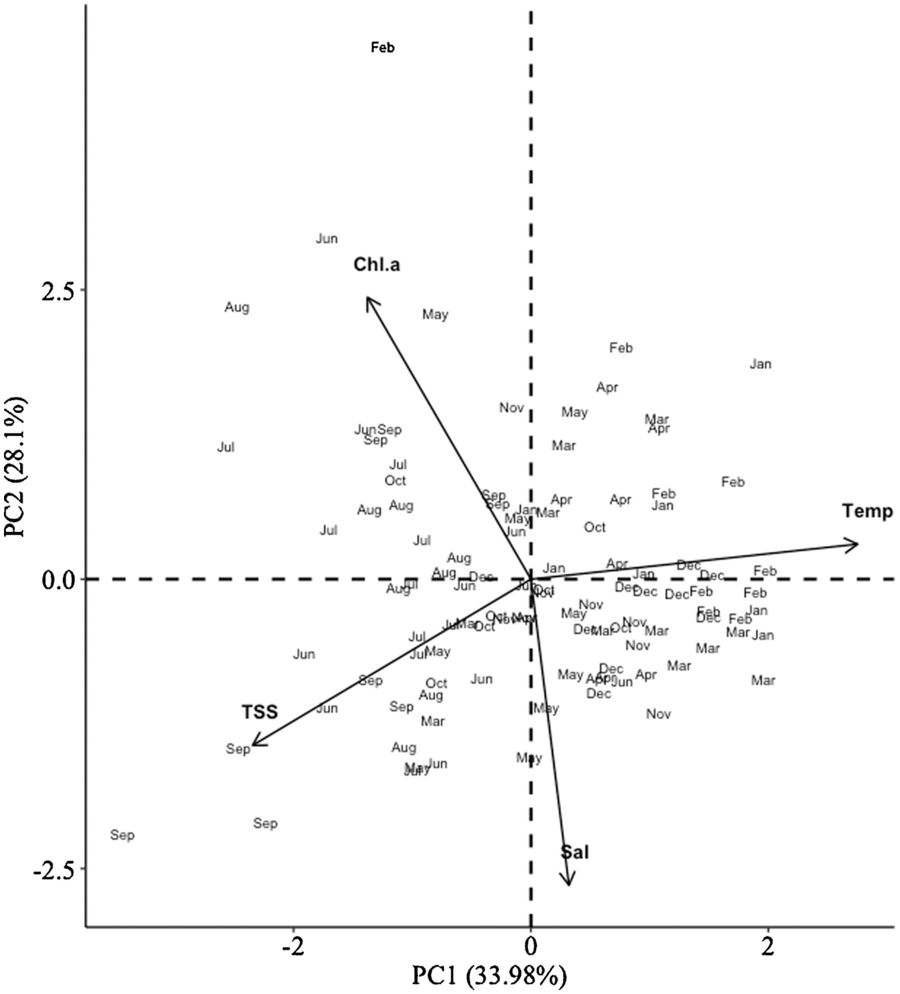

Fig. 2. PCA ordination biplot of the significant environmental variables from the Armação do Itapocoroy, during the 20-year period. Temp = Sea surface temperature; Sal. = Salinity; TSS = Total Solid Suspended; Chl-a = Chlorophyll *a*.

Astropecten marginatus and *Luidia senegalensis* were the most common and abundant. The remaining species occurred occasionally and at low abundance.

Eight cnidarian species were caught, all classified as discard, representing 9% of the biomass and 1.5% of the abundance in the surveyed area. The most frequent were *Bunodosoma caissarum*, which occurred in 31% of the samples, followed by *Chiropsalmus quadrumanus*, present in 7% of the samples, which was the most representative biomass.

The ichthyofauna was diverse, represented by 88 species distributed in 33 families, contributing 44% of the biomass and 25% of the abundance. Six elasmobranch species were caught, which were rare and less abundant, with most of them incidental (e.g., *Atlantoraja cyclophora* and *Pseudobatos horkelii*).

The teleost assemblage was composed of 82 species, of which 61 were classified as discards and 21 as incidental. The teleosts had a high number of infrequent species and a few abundant species. For instance, Sciaenidae were the most representative in trawls, with two very frequent and abundant species classified as incidental: *Isopisthus parvipinnis* and *Paralonchurus brasiliensis*. Although other sciaenids (e.g., *Ctenosciaena gracilicirrhus, Micropogonias furnieri*, and *Larimus breviceps*) were less frequent and abundant than *Stellifer* spp., they were a considerable resource in captures.

Flathead fishes were represented by 15 species belonging to the families Paralichthyidae, Achiridae, and Cynoglossidae, with the most representative species being *Symphurus tessellatus* and *Etropus crossotus*. Puffer fishes (i.e., Balistidae, Diodontidae, Monocanthidae, Tetraodontidae, and Gerreidae) were discards, characterized by low occurrence, biomass, and abundance in trawls.

Nine pelagic fishes (e.g., Pritisgasteridae, Engraulidae, and Clupeidae) were frequent in trawls with a high to moderate abundance and low weight, the latter because of their small individual biomass. *Pelona harroweri* and *Chirocentrodon bleekerianus* were the most frequent and abundant small pelagic species in this study. Other species, including discard species, such as Brazilian cod *Urophycis brasiliensi* and the incidental *Prionotus punctatus* and *Selene setapinnis,* were frequent and abundant in trawls.

3.3. Monthly dynamics of the target species

The GAM fitted for *X. kroyeri* CPUE_n (deviance explained = 18.6%) revealed a significant monthly variation ($p < 0.01$) with a two-peak pattern (Fig. 3A). The CPUE_n increased from February to April, when it reached the highest value, and progressively decreased along May and June. A second but lower peak was noted in September.

Both *A. longinaris* and *P. muelleri* had very low CPUE_n during the first five months, increasing from June, though with an unequal monthly pattern depending on the species ($p < 0.001$, Fig. 3B & C). For *A. longinaris*, abundance peaked in July–August and October (deviance explained = 13.9 %), whereas *P.* (deviance explained = 18.4 %) the CPUE_n was high from August to November.

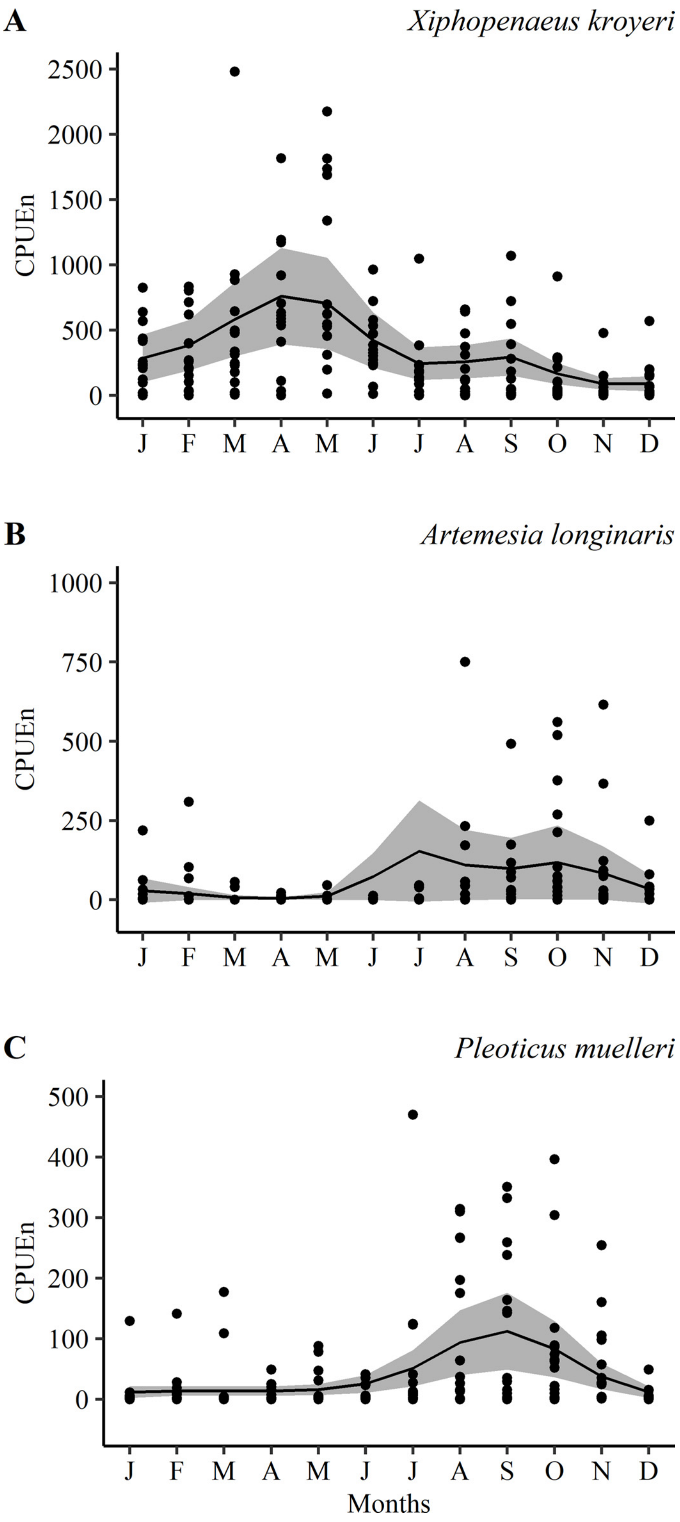

Fig. 3. Fitted negative binomial generalized additive model (GAM) applied to the (a) *Xiphopenaeus kroyeri*, (b) *Acetes americanus*, and (c) *Pleoticus mueleri* catch rates in the Armação do Itapocoroy, Brazilian Southern Coast. Solid black lines are the predict values, represents the approximate 95 % confidence intervals, and points are the observed data.

3.4. *Core and occasional species in bycatch*

A total of 158 species were considered bycatch. However, for the core species analysis, *A. americanus, Farfantepenaeus brasiliensis,* and *C. gracilicirrhus* were excluded because these species had very specific caught patterns, with low frequency but high abundance when caught. Of the 155 species remaining, only seven were core species, taking into account permanence and maximum abundance throughout the study period (Fig. 4), namely the crabs *C. ornatus* and *H. pudibundus*, sciaenids *P. brasiliensis*, *Stellifer* spp., and *I. parvipinnis*, and gastropods *B. cochlidium* and *O. urceus*. The remaining 148 species were considered occasional species. Additionally, our results showed distinct abundance and frequency patterns of the occasional species. For instance, there were species with a moderate frequency of occurrence values (between

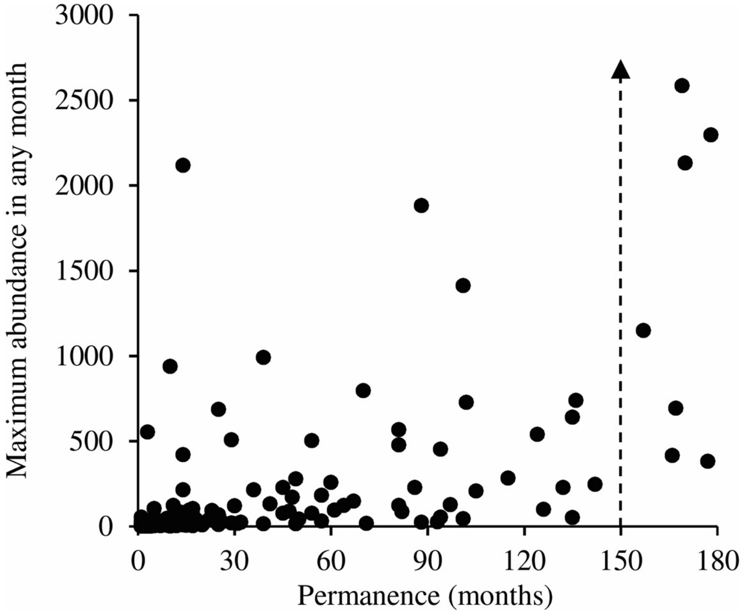

Fig. 4. The pattern of maximum abundance and permanence (frequency of occurrence) of the bycatch species, considering the monthly sampling efforts (180 months) from Armação do Itapocoroy, Brazilian Southern Coast. The vertical arrow indicates a discontinuity among common and occasional bycatch species.

200 and 300 appearances in samplings) and with high or moderate maximum abundance (around 500 individuals). Examples of these taxa are *Astropecten marginatus*, *Callinectes danae*, and *Trichiurus lepturus*.

3.5. Target and bycatch species association

The correlation analyses between target (3 species) and frequent bycatch species (> 10% frequency, which translated into 54 species) generated 144 correlation coefficients, of which 17 pairs were statistically significant ($p < 0.05$; critical correlation value from SEs = ± 0.2582, full correlation matrix available in Supplementary material 5). *X. kroyeri* was the target species that most correlated with the bycatch, with the following species positively associated with its capture: *Persephona lichtensteinii*, *P. punctata*, *L. senegalensis*, *B. cochlidium*, *Stellifer* spp., and *O. urceus*. In contrast, *Trachinotus falcatus* and *C. quadrumanus* were negatively associated with *X. kroyeri*. For *P. muelleri*, there were four species with positive and significant correlations: *S. dorsalis*, *U. brasiliensis*, *Symphurus tesselatus,* and *L. brevis*, whereas *A. americanus* had a negative association (−0.3). The target species *A. longinaris* correlated positively with the following species: *U. brasiliensis*, *S. dorsalis*, *L. brevis,* and *C. danae.*

3.6. Discard rate

There were pronounced variations in discard rate, with an estimated mean and confidence interval of 0.60 ± 0.024 during the study period. The best model selection (Gam9: AIC = −86.87; Deviance explained = 41.10 %), oscillations were influenced by year and abiotic variables of salinity, temperature, and TSS (Table 1). Only year and salinity ($p < 0.05$) were statistically significant for discard rate variations, whereas other covariates were not statically related to bycatch rate (Temperature: $p > 0.05$; TSS: $p > 0.05$). However, when these covariates were dropped out of the model, the AIC value increased. The partial effects of covariates on discard estimated from the best-fit GAM are shown in Fig. 5.

The best model revealed that the discard rate varied around 0.5 over the first seven years of the study, showing a tendency of constancy in this period (Fig. 5A). However, after 2008, there was an increase in discard rate values, reaching the highest values (~0.7) in the last year of this study, from 2012 to 2016. The discharge rate was higher (~0,8) at low temperature (< 16 °C), followed by a clear decreasing pattern to moderate temperature (~20 °C) and a stabilization with a progressive increase in temperature (Fig. 5B). The bycatch rate was positively related to salinity (Fig. 5C), reaching high values between 32 and 36 salinity. For TSS, a stable discard rate was observed between 1250 and 1750 $\mathrm{g\,m^{-3}}$ and, thereafter, a decreasing pattern related to three observed values to 2,250 $\mathrm{g\,m^{-3}}$. It is important to note that to TSS there were very high values over study, being that these results potentially influenced the relationship whit discard rate, generating low values for this parameter (Fig. 5D).

3.7. Bycatch diversity

Overall, diversity varied between 1.59. 15.08 for the whole study period (mean = 6.97 ± 2.33). The model that best explained the diversity variation (Gam1: AIC = 451.92; deviance explained = 43.5 %) was composed of year, month, salinity, chl-a, and TSS (Table 1, partial effects in Fig. 6).

The analysis of partial effects revealed a strong sinusoidal pattern of the covariate year ($p < 0.001$), with low diversity between 2002 and 2005 and an increasing trend from 2006 to 2008 (Fig. 6A). Higher diversity was observed around 2013 and 2015, followed by a decrease in 2016. No clear trend was observed per month ($p > 0.05$), except for a slightly increasing tendency in January, November, and December (Fig. 6B).

Regarding the contribution of the environmental variables, only salinity showed a linear and positive trend of variation with diversity ($p < 0.05$), with higher diversity occurring between 32 and 36 (Fig. 6D). There was no clear trend in Chl-*a* (Fig. 6C; $p > 0.05$) and TSS (Fig. 6E; $p > 0.05$). Although the effects of the covariates Month, Chl-*a*, and TSS were not statically related to diversity, dropping these covariates out of the model increased the AIC value.

4. Discussion

In the present study, the understanding of shrimp fisheries and their bycatch in the southern Brazilian coast were advanced using several methods, from simpler, such as a table comprising species frequency of occurrence and CPUE in number and biomass, to more complex, such as temporal models. The information evaluated here demanded an

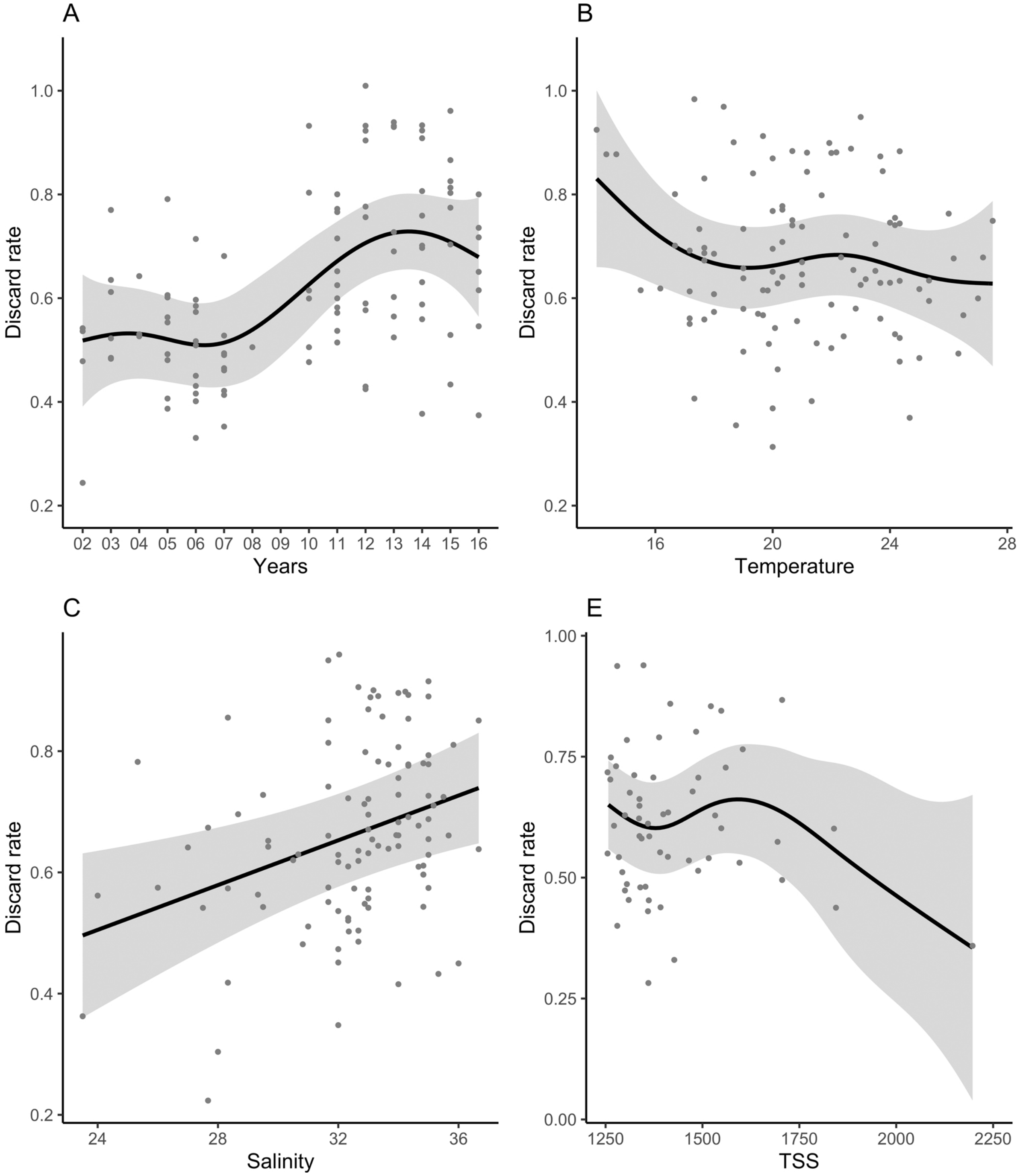

Fig. 5. Partial effects of the covariates on discard rate, extracted from best-fitted Gaussian GAM to temporal dataset in the AI ecosystem. Solid line represents the mean partial effect, grey bands represent the approximate 95 % confidence intervals, and points are the observed data. * Years were abbreviated as follow: 2002 = 02.

integrative approach owing to a distinct variable and factors associated with shrimp fisheries captures. In context with limited bycatch knowledge, our results, together with local fishermen knowledge, highlighted that few species are used from the many caught in the shrimp fishing activity and, furthermore, allowed the identification of the species used (e.g., *Paralonchurus brasiliensis* and *Paralichthys brasiliensis*) and discarded. Further, it was possible to clarify temporal patterns in captures, identifying February to May with the highest target species biomass, and lowest discard rate and bycatch diversity caught. The current closed season for the shrimp fishery in southern Brazil, from March to May, overlaps this period. However, this is a coincidence since this season was determined based on the target species biological aspects alone (Dias-Neto, 2011), without considering bycatch. The role of closed seasons in protecting shrimp populations is frequently debated by scientists, since this time period as a management action has been determined broadly (e.g., all South-Southern Brazilian coast), resulting in uneven levels of protection for species with asynchronous life cycles (Simões et al., 2017). However, our findings from the Armação do Itapocoroy area revealed that the closed season is effective in mitigating bycatch from an ecological perspective. This result highlights that this novel evaluation, combining target and bycatch information, can be very useful to determine more holistic actions to manage shrimp fisheries.

We also observed a strong temporal dynamics pattern in the

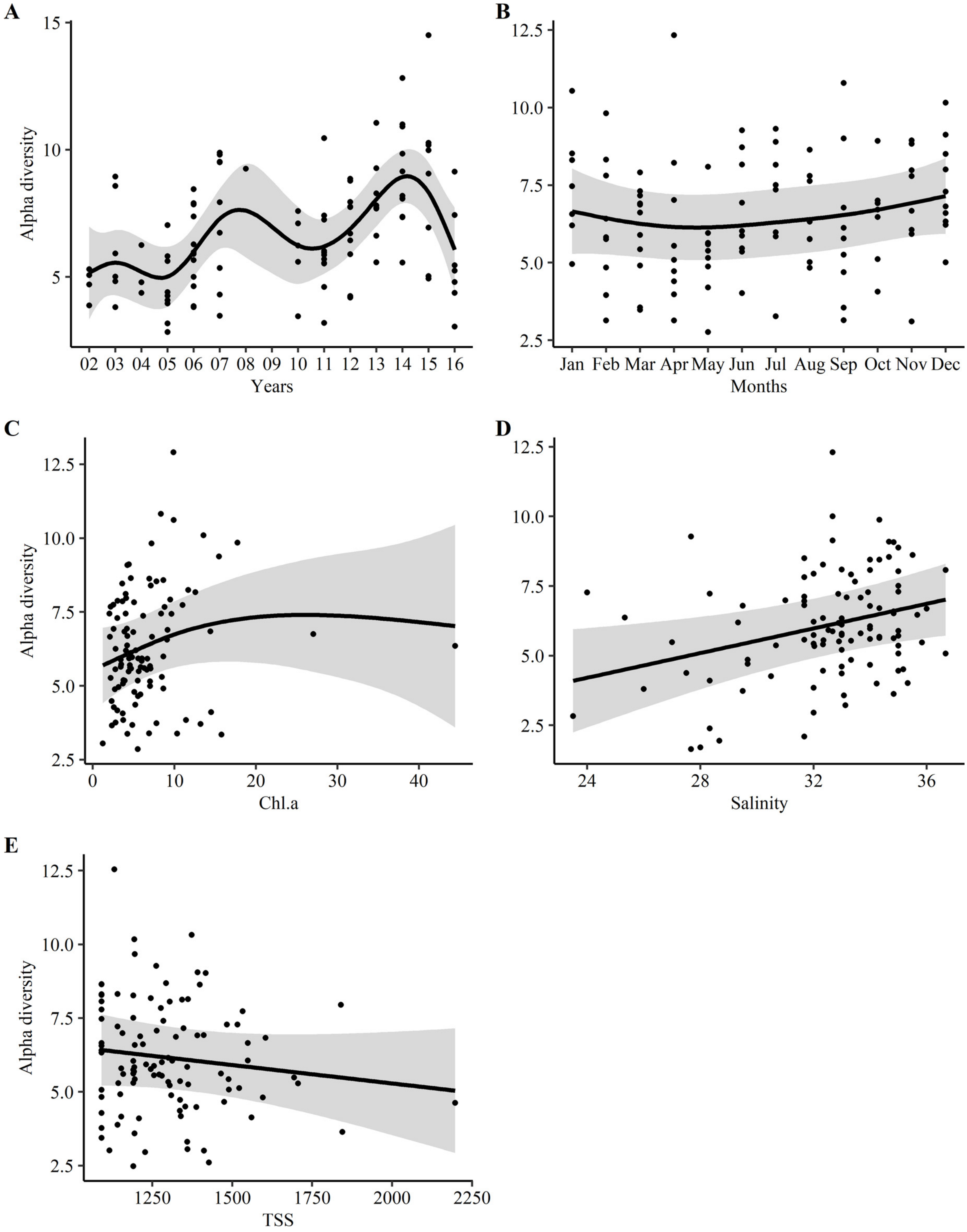

Fig. 6. Partial effects of covariates on bycatch diversity, extracted from the best-fitted GAM for temporal dataset in AI ecosystem. Solid line represents the mean partial effect, grey bands represent the approximate 95 % confidence intervals, and points are the observed data. * Years were abbreviated as follow: 2002 = 02.

captures in the study area, which is potentially related to oceanographic and chemical parameter variations. In general, there was an increase in temperature and decrease in Chl-*a* and TSS from winter to summer, whereas in autumn, the salinity increase was more pronounced (dry season). These periodic winter-spring oceanographic fronts are highly dynamic and complex, and probably related to different river discharge processes from nearby regions. On one hand, the Plata River plume advances into the ocean during the summer and rainy season, carrying bottom cold waters, nutrients, and sediments to the shallow marine areas in southern Brazil (Pereira et al., 2009). On the other hand, riverine discharge from Itajai-Açu and other small rivers in the summer also affects oceanographic fronts, generating coastal water with high temperatures and high concentrations of nutrients and organic material (Schettini & Carvalho, 1998). Both these oceanographic-riverine processes are related to high productivity in the Brazilian Southern Coast. The Plata River Front has been positively associated with an increase in abundance of subtropical species, such as *P. muelleri* and *A. longinaris* (Rodrigues-Filho et al., 2015), whereas the Itajai-Açu discharges have been related to higher abundances of *X. kroyeri* and other resident species (e.g., *C. ornatus*) (Branco, 2005; Rodrigues-Filho et al., 2015). The effects of these riverine processes were not completely mimicked in our measurements of the environmental parameters, presumably owing to the complexity of such processes and their interactions as well as by the limited number of parameters evaluated (some only by remote sensing, which reflects an averaged value).

Our results highlighted that target species had two abundance peaks, potentially associated with oceanographic features and a higher ecosystem productivity in the area, as discussed above. Between February and June (late summer and autumn) *X. kroyeri* reached a higher abundance, whereas, from August to October and November (late winter to spring), there was a moderate abundance of *X. kroyeri* and higher abundance of *P. muelleri* and *A. longinaris*. Correctly determining these periods is crucial to commercial trawling fleets in southern Brazil, which respond promptly to an increase in target species biomass, generating a high and concentrated effort in fisheries grounds, and a well-defined season shrimp (Dias-Neto, 2011). Commercial fleet effort is higher from January to February owing to restrictions from the closed season from March to May in the Southeast and South coast (IBAMA, 2008; Dias-Neto, 2011). Another restriction in the study area is the marine trawl exclusion zones from the coastline, which allows trawls only from one nautical mile of the coastline (IBAMA, 1992). Although both restrictions are important to shrimp fishery management in marine ecosystems, neither of them initially considered bycatch species, and there is no scientific data to evaluate how to mitigate fishing bycatch. This insufficiency of scientific management and lack of planning for the fishing sector are historically the norm in Brazil (Abdallah and Sumaila, 2007), adding further concerns in context with the current national increasing shrimp production and fisheries (Food Agriculture Organization - FAO, 2018), with potential for bycatch increase. For instance, in our study area, the number of vessels and income from shrimp fishing increased considerably (Acauan et al., 2018). This has generated more pressure on ecosystems, which reinforces the demand for more and scientifically based information on bycatch composition and its relationships with oceanographic, ecological, and fishery factors.

In our study area, bycatch is characterized by a high species richness, similarly to other shrimp fisheries from tropical and subtropical marine areas (Stobutzki et al., 2001). There were many occasional species with low abundance and few abundant and frequent species in our trawls, similarly to other tropical penaeid fisheries (Dell et al., 2009). The bycatch composition was dominated by Sciaenidae fish and crustaceans, with only seven species comprising the core bycatch species: *Bunodosoma caissarum*, *Olivaris urceus*, *H. pudibundus*, *C. ornatus*, *Isopisthus parvipinnis*, *Stellifer* spp., and *Paralonchurus brasiliensis*. All these species are abundantly distributed in coastal areas, and at least one ontogenetic phase form aggregates in shallow habitats with muddy/sandy bottoms (Melo, 1996; Froese & Pauly, 2019). These habitats overlap with areas used by shrimp trawlers, making these core species a substantial portion of the bycatch in Brazilian fisheries (Graça-Lopes et al., 2002).

In general, most of the bycatch resources were categorized as discards, with a few species categorized as incidental species. The presence of few desirable bycatch species and consequent high biomass discarded are typically related to trawl fisheries (Hall et al., 2000), mainly in areas without bycatch policies, such as Brazil (Guanais et al., 2015). The reasons for discarding a species vary and are frequently associated with economic or social aspects (Bellido et al., 2011; Damalas et al., 2015), such as the absence of a market value for the species and/or the non-recognition of the species as a usual fishing resource and/or food item. Independent of why species are discarded, it is fundamental to mitigate the discarding of this resource, which has contributed to the formulation of more rigorous policies to address this issue in some regions, as in countries from the European Union (European Commission, 2011). Even though discard reduction should be a priority to reach more sustainable fisheries, such reduction needs to be evaluated and adapted for local and regional contexts, taking into account social, economic, and ecological aspects (ex. Zhou, 2008; Veiga et al., 2016).

In this sense, discard rates provide valuable information about the fishery grounds (Davies et al., 2009, Kelleher, 2005). In the present study, this rate was approximately 0.60 ± 0.024, a value higher than the limits of the global mean for trawl fisheries (0.549 ± 0.049, Pérez Roda et al., 2019). This high discard rate associated with a considerable incidence of endangered species populations is a negative aspect of Brazilian shrimp fisheries (FAO, 2019). Therefore, there is currently an experimental effort conducted by the FAO (FAO; REBYC II, see: http://www.fao.org/in-action/rebyc-2/en) to establish baseline information and understand the bycatch from shrimp trawling, and to involve fishermen in this process. Although preliminary results were positive for capturing catch data using bycatch reduce devices (BRDs), with a bycatch reduction from 20% to 40% (FAO, 2019), this occurred only in three localities, and is not a reality in most of the Brazilian shrimp grounds.

Regarding temporal patterns, there were more months with high bycatch rates (> 0.90) in recent years, from 2010 to 2016. When contextualized with the already mentioned growth of the shrimp fishery activity (Acauan et al., 2018), our observations were a concern, owing to a possible scenario with more trawling to yield shrimp associated with higher bycatch biomass.

A greater diversity was obtained in salinities ranging from 32 to 35 and, possibly because some core species, such as *P. brasiliensis*, *Stellifer* spp., and *C. ornatus* had a negative relationship with salinity, allowing a wider influx of other occasional species throughout the community in high salinity (Rodrigues-Filho et al., 2015; Rodrigues-Filho et al., 2016). It was also possible to observe a high multiyear oscillation, which is common when analyzing temporal series (Magurran and Henderson, 2010). In our study area, there was a high variation in oceanographic conditions, which possibly led to alterations in community structure and diversity patterns over the years. In the 20 year study period, there were several El Niño-Southern Oscillation (ENSO) events, which are potential drivers to shift environmental conditions in coastal ecosystems (Pereira and D'Incao, 2012). Although ENSO effects were not formally explored in this study, we have evidence that these could influence marine communities and their diversity in our study area (Paes and Moraes, 2007).

Another crucial attribute from bycatch diversity data was its short-term fluctuation, with a slight increase in the initial years, followed by interannual changes from 2007 to 2016, but without changes in the long-term, which denoted depletion or increase in diversity over the years. This finding was positive and might be a result of the shrimp closed season, which started in southern Brazil in 1999 with temporarily decreased fishing efforts on marine habitats. Despite reports that some fishermen do not adhere to closed seasons (Musiello-Fernandes et al., 2017), this illegal fishing has not been on a massive scale in our study area, but was restricted to limited fishermen to avoid legal penalties (Prof. Dr. J.O. Branco, Vale do Itajai University, personal communication).

The management of small-scale fisheries is very complex (Berkes et al., 2001), as observed in the debate by researchers and fishermen regarding the closed season in Brazilian shrimp fisheries. From our results, the accuracy of the current closed season from March to May was corroborated at the community level, since this period had a greater abundance of target species, mainly *X. kroyeri*, and lower rate of disposal and low bycatch diversity than other possible periods of closure. In context, it is interesting to compare it with past closed seasons, such as between October and December (IBAMA, 2006), which revealed a lower abundance of target species and greater diversity and discard rate. It is evident that in a period with smaller shrimp and larger bycatch catches, efforts would be greater to maintain catches, resulting in more impacts on ecosystems and lower profits. However, based on our results, it is considered that shrimp fisheries in Brazil could be reassessed, with an alternative of exchanging the closed season for fishing seasons, which would be defined in months where the shrimp abundance is high and discard abundance and diversity is low. Potentially, this strategy would maintain a low discard rate, decreasing incidental captures. At this point, it is fundamental to understand the economic aspects of this alternative management method, with an evaluation of the subsistence and local value market for incidental resources that would not be caught in shrimp fishing seasons.

5. Conclusion

The long-term capture data provided a robust model to understand the bycatch dynamics in artisanal shrimp fisheries on the southern Brazilian coast, where bycatch is still high. Although we did not formally evaluate the use of BRDs to mitigate bycatch, this is effective to reduce incidental captures from commercial fishing. In Brazil, results from experimental studies with BRDs are promising; however, there is currently no obligation to implement BRD devices in commercial fleets in current fisheries policies.

It is not easy to manage shrimp fishing and its bycatch, mainly in areas where management structures are still being developed, and information is limit, as in our study area. However, it any action and/or goal established to reduce capture and ensure ecosystem health should be based on high-quality data and indicators estimated from primary data. The results from our study provided information from integrated analyses, which could be adopted to develop a more coherent approach for bycatch management in southern Brazil.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

L. Jorge Rodrigues-Filho: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Marina Dolbeth:** Methodology, Writing - review & editing. **Jurandir J. Bernardes Jr:** Formal analysis, Writing - review & editing. **Igor Ogashawara:** Methodology, Resources. **Joaquim O. Branco:** Writing - review & editing, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105587.

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