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Vulnerability of teleosts caught by the pelagic tuna longline fleets in South Atlantic and Western Indian Oceans



Flávia Lucena-Frédou^{a,b,*}, Laurie Kell^c, Thierry Frédou^{a,b}, Daniel Gaertner^b, Michel Potier^b, Pascal Bach^b, Paulo Travassos^a, Fábio Hazin^a, Frédéric Ménard^d

^a Universidade Federal Rural de Pernambuco (UFRPE), Departamento de Pesca e Aquicultura, Av. Dom Manuel s/n, Recife, Pernambuco 52171-900, Brazil

^b Institut de Recherche pour le Développement (IRD), UMR MARBEC (IRD, IFREMER, Univ. Montpellier, CNRS), CS 30171, 34203 Sète Cedex, France

^c International Commission for the Conservation of Atlantic Tunas (ICCAT), Corazón de María, 28002 Madrid, Spain

^d IRD, Mediterranean Institute of Oceanography (MIO), Aix-Marseille Université/CNRS/IRD/Université de Toulon, 13288 Marseille, France

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ABSTRACT

Productivity and Susceptibility Analysis (PSA) is a methodology for evaluating the vulnerability of a stock based on its biological productivity and susceptibility to fishing. In this study, we evaluated the vulnerability of 60 stocks of tuna, billfishes and other teleosts caught by the tuna longline fleets operating in the South Atlantic and Indian Ocean using a semi-quantitative PSA. We (a) evaluated the vulnerability of the species in the study areas; (b) compared the vulnerability of target and non-target species and oceans; (c) analyzed the sensitivity of data entry; and (d) compared the results of the PSA to other fully quantitative assessment methods. Istiophoridae exhibited the highest scores for vulnerability. The top 10 species at risk were: Atlantic *Istiophorus albicans*; Indian Ocean *Istiompax indica*; Atlantic *Makaira nigricans* and *Thunnus alalunga*; Indian Ocean *Xiphias gladius*; Atlantic *T. albacares*, *Gempylus serpens*, *Ranzania laevis* and *X. gladius*; and Indian Ocean *T. alalunga*. All species considered at high risk were targeted or were commercialized bycatch, except for the Atlantic *G. serpens* and *R. laevis* which were discarded, and may be considered as a false positive. Those species and others at high risk should be prioritized for further assessment and/or data collection. Most species at moderate risk were bycatch species kept for sale. Conversely, species classified at low risk were mostly discarded. Overall, species at high risk were overfished and/or subjected to overfishing. Moreover, all species considered to be within extinction risk (Critically Endangered, Endangered and Vulnerable) were in the high-risk category. The good concordance between approaches corroborates the results of our analysis. PSA is not a replacement for traditional stock assessments, where a stock is assessed at regular intervals to provide management advice. It is of importance, however, where there is uncertainty about catches and life history parameters, since it can identify species at risk, and where management action and data collection is required, e.g. for many species at high and most at moderate risk in the South Atlantic and Indian oceans.

1. Introduction

Several frameworks and approaches have been developed to help manage the risks posed to species bycaught in a range of fisheries (Astles et al., 2006; Arrizabalaga et al., 2011; Brown et al., 2015). One

(Hobday et al., 2011; Cortés et al., 2015).

PSA is a semi-quantitative risk analysis which has been used by several management and advisory bodies for a range of taxa: e.g. the Australian Fisheries Management Authority (Hobday et al., 2007; Smith et al., 2007), the Lenfest Working Group (Rosenberg et al., 2007) and for assessing the vulnerability of US fisheries (Pattin

of Atlantic Tunas (ICCAT) has conducted a PSA for sharks, which subsequently resulted in the implementation of a range of management measures for their conservation (Cortés et al., 2015).

Tuna and tuna-like species are important social and economic resources worldwide, both for industrial fleets operating offshore in areas beyond national jurisdiction and for artisanal fleets operating in coastal waters (Arrizabalaga et al., 2011). The tuna longline fishery is one of the main large-scale fishing activities in the world. Due to their highly migratory nature and widespread distribution, five Regional Fisheries Management Organizations (RFMOs) are in charge of the management and conservation of tunas and billfishes: ICCAT (Atlantic Ocean), the Indian Ocean Tuna Commission (IOTC, Indian Ocean), the Inter-American Tropical Tuna Commission (IATTC, Eastern Pacific Ocean), the Western and Central Pacific Fisheries Commission (WCPFC, Western Pacific Ocean), and the Commission for the Conservation of Southern Bluefin Tuna (CCSBT, Southern Ocean).

There is a growing concern about the status of several pelagic fish stocks targeted or caught incidentally in the tuna longline fishery, especially for Scombrids and billfishes, which may be heavily overfished or are recovering from being overfished (Collette et al., 2011). The assessment and management of bycatch and byproduct caught by the tuna longline fisheries is hampered because species-specific catch and biological data are limited or are aggregated with other species, making it difficult to run conventional stock assessment models. Even for the main target tunas (e.g. *Thunnus thynnus*, *T. alalunga*, *T. obesus*, *T. albacares* and *T. maccoyii*) and swordfish (*Xiphias gladius*), where relatively good data exist, stock assessments rely on fisheries dependent data. The PSA approach therefore is useful as an exploratory or triage tool for fisheries managers helping to identify species, populations, stocks or regions where the risk of negative interaction with the fishery activity is greatest, being also used in determining priorities for data collection, stock assessment and management.

In the current study, the relative vulnerability of tuna, billfishes and other teleost species caught in pelagic longlines in the South Atlantic and Indian Oceans is assessed by applying a semi-quantitative PSA. Specifically, (a) the vulnerability of the species in the study areas was evaluated; (b) the vulnerability of target and non-target species by ocean was compared; (c) the sensitivity of the results to data quality was analyzed; and (d) the results of the PSA were compared to other more quantitative assessments methods.

2. Material and methods

2.1. Catch composition of the tuna longline fishery in South Atlantic and Indian Oceans

A list of species of the infraclass Teleostei caught by the tuna longline fishery in the South Atlantic and the Indian Ocean was compiled from a variety of sources. The initial list was based on official statistics from ICCAT and IOTC. The list was then updated using published documents (Marín et al., 1998; Bach et al., 2008, 2009; Hargrave et al., 2010; Pardo et al., 2011), the national Brazilian

low susceptibility score were considered to be the least vulnerable. Each attribute of *P* (productivity) and *S* (susceptibility) was scored on a three-point scale, indicating low (1), medium (2), and high (3) values. For productivity, 1 indicates a relative low productivity and high risk and 3 indicates a relative high productivity and low risk. Conversely, for the susceptibility attributes, 3 indicates relatively high susceptibility and high risk and 1 relatively low susceptibility and low risk. Where attributes were missing, a score was not assigned and were not used in the computation of the final *P* or *S* scores. Each attribute score was then weighted and the overall species productivity and susceptibility scores were a weighted mean of the attribute scores.

The two-dimensional nature of the PSA leads directly to the calculation of an overall vulnerability score (*v*) for a stock, defined as the Euclidean distance from the origin of a PSA scatter plot:

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

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

Stocks were then assigned to a risk category (high, moderate and low) by ranking the vulnerability scores using a quantile method. The scores can be depicted graphically in a scatter plot, with *P* on the x-axis and *S* on the y-axis. The x-axis is reversed (i.e. it starts at 3 and ends at 1) so that the region close to the origin (which was at 3, 1) corresponded to the less vulnerable stocks, i.e. those with high-productivity and low-susceptibility stocks, while the most vulnerable stocks are found furthest from the origin.

Vulnerability was assessed by ocean, family and considering the fate of the catch. The fate of the catch of each species was assigned into four categories (Bach et al., 2008; Lucena-Frédou et al., 2016), namely: target species (T), bycatch species kept for consumption on board (BY/KA), bycatch species kept for sale (BY/KC), bycatch and discarded species (BY/D). The fate category was assigned based on literature, market data and expert advice.

2.2.1. Productivity attributes

Seven life-history traits were selected for productivity attributes (Table 1), as follows:

- (1) Maximum size (L_{max} , cm): maximum reported fork length obtained from the literature, the RFMOs (ICCAT, IOTC and CCSBT) and national Brazilian and French databases. When fork length was missing, conversion factors from the literature or national observer program databases were used.
- (2) Fecundity (Fec, in millions of oocytes): mid-point of the reported range of number of eggs per individual for a given spawning event or period. Data were obtained from literature.
- (3) *r*: the intrinsic rate of population growth or maximum population growth that would occur in the absence of fishing at a small size, calculated from life history parameters for each stock using the approach of Fortuna et al. (2014) (see details in SOM 1).

Data on the following attributes were obtained from the literature and, when values were given by sex, these were averaged.

Table 2

Susceptibility attributes and rankings used to determine the vulnerability of a stock caught by tuna longline fishery in South Atlantic and Indian Oceans.

Attribute	Ranking		
	Low (1)	Moderate (2)	High (3)
Availability	< 25% of stock occurs in the area fished	Between 25% and 50% of the stock occurs in the area fished	> 50% of stock occurs in the area fished
Vertical overlap	< 25% of stock occurs in the depths fished	Between 25% and 50% of the stock occurs in the depths fished	> 50% of stock occurs in the depths fished
Mort	< 33	33–67%	> 67
% > L ₅₀ (Adults)	> 95%	50–95%	< 50%
Management strategy	Currently subject to a number of conservation and management measures	No specific regulation are in effect, but some indirect measures are in course	No regulation are in effect
Z/k	< 0.5	0.5–1.0	> 1

- (4) von Bertalanffy growth coefficient (k , cm.k^{-1}): measures how rapidly a fish reaches its maximum size.
- (5) Size at first maturity (L_{50} , cm): length at which 50% of the individuals attain sexual maturity for the first time.
- (6) Maximum age (T_{max} , years): maximum reported age.
- (7) L_{50}/L_{max} : a ratio that describes the relative investment into somatic and reproductive growth.

Many studies have shown that life history parameters are correlated (e.g. Roff, 1984; Jensen, 1996; Reynolds et al., 2001). Therefore, when data were missing, we used empirical relationships between life history parameters to estimate biological attributes. For instance, missing L_{50} and k were estimated from linear regressions against maximum size (SOM 2).

The boundaries between the three risk categories (low, medium, high) were established using the quantiles of the distribution of the vulnerability scores for the 60 stocks (Table 1).

2.2.2. Susceptibility attributes

Six attributes for susceptibility were considered (Table 2):

- (1) Availability or horizontal overlap: greater overlap implies greater susceptibility, since some degree of geographical overlap is necessary for a fishery to impact a stock (Patrick et al., 2010). Availability was evaluated qualitatively as the proportion of the spatial distribution of a given stock that overlaps with the fishery. Species distribution were obtained from the IUCN (*International Union for Conservation of Nature*) or FISHBASE (Froese and Pauly, 2007). Effort distribution, from year 2000 to 2011, was obtained for the South Atlantic Ocean from ICCAT and, for the

Brazilian (2005 to 2011) and the French national databases (2001 to 2011). For the southern bluefin tuna (*T. maccoyii*), the CCSBT database was used (2000 to 2011). Z/k is a life history invariant and a natural parameter in yield-per-recruit analysis (Beverton and Holt, 1993; Gallucci et al., 1995). Z/k is associated with different patterns of survivorship, e.g. how the number of survivors decreases at size (and age), and a high value of Z/k for a stock indicates reduced survivorship and hence higher susceptibility. Species with a ratio larger than 1 are considered the most susceptible (Pauly, 1984).

- (4) Percentage of adults in catches ($\% > L_{50}$): the percentage of individuals larger than the length at first maturity (L_{50}), obtained from the length distributions. The score threshold of this attribute was defined using the quantiles of the distribution.
- (5) Post-capture mortality (Mort): obtained from the literature (Ward and Curran, 2004; Poisson et al., 2010; Pacheco et al., 2011). The thresholds of this attribute were based on Patrick et al. (2010).
- (6) Management strategy: the management measures for each species were obtained from the reports of SCRS (Standing Committee on Research and Statistics, ICCAT, 2015a), for the South Atlantic, from the IOTC Scientific Committee, for the Indian Ocean (IOTC, 2015) and from CCSBT, specifically for the Southern Bluefin Tuna (see SOM 3 for a list of regulations in operation). Stocks subjected to a number of conservation and management measures were assumed to be less susceptible to be overfished and/or subjected to overfishing, while stocks with no effective regulation were considered more susceptible.

2.3. Attributing weights

Weights were adjusted within a scale from 1 to 3 (default weight of 2). Lucena Frédou et al. (2016) showed that differences between species and oceans were mainly explained by L_{max} and k . These two attributes, plus r (a key to resilience; Musick et al., 2001) were thus given weight 3. A default weight of 2 was used for all other susceptibility attributes except for Management Strategy for which a weight of 1 was assigned, given that, although there are often a large amount of regulations in force (see SOM 3), it is difficult to guarantee compliance with these by each flag state.

2.4. Measuring uncertainties

Data-poor stocks may receive inflated vulnerability scores due to a lack of information (Fujita et al., 2014). Therefore, a data-quality index, to identify cases with limited data, was adapted from Patrick et al. (2010). This was obtained for the productivity and susceptibility scores as a weighted average (using the same weights as applied to the productivity and susceptibility scores), allowing a mean risk score for vulnerability to be obtained (Ormseth and Spencer, 2011). The index was based on a comparison of the estimated vulnerability with the best data (or

Table 3

Tiers of data quality used when evaluating the productivity and susceptibility of the teleosts caught by tuna long line fisheries in South Atlantic and Indian Oceans.

Data quality tier	Description	Example
Best Data (1)	Data collected from the study stock and area, recent literature and appropriate stock assessment methods	Information used by RFMOs for systematic stock assessment
Good/adequate data (2)	Data collected from the study stock and area. Relatively old information, reasonably appropriate stock assessment	Short time series and/or more “robust” stock assessment (ex: using equilibrium methods and/or pseudocoast)
Acceptable data (3)	Parameters obtained by empirical relationships or on studies of the same species in adjacent area.	Parameters estimated from linear regressions or North Atlantic Ocean parameter considered for a South Atlantic species
Limited data (4)	Expert opinion or data of no adjacent area	General data not referenced
No data (5)	The person should give a score 5 and do not provide a score of productivity and susceptibility	

2.5. Statistical test

The differences between productivity, susceptibility and vulnerability scores by ocean, families and fate of the catch were assessed using Kruskal-Wallis rank sum tests and post-hoc multiple comparison tests. These tests were also used to test for differences in the data quality index. Statistical analyses were performed using the R statistical software v.3.0.2 (R Development Core Team, 2014).

2.6. Integrating data analysis

To gain a good understanding of the relative risks faced by teleosts species caught by the tuna longline fisheries, the results of the PSA were compared with two others approaches: (a) 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 (b) stock assessment conducted by the RFMO's (ICCAT, IOTC and CCSBT).

The IUCN Red List categories considered in this study comprised 6 levels of extinction risk: Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC) and Data Deficient (DD). The classification criteria, application guidelines and IUCN Red List methodology on how to apply the Criteria are detailed in IUCN (2014). For the South Atlantic Ocean, the categories 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, 2016). No regional assessment was available for the Indian Ocean, and so the Global Assessment categories were adopted in that case. IUCN assessments were carried out from 2009 to 2014 (see SOM 4 for assessment

species were present in both oceans (Table 4).

A wide range of productivity (1.00–2.87) and susceptibility (1.40–3.00) scores were seen (Table 4, Fig. 1). There was a significant ($P < 0.05$) difference between productivity scores by family. The Istiophoridae family exhibited the lowest scores compared to species of the family Bramidae (Table 5a, Fig. 2). *Scomberomorus regalis* (Scombridae, Atlantic) were the most productive, and *Nesiarchus nasutus* (Gempylidae, Atlantic) the less susceptible (Table 4, Fig. 1). No significant differences in productivity and susceptibility scores were observed between oceans ($P < 0.05$) (Table 5b).

A large range in vulnerability scores was also seen, ranging from 2.64 (Atlantic Sailfish *Istiophorus albicans*) to 0.67 (*N. nasutus* from the South Atlantic Ocean) (Table 4, Fig. 1). Again, the differences in vulnerability scores between oceans were not significant, but those between families were. Species of the Istiophoridae showed the highest vulnerability scores when compared to species of the family Bramidae ($P < 0.05$) (Table 5a, Fig. 2).

Significant differences were observed for productivity and vulnerability scores between the catch fate categories ($P < 0.05$) (Table 5c). Target species (T) showed lower scores of productivity than all the other categories and were also more vulnerable than non-commercialized species (BY/D and BY/KA) ($P < 0.05$) (Fig. 3, Table 5c).

The top 10 species at risk were Atlantic *Istiophorus albicans*; Indian Ocean *Istiompax indica*; Atlantic *Makaira nigricans* and *Thunnus alalunga*; Indian Ocean *X. gladius*; Atlantic *T. albacares*, *Gempylus serpens*, *Ranzania laevis* and *X. gladius* and Indian Ocean *T. alalunga*. Species considered at high risk (i.e. the 21 first ranked species) included all billfishes (Istiophoridae and Xiphiidae - except for Atlantic *T. pfluegeri* and Indian Ocean *K. audax*, which had a moderate risk) and most targeted species (except Atlantic *T. obesus* and Indian Ocean *T. albacares*, which were at moderate risk). Bycatch Scombridae species, such as *S. brasiliensis*, Atlantic *Katsuwonus pelamis* and the Indian Ocean *Acanthocybium solandri*, were in the high-risk group. All species considered at high risk were target or commercialized bycatch (BY/KC), except Atlantic *G. serpens* and *R. laevis*, which are discarded (BY/D) (Table 4).

Species from 8 different families occurred in the moderate risk group (rank 22 to 40; vulnerability score from 1.89 to 1.51) (Table 4). Most species at moderate risk are commercialized bycatch (BY/KC). Most discarded species (BY/D) were classified as being at low risk. Species classified at low risk (vulnerability scores varying from 1.49 to 0.67) belonged to several families (Table 4, Fig. 3). No target species were assessed as being at low risk.

The most common species, in both oceans, were classified as being in the same risk category. However, the target species *T. albacares* was considered as being at high risk in the Atlantic whereas it was categorized at only moderate risk in the Indian Ocean. The opposite was observed for the targeted species *T. obesus*, which was at high risk in the Indian Ocean and at moderate risk in the Atlantic. *K. pelamis* and *R. laevis* were at high risk in the Atlantic and low risk in the Indian Ocean (Table 4).

Table 4

Productivity, susceptibility and vulnerability scores, rank and risk of the teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans. Data quality index for productivity, susceptibility and vulnerability scores. Data-quality scores: poor > 3.5; moderate 2.0–3.5 and good < 2.0. T - target species, BY/KA - bycatch species kept for consumption on board, BY/KC - bycatch species kept for sale, BY/D - bycatch and discarded species. Alepsauridae (ALE), Bramidae (BRA), Carangidae (CAR), Coryphaenidae (COR), Gempylidae (GEM), Isthophoridae (IST), Lampridae (LAM), Molidae (MOL), Scombridae (SCO), Sphyrnidae (SPH), Trachipteridae (TRA), Xiphidae (XIP). South Atlantic Ocean (ATL), Indian Ocean (IND). Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD). Stocks considered overfished (SByear/SB_{MSY} < 1) and subject to overfishing (Fyear/F_{MSY} > 1) – red; Stocks considered overfished (SByear/SB_{MSY} < 1) but not subject to overfishing (Fyear/F_{MSY} < 1) – yellow; Stocks not overfished (SByear/SB_{MSY} > 1) and subject to overfishing (Fyear/F_{MSY} > 1) – orange and Stocks not overfished (SByear/SB_{MSY} > 1) and not subject to overfishing (Fyear/F_{MSY} < 1); grey – see explanation on Section 3.3 of the results. ? – uncertainty in the determination of the status of the stock.

Ocean	Species	Code	Family	Productivity	Susceptibility	Vulnerability		Fate of the catch	Risk	Data Quality				IUCN	Stock Asses.
						Score	Rank			QualProd	QualSus	Mean Qual	Data Qual.		
ATL	Istiophorus albigens	SAI	IST	1.000	2.727	2.643	1	BY/KC	High	1.35	1.00	1.18	Good	LC	?
IND	Istiompax indica	BLM	IST	1.000	2.545	2.528	2	BY/KC	High	1.82	1.00	1.41	Good	DD	
ATL	Makaira nigricans	BUM	IST	1.235	2.636	2.407	3	BY/KC	High	1.71	1.00	1.35	Good	EN	
ATL	Thunnus alalunga	ALB	SCO	1.294	2.636	2.364	4	T	High	1.35	1.00	1.18	Good	LC	
IND	Xiphias gladius	SWO	XIP	1.353	2.636	2.322	5	T	High	1.59	1.00	1.29	Good	LC	
ATL	Thunnus albacares	YFT	SCO	1.412	2.636	2.280	6	T	High	1.35	1.00	1.18	Good	LC	
ATL	Gempylus serpens	GES	GEM	1.667	2.714	2.172	7	BY/D	High	2.65	3.00	2.82	Moderate	LC	
ATL	Ranzania laevis	RZV	MOL	2.154	3.000	2.172	8	BY/D	High	3.12	3.18	3.15	Moderate	LC	
ATL	Xiphias gladius	SWO	XIP	1.588	2.636	2.161	9	T	High	1.35	1.00	1.18	Good	NT	?
IND	Thunnus alalunga	ALB	SCO	1.647	2.636	2.123	10	T	High	1.35	1.00	1.18	Good	NT	
IND	Istiophorus platypterus	SFA	IST	1.588	2.545	2.093	11	BY/KC	High	2.41	1.00	1.71	Good	LC	?
IND	Thunnus maccoyii	SBF	SCO	1.235	2.091	2.075	12	T	High	1.35	1.00	1.18	Good	CR	
IND	Thunnus obesus	BET	SCO	1.529	2.455	2.068	13	T	High	1.35	1.00	1.18	Good	VU	
ATL	Coryphaena equiselis	CFW	COR	2.533	3.000	2.054	14	BY/KC	High	2.88	3.18	3.03	Moderate	LC	
IND	Makaira nigricans	BUM	IST	1.471	2.364	2.049	15	BY/KC	High	2.41	1.00	1.71	Good	VU	
ATL	Tetrapturus georgii	SPG	IST	1.769	2.636	2.048	16	BY/KC	High	3.12	1.00	2.06	Moderate	DD	
ATL	Katsuwonus pelamis	SKJ	SCO	1.706	2.571	2.036	17	BY/KC	High	1.35	2.45	1.90	Good	LC	
ATL	Kajikia albidus	WHM	IST	1.824	2.636	2.015	18	BY/KC	High	1.35	1.00	1.18	Good	VU	?
ATL	Scomberomorus brasiliensis	BRS	SCO	1.824	2.600	1.986	19	BY/KC	High	1.35	3.18	2.27	Moderate	LC	
IND	Tetrapturus angustirostris	SSP	IST	1.769	2.556	1.984	20	BY/KC	High	2.88	2.09	2.49	Moderate	DD	
IND	Acanthocybium solandri	WAH	SCO	2.059	2.714	1.956	21	BY/KC	High	2.06	2.45	2.26	Moderate	LC	
ATL	Scomberomorus cavalla	KGM	SCO	1.529	2.200	1.898	22	BY/KC	Moderate	1.35	3.18	2.27	Moderate	LC	
IND	Kajikia audax	MLS	IST	1.941	2.545	1.873	23	BY/KC	Moderate	2.41	1.00	1.71	Good	NT	
ATL	Acanthocybium solandri	WAH	SCO	2.118	2.636	1.859	24	BY/KC	Moderate	1.94	1.00	1.47	Good	LC	
IND	Sphyrna barracuda	GBA	SPH	1.706	2.333	1.858	25	BY/KC	Moderate	2.06	2.64	2.35	Moderate	-	
ATL	Mola mola	MOX	MOL	1.538	2.143	1.855	26	BY/D	Moderate	3.47	3.00	3.24	Moderate	LC	
IND	Trachipterus ishikawae	TRI	TRA	1.538	2.143	1.855	26	BY/D	Moderate	3.12	3.00	3.06	Moderate	-	
ATL	Thunnus obesus	BET	SCO	1.706	2.273	1.815	28	T	Moderate	1.35	1.00	1.18	Good	NT	
ATL	Tetrapturus pfluegeri	SPF	IST	2.067	2.556	1.814	29	BY/KC	Moderate	1.82	1.73	1.78	Good	LC	
IND	Thunnus albacares	YFT	SCO	1.941	2.455	1.799	30	T	Moderate	1.35	1.00	1.18	Good	LC	
IND	Lampris guttatus	LAG	LAM	2.133	2.556	1.781	31	BY/KC	Moderate	3.00	2.64	2.82	Moderate	LC	
ATL	Sphyrna barracuda	GBA	SPH	2.000	2.429	1.744	32	BY/KA	Moderate	2.88	3.00	2.94	Moderate	LC	
ATL	Euthynnus alletteratus	LTA	SCO	2.412	2.600	1.705	33	BY/KC	Moderate	2.41	3.18	2.80	Moderate	LC	
IND	Gempylus serpens	GES	GEM	1.867	2.273	1.704	34	BY/D	Moderate	3.00	1.91	2.45	Moderate	-	
ATL	Auxis rochei	BLT	SCO	2.471	2.600	1.685	35	BY/KC	Moderate	3.00	3.18	3.09	Moderate	DD	
ATL	Auxis thazard	FRI	SCO	2.533	2.600	1.667	36	BY/KC	Moderate	3.24	3.18	3.21	Moderate	LC	
IND	Ruvettus pretiosus	OIL	GEM	1.800	2.091	1.622	37	BY/KC	Moderate	3.00	1.36	2.18	Moderate	LC	
IND	Alepisaurus ferox	ALX	ALE	2.154	2.273	1.528	38	BY/D	Moderate	2.65	1.00	1.82	Good	LC	
ATL	Alepisaurus ferox	ALX	ALE	2.000	2.143	1.519	39	BY/D	Moderate	3.12	2.82	2.97	Moderate	LC	
IND	Gasterochisma melampus	BUK	SCO	2.000	2.143	1.519	39	BY/D	Moderate	3.12	3.00	3.06	Moderate	LC	
ATL	Ruvettus pretiosus	OIL	GEM	1.800	1.889	1.493	41	BY/D	Low	1.35	2.27	1.81	Good	LC	
IND	Elagatis bipinnulata	RRU	CAR	2.692	2.429	1.461	42	BY/KC	Low	3.12	3.00	3.06	Moderate	LC	
IND	Brama brama	POA	BRA	2.692	2.429	1.461	42	BY/KA	Low	3.12	2.82	2.97	Moderate	LC	
IND	Ranzania laevis	RZV	MOL	2.692	2.429	1.461	42	BY/D	Low	3.12	2.82	2.97	Moderate	LC	
ATL	Elagatis bipinnulata	RRU	CAR	2.267	2.200	1.406	45	BY/KA	Low	2.18	3.18	2.68	Moderate	LC	
ATL	Sarda sarda	BOM	SCO	2.294	2.200	1.392	46	BY/KC	Low	1.82	3.18	2.50	Moderate	LC	
IND	Thyrssites atun	SNK	GEM	2.333	2.143	1.323	47	BY/D	Low	1.82	2.45	2.14	Moderate	-	
IND	Katsuwonus pelamis	SKJ	SCO	2.471	2.143	1.260	48	BY/KA	Low	1.35	2.45	1.90	Good	LC	
ATL	Lepidocybium flavobrunneum	LEC	GEM	2.538	2.143	1.233	49	BY/KC	Low	2.88	3.00	2.94	Moderate	LC	
ATL	Lampris guttatus	LAG	LAM	2.133	1.857	1.219	50	BY/KC	Low	2.88	2.82	2.85	Moderate	LC	
ATL	Coryphaena hippurus	DOL	COR	2.471	2.091	1.213	51	BY/KC	Low	1.59	1.00	1.29	Good	LC	
ATL	Scomberomorus regalis	CER	SCO	2.867	2.200	1.207	52	BY/KC	Low	2.88	3.18	3.03	Moderate	LC	
ATL	Thunnus atlanticus	BLF	SCO	2.529	2.111	1.207	53	BY/KC	Low	1.47	1.73	1.60	Good	LC	
ATL	Alepisaurus brevirostris	ALO	ALE	2.846	2.143	1.153	54	BY/D	Low	3.12	2.82	2.97	Moderate	LC	
IND	Coryphaena hippurus	DOL	COR	2.706	2.091	1.130	55	BY/KC	Low	1.71	1.55	1.63	Good	LC	

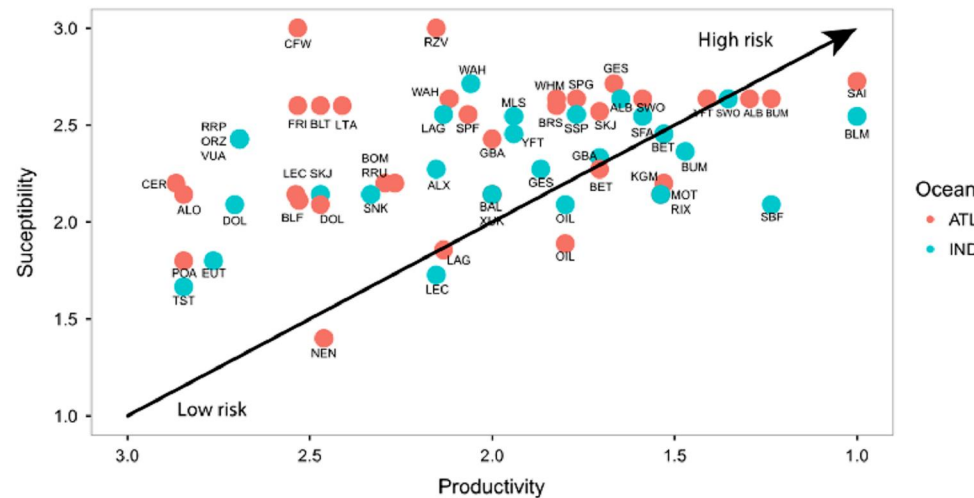


Fig. 1. Overall distribution of productivity and susceptibility plot for the teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans. Codes are in Table 4.

Table 5

Nonparametric post-hoc multiple comparison tests of the productivity, susceptibility and vulnerability scores of teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans by family (a); Ocean (b); and Fate of the catch (c). T=target species. BY/KA=bycatch species kept for consumption on board. BY/KC=bycatch species kept for sale. BY/D=bycatch and discarded species. Different letters indicate significant differences.

(a) Family	Productivity	Susceptibility	Vulnerability
Alepsauridae	2.33 ^{a,c}	2.18 ^a	1.40 ^{a,c}
Bramidae	2.79 ^{b,c}	1.96 ^a	0.98 ^{b,c}
Carangidae	2.47 ^{a,c}	2.31 ^a	1.43 ^{a,c}
Coryphaenidae	2.56 ^{a,c}	2.39 ^a	1.46 ^{a,c}
Gempylidae	2.08 ^{a,c}	2.04 ^a	1.41 ^{a,c}
Istiophoridae	1.56 ^a	2.57 ^a	2.14 ^a
Lampridae	2.13 ^{a,c}	2.20 ^a	1.49 ^{a,c}
Molidae	2.05 ^{a,c}	2.52 ^a	1.82 ^{a,c}
Scombridae	2.01 ^{a,c}	2.39 ^a	1.74 ^{a,c}
Sphyraenidae	1.85 ^{a,c}	2.38 ^a	1.80 ^{a,c}
Trachipteridae	1.53 ^{a,c}	2.14 ^a	1.85 ^{a,c}
Xiphiidae	1.47 ^{a,c}	2.63 ^a	2.24 ^{a,c}
Mean	2.05	2.26	1.60
(b) Ocean	Productivity	Susceptibility	Vulnerability
S. Atlantic	2.04 ^a	2.38 ^a	1.72 ^a
Indian	2.00 ^a	2.30 ^a	1.68 ^a
(c) Fate of the catch	Productivity	Susceptibility	Vulnerability
BY/D	2.12 ^b	2.14 ^a	1.48 ^b
BY/KA	2.51 ^b	2.13 ^a	1.25 ^b
BY/KC	2.02 ^b	2.44 ^a	1.78 ^{a,b}
T	1.52 ^a	2.49 ^a	2.11 ^a

4. Discussion

Ecosystem-based management (EBM) is widely considered to be a strategy for achieving sustainable delivery of marine ecosystem services (Francis et al., 2011). The application of the EBM framework to fisheries management, i.e. taking an Ecosystem Approach to Fisheries (EAF), is mandated in several nations around the world (Micheli et al., 2014). Ecological Risk Assessment (ERA), a hierarchical risk assessment framework, has been adopted by the Marine Stewardship Council and is one of the tools found in the FAO-EAF toolbox (Dunstan et al., 2016).

PSA, a semi-quantitative risk analysis procedure, has the ability to provide broad scientific advice to policy makers and stakeholders (Kwon et al., 2009). Even though this approach does not result in traditional fishery management reference points (Fujita et al., 2014), it does allow for the prioritization of monitoring, assessment and management for stocks and species that are at the greatest risk from fishing (Hobday et al., 2011). Under the Precautionary Approach (PA), undesirable outcomes should be anticipated and measures taken to reduce the probability of them occurring (Garcia, 1995). PSA is particularly useful in data poor situations, when catch or biological data are not comprehensive, often aggregated across species or are insufficient to run a quantitative stock assessment. The latter is the case for the tuna longline fishery in the South Atlantic and Indian Ocean.

A total of 33 and 27 species were recorded as the main teleost species caught by the tuna longline fisheries in the South Atlantic and Indian Ocean, respectively, although only four and five species respectively were considered as targets (T). Growing concerns over the impact of the tuna longline fishery on bycatch species (King and McFarlane, 2003) have therefore led RFMOs to develop holistic approaches to the assessment and management of all exploited species.

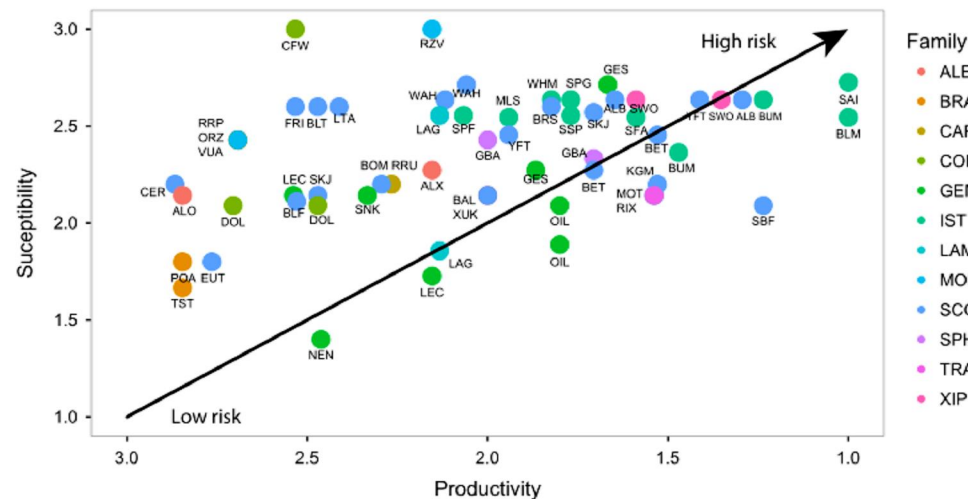


Fig. 2. Overall distribution of productivity and susceptibility plot by family of teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans. Codes are in Table 4.

These species have moderate to low productivity and high susceptibility, and so are vulnerable to potential negative impacts. For target species, this is perhaps not surprising as the objective of longline fisheries are to catch them, and hence encounterability and availability are high. Even if these species are well managed, they are likely to exhibit high rates of mortality, particularly for juveniles (see SOM 5). Those two latter attributes could be considered in future management scenarios, by using PSAs to re-score stocks under alternative management options (Phillips et al., 2015). This would help to identify the effects of alternatives strategies for reducing risk. For the North Atlantic Ocean, among the 10 species with the highest risk scores were coastal and pelagic sharks, non-ICCAT teleosts and two ICCAT species, *T. alalunga* and *T. obesus* (Arrizabalaga et al., 2011), species that were at high and moderate risk in our study, respectively. For the Pacific Ocean, *T. alalunga*, *T. obesus*, *T. albacares*, *K. pelamis*, and billfishes were considered at medium risk, while sharks were considered at high risk (Kwon et al., 2009).

Istiophoridae are inherently vulnerable due to their biological characteristics, coupled with moderate to high market values (Marín et al., 1998). They are also highly vulnerable in relation to encounterability and availability; being exposed to considerable mortality rates with important catches of juveniles. For Istiophoridae in the South Atlantic, mitigation measures are in place for *Makaira nigricans* and *Kajikia albidus* (see SOM 3). However, for the Indian Ocean, no species-specific conservation and management measures are currently

adopted for any of the billfishes.

Some stocks at high risk, such as the south Atlantic *Scomberomorus brasiliensis* and the Indian *Acanthocybium solandri*, and most species at moderate risk, were not assessed in recent years and there is an overall lack of regulation. The South Atlantic *S. brasiliensis* and *S. cavalla* stocks (high and moderate risk, respectively) were considered fully exploited using length-based methods with data collected up to 2000 (Lucena Frédou and Asano Filho, 2006; Lessa et al., 2009a, 2009b; Nóbrega and Lessa 2009). *A. solandri* was also considered at high risk in the Western and Central Pacific (Kwon et al., 2009). Coastal scombrids are important source of wealth and food security to local fishing communities, especially in the South Atlantic (Lessa et al., 2009a, 2009b; Nóbrega and Lessa, 2009; Isaac et al., 2012; Mourão et al., 2014). The small tunas group of ICCAT has therefore encouraged future studies and application of this approach for those species, and is considering an extension of this analysis to the North Atlantic (ICCAT, 2015b). Managers must also remain vigilant to species and stocks in the more intermediate rankings (Phillips et al., 2015), especially with regard to data requirements for future assessments. Most species at moderate risk are commercialized bycatch (BY/KC). Given its secondary nature from an economic point of view, these bycatch species are often ignored when management regulations are adopted (Lucena Frédou et al., 2016).

Different authors have adopted alternative definitions of productivity and or susceptibility, depending on the species characteristics and

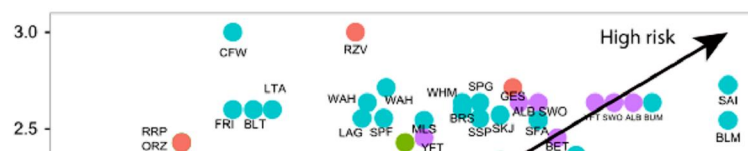


Table 6

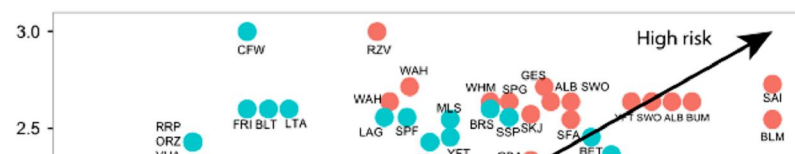
Nonparametric post-hoc multiple comparison tests of the data quality index (productivity, susceptibility and vulnerability) for teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans by family (a); Ocean (b) and Fate of the catch (c). T=target species. BY/KA=bycatch species kept for consumption on board. BY/KC=bycatch species kept for sale. BY/D=bycatch and discarded species. According to [Hobday et al. \(2007\)](#), data-quality scores were divided into three groupings: poor > 3.5; moderate 2.0–3.5; and good < 2.0. Different letters indicate significant differences.

a) Family	Productivity Data quality Index	Category	Susceptibility Data quality Index	Category	Vulnerability Data quality Index	Category
Alepsauridae	3.0 ^a	Moderate	2.2 ^a	Moderate	2.6 ^a	Moderate
Bramidae	3.1 ^a	Moderate	2.9 ^a	Moderate	3.0 ^a	Moderate
Carangidae	2.6 ^a	Moderate	3.1 ^a	Moderate	2.9 ^a	Moderate
Coryphaenidae	2.0 ^a	Moderate	1.9 ^a	Good	1.9 ^a	Good
Gempylidae	2.5 ^a	Moderate	2.3 ^a	Moderate	2.4 ^a	Moderate
Istiophoridae	2.1 ^a	Moderate	1.2 ^a	Good	1.6 ^a	Good
Lampridae	2.9 ^a	Moderate	2.7 ^a	Moderate	2.8 ^a	Moderate
Molidae	3.2 ^a	Moderate	3.0 ^a	Moderate	3.1 ^a	Moderate
Scombridae	1.8 ^a	Good	2.2 ^a	Moderate	1.9 ^a	Good
Sphyrnidae	2.5 ^a	Moderate	2.8 ^a	Moderate	2.6 ^a	Moderate
Trachipteridae	3.1 ^a	Moderate	3.0 ^a	Moderate	3.0 ^a	Moderate
Xiphiidae	1.5 ^a	Good	1.0 ^a	Good	1.2 ^a	Good
Mean	2.3	Moderate	2.3	Moderate	2.2	Moderate
b) Ocean	Productivity Data quality Index	Category	Susceptibility Data quality Index	Category	Vulnerability Data quality Index	Category
ATL	2.2 ^a	Moderate	2.3 ^a	Moderate	2.3 ^a	Moderate
IND	2.3 ^a	Moderate	1.9 ^b	Good	2.1 ^a	Moderate
c) Fate of the catch	Productivity Data quality Index	Category	Susceptibility Data quality Index	Category	Vulnerability Data quality Index	Category
BY/D	2.8 ^b	Moderate	2.6 ^b	Moderate	2.7 ^b	Moderate
BY/KA	2.3 ^{a,b}	Moderate	3.0 ^b	Moderate	2.6 ^b	Moderate
BY/KC	2.2 ^b	Moderate	2.1 ^b	Moderate	2.2 ^b	Moderate
T	1.4 ^a	Good	1.0 ^a	Good	1.2 ^a	Good

data availability ([Arrizabalaga et al., 2011](#)). Besides, attributes, scoring and threshold calculation procedures may differ between authors. In this study, as well as for many others, 3-level scores were used ([Patrick et al., 2010](#); [Cortés et al., 2009](#)), with thresholds obtained by quantile methods. [Devine et al. \(2012\)](#) stated that attributes (especially the susceptibility ones) need to be reevaluated in order to accommodate for species-fishery specificities. Although we used many attributes already used in other studies, we innovated by incorporating L_{50}/L_{max} amongst the productivity attributes and; Z/k and percentage of adults ($\% > L_{50}$) amongst the susceptibility attributes. L_{50}/L_{max} describes the differences among species in somatic and reproductive investments. As a strategy, smaller species tend to reach maturity at larger sizes relative to their maximum body sizes, while larger species tend to mature at relatively smaller sizes ([Juan-Jordá et al., 2013](#)). For example,

scombrids appear to mature early in life compared to their maximum life span, at around one quarter ([Juan-Jordá et al., 2013](#)). We used Z/k as an indicator of mortality in order to replace Z/M , which can be highly influenced by the uncertainty in estimating natural mortality (M), which remains as one of the most difficult parameters to estimate in fish stock assessments ([Hewitt and Hoenig, 2005](#)). The inclusion of % of adults as an attribute would help focus on the possible impact of growth overfishing.

The precautionary approach to fisheries management requires a formal consideration of uncertainty. Uncertainty has been incorporated in many different ways in Ecological Risk Assessments, in order to address such concern. Confidence scores were used by [Phillips et al. \(2015\)](#) to model the susceptibility attribute, as original scores, as beta probability distributions. When calculating the potential risk to ceta-



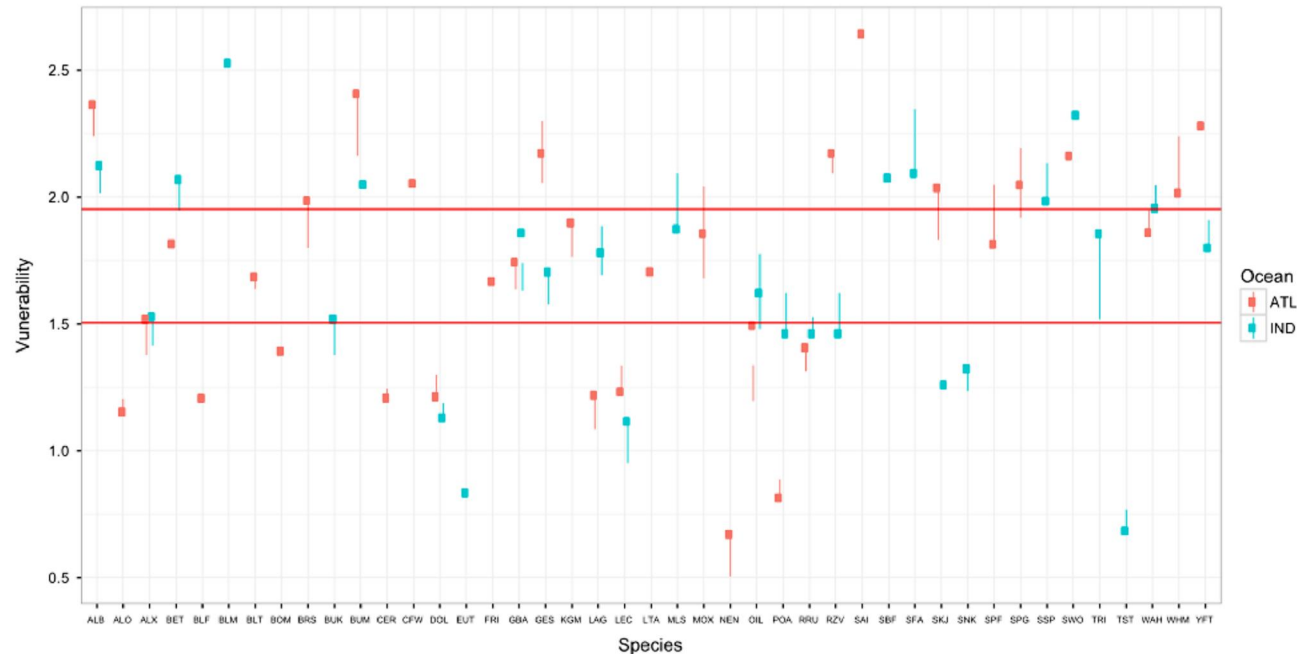
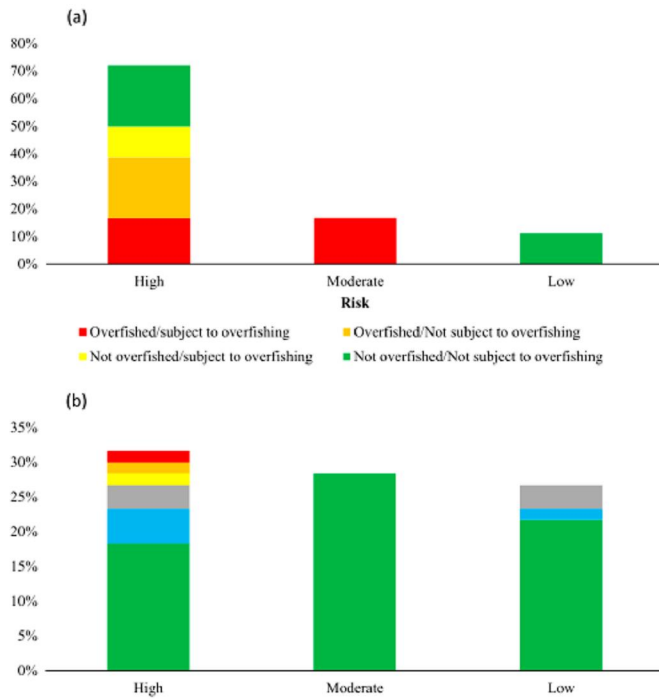


Fig. 5. Overall distribution of vulnerability scores with error bars corresponding to the scores when the lower and upper confidence limits of r is used for the calculation of Productivity score. Lines corresponds to the limits of Low to Moderate and Moderate to High Risks. Codes are in Table 4.



and (b) by evaluating the impact of the uncertainty of the estimated r (using the 2.5th and 97.5th percentiles) in rank and risk of the species. The uncertainty of the estimated intrinsic rate of population growth (r) altered the minority of the species. Data-poor stocks might receive inflated vulnerability scores due to lack of information (Fujita et al., 2014). In our study, data quality scores relied mainly within the moderate quality category although most species at high risk had good quality data. The conservative scoring approach classifies many stocks at high and major risk because of a lack of knowledge rather than true vulnerability, since PSA tends to over-classify species vulnerability (Osio et al., 2015). This occurs when a species is missing information on its productivity and susceptibility attributes and the risk score defaults to high risk.

There is a great scarcity of biological information for by-catch species caught by the tuna longline fishery (Lucena Frédou et al., 2016). This is the case of *Gempylus serpens* and *Ranzania laevis* (rank 7 and 8 respectively), classified as being at high risk. For those species, and also for *Coryphaena equiselis* (rank 14) (SOM 5) and *Katsuwonus pelamis* (rank 17), many susceptibility attributes are missing, and they are also within the high risk classification. According to Hobday et al. (2011), in general, this approach results in more false positives than false negatives (units scored at a lower risk than would occur when assessed at a higher level with more data). False positive results can be screened out at higher levels in the Ecological Risk Assessment hierarchy, while false negatives result in improper elimination of a

It appeared that vulnerability assessments were comparable. Overall, species at high risk were overfished and/or subjected to overfishing. Moreover, all species considered to be within extinction risk (CR, EN and VU) were in the high-risk category. These approaches have different level of complexities. Although some of the data used by IUCN, stock assessment methods and the PSA are similar, the criteria used to derive the risk, stock status and vulnerability are not and, converging conclusions are indeed a good indication of the health of these stocks and the robustness of PSA, even considering the limitations of the method. *Dulvy et al. (2005)* compared predictions of extinction risk for exploited marine fish and invertebrates (IUCN categories) with those of stock status reported in stock assessments, and found the results from the two approaches to be consistent. *Davies and Baum (2012)* also reported that IUCN categories and fisheries status (measured by whether the stock was above or below reference points) agreed well in assessing the status of marine fish, although they warned about equating falling below a fishery reference point with a Red List threatened status. *Osio et al. (2015)* compared vulnerability scores with IUCN extinction risk categories and found that species with higher vulnerability are, with few exceptions, ranked as most threatened by the IUCN.

Most species considered in our study are also caught by other gears, such as purse seine and pole and line. PSA, however, does not account for the relative cumulative risk to species from multiple activities. The method could be extended to assess individual and cumulative risk associated with different gears (see *Micheli et al., 2014*). The extension of PSA may provide a tool for evaluating risk posed by overlapping fisheries within an ecosystem-based management framework that accounts for the full suite of extractive activities and their possible interactions (*Micheli et al., 2014*). Also, for high-risk stocks, for which data quality is good, a move to quantitative ERA can be made.

Climate change and decadal variability are impacting marine fish and invertebrate species worldwide (*Hare et al., 2015*). The PSA approach could also take into account additional possible stressors due climate change in the future, particularly where changes are mainly related to life history and marine species distribution (*Perry et al., 2005; Petitgas et al., 2012; Lehodey et al., 2013*), which may negatively affect the populations by a decrease in productivity (*Hare et al., 2015*). When species distribution is changed, the distribution and magnitude of fishing effort (*Gamito et al., 2015; Pinsky and Fogarty, 2012*) may be affected and therefore the effectiveness of conservation and management measures (*Mackenzie et al., 2007*). Specifically for tuna populations, even if they have developed elaborated thermoregulation mechanisms (*Brill, 1994*), they are strongly influenced by the temperature and by other variables like dissolved oxygen, currents and prey concentration (*Lehodey et al., 2013*). The range of a stock is largely determined by environmental factors (*Arrizabalaga et al., 2015*), for example, the effect of climate change on Pacific skipjack is predicted to be an expansion of its range (*Lehodey et al., 2013*). Stocks may contract as a result of overfishing, which will affect fishing effort distribution and the PSA "horizontal overlap" attribute (*Sibert et al., 2006*). Such contraction could lead to the PSA misclassification of the risk of extinc-

tion, data collection and research. In this regard, special attention should be given to Isthiophoridae, which has the highest vulnerability and stock status in largely unknown. Scombrids, particularly small tunas, given their economic importance for local fishing communities, should also be prioritized.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.dsr2.2016.10.008>.

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