ICES Journal of Marine Science, 2022, **79**, 633–647
DOI: 10.1093/icesjms/fsac004
Advance access publication date: 10 February 2022
Original Article

Lira, A. S., Le Loc'h, F., Andrade, H. A., and Lucena-Frédou, F.Vulnerability of marine resources affected by a small-scale tropical shrimp fishery in Northeast Brazil

Alex Souza Lira [1,2,*], **François Le Loc'h** [2], **Humber Agrelli Andrade** [1] **and Flávia Lucena-Frédou** [1]

[1]Universidade Federal Rural de Pernambuco (UFRPE), DEPAq, Av. Dom Manuel s/n, Recife, Pernambuco 52171-900, Brazil
[2]IRD, University of Brest, CNRS, Ifremer, LEMAR, F-29280 Plouzané, France
*Corresponding author: Tel: +5581985515243; *e-mail*: alexliraufrpe@outlook.com

Tropical fisheries tend to be multispecies and require management approaches adapted to high diversity but scarce and poorly informative data. Productivity and Susceptibility Analysis-PSA is particularly useful where catch or biological data are incomplete, aggregated across species or insufficient for quantitative stock assessment. We applied PSA to estimate vulnerability and potential risk to target and non-target species caught by the small-scale shrimp fishery in northeast Brazil, adapting the method to regional conditions and incorporating an assessment of uncertainties caused by its subjective choices. Our findings suggest that non-target species can be more vulnerable than target ones. *Bagre marinus*, *Pseudobatos percellens*, *Micropogonias furnieri*, *Hypanus guttatus*, *Macrodon ancylodon*, *Polydactylus virginicus*, *Rhizoprionodon porosus*, *Cynoscion virescens*, *Larimus breviceps*, and *Menticirrhus americanus*, were the top 10 species potentially at risk due to their low productivity (long lifespans, low spawning), high capture rates of juveniles and overlap of feeding and breeding grounds with fishing areas. Most species (76%) maintained the same risk category (low, moderate, or high) regardless of the score weighting or productivity and susceptibility attribute boundaries applied. Overall, the target species are not currently the main ones threatened, but bycatch such as elasmobranchs, catfishes and Scianidae should be prioritized for assessment and data collection.

Keywords: artisanal fisheries, bycatch, productivity susceptibility analysis, shrimp, tropical fisheries, trawling.

Introduction

Bottom trawls are one of the most used fishing gear worldwide (Hintzen *et al.*, 2020), responsible for almost a quarter of marine landings (Watson and Tidd, 2018). Although economically important, bottom trawling causes significant adverse impacts on seabed habitats and biota (Jones, 1992; Kaiser *et al.*, 2002), including a high quantity of bycatch and discards (Zeller *et al.*, 2017). Such effects also lead to losses of protein sources, affecting food security and fishery sustainability (Belton and Thilsted, 2014).

In the southwestern Atlantic Ocean, along the Brazilian continental shelf, shrimp trawling is a widespread fishery activity, operating at three scales: (i) industrial, present in the North (Amazon river estuarine system), Southeast and South Regions of Brazil; (ii) semi-industrial, with an intermediate technology and fishing power; and (iii) artisanal, operating along the entire coast and involving a larger number of people but lower levels of technology, capture and profit (Dias-Neto, 2011). Management measures for bottom trawlers are mainly based on closed seasons (Nakamura and Hazin, 2020) and, particularly for the industrial fleet, the Turtle Excluder Device (TED). Apart from the TED, all other recommendations available in the country focus only on target species, thus neglecting the bycatch.

Brazilian fisheries were officially monitored up to 2010 when the government interrupted the fisheries data collection program. Since then, crucial information has been missing, mainly in terms of time series, hampering the use of traditional quantitative stock assessment models that are often reported as the best option. At that time, the bottom trawling fleet was one of the largest and most productive in Northeast Brazil, involving more than 100 000 persons, about 1 700 motorized and 20 000 non-motorized boats (Santos, 2010), representing approximately 10% of the total marine landings in the country (IBAMA, 2008). Within this region, the shrimp fishery in Barra de Sirinhaém (BSIR), south of Pernambuco, is predominantly small-scale, and accounted for 50% of the state shrimp production (Tischer and Santos, 2003) in the decade 2000–2010 (average of 62 tons per year), representing an important source of income and food for the local population (Lira *et al.*, 2010).

The incidental catch of the shrimp trawl fisheries in the region of BSIR represents about 26% of total landings, primarily removing juveniles, which are often consumed by the fishermen and local community as an additional source of food, or sold as a by-product (Lira *et al.*, 2021). In this case, the impact of the fishery on the ecosystems appears to be counterbalanced by the beneficial role of the bycatch for local communities (Carvalho *et al.*, 2020; Lira *et al.*, 2021). However, despite its great social relevance, the shrimp trawl fishery in Pernambuco currently has no regulations (Santos, 2010), mainly due to a lack of robust knowledge about target and non-target species at individual and ecosystem levels; environmental conditions (precipitation regimes, nutrient flows from river to shore) and habitat structure (depth and seabed morphology). In addition, the weak fisheries governance in the region also makes it challenging to apply management actions. Ultimately, these problems hamper the inclusion of the incidental catch in assess-

Received: May 5, 2021. **Revised:** January 6, 2022. **Accepted:** January 10, 2022

ment models (Yonvitner *et al.*, 2020) and increase the 'risk' (here defined as the probability of something undesirable happening to stocks; Francis and Shotton, 1997; Sethi, 2010) to these non-target species.

Productivity and Susceptibility Analysis (PSA) is a semi-quantitative risk analysis method that relies on the relationship between the biological productivity related to the life history characteristics (Stobutzki *et al.*, 2001) and the susceptibility of the stock to fishing (Patrick *et al.*, 2010; Lucena-Frédou *et al.*, 2017). The PSA approach is a well-accepted framework for estimating the vulnerability of species to fishing, having already been used in several fisheries around the world, but especially for small-scale tropical fisheries has been little used (Martínez-Candelas *et al.*, 2020; Yonvitner *et al.*, 2020). In Brazil, PSA has only been applied to large scale fisheries, such as the gillnet fishery in southeast Brazil (Visintin and Perez, 2016), however, has never been reported in Brazil for small-scale fishery. This approach is quite a promising member of the family of data-poor models, but its minimal data requirements and relatively subjective nature are weaknesses. In addition, given the particularities of different fishing gears and ecosystems, the approach must be adapted to the particular circumstances of each case study, taking into account appropriate attributes and scores.

Despite the world relevance of small-scale fisheries, particularly their bycatch, they are usually neglected by assessment approaches and decision-makers. For the first time, our study evaluates the vulnerability and potential risk of the target and non-target species exploited by the shrimp fishery in Sirinhaém coast as a case study of a small-scale fishery in northeast Brazil, indicating to decision-makers which species should be prioritized for urgent assessment and data collection. For this, we used a PSA adapted to regional conditions while also assessing any effects of the intrinsic subjectivity of the method.

Material and methods

Study area and gear description

Barra of Sirinhaém (BSIR), located on the southern coast of Pernambuco, in Northeast Brazil (Figure 1), has a tropical climate, with precipitation ranging from 20 to 450 mm·month^{-1} and a rainy season between May and October with mean surface water temperature of 29°C. Fishing, the sugar cane industry and other farming industries are the main anthropic activities in the area. The fishing zones are inside or close to the Marine Protected Areas around Santo Aleixo Island (MPAs of Guadalupe and Costa dos Corais) (Figure 1). The fleet operates from 1.5 to 3.0 miles off the coast, mainly between 10 and 20 m depth. Hauls last from 4 to 8 h and boat velocity varies between 2 and 4 knots. Boats measure 8–10 m in length, nets have horizontal opening of 6.1 m, and mesh sizes of the body and codend are 30 mm and 25 mm, respectively.

Target and non-target species

Fish and shrimp captures were first assessed monthly (August 2011 to July 2012) and then quarterly (October 2012 to July 2014) by accompanying the local trawling fishers (for details, see Silva Júnior *et al.*, 2019; Lira *et al.*, 2021 and supplementary material). Penaeid shrimps are the main targets, particularly seabob shrimp (*Xiphopenaeus kroyeri*), which is the most abundant, and pink shrimp (*Penaeus subtilis*) and white shrimp (*Penaeus schmitti*), which have higher market values (Santos, 2010). The amount of fish bycatch is 0.39 kg of fish captured for each 1 kg of shrimp (Silva Júnior *et al.*, 2019) (Figure 1). Thus, ninety species (87 non-target fish and 3 main target shrimp species) caught by trawling fishing in the region were considered in the PSA approach.

Vulnerability approach

The vulnerability assessed by PSA refers to the risk potential of a stock with regard to a specific fishing gear (Patrick *et al.*, 2009). It is defined as a function of productivity and susceptibility attributes (Stobutzki *et al.*, 2001; Hobday *et al.*, 2007; Patrick *et al.*, 2009) and the vulnerability score (v) is obtained by the calculation of Euclidean distance of the weighted productivity (P) and susceptibility (S) scores (see section *Measuring uncertainties* for details):

$$v = \sqrt{\left[(P - X_0)^2 + (S - Y_0)^2\right]}$$

where X_0 and Y_0 are the (x, y) origin coordinates of the biplot, respectively.

In this approach, the species were assigned to a risk category (high, moderate, and low) by ranking the vulnerability scores using a quantile method. For example, species most vulnerable to fishing have low productivity and high susceptibility scores, while the least vulnerable have high productivity and low susceptibility scores (Patrick *et al.*, 2010). Productivity and susceptibility scores are calculated by assigning attributes and scores. When attributes are missing for any species, they are not considered in the computation of this species' final P or S scores (Lucena-Frédou *et al.*, 2017).

Productivity

Eight life-history traits correlated with productivity were selected (Table 1) following Patrick *et al.*(2010), Lucena-Frédou *et al.* (2016) and Lucena-Frédou *et al.* (2017). Details of these traits as description and equations can be found in supplementary material SOM 1, SOM 2, and Table S1 for details.

Susceptibility

Three susceptibility attributes related to abundance, distribution and fishery were adapted from Patrick *et al.* (2010) and Lucena-Frédou *et al.* (2017). Given the specificities of the case study, another three attributes are proposed also (Table 2). See supplementary material SOM 1, SOM 2, Figure S1, Figure S2 and Table S2 for details.

Defining attributes boundaries

The values of productivity and sustainability attributes are classified according to a ranking of three levels (low = 1, moderate = 2, high = 3) (Tables 1 and 2). Given the intrinsic subjectivity of the model, two methods were used to calculate the boundaries of scoring. The first method was the quantile approach, as already used in some previous studies (Lucena-Frédou *et al.*, 2017; Duffy and Griffiths, 2019; Faruque and Matsuda, 2021), while a multivariate analysis was also employed to calculate the boundaries using the clustering k-means method (Altuna-Etxabe *et al.*, 2020) (See supplementary Figure S3 for more detail). For the productivity attributes (except breeding strategy) and susceptibility, specifically the MTI and % > L_{50} that do not have boundaries defined in the literature, the categories (high: 3; moderate: 2 and low:1) were defined by using the two approaches described above.

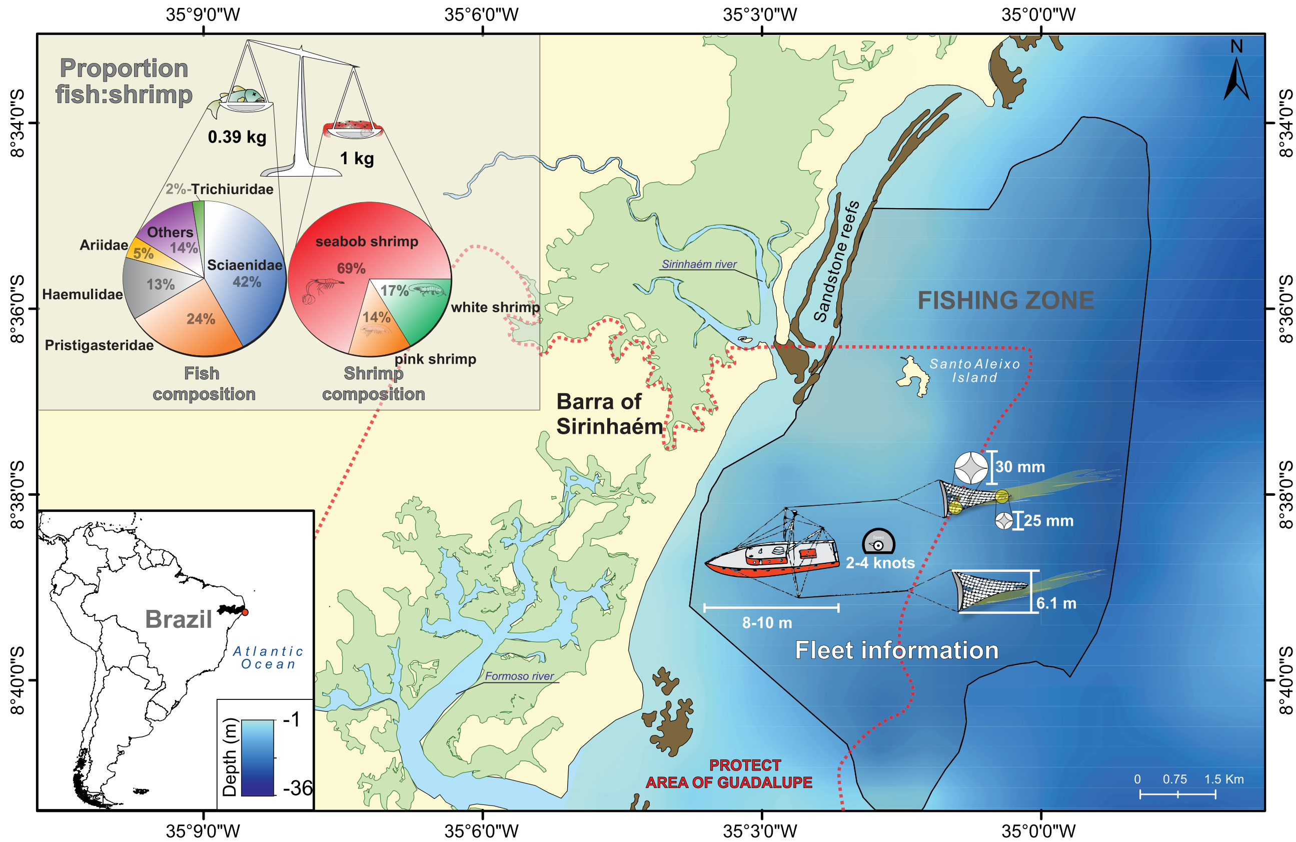

Figure 1. Study area, gear description and catch composition by bottom trawl fishing in Barra of Sirinhaém (BSIR), south of Pernambuco, Northeast Brazil (sources: Silva Júnior *et al.* (2019); Lira *et al.* (2021)).

Table 1. Productivity attributes and rankings used to determine the vulnerability of species caught by bottom trawl fishing in BSIR, south of Pernambuco, Northeast Brazil. Boundaries of scoring defined by quantile and k-means methods (for more details see section *Defining boundaries*).*classification from Patrick *et al.* (2010).

	Attribute	Ranking			Sources
		High (3)	Moderate (2)	Low (1)	
Quantile method	Von Bertalanffy growth coefficient (k, cm.year^{-1})	>0.47	0.34–0.47	<0.34	(1,2)
	Maximum length (L_{max}, cm)	<25.00	25.00–42.80	>42.80	(1,2)
	Size at first maturity (L_{50}, cm)	<12.00	12.00–18.90	>18.90	(1,2)
	Intrinsic growth rate (r)	>0.74	0.54–0.74	<0.54	(1,2)
	Trophic level (TL)	<3.10	3.10–3.42	>3.42	(1,2)
	L_{50}/L_{max}	<0.50	0.50–0.54	>0.54	(2)
	Maximum age (A_{max}; year^{-1})	< 5.92	5.92–8.24	>8.24	(1,2)
K-means method	Von Bertalanffy growth coefficient (k, cm.year^{-1})	>0.93	0.24–0.93	<0.24	(1,2)
	Maximum length (L_{max}, cm)	<41.68	41.68–112.00	>112.00	(1,2)
	Size at first maturity (L_{50}, cm)	<19.36	19.36–58.40	>58.40	(1,2)
	Intrinsic growth rate (r)	>1.52	0.51–1.52	<0.50	(1,2)
	Trophic level (TL)	<3.15	3.15–3.93	>3.93	(1,2)
	L_{50}/L_{max}	<0.51	0.51–0.53	>0.53	(2)
	Maximum age (A_{max}, year^{-1})	<8.48	8.48–15.04	>15.04	(1,2)
	Breeding strategy*	0.00	1.00–3.00	≥ 4.00	(1)

(1) Patrick *et al.* (2010); (2) Lucena-Frédou *et al.* (2017).

Measuring uncertainties

In this study, we evaluated the effect of subjectivities that could lead to uncertainties in the results, considering the following aspects: (i) definition of the boundaries of the scores (as previously described); (ii) assessing the potential redundancy between attributes; and (iii) attributing random weights.

Weights from 0 to 3 were set for each attribute (default weight of 2) (Stobutzki *et al.*, 2002; Hobday *et al.*, 2007;

Table 2. Susceptibility attributes and rankings used to determine the vulnerability of species caught by bottom trawl fishing in BSIR, south of Pernambuco, Northeast Brazil. FOA, Frequency of occurrence and abundance; OA, Overlap area; F/M, Ratio between fishing mortality and natural mortality; MTI, Mixed Trophic Impact; SPR, Spawning Potential Ratio; % > L_{50}, Percentage of individuals > L_{50}. The classifications of the species for overlap area are demersal (DE), pelagic (PE), reef-associated (RE), marine stragglers (MS), marine migrants (MM), estuarine (ES). Attributes had the boundaries of scoring defined by quantile (*) and k-means (**) methods (for more details see section *Defining boundaries*).

Attributes	Ranking			Sources
	Low (1)	Moderate (2)	High (3)	
FOA	Rare and less abundant	Frequent and less abundant	Frequent and higher abundant	Present study
OA	(ES + PE or DE) (MS or MM + RE)	(PE + MM or MS)	(DE + MM or MS)	Present study
F/M	<0.5	0.5–1	>1	(1)
SPR	>0.4	0.2–0.4	<0.2	(1)
MTI*	> − 0.005* > − 0.014**	(−0.022)–(−0.005)* (−0.014)–(−0.036)**	< − 0.022* < − 0.036**	Present study
% > L50	>0.6* >0.687**	0.198–0.6* 0.039–0.687**	<0.198* <0.039**	(2)

(1) Patrick *et al.* (2010); (2) Lucena-Frédou *et al.* (2017).

Lucena-Frédou *et al.*, 2017). A baseline scenario was set up based on Lucena-Frédou *et al.* (2017): weight 3 was assigned to the productivity attributes L_{max} and k, and (r) (a key to the resilience of the species), while a default weight of 2 was given to all other productivity and susceptibility attributes.

Assessing the potential redundancy between attributes

To avoid potential redundancy of some of the PSA attributes (Duffy and Griffiths, 2019), we evaluated relationships between pairs of productivity attributes using a scatterplot matrix and linear regressions. Some redundancies had already been indicated by Lucena-Frédou *et al.* (2016), concerning the parameters L_{50} and L_{max} with k. The correlations between TL, intrinsic growth rate (r) and the other attributes had not been previously evaluated and were investigated in this study. See supplementary material SOM 3, Figure S4 and Figure S5 for details.

Attributing random weights

Weight assignment is subjective. Hence, from the baseline scenario, a total of 10 000 simulations were performed, assigning a random sample of integer weights between 1 and 3 to all productivity and susceptibility attributes to evaluate the sensitivity of the vulnerability scores and ranks with the different weights. Standard deviations of the vulnerability values and the empirical probabilities of being classified as low, moderate, or highly vulnerable were calculated for each species. All analyses were performed using the R environment (R Core Team, 2020).

Integrating other approaches

PSA essentially attempts to assess the potential risk of overfishing for each species but not whether stocks are overfished (Zhou *et al.*, 2016). Considering the qualitative and rather subjective nature of this method, the results of the PSA were compared with two others approaches: (i) IUCN Red List of Threatened Species, which determines the species´ relative risk of extinction and threat category using a detailed set of qualitative and quantitative criteria; and (ii) Reference point from Traditional Stock Assessment (RP-SA) (Hoenig, 1983; Jensen, 1997).

The IUCN Red List categories considered in this study were obtained from a regional assessment, coordinated by the Brazilian Ministry of Environment (MMA), through the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBIO) (ICMbio, 2018) and comprised six levels of extinction risk: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), and Data Deficient (DD). The RP-SA considers the relationship between the fishing mortality (F) and maximum sustainable yield (F_{msy}). Species were classified as subject to "Overfishing" when $F > F_{msy}$ and "Not overfishing" when $F < F_{msy}$. Theoretically, by the "rule of the thumb", the fishing mortality at maximum sustainable yield is approximately equal to natural mortality (M) (Zhou *et al.*, 2012). Except for the three target shrimp species for which local estimates of mortality and exploitation rates as well as maximum sustainable yield are available (Lopes *et al.*, 2014; Silva *et al.*, 2015, 2018), for the remaining species, F_{msy} proxy were obtained by the relationship with M ($F_{msy} = 0.87$ M (teleost) and $F_{msy} = 0.41$ M (Chondrichthyes)), according Zhou *et al.* (2012). The estimates of mortalities (Z, M and F) were obtained as described in the susceptibility section. Finally, we evaluated the proportion of misclassification among the PSA three-level risk (high, moderate, low) and the reference point (RP-SA) (overfishing or not overfishing). We assumed that high-risk in PSA should be equivalent to overfishing in RP-SA and, moderate or low risk, to not-overfishing in RP-SA according Zhou *et al.* (2016). In addition, we also compared the PSA risk level, the reference point (RP-SA) and IUCN Red List categories.

Results

Vulnerability index

Considering the quantile method to define the boundaries of the attribute, all target species of the bottom trawl were considered as being at moderate risk (Table 3). Twenty-three species were classified as being at high risk ($v > 1.72$), with the top 10 all being non-target species: (*Bagre marinus, Pseudobatos percellens, Micropogonias furnieri, Menticirrhus americanus*, *Hypanus guttatus, Bagre Bagre, Macrodon ancylodon, Rhizoprionodon porosus, Polydactylus virginicus, Cynoscion virescens*), while the majority 44 species were categorized as being at moderate risk and 22 as being at low risk ($v < 1.15$) (Table 3, Figure 2a). Considering the k-means method, two of the target species (*P. subtilis* and *X. kroyeri*) were considered as being at high risk, while *P. schmitti* was assigned as moderate (Table 3), showing a mean vulnerability score similar to several bycatch species. Similarly, 23 species were clas-

Quantile method										K-means method									
		Vulnerability										Vulnerability							
Family	Species	Code	P	S	Score	Rank	Risk	IUCN	RP-SA	Family	Species	Code	P	S	Score	Rank	Risk	IUCN	RP-SA
ARI	*Bagre marinus*	bag.mar	1.42	2.60	2.24	1	high	DD	1	POL	*Polydactylus virginicus*	pol.vir	2.47	3.00	2.06	1	high	LC	NA
RHI	*Pseudobatos percellens*	pse.per	1.00	2.00	2.23	2	high	DD	NA	CARC	*Rhizoprionodon porosus*	rhi.por	1.00	1.00	2.00	2	high	DD	NA
SCI	*Micropogonias furnieri*	mic.fur	1.42	2.50	2.17	3	high	LC	NA	SCI	*Micropogonias furnieri*	mic.fur	1.68	2.50	1.99	3	high	LC	NA
SCI	*Menticirrhus americanus*	men.ame	1.63	2.60	2.10	4	high	DD	1	DAS	*Hypanus guttatus*	hyp.gut	1.31	2.00	1.95	4	high	LC	NA
DAS	*Hypanus guttatus*	hyp.gut	1.21	2.00	2.05	5	high	LC	NA	ARI	*Bagre marinus*	bag.mar	1.89	2.60	1.94	5	high	DD	1
ARI	*Bagre bagre*	bag.bag	1.47	2.33	2.02	6	high	NT	NA	RHI	*Pseudobatos percellens*	pse.per	1.36	2.00	1.91	6	high	DD	NA
SCI	*Macrodon ancylodon*	mac.anc	2.00	2.75	2.01	7	high	LC	NA	SCI	*Cynoscion virescens*	cyn.vir	1.63	2.33	1.91	7	high	LC	NA
CARC	*Rhizoprionodon porosus*	rhi.por	1.00	1.00	2.00	8	high	DD	NA	SCI	*Macrodon ancylodon*	mac.anc	2.31	2.75	1.87	8	high	LC	NA
POL	*Polydactylus virginicus*	pol.vir	2.10	2.75	1.96	9	high	LC	NA	SCI	*Paralonchurus brasiliensis*	par.bra	2.68	2.83	1.86	9	high	LC	1
SCI	*Cynoscion virescens*	cyn.vir	1.31	2.00	1.95	10	high	LC	NA	SCI	*Larimus breviceps*	lar.bre	2.57	2.83	1.84	10	high	LC	1
PAR	*Paralichthys brasiliensis*	para.bra	1.31	2.00	1.95	11	high	LC	NA	PEN	*Penaeus subtilis*	pen.sub	2.78	2.83	1.84	11	high	LC	2
TRI	*Prionotus punctatus*	pri.pun	1.31	2.00	1.95	12	high	LC	NA	ACH	*Trinectes paulistanus*	tri.pau	2.21	2.60	1.78	12	high	LC	1
GER	*Diapterus rhombeus*	dia.rho	1.89	2.50	1.86	13	high	LC	NA	TRIC	*Trichiurus lepturus*	tri.lep	2.05	2.50	1.77	13	high	LC	NA
SCI	*Larimus breviceps*	lar.bre	2.10	2.60	1.83	14	high	LC	1	SCI	*Stellifer rastrifer*	ste.ras	2.42	2.66	1.76	14	high	LC	1
ALB	*Albula nemoptera*	alb.nem	1.47	2.00	1.82	15	high	LC	NA	SCI	*Menticirrhus americanus*	men.ame	2.26	2.60	1.76	15	high	DD	1
TRIC	*Trichiurus lepturus*	tri.lep	2.00	2.50	1.80	16	high	LC	NA	PRI	*Pellona harroweri*	pel.har	2.47	2.66	1.74	16	high	LC	1
SCI	*Paralonchurus brasiliensis*	par.bra	2.31	2.66	1.80	17	high	LC	1	GER	*Diapterus rhombeus*	dia.rho	2.10	2.50	1.74	17	high	LC	NA
DAC	*Dactylopterus volitans*	dac.vol	1.21	1.00	1.78	18	high	LC	NA	TRI	*Prionotus punctatus*	pri.pun	1.57	2.00	1.73	18	high	LC	NA
ARI	*Aspistor luniscutis*	asp.lun	1.52	2.00	1.78	19	high	LC	1	CAR	*Caranx hippos*	car.hip	1.31	1.00	1.68	19	high	LC	NA
ARI	*Aspistor quadriscutis*	asp.qua	1.52	2.00	1.78	20	high	LC	NA	PEN	*Xiphopenaeus kroyeri*	xip.kro	2.78	2.66	1.68	20	high	DD	2
SCI	*Stellifer rastrifer*	ste.ras	2.05	2.50	1.77	21	high	LC	1	ARI	*Bagre bagre*	bag.bag	2.00	2.33	1.66	21	high	NT	NA
HAE	*Conodon nobilis*	con.nob	2.10	2.50	1.74	22	high	LC	1	SCI	*Stellifer microps*	ste.mic	2.31	2.50	1.64	22	high	LC	1
CAR	*Selene brownii*	sel.bro	1.57	2.00	1.73	23	high	LC	NA	ARI	*Aspistor luniscutis*	asp.lun	1.73	2.00	1.61	23	high	LC	1
PRI	*Odontognathus mucronatus*	odo.muc	2.21	2.50	1.69	24	moderate	LC	1	PRI	*Odontognathus mucronatus*	odo.muc	2.47	2.50	1.59	24	moderate	LC	1
CAR	*Selene vomer*	sel.vom	1.63	2.00	1.69	25	moderate	LC	NA	HAE	*Conodon nobilis*	con.nob	2.57	2.50	1.55	25	moderate	LC	1
SCI	*Umbrina coroides*	umb.cor	1.63	2.00	1.69	26	moderate	LC	NA	HAE	*Haemulopsis corvinaeformis*	hae.cor	2.57	2.50	1.55	26	moderate	DD	1
CAR	*Caranx hippos*	car.hip	1.31	1.00	1.68	27	moderate	LC	NA	SCI	*Ophioscion punctatissimus*	oph.pun	2.57	2.50	1.55	27	moderate	DD	1
OPH	*Myrichthys ocellatus*	myr.oce	1.31	1.00	1.68	28	moderate	LC	NA	SCI	*Isopisthus parvipinnis*	iso.par	2.36	2.40	1.53	28	moderate	LC	1
PEN	*Penaeus subtilis*	pen.sub	2.78	2.66	1.68	29	moderate	LC	2	PEN	*Penaeus schmitti*	pen.sch	2.78	2.50	1.51	29	moderate	DD	2
PRI	*Pellona harroweri*	pel.har	2.78	2.66	1.68	30	moderate	LC	1	SPH	*Sphyraena guachancho*	sph.gua	1.52	1.33	1.51	30	moderate	DD	NA
SCI	*Nebris microps*	neb.mic	1.89	2.25	1.66	31	moderate	LC	NA	CAR	*Selene brownii*	sel.bro	1.94	2.00	1.45	31	moderate	LC	NA
TET	*Lagocephalus laevigatus*	lag.lae	1.42	1.50	1.65	32	moderate	LC	NA	SCI	*Nebris microps*	neb.mic	2.26	2.25	1.45	32	moderate	LC	NA
SCI	*Stellifer microps*	ste.mic	2.05	2.33	1.63	33	moderate	LC	1	ENG	*Cetengraulis edentulus*	cet.ede	2.47	2.33	1.43	33	moderate	LC	1
SPH	*Sphyraena guachancho*	sph.gua	1.42	1.33	1.61	34	moderate	DD	NA	ARI	*Aspistor quadriscutis*	asp.qua	2.00	2.00	1.41	34	moderate	LC	NA
SCI	*Ophioscion punctatissimus*	oph.pun	2.47	2.50	1.59	35	moderate	DD	1	SCI	*Umbrina coroides*	umb.cor	2.00	2.00	1.41	35	moderate	LC	NA

	kroyeri																	
OPH	*Lepophidium brevibarbe*	lep.bre	1.89	2.00	1.49	45	moderate	DD	NA	PAR	*Citharichthys spilopterus*	cit.spi	2.36	2.00	1.18	45	moderate	LC	NA
MUL	*Upeneus parvus*	upe.par	1.89	2.00	1.49	46	moderate	LC	NA	PAR	*Cyclopsetta chittendeni*	cyc.chi	2.36	2.00	1.18	46	moderate	LC	NA
HAE	*Haemulon plumierii*	hae.plu	1.52	1.00	1.47	47	moderate	LC	NA	OPH	*Lepophidium brevibarbe*	lep.bre	2.36	2.00	1.18	47	moderate	DD	NA
LUT	*Lutjanus synagris*	lut.syn	1.52	1.00	1.47	48	moderate	NT	NA	CYN	*Symphurus plagusia*	sym.pla	2.36	2.00	1.18	48	moderate	LC	NA
CAR	*Chloroscombrus chrysurus*	chl.chr	1.63	1.50	1.45	49	moderate	LC	NA	MUL	*Upeneus parvus*	upe.par	2.36	2.00	1.18	49	moderate	LC	NA
SCI	*Menticirrhus littoralis*	men.lit	1.94	2.00	1.45	50	moderate	DD	NA	DAC	*Dactylopterus volitans*	dac.vol	1.84	1.00	1.15	50	moderate	LC	NA
HAE	*Haemulopsis corvinaeformis*	hae.cor	2.47	2.33	1.43	51	moderate	DD	1	ENG	*Anchoa spinifer*	anc.spi	2.47	2.00	1.13	51	moderate	LC	NA
URO	*Urotrygon microphthalmum*	uro.mic	2.00	2.00	1.41	52	moderate	DD	NA	HAE	*Anisotremus moricandi*	ani.mor	2.47	2.00	1.13	52	moderate	LC	NA
GER	*Eucinostomus gula*	euc.gul	1.89	1.80	1.36	53	moderate	LC	1	PAR	*Citharichthys macrops*	cit.mac	2.47	2.00	1.13	53	moderate	LC	NA
CYN	*Symphurus plagusia*	sym.pla	2.10	2.00	1.34	54	moderate	LC	NA	GER	*Diapterus auratus*	dia.aur	2.52	2.00	1.10	54	moderate	LC	NA
PRI	*Chirocentrodon bleekerianus*	chi.ble	3.00	2.33	1.33	55	moderate	LC	1	HAE	*Haemulon plumierii*	hae.plu	1.89	1.00	1.10	55	moderate	LC	NA
OST	*Acanthostracion polygonius*	aca.pol	1.68	1.00	1.31	56	moderate	LC	NA	LUT	*Lutjanus synagris*	lut.syn	1.89	1.00	1.10	56	moderate	NT	NA
GER	*Diapterus auratus*	dia.aur	2.15	2.00	1.30	57	moderate	LC	NA	SCI	*Bairdiella ronchus*	bai.ron	2.57	2.00	1.08	57	moderate	LC	NA
CYN	*Symphurus tessellatus*	sym.tes	2.68	2.25	1.28	58	moderate	LC	NA	ECH	*Echeneis naucrates*	ech.nau	1.94	1.00	1.05	58	moderate	LC	NA
SCI	*Bairdiella ronchus*	bai.ron	2.21	2.00	1.27	59	moderate	LC	NA	HAE	*Haemulon steindachneri*	hae.ste	1.94	1.00	1.05	59	moderate	LC	NA
ENG	*Lycengraulis grossidens*	lyc.gro	2.26	2.00	1.24	60	moderate	LC	1	ENG	*Lycengraulis grossidens*	lyc.gro	2.68	2.00	1.04	60	moderate	LC	1
PAR	*Cyclopsetta chittendeni*	cyc.chi	2.32	2.00	1.21	61	moderate	LC	NA	TET	*Lagocephalus laevigatus*	lag.lae	2.10	1.50	1.02	61	moderate	LC	NA
ARI	*Cathorops spixii*	cat.spi	1.78	1.00	1.21	62	moderate	LC	NA	PAR	*Etropus crossotus*	etr.cro	2.78	2.00	1.02	62	moderate	LC	NA
HAE	*Haemulon aurolineatum*	hae.aur	1.78	1.00	1.21	63	moderate	LC	NA	ARI	*Sciades herzbergii*	sci.her	2.00	1.00	1.00	63	moderate	LC	NA
ENG	*Cetengraulis edentulus*	cet.ede	2.78	2.16	1.18	64	moderate	LC	1	CAR	*Chloroscombrus chrysurus*	chl.chr	2.15	1.50	0.97	64	moderate	LC	NA
SCI	*Stellifer brasiliensis*	ste.bra	2.78	2.16	1.18	65	moderate	LC	1	EPH	*Chaetodipterus faber*	cha.fab	2.05	1.00	0.94	65	moderate	LC	NA
HAE	*Anisotremus moricandi*	ani.mor	2.36	2.00	1.18	66	moderate	LC	NA	CAR	*Carangoides bartholomaei*	car.bar	2.10	1.00	0.89	66	moderate	LC	NA
EPH	*Chaetodipterus faber*	cha.fab	1.84	1.00	1.15	67	moderate	LC	NA	ACH	*Achirus declivis*	ach.dec	2.36	1.60	0.87	67	moderate	LC	1
ENG	*Anchoa spinifer*	anc.spi	2.42	2.00	1.15	68	low	LC	NA	CLU	*Harengula clupeola*	har.clu	2.47	1.66	0.84	68	low	LC	NA
PAR	*Citharichthys spilopterus*	cit.spi	2.68	2.00	1.04	69	low	LC	NA	SCI	*Stellifer stellifer*	ste.ste	2.47	1.66	0.84	69	low	LC	2
PAR	*Etropus crossotus*	etr.cro	2.68	2.00	1.04	70	low	LC	NA	ARI	*Cathorops spixii*	cat.spi	2.15	1.00	0.84	70	low	LC	NA
PAR	*Citharichthys macrops*	cit.mac	2.78	2.00	1.02	71	low	LC	NA	HAE	*Haemulon aurolineatum*	hae.aur	2.15	1.00	0.84	71	low	LC	NA
HAE	*Genyatremus luteus*	gen.lut	2.00	1.00	1.00	72	low	LC	NA	GER	*Eucinostomus gula*	euc.gul	2.42	1.60	0.83	72	low	LC	1
OPH	*Ogcocephalus vespertilio*	ogc.ves	2.00	1.00	1.00	73	low	LC	NA	OST	*Acanthostracion polygonius*	aca.pol	2.21	1.00	0.78	73	low	LC	NA
STR	*Peprilus paru*	pep.par	2.21	1.50	0.93	74	low	LC	NA	OPH	*Myrichthys ocellatus*	myr.oce	2.21	1.00	0.78	74	low	LC	NA
CLU	*Harengula clupeola*	har.clu	2.36	1.66	0.91	75	low	LC	NA	ENG	*Anchoa januaria*	ach.jan	2.47	1.50	0.72	75	low	LC	NA
ACH	*Achirus lineatus*	ach.lin	2.10	1.00	0.89	76	low	LC	NA	ENG	*Anchoviella lepidentostole*	anc.lep	2.47	1.50	0.72	76	low	LC	NA
ACH	*Achirus declivis*	ach.dec	2.68	1.60	0.67	77	low	LC	1	STR	*Peprilus paru*	pep.par	2.57	1.50	0.65	77	low	LC	NA
ENG	*Anchoviella lepidentostole*	anc.lep	2.68	1.50	0.59	78	low	LC	NA	ATH	*Atherinella brasiliensis*	ath.bra	2.36	1.00	0.63	78	low	LC	NA
HEM	*Hyporhamphus unifasciatus*	hyp.uni	2.42	1.00	0.57	79	low	NT	NA	HAE	*Genyatremus luteus*	gen.lut	2.36	1.00	0.63	79	low	LC	NA
ENG	*Anchoa januaria*	ach.jan	2.78	1.50	0.54	80	low	LC	NA	OPH	*Ogcocephalus vespertilio*	ogc.ves	2.36	1.00	0.63	80	low	LC	NA
ENG	*Anchoa tricolor*	anc.tri	2.78	1.50	0.54	81	low	LC	NA	TET	*Sphoeroides greeleyi*	sph.gre	2.68	1.50	0.59	81	low	LC	NA
SCI	*Stellifer stellifer*	ste.ste	2.78	1.50	0.54	82	low	LC	2	ENG	*Anchoa tricolor*	anc.tri	2.78	1.50	0.54	82	low	LC	NA
TET	*Sphoeroides greeleyi*	sph.gre	3.00	1.50	0.50	83	low	LC	NA	ACH	*Achirus lineatus*	ach.lin	2.47	1.00	0.52	83	low	LC	NA

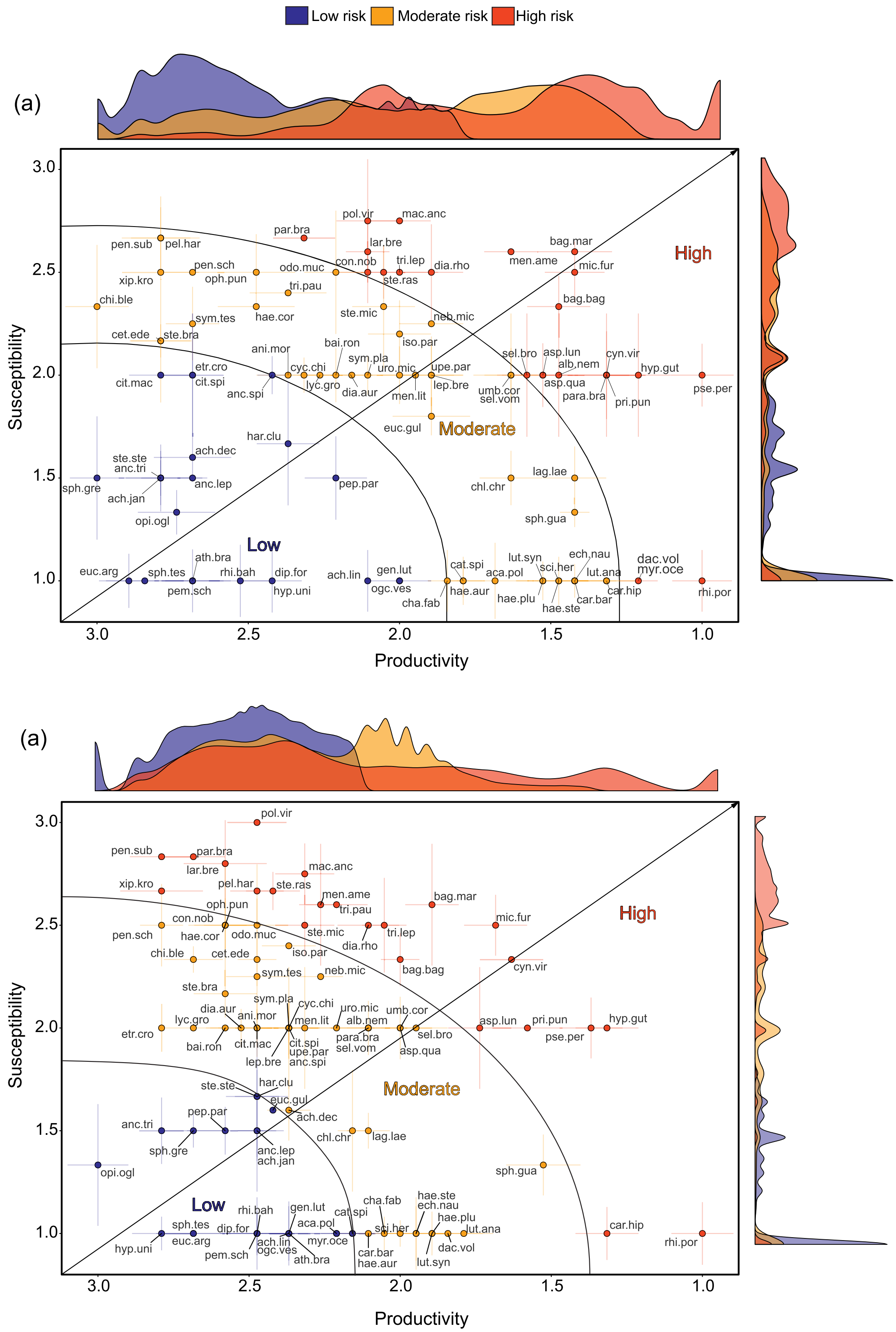

Figure 2. Scores of productivity (P), susceptibility (S) and vulnerability (v) of species caught by bottom trawl fishing in Barra of Sirinhaém (BSIR), south of Pernambuco, Northeast Brazil estimated by quantile (a) and k-means (b) methods (Species codes are given in Table 3). The range lines for each point show the standard deviation obtained from uncertainty simulations (10 000 runs). The density plots represent the total variation of the P and S scores, for each risk category (a) quantile (High $v > 1.72$; Moderate $1.72 > v > 1.15$; Low $v < 1.15$) and (b) k-means (High $v > 1.60$; Moderate $1.60 > v > 0.85$; Low $v < 0.85$).

sified as high risk ($v > 1.60$). Eight among the top 10 of these (excluding *Paraloncburus brasiliensis* and *Larimus breviceps*) were the same as for the quantile method, 44 as moderate risk and 22 as low risk ($v < 0.85$) (Table 3, Figure 2b).

Assessing uncertainties

In general, most species (76%; 68 species) did not change their risk category (low, moderate or high) according to the methods used to define of the boundaries of the attribute scores (Figure 3). From these, 17 species of high vulnerability were always classified as high, 33 as moderate and 18 as low (Figure 3).However, given the changes in productivity and susceptibility attribute values (Supplementary Figure S6), for 22 species (24%) a decrease in risk status was found (Figure 3), between high and moderate or moderate and low risk categories. Six species (e.g. *Albula nemoptera*, *Dactylopterus volitans*, *Paralichthys brasiliensis*) changed from high (quantile method) to moderate risk (k-means method) and five (e.g. *Acanthostracion polygonius*, *Haemulon aurolineatum*, *Myrichthys ocellatus*) from moderate (quantile) to low risk (k-means) (Table 3 and Figure 3). The risk status also increased for 11 species, six from moderate (quantile) to high (k-means) (e.g. *P. subtilis*, *X. kroyeri*), and five from low (quantile) to moderate risk categories (e.g. *Anchoa spinifer, Etropus crossotus*, *Citharichthys spilopterus*) (Table 3 and Figure 3).

For 94% of the species, the position in the vulnerability ranking changed, but within same risk category, such as the *B. marinus* (High risk; rank: 1 on quantile and 5 on k-means), *Chirocentrodon bleekerianus* (Moderate risk; rank 56 on quantile, rank 36 on k-means) and *Stellifer stellifer* (Low risk; rank 82 on quantile, rank 69 on k-means) (Figure 3).

Regardless of the weight assignments, including zeroing redundant attributes of productivity and susceptibility, most species did not show alterations in their classification of risk (Figure 2 and 3). For both methods (quantile and k-means), the top twelve species at risk, including *B. marinus, P. percellens, M. furnieri, M. americanus, H. guttatus, M. ancylodon, R. porosus, P. virginicus, C. virescens*, *L. breviceps*, *B. bagre*, and *P. brasiliensis* (Table 3), had a probability larger than 0.8 of being classified as at high risk (Figure 4a and 4b). Conversely, sardines, (e.g. *H. clupeola, O. oglinum, Anchoa tricolor, Rhinosardinia bahiensis*), estuarine fishes (e.g. *S. greeleyi, H. unifasciatus, A. brasiliensis*) and reef fishes (e.g. *Diplectrum formosum, Haemulon aurolineatum*) had a high probability (> 0.6) of being at low risk from bottom trawling fishing (Figure 4a and 4b).

Integrating other approaches

Considering the IUCN methodology, among the species assessed, none was classified as CR, EN, VU. Regardless of the method used (quantile and k-means), most of the species were classified as Least Concern for all risk categories (Figure 5a and b), especially those of moderate risk. However, four (quantile) and five (k-means) high-risk species were classified as Data Deficient - DD (e.g. *B. marinus*, *P. percellens* and *R. porosus*). Moreover, four species was classified as Near Threated (NT), one considered as high risk, two as moderate and one (*H. unifasciatus*) as low risk (Table 3).

From the 24 species out of 90 that had enough data to allow for comparison between PSA and RP-SA (Table 3), 46% showed similar classification between PSA and RP-SA (High risk and overfishing), considering both quantile and k-means methods (Figure 5c). Among them, two high-risk species from PSA (*B. marinus* and *M. americanus*) and classified as DD by IUCN were considered as overfished in RP-SA (Table 3).

Discussion

Although the Productivity and Susceptibility Analysis approach does not provide traditional fishery management reference points (Fujita *et al.*, 2014), it allows policy makers and stakeholders to focus on monitoring, assessment and management of the stocks and species shown to be at the highest risk from fishing (Hobday *et al.*, 2011). PSA is particularly useful in data-poor cases, where the catches or biological data are not comprehensive, are aggregated across species or are insufficient to run a quantitative stock assessment (Lucena-Frédou *et al.*, 2017), as is the case in many tropical multispecies fisheries including small-scale Brazilian fisheries.

The region and fishery of our case study have been very little studied. Thus, quantitative assessments of the stocks and how much they are affected by fishing are not available and data-limited analysis approaches, including PSA, are highly recommended. However, given its nature, PSA should be used with caution, its results applied prudently, and a comparison with other assessment approaches strongly recommended (Osio *et al.*, 2015). For example, Zhou *et al.* (2016), comparing stock assessments in Australia using Ecological Risk Assessment tools, found 50% of misclassification rate by PSA. The results presented here should, therefore, be considered with some caution and may refer, either for the target or non-target species, to one specific part of the population exploited by small-scale shrimp trawling in Sirinhaém, Northeast Brazil, since the species distribution has a high probability of being wider than that considered in the present study. We believe, however, that even with the limitations of the method, especially in data-poor areas such as ours, it is important to highlight the species that should be prioritized, either for urgent assessment or data collection with an acceptable level of reliability applying some uncertainty measures proposed.

Seventeen among the 90 species caught by bottom trawling in the region were categorized as high vulnerable, independently of the method (quantile and k-means) used to define the boundaries of the attribute scores. Among these, we reported Elasmobranchii (e.g. *H. guttatus P. percellens*) and catfishes (e.g. *B. marinus*, *B. bagre*), which are often discarded or consumed, and hake species (e.g. *M. ancylodon*) and croaker (*M. furnieri*), which are usually sold. The high vulnerability scores mainly resulted from the combination of very low productivity due to medium to long lifespans (Simpfendorfer *et al.*, 2011) and low spawning/potential reproduction (Pinheiro *et al.*, 2006; da Silva *et al.*, 2018) (in the case of Elasmobranchii and catfishes); or very high susceptibility to the bottom trawling due to high capture rates of young individuals (Silva Júnior *et al.*, 2015) and overlap of feeding and breeding grounds with fishing areas (Silva Júnior *et al.*, 2019) (in the case of Sciaenidae).

Hake species, croakers, catfishes and elasmobranchs, mainly as adults, are important fishery resources on the Brazilian coastline (MPA, 2011). Elasmobranch species are often reported as being highly vulnerable to multi-gear fisheries throughout the world(Martínez-Candelas *et al.*, 2020). In south Brazil, for example, the trawl fishery has already contributed to the depletion of some Elasmobranchs and Sciaenidae populations (Barreto *et al.*, 2016; Haimovici and Cardoso, 2017). Moreover, some of these exploited species are categorized as Data Deficient (DD) (e.g. *B. marinus* and *P. percellens*,) at the regional level according to IUCN Red List, indicating data is inadequate to assess the risk of extinction, rec-

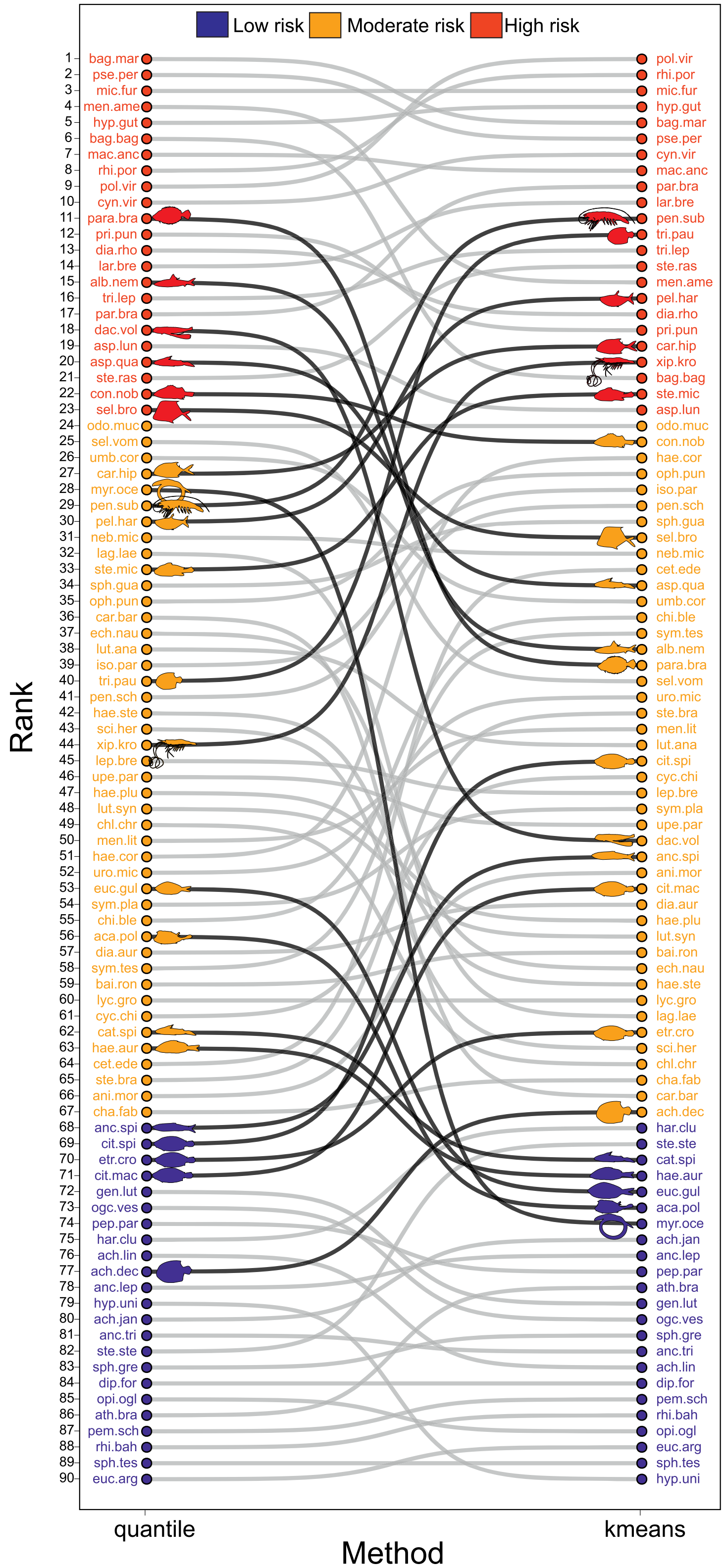

Figure 3. Difference in rank and risk categories of target and non-target species caught by bottom trawl fishing in Barra of Sirinhaém (BSIR) south of Pernambuco, Northeast Brazil. The lines show changes in rank between the methods (quantile and k-means) to define the boundaries of attribute scores. Black lines indicate that the species changed risk category and grey lines indicate that they did not. Species codes are given in Table 3.

ognizing the possibility of being endangered (ICMbio, 2018). *Bagre bagre* was considered the sixth most vulnerable species (quantile method) and is also classified as Near Threatened (NT) (ICMbio, 2018). In northeast Brazil, hake species, croakers, catfishes and elasmobranchs do not have adequate stock assessments or have not been evaluated due to lack of infor-

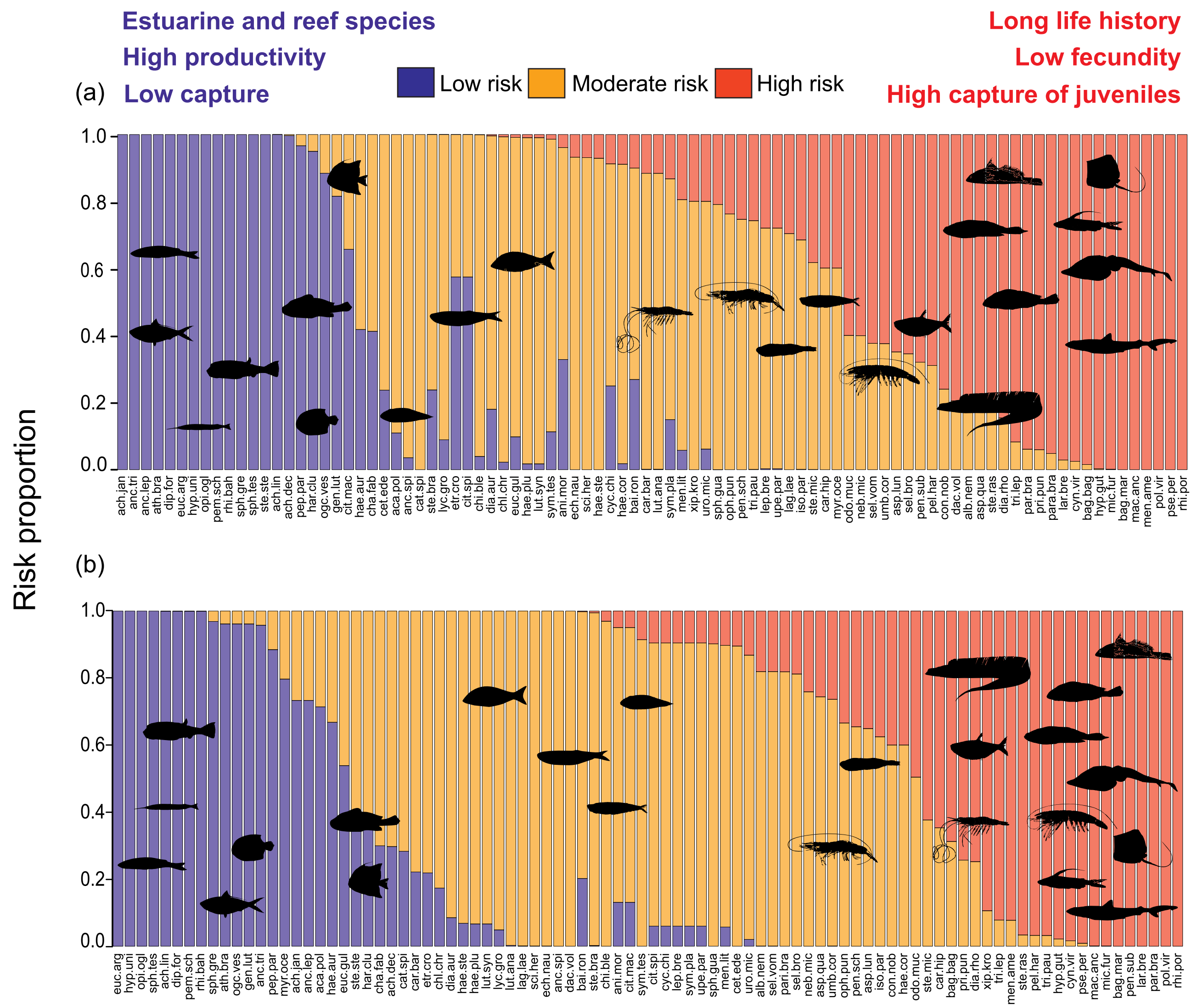

Figure 4. Probability of risk from uncertainty simulations by the methods: a) quantile and b) k-means for each species caught (species codes are given in Table 3) by bottom trawl fishing in Barra of Sirinhaém (BSIR), south of Pernambuco, Northeast Brazil. Species are ordered (left to right) according to vulnerability rank: low (blue), moderate (yellow) and high (red).

mation, although they deserve attention given the history of overexploitation and depletion already reported in the country.

Most species (33) were classified, regardless of the method used, as being at moderate risk, but two groups of species were differently affected by trawling. The first, including species of the main bycatch families, Pristigasteridae, Sciaenidae and Haemulidae, have reproduction and feeding sites that largely overlap the fishing area (Silva Júnior *et al.*, 2015; Eduardo *et al.*, 2018a; Lira *et al.*, 2019) and are also consumed by fishermen and local communities. Some of these species were categorized as Data Deficient (DD) (e.g. *Ophioscion punctatissimus*, *H. corvinaeformis*) (ICMbio, 2018). Moreover, Verba *et al.* (2020) recently classified many of these Sciaenidae and Haeumilidae species as fully or overexploited within the Brazilian Exclusive Economic Zone, in response to synergistic interaction between the warming of the sea, fishery exploitation and specific life-history traits. Our findings confirm the acceptable level of risk for these species. However, they should be considered a monitoring and research priority in the coming years.

Another group, composed of reef-associated and sand bottom fish species (grunts *Haemulon* spp., Jacks *Caranx* spp and snappers *Lutjanus* spp), are at moderate risk. They have long lifespans and low growth rates (Lessa *et al.*, 2004). However, they subjected to little incidental capture (Silva Júnior *et al.*, 2019) compared with the first group of species, and fishing has a lower overlap with their reproduction zones (Cardoso de Melo *et al.*, 2020). Although these species are not particularly threatened by shrimp trawling, they are heavily exploited in northeast Brazil by multiple gears (Lessa *et al.*, 2009), and some species have already been as fully or overexploited during the 2000's (Frédou *et al.*, 2009) and are classed as NT (Near Threatened) (ICMbio, 2018) (*Lutjanus analis* and *L. synagris*). Particular attention should therefore be paid to the additive effect of the artisanal shrimp fishery, especially because this fishing activity mainly targets juveniles.

Considering the target shrimps, all three species were classified as being at moderate risk by the quantile method or at

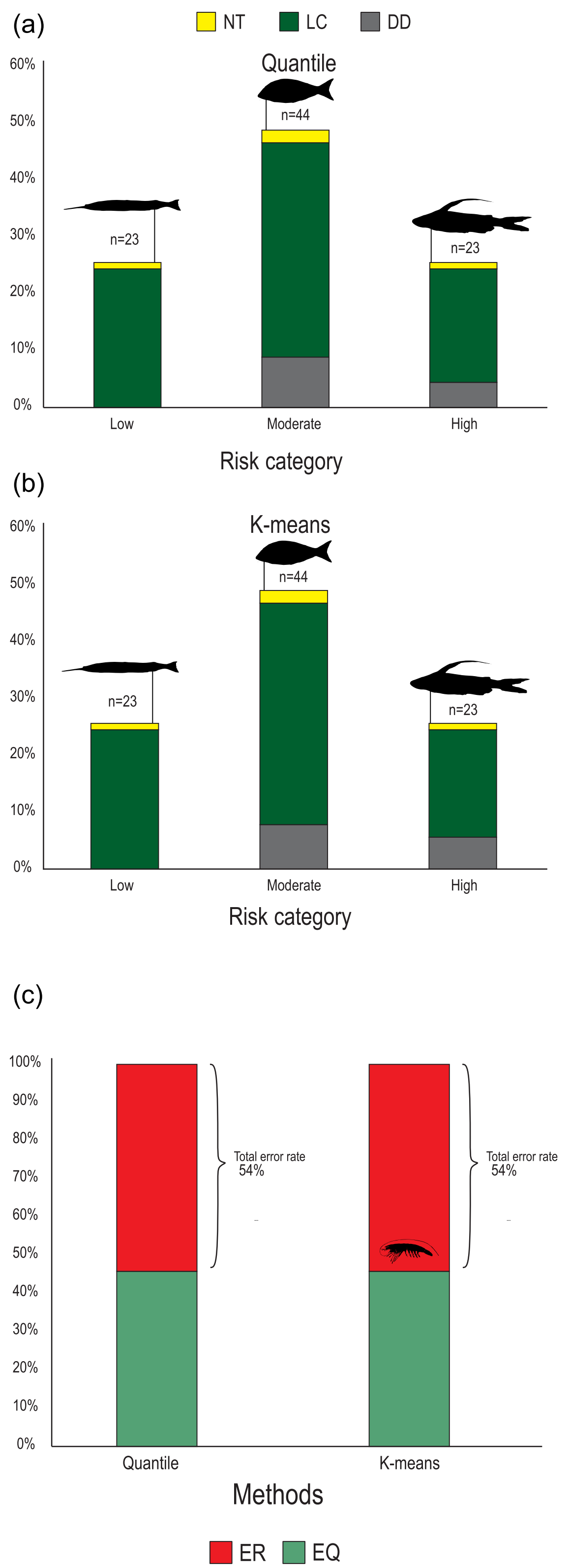

Figure 5. Status of the species caught by bottom trawl fishing considering the IUCN Red List categories risk categories (a, b), PSA risk category and Reference point from Traditional Stock Assessment (RP-SA) for quantile and k-means methods (c). Low, moderate and high are vulnerability risk category from PSA. Near Threatened (NT); Least Concern (LC) and Data Deficient (DD). EQ: Similar status among PSA results and RP-SA (High risk and overfishing; moderate or low risk and not-overfishing); ER: Misclassifications among PSA results and RP-SA.

high risk, in the cases of *X. kroyeri* and *P. subtilis*, by k-means method. They were not, however, in the top 10 of the vulnerability rankings. In general, *P. subtilis* showed higher vulnerability values and rank. This species spawns in the open sea with juveniles living in shallow zones and migrating to offshore waters when they become adults (Dall *et al.*, 1990). Hence, in our study fishery, which operates near the coast (Tischer and Santos, 2003), many young individuals are caught (Lopes *et al.*, 2014; Silva et al., 2015, 2018), increasing the susceptibility of the species. However, the current stock status does not indicate overexploitation in the region (Silva *et al.*, 2015).

Xiphopenaeus kroyeri and *P. schmitti* are the main targets of trawl fishing in the region in terms of catch volume and market value, respectively (Santos, 2010). Traditional stock assessments carried out in the region do not indicate overexploitation, which is supported by the species' short life cycle, rapid growth and high natural mortality (Lopes *et al.*, 2014; Silva et al., 2015, 2018). Both shrimp species were recently classified as DD (ICMbio, 2018) and present evidence of overexploitation on the southern coast of Brazil, with strong decreases in stock biomass and size of individual caugth (Davies *et al.*, 2018; Carvalho *et al.*, 2021). However, according to Lira *et al.* (2021), these two shrimp species are more resilient to changes in fishing efforts in the region studied.

Uncertainty measures

The subjective nature of PSA may lessen the reliability of the results and consequently the management measures adopted. Recently, some studies have addressed the fragilities of PSA (Brown *et al.*, 2015; McCully Phillips *et al.*, 2015; Lucena-Frédou *et al.*, 2017; Duffy and Griffiths, 2019). A new method to classify the vulnerability outputs into sustainability categories using a Gaussian mixture model (GMM) was applied by Baillargeon *et al.* (2020), who observed a more effectively grouped species with similar productivity and susceptibility scores. In our study, we addressed some of these obstacles, such as the choice of method to select attribute boundaries, the potential redundancy between attributes and the consequence of differential weights applied to productivity and susceptibility attributes. Moreover, we compared PSA risk classification with to other data-poor methods: (i) IUCN Red List of Threatened Species and (ii) Reference point from Traditional Stock Assessment.

High correlations between attributes suggest that two or more of them convey similar information, which would lead to overemphasis of their effect. To counter such misleading effects, one of the correlated attributes should be removed. Conversely, low correlations suggest that both attributes should be considered because each of them conveys unique biological information to define the vulnerability of a species (Stobutzki *et al.*, 2001). It is also necessary to consider the self-correlation between attributes in the estimates, especially those derived from empirical relations based on a single parameter (e.g. L_{max}). In data-poor species, as in our study case, the use of these equations is very useful (Zhou *et al.*, 2012). Although we have derived several life history traits from L_{max}, more than half of the species have had their LHPs obtained from local or regional specific studies. In addition, removal of one of the derived attributes, overall, did not change the scores or, consequently, the risk category of the species, hence all productivity attributes were considered in the analysis. When considering the different methods for defining boundaries, most species changed their vulnerability rank, but did not change their risk category (low, moderate, or high).

The clustering method has been successfully used in the PSA, mainly to identify similar groupings of species for different factors (Cope *et al.*, 2011; Furlong-Estrada *et al.*, 2017). More recently, Altuna-Etxabe *et al.* (2020) applied, for the first time, a criterion for defining the boundaries of attribute scores, but did not evaluate its effects in the estimation of the vulnerability risk of the species. Both methods of defining score boundaries have a weakness. They are dependent on the species included in the analysis, mainly species with discrepant attribute values (very low or high values). Therefore, its application must be cautious, according to the data structure. Although some species changed risk categories, no significant differences were observed in the overall PSA results when comparing the two methods.

Extreme values of the PSA vulnerability score are often well correlated with the risk of overexploitation, while intermediate values have high uncertainty concerning the risk posed by exploitation of the species (Hordyk and Carruthers, 2018). Extreme values may also be related to many false positives or negatives (Hobday *et al.*, 2011; Zhou *et al.*, 2016; Lucena-Frédou *et al.*, 2017) obtained when the attribute scores overestimate or underestimate the level of risk of a species relative to an assessment based on a larger dataset. Hence, the performed simulations were important for two reasons: first, to minimize the uncertainties of the results associated with the attribution of weights, mainly for the species at higher (high vulnerability) and lower (low vulnerability) risk; and second, through a probability estimation, to reinforce the risk status associated with each species.

Four (quantile) and five (k-means) high-risk species were classified as Data Deficient - DD. These species need more attention, because they have insufficient information available, but it is strongly suspected that it may be in a threat category (IUCN, 2012). Among the species classified as NT, two were considered as moderate risk, one as high and another as low risk. However, this divergence is expected. Due to its relative nature, PSA indicates those species that are at the highest vulnerability risk and therefore deserve special attention by the decision-makers since they are subjected to overfishing or as data priority. However, high risk species do not necessarily mean risk of extinction, as mainly evidenced by the results of the IUCN. Moreover, these approaches have different levels of complexities which can contribute to the divergences. Hornborg *et al.* (2020) assessing Swedish fisheries; Lucena Frédou et al. (2017) an Atlantic tuna fishery; Baillargeon *et al.* (2020) several global fishing; and Clarke *et al.*, (2018) a trawl fishery in Costa Rica have found a considerable degree of alignment between IUCN evaluations and risk status from PSA, but also disagreement between approaches was observed. Comparing the PSA with the reference point (F vs Fmsy), it was observed misclassification of 54% for both methods (quantile and k-means).

The largest percent of misclassifications were for those species classified as moderate risk by PSA, but as “overfishing” by the reference point. Many reasons may result in an underestimation of risk in PSA, e.g. (i) absence of life history traits, which may lead to bias in estimates; (ii) important factor or attributes not included in the analyse; (iii) defining attribute boundaries; and (iv) species distribution range overestimated, and/or when fish tend to aggregate in fished area (Zhou *et al.*, 2016). However, some of these weaknesses were observed in this study and were considered in sensitivity tests to minimize the potential bias. Similar bias rates were observed by Zhou *et al.* (2016) when comparing the PSA, the Sustainability Assessment for Fishing Effect (SAFE) with Fishery Status Reports (FSR) and data-rich quantitative stock assessments.

According to Zhou *et al.* (2016), in this case, PSA has low sensitivity, often resulting in a higher proportion of false positives. Some of the data used by IUCN, reference point assessment and the PSA are similar, but the criteria used to derive the risk, status and vulnerability of species are not. Despite some misclassifications between PSA, IUCN and RP-SA approaches, converging conclusions were also observed, indicating robustness of PSA results for some species, even considering the limitations of the method (Lucena-Frédou *et al.*, 2017). Nevertheless, it is necessary to consider the regional circumstances, assessing the potential vulnerability of species to the fisheries operating in the area (Hornborg *et al.*, 2020). Attributes and scores should, therefore, be chosen to reflect the specificities of study cases.

Management support conclusions

The shrimp fishery at Pernambuco is multispecies in nature and is currently unregulated, contradicting the Code of Conduct for Responsible Fisheries (CCRF) that recommends that entire catches should be managed in an ecologically sustainable manner considering the main species involved (target and bycatch) (FAO, 1995). Our findings suggest that some non-target species can be more vulnerable to bottom trawling fishing than the target species in the region, thus underlining that vulnerability of bycatch populations should be taken into account when making management decisions as part of an ecosystem approach.

Considering the previous studies on shrimp trawling activity in the region (Tischer and Santos, 2003; Lopes *et al.*, 2014; Eduardo *et al.*, 2018b; Silva *et al.*, 2018; Lira *et al.*, 2019, 2021; Silva Júnior *et al.*, 2019), the target species are not currently those principally at risk from this fishery. Some species of the bycatch, however, should be carefully assessed and considered as priorities for management. The combined effect of the fishery and ongoing environmental changes, in terms of rainfall or in primary production, should also be considered because their interaction could have significant adverse impacts on ecosystem functioning (Lira *et al.*, 2021).

Data Availability Statement

The data underlying this article are available in the article and in its online supplementary material.

Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Author contribution

The authors have materially participated in the manuscript preparation.

Alex Souza Lira: Research concept, database process, data analysis, illustrations, and manuscript preparation.
François Le Loc'h: Manuscript preparation.
Humber Agrelli Andrade: Data analysis and manuscript revision
Flávia Lucena-Frédou: Research concept, data analysis, and manuscript preparation

Conflict of interest

The authors declare that they know of no competing financial interests or personal relationships that may appear to have influenced the work reported in this article

Acknowledgments

We thank the CAPES (Coordination for the Improvement of Higher Education Personnel) and CNPq (Brazilian National Council for Scientific and Technological Development), who provided a student scholarship for Alex Souza Lira and a research grant for Flavia Lucena-Frédou. This work is also a contribution to SHRIMP_NNE/SAP (Secretaria de Aquicultura e Pesca; n°22 MPA/CNPq Process 445766/2015-8), LMI TAPIOCA, program CAPES/COFECUB (88881.142689/2017-01). The present study could not have been carried out without the work of all the members from the BIOIMPACT Laboratory.

References

Altuna-Etxabe, M., Ibaibarriaga, L., García, D., and Murua, H. 2020. Species prioritisation for the development of multiannual management plans for the Basque demersal fishery. Ocean and Coastal Management, 185: 105054. Elsevier Ltd. https://doi.org/10.1016/j.ocecoaman.2019.105054.

Baillargeon, G. A., Tlusty, M. F., Dougherty, E. T., and Rhyne, A. L. 2020. Improving the productivity-susceptibility analysis to assess data-limited fisheries. Marine Ecology Progress Series, 644: 143–156.

Barreto, R., Ferretti, F., Flemming, J. M., Amorim, A., Andrade, H., Worm, B., and Lessa, R. 2016. Trends in the exploitation of South Atlantic shark populations. Conservation biology, 30: 792–804.

Belton, B., and Thilsted, S. H. 2014. Fisheries in transition: Food and nutrition security implications for the global South. Global Food Security, 3: 59–66. Elsevier.http://dx.doi.org/10.1016/j.gfs.2013.10.001.

Brown, S. L., Reid, D., and Rogan, E. 2015. Spatial and temporal assessment of potential risk to cetaceans from static fishing gears. Marine Policy, 51: 267–280. Elsevier. http://dx.doi.org/10.1016/j.marpol.2014.09.009.

Cardoso de Melo, C., Soares, A. P. C., Pelage, L., Eduardo, L. N., Frédou, T., Lira, A. S., Ferreira, B. P. *et al.* 2020. Haemulidae distribution patterns along the Northeastern Brazilian continental shelf and size at first maturity of the most abundant species. Regional Studies in Marine Science, 35: 101226. Elsevier B.V.https://doi.org/10.1016/j.rsma.2020.101226.

Carvalho, A. R., Pennino, M. G., Bellido, J. M., and Olavo, G. 2020. Small-scale shrimp fisheries bycatch: A multi-criteria approach for data-scarse situations. Marine Policy, 116: 103613. Elsevier Ltd. https://doi.org/10.1016/j.marpol.2019.103613.

Carvalho, C., Oshiro, L. M. Y., and Keunecke, K. A. 2021. . Regional Studies in Marine Science, 42: 101641. Elsevier B.V.https://doi.org/10.1016/j.rsma.2021.101641.

Clarke, T. M., Espinoza, M., Chaves, Romero, and Wehrtmann, I. S. 2018. Assessing the vulnerability of demersal elasmobranchs to a data-poor shrimp trawl fishery in Costa Rica, Eastern Tropical Pacific. Biological Conservation, 217: 321–328. Elsevier.https://doi.org/10.1016/j.biocon.2017.11.015.

Cope, J. M., Devore, J., Dick, E. J., Ames, K., Budrick, J., Erickson, D. L., Grebel, J. *et al.* 2011. An approach to defining stock complexes for U.S. west coast groundfishes using vulnerabilities and ecological distributions. North American Journal of Fisheries Management, 31: 589–604.

da Silva, V. E. L., Teixeira, E. C., Fabré, N. N., and Batista, V. S. 2018. Reproductive biology of the longnose stingray *Hypanus guttatus* (Bloch & Schneider, 1801) from the northeastern coast of Brazil. Cahiers de Biologie Marine, 59: 467–472.

Dall, W., Hill, B. J., Rothlisberg, P. C., and Sharples, D. J. 1990. The Biology of the Penaeidae. Advances of Marine Biology, 27: 489.

Davies, R. W. D., Cripps, S. J., Nickson, A., Porter, G., Watson, R. A., Baisre, J. A.FAO (Food and Agriculture Organization of the United Nations), *et al.*, FAO (Food and Agriculture Organization of the United Nations) 2018. Target-based catch-per-unit-effort standardization in multispecies fisheries. Marine Policy, 148: 1–9. Elsevier. http://www.nature.com/doifinder/10.1038/ncomms10244.

Dias-Neto, J. 2011. Proposta de plano nacional de gestão para o uso sustentável de camarões marinhos no Brasil. Ibama, Brasília. 242pp.

Duffy, L. M., and Griffiths, S. P. 2019. Assessing attribute redundancy in the application of productivity-susceptibility analysis to data-limited fisheries. Aquatic Living Resources, 32.

Eduardo, L. N., Lira, A. S., Frédou, T., and Lucena-Frédou, F. 2018a. Population structure and reproductive biology of *Haemulopsis corvinaeformis* (Perciformes, Haemulidae) in the south coast of Pernambuco, northeastern Brazil. Iheringia - Série Zoologia, 108: 1–8.

Eduardo, L. N., Frédou, T., Lira, A. S., Silva, L. V. S., Ferreira, B. P., Bertrand, A., Ménard, F. *et al.* 2018b. Length-weight relationship of thirteen demersal fishes from the tropical Brazilian continental shelf. Journal of Applied Ichthyology, 2015–2018. http://doi.wiley.com/10.1111/jai.13831.

FAO. 1995. Code of Conduct for Responsible Fisheries. Rome. 41 pp.

Faruque, H., and Matsuda, H. 2021. Assessing the vulnerability of bycatch species from Hilsa gillnet fishing using productivity susceptibility analysis: Insights from Bangladesh. Fisheries Research, 234: 105808. Elsevier B.V. https://doi.org/10.1016/j.fishres.2020.105808.

Francis, R. I. C. C., and Shotton, R. 1997. 'Risk' in fisheries management: A review. Canadian Journal of Fisheries and Aquatic Sciences, 54: 1699–1715.

Frédou, T., Ferreira, B. P., and Letourneur, Y. 2009. Assessing the stocks of the primary snappers caught in Northeastern Brazilian reef systems. 1: Traditional modelling approaches. Fisheries Research, 99: 90–96.

Fujita, R., Thornhill, D. J., Karr, K., Cooper, C. H., and Dee, L. E. 2014. Assessing and managing data-limited ornamental fisheries in coral reefs. Fish and Fisheries, 15: 661–675.

Furlong-Estrada, E., Galván-Magaña, F., and Tovar-Ávila, J. 2017. Use of the productivity and susceptibility analysis and a rapid management-risk assessment to evaluate the vulnerability of sharks caught off the west coast of Baja California Sur, Mexico. Fisheries Research, 194: 197–208. Elsevier. http://dx.doi.org/10.1016/j.fishres.2017.06.008.

Haimovici, M., and Cardoso, L. G. 2017. Long-term changes in the fisheries in the Patos Lagoon estuary and adjacent coastal waters in Southern Brazil. Marine Biology Research, 13: 135–150.

Hintzen, N. T., Aarts, G., Poos, J. J., Van der Reijden, K. J., and Rijnsdorp, A. D. 2020. Quantifying habitat preference of bottom trawling gear. ICES Journal of Marine Science.

Hobday, A., Fuller, M., Griffiths, S., Kenyon, R., Bulman, C., Dowdney, J., Williams, A. *et al.* 2007. Ecological risk assessment for effects of fishing. Report for the Australian Fisheries Management Authority, 205. http://www.afma.gov.au/wp-content/uploads/2010/06/ERA_NPF_fishery_report_29_06_2007.pdf.

Hobday, A., Smith, A., Stobutzki, I., Bulman, C., Daley, R., Dambacher, J., Deng, R. *et al.* 2011. Ecological risk assessment for the effects of fishing. Fisheries Research, 108: 372–384. Elsevier B.V. http://linkinghub.elsevier.com/retrieve/pii/S0165783611000324.

Hoenig, J. 1983. Empirical use of longevity data to estimate mortality rates.

Hordyk, A. R., and Carruthers, T. R. 2018. A quantitative evaluation of a qualitative risk assessment framework: Examining the assumptions and predictions of the Productivity Susceptibility Analysis (PSA). 1–32 pp.

Hornborg, S., Hobday, A. J., Borthwick, L., and Valentinsson, D. 2020. Risk-based evaluation of the vulnerability of the Skagerrak–Kattegat marine fish community to Swedish fisheries. ICES Journal of Marine Science, 77: 2706–2717.

IBAMA. 2008. Estatística da Pesca - 2007, Grandes regiões e unidades da federação. Brasília-DF. 180pp.

ICMbio. 2018. Livro Vermelho da Fauna Brasileira Ameaçada de Extinção. Instituto Chico Mendes de Conservação da Biodiversidade, Brasília. 4162 pp.

IUCN. 2012. Guidelines for Application of IUCN Red List Criteria at Regional and National Levels: Version 4.0. 41 pp.

Jensen, A. L. 1997. Origin of the relation between K and Linf and synthesis of relations among life history parameters. Canadian Journal of Fisheries and Aquatic Sciences, 54: 987–989.

Jones, J. B. 1992. Environmental impact of trawling on the seabed: A review. New Zealand Journal of Marine and Freshwater Research, 26: 59–67.

Kaiser, M. J., Collie, J. S., Hall, S. J., Jennings, S., and Poiner, I. R. 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish and Fisheries, 3: 114–136. https://onlinelibrary.wiley.com/doi/abs/10.1046/j.1467-2979.2002.00079.x.

Lessa, R. P., Monteiro, A., Duarte-Neto, P. J., and Vieira, A. C. 2009. Multidimensional analysis of fishery production systems in the state of Pernambuco, Brazil. Journal of Applied Ichthyology, 25: 256–268. Blackwell Publishing Ltd. http://dx.doi.org/10.1111/j.1439-0426.2009.01264.x.

Lessa, R. P. T., Nóbrega, M. F., and Junior, J. L. B. 2004. Dinâmica de Populações e Avaliação de Estoques dos Recursos Pesqueiros da Região Nordeste - Revizee SCORE NE. REVIZEE Relatório, 19: 1–15.

Lira, A. S., Viana, A. P., Eduardo, L. N., Fredóu, F. L., and Frédou, T. 2019. Population structure, size at first sexual maturity, and feeding ecology of *Conodon nobilis* (Actinopterygii: Perciformes: Haemulidae) from the coasts of Pernambuco, north-eastern Brazil. Acta Ichthyologica et Piscatoria, 49: 389–398.

Lira, A. S., Lucena-Frédou, F., and Le Loc'h, F. 2021. How the fishing effort control and environmental changes affect the sustainability of a tropical shrimp small scale fishery. Fisheries Research, 235.

Lira, L., Mesquita, B., Souza, M. M. C., Leite, C. A., Leite, Ana, Paula de Almeida Farias, A. M., and Galvão, C. 2010. Diagnóstico socioeconômico da pesca artesanal do litoral de Pernambuco. Instituto Oceanário de Pernambuco, Recife. 191pp.

Lopes, D. F. C., Peixoto, S. R. M., Frédou, F. L., and da Silva, E. F. B. 2014. Population biology of seabob-shrimp *Xiphopenaeus kroyeri* (heller, 1862) captured on the south coast of pernambuco state, Northeastern Brazil. Brazilian Journal of Oceanography, 62: 331–340.

Lucena-Frédou, F., Kell, L., Frédou, T., Gaertner, D., Potier, M., Bach, P., Travassos, P. *et al.* 2017. Vulnerability of teleosts caught by the pelagic tuna longline fleets in South Atlantic and Western Indian Oceans. Deep-Sea Research Part II: Topical Studies in Oceanography, 140: 230–241. Elsevier. http://dx.doi.org/10.1016/j.dsr2.2016.10.008.

Lucena Frédou, F., Frédou, T., Gaertner, D., Kell, L., Potier, M., Bach, P., Travassos, P. *et al.* 2016. Life history traits and fishery patterns of teleosts caught by the tuna longline fishery in the South Atlantic and Indian Oceans. Fisheries Research, 179: 308–321. Elsevier B.V. http://dx.doi.org/10.1016/j.fishres.2016.03.013.

Martínez-Candelas, I. A., Pérez-Jiménez, J. C., Espinoza-Tenorio, A., McClenachan, L., and Méndez-Loeza, I. 2020. Use of historical data to assess changes in the vulnerability of sharks. Fisheries Research, 226: 105526. Elsevier. https://doi.org/10.1016/j.fishres.2020.105526.

Phillips, McCully, R., S., Scott, F., and Ellis, J. R. 2015. Having confidence in productivity susceptibility analyses: A method for underpinning scientific advice on skate stocks? Fisheries Research, 171: 87–100. Elsevier B.V. http://dx.doi.org/10.1016/j.fishres.2015.01.005.

MPA. 2011. Boletim Estatístico da Pesca e Aquicultura (2011). Brasília/DF. 1–60pp. http://www.icmbio.gov.br/cepsul/images/stories/biblioteca/download/estatistica/est_2011_bol__bra.pdf%0Ahttp://www.mma.gov.br/estruturas/253/_publicacao/253_publicacao02022012041757.pdf.

Nakamura, J., and Hazin, F. 2020. Assessing the Brazilian federal fisheries law and policy in light of the Voluntary Guidelines for Securing Sustainable Small-scale fisheries. Marine Policy, 113.

Osio, G. C., Orio, A., and Millar, C. P. 2015. Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. Fisheries Research, 171: 110–121. Elsevier B.V. http://dx.doi.org/10.1016/j.fishres.2015.02.005.

Patrick, W. S., Spencer, P., Ormseth, O., Cope, J., Field, J., Kobayashi, D. R., Gedamke, T. *et al.* 2009. Use of productivity and susceptibility indices to determine the vulnerability of a stock: with example applications to six US fisheries. NOAA Tech. Memo, 90. ftp://ftp.pcouncil.org/pub/Briefing Books/BB_CDs/BB_CD_0609/0609/E4a_ATT1_0609.pdf.

Patrick, W. S., Spencer, P., Link, J., Cope, J., Field, J., Kobayashi, D., Lawson, P. *et al.* 2010. Using productivity and susceptibility indices to assess the vulnerability of united states fish stocks to overfishing. Fishery Bulletin, 108: 305–322.

Pinheiro, P., Broadhurst, M. K., Hazin, F. H. V., Bezerra, T., and Hamilton, S. 2006. Reproduction in *Bagre marinus* (Ariidae) off Pernambuco, northeastern Brazil. Journal of Applied Ichthyology, 22: 189–192.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org.

Santos, M. D. C. F. 2010. Ordenamento Da Pesca De Camarões No Nordeste Do Brasil. Boletim Técnico-Científico do CEPENE, 18: 91–98.

Sethi, S. A. 2010. Risk management for fisheries. Fish and Fisheries, 11: 341–365.

Silva, E. F., Viana, A., Nolé, L., Soares, R., Peixoto, S., Frédou, F. L., and Calazans, N. 2015. Population dynamics of the pink shrimp *Farfantepenaeus subtilis* (Pérez-Farfante, 1967) in northeastern Brazil. Journal of Crustacean Biology, 35: 132–139. http://booksandjournals.brillonline.com/content/journals/10.1163/1937240x-00002325.

Silva, E. F., Calazans, N., Nolé, L., Soares, R., Frédou, F. L., and Peixoto, S. 2018. Population dynamics of the white shrimp Litopenaeus schmitti (Burkenroad, 1936) on the southern coast of Pernambuco, north-eastern Brazil. Journal of the Marine Biological Association of the United Kingdom, 1–7.

Silva Júnior, C. A., Viana, A. P., Frédou, F. L., and Frédou, T. 2015. Aspects of the reproductive biology and characterization of Sciaenidae captured as bycatch in the prawn trawling in the northeastern Brazil. Acta Scientiarum. Biological Sciences, 37: 1. http://periodicos.uem.br/ojs/index.php/ActaSciBiolSci/article/view/24962.

Silva Júnior, C. A., Lira, A. S., Eduardo, L. N., Viana, A. P., Lucena-Frédou, F., and Frédou, T. 2019. Ichthyofauna bycatch of the artisanal fishery of Penaeid shrimps in Pernambuco, Northeastern Brazil. Boletim do Instituto de Pesca, 45: 1–10.

Simpfendorfer, C. A., Heupel, M. R., White, W. T., and Dulvy, N. K. 2011. The importance of research and public opinion to conservation management of sharks and rays: A synthesis. Marine and Freshwater Research, 62: 518–527.

Stobutzki, I., Miller, M., and Brewer, D. 2001. Sustainability of fishery bycatch: A process for assessing highly diverse and numerous bycatch. Environmental Conservation, 28: 167–181.

Stobutzki, I. C., Miller, M. J., Heales, D. S., and Brewer, D. T. 2002. Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery. Fishery Bulletin, 100: 800–821.

Tischer, M., and Santos, M. C. F. 2003. Composição e diversidade da ictiofauna acompanhante de peneídeos no litoral sul de Pernambuco. Arquivos de Ciência do Mar, 36: 105–118. http://www.labomar.ufc.br/images/stories/arquivos/ArqCienMar/V36_2003/acm_2003_36_16.pdf.

Verba, J. T., Pennino, M. G., Coll, M., and Lopes, P. F. M. 2020. Assessing drivers of tropical and subtropical marine fish collapses of Brazilian Exclusive Economic Zone. Science of the Total Environment, 702: 134940. Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2019.134940.

Visintin, M. R., and Perez, J. A. A. 2016. Vulnerabilidade de espécies capturadas pela pesca de emalhe-de-fundono sudeste-sul do brasil: Produtividade-suscetibilidade (PSA). Boletim do Instituto de Pesca, 42: 119–133.

Watson, R. A., and Tidd, A. 2018. Mapping nearly a century and a half of global marine fishing: 1869–2015. Marine Policy, 93: 171–177. Elsevier Ltd. https://doi.org/10.1016/j.marpol.2018.04.023.

Yonvitner, Y., LIoret, J., Boer, M., Kurnia, R., Akmal, S. G., Yuliana, E., Yani, D. E. *et al.* 2020. Vulnerability of marine resources to small-scale fishing in a tropical area: The example of Sunda Strait in Indonesia. Fisheries Management and Ecology, 27: 472–480.

Zeller, D., Cashion, T., Palomares, M., and Pauly, D. 2017. Global marine fisheries discards: A synthesis of reconstructed data. Fish and Fisheries, 19: 1–10.

Zhou, S., Yin, S., Thorson, J. T., Smith, A. D. M., and Fuller, M. 2012. Linking fishing mortality reference points to life history traits: An empirical study. Canadian Journal of Fisheries and Aquatic Sciences, 69: 1292–1301.

Zhou, S., Hobday, A. J., Dichmont, C. M., and Smith, A. D. M. 2016. Ecological risk assessments for the effects of fishing: A comparison and validation of PSA and SAFE. Fisheries Research, 183: 518–529. Elsevier B.V. http://dx.doi.org/10.1016/j.fishres.2016.07.015.

Handling Editor: Shijie Zhou