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

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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 western 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 others fully quantitative assessment methods. Istiophoridae exhibited the highest scores for vulnerability. While 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*. All species considered at high risk were targeted or were commercialized bycatch, except 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, Vulnerable and Endangered) were in the high-risk category. The good concordance between approaches corroborates the results of our analysis. PSA do not replace the traditional stock assessments but is particularly important when the overall lack of quantitative stock assessments for many species at high risk and most at moderate risk, is considered.

Keywords: Productivity and susceptibility Analysis, bycatch, risk, fishery management

**1.Introduction**

Several frameworks and approaches have been developed to help manage the risks posed to species by caught in a range of fisheries (Astles et al., 2006; Arrizabalaga et al., 2011; Brown et al., 2015). One well-accepted framework is Productivity and Susceptibility Analysis (PSA; Hobday et al., 2007, 2011). PSA is a methodology for estimating the vulnerability of a stock based on its biological productivity and susceptibility to fishing. The approach relies on the relationship between the life history characteristics of a stock and its productivity, and its susceptibility to being caught in a fishery. PSA is considered a first step in data-poor situations to identify the main species at risk (Hobday et al., 2011; Cortés, 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 fish stocks (Patrick et al., 2010). The approach is included in the Marine Stewardship Council Fisheries Assessment Methodology (2011) and Expert Groups of the International Council for the Exploration of the Sea (ICES) have explored a range of data deficient assessment methods to support development of management advice including PSA (ICES, 2012a, 2012b). While the International Commission for the Conservation 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 oceans. Due to their highly migratory nature and widespread distributions, five Regional Fisheries Management Organizations (RFMOs) are in charge of the management and conservation of tunas and billfishes: the International Commission for the Conservation of Atlantic Tunas (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 stocks by 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.

PSA can help identify species, populations, stocks or regions where the risk of negative interactions with fishing activity is greatest and then used by managers to determine priorities for data collection, stock assessment and management. For example as in the current study, where the relative vulnerability of tuna, billfishes and other teleost species caught in pelagic longlines in the South Atlantic and western Indian Oceans is assessed by applying a semi-quantitative PSA. Specifically, we (a) evaluated the vulnerability of the species in the study areas; (b) compared the vulnerability of target and non-target species by ocean; (c) analyzed the sensitivity of the results to data quality; and (d) compared the results of the PSA to other more quantitative assessments methods.

**2. Material and Methods**

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

A list of species of the infraclass Teleostei caught by the tuna longline fishery in the South Atlantic and the western Indian Ocean was compiled from a variety of sources. The initial list of was based on official statistics from ICCAT and IOTC. The list was then updated using published documents (Bach et al., 2008, 2009; Marín et al., 1998; Huang and Liu, 2010; Pacheco et al., 2011), the national Brazilian On-board Observer Program database (South Atlantic Ocean), and the national database for observer data on-board pelagic longliners based in La Reunion (Indian Ocean) hosted by IRD (Institut de Recherche pour le Développement) (Bach et al., 2008, 2013).

*2.2. Determining the vulnerability of the stocks*

Vulnerability (v) is a measure of the extent to which fishing mortality on a species exceeds its biological ability to renew itself (Stobutzki et al., 2002). It is a function of productivity and susceptibility attributes, which are combined to produce a single score that quantifies the risk to a stock. Stocks that received a low productivity score and a high susceptibility score were considered to be the most vulnerable to overfishing, while stocks with a high productivity score and 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:

where X0 and Y0 are the (x, y) origin coordinates.

Stocks were then assigned into a risk categories (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 are found furthest from the origin.

Vulnerability was also consideringed by assigning the fate of the catch of each species was assigned into four categories by ocean (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 asigned 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:

Maximum Size (Lmax,cm): maximum reported fork length obtained from the literature, i.e. from 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.

Fecundity (in millions of oocyts): Mid-point of the reported range of number of eggs per individual for a given spawning event or period. Data were obtained from literature.

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, where values were given by sex these were averaged.

von Bertalanffy growth coefficient (k, cm.k-1): which measures how rapidly a fish reaches its maximum size.

Size at first maturity (L50, cm): Length at which 50% of the individuals attain sexual maturity for the first time.

Maximum age (Tmax, years): Maximum reported age.

L50/Lmax: 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 L50 and kwere 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 species (Table 1).

2.2.2. Susceptibility attributes

Six attributes for susceptibility were considered (Table 2):

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 (Froeser and Pauly, 2007). Effort distribution, from year 2000 to 2011, was obtained for the South Atlantic Ocean from ICCAT and for the Indian Ocean from IOTC. The score thresholds were based on Patrick et al. (2010).

Encounterability or vertical overlap: The position of the stock within the water column (in terms of depth range) in relation to the fishing gear. Data on depth by species were obtained from the literature and information on gear depth from national observer databases. The score thresholds of this attribute were based on Patrick et al. (2010).

Z/k: the ratio of total mortality (Z) to the von Bertalanffy growth rate (k) was estimated from length-frequency distributions using the Powell–Wetherall plot (Wetherall et al., 1987). Length-frequency distributions (from 2000 to 2011) were obtained from ICCAT and IOTC databases for the main target and bycatch species. For others bycatch species, data was obtained from 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 deceases 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).

Percentage of adults in catches (% > L50): The percentage of individuals larger than the length at first maturity (L50), obtained from the length distributions. The score threshold of this attributes was defined using the quantiles of the distribution.

Post-capture mortality (Mort): This was 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).

Management strategy: The management measures for each species were obtained from the reports of SCRS (Standing Committee on Research and Statistics, ICCAT, 2014) for South Atlantic, IOTC Scientific Committee for Indian Ocean (IOTC, 2014) and CCSBT, specifically for the Southern Bluefin Tuna (see SOM 3 for a list of regulations in operation). S**tocks 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*

Lucena-Frédou et al. (2016) showed that differences in productivity between species and oceans were mainly explained by Lmax 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 & Spencer, 2011). The index was based on five tiers, ranging from those stocks with the best data (or high belief in the score) to those with no data (or little belief in the score) (modified from Patrick et al., 2010) (Table 3). Like Hobday et al. (2007), the data-quality scores were then divided into three categories: poor >3.5; moderate 2.0–3.5; and good <2.0.

The reliability of the results were evaluated by considered the impact of uncertainty on r, a key parameters in the productivity analysis. To do this the ranking of the stocks were recalculated using the 2.5th and 97.5th percentiles of r (Cortés et al., 2009), where r was calculated using values of k and L50 estimated from the regressions on Lmax while keeping the other productivity attributes as in the original model. The percentiles were obtained using the standard errors of the predicted values of r, using the delta method (Rice, 1994) and the standard errors of the life history attributes. The ranks obtained in this analysis were then compared to those obtained by the original model.

*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 determine 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 pdetailed inIUCN (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). 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 data for each stock).

For the third comparative approach stock status for the major commercial tuna species worldwide, as assessed by the tuna RFMOs (CCBST, 2015; ICCAT, 2015a, IOTC, 2015) was used. Stock assessments were carried out from 2009 to 2015 (SOM 4).

**3. Results**

*3.1. Estimating vulnerability of teleosts caught by tuna longline fisheries in the South Atlantic and western Indian Oceans*

The catch composition of the tuna longline fishery in the South Atlantic Ocean was composed of 11 families and 33 species, while in the western Indian Ocean 27 species from 12 families were recorded. Seventeen 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 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 2.54 (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 Xiphidae - except for Atlantic *T. pfluegeri* and Indian *Ocean K. audax -* moderate risk) and most targeted species (except Atlantic *T. obesus* and Indian Ocean *T. albacares -* moderate risk). Bycatch Scombridae species, such as *S. brasiliensis,* Atlantic *Katsuwonus pelamis* and the Indian *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).

*3.2 Measuring uncertainties*

The quality of the data was considered moderate (with an average vulnerability quality score of 2.20) (Table 4). Differences in overall data quality between oceans and families were not significant (p > 0.05), however, average susceptibility scores were lower for the Atlantic Ocean (p < 0.05). Most families scored moderate for vulnerability quality, except for Scombridae, Coryphaenidae, Xiphidae and Istiophoridae, which had good data quality. Average susceptibility and overall data quality of target species (T) was higher when compared to other categories of catch fate (P < 0.05) (Table 6). Seven species at risk had moderate quality data (Table 4; Fig 4).

Using the 2.5th and 97.5th percentiles of r as the inputs for the productivity analysis (for species with estimated parameters), species in oceans barely changed their risk levels (i.e. high, medium and low), although the vulnerability ranks may change (Fig. 5). South Atlantic Scombrids *S. brasiliensis, A. solandri* and *K. pelamis* were either assessed as being at high or moderate risk, depending on the simulated r value. This was also the case for the Isthiophoridae *K. audax* (Indian Ocean), *T.georgii* and *T. pfluegeri* (South Atlantic Ocean) (Fig. 5).

*3.3. Integrating data analysis*

Overall, only 32% (27% and 41%, respectively, for the South Atlantic and Indian Oceans) of the teleost stocks were assessed by the RFMOs, however, 90% are assessed by the IUCN methodology. Most of the stocks assessed by the RFMOs are designated as overfished and/or subject to overfishing (72%) and were within the category of high risk (Table 5 and Fig. 6). Within the moderate risk group, three stocks were overfished and subject to overfishing. While only two stocks were assessed to be at low risk and considered to be currently at sustainable levels (i.e. neither overfished nor subject to overfishing). *X. gladius* of the Indian Ocean is a particular case: it is judged to be at sustainable levels in the Indian Ocean and overfished but not subjected to overfishing in the southwestern Indian Ocean (Table 4). Around 20% (4 stocks) of assessed stocks (all in the high risk category) have some uncertainty in life history parameters and hence in stock status.

With regard to the IUCN methodology, all species considered to be at extinction risk (CR, VU and EN) were in the high risk category. Within the moderate risk, 2 species were categorized as Near Threated, and all stocks evaluated to be at low risk were categorized as being of Least Concern.

**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). Applications 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 (Dustan 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 allows 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, 1996). 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 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 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.

Risk analysis have been applied to elasmobranchs (Zhou and Griffiths, 2008; Cortez et al., 2009; Phillips et al., 2015), cetaceans (Brown et al., 2013; 2015), seabirds (Waugh et al., 2012; Tuck et al., 2011), and teleosts (Stobutzki et al., 2001; Hobday et al., 2007, 2011; Patrick et al., 2010; Fujita et al., 2014; Osio et al., 2015). For tuna longline fisheries, Kwon et al. (2009) conducted a PSA analysis for species caught in the Western and Central Pacific Ocean which included marine mammals, turtles, teleosts, sharks and seabirds; while Arrizabalaga et al. (2011) assessed the relative risk of both target and bycatch species being negatively impacted by EU Purse Seine and US Pelagic Longline fleets in the North Atlantic.

In this study, no differences were found in vulnerability of the teleosts caught by tuna longline fisheries in the South Atlantic and Indian Ocean, while the main targets (tunas and swordfish) and bycatch billfishes (Istiophoridae) were within the highest risk group. These species have moderate to low productivity and high susceptibility, and so are susceptible to potential negative impacts. For target species, this is perhaps not surprising as the objective of longline fisheries are to catch them, and so no surprisingly 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* (Arritzabala 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).

Isthiophoridae 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* (Rec. 06-09 and Rec. 12-04 of ICCAT, see SOM 4). 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 never 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 a extension of this analysis to the North Atlantic (SCRS, 2015b).

Managers must also remain vigilant to species and stocks in the more intermediate rankings (Phillips et al., 2015), especially in the 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 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 other authors, 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 revaluated in order to accommodate for species-fishery specificities. Although we used many attributes already used in other studies, we innovated by incorporating L50/Lmax amongst the productivity attributes and; Z/k, percentage of adults (% > L50) amongst the susceptibility attributes. L50/Lmax 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 over fishing.

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 cetaceans, Brown et al. (2015) tested the appropriateness of the attributes used to produce the risk scores by dropping each attribute each turn until all attribute combinations had been used. The standard deviation of the resulting PSA scores was a measure of the uncertainty of the scores generated for each species (Brown et al., 2015).

Uncertainty in this study was addressed in two ways: (a) by a data-quality index, proposed by Hobday et al (2007) and Patrick et al. (2010), used to balance for inflated scores resulting from limited data; 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), however, altered the minority of the species.

Data-poor stocks might receive inflated vulnerability scores due to lack of information (Fugita 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 this 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 tuna longline fishery (Lucena Frédou et al., 2016). This is the case of *Gempylus serpens*  and *Ranzania laevis* (rank 8 and 9 respectively), classified as being at high risk. For those species and also *Coryphaena equiselis* (rank 14) (SOM 5) and *Katsuwonus pelamis* (rank 17), many susceptibility attributes are missing, and those species are also within the high risk classification. According to Hobday et al. (2011), in general, that 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) is important. 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 hazard or unit. The uncertainty associated with the qualitative and semi-quantitative risk assessments argues in favour of maintaining a bias against false negative results. Those species may also be considered by managers as priorities for data collection given the limited resources.

The amount of false positive and the semi-quantitative nature of the PSA, sometimes raises a credibility issue with knowledgeable stakeholders (Hobday et al., 2011). One way to address this issue, even when available life history information is partial, is to compare the results from PSA with other assessment approaches (Goodman et al., 2012; Osio et al, 2015), i.e. to check whether a risk assessment reflects actual stock status. To do this, we compared how the risk obtained by PSA compares to other approaches, namely the IUCN extinction risk categories and the status of stock assessed by the RFMOs.

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, VU and EN) were in the high-risk category. These approaches have different data entries and level of complexities and converging conclusions are indeed a good indication of the health of these stocks and the robustness of PSA. 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. (2012) 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.

We believe that, even considering the limitations of the PSA, these findings are indicative of a good qualitative agreement between the different scoring methods. Although some of the data used by IUCN, stock assessment methods and the PSA are similar, however, the criteria used to derive vulnerability are not. The good concordance between the approaches points to the robustness of the PSA approach. For high-risk stocks, for which data quality is good, a move to quantitative ERA can be made.

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 and Olso et al., 2015). 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).

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 and changes in distribution (Hare et al., 2015). In the latter case the distribution and magnitude of fishing effort (Pinsky et al., 2013; Gamito et al., 2012) may be affected and therefore the effectiveness of management measures (Makenzie et al., 2007). Specifically for tuna populations, even if they have developed elaborated thermoregulation mechanisms (Brill 1994), they are strongly influenced by the temperature environment and by other variables like dissolved oxygen, currents and prey concentration (Lehodeay et al., 2013). The range of a stock is therefore determined by environmental factors (Arrizabalaga et al., 2015) and environmental variability may result in a contraction of range. Fishing, may also result in range reduction and if not included in the PSA may underestimate the risk of a stock being overfished.

The effect of climate change on skipjack, a tropical tuna species, in the Pacific Ocean was assessed by Lehodeay et al. (2013). A general expansion of its habitat was predicted. Hence, it is expected that climate changes could affect the results of PSA model in future and the inclusion of this aspects into assessment models is encouraged. Hare et al. (2015) mentioned that there are potential links that could be made between Ecological Risk Assessment with climate change vulnerability assessments, since they are complementary tools which support the broader implementation of Ecosystem-Based Management and climate change adaptation strategies.

Cortés et al (2015) considered stock assessment as part of the continuum of ERA, where the appropriate method depends on the amount of data available. The PSA conducted in this study does not replace the traditional stock assessments but helps to identify of which species are at higher risk and/or should be prioritized for further assessment and data collection. This is particularly important, when the overall lack of quantitative stock assessments for many species at high risk and most at moderate risk is considered, which is the case of the South Atlantic and Indian Oceans tuna longline fisheries.

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**Legend of figures**

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

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

Fig. 3 - Overall distribution of productivity and susceptibility x-y plot by fate of the catch for the teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans. Codes are in Table 4.

Fig. 4 – Overall distribution of productivity and susceptibility x-y plot by data quality index of the teleosts caught by tuna longline fisheries in South Atlantic and Indian Oceans. Codes are in Table 4.

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.

Fig. 6 – Status of the stock (upper panel) and IUCN Red List categories (lower panel) by risk categories. Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC) and Data Deficient (DD)