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Review

A review of the dog snapper (*Lutjanus jocu*) along the Brazilian Province: Distributional records, ecology, fisheries and conservation

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ABSTRACT

The dog snapper, *Lutjanus jocu*, is a commercially exploited fish throughout the Brazilian Province (BP) and has been facing overexploitation. However, there are no systematized data on the species to date, which hinders management strategies for mitigating this scenario. In this review, we gathered the existing literature information on *L. jocu* along the BP, focusing on distributional records, ecology, fisheries and conservation. A total of 253 records were attained in 212 studies, with the highest number found on the northeastern Brazilian coast. The species occurred in a multitude of habitats, such as estuaries, tidepools and reef systems, and was caught by a variety of fishing gear. We evidenced that ecological and fishery information on *L. jocu* is geographically biased in the BP, being prevalent on the northeastern coast and scarce or even absent in all other regions. To guide a *L. jocu* fisheries management in the BP, we propose a low-cost framework containing three major initiatives: i) participatory mapping of fishing and aggregation grounds, ii) slot size limit regulation backed by eco-labeling, and iii) citizen science-based monitoring. Efforts to establish dog snapper fisheries management and monitoring should be urgently implemented to avoid the collapse of the stock in the BP.

1. Introduction

Snappers (Lutjanidae, Perciformes) are large-bodied mesopredator reef fishes widely distributed across the globe. Most species inhabit broad depth ranges in a variety of habitats, such as mangroves, estuaries, hard bottoms, coral reefs and rocky outcrops (Allen, 1985). These fishes have distinct sexes throughout life (gonochoristic), r-strategist reproductive modes and a long pelagic larval phase (25–45 days) (Carter and Perrine, 1994). Although many snappers are historically targeted by artisanal, recreational and industrial fleets, the current status of their fisheries is unknown (Amorim et al., 2019). Moreover, life-history traits such as high longevity, slow-growth, late maturation and spawning aggregation behavior (Claro and Lindeman, 2003), make snappers particularly vulnerable to overfishing.

Lutjanidae is a relatively speciose family (>100 species), with the greatest richness found in the Indo-Pacific, followed by the Neotropics (Allen, 1985). Genetic-based studies have supported the hypothesis that Neotropical lutjanines (subfamily Lutjaninae) are derived from an Indo-Pacific lineage that diversified in the early Miocene (Gold et al., 2011, 2015). After the closure of the Isthmus of Panama, two groups of species were allopatrically isolated: eastern Pacific and western Atlantic. Currently, 13 lutjanine species occur in the western Atlantic, two of which comprise monotypic genera (*Ocyurus chrysurus* and *Rhomboplites aurorubens*) and 11 belong to the genus *Lutjanus* (Gold et al., 2011, 2015).

Eight species of the genus *Lutjanus* occur along the Brazilian Province (BP): dog snapper (*Lutjanus jocu* Bloch and Schneider, 1801), Brazilian snapper (*L. alexandrei* Moura and Lindeman, 2007), mutton snapper (*L. analis* Cuvier, 1828), blackfin snapper (*L. buccanella* Cuvier, 1828), cubera snapper (*L. cyanopterus* Cuvier, 1828), southern red snapper

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(*L. purpureus* Poey, 1876), lane snapper (*L. synagris* Linnaeus, 1758) and silk snapper (*L. vivanus* Cuvier, 1828) (Pinheiro et al., 2018). The dog snapper, which is the focus of this review, is a carnivorous reef fish widespread throughout the tropical Atlantic Ocean, occurring from the state of Massachusetts (USA) to southern Brazil (Menezes et al., 2003), with records for the Ascension and St. Helena islands (Wirtz et al., 2017; Brown et al., 2019) and Mediterranean Sea (Vacchi et al., 2010). This species is easily identifiable by morphological traits, such as a narrow bluish line close to the eye and vertical white bars along the body in juveniles as well as large canine teeth and a triangular whitish band below the eye in adults (Allen, 1985). Regarding conservation status, *L. jocu* is currently classified as 'Data Deficient' on the IUCN Red List of Threatened Species and 'Near Threatened' on the Brazilian Red List (ICMBio, 2018).

The dog snapper is a commercially exploited species throughout the BP, especially in the northeastern region (Rezende et al., 2003). Its fishery has intensified since the 1980s (Paiva, 1997; Rezende et al., 2003) and it has recently been regarded as exploited to the potential maximum level (Vasconcellos et al., 2007) or even overexploited (Frédou et al., 2009a). This scenario results mainly from a lack of the suitable fisheries management backed by long-term landing statistics, which has led to a fast population decline. Over the last decade, increasing research efforts have accumulated data on ecological, fisheries and population aspects of *L. jocu* along the BP (e.g. Freitas et al., 2011; Moura et al., 2011; Previero et al., 2011; França and Olavo, 2015; Previero and Gasalla, 2018, 2019; Souza et al., 2019; Menezes et al., 2021). However, most available information is not systematized and there is a need to identify gaps in research and management strategies to mitigate the current trend of overexploitation. As the BP covers roughly half of the distribution extension of *L. jocu* (southern portion), gathering data along this range is imperative for future transboundary management policies directed at the species.

In this paper, we review existing information in the literature on *L. jocu* along the Brazilian Province, with an emphasis on distributional records, ecology, fisheries and conservation aspects. We pinpoint gaps in knowledge and major threats to the dog snapper in the BP and propose a low-cost fisheries management framework with three major initiatives: i) participatory mapping of fishing and aggregation grounds, ii) slot size limit regulation backed by eco-labeling, and iii) citizen science-based monitoring.

2. Material and methods

The Brazilian Province extends from the mouth of the Amazon River (4°N) to the state of Santa Catarina (29°S) and includes four oceanic islands (Floeter et al., 2008). We used this concept solely based on its geographic coverage to assign records of *L. jocu* without any biogeographic scope.

Extensive surveys were performed up to December 2020 using Boolean terms in the Google Scholar, Web of Science and Scielo databases. Multiple combinations were created involving the species name, geographic range and topic to find the largest possible number of bibliographic references (Fig. 1). These terms were used in both English and Portuguese and verified in the title, keywords and abstract of the studies surveyed. Books and digitally unavailable papers (older documents) were also accessed at the library of the Ichthyology Laboratory of Universidade Federal da Paraíba. Peer-reviewed studies, technical reports and theses/dissertations with specific localities were considered for species records, but not those with only general distribution data (e.g. 'ranging from the Caribbean to Brazil'). Moreover, inventory studies based on secondary data were not included to avoid duplicate records.

For each record of *L. jocu*, the respective occurrence was classified according to the coastal states of Brazil: Amapá, Pará, Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia, Espírito Santo, Rio de Janeiro, São Paulo, Paraná and Santa Catarina. When the sampling of a given study covered two neighboring states that were not clearly discriminated, the presence of the species was marked for both. Records for Brazilian oceanic banks and islands were also quantified, as follows: Fernando de Noronha Archipelago, Rocas Atoll, Saint Peter and Saint Paul's Rocks, Sirius Seamount and Vitória-Trindade Seamount Chain. Vernacular names of the species were compiled from the studies surveyed to create an annotated list per site.

Habitat information was compiled based on Pinheiro et al. (2018), as follows: artificial habitats, biogenic reefs, estuarine-mangrove, rocky reefs, sandy bottom, surf zone and tidepools. Records without habitat information were assigned only to the geographic site. Sampling methods of the studies surveyed were categorized according to type of fishing gear (e.g. cast net, fish trap, gillnet, handline, hand net, harpoon, longline, light trap and trawl net), interview with stakeholders and *in situ* data collection (e.g. photo/video and underwater visual census). 'Landing data' was added to quantify the studies based on landings that lack detailed information on fishing gear. 'Trawl net' included three types of nets: small seine used mainly in estuaries (popularly known as *picaré*), beach seine used particularly in intertidal zones and bottom trawl deployed in deeper areas. 'Fish trap' encompassed three types of gears: fish weir (denominated *curral*), fyke net and pot (denominated *covo*). When studies reported multiple fishing gears, each method was counted separately.

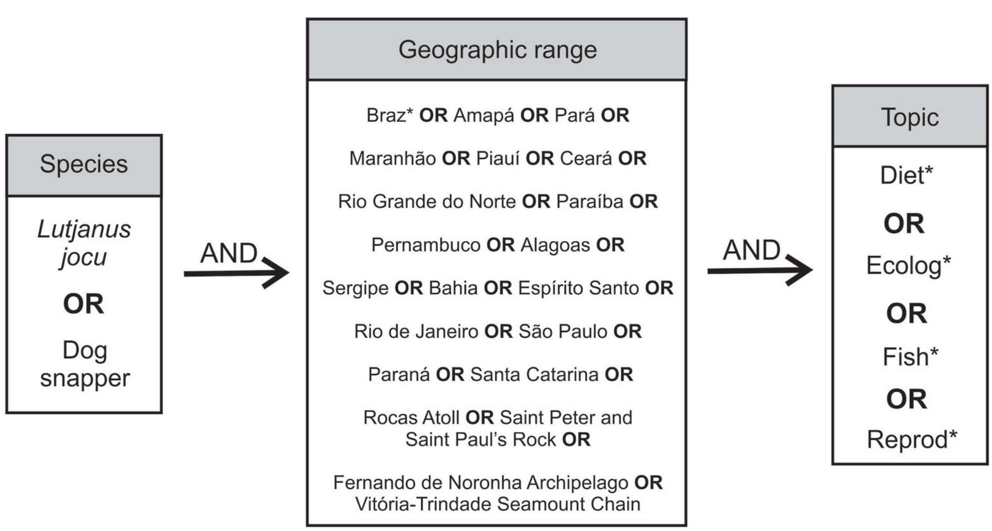

Fig. 1. Flowchart describing the search strings used in bibliographic survey.

3. Results and discussion

3.1. Distributional records

A total of 253 distributional records of *L. jocu* in 212 studies were compiled along the Brazilian Province (Table S1), with the northern limit in Amapá (03°37′N) and the southern limit at Arvoredo Island in the state of Santa Catarina (27°16′S) (Fig. 2). This comprehensive survey resulted in a broader geographic range than previously reported in the literature, which indicated the southern limit to be Rio Grande do Norte (Allen, 1985), Bahia (Cervigón, 1966) or São Paulo (Carvalho-Filho, 1999). Although records for Amapá were not state specific, the species has been documented for other regions farther north, such as French Guiana (Le Bail et al., 2012) and Venezuela (Cervigón, 1966). This reflects the paucity of ichthyological inventories and landing statistics in this state, which is of considerable concern due to high fishery production in the northern region of Brazil (Paiva, 1997; Vasconcellos et al., 2007).

The northeastern region accounted for the largest number of *L. jocu* records, followed by the southeastern, northern, oceanic banks and islands and southern regions (Fig. 2). Historically, the northeastern coast of Brazil has been home to artisanal fisheries and catches of snappers probably boosted studies in this region. Regarding states, most records were found in Bahia ($n = 43$) and Ceará ($n = 29$), whereas only one was found in Paraná. The larger number of records in Bahia may be related to its coastal extension, which is the longest in Brazil (~1183 km) and shelters the richest reef complex of the South Atlantic (Abrolhos Bank). With regards to oceanic banks and islands, the dog snapper was mostly recorded around the Fernando de Noronha Archipelago ($n = 10$). This site has been largely studied in the last twenty years to describe fish behavior and drivers structuring fish assemblages (e.g. Pereira et al., 2011).

Records of *L. jocu* in the BP were unevenly distributed in time and, despite beginning in 1855, the highest frequency was seen only recently (Fig. 3). The first records of the species date back to the second half of the 19th Century and start of the 20th Century derived from French and North American expeditions to catalog the native Brazilian ichthyofauna, with specimens sampled in the northern and northeastern regions (e.g. Castelnau, 1855; Jordan, 1891; Starks, 1913). Brazilian ichthyologist Alípio de Miranda Ribeiro also identified the species in material collected in the northeastern region (Miranda-Ribeiro, 1915). Such early studies often called the species by its synonyms: *Mesoprion jocu*, *Neomaenis jocu* or *Lutianus jocu*.

Between 1921 and 1980, dog snapper records were mostly associated with checklists on the state level, particularly in the northeastern region (e.g. Paiva and Holanda, 1962; Rosa, 1980). From 1981 to 2000, the species was relatively well-documented over the entire BP and its southern limit was expanded (Cannella and Frutuoso, 1993). The first records of *L. jocu* on Brazilian oceanic islands also occurred in this period, including the farthest oceanic range of the BP (Lubbock and Edwards, 1981).

An increasing trend of *L. jocu* records has been observed in the last two decades, representing 86% of all studies (Fig. 3). Such records were broadly distributed along the BP, with a remarkable increase in the northern region (e.g. Barletta et al., 2003). However, species-specific studies on its fishery, age and growth, habitat use, feeding, spawning season and genetic structure were predominant on the northeastern coast (e.g. Frédou et al., 2009a,b; Previero et al., 2011; Reis-Filho et al., 2019). Therefore, ecological and fishery information on *L. jocu* is geographically biased in the BP, being prevalent on the northeastern coast and scarce or even absent in all other regions. This pattern is likely due to the fact that the species has greater commercial importance in the northeastern region. We strongly recommend developing studies on *L. jocu* in the northern, southeastern and southern regions to narrow this gap in knowledge.

3.2. Sampling methods and vernacular names

Most records came from studies based on an underwater visual census ($n = 56$; 19.6%) as well as trawl net ($n = 52$; 18.2%), gillnet ($n = 32$; 11.4%) and landing data ($n = 27$; 9.7%), accounting for nearly 60% of all records (Fig. 4a). Non-destructive methods - especially underwater visual censuses and photos/videos - were prevalent in marine protected areas of the southern region as well as on oceanic banks and islands, whereas landing data were restricted to the northern and northeastern regions.

The greatest variety of fishing gear was recorded for the northeastern region. Some gear was site-specific, such as the fyke net (fish trap) used exclusively in mangrove-estuarine systems of Pará, and the harpoon, which was recorded only in biogenic reefs on the coast of Bahia (Fig. 4b).

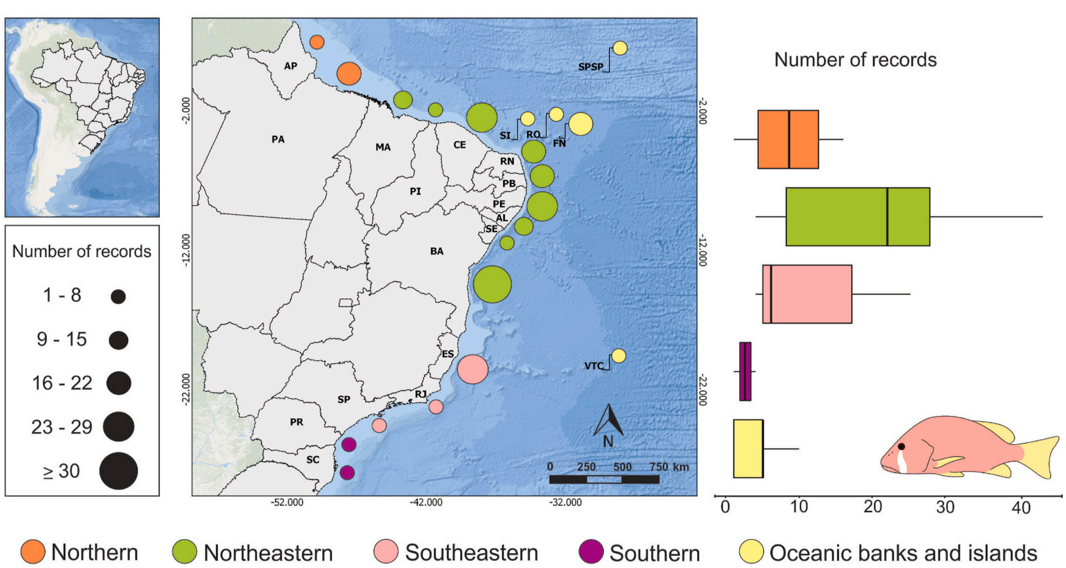

Fig. 2. Spatial distribution of records of *Lutjanus jocu* along Brazilian Province. Boxplots depict interquartile range, median (black line) and minimum and maximum values. AP: Amapá; PA: Pará; MA: Maranhão; PI: Piauí; CE: Ceará; RN: Rio Grande do Norte; PB: Paraíba; PE: Pernambuco; AL: Alagoas; SE: Sergipe; BA: Bahia; ES: Espírito Santo; RJ: Rio de Janeiro; SP: São Paulo; PR: Paraná; SC: Santa Catarina; SI: Sirius seamount; RO: Rocas Atoll; FN: Fernando de Noronha Archipelago; SPSP: Saint Peter and Saint Paul's Rocks; VTC: Vitória-Trindade Seamount Chain.

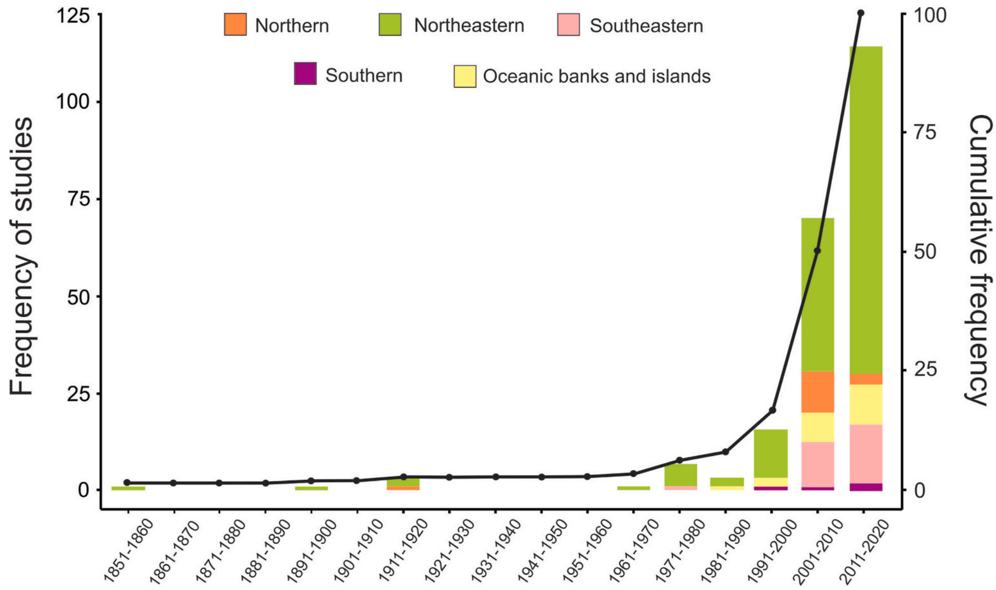

Fig. 3. Temporal trend of studies on *Lutjanus jocu* along Brazilian Province. Stacked bar plot depicts frequency of studies per region and line plot represents cumulative frequency in BP.

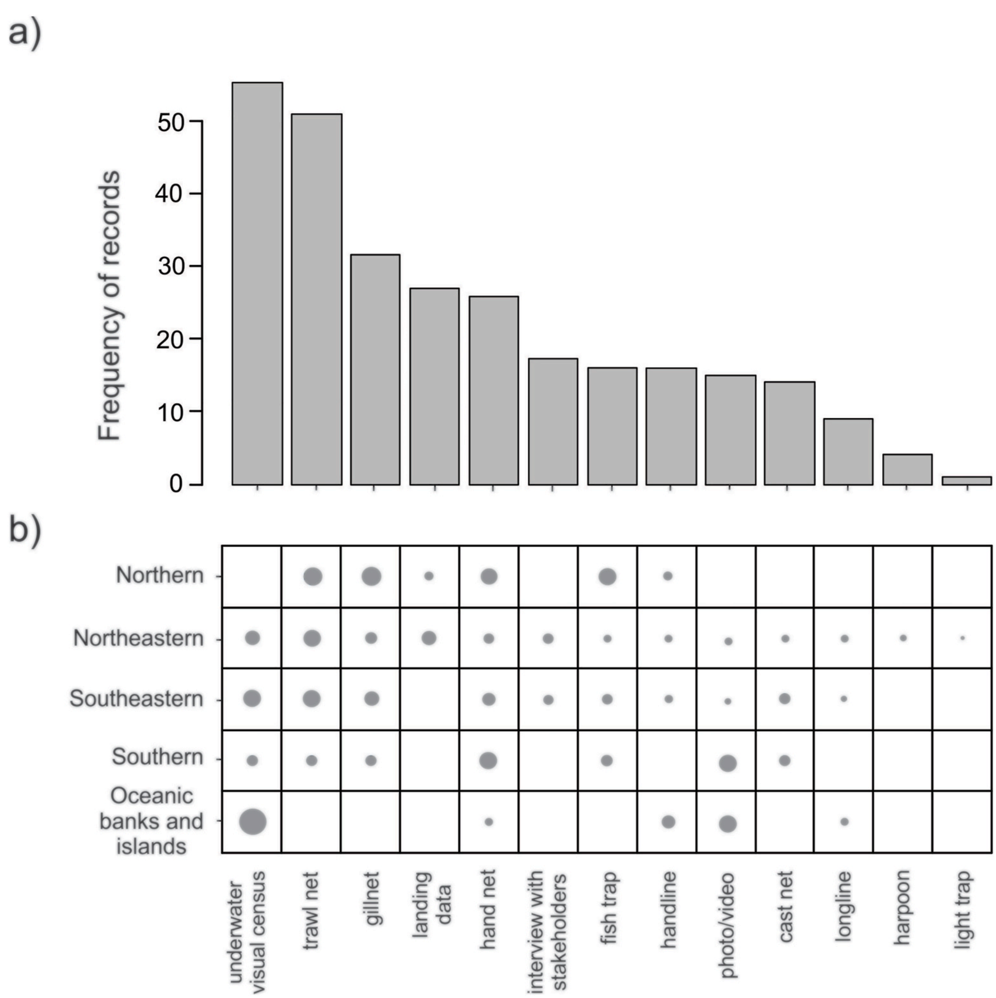

Fig. 4. a) Frequency of sampling methods used for *Lutjanus jocu* along Brazilian Province. b) Predominance of sampling methods per region (circle size represents the observed frequency).

However, fishing performed by harpoon (spearfishing) is disclosed mostly on social media (Roos and Longo, 2021) and has therefore been overlooked in traditional studies. Likewise, the use of handline is likely underreported, as this is the most common type of gear used by the artisanal fleet along the northeastern coast (Vasconcellos et al., 2007).

A considerable richness of popular names was recorded for *L. jocu* along the BP (Table S1), the most frequent was *Dentão* ($n = 29$), followed by *Carapitanga* ($n = 12$) and *Vermelho/Vermelha* ($n = 8$). *Dentão* is an allusion to the large canine teeth in the upper jaw, which is a diagnostic external character of the species. Some vernacular names were region-specific, such as *Baúna-de-Fogo* and *Caranha* in Sergipe, *Ariocó* in Bahia and *Pargo Jocú* in Rio de Janeiro. Most of these names had been reported by Carvalho-Filho (1999), but two names mentioned by this author (*Vermelho-Cachorro* and *Vermelho-Siriúba*) were not found in the literature reviewed in the present study. Some of these names are also used for other snappers on the Brazilian coast, such as *Ariocó* (*L. synagris*) and *Cioba* (*L. analis*). This type of information - especially recognizing relationships between common names and regions - is critical for fisheries management and monitoring along the BP. Some sites in Brazil are hotspots of common names (Previero et al., 2013) and this information needs to be taken into account in fishery statistics to avoid mismatched species identification.

3.3. Ecology

3.3.1. Habitats

The occurrence of the dog snapper was reported in a multitude of habitats: mangroves, estuaries, tidepools, surf zones, coral reefs, deep areas, rocky reefs and artificial structures (shipwrecks, prefabricated concrete and stacked tires). The estuarine-mangrove habitat accounted for the largest number of records ($n = 78$; 36.1%), followed by biogenic reefs ($n = 46$; 21.3%), rocky reefs ($n = 30$; 13.9%), sandy bottom ($n = 30$; 13.9%), tidepools ($n = 19$; 8.8%), artificial habitats ($n = 10$; 4.6%) and surf zone ($n = 3$; 1.4%) (Fig. 5a). Records in the estuarine-mangrove habitat, biogenic reefs and tidepools dominated in the northern and northeastern regions, whereas records in rocky reefs prevailed in the southeastern and southern regions as well as oceanic banks and islands (Fig. 5b). This generalist behavior on the part of the dog snapper may be associated with the use of different habitats throughout its lifetime, as supported by previous studies (e.g. Frédou and Ferreira, 2005; Moura et al., 2011; Aschenbrenner et al., 2016; Reis-Filho et al., 2019).

A slightly positive relationship between *L. jocu* body size and depth was found on the northeastern coast, possibly as a consequence of the depth-related movements throughout its ontogeny (Frédou and Ferreira, 2005). Size class-based studies have clarified this pattern, showing that

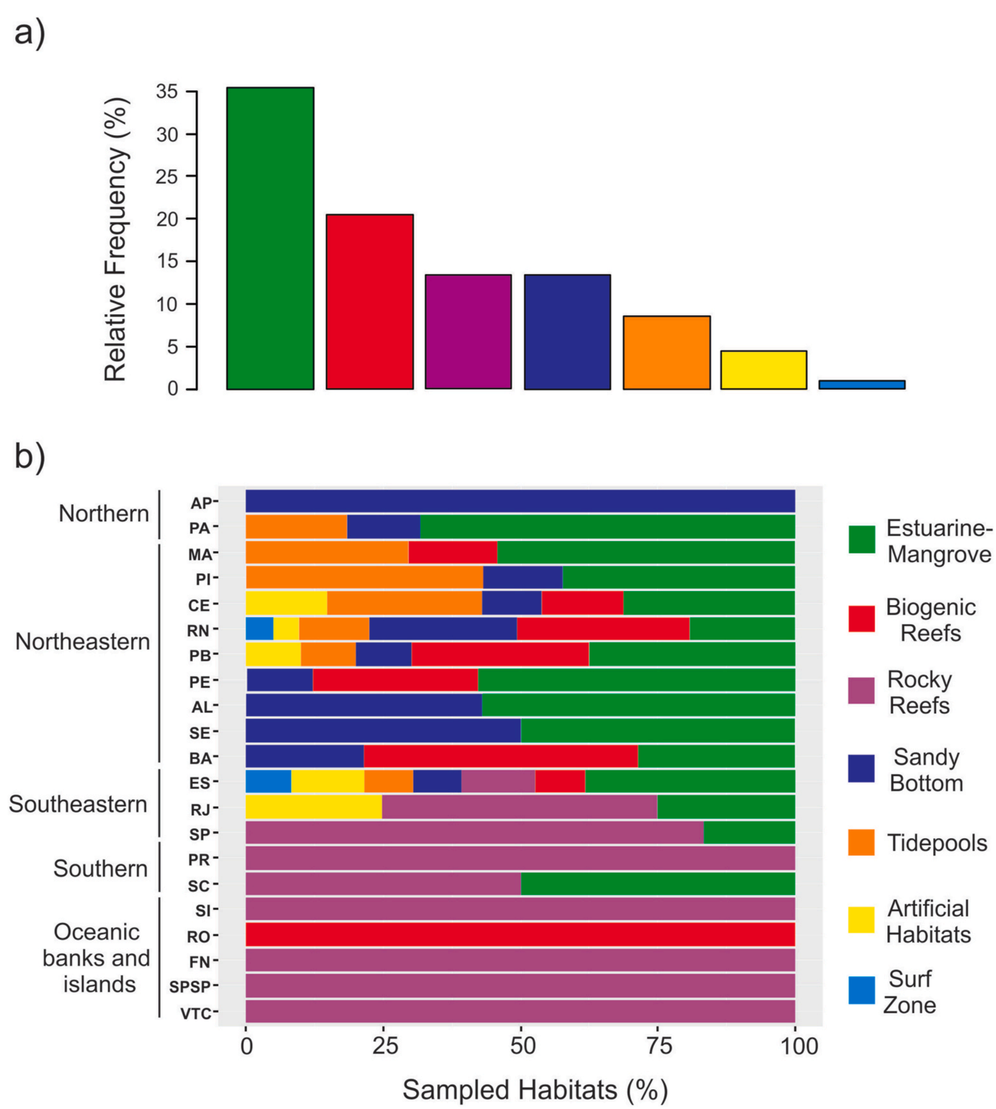

Fig. 5. a) Relative frequency of habitats sampled for *Lutjanus jocu* and b) percentage of sampled habitats per site along Brazilian Province. Abbreviations of site names are given in Fig. 1.

post-settled and juveniles (4–15 cm total length [TL]) predominantly use brackish environments (estuaries and mangroves), whereas adults (>40 cm TL) dwell in outer, deeper, reef-associated habitats (Moura et al., 2011; Aschenbrenner et al., 2016; Reis-Filho et al., 2019). Indeed, the species has previously been classified as 'migrant/settler' in estuarine systems (Castro, 1997) and 'secondary resident or occasional visitor' in tidepools (Rosa et al., 1997).

These studies support the hypothesis of cross-shelf ontogenetic migration for *L. jocu* in the BP, which has recently been revealed by otolith chemistry analysis (Menezes et al., 2021). Two contrasting habitat-use patterns for *L. jocu* were inferred by otolith Ba/Ca ratios across the Abrolhos Bank shelf: marine residents (fish that remain in marine systems throughout their lifetime) and marine migrants (juveniles that inhabit estuaries and move to marine systems with age) (Menezes et al., 2021). Overall, the dog snapper seems to depend on estuaries, tidepools and nearshore reefs in early life stages along the BP. These ecosystems are widely recognized as nurseries or refuges for juvenile stocks of coastal fishes due to the high availability of trophic resources and protection from predators (Horn et al., 1998; Nagelkerken et al., 2008). Given that the BP hosts a variety of coastal and oceanic habitats, such as seagrasses, sandy bottoms, rhodolith beds and mesophotic reefs (see examples in Fig. 5b) further studies - especially in oceanic systems - are required for a better understanding of habitat use by the species.

3.3.2. Trophic ecology and interactions

From the studies surveyed, the dog snapper has a carnivorous diet with opportunistic and generalist habits, feeding on Brachyura, shrimps (Penaeidae), microcrustaceans (Amphipoda and Cyclopodia) and teleosts in estuarine systems (e.g. Monteiro et al., 2009; Pimentel and Joyeux, 2010; Lustosa-Costa et al., 2020). The diet of the species appears to be strongly influenced by seasonal and ontogenetic changes, with a predominance of shrimps in dry months and Grapsidae, Portunidae and Xanthidae crabs in rainy months (Monteiro et al., 2009). Low or no trophic overlap was observed with other closely related snappers (e.g. *L. alexandrei, L. analis, L. synagris*; Pimentel and Joyeux, 2010; Lustosa-Costa et al., 2020). Stable isotope analyses revealed high $\delta^{15}N$ levels in *L. jocu* tissues collected around the Saint Peter and Saint Paul's Rocks, likely influenced by a carnivorous feeding habit (Pinheiro et al., 2016). No study recorded the occurrence of *L. jocu* as a food item of large piscivorous fishes, but the main potential predators are presumed to be coastal rays (e.g. smooth butterfly ray *Gymnura micrura*), which prey on juveniles of congeneric snappers in estuaries (Yokota et al., 2013). Further studies on the diet of *L. jocu* inhabiting coastal reef systems of the BP are required to assess its trophic role in highly biodiverse environments.

Regarding feeding behavior, three major interactions involving *L. jocu* have been documented: i) an association with the spinner dolphin, in which the dog snapper was observed feeding on dolphin excrement; ii) nuclear-follower behavior, in which the species was recorded following a nurse shark (*Ginglymostoma cirratum*) and *Octopus insularis*, and interacting with a variety of follower species when engaged as a nuclear, such as surgeonfishes, wrasses, the yellow jack (*Carangoides bartholomaei*) and the marbled grouper (*Dermatolepis inermis*); and iii) cleaning interaction, by which *L. jocu* acted as a client of shrimps and gobies (Sazima et al., 2006; Pereira et al., 2011; Quimbayo et al., 2017). Such interactions seem to be more frequent around oceanic islands and modulated by species richness, type of substrate cover and availability of food resources (Inagaki et al., 2020).

3.3.3. Reproductive biology

Reproduction information on *L. jocu* is scarce along the BP. Only five published studies were found: four on the northeastern coast (Freitas et al., 2011; França and Olavo, 2015; Bezerra et al., 2021; França et al., 2021) and one on an oceanic island (Krajewski and Bonaldo, 2005). Spawning aggregation events are often composed of large *L. jocu* schools of up to a thousand individuals (Carter and Perrine, 1994; Kadison et al., 2006). However, two disjunctive spawning events involving a single pair of adults (~50 cm TL) occurred around the Fernando de Noronha Archipelago, where courtship was observed just before ovules and milt were released into the water column (Krajewski and Bonaldo, 2005). The occurrence of isolated reproductive events may result from the lack of suitable aggregation grounds in the surrounding region (Krajewski and Bonaldo, 2005). Studies are needed to determine the frequency of such events around Brazilian oceanic islands.

Five putative *L. jocu* aggregation sites were identified on the southern coast of Bahia - all located at the shelf break and associated with deeper zones. Local fishers confirmed this information and reported that aggregation events occur in autumn and winter (França and Olavo, 2015). Important spawning aggregation sites for snappers were recently mapped based on local ecological knowledge and *L. jocu* was cited by 13% of the interviewees. Such sites are located in the northern portion of Espírito Santo and southern Bahia (Abrolhos Bank) and often near the continental shelf break (Bezerra et al., 2021). Moreover, four *L. jocu* spawning grounds along the coast of Pernambuco/Alagoas were validated by data from fisheries and histological analysis, with all sites situated on the outer shelf and close to shelf break (França et al., 2021). Recently, an extremely high abundance ($n = 640$) of *L. jocu* adults was documented at the Parcel do Manuel Luiz reef in the state of Maranhão (Cordeiro et al., 2020), possibly indicating this area or adjacent waters as spawning aggregation grounds.

Two spawning peaks for *L. jocu* were reported for the Abrolhos Bank - the longer one between June and October and the shorter between February and March. These periods were identified by gonadosomatic indices of specimens caught in the region. Regarding gonadal maturity, females attained first maturity at slightly smaller sizes than males, as supported by L_{50} estimations of 36 cm TL compared to 38.2 cm for males (Freitas et al., 2011). Similarly, two spawning periods for the dog snapper were also recorded on the Pernambuco/Alagoas coast, with one peak estimated between October and January (spring-summer) and another from March to May (autumn) (França et al., 2021).

Lutjanus jocu spawning events observed at Fernando de Noronha (Krajewski and Bonaldo, 2005) coincided seasonally with spawning periods on the Abrolhos Bank (Freitas et al., 2011) and the greatest catches on the southern coast of Bahia (França and Olavo, 2015). June is part of the winter season in Brazil, which suggests a spawning preference for cooler waters. Indeed, *L. jocu* spawning aggregations in winter have been reported in Belize (Carter and Perrine, 1994) and the Virgin Islands (Kadison et al., 2006). As aggregation events are spatially and temporally predictable, mapping these sites along the BP is critical to the management of the species.

3.4. Fisheries

3.4.1. Age, growth and length-weight relationships

Two studies on the age and growth of *L. jocu* used the reading of sagittal otolith growth increments (Rezende and Ferreira, 2004; Previero et al., 2011), whereas another used empirical methods (Klippel et al., 2005). Age estimates based on sectioned otoliths were more reliable than those using whole otoliths, especially for reading annual increments in small fish (Rezende and Ferreira, 2004; Previero et al., 2011). Compiled data on maximum size, age and growth and length-weight relationships are presented in Table 1.

Von Bertalanffy growth parameters of $L\infty$ ranged from 71.2 to 118 cm, with males attaining slightly larger sizes than females (Table 1). Relatively low growth coefficients were reported, which is in agreement with the fact that the dog snapper has the slowest growth among all snappers (Klippel et al., 2005). Overall, the species has short, fast growth over the first six years (~40 cm TL), when it attains first maturity, followed by a long, decreased growth over the next dozen years. Indeed, a long lifespan has been documented for the species in the BP (25 and 29 years) (Rezende and Ferreira, 2004; Previero et al., 2011) and in the

Table 1
Compiled data on age, growth, maximum length and age, von Bertalanffy parameters and length-weight relationships of *Lutjanus jocu* along Brazilian Province. *log-transformed data; FL = fork lenght; TL = total length; SL = standard length; W = weight; SVB = Constant variance for all ages; CVVB = Constant coefficient of variation for all ages.

References	Age and growth						Length-weight relationship	
	von Bertalanffy			Maximum		Methods	Equation	Size range (cm)
	L∞	K	t_0	Length	Age			
Rezende and Ferreira (2004)	84.14	0.080	−5.400	105 FL	25	whole	$W = 0.031FL^{2.88}$	25–90
	77.20	0.110	−3.730			sectioned		
	71.20	0.112	−4.320			back-calculation		
Klippel et al. (2005)	118.00	0.119	–	115 FL	–	–	$W = 0.005FL^{3.287}$	24.0–81.0
Previero et al. (2011)	82.10	0.105	−1.570	79.5 FL	29	SVB/sectioned/female	$W = 0.020FL^{2.9679}$	14.5–79.5
	92.80	0.009	−1.680			SVB/sectioned/male		
	117.60	0.060	−2.470			CVVB/sectioned		
Frota et al. (2004)	–	–	–	–	–	–	$W = 0.005FL^{3.28}$	24.1–81.1
Giarrizzo et al. (2006)	–	–	–	–	–	–	$W = 0.019TL^{2.96}$	8.5–31.5
Silva-Júnior et al. (2007)	–	–	–	–	–	–	$W = 0.007TL^{3.373}$	10.6–21.4
Joyeux et al. (2008)	–	–	–	–	–	–	$W = -4.114TL^{2.998*}$	2.4–30.7
Freitas et al. (2011)	–	–	–	–	–	–	$W = -3.001SL^{2.85*}$	11.1–69.5
Viana et al. (2016)	–	–	–	–	–	–	$W = 0.015TL^{3.00}$	3.2–24.9

southeastern USA (33 years) (Potts and Burton, 2017). This pattern may also be seen in length-weight relationships, as weight increases much slower before 65 cm TL than among larger sizes.

Future studies involving validation methods (e.g. use of chemical marks in otoliths) are required for an accurate estimate of the age and growth of *L. jocu*. This is particularly needed for lutjanids due to their i) ontogenetic migration, which creates unclear growth banding patterns, and ii) long lifespan, which hampers the reading of rings at older ages (Piddocke et al., 2015). Non-lethal ageing methods (e.g. scales and spines) could contribute to filling this gap in knowledge while assisting in protecting the declining stock.

3.4.2. Landing statistics and stock structure

The start of the *L. jocu* fishery in the BP is uncertain, but the first clue is perhaps the ichthyological survey carried out by Starks (1913), who purchased one specimen from the fish market of Pará (northern region). Clearly, the *L. jocu* fishery has grown steadily since the 1980s, especially on the northeastern coast, likely due to the drop in fisheries of the southern red snapper and lobster (Paiva, 1997; Rezende et al., 2003).

Data on *L. jocu* landing statistics (measured as gross catch in tons) in Brazil are available separately per state from 1994 to 2007 and for the country as a whole from 2008 to 2011 (www.icmbio.com.br/cepsul). This lack of detailed data after 2008 substantially compromises long-term landing statistics, which are essential for delineating effective fisheries management. In this review, we present pooled landing statistics due to the large number of missing data both for states and years (Fig. 6). The temporal trend revealed landing peaks in 1998, 2003 and 2004, reaching roughly 1500 t per year. Overall, dog snapper landings predominated in northeastern states, such as Bahia, Ceará and Rio Grande Norte.

Landings of the dog snapper were lower than those of other snappers along the northeastern coast (Rezende et al., 2003). For instance, dog snapper landings yielded only 8 t compared to 12.5 t for the mutton snapper and 64.5 t for the yellowtail snapper from 1997 to 1999 in southern Bahia (Costa et al., 2003). Likewise, *L. jocu* landings were consistently lower than compared to other traditional fishery resources (tuna and tuna-like fishes) at the Fernando de Noronha Archipelago, representing ~ 1–2% of the total biomass landed (Lessa et al., 1998). The *L. jocu* fishery is strongly dependent on the type of fleet, as the species is mostly caught by motorized boats (Frédou et al., 2009b). This fleet is able to explore farther, deeper fishing grounds, often catching larger individuals. Indeed, catches of mature adults (45–97 cm TL) were concentrated in outer, deeper areas (40–60 m) in Bahia (Costa et al., 2003). These *L. jocu* fishing grounds are often shared by the black grouper (*Mycteroperca bonaci*) across the Abrolhos Bank shelf (Previero and Gasalla, 2018), which is also a declining species in Brazil.

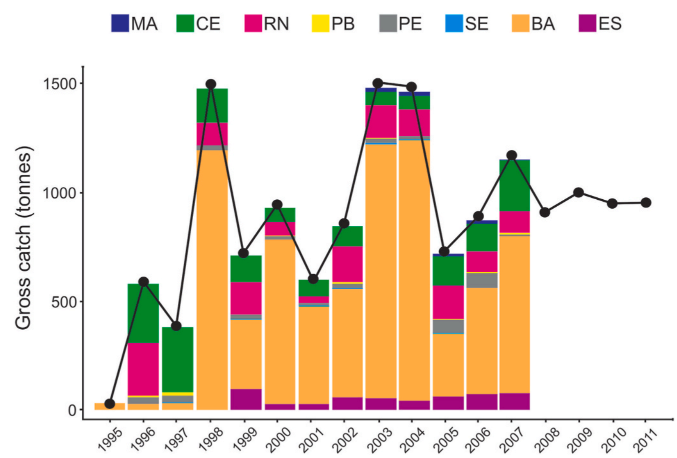

Fig. 6. Temporal trend of gross catch of *Lutjanus jocu* along Brazilian Province. Data were pooled for Maranhão (2003–2007), Ceará, Rio Grande do Norte, Paraíba and Pernambuco (1996–2007), Sergipe (1997–2007), Bahia (1995–2007) and Espírito Santo (2000–2007). MA: Maranhão; CE: Ceará; RN: Rio Grande do Norte; PB: Paraíba; PE: Pernambuco; SE: Sergipe; BA: Bahia; ES: Espírito Santo.

Regarding the *L. jocu* stock assessment, a recent study has suggested a panmictic unit ranging from Ceará to Espírito Santo, as evidenced by the high genetic homogeneity of mtDNA lineages (Souza et al., 2019). This demonstrates the considerable dispersal ability of the species, which tends to cross broad latitudinal ranges. Nevertheless, the lack of studies involving integrative approaches, such as otolith-based techniques, multiple genetic markers, ecomorphology and parasite assemblages, precludes a better understanding of the stock structure and dynamics.

3.5. Conservation

3.5.1. Threats along the Brazilian Province

The major threats to the *L. jocu* population are overfishing and the loss of habitat quality in the BP (Previero and Gasalla, 2019). Signs of overexploitation are indicated by the fleet behavior, which has moved offshore to near the shelf break (Previero and Gasalla, 2018, 2019). Another clue is related to the maximum lengths of the dog snappers caught, with a decreasing trend in fish size in recent years (Table 1). Current fisheries management strategies have been insufficient to change this scenario.

In the northern region, the major threats come from industrial fleets operating across the Great Amazon Reefs (Francini-Filho et al., 2018). A high volume of *L. jocu* is caught by snapper and bottom longline fisheries and, secondly, by shrimp bottom trawling (Marceniuk et al., 2021). These bottom fisheries also cause the destruction of unique reef formations of the region, which are vital habitats for snappers. In the northeastern region, the oil spill that occurred off Brazil constitutes a long-term threat (Soares et al., 2020) that may cause mass mortality of marine biota, bioaccumulation through the food web and recurrent coral bleaching events. Moreover, the largest Brazilian environmental disaster (collapse of the Fundão dam in 2015) is probably the main risk factor for *L. jocu* in the northeastern and southeastern regions (Previero and Gasalla, 2019). Immediately after the mining tailings reached the reefs of the southern Abrolhos Bank (Espírito Santo) in June 2016, a high cyanobacteria abundance was recorded in coastal waters (Francini-Filho et al., 2019) indicating early eutrophication and raising concerns about the cascade effects on ecosystem. Worryingly, the Abrolhos Bank reef complex is a stronghold for snappers and groupers in Brazil (Paiva, 1997; Freitas et al., 2011; Previero and Gasalla, 2018). Ineffective protection on oceanic banks and islands constitutes another threat to the *L. jocu* population. For instance, large protected areas were recently created around Saint Peter and Saint Paul's Rocks and Vitória-Trindade Seamount Chain, but only complying with Aichi Target 11, while disregarding vulnerable ecosystems and enabling fishing within no-take zones (Giglio et al., 2018). This is particularly concerning for *L. jocu*, as it is the only snapper that occurs around all four oceanic islands of the BP.

Table 2
Summary of a low-cost fisheries management framework for *Lutjanus jocu* along the Brazilian Province.

Management strategies	Method/Description	Stakeholders	Ecological importance	Socioeconomic benefits	Challenges	Solutions	Evidence of effectiveness
Mapping of fishing and aggregation grounds	**Cooperative research**: Mapping is performed with fishers' knowledge on fishing and aggregation sites using navigational charts, sketches or geographical coordinates. Mapped sites are incorporated into a spatial database available to researchers and managers to confirm the occurrence of aggregations.	Fishers, spearfishers and researchers.	Fishing and aggregation grounds are considered productivity hotspots and genetic variability reservoirs and are therefore priority areas for conservation.	Sustainment of long-term fisheries boosted by the enhancement of fish biomass and abundance; Improvement of the entire productive chain of the artisanal fleet.	1. Intensive work to confirm and systematize the sites surveyed by fishers; 2 Disinterest of some fishers to provide this type of information, assuming that it will be used to ban fishing; 3 Lack of experience in handling technological resources (GPS) on the part of fishers to conduct *in situ* mapping.	1 Use of qualified researchers and managers to ensure cost-effective mapping; 2 Environmental awareness initiatives to explain the actual reasons for mapping; 3 Free training for fishers offered by researchers in the use of georeferencing tools.	1 Mapping of up to 40 potential fish aggregation sites by fishers along the coast of Mexico (Fulton et al., 2018) 2 Thirty-one potential spawning aggregation grounds mapped using ecological knowledge of fishers in eastern Brazil (Bezerra et al., 2021)
Slot size limit regulation	**Environmental certification (eco-labeling)**: Individuals caught within slot size limit are duly certified, enabling fishers to sell at a premium price. Certification can be performed by managers of non-profit organizations or researchers on the local scale.	Fishers, consumers, researchers, managers and small enterprises.	Restricting the slot size limit ensures the first maturity of smaller fishes and a high reproductive output of bigger, older fishes (mega-spawners).	Changes in consumer habits to prioritize eco-labeled resources and consequently an increase in their sale price, generating a higher income for fishers.	1 Adaptation of fishing gear and longer effort time required to catch individuals within slot size limit; 2 Resistance of some consumers and enterprises to buy eco-labeled resources; 3 Need for a large group of researchers and NGO employees to certify fishes caught by the artisanal fleet.	1 Incentive to compensatory strategies, such as a sale price premium; 2 Long-term environmental education campaigns to raise stakeholder awareness; 3 Proper training of engaged stakeholders to capacitate them in the certification process.	1 15–24% increase in the average price of eco-labeled octopus derived from the artisanal fleet in Spain (Sánchez et al., 2020) 2 Stakeholders reported certification as being an effective fishery tool in Argentina (Pérez-Ramírez et al., 2012)
Fisheries monitoring	**Citizen science:** Field data on species are collected by fishers/divers and provided to researchers. Images, body size estimation and behavioral observations can be publicized on a website or in social media.	Fishers, recreational divers, dive operators and researchers.	Field data over large spatial scales enable the understanding population dynamics, fishery trends and effectiveness of marine protected areas.	Engagement of citizen volunteers in the scientific process and the recognition of their role as environmental agents.	1 Standardization of field data collected by fishers and divers; 2. Lack of interest on the part of some divers due to not understanding the purpose of monitoring.	1 Use of a simple, effective protocol created by researchers; 2 Environmental education campaigns directed at divers explaining the importance of their engagement to the conservation of species;	1 No difference found between volunteer- and researcher-based monitoring of reef fishes in north-eastern Brazil (Vieira et al., 2020) 2 Twelve fisheries citizen science projects successfully implemented in Mexico (Fulton et al., 2019)

4. Future perspectives: Proposal for a fisheries management framework

The gaps in knowledge pointed out in this review can help guide future studies on *L. jocu* in the BP. This is critical for optimizing the limited financial resources available for research, which have increasingly been slashed in Brazil. Thus, we propose a low-cost alternative framework with three major initiatives to support *L. jocu* fisheries management: i) participatory mapping of fishing and aggregation grounds; ii) slot size limit regulation backed by eco-labeling; and iii) citizen science-based monitoring.

One of the priority issues in the management of *L. jocu* is the mapping of fishing and spawning aggregation sites. The acknowledgment of these sites is an important step towards species management, including other reef fishes that use these sites (Heyman et al., 2010). For instance, the exploitation of the lane snapper mainly occurs during its spawning aggregations on the northeastern coast of Brazil (Freitas et al., 2014) and it is likely the same for the dog snapper. Fishing pressure on bigger, older, fatter individuals, especially females, may dramatically affect the reproductive output of a fish population, which is vital to the recovery of depleted stocks (Hixon et al., 2014; Barneche et al., 2018). Several methods have been employed to map fish spawning aggregation sites worldwide (e.g. remote sensing, acoustic tagging and videography) (Colin, 2012), but most are expensive. Hence, we suggest an approach based on cooperative research (Heyman et al., 2019), by which mapping is performed based on fishers' knowledge regarding fishing and aggregation sites, including historical information culturally conveyed over time (Table 2). Despite the challenges of such mapping, this type of information is needed, as no fish aggregation sites with known status (e.g. increasing or decreasing) have been reported for the Brazilian coast (Chollett et al., 2020) and transient aggregation sites are the most prone to overexploitation (Heyman et al., 2019).

Secondly, restricting catch of large and small *L. jocu* is a potentially effective management measure. Fishing *L. jocu* individuals smaller than 42 cm TL (based on 34 cm fork length) is already prohibited in southern Bahia (ICMBio decree nº 179/2013). We believe that embracing the protection of large fish (>70 cm TL) would positively impact the recovery of the stocks. Similarly, slot size limit strategies have been proposed for the management of the lane snapper on the Abrolhos Bank (Freitas et al., 2014; Aschenbrenner et al., 2017). However, length-based regulations are particularly challenging for artisanal fishers due to the need for adaptations to fishing gear and longer effort time required to catch fishes in particular size intervals. Therefore, we suggest that models based on environmental certification (eco-labeling) coupled with environmental awareness campaigns (Table 2) may be more effective than top-down actions via fishing decrees. Eco-labeling is the certification of seafood harvested using sustainable fishing practices. This market-based strategy has expanded to the fisheries sector boosted by the trend that consumers are more willing to purchase certified products (Gudmundson and Wessels, 2000). Although the most emblematic examples are species with a broad, profitable international market (e.g. tuna and cod), an increasing number of studies have demonstrated the effectiveness of eco-labeling for resources from small-scale fisheries (Sánchez et al., 2020). In Brazil, the market for *L. jocu* is primarily national, with southern Bahia and Maranhão serving as the major exporters of snappers to the entire northeastern region. As the artisanal fleet is the predominant throughout the BP, eco-labeling may be an effective strategy for encouraging local consumers and small businesses (restaurants and hotels) to buy certified fish.

Citizen science and recreational diving tourism may be useful tools for monitoring *L. jocu* in the BP (Table 2), as the species is easily identifiable by morphological traits. Citizen science-based monitoring has attracted attention around the world as a cost-effective tool for gathering large volumes of data on broad spatial scales (Fulton et al., 2018) and is therefore ideally applicable in the BP (e.g. Roos and Longo, 2021). Volunteer divers can provide valuable field data, such as images, body size estimations and behavioral observations, and easily upload them to a website or onto social media. In the Caribbean, diving tourism has centered on spawning aggregation events, with little disturbance to *L. jocu* when practiced carefully through the formation of small groups of properly trained divers obeying minimal distances between the observers and animals (Heyman et al., 2010). This practice reduces the negative impacts of fishing on aggregation sites and generates jobs and income for the local community. Investing in responsible diving tourism may be a profitable alternative, with artisanal fishers acting as tour guides during fishing moratorium periods (reproductive season). However, such activities must be carefully planned and well-managed, as intensive recreational diving pressure may cause cumulative ecological impacts to reef benthic sessile organisms (Giglio et al., 2020) and changes in fish behavior (Bessa et al., 2017).

Beyond these three initiatives, effective single-species management must consider how a fish population is spatially divided into subpopulations (stocks) (Cadrin et al., 2013). We suggest that *L. jocu* is a promising model for assessing stock structures and dynamics along the BP, as it is the only snapper that occurs in coastal waters and around all four major oceanic islands. As the BP encompasses ecologically distinct environments along a broad latitudinal range, it is possible that some stocks do not connect over large spatial scales. If segregated stocks are confirmed, stock-based fishery management should be established with the aim of sustainable exploitation. As coastal stocks of *L. jocu* appear to mix during spawning aggregation seasons, such stocks may function as genetic diversity reservoirs for their oceanic counterparts. Therefore, the protection of coastal nursery habitats is critical for the maintenance of the *L. jocu* population.

Lastly, fisheries management and monitoring measures for the dog snapper should be urgently implemented to avoid the collapse of the stock, as the species has been facing overexploitation. With the establishment of a management plan, *L. jocu* may serve as an umbrella species safeguarding other depleted fish stocks along the Brazilian Province.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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