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Ecological knowledge of oyster (*Crassostrea*) collectors on abiotic aspects: Implications for co-management

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ABSTRACT

Oysters of the *Crassostrea* genus are commercially and ecologically important species that inhabit coastal and estuarine waters. However, exploitation without proper species management can contribute to declining natural stocks, especially in regions with easy access. In this sense, the objective of this study was to analyze the local ecological knowledge (LEK) of the collectors about the biometry of *Crassostrea rhizophorae* and *Crassostrea brasiliana* oysters collected during the dry and rainy periods in the Mamanguape River Estuary (MRE) and the stock conditions of this resource, in order to provide information to complement the management plan of EPA Barra do Rio Mamanguape on the northern coast of the state of Paraíba, Brazil. The study was conducted between August 2019 and September 2020 through semi-structured interviews, participant observations, and meteorological data. The results showed the occurrence of the oysters *C. rhizophorae* and *C. brasiliana*, popularly named mangrove and bottom oysters, respectively. They were identified according to morphological and ecological characteristics and classified into different size groups. The size of the species varies according to the seasonal period; the oysters present a variation between 50-80 mm during the dry period, being larger than in the rainy period which presented a variation of 40-70 mm. In addition, collectors reported that there has been a decrease in stocks and the size of oysters collected over the last decade. According to this information, there is a threat to the sustainability of fishing in the MRE in the medium and long term. Thus, it is necessary to involve the local community in negotiations in defining and distributing management functions, rights, and responsibilities to maintain the livelihoods of MRE collectors and increase oyster stocks.

Keywords: Fishing resource; Seasonality; Environmental Protection area; co-management.

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SIGNIFICANCE STATEMENT

Coastal areas face increasing challenges due to human action, generating devastating consequences for coastal communities and the ecosystems, such as estuaries and mangroves. Mangroves are coastal ecosystems that provide ecosystem services that benefit humans and nature. These benefits range from the direct provision of resources to indirect services such as the production of sociocultural activities. This study sought to understand the Local Ecological Knowledge of oyster collectors of the *Crassotrea* genus from the Mamanguape River Estuary in northeastern Brazil. Ethnoecological research is essential for the use and composition of communities, and is essential for targeting mitigation strategies, providing data for zoning policies, conserving resources, identifying endangered species, and drawing up species and ecosystem management plans and maintaining local human communities. For the extraction of fishery resources to be sustainable, it is necessary to understand how users (collectors) view these resources, as well as to collect data on the current state of stocks (oysters), since these users can give us an idea of the current stock by reporting on previous fisheries in places where this information could not or was not collected.

INTRODUCTION

Fishing exploitation of benthic resources has been taking place for millennia by traditional populations living in coastal areas (Pinnegar and Engelhard 2008). These resources play a vital role in food and nutrition security in developing countries (Bell et al. 2009; FAO 2014; Kawarazuka and Béné 2010), and are the main source of financial income for traditional coastal populations (Rocha et al. 2008; Béné et al. 2010).

Among benthic resources, oysters of the genus *Crassostrea* (Sacco 1897) are the most commercially and ecologically important species that inhabit coastal and estuarine waters in tropical regions (Arakawa 1990; Damiano and Wilberg 2019). *Crassostrea rhizophorae* (Guilding 1828), and *Crassostrea brasiliana* (Lamarck 1819) (synonym of *Crassostrea gasar*) are currently recognized on the Brazilian coast (Absher 1989; Ignacio et al. 2000; Varela et al. 2007; Galvão et al. 2009; Amaral and Simone 2014). *Crassostrea brasiliana* (Lamarck 1819) occurs in infralittoral estuarine regions and has attains large sizes. *C. rhizophorae* (Guilding 1828) predominantly occurs in the intertidal region and has lower growth rates compared to *C. brasiliana* (Christo and Absher 2008). The adults of both species are sessile, characterized as having great plasticity in shell morphology depending on the substrate where they are attached (Absher 1989).

Oysters generally provide several ecosystem services such as: (i) food resources for humans and other predators; (ii) structural heterogeneity of substrate that provides refuge and habitat for oysters (Gutiérrez et al. 2003; Lenihan and Micheli 2001); and (iii) removal of suspended particulate matter through its filtration activity, promoting biodiversity (Newell 1988; Coen et al. 2007; Kellogg et al. 2014). However, these ecosystem services provided by oysters have greatly declined following the decline of their native populations (Beck et al. 2011; Zu Ermgassen et al. 2012). Furthermore, centuries of extracting these resources without proper management and intensified by coastal degradation have contributed to the decline of natural stocks, especially in regions with easy access. An estimated 85% of existing oyster banks have been decimated globally (Kirby 2004; Beck et al. 2011; Westphal and Ostrensky 2016).

In addition to exploitation without proper management, studies performed with *C. rhizophorae* and *C. brasiliana* indicate that changes in water temperature and salinity associated with rainfall in the rainy seasons in some regions can also influence the growth and survival of oysters in the larval, juvenile, and adult stages (Guimarães et al. 2008; Antonio et al. 2009; Dickinson et al. 2012; Eierman and Hare 2013; La Peyre et al. 2013; Lopes et al. 2013). Salinity should be considered among these factors because it presents daily and seasonal variations in estuaries, being influenced by the tidal regime and seasonal periods (Vilanova and Chaves 1988; Pantoja et al. 2020), in addition to being an important environmental factor that determines the distribution of bivalve mollusks in estuarine and marine environments.

However, management actions for the conservation of natural stocks should focus on extractive practices, controlling the number of resource users, and implementing regulations specifying the minimum size and limit for the extraction and commercialization of oysters (Mendonça and Machado 2010). In addition to measures aimed at controlling fishing efforts, it is essential to address the socioeconomic and ecological sustainability of the resource. Therefore, in these conservation efforts, it is necessary to identify the users of these resources and the stock conditions as integral parts of developing shared management plans for collecting the resources in question (Friedman et al. 2008). Therefore, in these conservation efforts, it is necessary to know who the users of these resources are and the stock conditions as an integral part of developing shared management plans for collecting the said resource (Friedman et al. 2008).

Working with resource users with extensive knowledge about the resources and environments they exploit is an important way of documenting biodiversity, environmental changes, and their causes, and achieving better conservation results (Nishida et al. 2006a; Wilder et al. 2016; Aswani et al. 2020). This detailed and rich knowledge is recognized by several researchers as Traditional Ecological Knowledge (TEK) (Alburquerque et al. 2021) or Local Ecological Knowledge (LEK) (Drew 2005; Davis and Rudle 2010; Rudle and Davis 2011). It is recognized by many researchers for its potential to enrich scientific knowledge; explain long-term processes in human-environment interactions; and be a reliable tool for guiding and prioritizing biodiversity conservation actions when integrated with scientific knowledge in environmental management and resource management (Medeiros et al. 2018; Colloca et al. 2020; Albuquerque et al. 2021).

The integration of LEK and scientific knowledge has been successfully demonstrated in the management of *Crassostrea* spp. oysters in the Mandira Extractive Reserve in Cananéia, SP, Brazil (Machado et al. 2011). The management practices used by *Crassostrea* spp. collectors were reducing the availability of the resource. As a result, resource users and scientists collaborated to adopt management measures to protect *Crassostrea* spp., such as implementing a closed season and defining a minimum size for commercialization and prohibiting other collectors from entering the Mandira Extractive Reserve; and increasing the number and supply of fattening ponds. The agreed measures were formalized in the Extractive Reserve Utilization Plan, which is a legal instrument that is valid until the Management Plan is drawn up. The definition of a commercial adult was based on the minimum extraction size allowed by law (Machado et al. 2011). Brown et al. (2021) demonstrated how to succeed with declining resources, such as the eastern *Crassostrea virginica* oyster, for which natural resource managers in Florida agree that there are some essential factors for successful management, such as: communication between stakeholders and LEK. Other researchers have demonstrated the importance of LEK in implementing fisheries management plans (Medeiros et al. 2018; Colloca et al. 2020; Garmendia et al. 2021; Ullah et al. 2023). Thus, LEK can be used as a resource management strategy, and being included in the management plan is essential to formulate and guarantee the efficiency of management plans (Nishida et al. 2006b; Heck et al. 2012).

Given the above, the present study aimed to analyze the knowledge of collectors about the folk taxonomy and biometry of *Crassostrea oysters* collected in the Environmental Protection Area (EPA) of Barra do Rio Mamanguape, to compare the oysters collected between the dry and rainy seasons and the stock conditions of this resource to contribute with relevant information to the EPA management plan, and in turn provide subsidies for the co-management of *C. brasiliana* and *C. rhizophorae* oysters.

MATERIAL AND METHODS

Study area

Data collection was carried out in the Mamanguape River Estuary (MRE) located on the northern coast of the state of Paraíba in Brazil (Figure 1). It is inserted in the Environmental Protection Area (EPA) of Barra do Rio Mamanguape, created by Decree no. 924 of September 10, 1993 (6° 43' 02"' S - 6° 51' 54"' S and 35° 07' 46" W - 34° 54' 04" W), delimited to the north by the municipalities of Marcação and Baía da Traição, to the West and South by the municipality of Rio Tinto, to the Southwest by the municipality of Lucena and to the East by the Atlantic Ocean (Mourão and Nordi 2003; Rocha et al. 2008; Rodrigues et al. 2008; Temoteo 2018).

The Barra do Rio Mamanguape EPA was created with the objective of guaranteeing the protection of coastal ecosystems and the Marine Manatee (*Trichechus manatus* Linnaeus 1758) and other endangered species at the regional level, as well as to control and sustainably use environmental resources. The EPA corresponds to an approximate area of 14,600 hectares, covering the continental, estuarine, and marine territory (Alves and Nishida 2003).

The region has a tropical climate, with rainy periods from February to July and dry periods from October to December, with an average annual rainfall of 1800 mm and air temperature ranging from 25 to 30°C (Pereira et al. 2020). The months of January, August, and September are transition periods between the rainy and dry seasons.

The villages within the Barra do Rio Mamanguape EPA on the banks of the MRE are communities that are constituted by a racial mixture of indigenous (*Potiguar*), black, and European origins, who develop fishing activities in the surrounding area and in the Mamanguape River itself (Mourão and Nordi 2003; Rocha et al. 2008). The Tramataia, Jaraguá, and Marcação communities that extract oysters were studied in the present study (*Crassostrea rhizophorae* and *C. brasiliana*).

Research authorization

The Chico Mendes Institute for Biodiversity Conservation (ICMBio) authorized this scientific research at the Barra do Rio Mamanguape EPA through the Authorization and Information System on Biodiversity (SISBIO) (No. 70741-1). The Research Ethics Committee (REC) of the State University of Paraíba

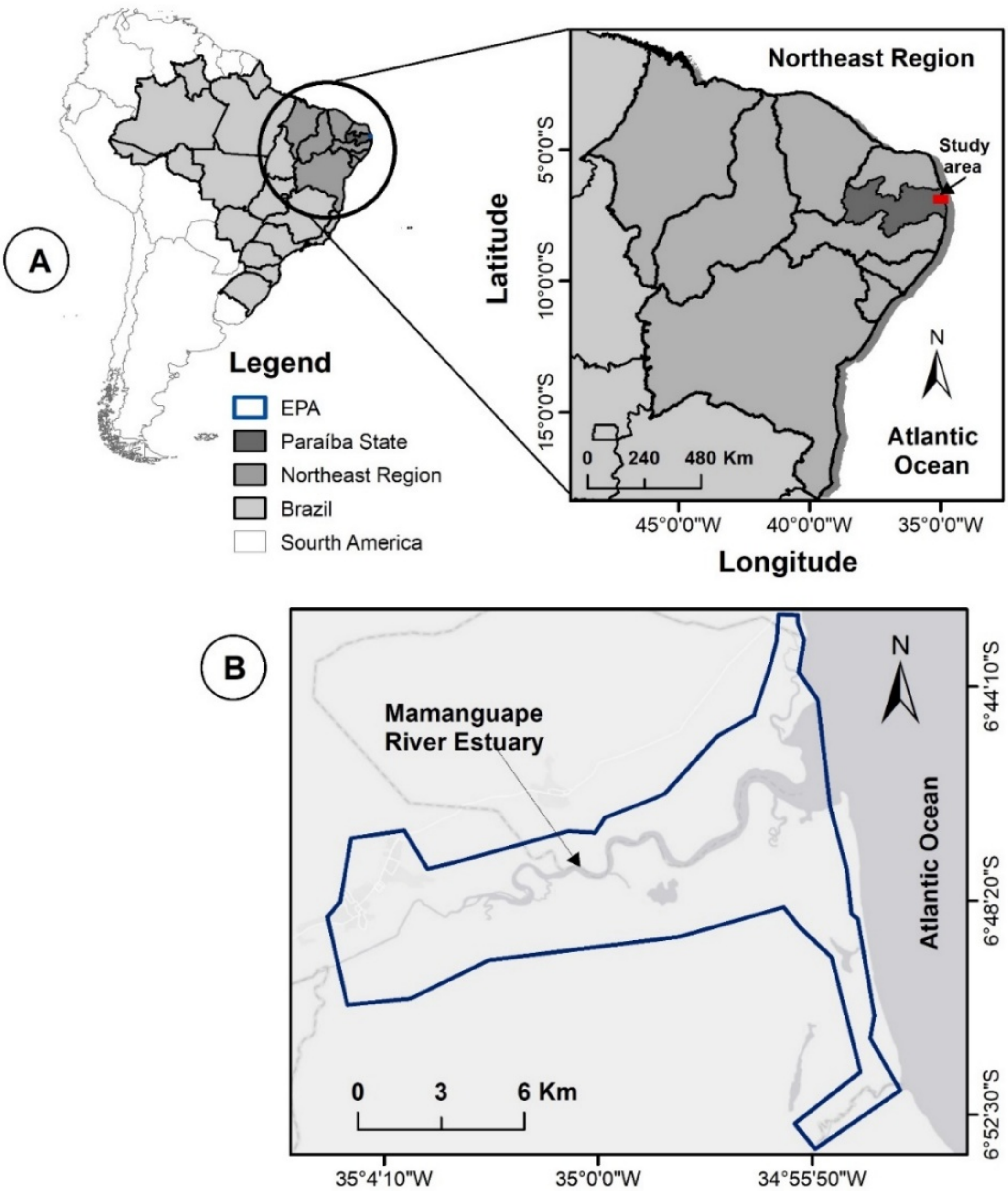

Figure 1. Geographic location of the Mamanguape River Estuary on the northern coast of the state of Paraíba, Northeastern Brazil.

(UEPB) granted authorization for research with human beings (No. 3,701,654) via the *Plataforma Brasil* website. The participants read the Informed Consent Form (ICF) before each interview and duly signed it when they consented to participate in the study voluntarily.

Sample design and data collection

Data collection was performed from August 2019 to September 2020 with monthly visits to the fishing communities of Tramataia, Jaraguá, and Marcação. Initial contact with the community of collectors participating in this study was made through periodic visits (fieldwork planning) to build a relationship of trust and share the symbolic world between the researcher and the researched (rapport) (Trivisios 1987). The first contacts made with the oyster collectors were through leaders (i.e. the president of the colonies, health workers, etc.), as well as researchers who have been doing research in the area for almost two decades.

The research participants were selected by stratified probability sampling (Albuquerque et al. 2014; Medeiros et al. 2018; Barbosa-Filho et al. 2020). The selection criteria were a minimum age of 18 and a minimum of 5 years in the activity. The snowball technique (Bailey 1982) was used to select only the "local consultants" (7 collectors), who provided consulting for the study (Medeiros et al. 2022). We chose these collectors because they had extensive knowledge of biology, the ecology of the resources collected, and of abiotic factors, which were confirmed by their peers. Data collection was conducted through semi-structured interviews and participant observations. The semi-structured interviews contained pre-formulated questions about the species of oysters collected, ecological aspects, size classification, sizes collected in the dry and rainy seasons, and the stock conditions of this resource. The questions for all respondents were identical and presented in the same sequence, facilitating subsequent comparisons of more reliable data (Bernard 2011).

The participant observation technique was used to obtain data on the biometry (or size) of individuals collected directly from the natural environment. A total of 800 oyster specimens were analyzed at random during the observations. Of these, 500 were analyzed during the dry season and 300 in the rainy season, in which the total length, width, and thickness of the shell were measured with a digital caliper with a precision of 0.01 mm (Figure 2), and the wet weight using a precision digital scale after removing the barnacles and mussels from the shell. All oysters came from natural banks and were extracted by the collectors themselves and subsequently returned after measurements.

In addition to the biometric data of the oysters, we characterized the dry and rainy seasons through water salinity and rainfall. Salinity measurements were taken in the tidal zone during low tide at seven locations along the estuary using a salinity refractometer (VX100SG model) to determine salinity at the sampling site. Meteorological data were obtained from the Executive Agency for Water Management of the State of Paraíba (AESA-PB; www.aesa.pb.gov.br) with rainfall values (mm) for the closest location to the study area.

Data analysis

The descriptive data regarding the oysters were analyzed by the content analysis method, defined by Bardin (2011) as the set of techniques that investigates communications, meaning that it uses systematic and objective procedures to describe the content of messages, as well as through photographic records made during the observations.

Data analysis was organized in three steps: 1) pre-analysis; 2) exploration of the material, separating them into categories and coding them; the topic chosen to be worked on at this stage was the variation in oyster sizes; 3) processing the results. The most recurrent observations of the interviewees regarding the collectors' perception of the variation in the oyster sizes were also analyzed using a descriptive statistical approach focused on presenting the absolute and relative frequencies of the collectors' citations.

All variables were tested for normality and homogeneity of variance by the Bartlett test to compare the biometric data of the oysters collected between the dry and rainy seasons. Non-normal data were subjected to the non-parametric Mann-Whitney U-test, and then the data were plotted using the barplot2 function of the gplots package (Gregory et al. 2020). All analyses were performed in the R version 4.0.3 program (R Core Team 2020).

RESULTS

Socio-professional profile of the study participants

A total of 27 interviews were carried out with oyster collectors in the communities of Tramataia, Marcação, and Jaraguá around the MRE. Regarding the interviewees, 12 were male and 15 were female, aged between 18 and 70 years (mean 42.25 ± 11.79). Most of the oyster collectors have significant local experience: six (6) interviewees have 5 to 7 years of experience, 13 have 10 to 25 years of experience, and eight (8) have 25 to 55 years of experience. At least 26 collectors claimed to collect oysters for trade and consumption, and 21 intend to continue their oyster collection activities (Additional File

Taxonomic differentiation of oyster species

Among the interviewees, 14 recognize the existence of two different types of oysters in the MRE. The taxonomic differentiation of the oyster species used by collectors takes into account the position in the water column, the attachment place and the shell color (Table 1).

Biometry of oyster species

In addition to differentiating the types of oysters through ecological aspects, the collectors classify the oysters into size classes: i) seeds (< 40 mm); ii) small oysters (50 – 60 mm); iii) medium oysters (70-80 mm); and iv) large oysters (> 90 mm). Among the interviewees, 14 reported collecting oysters of all sizes, collecting small individuals < 60 mm in length.

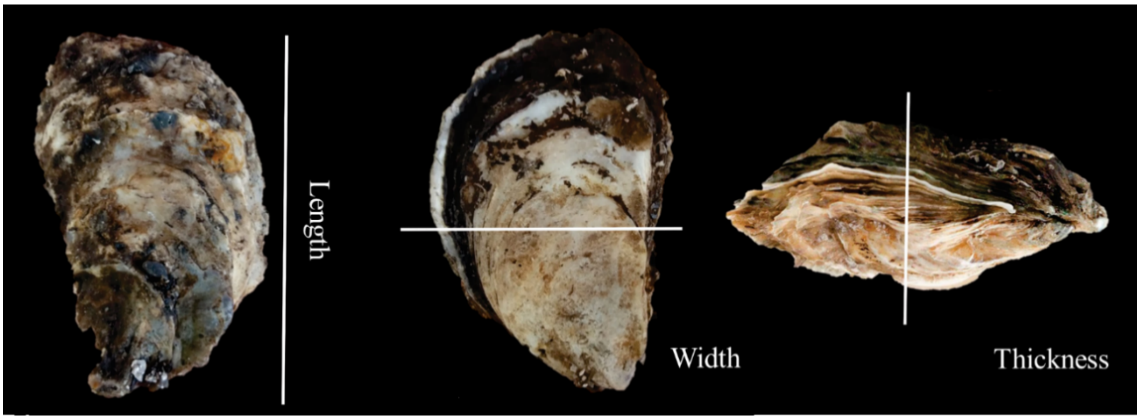

Figure 2. Representation of the measurements taken on *Crassostrea* spp. oysters.

Table 1. Ethnotaxonomic characteristics described by oyster collectors around the MRE.

Scientific taxonomy	***Crassostrea brasiliana***	***Crassostrea rhizophorae***
Ethnotaxonomy	Diving Oyster, Bottom Oyster, Black Oyster	Mangrove Oysters, Root Oysters, Wood Oysters, White Oysters
Position in the water column	Middle of the river *	In the roots of the mangrove at low tide *
Attachment place	On the rocks, loose at the bottom**, loose branches that have sunk	In the roots of the red mangrove***, in the mud loose from the wood (roots) *
Shell color	Dark colored shell	Light colored shell

Legend: * Infralittoral and midlittoral zoning.

** "Loose" oysters are attached to the shells of other possibly dead oysters which ensure a solid substrate for attachment.

*** Fixed to the rhizophores of the red mangrove (*Rhizophora mangle*) occupying the intertidal region (mesolitotal).

The collectors reported a difference in sizes among the oysters collected in the dry and rainy seasons. Oysters with larger sizes and in greater quantities are collected during the dry season.

The biometric measurement values in the oyster samples collected by the collectors showed significant differences between the dry and rainy seasons (Mann-Whitney U-test, $P < 0.01$) (Figure 3). The distribution of individuals in terms of weight (g) and in length, width and thickness (mm) classes confirmed that oysters collected in the dry season were larger. The weight (g), length, width and thickness (mm) measurements collected in the dry period were 45.87 g (±22.5), 62.25 mm (±12.60), 42.22 mm (±10.8) and 20.56 mm (±6.4) respectively, while for those in the rainy season it was 24.74 g (±12.10), 54.97 mm (±22.5), 35.96 mm (±7.90), and 17.56 mm (5.8).

In addition to the perception of collectors about the variation in sizes and abundance of species collected between seasons, respondents with more than 10 years of experience (N=21) also reported that the natural stock of oysters has decreased over the years and oysters with commercial sizes (> 90 mm) are difficult to find in natural banks.

Among the oyster samples collected, 71.2% of the oysters collected in the dry season belonged to the 50-80 mm length class, while 83.3 of the oysters collected in the rainy season belonged to the 40-70 mm length class, indicating an abundance of juveniles well below the expected size of maturity, presenting a large number of recruits observed throughout the sampled periods. Only 4.2% of the oysters collected in the dry season and 0.66% in the rainy season had sizes > 90 mm in length, called commercial size by collectors (Figure 4).

According to 22 collectors, the water salinity in the MRE is lower in the rainy season, with higher mortality rates of oysters in this period. According to 24 col-

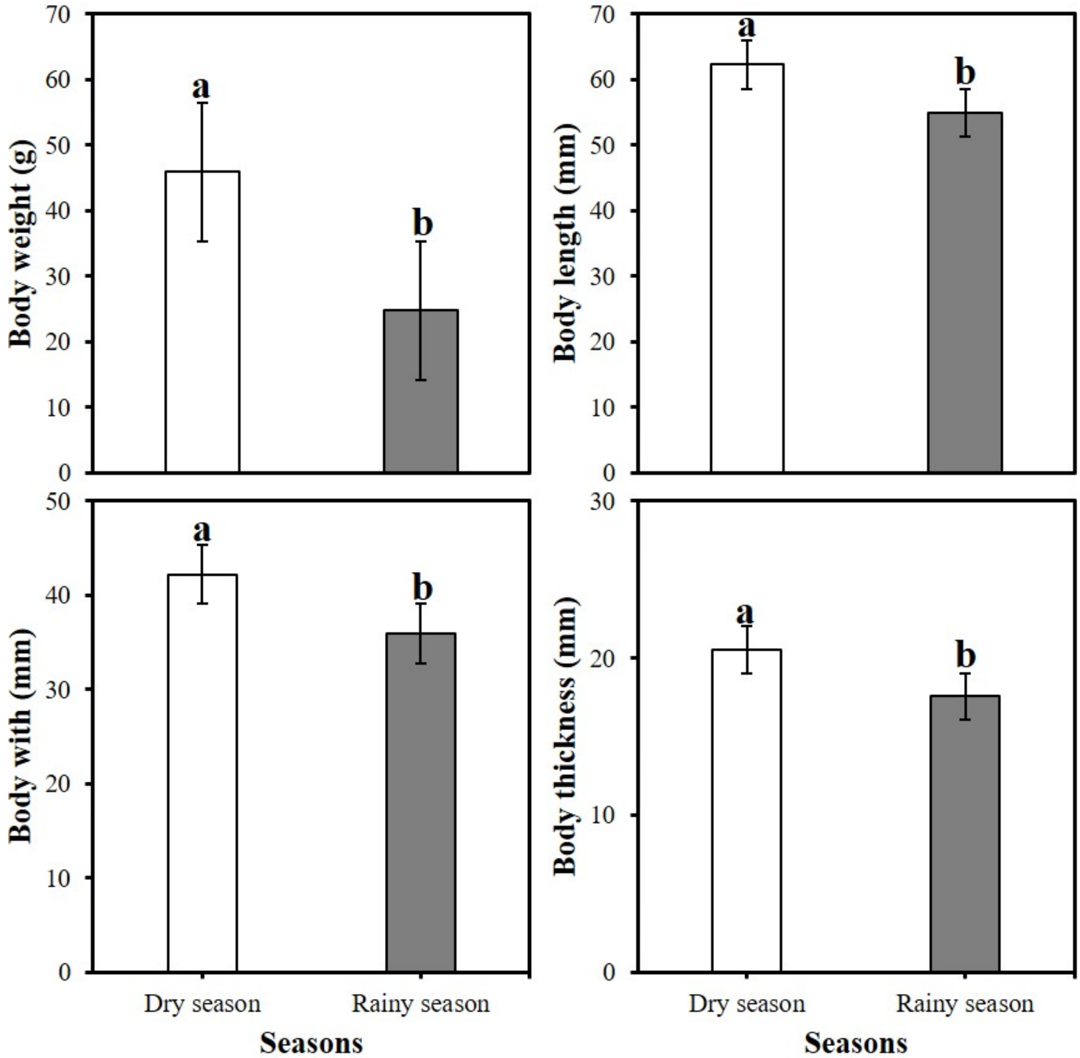

Figure 3. Biometric measurements of *Crassostrea* spp. (oysters) collected in the MRE in the dry and rainy seasons. Different letters indicate significant differences with $p < 0.01$.

lectors, both the low salinity and the low temperature of the period reduce oyster growth (Additional File 2).

The salinity in the dry season presented an average of 18.11 (±5.35) ppm, with a minimum of 5 ppm and a maximum of 28 ppm, while the rainy season presented an average of 9.02 (± 7.85), with minimum of 0 and maximum of 21. The average rainfall between the months of October/2019 to February/2020 (the dry period) was 5.43 mm, and between the months of May to September/2020 (the rainy season) was 32.59 mm.

DISCUSSION

Taxonomic differentiation of oyster species

Our results revealed that oyster collectors have characteristics commonly found in fishing communities, with individuals between 30 and 60 years of age and beginning to fish during childhood and adolescence, preventing them from carrying out other economic activities for subsistence (Musiello-Fernandes et al. 2018; Oliveira et al. 2016).

The interviewed collectors reported the occurrence of two types of oysters in the MRE, naming and identifying the species according to morphological and ecological characteristics. The characteristics presented by the ethnotaxonomic knowledge of the collectors ev-

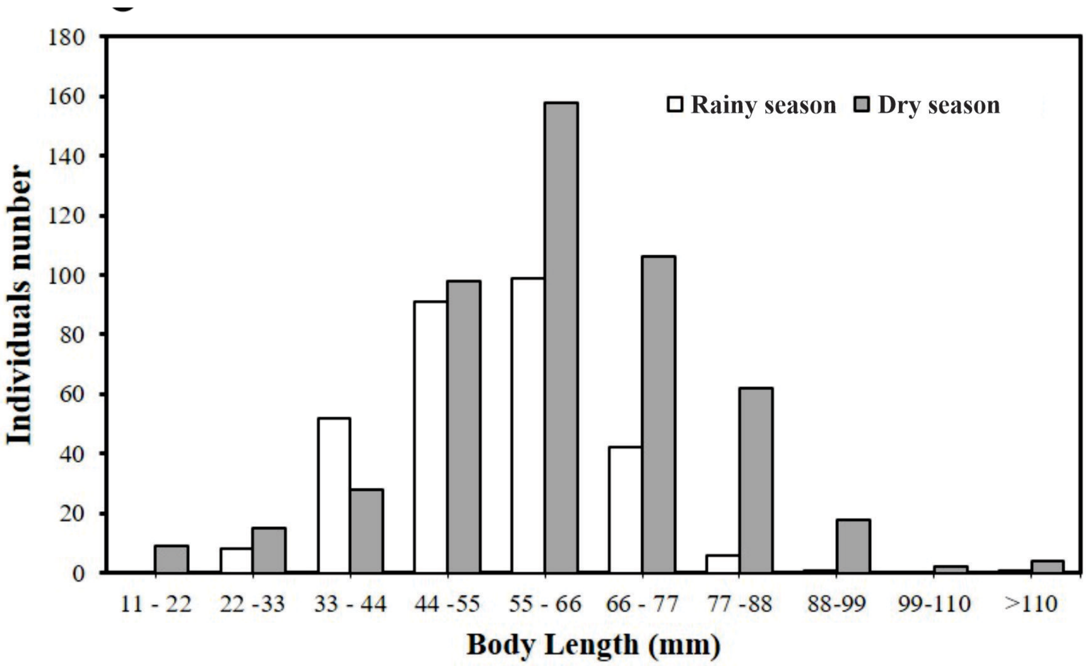

Figure 4. Relative shell length frequency distribution of *Crassostrea* spp. (oysters) collected in the dry and rainy season in the MRE.

idence the differentiation between the oysters (*C. rhizophorae* and *C. brasiliana*) and corroborate the scientific classification as described by Castilho-Westphal et al. (2014), Lira et al. (2010) and Souto and Martins (2009). Despite the plasticity in the morphology of the shell, which causes controversy in the identification and taxonomic uncertainty of species of *Crassostrea* (Varela et al. 2007; Christo 2006; Amaral and Simone 2014; Boehs et al. 2018), it is possible to identify two distinct species captured in the MRE, namely *C. brasiliana* (synonymous with *Crassostrea gasar*) and *C. rhizophorae* (nomenclature accepted in the MolluscaBase eds. 2020).

Crassostrea brasiliana is known as “bottom oyster” or “diving oyster”, and is considered a large species, reaching 200 mm in length, with shell color varying from white, brown, purple to greenish, living fixed in roots of submerged and rocky mangroves in the infralittoral zone (Galvão et al. 2000; Pereira et al. 2003; Amaral and Simone 2014; Boehs et al. 2018). *Crassostrea rhizophorae* is known as “mangrove oyster” or “root oyster”, occurs attached to the aerial roots of *Rhizophora mangle* or to rocks in the intertidal region and can reach up to 100 mm in length, with the shell color varying from white to yellowish brown (Nascimento 1982; Melo et al. 2010; Lazoski et al. 2011; Amaral and Simone 2014; Boehs et al. 2018).

Biometry of oyster species

Most of the interviewees reported collecting individuals from all classes, especially those smaller than 60 mm in length, claiming they were not able to let them grow due to the need to guarantee their livelihoods. This practice by collectors is perhaps associated with the absence of any rule, regulation, or legislation that prohibits the capture of small oysters or the absence of a minimum size standard allowed in the Barra do Rio Mamanguape EPA. However, there are rules, minimum size (50 mm), and closed season in other regions in Brazil, such as what occurs in Cananéia on the coast of the state of São Paulo (Mendonça and Machado 2010). In the Coastal Marine Extractive Reserves in the state of Pará and the Canavieiras Extractive Reserve in the state of Bahia, Ordinance No. 945/2018 (ICMBio 2018) and Ordinance No. 1124/2018 (ICMBio 2018) only have regulations and rules for the collection of oysters, referring to techniques and care for the environment, without any mention of the minimum size limit.

The data collected regarding the differences in size between seasons in the ERM showed that the oysters were larger in size and quantity in the dry period compared to the region’s rainy period, as reported by the collectors in this study. According to these collectors, this difference is due to salinity and temperature decreasing in the ERM’s rainy season, causing mortality and affecting oyster growth.

The data recorded in this study corroborates Funo et al. (2015), who state that oysters survive a salinity variation of 10 to 45 ppm, but with higher body growth rates with a salinity variation between 20 and 25 ppm, which represents an average value typical of bays and estuaries during periods of low rainfall. Adult oysters close their shells and stop filtering at salinities below eight ppm, compromising their growth and reproductive development (Nascimento and Pereira 2004), consequently showing smaller biometric sizes and lower abundances. Huang et al. (2015) reported the effect of salinity variation on the abundance of oysters of the Crassostrea genus, when an increase in rainfall caused a reduction in abundance and when an increase in salinity due to low rainfall and the insertion of the salt wedge in the estuary caused an increase in the abundance of this group.

Concerning the temporal variation of catches, it was observed that the period of lowest intensity of rainfall is responsible for most of the production in the Parnaíba River delta region in Piaui-Northeast Brazil, although there was a reasonable production of oysters (8,500 kg) in the period of peak rainfall (Santos et al. 2016). Other studies have assessed that oyster stocks of *Crassostrea* in Brazil, and also in some other places around the world, showing a seasonal influence on fishing activity, which is mostly correlated with the dry season (Wilber 1992; Castilho-Westehel 2012; Santos et al. 2016).

The interviewed collectors also pointed out that the low temperatures of the rainy season reduce the growth of oysters. This corroborates the experimental records of ideal temperatures for *C. rhizophorae* and *C. brasiliana*, which have an ideal range of 22 to 30ºC, being able to tolerate up to 34 ºC; however, temperatures below 22ºC may increase the mortality of the species (Lopes et al. 2013; Barliza and Quintana 1992; Fabioux et al. 2005).

In addition to abiotic factors (salinity, precipitation, and temperature) that alter the growth and abundance of the species, the interviewed collectors (10 years of experience) reported a decrease in the abundance and size of oysters collected in the last decade in the MRE. In addition, they claim that there is a growing demand for extraction and a greater difficulty in collecting individuals with sizes greater than 90 mm (commercial sizes).

Our results regarding biometry corroborate the reports presented by the interviewees. These results possibly indicate that this decrease in the length of individuals in the population of MRE is a reflection of the overexploitation of stocks, which may be influencing the natural recovery of oysters. This causal effect was observed by Castilho-Westphal and Ostrensky (2016) in Guaratuba Bay, southern Brazil.

Biometric and abundance patterns may be the result of seasonal fluctuations in environmental parameters (salinity, water temperature, precipitation) and excessive collection. However, it is difficult to determine which factor is most influential, as there is a general lack of basic ecological data, especially from experiments in a natural environment that include control areas (exclusion zones). In addition, the local knowledge and the perceptions of the interviewed collectors are important factors to be considered, as they have mastery of the cycles of the existing species, demonstrating an intense relationship with the natural environment. Moreover, the reported events directly affect their daily lives and the environment in which they live, and consequently their livelihood (Sousa et al. 2018).

In this sense, the data point to the need to implement measures that guarantee the increase of the natural oyster stocks to maintain the subsistence of the collectors of the MRE, involving them in the negotiations, and in defining and distributing management functions, rights and responsibilities.

Proposal for co-management

Co-management of resources at all coastal locations, but especially within Marine Protected Areas (MPAs), should consider the following management proposals: (1) minimum size for collection; (2) encouragement of alternative sustainable practices, such as implementing cropping systems. The implementation of these conservation measures will be essential for the proper functioning of the MPAs, as well as the management plan of the Barra do Rio Mamanguape EPA, guaranteeing the recovery of natural stocks and the livelihoods of traditional families who are dependent on the resource.

In this sense, co-management creates space for traditional communities and associated organizations to participate in ecosystem management (Berkes et al. 2000; Hanna 1998; Berkes et al. 2001). Co-management can be understood as the right to regulate internal use and transform the resource by making improvements (Ostrom and Schlager 1996). These activities can be performed by single actors or jointly by groups of individuals or as a result of cooperation between different groups, considering that co-management increases the efficiency of actions related to extractive practices and the control of the number of users. These measures reduce conflicts, provide legitimacy to the process, and promote sustainable resource management. Furthermore, building a co-management process requires the following steps: (1) mapping essential management tasks and problems to be solved; (2) enlightening participants in problem-solving processes; (3) assessing capacity-building needs to improve the skills and capacities of people and institutions at various levels; and (4) prescribing ways to improve policymaking and problem-solving (Carlsson and Berks 2005).

Measures and laws created by co-management should be enacted for local self-reliance, subsequently creating the policy space to support local community-based conservation, particularly in protected areas (Olsson et al. 2004). In turn, conducting constructive monitoring of ecosystem dynamics and processes involving users of local resources in monitoring can increase incentives to learn about local ecosystem dynamics and increase the likelihood of managing complex systems sustaining desirable ecosystem states (Berkes and Folke 1998; Olsson et al. 2004).

In addition, the use of LEK in the EPA management plan should improve the management of oyster collection in the MRE, providing a more informed and responsible management that is likely to lead to the success of the management plan. According to Hill et al. (2010), participation in the management process provides a collaborative environment of trust for all parties to work together.

CONCLUSION

Abiotic factors and seasonality are responsible for the changes that occur with oysters in the MRE, mainly influencing distribution, density, and biometry, with the rainy season being one of the factors responsible for the mortality and low growth of oysters.

In addition to abiotic factors, overexploitation by collectors has probably caused a decrease in oyster stocks. This decrease in the abundance and sizes of oysters collected in the natural environment probably indicates signs of imbalance in the natural oyster banks in the study area, which could threaten the sustainability of fisheries in the mid and long term, requiring more research on fisheries production, including estimations of Capture per Unit of Effort (CPUE) and the construction of a co-management process.

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DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

CONTRIBUTION STATEMENT

FRS conceived the presented idea, carried out the experiment and the data analysis, as well as composed the final writing of the manuscript.

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Additional Files

Add File 1. Number of interviewees and time of experience between female and male.

Interviewee	Sex	Age	Experience time	Future perspective
1	M	39	15	1
2	M	43	10	1
3	M	36	24	0
4	F	65	30	1
5	M	57	30	1
6	F	39	29	0
7	M	51	6	1
8	M	30	6	1
9	M	38	15	1
10	F	70	55	1
11	M	47	18	1
12	F	37	25	1
13	F	44	5	1
14	F	46	15	0
15	F	54	45	1
16	F	37	10	0
17	F	33	5	0
18	F	57	7	1
19	F	47	36	1
20	F	37	19	0
21	F	20	10	1
22	M	32	10	1
23	M	44	30	1
24	F	18	10	1
25	M	43	30	1
26	M	38	10	1
27	F	39	5	1

Legend. Experience time: Time in years that you develop the oyster collection activity.
Future perspective: Intends to continue with the oyster collection activity; 0 - no / 1 - yes.

Add File 2. Questionnaire

Questionnaire
Interview date:
1. IDENTIFICATION OF INTERVIEWEE

- Name (Full):
- Nickname: Sex: Age: years
- Address:
- Place of birth: City:
- Position in the Family: ( ) Head ( ) Spouse/partner ( ) Other (please specify)
- Marital status: ( ) Single ( ) Married ( ) Widowed ( ) Separated ( ) Other
- Do you have any kind of fishing licence? ( ) Yes ( ) No
- What is your level of schooling? ( ) Writes name ( ) Incomplete secondary school (1st to 2nd year) ( ) Elementary school incomplete (1st to 3rd) ( ) High school
- complete (3rd year) ( ) Completed primary schools (4th grade) ( ) Technical course ( ) Elementary school incomplete (5th to 7th) ( ) Higher education ( ) Complete primary schools (8th grade) ( ) Other ( ) Doesn't know/ Didn't answer
- Have you attended any training or specialisation courses? ( ) No ( ) Yes. Which one?

2. UNIT DATA AND FAMILY INCOME

- How many people live in the house:
- Do you have children? ( ) No ( ) Yes. How many?
- Do your children study? ( ) Yes ( ) No. Why?
- What is the family's source of income?
- How much is the family income? ( ) $<$ 1 minimum wage ( ) Between 1 and 2 minimum wages ( ) $>$ 2 minimum wages

3. DATA ON LIVING CONDITIONS

- Community:
- How long have you lived in the community?
- What type of house: ( ) Masonry ( ) Wood ( ) Taipa ( ) Mixed ( ) Improvised ( ) Other. What is it?
- The house is: ( ) Owned ( ) Rented ( ) Shared ( ) Other

4. OYSTERS' BIOLOGICAL DATA

- Where do you find oysters?
- Where do oysters settle?
- Do you know the breeding season? If so, which one?
- What do oysters eat?

- What are the predators of oysters?
- Does the salinity of the estuary affect oyster mortality? ( ) No ( ) Yes How?
- Does the estuary's water temperature affect oyster mortality? ( ) No ( ) Yes. How?
- Do salinity and temperature influence oyster growth? ( ) No ( ) Yes. How?

5. DATA ON OYSTER HARVESTING (OYSTER EXTRACTION)

- How long have you been harvesting oysters?
- What types of oysters do you know?
- How did you get into the business?
- Is oyster harvesting your main activity? ( ) Yes ( ) No. Other
- Do family members help you collect oysters? ( ) No ( ) Yes. Who?
- How many days a week do you harvest oysters?
- How many hours a day do you work collecting oysters?
- How many oysters do you shuck a day?
- What sizes do you harvest? ( ) Seed (larva) ( ) Small ( ) Medium ( ) Large ( ) Other
- Where do you shuck your oysters? ( ) In the mangrove roots ( ) Diving in the Estuary ( ) Other
- How do you harvest the oysters? What utensils do you use?
- When do you have the most oysters? (Tick all) ( ) Rainy season ( ) Dry season ( ) With high salinity ( ) With low salinity ( ) With high temperature ( ) With low temperature
- Which period are the oysters larger? ( ) Rainy season ( ) Dry season
- you sell them? ( ) Yes ( ) No, only for consumption.
- If 'Yes', how do you sell? ( ) By the piece ( ) By the dozen ( ) By the kilo ( ) Other
- How do you sell the oyster? ( ) Fresh ( ) Chilled ( ) Defrosted/Frozen ( ) Processed/Frozen
- How regular is the sale?
- Number of sales:
- Who do you sell to?
- How much does it cost?
- Where are the oysters sold?
- What precautions do you take when processing and storing oysters for sale?
- What period of the year sees the highest and lowest percentage of sales?
- What difficulties do you encounter in your business?
- What is the outlook for the future of the business?
- Are you aware of oyster cultivation in the region? ( ) Yes ( ) No
- Are you part of an oyster farm? ( ) No ( ) Yes
- If 'Yes', where do the seeds come from? ( ) Natural banks, taken by the oyster farmer himself ( ) Natural banks, taken by other collectors (bought) ( ) Laboratories (purchased)

- Price and quantity of seeds purchased:

6. ENVIRONMENTAL DATA

- Do you think the oysters you catch are contaminated by environmental pollution? ( ) Yes ( ) No
- Do you think the oysters are very small catches from the environment? ( ) Yes ( ) No
- Do you think that over-catching oysters can kill off the oysters in the environment? ( ) Yes ( ) No
- Do you think it's important to preserve the environment? ( ) Yes ( ) No
- Do you try to preserve the environment? ( ) Yes ( ) No
- Do you catch a lot of oysters in the region? ( ) Yes ( ) No
- Have you noticed a decrease in natural oyster stocks due to constant extraction in the region? ( ) Yes ( ) No
- Do you think that disrespect for the environment can harm the activity of catching/cultivating oysters? ( ) No ( ) Yes. How?
- What measures do you use to preserve the environment?
- What kind of pollution would you point out to the ERM?
- Would you adopt new procedures to improve ERM and the community? ( ) No ( ) Yes. Which? ( ) Don't know/ Didn't answer