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Preliminary Ecological Risk Assessment (ERA) for shark species caught in fisheries managed by the Indian Ocean Tuna Commission (IOTC)

by

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ABSTRACT

Ecological risk assessment (ERA), and specifically Productivity-Susceptibility Analysis (PSA), is a useful methodology for assisting the management of fisheries from an ecosystem perspective in a data poor situation. Indian Ocean tuna and tuna-like fisheries, managed by the Indian Ocean Tuna Commission (IOTC), are economically important both at local and international scales and interact with several non-target or bycatch species. In spite of these interactions, to the authors best knowledge, no comprehensive ERA has been conducted for sharks caught by IOTC fisheries.

A PSA for shark caught in various longline fleets and purse seiner fleet operating in the Indian Ocean was carried out. Specifically, the analysis for the effects of fishing on sharks was carried for the Soviet Union research longline, Portuguese longline, Japanese longline, Korean longline, La Reunion Island longline, and Chinese longline fleets combined and for the Purse seiner fleet operating in the Indian Ocean; for which observer or research data were available. We follow the methodology proposed by Cortés *et al.* (2010), which allow ranking the vulnerability of the species based on its productivity and susceptibility to the fishing gear. We estimate the species productivity parameters based on Leslie matrices analysis, in which the value of Lambda (λ), population finite growth rate, was calculated (Caswell 2001). The susceptibility analysis was carried out comparing the horizontal overlap between fisheries and stock distribution, the vertical overlap between the species and fishing gear, the gear selectivity, and post-capture mortality.

The species with the least productivity values are two coastal shark species (*Carcharhinus plumbeus* and *Carcharhinus obscurus*), followed by several Lamniformes (*Isurus paucus*, *Alopias superciliosus*, *Lamna nasus* and *Isurus oxyrinchus*). As had been previously observed for other Oceans, such as the Atlantic (ICCAT, 2012), the blue shark (*Prionace glauca*) seems to be the pelagic shark species with the higher values of biological productivity. The species more susceptible for the longline fishing fleets are the pelagic thresher (*Alopias pelagicus*) followed by blueshark, shortfin mako, bigeye thresher, and smooth hammerhead (*Sphyrna zygaena*). Then oceanic whitetip (*Carcharhinus longimanus*) and silky shark (*Carcharhinus falciformes*) are ranked in lower levels of susceptibility and the susceptibility of the rest of species is even lower. Overall, the most vulnerable species are the shortfin mako, bigeye and pelagic thresher, followed by silky shark, oceanic whitetip shark, smooth hammerhead, porbeagle (*Lamna nasus*), longfin mako (*Isurus paucus*), great hammerhead (*Sphyrna mokarran*) and blueshark.

The species more susceptible for the purse seine fishing fleets are the oceanig white-tip and silky shark followed by shortfin mako. The rest of species are ranked in much lower levels of susceptibility. The coastal shark species are less susceptible for the purse seiner fleets. Overall, and according to our analysis, for the purse seiner fleets the most vulnerable species are the oceanic white-tip and silky shark. The rest of species are ranked in much lower levels of vulnerability. In the purse seiner fleet, the vulnerability is in a large extent defined by the susceptibility of the species to the gear rather than for the productivity of the species.

Although the gillnet fleet is responsible for around 68 % of the total shark catches in the Indian Ocean, there was no data on gillnet effort distribution nor information from observers on shark size frequencies and post-capture mortality which will allow to carry out an ERA for sharks caught by gillnet and, hence, to analyse the effect of gillnet fishing on shark.

INTRODUCTION

While shark fisheries still account for a limited share of world fishing production, they have experienced rapid growth since the mid-1980s. This trend has been driven by an increased demand for shark products (fins in particular, but also meat, skin, cartilage, etc), especially in Asian market and has been sustained by a number of factors, including improvements in fishing technology, processing and consumer marketing and declines in other fish stocks. All these elements contributed to make sharks a more valuable fishery. Between 1984 and 2004, world catches of sharks grew from 600,000 to over 810,000 metric tons (Lack and Sant, 2011). Sharks are particularly vulnerable to overexploitation because of their biological characteristics of maturing late, low reproductive capacity and being long-lived. This results in these species having a limited capacity to recover from periods of over fishing or other negative impacts.

Despite the growing concern about vulnerability and overexploitation of sharks, lack of accurate, species-specific harvest data often hampers quantitative stock assessment and, thus, effective international shark management and conservation. Action on sharks by the Food and Agriculture Organization of the United Nations (FAO), international treaties such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), Regional Fisheries Management Organizations (RFMOs) and shark catching countries and entities has been prompted by increasing international concern about shark stocks as a result of a growing body of evidence that many shark species are threatened and continuing to decline because of fishing activity. This is also the case for Tuna RFMOs where the concern of shark is increasing and several actions have been taken in order to improve shark assessment and management.

In this regard, the IOTC Working Party on Ecosystem and Bycatch (WPEB) expressed considerable interest in the application of ERA and recommended that "*such an analysis should be undertaken for the Indian Ocean in the near future*" because "*ERA would assist the Commission to identify, in the first instance, the key species of sharks and other species to be focused on by the Commission*". Therefore the Scientific Committee of IOTC in its meeting of 2008 recommended that "*a preliminary examination of the feasibility of undertaking an Ecological Risk Assessment process for IOTC fisheries be undertaken by the Secretariat, in collaboration with WCPFC and ICCAT, and to report on this to the working party in 2009*".

The Ecological Risk Assessment (ERA) for the effects of fishing framework involves a hierarchical approach that moves from a comprehensive but largely qualitative analysis of risk (level 1), through a more focused and semi-quantitative approach (level 2), to a highly focused and fully quantitative approach (level 3, (Hobday *et al.*, 2006)). Level 1 (Scale, Intensity, Consequence Analysis) evaluation of the risk is mostly based on perception from interaction with stakeholders, while a semi-quantitative approach which relies on good scientific investigation forms the basis of level two (Productivity Susceptibility Analsis, PSA), and level 3 is fully quantitative (full stock assessment and analysis of uncertainty).

There have been some ERA applications to tuna and tuna like fisheries. For instance, a PSA analysis for species caught in WCPO tuna fisheries was conducted by Kirby (2006). Cortés *et al.* (2010) conducted a PSA analysis for eleven species of pelagic elasmobranchs to assess their vulnerability to pelagic longline fisheries in the Atlantic Ocean. Also, the seabird assessment which is being conducted within the ICCAT Sub-Committee on Ecosystems and Bycatch, included an initial PSA analysis that allowed the identification of seabird species most at risk, and those for which a level 3 risk assessment might be pursued (Anon., 2008). It was also applied to bycatch species caught in the Atlantic (Arrizabalaga *et al.*, 2011), Indian (Murua *et al.*, 2009) and Eastern Pacific (Olson, 2011) Oceans.

Recently, the Scientific Committee of IOTC in its 14th meeting in 2011 strongly recommended that "*Ecological Risk Assessment (ERA) is conducted for sharks caught in fisheries targeting tuna and tunalike species in the Indian Ocean before the next session of the WPEB in 2012*". Moreover, the Working Party on Ecosytem and Bycatch in 2011 also noted that "*although ERAs are typically conducted for a specific fishery, an ERA could be carried out for the main fisheries with separate susceptibility analyses combined into one via a weighting scheme*". Thus, the purpose of this paper is to conduct a productivity susceptibility analysis, i.e. level 2 of an ERA analysis, for shark species caught in various fisheries targeting tuna and tuna-like species in the Indian Ocean.

MATERIAL AND METHODS

The Productivity and Susceptibility Analysis was first developed to rank bycatch sustainability in the Australian prawn fishery (Milton, 2001; Stobutzki *et al.*, 2001) by contrasting the productivity (*p*) of the bycatch species and their susceptibility (*s*) to the fishery. Different methodology has been used since then to estimate productivity and susceptibility (Milton, 2001; Braccini *et al.*, 2006; Hobday *et al.*, 2007; Patrick *et al.*, 2010; Cortés *et al.*, 2010) which use qualitatively (Patrick *et al.*, 2010) or semi-quantitative (Cortes *et al.*, 2010) approach. The productivity and susceptibility scores are displayed graphically on an x-y scatter plot to visualize species with high productivity and low susceptibility, which are considered at low risk or vulnerability, and low productivity and high susceptibility or those at high risk. The PSA figure allows to estimate directly an overall vulnerability score (*v*), a measure of the resilience of the species to the impact of the fishery (Stobutzki *et al.*, 2002; Cortés *et al.*, 2010), as the Euclidean distance from the origin of x-y xcatter plot (r = 1, s = 1) or

$$v = \sqrt{(p-1)^2 + (s-1)^2}$$

Productivity

Productivity parameters were estimated based on Leslie matrices analysis, in which the value of Lambda (λ), population finite growth rate, is calculated (Caswell 2001). All models considered were of the pre-breeding survey type, in which reproduction and natality take place first and only then is the survivorship considered. The elements in the first row of the matrices were, therefore, calculated as the products of the number of female offspring produced annually by each mature female (mx) and the first year survivorship (s0): Fx = s0.mx.

For all species analyzed, a 1:1 male:female ratio in the offspring was considered. Following the methods described in Cortes *et al.* (2010), and due to the lack of maturity ogives for most species, the proportion of mature females was assumed to be 0 for the ages younger than the age-at-maturity, 0.5 for the age-at-maturity reported in the literature, and 1 for the older age classes. A time lapse delay was added to each species to account for the delay between a specimen achieving maturity and effectively contributing with offspring to the population. This time lapse delay corresponded to duration (in years) of the reproductive cycle reported in the literature. The matrices first rows were further corrected to take into consideration the species-specific reproductive cycles (i.e. biannual, annual, biennial or triennial), as reported in the literature.

The annual survivorship input parameters for the matrices were estimated based on several indirect life history equations, specifically Pauly (1980), Hoenig (1983), Jensen (1996), Peterson and Wroblewski (1984), Chen and Watanabe (1989). For details on the application of these methods see Cortés (2002, 2004), Simpfendorfer *et al.* (2004). This analysis was carried out only for the species for which sufficient data specific to the Indian Ocean is available from the literature (see material and methods for more details). However, for most species analyzed in this paper, no information specific to the Indian Ocean is available and, thus, biological information are gathered for other Oceans. Specifically for the case of survivorship parameters previously reported by ICCAT for the Atlantic Ocean were used (ICCAT, 2012) (Table 1). Uncertainty in the analysis was introduced in the survivorship and fecundity parameters. Uncertainty in the survivorship parameters was introduced by using a linearly increasing distribution with support defined between the minimum and maximum ranges of the estimated survivorship values. This method is similar, for example, to what had been previously applied by Cortes *et al.* (2010) for the Atlantic, and was used to simulate a compensatory density-dependent response from the species. Uncertainty in the reproductive parameters was introduced for the fecundity using a Normal distribution defined by the mean and with SD set to 25% of the mean. This approach to set the SD was chosen because of the general lack of information on the variability of the fecundity parameters for most species, and was based on personal observations from the authors.

Monte-Carlo simulation was used to introduce uncertainties in the analysis, with 10,000 matrices constructed for each species, based on the previously assumed distributions for the survivorship and fecundity parameters. The resulting 10,000 Leslie matrices were analyzed, and the distributions of the output parameters summarized as the mean λ values and the corresponding 95% confidence intervals (0.025 and 0.975 quantiles). This analysis was conducted using the R Project for Statistical Computing version 2.14.0 (R Development Core Team, 2011; Stevens, 2009; Stubben and Milligan, 2007)

Susceptibility

Following Walker (2004) and Cortés *et al.* (2010), susceptibility, defined as the potential effect of the fisheries in the stock, can be assessed as the product of four parameters: availability, encounterability, selectivity and post-capture mortality. Availability is the proportion of the species habitat area harvested by a given fleet or the probability that the stock will be available for a given fleet on the horizontal plane; for example a population that entirely lays in the fishing fleet range has a high availability equal to 1 whereas a population that distributes beyond fishing fleet range has low availability. Encounterability is the probability to encounter the available stock by one unit of fishing gear. Selectivity is the proportion of the individuals captured by the fishing gear provided that they are encountered. And post-capture mortality, is the proportion of animals that die as a result of the interaction with the gear (for more details see Walker (2004) or Cortés *et al.* (2010)).

Availability was estimated as the proportion of spatial overlap between the stock and the fleet. Spatial effort distribution for pelagic longline and purse seiner fleet, as total number of hooks or days/hours, were available from IOTC database for a various IOTC fishing fleets for different periods since 1950. Species distributions were obtained from the International Union for the Conservation of Nature (IUCN; Global marine species assessment distribution maps). Both effort and species distribution were compiled in 5° by 5° squares. Encounterability was estimated as the proportion of vertical overlap between the population vertical distribution and the vertical distribution of the gear. Information of species vertical distribution was obtained from literature and web based libraries (www.fishbase.org, www.sealifebase.org, www.iucn.org, www.searoundus.org, http://www.flmnh.ufl.edu/fish/), while information of gear depth distribution was provided by the observer programs of various fleet analysed in the study. Since the information of vertical preferences of sharks is scarce and the vertical distribution of the gear is very variable depending various factors, such as target species and/or gear configuration, a value of 1 was assigned when depth distribution of population and fishing gear overlaps. Selectivity was estimated as the proportion of overlap between the size distributions of the animals caught by the fishery from the scientific observer programs and the length distributions obtained from the Leslie matrix (see the productivity analysis). The latter was obtained transforming the stable-age distribution output of the Leslie matrix into length distributions using Von Bertalanffy growth curve parameters for each species. Post-capture mortality was estimated as the proportion of dead animals (retained plus discarded dead for longline and discarded dead for purse seiner) from the scientific observer programs analysed.

Data and analysis

First we identified all the shark by-catch species from the observed data for each fleets considered. In several cases only the genera or family is specified (no full species name is available) and, thus, to avoid potential duplication, we worked only with records with full species names. Then, we used web based libraries (www.fishbase.org, www.sealifebase.org, www.iucn.org, www.searoundus.org, http://www.flmnh.ufl.edu/fish/), as well as published documents in IOTC or elsewhere in relation to shark biology, to obtain biological and life history characteristic information about the shark species caught in IOTC fisheries. Based on observer records, we include 17 species in the analysis: blue (*Prionace glauca*; BSH), *shortfin mako* (*Isurus oxyrinchus*; SMA), longfin mako (*Isurus paucus*; LMA), bigeye thresher (*Alopias superciliosus*; BTH), common thresher (*Alopias vulpinus*; ALV), pelagic thresher (*Alopias pelagicus*; PTH), oceanic whitetip (*Carcharhinus longimanus*; OCS), silky (*Carcharhinus falciformis*; FAL), sandbar (*Carcharhinus plumbeus*; CCP), dusky (*Carcharhinus obscurus*; DUS), porbeagle (*Lamna nasus*; POR), scalloped hammerhead (*Sphyrna lewini*; SPL), smooth hammerhead (*Sphyrna zygaena*; SPZ), great hammerhead (*Sphyrna mokarran*; SPM), and tiger (*Galeocerdo cuvier*; GAC) sharks, and the pelagic stingray (*Pteroplatytrygon violacea*; PLS). We did not include the crocodile (*Pseudocarcharias kamoharai*) and whale shark (*Rhincodon typus*) because the biological information to conduct a Leslie matrix analysis or information to estimate susceptibility was not available. The biological information obtained specifically for Indian Ocean was scarce and, thus, in those cases information available for other Oceans was used.

The susceptibility analysis for the effects of fishing on sharks was carried for the combined longline fleet, including the Soviet Union research longline, Portuguese longline, Japanese longline, Korean longline, La Reunion Island longline, Chinese longline fleets, and for the combined Purse seiner fleet for which observer or research data were available. As such, the effort distribution for each fleet was combined to compare to the species distribution in order to estimate availability. The values of selectivity for different species were obtained from the observer length frequency distributions gathered by the Portuguese, Japanese, Chinese, Korean, La Reunion, and USSR longling observer program for the longline fleet and from the European Union observer program for the purse seiner fleet. The post-capture mortality for different species was obtained from the Portuguese (Coelho *et al.*, 2011a; 2011b), Korean, and La Reunion observer program data for the longline fleet and from the European Union observer program for the purse seine fleet. When more than one post-capture mortality value was available for one species, the combined figure was estimated as the average value for the various fleets weighted by the effort of the particular fleet.

The susceptibility analysis for the effects of fishing on sharks for the gillnet fleet was not possible to attempt due to the lack of information on fleet effort distribution and information collected from observer programs.

RESULTS AND DISCUSSION

Fisheries information

Although several countries have not collected shark fishery statistics in the early years of the time series, the shark nominal reported catches increased continuously from 1950 onwards but especially from around the beginning of the 90s (Figure 1) to reach the historic highest catch levels of the time series in 1999 with around 115,000 tonnes of sharks. Since then, the total nominal reported catches have slightly decreased and it was around 80,000 tonnes in 2010. The Commission adopted Resolution 10/02 and 12/03 which make mandatory the reporting of shark catch data for various shark species; however, the collection and reporting of shark catches in IOTC fisheries has been very irregular over time but have improved in the most recent years (Herrera and Pierre, 2012). Thus, the information on shark catch and bycatch available in the IOTC database is thought to be very incomplete. In this sense, it is considered that not all shark catches are reported and, if they are reported, they are not usually reported by species and they represent the catches of these species that are retained on board (or nominal catches) dressed with no indication on the type of processing that the different specimens underwent; which make very difficult the estimation of total shark catches by species (Herrera and Pierre, 2012). Herrera et al 2012 as well showed that most of the shark catches corresponds to pelagic sharks (around 60 %) while the coastal sharks amount around 30 % of the total shark catches. The total pelagic sharks correspond to species for which the fishery statistics are obliged to provide based on Resolution 12/03.

The contribution of each gear to total IOTC species catch and shark catches is shown in Figure 2. It can be observed that while the gillnet fishery contributed with 31 % of the total IOTC species its contribution increased up to a 68 % of the total shark catches being the main gear catching sharks. The gillnet fishery is followed by the longline with 16 % of the total shark contribution (around 17 % of the total IOTC species without sharks), whereas other fleets contributes with 12 % (2 % of the total IOTC species), the line fleet with 4 % (8 % of total IOTC species) and the purse seiner and the baitboat fleet with less than 1 % (32 % and 10 % of the total IOTC species, respectively). The contribution of the different species in each fleet showed that most of the shark catches are reported as a group without identifying the species (Figure 3). For example, in the gillnet fishery most of the shark are reported as shark group (88 % SHK), Requiems nei (3%), Threshers (1%) and hammerheads (1%) whereas the main sharks reported by species are silky shark (4 %), blueshark (2%), and oceanic whitetip shark (1%). In the line and other fleets most of the sharks are reported as sharks altogether (99 % and 100 % respectively). However, in the longline around 35 % is reported as sharks in general and 65 % as species being blueshark (47 %) the main shark caught, followed by shortfin mako (7 %) and various species (9 % of the total catch) (Figure 3).

Biological and observer information

According to the observer data, in all fleets combined 22 shark species were recorded. However, in several cases only the genera or family was specified (no full species name is available) and, thus, it was difficult to identify fully the number of shark species recorded. For the most common shark species present in the fleets analysed, the biological information compiled for the estimation of productivity is showed in Table 1. It can be observed that little biological information is available for most of the species specifically for the Indian Ocean. In fact, the complete set of biological information needed to run the Leslie matrix is only available specifically for the Indian Ocean for tiger, silky and white great sharks. For the rest of the species, although some information is specific to Indian Ocean, most of the values of biological parameters were obtained from other Oceans (mainly from the Atlantic Ocean).

For the susceptibility analysis, Table 2 shows the data available to estimate the different parameters such as availability, encounterability, selectivity and post-capture mortality for the longline fleet. Although data to estimate availability and encounterability is available for all fleets, it should be mentioned that species distribution maps from IUCN are in constant process of improvement and, thus, update maps (e.g. for pelagic stingray) will affect in some extend the values of availability. However, the values of selectivity and post-capture mortality are not widely collected by different observer programs which, in turn, affect the precision of the susceptibility analysis. For example in our case, most of the data for post-capture mortality was obtained from Portugal (mainly), Korea and La Reunion fleets for the most recent period. For example, no data for post-capture mortality was available for common thresher (ALV) and data from Atlantic was used (Cortes *et al.*, 2010). Moreover, in some species the length frequencies used to estimate selectivity and the post-capture mortality values are estimated using a small sample which will have great impact in the final estimation. In this case, no data for great hammerhead was available.

In the case of the purse seine fleet, most of the data available to estimate the different parameters of susceptibility was available. For some species, as the level of bycatch was very low there were not size frequency data available and, thus, in those cases the selectivity of the fleet was considered 0 (e.g. *Carcharhinus plumbeus* and *Carcharodon carcharias*). The same can be applied to the estimation of post-capture mortality; which due to very low number of bycatch individuals was not well recorded in the observer program. Nevertheless, in those cases the post-capture mortality was assigned the highest value of 1 (e.g. *Carcharhinus plumbeus, Isurus paucus, Alopias superciliosus, Alopias pelagicus, Sphyrna mokarran,* and *Carcharodon carcharias*).

Productivity Analysis

A summary of the species productivity, with the respective point estimates and 95% confidence intervals in presented in Table 3. The species with the least productivity values are two more coastal shark species (Sandbar shark-CCP and Dusky shark-DUS), followed by several Lamniformes (Longfin mako-LMA, Bigeye Thresher-BTH, Porbeagle-POR and Shortfin mako-SMA). As had been previously observed for other Oceans, such as the Atlantic (ICCAT, 2012), the blue shark (BSH) seems to be the pelagic shark species with the higher values of biological productivity. Examples of the Monte-Carlo simulation on the Lambda estimates from the matrices are presented for two of the species analyzed, specifically for the blue shark and the bigeye thresher (Figure 4).

Susceptibility Analysis

The susceptibility analysed for the longline fleet is presented in Table 4. The species more susceptible for the longline fishing fleets are the pelagic thresher followed by blueshark, shortfin mako, bigeye thresher, and smooth hammerhead. Then oceanic whitetip and silky shark are ranked in lower levels of susceptibility and the susceptibility of the rest of species is even lower. With the exception of smooth hammerhead, the coastal shark species are less susceptible for the longline fleets. The overlap between shark species spatial distribution and the spatial distribution of the longline fleet can be observed in Figure 5. According to our results, availability is high for most of the species with values greater than 91 % in all cases with the exception of porbeagle for which an availability of 80 % was estimated. The estimated selectivity varied between 17 % for sandbar shark to 100 % for blueshark, smooth hammerhead and pelagic thresher. In most of the cases this value, with the exception of blueshark and shortfin mako, was estimated with few samples and, thus, as this has a great impact on the final estimation of susceptibility (and hence vulnerability), it should be revisited once better length distribution form observer program are made available. The post-capture mortality varied from very low values of common thresher (18 %) and pelagic stingray (27 %) to values around 88 % for scalloped hammerhead and values larger than 90 % for the rest of species. The post-capture mortality was estimated to be 100 % for pelagic thresher, smooth and great hammerhead, and dusky and sandbar sharks. This is different from what has been observed in other oceans where the post-capture mortality did not reach a 100 % value (Cortes *et al.*, 2010).

The susceptibility analysis for the purse seine fleet is presented in Table 5. The species more susceptible for the purse seine fishing fleets are the oceanig white-tip and silky shark followed by shortfin mako. The rest of species are ranked in much lower levels of susceptibility. The coastal shark species are less susceptible for the purse seiner fleets. The overlap between shark species spatial distribution and the spatial distribution of the purse seiner fleet can be observed in Figure 6. According to our results, availability is intermediate for most of the species whereas is very low for some species such as porbleage and pelagic stingray and, in a lesser extent, for blue shark, commong thresher, dusky shark, smooth hammerhead, and shortfin mako. In any case, the availability estimated for the purse seiner fishery is much lower thatn the one estimated for longline as the latter is covering a larger area in the Indian Ocean. The estimated selectivity varied between 0 % for pelagic tresher and great white shark and to 100 % for oceanic white tip shark but with values lower than 50 % in most of the cases (99 % for silky and 75 % for pelagic stingray). In most of the cases this value, with the exception of silky sark and oceanic white tip shark, was estimated with few samples and, thus, as this has a great impact on the final estimation of susceptibility (and hence vulnerability), it should be revisited once better length distribution form observer program are made available. The post-capture mortality varies from 50 % of scalloped and smooth hammerhead, to values of 60 % of blueshark and larger than 70 % for the rest of the species. The post-capture mortality was estimated to be 100 % for several species, however, it should be taken into account that in most cases only with few specimens were available to estimate the post-capture mortality.

Vulnerability

According to our analysis, for the longline fleet the most vulnerable species are the shortfin mako, bigeye and pelagic thresher, followed by silky shark, oceanic whitetip shark, smooth hammerhead, porbeagle, longfin mako, great hammerhead and blueshark (Table 4 and Figure 7). The first four vulnerable species are characterized by low productivity and high susceptibility; while oceanich whitetip and smooth hammerhead are showing higher productivity but the same level of susceptibility. Porbeagle, longfin mako and great hammerhead are showing low productivity but also lower susceptibility. Blue sharks are the most productivity species but are characterized by the second highest susceptibility. The rest of the species show variable productivity (from lowest to intermediate levels) but lower susceptibility values for the fishery and, thus, they have a lower overall vulnerability corresponding to lower rank of vulnerability (Table 4). Therefore, a priority should be given to those species with may request more attention from a biological point of view but also from a management point of view.

According to our analysis, for the purse seiner fleets the most vulnerable species are the oceanic white-tip and silky shark. The rest of species are ranked in much lower levels of vulnerability. In the purse seiner fleet, the vulnerability is in a large extent defined by the susceptibility of the species to the gear rather than for the productivity of the species. As such, less productive species are not as susceptible as others and, hence, their vulnerability to the purse seine gear is low due to their low availability to the gear (Table 5 and Figure 8). The two most vulnerable species are characterized by medium productivity and high susceptibility. The rest of the species show variable productivity (from lowest to intermediate levels) but lower susceptibility values for the fishery and, thus, they have a lower overall vulnerability corresponding to lower rank of vulnerability (Table 5). Therefore, a priority should be given to those species ranked high with may request more attention from a biological point of view but also from a management point of view.

CONCLUSIONS

Although it was planned to carry out a complete Productivity and Susceptibility analysis for the major fishing fleets operating in the Indian Ocean, due to lack of data the analysis presented here focused only in the longline and purse seiner fishery. Thus, it should be considered as preliminary and a starting point for future analysis as soon as information from other fleets becomes available. However, the study showed that there is a lack of biological parameters information specific for the Indian Ocean for those sharks caught in longline fisheries as well as there is a limited length frequency and post-capture mortality data from observes for most of the longline fleets. Therefore, it is strongly recommended that shark biological information specific to the Indian Ocean as well as observer data compilation is improved and as such the analysis will be improved as observer data compilation becomes available. Taking into account that the current study does not consider the major fleet catching shark (i.e. gillnet) fishery it is strongly recommended to start the compilation of shark fishery data (catch and effort) as well as observer data for the gillnet fleet, because they are also supposed to catch large quantities of shark species both pelagic and coastal species that showed highest intrinsic vulnerability indices.

The PSA analysis carried out in this study can be considered quantitative but restricted to species caught by 6 longline fleets and purse seiner fleet, for which there was enough fishery and observer data available. This kind of global analysis, followed by more concentrated analyses could correspond to different levels within the ERA framework (Hobday *et al.*, 2006), can be regarded as a way to triage or rapidly assess different numbers of species to identify potentially vulnerable species that can then be subject to more detailed and rigorous analyses (Dulvy *et al.*, 2004) as well as data gaps that needs to be filled in immediately and research priorities. In this sense, the present study contributes to rank the vulnerability or relative risk to overexplotation of different shark species harvested by the longline and purse seiner fleet in the Indian Ocean. In summary, for the longline fleet the most vulnerable species are the shortfin mako, bigeye and pelagic thresher, followed by silky shark, oceanic whitetip shark, smooth hammerhead, porbeagle, longfin mako, great hammerhead and blueshark. The first four vulnerable species are characterized by low productivity and high susceptibility; while oceanich whitetip and smooth hammerhead are showing higher productivity but the same level of susceptibility. Porbeagle, longfin mako and great hammerhead are showing low productivity but also lower susceptibility. Blue sharks are the most productivity species but are characterized by the second highest susceptibility. For the purse seiner fleets the most vulnerable species are the oceanic white-tip and silky shark. The rest of species are ranked in much lower levels of vulnerability. Although it is difficult to compare the PSA analysis of different fleets, it is clearly observed from the tables and figures that having the same productivity most of the species are more vulnerable for the longline fleet in comparison with the purse seiner fleet. In the longline fleet, more species are considered at higher vulnerability due to higher susceptibility to the gear in comparison to the purse seiner gear that is showing a lower susceptibility for sharks. Even the highest ranked species in the purse seiner fleet (i.e. oceanic white tip and silky sharks) are showing a lower vulnerability value in the purse seiner than in the longline (Figure 9). However, this comparison should be refined taking into consideration the total catch and effort of different fleets in different areas and periods.

However, the current PSA study does not evaluate the status of the stocks because it does not estimate the fishing mortality neither the biomass in relation to their biological reference points. Nevertheless, it is a step in a good direction to identify the species most vulnerable or more at risks for which more attention should be paid (e.g. data collection, surveys, assessment, etc…) and helps to identify the species most at risk due to a combination of low productivity and high susceptibility to the pelagic longline and purse seiner fleet.

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TABLES

Table 1.- Biological data inputs for the productivity component of the ERA analysis. In bold: data specific to the Indian Ocean; rest of data from the region specified in the "Biological data region" (the North Atlantic corresponds to ICCAT North Stocks). Although information for crocodile shark and whale shark is presented in the table, there was not sufficient information to estimate survivorship and, thus, to apply Leslie matrix for productivity analysis.

Species	Common name	Biological data region	Depth range (m)	Mean litter (n)	Reproductive periodicity (yr)	Female K (yr-1)	L∞ (cm FL)	t0	Median age at maturity (yr)	Female longevity (yr)	S0 (yr-1)	S1+(yr-1)
Alopias superciliosus (BTH)	Bigeye thresher	N Atlantic	*0-700*	**3**	1	0.06	293	102*	**12.5**	22	0.88	0.83-0.92
Alopias pelagicus (xxx)	Pelagic thresher	Pacific	*0-150*	**2**	1***	0.09	197	-7.67	**8.5**	**28**	0.89	0.82-0.97
Alopias vulpinus (ALV)	Common thresher	N Atlantic	*0-370*	**4**	1	0.11	483	121*	**6**	**24**	0.82	0.76-0.93
Carcharhinus falciformis (FAL)	Silky shark	Indian Ocean	*0-500*	**7.2**	**2**	**0.057**	**320.4**	**81.1***	**15**	**35.8**	0.88	0.82-98
Carcharhinus longimanus (OCS)	Oceanic whitetip shark	N Atlantic	*0-152*	5.4	1	0.1	285	-3.39	6	17	0.82	0.78-0.90
Pseudocarcharias kamoharai (PSK)	Crocodile shark	N Atlantic	*0-590*	**4**	-	-	-	-	89 cm	122 cm	-	-
Carcharhinus obscurus (DUS)	Dusky shark	N Atlantic	*0-400*	7	3	0.04	421	-7.04	20	40	0.90	0.80-0.98
Carcharhinus plumbeus (CCP)	Sandbar shark	N Atlantic	*0-280*	8.4	2.5	0.12	181.15	-2.33	15.5	24	0.82	0.71-0.94
Galeocerdo cuvier (GAC)	Tiger shark	Indian Ocean	*0-140*	**55**	**2**	**0.202**	**301**	**-1.11**	**11**	29	0.77	0.56-0.99
Isurus oxyrinchus (SMA)	Shortfin mako	N Atlantic	*0-500*	**15**	**2**	0.054	432	70*	**18**	**32**	0.87	0.78-0.97
*Isurus paucus (LMA)***	Longfin mako	N Atlantic	*0-200*	4	2	0.054	432	70*	**14**	32	0.87	0.78-097
Lamna nasus (POR)	Porbeagle	N Atlantic	*0-700*	**4**	1	0.061	289	-5.9	14	**26**	0.88	0.81-0.93
Prionace glauca (BSH)	Blue shark	N Atlantic	*0-220*	**38**	**1**	0.15	375	-0.87	**5**	**21**	0.71	0.72-091
Pteroplatytrygon violacea (PLS)	Pelagic stingray	N Atlantic	*0-240*	6	0.5	0.2	116	17*	3	12	0.64	0.58-0.88
Sphyrna lewini (SPL)	Scalloped hammerhead	N Atlantic	*0-512*	**17**	2	0.09	303	-2.22	15	31	0.84	0.76-0.94
Sphyrna mokarran (SPM)	Great hammerhead	N Atlantic	*0-300*	**28**	2	0.13	286.7	-2.51	20	42	0.89	0.81-0.98
Sphyrna zygaena (SPZ)	Smooth hammerhead	N Atlantic	*0-200*	**33**	1	0.07	285	-7.3	9	18	0.85	0.85-0.90
Rhincodon typus	Whale shark	Indian Ocean	*0-250*	**55**	-	**0.032**	**1496**	**0.85**	**30 yr (males)**	**1900 cm**	-	-
Carcharodon carcharias	Great white shark	Indian Ocean	*0-250*	**10**	**2**	**0.07**	**660**	**-2.33**	**9.5**	**36**	**0.80**	**0.71-0.99**

* L0 (cm): FL for BTH, ALV, SMA, LMA, DW for PLS; TL for FAL; ** All parameters, except for litter size and reproductive frequency, as for shortfin mako; *** Reproductive periodicity assumed to be 1, similar to other species in the same genus.

Table 2- Available data to estimate susceptibility parameters in the longline fleet.

			Susceptivility			
FAO Code	**Species/Stock**	**Common name**	**Availability**	**Encounterability**	**Selectivity**	**Post-capture mortality**
CCP	*Carcharhinus plumbeus*	Sandbar shark	All	All	Korea	Korea
DUS	*Carcharhinus obscurus*	Dusky shark	All	All	Korea (2 specimens)	Korea
LMA	*Isurus paucus*	Longfin mako	All	All	Portugal/Japan/Korea/USSR	Portugal
BTH	*Alopias superciliosus*	Bigeye thresher	All	All	Portugal/Japan/USSR	Portugal/Korea
POR	*Lamna nasus*	Porbeagle	All	All	Japan/Korea	Portugal/Korea
SMA	*Isurus oxyrinchus*	Shortfin mako	All	All	Portugal/Japan/Korea/USSR	Portugal/Reunion/Korea
SPL	*Sphyrna lewini*	Scalloped hammerhead	All	All	Korea (4 specimens)	Portugal/Reunion/Korea
FAL	*Carcharhinus falciformis*	Silky shark	All	All	Portugal/Japan/Korea/USSR	Portugal/Reunion/Korea
PTH	*Alopias pelagicus*	Pelagic thresher	All	All	Japan/Korea	Korea
SPM	*Sphyrna mokarran*	Great hammerhead	All	All	n/a	Portugal
WSH	*Carcharodon carcharias*	Great white shark	All	All	n/a	n/a
GAC	*Galeocerdo cuvier*	Tiger shark	All	All	Portugal/Korea	Portugal/Korea
ALV	*Alopias vulpinus*	Common thresher	All	All	Japan	n/a
OCS	*Carcharhinus longimanus*	Oceanic whitetip shark	All	All	Portugal/Japan/Korea/USSR	Portugal/Reunion/Korea
PLS	*Pteroplatytrygon violacea*	Pelagic stingray	All	All	China/Korea (few specimens)	Portugal/Reunion/Korea
SPZ	*Sphyrna zygaena*	Smooth hammerhead	All	All	Portugal/Japan/Korea	Portugal/Korea
BSH	*Prionace glauca*	Blue shark	All	All	Portugal/Japan/Korea/China/USSR	Portugal/Reunion/Korea

Table 3- Productivity parameters for shark species captured and impacted in pelagic fisheries in the Indian Ocean in the IOTC area. The species list is sorted from lower to higher biological productivity.

FAO Code	Species/Stock	Common name	Lambda	95%CI (low)	95%CI (upp)
CCP	*Carcharhinus plumbeus*	Sandbar shark	0.978	0.950	1.005
DUS	*Carcharhinus obscurus*	Dusky shark	1.027	1.009	1.044
LMA	*Isurus paucus*	Longfin mako	1.029	1.007	1.049
BTH	*Alopias superciliosus*	Bigeye thresher	1.033	1.017	1.047
POR	*Lamna nasus*	Porbeagle	1.041	1.024	1.057
SMA	*Isurus oxyrinchus*	Shortfin mako	1.061	1.040	1.081
SPL	*Sphyrna lewini*	Scalloped hammerhead	1.062	1.039	1.083
FAL	*Carcharhinus falciformis*	Silky shark	1.075	1.057	1.093
PTH	*Alopias pelagicus*	Pelagic thresher	1.098	1.075	1.119
SPM	*Sphyrna mokarran*	Great hammerhead	1.098	1.079	1.115
WSH	*Carcharodon carcharias*	Great white shark	1.117	1.077	1.155
GAC	*Galeocerdo cuvier*	Tiger shark	1.147	1.078	1.211
ALV	*Alopias vulpinus*	Common thresher	1.148	1.114	1.181
OCS	*Carcharhinus longimanus*	Oceanic whitetip shark	1.162	1.132	1.192
PLS	*Pteroplatytrygon violacea*	Pelagic stingray	1.242	1.156	1.323
SPZ	*Sphyrna zygaena*	Smooth hammerhead	1.281	1.257	1.303
BSH	*Prionace glauca*	Blue shark	1.483	1.414	1.546

Table 4- Productivity and susceptibility analysis for shark species captured and impacted in pelagic Longline fisheries in the Indian Ocean in the IOTC area.

			Productivity	Susceptibility					Vulnerability	
FAO Code	**Species/Stock**	**Common name**	**Lambda**	**Availability**	**Encounterability**	**Selectivity**	**Post-captura mortality**	**Susceptibility**	**Vulnerability**	**RANK**
SMA	*Isurus oxyrinchus*	Shortfin mako	1.061 (1.040-1.081)	0.963	1.000	0.970	0.994	0.929	0.094	1
BTH	*Alopias superciliosus*	Bigeye thresher	1.033 (1.017-1.047)	0.968	1.000	0.968	0.970	0.909	0.097	2
PTH	*Alopias pelagicus*	Pelagic thresher	1.098 (1.075-1.119)	0.974	1.000	0.997	1.000	0.971	0.102	3
FAL	*Carcharhinus falciformis*	Silky shark	1.075 (1.057-1.093)	0.961	1.000	0.925	0.990	0.880	0.142	4
OCS	*Carcharhinus longimanus*	Oceanic whitetip shark	1.162 (1.132-1.192)	0.961	1.000	0.939	0.974	0.880	0.202	5
SPZ	*Sphyrna zygaena*	Smooth hammerhead	1.281(1.257-1.303)	0.909	1.000	0.997	0.997	0.904	0.298	6
POR	*Lamna nasus*	Porbeagle	1.041 (1.024-1.057)	0.796	1.000	0.885	0.905	0.638	0.364	7
LMA	*Isurus paucus*	Longfin mako	1.029 (1.007-1.049)	0.956	1.000	0.600	0.992	0.569	0.432	8
SPM	*Sphyrna mokarran*	Great hammerhead	1.098 (1.079-1.115)	0.925	1.000	0.622**	1.000	0.575	0.436	9
BSH	*Prionace glauca*	Blue shark	1.483 (1.414-1.546)	0.952	1.000	0.996	0.984	0.933	0.489	10
GAC	*Galeocerdo cuvier*	Tiger shark	1.147 (1.078-1.211)	0.923	1.000	0.521	0.903	0.434	0.585	11
DUS	*Carcharhinus obscurus*	Dusky shark	1.027 (1.009-1.044)	0.943	1.000	0.245	1.000	0.231	0.770	12
PLS	*Pteroplatytrygon violacea*	Pelagic stingray	1.242 (1.156-1.323)	0.941	1.000	0.758	0.370	0.264	0.775	13
SPL	*Sphyrna lewini*	Scalloped hammerhead	1.062 (1.039-1.083)	0.942	1.000	0.246	0.875	0.203	0.799	14
CCP	*Carcharhinus plumbeus*	Sandbar shark	0.978 (0.950-1.005)	0.935	1.000	0.172	1.000	0.161	0.840	15
ALV	*Alopias vulpinus*	Common thresher	1.148 (1.114-1.181)	0.970	1.000	0.562	0.180*	0.098	0.914	16
WSH	*Carcharodon carcharias*	Great white shark	1.117 (1.077-1.155)	0.974	1.000	n/a	n/a	n/a	n/a	n/a

* Mean selectivity of *Sphyrna lewini* and *Sphyrna zygaena*

** From Cortes et al., 2010

Table 5- Productivity and susceptibility analysis for shark species captured and impacted in the Purse Seiner fisheries in the Indian Ocean in the IOTC area.

			Productivity	Susceptibility					Vulnerability	
FAO Code	**Species/Stock**	**Common name**	**Lambda**	**Availability**	**Encounterability**	**Selectivity**	**Post-captura mortality**	**Susceptibility**	**Vulnerability**	**RANK**
OCS	*Carcharhinus longimanus*	Oceanic whitetip shark	1.162 (1.132-1.192)	0.694	1.000	1.000	0.981	0.681	0.358	1
FAL	*Carcharhinus falciformis*	Silky shark	1.075 (1.057-1.093)	0.676	1.000	0.989	0.736	0.492	0.514	2
SMA	*Isurus oxyrinchus*	Shortfin mako	1.061 (1.040-1.081)	0.525	1.000	0.450	1.000	0.236	0.766	3
SPM	*Sphyrna mokarran*	Great hammerhead	1.098 (1.079-1.115)	0.667	1.000	0.273	1.000	0.182	0.824	4
PLS	*Pteroplatytrygon violacea*	Pelagic stingray	1.242 (1.156-1.323)	0.267	1.000	0.758	0.673	0.136	0.897	5
SPL	*Sphyrna lewini*	Scalloped hammerhead	1.062 (1.039-1.083)	0.587	1.000	0.219	0.500	0.064	0.938	6
SPZ	*Sphyrna zygaena*	Smooth hammerhead	1.281 (1.257-1.303)	0.480	1.000	0.327	0.500	0.078	0.964	7
LMA	*Isurus paucus*	Longfin mako	1.029 (1.007-1.049)	0.714	1.000	0.044	1.000	0.003	0.969	8
DUS	*Carcharhinus obscurus*	Dusky shark	1.027 (1.009-1.044)	0.510	1.000	0.055	1.000	0.028	0.973	9
GAC	*Galeocerdo cuvier*	Tiger shark	1.147 (1.078-1.211)	0.661	1.000	0.057	1.000	0.038	0.974	10
ALV	*Alopias vulpinus*	Common thresher	1.148 (1.114-1.181)	0.433	1.000	0.082	1.000	0.036	0.976	11
BTH	*Alopias superciliosus*	Bigeye thresher	1.033 (1.017-1.047)	0.624	1.000	0.022	1.000	0.014	0.987	12
CCP	*Carcharhinus plumbeus*	Sandbar shark	0.978 (0.950-1.005)	0.652	1.000	0.000	1.000	0.000	1.000	13
POR	*Lamna nasus*	Porbeagle	1.041 (1.024-1.057)	0.057	1.000	0.005	1.000	0.000	1.001	14
PTH	*Alopias pelagicus*	Pelagic thresher	1.098 (1.075-1.119)	0.714	1.000	0.000	1.000	0.000	1.005	15
WSH	*Carcharodon carcharias*	Great white shark	1.117 (1.077-1.155)	0.473	1.000	0.000	1.000	0.000	1.007	16
BSH	*Prionace glauca*	Blue shark	1.483 (1.414-1.546)	0.451	1.000	0.102	0.600	0.028	1.086	17

FIGURES

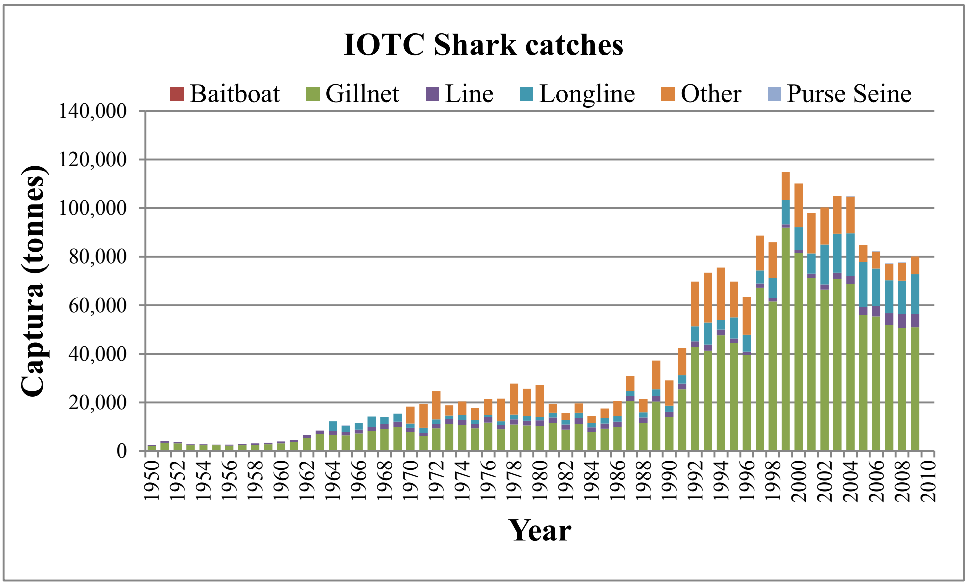
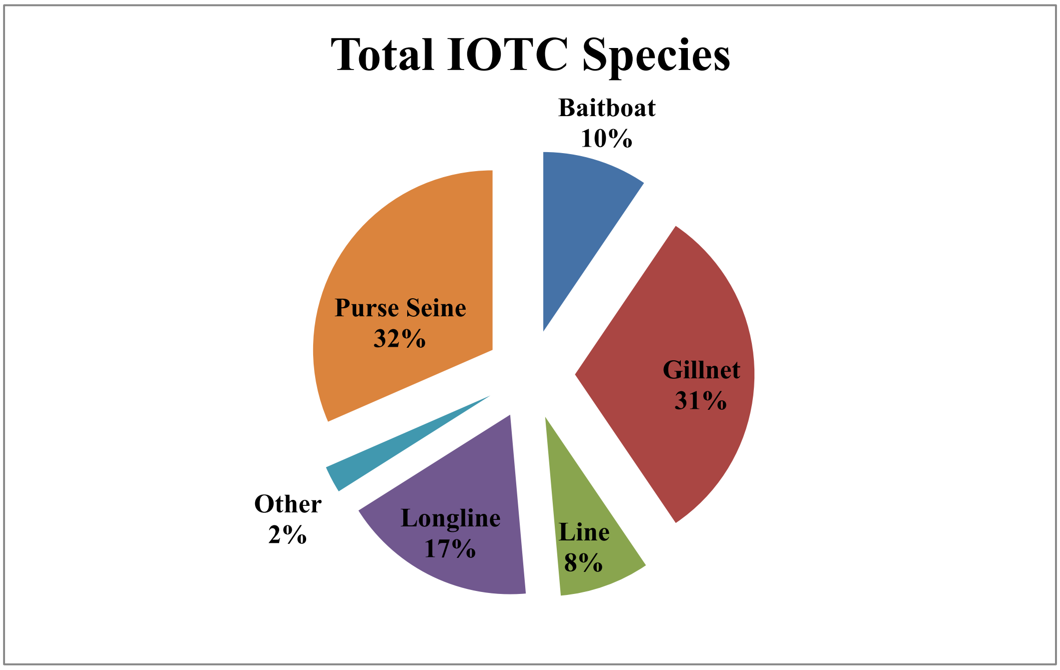


Figure 1.- Total nominal catch of IOTC Shark species for the period 1950-2010.



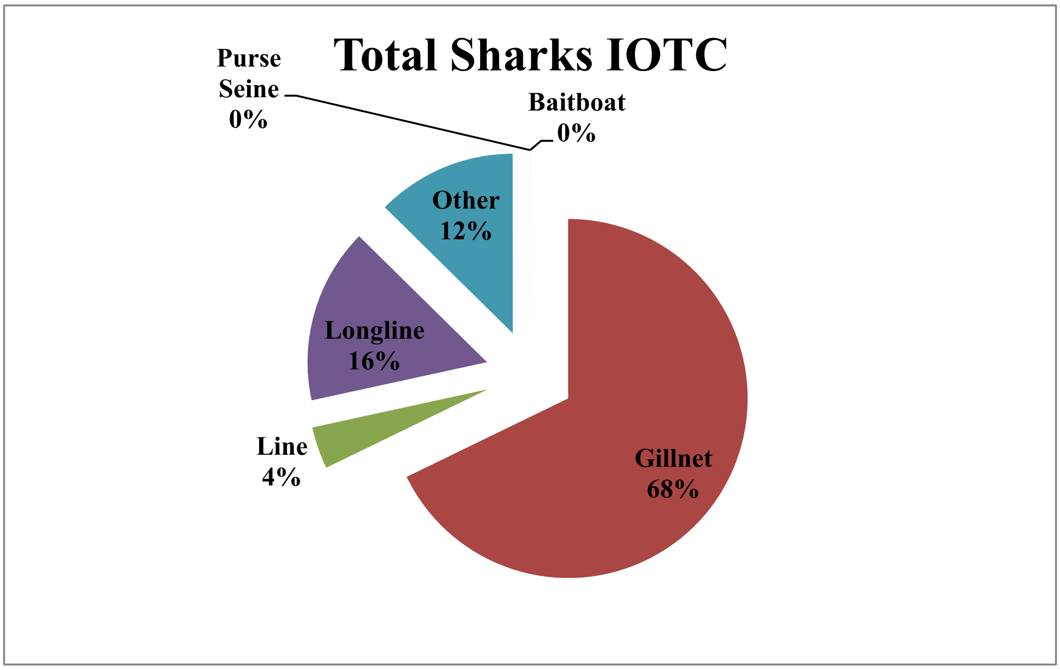


Figure 2.- Relative contribution to total IOTC species catch and total IOTC shark catch by different gears for the period 2000-2009.

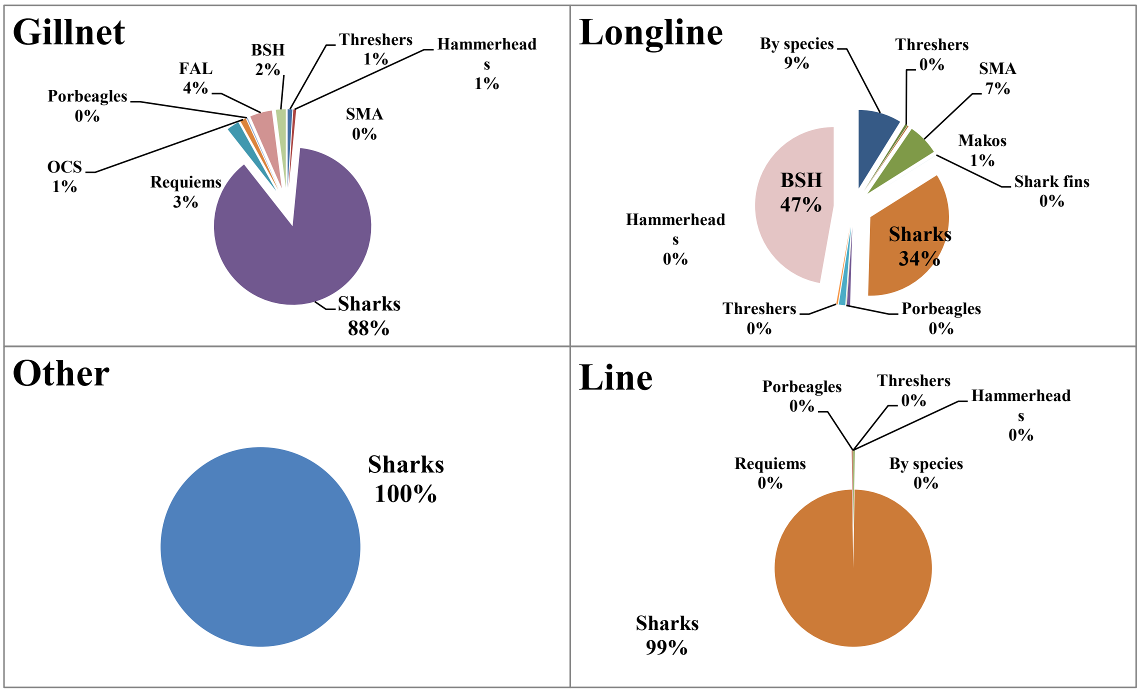


Figure 3.- Relative contribution of different species group and different species to total shark catches by gears for the period 2000-2009.

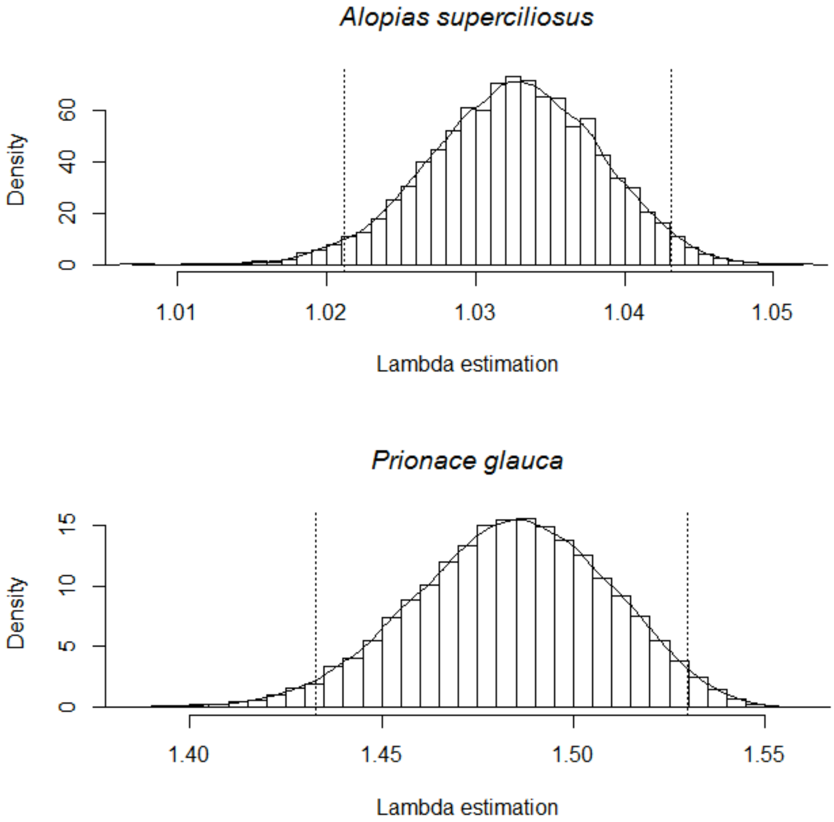


Figure 4.- Frequency distribution of Lambdas estimated by Monte-Carlo simulation (10,000 runs) for the bigeye thresher and the blue shark. The vertical lines represent the 95% confidence interval in the data, defined by the 0.025 and 0.975 quantiles of the distribution.

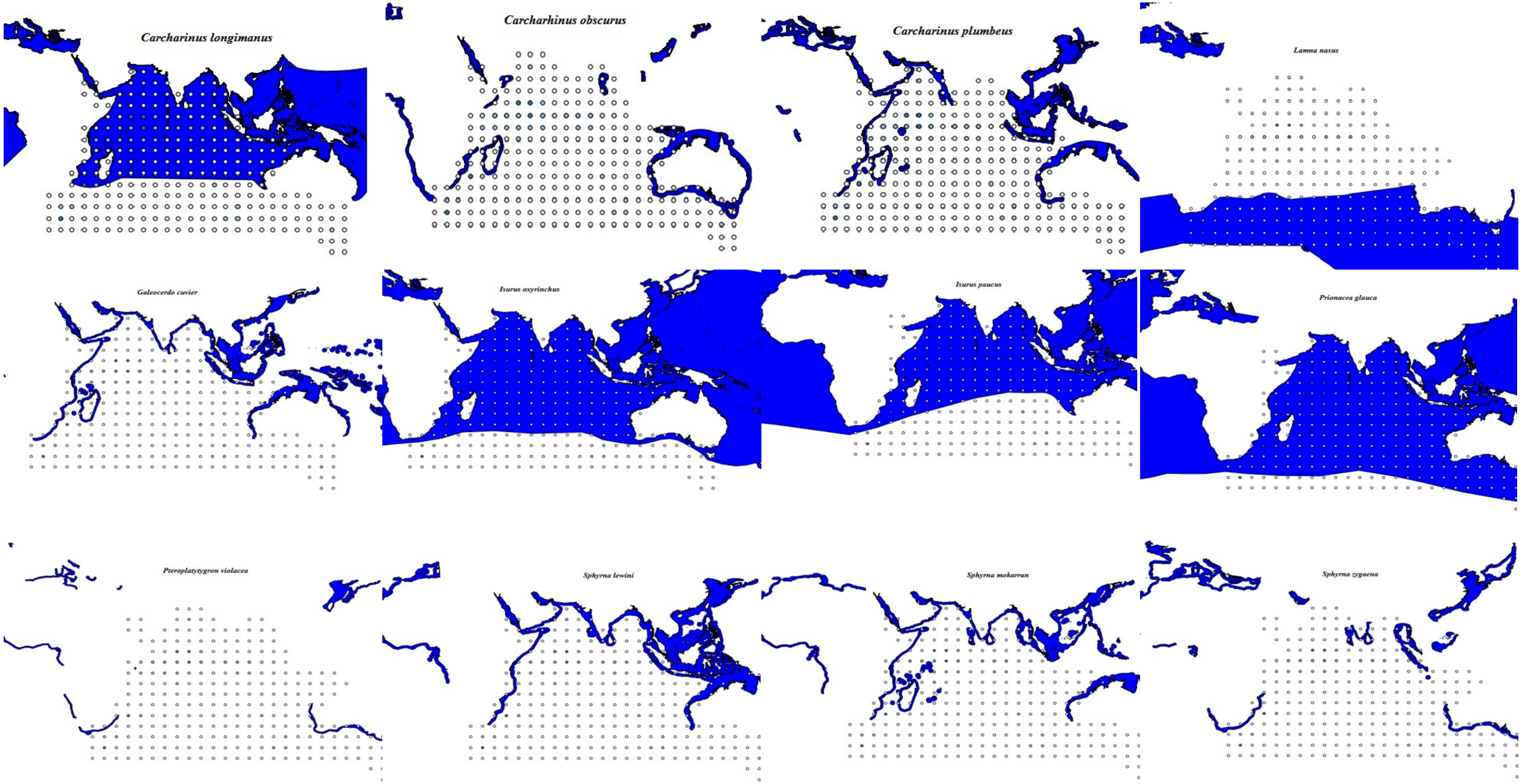


Figure 5.- Overlap between shark species distribution area (blue; source: IUCN SSG GMSA species distribution maps) and Longline total effort (total number of hooks) distribution for the Portuguese; Japanese, Reunion, Chinese, Taiwanese, and Spanish Longline fleet for the period 1950-2010.

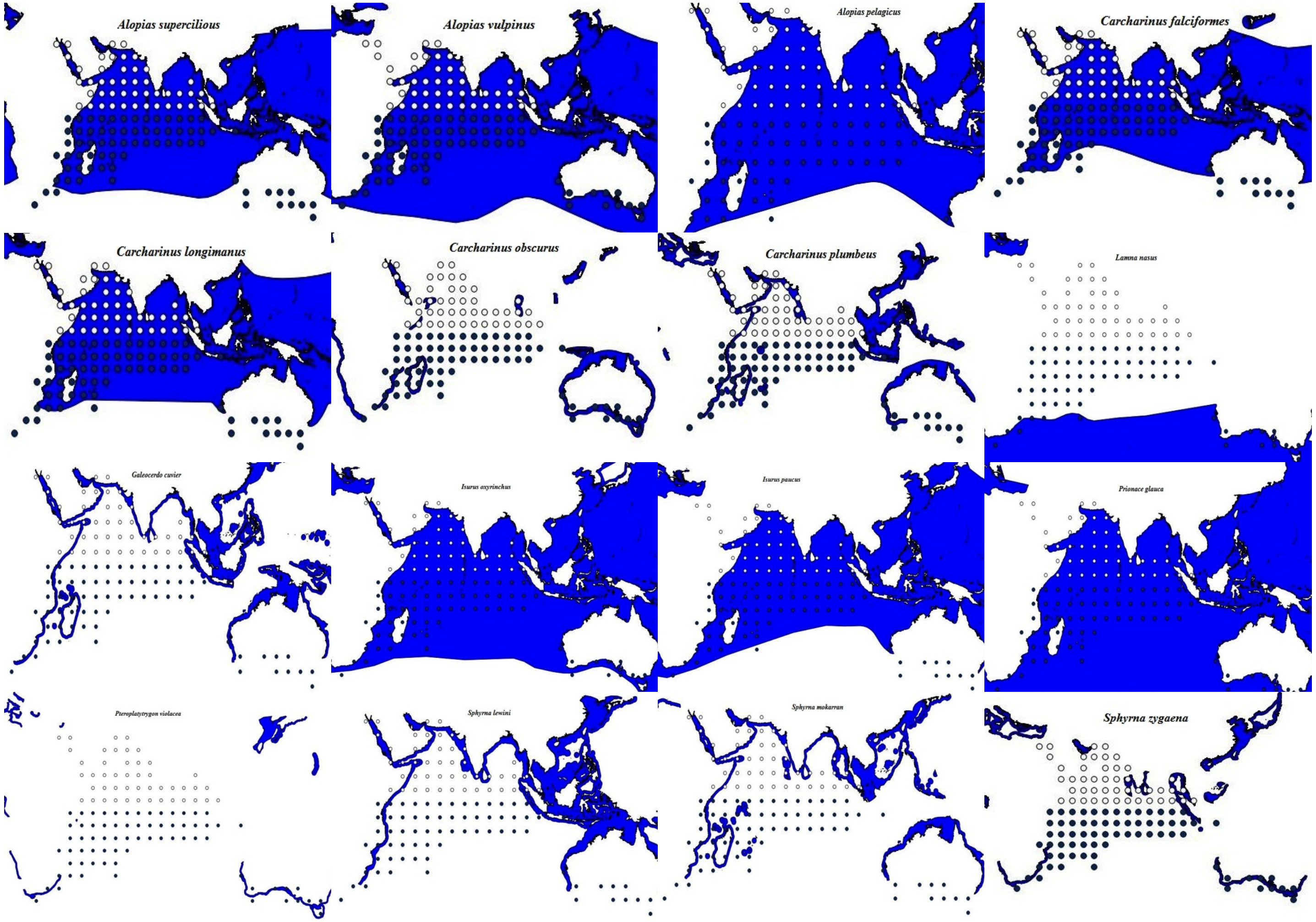


Figure 6.- Overlap between shark species distribution area (blue; source: IUCN SSG GMSA species distribution maps) and purse seiner total effort (total number of days/hours) for the period 1990-2010.

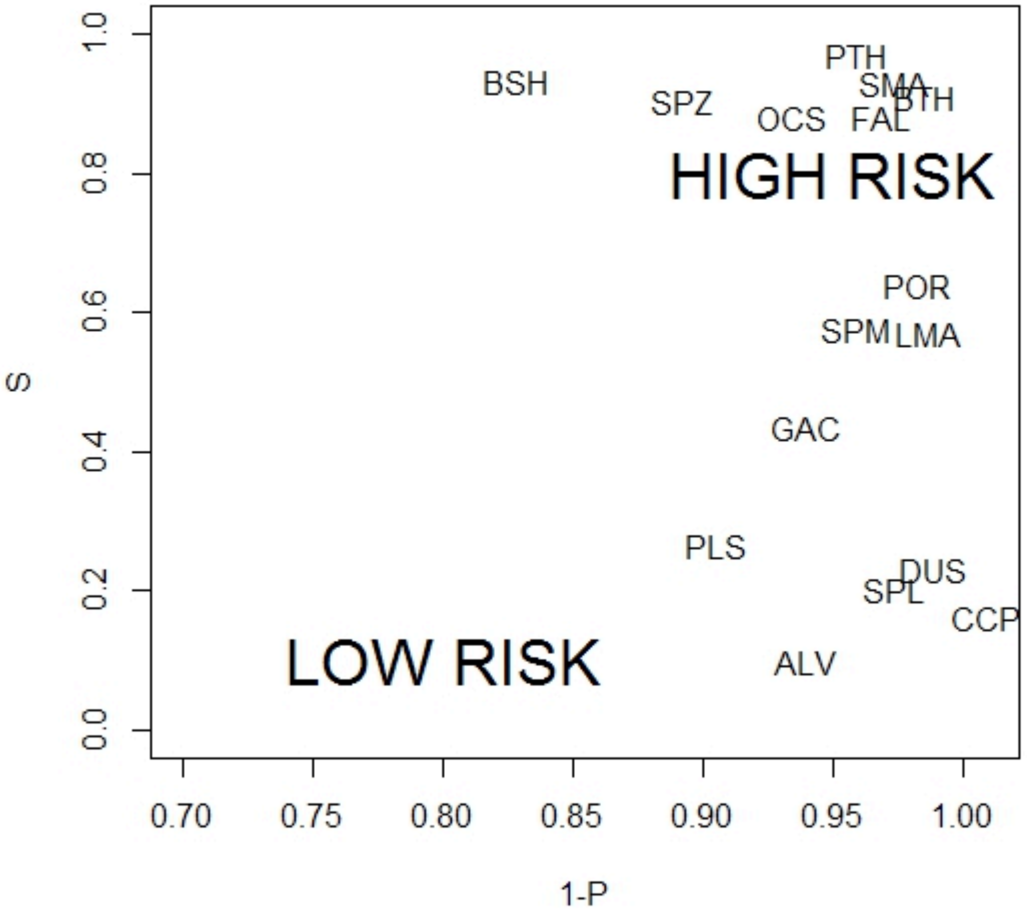


Figure 7.- Productivity susceptibility analysis for species caught by IOTC Longline fleet.

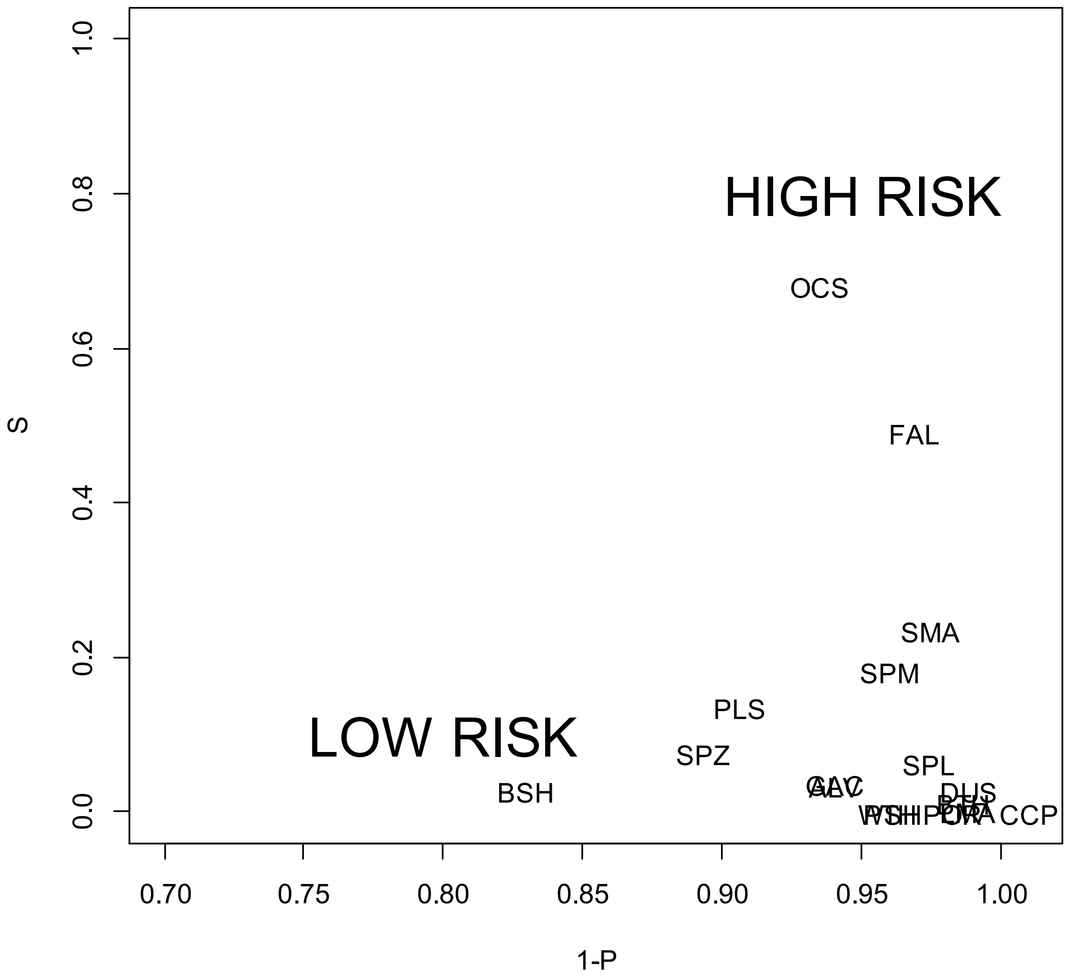


Figure 8.- Productivity susceptibility analysis for species caught by IOTC Purse seiner fleet.

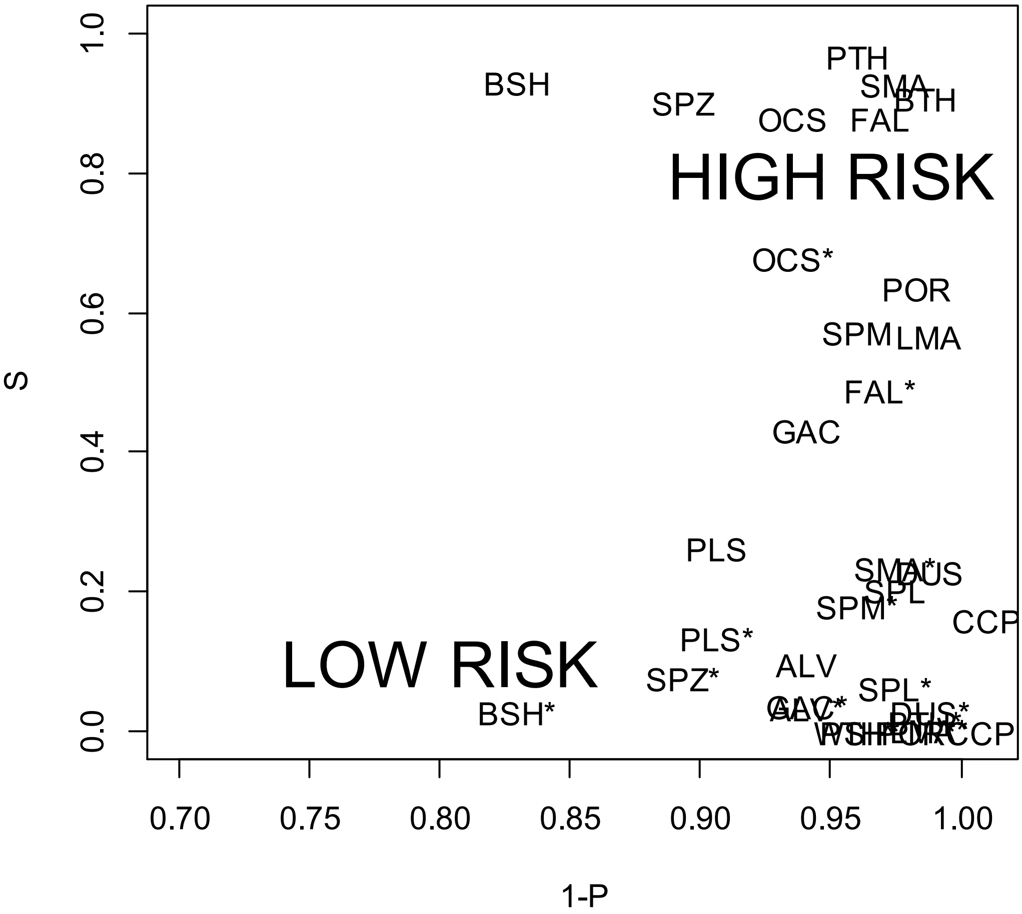


Figure 9.- Productivity susceptibility analysis for species caught by IOTC Purse seiner fleet (*) and longline.