Rev Fish Biol Fisheries
https://doi.org/10.1007/s11160-023-09826-y

ORIGINAL RESEARCH

Complexities of reef fisheries in Brazil: a retrospective and functional approach

Linda Eggertsen · André L. Luza · César A. M. M. Cordeiro · Cristian Dambros · Carlos E. L. Ferreira · Sergio R. Floeter · Ronaldo B. Francini-Filho · Kátia M. F. Freire · Maria A. Gasalla · Tommaso Giarrizzo · Vinicius J. Giglio · Natalia Hanazaki · Priscila F. M. Lopes · Guilherme O. Longo · Osmar J. Luiz · Rafael A. Magris · Thiago C. Mendes · Hudson T. Pinheiro · Juan P. Quimbayo · José Amorim Reis-Filho · Daniele A. Vila-Nova · Mariana G. Bender

Received: 5 September 2023 / Accepted: 21 November 2023

Abstract Reef fisheries are multispecific and employ a variety of fishing gears across marine environments, even in remote areas. This intricate and multifaceted nature of reef fisheries is often overlooked in management strategies, leading to global management failures. In Brazil, information about reef fisheries is often scarce and scattered. This stems from inadequate policies and an unrecognized societal value of reef fisheries. Here, we combine nationwide reef fish landing data (1950–2015) with an extensive literature review on Brazilian reef fisheries. We explore temporal and spatial patterns in total landings, species traits, functional diversity and composition to understand the current scenario, identify drivers of change and highlight information gaps. Brazilian reef fisheries rapidly increased in landing volume, number of targeted species and exploited traits in the 1980's,

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11160-023-09826-y.

L. Eggertsen (✉)
Hawai'i Institute of Marine Biology, University of Hawai'i at Manoa, Kaneohe, HI 96744, USA
e-mail: eggertsen.linda@gmail.com

L. Eggertsen · A. Luza · C. Dambros · D. A. Vila-Nova · M. G. Bender
Department of Ecology and Evolution, Universidade Federal de Santa Maria, Santa Maria, RS 97105-900, Brazil

C. A. M. M. Cordeiro
Laboratório de Ciências Ambientais, Universidade Estadual do Norte Fluminense Darcy Ribeiro, Campos dos Goytacazes, RJ, Brazil

C. E. L. Ferreira · T. C. Mendes
Departamento de Biologia Marinha, Universidade Federal Fluminense, Niterói, RJ 24210-201, Brazil

S. R. Floeter · N. Hanazaki
Departamento de Ecologia e Zoologia, Universidade Federal de Santa Catarina, Florianópolis, SC 88040-900, Brazil

R. B. Francini-Filho · H. T. Pinheiro
Centro de Biologia Marinha, Universidade de São Paulo, São Sebastião, SP 11612-109, Brazil

K. M. F. Freire
Laboratório de Ecologia Pesqueira, Departamento de Engenharia de Pesca e Aquicultura, Universidade Federal de Sergipe, São Cristóvão, SE, Brazil

M. A. Gasalla
Fisheries Ecosystems Laboratory, Oceanographic Institute, University of Sao Paulo, São Paulo, SP 05508-130, Brazil

T. Giarrizzo
Instituto de Ciências do Mar, Universidade Federal do Ceará, Fortaleza, CE, Brazil

T. Giarrizzo
Núcleo de Ecologia Aquática e Pesca da Amazônia, Universidade Federal do Pará (UFPA), Belém, PA, Brazil

V. J. Giglio
Universidade Federal do Oeste do Pará, Campus Oriximiná, Oriximiná, PA 68270-000, Brazil

Published online: 02 January 2024

despite mainly targeting carnivorous fish (groupers, snappers, jacks and trevallies). Exploited functional space increased over time, mainly due to the incorporation of smaller and lower-trophic level species that gradually were added to the pool of fished species. Local and international markets have been the main drivers behind these patterns, while subsistence fishing is marginal. Lack of proper management and enforcement of existing regulations have led to population declines, dwindling total catches since the early 2000's, and numerous threatened species. Artisanal fishing accounts for the majority of catches, raising concern on the social impacts of degraded reef fisheries. We highlight the urgent need for adequate fishing statistics, and the use/application of science-based management and policy actions to secure productive fisheries and healthy reef ecosystems in Brazil.

Keywords Artisanal fishing · Brazilian reefs · Catch composition turnover · Ecological traits · Functional space · Reef fisheries

Introduction

Reefs provide a wide range of ecosystem services that sustain millions of people (Moberg and Folke 1999; Woodhead et al. 2019), with 6 million reef fishers estimated to operate worldwide (Teh et al. 2013). Their contribution to livelihoods, protein and nutrient intake by coastal populations is remarkable and widely recognized by scientists (e.g. Hughes et al. 2012; Woodhead et al. 2019; Hicks et al. 2021) and policymakers (e.g. The Food and Agriculture Organization of the United Nations, FAO). Coral reefs are also one of the most threatened ecosystems on earth, so decisions need to be made to prioritize their conservation while allowing people to use reefs for social and economic purposes (Cinner 2014). Illuminating the services provided by an ecosystem may draw attention of decision-makers and incentivize informed policies towards a more sustainable and ecosystem-based use of resources (TEEB 2012).

Reef fisheries can be defined as recreational, subsistence or commercial fishing for supplying national and international markets (Munro et al. 1996; Kittinger et al. 2015; Mora 2015). They are difficult to characterize and manage because of their inherent complexity as they comprise multiple target species and gears within complex social-ecological systems (Fenner 2012; Mora 2015). Consequently, multispecies coral reef fisheries are overwhelmingly data-poor (Worm and Branch 2012). Lack of resources and investment in environmental and fisheries management combined with urbanization, and increasing human population, have led to rapid overexploitation, yield declines, habitat loss and local extinctions of targeted reef fishes worldwide (Newton et al. 2007; Fenner 2012; Mora 2015). Overexploitation of resources is a serious and common problem in reef fisheries, causing changes in community structure and interactions and may lead to trophic cascades due to the removal of keystone species (Bascompte et al. 2005; Ledlie et al. 2007; Wallner-Hahn et al. 2015), such as top predators (piscivores). The removal of large herbivores and piscivores is particularly critical for coral reefs since these two groups perform key

N. Hanazaki
Department of Environmental Sciences, Informatics and Statistics, Ca'Foscari University of Venice, Mestre, VE, Italy

P. F. M. Lopes
Department of Ecology, Universidade Federal do Rio Grande do Norte, Natal, RN 59078-900, Brazil

G. O. Longo
Marine Ecology Laboratory, Department of Oceanography and Limnology, Universidade Federal do Rio Grande do Norte, Natal, RN 59078-900, Brazil

O. J. Luiz
Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT 0810 , Australia

R. A. Magris
Inst Chico Mendes de Conservação da Biodiversidade, Brasília, DF 70673-401, Brazil

J. P. Quimbayo
Department of Evolution, Ecology and Organismal Biology, The Ohio State University, Columbus, OH 43210, USA

J. A. Reis-Filho
Graduate Studies Program in Ecology: Theory, Application and Values, Universidade Federal da Bahia, Salvador, BA 40170-115, Brazil

J. A. Reis-Filho
Núcleo de Ecologia Aquática e Pesca da Amazônia, Universidade Federal do Pará (UFPA), Belém, Brazil

functions on the reefs such as the mediation of coral-algae relationships and maintenance of food web structure (Darling and D'Agata 2017; Graham et al. 2017).

Brazil is a megadiverse country with continental dimensions on land and sea, with more than 8000 km of a heterogeneous coastline and 4.5 million km^2 of Exclusive Economic Zone (EEZ), known as "the Blue Amazon" (Marroni 2014). The Brazilian coast shelters extensive shallow and mesophotic reefs, extensive mangroves, the largest rhodolith beds in the world, rocky shores and several estuaries and lagoons (Leão et al. 2003; Miloslavich et al. 2011; Viana et al. 2021). Tropical reefs extend from the north to the northeastern coast, while subtropical rocky reefs predominate in the southern and southeastern coast (Ferreira et al. 2004). The Brazilian Province constitutes a distinct biogeographic province characterized by a high degree of endemism (Kulbicki et al. 2013; Pinheiro et al. 2018a). The reef fish community composition varies along the latitudinal gradient, with a peak in species richness in the transition zone between tropical and subtropical conditions, and with the lowest diversity in the south (Pinheiro et al. 2018a). Fish biomass also changes in response to variation in temperature, productivity, depth and human density along the coast (Morais et al. 2017). Despite the vast extent of the Blue Amazon and the importance of marine resources for the coastal population, Brazil historically has a poor investment in ocean protection and marine resource monitoring and management. Consequently, the country has only a small portion of its continental shelf currently under some degree of protection (~4%; Miloslavich et al. 2011; Magris 2021), with insufficient conservation policies, education investments and surveillance to avoid overfishing and capture of threatened species (Pinheiro et al. 2021).

Reef fisheries comprise about 15% of total marine fisheries in Brazil and are mainly harvested by the artisanal fishery fleet (Oliveira and Silva 2012; Mattos et al. 2020). Information on fisheries and social-ecological relationships between coastal communities and reef resources are scarce for most of the coastal region (but see Begossi et al. 2009; Previero and Gasalla 2018; Silva et al. 2019; Previero and Gasalla 2020). Although the artisanal fisheries employ a much larger number of fishers (> one million artisanal fishers, here defined as vessels < 20 gross tonnage), government investments in the fishing sector have almost entirely focused on the industrial fisheries (Diegues 1983; MPA 2011; Oliveira and da Silva 2012; Gonçalves-Neto et al. 2021). Marine fisheries in Brazil have a history of mismanagement and discontinuity in organization, monitoring and enforcement, with huge gaps in official fishing landing statistics, which have been discontinued since 2011 (Oliveira and Silva 2012; Vilar et al. 2020; Gonçalves-Neto et al. 2021). This lack of data impedes regular stock assessments, the estimation of location-specific sustainable reference points and adaptive management. Because of the heterogeneity in the coastal seascape, socio-cultural characteristics, economic development and infrastructure along the Brazilian coast, there is great diversification of reef fisheries in terms of fishing gear, fishing effort and target species (Munro et al. 1996; Kittinger et al. 2015; Previero and Gasalla 2018). Thus, assessing reef fisheries at relatively small spatial scales, rather than the entire coast, is critical for the identification of patterns and drivers of reef fisheries and for adequate fishing policies and management plans.

Despite the limited availability of historical data on pristine Brazilian reef ecosystems, there is strong evidence that fishing has profoundly changed fish community structure. This has resulted in biomass declines of top predators and large herbivorous fish, local extinctions, as well as shifted environmental baselines among fishers (Floeter et al. 2006; Francini-Filho and Moura 2008; Luiz and Edwards 2011; Bender et al. 2014; Roos et al. 2016; Leduc et al. 2021; Fogliarini et al. 2021). These changes in fish community structure might affect functions on an ecosystem scale (Luza et al. 2023).

A trait-based approach can support biodiversity conservation and fisheries management by improving our ability to associate changes in relative abundances or biomass of species to changes in traits that, in turn, affect ecosystem services provided by fishes (Luiz et al. 2019). An example is removal of invertivores that feed on sea urchins, causing sea urchin populations to explode with detrimental effects on marine ecosystem health (Mcclanahan and Muthiga 2016). Historically, functional-trait approaches to evaluate fishing impacts on ecosystem functionality have been underutilized (Villéger et al. 2017). Recent studies, however, have shown critical links between functional traits and vulnerability to specific fishing gears (Mbaru et al. 2020; Barbosa et al. 2021), demonstrating that the use of species traits can aid fisheries management (Pincinato and Gasalla 2010, 2019; Anderson et al. 2022), particularly in complex multispecies reef fisheries. For example, the position and configuration of a selective fishing device may be adapted to the specific behavior or swimming capacity of certain bycatch species (Mouchet et al. 2019). Understanding the combined patterns of abundance and species traits, as well as the distribution of functional traits within natural assemblages, may enable resource managers to establish goals for maintaining or restoring ecosystem processes and services (Coleman et al. 2015).

This study presents the first comprehensive characterization and analysis of the Brazilian reef fisheries coupling both spatio-temporal and functional approaches while aiming to elucidate drivers of the reef fisheries through space and time. We analyze changes in the taxonomic and functional trait composition of reef fisheries in Brazil since the 1950s by main geographic regions (the North, Northeast, Southeast and South) and determine changes over time in volume and trait composition (average trophic level, body size, depth range, water column level and group size) in fish landings. Further, we characterize the Brazilian reef fisheries in space and time by an extensive literature review, and describe the development and drivers of reef fisheries in each region, providing context to the patterns identified in the landing data. Finally, we highlight information gaps that should be incorporated into ecosystem-based policies and management towards sustainable reef fisheries in the Blue Amazon.

Methods

Study area

The Brazilian coast can be divided into four major regions, the North, the Northeast, the Southeast and the South (Fig. 1). The North is located in the tropics (4°N–1°S) and is a highly productive area due to the input of nutrients discharged by the Amazon River and carbon export from the second largest mangrove area in the world (Dittmar and Lara 2001; Araujo et al. 2021). The reefs in the North are predominantly deep, including the Great Amazon Reef System (GARS) (Collette and Rutzler 1977; Moura et al. 2016; Francini-Filho et al. 2018), but mesophotic reefs are also common along the coast and in oceanic locations (Francini-Filho et al. 2019, Table 1).

The Northeast region (01°S–18°S) is predominantly oligotrophic (Viana et al. 2021) and comprises the largest area of shallow coral reefs in Brazil (Table 1), which are composed by pinnacles, fringing and bank reefs, in addition to sandstone reefs (Leão et al. 2003). "The Coral Coast", along the states of Rio Grande do Norte, Paraíba, Pernambuco and Alagoas, constitute a long stretch (~3000 km) of shallow reefs, where the southern part (~130 km) form a barrier reef which creates a lagoon/back reef area interspersed with patch reefs (Castro and Pires 2001). The easy access and proximity to large coastal cities have contributed to severe degradation especially of the southern part of the Coral Coast (Castro and Pires 2001). The continental shelf expands in the southernmost part of the Northeast region to about 200 km wide, forming the Royal Charlotte and Abrolhos banks (Castro and Pires 2001; Negrão et al. 2021). The large and shallow Abrolhos Bank (depths rarely exceed 30 m and the shelf edge at about 70 m) (Francini-Filho et al. 2013) harbors the largest extent of biogenic reefs in Brazil, with patch and bank reefs and large mushroom-shaped "*chapeirões*" (a unique type of pinnacles), and extensive rhodolith beds (Leão et al. 2003; Moura et al. 2013).

The Southeast (18°S–25°S) is characterized by rocky reefs (Castro and Pires 2001). It is a transition zone between tropical and subtropical conditions, influenced by upwelling (Castelão et al. 2004; Miloslavich et al. 2011). Large areas of rhodolith beds are located in Espiríto Santo, as well as a chain of seamounts (the Vitoria-Trindade seamount chain), while a large part of the shallow continental shelf of Rio de Janeiro and São Paulo is composed of sand or mud (Miloslavich et al. 2011, Pinheiro et al. 2015).

The South (25°S–34°S) is subtropical to temperate, with most of its coastal waters influenced by the South Atlantic Central Water (SACW) intrusion during the summer and by the runoff from La Plata River and the Patos Lagoon (Piola et al. 2018), which creates productive coastal waters (Castello et al. 1997). The coastlines of Santa Catarina and Paraná are composed of rocky shores, estuaries, lagoons and sandy beaches (Brandini 2013). The southernmost

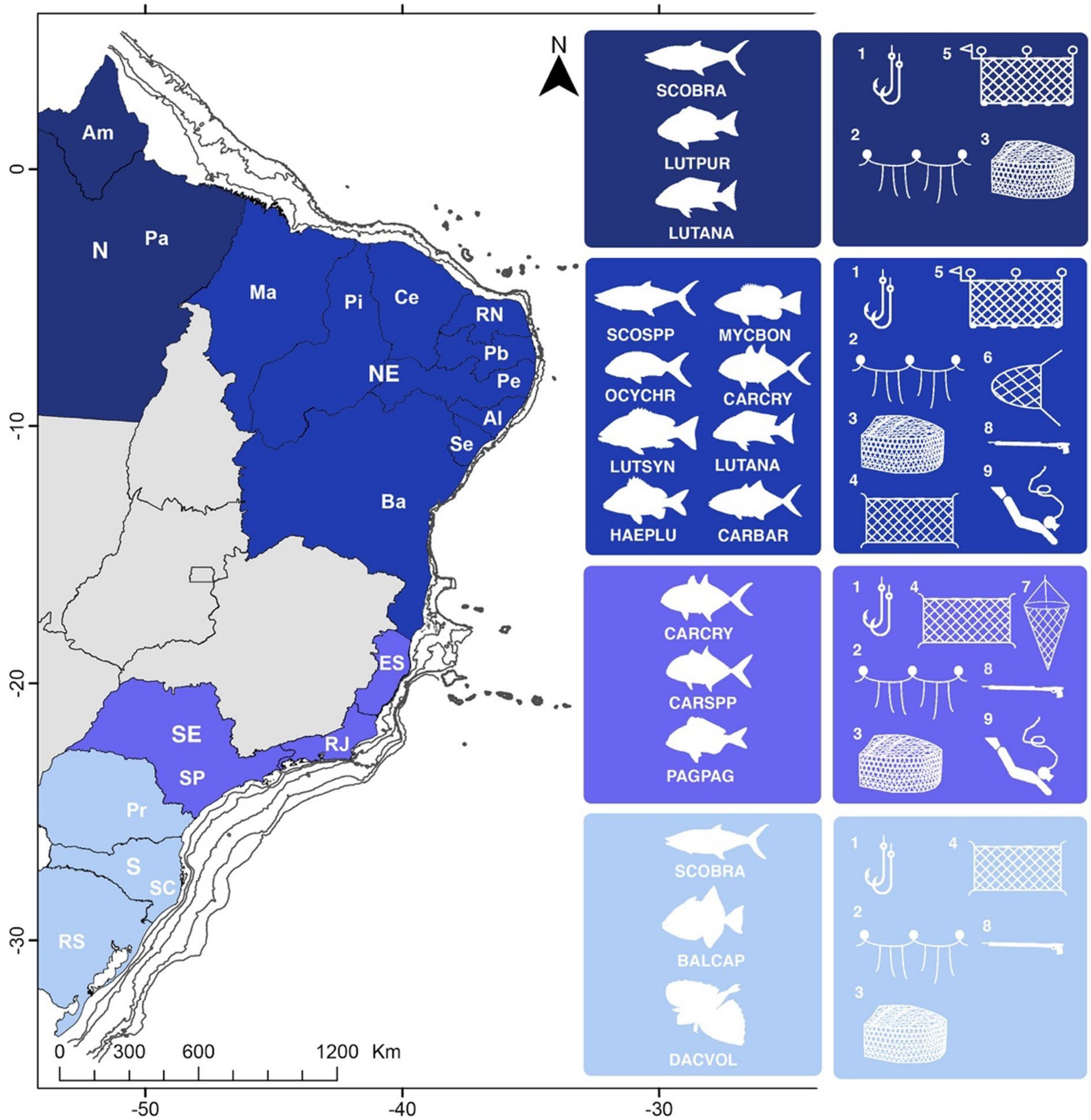


Fig. 1 Map showing the coast of Brazil colored by main regions (N = North, NE = Northeast, SE = Southeast, and S = South). State abbreviations as in Table 1. Fish silhouettes represent the most landed taxa in 2015 in each region and the most common fishing gears utilized in each region (see Table 2 for gear types). *BALCAP* Balistes capriscus, *CARBAR* Caranx bartholomaei, *CARCRY* Caranx crysos, *CARSPP* Caranx spp., *DACVOL* Dactylopterus volitans, *HAEPLU* Haemulon plumieri, *LUTANA* Lutjanus analis, *LUTPUR* Lutjanus purpureus, *LUTSYN* Lutjanus synagris, *MYCBON* Mycteroperca bonaci, *OCYCHR* Ocyurus chrysurus, *PAGPAG* Pagrus pagrus, *SCOBRA* Scomberomorus brasiliensis, *SCOSPP* Scomberomorus spp.

coast of Rio Grande do Sul is dominated by sand, and also harbors an extensive system of coastal lagoons.

The estimated number of fishers, reef area and most fished species vary among the four regions along the coast (Table 1, Fig. 1). The largest

Table 1 Reef areas for each region in km^2 (Magris 2021)

Region	States	Number of fishers[a]	Shallow-water coral reef	Mesophotic reef	Rhodolith beds	Shallow water rocky reef	Total reef area
N	Amapá (AM), Pará (PA)	251 066		21 641.64	17 856.51		39 498.15
NE	Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Pernambuco (PE), Paraíba (PB), Alagoas (AL), Sergipe (SE), Bahia (BA)	467 550	730.4	9 120.22	11 740.77		21 591.39
SE	Espírito Santo (ES), Rio de Janeiro (RJ), São Paulo (SP)	49 196		7057.17	36 870.64	1 811.2	45 739.01
S	Santa Catarina (SC), Paraná (PR), Rio Grande do Sul (RS)	53 667				58.23	58.23

N the North, *NE* Northeast, *SE* Southeast and *S* the South region

[a]Registered in the SiSRGP ("Sistema Informatizado do Registro Geral da Atividade Pesqueira") in 2021 (Conab 2022)(freshwater and marine fisheries)

shallow-water reef areas are located in the Northeast region, as well as the highest number of registered commercial fishers, and the highest number of targeted reef fish species (Table 1, Table S1 Suppl Info 1).

Literature review

We performed a targeted literature review, using Google Scholar and combining the words "reef fisheries Brazil", "fisheries", names of certain species (e.g. *Scomberomorus*, *Lutjanus cyanopterus*), "socio-ecologic" + "fisheries", "fisheries management", "artisanal fisheries Brazil" both in English and Portuguese. We included peer-reviewed scientific articles and grey literature such as theses and reports. The search for literature was conducted between May and August 2022.

Fish and fisheries data

We extracted information on reef-associated species from a fishery landing database for the period 1950–2015 hosted by the Instituto de Pesca (www.propesq.pesca.sp.gov.br) (IP 2021), based on the reef fish species definition of Pinheiro et al. (2018a). The database consists of fishery landing data per state, and is based on reported and reconstructed data since the 1950s from a range of different institutions such as the Centro de Pesquisa Nordeste (CEPENE), Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Ministério de Agricultura e Pecuária and several universities. The reconstructed data refers to cases when data on state level was missing (i.e., only existed from a few municipalities within a state), and existing data was used to extrapolate values for the whole state (for details see Freire et al. 2021). The database includes landings of commercial fisheries by the artisanal and industrial fleets, where artisanal fishing is defined as vessel size < 20 gross tonnage and industrial fishing vessels as size > 20 gross tonnage (Freire et al. 2021). Subsistence and recreational fishing were not included in the analyses. There are 176 reef fish genera occurring in Brazil (Pinheiro et al. 2018), of which 53 were targeted by commercial fisheries (i.e., included in Freire et al. 2021) (Table S1, Suppl Info 1).

We selected six fish traits associated to fishing vulnerability within reefs (Anderson et al. 2021, Carvalho et al. 2021; Mbaru et al. 2020): (i) fish body size (maximum total length; continuous trait); (ii) trophic level (position in the food web; continuous trait); (iii) maximum and minimum depth of occurrence (meters; continuous trait); (iv) diet (piscivore-cephalopod feeders (PC), mobile invertivores (IM), sessile invertivores (IS), omnivores (OM), planktivores (PL), macroalgae herbivores (HM), and herbivore-detritivores (HD); categorical variable); (v) school size (solitary, pair, small-sized group, medium-sized group, large-sized group; categorical variable) and; (vi) position in the water column (levels: high, low, bottom; categorical variable). We gathered these data from Quimbayo et al. (2021) for bony fish and from FishBase (Froese and Pauly 2022) for cartilaginous fish, and summarized trait values (average for continuous traits, modal for categorical traits across species within genera) at the genus level to match the taxonomic resolution of landing compositions from Freire et al. (2021).

Data analyses

To understand the contribution of artisanal and industrial fishing to Brazilian reef fisheries, we organized the reef fish landings in tonnes by fishing sector (artisanal and industrial) and region (North, Northeast, Southeast, South), for each year, from 1950 to 2015. We ran a similar analysis for: (i) diet categories (PC, IM, IS, OM, HM, HD) to define catches related to diet; and, (ii) selected genus of bony and cartilaginous fish that are not among the most harvested taxa but nevertheless have suffered population reductions from fisheries, which was defined in the literature review.

We used Principal Coordinate Analysis (PCoA) to investigate whether reef fisheries changed in taxonomic composition over time, as expected in scenarios of overexploitation of stocks and shifts in targeted species (Graham et al. 2017). Genera with an annual volume $<1\%$ of total landings per year were excluded from all further analyses. We built a matrix of fish genera composition per year (53 genera, 66 years), with cell values consisting of the summed landing amount per year and genus. As catch amount showed substantial variation (0 to 15 880.75 tonnes across genera and years, average of 1 413.564 $\pm$ 2 591.12 standard deviation (SD)), we used Hellinger transformation to normalize these differences between abundant and rare taxa (Legendre and Gallagher 2001). We calculated the Bray–Curtis distance between years regarding genera composition and catch amount, and then submitted this distance matrix to a PCoA (Legendre and Legendre 1998). To explore changes in genera composition per region, we ran the same analysis, using a PCoA applied to a Bray–Curtis distance matrix of genera composition per year and catch amount for each region.

We associated the change in genera composition to changes in fish traits by relating the first PCoA axis, depicting the major changes in genera composition over time, with trait averages at the year level weighted by its catch amount (also known as Community Weighted Means, Garnier et al. 2004). We calculated trait averages for five traits: (i) maximum genera length, (ii) trophic level, (iii) minimum and (iv) maximum depth occurrence, and (v) the interaction between position in the water column and group size (treated as ranked variables where species occurring close to the bottom and forming larger schools had higher ranks). To explore the spatial/regional patterns in traits of landed catch, we used a PCoA and projected the trait space filled by harvested genera in each region over the complete trait space (i.e. the space composed by the whole set of fishes landed in Brazil since the 1950s). This analysis reveals the patterns of trait space change across regions (not including temporal trends). This PCoA was built on the Gower distances between standardized values of the five traits. We filled the trait space with a gradient of colors depicting variation in fish trophic levels across genera. The gradient was created using an Inverse Distance Weighting kriging applied to trophic level and the first two PCoA axes. All analyses were run in the R Programming Environment (R Core Team 2022). Distance matrices and the PCoAs were performed using functions of the *vegan* (Oksanen et al. 2020) and *ape* R packages (Paradis and Schliep 2019), the community trait averages using the *SYNCSA* package (Debastiani and Pillar 2012), and the kriging using the *gstat* package (Pebesma 2004).

Results

Fisheries description

The North region

Fisheries in this region almost exclusively exploit carnivorous fish with the Southern red snapper, *Lutjanus purpureus*, as the main target, using specially adapted

Table 2 Main fishing gears used to harvest reef fish

	Type of gear	Associated gears	Region	Comment	Reference
1	Hook and line—*linha de mão*		All	The most common gears used in artisanal fisheries, targeting a wide range of species	Nóbrega and Lessa (2007), Reis-Filho et al. (2021)
2	Longline—*espinhel*	Bottom and surface long-lines and vertical long -lines *linha pargueira*	All	*Linha pargueira* is specially adapted for the *Lutjanus purpureus* fisheries in the North, otherwise a range of species are captured with longlines such as serranids, lutjanids, carangids, rays and sharks	Viana et al. 2021, Silva et al. 2017
3	Traps—*covo* or *manzuá*	Constructed with metal or wooden frames, often with plastic mesh	All	Used both for fish and lobster, for parrotfish and goatfish in the Northeast (< 60 m depth), red porgy in the South, for serranids in the Southeast and by the industrial fishery in the North to harvest *L. purpureus*	Nóbrega and Lessa (2007), Carvalho et al. (2013), de Oliveira et al. (2018), Silva et al. (2017), Marques and Ferreira (2010), Beneditto (2001)
4	Gillnets—*rede de espera, emalhe de fundo/superfície*	Bottom and surface nets	NortheastSoutheast, South	Capturing bony reef fish and sharks, and widely used for lobster fishing in the Northeast, although illegal	Nóbrega and Lessa (2007), Reis-Filho and Giarrizzo (2022)
5	Drift nets—*rede de corrico*	Bottom and surface nets	North, Northeast	Mainly for lobster fishing, but also for groupers in the Northeast	Bentes et al. (2012)
6	Purse/Seine nets—*rede de cerco*		Northeast		Nóbrega and Lessa (2007)
7	Liftnets – *puçá-grande*		Southeast (Espírito Santos and Rio de Janeiro)	Used for *Balistes capriscus*	Vianna et al. (2007)
8	Spear gun—*arpão*		Northeast, Southeast, South	Especially common in commercial fisheries on the Abrolhos Bank	Previeiro and Gasalla (2018)
9	Hookah diving—*pesca de compressor*		Northeast, Southeast,	Illegal since 2007, except in Resex Arraial do Cabo, where it is used for lobster and serranids	IBAMA (2008), ICMBio (2020)
10	*Bicheiro*		Northeast	Metal stick with a hook to extract octopuses or lobster	Leite et al. (2010)
11	Pots	Pots mounted on lines	Northeast, Southeast, South	Used in octopus fisheries	Carvalho Braga et al. (2007), Haimovici et al. (2014)

longlines and traps (Fig. 1, Table 2). The Southern red snapper fishery also harvests other reef species, such as the yellowtail snapper (*Ocyurus chrysurus*), dog snapper (*Lutjanus jocu*), groupers (*Epinephelus* spp. and *Mycteroperca* spp.), jacks (Carangidae) and Spanish mackerel (*Scomberomorus brasiliensis*) (Bentes et al. 2012, IP 2021). *Scomberomorus* spp. have always been a primary resource in the North and one of the most landed genera (5765 tonnes in 2015; IP 2021) (Maia et al. 2015), and sharks and rays are also frequently landed.

The main fishing grounds in the North region are located on the mesophotic Great Amazon Reef System (GARS), since the coast is lined with mangroves. Fishing directed towards reef fish was initiated on a small scale in the 1970s as a result of depleted Southern red snapper (*L. purpureus*) stocks in the Northeast region (Aragão 2018). Driven by the international market (primarily in the USA), fisheries peaked in the 1990s (Aragão 2018, Freire et al. 2021) and comprise one of the largest Brazilian marine resource exports (37.5 million USD in 2021) (MDIC 2021, Araujo et al. 2021). The North region is considered one of the world's elasmobranch conservation hotspots (Dulvy et al. 2014) and species from the genera *Carcharhinus*, *Sphyrna*, *Rhizoprionodon, Ginglymostoma*, batoids such as eagle rays (*Aetobatus narinari*) and whiptail stingrays (*Hypanus* spp.) are frequently caught with longlines (Feitosa et al. 2018; Rodrigues-Filho et al. 2020). For more details, see Table S1 Suppl. Info. 2.

The Northeast region

Similar to many tropical coral reef fisheries worldwide, the snapper-grouper complex is the most important reef fish group targeted in the Northeast region (Frédou 2004; Frédou et al. 2009). This includes *Lutjanus analis*, *L. synagris*, *L. jocu*, *O. chrysurus*, *L. cyanopterus*, *Rhomboplites aurorubens*, *M. bonaci, E. morio,* among others (Frédou et al. 2009; Freitas et al. 2011; Aschenbrenner et al. 2017; Previeiro and Gasalla 2020). The fisheries in the Northeast are diverse and include a number of different vessels and fishing gears (Fig. 1, Table 2). They target a range of species, such as Spanish mackerel (*Scomberomorus brasiliensis*), jacks (*Caranx* spp.), permits and pompanos (*Trachinotus falcatus* and *T. goodei*), halfbeaks (*Hemiramphus* spp.) and, in Rio Grande do Norte and Pernambuco, parrotfish (mainly *Sparisoma axillare* and *S. frondosum*) and goatfish (*Pseudupeneus maculatus* and *Mulloidichthys martinicus*) in larger volumes in the trap fisheries (Bevilacqua et al. 2016; Roos et al. 2016, IP 2021). Other important species, but in lower volumes, are the queen triggerfish (*Balistes vetula*), grunts (*Haemulon* spp.), rays and sharks (MMA 2006; de Souza 2018).

The fishing sector in the Northeast region grew slowly until the 1970s compared to the South and Southeast regions, due to a lack of infrastructure, such as freezers and access to markets (Diegues 1983). Since then, fisheries have increased gradually by exploring the shallow reefs along the coast and incorporating new species over time (for more detailed information, see Table S1 Suppl. Info. 2.). The fisheries in the Northeast predominantly supply national and international markets (Previeiro and Gasalla 2020). For example, commercial fisheries targeting the largest parrotfish species in Brazil, the endemic *Scarus trispinosus,* started at a larger scale at the Abrolhos Bank in the late 1980s due to the scarceness of large top-predators (primarily *M. bonaci* and *Lutjanus jocu*) (Previero 2014).

The Southeast region

The fisheries in the north part of the Southeast region, the Espírito Santo state, target mainly snappers, groupers and triggerfish (Balistidae), on the shallow part of the continental shelf (50–100 m), using lines and nets (Fig. 1, Table 2). The majority of the catch comprises the gray triggerfish *Balistes capriscus* and the yellowtail snapper *O. chrysurus*, but also includes other snappers such as *L. jocu* and a variety of trevallies (*Seriola* spp., *Caranx* spp., *Carangoides* spp.; Martins et al. 2006). Most of these species are considered overfished or at their maximum level of exploitation (Martins et al. 2006).

Catches further south (in Rio de Janeiro and São Paulo state) are less diverse in terms of reef fish species, but include species such as trevallies and jacks (*Seriola* spp., *Caranx* spp.), the gray triggerfish (*B. capriscus*), sharks (*Carcharhinus* spp.), *Scomberomorus* spp., *P. pagrus* and a few other species in smaller volumes (Almeida et al. 2011; Motta et al. 2014, Freire et al. 2021). Groupers (*M. bonaci, E. marginatus* and *E. morio*) and the cubera snapper (*L.*

cyanopterus) are fished in rather low quantities, but nevertheless, are considered valuable resources.

The longline fishery also targets some deep-water reef species such as the snowy grouper (*Hyporthodus niveatus*), wreckfish (*Polyprion americanus*) and sharks of the genus *Carcharhinus* at the continental shelf down to depths of 600 m (MMA 2006). Other elasmobranchs captured in the Southeast include eagle rays (*Aetobatus narinari*) and tiger sharks (*Galeocerdo cuvier*).

The line reef fisheries in the northernmost Espírito Santo almost exclusively targeted large groupers (e.g. *M. bonaci* and *E. morio*) until the end of the 1980s, when the fishery shifted towards smaller species such as *O. chrysurus*, *Cephalopholis fulva* and *Rhomboplites aurorubens* (Martins et al. 2005). Many of the smaller species are destined for the international market, where they are marketed whole (*"peixes de choque"*, referring to the rapid freezing method to preserve the whole fish for export) (Martins et al. 2005). The interest for smaller, plate sized fish (~1 kg) on the international market was the main driver for this change in target species (Martins et al. 2005). In the end of the 1980s, tuna was discovered in the area and the fisheries shifted from targeting demersal deep-reef species (> 100 m) such as *H. niveatus* to the new resource (Martins et al. 2005, 2006). For more details, see Table S1, Suppl. Info. 2.

The South region

Harvested species include *Scomberomorus* spp., trevallies (*Caranx* spp. and *Seriola* spp.), red porgy (*Pagrus pagrus*), the gray triggerfish (*B. capriscus*), spadefish (*Chaetodipterus faber*), snappers and groupers (*Epinephelus* spp., *Mycteroperca* spp. and *Hyporthodus* spp.), although reef fish species are not a large proportion of overall catch in the region. The dusky grouper *Epinephelus marginatus* is one of the most important grouper species of Southern fisheries (Begossi and Silvano 2008). This species is targeted with bottom longlines, hook and line, and spearfishing (Fig. 1, Table 2).

The coastal zone in the states of Paraná and Rio Grande do Sul is mainly composed of sand and possesses few rocky habitats, but reef fish are fished on the few rocky areas that exist.

Large quantities of red porgy (*P. pagrus*) were discovered in the 1970s in deeper waters (50–120 m) off the coast of Rio Grande do Sul, which led to a heavy exploitation of this species (Haimovici 1997; Haimovici et al. 2020). In the 1980s, the stock crashed and little recovery has been recorded (Haimovici et al. 2020). Another species fished at greater depths (< 500 m) is the Atlantic wreckfish (*Polyprion americanus*). This is a commercially valuable species that has been targeted since the 1970s, with a gradually evolving fishery (Haimovici 1997; Peres and Haimovici 1998), although technically protected due to its threatened status (the Brazilian red list) (MMA 2014). For a more detailed description, see Table S1, Suppl. Info. 2.

Invertebrate fisheries

The spiny lobster (*Panulirus* spp.) is an extremely valuable resource, and its fishery has also impacted other species (Nogueira 2016; Cruz et al. 2020). Additional organisms extracted from reefs are octopus, conches and starfish (Gasparini et al. 2005; Dias et al. 2008; Martins et al. 2012b; Gurjão and Lotufo 2018) (see Box 1).

Fishing data

One hundred and ten species from 57 genera and 33 families are reported in the reef fisheries landing data, represented mainly by Lutjanidae, Scombridae, Epinephelidae and Carangidae (Fig. 1) (including taxa with low catch volumes that were excluded in the statistical analyses; Table S1; statistical analyses used 53 taxa). Overall, landings of reef fishes were highest in the Northeast region, followed by the Southeast and the North regions, whereas the South region showed the lowest catches. Landings peaked in the early 2000s in all regions except in the South, followed by declines especially in the North and Southeast regions (Fig. 2). Artisanal fishing predominated in the North and Northeast, while landings were more similar between industrial and artisanal fishing in the Southeast and South regions (Fig. 2). Mobile invertivores (IM) were the most captured group over time across regions, with a steep decline in the North and Southeast regions after the 2010s (Fig. 3). Furthermore, piscivores (PC) contributed considerably to total landings across regions (Fig. 3). In contrast, landings of herbivore-detritivores (HD) increased in the Northeast region only after the 1990s (Fig. 3).

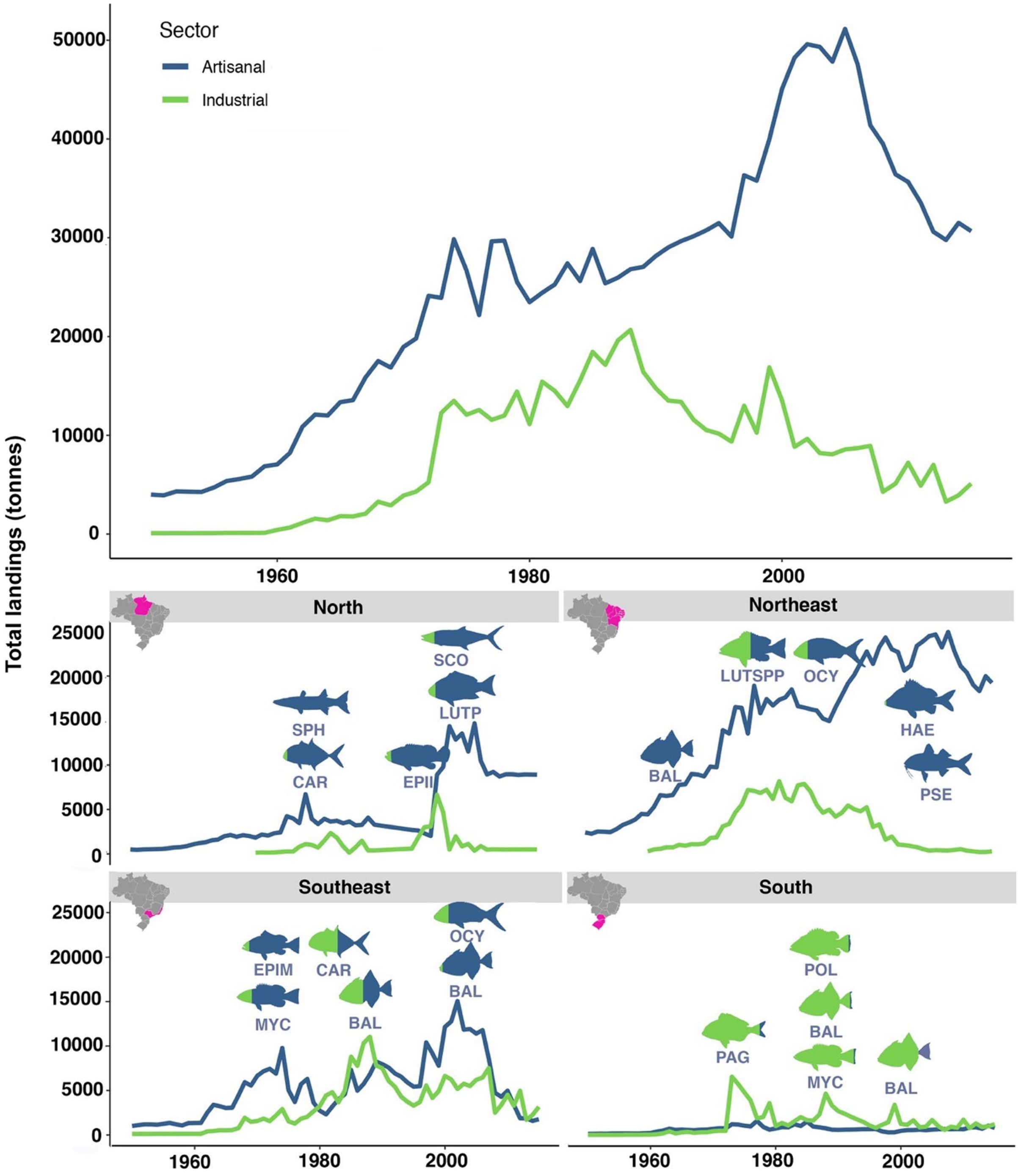


Fig. 2 Landings of reef fish catch over time (1950–2015), shown per region and fishing sector (artisanal and industrial). The fish silhouettes represent a large amount of this taxa in landings. Abbreviations: *BAL Balistes, CAR* Caranx, *EPII* Epinephelus itajara, *EPIM* Epinephelus morio, *HAE* Haemulon, *LUTP* Lutjanus purpureus, *LUTSPP* Lutjanus spp, *MYC* Mycteroperca, *OCY* Ocyurus, *PAG* Pagrus, *POL* Polyprion, *SCO* Scomberomorus and SPH = Sphyraena. Colors represent approximately % landed by each fishing sector at that specific time

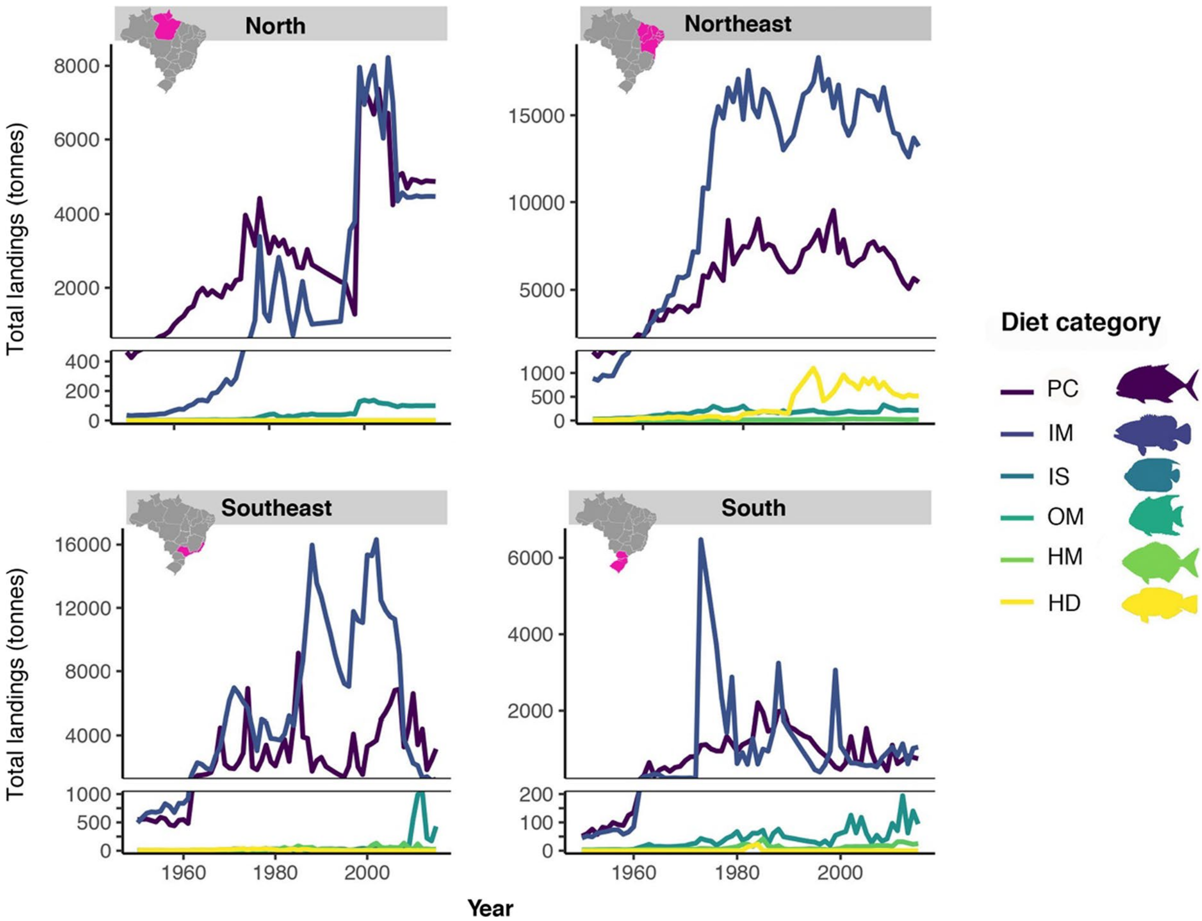


Fig. 3 Temporal variation in the landings of reef fish belonging to different diet categories in Brazilian fisheries in 1950–2015. Values shown in the Y-axis represent the sum of landings per year. Notice the different y-axis cuts for improved visualization. The groups listed in the legend are: *PC* piscivore-cephalopod feeders, *IM* mobile invertivores; *IS* sessile invertivore feeders; *OM* omnivores; *HM* macroalgae herbivores; *HD* herbivore-detritivores

Temporal trends on historically heavily exploited genera unveiled causes for patterns within diet categories (Fig. 4). For example, declines observed for PC and IM were mostly caused by declines in total landings of the genera *Epinephelus*, *Mycteroperca*, *Ocyurus* and *Carcharinus* sharks (Fig. 4).

Overall, landing composition differed between regions, with 9, 23, 14, and 15 genera harvested in the North, Northeast, Southeast and South, respectively. The PCoA summarized most variation in genera composition over the years in a few axes (mainly in the first PCoA axis) (Fig. 5). There were changes in the identity of the targeted genera since the start of the fish landing statistics in all regions, shown by a steep variation in the first PCoA axis (Fig. 5). Variation in taxonomic composition per region showed that, in the North region, catch composition changed due to increases in landings of *Epinephelus* (1980–2007), and *Hyporthodus*, *Ocyurus* and *Lutjanus* after the 2000s (Fig. S1.1). In the Northeast, *Caranx*, *Seriola*, *Epinephelus* and *Ginglymostoma* had a larger influence on catch composition during the 1950–1960s, and *Alphestes*, *Cookeolus*, *Mycteroperca*, *Ocyurus* and *Haemulon* after the 2000s (Fig. S1). In the Southeast, these changes were due to *Lutjanus*, *Mycteroperca*, *Epinephelus* and *Ocyurus* (fished at the Abrolhos Bank by the fleets of Espírito Santo) in the 1950–1980s to *Priacanthus*, *Kyphosus*, *Sphyraena* and declines of *Balistes* after the 2000s. In the South, there was a

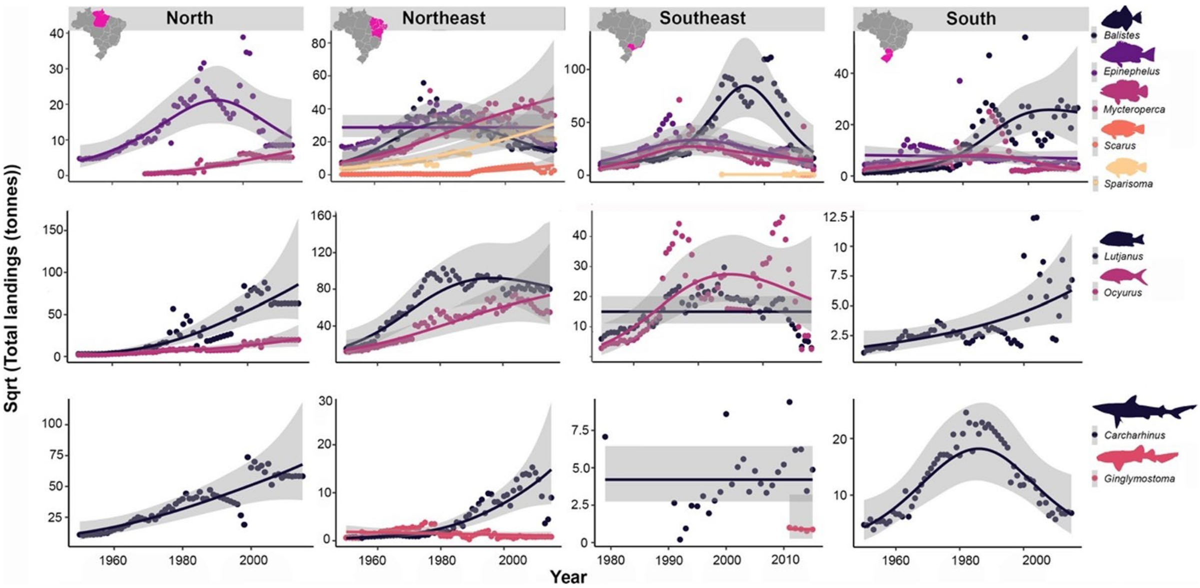


Fig. 4 Temporal and regional trends of landings for selected taxonomic groups targeted by fisheries. The Y-axis shows the square root (Sqrt) of the total landings per year. Note that the scale is not the same across plots. The trend line and uncertainty (standard error bands) were produced by fitting a Loess smoothing function to the catch amount data at the square-root scale

change from *Anisotremus*, *Mycteroperca* and *Carcharhinus* in the 1950s–1970s to *Balistes*, *Priacanthus* and *Caulolatilus* after the 2000s (Fig. S1.1).

Changes in taxonomic composition resulted in changes in trait composition. The relationship between the first PCoA axis and the average trait values per year showed a decrease in maximum size of targeted genera over time, and a decrease in the overall trophic level (from 3.92 to 3.85) (Fig. 6). Changes in the maximum and minimum depth range of the exploited genus showed more complex patterns. The maximum depth range peaked during the 1980s (~ 160 m) and then decreased (~ 145 m in 2015). The minimum depth range showed that in the 1990s, depth decreased to 5.8 m, whereas in recent years (2010 onwards) reef fisheries targeted species from ~ 6.1 m depth (Fig. 6). We did not find any relationship between genera composition and the water level—school size interaction (Fig. 6).

Finally, after projecting the genus trait space in each region over the provincial trait space, we found that the Northeast and South fisheries harvested more functionally diverse/distant species and as such exploited a larger fraction of the provincial trait space. Contrastingly, the fisheries in the Northern region were concentrated in a smaller fraction of trait space, exploiting species with greater trait similarities (Fig. 7). Moreover, relative to other regions, there is a predominance of fish from higher trophic levels in landings from the Northern region since the 1950s (see the color gradient in Fig. 7). The first two PCoA axes explained 57% of the variation in trait data.

Discussion

The Brazilian coast, namely “the Blue Amazon”, consist of a vast coast with a latitudinal gradient from tropical to warm temperate reefs, with multigear fisheries and distinct target species, making fisheries monitoring and management a real challenge. In addition, research on Brazilian reef fisheries has mostly been conducted since the 1990s (Pinheiro et al. 2018). Information consists of scarce, inconsistent and incomplete official landing data, in addition to reports, scientific peer-reviewed articles and gray literature. Yet, our results reveal dramatic changes in Brazilian reef fisheries over the past 60 years, particularly in four aspects; (1) changes in trophic

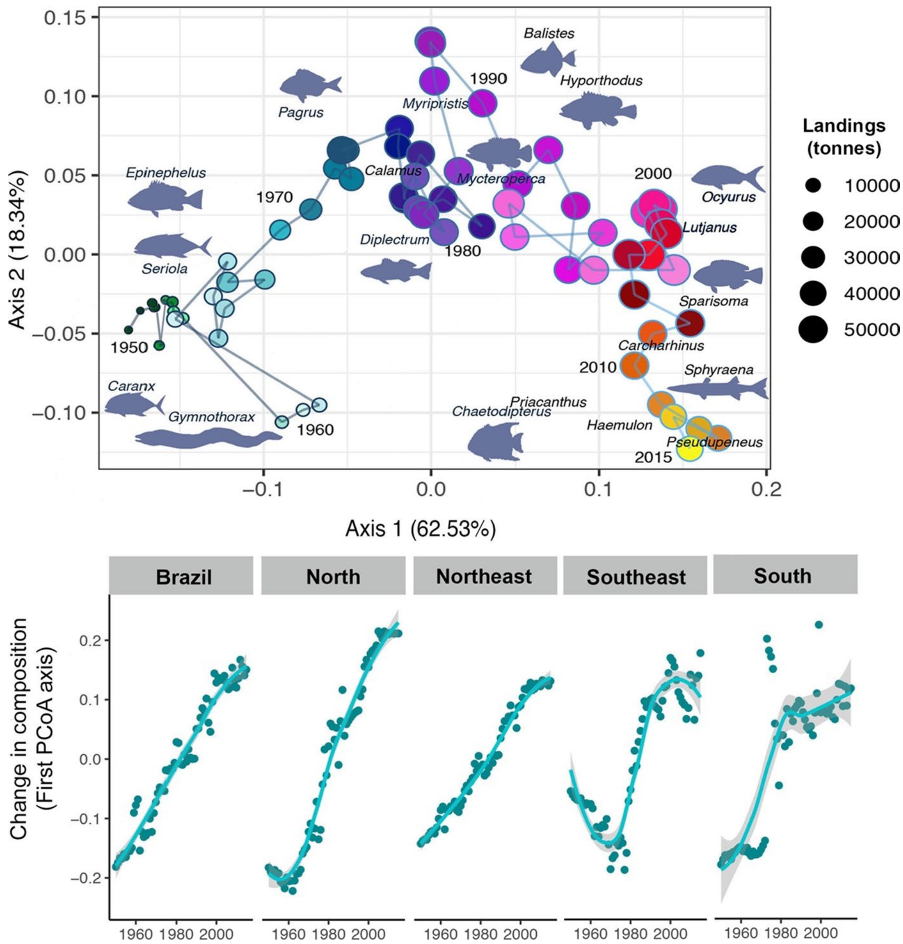


Fig. 5 Turnover in the composition of fish genera in fish landings over time plotted in two-dimensional space with Principal Coordinate Analysis (PCoA). The genera shown in the biplot (upper panel) are those presenting the strongest negative (left, $\rho <= -0.7$) and positive (right, $\rho >= 0.84$) Pearson's correlation coefficient with axis 1, and the strongest positive correlation coefficient (top, $\rho >= 0.4$) with axis 2. Bubble color represents the year, and bubble size represents the year's total landing. Note that most variation was explained by the first ordination axis, with most genera varying in catch amount along this axis; fewer genera were correlated to axis 2. Lower panels show changes in genus composition over time for all the coast and separated by region. The trend line and uncertainty (standard error bands) were produced by fitting a Loess smoothing function to the eigenvectors of the first PCoA axis

composition of landings; (2) a decrease in size of targeted genera; (3) changes in depth of species within targeted genera and (4) large differences in landing composition and volume between the four main regions (the North, Northeast, Southeast and South regions).

The average trophic level of the most harvested genera shows a similar pattern to a "fishing through the food web" scenario (sensu Essington et al. 2006), where species from lower trophic levels gradually have been added, while high-trophic level species continue to be fished. As large predators such as groupers and snappers declined, fisheries expanded to include other target species, such as triggerfish, goatfish and grunts, but also surgeon and parrotfish depending on the region (Suppl. Mat. 2). Examples of fishing down the food web are less common in coral reef ecosystems compared to other fisheries (but see Scheffer et al. 2001; Mumby et al. 2012). However, there are documented cases of phase shifts from coral to algae-dominated states when lower-trophic level species (parrotfish) have been overexploited. This

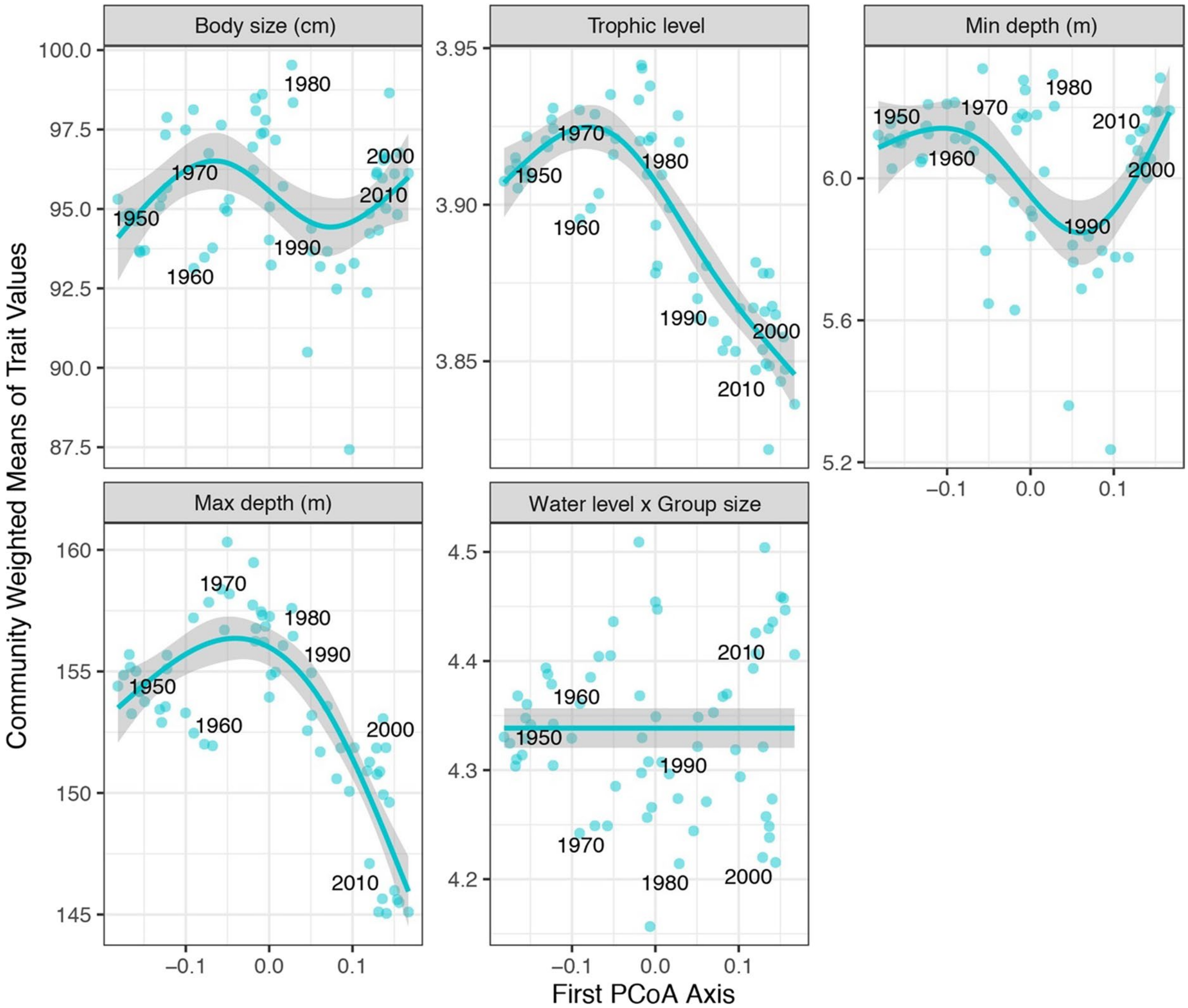
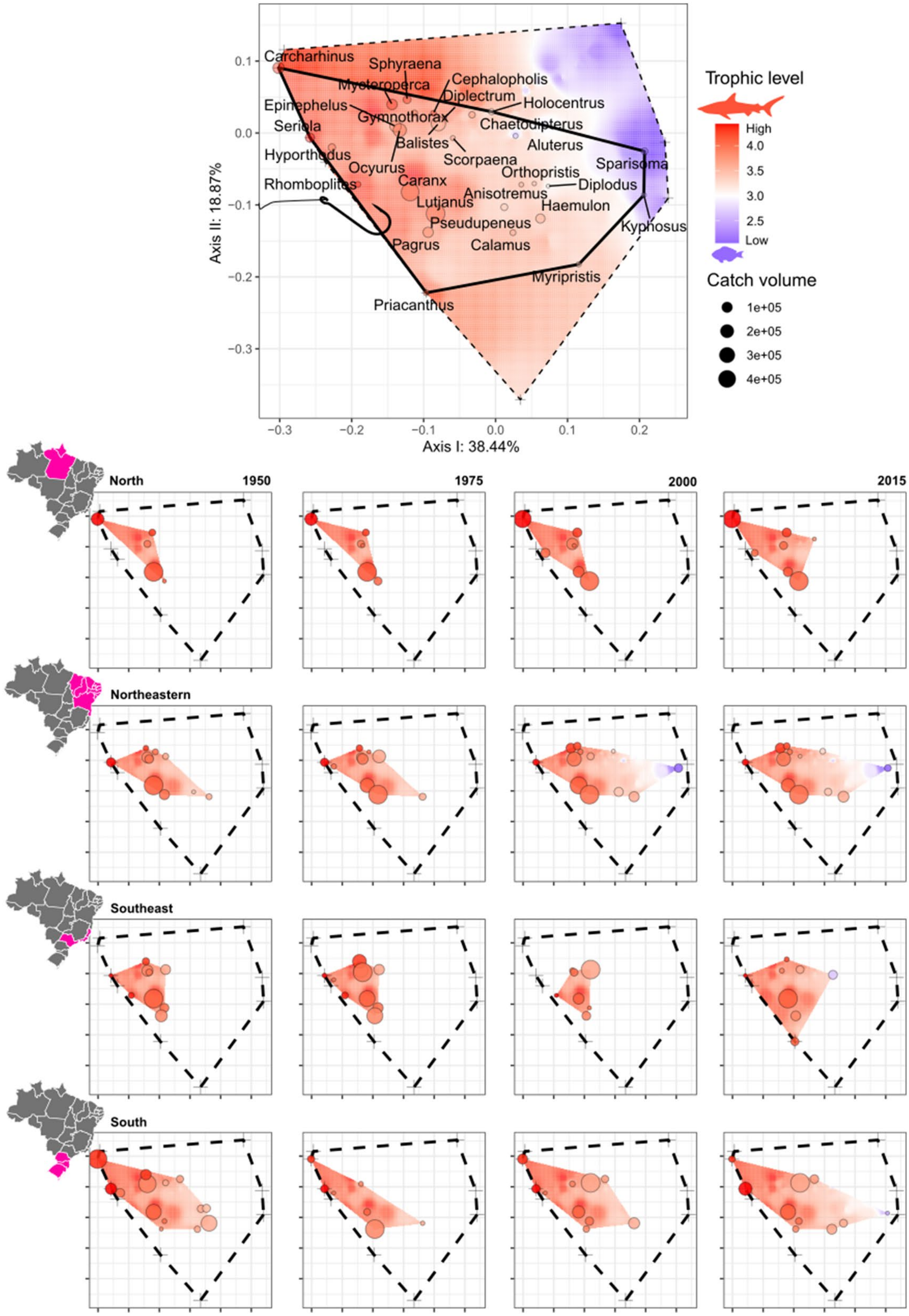


Fig. 6 Change in average maximum body size, trophic level, depth range and the interaction between level in water column and fish group size of the 15 most harvested genera of reef fish in Brazilian reef fisheries over time. The First PCoA Axis (the x-axis) comprises the main axis of change in the composition of fish genera (shown in Fig. 3), and the community weighted means of trait values (the y-axis) refer to genera trait values weighted by their landings. The trend line and uncertainty (standard error bands) were produced by fitting a Generalized Additive Model with a cubic spline and four knots to the community weighted means of trait values

is usually driven by declines of large predatory species (e.g. Hughes 1994). Trophic cascades have also been recorded such as overgrazing of seagrasses by sea urchins as a result from triggerfish overharvesting (Eklöf et al. 2008). Unfortunately, there is no documentation of or research exploring cascade effects on Brazilian reefs.

The average maximum body size of targeted species has been decreasing since the 1990s, whereas the depth range increased in the middle of the time series, but decreased again at its end. The changes in depth suggest that fisheries started to exploit deeper reefs (for species such as *Hyporthodus* spp.) and then returned to fish species that span shallower waters in recent decades, including many meso-predators, but also lower trophic level species. This reflects temporal changes in target species and market demands, but clearly indicates the classical collapse of stocks of some of the larger reef predators due to overfishing (Suppl. Mat. 2). Shifts in targeted species may be culturally or commercially driven (Yadav et al. 2021), and the international market strongly contributed


Carcharhinus
Sphyraena
Mycteroperca
Cephalopholis
Diplectrum
Holocentrus
Epinephelus
Gymnothorax
Chaetodipterus
Seriola
Balistes
Aluterus
Hyporthodus
Scorpaena
Ocyurus
Orthopristis
Sparisoma
Caranx
Diplodus
Rhomboplites
Anisotremus
Lutjanus
Haemulon
Pseudupeneus
Kyphosus
Pagrus
Calamus
Myripristis
Priacanthus
Axis II: 18.87%
Axis I: 38.44%
Trophic level
High
4.0
3.5
3.0
2.5
Low
Catch volume
1e+05
2e+05
3e+05
4e+05
North
Northeastern
Southeast
South
1950
1975
2000
2015

◂**Fig. 7** Patterns of exploitation of the functional trait space of Brazilian reef fish. The upper panel delineates the functional trait space of landed reef fish genera (represented by a polygon outlined by a solid line, marked with a hook) in relation to the total trait space of the Brazilian province (outlined by a dotted line). The lower panels illustrate the functional trait space of reef fish genera landed per region in selected years, with circle size proportional to landing amounts. The color gradient in the lower panels represents variations in fish trophic levels across genera, generated using an Inverse Distance Weighting kriging

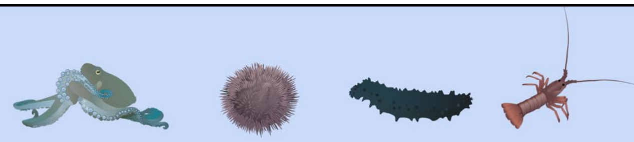
in shaping the reef fisheries through demand for red snapper, and by exploiting smaller "plate-sized fish" (Martins et al. 2005). This includes smaller snappers, parrotfish and goatfish from the Northeast, and sea breams from the Southeast (Suppl. Mat. 2). This pattern also indicates the classical collapse of stocks of some of the larger reef predators due to overfishing, especially on the shallower reefs.

Finally, regional differences in fisheries result in some areas landing a greater quantity and higher diversity of reef fish caught by artisanal fisheries (the North and Northeast regions), while others rely more heavily on industrial fisheries (the South and Southeast regions) focusing on fewer species. The more recent Northern fisheries are largely focused on the Southern red snapper *L. purpureus, Scomberomorus* spp. and spiny lobster, almost exclusively targeting carnivorous species. There is a considerable overlap in target species between the Northeast and Southeast, with the tropical reefs of the Northeast the most diverse regarding reef-associated fish, harvesting species from a large range of trophic categories such as spiny lobster, groupers, snappers, parrotfish (*Scarus* spp., *Sparisoma* spp.), goatfish (Mullidae) and surgeonfish (*Acanthurus* spp.). Subtropical reefs of the Southeast and South regions provide a comparatively higher biomass of cold-water species such as sea breams (Sparidae).

Targeting fish from a range of different trophic levels is common in tropical coral reef fisheries and does not necessarily mean that fisheries are unsustainable (Munro et al. 1996; Martin et al. 2017). Balanced harvest (e.g. targeting fish from an equal range of trophic levels and sizes; Garcia et al. 2012), has been suggested as an option in reef fishery management (Pelage et al. 2021). Indeed, for some regions it has proved to reduce biomass fluctuations, which could mitigate the impact of changing environmental and fisheries conditions as long as fishers exploit a diverse set of species (Vargas et al. 2022). The current situation in Brazil is problematic because many of the stocks are overexploited or subjected to intense fishing pressure without information on population status (Vasconcelos et al. 2007; MMA 2018a, b, c; Dias 2022). Effects of fishing are clearly visible on shallower reef systems, where there are low abundances and biomass of larger species (e.g. *E. itajara, M. bonaci, S. trispinosus*) (Morais et al. 2017). Top predators such as reef-associated sharks comprise a small part of fish landings, but have nevertheless suffered severe reductions in population size (MMA 2018a, b, c). Statistical catch data of elasmobranchs has always been neglected due to illegal fishing and underreporting of the true catch, but even with poor data on landings, our findings show that landings of *Carcharhinus* in the North region are the highest in the country and have increased more than twofold in 40 years (Fig. 5). Brazil is one of the top countries in shark fisheries and consumption, and also importing shark meat to meet market demands (Almerón-Souza et al. 2018; Bornatowski et al. 2018; Pincinato et al. 2022). This is worrisome, as shark meat is cheap and there is low public awareness regarding the unsustainability of this resource (Pincinato et al. 2022).

Apart from top predators, a number of key stone species are targeted, such as *Balistes vetula*, an important sea urchin consumer, which was heavily targeted with no information on sustainable levels before long term monitoring programs using visual census could report declines of this species. Nevertheless, *B. vetula* continues to be targeted by fishing fleets in the Northeast and Southeast regions. Likewise, a large dimension of reef fish trait diversity might be compromised by overfishing and lack of management. Due to low regional species richness and low functional redundancy in the Brazilian biogeographic province, the loss of taxa possessing specific or unique traits caused by overfishing may have disproportionate effects on reef ecosystem functions and services (Halpern & Floeter 2008; Martins et al. 2012a). The focus on top predators and large carnivores by fisheries has led to decreased functional diversity on fished reefs (Rolim et al. 2022), although few studies have investigated this subject and associated ecosystem effects. To that end, there is an urgent need to increase the collection and accessibility of biodiversity monitoring data (including both taxonomic and functional assessments), as well as to identify which traits confer

Invertebrate fisheries on reefs



Invertebrates including lobster, octopus and echinoderms (e.g. sea urchins, starfish and sea cucumbers) are harvested on Brazilian reefs. The first two constitute valuable monetary resources to coastal populations, while the latter is usually only locally exploited for subsistence or souvenirs. The lobster fishery is the largest fishery, targeting *Panulirus* spp. and operating in the North, Northeast and Southeast regions, where it is mainly fished in Espírito Santo (Bentes et al. 2012, Cruz et al. 2020, Freire et al. 2021). In the Northeast Region, spiny lobsters (*Panulirus meripurpuratus*, *P. laevicauda* and *P. echinatus*) are one of the most valuable fishery resources, supplying both national and international markets (91.8 million USD in exports 2019) (Cruz et al. 2020) as well as providing job opportunities (Ivo and Pereira 1996). On the Great Amazon Reef System, bottom driftnets and traps are used (Bentes et al. 2012) and in the Northeast and Southeast regions, traps and prohibited gears (hookah diving and gillnets) are also practiced (Netto and Beneditto 2007, Duarte et al. 2011, Cavalcante 2014, Cruz et al. 2020).

The commercial lobster fishery was initiated in the Northeast region by 1955, in Ceará (Paiva et al. 1971), and in the Abrolhos Bank in the late 1970s (Ivo & Pereira 1996), and then expanded to the North region in the late 1980s (Bentes et al. 2012, Alves et al. 2020). This fishery has suffered from insufficient monitoring, ineffective management and unsustainable practices with negative socio-ecological consequences (Cintra et al. 2013, Cavalcante 2014). Signs of overexploitation were detected in the 1970s, with catches peaking in 1979 (11 033 tonnes) and then declining (Cruz et al. 2020). Although there is still debate on its sustainability, catches have remained below maximum sustainable yield over the last decade although with increasing CPUE (Dias Neto 2008, Cruz et al. 2020).

The lobster fishery has been subjected to management aiming at improving and regulating fisheries, including periodic closures, size limits, prohibition to fish berried females (i.e. females carrying eggs) and gear restrictions (Cavalcante 2014). One of the most devastating resolutions for coastal ecosystems were the legalization of gillnets between 1995 and 2007 (Cavalcante 2014, Nogueira 2016). Gillnets have negative effects on stocks from catching immature individuals, with substantial bycatch (Giglio & Bornatowski 2016, Nogueira 2016). When gillnets were prohibited in 2007, more than 12 million meters of nets were confiscated (Cavalcante 2014). Unfortunately, gillnets continue to be used illegally due to lack of enforcement (Cruz et al. 2020).

The octopus fishery is one of the least studied reef fisheries in Brazil, despite occurring in the Northeast (mainly *O. insularis*), Southeast and South regions (mainly *O. americanus*). In the Northeast, consumption has historically been low (Nóbrega et al. 1975), but octopus is a profitable fishery today and an important source of income for coastal communities (Andrade 2015, Batista et al. 2022). Octopus is fished either by diving or walking on the coastal reefs in low tide (i.e. gleaning), using simple tools such a metal

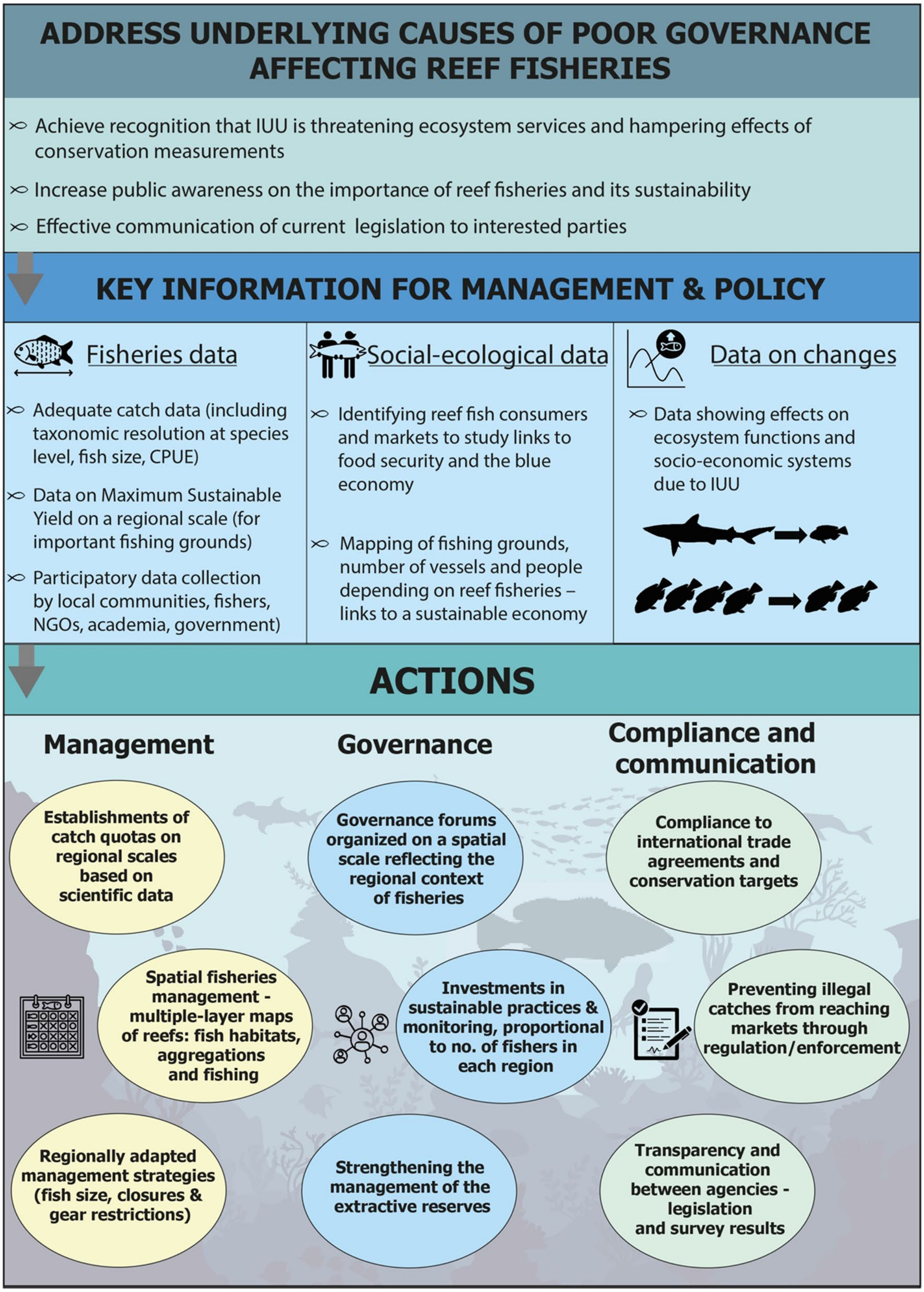
Box 1 Invertebrate fisheries on Brazilian reefs. Images from the Integration and Application Network, University of Maryland stick with a bent end (Table 2) (Leite et al. 2010, Haimovici et al. 2014, Lopes et al. 2021). Octopus is one of the few resources that remain on the most accessible reefs (e.g. accessible by walking). Fishing with pots mounted on longlines is common on subtidal reefs (Braga et al. 2007, Haimovici et al. 2014, Lopes et al. 2022), and hookah or free diving also occurs (Haimovici et al. 2014). Octopus landings increased substantially 2021, Batista et al. in the first decade of the 2000s (from about 200 tonnesin 2000 to 1000 tonnesin 2009), followed by a decline in 2010, probably due to overexploitation (Haimovici et al. 2014, IP 2021). In 2015, the total reported catch from the Northeast region was 156 tonnes (IP 2021),with no sharp decline in harvest during the last decades (Batista et al. 2022). Across regions, licenses, minimum sizes and maximum number of pots per vessel were introduced as management strategies (Haimovici et al. 2014; Batista et al. 2022), but enforcement is limited (Batista et al. 2022).

Other invertebrates such as sea urchins, starfish, corals, conchs and sea cucumbers, are exploited commercially for food, aquarium, and souvenir trade in Brazil (Gasparini et al. 2005, Dias et al. 2008, Martins et al. 2012b, Gurjão and Lotufo 2018), including endangered species (Pinheiro et al. 2018b). Sea urchins have been consumed as a delicacy and harvested at small scales in São Paulo (Marenzi et al. 2006), Bahia (Carneiro and Cerqueira, 2008), and Pernambuco (Santos et al. 2021). Sea cucumbers have a high value on the Asian market (Rahman et al. 2020) and have been exploited in Brazil (Hadel et al. 1999, Freire et al. 2021), although prohibited to fish in Brazil since 1998 (Brasil 1998, 2009). Different shellfish, especially large conchs, but also starfish disappeared in many places before the 1980s, following reports of local extinctions (Gasparini et al. 2005; Dias et al. 2011). The aquarium and souvenir trade also target corals (Pinheiro et al. 2018b), where the majority of the extraction was initiated in the 1980s (Gasparini et al. 2005). Collecting of fire corals (Milleporids) have damaged the reefs by decreasing its structural complexity. Fishing efforts of these species are unreported and, because of the sensitivity of many invertebrate populations to harvesting and their functional importance on reefs, there is a need for urgent monitoring, regulation and enforcement (Uthicke et al. 2009).

Box 1 (continued)

species vulnerability to overexploitation and how the loss of these species may impact ecosystem function.

Fishing along the latitudinal gradient of the Brazilian coast, including tropical to subtropical/warm-temperate reef species, consists of a complex scenario for multitarget management priorities. A factor that contributes to the spatial heterogeneity in landing volumes is productivity, which varies strongly along the coast, with high productivity in upwelling, subtropical regions (e.g., Espírito Santo and Rio de Janeiro in the Southeast), and in the tropical region where there are large rivers (e.g., the North region), with oligotrophic conditions where these are lacking (e.g., much of the Northeast region) (Miloslavich et al. 2011; Morais et al. 2017). Consequently, maximum multispecies sustainable yield should vary along the coast, which is why management and quotas would need to be locally adapted. Maximum possible harvest for shallow reefs in Brazil may be lower than in the tropical Pacific, based on a smaller area of shallow flats suitable for gleaning (e.g. harvesting resources by walking with no or very simple tools), and the lower richness and abundance of planktivorous fish (Pinheiro et al. 2018), which in the Indo-Pacific has been linked to productive fishing spots (Morais et al. 2021). The Caribbean is less productive


ADDRESS UNDERLYING CAUSES OF POOR GOVERNANCE AFFECTING REEF FISHERIES
Achieve recognition that IUU is threatening ecosystem services and hampering effects of conservation measurements
Increase public awareness on the importance of reef fisheries and its sustainability
Effective communication of current legislation to interested parties
KEY INFORMATION FOR MANAGEMENT & POLICY
Fisheries data
Adequate catch data (including taxonomic resolution at species level, fish size, CPUE)
Data on Maximum Sustainable Yield on a regional scale (for important fishing grounds)
Participatory data collection by local communities, fishers, NGOs, academia, government)
Social-ecological data
Identifying reef fish consumers and markets to study links to food security and the blue economy
Mapping of fishing grounds, number of vessels and people depending on reef fisheries – links to a sustainable economy
Data on changes
Data showing effects on ecosystem functions and socio-economic systems due to IUU
ACTIONS
Management
Governance
Compliance and communication
Establishments of catch quotas on regional scales based on scientific data
Governance forums organized on a spatial scale reflecting the regional context of fisheries
Compliance to international trade agreements and conservation targets
Spatial fisheries management - multiple-layer maps of reefs: fish habitats, aggregations and fishing
Investments in sustainable practices & monitoring, proportional to no. of fishers in each region
Preventing illegal catches from reaching markets through regulation/enforcement
Regionally adapted management strategies (fish size, closures & gear restrictions)
Strengthening the management of the extractive reserves
Transparency and communication between agencies - legislation and survey results

◂**Box 2** Suggestions for management of reef fisheries. Abbreviations: *IUU* Illegal, Unreported and Unregulated fisheries, CPUE = Catch Per Unit Effort

than the Indo-Pacific, and Brazil probably falls in the same category (Munro et al. 1996). Determining the maximum multispecies sustainable yield of Brazilian reef fisheries, considering local characteristics, would be a fundamental step in ecosystem-based resource management (e.g. McClanahan et al. 2023). On species level, tropical-associated species like parrotfish, which occur on both subtropical and tropical reefs (Ferreira et al. 2004; Morais et al. 2017), need differential management models within regions, as demonstrated by the collapse of the endemic Greenbeak parrotfish in the Southeast (Bender et al. 2014). Parrotfish like the large Greenbeak parrotfish and other species endemic to the Brazilian Province do not find optimal refuge in deep cold habitats of the subtropical southeast and southern rocky reefs. The population collapse on the shallow reefs for these tropical-associated species therefore means local extinction (Bender et al. 2014). In the tropical regions, mesophotic reefs can still provide refuge for many of the larger parrotfish species as well as a number of tropical-associated reef fish species.

Brazilian reef fisheries differ from reef fisheries in other low- and middle- income countries in several social-economic aspects. The importance of subsistence fishing on reefs appears to be low or restricted to few locations (see, e.g., Santos 2015), while in many other countries subsistence fishing is the main purpose of tropical reef fisheries (Munro et al. 1996; Kittinger et al. 2015; Mora 2015). This pattern can usually be linked to the local availability of agricultural products and cultural customs with preference for other protein sources (Munro et al. 1996; Viana et al. 2021). In the Maldives, for example, tuna has historically been preferred over reef fish (Yadav et al. 2021), while in Asia and the Indian Ocean, hundreds of reef species compose the catch (Unsworth et al. 2018). In many regions of Brazil, beef is preferred to fish, and hence consumption of marine fish is low (< 10 kg per person and year, OWID 2022). Fish consumed in Brazil include pelagic fish (mainly sardines) or mullets in the south, while codfish (following the Portuguese tradition), salmon (for sushi) and shark meat is imported (IBGE 2020; MDIC 2022). In the tropical Northeast, reef fish are more commonly consumed by coastal communities and largely available in restaurants when compared to subtropical regions of the country. High-trophic level species are often more valuable on the commercial market and will be sold, while low-trophic level, less valuable species may be consumed by fishers (da Cunha et al 2023). It is possible that availability of other food sources (agricultural products and estuarine food resources) have prevented exploitation of a more diverse set of reef species. In this sense, reef resources may be more important as a source of income than as protein for most coastal communities. Commercial fisheries targeting the national and international markets seem to be the main drivers of extraction of reef resources, along with recreational spearfishing in some parts of the country. To elucidate the importance of reef fish as protein for coastal communities and consumer habits, there is an urgent need for studies targeting consumption habits and socio-ecological contexts as well as data from local fisheries.

Management strategies for reef fish in Brazil currently in place consist mainly of marine protected areas, offering partial protection (Magris 2021; Ferreira et al. 2022). However, only a small percentage of the reefs are in no-take zones (3.6%) (Magris et al. 2020). Fisheries management measures include some species-specific rules, and those are applied throughout the EEZ. An exception are the rules for gillnet fishing and trawling, which are region-specific (IN n.º12/2012, IN MMA n.º14/2004). Gear restrictions and seasonal bans for a few species also exist (e.g., lobster, cubera snapper, red snapper and black, red and yellowmouth grouper) (Decree MMA N. 6 and N. 59C), as well as minimum sizes for lobster, certain grouper species and red snapper (MMA 2005, 2018a, c). These are strategies usually considered to minimize damage in a system already exposed to intense fishing (Munro et al. 1996), but their level of implementation is uncertain. While size limits are the same across the whole country for the majority of species, despite possible regional differences, certain species are subjected to size limits only in restricted parts of the country (e.g., *B. vetula*, *Mycteroperca* spp.) (MMA 2018c). In addition, 42 species are under permanent fishing bans due to their threatened population status (e.g., the Atlantic Goliath grouper—*Epinephelus itajara*, the Greenbeak parrotfish—*Scarus trispinosus*), except for in certain areas with management plans (such as extractive reserves or other types of MPAs) (MMA Nº 445 2014; MMA/ICMBio Nº 285 2021, Pinheiro et al 2021). However, nine species that are considered facing the lowest risk of extinction (listed as "Vulnerable" in the official national red list) are allowed to be fished within MPAs, but monitoring of their population status is lacking. In general, more reef-associated species such as groupers and parrotfish seem to be more severely impacted by fishing compared to fast-swimming, more pelagic trevallies and jacks. Management strategies for these species are contained in recovery plans (e.g., for *M. bonaci L. cyanopterus,* and most parrotfish), but there is no available information on current landings or what would be considered acceptable, indicating that the management plans are not really applied. From the last official statistics in 2015, more than 800 t of *M. bonaci* were landed only in the Northeast region. Unfortunately, most management strategies suffer from weak enforcement and certain species remain being exploited illegally and appear in large volumes in the fish landings (e.g., *Epinephelus morio* and *S. trispinosus*) (Roos et al. 2020; Pinheiro et al. 2021). There appear to be limited communication of fishing rules and legislation to rightholders such as fishing communities and stakeholders such as markets and consumers.

Considering the impacts of overfishing on ecosystem services, as well as the socioeconomic importance of reef resources in Brazil with hundreds of thousands of fishers operating on the reefs (although the precise dimension of the number of reef fishers is not available) and people involved in the productive chains, we emphasize the need for investments in obtaining, systematizing and integrating information and data on reef fisheries across the country (Box 2). Landing and fishing effort data represent a baseline information to achieve a sound management for future sustainable harvest and ecosystem functioning (Pitcher et al. 2002). We highlight the urgent need for accurate landing data, including proper species identification, fish sizes and catch per unit effort (CPUE) (see Box 2). This information could be incorporated in ecosystem-based policies for management. Basic information from fisheries monitoring is imperative, since the data-poor scenario makes management of reef resources a difficult challenge in the Brazilian Blue Amazon.

Acknowledgements This research was conducted by the Reef Synthesis Working Group (ReefSYN) funded by the Synthesis Center on Biodiversity and Ecosystem Services, National Council for Scientific & Technological Development (SinBiose, CNPq, #442417/2019-5 to MGB). LE received a post-doctoral fellowship from CNPq (#150095/2022-8). ALL received post-doctoral fellowships from CNPq (#153024/2022-4, #164240/2021-7, #151228/2021-3, #152410/2020-1). HTP thanks Fundação de Amparo à Pesquisa do Estado de São Paulo (grant 2019/24215-2; 2021/07039-6). PFML thanks CNPq for a productivity grant (302365/2022-2), TCM thanks CNPq for a postdoctoral fellowship (#102450/2022-6) and GOL is also grateful to a research productivity scholarship provided by CNPq (308072/2022-7). JAR-F received a scholarship for post-doctoral fellowship from FADESP (#339020/2022). The authors also wish to thank M. Dias, M. Vianna and J. Anchieta for advice and information regarding Brazilian fisheries and an anonymous reviewer for useful comments.

Authors' contributions

L Eggertsen led the literature review and manuscript writing, supervised by MG Bender. AL Luza led data analysis, supervised by CS Dambros, MS Dias, and CAMM Cordeiro. All authors contributed to the conceptualization and the text of the manuscript.

Data availability The data and R routine used to conduct this research are available at https://github.com/Sinbiose-Reefs/diagnostics

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Almerón-Souza F, Sperb C, Castilho CL, Figueiredo P I, Gonçalves LT, Machado R, Fagundes NJ (2018) Molecular identification of shark meat from local markets in Southern Brazil based on DNA barcoding: evidence for mislabeling and trade of endangered species. Frontiers in Genetics 9: 38

Almeida Z, Andrade-Tubino M, Andriguetto-Filho J, Bentes da Silva J, Cardoso A, Castello J, Doxsey J, Duarte-Neto P, Espirito Santo R, Feitosa S, Frédou T, Haimovici M, Hellebrandt D, Isaac V, Krul R, Lessa R, Lucena Fredou F, Martins A, Monteiro A, Monteiro-Neto C, Mourão K, Papoula N, Paz A, Pizetta G, Prestelo L, Rodrigues C, Santos L, Santos N, Silva P, Sunyé P, Tubino R, Vieira A, Wanderley A (2011) Sistemas pesqueiros marinhos e estuarinos do Brasil caracterização e análise da sustentabilidade. FURG, Rio Grande do Sul, Brazil

Alves ADB, Daniel F, Lima M (2020) Trabalhadores das águas: impactos socioeconômicos e mudanças na pesca artesanal (Bragança-PA). Pap Do Naea 1:1–26

Anderson L, Houk P, Miller MG, Cuetos-Bueno J, Graham C, Kanemoto K, Terk E, McLeod E, Beger M (2022) Trait groups as management entities in a complex, multispecies reef fishery. Conserv Biol 36:e13866

Andrade L (2015) Estratégias de exploração e comércio da pesca artesanal de polvo. 129f. PhD thesis - Centro de Biociências, Universidade Federal do Rio Grande do Norte, Natal

Aragão JA (2018) Plano de Recuperação do Pargo (*Lutjanus purpureus*), Ministério de Meio Ambiente, Brasília

Araujo LS, Rodrigo U, Louzada TS, Salomon PS, Moraes FC, Ferreira BP, Paes ETC, Bastos AC, Pereira RC, Salgado LT, Lucia M, Yager P, Moura RL (2021) Growing industrialization and poor conservation planning challenge natural resources' management in the Amazon Shelf off Brazil. Mar Policy 128:104465

Aschenbrenner A, Oliveira M, Rodrigues G, Rocha A, Leão R, Moura D, Francini-Filho RB, Minte-Vera C, Padovani B (2017) Age, growth parameters and fisheries indices for the lane snapper in the Abrolhos Bank, SW Atlantic. Fish Res 194:155–163

Barbosa MC, Luiz OJ, Cordeiro CA, Giglio VJ, Ferreira CE (2021) Fish and spearfisher traits contributing to catch composition. Fish Res 241:105988

Bascompte J, Melia CJ, Sala E (2005) Interaction strength combinations and the overfishing of a marine food web. PNAS 102:5443–5447

Batista B, Matthews-Cascon H, Marinho R, Kikuchi E, Haimovici M (2022) The growth and population dynamics of *Octopus insularis* targeted by a pot longline fishery in north-eastern Brazil. J Mar Biol Assoc UK 101:935–946

Begossi A, Silvano RAM (2008) Ecology and ethnoecology of dusky grouper [garoupa, *Epinephelus marginatus* (Lowe, 1834)] along the coast of Brazil. J Ethnobiol Ethnomed 14:1–14

Begossi A, Lopes P, de Oliveira L, Nakano H (2009) Ecologia de Pescadores Artesanais da Baía da Ilha Grande. RIMA Editora, São Carlos, Brazil

Bevilacqua AHV, Carvalho AR, Angelini R, Christensen V (2016) More than Anecdotes: fishers' ecological knowledge can fill gaps for ecosystem modeling. PLoS ONE 11:e0155655

Bender MG, Machado GR, de Azevedo Silva PJ, Floeter SR, Monteiro-Netto C, Luiz OJ, Ferreira CEL (2014) Local ecological knowledge and scientific data reveal overexploitation by multigear artisanal fisheries in the Southwestern Atlantic. PLoS ONE 9:e110332

Beneditto A (2001) A pesca artesanal na costa norte do Rio de Janeiro. Bioikos 15:103–107

Bentes B, Isaac VJ, Almeida MC (2012) Multidisciplinary approach to identification of fishery production systems on the northern coast of Brazil. Biota Neotrop 12:81–92

Bornatowski H, Braga RR, Barreto RP (2018) Elasmobranchs consumption in Brazil: impacts and consequences. Advances in Marine Vertebrate Research in Latin America: Technological Innovation and Conservation 251–262

Brandini F (2013) Marine biodiversity and sustainability of fishing resources' state in Brazil: a case study of the coast of Paraná. Reg Environ Chang 14:2127–2137

BRASIL (1998) Lei Federal Nº 9605/1998, de 12 de fevereiro de 1998. Federal law that regulates criminal and adminstrative sanctions arising from harmful conducts and activities against the environment. (Portuguese only)

BRASIL (2009) Lei Nº 11,959/2009, de 29 de junho de 2009. Federal law that deals with the National Policy for the Sustainable Development of Aquaculture and Fisheries, regulates fishing activity and other subjects. indicates general rules about the sustainable use marine resources, aquaculture and related subjects. (Portuguese only)

Carneiro LS, Cerqueira WRP (2008) Informações sobre o ouriço-do-mar *Echinometra lucunter* (Linnaeus, 1758) (Echinodermata: Echinoidea) para o litoral de Salvador e adjacências. Sitientibus 8(1):168–171

Carvalho R, Cunha F, Montezuma A, Araújo ME (2013) Captura e processamento de peixes recifais no estado do Rio Grande do Norte, Brasil. Acta Fish Aquat Resour 1:91–103

Carvalho F, Castello L, Ferreira B, McDonald G, Power M (2021) Gear selectivity of functional traits in coral reef fisheries in Brazil. Coral Reefs 40:1915–1929

Carvalho Braga MSDC, Marinho RA, Batista BB, Rocha EP (2007) Histórico e descrição da pesca do polvo, Octopus cf vulgaris, com potes, no estado do Ceará

Castelao RM, Campos EJD, Miller JL (2004) A modelling study of coastal upwelling driven by wind and meanders of the Brazil current. J Coastal Res 20(3):662–671

Castello J, Haimovici M, Odebrecht C, Vooren C (1997) The Continental Shelf and Slope. Subtropical convergence environments: the coast and sea in the southwestern Atlantic. Springer, New York, pp 171–179

Castro CB, Pires DO (2001) Brazilian coral reefs: what we already know and what is still missing. Bull Mar Sci 69:357–371

Cavalcante P (2014) Ordenamento da pesca de lagosta *Panulirus argus* e *Panulirus laevicauda* e a recuperação da sustentabilidade das pescarias no litoral do Brasil: uma proposta inovadora do ordenamento pesqueiro. PhD thesis, Universidade Federal do Ceará

Cinner J (2014) Coral reef livelihoods. Curr Opin Environ Sustain 7:65–71

Cintra I, Gasalla M, Bert P (2013) Assessment of wild spiny lobster stocks on the Brazilian continental shelf. Crustaceana 86:336–356

Coleman MA, Bates AE, Stuart-Smith RD, Malcolm HA, Harasti D, Jordan A, Knott NA, Edgar GJ, Kelaher BP (2015) Functional traits reveal early responses in marine reserves following protection from fishing. Divers Distrib 21:876–887

Collette BB, Rutzler K (1977) Reef fishes over sponge bottoms off the mouth of the Amazon. In: Proceedings of the 3rd International Coral Reef Symposium, pp 305–310

CONAB (2022) Boletim Hortigranjeiro. Edição Especial Pescados. Distrito Federal, v. 8, n. 4, Companhia Nacional de Abastecimento, Brasília, Brazil

Cruz R, Santana J, Barreto C, Borda C, Torres M, Gaeta J, da Silva J, Saraiva S, Salazar I, Cintra I (2020) Towards the rebuilding of spiny lobster stocks in Brazil: a review. Crustaceana 93:957–983

Cunha S, Firme Hebst D, Macedo-Soares LCP, Jussara M, Hanazaki N (2023) Selection of fish resources for consumption and sale by artisanal fishers and implications to fisheries sustainability. Fish Res 261:106615

Darling ES, D'Agata S (2017) Coral Reefs Fishing for Sustainability. Curr Biol 27:57–76 de Oliveira VS, Andrade HA, Hazin FHV, Vieira AC (2018) Pesca da lagosta com covos na costa central de Pernambuco: taxas de captura da lagosta e fauna acompanhante. Boletim do Instituto de Pesca 41(2):373–385

Debastiani VJ, Pillar VD (2012) SYNCSA — R tool for analysis of metacommunities ased on functional traits and phylogeny of the community components. Bioinformatics 28:2067–2068

Dias M (2022) Uma avaliação integrada da governança, da situação dos estoques e das pescarias, 2nd ed. Oceana Brasil, Brasília

Dias TLP, Leo Neto NA, Alves RRN (2011) Molluscs in the marine curio and souvenir trade in NE Brazil: species composition and implications for their conservation and management. Biodivers Conserv 20:2393–2405. https://doi.org/10.1007/s10531-011-9991-5

Dias Neto J (2008) Plano de gestão para o uso sustentável de Lagostas no Brasil. Brasília: Ibama

Diegues C (1983) Pescadores, camponeses e trabalhadores do mar. Ed. Ática, São Paulo, Brazil

Dittmar T, Lara RJ (2001) Do mangroves rather than rivers provide nutrients to coastal environments south of the Amazon River? Evidence from long-term flux measurements. Marine Ecol Progress Series 213:67–77

Duarte L, Severino-Rodrigues E, Gasalla M (2011) Contextualization of world fisheries lobsters and trade characteristics of *Scyllarides* spp. and *Panulirus* spp. in Baixada Santista, São Paulo state. Brazil Bol Inst Pesca São Paulo 37:235–246

Dulvy NK, Fowler SL, Musick JA, Cavanagh RD, Kyne M, Harrison LR, Carlson JK, Davidson LNK, Fordham SV, Francis MP, Pollock CM, Simpfendorfer CA, Burgess GH, Carpenter KE, Compagno LJ, Ebert DA, Gibson C, Heupel MR, Livingstone SR, Sanciangco JC, Stevens JD, Valenti S, White WT (2014) Extinction risk and conservation of the world ' s sharks and rays. Elife 3:1–34

Eklöf J, Torre-Castro M, Gullström M, Uku J, Muthiga N, Lyimo T, Bandeira S (2008) Sea urchin overgrazing of seagrasses: a review of current knowledge on causes, consequences, and management. Estuar Coast Shelf Sci 79:569–580

Essington TE, Beaudreau AH, Wiedenmann J (2006) Fishing through marine food webs. PNAS 103:3171–3175

Feitosa LM, Paula A, Martins B, Giarrizzo T, Monteiro IL, Gemaq R, Luiz J, Nunes S, Gomes F, Schneider H, Sampaio I, Souza R, Braullio Sales J, Rodrigues-Filho LF, Tchaicka L, Carvalho-Costa LF (2018) DNA-based identification reveals illegal trade of threatened shark species in a global elasmobranch conservation hotspot. Sci Rep 8:1–11

Fenner D (2012) Challenges for managing fisheries on diverse coral reefs. Diversity 4:105–160

Ferreira CEL, Floeter SR, Gasparini JL, Ferreira BP (2004) Trophic structure patterns of Brazilian reef fishes: a latitudinal comparison. J Biogeog 31:1093–1106

Ferreira HM, Magris RA, Floeter SR, Ferreira CE (2022) Drivers of ecological effectiveness of marine protected areas: A meta-analytic approach from the Southwestern Atlantic Ocean (Brazil). J of Environ Manage 301:113889

Floeter SR, Halpern BS, Ferreira CEL (2006) Effects of fishing and protection on Brazilian reef fishes. Biol Conserv 128:391–402

Fogliarini C, Ferreira C, Bornholdt J, Barbosa M, Giglio V, Bender M (2021) Telling the same story: fishers and landing data reveal changes in fisheries on the Southeastern Brazilian Coast. PLoS ONE 16:e0252391

Francini-Filho RB, Moura RL (2008) Evidence for spillover of reef fishes from a no-take marine reserve: an evaluation using the before-after control-impact (BACI) approach. Fish Res 93:346–356

Francini-Filho RB, Coni EOC, Meirelles PM, Amado-Filho GM, Thompson FL et al (2013) Dynamics of coral reef Benthic assemblages of the Abrolhos Bank, Eastern Brazil: inferences on Natural and Anthropogenic Drivers. PLoS ONE 8(1):e54260. https://doi.org/10.1371/journal.pone.0054260

Francini-Filho RB, Asp NE, Siegle E, Hocevar J, Lowyck K, D'Avila N, Vasconcelos AA, Baitelo R, Rezende CE, Omachi CY, Thompson CC, Thompson FL (2018) Perspectives on the Great Amazon Reef: extension, biodiversity, and threats. Front Mar Sci 5:142. https://doi.org/10.3389/fmars.2018.00142

Francini-Filho RB et al (2019) Brazil. In: Loya Y, Puglise K, Bridge T (eds) Mesophotic Coral Ecosystems. Coral Reefs of the World, vol 12. Springer, Cham. https://doi.org/10.1007/978-3-319-92735-0_10

Frédou T (2004) The fishing activity on coral reefs and adjacent ecosystems. A case study of the Northeast of Brazil. PhD thesis, Universidade Federal de Pernambuco, Brazil

Frédou T, Ferreira BP, Letourneur Y (2009) Assessing the stocks of the primary snappers caught in Northeastern Brazilian reef systems. 1: traditional modelling approaches. Fish Res 99:90–96

Freire K, Almeida da Silva Z, Trindade Amador J et al (2021) Reconstruction of marine commercial landings for the Brazilian industrial and artisanal fisheries From 1950 to 2015. Front Mar Sci 8:1–16

Freitas MO, Moura RLDE, Francini-Filho BR, Minte-Vera CV (2011) Spawning patterns of commercially important reef fish (Lutjanidae and Serranidae) in the tropical western South Atlantic. Sci Mar 75:135–146

Froese R, Pauly D (2022) FishBase. World Wide Web electronic publication. http://www.fishbase.org/

Garcia SM, Kolding J, Rice J, Rochet M-J, Zhou S, Arimoto T, Beyer JE, Borges L, Bundy A, Dunn D, Fulton EA, Hall M, Heino M, Law R, Makino M, Rijnsdorp AD, Simard F, Smith ADM (2012) Reconsidering the Consequences of Selective Fisheries. Science (80-) 335:1045–1047

Garnier E, Cortez J, Billès G, Navas ML, Roumet C, Debussche M, Toussaint J P (2004) Plant functional markers capture ecosystem properties during secondary succession. Ecology 85(9):2630–2637

Gasparini JL, Floeter SR, Ferreira CEL, Sazima I (2005) Marine ornamental trade in Brazil. Biodivers Conserv 14:2883–2899. https://doi.org/10.1007/s10531-004-0222-1

Giglio VJ, Bornatowski H (2016) Fishers' ecological knowledge of smalleye hammerhead, *Sphyrna tudes*, in a tropical estuary. Neotrop Ichthyol 14:e150103

Graham NAJ, Mcclanahan TR, Macneil MA, Wilson SK, Cinner JE, Huchery C, Holmes TH, Graham NAJ, Mcclanahan TR, Macneil MA, Wilson SK, Cinner JE (2017) Human disruption of coral reef trophic structure. Curr Biol 27:231–236

Gurjão LM, Lotufo TMC (2018) Native species exploited by marine aquarium trade in Brazil. Biota Neotrop 18(3):e20170387. https://doi.org/10.1590/1676-0611-BN-2017-0387

Hadel VF, Monteiro AMG, Ditadi ASF, Tiago CG, Tommassi LR (1999) Echinodermata, pp 261–271. In: Migotto AE and Tiago CG (eds) Biodiversidade do Estado de São Paulo, Brasil: síntese do conhecimento ao final do século XX, 3: invertebrados marinhos. São Paulo, FAPESP, 310p

Haimovici M (1997) Recursos pesqueiros demersais da região sul. Avaliação do Potencial Sustentável de Recursos vivos da Zona Econômica Exclusiva (Revizee). Rio de Janeiro, 81p

Haimovici M, Andriguetto-Filho J, Sunyé P (2014) A pesca marinha e estuarina no Brasil estudos de caso multidisciplinares. Editora da FURG, Rio Grande do Sul

Haimovici M, Kikuchi E, Cardoso LG, Moralles R (2020) The population dynamics of the red porgy *Pagrus pagrus* along southern Brazil, before its fishery collapse in the 1980s: a baseline study. Aquat Living Resour 33:1–15

Halpern BS, Floeter SR (2008) Functional diversity responses to changing species richness in reef fish communities. Mar Ecol Prog Ser 364:147–156

Hicks CC, Graham NAJ, Maire E, Robinson JPW (2021) Secure local aquatic food systems in the face of declining coral reefs. One Earth 4:1214–1216

Hughes TP (1994) Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science 265:1547–1552

Hughes S, Yau A, Max L, Petrovic N, Davenport F, Marshall M, Mcclanahan TR, Allison EH, Cinner JE (2012) A framework to assess national level vulnerability from the perspective of food security: the case of coral reef fisheries. Environ Sci Policy 23:95–108

Instituto Brasileiro do Meio Ambiente e os Recursos Naturais Renováveis (Ibama) (2008) Plano de gestão para o uso sustentavel de Lagostas no Brasil. Brasilia, 121p

IBGE (2020) Pesquisa de Orçamentos Familiares 2017–2018: análise de consumo alimentar pessoal no Brasil. Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro

ICMBio/MMA (2018) Livro Vermelho da Fauna Brasileira Ameaçada de Extinção: Volume VI - Peixes (R Subirá, A Galvão, and C Carvalho, Eds.). Brasília

ICMBio (2020) Plano de Manejo da Reserva Extrativista Marinha do Arraial do Cabo. 67p

Ivo C, Pereira J (1996) Sinopse das principais observações sobre as lagostas *Panulirus argus* (Latreille) e *Panulirus laevicauda* (Latreille), capturadas em águas costeiras do Brasil, entre os estados do Amapá e do Espírito Santo. Bol Técnico Cient CEPENE 4:7–94

Kulbicki M, Parravicini V, Bellwood DR, Arias-Gonzàlez E, Chabanet P, Floeter SR, Friedlander A, McPherson J, Myers RE, Vigliola L, Mouillot D (2013) Global biogeography of reef fishes: A hierarchical quantitative delineation of regions. PLoS One 8

Kittinger J, Teneva L, Koike H, Konstantinos S, Kittinger D, Oleson K, Conklin E, Gomes M, Wilcox B, Friedlander A (2015) From reef to table social and ecological factors affecting coral reef fisheries, Artisanal Seafood supply chains, and seafood security. PLoS ONE 10:e0123856

Leão ZMN, Kikuchi R, Testa V (2003) Corals and coral reefs of Brazil (J Cortes, Ed). In: Latin American coral reefs, Elsevier Science, pp 9–52

Ledlie MH, Graham NAJ, Bythell JC, Wilson SK, Jennings S, Polunin NVC, Hardcastle J (2007) Phase shifts and the role of herbivory in the resilience of coral reefs. Coral Reefs 26:641–653

Leduc AOHC, Carvalho FHD, Hussey NE (2021) Local ecological knowledge to assist conservation status assessments in data poor contexts: a case study with the threatened sharks of the Brazilian Northeast. Biodivers Conserv 30:819–845

Leite TS, Corrêa R, Lima F, Vasconcelos J, Oliveira J, Haimovici M (2010) A pescaria artesanal de polvo (Octopus) no Rio Grande do Norte. In: II Congresso Brasileiro de Oceanografia – CBO 2010, pp 3025–3027

Legendre P, Legendre L (1998) Numerical ecology. Second English edition. Elsevier, Amsterdam, The Netherlands

Legendre P, Gallagher ED (2001) Ecologically meaningful transformations for ordination of species data. Oecologia 129:271–280. https://doi.org/10.1007/s004420100716

Lopes PFM, Andrade LCA, Pennino MG, Leite TS (2021) The inter- annual fishing variability in *Octopus insularis* (Leite & Haimovici 2008) as a result of oceanographic factors. Fish Oceanogr 30:515–526

Luiz OJ, Edwards AJ (2011) Extinction of a shark population in the Archipelago of Saint Paul's Rocks (equatorial Atlantic) inferred from the historical record. Biol Conserv 144:2873–2881

Luiz OJ, Olden JD, Kennard MJ, Crook DA, Douglas MM, Saunders TM, King AJ (2019) Trait-based ecology of fishes: a quantitative assessment of literature trends and knowledge gaps using topic modelling. Fish Fish 20:1100–1110

Luza AL, Aued AW, Barneche DR, Dias MS, Ferreira CE, Floeter SR, Bender MG (2023) Functional diversity patterns of reef fish, corals and algae in the Brazilian biogeographical province. J Biogeogr 50(6):1163–1176

Maia RC, Bentes B, Pereira Gomes L, Holanda FC (2015) Pesca comercial e estrutura populacional da serra, *Scomberomorus brasiliensis* (Collette, Russo & Zavala, 1978), desembarcada em um pólo pesqueiro na Costa Norte do Brasil. Biota Amaz, 5: 99–106

Magris RA (2021) Effectiveness of Large-Scale Marine Protected Areas in the Atlantic Ocean for Reducing Fishing Activities. Front Mar Sci 8:1–7

Magris RA, Costa MDP, Ferreira CEL, Vilar CC, Joyeux JC, Creed JC, Copertino M, Horta P, Sumida P, Francini-Filho RB, Floeter SR (2020) A blueprint for securing Brazil ' s marine biodiversity and supporting the achievement of global conservation goals. Divers Distrib 27:1–18

Marceniuk AP, Caires RA, Carvalho-Filho A, Rotundo M, Rosa dos Santos W, Klautau A (2020) Peixes teleósteos da costa norte do Brasil. Museu Paraense Emílio Goeldi, Belém, Brasil, 775p

Marenzi AWC, Tamaki NT, Manzoni GC (2006) Biological and economic subsidies for rational exploration of the sea-urchin *Echinometra locunter* (l., 1758). J Coast Res, 39: 1299–1301

Marroni VE (2014) The importance of public policy for Blue Amazon marine spatial planning. Dev Stud Res 1:161–167

Martin TSH, Connolly RM, Olds AD, Ceccarelli DM, Fenner DE, Schlacher TA, Beger M (2017) Subsistence harvesting by a small community does not substantially compromise coral reef fish assemblages. ICES J Mar Sci 74:2191–2200

Martins A, Costa P, Olavo G, Hamovici M (2006) Recursos pesqueiros da região central. In: Avaliação do Potencial Sustentável de Recursos Vivos na Zona Econômica Exclusiva. MMA/Secretaria de Qualidade Ambiental, (Org.). Programa REVIZEE, Brasília, pp 181–206

Martins AS, Olavo G, Costa PAS (2005) A Pesca de Linha de Alto Mar Realizada por Frotas Sediadas no Espírito Santo, Brasil. In: Costa P, Martins A, Olavo G (eds) Pesca e potenciais de exploração de recursos vivos na região central da Zona Econômica Exclusiva Brasileira. Museu Nacional, Rio de Janeiro, pp 35–55

Martins GM, Arenas F, Neto AI, Jenkins SR (2012a) Effects of fishing and regional species pool on the functional diversity of fish communities. PLoS ONE 7:1–9

Martins L, Souto C, Magalhães WF, Alves OF, Rosa IL, Sampaio CLS (2012b) Echinoderm harvesting in Todos-os-Santos Bay, Bahia State, Brazil: the aquarium trade. Sitientibus - Série Ciências Biológicas 12(1):53–59

Mbaru EK, Graham NA, McClanahan TR, Cinner JE (2020) Functional traits illuminate the selective impacts of different fishing gears on coral reefs. J Appl Ecol 57:241–252

Mattos S, Wojciechowski M, Gandini F (2020) Iluminando as capturas ocultas da pesca artesanal costeira no Brasil: um estudo de caso. Instituto Maramar para a Gestão Responsável dos Ambientes Costeiros e Marinhos (Maramar Institute for Coastal Management). Brasil, 71p

McClanahan TR, Agata SD, Graham NAJ, Azali M, Maina JM (2023) Multivariate environment-fish biomass model informs sustainability and lost income in Indian Ocean coral reefs. Mar Policy 152:105590

McClanahan TR, Muthiga NA (2016) Geographic extent and variation of a coral reef trophic cascade. Ecology 97(7):1862–1872

Miloslavich P, Klein E, Dıas JM, Hernández CE, Bigatti G, Campos L, Artigas F, Castillo J, Penchaszadeh PE, Neill PE, Carranza A, Retana M V, Diaz de Astarloa J, Lewis M, Yorio P, Piriz ML, Rodriguez D, Yoneshigue-Valentin Y, Gamboa L, Martin A (2011) Marine Biodiversity in the Atlantic and Pacific Coasts of South America: Knowledge and Gaps. PLoS One 6:e14631

Ministério de Desenvolvimento, Indústria, Comércio e Serviços (MDIC)(2022), available at http://comexstat.mdic.gov.br/pt/geral, accessed 01/04/2022

MMA (2005) Instrução normativa MMA N° 53 de 22 de novembro 2005, Ministério de Meio Ambiente, available at https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Instrucao_normativa/2005/in_mma_53_2005_tamanhominimoespeciesmarinhaseestuarinas_se_s_altrd_in_mma_03_2006.pdf

MMA (2006) Avaliação do Potencial Sustentável de Recursos Vivos na Zona Econômica Exclusiva, Programa Revizee, Ministério de Meio Ambiente, Brazil, 279p

MMA (2014) Portaria 445 de 17 de dezembro de 2014. Minist. rio de Meio Ambiente, Diário Oficial da União, Seção 1:245:126–130

MMA (2018a) Plano de recuperação para espécies ameaçadas de peixes recifais: *Mycteroperca interstitialis*, *Mycteroperca bonaci*, *Epinephelus morio* e *Lutjanus cyanopterus*. Ministério de Meio Ambiente, Brazil

MMA (2018b) Plano de recuperação da Garoupa-verdadeira (*Epinephelus marginatus*), no litoral sudeste e sul do Brasil. Ministério de Meio Ambiente, Brasília, Brazil

MMA (2018c) Portaria Interministerial Nº 59-C de 9 de novembro de 2018, Ministério de Meio Ambiente, Brazil, available at https://www.gov.br/agricultura/pt-br/assuntos/mpa/legislacao/especies-permitidas-portaria-mma-no-445-2014/portaria-interministerial-seap-pr_mma-no-59-c-de-9-11-2018.pdf/view

MPA/MMA (2012) Instrução normativa interministerial N° 12, de 22 de agosto de 2012. Ministério de Meio Ambiente, Brazil. Available at https://www.gov.br/agricultura/pt-br/assuntos/aquicultura-e-pesca/legislacao/emalhe/instrucao-normativa-mpa-mma-no-12-de-22-08-2012.pdf/view

MMA & ICMBio (2021) Portaria Nº 285, de 11 de maio de 2021: Aprova o Plano de Gestão Local do Guaiamum (*Cardisoma guanhumi*) e Budiões (*Scarus trispinosus, Scarus zelindae, Sparisoma frondosum* e *Sparisoma axillare*) da Reserva Extrativista de Cassurubá e define regras para pesca e manejo (Processo n° 02125.000649/2019-68)

Moberg F, Folke C (1999) Ecological goods and services of coral reef ecosystems. Ecol Econ 29:215–233

Mora C (2015) Ecology of Fishes on Coral Reefs (C Mora, Ed), 1st ed. Cambridge University Press, Cambridge

Morais RA, Ferreira CEL, Floeter SR (2017) Spatial patterns of fish standing biomass across Brazilian. J Fish Biol 91:1642–1667

Marques S, Ferreira B (2010) Composição e características da pesca de armadilhas no litoral norte de Pernambuco, Brasil. Bol Téc Cient CEPENE 18:49–60

Motta F, Rosa M, Namora RC, Gadig O (2014) Bony fishes (Teleostei) caught by small-scale fisheries off central to south coast of São Paulo state, Southeastern Brazil. Biota Neotrop 14:1–7

Mouchet M, Poirson M, Morandeau F, Vogel C, Méhault S (2019) Using a trait-based approach to understand the efficiency of a selective device in a multispecific fishery. Scientific 9:1–8

Moura R, Augusto N, Amado-Filho GM, Francini-Filho RB, Oliveira M, Minte-Vera CV, Batista J, Lopes F, Fraga G, Yukio P, Sumida G, Zigliatti A, Mendes R, Cardoso A (2013) Spatial patterns of benthic megahabitats and conservation planning in the Abrolhos Bank. Cont Shelf Res 70:109–117

Moura RL, Amado-Filho GM, Moraes FC et al (2016) An extensive reef system at the Amazon River mouth. Sci Adv 2:1–12

Mumby PJ, Steneck RS, Edwards AJ, Ferrari R, Coleman R, Harborne AR, Gibson JP (2012) Fishing down a

Caribbean food web relaxes trophic cascades. Mar Ecol Prog Ser 445:13–24
Munro JL, Sadovy Y, Boehlert G, Roberts C, Polunin N, Ruddle K, Dalzell P, Jennings S, Lock J, Appledoorn R, McManus J, Bohnsack J, Ruddle K, Adams T, Pauly D (1996) Reef Fisheries (N Polunin and C Roberts, Eds), 1st ed. Springer Science, Salisbury, 488p
Negrão F, Lacerda CHF, Melo TH, Bianchini A, Calderon EN, Castro CB, Cordeiro S, Dias RJS, Francini-Filho RB, Guebert FM, Güth AZ, Hetzel B, Horta A, Lotufo TMC, Mahiques MM, Mies M, Pires DO, Salvi KP, Sumida G (2021) The first biological survey of the Royal Charlotte Bank (SW Atlantic) reveals a large and diverse ecosystem complex. Estuar Coast Shelf Sci 255:107363
Gonçalves Neto JB, Goyanna Alencar FA, Vieira C, Oliveira Soares M (2021) A sleeping giant: the historically neglected Brazilian fishing sector. Ocean Coast Manag 209:105699
Netto RDF, Beneditto A (2007) Diversidade de artefatos da pesca artesanal marinha do Espírito Santo. Biotemas 20:107–119
Newton K, Côté IM, Pilling G, Jennings S, Dulvy NK (2007) Current and future sustainability of island coral reef fisheries. Curr Biol 17:655–658
Nóbrega J, Lima Maia E, Siqueira Telles F, Ogawa M (1975) Conservação e industrialização do polvo no nordeste brasileiro. Arq Ciências do Mar 15:53–57
Nóbrega MF, Lessa RP (2007) Descrição e composição das capturas da frota pesqueira artesanal da região nordeste do Brasil. Arq Ciências do Mar 40:64–74
Nogueira W (2016) Caracterização da pesca lagosteira no Brasil: impactos e empasses relacionados a proibição da atividade pesqueira. Rev Cient Sem Acadêmica 18:1–16
Oksanen J, Guillaume Blanchet F, Friendly M, Kindt R, Legendre P, McGlinn D, Minchin PR, O'Hara RB, Simpson GL, Solymos PM, Stevens H, Szoecs E, Wagner H (2020) vegan: Community Ecology Package. R package version 2.5–7. https://CRAN.R-project.org/package=vegan
Oliveira O, da Silva V (2012) O Processo de Industrialização do Setor Pesqueiro e a Desestruturação da Pesca Artesanal no Brasil a partir do Código de Pesca de 1967. Seqüência 65:329–357
OWID - www.ourworldindata.org, accessed december 2022
Paiva M, Bezerra R, Fonteles-Filho A (1971) Tentativa de avaliação dos recursos pesqueiros do nordeste Brasileiro. Arq Ciências do Mar 11:1–43
Paradis E, Schliep K (2019) Ape 5.0: an environment for modern phylogenetics and evolutionary analyses in R. Bioinformatics 35:526–528
Pebesma EJ (2004) Multivariable geostatistics in S: the gstat package. Comput Geosci 30:683–691
Pelage L, Bertrand A, Ferreira BP, Lucena-Frédou F, Justino AK, Frédou T (2021) Balanced harvest as a potential management strategy for tropical small-scale fisheries. ICES J Marine Sci 78(7): 2547–2561
Peres M, Haimovici M (1998) A pesca dirigida ao cherne- poveiro *Polyprion americanus* no sul do Brasil. Atlântica 20:141–161
Pincinato RBM, Gasalla MA (2010) Priceless prices and marine food webs: long-term patterns of change and fishing impacts in the South Brazil Bight as reflected by the seafood market. Prog Oceanogr 87:320–330
Pincinato RBM, Gasalla MA (2019) Exploring simple ecological indicators on landings and market trends in the South Brazil Shelf Large Marine Ecosystem. Fish Manag Ecol 26:200–210
Pinheiro HT, Mazzei E, Moura RL, Amado-Filho GM, Ferreira CEL, Floeter SR, Francini-Filho RB (2015) Fish biodiversity of the Vitória-Trindade Seamount Chain, Southwestern Atlantic : an updated database. PLoS ONE 10:e0118180
Pinheiro HT, Rocha LA, Macieira RM et al (2018a) South-western Atlantic reef fishes: zoogeographical patterns and ecological drivers reveal a secondary biodiversity centre in the Atlantic Ocean. Divers Distrib 24:951–965
Pinheiro F, Pinheiro H, Costa TJF, Teixeira J, Gasparini J, Joyeux J, Martins A (2018b) Harvest of endangered marine invertebrates in a priority area for conservation in Brazil. Nat Conserv Res 3:78–81
Pinheiro HT, Nunes JACC, Coni EOC, Almeida ECG, Villaseñor-Derbez JC (2021) An inverted management strategy for the fishery of endangered Marine species. Front Mar Sci 8:604108
Pincinato RBM, Gasalla MA, Garlock T, Anderson JL (2022) Market incentives for shark fisheries. Marine Policy 139:105031
Pitcher TJ, Watson R, Forres R, Valússon HP, Guénette S (2002) Estimating illegal and unreported catches from marine ecosystems: a basis for change. Fish Fish 3:317–339
Piola AR, Palma ED, Bianchi AA, Castro BM, Dottori M, Guerrero RA, Marrari M, Matano RP, Möller OO, Saraceno M (2018) Physical oceanography of the SW Atlantic Shelf: a review. Plankton ecology of the Southwestern Atlantic: from the subtropical to the subantarctic realm, pp 37–56. https://doi.org/10.1007/978-3-319-77869-3_2
Previero M (2014) A pesca do budião-azul (*Scarus trispinosus* Valenciennes, 1840) no maior complexo coralíneo do Atlântico Sul. MSc thesis, Universidade Estadual de Maringá
Previero M, Gasalla MA (2018) 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 Coast Manag 154:83–95
Previero M, Gasalla MA (2020) Risk assessment of small-scale reef fisheries off the Abrolhos Bank: Snappers and groupers under a multidimensional evaluation. Fish Manag Ecol 27:231–247
Quimbayo JP, Silva FCD, Mendes TC, Ferrari DS, Danielski SL, Bender MG, Floeter SR (2021) Life-history traits, geographical range, and conservation aspects of reef fishes from the Atlantic and Eastern Pacific. Ecology e03298
R Core Team (2022). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/
Reis-Filho A, Miranda R, Sampaio C, Nunes JA, Leduc A (2021) Web-based and logbook catch data of permits and pompanos by small-scale and recreational fishers: predictable spawning aggregation and exploitation pressure. Fish Res 243:106064. https://doi.org/10.1016/j.fishres.2021.106064

Reis-Filho JA, Giarrizzo T (2022) Drone surveys are more efficient and cost effective than ground- and boat-based surveys for the inspection of fishing fleet at harbors. Coasts 2:355–368
Rodrigues Filho LF, Manir Feitosa L, Nunes Silva LJ, Palmeira Onodera AR, Martins Barbosa AP, Giarrizzo T, Carvalho-Costa LF, Leonardo I, Monteiro P, Gemaque R, Gomes F, Furtado Souza R, Sampaio I, Sales de Luna BJ (2020) Molecular identification of ray species traded along the Brazilian Amazon coast. Fish Res 223:105407
Rolim F, Langlois T, Santos Motta F, Malagutti de Castro G, Lester E, Abieri M, Bismarck O, Moura RL (2022) Habitat and marine reserve status drive reef fish biomass and functional diversity in the Largest South Atlantic Coral Reef System (Abrolhos, Brazil). Front Mar Sci 9:1–17
Roos NC, Pennino MG, de Lopes PFM, Carvalho AR (2016) Multiple management strategies to control selectivity on parrotfish harvesting. Ocean Coast Manag 134:20–29
Roos NC, Taylor BM, Carvalho AR, Longo GO (2020) Demography of the largest and most endangered Brazilian parrotfish, *Scarus trispinosus*, reveals overfishing. Endanger Species Res 41:319–327
Santos AN (2015) Fisheries as a way of life: gendered livelihoods, identities and perspectives of artisanal fisheries in eastern Brazil. Mar Policy 62:279–288
Santos JO, Martínez-Torres ME, Andrade MO (2021) Beyond the nature-culture frontier sea Urchin festivals in French and Brazilian Communities. J Fest Stud 3:151–176
Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591–596
Silva B, Aragão J, Freire J, Lutz I, Sarmento G, Gomes T (2017) Documento técnico sobre a situação atual das pescarias do pargo na região norte do Brasil. Universidade Federal do Pará, Bragança, Brazil, 132p
Silva MRO, Pennino MG, Lopes PFM (2019) Social-ecological trends: managing the vulnerability of coastal fishing. Ecol Soc 24:4
de Souza K (2018) Biologia reprodutiva do Cangulo-rei (*Balistes vetula* Linnaeus 1758) no litoral de Pernambuco, Brasil. MSc thesis, Universidade Federal Rural de Pernambuco
TEEB (2012) The Economics of Ecosystems and Biodiversity in Business and Enterprise. Edited by Joshua Bishop. Earthscan: London and New York
Teh LSL, Teh LCL, Sumaila UR (2013) A global estimate of the number of coral reef fishers. PLoS ONE 8(6):e65397. https://doi.org/10.1371/journal.pone.0065397
Unsworth RKF, Mtwana Nordlund L, Cullen-Unsworth LC (2018) Seagrass meadows support global fisheries production. Conserv Lett 12:1–8
Uthicke S, Schaffelke B, Byrne M (2009) A boom–bust phylum? Ecological and evolutionary consequences of density variations in echinoderms. Ecol Monogr 79(1):3–24. https://doi.org/10.1890/07-2136.1
Vargas A, Restrepo S, Diaz D (2022) The portfolio effect in a small-scale fishery reduces catch and fishing income variability in a highly dynamic ecosystem. PLoS ONE. https://doi.org/10.1371/jjournal.pone.0271172
Vasconcelos MDAC, Diegues AC, Sales RRD (2007) Alguns aspectos relevantes relacionados à pesca artesanal costeira nacional. São Paulo: NUPAUB, Universidade de São Paulo
Viana DDL, Lins-Oliveira LE, Antonio M, Carvalho de Souza C (2021) Ciências do Mar: dos oceanos do mundo ao Nordeste do Brasil, Volume 2 Bioecologia, Pesca e Aquicultura. 1st ed, Via Design Publicações, Olinda, Brazil
Vianna M, Rodrigues AM, Lin C (2007) Descrição da pescaria de peroá (*Balistes capriscus*) com a utilização do puçá-grande no sudeste do Brasil. Bol Inst Pesca 33:229–236
Vilar CC, Magris RA, Loyola R, Joyeux J-C (2020) Strengthening the synergies among global biodiversity targets to reconcile conservation and socio-economic demands. Aquatic Conserv: Mar Freshw Ecosyst 30:497–513. https://doi.org/10.1002/aqc.3269
Villéger S, Brosse S, Mouchet M, Mouillot D, Vanni MJ (2017) Functional ecology of fish: current approaches and future challenges. Aquat Sci 79:783–801
Wallner-Hahn S, de la Torre-Castro M, Eklöf J, Gullström M, Muthiga N, Uku J (2015) Cascade effects and sea-urchin overgrazing: an analysis of drivers behind the exploitation of sea urchin predators for management improvement. Ocean Coast Manag 107:16–27
Woodhead AJ, Williams GJ, Hicks CC, Norström AV, Graham NAJ (2019) Coral reef ecosystem services in the Anthropocene. Funct Ecol 33:1023–1034
Worm B, Branch TA (2012) The future of fish. Trends Ecol Evol 27:594–599
Yadav S, Fisam A, Dacks R, Madin JS, Mawyer A (2021) Shifting fish consumption preferences can impact coral reef resilience in the Maldives: a case study. Mar Policy 134:104773