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Abstract

Ecological risk assessment is a useful methodology for assisting the management of fisheries from an ecosystem perspective. Atlantic tuna fisheries, managed by the International Commission for the Conservation of Atlantic Tunas (ICCAT), are economically important and interact with several bycatch species. In spite of these interactions, no comprehensive ecological risk assessment has been conducted for bycatch species caught in ICCAT fisheries. In this paper, we followed a two stage approach with the objective of assessing the relative risk of species being negatively impacted by Atlantic tuna fisheries. An analysis of the ICCAT bycatch species list (which includes all species reported to have interacted with different tuna fishing gears operating in the Atlantic) revealed that most of these species are caught in longline fisheries, followed by gillnets and purse seines. According to the IUCN red list, 7 species of the ICCAT bycatch list (3 coastal sharks, 3 sea turtles and one seabird) are categorized as critically endangered. In our study, and based on their life history characteristics, marine mammals and coastal sharks caught in ICCAT fisheries showed the highest intrinsic vulnerability values. A productivity susceptibility analysis for the European Union (EU) tropical tuna purse seine fleet and the United States (US) pelagic longline fleet revealed two groups with high relative risk scores. The first one included pelagic and coastal sharks, characterized by relatively low productivities, and the second one included teleosts, characterized by higher productivities but high susceptibility to purse seine and longline gears. Some alternative approaches to conduct productivity susceptibility analyses in the context of ecological risk assessments are discussed.

Keywords

Ecological risk assessment, productivity, susceptibility, ecosystem approach, bycatch, purse seine, longline

Introduction

Risk assessment approaches are commonly used to assist fishery management (Francis and Shotten 1997), but they are less developed in the framework of the ecosystem approach to fisheries management. Murawski (2000) highlighted the lack of consensus for defining "ecosystem overfishing" and suggested the need for objective metrics that gauge properties associated with the main features of the ecosystem (e.g. production, diversity, and variability). To evaluate management options that are both scientifically credible and economically practical regarding the use of ecosystems, decision makers require information regarding the effects of fishing on ecological processes, as well as on human activities. With respect to the first point, the ecological risk assessment framework (ERA) appears as a relevant methodology to provide ecosystem indicators and to enable implementation of an ecosystem approach to fisheries management. Ecological risk assessments were first proposed in the 1980s (Hope 2006) and a variety of different approaches have subsequently been developed (e.g. Scandol et al. 2009). Astles (2008) provided a review of recent developments of ERA in marine fisheries and the elements required to estimate ecological risk. There is a particular need for a simple and transparent way to classify marine stocks and their limits to controllable exploitation in order to prioritise data collection, scientific assessment, and management action.

Quantitative assessments relying on increasingly complex mathematical models have been used to predict the response of the ecological receptor to a changing environment, while qualitative risk assessments use a combination of attributes of the ecosystem, ecological receptor and stressor (Astles et al. 2006). Some authors (e.g. Griffiths et al.

2006) have suggested that qualitative risk assessments that provide relative indicators of risk may be inadequate for reflecting even the most obvious changes in fishing impacts on bycatch species as induced by concrete management actions. However, although quantitative ecosystem models have clearly improved the understanding of the dynamics of marine populations (Hollowed et al. 2000), there are a myriad of factors and processes influencing these systems and ecosystem models may have poor predictive capability. Also, in many cases quantitative assessments can only be conducted for a limited number of species, generally the most valuable ones. Consequently, qualitative assessments have been used as a tool to identify which species should be the subject of quantitative assessment (Smith et al. 2007) and to prioritize issues for fisheries management (Fletcher 2005; Fletcher et al. 2005).

There are only few methods that are useful for assessing large numbers of species for which biological data are scarce (Dulvy et al. 2004). Qualitative risk assessments have proved to be important at this initial stage of the assessment of ecosystem state by providing the relative risks of species to prioritize research and management (e.g. Stobutzki et al. 2001a,b). In contrast, quantitative assessments require more data and are usually applied to a more restricted group of species (e.g. Goldsworthy and Page 2007; Zhou and Griffiths 2008; Zhou et al. 2009).

To date, application of ERAs to fisheries that include species and species groups of significantly different nature (e.g. marine mammals, turtles, sharks and teleosts) are scarce. The development of comprehensive ERAs is essential to not exclude potentially important species from the overall analysis at an early stage. An ERA can provide a transparent methodology to pursue more complex risk assessments and/or take immediate management action for a range of species and fisheries. This is of particular relevance if it involves a hierarchical approach that moves from a comprehensive, but largely qualitative analysis of risk (level 1), to a more focused and semi-quantitative approach (level 2), and finally to a highly focused and fully quantitative approach (level 3, Hobday et al. 2011; Smith et al. 2007). Level 1 (Scale, Intensity, Consequence Analysis) evaluation of risk is mostly based on the perception from interaction with stakeholders, level 2 (Productivity Susceptibility Analysis, PSA) is semi-quantitative in nature but it relies on a good scientific basis, and level 3 is fully quantitative (full stock assessment and analysis of uncertainty).

Tuna and tuna-like species are important socio-economic resources worldwide, both for industrial fleets operating in distant waters as well as for artisanal fleets operating in coastal waters. Until recently, there have been few ERA applications to tuna and tuna-like fisheries, in spite of the fact that many bycatch species are caught in association with the main target species. Kirby (2006) conducted a PSA analysis for species caught in the Western and Central Pacific Ocean tuna fisheries which included marine mammals, turtles, teleosts, sharks and seabirds. This approach was also applied in the Indian Ocean by Murua et al. (2009). In the Atlantic, Cortés et al. (2009) conducted a PSA analysis restricted to eleven species of pelagic elasmobranches in order to assess their vulnerability to pelagic longline fisheries. Also, the seabird assessment conducted by the International Commission for the Conservation of Atlantic Tunas (ICCAT, 2008) included an initial PSA analysis that facilitated the identification of those seabird species most at risk, and those for which a fully quantitative risk assessment could be pursued.

In this paper we followed a two step approach with the objective of assessing the relative risk of both target and bycatch species being negatively impacted by Atlantic tuna fisheries managed by ICCAT. First, a general descriptive analysis of species caught in ICCAT fisheries was conducted which included all species reported caught and all gears operating in the Atlantic tuna fisheries. The gears that interact with the most species groups were identified. Also, the biological characteristics and the intrinsic vulnerability of the species were analyzed. Secondly, a productivity and susceptibility analysis was conducted for two fleets for which data collected by scientific observer programs were readily available (i.e., EU Purse Seine and US Pelagic Longline fleets) with the aim of ranking the species most at risk. In this paper, we refer to productivity as the capacity of the stock to rapidly recover when depleted, whereas susceptibility is the potential for the stock to be negatively impacted by the fishery (Patrick et al 2010). Some alternative approaches to conduct productivity susceptibility analyses in the context of ecological risk assessments are also discussed.

Material and Methods

As a first step, we reviewed the list of all the ICCAT bycatch species that have been reported as caught in tuna fisheries. The ICCAT bycatch list includes 242 species recorded as having been caught by a major tuna fishery in the Atlantic at some time. The database includes information from three basic sources: (i) catch reports by the different countries, (ii) scientific documents presented to the ICCAT Standing

Committee for Research and Statistics, and, mainly, (iii) a survey in which each country's experts identified the species that have ever interacted with their fisheries.

The presence of a species in the list does not imply that it is caught in significant quantities, or that the individuals caught died as a result of the interaction. In fact, the database does not provide any information on the level or amount of catches and it is only a register of species names associated to one or various fishing gears (available at http://www.iccat.int/en/bycatchspp.htm). Neither there is any information about the potential fraction of species caught but not reported. We assumed that a reasonably high amount of the species interacting with Atlantic tuna fisheries are included in this database, and we used it to identify the contribution of each of the main fishing gears operating in the Atlantic (i.e. baitboat, gillnets, harpoon, longline, purse seine, traps and others) to the total bycatch and bycatch by species groups i.e. Scombridae and billfish, other teleosts, skates and rays, coastal sharks, pelagic sharks, marine mammals, sea turtles and seabirds in the ICCAT Convention area. Nineteen of the 242 species recorded in the database were only identified to the genera or the family level. Therefore, in order to avoid potential duplication, we only used records identified to the species level.

We consulted web based libraries (Froese and Pauly 2010, Palomares and Pauly 2010, www.searoundus.org, http://www.flmnh.ufl.edu/fish/) as well as published literature (Compagno 2001; ICCAT 2010; Jefferson et al. 1994; Marquez 1990), to collate additional information about life history parameters. The basic information collected included maximum length, length at maturity, intrinsic vulnerability (according to Cheung et al. 2005; Cheung et al. 2007) and IUCN red list status (IUCN 2010). The intrinsic vulnerability index measures vulnerability to exploitation based on life history traits (as opposed to total vulnerability that also takes into account environmental or fishing effects), while the IUCN status also considers population trends.

This information was used to calculate the average intrinsic vulnerability of all species within a group and of all species by gear type. Also, the number of species affected by ICCAT fisheries in the different categories of the IUCN red list, namely not evaluated (NE), data deficient (DD), least concern (LC), near threatened (NT), vulnerable (VU), endangered (EN) and critically endangered (CR), and the relative contribution of each fishing gear to the bycatch of those species was also analyzed.

Finally, we used data collected by scientific observer programs to conduct a productivity and susceptibility analysis on the effects of fishing for the European tropical tuna purse seine fishery operating in the eastern equatorial Atlantic and the US pelagic longline fishery operating in the northwestern Atlantic. The European tropical tuna purse seine fishery observer program has an observer coverage ranging between 5% and 10% and the dataset used includes years 2003 to 2007 (Amande et al. 2010), while the observer coverage for the US pelagic longline fishery ranges between 6% and 9% and the dataset includes years 1992 to 2008 (Diaz et al. 2009). Due to the relatively high observer coverage and the long observation period, we assumed that the list of species that interacted with these fisheries as recorded by each observer program is a representative sample. The PSA was conducted mainly following Kirby's (2006) approach, which identifies species most at risk among those caught by each of the fleets. The productivity index was defined according to Kirby (2006):

$$P_1 = (RS)/3 + (Lmat / Lmax)$$

Where *RS* is the reproductive strategy of a given specie, *Lmat* is its length at maturity, and *Lmax* is the maximum length. *RS* was scored as follows:

1.- Broadcast spawners-> external fertilization: Fish which release their gametes into the water, where fertilization may occur; without parental care.

2.- Egg layers-> internal fertilization: species that lay eggs (oviparity); species where the pups are protected by egg cases.

3.- Live bearers-> internal fertilization: ovoviviparity and viviparity; species where pups are born alive.

As a sensitivity test, a simpler alternative productivity index was defined as:

$$P_2 = Lmat / Lmax$$

High P_1 and P_2 values indicate high risk due to low productivity (broadcast spawners are considered to be more productive than egg layers and live bearers, and a low length at maturity to maximum length ratio indicates a higher chance of being able to reproduce as it is more likely to reach sexual maturity prior to capture). The susceptibility index was defined as:

$$S_1 = (Lcatch / Lmax + Pdead)/2$$

Where *Lcatch* is the average length of the catch for each species, according to the observer datasets, computed as the arithmetic mean of observed lengths over all fishing operations sampled, and *Pdead* is the proportion of dead animals after interacting with the fishing gear. Note that, according to Kirby (2006), the first term of the equation is proportional to susceptibility assuming that natural mortality is higher at smaller sizes and, thus, fishing mortality is a smaller component of total mortality than for larger sizes (as suggested by Fonteneau and Pallares, 2005). However, this term might also appear counter intuitive since the larger the size at capture is, the higher the chance for spawning. Thus, as a sensitivity test, a simpler alternative susceptibility index was defined as:

$$S_2 = Pdead$$

In the case of tropical purse seiners, *Pdead* was calculated assuming that the categories “escaped from net (for cetaceans and whale shark)”, “taken out of the net (for cetaceans and whale shark)” and “discarded alive” had no associated mortality. This assumption may well have resulted in an under-estimation of the proportion of dead animals. In the case of longliners, it was assumed that all finned sharks died. The categories “lost at surface” and “released” were not considered to estimate the percentage of dead animals since they do not provide information about the fate of the animals.

The productivity and susceptibility indices as well as alternative P and S indices were scaled to the maximum value of the series. The risk scores R_1 and R_2 for each species were calculated as the euclidean distance between the origin and their position in a bidimensional Productivity Susceptibility space,

$$R_1 = \sqrt{P_1^2 + S_1^2}$$

$$R_2 = \sqrt{P_2^2 + S_2^2}$$

Alternative productivity, susceptibility and risk scores were compared using Pearson correlation tests. For each of the fisheries (European Purse Seine and US Longline), the risk scores were ranked in order to highlight the species and species groups most at risk of being negatively impacted by the fisheries.

The susceptibility indices considered so far are independent of the number of individuals caught. Therefore, a species could score high even if a single individual was caught and died during the entire observed period. To overcome this situation, alternative risk scores could be developed by multiplying S_1 (or S_2) by the numbers caught by the fishery. However, the amounts of different species caught by a fishery not only depend on the species selectivity of the fishing gear, but also on the relative abundances of the species themselves (i.e. catching several tuna might have a smaller impact than catching one shark). Thus, we suggest that a better approach would be to multiply S_1 (or S_2) by the catch to abundance ratio of each species. To illustrate this, we compared alternative risk scores (R_c and $R_{c/a}$) that incorporate catch and catch to abundance ratio information on S_1, respectively, as described above, for those species caught by the EU Purse Seine fishery for which recent abundance estimates were available from ICCAT (2009).

Results

An "occurrence" was defined as a species reported to have interacted at least once with a fishing gear (i.e. it is included in the ICCAT bycatch list). The analysis of the ICCAT bycatch list revealed that most occurrences occurred in longline fisheries, followed by gillnets, purse seines, other fisheries, harpoons, traps and baitboats (Fig. 1a). Information on species specific intrinsic vulnerability was not available for some coastal sharks (2%), marine mammals (4%), seabirds (41%), skates and rays (8%) and other teleosts (15%). Based on the available information, the average intrinsic vulnerabilities for the species groups caught in ICCAT fisheries are given in Fig. 2a. Marine mammals and coastal sharks are the species groups which show the highest average intrinsic vulnerabilities, although their confidence intervals overlap with those of pelagic sharks, sea turtles and skates and rays. On the other hand, seabirds (for which there were no scores in 15 out of 37 species) show lowest average intrinsic vulnerability, their confidence interval overlapping with that for Scombridae and billfish, as well as sea turtles. Intrinsic vulnerability reflects vulnerability based on biological characteristics. Highest intrinsic vulnerabilities are expected for species with longer life spans, later sexual maturation, slower growth and lower natural mortalities (Morato et al. 2006). However, total vulnerability might significantly differ from intrinsic vulnerability, as it is also affected by the environment and fishing. Seabirds, for example, are highly vulnerable to longline fishing given their tendency to be hooked on longlines operating in certain regions of the Atlantic.

Harpoon and trap gears, in spite of their low contribution to total catch of tuna and tuna like species, showed the highest average intrinsic vulnerability of the species interacting with each gear (Fig. 2b). The average intrinsic vulnerability of species interacting with gillnets is similar to that of longliners and purse seiners.

Most species (including most teleosts) are not evaluated by the IUCN (Fig. 3a). Most ICCAT species (Scombridae and billfish) are either not evaluated (19) or categorized as data deficient (3), with only one species in each of the “low concern” and “vulnerable” categories. According to the IUCN red list, 7 species are critically endangered: 3 coastal sharks (*Squatina aculeata*, *Squatina oculata* and *Squatina squatina*), 3 turtles (*Dermochelys coriacea*, *Eretmochelys imbricata* and *Lepidochelys kempii*) and one seabird (*Puffinus mauritanicus*). Moreover,16 species are endangered (9 seabirds, 2 marine mammals, 2 turtles, 1 teleost, 1 coastal shark and 1 ray).

Among the species evaluated as CR by the IUCN, 45% of the interactions occurred in longline, 27% in purse seine, 18% in gillnets and 9% in harpoons (Fig. 3b). Traps, baitboats and others do not catch species evaluated as CR. Considering vulnerable (VU), endangered (EN) and CR species, 45% of occurrences occur in longline, 19% in gillnets, 15% in purse seine, 10% in harpoon fisheries, 7% in other fisheries, 2% in traps and 1% in baitboats.

Productivity Susceptibility Analysis:

According to the ICCAT bycatch list, the purse seine gear interacted with 75 different species. Observers on the EU tropical tuna purse seine fleet have recorded catch for 52 different species (including target and bycatch species). Thirty one of these species were assigned productivity and susceptibility scores. The information needed to estimate *P* and *S* was not available for the rest of the species. The species that were included in the PSA analysis included 3 coastal sharks, 12 Scombridae and billfish, 3 pelagic sharks, 2 skates and rays, 4 sea turtles and 7 other non-ICCAT teleosts. Only 2 individual marine mammals have been observed to interact with tropical tuna purse seiners during the observer program, neither of which died and their lengths were not recorded. Hence, it was not possible to compute a susceptibility score for any of the marine mammals and they were not included in the PSA analysis.

The results of the PSA analysis for European purse seiners identified two main risk groups according to the R_1 score (Fig. 4). The first group is comprised of pelagic and coastal sharks characterized by relatively low productivities. The second group comprised teleosts including both ICCAT (Scombridae and billfish) and non-ICCAT species characterized by higher productivities, but also higher susceptibility to purse seine gear. The 10 species with highest risk scores included 3 pelagic sharks, 2 coastal sharks, 4 Scombridae and billfish and 1 other teleost according to the R_1 score and 8 Scombridae and billfish, 1 pelagic shark and 1 coastal shark according to the R_2 score (Table 1).

According to the ICCAT bycatch list, 164 different species interacted with pelagic longline gear. Observers on the US pelagic longline fleet recorded catch of 82 different species (including target and bycatch species). Fifty four of these species were assigned productivity and susceptibility scores. The information needed to estimate P and S was not available for the rest of the species. The species that were included in the PSA analysis were 17 coastal sharks, 13 Scombridae and billfish, 11 other teleosts, 9 pelagic sharks and 4 sea turtles.

The PSA analysis for the US pelagic longline fishery revealed that some coastal sharks are, according to the R_1 score, at the top of the risk rank with both low productivities and relatively high susceptibility to the fishing gear (Table 2 and Fig. 5). A mixed group of pelagic and coastal sharks also share low productivity values, but slightly lower susceptibility to capture. Some teleosts (both ICCAT and other species) also showed high risk scores, mainly because of their high susceptibility to the fishing gear even though their productivity was relatively high. Among the teleosts, several non-ICCAT species (*Sciaenops ocellatus*, *Scomber scombrus* and *Scomber japonicus*) showed higher risk values than ICCAT species (e.g. albacore tuna). Among the 10 species with the highest risk scores were 7 coastal sharks, 2 pelagic sharks and 1 non-ICCAT teleost according to the R_1 score and 3 coastal sharks, 4 non-ICCAT teleosts, 2 ICCAT species and 1 pelagic shark according to the R_2 score (Table 2).

For both the European purse seine and the US pelagic longline fisheries, the evaluated sea turtles were not highly ranked in terms of R_1 or R_2. Although considered to be animals with relatively low productivity, their susceptibility scores were low for these fisheries, mainly due to the fact that most are released alive. Other sensitive species groups (like marine mammals or seabirds) were not included in the analysis essentially because the data showed that these two particular fisheries rarely interact with them (e.g. purse seine observer data contains no interaction with seabirds).

The alternative productivity scores (P_1 and P_2) showed positive correlations (R^2=0.6577; p=8.013e-12) as did the alternative susceptibility scores (S_1 and S_2, R^2=0.9045; p=2.2e-16) and the alternative risk scores (R_1 and R_2, R^2=0.5376, p=1.122e-07).

When including catch information on the risk score (R_c), target species (*Katsuwonus pelamis* and *Thunnus albacares*) were upgraded in the risk rank (Table 3). However, when including the catch to abundance ratio in the risk estimate ($R_{c/a}$), these two species had the lowest scores, while bycatch species (*Tetrapturus albidus*, *Makaira nigricans and Istiophorus albicans*) had the highest scores.

Discussion

In the paper we follow a two stage approach. The descriptive analysis of the ICCAT bycatch list is more inclusive than the PSA as it considers all species that were reported to interact with ICCAT fisheries. The subsequent PSA analysis we performed is more quantitative in nature, but it was restricted only to those species for which data collected by scientific observer programs and life history parameters were available. This kind of analysis that includes all species, followed by semi-quantitative PSA analysis is to some extent comparable to the multilevel ERA framework (Hobday et al. 2011) recommended by Dulvy et al. (2004) and Astles et al. (2006) as a way to triage or rapidly assess large numbers of species. However, it is not hierarchical in the sense that the first analysis does not restrict the scope of the second analysis. However, the first analysis is important as it stresses the relevance of the second analysis and it helps to identify future needs.

For both the ICCAT bycatch list and the observer datasets, we assumed that a reasonably high proportion of the species interacting with the respective gears and fisheries was included in these datasets. However, in the case of the ICCAT bycatch list, there is no information about the fraction of species that might have been non-reported, and the real number of species interacting with Atlantic tuna fisheries might be higher than the already high number (242 species) registered in the database. Similarly, in spite of the relatively long observed period and the high observer coverage for the US pelagic longline fishery and the EU tropical tuna purse seine fishery observer programs, the number of species recorded in the respective databases is likely to increase in the future as more fishing operations are observed. Thus, it must be stressed that the results of updated analyses might change as new species are identified as interacting with these fisheries.

The analysis of the ICCAT bycatch list showed that longline, gillnet and purse seine gears interact with the highest number of bycatch species which generally have relatively high intrinsic vulnerabilities. However, the number of species caught by each gear is only a coarse measure of potential impact since the risk itself is not evaluated. The species in the ICCAT bycatch list are not necessarily species at risk, or species at similar levels of risk. In fact, the presence of a species in the bycatch list does not imply that it is caught in significant quantities relative to its population size, or that the individuals that are caught necessarily died due to the interaction. For instance, although gillnets catch a lower number of species than longlines, they catch more marine mammals. On the other hand, almost all seabird interactions are reported to occur in longline fisheries (Fig. 1b). However, it should be taken into consideration that different longline types operate in different areas and at different depths, time of day, etc., potentially affecting and interacting with different species of different resilience. In fact, the interaction of a certain gear with a certain species might differ from one region to another, due to differences in environmental conditions.

The average intrinsic vulnerability of species interacting with a fishing gear depends on the relative proportion of species with differing vulnerabilities. It is clear that catches by harpoon and trap gears are minor when compared to other gears like longline, purse seine or baitboat. For that reason, the average vulnerability by gear should ideally be weighted by the relative magnitude of gear specific catches or mortalities (not estimated here). This may well provide a different picture to when vulnerability is considered in isolation and may be a more meaningful method for assessing the impact of a particular gear type. This is of course dependant on the availability and/or quality of catch data available for the bycatch species.

Given that purse seine and longline gears interact with a relatively high number of species and that the total tuna and tuna like species catch of both these gears is high in comparison to other gears, the selection of a purse seine and a longline fishery for the PSA seemed adequate for the purpose of this analysis. Moreover, both the EU purse seine and the US longline fisheries have relatively good observer coverage (Diaz et al.

2009; Amande et al. 2010). However, the list of bycatch species that interacted with these two fisheries might not be representative of all the longline and purse seine fisheries operating throughout the Atlantic. This suggests the need to conduct additional PSA analyses on other purse seine and longline fleets operating in different areas, at different times and with different targets, as they might interact with bycatch species at different levels of risk. In addition, it would also be of interest to analyze observer data on gillnet fisheries which are also reported to interact with many bycatch species, including a high proportion of marine mammals (which showed highest intrinsic vulnerability indices), and other critically endangered and vulnerable species. Extending the PSA analyses to gillnet fisheries would allow the development of a more global picture of fishing effects on the ecosystem and to better focus research and management efforts.

The PSA for the two fleets considered in this analysis showed several similarities. Overall, two high risk groups were identified that deserve enhanced scientific monitoring and management action in the near future, namely coastal and pelagic sharks characterized by low productivity and relatively high susceptibility to capture, and teleosts (both ICCAT and non-ICCAT species) with higher productivity but also higher susceptibility to capture. However, the PSA was conducted on a subset of species that are caught by these two fleets for which enough information was available to produce productivity and susceptibility scores. Thus, it should be noted that the results may change in the future as new information for other species becomes available.

Most of the “top 10” species identified by the R_1 score as being most negatively impacted by purse seine and longline fisheries were also identified by R_2, because strong positive correlations where obtained between both scores over the entire dataset mainly due to the high correlation between the alternative susceptibility scores. The correlation between alternative productivity scores is lower because they differ by an offset (i.e. the reproductive strategy) that, in the case of P_1, separates species into groups according to their different reproductive strategies. There is no point in using P_1 to score relative productivities of species with the same reproductive strategy, but the use of P_1 may be preferred when species with different reproductive strategies are being scored (as in the present analysis). However, the precise values for the alternative reproductive strategies should be discussed between experts in the different species groups, as well as the relative weight between reproductive strategy and the length at maturity to maximum length ratio.

In fact, it should be taken into consideration that the risk ranking is likely to change under different definitions of risk. Different authors have adopted alternative definitions of productivity and or susceptibility, depending on the species characteristics and data availability. For instance, the scoring procedure for the same variable differs between authors (e.g. Stelzenmüller et al. 2010 considered 4 levels of Reproductive Strategy for their analysis, while only 3 levels were considered in our study). Moreover, the variables considered by Furness and Tasker (2000) to score seabird sensitivity to fishing (e.g. potential foraging range, ability to dive, ability to switch diet, cost of foraging, etc.) significantly differed from those used by Stelzenmüller et al. (2010) for their spatially explicit risk assessment for fish (e.g. importance for fisheries, habitat vulnerability and affinity to seabed). This raises the debate as to which are the most appropriate variables to use (and how to score them) when species of very different nature are simultaneously analyzed (e.g. seabirds, turtles, marine mammals and fish). Such analyses are of great importance to better focus research and management efforts. Scientists may, however, have difficulties in agreeing on the appropriate way to conduct this type of PSA. Interestingly enough, and according to our analysis, sea turtles do not appear to be at high risk even though the IUCN (that considers interactions with a wider range of stressors) lists 2 of the 5 sea turtle species as endangered, and the other 3 as critically endangered. The reason of this apparent discrepancy is that, although some sea turtle species have a relatively high interaction rate with longline gear, fishing practices by the US pelagic longline fleet (e.g. mandatory use of circle hooks and de-hooking devices for sea turtles) resulted in a high proportion of sea turtles being released alive.

In general, although the PSA has proved to be a useful methodology to simultaneously compare large numbers of species and identify those most at risk, further methodological development is needed to address analyses that include species groups of a significantly different nature (Hope 2006). Alternative risk scores could be developed that take into consideration the amount of catch for each of the species. This R_c would accentuate species most frequently caught by the fishery (usually the target species), and would avoid cases such as that for shortfin mako that appeared at the top of the R_1 risk rank for the EU purse seine fishery even though only one individual was captured during the entire observer program (which suggests that the total vulnerability of this species to the purse seine gear may not be high). In this sense, the catch to abundance ratio might better reflect susceptibility than catch itself. In fact, using R_c target species became most at risk while $R_{c/a}$ ranked species more in accordance with their respective population status. The disadvantage of using $R_{c/a}$ is that the number of species or populations included in the analysis is reduced substantially since more information is demanded. In fact, this is largely a circular argument as, according to Hobday et al. (2011), stock assessments from which abundance data for this kind of PSA analysis can be obtained correspond to fully quantitative analyses that are conducted to assess the risk to those species that have been prioritized in earlier PSA analyses and for which enough data were available. For that reason, it makes sense to use R_1 in the PSA analysis covering as many species as possible to prioritize those most at risk, and then to conduct fully quantitative risk assessments on those species. Our analysis produced relative risk scores for species belonging to different species groups. These scores (or those produced using the alternatives discussed above) allowed the identification of species most at risk and for which more quantitative risk assessments can be pursued (e.g. following Zhou and Griffiths 2008; Zhou et al. 2009). Spatially explicit risk assessments (e.g. Stelzenmüller et al. 2010) might also be conducted for species with known spatial distributions facilitating the identification of potential marine protected areas. In cases where not enough information is available to conduct such quantitative assessments, specific data collection and research programs can be designed.

In the mean time, the hierarchical approach is particularly useful for assessment of numerous Atlantic bycatch species in data-limited fisheries. In spite of the arguments against using a common risk metric for fish, birds, turtles and mammals, the steps involved and the decision criteria used to determine risk levels are transparent and logical and can be applied to a wide range of different fisheries, allowing stakeholders to be involved in the process. This approach allows for a management response at any level, optimizing research and management efforts by identifying and excluding low-risk species from data intensive assessments (Braccini et al. 2006). In essence, hierarchical ecological risk assessments are useful tools for the ecosystem approach to fishery management in the Atlantic Ocean.

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Figure legends:

Figure 1. Summary plots of the ICCAT bycatch list. a) Number of species reported to have interacted with each fishing gear, by species group. b) Number of species reported to have interacted with each species group, by fishing gear. An occurrence is defined as a species reported to have interacted at least once with a given fishing gear. The presence of a species in the list does not imply that it is caught in significant quantities, or that individuals that are caught necessarily died as a result of the interaction.

Figure 2. Average instrinsic vulnerability (sensu Cheung et al. 2005; Cheung et al. 2007) by a) species groups and b) main fishing gears. The line in b) represents average yearly catch by gear since 1990. Vertical bars indicate one standard error.

Figure 3. a) Number of species under the alternative IUCN red list status categories. b) Percentage of species caught by fishing gear under the alternative IUCN red list status categories.

Figure 4. Results of the productivity susceptibility analysis for species caught by EU tropical tuna purse seiners. Elliptical 80% confidence intervals are provided for each species group. See table 1 for correspondence between species codes and species names.

Figure 5. Results of the productivity susceptibility analysis for species caught by US longliners. Elliptical 80% confidence intervals are provided for each species group. See table 2 for correspondence between species codes and species names.

Table 1. Productivity Susceptibility Analysis for the European purse seine fishery: alternative risk scores (R_1 and R_2) obtained in the Productivity Susceptibility analysis for the European purse seine fishery. The table is ordered in descending order according to R_1 within each specie group. The species ranked among the top ten according to R_1 and R_2 are marked with [1] and [2] superscripts, respectively.

Species group	Species code	Species	R_1	R_2
Coastal sharks	SPL	[1,2]*Sphyrna lewini*	1.165	1.145
	SPZ	[1]*Sphyrna zygaena*	1.059	0.912
	RHN	*Rhincodon typus*	0.898	0.537
Pelagic sharks	SMA	[1,2]*Isurus oxyrinchus*	1.292	1.279
	FAL	[1]*Carcharhinus falciformis*	1.13	1.094
	OCS	[1]*Carcharhinus longimanus*	1.087	0.988
Scombridae and billfish	WHM	[1,2]*Tetrapturus albidus*	1.158	1.325
	FRT	[1,2]*Auxis rochei*	1.108	1.283
	ALB	[1,2]*Thunnus alalunga*	1.09	1.231
	SWO	[1,2]*Xiphias gladius*	1.053	1.148
	SAI	[2]*Istiophorus albicans*	0.968	1.142
	FRT	[2]*Auxis thazard*	0.953	1.125
	BUM	[2]*Makaira nigricans*	0.942	1.137
	WAH	*Acanthocybium solandri*	0.869	1.097
	LTA	*Euthynnus alletteratus*	0.837	1.085
	SKJ	*Katsuwonus pelamis*	0.825	1.082
	BET	[2]*Thunnus obesus*	0.82	1.179
	YFT	*Thunnus albacares*	0.728	1.081
Other teleosts	CFW	[1]*Coryphaena equiselis*	1.048	1.026
	GBA	*Sphyraena barracuda*	0.896	1.082
	TRG	*Balistes carolinensis*	0.87	1.06
	RUB	*Caranx crysos*	0.836	0.979
	DOL	*Coryphaena hippurus*	0.833	1.048
	RRU	*Elagatis bipinnulata*	0.831	1.069
	NAU	*Naucrates ductor*	0.529	0.527
Sea turtles	LKY	*Lepidochelys kempii*	0.974	0.915
	TUG	*Chelonia mydas*	0.922	1
	TTL	*Caretta caretta*	0.829	0.757
	DKK	*Dermochelys coriacea*	0.731	0.543
Skates and rays	PLS	*Dasyatis violacea*	1.033	0.75
	RMB	*Manta birostris*	0.866	0.499

Table 2. Productivity Susceptibility Analysis for the US pelagic longline fishery: risk scores (R_1 and R_2) obtained in the Productivity Susceptibility analysis for the US pelagic longline fishery. The table is ordered in descending order according to R_1 within each specie group. The species ranked among the top ten according to R_1 and R_2 are marked with [1] and [2] superscripts, respectively.

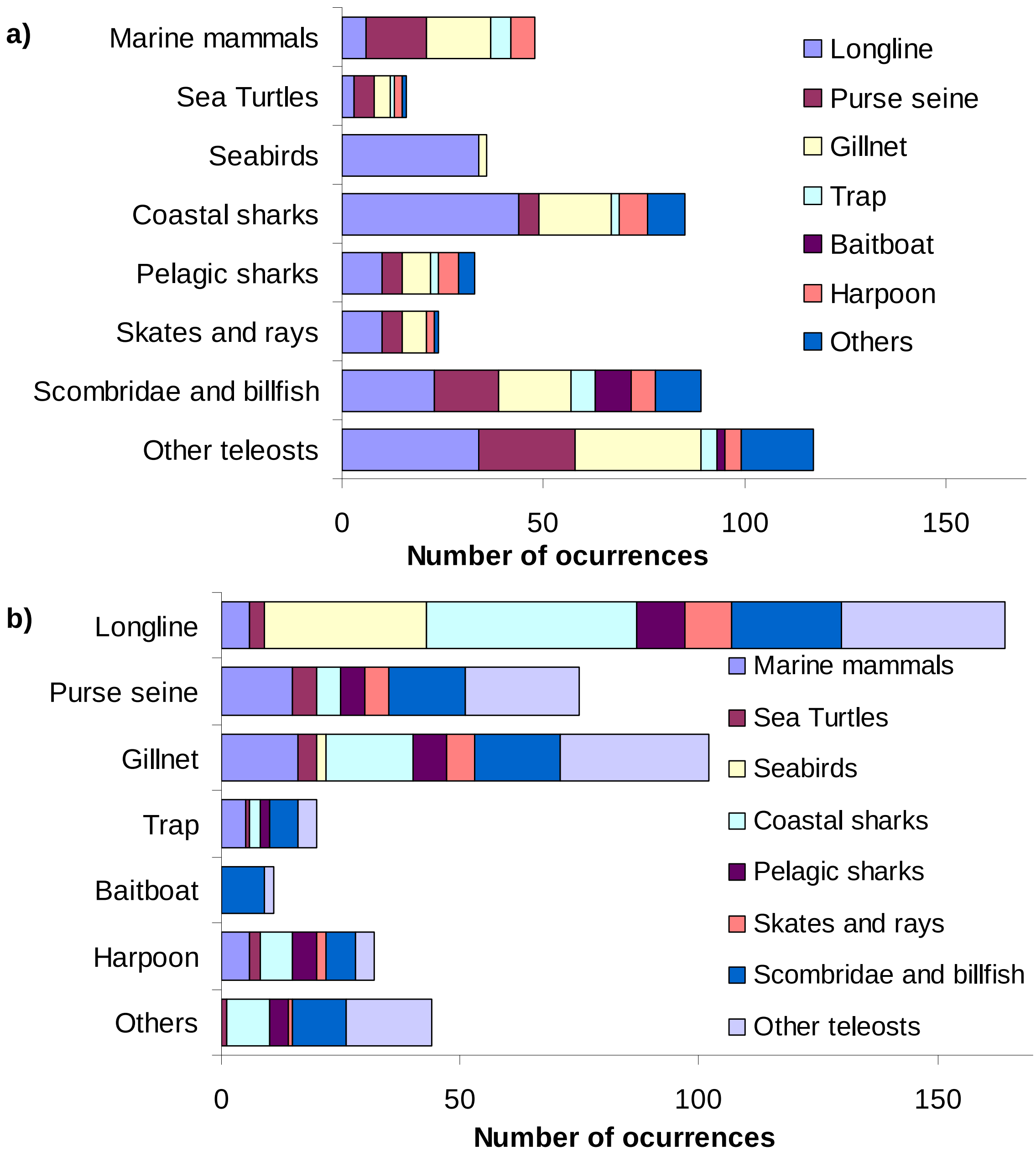
Species Group	Species code	Species	R_1	R_2
Coastal sharks	RHT	[1,2]*Rhizoprionodon terraenovae*	1.376	1.156
	HXT	[1,2]*Heptranchias perlo*	1.255	1.24
	CCA	[1,2]*Carcharhinus altimus*	1.184	1.162
	CCS	[1]*Carcharhinus signatus*	1.124	1.073
	CCP	[1]*Carcharhinus plumbeus*	1.113	0.9
	CCB	[1]*Carcharhinus brevipinna*	1.111	1.03
	DUS	[1]*Carcharhinus obscurus*	1.084	0.99
	BSK	*Cetorhinus maximus*	1.047	0.723
	CCL	*Carcharhinus limbatus*	1.047	0.893
	SPZ	*Sphyrna zygaena*	1.015	0.893
	CCE	*Carcharhinus leucas*	1.008	0.655
	SPL	*Sphyrna lewini*	0.998	0.803
	CTI	*Mustelus canis*	0.989	0.739
	CCV	*Carcharhinus perezi*	0.984	0.734
	SPK	*Sphyrna mokarran*	0.935	0.764
	DGS	*Squalus acanthias*	0.869	0.54
	TIG	*Galeocerdo cuvieri*	0.815	0.479
Pelagic sharks	PCH	[1]*Pseudocarcharias kamoharai*	1.18	0.934
	SMA	[1,2]*Isurus oxyrinchus*	1.128	1.106
	FAL	*Carcharhinus falciformis*	1.047	0.951
	LMA	*Isurus paucus*	1.016	0.801
	BSH	*Prionace glauca*	0.91	0.63
	BTH	*Alopias superciliosus*	0.905	0.635
	ALV	*Alopias vulpinus*	0.899	0.661
	POR	*Lamna nasus*	0.894	0.646
	OCS	*Carcharhinus longimanus*	0.882	0.632
Scombridae and billfish	ALB	[2]*Thunnus alalunga*	1.058	1.201
	BET	[2]*Thunnus obesus*	0.942	1.14
	WAH	*Acanthocybium solandri*	0.91	1.091
	BON	*Sarda sarda*	0.896	0.917
	WHM	*Tetrapturus albidus*	0.887	0.982
	SPF	*Tetrapturus pfluegeri*	0.859	0.977
	BFT	*Thunnus thynnus*	0.857	0.825
	LTA	*Euthynnus alletteratus*	0.851	0.924
	BLT	*Thunnus atlanticus*	0.834	0.826
	SWO	*Xiphias gladius*	0.832	1.057
	YFT	*Thunnus albacares*	0.83	1.05
	SAI	*Istiophorus albicans*	0.757	0.814
	BUM	*Makaira nigricans*	0.648	0.645

Other teleosts	MAS	[1,2]*Scomber japonicus*	1.131	1.221
	MAC	[2]*Scomber scombrus*	1.063	1.11
	RDM	[2]*Sciaenops ocellatus*	1.053	1.126
	GES	*Gempylus serpens*	1.024	0.992
	ANG	*Lophius americanus*	0.961	1.081
	NAU	*Naucrates doctor*	0.908	1.08
	RRU	[2]*Elagatis bipinnulata*	0.874	1.094
	LAG	*Lampris guttatus*	0.845	0.942
	BLU	*Pomatomus saltatrix*	0.81	0.885
	CBA	*Rachycentron canadum*	0.806	0.879
	CVJ	*Caranx hippos*	0.507	0.55
Sea turtles	TUG	*Chelonia mydas*	0.99	1.009
	LKY	*Lepidochelys kempii*	0.879	0.915
	TTL	*Caretta caretta*	0.819	0.742
	DKK	*Dermochelys coriacea*	0.722	0.543

Table 3. Productivity Susceptibility Analysis for the European purse seine fishery: alternative risk scores (R_1, R_c and $R_{c/a}$) obtained in the Productivity Susceptibility analysis for Scombridae and billfish caught by the European purse seine fishery for which enough data were available. In R_c and $R_{c/a}$, the susceptibility score (S_1) of each species is multiplied by the catch and by the catch to abundance ratio, respectively. The table is ordered in descending order according to R_1. The species ranked among the top three according to R_c and $R_{c/a}$ scores are marked with [1] and [2] superscripts, respectively.

Species code	Species	R_c	$R_{c/a}$	R_1
WHM	[1,2]*Tetrapturus albidus*	1.00	1.00	1.16
ALB	*Thunnus alalunga*	0.90	0.88	1.09
SWO	*Xiphias gladius*	0.75	0.75	1.05
SAI	[2]*Istiophorus albicans*	0.75	1.25	0.97
BUM	[2]*Makaira nigricans*	0.78	1.04	0.94
SKJ	[1]*Katsuwonus pelamis*	1.18	0.64	0.83
BET	*Thunnus obesus*	0.82	0.80	0.82
YFT	[1]*Thunnus albacares*	1.16	0.75	0.73

Arrizabalaga et al. Figure 1



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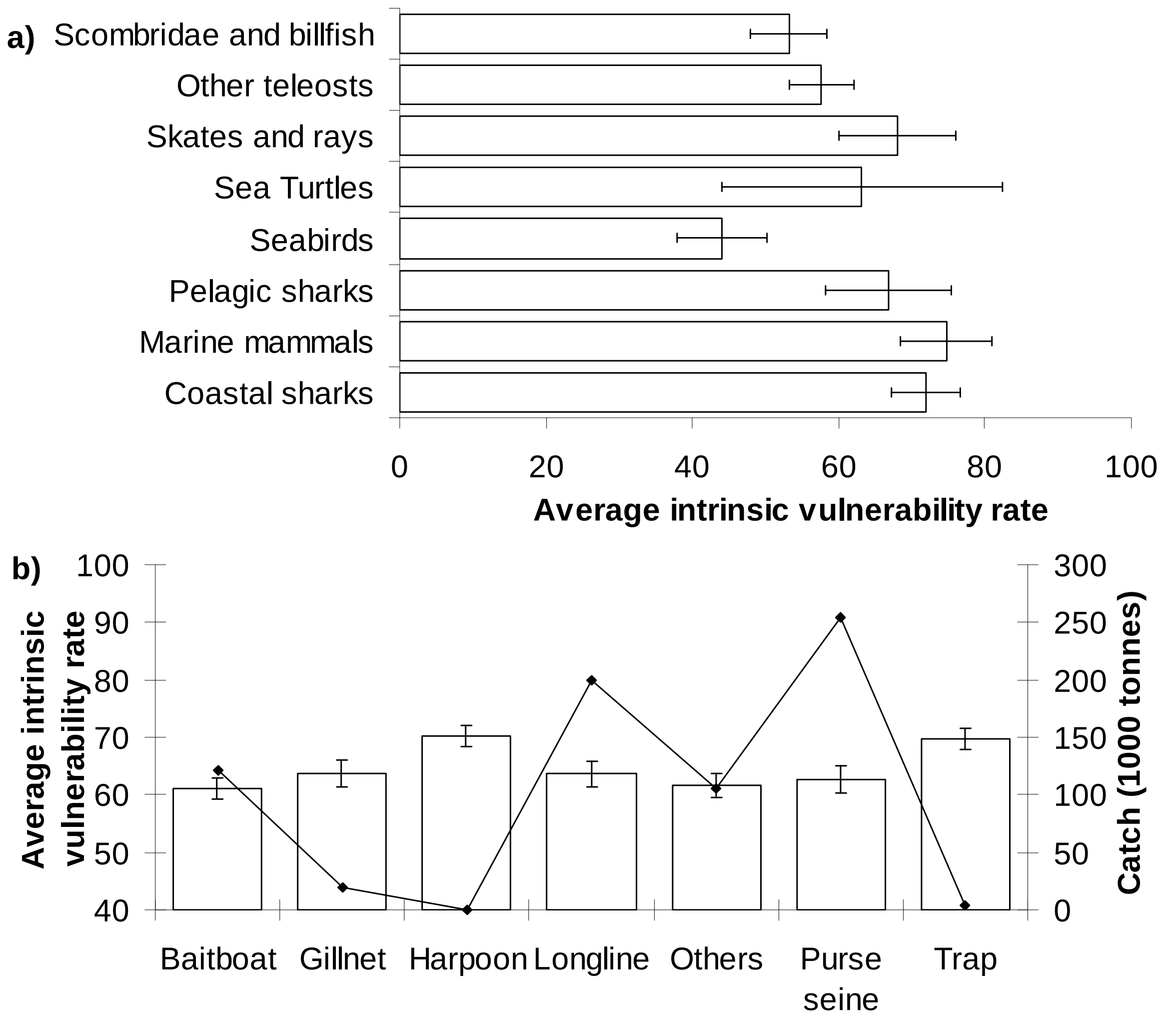
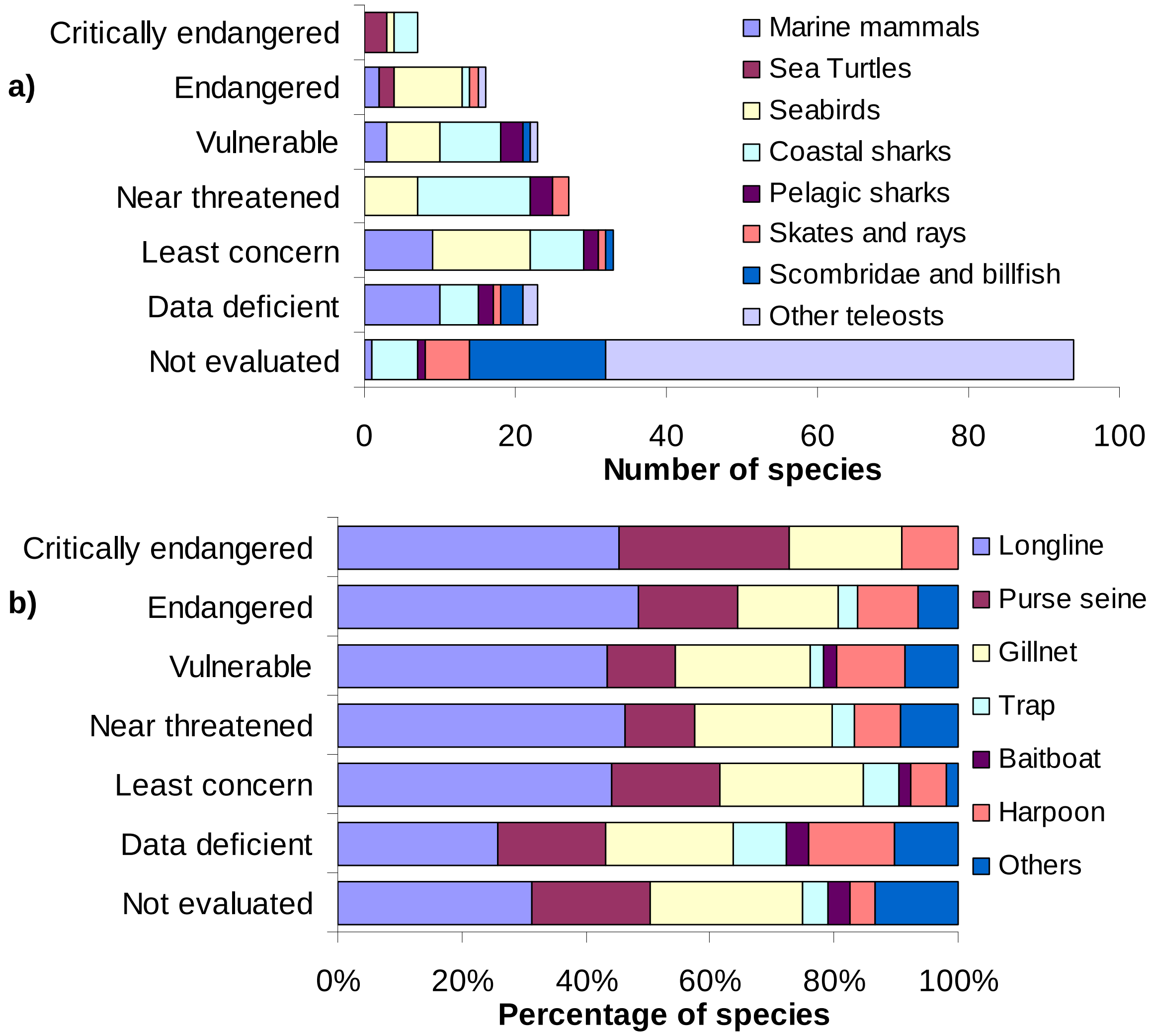
Arrizabalaga et al. Figure 2



675 Arrizabalaga et al. Figure 3



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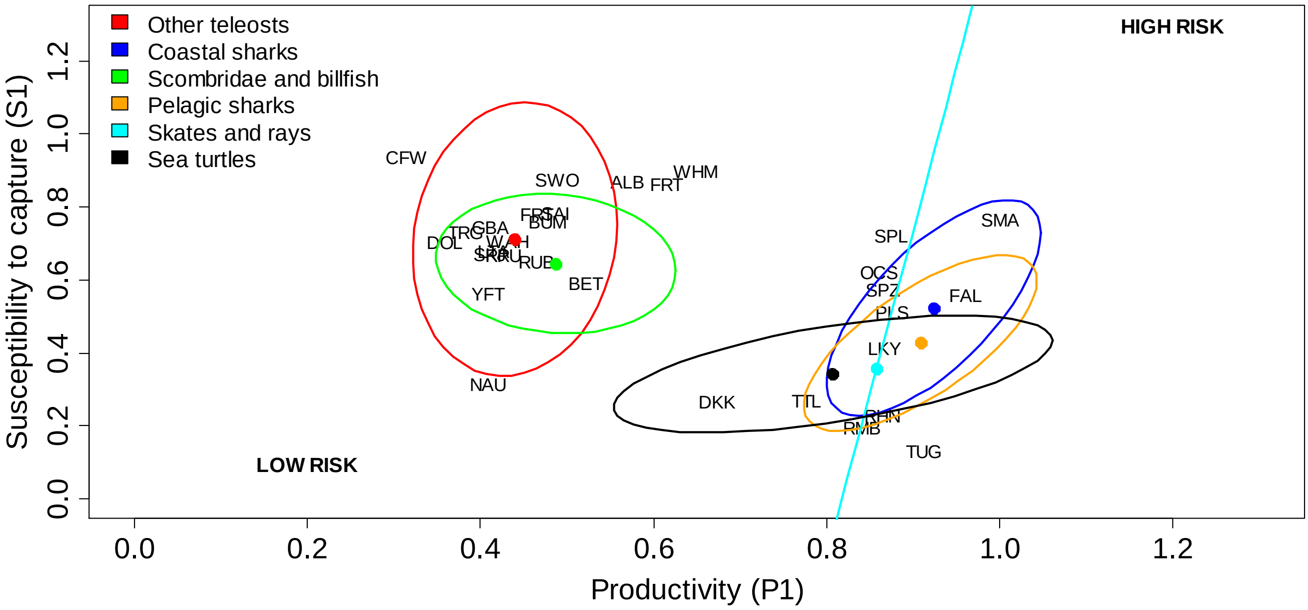

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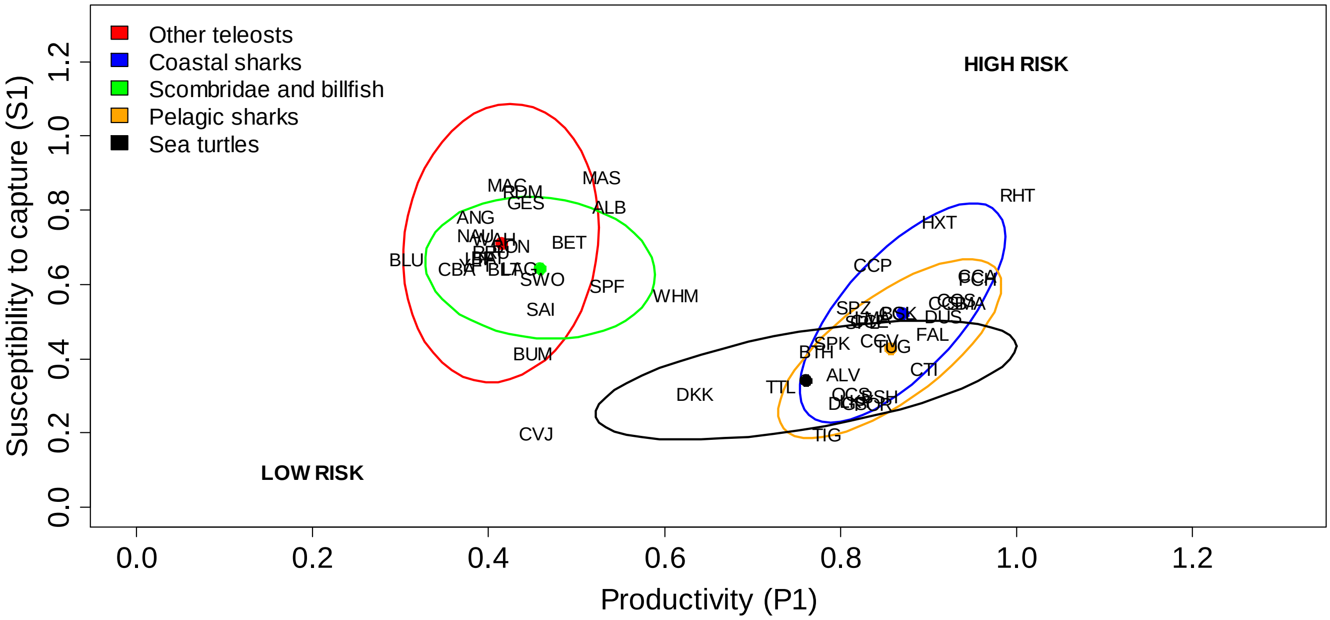

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