MARÍLIA PREVIERO

The snapper and grouper fisheries of the Abrolhos Bank, East Brazil shelf: fleet patterns, exploitation status and risk assessment

Thesis submitted to the Oceanographic Institute of the University of São Paulo, in partial fulfilment of the requirement for the degree of Doctor of Science, program of Oceanography, Biological Oceanography area.

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VERSÃO CORRIGIDA

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Ao meu marido Raul e aos meus pais Neiva e Sebastião
pelo apoio, força e confiança depositados
sobre mim durante o doutoramento.

Àqueles que tem na pesca seu meio de vida.

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Minha jangada vai sair pro mar
Vou trabalhar, meu bem querer
Se Deus quiser quando eu voltar do mar
Um peixe bom eu vou trazer

Meus companheiros também vão voltar
E a Deus do céu vamos agradecer
(Dorival Caymmi)

ABSTRACT

The fishery is a complex and dynamic socio-ecological system involving several actors and knowledge areas. Along the Brazilian coast the small-scale fisheries are very common and provide important ecosystem services. This fishery modality are usually data-poor in terms of catch and abundance data, landing records, quantification of vessels and fishing gear used. This data-limited condition frequently hampers fishery assessments and effective managements. That is the case in the Abrolhos Bank, East Brazil, a wide portion of the shallow continental shelf that encompass a complex benthic habitat with coral reefs, rhodoliths, *buracas*, mangroves, seaweed banks and with a great biodiversity. Over this area the small-scale fisheries are a traditional activity, extremely diverse in terms of exploitation capacity, fishing gears, target stocks and operating areas. On the Abrolhos Bank, snappers and groupers are very common resources, besides being predators important for the ecosystem equilibrium. However, these stocks are not evaluated or continuously monitored in the fishing landings and any regional fishery management is currently in place. The overall goal of this thesis was to elucidate questions on three snappers (*Lutjanus jocu*, *Lutjanus synagris* and *Ocyurus chrysurus*) and three groupers (*Cephalopholis fulva, Epinephelus morio* and *Mycteroperca bonaci*) fishery characteristics, impacts and sustainability in the Abrolhos Bank. The specific objectives were (1) to assess, organize, and analyze these fisheries to find out patterns on stocks occurrence, on fishing fleets and fishing areas, and to propose management units; (2) to examine the abundance trends and the exploitation status of the six stocks through indicators of size, biomass landed, mortality, spawning and yield, and (3) to evaluate the stocks risk to overexploitation and their fishery sustainability considering biological, environmental social and economic aspects. The study was conducted in four coastal communities of the Abrolhos Bank. The data were obtained by interviews with fishers, experts and stakeholders, from fishery landings monitoring databases, by specimens' measures in landings and from literature. Groups of stocks co-occurring in landings and groups of stocks co-occurring in fishing grounds were discovered. Seven similar fishing areas were determined and suggested as spatial management units. Overfishing and decline in the relative abundance were detected to five stocks. The major causes of overfishing were high fishing mortality, low spawning potential ratio, low mega-spawners and high juveniles in landings. The fishery has led some stocks on alert to overexploitation and the results revealed that coral reefs habitat and ecosystem are also threaten by mining waste and dredging. Furthermore, there is a weak environmental governance in the region and insufficient community participation in the construction of management proposals.

The results reveal a concerning situation regarding the stocks exploitation status but provide the key points to be worked on together the fishing communities. This thesis emphasizes the need for urgent elaboration of fishery regulation measures in the region and may contribute in the delineating of management proposals in this complex and threatened fishery system.

Keywords: Small-scale fisheries. Fisheries assessments. Fisher's knowledge. Reef fishes. Abrolhos Bank.

RESUMO

A pesca é um sistema sócio-ecológico complexo e dinâmico, envolvendo vários atores e áreas de conhecimento. Ao longo da costa brasileira as pescarias de pequena escala são muito comuns e provém importantes serviços ecossistêmicos. Essa modalidade de pesca frequentemente é pobre em dados de captura e abundância, registros de desembarques, quantificação de embarcações e de artes de pesca utilizadas. Essa condição frequentemente dificulta avaliações pesqueiras e o manejo eficaz. Isso ocorre no Banco dos Abrolhos, leste do Brasil, uma ampla porção da plataforma continental rasa que compreende um complexo habitat bentônico com recifes de corais, rodolitos, buracas, mangues, bancos de algas e com grande biodiversidade. Nesta área, a pesca de pequena escala é uma atividade tradicional extremamente diversificada em termos de capacidade de explotação, artes de pesca, estoques alvo e áreas de operação. No Banco dos Abrolhos vermelhos e garoupas são recursos muito comuns, além de predadores importantes para o equilíbrio do ecossistema. No entanto, estes estoques não são avaliados ou monitorados nos desembarques pesqueiros, e nenhuma gestão pesqueira regional está atualmente em vigor. O objetivo geral desta tese foi elucidar questões sobre as características, impactos e sustentabilidade da pesca de três vermelhos (*Lutjanus jocu*, *Lutjanus synagris* and *Ocyurus chrysurus*) e três garoupas (*Cephalopholis fulva, Epinephelus morio* and *Mycteroperca bonaci*) no Banco dos Abrolhos. Os objetivos específicos foram (1) avaliar, organizar e analisar essas pescarias para descobrir padrões de ocorrência de estoques, padrões de frotas e áreas de pesca, e propor unidades de manejo; (2) examinar as tendências na abundância e o status de explotação dos seis estoques por meio de indicadores de tamanho, biomassa desembarcada, mortalidade, desova e rendimento; e (3) avaliar o risco de sobreexplotação dos estoques e a sustentabilidade pesqueira considerando aspectos biológicos, ambientais, sociais e econômicos. O estudo foi realizado em quatro comunidades costeiras do Banco dos Abrolhos. Os dados foram obtidos em entrevistas com pescadores e especialistas locais, em bases de dados de monitoramentos pesqueiros, em medições de espécimes em desembarques e na literatura. Grupos de estoques co-ocorrendo em desembarques e grupos de estoques co-ocorrendo em áreas de pesca foram descobertos. Sete áreas de pesca semelhantes foram determinadas e sugeridas como unidades de manejo espaciais. Sobrepesca e declínio na abundância relativa foram detectados em cinco estoques. As principais causas da sobrepesca foram alta mortalidade por pesca, baixo potencial de desova, poucos mega-reprodutores e muitos juvenis nos desembarques. A pesca deixou alguns estoques em alerta de sobreexplotação e os resultados revelaram que o habitat recifal e o ecossistema são ameaçados também por resíduos de mineração e pela dragagem. Além disso, a governança ambiental na região é fraca e a participação comunitária em propostas de gestão é insuficiente. Os resultados revelam uma situação preocupante quanto ao estado de exploração dos estoques, mas fornecem os pontos-chave a serem trabalhados em conjunto com as comunidades pesqueiras. Esta tese enfatiza a necessidade de elaboração urgente de medidas de regulação pesqueira na região e pode contribuir para o delineamento de propostas de manejo neste complexo e ameaçado sistema pesqueiro.

Palavras-chave: Pesca de pequena escala. Avaliações pesqueiras. Conhecimento dos pescadores. Peixes recifais. Banco dos Abrolhos.

SUMMARY

GENERAL INTRODUCTION

1. Introduction

Along the Brazilian coast, the artisanal or small-scale fisheries are dominant in terms of number of vessels and number of fishers (MATTOS et al., 2017). This fishery modality provides important ecosystem services in several coastal communities, especially in developing countries (GASALLA; CASTRO, 2016). Small-scale or artisanal fisheries frequently use low developed technologies and usually are performed in a household or family, incorporating both subsistence and commercial fisheries (GARCIA et al., 2008). Despite this fishery modality has great importance for the livelihoods of many communities, small-scale fisheries frequently lack scientific information on stock biology, historical catches, efforts and abundance data as well as socio-economic information, being usually data-poor (BABCOCK et al., 2013; JOHNSON et al., 2017; NASH; GRAHAM, 2016; VASCONCELLOS; DIEGUES; SALES, 2007). One of the main reason for this data lacking is the scattered landing points (OLAVO; COSTA; MARTINS, 2005), which hampers a good and efficient data collection, besides the low resolution in species names in the fisheries monitoring registers. Another reason of the data-poor condition of the small-scale fisheries in Brazil is the inadequate approach frequently used in fisheries assessments, with only biological focus, disregarding human components such as social, economic and cultural aspects of the fishery communities (CASTELLO, 2008; VASCONCELLOS; DIEGUES; SALES, 2007).

In this sense, there is a difficulty to employ traditional stock assessment methods (GRAFELD et al., 2017). Thereby, some indicators of changes in fishing pressure and in stock size in a short time interval have been proposed to assess the stocks' exploitation status (e.g. COPE; PUNT, 2009; FROESE, 2004; HOUK et al., 2017; MINTE-VERA et al., 2017; PRINCE et al., 2011). Most of these fishery indicators are based on length-frequency, age-frequency and on CPUE (Catch per unit effort) and require only punctual data to inform the stocks exploitation status (BABCOCK et al., 2013). In the absence of fishery regulatory measures, the fish and other resources can be exploited until their capacity for replenishment be liquidated (JENNINGS et al., 2001). The fishery exploitation induces changes in the stocks, such as changes in the number-at-age, size, abundance, biomass and spatial distribution (HADDON, 2011). Through this process there are some phases: (1) fishery development; (2) fishery full exploitation; (3) fishery overexploitation; (4) fishery collapse and (5) fishery recovery

(HILBORN; WALTERS, 1992). Trends in stock abundance, fleet size, total catches and profits are related to each exploitation phase, which make possible to identify the actual development phase of a fishery (HILBORN; WALTERS, 1992). In this sense, the fishery studies on the dynamics of exploited stocks try to understand and estimate the stocks responses to different exploitation intensities (HADDON, 2011). The stocks exploitation status is an important information to the maintenance of reproductive capacity, to avoid overfishing (GUARDIA et al., 2018), and to support proposals of appropriate management objectives, strategies and measures (JENNINGS et al., 2001).

The one-species conventional approach to fisheries management is still very common, however, on the last decades some problems related to single species management in multispecies fisheries have emerged (REEVES et al., 2008). Thereby, recent fisheries studies and management plans have become increasingly holistic, using multidisciplinary methods (GARCIA et al., 2008; SYMES, 2006). In this sense, there was an openness of fisheries sciences that begin to encompass the fleets dynamics, the vessels characteristics, the fishery activities and social influences in fishery studies (REEVES et al., 2008).

The fishery is a complex and dynamic socio-ecological system that involves several actors and knowledge themes (GARCIA et al., 2008). In a fishing area, many fish stocks, fishery companies and technologies interact, which provides many levels of complexity to this system (CATAUDELLA; SPAGNOLO, 2011). The main components of a fishery system were listed and characterized by Trevor (2001), are them: the fishery resources, the fleets, the fishers, the ecosystem, the biophysical environment, the coastal communities, the socioeconomic environment, the fishery post harvests and the market. These diverse components belong to distinct science areas, such as biological, social and economic sciences and composes a multidisciplinary or ecosystem approach to fisheries. This approach encloses economic and governance needs on management plans, aiming to balance human and ecological well-being under the sustainable development context (FISCHER et al., 2015; LONG et al., 2017).

Socio-ecological assessments are an example of a multidisciplinary approach and combine interactions between humans and the environment (LIU et al., 2007). Socio-ecological methods are based in simplification of the complex relations among fishers, resources and the environment, using participatory approaches in the designing of management plans (SANTOS et al., 2017). An example of these methods is the observation of fishery or fleet patterns, which may help in the identification of different fishery impacts on the ecosystem and in the location of the main fishing areas. This occurs because the fishing effort, the strategies and tactics of the fishing fleets in an area are related to the availability of the target stocks and to the fishery opportunities (FORERO et al., 2017; OJEDA-RUIZ, et al., 2015; WALTERS; MARTELL, 2004). Mapping the main fishing areas are very useful in the design of management strategies, in the communication of the decisions and in the implementation of management actions (OJEDA-RUIZ, et al., 2015), especially when these maps are based in both fishers' knowledge and on geo-referenced data (FORERO et al., 2017). Furthermore, know the fishery patterns is also important to predict and to avoid conflicts among fishers as response to fishery spatial controls (IMOTO et al., 2016).

The ecosystem-based fisheries management (EBFM) is another example of a multidisciplinary study and considers major ecosystem components and services such as habitats, species range besides the abiotic components and processes in fisheries management (U.S. NATIONAL RESEARCH COUNCIL, 1998). The main EBFM objectives are to keep populations, species, biological communities, and marine ecosystems at sustainable levels with high productivity and biological diversity, asserting the ecosystem provision of goods and services (GARCIA et al., 2003; U.S. NATIONAL RESEARCH COUNCIL, 1998). To reach these objectives TROCHTA et al. (2018) argues that the ecosystem management can be accomplished by considering only some key components of the ecosystem, which carefully selected can ensure long-term fisheries sustainability. Furthermore, in the development of a successful EBFM, the involvement of fishers is primordial (GARCI; COCHRANE, 2005). The fishers have a sophisticated knowledge of the natural and supernatural world that is acquired through the teachings of the elders and also through personal observations and interactions with the aquatic environment, which is called fishers' Local Ecological Knowledge (LEK) (ALLUT, 2000; BERKES et al., 2000; DIEGUES, 2000; PELOQUIN; BERKES, 2009). For these reasons, the fishers present an accurate perception of long and short-term changes in the natural environment that can occur also before the scientific detections (ROCHET et al., 2008).

Risk assessment methods are approaches used in data limited fisheries, capable to measure the probability of a stocks become overexploited (FOGARTY et al., 1996; FRANCIS; SHOTTON, 1997). These methods may assess resource vulnerability based on simple considerations, such as information on life-trait parameters and fisheries intensity (FRANCIS; SHOTTON, 1997). The conduction of risk assessment to exploited stocks involves concluding the current condition of the stock relative to reference points or to management objectives (FRANCIS; SHOTTON, 1997). In the long-term stock sustainability, the risk assessment measures the ability of the population to replenish itself through reproduction (FOGARTY et al., 1996).

The Ecological Risk Assessment for the Effects of Fishing (ERAEF) are capable to highlight the most concerning stocks regarding the fishery activity and the major threats to habitats and to the whole ecosystem, based on qualitative and semi-quantitative methods (HOBDAY et al., 2011; QUESNE; JENNINGS, 2012). The ERAEF encompasses a hierarchical risk assessment methodology, from qualitative analyzes at level 1 to a more detailed and quantitative analysis at level 3 (HOBDAY et al., 2011). This approach is capable to score from the low risk components to the high risk components. Moreover, the data deficient stocks are assessed as high risk and may require further information, which makes this a precautionary approach (HOBDAY et al., 2011).

In Brazil, some of the main challenges for fisheries assessments and management are the implementation of an effective system of fisheries monitoring throughout the various landing points (MATTOS et al., 2017; MIRANDA et al., 2016), as well as the implementation of a management effectively participatory (CASTELLO, 2008). The fishers' participation in both data collection and management plans may represent alternative approaches to obtain fishery data successfully (BERKES et al., 2001). That is especially because the fishers' ecological knowledge is an important data source in the construction of participatory or community-based fisheries management (LEITE; GASALLA, 2013). Moreover, the fishers have already demonstrated high knowledge about the stocks and are capable to indicate tends in abundance of some target resources (BENDER et al., 2013b).

In the Abrolhos Bank, East Brazil shelf, the fishery is a traditional economic activity for many coastal communities. A large amount of fish and other resources are caught by small-scale fisheries and landed daily in scattered fishing ports. Some of the most common fish resources are the snappers (lutjanids) and the groupers (epinephelids and serranids). These stocks occur throughout the year and have a great economic importance to the fishers and to all the post-harvest sector. Personal observations in the area previous to performing this thesis gave rise to questions regarding the fishing ports peculiarities, the fisher' procedures and the fleet patterns. However, despite the great economic and ecological importance of the snappers and groupers, these questions have not been deep investigated and known by the fisheries managers. Furthermore, currently the fisheries are nor evaluated neither monitored and some relevant fishery aspects are unknown, such as the stocks exploitation status, the fishery sustainability, and the impacts from other threatening activities over the stocks and the ecosystem.

2. Study area

The Abrolhos Bank is a wide portion of the shallow continental shelf located in the South Atlantic Ocean on Brazil East shelf (Fig. 1). The width of the Abrolhos shelf is very irregular due to the development of extensive biogenic formations on the top of volcanic banks (MARTINS; COUTINHO, 1981), ranging from 30-160 nautical miles (Fig. 1). The inner shelf near the 20 m is predominantly smooth due to burial of the topography during the Holocene sedimentation, the middle and outer shelf surface is rougher, with small banks and steep-walled strait channels originated in the Pleistocene (MARTINS; COUTINHO, 1981). In this study, some other marine banks was considered as composing the "Abrolhos Bank shelf", are them: the Royal Charlote Bank, extending for approximately 60 nautical miles from the coast, forming a plateau of around 46 km in width (MARTINS; COUTINHO, 1981), the Minerva, Rodger and Hotspur banks (Fig. 1).

The Abrolhos Bank has two main deeper channels, the "*Canal de Abrolhos*" and the "*Canal de Sueste*" (LESSA; CIRANO, 2004). The region is dominated by the Brazil Current, also in the nearshore waters, characterized by low freshwater input (LEIPE et al., 1999). The surface Ekman transport prevail from Prado to Doce River (Fig. 1) (AGUIAR et al., 2014). The magnitude of the currents ranges from about 17 $cm*s^{-1}$ to 93 $cm*s^{-1}$ and the winds are an important forcing mechanism (LESSA; CIRANO, 2004). In the Abrolhos Bank the most frequent winds come from the Northeast and East, representing the fair weather (in summer), on the other hand, the Southeast, Southwest and South winds are storm winds (in autumn and winter) (LESSA; CIRANO, 2004). The water temperature is warm, ranging from 22°C to 28°C, with rare vertical temperature gradient (LEIPE et al., 1999).

The Abrolhos shelf substratum has volcanic origin (LEIPE et al., 1999). The suspended matter is composed primarily by kaolinite clay and biogenic components such as old sedimentary carbonate fragments derived from degradation of reefs, besides bio detritus and fossil components (LEÃO; DUTRA; SPANÓ, 2005; MARTINS; COUTINHO, 1981). The highest concentration of suspended matter is at the southern edge of the "*Parcel das Paredes*" (LEIPE et al., 1999). In the reefs there is low deposition of terrestrial sediment, especially because of a hydrodynamic barrier effect generated by strong southward currents enhanced by the constrainment of water in the "*Canal de Sueste*" (LEIPE et al., 1999). The Abrolhos Bank together the Vitória-Trindade chain form a topographic barrier to the Brazil Current, which causes meanders, vortices and resurgence in the southern part of the Abrolhos Bank and contributes to the enrichment of water in terms of primary production (VALENTIN at al., 2006).

Over the Abrolhos Bank there is the largest coral reef complex in the South Atlantic in which the reefs have distinct growth forms, a range of reef building fauna and depositional setting, besides diverse shapes and dimensions (e.g., *chapeirões* reefs and fringing reefs) (LEÃO; KIKUCHI; TESTA, 2003). On the region there are also a complex benthic habitat mosaic with (near 20,904 km²) of rhodolith beds, unconsolidated sediments, *buracas*, mangroves and seaweed banks (BASTOS et al., 2013; MOURA et al., 2013).

In this marine ecosystem there are approximately 18 coral reef species, 280 fish species, 293 species of molluscs, 90 species of polychaetes, 535 crustacean species, and about 100 species of marine plants, besides mammals such as dolphins and whales (ABSALÃO, 2005; CAVALCANTI et al., 2013; DANILEWICZ et al., 2013; DUTRA et al., 2005; FIGUEIREDO, 2005; LEÃO; KIKUCHI, 2001; MOURA; FRANCINI-FILHO, 2005; PAIVA, 2005; PREVIERO et al., 2013; YOUNG; SEREJO, 2005; ZERBINI et al., 2004).

In the region, there areAreas (MPAs) of restricted use (Abrolhos Marine National Park) and of sustainable use (e.g. Cassurubá Extractive Reserve, Corumbau Marine Extractive Reserve). These areas, however, protects only a portion of the whole ecosystem (Fig. 1). The main concerns regarding the conservation of the biodiversity and the ecosystem functions are related to possible future oil operations, dredging to large-scale Eucalyptus marine transportation (DUTRA et al., 2005), mining waste and fishery.

The region is also the main reef fishery area in the Brazilian East coast (OLAVO; COSTA; MARTINS, 2005). The small-scale is the prevalent fishery modality in the region, representing an important source of food, job and livelihood for the communities (OLAVO; COSTA; MARTINS, 2005). This is a secular activity in the region, the hand line fishery with hooks began during the Brazilian colonial period and nowadays is still a very common gear, responsible for a large percentage of the fishery catches in the region (OLAVO; COSTA; MARTINS, 2005). The grouper fisheries in the region occurs since the beginning of the 16th century, with commercialization of salted fish with the capital, Salvador (BUENO, 1998; OLAVO; COSTA; MARTINS, 2005). In the last decades, however, there has been a reduction in the landed volumes of predatory stocks combined with an increase in the landings and in the commercialization of herbivorous stocks (COSTA; BRAGA; ROCHA, 2003; KLIPPEl et al., 2005). This scenario may be an indication of occurrence of the phenomenon "Fishing down marine food webs" (PAULY et al. 1998).

From the 20^{th} century there was a modernization of the Abrolhos fishing fleets, which began to be made up of motorized boats with new fishing gears, such as the longline. Currently, the Abrolhos fleets are composed of vessels ranging from 4 to 20 m in length, also known as motorized *saveiros* that can fish to a depth of 1,200 m and stay at sea up to 30 days in widespread fishing points (IBAMA, 2008; MOURA et al., 2013; OLAVO et al., 2011; PREVIERO, 2014; SANTOS, 2015). The greater fishery productivity occurs from September to February and in the 20-60 m depth (OLAVO; COSTA; MARTINS, 2005). The landing points are distributed along the coast and have diverse characteristics and capacities (DRAPPER, 2011). Over this area there are also other human activities such as tourism in the coastal communities and over the coral reefs (GIGLIO et al., 2015; STORI, 2005).

This study was performed primarily in four fishing ports [1] (Prado, Alcobaça, Barra de Caravelas and Ponta de Areia) (Fig. 2), the latter two falling within the Caravelas municipality. These ports were selected because they have different dimensions and capacities, receive landings from different fishing fleets that operate in a complementary manner throughout all the study area.

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[1] The landings data used in the CPUE (Catch per unit effort) analyzes were obtained from six fishing ports (Corumbau, Prado, Alcobaça, Barra de Caravelas, Ponta de Areia and Nova Viçosa).

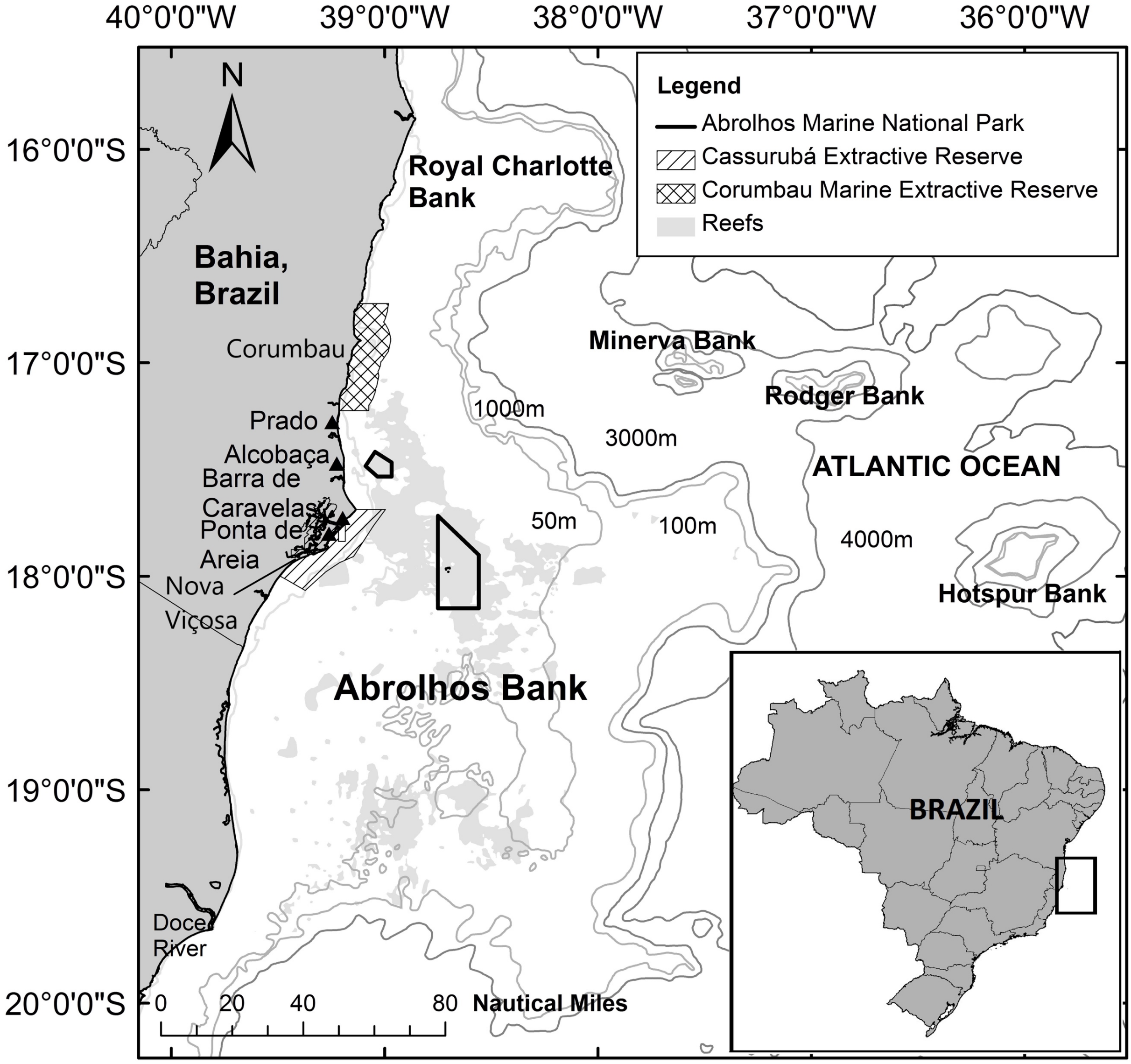

Figure 1. Map of the study area with the latitudes and longitudes, the location of fishing ports (Prado, Alcobaça, Barra de Caravelas and Ponta de Areia), the reefs and the Marine Protected Areas.

Figure 2. The four fishing ports studied in the Abrolhos Bank. (Photos by Marília Previero)

3. Studied stocks

In the Abrolhos Bank approximately 87 fish species are caught by the commercial fisheries (DRAPPER, 2011; IBAMA 2008). Of these, three snappers (*Lutjanus jocu, L. synagris, Ocyurus chrysurus*) and three groupers (*Cephalopholis fulva, Epinephelus morio, Mycteroperca bonaci*) are among the main reef fish stocks in commercial landings (Table 1, Fig. 3) (OLAVO; COSTA; MARTINS, 2005). These stocks have high market value (MARTINS et al., 2006; MPA, 2013) and are caught mainly by hand line and harpoon (OLAVO; COSTA; MARTINS, 2005; PREVIERO; GASALLA, 2018).

The snappers and groupers are recognized by the American Fisheries Society as a management unit, encompassing also other reef associated species, the by-catch stocks, composing the snapper-grouper complex (COLEMAN et al., 2000; OLAVO et al., 2011). These stocks are carnivorous and feed on fish and crustaceans (FREITAS et al., 2017), playing a fundamental role in the trophic equilibrium of the coral reef ecosystems (RIZZARI et al., 2014). These stocks are mostly long-lived, large-bodied, slow growth (Table 2). Their life-traits also indicate late sexual maturation and spawning aggregations, which make them highly vulnerable to the fisheries (COLEMAN et al., 1999; SADOVY DE MITCHESON et al., 2013). The snappers and groupers have also high fecundity, wide spawning period and low recruitment fails (OLAVO et al., 2011).

Table 1. The snapper and grouper stocks selected for this study.

Scientific name	Family	Group name	Local name	English name
Lutjanus jocu	Lutjanidae	Snapper	dentão	dog snapper
Lutjanus synagris	Lutjanidae	Snapper	ariocó	lane snapper
Ocyurus chrysurus	Lutjanidae	Snapper	guaiúba	yellowtail snapper
Cephalopholis fulva	Epinephelidae	Grouper	catuá	coney
Epinephelus morio	Epinephelidae	Grouper	garoupa	red grouper
Mycteroperca bonaci	Epinephelidae	Grouper	badejo	black grouper

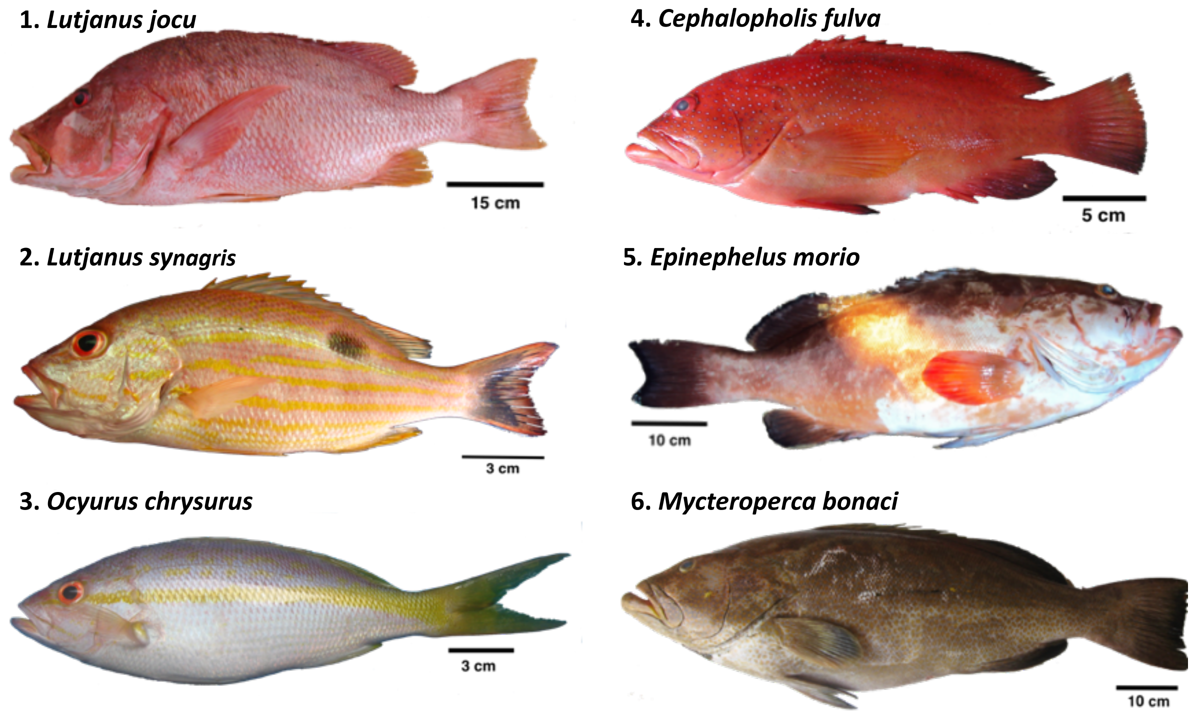

Figure 3. The six fish stocks studied here. On the left the snappers and on right the groupers. The photographed specimens were landed by commercial fishing in the Abrolhos Bank. Photo credits: M. Previero and M. O. Freitas.

Two of the six stocks studied here (*Epinephelus morio* and *Mycteroperca bonaci*) are currently classified as Vulnerable (VU) following IUCN Red Lists (IUCN, 2014; MMA, 2014) (Table 2). In December 2014, the Brazilian government issued a decree (MMA, 2014) prohibiting the capture, transportation, storage, handling, processing and marketing of species under threat criteria (MMA, 2014). Since then, several problems had occurred due to the lack of discussion with the fishery sector, and also because of legal disputes on the decree's jurisprudence. As a consequence, uncertainties and discussions involving fishers, fish traders, researchers and managers have been common, as well as a weakening of fishers' trust towards environmental managers and researchers.

Table 2. Summary of life-traits characteristics of the six stocks studied here. L_{max} (maximum total length recorded for the species); L_{50} (length at which 50% of individuals are mature); Reproductive season (data from Abrolhos Bank stocks); Feeding, habitat and threat category. SL is the Standard Length.

Specie	L_{max} (cm)	L_{50} (cm)	Reproductive season	Feeding	Habitat	Threat category	References
L. jocu	96.00	32.42 (SL)	jun- oct	Crustacea, Mollusca, Teleostei	10 to 115m. Lives around rocky or coral reefs, young in estuaries.	Near threatened	CALÓ et al 2009; FEITOZA et al, 2005; FREDOU; FERREIRA, 2005; FREITAS et al., 2011; FROESE; PAULY, 2017; MMA, 2014
L. synagris	60.00	23.00	sep- marc	Mollusca, Crustacea, Echinodermata, Teleostei	10 to 60m. All types of bottom, mainly around coral reefs and on vegetated sandy areas, turbid and clear water.	Near threatened	CALÓ et al 2009; FONSECA, 2009; FREDOU; FERREIRA, 2005; FREITAS et al., 2014; FROESE; PAULY, 2017; MMA, 2014
O. chrysurus	75.00	20.15 (SL)	jun- oct	Cnidaria, Annelida, Crustacea, Mollusca, Teleostei	7 to 188m. Lives on coastal areas around coral reefs. Young over weed beds.	Near threatened	CALÓ et al 2009; FEITOZA et al, 2005; FREDOU; FERREIRA, 2005; FREITAS et al., 2011; FROESE; PAULY, 2017; MMA, 2014; OLAVO et al., 2011
C. fulva	56.00	13.33 (SL)	jun- sep	Annelida, Crustacea, Teleostei, Testudinata	20 to 160m. Lives on deep reefs.	-	CALÓ et al 2009; FEITOZA et al, 2005; FREITAS et al., 2011; FROESE; PAULY, 2017; OLAVO et al., 2011
E. morio	99.00	38.19 (SL)	jun- sep	Decaopda, Teleostei	10 to 295m. Are found over rocky and muddy bottoms, juveniles live in shallow waters.	Vulnerable	FREITAS et al., 2011; FROESE; PAULY, 2017; MMA, 2014; MOURA; FRANCINI-FILHO, 2005; OLAVO et al., 2011
M. bonaci	160.00	63.33	aug- sep	Teleostei	35 to 250m. Lives on rocky and coral reefs.	Vulnerable	FEITOZA et al, 2005; FREITAS et al., 2011; FROESE; PAULY, 2017; MMA, 2014

Here, the term “stock” is used throughout the text, and the definition adopted here is “a species group or population of fish that maintains and sustains itself over time in a definable area” (BOOKE, 1981). The six stocks are populations occurring in the Abrolhos Bank area (more precisely from the Doce River mouth until the Jequitinhonha River mouth, in the upper limit of Royal Charlotte Bank and in terms of longitude, from the coastline until 36°W) (Fig. 1). Finally, the term stock was chosen as the most adequate, as this is a study in fishery sciences and the Abrolhos Bank is a hotspot area of these species in comparison with the whole species distribution.

4. Thesis objectives and structure

This research aimed to elucidate questions on the snapper and grouper fisheries characteristics, impacts and sustainability in the Abrolhos Bank. Thereby, this thesis was constructed in three chapters in order to encompass socio-ecological and quantitative fishery aspects that exert remarkable influence on the fishery sustainability.

The specific objectives were:

1) Organize, assess and analyze fisheries of the three snappers and three groupers, with the aim to find out patterns of stocks occurrence, patterns of fishing fleets and fishing areas and to propose management units.
2) Examine the relative abundance and the exploitation status of the six snappers and groupers through indicators of size, biomass landed, mortality, spawning and yield.
3) Evaluate the snapper and grouper risk or vulnerability to overexploitation and their fishery sustainability considering biological, environmental social and economic aspects.

In the first chapter the fisheries were assessed, organized, and analyzed mainly in terms of fleet types, fishing gears, fishing trips characteristics (duration, main seasons), labor relations, fishers’ organization, groups of stocks in landings, location of fishing spots and fishing grounds. The analyzes were particularly detailed by fisheries characterization, mappings of the fishing spots and the fishing grounds, grouping of the fish stocks, and clustering of the fishing areas. This chapter presents an overview of the Abrolhos Bank reef fisheries and contributes to the following chapters by improving the understanding of the fleets characteristics, besides indicating which stocks and fishing areas can be managed as a unit.

On the second chapter the overexploitation and biomass declining of the six snappers and groupers were checked through indicators of size, biomass landed, mortality, spawning and yield. For this, month variations and trends in the relative abundance of each stock were analyzed, specimens' sizes in the commercial fishing landings were examined for two periods (2005 - 2007 and 2014 - 2015), size-related overfishing and the occurrence of recruitment and growth overfishing were investigated and the exploitation level, the spawning potential and the yield per recruit of each stock were analyzed. This chapter provides a numeric contribution to the thesis, presenting the exploitation status of each stock and changes in their relative abundance during the study period. Also, the most threatened stocks are revealed as well as the most threatened sizes of each stock.

In the third chapter a risk assessment of the snapper and grouper fisheries was performed using an approach that considers several fishery aspects (biological, environmental, social and economic). An Ecological Risk Assessment for the Effects of Fishing (ERAEF) was conducted. ERAEF is a hierarchical approach used to assess stocks' overexploitation risk, as well as the main threats over habitats and ecosystem and the main social-economic gaps and challenges to obtain a sustainable fishery. Two main analysis were performed in this chapter: the semi-quantitative Productivity and Susceptibility Analysis (PSA) and the qualitative Scale Intensity Consequence Analysis (SICA) (MSC, 2010). The contribution of this chapter to the general objective of the thesis is providing a multidisciplinary risk assessment of the snapper and grouper fisheries and to present a comparison between the impacts of the fishery and of other activities over the reef habitat and over the Abrolhos Bank ecosystem

This thesis encompasses some complementary methods to afford a holistic view of the snappers and groupers reef fisheries in the Abrolhos Bank. The knowledge generated here is expected to clarify some fishery questions besides being applied in fishery management plans.

CHAPTER 1

Mapping fishing grounds, resource and fleet patterns to enhance management units in data-poor fisheries: the case of snappers and groupers in the Abrolhos Bank coral-reefs (South Atlantic).

CHAPTER 1 - MAPPING FISHING GROUNDS, RESOURCE AND FLEET PATTERNS TO ENHANCE MANAGEMENT UNITS IN DATA-POOR FISHERIES: THE CASE OF SNAPPERS AND GROUPERS IN THE ABROLHOS BANK CORAL-REEFS (SOUTH ATLANTIC).[2]

Abstract

In most small-scale fisheries, especially in developing countries, the collection of reliable fishing statistics is not regular, hampering traditional stock assessments. In those data-poor fisheries, a precise knowledge of resources co-occurrence at the ecosystem level, as well as the spatial mapping of fishing activities seem key to support management in a complex fishers-environment context. In the largest South Atlantic coralline reef, the Abrolhos Bank, fisheries are extremely diverse in terms of exploitation capacity, fishing gears, target stocks and operating areas, but any regional fisheries management is currently in place. The aim of this study was to assess, organize, and analyze fisheries of three snappers (*Lutjanus jocu*, *L. synagris* and *Ocyurus chrysurus*), and three groupers (*Cephalopholis fulva*, *Epinephelus morio* and *Mycteroperca bonaci*) along the Abrolhos Bank, with an ultimate goal of proposing useful management units. Surveys were conducted in the main fishing ports, including fishers' interviews and fish size measures in landings. Data analysis allowed a precise fishing characterization, a grouping of stocks co-occurrence, and the mapping of fishing spots and grounds. Three stocks and seven fishing areas clusters were obtained and defined statistically, suggesting useful management units. Specific fishers' groups per fleet were identified as the main stakeholders to be consulted in fisheries plans. Spatial units based on the occurrence of snappers and groupers stocks were defined, having the "*Parcel das Paredes*" the greatest number of fishing spots and the lower fish sizes. Overall, findings contain unprecedented fine scale resolution units that clarifies and simplifies the connections among species, fleets, fishing areas and fishers. They should also strength the call for action to implement fisheries management in a broader ecosystem-scale context.

Keywords: Small-scale fisheries; Fishers knowledge; Management units; Coral reefs; Lutjanidae; Epinephelidae.

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[2] This chapter is based on the scientific publication: PREVIERO, M.; GASALLA, M. A. Mapping fishing grounds, resource and fleet patterns to enhance management units in data-poor fisheries: the case of snappers and groupers in the Abrolhos Bank coral-reefs (South Atlantic). **Ocean & Coastal Management**, v. 154, p. 83-95, 2018.

1. Introduction

Small-scale and artisanal fisheries are a source of food, job, income, social and cultural knowledge for coastal communities, particularly in developing countries (GASALLA; CASTRO, 2016; VASCONCELLOS; DIEGUES; SALES, 2007). These fisheries are highly complex targeting many stocks, using diverse and low technology gears and vessels, which hinders the clear division of fishing fleets operations and subsequent assessments of fish resources (OURÉNS; CAMBIÈ; FREIRE, 2015; SALAS et al., 2007). The small-scale fisheries are usually data-poor, with non-continuous and unsystematic fisheries monitoring, unknown size range of fish specimens by fleet, inexistent assessments at the stock level, unknown fleets operation patterns and labor relations. As consequence, there are misleading estimates of the fishing pressures (RAMÍREZ et al., 2017) and deficiencies in information required for the management plans (HOUK et al., 2017). These problems are recurrent in the small-scale fisheries and frequently hinders and make ineffective any management action, especially at stock level (PENNINO et al., 2016).

The coupled human-environment systems approach combines the interactions among them and helps to understand patterns and processes in the human activities over the natural environment (CARTER et al., 2014; LIU et al., 2007). Socio-ecological assessments are important methods for coastal management and environmental planning (SANTOS et al., 2017). When using participatory approaches, it should help the designing of management plans based in simplification of the complex relations among fishers, resources and the environment (SANTOS et al., 2017).

Beyond that, proper management units are useful for a successful small-scale fishery management. They may integrate target and by-catch species, vessels, fishing gears and key ecosystem functions (BERKES et al., 2001). Proper management units may also provide information instigating management actions more easily.

Small fishery communities typically develop a traditional culture associated with fishery activity and a high dependence on natural resources (DIEGUES, 2001; SANTOS, 2015). Thereby, in the daily activities of artisanal fishers, to know the fishing grounds and the periods when fish are abundant are key tools to reach successful fisheries (DEEPANANDA et al., 2016; MALDONADO, 2000). Some studies have demonstrated that fishers' Local Ecological Knowledge has been an effective and a low-cost method to generate information in data-poor fisheries, especially in provide spatial information (AYLESWORTH et al., 2017; LEITE; GASALLA, 2013; SHEPPERSON et al., 2014). Therefore, including fishers' knowledge in studies and in management plans helps to build tools to provide effective fisheries management (ABREU et al., 2017; HILL et al., 2011). For example, fishing areas with high catch density may be key in management actions by maintain fishery productivity and protect vulnerable species (LÉOPOLD et al., 2014).

Small-scale coral reef fisheries are adapted to rocky and coral bottoms and generally captures multi-species (TOKESHI; ARAKAKI; DAUD, 2013) using multi-gear techniques. Nevertheless, coral reef overfishing has been occurring in several areas, affecting the functioning and stability of marine ecosystems, by reducing the fish sizes and the trophic levels in the catches (BENDER et al., 2013b; ZGLICZYNSKI; SANDIN, 2017) and increasing the sensitivity to disturbances, which may lead to a phase shift in many reefs (BELLWOOD et al., 2012; JACKSON et al., 2001).

In the largest South Atlantic coralline reefs, the Abrolhos Bank (8844 km^2 of reefs) (Fig. 1) there are widespread reef fisheries (MOURA et al., 2013). The catches are composed from several trophic levels, and the snappers and groupers are important reef fishery resources (35.3% of the total fish catch) (MPA, 2013). Currently, approximately 22 species of grouper worldwide are under threat, and the declines are primarily due to the high levels of exploitation not compatible with their life-traits (i.e., long life, late reproduction and sex-changing) (BENDER et al., 2013a; IUCN, 2014; SADOVY DE MITCHESON et al., 2013). The snappers and groupers from Abrolhos Bank are currently classified as "Vulnerable", "Near Threatened" or of "Least Concern" by the IUCN Red Lists (IUCN, 2014; MMA, 2014). The primary threats to these stocks are overexploitation and lack of management measures (SADOVY DE MITCHESON et al., 2013).

Abrolhos Bank fisheries are data-poor, multi-gear, multi-species, have complex relationships among fishers, lack of structured and systematic fisheries monitoring and enforcement. At present, there are no management actions that cover the whole Abrolhos Bank ecosystem neither an organization taking care of its fisheries. Without clear information on fisheries complexity and proper definition of management units, the snapper and grouper fisheries should suffer a greater delay in fisheries management processes, which leads to several losses of ecosystem goods and services. Thus, an in-depth fisheries characterization with some definition of potential management units is an essential step to contribute scientifically to an implementation of fisheries management actions. In the present study, we aimed to assess, organize, and analyze snapper and grouper fisheries along the Abrolhos Bank, mainly in terms of fleet types, fishing gears, fishing trips characteristics (duration, main seasons), labor relations, fishers' profile, groups of stocks in landings, location of fishing spots and fishing grounds.

The fisheries of the following six stocks of the Abrolhos Bank were studied with an ultimate goal of proposing useful management units: the snappers *Lutjanus jocu*, *L. synagris* and *Ocyurus chrysurus* and the groupers *Cephalopholis fulva, Epinephelus morio* and *Mycteroperca bonaci.* The analysis was particularly detailed by (1) characterizing the fisheries, (2) mapping fishing spots and fishing grounds, (3) grouping fish stocks, and (4) clustering fishing areas. The knowledge provided is expected to clarify key management questions besides being applied in spatial and fisheries planning.

2. Methods

2.1 Data collection

The data collection was designed based on:

1. Surveys with snapper and grouper fishers. A semi-structured questionnaire was applied to fishers from the Prado, Alcobaça, Barra de Caravelas and Ponta de Areia ports. Surveys were conducted in 2011 and in 2014-2015. The survey addressed the times and places of snapper and grouper catches in the Abrolhos Bank. Fishers marked their fishing grounds by stock on a nautical chart. The ages of fishers and information about the fishing trip and vessels were also registered. For the survey, the most expert fishers were selected according to the 'snowball' method (NEIS et al., 1999), and before each interview, we asked each fisher whether he would agree to participate.

2. Compilation and analysis of fisheries monitoring data from the national fishery statistics. Fisheries monitoring data from the years 2010 and 2011 was made available for the four ports studied (MPA, 2013). A program was initiated by the Brazilian government and designed by the Brazilian Institute of Geography and Statistics (IBGE), where data collection was performed in partnership with NGOs and local citizens who received specific training. Information about the vessels operating and landing in the region was analyzed, as well as the equipment and fishing gear used and information about the fishing trip (such as fishing gear and vessel characteristics, trip duration, fishing periods, hours of fishing per day and number of fishers per vessel), besides the composition of the catches.

3. Records of specimens' lengths at fish landings. Specimens were measured at the fishing ports (Total Length, in cm) between June 2014 and September 2015.

2.2 Data analysis

Three sets of analysis were conducted to consider the objectives:

1. Fishing characterization. The snapper and grouper fisheries in the Abrolhos Bank was characterized based on: fishers' age groups; the most common fleet types; the main fishing gear; the variety of fishing gear per vessel; the sizes of vessels; the number of fishers per vessel; the amount of fishing equipment per fisher; hook sizes; length of specimens by port; the duration of the fishing trip; the distance from shore and depth explored and the better months for fishing.

2. Mappings. Fishing grounds informed by fishers were transformed into fishing spots. For this a map with grids (0º15'00') was created and one point was plotted, per stock, in each quadrant (15') in the area reported by each fisher. The density of fishing spots per quadrant was analyzed on a scale of intensity (1 to 9 or more spots per 15' quadrant). The quadrants received fictitious names in order for subsequent analyses to be conducted. The fishing grounds that were locally named by fishers were mapped in order to maintain the original dimensions of the fishers' drawings. The program used to compute the data was ArcGIS 9.3.

3. Groupings. Similarities among fish stocks were grouped based on their co-occurrence in the monitored fishing landings, using a non-metric multidimensional scaling (NMDS) (R-mode). A cluster analysis was performed to identify similarities between the presence and absence of the stocks in the 15' quadrants (R-mode). Similarities among fishing quadrants were grouped based on the presence or absence of snapper and grouper stocks using a cluster analysis where stocks are the descriptors and the 15' quadrants are the objects (Q-mode). In grouping analyzes the method used was Unweighted Arithmetic Average Clustering (UPGMA), using binary data transformed into coefficients of Jaccard euclidean distance, using the average method (LEGENDRE; LEGENDRE, 1998). From these cluster results, the most similar areas were mapped in order to facilitate the understanding of spatial similarities between the fishing areas. Clustering analyses were carried out using the language and environment for statistical computation and graphics "R" (R DEVELOPMENT CORE TEAM, 2013).

3. Results

3.1 Fishing characterization

Based on the 82 interviews performed with fishers between 30 and 75 years old, some age patterns were found, being Ponta de Areia fishers the oldest (Table 3), and harpoon diving fishers the youngest. We found 8 different fleet types registered for the snapper and grouper landings based on a combination of fishing gear adopted and the vessel lengths (for Prado and Alcobaça, the only available data) (Table 3). The largest fishing port in terms of number of vessels is Alcobaça (Fig. 4), usually with four fishers per vessel (Table 4). There, the largest vessels were the longline, with the net vessels the smallest, while in Prado the largest vessels operated with hand line and bottom longline, and the smallest operated with gillnets (Table 4).

Table 3. Summary of fishing gears registered and interviewed fishers by studied port on Abrolhos Bank region.

Fishing port	Fleet type based on gears used and in parenthesis vessels average length	Number of interviewed fishers by period		Fisher's age	
		2011	2014-15	Range	Mean
1. Prado	Hand-line (9.42); Hand line and harpoon (10.22); Hand line and bottom longline (11.62); Gillnet (7.80); Hand line and gillnet (9.00)	6	4	43-59	49
2. Alcobaça	Harpoon (10.18); Hand line (10.80); Hand line and harpoon (10.28); Hand line and bottom longline (11.55); Gillnet (7.49); Hand line and gillnet (8.5)	15	21	31-72	51
3. Barra de Caravelas	Harpoon; Hand line; Hand line and harpoon; Hand line and bottom longline; Gillnet	15	12	30-75	43
4. Ponta de Areia	Hand line; Hand line and harpoon; Hand line and bottom longline; Gillnet; bottom longline and harpoon	4	5	42-66	57

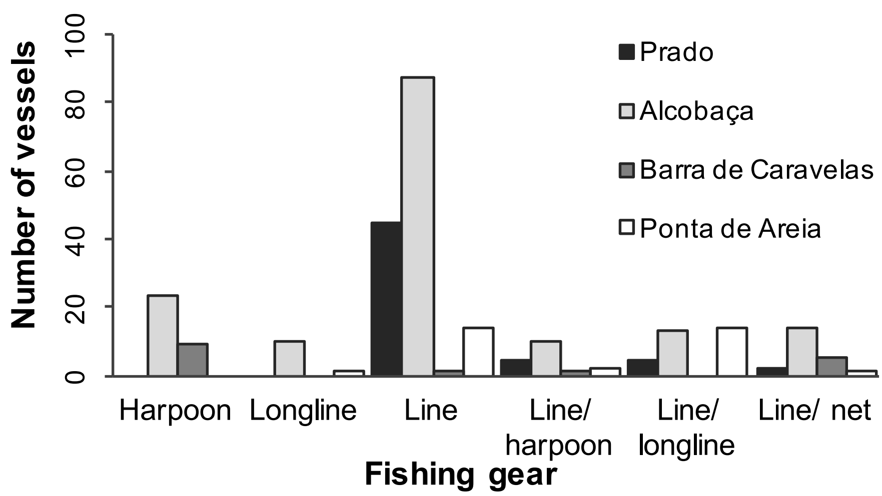


Figure 4. Fleet size by fishing gear and port in the Abrolhos Bank.

Table 4. Summary of fishing gears, number of fishers and fishing trip duration by fleet type and port on the Abrolhos Bank (mean ± standard deviation).

Fishing port	Fleet type	Mean of harpoons by fisher	Mean of lines by fisher	Mean of hooks by fisher	Mean of fisher by vessel	Mean fishing trip duration, in days	Main stocks	
							Snappers	Groupers
1. Prado	Harpoon	0.40 ±0.4	-	-	-	6.73 ±6.1	*L. jocu*	*E. morio, M. bonaci*
	Hand-line	-	1.00 ±0.7	4.56 ±3.8	4.30 ±0.2	10.30 ±5.1	*O. chrysurus,*	*C. fulva, M. bonaci*
	Hand-line/ harpoon	-	-	2.50 ±0.5	4.00 ±0.6	9.64 ±7.5	*O. chrysurus*	*E. morio*
	Hand-line/ bottom longline	-	-	2.57 ±1.8	5.70 ±0.3	15.53 ±7.4	*O. chrysurus*	*M. bonaci*
	Hand-line/ gillnet	0.66 ±0.0	-	2.0 ±0.0	3.00 ±0.0	8.67 ±3.6	*L. synagris, O. chrysurus*	*E. morio, M. bonaci*
2. Alcobaça	Harpoon	1.94 ±0.5	-	-	3.60 ±0.1	10.84 ±5.1	*L. jocu,*	*E. morio, M. bonaci*
	Bottom longline	-	-	-440.00 ±184.9	4.77 ±0.1	18.26 ±7.0	*L. jocu, O. chrysurus*	*M. bonaci*
	Hand-line	-	5.33 ±4.9	28.01 ±61.1	4.40 ±1.3	13.40 ±6.6	*O. chrysurus,*	*C. fulva*
	Hand-line/ harpoon	5.20 ±1.3	-	5.00 ±3.6	3.90 ±0.1	14.13 ±2.4	*L. jocu*	*M. bonaci*
	Hand-line/ bottom longline	-	-	3.95 ±1.6	4.80 ±0.4	15.76 ±2.2	*L. jocu*	*M. bonaci*
	Hand-line/ gillnet	-	-	9.00 ±0.0	3.00 ±0.0	3.00 ±0.0	*L. synagris*	*M. bonaci*
3. Barra de Caravelas	Harpoon	1.02 ±0.1	-	-	3.80 ±0.2	1.06 ±0.3	*L. jocu,*	*E. morio, M. bonaci*
	Bottom longline	-	-	15.00 ±0.0	-	-	*O. chrysurus,*	*M. bonaci*
	Hand-line	-	1.50 ±0.7	3.00 ±1.4	3.00 ±0.0	2.00 ±0.0	*L. synagris*	*E. morio*
	Hand-line/ harpoon	-	-	-	-	1.56 ±0.5	*L. synagris, O. chrysurus*	*E. morio, M. bonaci*
	Bottom longline/ harpoon	-	-	-	-	1.00 ±0.0	-	*E. morio*
	Gillnet	-	-	-	-	1.00 ±0.0	*L. synagris*	*E. morio*
4. Ponta de Areia	Hand-line	-	2.03 ±0.1	3.94 ±0.4	2.40 ±0.1	1.26 ±0.5	*L. synagris*	*E. morio*
	Bottom longline	-	-	-	2.10 ±0.4	1.39 ±0.5	*L. synagris*	*M. bonaci*
	Hand-line/ harpoon	-	-	-	2.20 ±0.0	1.56 ±0.5	*O. chrysurus*	*M. bonaci*
	Hand-line/	-	-	-	-	1.00 ±0.0	*L. synagris*	*M. bonaci*
	Gillnet	-	-	-	-	2.00 ±0.0	*L. synagris*	*E. morio*

The most common fleet for catching snappers and groupers were hand lining, followed by line/ bottom longline in Prado, Alcobaça and Ponta de Areia (Figs. 4, 5). Fishers used from 1 to 10 hand lines each and from 1 to 625 hooks per fisher in the studied ports (Table 4). The greatest variation in hook size was registered in Alcobaça and the smaller hooks used were in Ponta de Areia (Fig. 6). While in Alcobaça the specimens caught were among the largest of the four ports, in Ponta de Areia the specimens landed were smaller (Fig. 7).

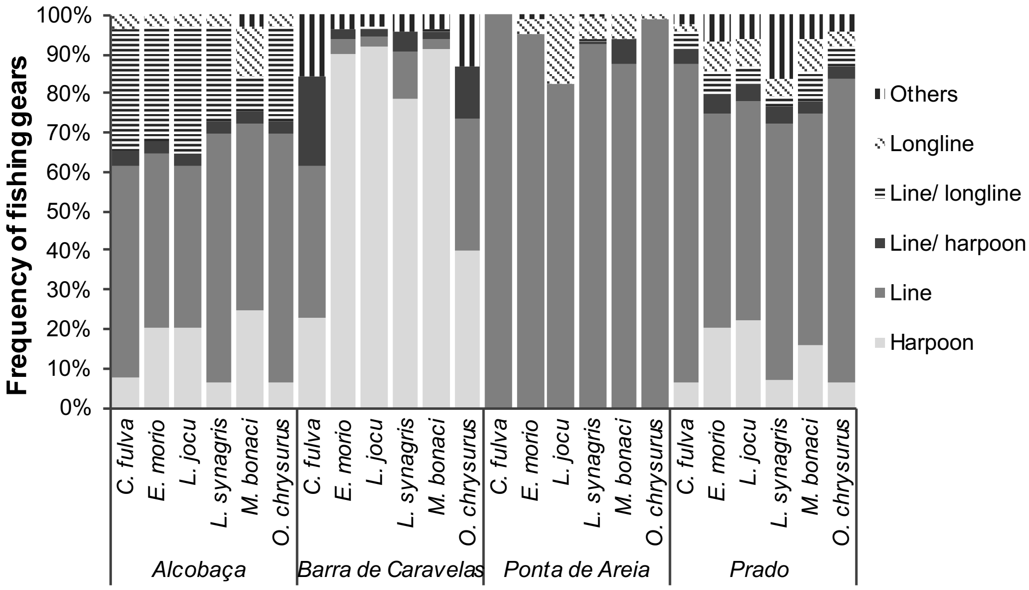


Figure 5. Frequency of fishing gears used to catch each stock by fishing port. The frequency corresponds to the sum of fishers' citations and landings records.

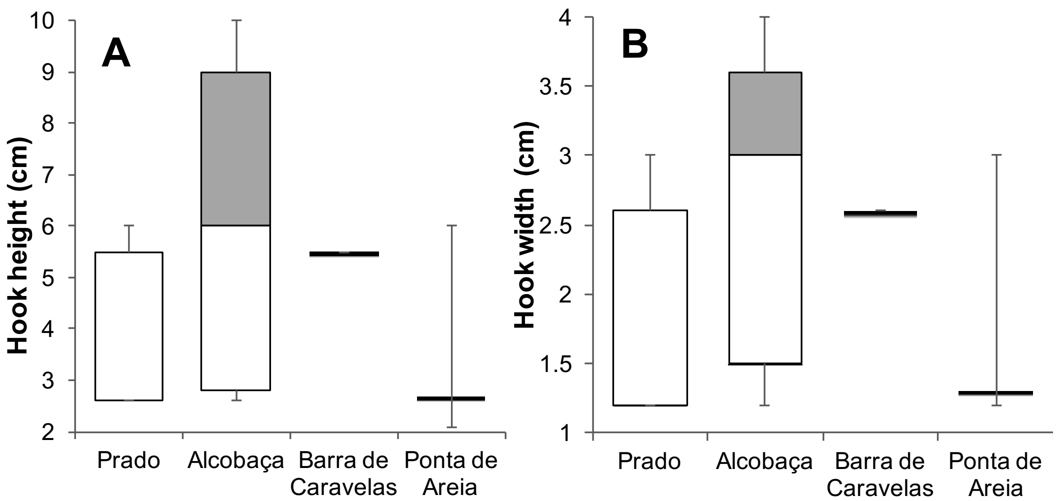


Figure 6. Hook sizes used in hand line and bottom longline fisheries in the Abrolhos Bank. A- hooks height, B- hooks width. The dark central lines represent the median sizes, the grey box represent 25% of the data above the median value, the white box represent 25% down the median value and the bars indicate the maximum and minimum values.

Harpoon diving fishery prevailed in the Alcobaça and Barra de Caravelas ports (Figs. 4, 5) with differences in the fishing sites, fishing equipment used and trip duration. On one hand, in Alcobaça harpoon diving fishery occurred in deep regions (up to 50 m), approximately 2 harpoons per fisher, often with equipment to assist breathing under water, and in average 10 days fishing trip (Figs. 8, 9, Table 4). On the other hand, in Barra de Caravelas this fishery occurred in coastal and shallow areas and was performed using one harpoon per fisher and apnea technique in one day trips (Figs. 8, 9, Table 4).

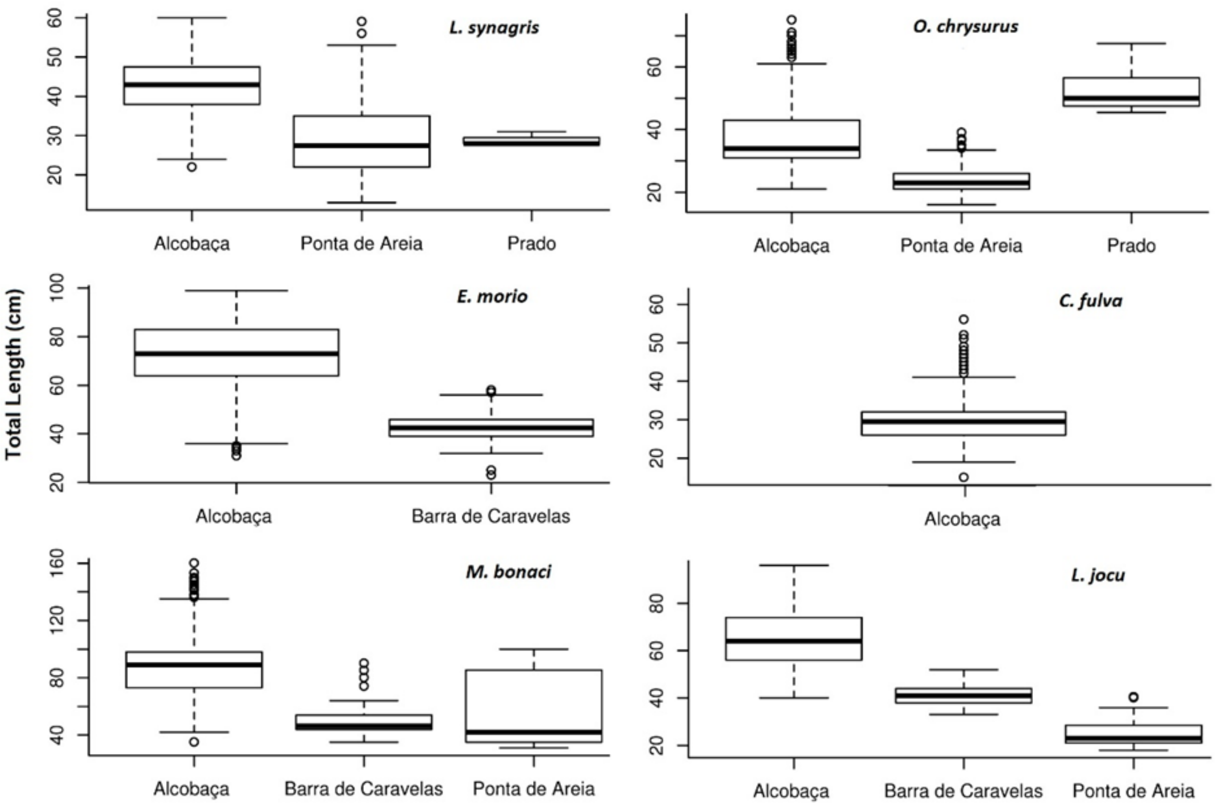


Figure 7. Fish sizes in landings by port in the Abrolhos Bank. The dark lines represent the median sizes, the box represent 25% of the data above and 25% down the median values and the balls are outliers.

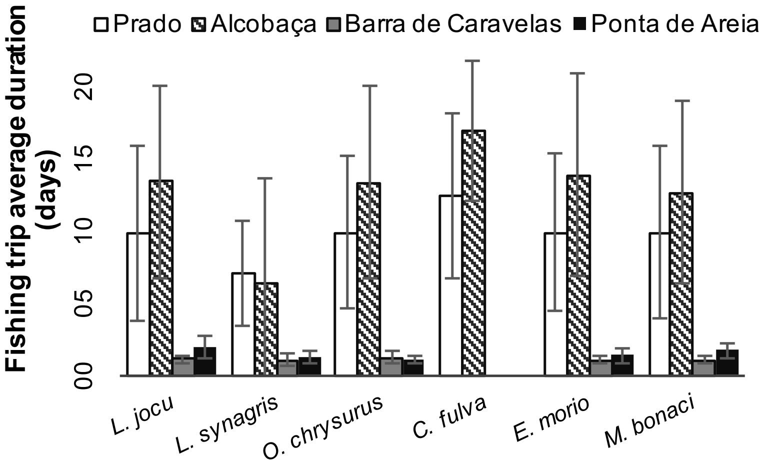


Figure 8. Fishing trips durations, in days, by stock and port in the Abrolhos Bank. The bars indicate the standard deviation.

According to the fishers the summer months are the most suitable for catching the six stocks (Fig. 10). The main reasons are the clearest seawater, the stocks are closer to the coast, and the winds have tow intensity. Winter months were also indicated as good for fishing *L. jocu, L. synagris*, *O. chrysurus* and *C. fulva* (Fig. 10).

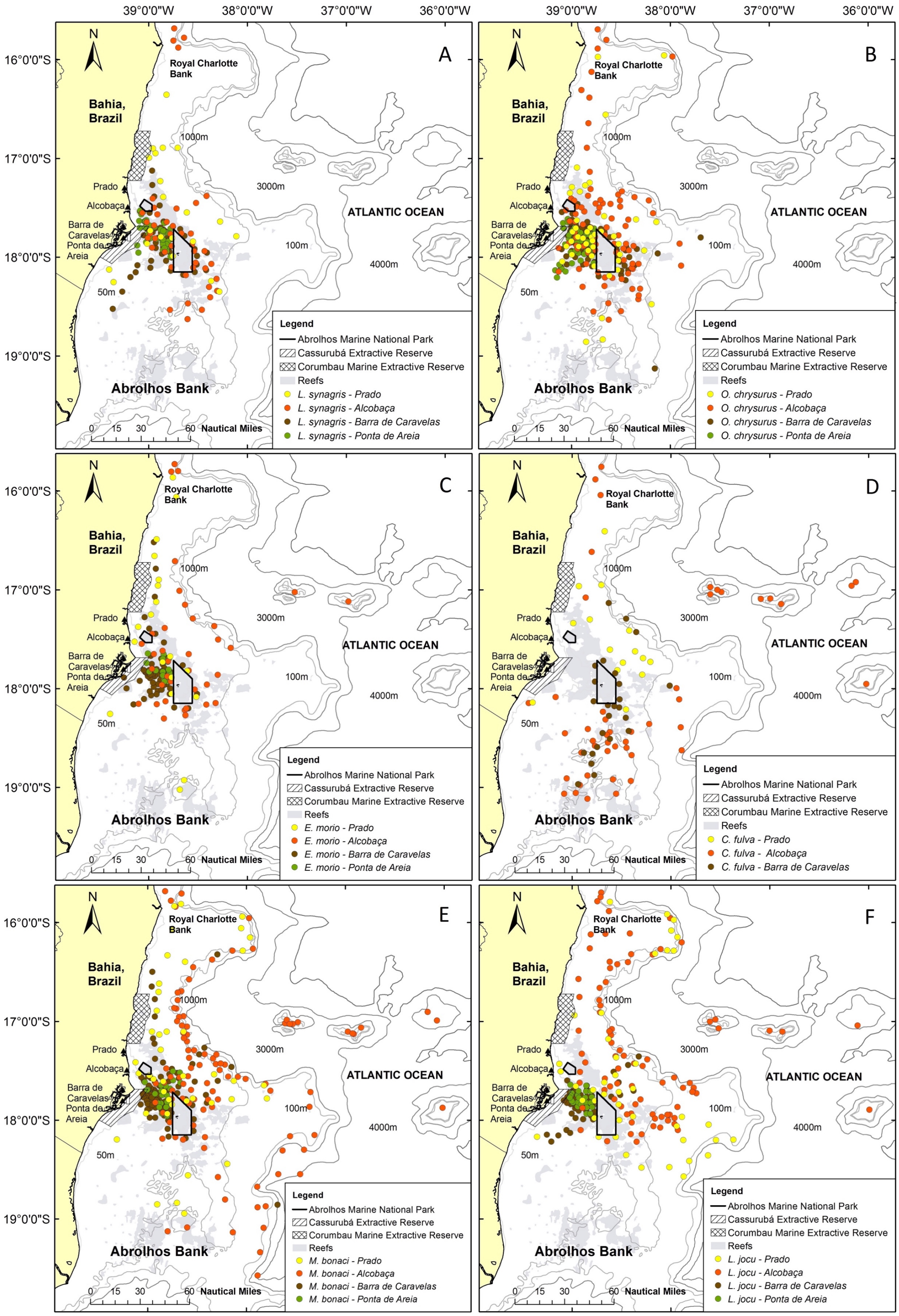


Figure 9. Maps of fishing spots by stock and port in the Abrolhos Bank. Each map represents one species (A- *L. synagris*, B- *O. chrysurus*, C- *E. morio*, D- *C. fulva*, E- *M. bonaci* and F- *L. jocu)*. The fleet of each port have a different spots color (Prado-yellow, Alcobaça - orange, Barra de Caravelas - green and Ponta de Areia – brown).

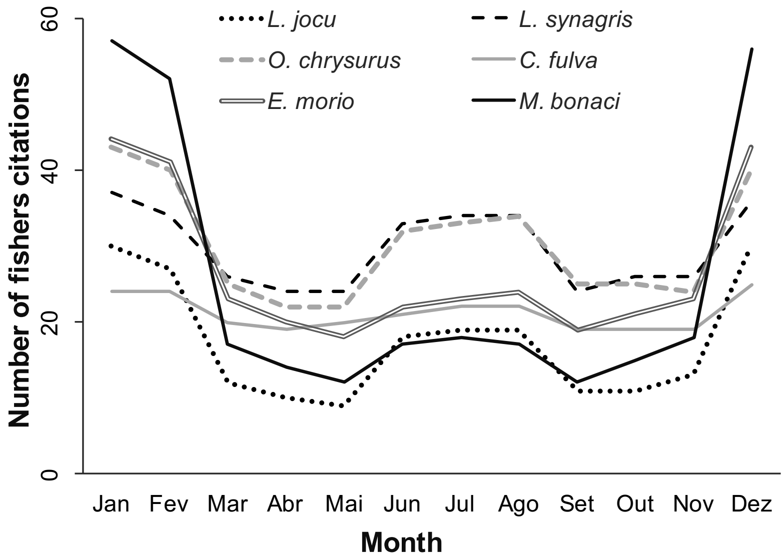


Figure 10. Better months to catch each stock in the Abrolhos Bank, according to fishers' citations.

3.2 Fishing spots and fishing grounds maps

Fishers from Prado and Alcobaça operated around the Abrolhos Bank, Royal Charlotte Bank and Minerva, Rodger and Hotspur banks (Fig. 9). On the "*Parcel das Paredes*" region a coastal and focused fishery landed in Ponta de Areia and Barra de Caravelas ports (Fig. 9). High-intensity fishing occurred in the "*Parcel das Paredes*" region in which almost all the stocks studied here can be found, also, around the Abrolhos MNP and on northeast of this area toward the continental slope, in the region between the Corumbau MER and the continental slope (Fig. 11). Some of the locally named fishing grounds marked by fishers were marked in different places by different fishers (Fig. 12).

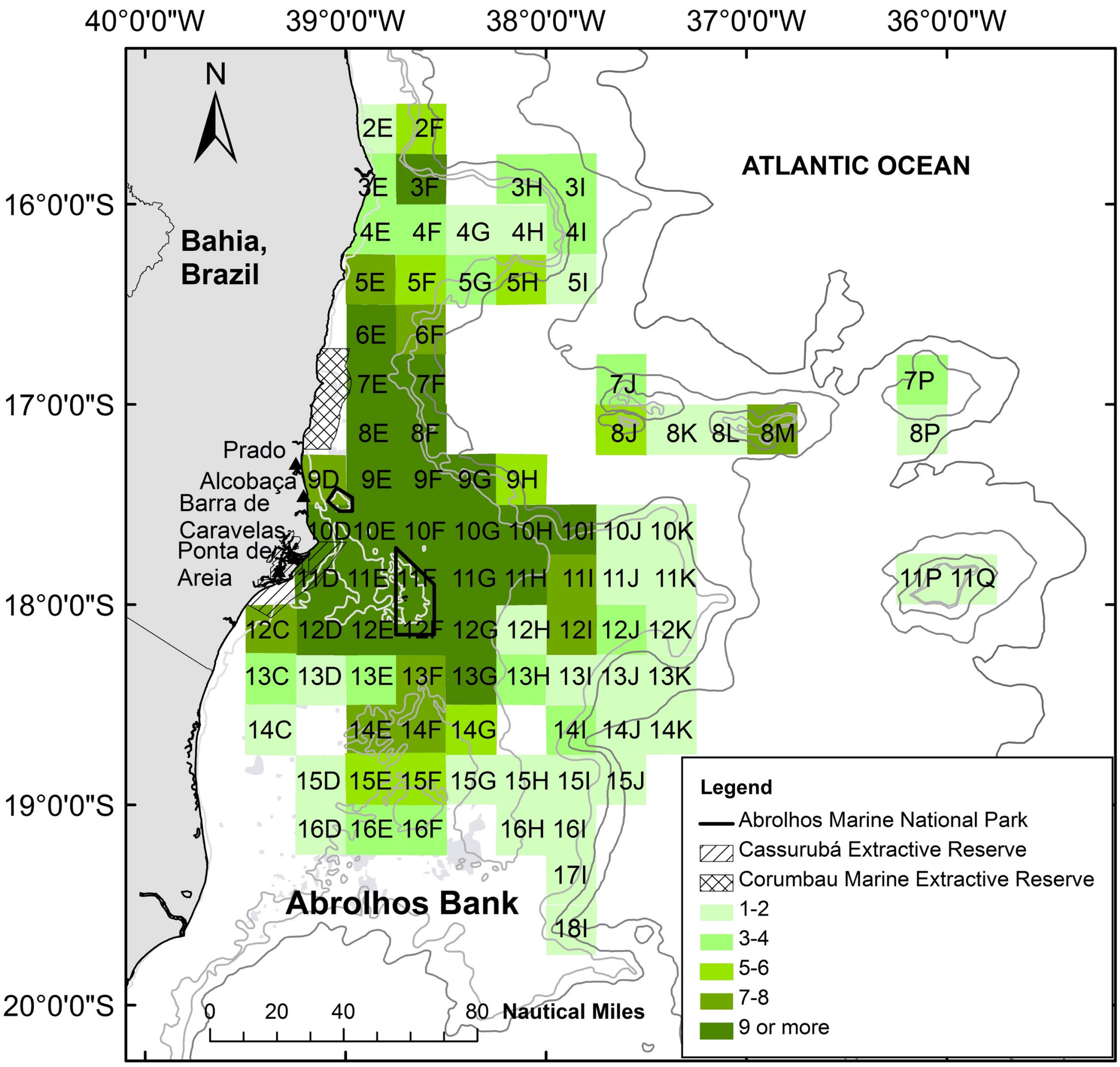


Figure 11. Map of fishery intensity in the Abrolhos Bank. The colors indicate the number of fishing spots informed by fishers by 15' quadrants. The codes inside the quadrants are fictitious names used in the cluster analysis.

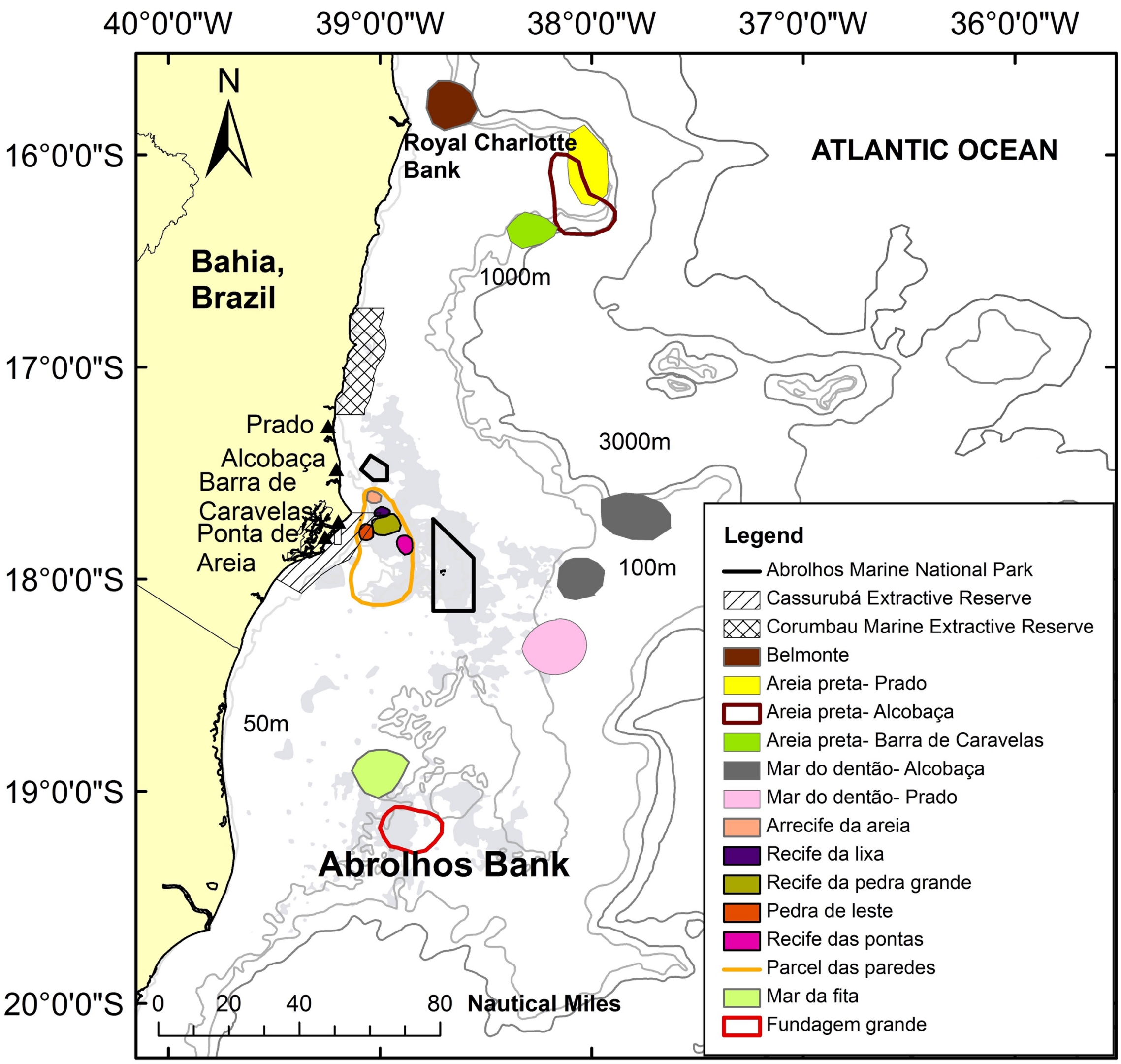


Figure 12. Map showing the locations and dimensions of the locally named fishing grounds in the Abrolhos Bank.

3.3 Clusters

The main groups of stocks observed co-occurring in the fishing landings were "*L. jocu, E. morio* and *M. bonaci*" mainly in harpoon fisheries from Alcobaça, Barra de Caravelas, and "*O. chrysurus* and *C. fulva*" mainly in hand-line fisheries from Alcobaça (Fig. 13). The *L. synagris* was the most distinct stock in fishing landings (Fig. 13).

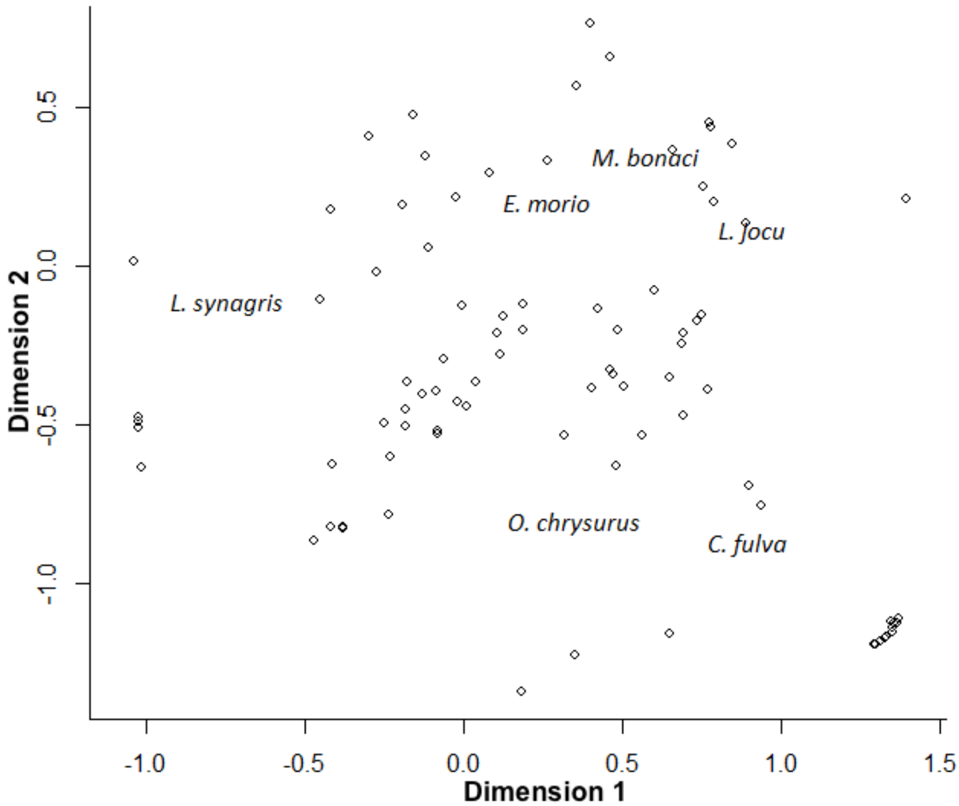


Fig. 13. Non-metric multidimensional scaling of the six stocks according to their co-occurrence in the fishing landings. The nearest stocks in the graphic were landed together more times. Points represent 15’ quadrants.

The grouping of stocks based on cluster analyses highlighted large overlap of *L. synagris* and *E. morio* (south of Caravelas, *Parcel das Paredes* and Belmonte) and *L. jocu and M. bonaci* (near the continental slope, *Parcel das Paredes* and around Abrolhos MNP) (Figs. 9; 14; Appendix, Fig. A.1). Whereas, using the same criteria, *C. fulva* was the most distinct from the other stocks, occurring primarily in the south of Abrolhos MNP (Figs. 9, 14; Appendix, Fig. A.1).

According to the clustering of quadrants, we identified seven mostly similar fishing areas (Fig. 14; Appendix, Fig. A.2). Among these, there were fishing quadrants with zero distance (composed of the same stocks in the same amounts) (Appendix, Fig. A.2).

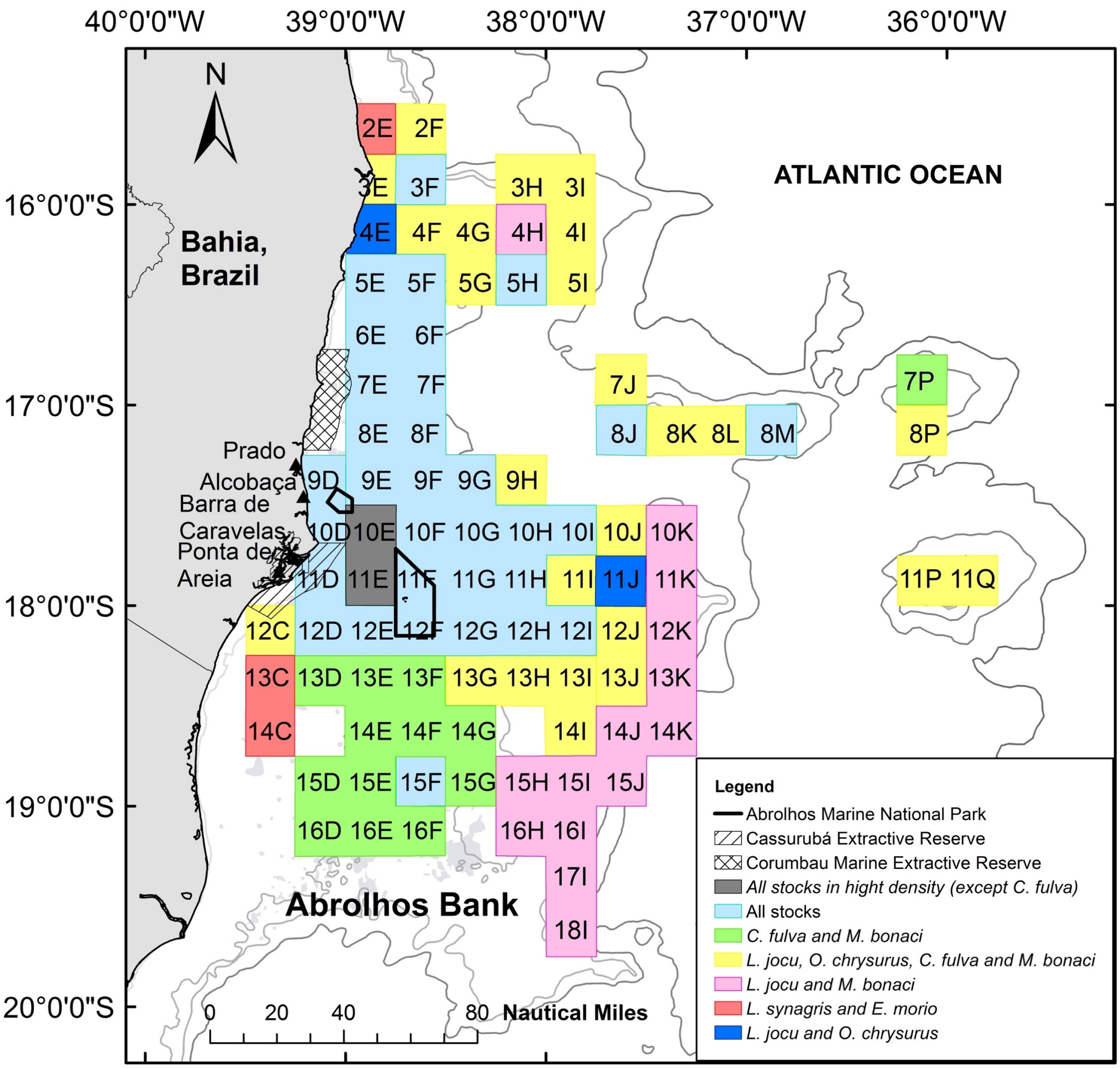


Fig. 14. Map of the most similar fishing areas resulting from the clustering of fishing quadrants. Each area enclosed by a color is similar regarding stocks occurrence. The codes inside the quadrants are fictitious names used in the cluster of fishing quadrants.

4. Discussion

In this study, we combined different data sources (survey with fishers, fisheries monitoring and biological data) to analyze and classify some snapper and grouper fisheries of the Abrolhos Bank. Fishers' knowledge, fleets, fishing areas and fish specimen's sizes were combined for the application of different analysis (fishing characterization, grouping of fish stocks and mapping of fishing areas). Finally, we explored and defined appropriate management units that would serve in fisheries management in the scale of the Abrolhos Bank ecosystem. Those management units were basically: groups of fish stocks (those caught by similar fishing methods and co-occurring in landings, and stocks co-occurring in one particular fishing ground), and groups of fishing areas (with co-occurrence of fish stocks). All findings were unprecedented and may be useful in regional management plans and helpful to elucidate and simplify complex connections among species, fleets, fishing areas and fishers.

4.1 Diving in fisheries characteristics

In order to provide understanding on snapper and grouper fisheries over the largest coral reef ecosystem of the South Atlantic Ocean, the compilation and analysis of intrinsic characteristics, such as fishers' profiles, fleet, vessel and gear types, duration of fishing trips and fishing areas, were undertaken. Based on the main differences found on these fisheries, the typology proposed by Diegues (2004) in respect to production systems of Brazilian small-scale fisheries may be used. Prado, Barra de Caravelas and Ponta de Areia fisheries would be within the type "Fishing held within the mold of small market production – the small market production of artisanal fishers". Alternatively, in Alcobaça, major fishing would be under the type "Fishing performed in the form of capitalist social organization of production – production of the owners of more than one vessel". Besides that, in Prado and Alcobaça fisheries a 'boss/employee' job relationship predominated, whereas in Barra de Caravelas and Ponta de Areia prevailed the family relationship among fishers in the same vessel (PREVIERO, 2014). Despite Prado being classified as the first type, some characteristics of its fisheries indicate a larger scale than in Barra de Caravelas and Ponta de Areia (employment relation, vessel sizes, offshore fishing spots and larger specimens' size). Nevertheless, none remarkable increasing scale trend was found in Prado, since those characteristics have been previously observed in 2005 by Freitas (2009).

These fisheries classifications are important tools for the elaboration and implementation of fishery management measures since it makes explicit the labor relations. By linking the fisheries classifications and the labor relations to the fishing spots arrangements by port (Fig. 9) we can better understand how the fisheries scale influence the spatial distribution of fishing. On one hand, the most heavily organized fisheries (Alcobaça and Prado) also operated in locations farther from the coast. On the other hand, the smaller scale fisheries (Barra de Caravelas and Ponta de Areia) operated in coastal locations and named small fishing grounds with high precision (Fig. 12). In summary, this classification as well as the understanding of the different scales of each fishery facilitate management proposals in a fine scale and enable a pre-evaluation of the effectiveness of a given management proposal.

Abrolhos Bank fisheries are particularly multi-gears (Table 4, Fig. 5). To achieve management effectiveness in this type of fishery, it is required special attention in considering the different gears and income alternatives (DAVIES et al., 2009; HICKS; MCCLANAHAN, 2012). Thus, we believe this work also contributed to future management plans by explicit which are the multi-gear fleets (their fishing areas, fishing ports and main stocks). Here we also registered diving with equipment that helps underwater breathing, a prohibited practice that occurs in this region, previously reported by Previero (2014). It represents an example of the difficulty to enforce fishing laws in the region, mainly due to the lack of trained staff and financial resources for this purpose.

Data-poor reef fisheries, especially in communities with low income alternatives usually can adapt the fishing gears to explore the various resource size spectra (TUDA; WOLFF; BRECKWOLDT, 2016). The smallest hooks used in the Abrolhos Bank are from fishers living in Ponta de Areia where the sizes of the specimens in landings were often below their average size at first maturity (FREITAS et al., 2011, 2014). As the hand line fishery practiced by fishers from Ponta de Areia occurred in a coastal region "*Parcel das Paredes*", two hypotheses might explain the smaller size of the specimens: (1) the coastal region was a recruitment site, and (2) the larger individuals were already removed by fishing. Recent studies have shown that such area is a recruitment site (SARTOR, 2015). Moreover, the limited navigation equipment, the moon phases and the intensity of the winds makes the smaller vessels to fish closer to the shore and as a consequence can only capture the fraction of the stock living in that area (TUDA; WOLFF; BRECKWOLDT, 2016), often a fraction of juveniles.

The best times for fishing indicated here were summer and winter (Fig. 10). For *E. morio* and *M. bonaci* the catches were limited in their spawning season (July to October) when they aggregate in areas that remain unknown to most of the local fishers, outside the MPAs existing in the Abrolhos Bank (FREITAS et al., 2017). Similar to our findings there is a high occurrence of *O. chrysurus* in winter in the coast of Ilhéus, a town immediately north of the Abrolhos Bank (CETRA; PETRERE, 2014). Moreover, to the fishers, fishing grounds away from shore were difficult to explore in the winter because of unfavorable weather conditions for navigation and location of stocks. Southeasterly (SE), south (S), and southwesterly (SW) winds are observed in the region in the autumn and winter months (TEIXEIRA, 2013). Regarding the largest catches occurred during the summer months and the fishers observed low winds intensity, Teixeira (2013) found a predominance of northeasterly winds. As a result, under such climatic conditions, many fishers could go out on longer fishing trips and reach fishing grounds farther away.

Similarly, fishers in Ilhéus argue that the primary factors influencing the catches are marine currents and climatic factors, with no change in abundance of stocks throughout the year (CALÓ et al., 2009).

4.2 Groups of stocks as fisheries management units

Three different fish stock groups were found for the two methods employed. The most co-occurring stocks in total catches were "*L. jocu*, *E. morio* and *M. bonaci"* (Fig. 13), and regarding this, we suggest that the management of these three stocks should be carried out jointly, with practices sufficient to protect the three stocks simultaneously. The most co-occurring stocks in fishing grounds were "*L. synagris* and *E. morio*" followed by "*L. jocu and M. bonaci*". Our results highlighted the multi-species fisheries along the Abrolhos Bank, as well as the necessity for considering groups of species rather than individual species for fisheries management actions, since they have greater efficacy (FARMER et al., 2016; JENNINGS et al., 2001). Furthermore, single-species fishery regulations such as size limits and gear restrictions have shown inadequate to avoid the depletion of fish stocks in multi-species and multi-gear fisheries (TUDA; WOLFF; BRECKWOLDT, 2016).

Over the fishing ground locally-named "*Parcel das Paredes*", we found large amount of fishing spots mainly from Barra de Caravelas and Ponta de Areia (Fig. 12), the ports with the smallest fish sizes in landings (Fig. 5). Similar to our findings, Sartor (2015) observed an overlap in the recruitment sites for *L. jocu*, *L. synagris, O. chrysurus, E. morio* and *M. bonaci* (*Parcel das Paredes*) while the *C. fulva* stock recruitment site was observed away from these stocks, near the Abrolhos National Marine Park. Likewise, Martins, Olavo and Costa (2007) also found co-occurrence among *L. jocu*, *L. synagris, O. chrysurus,* and *M. bonaci*, whereas the *C. fulva* stock also occurred in locations different from those of the other stocks. Recalling that in this study, *L. jocu and M. bonaci* were the most similar stocks (Appendix, Fig. A.1), being largely captured near the continental slope (Fig. 9), Pennino et al. (2016) also registered their co-occurrence in other areas along the Brazilian northeast coast. Moreover, they are found together in the "*correção*" phenomenon described by Teixeira et al. (2004), which was also detected by some fishers interviewed in this study.

With respect to the ecological characteristics of fish, snappers and groupers are carnivorous, with crustaceans and fishes being their primary prey (RANDALL, 1968). Snappers are usually benthic, occur primarily on coral reefs, with *L. jocu* juveniles found in estuaries, *L.*

synagris over mud bottoms in turbid water and vegetated sandy areas and *O. chrysurus* over weed beds (RANDALL, 1968). Most groupers can change their body color according to the brightness, turbidity, bottom type or activity engaged (DELOACH, 1999). The groupers studied here are usually hermaphroditic, starting the life as females and changing to males at larger sizes (DELOACH, 1999; RANDALL, 1968), however this sex change has not yet been registered for Abrolhos Bank groupers (FREITAS et al., 2017).

When comparing the fishing spots mapped here (Fig. 9) with the seabed map of the Abrolhos Bank (MOURA et al., 2013), *L. synagris* occurred primarily on reefs; *O. chrysurus* and *E. morio* occurred mainly on reefs, but also upon rhodolith beds; *C. fulva* catches occurs on reefs, rhodoliths and on unconsolidated sediments; *L. jocu* and *M. bonaci* occurred on both reefs and rhodolith beds. Although *L. jocu* occurs in estuaries, none of the interviewed fishers reported catching this species in that environment, possibly because sizes were uninteresting (juveniles). Regarding the variety of bottoms on which *O. chrysurus* and *L. synagris* occurred (Fig. 9), we assume a high diversity of bottoms in the Abrolhos Bank reefs, being surrounded and even filled with muddy silicastic sediments derived from river loads and coastal erosion (LEÃO; KIKUCHI; TESTA, 2003).

4.3 Fishing areas as spatial management units

There is an increasing trend of applying area-based methods in the management of marine resources and fisheries (GASALLA; GANDINI, 2016). In this study, the mapping of fisheries may facilitate and guide future fisheries management actions by using different set of regulations for each fleet (PENNINO et al., 2016) and by considering a relevant scale for area-based management and governance (LÉOPOLD et al., 2014; OURÉNS; CAMBIÈ; FREIRE, 2015).

Previous studies had already shown fishing spots throughout the Abrolhos Bank (MOURA et al., 2013). Here we registered and mapped the areas with the highest concentration of fishing spots differentiating it by stock and port (Fig. 9). By this way we could reveal the spatially-structured fisheries, probably related to the spatial arrangements of habitats (PENNINO et al., 2016).

Seven mostly similar fishing areas were identified, some of them were composed of the same stocks in the same amounts (Fig. 14). The light blue area clearly corresponds to the highest intensity fishing area (Fig. 11), with fishing spots of all the stocks studied here being exploited by the four fishing ports. The gray area undoubtedly corresponds to "*Parcel das Paredes*", with the greatest number of fishing spots (Figs. 9, 11). Therefore, such fishing areas can indicate regions suited to governance by the same fishery regulations, based on the presence of the six stocks of snappers and groupers studied here. Even so special attention to area-based management should be given, the adequate participation of fishers and stakeholders in monitoring fisheries operation seems essential (TUDA; WOLFF; BRECKWOLDT, 2016).

The method we used here, based on fishers' interviews and mappings provided valuable information for these data-poor fisheries. The creation of maps with the input of fishers to chart the fishing grounds was effective in identifying these sites (e.g., BERKES et al., 2001; LEITE; GASALLA, 2013). Many traditional cultures are based on fishery territories, which are places abundant in fishery resources that were either discovered or inherited within the fishery community (CORDELL, 2001; DIEGUES, 2001). To identify these territories and achieve good fishery, the fishers count on the vast knowledge acquired by observing the older fishers and by relying on their personal experiences (ALLUT, 2000; DIEGUES, 2000), using a division of the maritime area (MALDONADO, 2000). For example, in the *Parcel das Paredes* region, fishers identified five named fishing grounds (Fig. 12). Because the fishery over this area had an artisanal character, we associated all the fishing ground marks with what Diegues (2000) describes as "a space full of *pedras* and *cabeços* landmarks along Brazil's northeast coast". In the local context of small-scale fisheries to known these marks represents a prestige of fishers among their peers, because the most knowledgeable fishers are more competent, have greater leadership and catch more fish (DIEGUES, 2000).

Indeed, in this study, we observed some fishing grounds that received the same name by fishers from different ports and that had different locations on the map. This difference occurred for "*Mar do Dentão*" and "*Areia Preta*" (Fig. 12). In offshore spacing this difference is related to the cognitive abilities of fishers resulting from the social and cultural trainings in their communities (MALDONADO, 2000), which might differ among the municipalities studied here. Moreover, in this work, the location of the "Mar do Dentão" fishing ground by Alcobaça fishers was similar to the "*Buracas*" location (BASTOS et al., 2013), which are structures in the Abrolhos Bank concentrating snappers and groupers, among other reef species (CAVALCANTI et al., 2013). We conclude that these locally named fishing grounds can facilitate communication with fishers in drawing spatial units and contribute to defining accurate management units.

In summary, the mapping of fishing grounds and the seven fishing areas defined as spatial management units may be potentially relevant for both the Ecosystem-Based Fisheries Management (EBFM) and Marine Spatial Planning (MSP) of the Abrolhos Bank. These approaches helped to understand how the fishers use specific coastal areas and fishing grounds (EHLER, 2008; MAINA et al., 2016), and may contribute to territorial approaches of access rights and benefits to specific social groups involved (GASALLA; GANDINI, 2016).

4.4 Potential management interventions

Based on the findings revealed here, we suggest some potential management interventions. The first one is the consideration of these management units in an EBFM context for the Abrolhos Bank. Second, the definition of management actions for the groups of stocks found here. Third, the use of the fishing areas for the implementation of some fishery restrictions. This study clarifies on the areas used by each fleet and which are the main species by area, and suggests that the "*Parcel das Paredes"* (Fig. 12) and the gray area shown in Fig. 14 should be a starting point for fisheries management, that are also juvenile fish areas. In addition, it is an area close to the mainland, which makes inspection actions easier.

5. Conclusions

Two types of management units were defined (stocks and areas groups) and were associated to fleets and fishers. It also helped to identify main stakeholders to be considered and consulted in future fisheries management plans in the region. The stocks groups co-occurring in fishing grounds were "*L. synagris* and *E. morio*" and "*L. jocu* and *M. bonaci*", and the group co-occurring in catches was "*L. jocu*, *E. morio* and *M. bonaci*". Seven areas were suggested as spatial units. Among them, the "*Parcel das Paredes*" was notable for the many snappers and groupers fishing spots and for the small size of fish caught there. Findings indicate that that area is key to implement measures to avoid growth overfishing.

Over the Abrolhos Bank, the primary fleets for snappers and groupers use hand lining and harpoon diving. Each port has particular features and production systems type, with Alcobaça landing the broader-scale fisheries in terms of fishing trip duration, fishing autonomy, number and size of vessels, labor relations and fish sizes. Under the same criteria, Prado, Barra de Caravelas and Ponta de Areia were smaller-scale ports, with Barra de Caravelas and Ponta de Areia placing coastal fisheries from daily trips, catching mainly small size fish.

Finally, the method adopted in the analysis, combining interviews with fishers, monitoring data and size measures, allowed a precise fishing characterization, besides the definition of three stocks and seven fishing areas groups as unprecedented fine resolution management units seems to have clarified and simplified complex interactions among species, fleets, fishing areas and fishers. That methodological approach may help to delineate management units in other small-scale data-poor fisheries elsewhere. Our findings should also help the call for action to implement fisheries management in the scale of the whole Abrolhos Bank ecosystem.

CHAPTER 2

Snappers and groupers exploitation status based on fishery indicators: an approach to data-limited reef fisheries in Brazil

CHAPTER 2 - SNAPPERS AND GROUPERS EXPLOITATION STATUS BASED ON FISHERY INDICATORS: AN APPROACH TO DATA-LIMITED REEF FISHERIES IN BRAZIL

Abstract

Small-scale fisheries provide important ecosystem services for many coastal communities, but their impacts on biological populations are still poorly understood. The use of indicators may be an alternative to data-poor fishery assessments because they require only punctual data. In this work, we used fishery indicators (size, biomass-landed, mortality, spawning and yield) to investigate biomass trends as well as the exploitation status of some of the main commercial snapper and grouper stocks from the Abrolhos Bank, Brazil. Trends and monthly variations in the relative stock abundance were analyzed, and specimen size frequencies and commercial landing changes were examined as well as the occurrence of recruitment overfishing and growth overfishing. The spawning potential and the exploitation status of each stock were also investigated. Of the six stocks studied, five were declining (*Lutjanus jocu, Ocyurus chrysurus, Cephalopholis fulva, Epinephelus morio* and *Mycteroperca bonaci*) and five were overfished (*L. jocu, L. synagris, O. chrysurus, E. morio* and *M. bonaci*). The main threats were reductions in abundance and in specimen sizes, recruitment overfishing and growth overfishing. We also observed high fishing mortality and low yield per recruit for all stocks. We hope that this work contributes to fish stock recovery in terms of abundance and individual size. As such, we have presented management suggestions according to stock threats, as we hope to subsidize future but urgent fishery management policies.

Keywords: Small-scale fisheries; CPUE standardization; Size indicators; Lutjanidae; Epinephelidae; Abrolhos Bank.

1. Introduction

Small-scale fisheries provide important ecosystem services in several coastal communities in developing countries (GASALLA; CASTRO, 2016) and may also impact some marine resources, the environment and the fishery community (BEGOSSI et al., 2017). However, there are reports that small-scale fisheries can do not strongly alter the resource biomass or the main trophic levels of a biological community due to the use of traditional methods (MARTIN et al., 2017). In the tropics, the reef fisheries are usually small-scale, artisanal and multispecies (POLUNIN; ROBERTS, 1996). The main resources in the reef catches are of large commercial value (e.g., snappers, groupers, and lobsters) (POLUNIN; ROBERTS, 1996). Typically, the most common fishing gear types in reef fisheries are harpoon diving (spearfishing) and hand lining (e.g., CINNER et al., 2009; MEYER, 2007; SAMOILYS et al., 2017). These fishing gear types may be equivalent with respect to collateral damage to the stocks and the ecosystem (FRISCH et al., 2008).

In the South Atlantic Ocean, on Brazil's East coast, there are a range of small-scale fisheries, many of them occurring over the Abrolhos Bank, the largest coralline reef ecosystem in that Ocean. The Abrolhos Bank encompasses mosaics of benthic habitat, reefs (LEÃO; DUTRA; SPANÓ, 2005) and fishing grounds (PREVIERO; GASALLA, 2018) on an enlargement of the shallow continental shelf (Fig. 1). Three snappers *Lutjanus jocu* (dentão), *L. synagris* (ariocó), and *Ocyurus chrysurus* (guaiúba) and three groupers *Cephalopholis fulva* (catuá), *Epinephelus morio* (garoupa) and *Mycteroperca bonaci* (badejo) are among the main reef fishes in commercial landings. These stocks are mostly long-lived and large-bodied (FREITAS et al., 2017; PREVIERO et al., 2011). Their life traits also include late sexual maturation and spawning aggregations (SADOVY DE MITCHESON et al., 2013), which make them highly vulnerable to fisheries (COLEMAN et al., 1999). Additionally, recent IUCN Red List assessments classified these stocks as "Vulnerable", "Near Threatened" or "Least Concern" (ICMBIO, 2014, IUCN, 2014).

Small-scale fisheries in Brazil and in many developing countries are very data-poor. There are no historical catch and effort data, only punctual records, which are sometimes incomplete (e.g., only catch data), unreported catches, and a lack of resolution in the correspondence between popular and scientific names, among other problems. Until now, none of these six snappers or groupers have been assessed or managed in the Abrolhos Bank. Small-scale fisheries are usually data-poor in terms of the quantification of vessels, gear types used, landing records and historical catch and abundance data (BABCOCK et al., 2013; JOHNSON et al., 2017; NASH; GRAHAM, 2016). This condition makes conducting traditional stock assessments very difficult, hampering the successful management of fisheries (GRAFELD et al., 2017).

Under data-poor conditions, fishery indicators based on length frequency, age frequency and CPUE (Catch per unit effort) have been proposed to assess stock exploitation status (e.g., COPE; PUNT, 2009; FROESE, 2004; HOUK et al., 2017; MINTE-VERA et al., 2017; PRINCE et al., 2011). These indicators can show changes in fishing pressure and in stock size within a short time interval (SALDAÑA et al., 2017). Therefore, these methods have a greater chance of success in tropical fisheries because they require only punctual fish size and catch and effort data to determine the status of the stocks (BABCOCK et al., 2013).

The fishery indicators created by Froese (2004) can suggest an instantaneous stock status in terms of exploitation level, recruitment and growth overfishing by showing the percentage of individuals in size classes (juveniles, optimum and mega-spawner sizes). Another indicator that can be used in data-poor fisheries is the spawning potential ratio (SPR), an index able to identify recruitment overfishing (HORDYK et al., 2015b), based on biological reference points and on biological parameters such as natural mortality (M), fishing mortality (F), size at first capture (L_c), the von Bertalanffy growth rate coefficient (K) and the maximum asymptotic length (L_∞) (HORDYK et al., 2017). SPR indicates the total reproductive potential of a fished stock in relation to the reproductive potential of the same stock in the absence of fishing (GOODYEAR, 1993; PRINCE et al., 2015; WALTERS; MARTELL, 2004). Similarly, the F/M ratio can indicate overfishing with few data requirements and is important in the assessment and management of data-poor stocks (ZHOU et al., 2012).

CPUE is a measure of relative success of fishery operations and is frequently used in stock assessments as a relative index of abundance (HINTON; MAUNDER, 2004; NOAA, 2018). However, CPUE is only related to the portion of the stock vulnerable to fishing gear (MAUNDER et al., 2006). In addition, this index is commonly influenced by factors unrelated to the stock abundance (e.g., season, fishing area, and fleet technology) (MAUNDER et al., 2006). To make this index proportional to the stock abundance and discount the influence of factors changing the catchability of the stock, a common method is CPUE standardization (HINTON; MAUNDER, 2004; MAUNDER; PUNT, 2004). The most common approaches to standardize CPUE are generalized linear models (GLM) and generalized additive models (GAM)(HINTON; MAUNDER, 2004; MATEO; HANSELMAN, 2014; MAUNDER; PUNT, 2004; STASINOPOULOS; RIGBY, 2007). GLM assumes that the relationship between the response variable and the explanatory variables is linear and that it includes exponential data distributions other than normal (MCCULLAGH; NELDER, 1989) and allows fitting categorical and non-continuous variables (MATEO; HANSELMAN, 2014; MAUNDER; PUNT, 2004). GAM is an extension of GLM, with the linear predictor replaced by an additive predictor that fits a smooth function and makes GAM have a non-parametric aspect (HASTIE; TIBSHIRANI, 1986; LI et al., 2005). The Generalized Additive Models for Location, Scale and Shape (GAMLSS) enable modeling the parameters of the distribution of the response variable as linear, non-linear or smooth functions of the explanatory variables (STASINOPOULOS; RIGBY, 2007). Therefore, GAMLSS offers substantial flexibility by expanding the possible relationships between CPUE and a suite of explanatory variables (DREXLER; AINSWORTH, 2013; HINTON; MAUNDER, 2004; MATEO; HANSELMAN, 2014).

The aim of this study was to evaluate the biomass trends and exploitation status of the main commercial snapper and grouper stocks from Abrolhos Bank through indicators of size, biomass landed, mortality, spawning and yield. Accordingly, we analyzed trends and monthly variations in the relative abundance of each stock, we examined specimen size changes in the commercial fishing landings, we investigated the occurrence of recruitment overfishing and growth overfishing, and we verified the spawning potential and exploitation level and the yield per recruit of each stock.

2. Methods

2.1 Data collection

The landing data were obtained for six fishing ports on the Abrolhos Bank coast (Corumbau, Prado, Alcobaça, Barra de Caravelas, Ponta de Areia and Nova Viçosa) (Fig. 1). The data records were collected by three different organizations in three fisheries monitoring programs, delimited by period (2005-2007, 2010-2011 and 2013) (Table 5). In the period from 2010-2011, between 33% and 100% of the fish landings occurring in Nova Viçosa were sampled, in addition to 50% of the landings occurring in Alcobaça and Prado fishing ports and 100% of the landings in Barra de Caravelas, Ponta de Areia and Corumbau (DRAPPER, 2011; MINTE-VERA; SOUZA-JUNIOR, 2014).

The total length measurements of the six snappers and groupers were performed on hand line, bottom longline and harpoon landings in Prado, Alcobaça, Barra de Caravelas and Ponta de Areia during two periods (2005-2007 and 2014-2015). Sampling of the six stocks was conducted weekly on landings occurring during the day, and at least 10% of the total catch from a given fishing trip was measured with at least 0.5-cm precision.

The biological life traits data for the six snapper and grouper stocks from Abrolhos Bank were compiled from the literature (Table 2).

Table 5. Landings information and a brief description of the data with the periods and the covered fishing ports in the Abrolhos Bank. Source are the institution that performed the data collection.

Data type	Description	Period	Fishing ports	Source
Fishing landings	Total catch by specie (kg); Number of specimens by specie; Gear data; Effort (e.g. Number of fishers, Fishing trip duration, Number of lines; Liters of fuel); Information from vessel, fishing trip, fishing area and climate.	2005-07	Corumbau, Prado, Alcobaça, Barra de Caravelas, Ponta de Areia and Nova Viçosa	Project Marine Management Areas Science (MMAS)
Fishing landings	Total catch by specie (kg); Number of specimens by specie; Gear data; Effort (e.g. Number of fishers, Fishing trip duration, Number of lines; Liters of fuel); Information from vessel, fishing trip and fishing area.	2010-11	Prado, Alcobaça, Barra de Caravelas and Ponta de Areia	Brazilian Ministry of Fisheries and Aquaculture (MPA)
Fishing landings	Total catch by specie (kg); Gear data; Effort (e.g. Number of fishers, Fishing trip duration, Number of lines; Liters of fuel); Information from vessel, fishing trip and fishing area.	2013	Barra de Caravelas and Ponta de Areia	CTA Meio Ambiente (private enterprise)
Fish sizes	Specimens total length (cm); Landing place and date	2005-07 2014-15	Prado, Alcobaça, Barra de Caravelas and Ponta de Areia	Project Marine Management Areas Science (MMAS)/ This work

2.2 Treatment and data analysis

The fishery monitoring data were compiled, combined into the same spreadsheet and, if necessary, the units were converted to make the data comparable. To investigate oscillations and temporal trends in the relative abundance of each stock, CPUE was standardized. Additionally, the following analyzes were conducted:

1. The fishing effort was determined for each stock for the landings with the main fishing gear types recorded in each of the projects (hand line for all species as well as harpoon for *L. jocu* and *M. bonaci*). Thereafter, a generalized linear model (GLM) was performed to identify the unit effort by the stock and gear most correlated with the catches. The options for effort units were combinations among the variables: number of fishers on a trip; fishing trip duration; fishing hours by day; number of lines used by fisher and liters of fuel used during the fishing trip (Table

6). The collinearity between the variables was verified by the Variance Inflator Factor (VIF) as well as visual inspections. The unit of effort was chosen based on the visual inspection of the better residuals adjustment of the model:

$$ln(catch)_i = \beta ln(effort)_i + \varepsilon$$

where $ln(catch)_i$ is the neperian logarithm of the catch in fish landing *i*, $\beta ln(effort)_i$ is the neperian logarithm of the fishing effort in fish landing i, and ε is a random error term, with a normal distribution.

2. The nominal CPUE by fishing trip ($CPUE_i$) was obtained by stock for the main fishing gear types with the following equation:

$$CPUE_i = \frac{catch_i}{effort_i} + \varepsilon$$

where $catch_i$ is the total catch in fish landing *i*, $effort_i$ is the effort in fish landing *i* in the units that were chosen with the previous analysis, and ε is a random error term. As the normality hypothesis of the error terms was rejected, we proposed the use of the GAMLSS model, which has the property of adjusting to several distributions. The analyzed fisheries are multi-species, and the absence of capture of a particular stock in a fishing trip may mean both that there were no individuals of this stock in the fishing area and that the fishery aimed to capture another target resource. Thus, we only considered landings with positive catches of each stock. The data were grouped by year and month to obtain the total monthly catch (kg) and the mean monthly catch per unit effort.

3. The standardized CPUE by month and year was obtained by stock for the main fishing gear types. The aim was to obtain a temporal CPUE trend standardized to discount effects unrelated to the stock abundance. A GAMLSS analysis was performed using the GAMLSS package in R (R DEVELOPMENT CORE TEAM, 2013), with a cubic spline smoothing function (cs) (STASINOPOULOS; RIGBY, 2007). The tested variables, which could produce effects unrelated to the stock abundance were: days; hours; number of lines; fuel; year; month; area; season; port and vessel size (Table 6). The collinearity between the variables was verified by the Variance Inflator Factor (VIF) as well as visual inspection. The GAMLSS model was chosen for this analysis group since it presents an approach to fit regression type models in which the response variable distribution does not have to belong to the exponential family or have highly skew and kurtotic continuous and discrete distribution (STASINOPOULOS; RIGBY, 2007). The distribution assumptions for the response variables were selected after visual inspection of the residuals obtained from a range of distributions tested sequentially (STASINOPOULOS;

RIGBY, 2007). The best-fitted models by stock and gear were selected using the Akaike Information Criterion (AIC) (BURNHAM; ANDERSON, 2002), using the forward stepwise selection procedure (stepAIC function). The relative importance of each tested variable was assessed accordingly with the AIC, Likelihood-Ratio Test (LRT) and the probability of the Chi-squared test criteria (PrChi). The CPUE standardization procedure was based on GAMLSS prediction (MCCULLAGH; NELDER, 1989).

Table 6. List of variables used to fit the General Linear Models (GLM) and the Generalized Additive Model for Location Scale and Shape (GAMLSS), the basic description of each variable, the range of values and the model in which the variables were used.

Variable	Description	Variable type	Values	Models
Catch	Fishery catch (kg)	Response, numeric	0.1 - 8720	GLM
N.fishers	Number of fishers in a trip	Explanatory, numeric	1 - 14	GLM
Days	Fishing trip duration	Explanatory, numeric	1 - 35	GLM
Hours*	Fishing hours by day	Explanatory, numeric	3 - 24	GLM/ GAMLSS
N.lines*	Number of lines used by fisher	Explanatory, numeric	1 - 40	GLM/ GAMLSS
Fuel*	Liters of fuel used in the fishing trip	Explanatory, numeric	10 - 4340	GLM/ GAMLSS
CPUE	Catch Per Unit of Effort (kg/ effort)	Response, numeric		GAMLSS
Year	Year of the fishing landing	Explanatory, categorical fixed factor	2005, 2006, 2007, 2010, 2011, 2013	GAMLSS
Month	Month of the fishing landing	Explanatory, categorical fixed factor	01 - 12	GAMLSS
Area	Fishing area	Explanatory, categorical fixed factor	inshore, offshore	GAMLSS
Season	Season of the year	Explanatory, categorical fixed factor	summer, autumn, winter, spring	GAMLSS
Port	Fishing landing port	Explanatory, categorical random factor	Alcobaça (ALC), Barra de Caravelas (BCA), Corumbau (COR), Nova Viçosa (NVC), Ponta de Areia (PARE), Prado (PRA)	GAMLSS
Ves.size	Vessel size (m)	Explanatory, numeric	2.5 - 20	GAMLSS

* Only used in CPUE model if not included in effort

To verify changes in fish size in the landings, we compared the Total Length measurements obtained during two periods (2005-2007 and 2014-2015) using a t-test on the whole distribution of each stock and visual interpretation. For these comparisons, for each stock, the same amount of length measurements was considered by fishing port and period. Thus, the data was organized by obtaining random sub-samples of each stock from the period and port with more measurements.

To verify size-related overfishing, specimen size indicators were applied to each stock using the method developed by Froese (2004). For this analysis, we considered specimen sizes from the commercial fishing landings in the period 2014-15, and we estimated: i) the percentage of mature specimens (based on the L_{50} - mean length at which 50% of the fish are mature); ii) the percentage of specimens at their optimum length L_{opt} interval (L_{opt} is the size at which the number of fish in an age group, multiplied by the individual mean weight, the results in the highest value. The interval is from the 10% smaller to the 10% larger than the L_{opt}); iii) the percentage of mega-spawners in the catches (the large, old and highly fecund individuals, with a length 10% or more, in addition to the optimal size) (FROESE, 2004). According to this method, growth overfishing is occurring if there are many juveniles and few optimal size individuals in catches, and recruitment overfishing is occurring if the mega-spawners comprise less than approximately 30% of the landed individuals. Here the growth overfishing is defined as a high percentage of the stock being caught before they have time to reach their optima size (HADDON, 2011). Recruitment overfishing is defined as the impossibility of a stock to produce enough new recruits to replace the deaths (HADDON, 2011).

To evaluate the exploitation status of the six stocks, we computed the ratio between fishing mortality (F) and natural mortality (M) and verified whether the final value was greater than 0.922 (ZHOU et al., 2012). First, the total mortality (Z) was obtained with the age-based "catch curve" method (BEVERTON; HOLT, 1957, QUINN; DERISO 1999), following the equation:

$$\log(C_a) = b - Z_a$$

where C_a is the catch-at-age a , b is the intercept and Z_a is the slope of the regression. The total mortality Z is the absolute value of the slope parameter in the model (HILBORN; WALTERS, 1992).

To transform length frequencies in age-frequencies we used the Sparre and Venema (1998) reference and considered growth parameters from the literature, estimated for these stocks on the Abrolhos Bank (Table 7), as follows: (i) we obtained age classes (t_i) using the inverse von Bertalanffy growth formula:

$$t_i = t_0 - \frac{1}{K} * ln\left(1 - \frac{L_i}{L_\infty}\right)$$

where Li is a length class, t_0 is the theoretical age at zero length, K is the growth rate coefficient and L_∞ is the theoretical maximum asymptotic length from the von Bertalanffy growth function. (ii) We estimated the duration of each length class (d_t) using the formula:

$$d_t = t_{i+1} - t_i$$

(iii) We divided the catch (in number of individuals, *N*) by the duration of each length class (N/d_t) and converted the results to a percentage of all measured individuals by stock. (iv) We obtained the logarithm of the (N/d_t) percentage and (v) We calculated the relative age of each length class according to the following formula:

$$t'_i = t_0 - \frac{1}{K} * ln\left(1 - \left(\frac{(L_i + L_{i+1})}{2}\right) / L_\infty\right)$$

The natural mortality M was calculated for snappers and groupers using the methods from Alverson and Carney (1975), Hoenig (1983) and Jensen (1996) and the subsequent analysis were based on the average of the M values from these three methods. The fishing mortality was obtained from the difference between Z and M.

Table 7. Values from the von Bertalanffy parameters adopted in this study. The reference studies are from Abrolhos Bank stocks. t_{max} is the maximum observed age in the growth study; t_{L50} is the age correspondent to the length at which 50% of individuals are mature (see Table 2).

Stock	L_∞ (cm)	*K*	t_0	t_{max}	t_{L50}	References
L. jocu	87.82	0.100	-1.486	29	3	FREITAS et al., 2011; PREVIERO et al., 2011
L. synagris	56.00	0.220	-0.200	18	2	ASCHENBRENNER et al., 2017; FREITAS et al., 2014
O. chrysurus	56.70	0.130	0.773	19	2	ARAUJO; MARTINS; COSTA, 2002; FREITAS et al., 2011
C. fulva	31.60	0.140	-5.740	25	2	ARAUJO; MARTINS; COSTA, 2002; FREITAS et al., 2011
E. morio	115.15	0.041	-5.353	30	7	FREITAS et al., 2011; FREITAS, 2014
M. bonaci	172.78	0.031	-6.264	34	10	FREITAS et al., 2011; FREITAS, 2014

Recruitment overfishing was also investigated with the spawning potential ratio (SPR) to each stock. This ratio is related to the number of eggs that could be produced by an average recruit in a fished stock divided by the number of eggs that could be produced by an average recruit in an unfished stock. SPR can be represented by the follow equation, elaborated by (HORDYK et al., 2015b):

$$SPR = \frac{TotalEggProduction_{Fished}}{TotalEggProduction_{Unfished}} = \frac{\sum(1-L_x)^{\left(\frac{M}{K\left[\left(\frac{F}{M}\right)+1\right]}\right)} L_x^b}{\sum(1-L_x)^{\frac{M}{K}} L_x^b} \quad \text{, for } x_m \leq x \leq 1$$

where L_x is the length at each a standardized age *x* and *b* is the recruit per spawners (HILBORN; WALTERS, 1992)

To calculate the SPR rate we obtained the age-structured length-based model (HORDYK, 2017). We used the parameters M, F, L_∞, *K*, L_{50}, L_{95} (mean length at which 95% of the fish are mature), SL_{50} (length at which 50% of the stock is selected by the fishery), and SL_{95} (length at which 95% of the stock is selected by the fishery). The L_∞, *K*, and L_{50} values were obtained from literature

(Table 7). On the estimation of the SL_{50} and SL_{95} we obtained the length at which each stock is 50% and 95% selected by the fishery (according to the 2014-15 length measures), this length were transformed in age, following on the age-length keys or the von Bertalanffy growth curves of each stock, available in the literature. The SPR computing was performed in R using the package "LBSPR". In this case the overfishing would occur to SPR values below 0.4 (CLARK, 2002; HORDYK et al., 2015a; LEGAULT; BROOKS, 2013).

Growth overfishing by stock was also investigated using the yield per recruit model (YPR), also known as Catch Per Recruit model, from Beverton and Holt (1957). We used the following equation:

$$Y/R = F * \exp[-M * (Tc - Tr)] * W_\infty * [\frac{1}{Z} - \frac{3S}{Z+K} + \frac{3S^2}{Z+2K} - \frac{S^3}{Z+3K}]$$

where $S = \exp[-K * (Tc - T_0)]$, Tc is the age of first capture, Tr is the age at recruitment, W_∞ is the asymptotic weight and $Z = F + M$, is the total mortality. The Tr was the first age in the catch curve from which all ages are selected (the black points in the Fig. 18). We estimated the YPR for a range of F values and plotted the data, which enabled determination of the F_{max} (fishing mortality corresponding to the maximum sustainable yield per recruit). We also estimated the $F_{0.1}$ (the value of F in which the slope of the YPR curve correspond to one-tenth of its value near the origin (KING, 2007). After estimating these reference points, we compared them with the estimated F for each stock. In this case, growth overfishing would occur if the estimated F is greater than the $F_{0.1}$.

The GLM and GAMLSS models, F, M and SPR indexes calculations were performed in "R", version 3.3.3 (R DEVELOPMENT CORE TEAM, 2013). Nominal CPUE, size indicators, YPR, F_{max}, $F_{0.1}$, Z, tables and some figures were calculated and formulated in Excel 2016.

3. Results

During the five years of fisheries monitoring, 5,967 landings were registered in which at least one of the six species was recorded. The main gear types were hand line, ranging from 450 to 1,779 landings by stock, followed by harpoon in the catches of *L. jocu* and *E. morio*, with 166 and 253 landings registered in the period, respectively (Table 8).

3.1 Trends in CPUE

The units of effort by stock and gear selected by the GLM model are summarized in Table 8. The residuals diagnostic plots of the selected GLM models are in Appendix (Fig. A.3.). The models used to standardize CPUE, resulting from the GAMLSS fitting process, are summarized by stock and gear in Table 9. The GAMLSS diagnostic plots for the selected models revealed good adjustments of the data to the model. The diagnostic plots and the AIC for the candidate models are included in the Appendix (Figs. A.4 – A.19.; Tables A.1- A.16.).

The CPUE compilation by year and month revealed greater monthly variation in the nominal CPUE than in the standardized CPUE (Fig. 15), as expected. Furthermore, trends in the standardized CPUE were easier to identify than in the nominal. The stocks with the greatest CPUE reduction trends in the period 2005-2013 were *L. jocu*, *O. chrysurus*, *C. fulva* and *M. bonaci* (both line and harpoon) (Fig. 15).

Table 8. Summary of the units of effort tested by the GLM as the better correlated with the Catch. In bold, the predictor variables selected for each stock /gear. The final unit of effort for each stock / gear was the multiplication of the selected variables (in bold). For all the models the better data distribution was Gaussian. Sample size is the number of fishing landings by stock. The residuals adjustments are in Appendix (Fig. A.3.).

Stock	Fishing gear	Variable response (log, kg)	Predictor 1 (log)	Predictor 2 (log)	Predictor 3 (log)	Predictor 4 (log)	Catch data distribution	Sample size
L. jocu	Line	Catch	**number of fishers**	**fishing days**	**number of lines by fisher**	**fishing hours by day**	Gaussian	591
	Harpoon	Catch	**number of fishers**	**fishing days**		fishing hours by day	Gaussian	166
L. synagris	Line	Catch	**number of fishers**	**fishing days**	number of lines by fisher		Gaussian	1779
O. chrysurus	Line	Catch	**number of fishers**	**fishing days**	**number of lines by fisher**	**fishing hours by day**	Gaussian	1390
C. fulva	Line	Catch	**number of fishers**	fishing days	**number of lines by fisher**	fishing hours by day	Gaussian	450
E. morio	Line	Catch	**number of fishers**	**fishing days**	number of lines by fisher	fishing hours by day	Gaussian	1062
M. bonaci	Line	Catch	**number of fishers**	**fishing days**	**number of lines by fisher**		Gaussian	626
	Harpoon	Catch	**number of fishers**	**fishing days**	diesel (lts)		Gaussian	253

Table 9. Final GAMLSS fitted models selected for CPUE standardization; distribution assumptions of CPUE data used in GAMLSS; and the number of fishing landings used to fit each model.

Stock	Fishing gear	Model (Best fitted model by GAMLSS)	CPUE data distribution	Sample size
L. jocu	Line	CPUE ~ Year + Port + cs(Vessel size, df = 4)	Generalized Gamma (GG)	591
	Harpoon	CPUE ~ Year + Month + Port	Generalized Beta type 2 (GB2)	166
L. synagris	Line	CPUE ~ Year + Month + Area + Port + cs(Fishing hours by day, df = 3)	Generalized Beta type 2 (GB2)	1779
O. chrysurus	Line	CPUE ~ Year + Month + Area + Port + cs(Vessel size, df = 3)	Generalized Beta type 2 (GB2)	1390
C. fulva	Line	CPUE ~ Year + Month + Port + cs(Vessel size, df = 3)	Generalized Beta type 2 (GB2)	450
E. morio	Line	CPUE ~ Year +Port	Generalized Gamma (GG)	1062
M. bonaci	Line	CPUE ~ Year + Month + Area + cs(Vessel size, df = 3) + cs(Fishing hours by day, df = 3)	Generalized Inverse Gaussian (GIG)	626
	Harpoon	CPUE ~ Year + Month + Port + cs(Fishing hours by day,df = 3)	Gamma (GA)	253

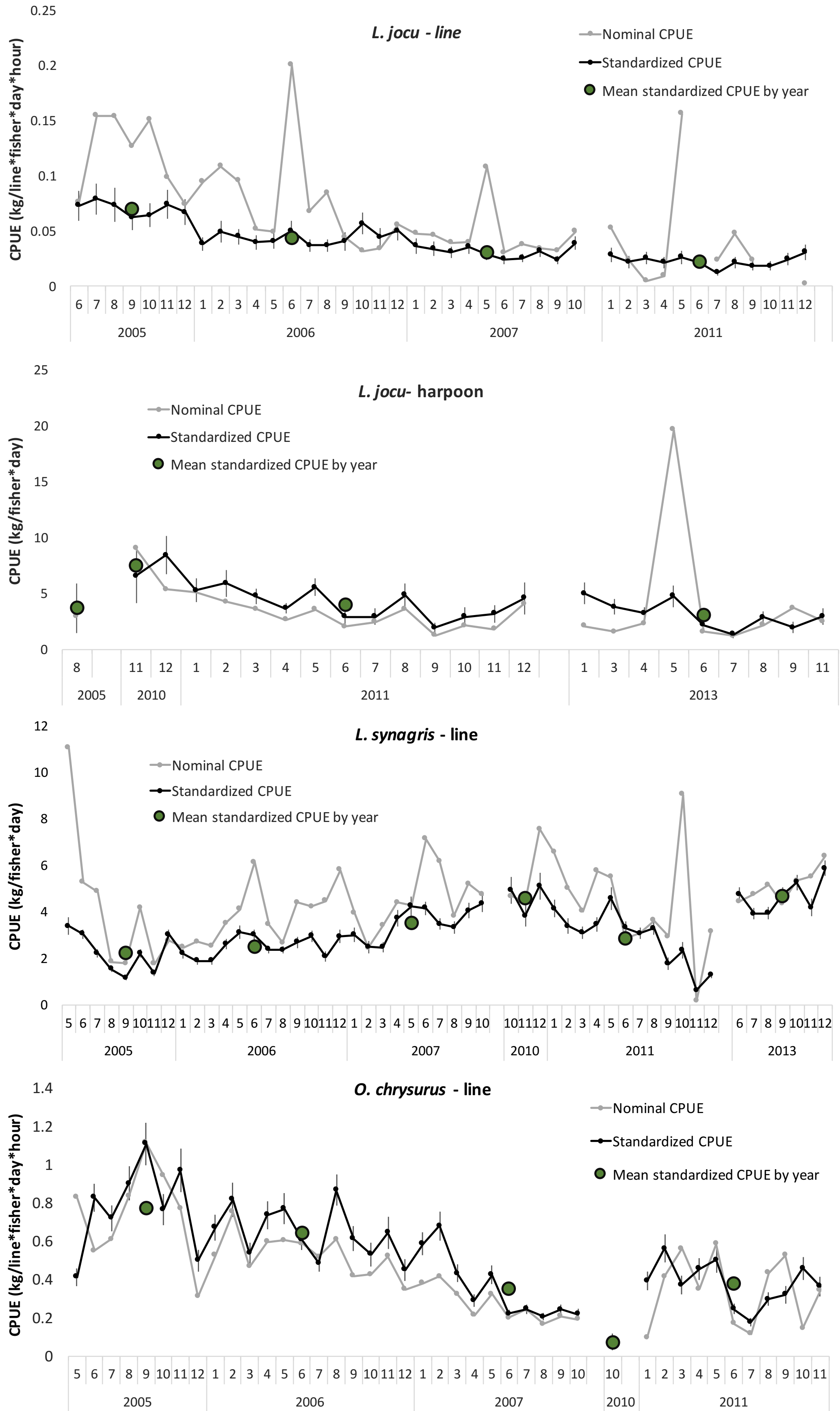
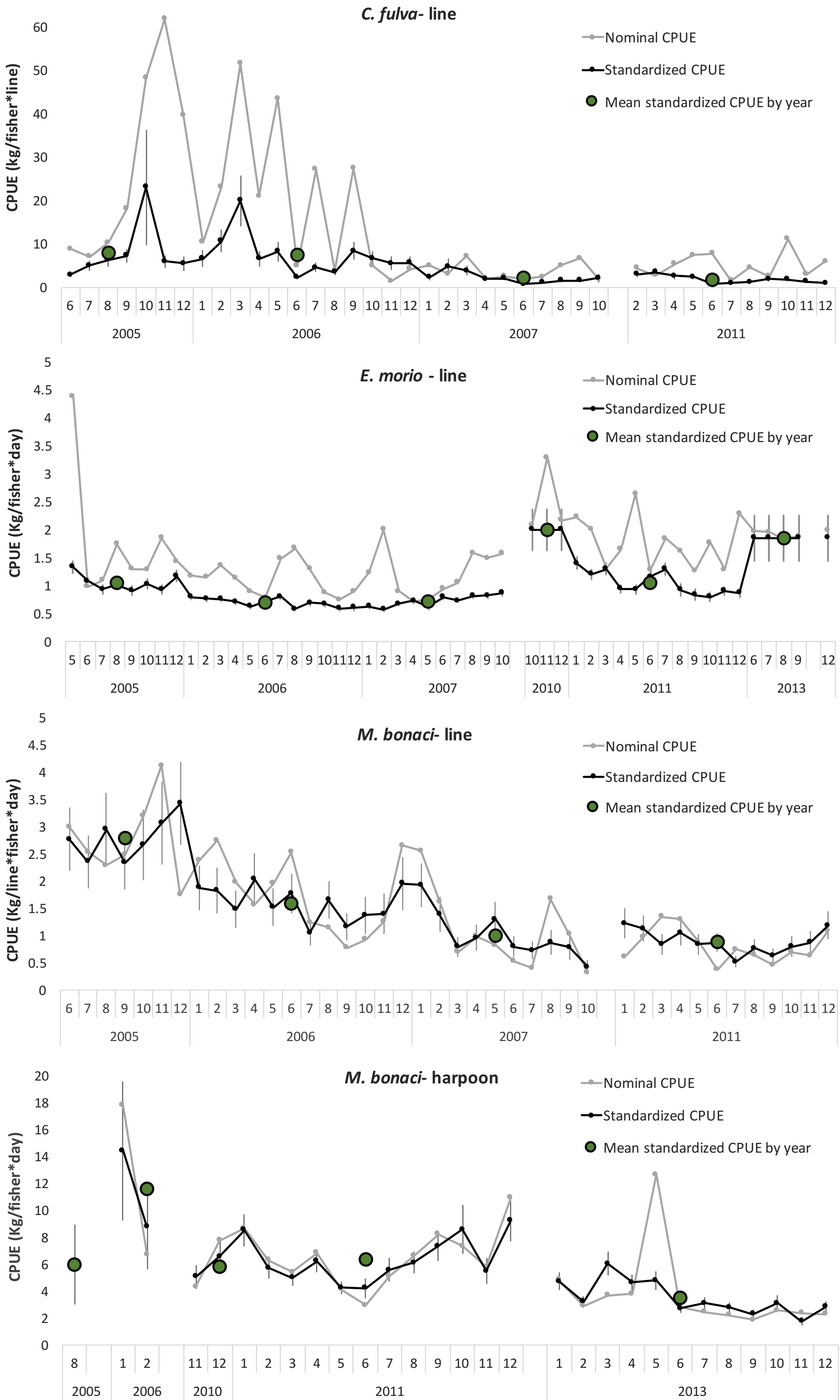


Figure 15. CPUE (nominal and standardized) by stock and gear analyzed by month and year in the Abrolhos Bank. The dots are the means of the standardized CPUE by year. The bars indicate the standard errors.

Figure continued



3.2 Fish sizes: trends and indexes

The visual comparison of fish sizes in commercial landings in 2005-07 and 2014-15 revealed few variations in the average length frequencies by stock (Fig. 16). The statistical comparisons proved not significant variation in the whole size distribution for five stocks (Table 10), except for *C. fulva*, which had a significant increase in specimen sizes. On the other hand, visual inspections make explicit decreases in the modal length values in 2014-15 in comparison with the first sampled period to five stocks (except *C. fulva*).

Table 10. Statistical comparisons (t-tests) of fish sizes in commercial fishing landings in the Abrolhos Bank between the two sampled periods (2005-07 and 2014-15).

Stock	t	Df	p-value
L. jocu	1.69	140	0.094
L. synagris	-1.34	958	0.181
O. chrysurus	0.17	411	0.868
C. fulva	-12.06	934	0.000
E. morio	-1.27	140	0.206
M. bonaci	-0.44	182	0.662

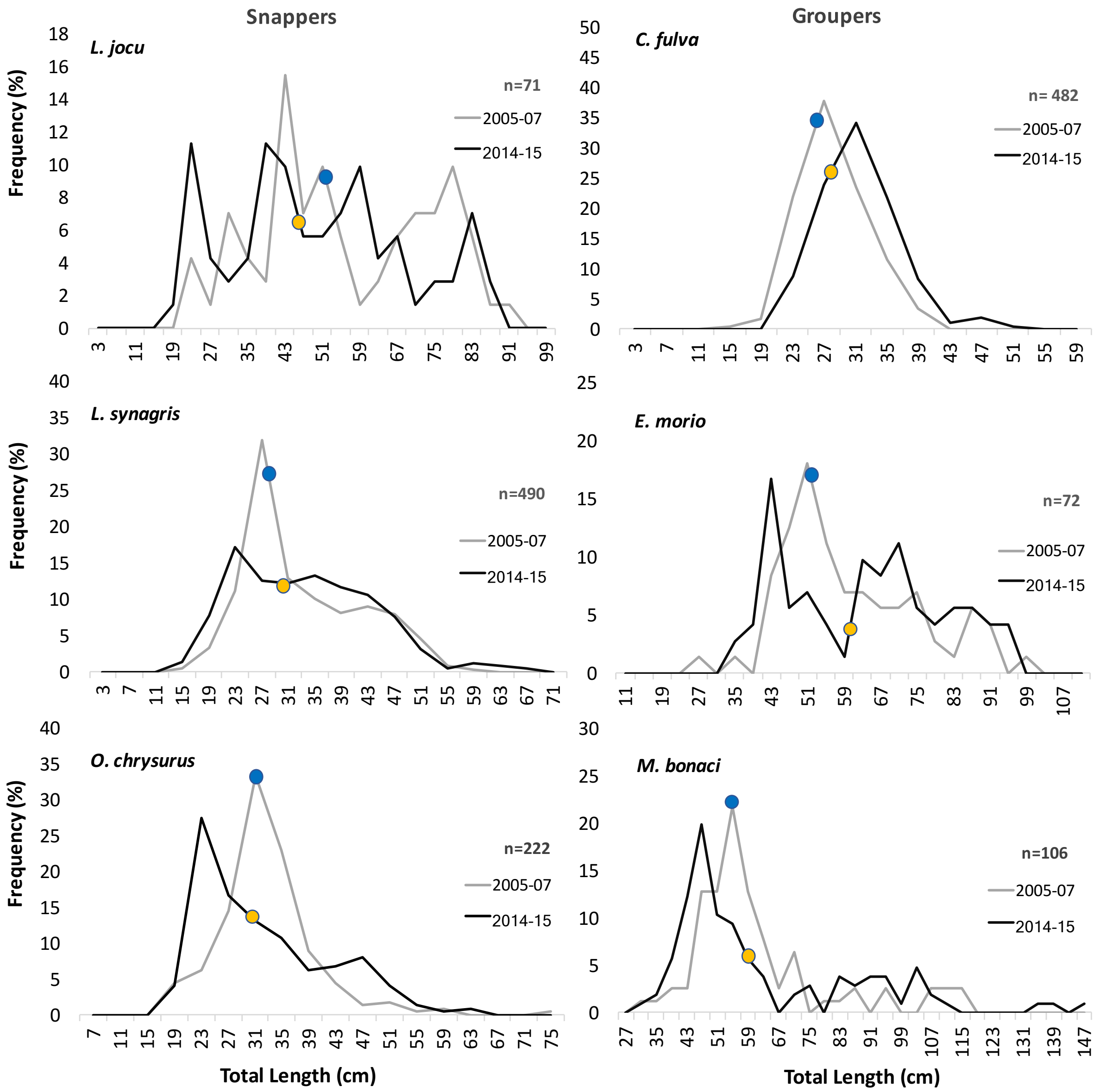


Figure 16. Length frequencies in the fish landings for the studied stocks in the two sampled periods. The blue dots are mean sizes of the fish caught by stock in the period 2005-07, the yellow dots are the mean sizes of the fish caught in the period 2014-15, and *n* is the sample size by period.

According to the size-based indicators, there was a high percentage of specimen in landings that were higher than the L_{50} (Indicator 1, Table 11). However, few individuals were caught at the L_{opt} (Indicator 2), especially *O. chrysurus* and *M. bonaci* (Table 11, Fig. 17). These two stocks also presented the lowest percentage of mega-spawners in landings (Indicator 3, Table 11, Fig. 17).

Table 11. Summary of parameters and size indicators for the six snapper and grouper stocks from Abrolhos Bank.

Stock	L_{50} (cm, TL)	L*opt* range (cm, TL)	L*max* (cm, TL)	Indicator 1 (% of mature specimens)	Indicator 2 (% in optimum length)	Indicator 3 (% of mega-spawners)	Sample size
L. jocu	43.00	56.8 - 69.5	96.00	92.15	32.72	34.29	382
L. synagris	23.00	31.7 - 38.8	68.00	78.38	21.08	29.32	740
O. chrysurus	31.00	45.1 - 55.2	76.00	64.64	13.52	2.87	1465
C. fulva	16.00	28.0 - 31.9	56.00	99.88	34.74	31.13	803
E. morio	47.00	67.3 - 81.5	99.00	88.74	35.21	27.75	764
M. bonaci	62.00	102.7 - 125.6	160.00	81.79	13.46	4.49	780

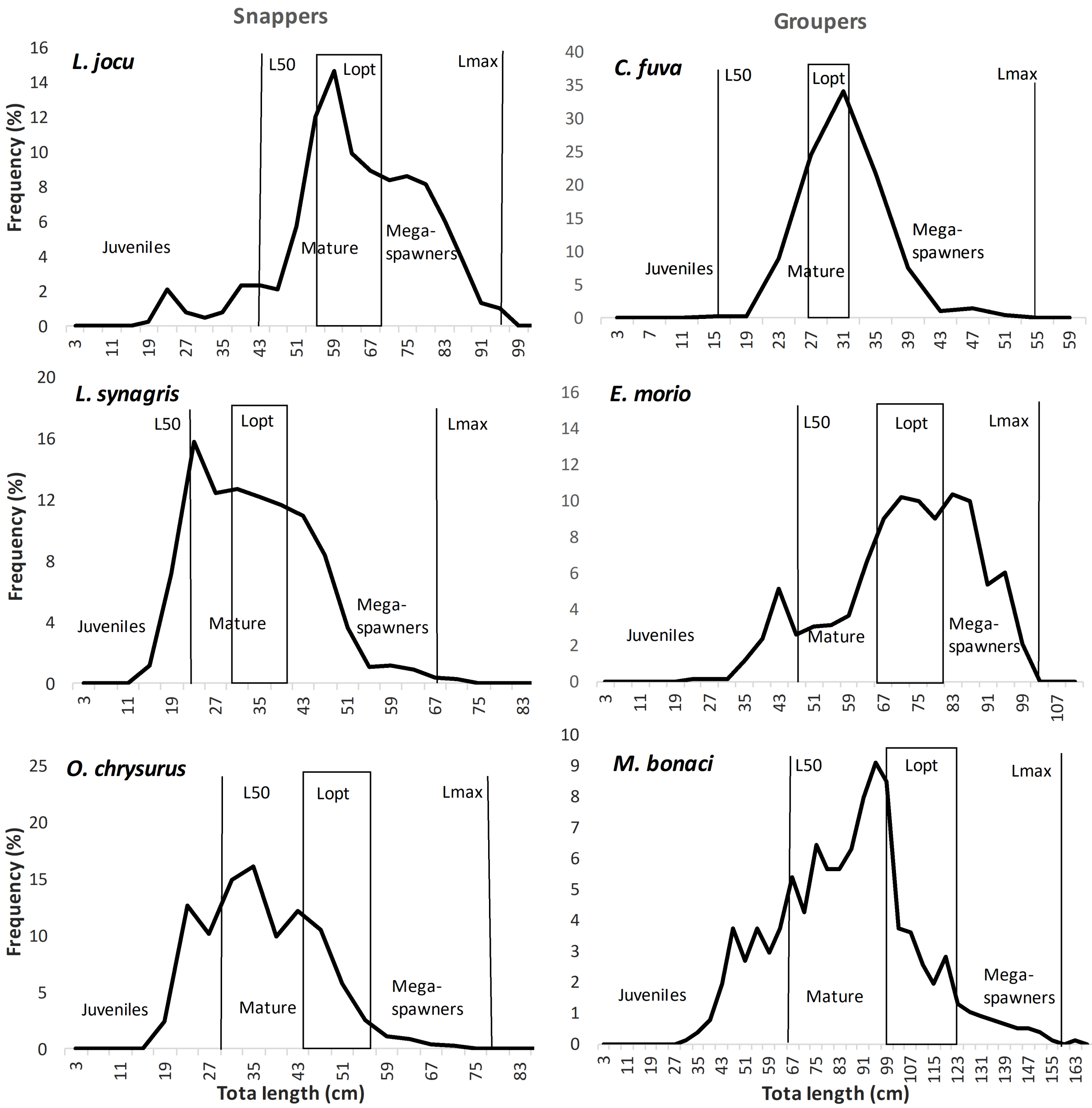


Figure 17. Length frequencies of stocks in landings in the period 2014-2015. The bars indicate the L_{50} and the L_{max}, and the rectangles indicate the L_{opt}.

3.3 Exploitation status indexes

The total mortality Z ranged from 0.156 for *E. morio* to 0.445 for *L. synagris* (Fig. 18). The natural mortality M ranged from 0.05 for *M. bonaci* (method JENSEN, 1996) to 0.33 for *L. synagris* (Table 12). The fishing mortality F exceeded M for all analyzed stocks, and the highest F/M ratio was observed in *E. morio* (Table 12).

The natural mortality M rate was highest for *L. synagris* and lowest for *M. bonaci* (Table 12). The fishing mortality F varied from 0.10 for *E. morio* and *M. bonaci* to 0.25 for *C. fulva* (Table 13). For all six stocks, the F/M index was higher than 0.922 (Table 13, Fig. 19), which indicates that these stocks are over or fully exploited in the Abrolhos Bank.

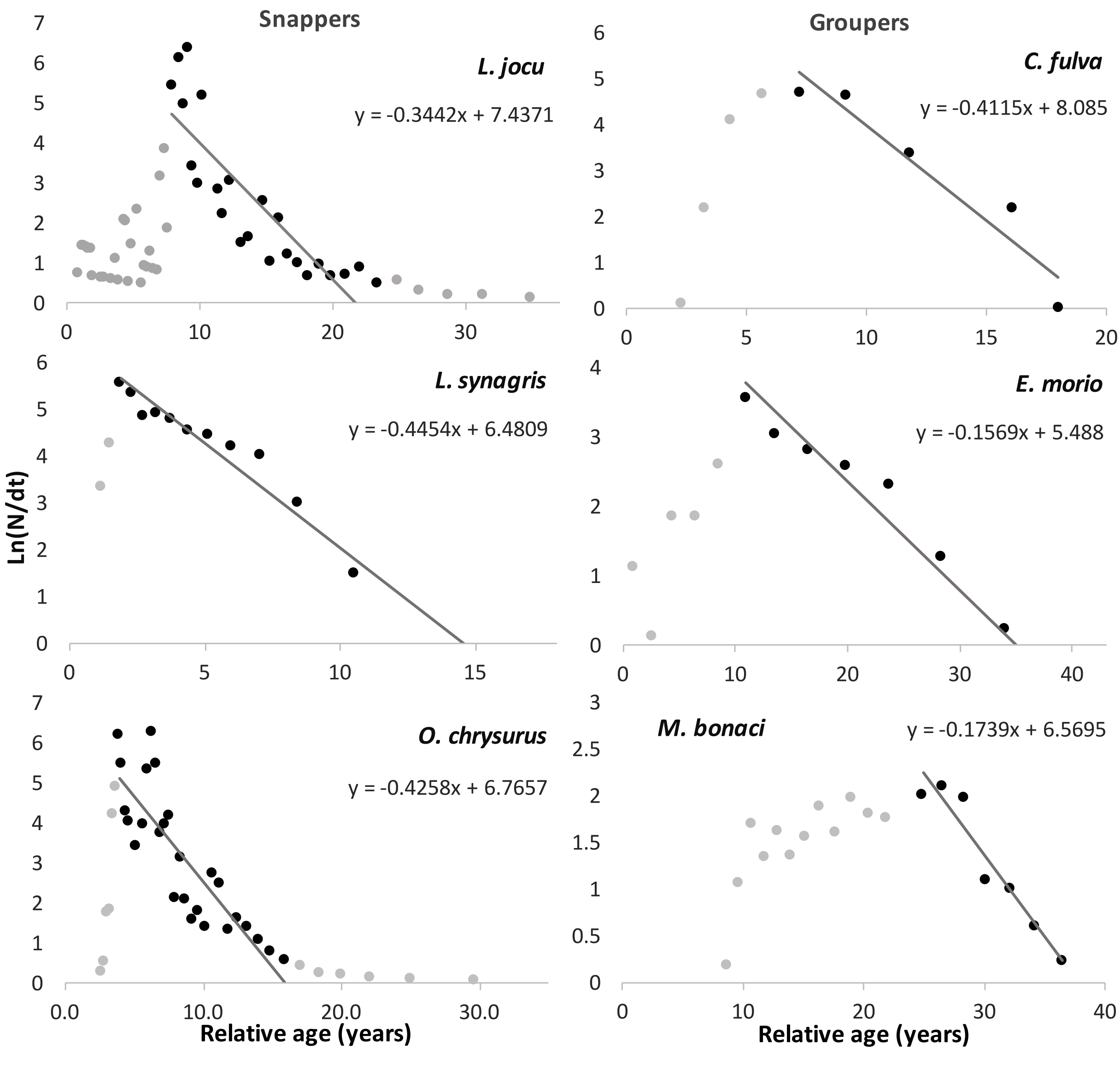


Figure 18. Catch curve by stock and total mortality Z are indicated by the slope of the line. Data are from landings from 2014-15 in Abrolhos Bank fishing ports.

Table 12. Natural mortality (M) values estimated to the studied stock by different methods, and the average of the three methods, used in the subsequent analysis.

Stock	Alverson and Carney (1975)	Hoenig (1983)	Jensen (1996)	M Average*
L. jocu	0.14	0.10	0.15	0.13
L. synagris	0.17	0.17	0.33	0.22
O. chrysurus	0.25	0.16	0.20	0.20
C. fulva	0.16	0.12	0.20	0.16
E. morio	0.20	0.10	0.06	0.08
M. bonaci	0.07	0.09	0.05	0.07

**Excluding values gratest than the Z value of the stock*

Table 13. Results of estimation of Z, M and F/M to snappers and groupers from Abrolhos Bank. The method used to obtain Z was catch curve, and the methods M value is the average of the M values obtained by the three methods (ALVERSON; CARNEY,1975; HOENIG, 1983; JENSEN, 1996).

Stock	Z	M	F	F/M	SPR
L. jocu	0.34	0.13	0.21	1.62	0.46
L. synagris	0.44	0.22	0.22	0.98	0.41
O. chrysurus	0.43	0.20	0.22	1.09	0.43
C. fulva	0.41	0.16	0.25	1.60	0.38
E. morio	0.16	0.08	0.10	1.81	0.37
M. bonaci	0.17	0.07	0.10	1.46	0.39

The stocks *E. morio*, *C. fulva* and *M. bonaci* presented the lowest SPR values, between the target reference point (0.4) and the limit reference point (0.3) (Table 13, Fig. 19).

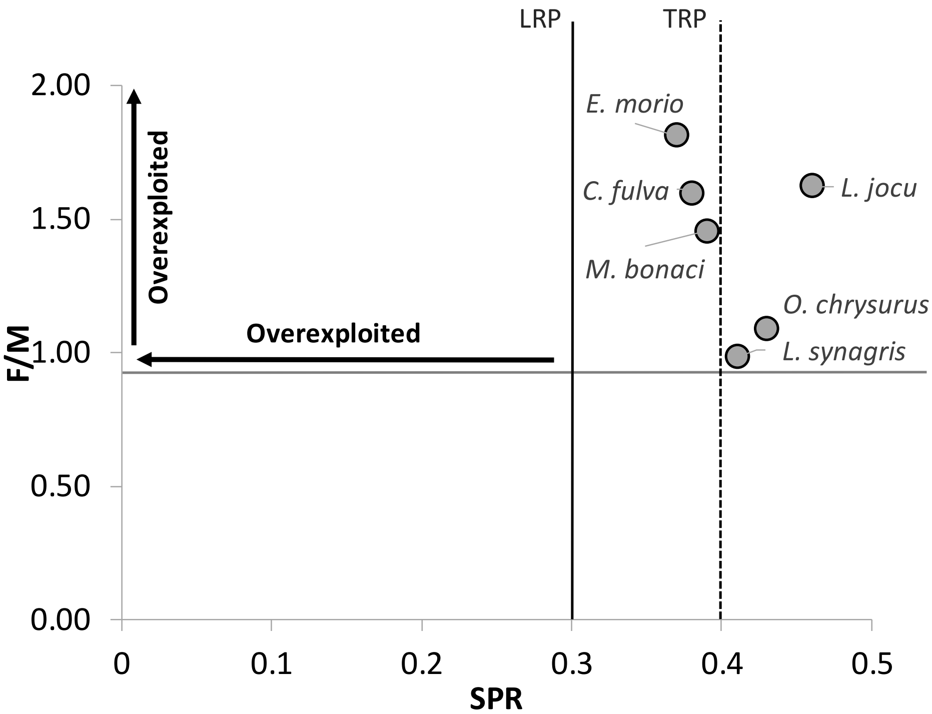


Figure 19. Fishery status for the six snapper and grouper stocks according to the fishing and natural mortality ratio (F/M) and spawning potential ratio (SPR). TRP=Target reference point; LRP= Limit reference point.

The yield per recruit revealed growth overfishing in the six stocks (Fig. 20). For these stocks, the F was greater than the $F_{0.1}$ reference point. For *E. morio,* the F_{max} was the same value as the actual F, and for *C. fulva* F is between the reference values (Fig. 20). On the Table 14 it is possible to observe a summary with all the results of the indicators estimated in this chapter, as well as the reference points.

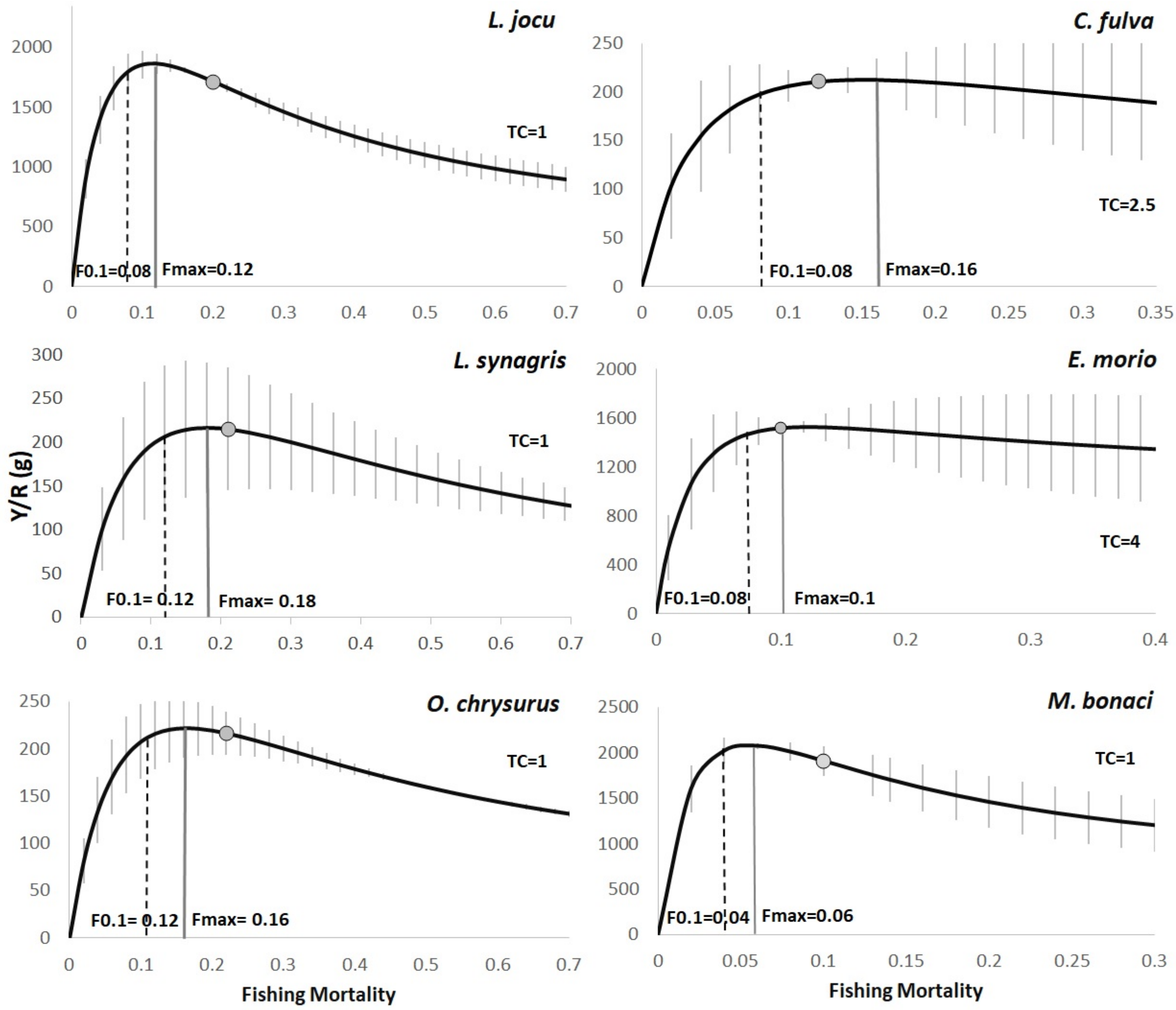


Figure 20. Yield per recruit for the three snapper and three grouper stocks from this study. The grey dot is the calculated F (Table 11). TC is the age of first capture considered in the analysis. The bars are the standard deviation of the yield per recruit based on the three natural mortality methods (Table 12). The black dashed line represents $F_{0.1}$ and the gray line represents Fmax.

Table 14. Summary of the indicators and some reference values used to estimate the exploitation status of the snappers and groupers in this study.

Stock	CPUE	Size indicators	Changes in size	F	$F_{0.1}$	F/M	F/M reference	SPR	SPR reference
L. jocu	Reducing	Suitable	Reduction	0.21	0.08	1.62		0.46	
L. synagris	Not reducing	Many juveniles, few mega-spawners	No reduction	0.22	0.12	0.98		0.41	
O. chrysurus	Reducing	Many juveniles, very few mega-spawners	Reduction	0.22	0.12	1.09	0.92	0.43	0.40
C. fulva	Reducing	Suitable	No reduction	0.25	0.08	1.60		0.38	
E. morio	Reducing	Many juveniles	Reduction	0.10	0.08	1.81		0.37	
M. bonaci	Reducing	Many juveniles, very few mega-spawners	Reduction	0.10	0.04	1.46		0.39	

4. Discussion

Despite the limited time series for landing data in this study, we were able to assess the exploitation status of some of the main commercial reef stocks from the Abrolhos Bank. The combination of fishery indicators was revealed as a low-cost tool, able to provide relevant stock status information. For these data-limited stocks, the CPUE standardization procedure profoundly contributed to an estimate of the stock abundance approaching the actual abundance. The comparison of individual size in the fish landings was essential to understand changes in the stock size structure over a period of approximately ten years in which there were no fishery management measures directed toward the studied stocks. The size index provided relevant information on the most threatened portion of each stock. Moreover, the mortality rate comparisons, the spawning potential ratio and the yield per recruit were crucial for detecting the exploitation levels of the stocks.

4.1 Main factors affecting stocks' abundance

Abundance indexes based on standardized CPUE are important components of many stock assessments; therefore, to accurately reflect the stock condition, the correct construction of a CPUE index is important (CAMPBELL, 2015). Problems due to errors in the construction of abundance indexes and in CPUE estimation, and consequent errors in fishery management have been reported, mainly those resulting from stock and fleet spatial distribution (CAMPBELL, 2004; CAMPBELL, 2015). To minimize such effects, we included the factors "fishing area" (coastal and offshore) and "port" in the model. In addition, CPUE estimates were generated separately for each fishing gear type.

Among the main factors affecting CPUE, selected by GAMLSS for the standardizations, year was included in all models and was the variable that most affected CPUE. The factor "port" had greater influence on CPUE and was selected in seven of the eight CPUE standardization models. That selection may be because the fisheries considered here have different characteristics observed mainly among the fishing ports (such as labor relations, fishing areas, fishing duration and vessel sizes) (PREVIERO; GASALLA, 2018). The factors "month" and "fishing area" were also selected in most models, which indicated high seasonality and spatial division of the fishing fleets. The highest CPUE values were from December to May (Appendix, Figs. A.7.; A.9.; A.11.; A.13.; A.17.), which corresponds to summer - autumn months. Similar results were found in Previero and Gasalla (2018) in which the better months informed by the fishers were the summer months. For *O. chrysurus* and *M. bonaci* the offshore areas have greater CPUE, and for *L. synagris* the greater CPUE values were found in inshore areas (Appendix, Figs. A.9.; A.11.; A.17.). The same trend was found in Previero and Gasalla (2018) to *L. synagris* and *M. bonaci.*

4.2 Relative abundance and size distribution of the stocks

1 - *L. jocu*

The results of the standardized CPUE analysis indicated a decline in *L. jocu* relative abundance in the Abrolhos Bank between the years 2005 and 2013, both for line and harpoon fisheries (Fig. 15). Without the standardization procedure, it would be difficult to adequately interpret abundance trends for the dog snapper as there are peaks in the nominal CPUE (both in line and harpoon fisheries) unrelated to the abundance of this stock that disappeared in the standardized CPUE.

By analyzing the *L. jocu* size changes in the landings between 2005-07 and 2014-15 (Fig. 16), we observed a minor variation in the mean size and a catch peak of approximately 23 cm total length, which is smaller than the average size at first maturity. We observed dog snapper in the fish landings from 12 cm. Coupled with this observation, there was a reduction in landings of large individuals between the sizes of 67-83 cm. To avoid juvenile catches, we suggest some restrictions in the hook size, which may benefit a range of target and bycatch stocks. There is evidence that in Abrolhos Bank, *L. jocu* performs cross-shelf ontogenetic migrations, occurring in mangroves to approximately 30-40 cm and in coastal reefs from 5-10 cm (FREITAS et al., 2011; MOURA et al., 2011). Therefore, to protect the mega-spawners, we suggest the creation of an MPA near the edge of the slope, where this stock co-occurs with *M. bonaci* (PREVIERO; GASALLA, 2018).

The amount of *L. jocu* at optimum length represent a reasonable percentage in landings (32.72%, Table 11). However, when considering the target number at L_{opt} (100% of the catches) (FROESE, 2004), is clear that this stock must be managed to increase the number of individuals in L_{opt}. As there are no laws to regulate the capture of large individuals, an adequate portion of individuals in landings were mega-spawners, indicating the absence of recruitment overfishing for the *dentão*.

2 - *L. synagris*

In this study, we observed an increase in the relative abundance of *L. synagris* in the years 2010 and 2013 (Fig. 15). This could be related to the reduction of other stocks, such as *O. chrysurus* and *M. bonaci*, as a partial replacement of the fishery resource. Another reason for this increase could be related to the increase of the *E. morio* CPUE in the same period, since the two stocks co-occur in some fishing areas (PREVIERO; GASALLA, 2018). Although seasonality was not a factor affecting the lane snapper CPUE, fishers indicated that only summer and winter months were suitable for catching this stock (PREVIERO; GASALLA, 2018).

Several changes were observed in the modal fish size in the landings between the periods 2005-2007 and 2014-2015 (Fig. 16). For example, the peak of individuals landed at 27 cm total length disappeared, and there was an increase in the proportion of individuals in the 35-43 cm interval. The most frequent lane snapper size in landings was at the L_{50} size, with a considerable number of landed individuals smaller than the L_{50}, an indication of growth overfishing. In addition, few individuals were landed at the optimum size (Table 11), and a reasonable number of specimens belonged to the group of mega-spawners.

3 - *O. chrysurus*

In the period 1976-1980, *O. chrysurus* was one of the main fishery resources captured in the Abrolhos Bank (together with *M. bonaci* and *E. morio*) (LIMA et al., 1985). Costa et al. (2005) argues that the increase in CPUE for *O. chrysurus* in the late 1980s may be related to both the reduction in groupers due to overfishing and due to the increase in the export of this species. At present, despite the observed reduction in the groupers (*C. fulva* and *M. bonaci*), the *guaiúba* is rarely exported, being extensively traded with large markets within Brazil (CHAPTER 3). So, the *guaiúba* recovery in 2011 may be associated with a reduction in fishing effort between 2008 and 2010, when there were changes in the marketing of such stock, with reductions in fish exportation due to cambial changes, and the closing of many regional companies of fish processing and exportation.

Through the analysis of the specimen size changes in the landings from 2005-07 and 2014-15, we observed an explicit increase in the relative number of small individuals in catches. At the second period there were three size peaks of *O. chrysurus* in the landings (Fig. 17). One of these peaks was composed of individuals smaller than the L_{50}, and another peak was composed of individuals larger than the L_{50}, but smaller than the optimal size. A small percentage of individuals in the fishing landings belonged to the L_{opt}, and an extremely low portion of individuals belonged to the group of mega-spawners. In the absence of management measures for the largest specimens in Abrolhos Bank, that findings are a strong indicator of recruitment overfishing for the *guaiúba* stock.

4 - *C. fulva*

The standardized CPUE indicated downward trends in the relative abundance of *C. fulva* in the period 2005-2011 (Fig. 15). The changes in specimen size from 2005-07 to 2014-15 in the fish landings (Fig. 16) reveals a meaningful increase in the specimen modal size (from 27 to 31 cm). One explanation may be the trading of these fishes to external markets (CHAPTER 3; COSTA et al., 2005), compelling the fisheries to follow strict standards, among them, the specimen size (only individuals weighing between 300 g and 700 g are traded to external markets and receive higher selling prices). This weight interval corresponds to the L_{opt} and to the peak size of this stock. The strong influence of the market on this fishery may be the reason for the lack of records for individuals smaller than the L_{50}.

5 - *E. morio*

Regarding the *E. morio* specimen sizes in catches, there were changes in the modal sizes from 50 cm during 2005-07 to 45 cm and 70 cm in 2014-15 (Fig. 16). One possible explanation is the occurrence of growth overfishing, and another explanation could be the recent displacement of the fishing fleet to deeper and farther offshore areas where they find individuals in the 70 cm range. Currently, most of the *garoupa* fisheries harvested by Alcobaça fleets occur in outer shelf areas (PREVIERO; GASALLA, 2018).

A small catch peak of *E. morio* specimens smaller than the L_{50} was observed (Fig. 17), which is indicative of growth overfishing. However, a considerable percentage of *garoupa* individuals in landings were the in optimum size, and approximately 30% of individuals were mega-spawners (Table 11). Furthermore, the SPR value was greater than 0.4, which may indicate absence of recruitment overfishing to this stock.

6 - *M. bonaci*

According to the standardized CPUE, there were reductions in the relative abundance of *M. bonaci* in the period 2005-2013 (Fig. 15). A downward trend in the *M. bonaci* CPUE was also recorded for the period 2005-2009 in a region close to Abrolhos Bank, on the southern coast of Bahia state (FRANÇA; OLAVO, 2015).

From 2005-07 to 2014-15, there was an explicit increase in the relative number of small individuals in landings, combined with a modal size reduction from 55 cm to 46 cm in total length (Fig. 16), which may indicate growth overfishing, especially because there is a substantial percentage of individuals smaller than the L_{50} in landings (18.21%, Table 11). As few individuals were caught at the optimum size and we observed a low percentage of mega-spawners in landings (4.49%, Table 11), this stock probably is suffering recruitment overfishing. This very worrisome since there are no fisheries management measures regulating the maximum catch size for the *badejo* in the Abrolhos Bank.

4.3 Fish sex change and size indicators

A recent study proved protogynous hermaphroditism in *E. morio* and *M. bonaci* from Abrolhos Bank (FREITAS et al., 2017). By comparing the length frequencies of these stocks (Fig. 17) with the size composition by sex (FREITAS et al., 2017), we observed that all *E. morio* males were mature and the largest proportion of males were mega-spawners (greater than 80 cm). As an adequate percentage of mega-spawners has been recorded for the *garoupa*, at this time, there is no evidence that the reproduction of this stock can be affected by a reduction in males. For *M. bonaci*, the highest proportion of males (80 to 89.9 cm) (FREITAS et al., 2017) corresponded to the specimen modal size in landings (Fig. 17). Although there were a few mega-spawners, the black grouper tends to not be harmed by a reduction of males. *C. fulva* also presents a sexual change throughout its lifespan, which starts at approximately 18 cm standard length (FREITAS et al., 2011), the size in which they begin to be recruited by the fishery (Fig. 17). Therefore, for the *catuá*, there were no problems with the proportion of males and females caused by the fishery.

4.4 Exploitation status

The index M determined for the snapper stocks in this study is within the observed M range for *L. jocu*, *L. synagris* and *O. chrysurus* in a region farther north in Brazil (0.1 to 0.3) (FRÉDOU et al., 2009). The M values from Hoenig (1983) are highly related to the longevity, and recent age studies using sectioned otoliths have shown high longevity for these stocks (see Table 7). The Hoenig's method resulted in low M values for the snappers and may represent a conservative or precautionary approach in the exploitation status assessments, especially because there are elevated uncertainties in the estimation of M in a range of current methods (BRODZIAK et al., 2011). Regarding the groupers, the M estimated for *C. fulva* (0.20) is slightly higher than that estimated for the same stock in the Abrolhos Bank between 1997 and 1999 (0.17) (ARAUJO; MARTINS, 2009), but lower than that of *catuá* stock from the southeastern United States (0.22) (BURTON et al., 2015). The estimated M values for *E. morio* and for *M. bonaci* are lower than the M determined for these species in the literature (BURGOS; DEFEO, 2004; GIMENEZ-HURTADO et al., 2009; POTTS; BRENNAN, 2001). Thereby, we choose to use the average of the M from the different methods.

According to Zhou et al. (2012) the fishing mortality rate F equivalent to the maximum sustainable yield for Perciformes corresponds to 0.922 the value of the natural mortality rate M. Considering this reference value, all stocks studied here are overfished (with an F/M ratio greater than 0.922). On one hand, *E. morio* and *L. jocu* are the stocks with the highest F/M values and have the highest exploitation levels among the stocks studied here. On the other hand, *L. synagris* and *C. fulva* have the lowest F/M ratio among the studied stocks, slightly higher than the reference value (Table 13), indicating these stocks could be overexploited soon.

The SPR reference points change with many factors, such as different biological and fishery conditions of the cohorts during their lifespan, and additional years of data (LEGAULT; BROOKS, 2013). The SPR reference points usually range from 0.3 to 0.4 (CLARK, 2002; HORDYK et al., 2015a; LEGAULT; BROOKS, 2013), so here we adopted a precautionary approach and considered as experiencing recruitment overfishing the stocks with SPR values smaller than 0.4. Accordlingly that, the three groupers are suffering from recruitment overfishing. Comparing these results with other stocks, Nadon et al. (2015) found an SPR ranging from 0.08 to 0.99 in reef fishes; among them, SPR = 0.23-0.63 for snappers and SPR = 0.99 in a *Cephalopholis* stock. In Hawaii, reef species with the lowest SPRs were mostly longer-lived and had lower natural mortality rates (NADON et al., 2015). The same pattern was observed in this study, with longer-lived and lower natural mortality species presenting low SPR (*badejo, garoupa* and *catuá*).

Regarding the yield per recruit analyzes, all the stocks are suffering from growth overfishing, considering the reference point $F_{0.1}$. Among the snappers, *L. jocu* presented the largest difference between the estimated F value and the $F_{0.1}$. *O. chrysurus* has been exploited on a level higher than the sustainable since the year 1997 at the East Brazilian coast (KLIPPEL et al., 2005). Among the groupers, the greatest difference between F and $F_{0.1}$ occurred for the *M. bonaci* (Table 14). To the *C. fulva,* F was smaller than the F_{max}, and to the *E. morio* F corresponded to F_{max}.

There are a lot of uncertainties regarding the YPR analyses, especially because of the parameters estimates are made with a limited precision (HADDON, 2011). The use of a more conservative reference point (e.g. the $F_{0.1}$), is a first approach to assuage the YPR uncertainties (HADDON, 2011). Thereby, with the aim to reverse and to avoid growth overfishing we suggest a reduction in the fishing mortality to the six stocks to reach the $F_{0.1}$. While the F_{max} are usually used as a limit reference point, the $F_{0.1}$ should be a target reference point (KING, 2007). Despite the loss in yield, this approach can increase the fishery profitability and may represent a gain in stock resilience to years of poor recruitment (HADDON, 2011; KING, 2007).

4.5 Summary of the stocks' threatened status

L. jocu - (i) Declining: Reductions in abundance and in specimen sizes (increased juveniles and decreased large individuals in landings). (ii) Overfished: Despite the size indicators revealed a sustainable fishery, and the not detection of recruitment overfishing, the F/M was higher than 0.922 and F was higher than the $F_{0.1}$ so the YPR indicated growth overfishing.

L. synagris - (i) Not declining: No declines in abundance and no reduction in specimen size were observed in the period. (ii) Not overfished: The size indicators revealed a high percentage of juveniles in landings. The F/M was slightly above 0.922, the F was higher than the $F_{0.1}$, and the YPR indicated growth overfishing.

O. chrysurus - (i) Declining: Reductions in abundance and in the modal specimen size in the period. (ii) Overfished: The size indicators showed a high percentage of juveniles in landings, a low percentage of individuals in L_{opt} and very few mega-spawners. The F/M was higher than 0.922, the F was higher than the $F_{0.1}$ and the YPR indicated growth overfishing.

C. fulva - (i) Declining: Reduction in abundance. No reduction in specimen size in the period. (ii) Not overfished: Size indicators revealed a sustainable fishery. The F/M ratio was slightly above 0.922, the SPR was near the target reference point, indicating the possibility of recruitment overfishing, the F was higher than the $F_{0.1}$ but lower than the F_{max}.

E. morio - (i) Declining: Reduction in abundance compared to previous periods. Reduction in the specimen modal size. (ii) Overfished: there was a small peak of juveniles in landings and the SPR was smaller than the target reference point, indicating recruitment overfishing. The F/M was higher than 0.922, the F was higher than the $F_{0.1}$ so the YPR indicated growth overfishing.

M. bonaci - (i) Declining: Reduction in abundance and reduction in the specimen modal size. (ii) Overfished: The size indicators revealed a high percentage of juveniles, few individuals at the L_{opt} and few mega-spawners in landings. The F/M was higher than 0.922, the SPR was smaller than 0.4, indicating recruitment overfishing, the F was higher than the $F_{0.1}$ so the YPR indicated growth overfishing.

Considering that all the stocks studied here were declining and/or overfished, we elaborated several management suggestions aimed toward the recovery of such stocks. (i) The creation of fishing quotas to reduce fishing mortality; (ii) the creation of minimum and maximum size limits; (iii) the creation of fishing exclusion areas (mainly in recruitment areas); and (iv) fishing closures during the spawning season.

5. Conclusions

In this study we found five stocks declining and four stocks overfished. The main reasons for the decline of the snappers and groupers are the reductions in abundance and in the specimen size in the landings. The results of the exploitation indexes most concerning were: (1) high fishing mortality (mainly for *E. morio* and *L. jocu*); (2) low yield per recruit (all stocks had the estimated F greater than the reference point); (3) low spawning potential ratio to the groupers and few mega-spawners in landings to *L. synagris*, *M. bonaci* and *O. chrysurus*; and (4) high percentage of juveniles in landings (mainly for *L. synagris* and *O. chrysurus*).

The results obtained in this study can support fishery management according to the exploitation status of each stock and in accordance with the problems faced by each stock (inadequate size structure, reduction in abundance, many juveniles and few mega-spawners in landings). We hope that this study will accelerate the elaboration of policies and fishing agreements capable of preventing stock reductions before the species become reproductively unfeasible or locally extinct. Finally, we expect that the results obtained herein may help to elucidate recurring problems for several stocks, such as the absence of fishing rules alternating with a complete ban on fishery, which causes serious impacts on the daily life of fishing-dependent communities.

CHAPTER 3

Risk assessment and fishery sustainability of snappers and groupers of the Abrolhos Bank ecosystem based on biological, social and economic components of the fishery.

CHAPTER 3 – RISK ASSESSMENT AND FISHERY SUSTAINABILITY OF SNAPPERS AND GROUPERS OF THE ABROLHOS BANK ECOSYSTEM BASED ON BIOLOGICAL, SOCIAL AND ECONOMIC COMPONENTS OF THE FISHERY.

Abstract

In data-poor fisheries, multidisciplinary indicators may contribute to sustainability assessments. In the Abrolhos Bank coral reefs in the South Atlantic Ocean, an ecosystem-based fisheries assessment was conducted on three snappers (*Lutjanus jocu*, *L. synagris* and *Ocyurus chrysurus*) and three groupers (*Cephalopholis fulva, Epinephelus morio* and *Mycteroperca bonaci*). The potential impacts, risks and stock vulnerabilities were evaluated based on biological (e.g., life-history traits), environmental (e.g., risks to habitat and ecosystem), social (e.g., fisher participation in governance) and fishery economic aspects (e.g., fisher bargaining power) by integrating both a productivity and susceptibility analysis and scale intensity consequence analysis. Data were obtained from surveys with stakeholders and experts and from the literature. Three stocks had moderate risk and three had low risk to overexploitation. The main threat to the stocks was fishery catches, and the main threat to the coral reef habitats and ecosystems was mining waste. To obtain better fishery sustainability, governance must be strengthened, and fishers must be empowered in terms of both the governance and post-harvest processes.

Keywords: Data-poor fisheries; Ecosystem-based fisheries management; Production chain; Sustainability certifications; coral reefs.

1. Introduction

Small-scale fisheries provide a broad of benefits to both local fishery communities and those involved in the production chain (BJORNDAL, CHILD; LEM, 2014). Despite its social-economic importance, the fishery modality usually lacks long-term statistical data, especially in developing countries (RAMÍREZ et al., 2017). As a consequence, management measures based on stock assessments are frequently unfeasible or inadequate because of incorrect projections or estimates (SALAS et al., 2007). Nevertheless, the fishery effects go beyond the target stocks and affect other species, habitats and ecosystems (HOBDAY et al., 2011). Similarly, fishery activities can also be affected by external factors, such as natural or environmental disasters (GEPHART et al., 2017), human disasters (e.g. FERNANDES et al., 2016), climate changes (ALLISON; BASSETT, 2015; GASALLA; DIEGUES, 2011), labor and production relations changes (DIEGUES, 1983) and variations in demand and in fishery profits (CUETOS-BUENO; HOUK, 2018). In addition, fishery communities and the whole fishery production chain may also be affected at different levels in response to the human stresses on the fishery systems. In this sense, fish stock assessments do not represent the real threat to all the fishery systems (CRYER, MACE; SULLIVAN, 2016).

Fisheries studies encompassing a multidisciplinary approach and considering the fishery ecosystem dimension, such as the ecosystem approach to fisheries (EAF) or ecosystem-based fisheries management (EBFM), can be considered revolutionary (BERKES, 2012). These studies involve management approaches that allow the incorporation of alternative information sources (such as stakeholders and fishers' knowledge) into the assessment models and decision-making processes (FISCHER et al., 2015). The multidisciplinary fishery approaches aim to balance human and ecological well-being under the sustainable development context (FISCHER et al., 2015) by incorporating the fishery ecological, social, economic and governance needs into management plans (LONG, CHARLES; STEPHENSON, 2017). In practice, EBFM is a relevant step forward for the integrated management of natural resources because it enables a holistic consideration of stakeholder and government questions (FLETCHER, et al., 2010). Furthermore, this approach is precautionary and adaptive and is also considered strategic for a holistic fisheries management also in data-poor situations (BENSON; STEPHENSON, 2018; FISCHER et al., 2015).

Risk assessment methods such as the Ecological Risk Assessment for the Effects of Fishing (ERAEF) have been practical tools to support the implementation of EBFM approaches (HOBDAY et al., 2011). These methods are used in planning fisheries research and management activities that use fishery risk assessments and consider a range of activities potentially impacting the target and by-catch stocks, habitats, and biological communities (HOBDAY et al., 2011). Furthermore, in regional contexts, ERAEF can also consider fishery economic aspects (BENSON; STEPHENSON, 2018). This risk assessment methods contain a framework that includes a hierarchical structure with different levels of quantification, and a precautionary approach to ecological uncertainty (HOBDAY et al., 2011). The ERAEF analysis can be qualitative (involving stakeholder participation), semiquantitative or quantitative. While the less hazardous activities are detected by qualitative analyses, the more hazardous activities are detected by the semiquantitative and quantitative analyses (MSC, 2010; HOBDAY et al., 2011). Lastly, the ERAEF is able to screen out the low-risk elements for each analysis type and focus on the potential issues of higher or uncertain risk (HOBDAY et al., 2011).

Coral reefs are a diverse ecosystem in terms of the number of associated species and geological structures and provide habitat to many fishes (COKER, WILSON; PRATCHETT, 2014; KNOWLTON et al., 2010). They are important in the provision of goods, income and services (such as ecological, social, information, biogeochemical and biotic) (MOBERG; FOLKE, 1999; THE et al., 2013) and in the livelihoods of many fishery dependent coastal communities (BURKE et al., 2011). Coral reef ecosystems and the human dependent populations are in danger as a result of threats such as climate change, pollution, overfishing, invasive species and sedimentation (ARIAS-GONZÁLES et al., 2011). Along with these threats, many coral reef fisheries are located in less developed countries (WHITTINGHAM; CAMPBELL; TOWNSLEY, 2003), where fisheries management and monitoring of environments, biodiversity and commercial landings are scarce (DELANEY et al., 2017). Therefore, EBFM in coral reef ecosystems is a key approach used to assess the fishery effects and promote ecosystem recovery (FENNER, 2012).

In Brazil, both the small-scale reef fisheries and medium scale offshore fisheries are not consistently monitored nor monitored over the long term (MIRANDA et al., 2016). Typically, the only registered data are catch data, while effort information is available only for some major stocks, such as for the sardines (FREIRE; OLIVEIRA, 2007). Thus, long-term catch and effort data for marine fish stocks are rare. The major obstacle is the lack of investment and commitment from governments. Currently, several Brazilian marine fish populations are threatened according to IUCN criteria (MMA, 2014; IUCN, 2014), and the stocks' status in terms of abundance and biomass is poorly known. In this context, an ERAEF approach seems to be a hopeful alternative to fisheries assessments, which can subsidize future fisheries management.

Along the Brazilian coast, the Abrolhos Bank is the largest coral-reefs, encompassing complex benthic mega habitats with rodolith beds and coralline-reefs (MOURA et al., 2013). Across this region, snappers and groupers are common fishery resources (MARTINS; OLAVO; COSTA, 2007; MPA, 2013), caught mainly by handline and harpoon (OLAVO; COSTA; MARTINS, 2005; PREVIERO; GASALLA, 2018). They are carnivorous species that feed on fish and crustaceans (FREITAS et al., 2017), and they play a fundamental role in the trophic equilibrium of the coral reef ecosystems (RIZZARI et al., 2014). Despite the explicit snapper and grouper economic and ecological importance, their fisheries are not evaluated or monitored. Moreover, the sustainability of these fisheries is unknown as are the impacts from other threatening activities on these stocks. Some of the grouper fisheries are threatened by closures as a consequence of the IUCN status in the last assessment (MMA, 2014), which has caused several conflicts along the Brazilian coast.

In this study, we performed a holistic fishery sustainability evaluation of three snappers (*Lutjanus jocu, L. synagris, Ocyurus chrysurus*) and three groupers (*Cephalopholis fulva, Epinephelus morio, Mycteroperca bonaci*) and considered the biological, environmental, social and economic components of the fisheries over the Abrolhos Bank. Our objectives were to conduct the following: 1) Assess the vulnerability or risk of these six target stocks and their by-catch stocks to overexploitation related to the life history and susceptibility attributes of the fisheries; 2) Evaluate the fishery sustainability of the six snappers and groupers considering fishery attributes and impacts over the target and the by-catch stocks; 3) Determine the main threats to the Abrolhos Bank coral reef habitat and ecosystem; 4) Investigate the effectiveness of regional fishery policies as well as fisher relative importance and participation in the construction of such policies; and 5) Investigate the economical sustainability regarding the post-harvest characteristics of the six stocks.

2. Methods

2.1 Data collection

Fisheries information (such as the main fishing areas, main fish stocks, main by-catch stocks, impacts on target and by-catch stocks, impacts over the habitat and over the ecosystem) were obtained by interviews with major stakeholders and experts (fishers, fish processors and researchers). Social information (such as governance, community organization and empowerment) was obtained by interviews with major stakeholders and experts (fishers, presidents of fisher's associations, managers of nearby protected areas and researchers). Economic information regarding the value chain (e.g., vessel, intermediates and consumer prices) were obtained by interviews with fishers, middlemen and fish sellers and by the registration of prices in supermarkets and fairs. Biological information of the stocks (species life-traits) were obtained by a literature review. The survey with fishers, fish processors, researchers and middlemen were conducted in the years 2014-2015 in the fishing ports of Prado, Alcobaça, Barra de Caravelas and Ponta de Areia (Fig. 1). The interviews with researchers were also conducted in other municipalities during research meetings, and the interviews with middlemen and fish sellers were also conducted in nearby municipalities where the fish are traded.

2.2 Data analysis

To address the objectives, we applied the ERAEF method following the Marine Stewardship Council (MSC) guidelines (MSC, 2010) with adaptations in the by-catch analysis as well as the inclusion of the economic aspects of the six snappers and groupers. To assess the overexploitation risk to the target and by-catch stocks, we conducted a productivity and susceptibility analysis (PSA) (MSC, 2010). The stocks were scored from 1 (low risk) to 3 (high risk) in the productivity score, considering the following life-traits attributes: average age at maturity; average maximum age; fecundity; average maximum size; average size at first maturity; reproductive strategy and trophic level. The final productivity score by stock was obtained by the average of these attributes. The susceptibility score was based on the following attributes: availability (the overlap of the fishery with the stock distribution); encounterability (the likelihood of a stock to encounter fishing gear); selectivity (the potential of gear to capture or retain individuals of a stock); and post-capture mortality (the survival probability of a fish after the catch). The final susceptibility scores by target stock were obtained by the equation:

$$S = \frac{[(Av * En * Se * Pm) - 1]}{40} + 1$$

where *Av* is the Availability, *En* is the encounterability and *Se* is the selectivity, *Pm* is the post-capture mortality. The Susceptibility score for the by-catch stocks were adapted from MSC (2010) and was obtained by the average of the availability and by the frequency of by-catch stocks in fisheries. The final PSA score was obtained by stock by the equation:

$$PSA = (TP^2 + TS^2)^{0.5}$$

where TP is the total productivity by stock and TS is the total susceptibility by stock. In cases for which the biological information was not available for the stock, we used species information. When the information was not available for the species, we used information from a congener species but with a precautionary approach, using a higher score. Detailed information about punctuation is in the Appendix (Table A.17.).

To evaluate the fishery sustainability of the three snappers and three groupers and to determine the main threats to the Abrolhos Bank coral reef habitats and ecosystems, we conducted a scale intensity consequence analysis (SICA), adapted from MSC (2010). The SICA risk score components were adapted, ranging from 1 (low risk) to 3 (high risk) and integrated as follows: (i) Fishery exploitation level of target and by-catch stocks (including baits); (ii) Risk causing activities to habitat; (iii) Risk causing activities to ecosystem; (iv) Social aspects (fisheries management and governance); and (v) Fisheries economic aspects (in the post-harvest). First, we considered the fishery as the main risk activity to the stocks and listed other potentially damaging activities to the habitat and to the ecosystem. Second, we scored the spatial, temporal and intensity scales of each risk activity, considering the information obtained from the surveys and literature. Third, we listed the main consequence of the risk activities and scored it (1 low to 3 high). Finally, we calculated a final risk score, considering also other relevant information about the stocks, habitat and ecosystem exploitation and threats (MSC, 2010). The punctuation values used in scoring are in the Appendix (Tables A.18. – A.21.).

Regarding the SICA social aspects, we followed the literature (MSC, 2010) to investigate the effectiveness of local fishery policies and to list and score some governance attributes: 1) The decision-making process on management measures, 2) The existence of monitoring and review of management measures, 3) The existence of appropriate management measures, 4) The compliance and enforcement of management measures, 5) The existence of local laws guaranteeing the fisher rights, 6) The laws and people trained for law enforcement, 7) The fishery incentives, 8) The available information on habitats monitoring, 9) The effectiveness of fisheries management within MPAs, 10) The existence of effective MPAs, 11) Fishers participation in fisheries management, 12) The existence of studies required to propose management actions and 13) The existence of long-term goals. The detailed attribute values used in the governance scores are in the Appendix (Table A.21.).

In terms of the fisheries economic aspects, we investigated the economic sustainability of the snappers and groupers in the post-harvest by the evaluation of 1) fishers' negotiation power in the production chain (fisher control on the fish selling price; fisher choice of to whom to sell;

fisher capacity to store the fish; fisher ownership of the vessel; fisher usually selling the fish in another municipality and obtaining a better price), 2) market chain sustainability (number of links), 3) value chain equity (the percentage that fishers received in relation to the final value and the existence of price speculation) and 4) fish traceability (the ease in tracing a market chain). These attributes were elaborated based on the literature. The final score of each attribute was the average of surveys. The values considered for the punctuation are in the Appendix (Table A.22.). We also drew a schematic production chain of the six stocks studied.

3. Results

A total of 70 experts were interviewed including fishers (32), fish traders (27) and researchers (11). By using these surveys, we discovered the main by-catch or bait stocks. While the *Xiphopenaeus kroyeri* (camarão sete barbas) was usually used as bait in the *L. synagris* and *O. chrysurus* fisheries, *Katsuwonus pelamis* (bonito-listrado) was used as bait in the *M. bonaci* and *E. morio* fisheries. *Haemulon plumierii* (biquara) and *Calamus pennatula* (peixe-pena) were mainly by-catch from the hand-line fisheries of the six target stocks.

According to the productivity and susceptibility Analysis (PSA), the target stocks, *L. jocu*, *E. morio* and *M. bonaci*, had medium overexploitation risk, and *L. synagris*, *O. chrysurus* and *C. fulva* had low overexploitation risk (Table 15, Fig. 21). Regarding the by-catch (and bait) stocks, *X. kroyeri* and *K. pelamis* were in low overexploitation risk, and *H. plumierii* and *C. pennatula* were in the medium risk (Table 15, Fig. 22).

Table 15. Productivity and susceptibility analysis table with scores and the corresponding risk category for the six snappers and groupers and their by-catch stocks in the Abrolhos Bank. The scoring guide is in MSC (2010, page 105). The reference values by species are in the Appendix (Table A.17.).

	Productivity score								Susceptibility score						PSA scores	
Stock	Average age at maturity	Average max	Fecundity	Average max	Average size at Maturity	Reproductive strategy	Trophic level	Total Productivity	Availability	Encounterability	Selectivity	Post-capture mortality	Fishery intensity	Total	PSA Score	Risk Category Name
L. jocu	2	3	2	1	2	2	3	2.14	3	3	2	3		2.33	3.16	Medium
L. synagris	1	2	1	1	1	2	3	1.57	3	3	2	2		1.88	2.45	Low
O. chrysurus	2	2	1	1	1	2	3	1.71	3	3	2	2		1.88	2.54	Low
C. fulva	1	2	1	1	1	2	3	1.57	2	2	2	2		1.38	2.09	Low
E. morio	2	3	1	2	2	2	3	2.14	3	3	2	2		1.88	2.85	Medium
M. bonaci	2	3	1	2	2	2	3	2.14	3	3	2	2		1.88	2.85	Medium
X. kroyeri	1	1	2	1	1	2	1	1.29	1.0				2.75	1.88	2.27	Low
H. plumieri	1	2	1	1	1	2	3	1.57	2.8				1.88	2.34	2.85	Medium
C. pannatula	1	2	1	1	1	2	3	1.57	3.0				1.75	2.38	2.85	Medium
K. pelamis	1	2	1	2	2	2	3	1.86	1.5				1.00	1.25	2.24	Low

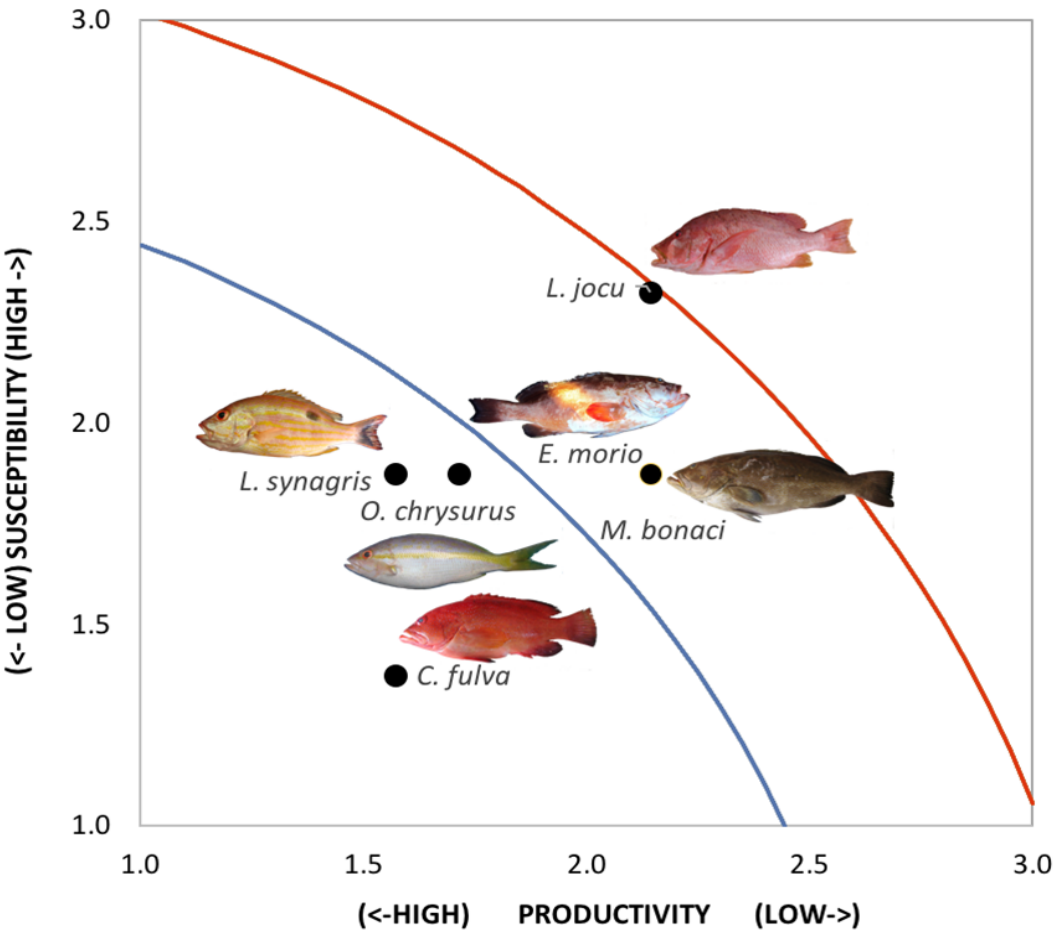


Figure 21. PSA plot of the three snapper and three grouper stocks that were studied. The stocks near to the origin point are less threatened. The blue line represents the limit between the low risk and the medium risk, the red line represents the limit between the medium risk and the high risk.

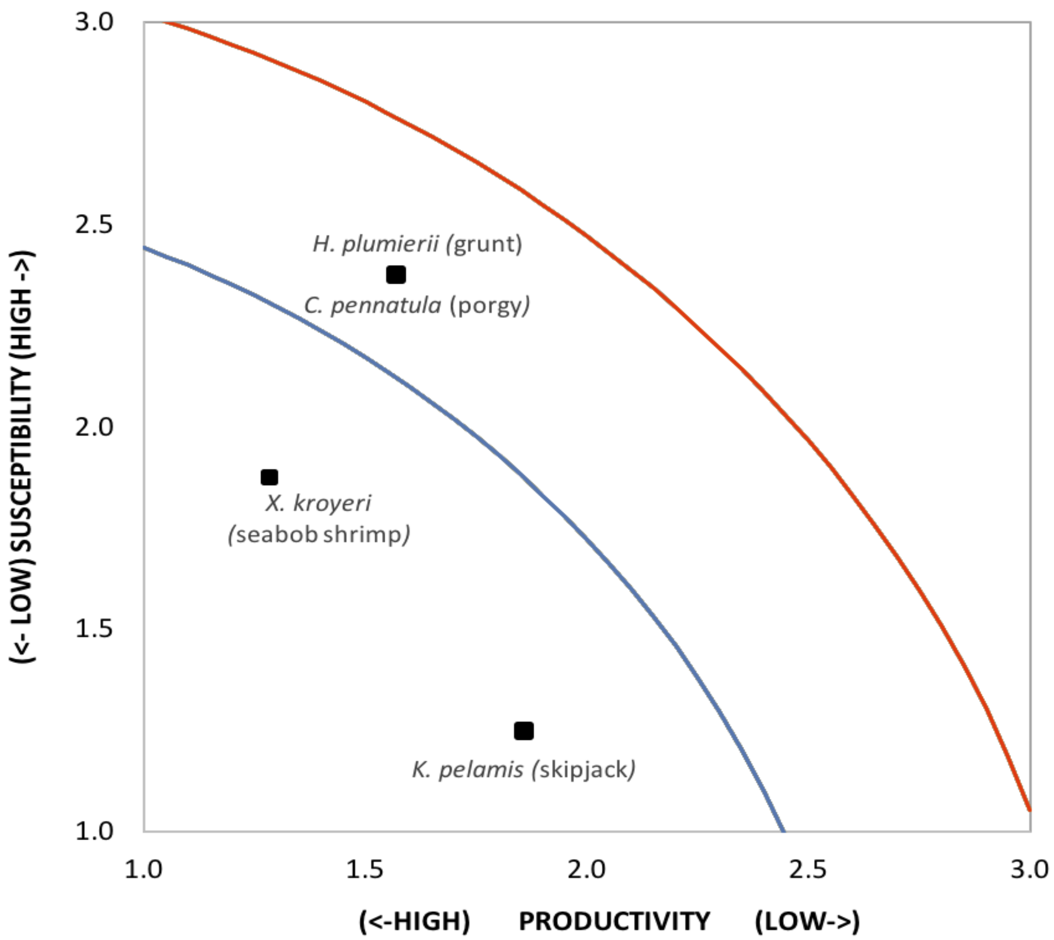


Figure 22. PSA plot of the main by-catch and bait stocks of the six target snappers and groupers that were studied. The stocks near to the origin point are less threatened. The blue line represents the limit between the low risk and the medium risk, the red line represents the limit between the medium risk and the high risk.

According to the scale intensity consequence analysis (SICA), the major risk activity resulting from fishing was direct capture. The fishery spatial scale received the greater risk score to the target stocks because the direct capture that occurred in almost all of the stock distribution areas (average of 72%) in the Abrolhos Bank (Table 16). The greatest consequences of direct capture were the reduction in population size and changes in stock ages and size structures. The intensity of these consequences resulted in the major risk score being assigned to five of the target stocks and medium risk being assigned to *C. fulva* (Table 16). The by-catch stocks received medium and low risk scores towards the reduction in population size as consequence of their use as bait or by-catch (Table 16).

Table 16. SICA results of target and by-catch stocks with the attributes punctuation, the greatest risk activity and its consequence, and the final risk score by stock, related to the relevant subcomponent.

Target and by-catch stocks	Risk activity	Spatial scale	Temporal scale	Intensity scale	Major consequence	Risk score
Lutjanus jocu	Direct capture	3.0	2.0	2.2	Population size	3
Lutjanus synagris	Direct capture	3.0	2.0	2.5	Population size	3
Ocyurus chrysurus	Direct capture	3.0	2.0	2.4	Age/size structure	3
Cephalopholis fulva	Direct capture	3.0	2.5	1.5	Population size	2
Epinephelus morio	Direct capture	3.0	2.0	2.0	Population size	3
Mycteroperca bonaci	Direct capture	3.0	2.5	2.0	Population size	3
Xyphopenaeus kroyeri	Direct capture	1.0	2.0	2.8	Population size	1
Haemulon plumieri	Direct capture	3.0	2.0	2.0	Population size	2
Calamus pannatula	Direct capture	3.0	2.5	1.8	Population size	2
Katsuwonus pelamis	Direct capture	1.5	2.5	1.0	Population size	1

The risk activities affecting the Abrolhos Bank coral reef habitats considered in this study were mining waste, dredging and fisheries. Among them, the major risk was mining waste, followed by dredging, especially in terms of the temporal scale and intensity of these activities (Table 17). As a consequence, the loss of habitat quality and structure were the main sources of damage to the coral reefs and received a high-risk score (Table 17).

Table 17. SICA habitat results with the risk activities and the spatial, temporal and intensity scales, the major consequence of each risk activity and the corresponding risk score.

Habitat	Risk activity	Spatial scale	Temporal scale	Intensity scale	Major consequence	Risk score
Tropical coral reef	Mining waste	1.5	3.0	3.0	Habitat quality	3
	Dredging	1.0	2.0	2.0	Habitat structure and function	3
	Hand line fishery	2.5	1.3	1.7	Habitat structure and function	2
	Harpoon fishery	1.5	2.0	1.0	Habitat structure and function	2

Similar to the coral reef habitats, the highest risk activities affecting the Abrolhos Bank ecosystem were mining waste and dredging, especially because of the time necessary for the recovery of some environmental damage and as a result of the intensity of these activities (Table 18). The major consequence of these activities was the loss of the Abrolhos Bank ecosystem structure and function (Table 18).

Table 18. SICA ecosystem results of the risk activities at spatial, temporal and intensity scales, the major consequences of these activities and the corresponding risk score.

Ecosystem	Risk activity	Spatial scale	Temporal scale	Intensity scale	Major consequence	Risk score
Abrolhos Bank	Mining waste	1.5	3.0	3.0	Ecosystem structure and function	3
	Dredging	1.5	2.5	2.5		3
	Hand line fishery	2.5	1.0	1.7	Ecosystem structure and function	2
	Harpoon fishery	2.0	1.0	1.6		2

In terms of governance and fisheries management in the Abrolhos Bank, the most effective activities (low risk score) were the monitoring and review of management measures, followed by the fishery incentives (Table 19). On the other hand, the less effective activities (high risk score) were both the effective management of the marine protected areas and effective fisheries management (Table 19).

Table 19. SICA results of social aspects (fisheries management and governance) in the Abrolhos Bank.

Fishery management and governance policy	Punctuation	Average score	Risk score
Decision-making on management measures	1.4	1.6	1.6
Monitoring and review of management measures	0.9		
The management measures are appropriate	1.3		
Compliance and enforcement of management measures	1.3		
There are local laws guaranteeing the fishers rights	1.7		
There are laws and people trained for law enforcement	2.3		
There are fishery incentives	1.0		
There are available information on habitats monitoring	1.3		
Effective fisheries management within MPAs	2.3		
Effective MPAs management	2.5		
Fishers participation in fisheries management	2.2		
There are researches needed to propose management	1.5		
There are long-term goals	1.5		

The analysis of the SICA economic aspects regarding the post-harvest revealed a low fisher negotiation power among the target stocks analyzed, which was the main obstacle to selling the resources in another municipality (Table 20). There was an intermediate level of fish traceability and a reasonable number of links along the market chain (2-6) (Table 20, Fig. 23). The final consumers were in sixteen different national municipalities and on two other continents (Fig. 23). Most of the fish go through a middleman before arriving at the final consumption city.

There was no direct marketing between the fishers and the final consumer nor between the fishers and the middleman. The fishers always traded with a fish market or fridge. There was also one processing center in Itapemirim, ES, from where *C. fulva* was exported to Europe and the United States.

Table 20. SICA results of economic aspects of the six snappers and groupers fisheries with the attributes scores by stock.

Production chain – Target species	Fisher's negotiating power					Market chain	Value chain	Traceability of fish	Average	Risk score
	Controls selling price	Choose whom to sell	Store the fish	Own vessel	Sell in another municipality					
L. jocu	2.3	2.1	2.4	1.2	2.8	2.0	1.9	2.0	2	2.5
L. synagris	2.3	2.2	2.3	1.2	2.8	2.0	1.9	1.9	2	
O. chrysurus	2.3	2.1	2.3	1.2	2.7	2.0	2.0	1.9	2	
C. fulva	2.1	1.9	2.0	1.3	3.0	2.0	2.1	2.0	2	
E. morio	2.3	2.0	2.3	1.2	2.8	2.0	2.1	1.9	2	
M. bonaci	2.3	2.0	2.3	1.2	2.8	2.0	2.1	1.9	2	

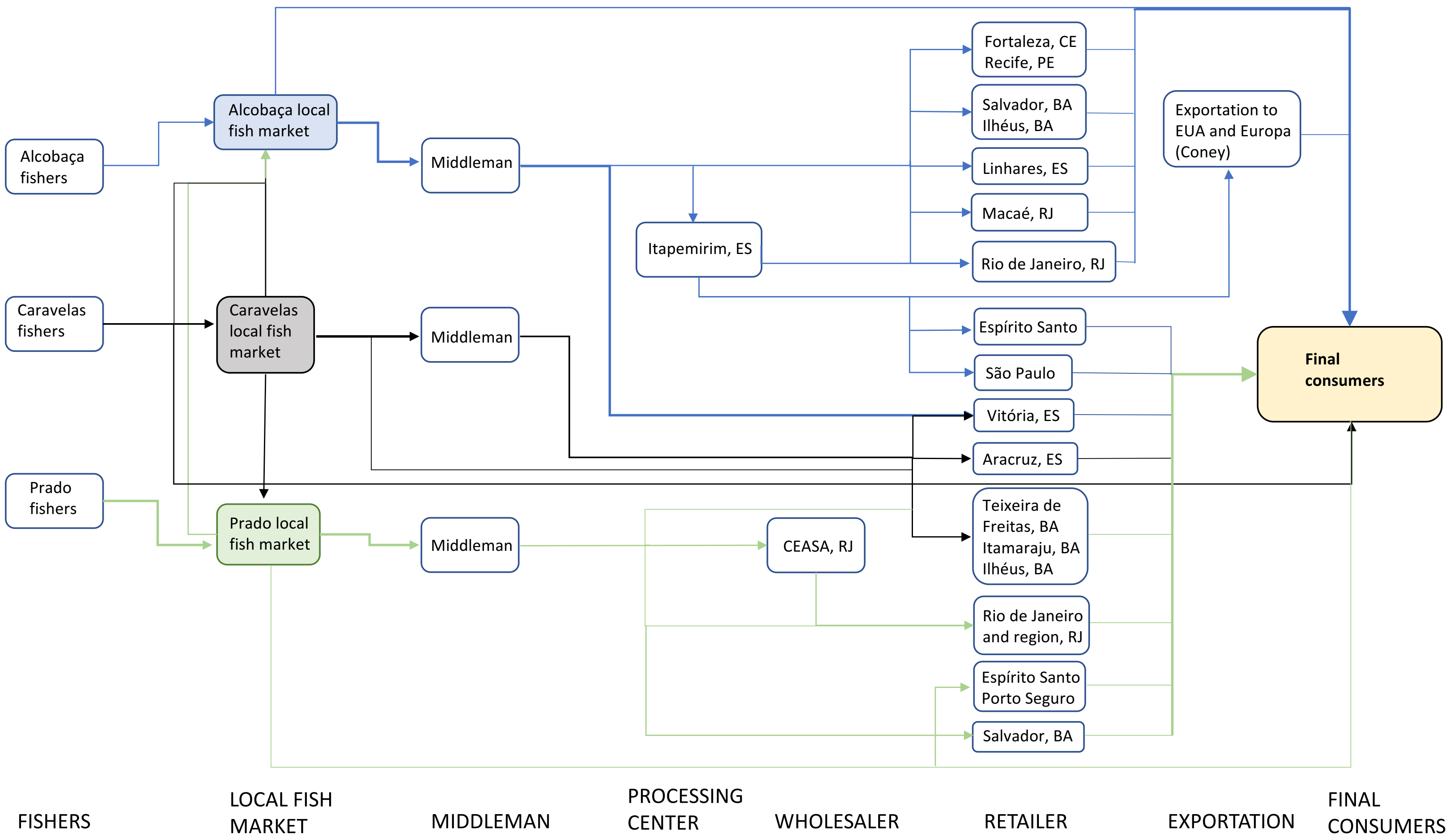


Figure 23. Schematic representation of snappers and groupers production chains captured in the Abrolhos Bank and landed in Alcobaça, Caravelas and Prado municipalities.

4. Discussion

Semiquantitative and qualitative tools, such as PSA and SICA, have been crucial in many data-poor fisheries from developing countries to subsidize fisheries management, as an alternative to fully quantitative assessments (ZHOU et al., 2016). Although these low-cost approaches were recognized as a first step in identifying stock risk in data-poor situations (HOBDAY et al., 2011), in Brazil, few studies have used them (e.g., FRÉDOU et al., 2017). This precautionary ERAEF method was developed by Hobday et al. (2007) and was disseminated by management and advisory bodies (FRÉDOU et al., 2017) and by the Marine Stewardship Council in fishery certifications all over the world (MSC, 2010). These certifications, however, are not a reality for Brazilian fisheries (MSC, 2018; PÉREZ-RAMÍREZ et al., 2016), especially due to the lack of knowledge (stocks usually lack necessary data) and the lack of investment in fisheries tracking and in the entire certification process (FRÉDOU et al., 2017). In this study, we applied the ERAEF method with some adaptations, such as the inclusion of post-harvest fisheries aspects, which can guide future regional multidisciplinary assessments and certifications. We determined the vulnerability to overexploitation of the six target stocks and a preliminary risk score of the by-catch stocks. We also determined the main threats to habitats and ecosystems, the main gaps in effective fisheries management and governance, and the main obstacles to achieving sustainability on the production chains.

4.1 Vulnerability to overexploitation

4.1.1 Target stocks

From the six target stocks analyzed, three stocks are classified as substantially threatened. Among them, *L. jocu* has the greater risk or vulnerability to overexploitation, especially because of its fast post-capture mortality and high maximum age (29 years; PREVIERO, et al., 2011). High maximum age, body-size and trophic level are relevant characteristics for the *M. bonaci* and *E. morio* classification as medium risk. Major stock susceptibility was from the availability and encounterability indices because the fishing fleets are spread over the Abrolhos Bank, from coastal to offshore areas of approximately 140 nautical miles (PREVIERO; GASALLA, 2018). Thereby, as management measures for these three stocks, we suggest the restriction of the fishing areas to reduce the fisheries overlapping the stocks in the coral reefs habitats. The main fishing areas for these stocks can be found in Previero and Gasalla (2018). We also suggest fishing gear regulations to make them more size-selective (CHAPTER 2; OLAVO et al., 2011).

The three target stocks that have a low vulnerability to overexploitation (*C. fulva, L. synagris* and *O. chrysurus*) have a lower body-size and lower maximum ages (18- 25 years) (ARAUJO, MARTINS; COSTA, 2002; ARAUJO; MARTINS, 2009; ASCHENBRENNER et al., 2017) than the most vulnerable stocks. According to Zhou et al., (2016), the PSA shows a low sensitivity for the most productive species or a relatively high fishing impact. In fact, we observed that the productivity attributes related to reproduction (fecundity and reproductive strategy) are very similar between the six target stocks. To avoid an increase in the vulnerability to overexploitation, we suggest periodic assessments of these stocks and continuous fisheries monitoring.

4.1.2 By-catch stocks

The stocks *X. kroyeri* and *K. pelamis* have a low overexploitation risk, especially because they are used as bait and have a low encounterability score because they do not occur in the same fishing areas (coral-reefs) of the target stocks. On the other hand, the two medium-risk by-catch stocks (*H. plumierii* and *C. pennatula*) occur at in similar target stock area and their main catches are as by-catch.

The *X. kroyeri* was the main fishery resource in Caravelas in the year 2010 (MINTE-VERA; SOUZA-JÚNIOR, 2014). In this study, their fishery as bait is considered low risk, but this is a preliminary risk assessment to the by-catch stocks, and because of its local importance, we advise carrying out directed evaluations of this shrimp stock. In the first commercialization in the study area, *H. plumierii* and *C. pennatula* are usually registered as “mistura”, a local fish category encompassing a variety of species traded without identification at low values (FREITAS, 2009). As these stocks are classified as medium risk, we suggest continuous monitoring and fishing records at the species or ethnospecies level (FISCHER, 2013; PREVIERO, MINTE-VERA; MOURA, 2013) because the low resolution in fish identification during monitoring may mask a serial depletion (DENT; CLARKE, 2015; KAPROV et al., 2000).

4.2 Fishery sustainability

4.2.1 Fishery impacts over stocks

As a consequence of direct capture, five of the target stocks had a maximum overexploitation risk (Table 16). The broad fishery spatial distribution is the major threat to such stocks because the fishery restricted areas are a small zone of the region, and their effectiveness is inadequate as a result of lack of oversight. In the Abrolhos Bank, many vessels are small, belong to artisanal fisheries, and are restricted due to adverse weather conditions (PREVIERO, 2014). Therefore, the temporal scale of the studied fisheries is medium. In terms of the impossibility of going out to fish in adverse weather conditions, many fishers from Caravelas claim that "there is a natural fishing closure". For the five stocks for which the main fishery effect is population reduction, the fisheries have captured a broad size range. However, for *O. chrysurus*, the major fishery effect is the change in age and size structure because the fisheries have captured a large proportion of small, immature individuals (CHAPTER 2). *C. fulva* is the least threatened fishery stock, not only in the SICA (Table 16) but also in the PSA analysis (Fig. 21). On the one hand, this stock has a direct export fishery (Fig. 23), for which its fleet has great autonomy and few restrictions due to climatic conditions (PREVIERO; GASALLA, 2018). On the other hand, few vessels make up such fleets, which confers a low intensity score for this fishery and a medium risk score for *C. fulva*.

The by-catch stocks co-occurring in the target stock area are at a moderate risk, especially because of the wide fishing spatial distribution. Both target and by-catch stocks need fisheries management that mainly addresses total fishing area reduction (with the exception of *X. kroyeri* and *K. pelamis*, which had a low risk in PSA and SICA). A spatial management measure, such as marine protected areas (MPAs) in critical habitats, had been previously shown as an option for these reef-associated stocks (MOURA et al., 2011). This measure can promote stock recovery and spill over to adjacent areas (FRANCINI-FILHO; MOURA, 2008) to promote the balance of the whole biological community (BRUCE et al., 2012). Furthermore, fishery management as a marine protected area is a tool to support an ecosystem approach (SEIXAS; VIEIRA, 2015), especially when it is designed and implemented as a network of MPAs encompassing a range of habitats (PRATES; BLANC., 2007).

4.2.2 Threats to habitat and ecosystem

In this study, we compare and evaluate the main activities impacting the Abrolhos Bank ecosystem and coral reef habitat. It is known that all fishing modalities can cause environmental damage, such as physical damage to habitats and ecological disturbances to the ecosystem by means of changes in food chains (KING, 2007). However, hand line and harpoon fisheries are considered to be less harmful to the environment in terms of physical damages and fish size selection (BJORDAL, 2002). Considering the spatial distribution of activities impacting the coral reefs, while harpoon fishing occurs in restricted area (only on the shallower coral reefs), line fishing is the most widespread activity in the region (PREVIERO; GASALLA, 2018). Local dredging has begun in the year 2003 with the purpose of enabling the entrance and the exit of barges carrying Eucalyptus (NOGUEIRA, 2009). This activity is restricted to the Caravelas Estuary (MOURA et al., 2013), a mangrove area nursery of several reef fish species (GIGLIO; FREITAS, 2013; MOURA et al., 2011). Although dredging has effects on coral reefs closer to the coastline (DUTRA et al., 2006), which is still a restricted area, considering the entire Abrolhos Bank. Until this date, mining waste has not been distributed broadly in the study area (LARAMG, 2018; MAZZEI et al., 2017). However, the biological community, habitats and ecosystem destruction are very intense and require a long recovery period (FERNANDES et al., 2016). The main possible damage from mining waste to the Abrolhos Bank ecosystem include metal bioaccumulation through food webs, toxic algal blooms, and changes in fish growth, survival and behavior (MAZZEI et al., 2017).

In summary, while fishery operations are widespread in the region completely impacting it, mining waste and dredging currently impact only a portion of the coral reef habitats and ecosystems. On the other hand, while the fishery impacts are relatively less intense, as they involve hand-line and harpoon ecosystem-friendly fishing gears (BJORDAL, 2002), the mining-waste and dredging impacts are devastating where they occur, impacting marine organisms (KING, 2007) and promoting an absolute loss of habitat and ecosystem structures and functions (HADJIBIROS et al., 2006).

In this sense, the primary management action to protect the Abrolhos Bank reefs is the creation of measures to contain the mining waste with spatially explicit long-term monitoring (FERNANDES et al., 2016). Furthermore, measures to prevent future accidents involving mining waste and other damaging activities, such as petroleum leaks, are essential to protect this ecosystem. Another management measure is the containment and reduction of dredging effects by greater control of this activity in the region.

4.2.3 Fisheries governance problems and challenges

In this study, monitoring and review of fisheries management measures in the Abrolhos Bank is the most effective governance activity (Table 19). However, in the Cassurubá Extractive Reserve in Caravelas, Nobre et al. (2017) found no regular monitoring of fishery resources, especially because of the lack of effective monitoring implementation. On the other hand, this study found similar results as Nobre et al. (2017) in terms of “local laws guaranteeing the fishers rights” and “fishers participation in fisheries management”. According to these authors, there is a need for formalizing local laws that ensure long-term user rights and that direct fisher participation in fisheries management plans. Moreover, the lack of enforcement is another characteristic found both in Nobre et al. (2017) and our study, which explains the observed regional demand of people trained for law enforcement. Despite the low effectiveness of the MPA management in the Abrolhos Bank, in terms of worldwide comparisons, these MPAs are not so bad (EDGAR et al., 2014). The previously mentioned study revealed a “poor overall performance of MPAs worldwide in terms of recovery of fish biomass”; however, Abrolhos Bank MPAs are classified as medium performance level according to the attributes of governance, effectiveness, isolation, size of the area and age (EDGAR et al., 2014).

The governance in the Abrolhos Bank ecosystem presents at least some type of problem in each topic evaluated. The resolution of these gaps is mainly through the decentralization of the entire management and decision-making processes, with an effective increase in fisher and community participation (GARZA-GIL; AMIGO-DOBAÑO; SURÍS-REGUEIRO, 2017; JENTOFT, 2000; KING, 2007). In this sense, fishers need to be empowered and proactive and have a sense of ownership and independence in the whole process (NUTTERS; SILVA, 2012). Thereby, in the long term, fishers become guardians or defenders of the resources they can exploit for generations. Moreover, the whole community will feel responsible for the conservation of fishery resources (GARZA-GIL; AMIGO-DOBAÑO; SURÍS-REGUEIRO, 2017). This process is called fishery self-governance and has been successful in many countries (TOWNSEND, 2008). Self-governance is usually implemented by regional community organizations, with governmental oversight, and has communal objectives, targets and paths aiming at an effective fishery management (LEE; MIDANI, 2015).

4.2.4 Fisheries post-harvest

The major economical hindrances for the local fishers are their lack of means to store fish and their low bargaining power (Table 20), with high middlemen power in determining the first trading prices. This scenario is common in several small-scale fisheries in Brazil (YKUTA, 2015), and in the world (MANGUBHAI et al., 2016; PURCELL et al., 2017). As weighting measures, some subsidies to small-scale fishers, such as the provision of infrastructure (ice factories, cold rooms, piers) can strengthen and balance the fishery productive chain through the fishers' empowerment (YKUTA, 2015). When fishers have greater negotiating power, they become more autonomous, selling the fish for higher prices, which is a first step towards a more homogeneous value chain and a more sustainable production chain (BJORNDAL; CHILD; LEM, 2014). Some practical ways to improve the production chain are (1) the development of fisher cooperatives (PURCELL et al., 2017), (2) the resource valorization in landing municipalities and (3) fisher or intermediate competences application to a different production chain sector (with the aim of reducing the number of links in the chain) (HUMPHREY; SCHMITZ, 2002).

Although we can map the production chain, the fish trajectory from the landing to the final consumer is not completely linear, which hinders good fish traceability. Some benefits of good fish traceability are food security, the improvement in food resources management, price control along the production chain and reducing mislabeling and illegal fish marketing (METREF; CALVO-DOPICO, 2016; STAWITZ et al. 2017). In summary, fish traceability is a tool that is especially used in certifying the resource origin and sustainability (CARVALHO; MARTINSOHN, 2013). The main challenges for the implementation of good fish traceability in developing countries include development of adequate fishery public policies and strong law enforcement. Some tools to improve fish traceability are the collection of fisheries data, the establishment of fishery product legitimacy, and the implementation of laws to ban illegal fish commercialization (BHATT et al., 2015).

Although the six snappers and groupers presented some threatened and overfishing levels (CHAPTER 2), the production chain revealed large consumption of these stocks in other Brazilian states (Fig. 23). A recognized management option is the reduction in the links in the chain, which may maximize profits, especially in the base (fishers), and minimize problems such as bottlenecks in supply, costs incurred, and the time to market (BJORNDAL; CHILD; LEM, 2014; SHAMSUDDOHA, 2007). In addition, the exportation or distant marketing of threatened species is not a sustainable feature because it can reduce local fish availability and raise its local price, damaging vulnerable fisher communities (BJORNDAL; CHILD; LEM, 2014). Furthermore, when a fishing resource is marketed in a situation without context, away from the place of origin, it is not appreciated as when its final trading occurs as a typical product or as an endemic species in the consumption place, receiving a greater added value.

In this sense, following one of the suggestions for upgrading production chains described by Humphrey and Schmitz (2002), the functional upgrade, we propose the creation of public policies for local fish valorization. That can be conducted through the promotion of economic development projects based on local cooperatives and the sustainable use of fish and other natural resources, with community protagonism. These measures can attract financial resources and generate income for the local communities.

5. Conclusions

In this study we could obtain a whole picture of the activities that threaten the Abrolhos Bank ecosystem. Although fishery is a very common activity distributed throughout the Abrolhos Bank, it is not the main threat to the coral reef habitat or ecosystem. The fishery is threatening mainly the stocks *L. jocu, M. bonaci* and *E. morio,* classified as on alert to overexploitation. However, the major threat to the Abrolhos Bank habitats and ecosystems came from highly destructive mining waste in the south coast. Another high-impact threat is the dredging on the Caravelas River, reaching mangroves, the estuary and even the coastal reefs. Regarding fishery economic aspects, the main problems are the lack of fisher bargaining power and low infrastructure to support both fishery and post-harvest activities. Finally, the regional governance must be strengthened to support the elaboration and implementation of some necessary management measures.

In summary, a consolidated governance structure, a decentralized fisheries management, the empowerment of fishers, the dissemination of fisher and community senses of responsibility for natural resources, and the appreciation of local natural and cultural resources are essential steps towards balance in the Abrolhos Bank ecosystem.

GENERAL CONCLUSION

In this thesis, essential questions about the complex fishery system in the Abrolhos Bank shelf and fishery communities could be clarified. The fisheries studied here are multi-gear, multi-species and have many arrangements involving: interactions among species and habitats, fishing methods, fleet spatial dynamics, fisher and community interactions, the stocks post-harvest, the local fisheries governance, among others. Before this work, these complex arrangements made difficult the understanding of the fishery system, and in some situations hampered or discouraged the management planning. On this thesis we elucidated some complex questions over the fisheries of six fish stocks with high ecological and economic importance, that are currently threatened. To make possible to understand this complex fishery system, first of all a fishery characterization with stocks and fishing areas groupings was conducted, resulting in fleet patterns and proper management units. Then, the stocks exploitation status was necessary to generate statistical data to support future management plans. Finally, to have a holistic view of the studied fishery system, we investigated the fishery sustainability in the biological, environmental, social and economic approaches and compared the fishery with other regional damaging activities.

In this sense, in the first chapter the fleets were described and classified, the fishing spots and fishing grounds were mapped, and fishing areas and stocks were grouped. The results revealed groups of stocks co-occurring in the same fishing grounds "*L. synagris* (ariocó) and *E. morio* (garoupa)"; "*L. jocu* (dentão) and *M. bonaci* (badejo)", and group of stocks co-occurring in the catches "*L. jocu, E. morio* and *M. bonaci*". The results also indicated seven similar areas in terms of stocks co-occurrence. This chapter provided a better understanding of the reef fishery characteristics of the Abrolhos Bank and supported the elaboration of spatial and multi-species management units.

In the second chapter some preliminary stock assessments revealed overfishing to *L. jocu, O. chrysurus*, *E. morio* and *M. bonaci* and decline in the relative abundance to *L. jocu, O. chrysurus, C. fulva* (catuá), *E. morio* and *M. bonaci.* The major overfishing reasons were 1) high fishing mortality (especially to *E. morio* and *L. jocu*) and F greater than the $F_{0.1}$ reference points to all stocks 2) low spawning potential ratio, especially to the groupers, which is an indicative of recruitment overfishing; 3) low percentage of mega-spawners in landings, especially to *O. chrysurus* and *M. bonaci*, which increases the possibility of recruitment overfishing to these stocks; and 4) high percentage of juveniles in landings, especially to *O.*

chrysurus, *M. bonaci*, *E. morio* and *L. synagris*, which may indicate growth overfishing. These findings contributed to have specific and quantitative information on the stocks threaten status; to know the stocks structure in terms of abundance and size composition, as well as to know the fraction of each stock most threatened by the fishery. This chapter provided subsidies for the management of these stocks by making possible comparisons between the estimated population indexes and the respective reference points, which indicated the exploitation level and the target values to achieve a sustainable exploitation status.

The precise estimative of the threaten level of each stock and the knowledge of the most threatened fractions of a stock is absolutely important in terms of management implications (HILBORN; WALTERS, 1992). However, the unitary stock assessments can do not represent the real threat to all the fishery system (JENNINGS, 2001). Other external impacts may represent greater danger than the fishery to both the fish stocks and the ecosystem. In these cases, the fishery management may be accompanied by other measures to mitigate external impacts over the fishery system (KING, 2007).

In this sense, on the third chapter a multidisciplinary approach was used to assess the six snappers and groupers fishery sustainability in the Abrolhos Bank ecosystem. This approach corroborated that the fishery has led some stocks on alert to overexploitation (especially *L. jocu*, *E. morio* and *M. bonaci*), which is a worrying threat. In this sense, the reduction of the availability and of the encounterability (between fleets and stocks) by seasonal closures or fishing area restrictions represent management options, especially when considering the spatial management units suggested in the first chapter. Furthermore, the chapter 3 revealed a great threat on the coral reefs habitat and on the whole ecosystem, originating mainly from sources other than fishery (mining waste and dredging), which may affect the food webs, nursery habitats or spawning areas (KING, 2007). Moreover, two of the main gaps found to reach a sustainable fishery were the weak environmental governance in the region and the insufficient community participation on the construction of management proposals. These conditions must be worked on to avoid disrepute or non-compliance of the rules (KING, 2007). In this sense, the fishery effects over the stocks and the environment, as well as the effects of mining and dredging must be urgently thought and handled with care and attention.

By the coupled evaluations conducted on the three chapters of this thesis (Table 21) is possible to concludes that *M. bonaci, L. jocu* and *E. morio* are the most threatened stocks. As seen in the first chapter, these three stocks may be considered a management unit regarding its co-occurrence in landings. Thus, managing the fisheries of these stocks should consider some common aspects such as the fishing effort control or some fishing gear regulation (these stocks are caught mainly by hand line in Prado, Alcobaça and Ponta de Areia and by harpoon in Barra de Caravelas and Alcobaça). For the size regulations, an easier management action may occur in the post-harvest sector (KING, 2007). The fishing effort control of these fleets is an important way to manage these threaten stocks as a unit (KING, 2007). For example, the effort reduction of the harpoon and hand-line fleets to reach the $F_{0.1}$ for the *M. bonaci* may improve the recovery of the two other stocks of the unit (*L. jocu* and *E. morio*) (Fig. 24), and make easier the implementation of a unique management measure for the three stocks that compose this management unit.

Another management unit suggested in chapter 1 is the grey area (Fig. 14), also known as "*Parcel das Paredes*". In this area there is a concentration of the five most threaten stocks according the exploitation status estimated in chapter 2 (*M. bonaci*, *L. jocu*, *E. morio, O. chrysurus*, and *L. synagris*). Thereby, we suggest an area-based fishery management using these results, especially because this is a multi-species management option capable to protect also the coral reef habitat besides other ecosystem biotic and abiotic components. Thus, a spatial management unit in the "*Parcel das Paredes*" may help also to reinforce measures to mitigate the effects of dredging in the Caravelas estuary, over the coastal coral reefs.

Regarding the large specimens, the stocks with the percentage of mega-spawners most worrying are *M. bonaci* and *O. chrysurus* (Table 11, Fig. 19). The main reasons of this condition are the high fleet encounterability and the high fleet spatial overlapping to these stocks occurrence (Tables 14 – 15). Thereby, we suggest the creation of Marine Protected Areas to the mega-spawners recovery. On the chapter 1 we found the fleets that caught the largest specimens of *M. bonaci* (Alcobaça) and *O. chrysurus* (Prado) (Fig. 7), as well as the operation area of each fleet by stock (Fig. 9 b-e). In this sense, to protect the mega-spawners, the MPAs may be in areas offshore, where the largest specimens are caught, for example, the green and the yellow areas (Fig. 14).

In the chapter 2, the stocks classified as not overfished were *L. synagris* and *C. fulva*. The last one was also the only to receive medium risk score in the SICA analysis, besides receive low risk in PSA analysis in the chapter 3. The negative points of the catuá fishery is the reduction in the relative abundance in the period 2005 – 2011 as well as the low spawning potential ratio. This fishery may be promising to receive a sustainable certification but needs previously to be continuously monitored and to have an effort control.

Table 21. Summary of the fisheries indicators used to estimate exploitation status, risk to overfishing and fishery sustainability of the snapper and grouper stocks of the Abrolhos Bank.

								SICA final scores				
Stock	F/M	SPR	YPR	CPUE	Changes in size	Size indicators	PSA risk	stocks	habitat	ecosystem	governance	economic
L. jocu	1.62	0.46	F> $F_{0.1}$	Declining	Reduction	Reasonable	Medium	3				
L. synagris	0.98	0.41	F> $F_{0.1}$	Not declining	No reduction	Overfished	Low	3				
O. chrysurus	1.09	0.43	F> $F_{0.1}$	Declining	Reduction	Overfished	Low	3	3	3	1.6	2
C. fulva	1.60	0.38	F> $F_{0.1}$	Declining	No reduction	Reasonable	Low	2				
E. morio	1.81	0.37	F> $F_{0.1}$	Declining	Reduction	Overfished	Medium	3				
M. bonaci	1.46	0.39	F> $F_{0.1}$	Declining	Reduction	Overfished	Medium	3				

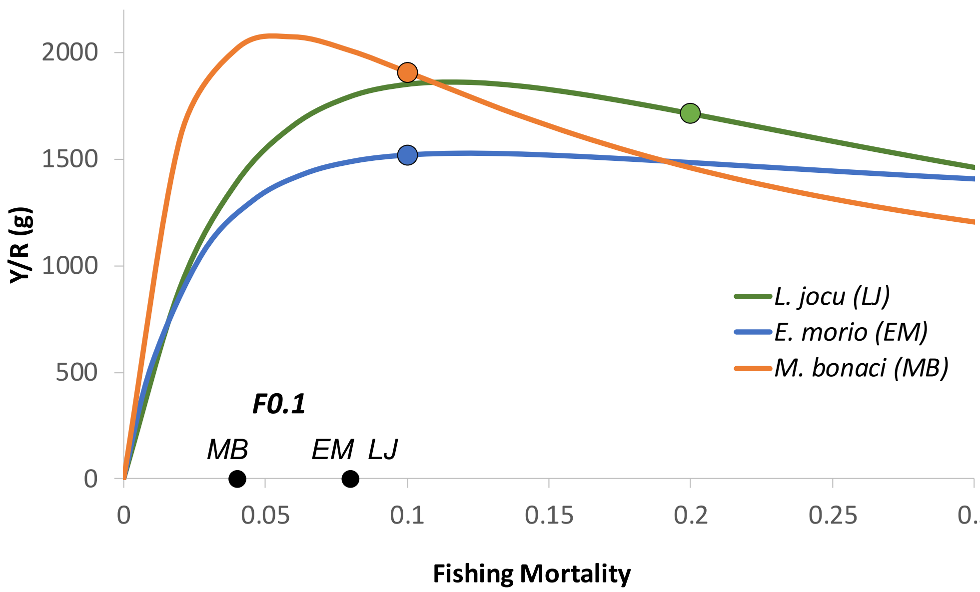


Figure 24. Yield per recruit to the three stocks that compose the management unit of "stocks landed together" in chapter 1, else these are the three most threatened stocks according to risk assessment (chapter 3).

Throughout the three chapters of this thesis we could to characterize, map and group fisheries and stocks, to evaluate the stocks even with limited data, and to highlight the main threats to snappers and groupers, to coral reef habitat and to the Abrolhos Bank ecosystem. Also, the main topics to be explored in order to achieve the sustainability in the fisheries are indicated. The methods used in this work represent an approach able to be applied in data-limited fisheries assessments all over the world. The results found in this thesis reveal a concerning situation regarding the exploitation status of the stocks but provide a framework with the key points to be worked on for they recovery. Beyond that, the results and the suggestions from this thesis should be strictly helpful in delineating management proposals in this complex and threatened fishery system. Finally, the urgent elaboration of management measures together the fishery communities is suggested, especially because this is a really important condition to reach success in the implementation of a fishery management in the Abrolhos Bank.

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APPENDIX

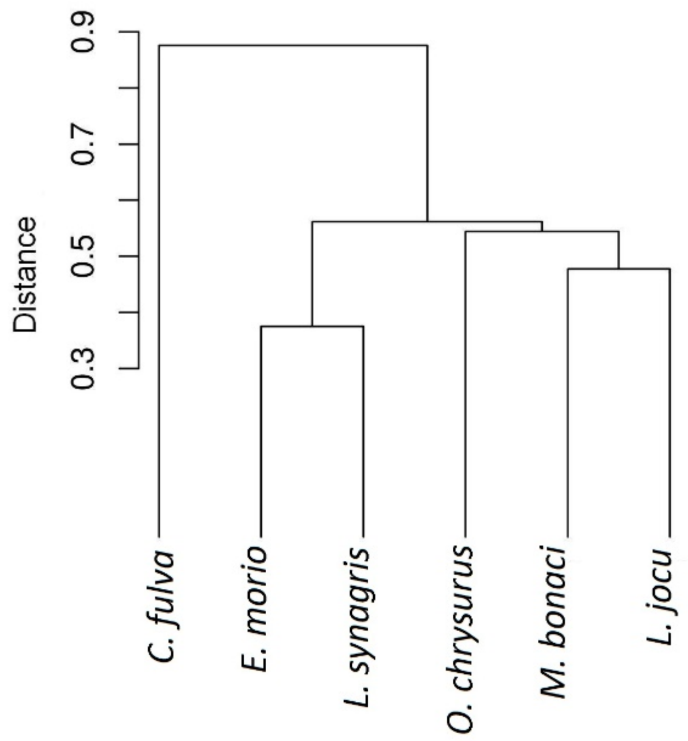


Figure A.1. Dendrogram of fish stocks according to their presence or absence in particular fishing grounds (15’ quadrants; R-mode). Most similar stocks are nearly in the cluster.

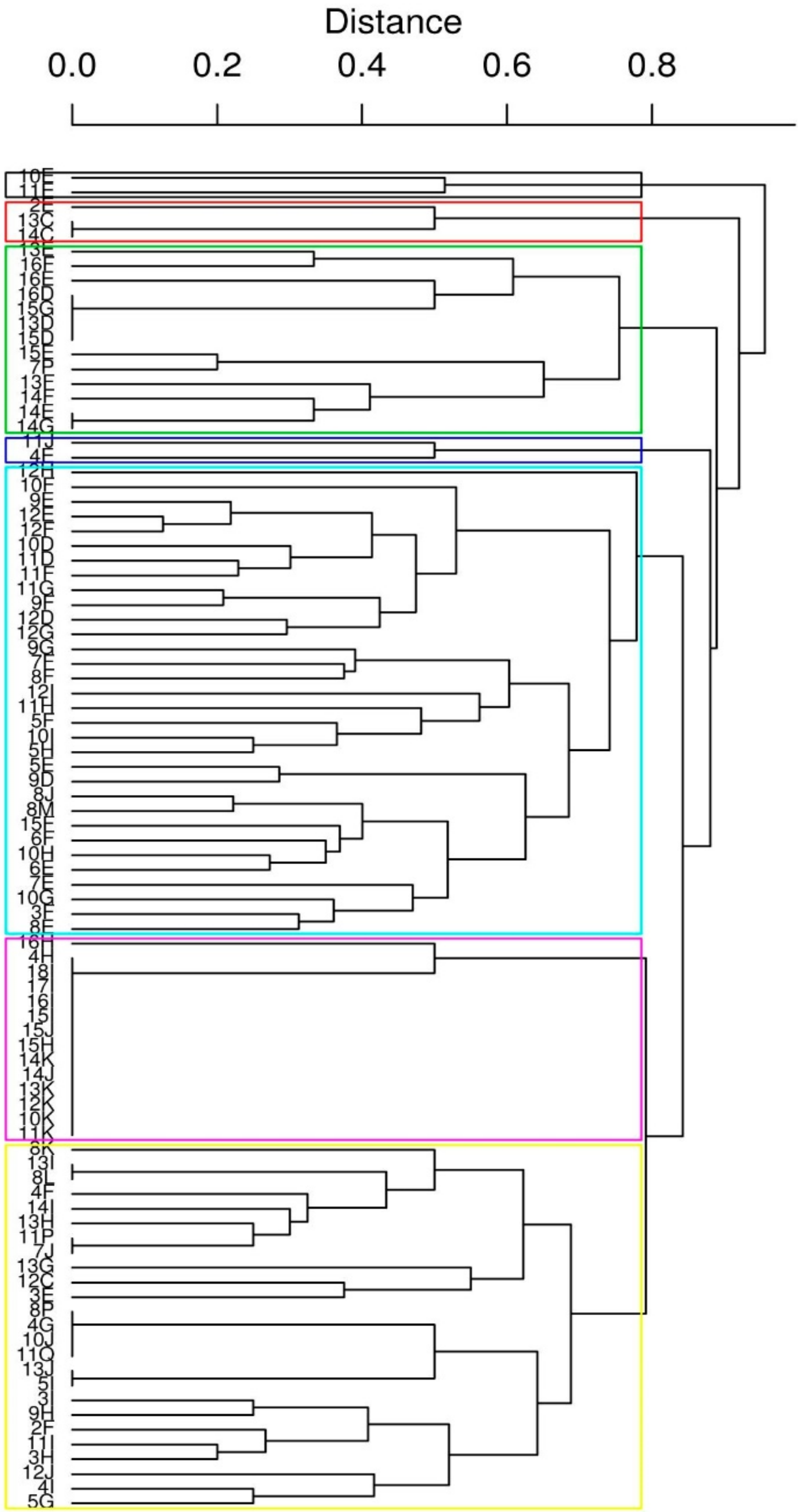
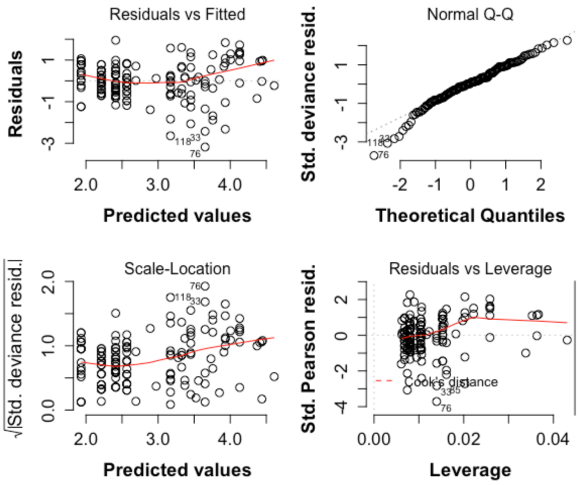
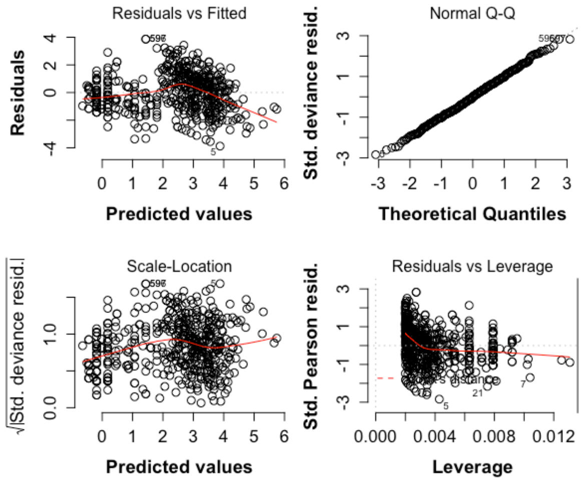


Figure A.2. Dendrogram of fishing quadrants cluster based on the occurrence of fish stocks (Q-mode). The colored frames divided the dendrogram into seven main groups of similar quadrants (the seven fishing areas) to be considered as spatial management units.

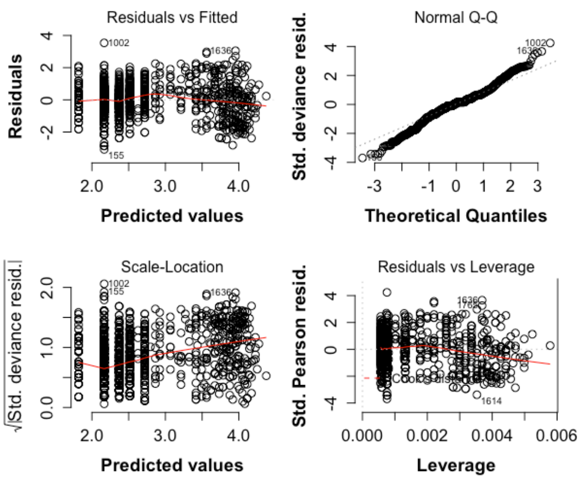
L. jocu - hand line



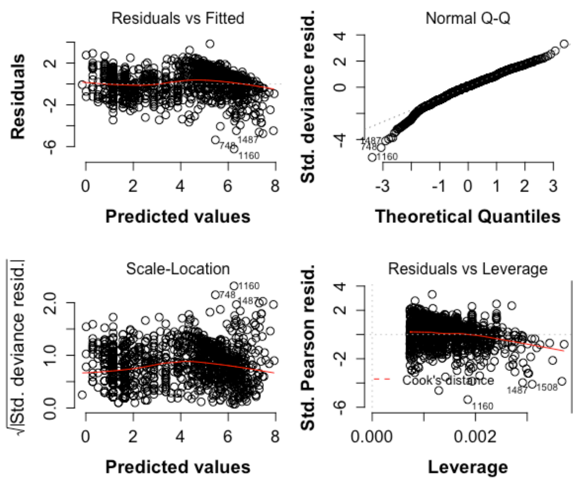
L. jocu - harpoon



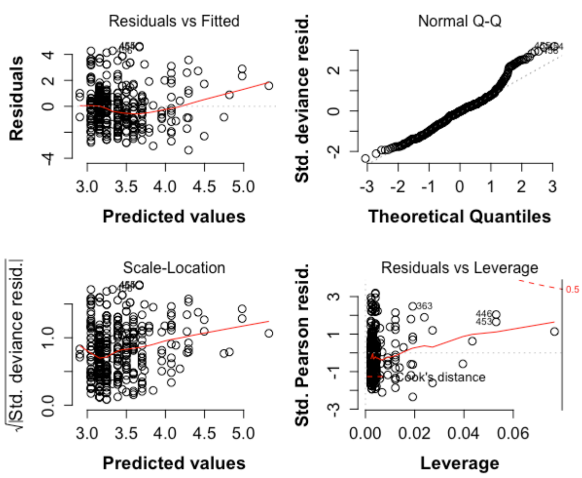
L. synagris - hand line



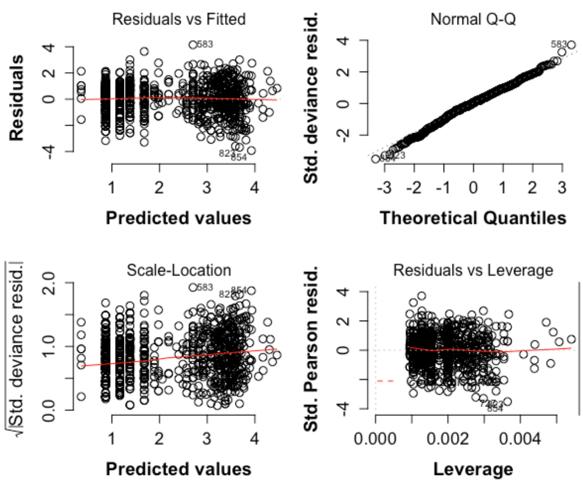
O. chrysurus- hand line



C. fulva – hand line



E. morio- hand line



M. bonaci- hand line *M. bonaci* - harpoon

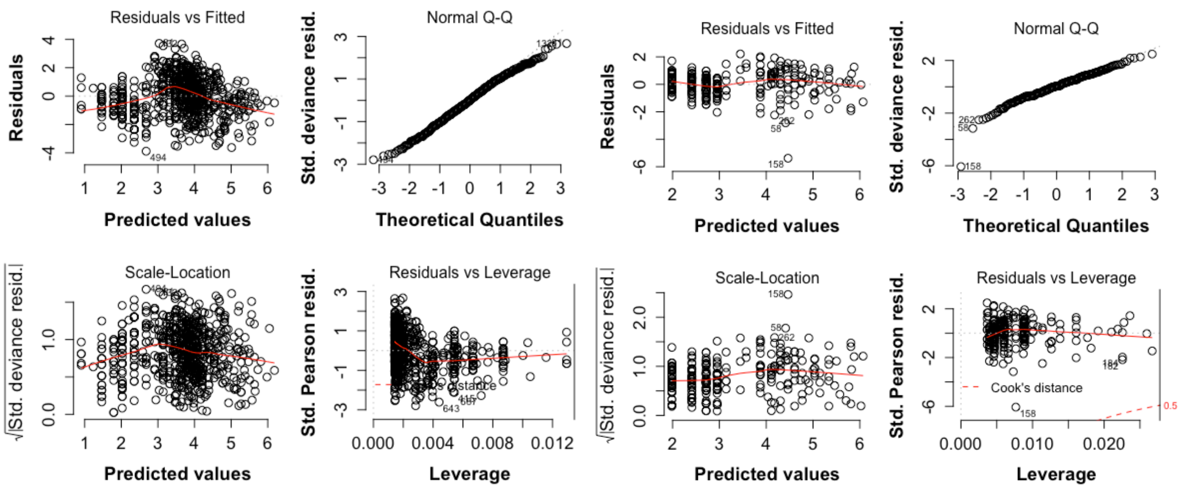


Figure A.3. Generalized linear model diagnostics to the selected effort by stock-gear analyzed. Red line represents smooth fit, in the leverage plot dashed red line represents Cook's distance.

<u>SNAPPERS</u>

1. *L. jocu*

1.1 Line

Model: m1.1<- gamlss(CPUE3 ~ Year + Port + cs(Vessel_size, df = 4), family = GG, data = esp, trace = F)

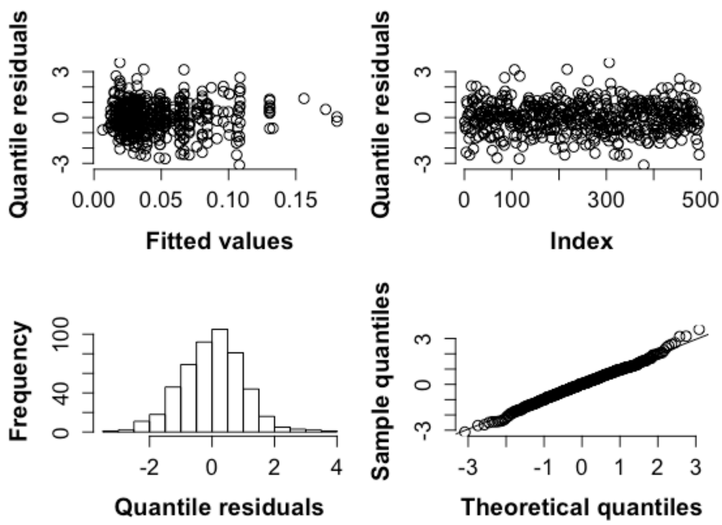


Figure A.4. Normalized residual graphs generated by the Generalized Gamma distribution to diagnose the fit quality of the CPUE and significant variables model in *Lutjanus jocu* line fishing.

Table A.1. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise*. Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>		-1783.4		
Year	**3**	**-1734.5**	**54.95**	**0.00**
Month	8	-1785.0	14.48	0.07
Area	7	-1783.4	0.00	1.00
Season	0	-1783.4	0.00	
Port	**1**	**-1758.4**	**27.07**	**0.00**
cs(Vessel_size, df = 3)	**3**	**-1777.0**	**14.39**	**0.01**

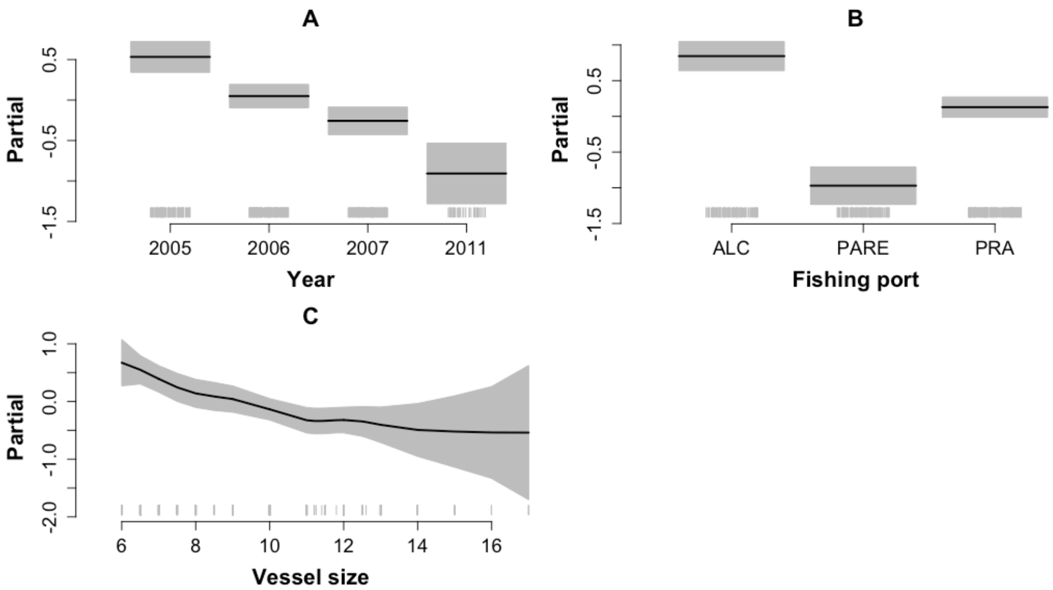


Figure A.5. Generalized additive model-derived effects of covariates used to model the *Lutjanus jocu* line CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicate 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.2. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the line CPUE standardization of the *Lutjanus jocu* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.543	0.407	-1.334	0.18
Year2006	-0.484	0.143	-3.387	0.00
Year2007	-0.790	0.154	-5.149	0.00
Year2011	-1.441	0.223	-6.462	0.00
PortPARE	-1.814	0.212	-8.566	< 2e-16
PortPRA	-0.715	0.141	-5.054	0.00
cs(Vessel_size, df = 4)	-0.141	0.034	-4.169	0.00

1.2. Harpoon

Model: m1.1<- gamlss(CPUE1 ~ Year + Month + Port, family = GB2, data = esp2, trace = F)

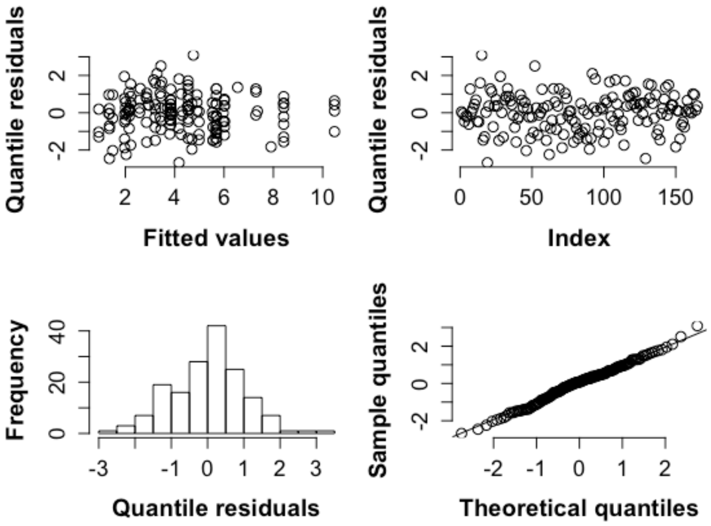


Figure A.6. Normalized residual graphs generated by the Box-Cox-t distribution to diagnose the fit quality of the CPUE and significant variables model in *Lutjanus jocu* harpoon fishing.

Table A.3. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise*. Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>		655.01		
Year	**3**	**658.04**	**9.03**	**0.03**
Month	**8**	**655.84**	**16.82**	**0.03**
Area	0	655.01	0.00	
Season	0	655.01	0.00	
Port	**2**	**675.78**	**24.77**	**0.00**
cs(Diesel.l.,df = 3	3	654.82	7.81	0.10

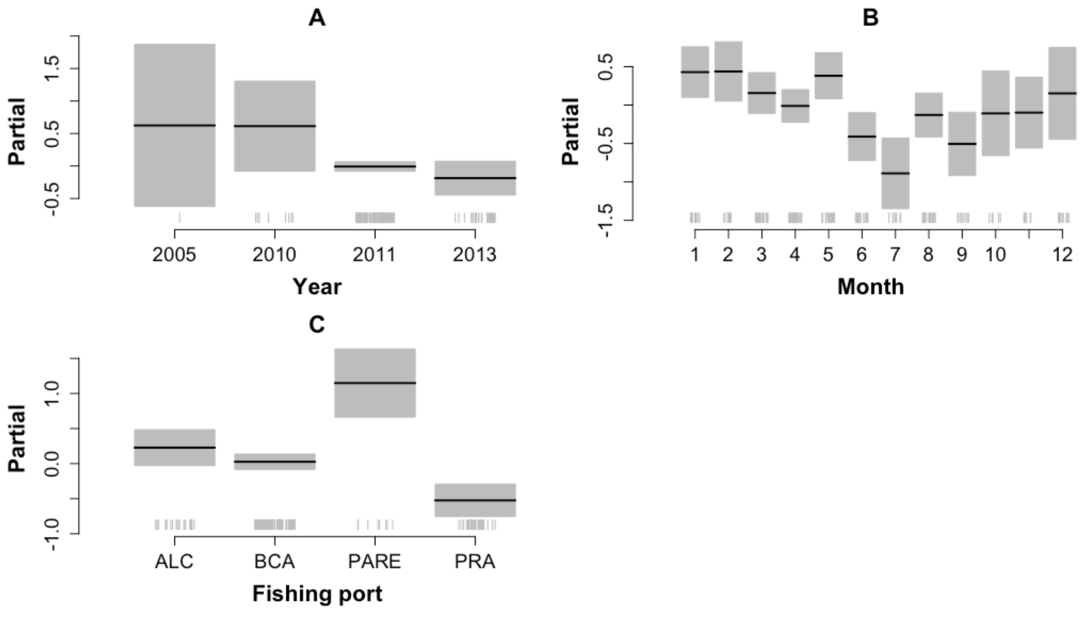


Figure A.7. Generalized additive model-derived effects of covariates used to model the *Lutjanus jocu* harpoon CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.4. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the harpoon CPUE standardization of the *Lutjanus jocu* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	2.619	0.571	4.586	0.000
Year2010	-0.011	0.670	-0.016	0.987
Year2011	-0.632	0.520	-1.215	0.227
Year2013	-0.811	0.566	-1.433	0.154
Month2	0.008	0.271	0.030	0.976
Month3	-0.272	0.251	-1.086	0.279
Month4	-0.440	0.225	-1.955	0.052
Month5	-0.047	0.302	-0.157	0.876
Month6	-0.840	0.248	-3.381	0.001
Month7	-1.318	0.307	-4.294	0.000
Month8	-0.558	0.254	-2.199	0.029
Month9	-0.934	0.287	-3.255	0.001
Month10	-0.537	0.319	-1.683	0.095
Month11	-0.527	0.291	-1.813	0.072
Month12	-0.277	0.326	-0.849	0.397
PortBCA	-0.201	0.214	-0.941	0.348
PortPARE	0.920	0.298	3.090	0.002
PortPRA	-0.751	0.181	-4.142	0.000

2. *L. synagris*

2.1. Line

Model: m1.1<- gamlss (CPUE3 ~ Year + Month + Area + Port + cs(Hour_fishing_day, df = 3), family = GB2, data = esp1, trace = F)

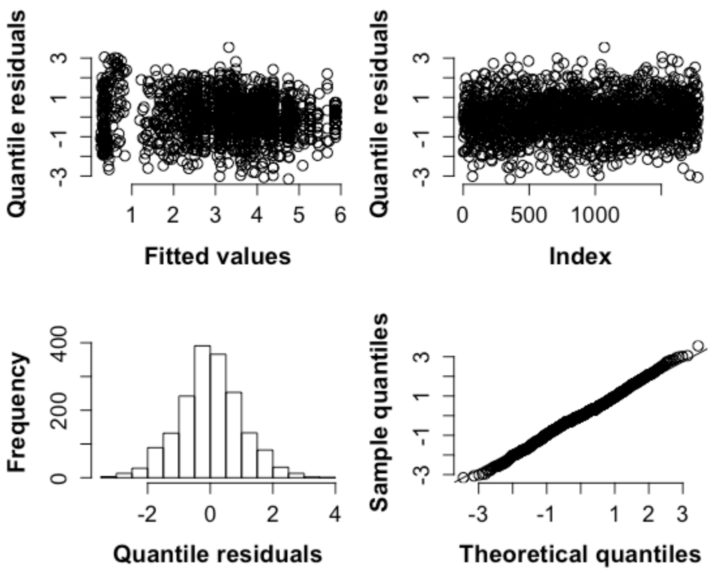


Figure A.8. Normalized residual graphs generated by the Generalized Beta type 2 distribution to diagnose the fit quality of the CPUE and significant variables model in *Lutjanus synagris* line fishing.

Table A.5. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise*. Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>		8061.4		
Year	**5**	**8138.90**	**87.45**	**< 2.2e-16**
Month	**8**	**8088.10**	**42.66**	**0.00**
Area	**0**	**8061.40**	**0.00**	
Season	0	8061.40	0.00	
Port	**4**	**8257.10**	**203.65**	**< 2.2e-16**
cs(Hour_fishing_day,df = 3)	**3**	**8068.20**	**14.80**	**0.01**

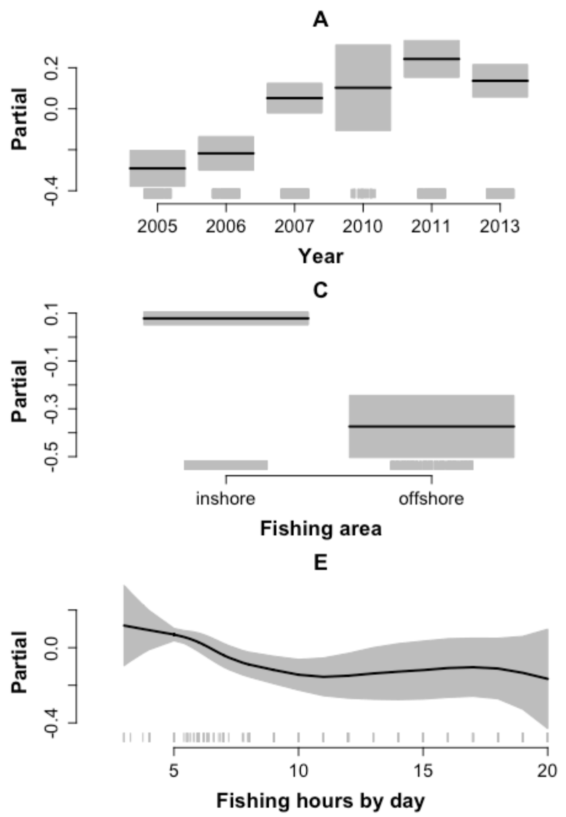


Figure A.9. Generalized additive model-derived effects of covariates used to model the *Lutjanus synagris* line CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.6. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the line CPUE standardization of the *Lutjanus synagris* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.149	0.135	8.506	0.000
Year2006	0.073	0.072	1.019	0.308
Year2007	0.343	0.068	5.009	0.000
Year2010	0.393	0.111	3.531	0.000
Year2011	0.534	0.078	6.885	0.000
Year2013	0.427	0.064	6.714	0.000
Month2	-0.050	0.101	-0.499	0.618
Month3	-0.301	0.100	-3.027	0.003
Month4	0.027	0.104	0.257	0.797
Month5	0.138	0.113	1.223	0.221
Month6	0.063	0.093	0.670	0.503
Month7	-0.133	0.094	-1.415	0.157
Month8	-0.128	0.096	-1.334	0.182
Month9	0.050	0.103	0.486	0.627
Month10	0.162	0.100	1.617	0.106
Month11	-0.067	0.124	-0.541	0.589
Month12	0.271	0.099	2.744	0.006
Areaoffshore	-0.452	0.094	-4.807	0.000
PortBCA	-0.734	0.152	-4.842	0.000
PortCOR	-0.040	0.080	-0.495	0.621
PortNVC	0.054	0.179	0.299	0.765
PortPRA	-1.523	0.110	-13.847	0.000
cs(Hour_fishing_day,df=3)	-0.020	0.007	-2.864	0.004

3. *O. chrysurus*

3.1. Line

Model: gamlss(CPUE3 ~ Year + Month + Area + Port + cs(Vessel_size, df = 3), family = GB2, data = esp, trace = F)

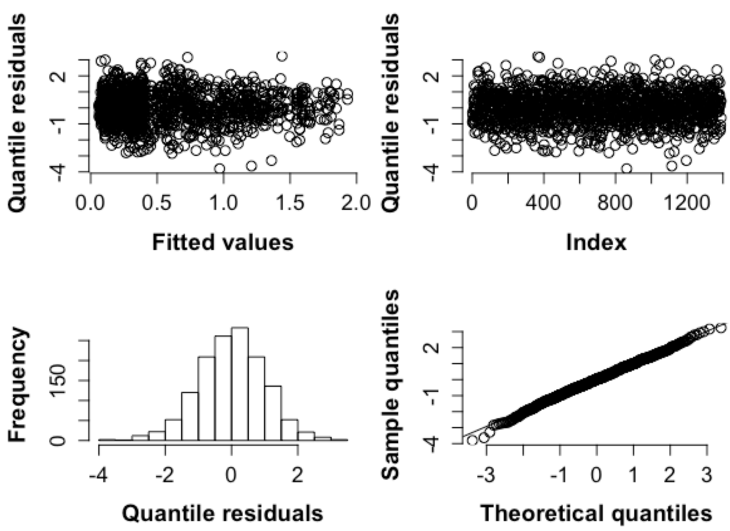


Figure A.10. Normalized residual graphs generated by the Generalized Beta type 2 distribution to diagnose the fit quality of the CPUE and significant variables model in *Ocyurus chrysurus* line fishing.

Table A.7. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise.* Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>		-189.49		
Year	**4**	**-24.84**	**172.65**	**< 2.2e-16**
Month	**8**	**-178.74**	**26.75**	**0.00**
Area	**0**	**-189.49**	**0.00**	
Season	0	-189.49	0.00	
Port	**4**	**-73.47**	**124.02**	**< 2.2e-16**
cs(Vessel_size, df=3)	**3**	**-172.05**	**25.44**	**0.00**

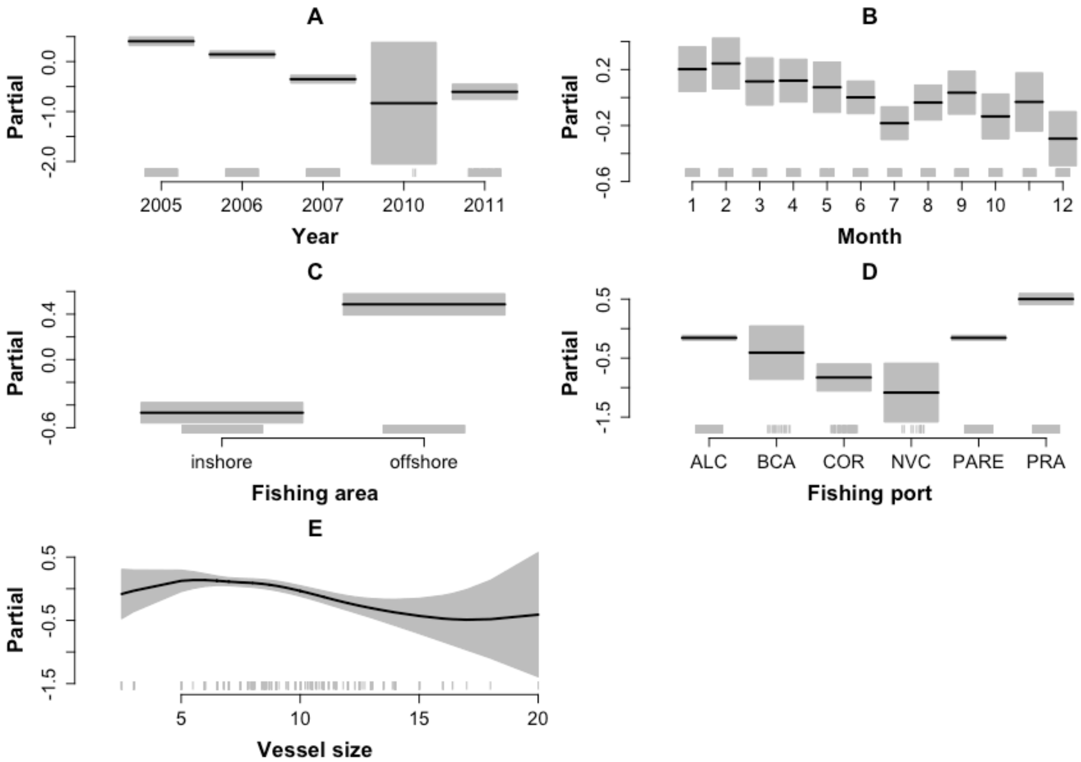


Figure A.11. Generalized additive model-derived effects of covariates used to model the *Ocyurus chrysurus* line CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.8. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the line CPUE standardization of the *Ocyurus chrysurus* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.380	0.173	-2.192	0.029
Year2006	-0.263	0.067	-3.940	0.000
Year2007	-0.759	0.070	-10.816	< 2e-16
Year2010	-1.240	0.493	-2.513	0.012
Year2011	-1.013	0.100	-10.077	< 2e-16
Month2	0.040	0.123	0.329	0.742
Month3	-0.088	0.121	-0.724	0.469
Month4	-0.082	0.115	-0.714	0.476
Month5	-0.129	0.124	-1.043	0.297
Month6	-0.202	0.109	-1.857	0.064
Month7	-0.386	0.108	-3.572	0.000
Month8	-0.239	0.114	-2.099	0.036
Month9	-0.168	0.120	-1.402	0.161
Month10	-0.338	0.122	-2.758	0.006
Month11	-0.234	0.139	-1.686	0.092
Month12	-0.497	0.133	-3.743	0.000
Areaoffshore	0.955	0.095	10.051	< 2e-16
PortBCA	-0.251	0.246	-1.019	0.308
PortCOR	-0.672	0.117	-5.732	0.000
PortNVC	-0.928	0.251	-3.702	0.000
PortPRA	0.658	0.072	9.162	< 2e-16
cs(Vessel_size, df = 3)	-0.057	0.016	-3.542	0.000

GROUPERS

4. C. fulva

4.1. Line

Model: gamlss(CPUE1 ~ Year + Month + Port + cs(Vessel_size, df = 3), family = GB2, data = esp1, trace = F)

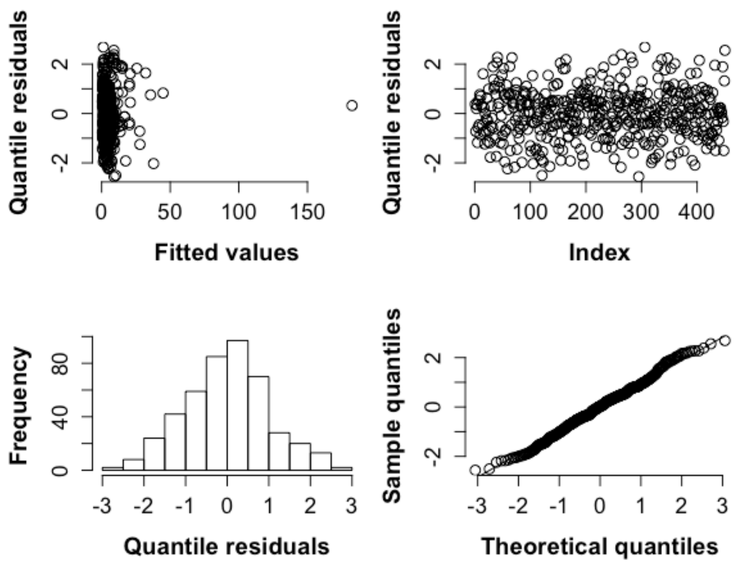


Figure A.12. Normalized residual graphs generated by the Generalized Gamma distribution to diagnose the fit quality of the CPUE and significant variables model in *Cephalopholis fulva* line fishing.

Table A.9. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise*. Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>		2711.60		
Year	**3**	**2788.00**	**82.40**	**< 2.2e-16**
Month	**8**	**2710.70**	**15.10**	**0.06**
Season	0	2711.60	0.00	
Port	**1**	**2733.80**	**24.21**	**0.00**
cs(Vessel_size,df=3)	**3**	**2722.10**	**18.46**	**0.00**

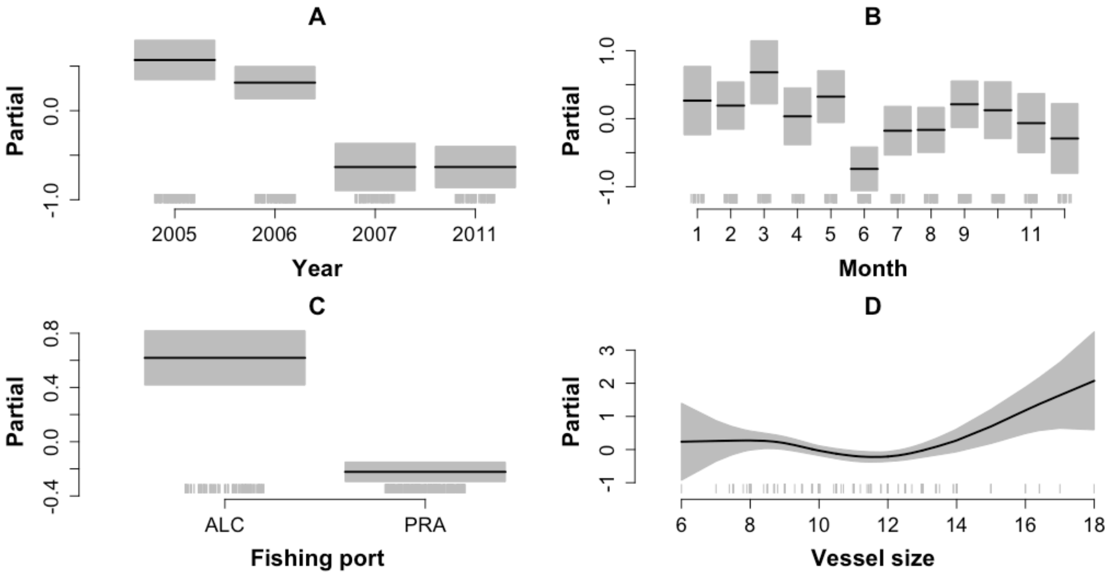


Figure A.13. Generalized additive model-derived effects of covariates used to model the *Cephalopholis fulva* line CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.10. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the line CPUE standardization of the *Cephalopholis fulva* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.854	0.564	3.287	0.001
Year2006	-0.166	0.173	-0.956	0.340
Year2007	-1.248	0.201	-6.203	0.000
Year2011	-1.336	0.178	-7.526	0.000
Month2	0.145	0.304	0.477	0.634
Month3	0.467	0.320	1.458	0.145
Month4	-0.186	0.317	-0.588	0.557
Month5	0.037	0.313	0.117	0.907
Month6	-0.983	0.308	-3.190	0.002
Month7	-0.460	0.307	-1.495	0.136
Month8	-0.530	0.304	-1.742	0.082
Month9	-0.025	0.314	-0.078	0.938
Month10	-0.175	0.335	-0.524	0.601
Month11	-0.358	0.352	-1.017	0.310
Month12	-0.488	0.370	-1.319	0.188
PortPRA	-0.759	0.158	-4.806	0.000
cs(Vessel_size, df = 3)	0.071	0.033	2.132	0.034

5. E. morio

5.1. Line

Model: gamlss(CPUE4 ~ Year +Port, family = GG, data = esp3, trace = F)

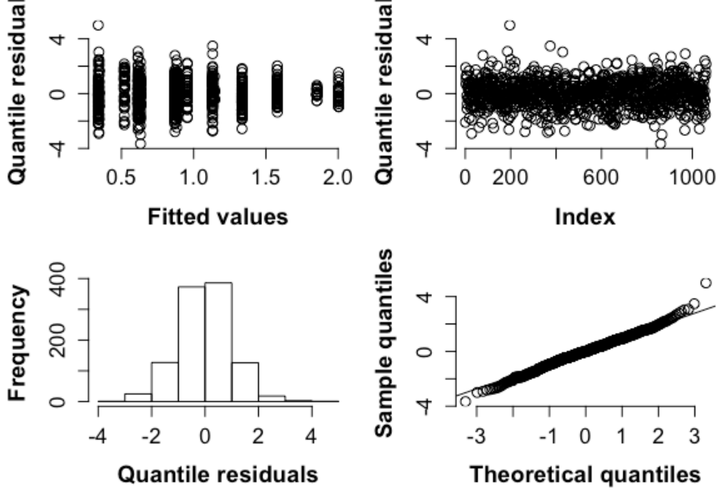


Figure A.14. Normalized residual graphs generated by the Generalized Gamma distribution to diagnose the fit quality of the CPUE and significant variables model in *Epinephelis morio* line fishing.

Table A.11. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise* Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>		2696.20		
Year	5	2741.00	54.75	0.00
Month	8	2696.80	16.56	0.04
Season	1	2694.40	0.15	0.70
Area	0	2696.20	0.00	
Port	**3**	**2715.30**	**25.06**	**0.00**
Lines number	13	2685.20	14.96	0.31

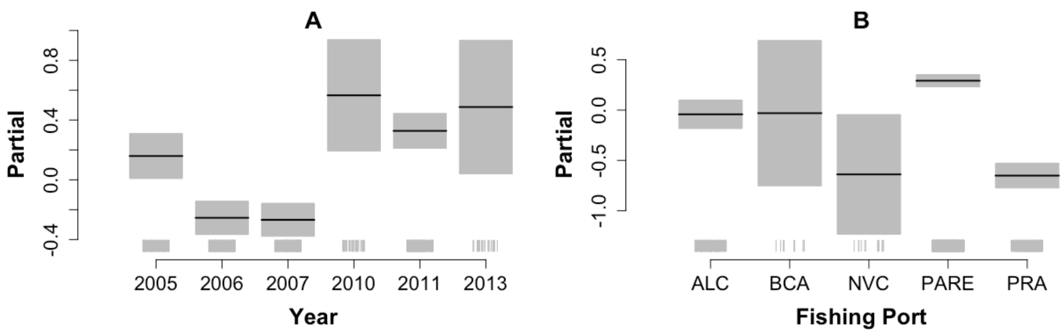


Figure A.15. Generalized additive model-derived effects of covariates used to model the *Epinephelus morio* line CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.12. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the line CPUE standardization of the *Epinephelus morio* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.045	0.114	-0.396	0.692
Year2006	-0.414	0.105	-3.952	0.000
Year2007	-0.427	0.105	-4.064	0.000
Year2010	0.406	0.208	1.955	0.051
Year2011	0.168	0.106	1.590	0.112
Year2013	0.328	0.243	1.352	0.177
PortBCA	0.011	0.371	0.031	0.976
PortNVC	-0.597	0.309	-1.933	0.054
PortPARE	0.334	0.093	3.594	0.000
PortPRA	-0.609	0.104	-5.856	0.000

6. *M. bonaci*

6.1. Line

Model: gamlss(CPUE2 ~ Year + Month + Area + cs(Vesselsiz, df = 3) + cs(Hour_fishingd, df = 3), family = GIG, data = esp1, trace = F)

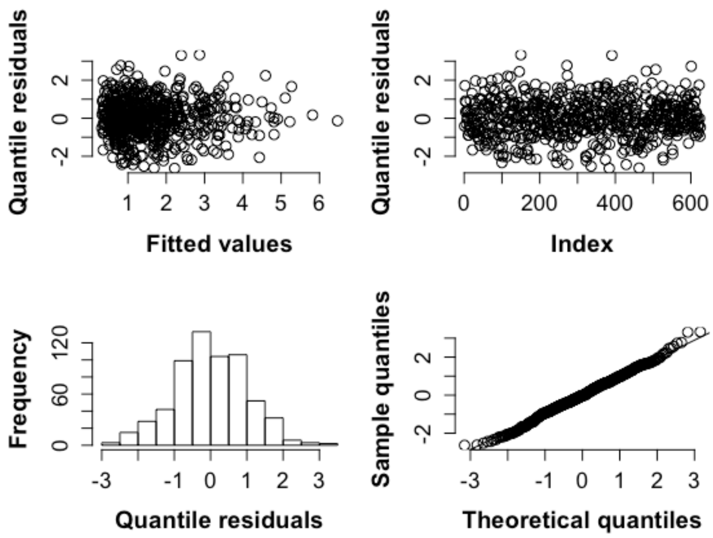


Figure A.16. Normalized residual graphs generated by the Generalized Inverse Gaussian distribution to diagnose the fit quality of the CPUE and significant variables model in *Mycteroperca bonaci* line fishing.

Table A.13. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise*. Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>	99	2273.00	0.10	
Year	**3**	**2297.50**	**30.39**	**0.00**
Month	**8**	**2268.40**	**11.31**	**0.18**
Area	**1**	**2284.60**	**13.43**	**0.00**
Season	0	2273.10	0.00	
Port	5	2272.10	8.97	0.11
cs(Vesselsiz, df=3)	**4**	**2278.10**	**12.99**	**0.01**
Linesnumber	6	2268.10	6.94	0.33
cs(Hour_fishingday,df=3)	**3**	**2283.40**	**18.26**	**0.00**

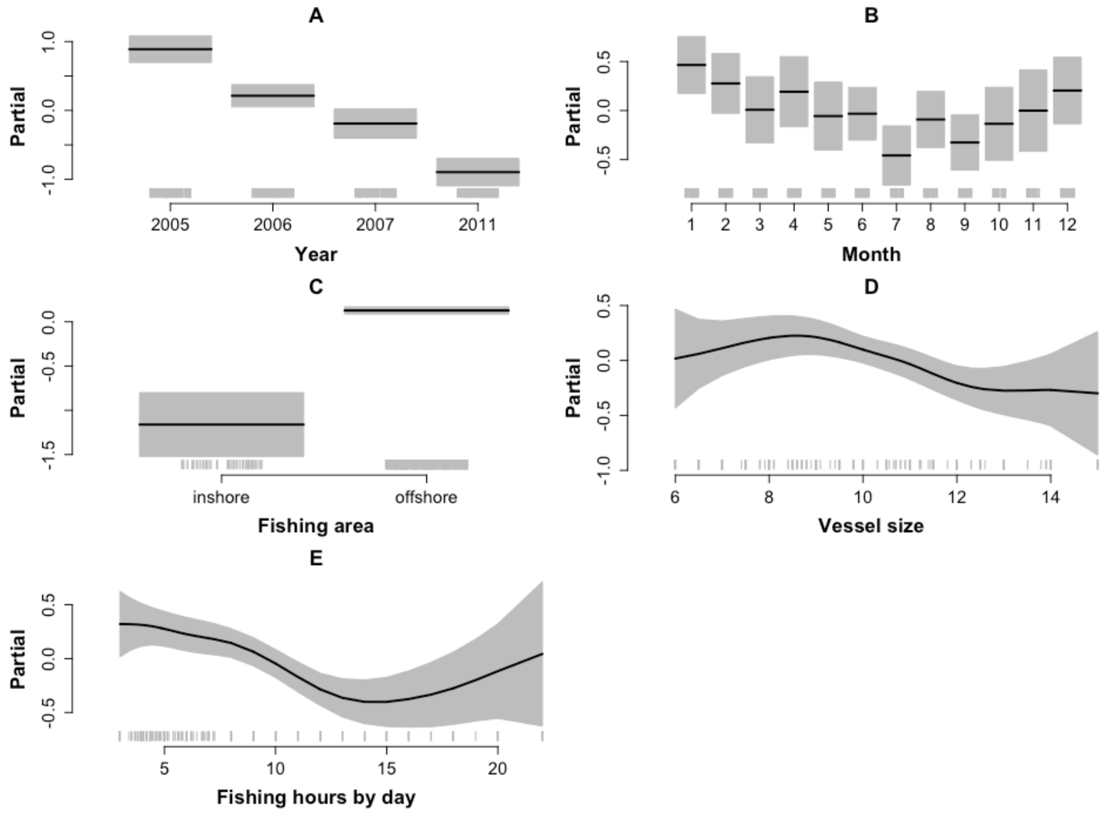


Figure A.17. Generalized additive model-derived effects of covariates used to model the *Mycteroperca bonaci* line CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.14. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the line CPUE standardization of the *Mycteroperca bonaci* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.723	0.354	4.874	0.000
Year2006	-0.677	0.146	-4.638	0.000
Year2007	-1.081	0.171	-6.319	0.000
Year2011	-1.786	0.168	-10.610	< 2e-16
Month2	-0.188	0.213	-0.881	0.379
Month3	-0.457	0.221	-2.069	0.039
Month4	-0.273	0.237	-1.153	0.249
Month5	-0.521	0.232	-2.251	0.025
Month6	-0.497	0.214	-2.320	0.021
Month7	-0.923	0.223	-4.143	0.000
Month8	-0.556	0.224	-2.482	0.013
Month9	-0.791	0.226	-3.503	0.000
Month10	-0.600	0.263	-2.278	0.023
Month11	-0.465	0.268	-1.737	0.083
Month12	-0.260	0.234	-1.113	0.266
Areaoffshore	1.289	0.218	5.901	0.000
cs(Vesselsiz, df = 3)	-0.072	0.031	-2.311	0.021
cs(Hour_fishingd, df = 3)	-0.052	0.014	-3.660	0.000

6.2. Harpoon

Model: gamlss(CPUE1 ~ Year + Month + Port + cs(Hour_fishing_day,df = 3), family = GA, data = esp1, trace = F)

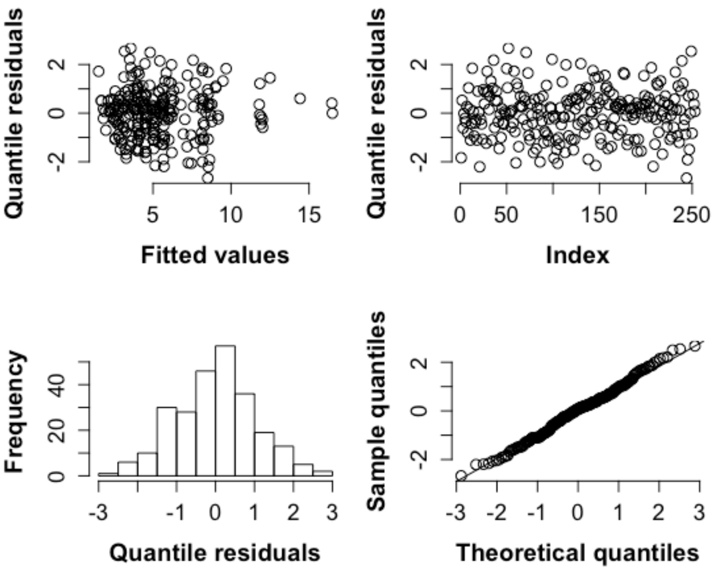


Figure A.18. Normalized residual graphs generated by the Gamma distribution to diagnose the fit quality of the CPUE and significant variables model in *Mycteroperca bonaci* harpoon fishing.

Table A.15. Explanatory variables used in GAM model. In bold the variables selected to the model by the method *stepwise*. Df- degree of freedom, AIC – Akaike Information Criterion, LRT – Likelihood Ratio Test, and Pr(Chi), p value.

	Df	AIC	LRT	Pr(Chi)
<none>	99	1168.00	0.20	
Year	**4**	**1168.50**	**8.36**	**0.08**
Month	**8**	**1164.70**	**12.51**	**0.13**
Area	1	1167.50	1.37	0.24
Season	0	1168.20	0.00	
Port	**3**	**1173.80**	**11.68**	**0.01**
cs(Hour_fishing_day, df=3)	**3**	**1204.80**	**44.62**	**0.00**
cs(Diesel.l., df=3)	3	1161.80	1.60	0.81

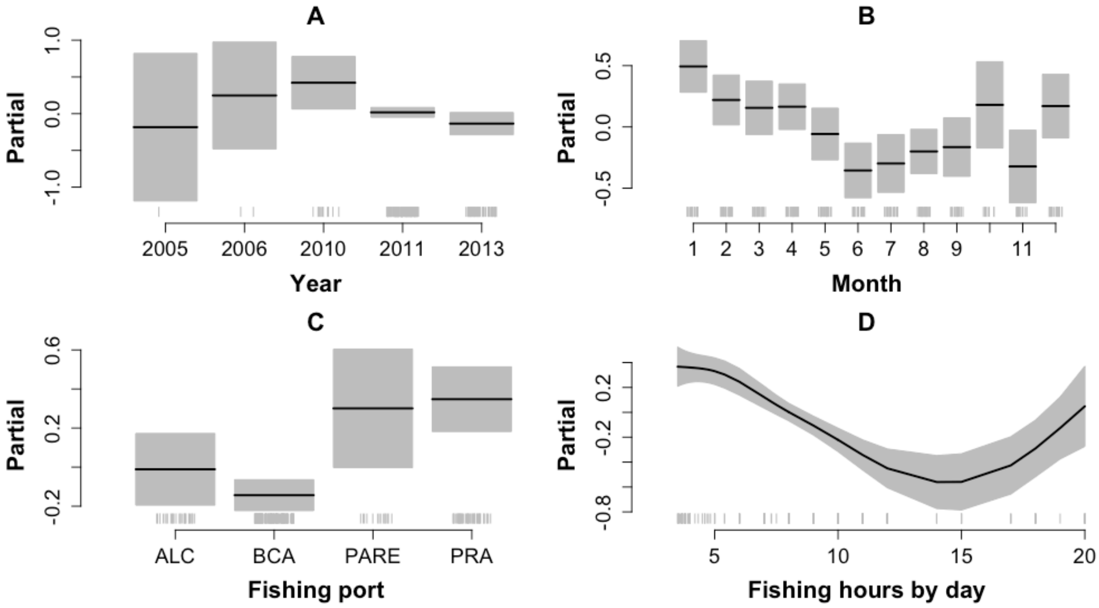


Figure A.19. Generalized additive model-derived effects of covariates used to model the *Mycteroperca bonaci* harpoon CPUE on Abrolhos Bank in the period 2005–2011. In the plots, the partial residual of model terms, the solid line is the estimate of the smooth function, the grey area indicates 95% confidence intervals, and the bars on the x-axis show the relative density of data points.

Table A.16. Estimation of coefficients, standard error, t value and p value for the estimated t test with GAM for the harpoon CPUE standardization of the *Mycteroperca bonaci* in the Abrolhos Bank.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	2.328	0.527	4.416	0.000
Year2006	0.432	0.614	0.702	0.483
Year2010	0.605	0.545	1.110	0.268
Year2011	0.201	0.503	0.400	0.689
Year2013	0.049	0.515	0.094	0.925
Month2	-0.274	0.151	-1.807	0.072
Month3	-0.338	0.158	-2.137	0.034
Month4	-0.329	0.145	-2.262	0.025
Month5	-0.551	0.152	-3.616	0.000
Month6	-0.849	0.158	-5.360	0.000
Month7	-0.792	0.163	-4.864	0.000
Month8	-0.694	0.148	-4.697	0.000
Month9	-0.658	0.164	-4.006	0.000
Month10	-0.313	0.208	-1.508	0.133
Month11	-0.816	0.187	-4.372	0.000
Month12	-0.323	0.179	-1.809	0.072
PortBCA	-0.133	0.116	-1.140	0.255
PortPARE	0.312	0.174	1.790	0.075
PortPRA	0.359	0.117	3.079	0.002
cs(Hour_fishing_day, df = 3)	-0.053	0.009	-6.013	0.000

Table A.17. Productivity and susceptibility values used to score the PSA by stock.

	Productivity							Susceptibility						
Stock	Average age at maturity	Average max age (years)	Fecundity	Average max size (cm)	Average size at Maturity	Reproductive strategy	Trophic level (fishbase)	Availability (%)	Encounterability	Selectivity	Post-capture mortality	Fishery intensity	Risk Category Name	References
L. jocu	5	29	NA	96	43	Demersal egg layer	4.4	75	4	2	2.2		Medium	Freitas et al., 2011; Previero et al., 2011
L. synagris	3	18	100,000 to 700,000	68	23	Demersal egg layer	3.8	67	3	3	1.7		Low	Freitas et al., 2014; Aschenbrenner et al.2017
O. chrysurus	5	19	14,102 to 164,756	76	31	Demersal egg layer	3.6	72	4	3	1.6		Low	Araujo et al., 2002; Freitas et al., 2011; Trejo-Martınez et al., 2011
C. fulva	2	25	150,000 to 282,000	46	16	Demersal egg layer	4.1	65	3	3	1.4		Low	Araujo e Martins, 2006; IUCN, 2008; Freitas et al., 2011
E. morio	11	30	24,300 to 2,322,517	99	47	Demersal egg layer	3.6	79	4	2	2.1		Medium	Collins et al., 2002; Freitas, 2014; Freitas et al., 2017
M. bonaci	8	34	500,000	160	62	Demersal egg layer	4.5	78	4	2	2.1		High	Freitas, 2014; Freitas et al., 2017; Froese and Pauly, 2017
X. kroyeri	0.4	1.2	NA	3.8	1.2	NA	1	12				Widespread and frequent	Low	Guimaraes, 2009
H. plumierii	2	18	34,000 to 1,000,000	53	22	Demersal egg layer	3.7	77				Occurs at broad spatial scale	Medium	Froese and Pauly, 2017 Hoffman et al 2017
C. pannatula	4	10	30,000 to 1,500,000	37	22	Demersal egg layer	3.7	90				Occurs at broad spatial scale	Medium	Froese and Pauly, 2017
K. pelamis	1.5	10	255,000 to 1,300,000	108	45	Demersal egg layer	4.5	30				Rare in few locations	Low	Vilela and Castello, 1993; Froese and Pauly, 2017

Encounterability punctuation (0 to 5: 0-1.5=low; 1.6-3.5= medium; 3.6-5= high)

Selectivity punctuation (0 to 5: 0-1.5=low; 1.6-3.5= medium; 3.6-5= high)

Post-capture mortality punctuation (1 to 3: 1-1.5=low; 1.6-2.1= medium; 2.2-3= high)

Table A.18. Scale intensity consequence analysis table with the absolute values used to score the fishery risks over the stocks.

Performance Indicator Target and by-catch stocks	Risk activity	Spatial scale of activity (%)	Temporal scale (number of fishing days per year)	Intensity of activity	Relevant subcomponent	Risk score
L. jocu	Direct capture	75	192	Major	Population size	3
L. synagris	Direct capture	67	186	Severe	Population size	3
O. chrysurus	Direct capture	72	186	Severe	Age/size structure	3
C. fulva	Direct capture	65	204	Moderate	Population size	2
E. morio	Direct capture	78	192	Major	Population size	3
M. bonaci	Direct capture	78	204	Major	Population size	3
X. kroyeri	Direct capture	12	156	Catastrophic	Population size	1
H. plumieri	Direct capture	77	202.8	Major	Population size	2
C. pannatula	Direct capture	90	226.5	Major	Population size	2
K. pelamis	Direct capture	30	240	Minor	Population size	1

**The final risk score to by-catch was regarding the by-catch or bait fishery*

Table A.19. Scale intensity consequence analysis table with the reference values used to score the risk activities over the habitat.

Habitat	Risk-causing activity	Spatial scale of activity (%)	Time necessary to recovery	Intensity of activity	Relevant subcomponent	Risk score
Tropical coral reef	Mining waste	20	Decades	Catastrophic	Habitat quality	3
	Dredging	10	Years	Major	Habitat structure and function	3
	Hand line fishery	54	Years	Major	Habitat structure and function	2
	Harpoon fishery	30	Years	Minor	Habitat structure and function	2

Table A.20. Scale intensity consequence analysis table with reference values used to score the risk activities over the ecosystem.

Ecosystem	Risk-causing activity	Spatial scale of activity (%)	Time necessary to recovery	Intensity of activity	Relevant subcomponent	Risk score
Abrolhos Bank	Mining waste	20	Decades	Catastrophic	Ecosystem structure and function	3
	Dredging	10	Years	Severe	Ecosystem structure and function	3
	Hand line fishery	55	Years	Moderate	Ecosystem structure and function	2
	Harpoon fishery	44	Years	Moderate	Ecosystem structure and function	2

Table A.21. Scale intensity consequence analysis table with reference values used to score governance attributes over the Abrolhos Bank fisheries, following stakeholder answers.

Fishery management and governance policy	Answer	Punctuation
Decision-making on management measures	good/ reasonable/ bad or missing	1/2/3
Monitoring and review of management measures	good/ reasonable/ bad or missing	1/2/3
The management measures are appropriate	good/ reasonable/ bad or missing	1/2/3
Compliance and enforcement of management measures	good/ reasonable/ bad or missing	1/2/3
There are local laws guaranteeing the fishers rights	yes/ no	1/3
There are laws and people trained for law enforcement	good/ reasonable/ bad or missing	1/2/3
There are fishing incentives	good/ reasonable/ bad or missing	1/2/3
There are available information on habitats monitoring	good/ reasonable/ bad or missing	1/2/3
Effective fisheries management within MPAs	good/ reasonable/ bad or missing	1/2/3
Effective MPAs management	good/ reasonable/ bad or missing	1/2/3
Fishers participation in fisheries management	good/ reasonable/ bad or missing	1/2/3
There are researches needed to propose management	good/ reasonable/ bad or missing	1/2/3
There are long-term goals	good/ reasonable/ bad or missing	1/2/3

Table A.22. Summary of the indicators used to score economic aspects of snapper and grouper fisheries, the specific questions used to score each indicator, and the scores corresponding to fisher answers.

Indicator	Indicator details	Answer	Punctuation
Fisher's negotiation power	Fishers control the fish selling price	yes/ sometimes/no	1/2/3
	Fishers choose whom to sell	yes/ sometimes/no	1/2/3
	Fishers can store the fish	yes/ sometimes/no	1/2/3
	Fishers have their own vessel	yes/no	1/3
	Fishers usually sell the fish in another municipality and obtain a better price	yes/ sometimes/no	1/2/3
Market chain	Number of links	1 or 2/ 3 or 4/ 5 or more	1/2/3
Value chain	The percentage that fishers receive in relation to the final value.	60% or more/ 30%-59% / less than 30%	1/2/3
	There is price speculation	yes/ sometimes/no	1/2/3
Traceability	The easiness in trace a market chain; with whom the fishers trade	trade with final consumer	1
		trade withfish markets in the region	2
		trade with middlemen from other states or different buyers	3

Complementary references from appendix

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