Fisheries Research 175 (2016) 132–141

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

A spatial multivariate approach to understand what controls species catch composition in small-scale fisheries

M. Grazia Pennino[a,*], Mario J.F. Thomé-Souza[b], Adriana R. Carvalho[a], Luiz Carlos da Silveira Fontes[b], Cristiano Parente[c], Priscila F.M. Lopes[a]

[a] Fishing Ecology Management and Economics (FEME)—Universidade Federal do Rio Grande do Norte—UFRN, Depto. de Ecologia, Natal, RN, Brazil
[b] Universidade Federal de Sergipe—UFS, Depto. de Engenharia de Pesca e Aquicultura—DEPAq, São Cristóvão, SE, Brazil
[c] Unidade de Operação e Produção de Petróleo e Gás da bacia de Sergipe e Alagoas—UOSEAL, Arcaju, SE, Brazil

ARTICLE INFO

Article history:
Received 5 August 2015
Received in revised form
30 November 2015
Accepted 30 November 2015

Keywords:
Catch composition
Fishing effort
Multivariate analysis
Multi-species

ABSTRACT

Many multivariate methods have been applied to small-scale fishery data in an attempt to distinguish factors that characterize the fishing activity and influence catch composition. While such approaches are important, they are still incomplete for including the spatial structuring in the analysis, a non-random fundamental and functional component of the ecosystem. This study fills this gap by identifying, describing, and quantifying factors that influence the fleet type of tropical small-scale fisheries using a multivariate spatial approach. The example data came from two Brazilian States where two main fleets, open water canoes and motorized boats, operate. Different complex combinations of fishing, environmental and spatial factors affect the structure of the fish catch composition of each fleet. Motorized boats showed strong spatially-structured species catch composition in comparison with open water canoes. Similar environmental factors, such as type of the seabed and depth, but different fishing variables (gear vs crew size), affected the species catch composition of these vessel categories. Despite some overlap, each fleet focuses on a relatively distinct set of species groups and exploits habitats at different spatial scales. These results suggest that different sets of regulations should be considered for each fleet type within a specific spatial scale. It also shows that multi-species models that aggregate groups of species is a more efficient alternative than single-species assessment models for small-scale fisheries, as these are multi-specific and multi-gear, with scattered landing harbors, features that make such fisheries a complex challenge for management.

1. Introduction

Marine fisheries worldwide are characterized by the coexistence of small-scale fisheries with large-scale or industrial fisheries (Panayotou, 1982). Such coexistence is limited however to the wider notion of sharing the oceans, as the two kinds of fisheries differ in all other regards, besides the scale of operations, such as technology used, degree of capital investment and employment generation (Ruttan et al., 2000). Nevertheless, data collection systems and public policies on fisheries have focused almost exclusively on the industrialized fishing sector, presumably because it is easier to monitor and collect more data at large scale.

However, after more than three decades of intense fisheries development, it is estimated that small-scale fisheries still account for more than 90% of the world's capture fisheries and fish workers, and supply around 50% of all global fish catches, inland fisheries included (Béné, 2005; FAO, 2012). Such fisheries provide a valuable source of animal protein for billions of people worldwide and often underpin local economies in coastal, lake and river-side communities (www.fao.org/cofi/en). Despite their importance, many small-scale fishing communities continue to be marginalized and this has led to policies that inadvertently undermine their ability to adapt to global change processes, such as urbanization, globalization and climate change (Béné and Friend, 2011). Thus, there is an urgent need to fully understand the dynamics of small-scale fisheries and explore the factors that drive the activity.

In particular, small-scale fisheries, especially the ones taking place in tropical countries, capture multiple species using various fleets and gear types across multiple landing stations. Consequently, traditional management options based on single-species assessments can be challenging to implement (Lucena et al., 2002). The Ecosystem Approach to Fisheries Management (EAFM) could

* Corresponding author.
E-mail address: graziapennino@yahoo.it (M. Grazia Pennino).

http://dx.doi.org/10.1016/j.fishres.2015.11.028
0165-7836/

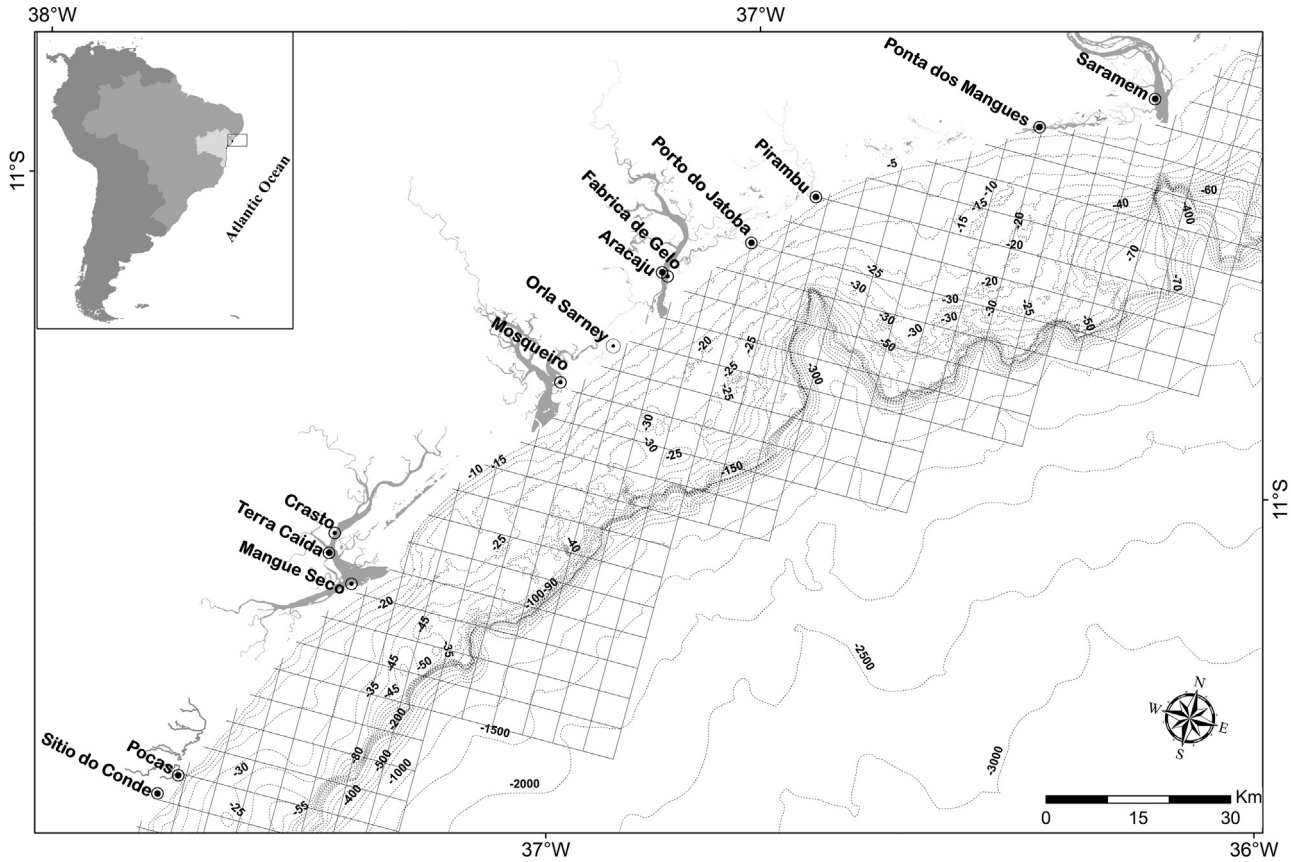

Fig. 1. Map of the study area. Feature on the coast of Brazil the states of Sergipe and the North Bahia showing the sampled harbors along the coast and the rivers, from the North to the South: São Francisco, Japaratuba, Sergipe, Vaza-Baris, Real-Piauí and Itapicuru. In the marine area the depth contours in meters and the spatial grid used for data analysis.

be a viable alternative to this type of situation, as it recognizes that fisheries are embedded into the environment, and fish species are related to each other, not being harvested independently (Jennings et al., 2001; Gascuel et al., 2012). Some of the mandatory requirements for the implementation of the EAFM are the identification and quantification of factors influencing the dynamics of fishing activities and the structure of the fish community (http://www.fao.org/fishery/topic/13261/en).

Several studies have tried to characterize the fleet dynamics of small-scale fisheries by analyzing catch composition using multivariate methods (e.g., Pelletier and Ferraris, 2000; Frédou et al., 2006; Cetra and Petrere, 2014). Such techniques help obtain an integrated picture of the structure of the system, the factors that characterize the fishing activity and influence catch composition, and the species that drive fishing dynamics (Frédou et al., 2006). While such approach is important, it is still incomplete if it ignoring spatial structuring of species communities, a fundamental non-random functional component of the ecosystem. Spatial structuring affects species distribution either because biotic processes such as growth, mortality or predation can only occur under certain spatial conditions and/or because species distribution are shaped by other spatially-structured data (Legendre and Legendre, 1998).

However, spatially structured data are seldom incorporated into catch composition analyses for multi-species fisheries, especially marine fisheries (Erisman et al., 2011). This study fills this gap by identifying, describing, and quantifying factors that influence tropical small-scale fisheries in Brazil, using a spatial multivariate approach to understand catch composition as an outcome of the environment, fishing factors and space.

Identifying this sort of baseline for small-scale fisheries could be a critical step to implement marine tropical fisheries management measures that are more likely to succeed. In particular, understanding how and if the spatial scale influences fishing activities and the fish catch composition will help to determine the proper spatial scale for management, and evaluate how different conservation policies may affect fishing economies.

2. Material and methods

2.1. Background

In Brazil, as in other coastal developing countries, small-scale fisheries play a unique role of biological, economic and social relevance. Nevertheless, worldwide, such fisheries have also been disregarded by uniform official measures applied over entire countries, ignoring cultural, social and environmental local differences. For instance, Brazil is everything but uniform when it comes to fisheries, especially given its more than 8000 km of coastline, with large estuaries and a continental shelf that varies widely. Such breadth in coastline and habitat implies a high degree of heterogeneity. In the Brazilian northeast, for example, small-scale fisheries can comprise up to 90% of the catch, a figure that varies from year to year, depending on many economic and social factors.

2.2. Study area

This study was based on information from fisheries that took place on the continental shelf of the states of Sergipe and the north-

ernmost coast of Bahia, along approximately 240 km of coastline (Fig. 1). This area receives the flow of six rivers: São Francisco (Brazil's second longest river), Japaratuba, Sergipe, Vaza-Barris, Piauí-Real and Itapicuru. The area comprises the narrowest portion of the continental shelf in Brazil, ranging between 15 and 35 km, with a depth in the shelf break of approximately 50 m.

2.3. Data

Landings data were collected daily from January 2012 to August 2014 at 13 landings sites of small-scale fisheries, by harbor observers, distributed along this coast. Information on fishing operations (date, vessel name, landing site, fishing ground) and vessel category (type, gear, and fishing crew) was obtained directly from the fishers. Among the fishers that were landing in these harbors, 50 had been previously invited to track their fishing operations, with the use of a GPS. In particular, 30 GPS Garmin® e-Trex units were distributed among open water canoes (hereafter "OWC"), while 20 GPS Garmin® Chartplotter 421S units were distributed to motorized boats ("MB"). Tracks were downloaded at the moment of the landings as. DXF files using the MapSource® software and were then plotted on a geo-referred spatial $1^\circ \times 1^\circ$ grid of the ocean area. Fishing grounds were identified taking into account the track, speed and distance from the coast, using an average point between the starting and finishing point of each fishery operation. In cases in which hauls were performed in different fishing grounds in a fishing trip, we considered them as independent trips.

Whenever possible, catches were identified to species level, otherwise to genus or family level. After identification, the species abundance was measured. We identified 84 species, but excluded those that comprised less than 1% of the landings in kg. The OWC vessel category comprised 7169 fishing trips and 13 species comprising >1% of OWC landings (Table 1), while the MB category comprised 555 fishing trips and 19 species comprising >1% of MB landings (Table 2). The species included in the analyses represented 88% and 94% of the total landings, respectively.

2.4. Fishing factors

We considered four factors as descriptors of fishing tactics: trip duration, type of gear, crew size and month of the fishing trip (Table 3). The duration of a trip usually depends on the vessel characteristics, such as type of propulsion, engine power (if any), and storage and preservation capacity, and hence influences the fishing grounds that can be reached. Consequently we used trip duration as a proxy for fishing grounds.

Although 14 gears were identified, we analyzed the data for three main groups, which comprised 97.8% of the landings. The first gear group (hereafter "LIN") includes handline and longline. Gillnets, which were generally made of monofilament nylon and could be fixed to the bottom or drifted, were categorized as "GIL". Their meshes ranged from 35 to 130 mm knot to knot, while their overall length ranged between 800 and 3600 m. The third gear group included trawl fishing ("TRA"), which was done on the continental platform, with the use of 20 mm meshes.

The OWC category includes sailing motorized boats shorter than <10 m, without a cabin. The MB group includes motorized vessels with cabins, ranging between 10–15 m long. All the vessels considered in these two categories operate from the coastline to the shelf break up to 60 m deep. Trips can last from one day, for the fishing trips that take place along the coastlines, to three to ten days, for the fisheries that operate close to the continental slope.

2.5. Environmental variables

We considered three oceanographic variables, (1) Sea Surface Temperature—SST, (2) Mixed Layer Depth—MLD, and (3) Net Primary Production—NPP, and four bathymetric features, (1) depth—DEPTH, (2) slope—SLOPE, (3) distance to land—LANDDIST and (4) type of seabed—SEABED (Table 3).

MLD and SST were extracted from NODS_WOA94 long-term monthly mean climatology data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site (http://www.esrl.noaa.gov/psd/). MLD was computed from climatological monthly mean profile of potential temperature and potential density based on a density change from the ocean surface of 0.125 sigma units (Monterey and Levitus, 1997). NODS_WOA94 SST field calculation is described in Levitus and Boyer (1994). For the NPP variable we retrieved global grids, calculated as a function of chlorophyll, available light, and photosynthetic efficiency using the entire SeaWIFS chlorophyll record, on the Ocean Productivity web site (http://www.science.oregonstate.edu/ocean.productivity/index.php).

We obtained DEPTH and SEABED from oceanographic surveys performed in the study area within 1934 km^2 along 36 linear transects covering 800 km. Bathymetric maps were obtained using an ecosonda, while a Van Veen dredge was used to collect sediment samples, at distance points of 2.0×2.5 km, until a maximum depth of 60 m. Samples were taken during March, July and October 2012 and January 2013. The sediment analyses were conducted a posteriori for particle size using mechanical sieving through a laser particle size analyzer. In order to obtain the depth at any location of the study area we interpolated the bathymetric maps, using GRASS GIS (http://grass.fbk.eu). For that, we first rasterized the contours with a resolution of 500 m and then we used the function "*r.surf.contour*", following the guidelines provided in the website http://grass.osegeo.ord/wikiContournlines_to_DEM. A slope map was derived from the DEPTH map, using the "*slope*" function of the "*raster*" package in R software (Hijmans, 2013). We retrieved distance to land at a $0.5^\circ \times 0.5^\circ$ resolution from the AquaMaps dataset (Kaschner et al., 2008).

The shapefile "type of seabed" classified the seabed in six levels: Sand, Fine-sand, Coarse-sand, Gravel, Mud and Sandy-mud. However, to simplify the analysis, we re-aggregated the categories as: Sand (including sand, fine-sand and coarse-sand), Mud (mud and sandy-mud) and Gravel.

Finally, all the environmental data were gridded at $1^\circ \times 1^\circ$ resolution using the "*raster*" package in R to match fishing data.

In order to deal with variable correlations, a Principal Component Analysis (PCA) was applied to all the environmental descriptors. The PCA was performed using the "*pca*" function of the "*vegan*" package of the R software (Oksanen et al., 2014).

2.6. Data analyses

The analytical strategy involved five steps (Fig. 2): (1) Cluster Analysis (CA) to analyze the species catch composition for each vessel type category; (2) Similarity percentage analysis (SIMPER) to assess the most representative species of each identified cluster for each vessel category; (3) non-metric multidimensional scaling (NMDS) to discriminate harbor sites with respect to species catch composition for each vessel category; (4) partial Redundancy Analysis (RDA) to explore links between fishing and environmental factors and the species catch composition for each vessel category; (5) partial RDA to assess influences between spatial and environmental factors and the species catch composition for each vessel category.

While the first three steps of the methodology followed the procedure of Clarke and Warwick (1994), the last two ones are a new

Table 1
Main species (>1% of the landings in kg) caught by the artisanal coastal fishery performed with o pen water canoes in the Northeastern Brazil.

Family	Species	Total weight (kg)	Relative abundance (%)
Sciaenidae	*Micropogonias furnieri*	54,794.90	19.58%
Sciaenidae	*Macrodon ancylodon*	40,297.22	14.40%
Ariidae	*Bagre* spp., *Sciades* spp. (Ariid group)	30,531.00	10.91%
Carcharhinidae	*Rhizoprionodon porosus*, *Carcharhinus limbatus* (Shark group)	25,859.50	9.24%
Ariidae	*Sciades proops*	24,041.09	8.59%
Sciaenidae	*Cynoscion* spp.	23,472.92	8.39%
Dasyatidae	*Dasyatis* spp.	16,152.39	5.77%
Haemulidae	*Conodon nobilis*	12,801.71	4.57%
Lutjanidae	*Larimus breviceps*	12,498.70	4.47%
Centropomidae	*Centropomus* spp.	6933.99	2.48%
Scombridae	*Scomberomorus brasiliensis*	3112.29	2.34%
Carangidae	*Caranx hippos*	3329.00	1.19%
Gerreidae	*Diapterus auratus*	3112.29	1.11%

Table 2
Main species (>1% of the landings in kg) caught by the artisanal coastal fishery performed with motorized boats in the Northeastern Brazil.

Family	Species	Total weight (kg)	Relative abundance (%)
Penaeidae	*Xiphopenaeus kroyeri*	143,447.36	38.58%
Penaeidae	Prawn group	21,746.50	5.85%
Lutjanidae	*Lutjanus jocu*	17,937.50	4.82%
Lutjanidae	*Lutjanus* spp.	16,728.40	4.50%
Penaeidae	*Litopenaeus schmitti*	14,941.50	4.02%
Lutjanidae	*Lutjanus analis*	13,796.39	3.71%
Sciaenidae	*Macrodon ancylodon*	13,252.50	3.56%
Carangidae	*Caranx crysos*	11,528.50	3.10%
Serranidae	*Mycteroperca bonaci*	10,492.50	2.82%
Scombridae	*Acanthocybium solandri*, *Scomberomorus cavalla*(Scombrid group)	9065.50	2.44%
Carcharhinidae	*Rhizoprionodon porosus*, *Carcharhinus limbatus* (Shark group)	8703.50	2.34%
Carangidae	*Seriola* spp.	8476.42	2.28%
Scombridae	*Thunnus* spp., *Katsuwonus pelamis*, *Auxis* spp. (Tuna group)	7073.50	1.90%
Carangidae	*Caranx hippos*	5276.52	1.42%
Lutjanidae	*Ocyurus chrysurus*	5188.45	1.40%
Sciaenidae	*Cynoscion* spp.	5154.43	1.39%
Ariidae	*Bagre* spp., *Sciades* spp. (Ariid group)	4429.45	1.19%
Dasyatidae	*Dasyatis* spp.	4738.50	1.45%
Lutjanidae	*Lutjanus synagris*	3871.45	1.04%

Table 3
Summary of variables included in analyses as potential effects influencing species catch composition.

Variable	Description	Units	Thematic group
Depth	Mean fishing depth in the fishing location	In meters	Environmental
Distance to land (LANDDIST)	Mean distance to land in the fishing location	In meters	Environmental
Slope	Seabed slope in the fishing location	From 0 to 90°	Environmental
Type of Seabed	Type of seabed in the fishing location	Sand, Mud and Gravel types	Environmental
Sea Surface Temperature	Monthly SST mean in the fishing location	In °C	Environmental
Mixed Layer Depth (MLD)	Monthly mean profile of temperature and density in the fishing location	In 0.125 sigma units	Environmental
Net Primary Production (NPP)	Monthly NPP in the fishing location	In mg C/m^2/month	Environmental
Trip duration	Time duration of the trip	From 1 to 10 days	Fishery
Type of gear	Fishing gear used during the fishing trip	LIN/GIL/TRA	Fishery
Crew size	Number of fishers present during the fishing trip	From 1 to 8	Fishery
Month	Month in which the fishing trip took place	From January to December	Fishery
Latitude	Mean latitude of the fishing trip	Geographical coordinates	Spatial
Longitude	Mean longitude of the fishing trip	Geographical coordinates	Spatial

attempt to better understand the species catch composition in a spatial framework.

2.6.1. Identifying species catch composition

A standardized species landing data matrix was created for each vessel category using fishing trip as the data unit. Data were log transformed to down-weight extreme values. CA was used to explore the catch composition in each vessel type category and to identify which species are usually caught together. The Bray–Curtis index was used as a similarity measure and the Ward's method as the clustering algorithm. Ward's method uses an analysis of variance to evaluate the distances between clusters, attempting to minimize the total within-cluster variance. This makes it especially useful to find compact clusters, which is essential for the identification of assemblages showing a significant degree of association (Shimodaira, 2002). In addition, it is possible to assess each cluster uncertainty by obtaining their approximate unbiased *p*-values (AU *p*-values) (Shimodaira, 2004).

The CA analyses were carried out using "*pvclust*" package in R software (Suzuki and Shimodaira, 2006).

2.6.2. Assessing the most representative species

SIMPER was used to determine the species that most characterize the identified clusters. SIMPER breaks down the contribution of each species to the observed similarity between clusters by decomposing average Bray–Curtis dissimilarities into percentage contributions. Therefore, variations in the landings of the most

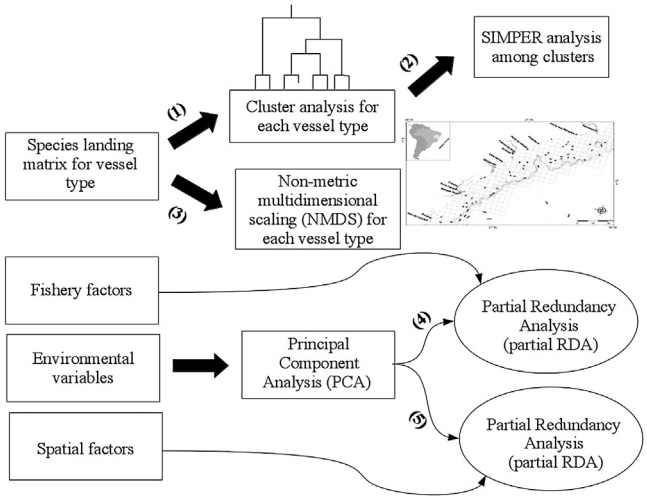

Fig. 2. Flowchart of major statistical analyses used to assess structure of species catch composition in relation to fishing, environmental and spatial factors.

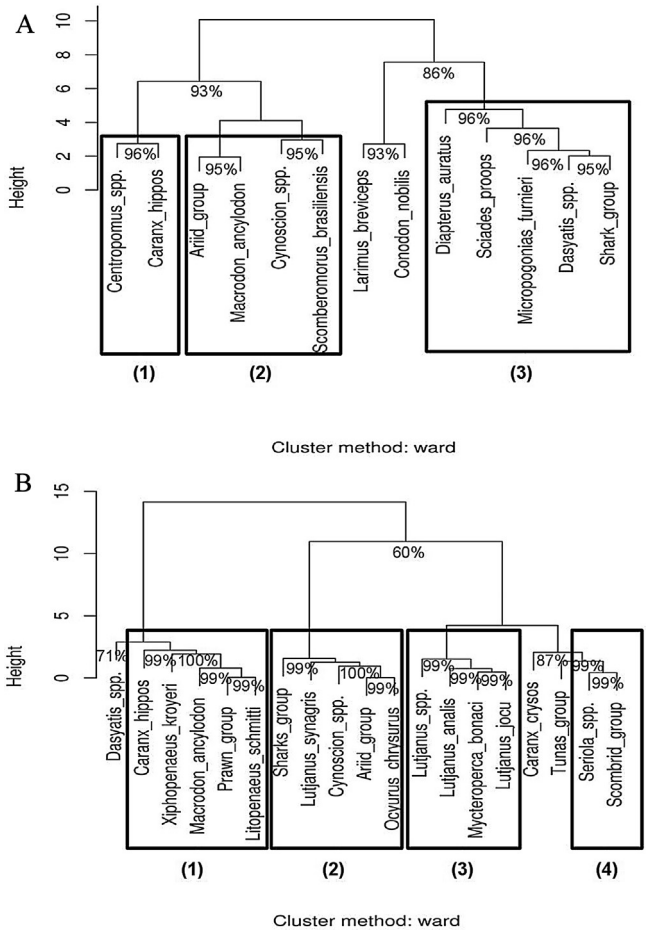

Fig. 3. Cluster dendrogram with BP (Bootstrap Probability) value (%): (a) open water canoes vessel category; (b) motorized boats vessel category.

representative species generate the main sources of dissimilarity between assemblages.

2.6.3. Discrimination of harbor sites

Patterns in species catch composition among harbor sites were examined using non-metric multidimensional scaling (NMDS). This method plots similar objects close to one another in the ordination space, using an iterative approach to ordinate samples in a reduced number of dimensions (Legendre and Legendre, 1998). Bray–Curtis was again used as the distance measure. The SIMPER and NMDS analyses were performed for both vessel types using the "*vegan*" package in R software.

2.6.4. Assessing links among fishing and environmental factors and species composition

We ran a RDA to explore the relationships between catches, fishing and environmental factors. In RDA it is possible to specify co-variables (partial RDA), which allows testing the effect of a particular explanatory variable after removing the variation explained by the co-variables. We used this technique to assess how much of the variation in the catch composition is uniquely explained by fishing factors (fishing set), by the environment (environmental set) or by both.

The fishing set included the following variables: trip duration, gear, crew size and month, while the environmental set included DEPTH, LANDIST, SEABED, NPP and SLOPE. The latter were the variables selected after the PCA, whose first and second principal component explained together 67.3% of the variability of the dataset.

To divide the total variance of the catch, we ran three different RDA models: a full model with all environmental and fishing sets as explanatory variables, a partial model only with the environmental set, and a third one only with the fishing set.

The significance of each RDA model was tested by Monte Carlo permutation tests (Manly, 1991) to retain the ten variables that best explain the variation in species composition. For this purpose we used the "*vegan*" package of the R software.

2.6.5. Distinction between environmental and spatial effect

Spatial autocorrelation can be defined as the property of random variables taking values, at pairs of locations a certain distance apart, that are more (positive autocorrelation) or less (negative autocorrelation) similar than what would have been expected for randomly associated pairs of observations (Legendre, 1993). In our case, the observed species catch composition might be influenced by the species composition in the surrounding locations due to contagious a biotic and biotic processes. Similarly, environmental variables used to describe the locations are neither randomly nor uniformly spatially distributed, but structured by physical processes causing gradients and/or patchy structures. One consequence of this general property of ecological variables is that the assumption of independence of the observations is not respected (Legendre, 1993). Therefore, it is necessary to incorporate the spatial structure of the data within the modeling process.

We therefore ran three models using RDA to explain catch composition: a full model with all environmental and geographical coordinates as explanatory variables, a partial model only with the environmental variables, and a partial model only with the spatial variable (location). By doing so, we could divide the variation of the species assemblages as follows: (a) non-spatial environmental variation, (b) spatially-structured environmental variation, (c) spatial variation that is not shared by the environmental variables and (d) unexplained, non-spatial variation.

3. Results

3.1. Open water canoes (OWC) vessel category

The catches analyzed for open water canoes (OWC) comprised 13 species of nine families. The Sciaenidae family dominated the catch by abundance (in weight) (48.84%), followed by Ariidae (19.50%), Carcharhinidae (9.24%), Daysatidae (5.77%), Haemulidae (4.57%), Centropomidae (2.48%), Scombridae (2.34%), Carangidae

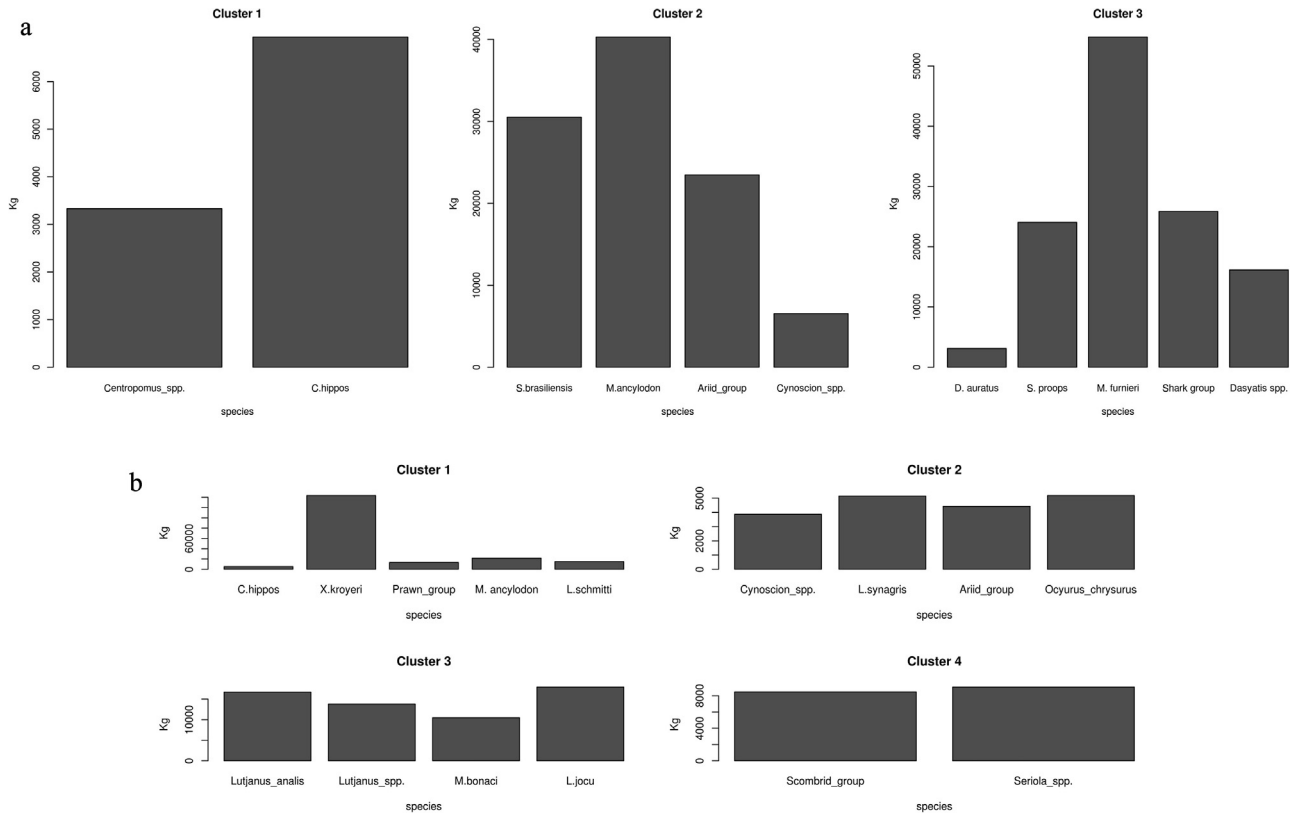

Fig. 4. Total catch of species belonging to the different clusters of (a) open water canoes vessel category and (b) motorized boats vessel category.

(1.19%) and Gerreidae (1.11%). The main fishing gears used by fishers fishing by OWC were gillnets (88.03%) and lines (11.97%).

The dendrogram resulting from the CA analysis together with the AU (Approximately Unbiased), *p*-values and BP (Bootstrap Probability), shows three main groups, significant at least at the 95% confidence interval ($p < 0.05$) (Fig. 3a; Table 4). The first discernible cluster comprised *Caranx hippos* and *Centroppomus* spp. The second included the Ariidae, *Macrodon ancylodon*, *Scomberomorus brasiliensis*, and *Cynoscion* spp. The third cluster was represented by *Diapterus auratus*, *Sciades proops*, *Micropogonias furnieri*, *Dasyatis* spp. and Carcharhinidae. All the other species were included in non-significant groups.

According to the results of the SIMPER analysis, *C. hippos* was the main contributor (43%) to the similarity between the samples of the first cluster and to the dissimilarity in relation to the other clusters (Table 4). The second cluster is distinguished from the others by the high contribution of *S. brasiliensis* and *M. ancylodon* (25% and 26% respectively). The third group is mainly represented by *M. furnieri* (42%).

The first cluster had the lowest landing mean values (5131 kg), while the second cluster had the highest values (25,209 kg). Mean landings values of the third cluster (24,792 kg) are similar to the second one (Table 4). Fig. 4a shows that in the first cluster the most abundant species is *C. hippos,* whereas *M. ancylodon* and *M. furnieri* are the most abundant ones in clusters 2 and 3, respectively.

The NMDS plot supports aggregations resulting from the CA dendrogram. In addition, Fig. 5a shows the harbor names on the NMDS plot, highlighting which species drive the difference in species composition in landings of the different harbors (see also Table 4). For example, the catch compositions of the harbors "Mangue Seco" and "Saramem" were driven by species included in the first cluster, specifically by *C. hippos*. The harbors "Pirambu" and "Ponta dos Mangues" were mostly represented by catches of *M. ancylodon,* while "Sítio do Conde" and "Mosqueiro" by *S. brasiliensis.* Finally, "Castro", "Porto Jotoba", "Orla Sarney" and "Terra Caída" was represented by species of the third clusters. Particularly, landing of "Orla Sarney" was mostly driven by *S. proops,* "Castro" and "Porto Jotoba" by *M. furnieri* and "Terra Caída" by Carcharhinidade. No spatial cohesion among landings harbors was found.

The RDA showed that environmental and fishing factors had a significant effect on the catch of fish species for OWS ($t = 3.19$, df = 10, *p*-value <0.001). These variables explained jointly 71% of the total variance of the selected species. Among the fishing factors, the type of gear was the most important, explaining 35% of the total variance, followed by month (20%) and trip duration (15%). Among the environmental variables, DEPTH was the most relevant factor: it explained 16% of the total variance, followed by SEABED (8%). Type of gear and month of the fishing trip were the most important factors driving species composition in the first and second cluster (Table 4). Species composition of the second cluster was also influenced by NPP and LANDDIST. In contrast, trip duration and SEABED were the most important drivers of species composition of the third cluster (Table 4). The partial RDA, conditioned to environmental variables, explained 35% of the variance (Monte Carlos, $F = 3.16$, *p*-value <0.001), showing that fishing factors explain a significant proportion of the variation in species catch composition. On the other hand, 21% of the variance of the partial RDA was explained by the removal of fishing variables (Monte Carlo: $F = 2.06$, *p*-value <0.001). This suggests that environmental variables were also important, although less than the fishing ones, to explain the variation in the catch composition (Table 4).

The full model RDA (environmental and spatial variables together) for catch composition explained about 54% of its total variance ($t = 3.54$, df = 8, *p*-value <0.001). SEABED was the most important environmental factor, explaining 25% of the total variance, followed by DEPTH (15%). NPP, LANDIST and latitude and

Table 4
Summary of main results of the analytical approach. Data refer to landings by open water canoes.

Cluster	Main species	Associated species	Mean total catch (kg) for cluster	Landing harbors	No. of trips	Main gear	Fishing period (month)	Mean trip duration (h)	Main aspects fishing ground	Main drivers	Main thematic group
1	*C. hippos*	*Centropomus* spp.	5131	Mangue Seco, Saramem	1257	Seine & Gill net	May & June	>1 day	Reef & Muddy seabeds 2–10 m	Type of gear Month	Fishing factors
2	*M. ancylodon* & *S. brasiliensis*	*Cynoscion* spp. Ariid group	25,209	Mosqueiro Sitio do Conde Pirambu Ponta dos Mangues	3176	Gill net	Dec, Jan, Feb. & March	>1 day	Reef & Muddy seabeds 5–10 m	Type of gear Month NPP LANDIST	Fishing factors
3	*M. furnieri*	*S. proops* Shark group *Dasyatis* spp. *D. auratus*	24,792	Castro Porto Jatoba Terra Caída Orla Sarney	5071	Gill net	All month	>1 day	Muddy & sandy seabeds 5–10 m	Trip duration SEABED	Fishing factors
Not significant	*L. breviceps* *C. nobilis*										

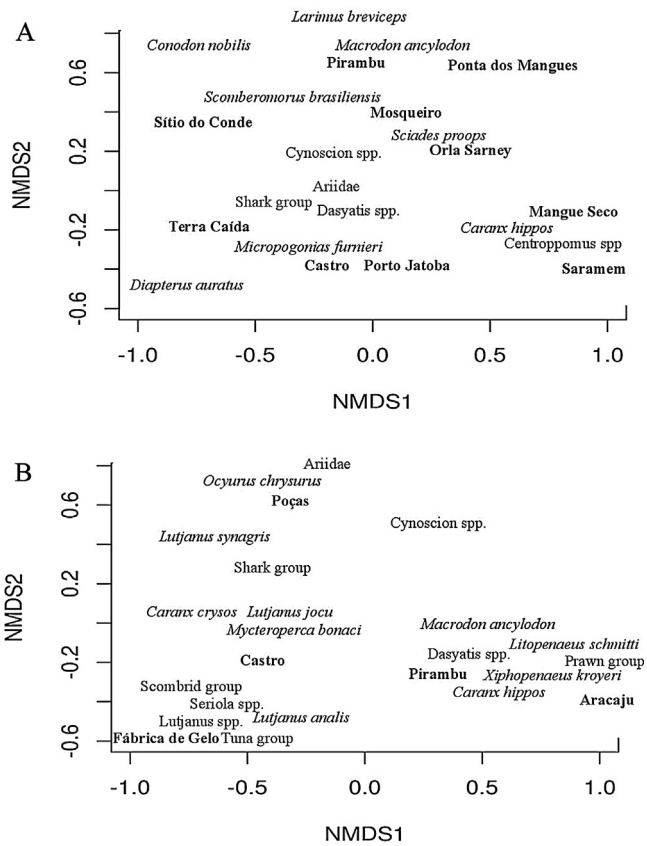

Fig. 5. Two-dimensional NMDS plot of catch groups for harbors on Bray–Curtis similarity: (a) abundance is relative only for the 13 selected species for the open water canoes (vessel category and harbors' names) (b) abundance is relative only for the 19 selected species for the motorized boats (vessel category and harbors' names).

longitude showed a positive relationship with catch composition, while DEPTH, Sand, Mud and Gravel SEABEDS showed a negative relationship. This last group of factors influenced mostly the assemblage of *M. furnieri*, *M. ancylodon*, *D. auratus* and the Carcharhinidae. The partial RDA that included only the environmental variables explained 23% of the variance in the composition of species (Monte Carlo: $F = 3.08$, p-value <0.001). When the RDA was run only with the spatial effect, it explained 24% of the variance (Monte Carlo $F = 2.34$, p-value <0.001).

3.2. Motorized boats (MB) vessel category

The motorized boats (MB) caught 19 species from 10 families, excluding those that corresponded to less than 1% of the total catch. The Penaeidae family was the most abundant (55.28%), followed by Lutjanidae (17.65%), Carangidae (7.76%), Sciaenidae (5.65%), Scombridae (4.95%), Serranidae (3.22%), Carcharhinidae (2.67%), Daysatidae (1.45%), and Ariidae (1.36%). The main fishing gears used by fishers using motorized boats were trawls (60.48%), lines (31.37%) and gillnets (8.05%).

The cluster analysis showed four main significant groups ($p < 0.05$) (Fig. 3b; Table 5). The first cluster comprised *C. hippos, Xiphopenaeus kroyeri, M. ancylodon, Litopenaeus schmitti* and the prawn group. The second cluster included *Ocyurus chrysurus, Cynoscion* spp., *Lutjanus synagris* and the arid group. *Mycteroperca bonaci, Lutjanus analis, Lutjanus jocu* and *Lutjanus* spp. represented the third cluster. The last cluster comprised only *Seriola* spp. and the scombrid group. The remaining species are included in non-significant groups.

For the SIMPER analysis, *X. kroyeri* and *M. ancylodon* were the main contributors for average similarity of the first group (32% and 33%, respectively) (Table 5). For the second group, *L. synagris* was the main contributor (54%). The third group was mainly represented by *L. jocu* and *L. analis* (36% and 34% respectively), while the fourth group was mostly represented by *Seriola* spp. (44%).

The highest mean landing was observed in the first cluster (39,732 kg), followed by the third cluster (14,738 kg) (Table 5). The lowest landing mean values were recorded in the second cluster (4660 kg) (Table 5).

Fig. 4b shows that only cluster one has a species, *X. kroyeri*, that is much more abundant than the remaining clusters. There is no species in clusters 2–4 that is clearly more abundant than the others.

The NMDS confirmed the groups identified by the CA, despite some differences in the grouping pattern (Fig. 5b; Table 5). For example, species of the first and second clusters are exactly the same in the CA and in the NMDS plots, while there is some exchange of species between the third and fourth clusters when compared to the CA clusters. It is clear that different harbors land differ-

Table 5
Summary of the main results of the analytical approach. Data refer to landings by motorized boats.

Cluster	Main species	Associated species	Mean total catch (kg) for cluster	Landing harbors	Main gear	Fishing period (month)	Mean trip duration (h)	Main aspects fishing ground	Main drivers	Main thematic group
1	*X. kroyeri* & *M. ancylodon*	*C. hippos* *Prawn group* *L. schmitti*	39,732	Aracaju Pirambu	Trawl	All month & August and October	8–10 days	Muddy seabeds 10–30 m	Latitude Longitude Seabed	Spatial factor
2	*L. synagris*	*Ariid* group *Cynoscion* spp. *O. chrysurus*	4660	Poças	Line	April & December	3–4 days	Reef seabeds 50–80 m	Latitude Longitude Depth Type of gear	Spatial factor
3	*L. jocu* & *L. analis*	*M. bonaci* *Lutjanus* spp.	14,738	Castro Fabrica de Gelo	Line	March	6–11 days	Reef seabeds 50–80 m	Latitude Longitude Crew size	Spatial factor
4	*Seriola* spp.	Scombrid group	8770		Line	March	6–11 days	Reef seabeds 50–80 m	Latitude Longitude Crew size	Spatial factor
Not Significant	*C. crysos* *Dasyatis spp.* Shark group Tuna group									

ent species. For instance, "Pirambu" and "Aracaju" are represented by species included in the first cluster. In contrast, "Crasto" and "Fábrica de Gelo" are mostly represented by species comprised in the third cluster. Finally, second cluster represented the harbor "Poças".

Both environmental and fishing factors had a significant effect on the catch of fish species for motorized boats (RDA analysis: $t = 12.63$, df = 10, p-value <0.001; 66% of the total variance). Among the fishing factors, crew size was the most important (25% of the total variance), followed by type of gear (15%). Among the environmental variables, SEABED was the most relevant factor (17%), while NPP and SLOPE were not significant. Specifically, SEABED was the most important factor driving the species composition of the first cluster found by the CA, DEPTH and type of gear for the second cluster, while crew size for the third and fourth clusters (Table 5).

When the environmental variables were removed, the partial RDA explained 31% of the variance (Monte Carlo: $F = 2.07$, p-value <0.05), indicating that fishing factors explain a significant proportion of variation in species composition. Likewise, the removal of the fishing variables also resulted in a significant explanation of 23% of the variance (Monte Carlo: $F = 4.06$, p-value <0.05). Hence, again, while the composition of fish species was mostly explained by fishing factors, environmental variables also played a notable role.

Species composition wasalso explained by environmental variables and by the spatial effect (84%) (RDA analysis: $t = 8.47$, df = 6, p-value <0.001). When the spatial effect was removed, about 28% of the variance of species composition was explained by environmental variables (Monte Carlo: F = 2.88, p-value <0.05). However, much more of the variance of the species composition is explained by the spatial effect (57%), once the environmental variables were removed (Monte Carlo: $F = 3.04$, p-value <0.05).

4. Discussion

Many multivariate methods have been applied to fishery data in an attempt to understand factors such as habitat features or fishing factors (Pelletier and Ferraris, 2000; Rice, 2000; Stergiou et al., 2002; Willis and Anderson, 2003). In this study, multivariate techniques were used to understand and model the spatial structure of a tropical small-scale fishery marked by multiple species being simultaneously by distinct fleets. The results showed that the structure of fish catch composition of each fleet type is influenced by a complex combination of fishing, environmental and spatial factors. Our study identified the fish catch composition, the most representative species and the factors that drive these aggregations for the two main vessel type categories of the fishery. All the factors included in the analysis, except for the slope of the seabed, significantly explained the variability of the fish catch composition for both vessel categories, although different results were found between them.

4.1. Effect of different factors upon fish catch composition

4.1.1. Fishing factors

For the open water canoes, the combination between fishing and environmental variables best explained the catch composition. In particular, the type of gear used was the main factor affecting the catch of these canoes.

Differences in species composition are a common outcome if different gears are used (e.g., Feyrer and Healey, 2002; Lapointe et al., 2006) and can be attributed to many interacting factors. The results suggest that analyzing multiple sampling gears provides a more comprehensive inventory of the fish composition of a habitat, and underlines the need for a better understanding of the dynamics of a specific fleet.

The significance of other fishing variables, such as month and trip duration, indicates that both the vessel characteristics and a temporal pattern affects the species catch composition for open water canoes. Vessel features were expected to affect catch composition, because they limit the access to specific fishing grounds. Sailing boats, for example, tend to make shorter trips closer to the coast, where the species composition is different from the deeper zones. On the other hand, the temporal effect likely reflects two aspects: migration periods of important target species (e.g., mackerels) and calmer weather conditions. These canoes are indeed mostly used in the summer when the navigability conditions are safer and farther fishing grounds can be reached.

For motorized boats (MB), crew size was the most important fishing factor influencing assemblage catches. Unlike open water

canoes, which usually has two fishers boarded, MB varies its crew number, depending on the gear used.

4.2. Spatial factors

The intrinsic spatial variability of the data is the major descriptor of fish catch composition. Most of the spatial distribution of species is due to the spatial arrangement of their habitats. The remaining pure spatial variation reflects biological processes that bear no relationships with the environmental variables considered here, such as growth, predation, reproduction and social aggregation.

The effect of this pure space in the catches by larger motorized boats indicates that fish catch composition is strongly spatially-structured, contrasting to what was observed for smaller open water canoes. The type of vessel and its associated technologies used by ocean water canoes likely prompted this distinction by limiting most fishers to operate within a narrower geographical range.

This spatial variability could also be due to a spatial segregation of the vessels included in the larger motorized boats category, which depends on the species target and the gear used. For example, shrimp trawls usually operate on muddy and sandy seabed on the continental shelf, while vessels that use lines fish in deeper waters targeting snappers and pelagic species. While gillnets are used on the same type of seabeds used by trawls, they do not overlap their fishing grounds. However, the best explanation for the fish composition caught by these larger boats is reached when the spatial effect and environmental variables are considered as well.

4.3. Environmental factors

Open water canoes do not reach deep water easily, so most of their catch comes from a homogeneous environment, whereas fleets operating on deeper waters can exploit a larger range of environments and quite probably a more diverse species assemblage.

Fish composition of catches from fishing operations performed by open water canoes, which usually occurred in waters shallower than those fished by motorized boats, was significantly affected by primary production. Primary production affects the amount of nutrients available in the pelagic zone and the episodic deposition of particulate material on the sea floor, which on its turn will affect the biological activity (Nodder et al., 2003). The distribution of many demersal species, such as some of the most representative species of the fish catch composition for open water boats (*M. ancylodon* and *M. furnieri*), is likely to be influenced by the overall ecosystem productivity (Leathwick et al., 2006). Also, reports obtained from local fishers show that during autumn and winter, when the rain and wind peak in this area (Souza and Knoppers, 2003), algae blooms are visible on the surface of the shallower waters over the entire coast, which they take as an indicator of greater fish abundance.

The catches of the larger motorized boats especially if they were fishing with lines, were dominated by snappers (Lutjanidae), which also contributed to the similarity between groups in the cluster analyses. The lutjanid community has been shown to dominate the Bahamas, the Antilles and other Caribbean islands, besides the Central American coast from Yucatan to Panama (Longhurst and Pauly, 1987). The fact that the same family has been shown to dominate the studied coast is presumably because it is a region marked by coral reefs distributed from shallow waters all the way to the shelf break (Maida and Ferreira, 1997).

4.4. Drivers of species composition and the analytical approach

Despite some overlap in the use of fishing grounds by the two fleet categories, each fishery consisted of a relatively distinct set of species groups and habitats exploited at a different spatial scale.

Environmental variables appeared to have an important influence in separating the groups of species for both fleet type, mostly due to depth and seabed. Notwithstanding, fishing factors such as gear type also explained species composition at different degrees in both vessels groups. Together these factors may play an important role in understanding the catches of the most representative and the highest market valued resources, such as *C. hippos*, *M. furnieri* and *X. kroyeri*, which have specific spatial occurrence in the fishing grounds.

Many small-scale fisheries worldwide use different fleets and gear types to catch capture various species across multiple landing locations (Béné, 2003). However, the inclusion of spatial structure into modeling is rarely performed in such cases, especially for marine resources (Erisman et al., 2011). Therefore, the incorporation of all of these factors in the analysis performed here provides an important tool to better understand the dynamics of small-scale fisheries. It underlines for example, the importance of studying small-scale fisheries with multi-species models for both interacting and non-interacting species. In addition, it highlights the ability of such an approach to better representing reality, where there is no specific target species, but rather a group of aggregated species. Such knowledge could allow researchers and managers to focus on specific information to optimize the resources at their availability for better fisheries management and sustainability of regional fisheries in the area and for similar fisheries.

In the specific case showed here, managers could be aware of how different fleets put different pressure on fishing resources, besides being aware of the relevance of knowing the environmental variables to predict how the exploitation will happen in different fishing grounds. This suggests that a different set of regulations should be considered for each fleet category. An arrangement guided by the EAFM philosophy would facilitate more informative investigations aiming to identify the environmental, societal, and economic issues faced by each fishery currently. Specifically, by considering all issues (ecosystems, fishing activities, and harvested species) at the proper spatial scale, managers could be able to plan a management framework capable of improving decision-making processes related to stock assessments, marine reserves, and other fisheries or conservation actions.

Acknowledgments

Authors would like to thank Petrobras for the financial support. MGP received financial support from CAPES, as a Post-Doctoral Grant (88881.030502. 2013-01). Authors would like to thank all the fishers for their kind support and patience. We also thank the technical team of the “Projeto de Monitoramento Participativo do Desembarque Pesqueiro (PMPDP), also sponsored by Petrobras, and the Geo-Rio Mar Lab, in particular João Bosco Souza Mendonça, Jonas Ricardo dos Santos, Landerlei Almeida Santos e Marciléia Silva dos Santos. Authors would like to thanks Dr. James Cowan Jr. from the Louisiana State University (LSU) for supervising MJFTS during his Post-Doctoral Grant (CAPES, 1728/14-8). This study used data produced through the PMPDP performed by the UFS/PETROBRAS/FAPESE and demanded by the Brazilian Environmental Agency (IBAMA) in areas where there is oil and gas exploitation in the Sergipe-Alagoas basin.

References

Béné, C., Friend, R.M., 2011. Poverty in small-scale fisheries: old issue, new analysis. Prog. Dev. Stud. 11, 119–144.

Béné, C., 2003. Contribution of small-scale fisheries to rural livelihoods in a water multi-use context (with a particular emphasis on the role of fishing as last resort activity for the poor). In: FAO Advisory Committee on Fisheries Research. Working Party on Small-Scale Fisheries. Technical Report, Bangkok, Thailand.

Béné, C., 2005. Small-scale Fisheries: Assessing their Contribution to Rural Livelihoods in Developing Countries. FAO Fisheries Circular N. 1008, Rome.

Cetra, M., Petrere, M., 2014. Seasonal and annual cycles in marine small-scale fisheries (Ilhéus—Brazil). Fish. Manag. Ecol. 21 (3), 244–249.
Clarke, K.R., Warwick, R.M., 1994. Change in Marine Communities: An approach to Statistical Analysis and Interpretation. Plymouth Marine Laboratory, 144 pp.
Erisman, B.E., Paredes, G.A., Plomozo-Lugo, T., Cota-Nieto, J.J., Hastings, P.A., Aburto-Oropeza, O., 2011. Spatial structure of commercial marine fisheries in Northwest Mexico. ICES J. Mar. Sci. 68 (3), 564–571.
FAO, 2012. The State of World Fisheries and Aquaculture 2012. Food and Agriculture Organization of the United Nations, Rome.
Feyrer, F., Healey, M.P., 2002. Structure, sampling gear and environmental associations, and historical changes in the fish assemblage of the southern Sacramento-San Joaquin Delta. Calif. Fish Game 88 (3), 126–138.
Frédou, T., Ferreira, B.P., Letourneur, Y., 2006. A univariate and multivariate study of reef fisheries off northeastern Brazil. ICES J. Mar. Sci. 63 (5), 883–896.
Gascuel, D., Merino, G., Doring, R., Druon, J.N., Goti, L., Guenette, S., Macher, C., Soma, K., Travers-Trolet, M., Mackinson, S., 2012. Towards the implementation of an integrated ecosystem fleet-based management of European fisheries. Mar. Policy 36 (5), 1022–1032.
Hijmans, R.J., 2013. Introduction to the raster package.
Jennings, S., Kaiser, M.J., Reynolds, J.D., 2001. Marine Fisheries Ecology. Blackwell Science, Oxford, 417 pp.
Kaschner, K. et al. 2008. AquaMaps Environmental Dataset: Half-Degree Cells Authority File (HCAF). World Wide Web electronic publication, www.aquamaps.org/data, Version 07/2010. Available from http://www.aquamaps.org/download/main.php.
Lapointe, N.W., Corkum, L.D., Mandrak, N.E., 2006. A comparison of methods for sampling fish diversity in shallow offshore waters of large rivers. N. Am. J. Fish. Manag. 26 (3), 503–513.
Leathwick, J., Elith, J., Francis, M., Hastie, T., Taylor, P., 2006. Variation in demersal fish species richness in the oceans surrounding New Zealand: an analysis using boosted regression trees. Mar. Ecol. Prog. Ser. 321, 267–281.
Legendre, P., Legendre, L., 1998. Numerical Ecology. Elsevier Health Sciences B.V, Amsterdam.
Legendre, P., 1993. Spatial autocorrelation—trouble or new paradigm? Ecology 74, 1659–1673.
Levitus, S., Boyer, T., 1994. World Ocean Atlas 1994, Volume 4: Temperature. NOAA Atlas NESDIS 14, U.S. Gov. Printing Office, Washington, D.C., 117.
Longhurst, A., Pauly, D., 1987. Function, Biodiversity, Ecology. Oxford University Press, Oxford, UK, 515 pp.
Lucena, F.M., O'Brien, C.M., Reis, E.G., 2002. Effect of exploitation of the bluefish *Pomatamus saltatrix* by two competing fleets in southern Brazil: an application of a catch-at-age model. Mar. Freshwater Res. 53, 1–13.
Maida, M., Ferreira, B.P., 1997. Coral reefs of Brazil: over-view and field guide. Eighth International Coral reef Symposium, 263–274.
Manly, B.F.J., 1991. Randomization and Monte Carlo Methods in Biology. Chapman & Hall, New York.
Monterey, G., Levitus, S., 1997. Seasonal Variability of Mixed Layer Depth for the World Ocean, NOAA Atlas NESDIS 14. U.S. Government Printing Office, Washington, D.C, 96 pp.
Nodder, S.D., Pilditch, C.A., Probert, P.K., Hall, J.A., 2003. Variability in benthic biomass and activity beneath the Subtropical Front, Chatham Rise, SW Pacific Ocean. Deep Sea Res. Part 1 Oceanogr. Res. Pap. 50, 959–985.
Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, R.P., O'Hara, R.B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Wagne., H., 2014. Community Ecology Package.
Panayotou, T., 1982. Management concepts for small-scale fisheries: economic and social aspects. FAO Fishery Technical Papers N. 228, 53 pp.
Pelletier, D., Ferraris, J., 2000. A multivariate approach for defining fishing tactics from commercial catch and effort data. Can. J. Fish Aquat. Sci. 57, 51–65.
Rice, J.C., 2000. Evaluating fishery impacts using metrics of community structure. ICES J. Mar. Sci. 57, 682–688.
Ruttan, L.M., Gayanilo Jr., F.C., Sumaila, U.R., Pauly, D., 2000. Small versus large scale fisheries: a multi-species, multi-fleet model for evaluations and potential benefits., Methods for Evaluating the Impacts of Fisheries on North Atlantic Ecosystems. In: Pauly, D., Pitcher, T.J. (Eds.) Fisheries Centre Research Reports, pp. 64–75.
Shimodaira, H., 2002. An approximately unbiased test of phylogenetic tree selection. Syst. Biol. 51 (3), 492–508.
Shimodaira, H., 2004. Approximately unbiased tests of regions using multistep-multiscale bootstrap resampling. Ann. Stat. 32 (6), 2616–2641.
Souza, W.F.L., Knoppers, B., 2003. Fluxos de água e sedimentos a costa leste do Brasil: relações entre a tipologia e as presses antropológicas. Geochim. Brasil 17 (1), 57–74.
Stergiou, K.I., Moutopoulos, D.K., Erzini, K., 2002. Gill net and longline fisheries in Cyclades waters (Aegean Sea): species composition and gear competition. Fish. Res. 57, 25–37.
Suzuki, R., Shimodaira, H., 2006. Pvclust: an R package for assessing the uncertainty in hierarchical clustering. BMC 22 (12), 1540–1542.
Willis, T.J., Anderson, M.J., 2003. Structure of cryptic reef fish catch composition: relationships with habitat characteristics and predator density. Mar. Ecol. Prog. Ser. 257, 209–221.