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Research, part of a Special Feature on Managing local and global fisheries in the Anthropocene

Social-ecological trends: managing the vulnerability of coastal fishing communities

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ABSTRACT. The loss of biodiversity, including the collapse of fish stocks, affects the vulnerability of social-ecological systems (SESs) and threatens local livelihoods. Incorporating community-centered indicators and SES drivers and exposures of change into coastal management can help anticipate and mitigate human and/or coastal vulnerability. We have proposed a new index to measure the social-ecological vulnerability of coastal fishing communities (Index of Coastal Vulnerability [ICV]) based on species, ecosystem, and social indicators. The ICV varies from 0 (no vulnerability) to 1 (very high vulnerability) and is composed of 3 components: species vulnerability, i.e., fish biological traits; ecosystem vulnerability, i.e., environmental indicators of ecosystem health; and adaptive capacity, i.e., human ability to cope with changes. We tested the ICV of Brazil's 17 coastal states. The average ICV for the Brazilian coast was 0.77, and variation was low among states. More than half of the coastal states revealed very high vulnerability (> 0.8). The ecosystem vulnerability values were worse than the adaptive capacity and species vulnerability values, and the North and Northeast regions were revealed to be vulnerable hot spots. Additionally, we investigated how the ICV related to specific anthropogenic risks, i.e., fish landing richness, fishery instability, market, coastal extension, and coastal population, and found that states with fewer species landings and higher coastal populations presented higher ICVs. At a time when human impacts are overtaking natural processes, understanding how these impacts lead to coastal vulnerability can help improve conservation policies. For this case study, we suggest both fisheries management measures and restoration of sensitive habitats to protect species and decrease vulnerability. The integrated evaluation developed here could be used as a baseline for coastal monitoring and conservation planning and be applied to coastal regions in which governments evaluate both social and biological aspects.

Key Words: *Anthropocene; coupled system; ecosystem services; human ecology; resource dependency*

INTRODUCTION

Anthropogenic activities are pushing ecosystems beyond their ability to maintain processes and services that are fundamental to human societies (Ripple et al. 2017, Aswani et al. 2018). Intense consumption of natural resources has threatened and extinguished species and led to the current biodiversity crises (Corlett 2015), thus impacting the provision of ecosystem services (Cardinale et al. 2012). For instance, coral reefs have been rapidly degrading in response to anthropogenic drivers (Hughes et al. 2017), and top predators have become absent or threatened, both at sea and on land (McGill et al. 2015). The current situation of fisheries around the world indicates that the productive capacity of the fish stocks is reaching its limit (Food and Agriculture Organization of the United Nations [FAO] 2016).

Overfishing can cause fluctuations in fish catches (Pomeroy et al. 2016), reduce biodiversity, and affect the provision of marine services (Christensen et al. 2014), which directly threatens food, income, and livelihood security, especially in the developing world (FAO 2012). Depletion of fish stocks also has serious consequences on human livelihoods (Kleisner et al. 2013*b*, Teh and Sumaila 2013). The sustainability of vital ecosystem services that humans depend on for their livelihoods is crucial to maintaining balanced social-ecological systems (SESs). Although many groups of people in different social-ecological contexts can adapt reasonably well to an environmentally changing world, these adaptations do not necessarily imply better lives. People, such as artisanal fishers for example, who rely heavily on natural resources, have been burdened by multiple changes in the ecosystems, e.g., depletion of fish stocks, that vary according to their own social-ecological context (Berkes et al. 2000, Perry et al. 2010). By knowing how vulnerable a system is and the specific conditions that make it vulnerable, key actions can be developed to minimize the impacts of environmental changes and sustain ecosystem services and livelihoods.

Vulnerability can be defined as the state of susceptibility to damage from multiple stressors (Cinner et al. 2013), or as a condition of a system to cope and adapt to changes caused by these disturbances (Adger 2006, Intergovernmental Panel on Climate Change [IPCC] 2014). Social vulnerability, specifically, can be evaluated through indicators of the factors that influence a community's ability to sustain itself against changes to the SES (Liu et al. 2007). In addition to environmental fluctuations, these communities are exposed to other changes, such as economic, social, demographic, and governance-related changes (Bennet et al. 2015, Khan and Cundill 2019). Governance, specifically, which is defined as a continuous process of negotiation on how to manage ecosystems, is considered to be a critical element to solving the problems identified in fisheries (Basurto et al. 2017, Bennett et al. 2019) and needs to be adaptable given that changes to SESs are inevitable (Bennett and Satterfield 2018). From an ethics perspective, coastal governance contributes to identifying blind spots that are overlooked in some fishing SESs, such as issues related to gender inequality, property rights, and social actors (Basurto et al. 2017).

Many coastal marine systems and their associated SESs still retain outstanding biological features, but changes are expected to increase their vulnerability, as the Anthropocene continues to unfold (Steffen et al. 2011). In an SES, more exposed groups, such as those made more vulnerable because of their gender, age, class,

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and/or ethnicity usually feel these changes first (O'Brien et al. 2010). This is true even for groups, such as women, whose contribution to collective action in fisheries is crucial (Di Ciommo and Schiavetti 2012, Alonso-Población and Siar 2018) but who are still subjected to high levels of discrimination (Harper et al. 2013, Siar and Kalikoski 2016). To date, most of the social vulnerability research has focused on the effects of climate change (Dolan and Walker 2004, Cinner et al. 2013). However, vulnerability driven by other factors, such as overfishing, population growth, market fluctuations that impact seafood prices, fisheries technology, infrastructure developments, and governance and policies, should not be disregarded (Bennett et al. 2017).

Given the diverse methods by which fish are caught and the different governance regimes (World Wildlife Fund [WWF] 2016), coastal communities in Brazil serve as an important case study. Although the country has one of the largest coastlines in the world and a huge Exclusive Economic Zone, fish production has declined over the last decades, and some estimates suggest that there are few, if any, unexploited fishing resources that could endure additional harvest (Ruffino and Abdallah 2016). Moreover, the Brazilian coastline has undergone multiple environmental and socioeconomic changes over the last 50 years, which have negatively impacted both fish stocks and local livelihoods (Prates et al. 2012, Reis et al. 2016). Lack of effective governance to promote sustainable fishing in a changing world is an important part of this failure to preserve fish stocks and protect local livelihoods and is possibly the main threat to the Brazilian marine systems (Dias-Neto and Dias 2015, Ruffino and Abdallah 2016).

The need to evaluate the relationships between the social and ecological dimensions of human vulnerability is now urgent (Cinner et al. 2013, Daw et al. 2016) if healthier governance regimes are to be established. It is especially important to consider that changes to SESs occur at different scales and speeds and thus produce different outcomes from one community to the next (IPCC 2014, Bennett et al. 2016). Therefore, it is crucial to understand who and where the vulnerable people and species are, how to reduce their vulnerability, and where the economic consequences of vulnerable fisheries systems will be felt the most.

We used an innovative and integrative approach to explore social-ecological vulnerabilities driven by multiple interacting socioeconomic and ecological changes along the Brazilian coast in fishery-dependent communities. Adopting the perspective that humans and the natural environment constantly interact (Liu et al. 2007, Aswani et al. 2018), we constructed an index of coastal vulnerability that is composed of biological and social-related variables and that considers the interactions between the system, pressures, and threats. We first identified which aspects are important to determining coastal vulnerability and then related the index to ecological, demographic, geographic, and socioeconomic indicators. Second, we investigated two hypotheses to explain the vulnerability of coastal communities: (1) whether lower fish richness in landings and stability of fishing resources were associated with high coastal vulnerability; and (2) whether regions with larger coastal extensions, greater populations, and higher market indexes tend to be more vulnerable. Social-ecological approaches to assessing coastal vulnerabilities can identify where to focus attention to mitigate the anthropogenic impacts and improve the sustainability measures of marine resources to avoid further collapses. As part of the test of our index, we also generated an index that ranked the vulnerability of all the Brazilian states. This additional result could encourage policy makers to improve their state's index by implementing public and environmental initiatives directed toward conservation and meeting regional needs. Gaining new insights into marine SESs using interdisciplinary modeling approaches will better prepare us to manage marine resources in the Anthropocene.

MATERIAL AND METHODS

A brief review of vulnerability assessments

Marine SESs face different types of stressors at different scales and speeds, such as climatic, socio-cultural, economic, and governance (Millenium Ecosystem Assessment 2005, Bennett et al. 2016). Understanding the systems' vulnerabilities is an important step to design means for the SESs to deal with such stressors. However, vulnerability is neither easily defined nor measured (Comte et al. 2019). We specifically adopted the definition that vulnerability corresponds to how natural resources, resource users, and the governance systems are linked and respond to changes (Berkes and Folke 1998, Gunderson 2010).

Consideration of different perspectives, scales, indicators, and the interactions between ecological and human dimensions is crucial to capturing changes in the SES. For this reason, we envisioned the SES to be a single and coupled system where social and ecological components interact closely (Marshall et al. 2013, López-Angarita et al. 2014). Additionally, to date most approaches to dealing with coastal vulnerability have considered the ongoing and expected impacts of climate change (Beck 2014, Lee et al. 2018) and overlooked other harmful structural and systemic factors driving vulnerability (Hinkel 2011, Tschakert et al. 2013). To partially avoid this shortcoming, we used overfishing as a crucial environmental factor that is both affected by and affects the environment, food security, and livelihoods and is capable of triggering regime shifts in SESs. We also used various easy-to-collect indicators that encompass assorted social-ecological variables, such as biophysical, social, economic, and governance-related ones, for rapid vulnerability assessments. This is different from most approaches that use a large and/or oversimplified range of indicators (Aswani et al. 2019, Comte et al. 2019).

Finally, given that one of the objectives of conducting vulnerability assessments is to inform policy and decision makers, especially because vulnerability is context specific (O'Brien et al. 2007), we adopted a local-level approach (Hinkel 2011). At the local level, the chances of having enough data on the ecology of species and on the synergism of interactions between humans and the environment are also higher, and, therefore, there is less room for misrepresentation of the system's vulnerability (Tschakert et al. 2013, Khan and Cundill 2019). Our intention is to determine how to most effectively support and enable local and regional efforts to conserve coastal areas and sustainably manage the provision of fisheries ecosystem services. To emphasize the novelty of the proposed approach, we reviewed and compared the existent vulnerability approaches to ours (Table 1).

Table 1. Comparison of different approaches used in marine hot spot countries. Information regarding the framework used, indicators, spatial scale, geographic area, and other determinants in the vulnerability assessments. FS, food security; IPCC, Intergovernmental Panel on Climate Change; LVI, Livelihood Vulnerability Index.

Study	Approach	Context	Spatial Level	Main Focus of Indicators	Regime Shift
Allison et al. (2009)	IPCC (2001)	Climate change	Global	Socioeconomic dimension of vulnerability	Declining fish stocks from climate change
Hughes et al. (2012)	Adger (2006)	Food security	Global	Ecological and socioeconomic dimensions of vulnerability	Declining coral reefs resources from different drivers
Mamauag et al. (2013)	IPCC (2001)	Climate change	Regional	Ecological and socioeconomic dimensions of vulnerability	Shifting in coral reef from climate change
Orencio and Fujii (2013)	Buckle et al. (2001)	Food security/ livelihood	Regional	Socioeconomic dimensions of vulnerability, specifically adaptive capacity	Declining fish stocks from socioeconomic drivers
Beck (2014)	IPCC (2012)	Climate change	Global	Socioeconomic dimensions of vulnerability, specifically on exposure and adaptive capacity	Climate-driven changes in the coastal areas
Metfcalf et al. (2015)	IPCC (2001)/LVI[†]	Climate change	National	Socioeconomic dimension of vulnerability	Shifting socioeconomic activities in coastal communities
Lee et al. (2018)	IPCC (2001), Adger (2006), and Lovelock et al. (2015)	Climate change	National	Ecological dimension of vulnerability, specifically biophysical processes	Loss of primary productivity in mangrove
Aswani et al. (2018)	IPCC (2001)/FS[‡]/ LVI	Food security	Global	Social dimension of vulnerability	Climate-driven changes in the marine environment

[†] The livelihood analysis combines a conceptual framework with a set of operational principles to provide guidance on policy formulation (Allison and Horemans 2006).
[‡] The food security approach focuses on food availability and access and tends to be used at higher scales (Godfray et al. 2010).

Measuring coastal vulnerability

The proposed index, the Index of Coastal Vulnerability (ICV), focuses on the characteristics of fishers, communities, fishing sectors, governance, and ecosystems to estimate their susceptibility to harm (loss or decreased fisheries) at the local level (Fig. 1). This is the level where impacts are mostly felt; therefore, it is the most suited to carry out vulnerability assessments (Hinkel 2011).

We assessed vulnerability by breaking it into three attributes known to affect it: exposure, sensitivity, and adaptive capacity (Adger 2006, Cinner et al. 2013). The combination of exposure and sensitivity represents the potential harm from a given environmental change, and adaptive capacity is determined by the ability to cope with this change through learning (Adger 2006, Bennett et al. 2016). Based on these concepts and the equation proposed by Adger (2006), which includes these three attributes, we created a new equation that simplified the theory behind them. Additionally, we selected our variables by considering both vulnerability and harm indicator concepts: the first one indicates the possibility of being harmed, and the others evaluate the current or future states (good or bad) of a system (Hinkel 2011; Fig. 1).

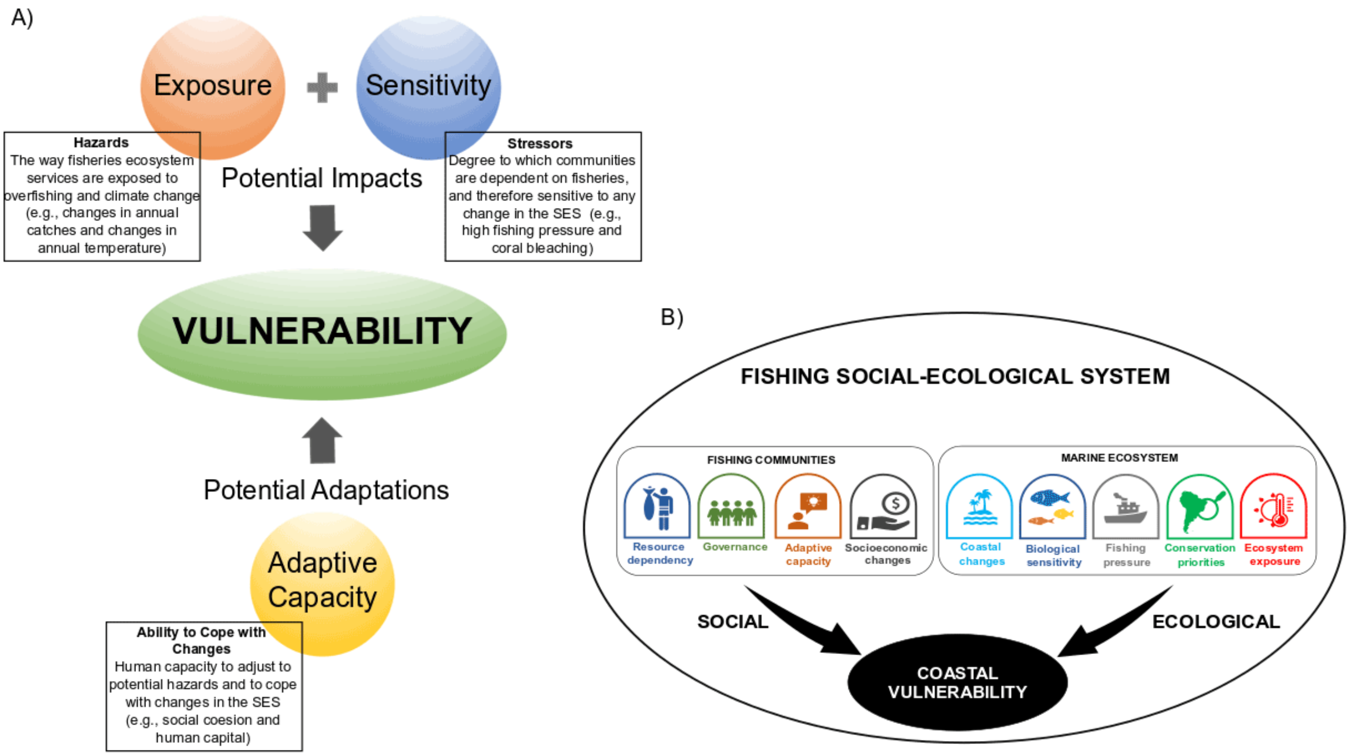
Given that the ICV was focused on the sustainable provision of fisheries ecosystem services, the vulnerability assessment encompassed three components of SESs: species vulnerability (SP), ecosystem vulnerability (ECO), and adaptive capacity of coastal communities (AC). Each component was formed by different indicators and variables (to be described in the next section) that varied from 0 to 4 (AC component), 0 to 8 (SP component), and 0 to 5 (ECO component). An equal weighting approach was used to weigh components as it was assumed that each component is equally important to coastal vulnerability.

However, given that our decisions in the process of weighting the indicators could be unclear, we ran a sensitivity analysis to improve transparency in the construction of the composite index and to check the robustness of our findings. In addition to the equal weight approach, we tested three other weighting schemes to check how each component contributed to estimating the index values. To do so, we calculated the index by emphasizing one dimension at a time and assigning a 1/2 to the emphasized component and 1/4 to the other two. For example, in the first test, the AC component receives a 1/2 weight, whereas SP and ECO would receive a 1/4 weight each. In the next round, a different component would receive a 1/2 weight and so on. Although each of these weighting approaches affected the index values, the final ranking of coastal states was very similar across them (Appendix 1). Furthermore, from a social-ecological perspective, social and ecological parts of a system are equally important, thus further supporting the adopted equal weighting approach. Finally, the weighting approach we used has been applied in other composite indexes in environmental contexts (Swanson et al. 2009, Moreno-Sánchez and Maldonado 2013).

To build the ICV, all variables were turned into quantitative data, and each component was normalized to vary from 0 to 1. We considered the median of each component to calculate the ICV value. A higher AC implies lower vulnerability; therefore, the lower the index value, the lower the system's vulnerability. The final value of the ICV was determined as follows:

$$ICV = (SP + ECO) - AC \qquad (1)$$

Fig. 1. (A) Conceptual model of vulnerability (V): the state of susceptibility to harm is the system's vulnerability, which is determined by exposure (E), sensitivity (S), and adaptive capacity (AC) attributes (Adger 2006), and where V = (E + S) − AC. (B) Conceptual framework of coastal vulnerability nested in the social-ecological fishing system, which presents the interaction between fishing communities and marine ecosystems. Following this framework, variables were created to estimate the system's susceptibility to be harmed and to capture its vulnerability to social and/or environmental changes at the local/regional scale. SES, social-ecological system.



We calculated the ICV for each state along the Brazilian coastline (N = 17; Fig. 2). The ICV value varied from 0 to 2 points, i.e., the sum of maximum scores for SP and ECO components. However, we also rescaled the final values to range from 0 to 1. The total points were then assigned to a qualitative scale with 5 levels, ranging from least vulnerable (very low) to most vulnerable (very high), and each state was categorized according to its final index value (the categories were arbitrarily defined): very low (0 to 0.20), low (0.21 to 0.40), moderate (0.41 to 0.60), high (0.61 to 0.80), and very high (0.81 to 1.00). To better examine the results, we created sensitivity maps from these categories for each component and for the final value of the coastal vulnerability index: AC (green sale), SP (orange scale), ECO (blue scale), and ICV (red scale).

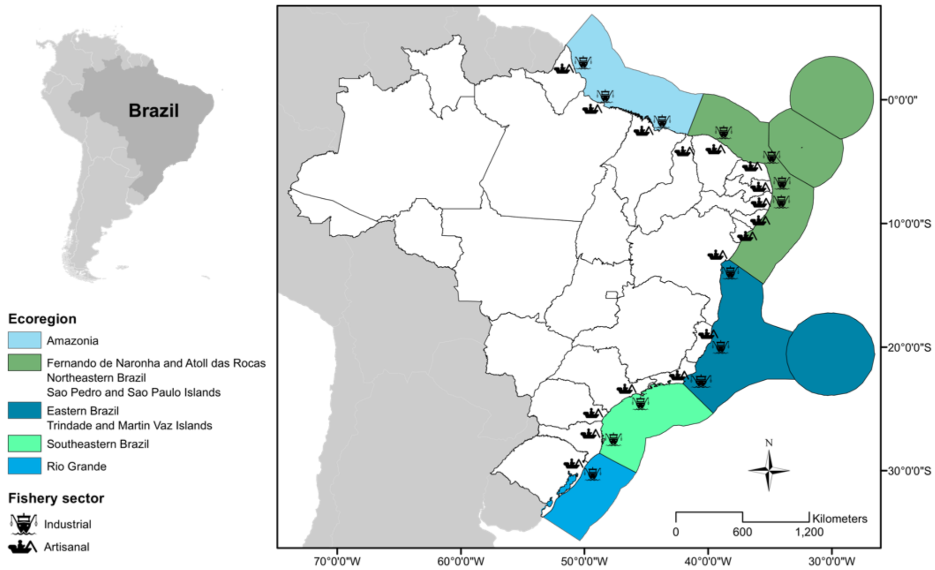
Thus, the index was designed by combining information from different sources with feasible and low-cost variables. Moreover, the index is easily replicable by nonexperts and provides a quick and general overview of large geographic areas without exhaustive and expensive data collection, thus enabling policy makers to better anticipate future regime shifts.

Assessing adaptive capacity

Adaptive capacity (AC), which is defined by the ability of households to anticipate and respond to changes and to minimize, cope with, and recover from the consequences of such changes (McClanahan et al. 2008), was included in the equation as it contributes to decreasing vulnerability (Béné et al. 2016). It can be estimated by social and human capital, ability to learn, and governance aspects of a given society (Adger 2003, Lebel et al. 2006). Social capital, e.g., social cohesion, specifically, contributes to decreasing vulnerability because it can create an appropriate social environment to sustain the changes and unlock the capacities of communities to adapt to changes (Adger 2003, Béné et al. 2016). Human capital, such as livelihood resources or human conditions, is an important contributor to community resilience (McClanahan et al. 2008). The ability to learn refers to how communities can learn from environmental disturbances and social-environmental actions that occur in their area (Marshall and Marshall 2007). Social or environmental changes may teach people how to behave when facing future disturbances; hence, communities that can learn from such changes tend to be more resilient. Governance, e.g., structures and processes used by societies to share power and collective actions, can be expressed through norms of interaction, which shape the contexts in which human groups challenge decisions and determine access to resources (Lebel et al. 2006). Good governance regimes have attributes that can improve the fit between knowledge, action, and social-ecological contexts, thereby allowing societies to better respond to changes (Lebel et al. 2006).

Although it is important to recognize that coastal populations are not homogeneous (Khan et al. 2018), and that existing groups, e.g., minority groups and different social classes, are not equally

Fig. 2. Study area encompassing 17 coastal states distributed over 5 marine ecoregions, according to the ecoregions proposed by Spalding et al. (2007), along the Brazilian coastline (ecoregions presented from north to south). State fisheries sectors are identified on the map.



vulnerable when faced with changes (Cinner et al. 2015), we do not have this type of social data to analyze how equity and justice influence the distribution of impacts. For instance, the inclusion of women in fisheries and fisheries governance can reduce their vulnerability and improve their livelihoods (Alonso-Población and Siar 2018). Knowing this could improve actions to deal with uneven vulnerability. However, studies examining gender inequalities in fisheries remain incipient in Brazil.

The specific measures of adaptive capacity we used were the human development index, a proxy for social and human capital; educational attainment, a proxy for ability to learn; presence of an environmental council with solid environmental laws and investment in environmental actions, a proxy for governance; and presence of social and fishery organizations, a proxy for social capital, to assess the ability of human groups to cope with changes and sustain resource users and local institutions (Table 2).

Assessing species vulnerability

The species vulnerability (SP) dimension includes biological and ecological information on the fish stocks used by artisanal and industrial sectors in the coastal region. For each state, we used landing data and selected the 10 target species with the most recorded landings (in weight) considering both the industrial and artisanal sectors together. In 4 states, the species targeted exclusively by the artisanal sector comprised the bulk of the 10 most abundantly landed species (Fig. 2). We collected biological information on these fish using the information already provided by FishBase: resilience, vulnerability, price category, threat category, trophic level, and distribution range (Froese and Pauly 2017). We also considered the fishing pressure, whether species were caught by 1 or 2 sectors, and the status of the fish stocks (Appendix 2). We did not consider the size or mobility of the fleet. We used the average scores for the 10 fish in each of the indicators that form the species vulnerability component. These indicators represent a proxy for biodiversity security because they capture fish species exposure, ecological vulnerability, and distribution aspects (Table 2).

Assessing ecosystem vulnerability

Communities, such as coastal communities, that depend directly on natural resources, are highly vulnerable to the effects of mismanagement, climate change, overfishing, and environmental degradation, which can negatively impact social-ecological vulnerability (Metcalf et al. 2015). We estimated some environmental indicators of marine ecosystems that can influence fisheries. Ecological studies predict that biological impoverishment will increase in the future, which will eventually threaten fisheries (Cardinale et al. 2012) and affect ecosystem health (Béné et al. 2017). Moreover, ecosystem health is a growing concern, especially around densely populated coastal areas where hot spots have been identified (Heileman 2009). We used estimates of primary productivity, level of marine protection, coastal pollution, climate exposure, and the percentage of conservation priority areas as input indicators to determine ecosystem vulnerability (ECO; Table 2).

Coastal social-ecological systems in Brazil

To test the ICV, we considered the SESs of fishing communities located along the coast of Brazil, an area covering 8500 km along the western Atlantic, together with their marine environment, including their fishing area in the exclusive economic zone (3.5 million km²). The regional level adopted was based on the political state scope needed to help implement coastal management policies in the future. Brazil has 17 coastal states distributed across 4 regions: North, Northeast, Southeast, and South. For most of them (11), the state capital is located near the coast.

We also discuss the data in terms of the marine ecoregions they represent, following the ecoregion definition of Spalding et al. (2007). Specifically, these 17 states are distributed over 5 marine

Table 2. Design of the Index of Coastal Vulnerability (ICV). Components and their indicators, description of each variable, score calculation, and source of variables are detailed. ICV is the sum of species vulnerability and ecosystem vulnerability components minus the adaptive capacity of the coastal states. IBGE, Brazilian Institute of Geography and Statistics.

Components	Indicators (0 to 1)	Description	Scores	Source of Variables
Adaptive capacity	Human development index	Human development index as a proxy for human well-being. Values are from 2010 (IBGE 2011). It ranges from 0 to 1, i.e., the closer to 1, the greater the human development.	Range from 0 to 1. The closer to 1, the lower the coastal vulnerability, and vice versa.	http://www.ibge.gov.br
	Educational attainment	A proxy for human capital that was measured by the illiteracy rate of each state, compared with the regional and national rates (IBGE 2011).	State educational attainment < regional average = 0.3 points; state educational attainment > regional average or national average = 0.6 points; state educational attainment > regional average and > national average = 1 point.	http://www.ibge.gov.br
	Governance	Estimated by a combination of three indicators: (1) proportion of municipalities with environmental laws, (2) proportion of municipalities with active environmental councils, and (3) proportion of municipalities with local investments in environmental actions.	For all indicators: ≤ 30% = 0.3 points, between 31% and 60% = 0.6 points, and > 60% = 1 point. The governance value was the average of the 3 indicators.	http://www.ibge.gov.br
	Social capital	Presence of social and fisheries organizations in coastal municipalities, by state.	More than 50% of municipalities have social organizations and > 50% of municipalities have fisheries organizations = 1 point; > 50% of municipalities have social organizations, but < 50% of municipalities have fisheries organizations = 0.3 points.	http://mapaosc.ipea.gov.br
Species vulnerability†	Resilience	Resilience of fish species caught.	Low = 1 point; medium = 0.5 points; high = 0 points.	http://www.fishbase.org
	Vulnerability	Vulnerability of fish species caught.	Low = 0 points; medium = 0.5 points; very high/high = 1 point.	http://www.fishbase.org
	Price category	Price category of target species in the coastal states.	Low = 0 points; medium = 0.5 points; high = 1 point.	http://www.fishbase.org
	Threat level	Threat level of fish species caught.	Critical endangered/endangered/ vulnerable = 1 point; near threatened = 0.5 points; not threatened/least concern/ data deficient = 0 points.	http://www.fishbase.org; http://www.mma.gov.br
	Trophic level	Trophic level of fish species caught.	Very high (TL > 4) = 1 point; high (3.5 < TL < 4) = 0.8 points; medium (3 < TL < 3.5) = 0.4 points; low (TL< 3) = 0 points.	http://www.fishbase.org
	Distribution range	Either the number of oceans or the areas of them where the fish stocks are distributed. For instance: western Atlantic, only 1 area of the Atlantic ocean (low); western and eastern Atlantic, 2 areas of the Atlantic ocean (medium); and Atlantic and Indian oceans, 2 oceans (high). This variable can be adapted for other species distributions around the world, but it should follow the logic of the 3 categories.	High = 0 points; medium = 0.5 points; low = 1 point.	http://www.fishbase.org
	Fishing pressure	Whether the fish stock is caught by only 1 sector or by both sectors (artisanal and industrial).	Only artisanal = 0.3 points; Only industrial = 0.6 points; Both sectors = 1 point.	http://www.seaaroundus.org
	Stock status	Stock status assessment of the 10 fish species caught by artisanal and industrial sectors. This calculation followed Kleisner et al. (2013*a*) and used the categories most frequently observed over the last 10 years of the temporal series.	Status: developing = 0 points, exploited = 0.4 points, rebuilding = 0.5 points, overexploited = 0.8 points, and collapsed = 1 point.	http://www.seaaroundus.org

(con'd)

Ecosystem vulnerability	Climate exposure	Combination of aspects related to climate exposure, such as sea surface temperature (°C) and salinity (psu). Higher temperature and higher salinity may imply higher ecosystem vulnerability (Welch et al. 2014, Bennet et al. 2016).	A normalization process‡ was used to attribute a proportional score to each aspect; the climate exposure value was the average value of the 2 aspects.	http://www.bio-oracle.org
	Productivity	Measured by chlorophyll-a (mg/m³), where higher concentrations were considered to be less vulnerable (Cinner et al. 2013).	Normalization process‡	http://www.bio-oracle.org
	Coastal protection	Combination of aspects related to marine protected areas, such as (1) the percentage of the area that is protected and (2) the existence of a management plan.	(1) Normalization process‡; (2) ≥ 50% of the protected areas have management plans = 0 points or < 50% of the protected areas have management plans = 1 point. Coastal protection was the average value of the 2 aspects.	http://www.mma.gov.br
	Coastal pollution	Percentage of coastal municipalities without sewage disposal.	More than 70% of the municipalities = 1 point; between 69% and 31% = 0.5 points; ≤ 30% = 0 points.	http://www.ibge.gov.br
	Priority index	Percentage of priority coastal areas (high, very high, and extremely high) in the 5 marine ecoregions, according to the latest assessment by the Brazilian government (Prates et al. 2012). It was measured by an ecoregion ordination based on the percentage of km² of priority areas in each ecoregion. States were classified according to their ecoregion rankings. For states with more than 1 ecoregion, we summed the values of these ecoregions.	Ecoregions were ordered according to the following scale: first (lowest priority area), 0.2 points; second, 0.4 points; third, 0.6 points; fourth, 0.8 points; fifth, 1 point (highest priority area).	http://www.mma.gov.br

† In the species vulnerability component, the average value for the 10 species was used as the final value for each variable.
‡ A normalization process is a standardization ranging from 0 (least vulnerable) to 1 (most vulnerable). We designated the highest value of the variable with 1 point and calculated a proportion for each state.

ecoregions: Amazonia; Northeastern Brazil, including Fernando de Noronha/Atoll das Rocas/Sao Pedro and Sao Paulo Islands; Eastern Brazil, including Trindade and Martin Vaz Islands; Southeastern Brazil; and Rio Grande (Fig. 2).

The Brazilian coast encompasses a vast diversity of ecosystems, including mangroves, coral and rocky reefs, lagoons, and estuaries (Prates et al. 2012). These ecosystems provide a variety of marine resources and benefits that play an important role in the Brazilian economy (Elfes et al. 2014), such as those resulting from coastal and oceanic fisheries.

The Northeast region is the quantitatively most important as it produces more than 36% of total catches in the country, and this total is mainly because of artisanal fishing (WWF 2016). The South region is the second most productive, followed by the Southeast and North regions (WWF 2016). The industrial fishing sector is present mainly in the South and Southeast states (Dias-Neto and Dias 2015). Considering the most recent and reliable estimates of fish production per state in Brazil, the states of Santa Catarina (South), Pará (North), Bahia (Northeast), Rio de Janeiro (Southeast), Maranhão (Northeast), São Paulo (Southeast), Rio Grande do Norte (Northeast), and Ceará (Northeast) are the most productive (Dias-Neto and Dias 2015). The total fishing fleet is roughly 65,400 vessels and is formed mostly by small boats, e.g., rowboats, sailboats, or small motorized boats, used mainly by the artisanal fishers in the Northeast region (Dias-Neto and Dias 2015). The industrial and artisanal fishing sector catches increased from an estimated average of 190,000 t/yr in the early 1950s to about 840,000 t/yr in the late 2000s (Freire et al. 2014, 2015). Such an increase has put most Brazilian marine fish stocks under intense exploitation or in a situation of overfishing (Ruffino and Abdallah 2016, WWF 2016).

In general, fishing is carried out using gill nets, bottom trawling, fish and crustacean bottom traps, longlines, and hook and lines. Artisanal fisheries target reef and coastal fish, e.g., groupers and snappers, such as species from the genera *Epinephelus* and *Lutjanus*; whereas industrial fisheries target small and large pelagics, e.g., sardines and albacores, such as species from the genera *Sardinella* and *Thunnus* (Dias-Neto and Dias 2015, Freire et al. 2014, 2015). It is estimated that fisheries in Brazil employ more than 1 million fishers, with 41% represented by women (Ministério da Pesca e Aquicultura 2013), although these data are controversial because of low credibility. The majority of fishers (84%) are concentrated in the North and Northeast regions, led by Pará (24%), Maranhão (17%), and Bahia (12%; Ministério da Pesca e Aquicultura 2013). If we include everyone along the fishing value chain, the number of people involved in the fishing sector can reach up to 3.5 million people (Dias-Neto and Dias 2015). Moreover, there are 2081 registered fishery associations in the country (Lopez 2018).

Pollution, overfishing, and socioeconomic changes, e.g., urbanization and tourism, are the main drivers of changes to coastal SESs in Brazil (Ministério do Meio Ambiente [MMA] 2011). In general, Brazilian fisheries management is inadequate and incapable of promoting sustainability for fishing SESs (Dias-Neto 2010, WWF 2016). Some initiatives, such as comanagement, have been helping decrease pressure on these systems (Kalikoski et al. 2009). However, lack of regulations, enforcement, and engagement of fishers to maintain fisheries in the long term creates a gap of information and increases exploitation rates and the risk of species extinction. Furthermore, the increased degradation and environmental changes to marine ecosystems have affected their ability to provide marine ecosystem services.

Data sources

We assessed fish stock characteristics, e.g., stock status and species biological traits; ecosystem indicators, e.g., biotic and abiotic variables; and social aspects, e.g., socioeconomic, demographic, and governance factors, in the 17 coastal states (Table 2). The information used to build all indicators was extracted from the most recent data sets available online: the Brazilian Institute of Geography and Statistics (IBGE; http://www.ibge.gov.br), the Institute for Applied Economic Research (IPEA; http://mapaosc.ipea.gov.br), the Brazilian Ministry of the Environment (MMA; http://mma.gov.br), Oracle data set (Bio-ORACLE; http://www.bio-oracle.org/), and FishBase (http://fishbase.org).

Industrial and artisanal fisheries landing data were extracted from the Sea Around Us database, which is a temporal series that spans from 1950 to 2010 (Freire et al. 2015). Abiotic variables, e.g., sea surface temperature, salinity, and chlorophyll-a, were extracted from the Bio-ORACLE database, comprising data from 2005 to 2010 (http://www.bio-oracle.org.; Tyberghein et al. 2012, Assis et al. 2018). Fish species information was extracted for 2017 from the FishBase database (Froese and Pauly 2017). Social aspects were extracted from the demographic census data set from 2010 (IBGE 2011) and from the latest update of the civil society organizations registered by the government in 2015 (IPEA 2017). Information about marine protected areas (MPAs) was aggregated using national data published by the Brazilian government in 2012 (Prates et al. 2012).

Data analyses

We used a Bayesian generalized linear model (BGLM) to analyze the influence of five independent variables on the states' ICV (dependent variable), namely, fish landing richness, fisheries instability indicator, market indicator, coastal extension, and coastal population. Richness was calculated for the period 2001 to 2010 because the data used for the construction of the ICV were from this period. The fisheries instability indicator refers to the tendency of fisheries provision to either remain stable in the face of some perturbation or rapidly return to preperturbation levels (Appendix 3). Per capita fish consumption (kilograms per inhabitant per year) and urban access (linear distance between landing port and state capital) were combined to form a market indicator that attempts to capture fisheries market demand in the coastal states (Appendix 4). To account for the possibility that coastal extension could intensify the degree of anthropogenic changes and economic development and lead to increasing pressure on local ecosystems, we used the coastal extension of each state, measured in kilometers. We examined whether coastal population was affecting ICV because previous studies have suggested that this is an important predictor of fish assemblage structure in rocky shores (Teixeira-Neves et al. 2015) and that population growth and urban expansion are important threats to biodiversity because of increasing exploitation rates (McGill et al. 2015). We used the most recent information regarding coastal population as a percentage of total state population (IBGE 2011).

All predictor variables were extracted from the landing data set and IBGE reports.

The final model was selected using a forward stepwise procedure from the starting model. To compare the goodness of fit between each model, two different measures were computed: the Watanabe-Akaike information criterion (WAIC) and the deviance information criterion (DIC). WAIC is a fully Bayesian measure that is better suited than the Akaike information criterion because it uses the entire posterior distribution to make inferences about the parameters and, therefore, provides more precise estimates (Watanabe 2010). DIC is the most popular measure to compare and select the best Bayesian model by a sensitivity analysis performance (Spiegelhalter et al. 2002). Only the final model will be considered and discussed, although the others will be shown as well. The analyses were carried out with the R-INLA package (Rue et al. 2009) of R software (R Core Team 2017) to perform the BGLM.

RESULTS

Index of coastal vulnerability

The average ICV for the Brazilian coast was 0.77, which, according to the proposed qualitative scale (high category ranges from 0.61 to 0.80), is considered high vulnerability. The ICV ranged from 0.33 to 1, with the state of Ceará (ICV = 1) being the most vulnerable and Alagoas (ICV = 0.33) the least vulnerable. Both states are located in the Northeastern ecoregion. Most states in the Northeastern and Eastern ecoregions presented higher scores than the Brazilian average, as did the states of Santa Catarina, in the Southeastern ecoregion, and Amapá, in the Amazonia ecoregion (Table 3, Fig. 3).

Fig. 3. Brazil study region showing all coastal states (N = 17) colored according to the final Index of Coastal Vulnerability (ICV) score. The ICV scores ranged from 0.33 (low vulnerability) to 1.00 (high vulnerability). The average value for the index was 0.77 (high vulnerability). State acronyms: AL, Alagoas; AP, Amapá; BA, Bahia; CE, Ceará; ES, Espírito Santo; MA, Maranhão; PA, Pará; PB, Paraíba; PE, Pernambuco; PI, Piauí; PR, Paraná; RJ, Rio de Janeiro; RN, Rio Grande do Norte; RS, Rio Grande do Sul; SC, Santa Catarina; SE, Sergipe; SP, São Paulo.

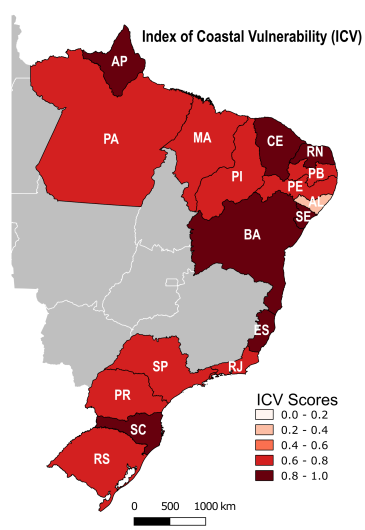


Table 3. Scores for the 3 components and the Index of Coastal Vulnerability (ICV) in the 5 Brazilian marine ecoregions and their 17 coastal states. Both the components and the index ranged from 0 to 1. States with very high ICVs are in bold (ranges between 0.8 and 1.0).

Marine Ecoregion	States	Components			ICV
		Adaptive Capacity	Species Vulnerability	Ecosystem Vulnerability	
Amazonia	Amapá (AP)	0.51	0.59	0.80	**0.98**
	Pará (PA)	0.83	0.60	0.80	0.63
	Maranhão (MA)	0.82	0.54	0.90	0.68
Northeastern	Piauí (PI)	0.83	0.58	0.96	0.79
	Ceará (CE)	0.71	0.63	0.98	**1.00**
	Rio Grande do Norte (RN)	0.64	0.51	0.98	**0.94**
	Paraíba (PB)	0.53	0.59	0.60	0.73
	Pernambuco (PE)	0.50	0.57	0.60	0.74
	Alagoas (AL)	0.82	0.51	0.60	0.33
	Sergipe (SE)	0.64	0.48	0.98	**0.91**
Eastern	Bahia (BA)†	0.70	0.50	0.99	**0.88**
	Espírito Santo (ES)	0.74	0.50	0.96	**0.81**
	Rio de Janeiro (RJ)†	0.88	0.60	0.97	0.77
Southeastern	São Paulo (SP)	0.83	0.62	0.84	0.70
	Paraná (PR)	0.74	0.40	0.90	0.61
	Santa Catarina (SC)†	0.64	0.53	0.90	**0.87**
Rio Grande	Rio Grande do Sul (RS)	0.88	0.62	0.85	0.65
	Median	0.74	0.57	0.90	0.77

† Coastal states that cover 2 marine ecoregions: Bahia = Northeastern and Eastern; Rio de Janeiro = Eastern and Southeastern; Santa Catarina = Southeastern and Rio Grande.

The average value for adaptive capacity was 0.74 and ranged from 0.50 to 0.88. More than half of the states (53%) presented scores below the national average. The state of Pernambuco had the lowest score (AC = 0.50), and the states of Rio de Janeiro (AC = 0.88) and Rio Grande do Sul (AC = 0.88) had the highest adaptive capacities. For the species vulnerability component, the country average was 0.57 and ranged from 0.40 to 0.63 among states. The vulnerability of fish species was highest in the state of Ceará (SP = 0.63) and lowest in Paraná (SP = 0.40). Finally, the ecosystem component revealed that the state of Bahia (ECO = 0.99) was more vulnerable than the others. The country average for this component was 0.90 and ranged from 0.60 to 0.99 (Table 3, Fig. 4).

In general, the species vulnerability component was classified as moderate, the adaptive capacity component as high vulnerability, and the ecosystem vulnerability was considered very high in almost all coastal states (N = 14; Table 3). The coastal vulnerability index and the 3 vulnerability components revealed little variation among the 5 ecoregions. However, in general, the Amazonia and Northeastern ecoregions were more vulnerable. Almost half of the states presented ICV values classified as very high and above the national average values (0.77 out of 1).

Aspects defining coastal vulnerability in Brazil

The final BGLM, based on the lowest WAIC, included fish landing richness and coastal population as relevant variables to explain coastal state ICVs (Table 4). There was a 79% probability that states with lower numbers of species in their landings were more vulnerable (Fig. 5A), and a probability of 94% that a higher coastal population indicates higher coastal vulnerability (Fig. 5B). Stability in fish provision, the market indicator, and the extension of coastal states did not affect a state's vulnerability.

Table 4. Comparison of the Bayesian models used. Statistical acronyms: DIC, deviance information criterion; WAIC, Watanabe Akaike information criterion. Predictor acronyms: Coa_Ext, state coastal extension; Coa_Pop, percentage of coastal population; Insta, fisheries instability indicator; Mar, market index; Rich, landing richness. The model in bold was considered the best model.

Model	WAIC	DIC
1 + Rich + Coa_Ext + Insta + Mar + Coa_Pop	−3.453	−3.506
1 + Rich + Insta + Market + Coa_Pop	−4.467	−4.855
1 + Rich + Coa_Ext + Market + Coa_Pop	−4.467	−4.855
1 + Rich + Market + Coa_Pop	−6.404	−7.210
1 + Rich + Insta + Coa_Pop	−6.446	−7.036
1 + Rich + Insta	−6.376	−6.730
1 + Rich + Coa_Pop	**−8.331**	**−9.288**

DISCUSSION

Notwithstanding the importance of the ecosystem services provided by coastal regions, increasing evidence indicates that coastal ecosystems have been deeply altered, thus reducing their productivity and resilience (Jackson et al. 2001, Ojea et al. 2017). Such effects have intensified conflicts over resources (Prestrelo and Vianna 2016), thereby affecting social-ecological vulnerability in coastal areas. The vulnerability index we created sought to develop an integrative approach that embraces different perspectives of the fisheries system. Given the difficulty and complexity in operationalizing vulnerability (Bennett et al. 2016, Comte et al. 2019), the ICV holistic approach helps untangle the root of anthropic stressors in coastal areas, given that centralized

Fig. 4. Maps with all coastal states colored by final Index of Coastal Vulnerability (ICV) component scores: adaptive capacity (green scale), species vulnerability (orange scale), and ecosystem vulnerability (blue scale). All component scores were divided into 5 categories, with the lowest values represented by the lightest shades of the color scale. For the AC score only, the lower the value, the worse the situation. State acronyms: AL, Alagoas; AP, Amapá; BA, Bahia; CE, Ceará; ES, Espírito Santo; MA, Maranhão; PA, Pará; PB, Paraíba; PE, Pernambuco; PI, Piauí; PR, Paraná; RJ, Rio de Janeiro; RN, Rio Grande do Norte; RS, Rio Grande do Sul; SE, Sergipe; SC, Santa Catarina; SP, São Paulo.

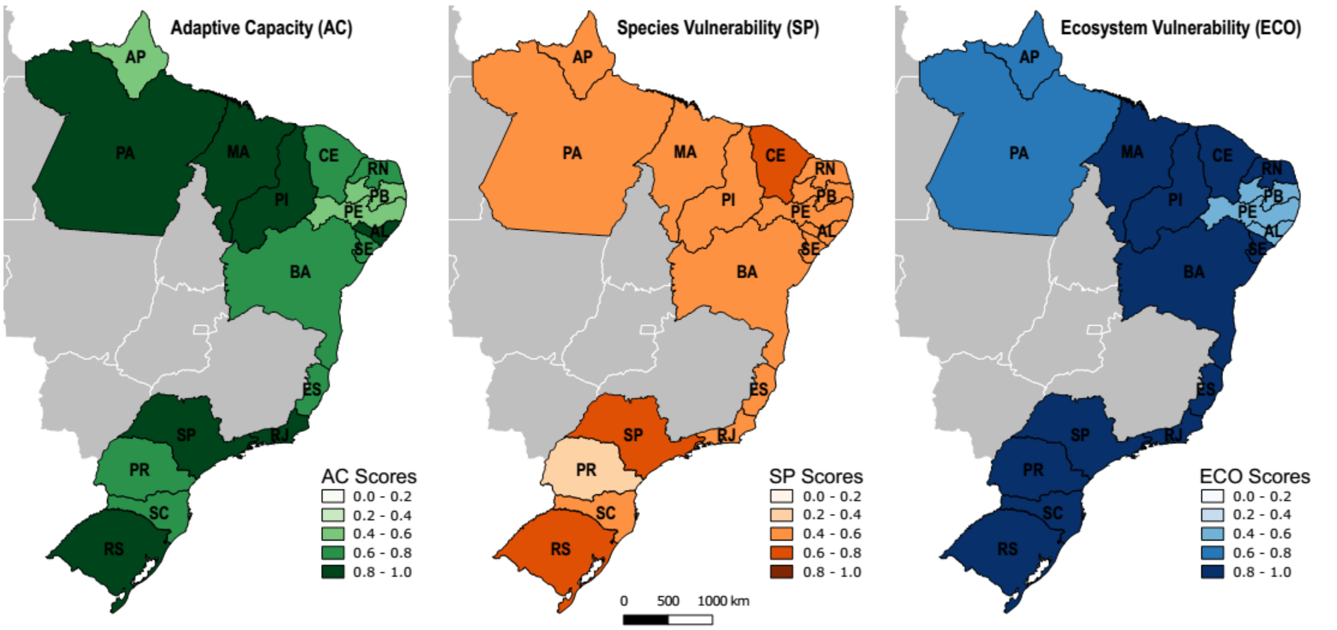
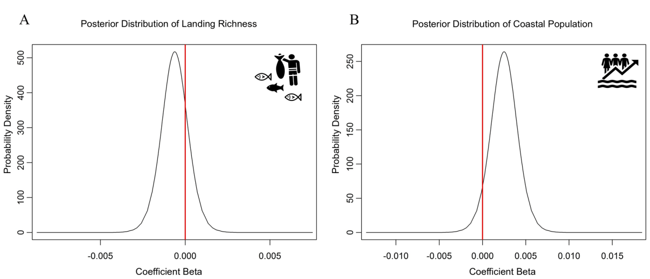


Fig. 5. Posterior probabilities of the relevant effects of the Bayesian model to landing richness (A) and coastal population (B) on coastal vulnerability.



solutions to climate change seem insufficient. At the local level, the ICV facilitates assessments and comparative analyses of community vulnerability. Additionally, it enables a robust assessment of fisheries vulnerability and identifies locations where supplementary analyses should be conducted to better plan priorities for investment along the coast. By relating the ICV to external variables, it is also possible to identify the main drivers of poor vulnerability performance in a given region. For example, in the Brazilian case study we explored, the number of species presented in fish landings and the size of coastal populations were strongly related to coastal vulnerability. Our case study also highlighted how adaptive capacity alone, without investments in performance of how we exploit ecosystems services, is not enough to assure lower levels of SES vulnerability.

Considering the assessed components of the ICV, ecosystem vulnerability performed the worst, whereas climate exposure, primary productivity, and coastal protection presented high scores (above 0.9 points, the very high vulnerability category) and must be considered by managers (Appendix 5). Based on the climate scenarios that point toward a warmer future in Brazil, coastal ecosystems are expected to suffer thermal stress above their adaptative capacity (Soares et al. 2014, Bernardino et al. 2015). Thus, to prevent and minimize climate-induced damages to fishing SESs, ecosystem responses to global climate changes need to be taken seriously by improving the adaptive capacity and resilience of coastal communities to deal with future scenarios. Moreover, unsurprisingly, primary productivity and coastal protection performed badly. Fishery nursery areas, e.g., coral reefs and mangroves, in Brazil have been affected by many human threats, such as coastal development, pollution, deforestation, and, again, climate change (Prates et al. 2012). Some predictions have suggested that 40% of Brazilian reefs are at a high risk of declining in the very short term (Rodríguez-Ramírez et al. 2008). Estuarine environments, which support relevant ecological functions, are considered to be the most threatened coastal ecosystems in the Brazilian marine ecoregions (Bernardino et al. 2015, Sunday et al. 2015).

Although the Northeastern and Eastern ecoregions present moderate coastal habitat modification when compared with the other regions that have been severely modified (Heileman 2009), we have identified these to be the most vulnerable coastal areas. This is in accordance with a global study that analyzed species richness, endemism, and higher taxonomic uniqueness and concluded that the Northeastern ecoregion is vulnerable and should be included as a priority ecoregion for conservation purposes (Olson and Dinerstein 2002). For instance, the state of Rio Grande do Norte, which was identified to be the third most vulnerable state, showed the largest coastal degradation with about 56% of the mangrove area converted into shrimp farms (Prates et al. 2012). This state has also been affected by the high mobility of the industrial fleet from Ceará (Freire and Pauly 2010), the northeastern state in the worst situation.

Despite the increased effectiveness of Brazilian MPAs (Araújo and Bernard 2016), lack of protection, institutional support, and unsatisfactory management continue to be reported in coastal areas (Maretti 2001, Schiavetti et al. 2013, Santos and Schiavetti 2014). Additionally, MPAs still fail to protect critical nursery areas (Ervin et al. 2010, Nagelkerken et al. 2015), a factor widely aggravated by the biased distribution of MPAs across Brazilian ecoregions (Magris et al. 2013). Only part of the Northeastern marine ecoregion has some sort of no-take protection, and the distant islands of São Pedro and São Paulo lack protection entirely (Magris et al. 2013). Notwithstanding the proposed governmental initiatives to establish and monitor MPAs, which includes analyzing new priority areas along the coast (Prates et al. 2012), no concrete action has been taken.

On the other hand, adaptive capacity performed better than the other ICV components, which was mainly attributed to the fact that more than 50% of coastal municipalities have social and fisheries organizations. Communities that are more socially organized are considered less vulnerable because organization decreases the transaction costs for collective actions (Cinner et al. 2009). However, of the total 820,000 civil society organizations distributed throughout Brazil, there are only 2081 registered with the government that are associated with developing and advocating for the rights and interests of fishermen and fisherwomen (Lopez 2018). Despite the overall presence of social organizations, the low participation of people in local decision making has been widely recognized in coastal areas, including in Brazil (Lopes et al. 2011, Silva and Lopes 2015). Nevertheless, the existence of environmental laws, environmental councils, and some financial investment in environmental programs may nudge the political willingness toward supporting the protection of coastal areas. However, it is important to highlight that we considered only some aspects of human and social capital (e.g., educational attainment and presence of social organizations). Other adaptive capacity indicators, such as collective action, ability to organize, livelihood resources, and human conditions, should be considered in future studies whenever this information is available to refine the index.

Different fishers' groups from coastal communities can respond differently when facing ecosystem changes (Cinner et al. 2015, Silva and Lopes 2015). A clear role for people and the equitable sharing of costs and benefits is needed in vulnerability assessments (Tschakert et al. 2013). For instance, gender inequality has gained increasing attention in environmental management initiatives over the last decades (Agarwal 2010, Kleiber et al. 2017). Within small-scale fisheries, the recent female empowerment movement has promoted good examples of collective action and adaptation (Alonso-Población and Siar 2018, de la Torre-Castro 2019). Furthermore, given that over the last 10 years the Brazilian fishing policy (National Policy of Sustainable Development of the Aquaculture and Fisheries, Federal Law No. 11.959/2009; Federative Republic of Brazil 2009) has considered the production and repair of fishing gear and boats and fish processing to be fisheries activities, the percentage of fisherwomen has increased (Dias-Neto and Dias 2015). Still, the lack of social data on gender inequalities remains. Considering the social and gender inequalities in fisheries, any work toward decreasing them should have direct consequences on female livelihoods and female engagement in fisheries management and, thereby, reduce vulnerability and negative effects on the SESs (Biswas 2017). Although we do not have social data to analyze uneven vulnerabilities, we recognize this to be a fundamental contributing factor to achieving sustainable and equitable goals in marine conservation.

Similar to the other components of the ICV, the results of species vulnerability revealed regional differences. Although most species were found to have low threat levels (moderate vulnerability), the Northeastern and Eastern ecoregions included the most vulnerable states, mostly because of their elevated artisanal and industrial fishing pressures. Some species, e.g., *Cynoscion acoupa*, *Lutjanus purpureus*, *Micropogonias furnieri*, *Mugil liza*, *Sardinella brasiliensis*, *Thunnus albacares*, and *Scomberomorus cavalla*, are targeted by both sectors, whereas others have limited distribution ranges, e.g., *Anchoviella* spp., *Cynoscion* spp., *Diapterus rhombeus*, *Haemulon plumierii*, *Lutjanus* spp., *Macrodon* spp., *M. furnieri*, *Opisthonema oglinum*, *S. brasiliensis*, and *Sparisoma* spp. (Appendix 6). Distribution range, specifically, is one of the most important predictors of extinction risk among terrestrial and aquatic mammals (Davidson et al. 2009, 2012), amphibians, reptiles (Veron et al. 2016), and fish (Sunday et al. 2015). In the ocean, range shifts have been faster than in terrestrial ecosystems (Pinsky et al. 2013), and species with lower latitudinal ranges are more vulnerable because they become less able to find spots that fit their thermal preferences (Sunday et al. 2015). Some fish are also shifting to deeper waters or higher latitudes in response to climate change, e.g., because of increased seawater temperature, prey distribution, and so on (Perry et al. 2005). These changes in distribution patterns are likely to have tremendous impacts on fisheries and, consequently, result in alterations in community interactions. Thus, because local impacts could cause biodiversity loss of marine ecosystems on a global scale (Hawkins et al. 2000), it is crucial to consider the high vulnerability of restricted-range species in future coastal management to avoid even higher risks of extinction.

Although the ecosystem services approach has been largely incorporated into current societal discourse, anthropogenic influence on biodiversity loss will eventually threaten these services, especially through species extinctions caused by excessive fishing, pollution, habitat destruction, and other anthropogenic drivers (Cardinale et al. 2012, Bennett et al. 2016). Our findings agree with the Anthropocene concept applied to the fields of ecology and conservation, which refers to the epoch in which human impacts started to overtake natural processes (Gibbard and Walker 2014). Specifically, we observed that the lower the fish landing richness and the higher the coastal population, the higher the vulnerability of the state. This was an expected relationship because the typical models of human development in Brazil and in most places are based on the intensification of human exploitation of nearby coastal resources and increased coastal pollution, which affect coastal environments (Teixeira-Neves and Neves 2015, Hughes et al. 2017). Changing such models is a task that is overdue to be accepted, internalized, and performed by managers and policy makers, as we run out of time to maintain society's minimum livelihood standards.

MANAGEMENT IMPLICATIONS FOR COASTAL VULNERABILITY IN BRAZIL

The national score of 0.77 (out of 1) suggests that overall vulnerability is high, despite the high levels of adaptive capacity identified. Because of the low variation among ecoregions and/or states, our findings suggest that the entire Brazilian coast has been widely compromised, making marine biodiversity conservation an urgent need. Some states, such as Ceará, clearly perform worse than others and require immediate attention.

In general, fishing communities in Brazil are culturally diverse, but characterized by the same precarious socioeconomic conditions and governability problems. This scenario can be smoothed by investments in coastal management to maintain long-term marine fisheries sustainability. Furthermore, to decrease the vulnerability of coastal habitats, we recommend enhancing fisheries management by monitoring coastal areas, restoring vulnerable habitats (mangroves, estuaries, and coral reefs), increasing actions to improve adaptive capacity, and expanding MPAs and comanagement approaches.

The low variation among marine ecoregions does not mean that the index is not effective at capturing changes over time, but rather that Brazilian coastal states share many similarities and have been affected by the same social and ecological problems. We suggest that this index be applied to other coastal systems for further evaluations and comparisons.

BLIND SPOTS

The ICV index helps determine the vulnerability of coastal communities in a straightforward way by synthesizing a complex system into a unique number that enables comparison of different areas. However, some gaps should be filled by further research to refine the index. For instance, fleet dynamics, such as size, and fleet mobility were not considered but could bring important information about fisheries dynamics and their impacts on the coast. Despite the fact that catch data is the most basic data needed to manage fish stocks, some countries, such as Brazil, do not have a history of fisheries statistics, thereby making it difficult to accurately define stocks in need of protection and measure coastal vulnerability accordingly. Additionally, even though our study supports the usefulness of the index for analysis on a local scale, some calibration would help its application in other coastal areas. In specific community-level scenarios, different variables may be required to form each indicator and component to track the context information of a given coastal area. Future research is also needed to identify better surrogates for social inequalities, to develop more appropriate objectives to represent minority social groups (e.g., fisherwomen), and to identify the processes that threaten them.

Even though the adaptive capacity component only has a few indicators, because of the data-poor situation in Brazil, when compared with the other components, the sensitivity analysis supported the robustness of the index. Still, whenever possible, additional measures of adaptive capacity should be used, such as those relating to diversity and occupation flexibility, e.g., livelihood characteristics and willingness to change; access to assets, e.g., cultural memory and natural capital; learning and knowledge, e.g., ability to learn and environmental perception; and governance and institutions, e.g., gender relations and levels of trust and cooperation (Adger 2006, Whitney et al. 2017).

However, the index was tested in a marine hot spot country, where coastal areas are undergoing negative changes faster than in other marine areas worldwide (Pecl et al. 2014). These marine hot spots are natural laboratories for social-ecological changes. They are also priority areas for research as they provide valuable case studies to help identify adaptation strategies that can be adopted in other coastal communities facing threats caused by a rapidly changing world (Pecl et al. 2014). Unfortunately, the index, whether applied to Brazil or elsewhere, is limited by the availability of reliable variables at different scales, making it difficult to have a more complete and expert-based process in the selection of variables. Despite these limitations, the ICV used robust Bayesian methods to analyze qualitative and quantitative data from social-ecological fishery systems, an important new contribution to coastal fishery management in developing countries.

CONCLUSIONS

We are likely living in a catastrophic geologic era that demands new ways of thinking about human-nature relations. Our study helps us consider vulnerability in a new light, i.e., with a focus on communities and their individuals and experiences. At this level, it is possible to identify multiple interacting drivers of change and exposure to vulnerabilities and propose locally feasible solutions to improve the sustainability of human-coastal relationships. Among the most important advantages of the new index are its low cost to generate powerful results and its flexibility to adjust to other social-ecological contexts depending on data availability. However, it is important to highlight that, when applying the ICV to other contexts, it is necessary to adapt it to the local social-ecological reality by considering the available variables without compromising the robustness of the index, for example, by attributing enough and meaningful variables to each component.

Our findings are consistent with the literature on small-scale fisheries in the Anthropocene that shows the risks derived from the rapid increase in population density in coastal areas. By pointing out weaker spots in the coastal system, the index helps provide some of the baseline necessary to manage fisheries in a holistic way with the goal of maintaining social-ecological benefits. Finally, there is growing scientific evidence about coastal vulnerabilities worldwide, and excuses about lack of knowledge will not be accepted in the future. It is past time we shed some light on the complex relationships in SES systems in the global south.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/11185

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Appendix 1. Sensitivity analyses.

Given that the decisions taken in the process of weighing the indicators equally could be unclear, we ran a sensitivity analysis to check the robustness of our findings. A sensitivity analysis is a repeat of the primary analysis but uses alternative decisions (or weights) to check uncertainty in the output of a mathematical model (Deeks et al. 2008, Nardo et al. 2008). It is also used to prove that the findings are not dependent on arbitrary decisions.

We chose four weighting schemes to check how each component contributes to estimating index values. In addition to assigning the same weight to the three components (equal weight), we also calculated the index by emphasizing one dimension at a time. We did that by assigning a ½ weight to the emphasized component and ¼ to the remaining two. This alternative was run three times: once for each emphasized component. Although the weight variations changed index values (Table A3.1), rankings of the coastal states where the index was tested were very similar. In other words, looking at the most and least vulnerable coastal states across weighting schemes, the states of CE, AP, and RN are among the most vulnerable and the states of AL, PR, and PA are the least vulnerable.

Table A1.1: Components and index values in the weighting scheme: equal weight (same weight among components), Emphasis AC (AC component weighing ½ and the other two weighing ¼), Emphasis SP (SP component weighing ½ and the other two weighing ¼), and Emphasis ECO (ECO component weighing ½ and the other two weighing ¼). AC = Adaptive capacity; SP = Species vulnerability; ECO = Ecosystem vulnerability; ICV = Index of Coastal Vulnerability. Highlighting the most vulnerable states (italic) and the least vulnerable states (bold).

	Components			ICV values			
States	AC	SP	ECO	Equal weight	Emphasis AC	Emphasis SP	Emphasis ECO
Amapá (AP)	0.51	0.59	0.80	0.98	0.095	0.369	0.421
Pará (PA)	0.83	0.60	0.80	**0.63**	**-0.064**	**0.291**	**0.343**
Maranhão (MA)	0.82	0.54	0.90	**0.68**	**-0.051**	**0.288**	**0.379**
Piauí (PI)	0.83	0.58	0.96	0.79	-0.029	0.321	0.418
Ceará (CE)	0.71	0.63	0.98	1.00	0.049	0.381	0.470
Rio Grande do Norte (RN)	0.64	0.51	0.98	0.94	0.053	0.340	0.458
Paraíba (PB)	0.53	0.59	0.60	0.73	0.033	0.313	0.315
Pernambuco (PE)	0.50	0.57	0.60	0.74	0.041	0.308	0.316
Alagoas (AL)	0.82	0.51	0.60	**0.33**	**-0.130**	**0.201**	**0.224**
Sergipe (SE)	0.64	0.48	0.98	0.91	0.046	0.324	0.450
Bahia (BA)	0.70	0.50	0.99	0.88	0.024	0.323	0.444
Espírito Santo (ES)	0.74	0.50	0.96	0.81	-0.003	0.306	0.421
Rio de Janeiro (RJ)	0.88	0.60	0.97	0.77	-0.048	0.323	0.415
São Paulo (SP)	0.83	0.62	0.84	**0.70**	**-0.049**	**0.311**	**0.368**
Paraná (PR)	0.74	0.40	0.90	**0.61**	**-0.048**	**0.236**	**0.361**
Santa Catarina (SC)	0.64	0.53	0.90	0.87	0.038	0.328	0.420
Rio Grande do Sul (RS)	0.88	0.62	0.85	**0.65**	**-0.073**	**0.300**	**0.358**

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Appendix 2. Target species in all 17 states analyzed along the Brazilian coastline with their vulnerability variables.

Table A2.1: Target species in all 17 states analyzed along the Brazilian coastline with their vulnerability variables. Information is described for each species of the 10 main fish targets in weight by artisanal and industrial sectors. FP = fishing pressure, SS = stock status, ThoL = trophic level, RES = resilience, VUL = vulnerability, TheL = Threat level, PC = price category, DR = distribution range, art = artisanal, ind = industrial, mod = moderate, vul = vulnerable, lc = least concern, nt = near threatened, not = not threat, dd = data deficient.

STATES	SPECIES	FP	SS	ThoL	RES	VUL	TheL	PC	DR
AP	Sciades parkeri	ind/art	overexploited	4.1	High	high	vul	medium	Western_Atlantic
AP	Cynoscion acoupa	ind/art	exploited	4.1	medium	high	lc	medium	Western_Atlantic
AP	Sciades couma	ind/art	exploited	3.9	medium	mod	lc	medium	South_America
AP	Coryphaena hippurus	art	exploited	4.4	High	mod	lc	high	Atlantic_Indian_Pacific
AP	Micropogonias furnieri	art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
AP	Sciades proops	art	exploited	4.4	High	mod	na	medium	WesternAtlantic
AP	Cynoscion virescens	art	overexploited	4	Low	high	lc	medium	WesternAtlantic
AP	Megalops atlanticus	art	rebuilding	4.5	Low	very high	vul	medium	Atlantic_Pacific
AP	Bagre bagre	art	exploited	4	Low	high	lc	medium	South_America
AP	Lutjanus purpureus	ind/art	overexploited	3.6	Low	high	vul	high	WesternAtlantic
PA	Cynoscion acoupa	ind/art	exploited	4.1	medium	high	lc	medium	Western_Atlantic
PA	Sciades parkeri	art	overexploited	4.1	High	high	vul	medium	Western_Atlantic
PA	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	high	Western_Atlantic
PA	Lutjanus purpureus	ind/art	overexploited	3.6	Low	high	vul	high	WesternAtlantic
PA	Sciades proops	art	exploited	4.4	High	mod	na	medium	WesternAtlantic
PA	Cynoscion microlepidotus	art	exploited	4	Low	high	lc	medium	WesternAtlantic
PA	Sciades herzbergii	art	overexploited	3.3	medium	mod	lc	medium	South_America
PA	Macrodon ancylodon	ind/art	exploited	3.9	medium	mod	lc	medium	WesternAtlantic
PA	Coryphaena hippurus	art	exploited	4.4	High	mod	lc	high	Atlantic_Indian_Pacific
PA	Sciades couma	ind	exploited	3.9	medium	mod	lc	medium	South_America
MA	Cynoscion acoupa	art	exploited	4.1	medium	high	lc	medium	Western_Atlantic
MA	Macrodon ancylodon	art	exploited	3.9	medium	mod	lc	medium	WesternAtlantic
MA	Hexanematichthys herzbergii	art	overexploited	3.3	medium	mod	lc	medium	South_America

MA	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	high	Western_Atlantic
MA	Aspistor quadriscutis	art	exploited	3.5	medium	mod	lc	medium	South_America
MA	Micropogonias furnieri	art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
MA	Sciades proops	art	exploited	4.4	High	mod	na	medium	WesternAtlantic
MA	Bagre bagre	art	exploited	4	Low	high	lc	medium	South_America
MA	Cynoscion leiarchus	art	overexploited	3.1	medium	mod	lc	medium	WesternAtlantic
MA	Genyatremus luteus	art	overexploited	3.5	medium	mod	dd	medium	WesternAtlantic
PI	Lutjanus synagris	art	exploited	3.8	medium	mod	nt	medium	WesternAtlantic
PI	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	high	Western_Atlantic
PI	Scomberomorus cavalla	art	exploited	4.4	Low	high	lc	medium	WesternAtlantic_EasternCentral Atlantic
PI	Euthynnus alletteratus	art	exploited	4.5	medium	high	lc	medium	Atlantic
PI	Ocyurus chrysurus	art	exploited	4	Low	high	dd	medium	WesternAtlantic_EasternCentral Atlantic
PI	Lutjanus purpureus	art	overexploited	3.6	Low	high	vul	high	WesternAtlantic
PI	Micropogonias furnieri	art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
PI	Conodon nobilis	art	overexploited	3.6	medium	mod	lc	low	WesternAtlantic_WesternGulfof Mexico
PI	Chloroscombrus chrysurus	art	exploited	3.5	medium	mod	lc	low	WesternAtlantic_EasternAtlantic
PI	Lycengraulis grossidens	art	exploited	3.7	medium	mod	lc	medium	WesternAtlantic
CE	Ocyurus chrysurus	art	exploited	4	Low	high	dd	medium	WesternAtlantic_EasternCentral Atlantic
CE	Opisthonema oglinum	art	exploited	4.5	medium	low	lc	medium	WesternAtlantic
CE	Scomberomorus cavalla	ind/art	exploited	4.4	Low	high	lc	medium	WesternAtlantic_EasternCentral Atlantic
CE	Lutjanus synagris	art	exploited	3.8	medium	mod	nt	medium	WesternAtlantic
CE	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	high	Western_Atlantic
CE	Haemulon plumierii	art	exploited	3.8	medium	high	lc	medium	Western_Atlantic

CE	Chloroscombrus chrysurus	art	exploited	3.5	medium	mod	lc	low	WesternAtlantic_EasternAtlantic
CE	Carangoides bartholomaei	art	exploited	4.5	High	high	lc	medium	Western_EasternCentral_Atlantic
CE	Mycteroperca bonaci	art	overexploited	4.3	Low	high	vul	very high	Western_Atlantic
CE	Lutjanus purpureus	ind/art	overexploited	3.6	Low	high	vul	high	WesternAtlantic
RN	Xiphias gladius	ind	exploited	4.5	medium	very high	lc	very high	Atlantic_Indian_Pacific
RN	Thunnus albacares	ind/art	exploited	4.4	medium	high	nt	high	Worldwide
RN	Opisthonema oglinum	art	exploited	4.5	medium	low	lc	medium	WesternAtlantic
RN	Hirundichthys affinis	art	overexploited	3.8	High	low	lc	medium	Eastern_Western_NorthwestAtlantic
RN	Thunnus obesus	ind	overexploited	4.5	medium	high	vul	very high	Atlantic_Indian_Pacific
RN	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	high	Western_Atlantic
RN	Prionace glauca	ind	exploited	4.4	very low	very high	nt	medium	Circumglobal_Atlantic_Pacific
RN	Xyrichtys novacula	art	overexploited	3.5	medium	mod	lc	very high	Western_Eastern_Atlantic
RN	Haemulon plumierii	art	exploited	3.8	medium	high	lc	medium	Western_Atlantic
RN	Ocyurus chrysurus	art	exploited	4	Low	high	dd	medium	WesternAtlantic_EasternCentral Atlantic
PB	Thunnus albacares	ind	exploited	4.4	medium	high	nt	high	Worldwide
PB	Thunnus obesus	ind	overexploited	4.5	medium	high	vul	very high	Atlantic_Indian_Pacific
PB	Xiphias gladius	ind	exploited	4.5	medium	very high	lc	very high	Atlantic_Indian_Pacific
PB	Thunnus alalunga	ind	overexploited	4.3	medium	high	nt	high	Cosmopolitan_tropical_temperate
PB	Prionace glauca	ind	exploited	4.4	very low	very high	nt	medium	Circumglobal_Atlantic_Pacific
PB	Mugil curema	art	collapsed	2	medium	high	lc	medium	Western_EasternAtlantic_EasternPacific

PB	Istiophorus platypterus	ind	overexploited	4.5	Low	very high	lc	very high	Worldwide_IndoPacific_Eastern Pacific_Indian
PB	Centropomus undecimalis	art	exploited	4.2	medium	high	lc	Low	Western_Atlantic
PB	Trachinotus falcatus	art	overexploited	4	medium	mod	lc	medium	Western_Atlantic
PB	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	High	Western_Atlantic
PE	Anchovia clupeoides	art	exploited	3.4	High	mod	lc	medium	Western_Atlantic
PE	Thunnus albacares	ind	exploited	4.4	medium	high	nt	High	Worldwide
PE	Pseudupeneus maculatus	art	exploited	3.7	High	mod	lc	medium	Western_Atlantic
PE	Mugil curema	art	collapsed	2	medium	high	lc	medium	Western_EasternAtlantic_EasternPacific
PE	Opisthonema oglinum	art	exploited	4.5	medium	low	lc	medium	WesternAtlantic
PE	Haemulon aurolineatum	art	rebuilding	4.4	medium	mod	lc	medium	Western_Atlantic
PE	Conodon nobilis	art	overexploited	3.6	medium	mod	lc	low	WesternAtlantic_WesternGulfof Mexico
PE	Sparisoma spp_axillare	art	exploited	2	medium	mod	vul	na	Southwest_Atlantic_endemic
PE	Lutjanus analis	art	exploited	3.9	Low	high	nt	high	Western_Atlantic
PE	Acanthocybium solandri	ind	rebuilding	4.3	medium	high	lc	very high	Atlantic_Indian_Pacific
AL	Mugil curvidens	art	exploited	2	medium	mod	nt	na	Western_Atlantic
AL	Opisthonema oglinum	art	exploited	4.5	medium	low	lc	medium	WesternAtlantic
AL	Macrodon ancylodon	art	exploited	3.9	medium	mod	lc	medium	WesternAtlantic
AL	Caranx hippos	art	exploited	3.6	medium	mod	lc	medium	Western_Eastern_Atlantic
AL	Diapterus auratus	art	exploited	2.4	High	mod	lc	medium	Western_Atlantic
AL	Scomberomorus brasiliensis	art	exploited	3.3	medium	very high	lc	high	Western_Atlantic
AL	Balistes vetula	art	rebuilding	3.8	medium	mod	nt	medium	Western_Eastern_Atlantic
AL	Scomberomorus cavalla	art	exploited	4.4	Low	high	lc	medium	WesternAtlantic_EasternCentral Atlantic

AL	Mugil liza	art	rebuilding	2	medium	mod	dd	high	Western_Atlantic
AL	Sciades herzbergii	art	overexploited	3.3	medium	mod	lc	medium	South_America
SE	Mugil curema	art	collapsed	2	medium	high	lc	medium	Western_EasternAtlantic_EasternPacific
SE	Macrodon ancylodon	art	exploited	3.9	medium	mod	lc	medium	WesternAtlantic
SE	Sciades herzbergii	art	overexploited	3.3	medium	mod	lc	medium	South_America
SE	Anchoviella vaillanti	art	overexploited	3.2	High	low	nt	na	South_America
SE	Caranx hippos	art	exploited	3.6	medium	mod	lc	medium	Western_Eastern_Atlantic
SE	Micropogonias furnieri	art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
SE	Diapterus rhombeus	art	overexploited	3	High	low	lc	medium	Western_Atlantic
SE	Cathorops spixii	art	overexploited	3.5	medium	high	na	medium	Western_Atlantic
SE	Scomberomorus cavalla	art	exploited	4.4	Low	high	lc	medium	WesternAtlantic_EasternCentral Atlantic
SE	Conodon nobilis	art	overexploited	3.6	medium	mod	lc	low	WesternAtlantic_WesternGulfof Mexico
BA	Sardinella brasiliensis	art	rebuilding	3.1	High	low	na	medium	Western_Atlantic
BA	Ocyurus chrysurus	art	exploited	4	Low	high	dd	medium	WesternAtlantic_EasternCentral Atlantic
BA	Opisthonema oglinum	art	exploited	4.5	medium	low	lc	medium	WesternAtlantic
BA	Diapterus rhombeus	art	overexploited	3	High	low	lc	medium	Western_Atlantic
BA	Cetengraulis edentulus	art	rebuilding	2.1	medium	mod	lc	medium	Western_Atlantic
BA	Lutjanus jocu	art	exploited	4.4	Low	very high	dd	high	Western_Eastern_Atlantic
BA	Coryphaena hippurus	art	exploited	4.4	High	mod	lc	high	Atlantic_Indian_Pacific
BA	Mycteroperca spp_bonaci	art	overexploited	4.3	Low	high	vul	very high	Western_Atlantic
BA	Caranx crysos	art	exploited	4.1	medium	mod	lc	low	Western_Eastern_Atlantic

BA	Pomacanthus paru	ind	exploited	2.8	medium	mod	lc	high	Western_Eastern_Atlantic
ES	Coryphaena hippurus	art	exploited	4.4	High	mod	lc	high	Atlantic_Indian_Pacific
ES	Balistes capriscus	art	overexploited	4.1	medium	high	vul	high	Western_Eastern_Atlantic
ES	Thunnus albacares	ind/art	exploited	4.4	medium	high	nt	high	Worldwide
ES	Ocyurus chrysurus	art	exploited	4	Low	high	dd	medium	WesternAtlantic_EasternCentral Atlantic
ES	Trachurus lathami	ind	rebuilding	4	medium	mod	lc	low	Western_Atlantic
ES	Pagrus pagrus	art	rebuilding	3.9	medium	very high	lc	very high	Western_Eastern_Atlantic
ES	Caranx crysos	ind	exploited	4.1	medium	mod	lc	low	Western_Eastern_Atlantic
ES	Katsuwonus pelamis	ind	exploited	4.4	medium	mod	lc	high	Cosmopolitan_tropical_warmte mperate
ES	Lutjanus purpureus	art	overexploited	3.6	Low	high	vul	high	WesternAtlantic
ES	Coryphaena hippurus	ind	exploited	4.4	High	mod	lc	high	Atlantic_Indian_Pacific
RJ	Sardinella brasiliensis	ind/art	rebuilding	3.1	High	low	na	medium	Western_Atlantic
RJ	Cetengraulis edentulus	ind	rebuilding	2.1	medium	mod	lc	medium	Western_Atlantic
RJ	Katsuwonus pelamis	art	exploited	4.4	medium	mod	lc	high	Cosmopolitan_tropical_warmte mperate
RJ	Stephanolepis hispidus	art	collapsed	2.6	High	mod	lc	na	Western_Eastern_Atlantic
RJ	Scomber colias	ind/art	collapsed	3.9	medium	mod	lc	na	Atlantic
RJ	Micropogonias furnieri	ind	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
RJ	Caranx latus	ind	exploited	4.2	medium	high	lc	high	Western_Eastern_Atlantic
RJ	Thunnus albacares	ind	exploited	4.4	medium	high	nt	high	Worldwide
RJ	Opisthonema oglinum	ind	exploited	4.5	medium	low	lc	medium	WesternAtlantic

RJ	Lophius gastrophysus	ind	overexploited	4.5	medium	high	lc	low	WesternAtlantic
SP	Sardinella brasiliensis	ind/art	rebuilding	3.1	High	low	na	medium	Western_Atlantic
SP	Micropogonias furnieri	ind/art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
SP	Cynoscion jamaicensis	ind	overexploited	3.8	High	low	lc	medium	Western_Atlantic
SP	Anchoviella lepidentostole	art	exploited	3.1	High	low	lc	medium	Western_Atlantic
SP	Macrodon atricauda	ind/art	overexploited	4	High	low	na	na	Southwest_Atlantic
SP	Scomber colias	ind	collapsed	3.9	medium	mod	lc	na	Atlantic
SP	Lophius gastrophysus	ind	overexploited	4.5	medium	high	lc	low	WesternAtlantic
SP	Xiphias gladius	ind	exploited	4.5	medium	very high	lc	very high	Atlantic_Indian_Pacific
SP	Mugil liza	ind/art	rebuilding	2	medium	mod	dd	High	Western_Atlantic
SP	Coryphaena hippurus	art	exploited	4.4	High	mod	lc	High	Atlantic_Indian_Pacific
PR	Sardinella brasiliensis	art	rebuilding	3.1	High	low	na	medium	Western_Atlantic
PR	Harengula clupeola	art	overexploited	3.3	High	low	lc	low	Western_Atlantic
PR	Chloroscombrus chrysurus	art	exploited	3.5	medium	mod	lc	low	WesternAtlantic_EasternAtlantic
PR	Micropogonias furnieri	art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
PR	Opisthonema oglinum	art	exploited	4.5	medium	low	lc	medium	WesternAtlantic
PR	Cynoscion virescens	art	overexploited	4	Low	high	lc	medium	WesternAtlantic
PR	Oligoplites saurus_saliens	art	collapsed/rebuilding	4.05	High	mod	lc	medium	WesternAtlantic_EasternPacific_WesternAtlantic
PR	Pogonias cromis	art	collapsed	3.9	medium	high	vul	low	WesternAtlantic
PR	Macrodon atricauda	art	overexploited	4	High	low	na	na	Southwest_Atlantic
PR	Mugil liza	art	rebuilding	2	medium	mod	dd	high	Western_Atlantic
SC	Sardinella brasiliensis	ind/art	rebuilding	3.1	High	low	na	medium	Western_Atlantic
SC	Katsuwonus pelamis	ind	exploited	4.4	medium	mod	lc	high	Cosmopolitan_tropical_warmtemperate
SC	Micropogonias furnieri	ind/art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
SC	Opisthonema oglinum	ind	exploited	4.5	medium	low	lc	medium	WesternAtlantic

SC	Umbrina canosai	ind	exploited	3.9	medium	mod	na	low	Southwest_Atlantic
SC	Prionotus punctatus	ind	exploited	3.8	Low	high	lc	medium	WesternAtlantic
SC	Urophycis mystacea	ind	exploited	4	Low	high	na	na	Southwest_Atlantic
SC	Cynoscion guatucupa	ind	exploited	3.7	medium	mod	na	na	Southwest_Atlantic
SC	Chloroscombrus chrysurus	ind	exploited	3.5	medium	mod	lc	low	WesternAtlantic_EasternAtlantic
SC	Mugil liza	ind/art	rebuilding	2	medium	mod	dd	high	Western_Atlantic
RS	Micropogonias furnieri	ind/art	exploited	3.1	medium	mod	lc	medium	Western_Atlantic
RS	Umbrina canosai	ind/art	exploited	3.9	medium	mod	na	low	Southwest_Atlantic
RS	Cynoscion guatucupa	ind/art	exploited	3.7	medium	mod	na	na	Southwest_Atlantic
RS	Katsuwonus pelamis	ind	exploited	4.4	medium	mod	lc	high	Cosmopolitan_tropical_warmte mperate
RS	Macrodon atricauda	ind	overexploited	4	High	low	na	na	Southwest_Atlantic
RS	Prionotus punctatus	art	exploited	3.8	Low	high	lc	medium	WesternAtlantic
RS	Pomatomus saltatrix	ind	collapsed	4.5	medium	high	vul	very high	Circumglobal_Atlantic_Indian_ Pacific
RS	Mugil liza	ind/art	rebuilding	2	medium	mod	dd	high	Western_Atlantic
RS	Urophycis brasiliensis	ind	exploited	3.8	medium	mod	na	low	Southwest_Atlantic
RS	Thunnus albacares	ind	exploited	4.4	medium	high	nt	high	Worldwide

Appendix 3. Measuring the fisheries instability indicator.

This indicator was based on resilience levels of an ecosystem function to environmental perturbations (see Oliver *et al.* 2015). In the context used here, we referred to the tendency of fisheries provision to remain stable in the face of some perturbation and rapidly return to pre-perturbation levels. This instability was estimated to be the total deficit of the ecosystem function in time. To measure this deficit, we calculated the annual instability by attributing one point for each year that catch data were provided below the minimum threshold (inferior quantile of the time series), plus the difference between the minimum threshold and annual catch, as follows:

$$Annual\ Instability = 1 + (minimum\ threshold - annual\ catch)$$

The minimum threshold represents a measure of resistance of ecosystem function to perturbation, while the annual catch represents a recovery measure (Oliver et al. 2015). Annual instability values were calculated for time series and averaged for each coastal state. We used Z-transformations for both data normalization and to reduce the variability among states (Zuur et al. 2010).

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Appendix 4. Measuring market indicator.

To assess coastal-urban integration, we used the linear distance between each coastal municipality and its respective state capital. Based on the walking distance from Google Maps, we calculated the average distance for all coastal municipalities, by state. This measure was used to represent an economic concern for fishers. Given the poor local transportation infrastructure, urban access can be used as a proxy for external transaction commerce costs (Davidova et al. 2009, Basurto et al. 2013). Even if fish value chains are networks with non-linear movements, for the sake of simplicity we assumed that longer distances to the urban center may imply fewer exploitation rates due to higher costs and, thereby, result in less ecological vulnerability to the SES. Moreover, we used per capita fish consumption (KG/Inhabitant/Year) because higher consumption implies more fish biomass required, which increases the system's vulnerability. We know that higher consumption could also be associated with cultural or economic issues, but we chose to focus on the consumption/demand for fish and not necessarily for a market analysis. Even if the linear distance and the per capita consumption adopted here are not the best variables, they are good proxies for fisheries demand in the absence of more refined data. Thus, these variables were combined to form a single market indicator that attempts to capture fisheries market demand in the coastal states.

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Appendix 5. Indicator scores for the three components of the composite index, including all indicators.

Table A5.1: Indicator scores for the three components in all 17 Brazilian coastal states.

Components	Indicators	Coastal States																	Median
		AP	PA	MA	PI	CE	RN	PB	PE	AL	SE	BA	ES	RJ	SP	PR	SC	RS	
Adaptive Capacity	Human development index	0.71	0.65	0.64	0.65	0.68	0.68	0.66	0.67	0.63	0.67	0.66	0.74	0.76	0.78	0.75	0.77	0.75	0.68
	Educational attainment	0.30	0.30	1.00	1.00	0.60	0.60	1.00	0.60	1.00	0.60	0.60	0.60	0.30	0.30	0.60	0.30	0.30	0.60
	Governance	0.87	1.00	0.40	0.30	0.73	0.40	0.40	0.40	0.40	0.40	0.73	0.73	1.00	0.87	0.73	0.50	1.00	0.73
	Social capital	0.30	1.00	1.00	1.00	1.00	1.00	0.30	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Species Vulnerability	Resilience	0.55	0.45	0.50	0.65	0.65	0.50	0.56	0.45	0.50	0.45	0.50	0.50	0.40	0.25	0.35	0.55	0.50	0.50
	Vulnerability	0.80	0.75	0.65	0.75	0.80	0.75	0.95	0.65	0.55	0.55	0.50	0.75	0.55	0.40	0.40	0.50	0.60	0.65
	Price category	0.60	0.65	0.55	0.50	0.60	0.75	0.75	0.61	0.61	0.44	0.65	0.75	0.63	0.63	0.39	0.50	0.63	0.61
	Threat level	0.90	0.82	0.62	0.74	0.82	0.84	0.84	0.68	0.52	0.50	0.64	0.96	0.66	0.68	0.64	0.66	0.76	0.68
	Trophic level	0.30	0.20	0.00	0.15	0.25	0.20	0.25	0.20	0.05	0.00	0.10	0.25	0.05	0.00	0.10	0.00	0.15	0.15
	Distribution range	0.80	0.90	1.00	0.75	0.80	0.45	0.30	0.65	0.85	0.75	0.70	0.40	0.65	0.75	0.90	0.85	0.70	0.75
	Fishing pressure	0.58	0.54	0.30	0.30	0.44	0.46	0.48	0.36	0.30	0.30	0.33	0.49	0.62	0.70	0.30	0.72	0.73	0.46
	Stock status	0.53	0.52	0.52	0.48	0.48	0.52	0.62	0.52	0.46	0.66	0.50	0.50	0.58	0.60	0.64	0.42	0.51	0.52
Ecosystem Vulnerability	Climate exposure	0.94	0.97	0.99	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.96	0.93	0.91	0.90	0.90	0.85	0.98
	Productivity	0.00	0.66	0.90	0.96	0.98	0.98	0.98	0.99	0.99	0.98	0.99	0.96	0.97	0.96	0.95	0.94	0.98	0.97
	Coastal protection	0.91	0.50	0.60	0.48	1.00	1.00	0.50	0.47	0.47	1.00	0.36	0.99	0.97	0.84	1.00	0.99	1.00	0.91
	Coastal pollution	0.50	1.00	1.00	1.00	0.00	0.50	0.00	0.00	0.50	0.50	0.50	0.00	0.00	0.00	0.50	0.50	0.50	0.50
	Priority index	0.80	0.80	0.80	0.60	0.60	0.60	0.60	0.60	0.60	0.60	1.60	1.00	1.20	0.20	0.20	0.60	0.40	0.60

Appendix 6. Measuring stock status.

Following Kleisner *et al.* (2012), we assessed the stock status of the 10 main fish species caught by artisanal and industrial sectors per year. This calculation used the categories of exploitation that were most frequent over the last 10 years of the temporal series, such as developing, exploited, rebuilding, overexploited and collapsed. The score of the stock status variable ranged from 0 (least vulnerable) to 1 (most vulnerable), which we assigned points as follows: developing = 0 points, exploited = 0.4 points, rebuilding = 0.5 points, overexploited = 0.8 points, and collapsed = 1 point.

*Table A6.1: Stock status assessment of the 10 fish species caught along the Brazilian coastline by artisanal and industrial sectors. *These were not identified at the species level, so we used the average value of the categories for the two more frequent species in that state.*

STATES	SPECIES	STOCK STATUS	SCORE
AP	Sciades parkeri	overexploited	0.8
AP	Cynoscion acoupa	exploited	0.4
AP	Sciades couma	exploited	0.4
AP	Coryphaena hippurus	exploited	0.4
AP	Micropogonias furnieri	exploited	0.4
AP	Sciades proops	exploited	0.4
AP	Cynoscion virescens	overexploited	0.8
AP	Megalops atlanticus	rebuilding	0.5
AP	Bagre bagre	exploited	0.4
AP	Lutjanus purpureus	overexploited	0.8
PA	Cynoscion acoupa	exploited	0.4
PA	Sciades parkeri	overexploited	0.8
PA	Scomberomorus brasiliensis	exploited	0.4
PA	Lutjanus purpureus	overexploited	0.8
PA	Sciades proops	exploited	0.4
PA	Cynoscion microlepidotus	exploited	0.4
PA	Sciades herzbergii	overexploited	0.8
PA	Macrodon ancylodon	exploited	0.4
PA	Coryphaena hippurus	exploited	0.4
PA	Sciades couma	exploited	0.4
MA	Cynoscion acoupa	exploited	0.4
MA	Macrodon ancylodon	exploited	0.4

MA	Hexanematichthys herzbergii	overexploited	0.8
MA	Scomberomorus brasiliensis	exploited	0.4
MA	Aspistor quadriscutis	exploited	0.4
MA	Micropogonias furnieri	exploited	0.4
MA	Sciades proops	exploited	0.4
MA	Bagre bagre	exploited	0.4
MA	Cynoscion leiarchus	overexploited	0.8
MA	Genyatremus luteus	overexploited	0.8
PI	Lutjanus synagris	exploited	0.4
PI	Scomberomorus brasiliensis	exploited	0.4
PI	Scomberomorus cavalla	exploited	0.4
PI	Euthynnus alletteratus	exploited	0.4
PI	Ocyurus chrysurus	exploited	0.4
PI	Lutjanus purpureus	overexploited	0.8
PI	Micropogonias furnieri	exploited	0.4
PI	Conodon nobilis	overexploited	0.8
PI	Chloroscombrus chrysurus	exploited	0.4
PI	Lycengraulis grossidens	exploited	0.4
CE	Ocyurus chrysurus	exploited	0.4
CE	Opisthonema oglinum	exploited	0.4
CE	Scomberomorus cavalla	exploited	0.4
CE	Lutjanus synagris	exploited	0.4
CE	Scomberomorus brasiliensis	exploited	0.4
CE	Haemulon plumierii	exploited	0.4
CE	Chloroscombrus chrysurus	exploited	0.4
CE	Carangoides bartholomaei	exploited	0.4
CE	Mycteroperca bonaci	overexploited	0.8
CE	Lutjanus purpureus	overexploited	0.8
RN	Xiphias gladius	exploited	0.4
RN	Thunnus albacares	exploited	0.4
RN	Opisthonema oglinum	exploited	0.4
RN	Hirundichthys affinis	overexploited	0.8
RN	Thunnus obesus	overexploited	0.8
RN	Scomberomorus brasiliensis	exploited	0.4
RN	Prionace glauca	exploited	0.4
RN	Xyrichtys novacula	overexploited	0.8
RN	Haemulon plumierii	exploited	0.4
RN	Ocyurus chrysurus	exploited	0.4
PB	Thunnus albacares	exploited	0.4
PB	Thunnus obesus	overexploited	0.8
PB	Xiphias gladius	exploited	0.4
PB	Thunnus alalunga	overexploited	0.8
PB	Prionace glauca	exploited	0.4

PB	Mugil curema	collapsed	1
PB	Istiophorus platypterus	overexploited	0.8
PB	Centropomus undecimalis	exploited	0.4
PB	Trachinotus falcatus	overexploited	0.8
PB	Scomberomorus brasiliensis	exploited	0.4
PE	Anchovia clupeoides	exploited	0.4
PE	Thunnus albacares	exploited	0.4
PE	Pseudupeneus maculatus	exploited	0.4
PE	Mugil curema	collapsed	1
PE	Opisthonema oglinum	exploited	0.4
PE	Haemulon aurolineatum	rebuilding	0.5
PE	Conodon nobilis	overexploited	0.8
PE	Sparisoma spp_axillare	exploited	0.4
PE	Lutjanus analis	exploited	0.4
PE	Acanthocybium solandri	rebuilding	0.5
AL	Mugil curvidens	exploited	0.4
AL	Opisthonema oglinum	exploited	0.4
AL	Macrodon ancylodon	exploited	0.4
AL	Caranx hippos	exploited	0.4
AL	Diapterus auratus	exploited	0.4
AL	Scomberomorus brasiliensis	exploited	0.4
AL	Balistes vetula	rebuilding	0.5
AL	Scomberomorus cavalla	exploited	0.4
AL	Mugil liza	rebuilding	0.5
AL	Sciades herzbergii	overexploited	0.8
SE	Mugil curema	collapsed	1
SE	Macrodon ancylodon	exploited	0.4
SE	Sciades herzbergii	overexploited	0.8
SE	Anchoviella vaillanti	overexploited	0.8
SE	Caranx hippos	exploited	0.4
SE	Micropogonias furnieri	exploited	0.4
SE	Diapterus rhombeus	overexploited	0.8
SE	Cathorops spixii	overexploited	0.8
SE	Scomberomorus cavalla	exploited	0.4
SE	Conodon nobilis	overexploited	0.8
BA	Sardinella brasiliensis	rebuilding	0.5
BA	Ocyurus chrysurus	exploited	0.4
BA	Opisthonema oglinum	exploited	0.4
BA	Diapterus rhombeus	overexploited	0.8
BA	Cetengraulis edentulus	rebuilding	0.5
BA	Lutjanus jocu	exploited	0.4
BA	Coryphaena hippurus	exploited	0.4
BA	Mycteroperca spp_bonaci	overexploited	0.8

BA	Caranx crysos	exploited	0.4
BA	Pomacanthus paru	exploited	0.4
ES	Coryphaena hippurus	exploited	0.4
ES	Balistes capriscus	overexploited	0.8
ES	Thunnus albacares	exploited	0.4
ES	Ocyurus chrysurus	exploited	0.4
ES	Trachurus lathami	rebuilding	0.5
ES	Pagrus pagrus	rebuilding	0.5
ES	Caranx crysos	exploited	0.4
ES	Katsuwonus pelamis	exploited	0.4
ES	Lutjanus purpureus	overexploited	0.8
ES	Coryphaena hippurus	exploited	0.4
RJ	Sardinella brasiliensis	rebuilding	0.5
RJ	Cetengraulis edentulus	rebuilding	0.5
RJ	Katsuwonus pelamis	exploited	0.4
RJ	Stephanolepis hispidus	collapsed	1
RJ	Scomber colias	collapsed	1
RJ	Micropogonias furnieri	exploited	0.4
RJ	Caranx latus	exploited	0.4
RJ	Thunnus albacares	exploited	0.4
RJ	Opisthonema oglinum	exploited	0.4
RJ	Lophius gastrophysus	overexploited	0.8
SP	Sardinella brasiliensis	rebuilding	0.5
SP	Micropogonias furnieri	exploited	0.4
SP	Cynoscion jamaicensis	overexploited	0.8
SP	Anchoviella lepidentostole	exploited	0.4
SP	Macrodon atricauda	overexploited	0.8
SP	Scomber colias	collapsed	1
SP	Lophius gastrophysus	overexploited	0.8
SP	Xiphias gladius	exploited	0.4
SP	Mugil liza	rebuilding	0.5
SP	Coryphaena hippurus	exploited	0.4
PR	Sardinella brasiliensis	rebuilding	0.5
PR	Harengula clupeola	overexploited	0.8
PR	Chloroscombrus chrysurus	exploited	0.4
PR	Micropogonias furnieri	exploited	0.4
PR	Opisthonema oglinum	exploited	0.4
PR	Cynoscion virescens	overexploited	0.8
PR	Oligoplites spp_saurus_saliens*	collapsed/rebuilding	0.75
PR	Pogonias cromis	collapsed	1
PR	Macrodon atricauda	overexploited	0.8
PR	Mugil liza	rebuilding	0.5
SC	Sardinella brasiliensis	rebuilding	0.5

SC	Katsuwonus pelamis	exploited	0.4
SC	Micropogonias furnieri	exploited	0.4
SC	Opisthonema oglinum	exploited	0.4
SC	Umbrina canosai	exploited	0.4
SC	Prionotus punctatus	exploited	0.4
SC	Urophycis mystacea	exploited	0.4
SC	Cynoscion guatucupa	exploited	0.4
SC	Chloroscombrus chrysurus	exploited	0.4
SC	Mugil liza	rebuilding	0.5
RS	Micropogonias furnieri	exploited	0.4
RS	Umbrina canosai	exploited	0.4
RS	Cynoscion guatucupa	exploited	0.4
RS	Katsuwonus pelamis	exploited	0.4
RS	Macrodon atricauda	overexploited	0.8
RS	Prionotus punctatus	exploited	0.4
RS	Pomatomus saltatrix	collapsed	1
RS	Mugil liza	rebuilding	0.5
RS	Urophycis brasiliensis	exploited	0.4
RS	Thunnus albacares	exploited	0.4