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Impact de la pêche thonière à la senne sur les communautés pélagique de l'océan Atlantique et de l'océan Indien : comparaison de la pêche sous dispositifs de concentration de poissons et de la pêche en bancs libres.

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Titre français : Impact de la pêche thonière à la senne sur les communautés pélagiques de l'océan Atlantique tropical et de l'océan Indien : comparaison de la pêche sous dispositifs de concentrations de poissons et sur bancs libres.

Titre anglais : Impact of purse-seine tuna fishery on pelagic communities in the Tropical Atlantic and Indian Oceans: comparison of fishing on Fish Aggregating Devices and on Free-Swimming schools.

Résumé : La pêche sous DCP rejette 10% de ses captures contre 3% en bancs libres. Sur les 114 taxa observés entre l'océan Atlantique et l'océan Indien un total de 68 taxa étaient communs aux deux océans, 13 exclusifs à l'océan Atlantique et 34 à l'océan Indien. Pour éviter des soucis d'identification d'espèces, un total de 22 groupes taxonomiques ont été développés. Les analyses de richesse, diversité et d'équitabilité conduites sur ces 22 groupes ont montré que ces index étaient plus élevés sous DCP et dans l'océan Indien. En même temps, les analyses de niveaux trophiques et de classe de taille ont révélé que le niveau trophique moyen des prises accessoires était plus haut sur bancs libres que sous DCP en même temps que les classes de taille étaient légèrement plus petites sous DCP. La pêche sous DCP capture des individus plus petits et de niveau torchis plus faible en plus grande proportion. Les spectres de biomasse-taille construits dans cette étude ont révélé des différences significatives entre les modes de pêche et les océans. La pêche sous DCP impacte plus les communautés marines et une plus grosse part de l'écosystème. La majeure partie des requins soyeux attrapés par la pêche à seine française est capturée sous la DCP et est principalement caractérisée par des individus immatures. Le modèle a montré des effets spatiaux et temporels forts sur les niveaux de captures accessoires de requins soyeux. La côte somalienne et l'intérieur du Golfe de Guinée sont des zones fortement sujettes aux prises accessoires de requins soyeux et pourraient être protégées afin réduire les captures de cette espèce. Les résultats de notre modèle multispécifique ont révélé des effets spatiaux et temporels sur les valeurs de l'indice de diversité de Simpson qui pourraient être utilisés dans le cadre d'une gestion écosystémique des pêcheries thonières à la seine.

Mots-clés : Captures accessoires, Dispositifs de Concentration de Poissons, Modèle zéro-inflaté, Indices de diversité, Spectre de biomasse-taille

Abstract: FAD-fishing discards 10% of its capture versus 3% in FSC-fishing. In the 114 taxa observed between the Atlantic and the Indian ocean a total of 68 taxa were common to both oceans, 13 exclusive to the Atlantic and 34 to the Indian ocean. To avoid species identification issues, a total of 22 taxonomic groups were developed. The richness, the diversity and the equitability analysis conducted on those 22 groups showed that these index were higher under FAD and in the Indian ocean. At the same time, trophic and length class analysis revealed that the mean trophic level of the bycatch was higher on FSC than under FAD and length class were slightly smaller under FAD. FAD fishing catches smaller individual of a larger portion of lower trophic level. The biomass-size spectra constructed in this study revealed significant difference between fishing modes and oceans. Fishing under FAD impact more marine communities and a larger part of the ecosystem. Most of silky sharks caught by the french tuna purse-seine fishery are captured under FAD and are mainly dominated by immature individuals. The model showed a strong spatial and temporal effect on the silky sharks bycatch level. The Somalian coast and the inner Guinean Gulf are hotspots of silky sharks bycatch and could be protected in order to reduce the capture of this species. The results of our multispecific model have shown spatial and seasonal pattern characterised by high and low value of Simpson diversity index and could be used for an ecosystem based fishery management for tuna purse-seine fisheries.

Key Words: Bycatch, Fish Aggregating Device,, Zero-inflated model, Diversity indicators, Biomass-size spectrum.

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Introduction:

Tuna fisheries exploitation effects not only target species populations but can also affect the associated communities structure and diversity by removing non-target species through bycatch. Following the PCP reform (a discard ban) and public perception, an ecosystem approach to tuna fisheries management is a strongly recommended goal (Pikitch et al. 2004; Levin et al.2009; Mc Leod and Leslie 2009). The degree to which fisheries affect the structure and function of ecosystems depends on the biomass, composition, life history, and ecological role of the different species captured (Gerrodette et al. 2012). Purse-seine fishing is conducted in the Tropical Atlantic and Indian Oceans in two main ways: fishing on Free-Swimming Schools (FSC) or on Fish Aggregating Device (FAD, Annex 1). Tuna are known for aggregating in proximity of floating objects, both natural and artificial. Many types of FAD can be distinguished: natural floating objects or artificial object for example. Tropical tuna fishery is a multi species fishery targeting yellowfin tuna (YFT, *Thunnus albacares*), skipjack (SKJ, *Katsuwonus pelamis*), bigeye tuna (BET, *Thunnus obesus*) and, to a lesser extent, albacore tuna (ALB, *Thunnus alalunga*). A significant amount of non-target species such as billfishes, sharks, rays and miscellaneous fishes are caught. Where catch refers to all animals captured and removed from the ocean, discards refers to all animals dropped back dead, most of the time, in the ocean. bycatch is the part of the catch that is not targeted by fishermen (Kelleher 2005) and can be either discarded (because the animals are too small, damaged or have no value) or retained on board as byproduct when having a high value in local market (Hall 1996; Romagny et al. 2000). bycatch is thus distinct from discarded catch even if bycatch species caught are often discarded. Both fishing methods (FAD and FSC) produce bycatch in different species composition and proportion. Reduction of bycatch is an explicit goal of the Food and Agriculture Organisation's (FAO) guidelines for responsible fisheries management plans. The european project 'Catch, Effort, and eCOsystem impacts of FAD-fishing' (CECOFAD) pursues to improve the knowledge on Fish Aggregating Device and provide reliable estimates of abundance indices and accurate indicator on the impact of FAD-fishing on juveniles of tuna and on bycatch species. This project, co-Financed under European Fisheries Policy and the DG MARE policy is supervised by IRD (Institut de Recherche pour le Développement) in association with AZTI and IEO (Spanish research institutes). Its main objectives are: (i) to define a unit of fishing effort for purse seiners using FAD that accounts for different factors influencing catchability, (ii) to standardize catch-per-unit-effort series of the EU purse-seine fleet, and (iii) to provide information on catch composition around FAD and estimate impacts on other marine organisms. The project is structured in four working packages: (WP1) defining a unit of fishing effort for purse-seiners using FAD, (WP2) standardizing the catch-per-unit-effort of the EU purse-seine fleet and exploring some FAD-regulations in management strategies, (WP3) alternatives to catch rates and (WP4) providing information on catch composition around FAD and estimating potential impacts on other marine organisms. The present study is conducted within the framework of the WP4. Data were derived from observer trips conducted during 2005-2014 in the Tropical Atlantic and Indian Oceans within the framework of the European 'Data collection Regulation DCF' (Reg. 1543/2000) for the recent period. FAD-fishing bycatch is greater than that obtained from fishing on FSC (Amandé et al 2008). In his study, Gerrodette (2012) studied bycatch in tuna purse-seine in the western Pacific Ocean by using diversity indexes, trophic analyzes etc. The main purpose of this study is to extend previous assessments of these purse-seine fisheries by (1) quantifying the impact on targeted and bycatch species captured by purse-seine fishing for tuna in the Atlantic and Indian Oceans, (2) using descriptors of the composition of total

capture (catch and bycatch) in terms of species diversity, numbers of individuals, weight, etc. and through these previous goals (3) giving some help for an ecosystem approach to purse-seine fisheries management. A special interest is carried on endangered or vulnerable species defined by the 'Convention on International Trade in Endangered Species of Wild Fauna and Flora' (CITES) and Regional Fisheries Management Organisations (RFMOs) such as sharks (*Carcharhinus falciformis*, the silky shark and *Carcharhinus longimanus*, the oceanic whitecap shark), turtles (*Lepidochelis olivacea*, the olive ridley turtle and *Chelonia mydas*, the green turtle) and rays (*Manta birostris*, the giant manta).

1 Materials and Methods

1.1 Data

1.1.1 Data collection

Records for the french purse-seine fisheries were collected by observer trips conducted during 2005-2014 within the framework defined by the European Council Regulation n° 1543/2000 and the European Commission Regulation n° 1639/2001, targeting the whole purse-seine bycatch species. The data collection process takes place in a large sampling project attempting to collect data on tuna fisheries. This sampling plan is subdivided in two main strategies: a sampling effort focused on tuna and conducted in the harbour (data from this approach are compiled in a large database called Balbaya), the second sampling approach is conducted directly on board and focused on bycatch species and discarded tuna (data are then compiled in the database Obstuna). The average coverage rate in the DCF IRD (Table 1) has been computed in the ratio $\frac{observedProduction}{totalProduction}$. The coverage rate in the Indian Ocean is widely below than in the Atlantic Ocean. Observers onboard have to fill five forms : (A) Shipping route and environmental parameters, (B) Fishing set characteristics, (C1) tuna length and weight samples, (C2) bycatch length and weight samples and finally (D) FAD description and characteristics. For the species identification, observers have been trained. Depending on the qualification and skills of the observer, some bycatch species may have been grossly identified and classified at genus or family level. Generally the catch is boarded and observers have to select a representative sample of bycatch by sampling 100 to 150 individuals. Sampling the bycatch and discard is the priority: estimations of weight, length class distribution and number of individual caught. Sometimes, when the net is opened in the sea without being boarded, the observers have to register the weight estimated by the captain.

Table 1: Coverage rate of the french purse-seine fisheries in the Atlantic and Indian Ocean

	Year	Average coverage rate		Year	Average coverage rate
Atlantic	2006	7.3	Indian	2006	3.1
	2007	10.5		2007	8.4
	2008	14.2		2008	10.7
	2009	9.6		2009	NA
	2010	15.7		2010	NA
	2011	11.8		2011	4.1
	2012	14.9		2012	9.5
	2013	16.5		2013	8.3

For most species, the fork length is preferred rather other length measurements. The fork length is the distance in a straight line from the tip of the nose to the fork of the

tail. For billfishes, the straight line starts from the tip of the lower jaw, for rays, the width is measured and for sharks or some fishes such as balistidae, observers measure the total length. All the length are taken at the centimetre below. Twenty random individuals (taken as a representative subsample) from the 100-150 sampled individuals are measured. When it is possible, the observer has to determine the sex of the individual. Observers sample bycatch species giving priority to certain species following the order below:

(i) Selachians - Sharks and Rays

(ii) Turtles

(iii) Billfishes - Marlins, Sailfishes and Swordfishes

(iv) Miscellaneous fishes

1.1.2 Data description

Data collected by observer trips (table 2) are organized in a R-data object with multiple tables ("tr" fishing trip details, "hh" fishing station details, "hl" samples, "sl" species details). The organization of the R-data file is described by the entity diagram (Annex 2 - entity diagram). The sampling method is explained in a manual given to the observers which describes the different handling the observers have to do depending on what species occur in the net.

Table 2: Number of french purse-seine set sampled by observers program in the Atlantic and Indian Ocean. ** Fish Aggregating Device [a] Free-Swimming Schools*

Ocean	mode	Positive sets	Null sets	Total
Atlantic	FAD*	548	13	561
	FSC[a]	753	204	957
Indian	FAD	993	48	1 041
	FSC	751	361	1 112

Observers recorded the month, the time (hour/minutes), the ocean ("AtlOcean" for Atlantic Ocean, "IndOcean" for Indian Ocean) or more precisely the FAO area or the statistical square ("area" for the FAO fishing area, and "rect" for the 1°x1° statistical square), the type of fishing set ("FAD" or "FSC"), estimations of total weight of catch including bycatch ("wt" if it is from the logbook or "subSampWt" from the samples), length (subdivided in length classes of one centimetre each : "lenCls"), geographic location of the fishing set (geographic coordinates "lonIni" and "latIni"), species or at least genus encountered ("spp"), the commercial category (discard "DIS" or landed "LAN"). There is an important inter-annual variability in terms of number of purse seine sets regardless of the ocean or the fishing method. We thus decided to conduct this work at the scale of the whole study period rather at a year scale (table 2). The amount of FAD sets in the Indian Ocean is twice higher than in the Atlantic Ocean, even if there was an interruption/reduction of any fishing activity in the Indian Ocean between 2009 and 2010. Seasons have been defined (warm season from December to May or cold season from June to November in the Atlantic and austral summer from October to march or austral winter April to September in the Indian Ocean).

1.2 Species composition and diversity indexes

In addition of studying the catch composition in terms of species list, using taxonomic richness, evenness and diversity indexes is a simple way to describe community and regional diversity.

1.2.1 Taxonomic richness, diversity and evenness

A. Taxonomic richness

We estimated the richness in purse-seine sets by computing the taxonomic richness indexes S_{obs} for all the modalities of the factors of interest (year, fishing mode). The best way to compare taxonomic richness between different strates is to build rarefaction curves. Those curves are used first to show up the richness in a strate. Because hypothetical rarefaction curves should converge to an asymptote, we could use the curves build from the data to decide if there were enough sets to sample the total richness of the strate (asymptote reached or not) (Gotelli et al. 2001). Sample size (here the number of sets) strongly influences taxonomic richness. To deal with this bias, we applied a bootstrap procedure and randomly took with replacement 400 sets from the total number of sets in a modality of a given factor. This procedure was repeated 500 times and a $S_{boot,i}$ was calculated for all the samples $i = 1, \cdots, 500$. Finally we computed the mean and standard deviation of the bootstrap samples $S_{boot,i}$ for each modality and for all the factors of interest.

B. Taxonomic diversity and evenness

For practical and interpretational reasons, *Simpson* diversity and *Simpson* evenness indexes (λ and $E_{Simpson}$) (Equations 1 and 2) were used to compare taxonomic diversity and evenness among oceans and fishing methods (Hortal et al. 2006, Magurran 1988).

$$\lambda = 1 - \Sigma_{i=1}^{S}(p_i^2) \quad \textbf{(1)}$$

$$E_{Simpson} = \frac{1 - D}{1 - \frac{1}{S}} \quad \textbf{(2)}$$

With p_i the proportion of biomass belonging to the ith species, S the number of present species and $D = \Sigma_{i=1}^{S}(p_i^2)$

Where λ is the probability for drawing randomly two different species, $E_{Simpson}$ is the probability for drawing two different individuals. We tested then the significance of those indexes with variance analyses.

1.2.2 Species identification by ocean - species listing and grouping

Maximising species richness is often an explicit or implicit goal of conservation studies. However, estimated species richness scores depend both on the estimator considered and on the grain size used to aggregate data (Gotelli et al. 2001). There were up to 114 taxa observed between the Atlantic and the Indian ocean (table 3) regardless of the fishing method.

Whales, dolphins and whale sharks are released before the closure of the net uninjured. However, observers estimated the weight of the animals encountered. Some turtles died in the net by suffocation because they got tided in the net. Silky sharks have been pulled out from the global group of sharks because of their emblematic and sensitivity to fishing despite their near-threatened status on the CITES list and frequency of occurrences in

Table 3: Taxa listing and presence/absence per ocean and fishing mode. (The presence in an ocean and under a fishing mode is symbolised by a + and absence with a -)

Taxonomic Groups	Family	Taxa	Atlantic Ocean FAD	Atlantic Ocean FSC	Indian Ocean FAD	Indian Ocean FSC
Whales	Balaenopteridae	Balaenoptera pysalus	-	+	-	+
	Mysticetidae	Mysticeti	-	+	-	-
Dolphins	Globicephalidae	Globicephala macrorhynchus	-	+	-	-
		Pseudorca crassidens	-	-	+	-
Turtles	Chelonidae	Chelonia mydas	+	+	+	+
		Eretmochelys imbricata	+	+	+	+
		Caretta caretta	+	+	+	-
	Dermochelidae	Dermochelys coriacea	+	+	+	+
	Lepidochelidae	Lepidochelys kempii	+	+	-	-
		Lepidochelys olivacea	+	+	+	+
	Testitudinae	Testitudinae spp.	+	+	+	+
	Unknown	Unknown	+	+	+	-
Rays	Dasyatidae	Dasyatidae spp.	+	+	-	+
		Dasyatidys violacea	+	+	+	+
	Mobulidae	Mobula japanica	+	-	+	+
		Mobula mobular	+	+	+	+
		Mobula spp.	+	+	+	+
		Manta alfredi	-	-	-	+
		Manta birostris	+	+	+	+
		Manta spp.	-	-	-	+
		Mobulidae spp.	+	-	-	+
	Unknown	Unknown	-	+	+	-
Sharks	Etmopteridae	Etmopterus spp.	-	-	+	-
	Lamnidae	Isurus oxyrinchus	+	+	+	+
		Isurus spp.	-	-	-	+
	Rhincodontidae	Rhincodon typus	+	+	+	+
	Sphyrnidae	Sphyrna lewini	+	+	+	-
		Sphyrna mokarran	-	+	-	-
		Sphyrna zyganea	+	+	-	-
		Sphyrnidae spp.	+	-	+	-
	Unknown	Unknown	+	+	+	-
	Carcharhinidae	Carcharhinidae spp.	+	+	+	+
		Carcharhinidae	-	+	-	-
		Carcharhinus leucas	+	-	-	-
		Carcharhinus longimanus	+	+	+	+
		Galeocerdo cuvier	-	-	-	+
		Prionace glauca	+	+	+	+
Silky shark	Carcharhinidae	Carcharhinus falciformis	+	+	+	+
Sailfish	Istiophoridae	Istiophoridae. spp	+	+	+	+
		Istiophorus albicans	+	+	+	+
		Istiophorus platypterus	-	-	+	+
Swordfish	Xiphiidae	Xiphius gladius	+	+	+	+
Marlin	Makairidae	Makaira indica	+	+	+	+
		Makaira mazara	-	-	-	+
		Makaira nigricans	+	+	+	+
	Tetrapturidae	Tetrapturus albidus	+	+	-	-
		Tetrapturus angustirostris	-	-	+	+
		Tetrapturus audax	-	-	+	+
Misc. Fishes	Belonidae	Ablennes hians	-	-	+	+
		Tylosurus crocodilus	+	-	+	-
		Belonidae spp.	-	-	+	+
	Ephippidae	Platax spp.	-	-	+	-
		Platax teira	-	-	+	+
	Kyphosidae	Kyphosus cinerascens	-	-	+	+
		Kyphosus sectratrix	+	+	-	-
		Kyphosus vaigiensis	-	-	+	+
		Kyphosus spp.	+	+	+	+
	Lampridae	Lampris gutatus	-	-	+	-
	Lobotidae	Lobotes surinamensis	+	+	+	+
	Monacanthidae	Aluterus monoceros	+	+	+	+
		Aluterus scriptus	+	+	+	+
	Tetraodontidae	Lagocephalus lagocephalus	+	+	+	+
		Tetraodontidae spp.	+	+	+	+
	Bramidae	Bramidae spp.	-	-	+	+
	Diodontidae	Diodon eydouxii	-	-	+	-
		Diodon hystrix	+	+	-	-
		Diodontidae spp.	+	+	+	+

Taxonomic Groups	Family	Taxa	Atlantic Ocean FAD	Atlantic Ocean FSC	Indian Ocean FAD	Indian Ocean FSC
Misc. Fishes	Exocoetidae	Exocoetidae spp.	+	+	+	+
	Serranidae	Seriola rivoliana	+	+	+	+
		Serranidae spp.	-	-	+	-
	Sphyraenidae	Sphyraena barracuda	+	+	+	+
		Sphyraenidae spp.	-	-	+	-
Balistidae	Balistidae	Abalistes stellatus	-	-	+	+
		Balistes carolenensis	+	+	-	-
		Balistes punctatus	+	-	-	-
		Balistidae spp.	+	+	+	+
		Canthidermis maculata	+	+	+	+
Molidae	Molidae	Masturus lanceolatus	+	+	+	+
		Mola mola	+	+	+	+
		Molidae spp.	-	-	-	+
		Ranzania laevis	+	+	-	-
Carangidae	Carangidae	Carangidae spp.	+	+	+	+
		Carangoides orthogrammus	-	-	+	-
		Caranx crysos	+	+	+	+
		Caranx sexfasciatus	-	-	+	+
		Decapterus macarellus	-	-	+	-
		Decapterus spp.	-	-	+	+
		Naucrates ductor	+	+	+	+
		Uraspis helvola	-	-	+	-
		Uraspis secunda	+	+	+	+
		Uraspis spp.	+	-	+	-
		Uraspis uraspis	-	-	+	+
Echeneidae	Echeneidae	Phtheririchthys lineatus	+	+	+	+
		Remora remora	+	+	+	+
		Remorina albescens	+	+	+	+
		Echeneis naucrates	+	+	+	+
		Elagatis bipinnulata	+	+	+	+
		Echeneidae spp.	+	+	+	+
Dorado	Coryphaenidae	Coryphaena equiselis	+	+	+	+
		Coryphaena hippurus	+	+	+	+
		Coryphaenidae spp.	+	-	+	-
Wahoo	Scombridae	Acanthocybium solandri	+	+	+	+
Auxis spp.	Scombridae	Auxis rochei	+	+	+	+
		Auxis thazard	+	+	+	+
		Auxis spp.	+	+	+	+
Misc. Scombridae	Scombridae	Euthynnus affinis	+	+	+	+
		Euthynnus alletteratus	+	+	+	+
		Sarda sarda	+	-	-	-
		Scomber japonicus	-	-	+	-
		Scombridae spp.	-	-	+	-
ALB	Scombridae	Thunnus alalunga	+	+	+	+
YFT	Scombridae	Thunnus albacares	+	+	+	+
SKJ	Scombridae	Katsuwonus pelamis	+	+	+	+
BET	Scombridae	Thunnus obesus	+	+	+	+

the net. Whale sharks haven't been taken separately because there are just 13 sets with *Rhyncodon typus* in the net and it has been released without any injuries. Whales and dolphins occur in fishing operation report but are released safely and uninjured. Auxis spp. compared to Scombridae are dealt with separately because of their relative abundance compare to other small Scombridae.

The identification of the various taxa depends on how closed morphologically they are or on the ability of the observers to distinguish one taxon from another. Some bycatch species may have been grossly identified and were classified at genus or family level because of the difficulty to identify precisely some of them (33 taxa in 114). As a consequence to this, 22 taxonomic groups were developed. It helped to reduce the variability of the catch composition. Taxonomic groups help to smooth species identification issues by aggregating captures.

1.3 Impact descriptors methodology

Additional criterions, other than richness, diversity and evenness indexes, have been used to compare the composition and changes of the taxonomic groups: length-class distribution trophic and length-biomass spectrum amongst others.

1.3.1 Mean trophic level of the bycatch

The mean trophic level of the total catch and bycatch may help to understand the targeted part of the marine community structure. It is one of the most used indicators to describe the health of an ecosystem (Borcard et al. 2011). It gives a schematic illustration of the average composition of the studied community. The trophic level of each taxon has been resumed (Froese and Pauly 2014, Olson and Watters 2003) considering the maturity state (juvenile and adult) depending on the size of the individual. Then a geometric mean has been calculated among taxa of a same taxonomic group to give a mean trophic level of this group.

1.3.2 Length-class frequency of the bycatch

The length class distribution may be the easiest way to explore the range of size of the bycatch captured by a fishing mode. Size of the individuals are computed by fishing set in the subsample data of Obstuna and have been elevated to the whole fishing set using the ratio $\frac{totalweight_{taxa}}{sampleweight_{taxa}}$.

1.3.3 Biomass-size spectrum of the whole capture

Biomass size spectra, the distribution of biomass across body size classes, appears to be a very conservative feature of marine communities. It summaries complex communities, comprising numerous species with complex trophic interactions, within a simple plot and two numbers: the slope (describing the exploitation rate of the ecosystem) and intercept (the accessible biomass) of the spectrum (Jul-Larsen et al. 2003). It allows also predictions of the effect of various human perturbations. It has been shown that linear biomass-size spectra are stationary solutions of the model. At the same time it was found that realistic fishing should affect the curvature and stability of the biomass-size spectrum rather than its slope. When there is no fishing activity, the spectrum is in a non impacted stationary state (*i.e.* the slope of the spectrum is -1). Introducing a fishing activity will change the slope and the intercept of the spectrum or the amount of accessible biomass. Slopes (λ) of log numbers versus log length have been ranged from -4 to -10 for weakly to heavily exploited fish communities (Benoît et al. 2003). In our case, we investigate the relation between log weight and log length and not log numbers *versus* log length, but there is a proportional relation between numbers and weight. The reasoning applies to any spectrum of this kind. According to Figure 1, three main stationary state could be possibly observed: non impacted stationary state, the fishing activity targets a specific size range but does not change the intercept (or the biomass accessible to the fishery) and a size-selective fishing which could occasionally release preys in the environment (both slope and intercept change).

There is a bias in the observer database: tuna are sampled only when they are discarded (so only the smallest ones are sampled). To correct that bias, we used the Balbaya database which corresponds to the sampling process conducted in the harbour at the landing. We then made the length classes corresponding to our fishing operations) because the sampling conducted in the harbour covers a whole boat slip and it is very difficult to tell to what fishing operation correspond a fish or another. There is a corrective process

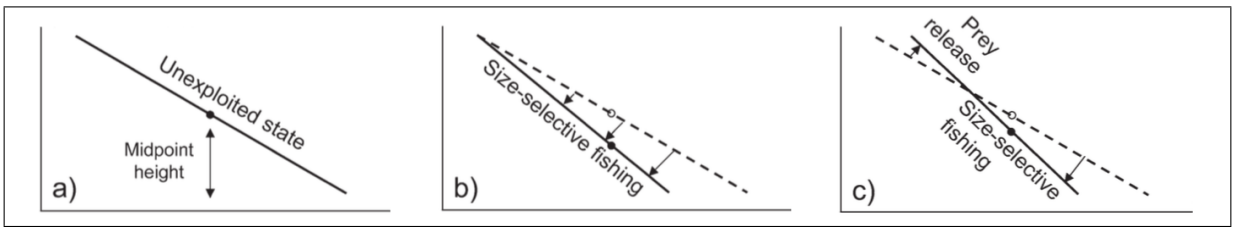


Figure 1: How the biomass-size spectrum is modified from (a) an unexploited community, (b) alters as a results of size-selective fishing, and (c) potential prey release. *(the dashed line: unexploited stationary state)* (Jul-Larsen et al. 2003)

used for Balbaya which reduces that bias. By this operation, we reconstructed the length distribution for targeted tuna and corresponding biomass.

1.4 Explicative and predictive model of species composition and abundance among space and seasons

1.4.1 Monospecific model

Silky sharks are mainly found in warm water in the Atlantic, Indian and Pacific Oceans. It is a large and slim shark growing up to a maximum length of 3.3 m. This shark is known to feed on bony fish such as tuna, mackerel, sardines and mullets.
Silky sharks occurred only in 161 sets on 1518 in the Atlantic ocean (11%) *versus* 704 sets on 2153 (32%) in the Indian Ocean. The captures data are zero inflated. A poisson distribution is more appropriated to low number of individuals where a negative binomial distribution is useful with rare high number of individuals. According to Figure 2, a zero-inflated *N*egative *B*inomial distribution *ZINB* with a logit-link function was selected to predict the presence/absence and number of Silky sharks caught (Amandé et al. 2011).

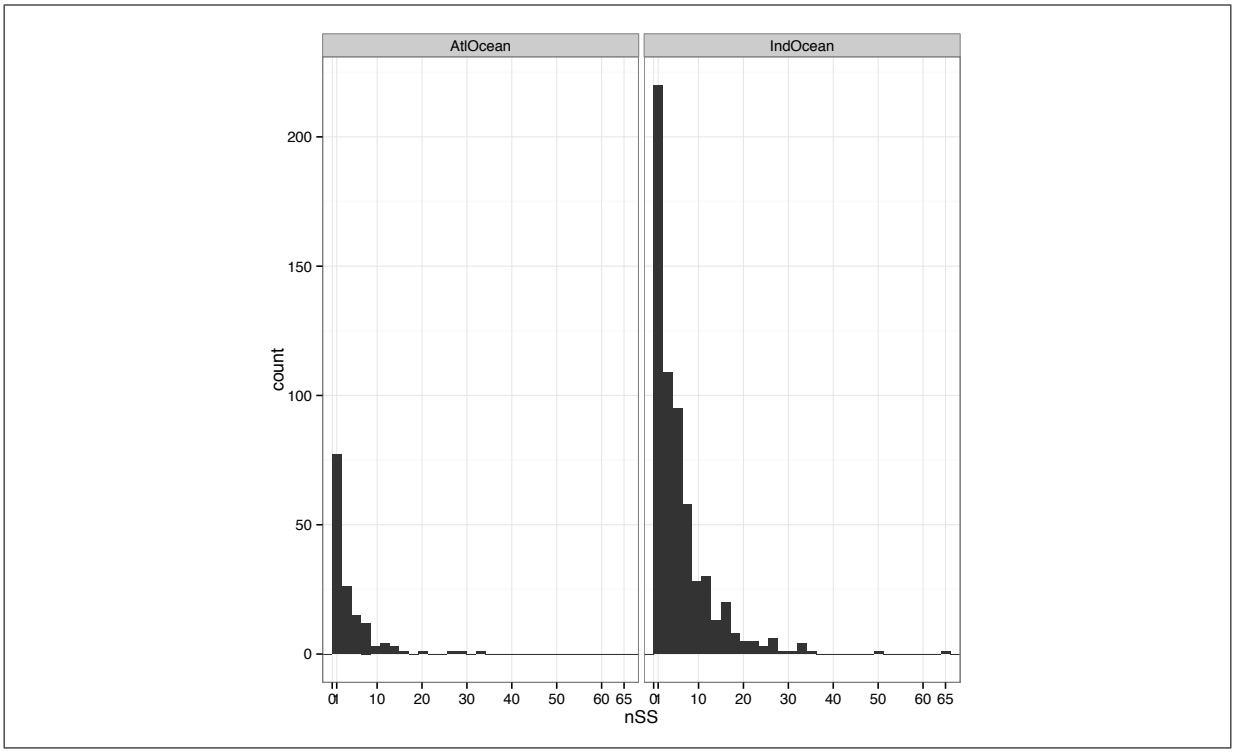


Figure 2: Frequency distribution of silky sharks in purse-seine set per Oceans (captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

Parameters we decided to use in the model are: two spatial parameters (longitude and latitude), a temporal variable (the season) and the fishing mode. We will also extract the residuals from the ZINB and inspect these for any spatial correlation we could have forgotten in the model (Zuur et al. 2012). The zero inflated model fits two separate models: one to the zeros (absences) only, and the other to the counts. The mathematical equation for the model is:

$$Y_i \sim ZINB(\mu_i, \pi_i, \theta) \textbf{ (3)}$$

$$log(\mu_i) = \beta_0 + \beta_1.longitude_i + \beta_2.latitude_i + \beta_3.Season_i + \beta_4.mode_i \textbf{ (4)}$$

$$logit(\pi_i) = \gamma_0 + \gamma_1.longitude_i + \gamma_2.latitude_i + \gamma_3.Season_i + \gamma_4.mode_i \textbf{ (5)}$$

$$With\ E(Y_i) = \mu_i.(1 - \pi_i)\ and\ var(Y_i) = (1 - \mu_i).\mu_i.(1 + \pi_i.\mu_i + \frac{\mu_i^2}{\theta})$$

If we just consider a Negative Binomial distribution, its variance is given by the formula $V = \mu_i + \frac{\mu_i^2}{\theta} \Leftrightarrow V = \mu_i + \alpha_i * \mu_i^2$ with $\alpha_i = \frac{1}{\theta}$. $\theta, \beta_i, \gamma_i$ are unknown parameters to estimate. If θ is large ($\theta \gg 0 \Leftrightarrow \alpha \mapsto 0$), the Negative Binomial distribution converge to a Poisson distribution. In the other way, when $\theta \mapsto 0$, the variance is larger than in a Poisson distribution and it was right to select a Negative Binomial distribution rather a Poisson's.

1.4.2 Expansion of the model to the total catch composition

Diversity in purse-seine sets is an important component of the understanding of the impact of fishing activities on the ecosystem because it gives clues to determine how large is the community impacted. In their model, Oxbrough et al. (2005) investigated how spider communities change over forestation cycles in conifer and broadleaf plantations. They identified environmental and structural features of the habitat that can be used as indicators of spiders biodiversity. This model structure was used to describe how bycatch diversity changes across fishing methods and among oceans using structural, temporal and spatial parameters (Oxbrough et al. 2005 and Zuur, 2013). Inspired by this model, the objective was to determine what could affect the diversity in purse-seine sets . The effect of structural, temporal and spatial parameters on Simpson index among oceans and fishing methods were investigated. A General Addidive Model with a Binomial distribution $GAM_{binomial}$ with a logit-link function was selected to predict the value of the Simpson index because of its range from 0 to 1. Parameters we decided to use in the model are: two spatial parameters (longitude and latitude), a temporal variable (the season) and the fishing mode. Residuals from the $GAM_{binomial}$ were extracted and inspected for any spatial correlation we could have forgotten in the model (Zuur et al. 2013). The mathematical equation for the model is:

$$Y_i \sim GAM_{binomial}(\pi_i) \textbf{ (6)}$$

$$logit(\pi_i) = \alpha + s(longitude_i) + s(latitude_i) + f(Season_i) + f(mode_i) \textbf{ (7)}$$

$$With\ E(Y_i) = \pi_i\ and\ var(Y_i) = \pi_i.(1 - \pi_i)$$

Because GAM models are non-parametric models, the smoothing splines approach the relation between the predictive variable and the explicative parameters (Maindonald, 2010).

2 Results

2.1 Descriptive approach

2.1.1 Distribution of purse seine set

The purse-seine sets are located in the Atlantic Ocean between 30° West to 12° East and 15° South to 20° North. For the Indian Ocean, the range of longitudes and latitudes is: 40° West to 80° East and 21° South to 10° North (Figure 3). The spatial location in the Atlantic Ocean has not really changed along years of the time series but changes along seasons. During the beginning of the warm season (from December to February), the fishing trips are conducted in the north of the Gulf of Guinea before moving offshore near the Senegal Coast at the end of the warm season (from march to may), then the prospection goes down to the extreme south of the Gulf of Guinea for the beginning of the cold season (from June to September) and then moves back inside the Gulf at the end of the cold season (from October to November). In the Indian Ocean, from December to march (austral summer), fishing sets are conducted in the Mozambican Channel and offshore of the Somalia coast before moving in the central part of the ocean from April to September (austral winter). In the Indian Ocean, fishing operations were disturbed in 2009 and 2010 by Somalian piracy and the number of observers onboard has been reduced to make place for marines (for the safety of the crew). As a consequence, in the Indian Ocean, there is a gap in the coverage rate and number of set between 2009 and 2010, period of the highest level of piracy.

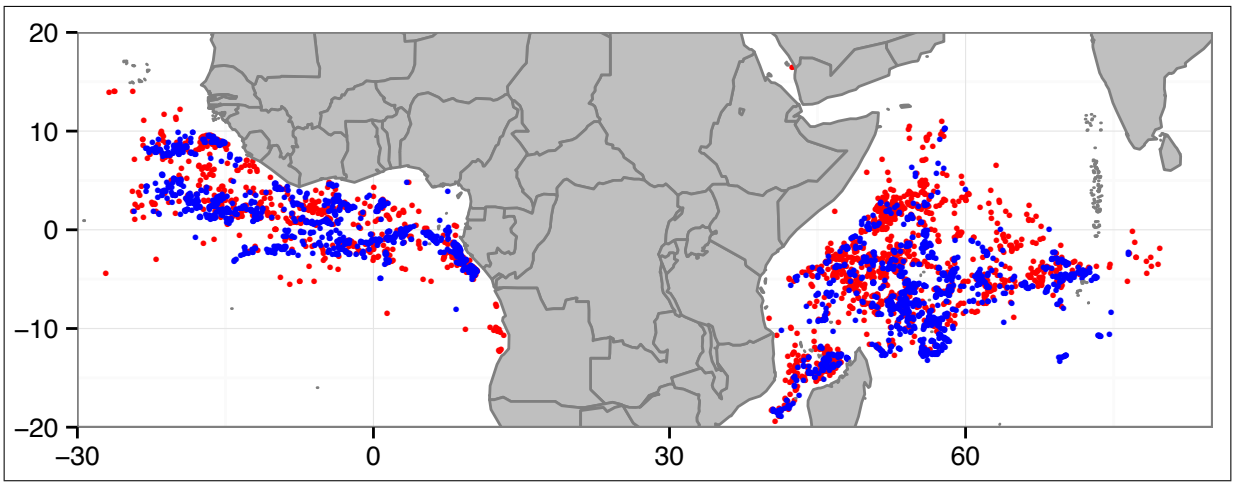


Figure 3: Purse-seine FAD and FSC set in the Atlantic and Indian Ocean from 2006 to 2013 (*under FAD in red and under FSC in blue*)

2.1.2 Catch over Oceans and fishing methods

Discards are much higher under FAD (table 4). Captures are higher in the Indian Ocean regardless to the fishing mode due to the lower number of set in the Atlantic Ocean compared to the Indian Ocean. Furthermore, in the Atlantic Ocean, captures under FAD are slightly lower than in FSCs. It is the contrary in the Indian Ocean where captures are slightly higher under FAD.

Table 4: Landings and discards proportion and amount under FAD and FSC among oceans (captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

	Atlantic Ocean		Indian Ocean	
	FAD	FSC	FAD	FSC
Discards (t)	1 409	425	1 504	778
Landings (t)	11 745	17 464	22 743	19 928
Discards (%)	10.71	2.38	6.39	3.76

2.1.3 Richness, diversity and evenness indexes

On the 114 taxa, a total of 68 taxa were common to both oceans (table 5), 13 exclusive to the Atlantic (such as *Tetrapturus albidus* and *Kyphosus sectatrix*) and 34 to the Indian ocean (such as *Galeocerdo cuvier* or *Manta alfredi*).

Table 5: Exclusive and common taxa over fishing modes and oceans.

	Atlantic Ocean		Indian Ocean	
	FAD	FSC	FAD	FSC
Exclusive Taxa per fishing mode	2	4	13	5
Exclusive taxa per ocean	13		34	
Taxa in common between fishing mode	62		63	
Taxa in common between oceans	68			
Total number of taxa	68+13 = 81		68+34 = 102	

Rarefaction curves have been constructed by ocean and fishing mode (figure 4). The FAD rarefaction curve converges in the Atlantic ocean to an asymptotic value of 80 taxa where the FSC rarefaction curve converges to 70. In the Indian Ocean, the asymptotic value under FAD is 90 and under FSC it is 75 (captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

The bootstrap procedure had for result an estimation of both the richness and the uncertainty of measurement (table 6). As expected, richness under FAD is higher than in FSC. Moreover, richness is higher in the Indian Ocean than in the Atlantic Ocean.

Table 6: Estimated richness from bootstrap (400 samples and 500 iterations).

	Atlantic Ocean		Indian Ocean	
	FAD	FSC	FAD	FSC
Richness	66	57	74	58
Ecart type	± 2.5	± 2.9	± 3	± 3.6

Both Simpson diversity and Simpson evenness indexes are higher under FAD than under FSC for a given ocean (figure 5 and table 7). The value of those indexes under FAD is significantly higher in the Indian Ocean (anova with a p-value<5%). Captures under FSC are often monospecific. As a consequence of that, the value of the Simpson diversity and evenness indexes are 0. It explains the box plot sprawl under FSC. Fishing under FAD impacts a larger range of the species spectrum.

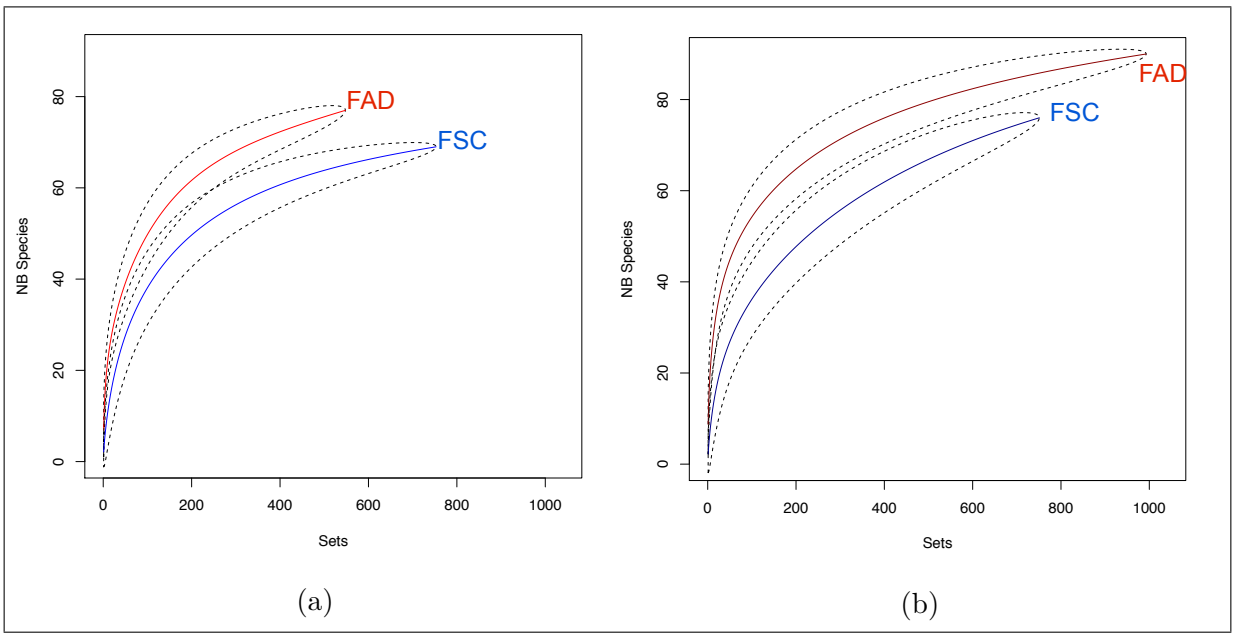


Figure 4: The rarefaction curves for the Atlantic Ocean (a) and the Indian Ocean (b) (*FAD in red and FSC in blue*) shows sample-based rarefaction and asymptotic richness for the different fishing mode in both oceans.

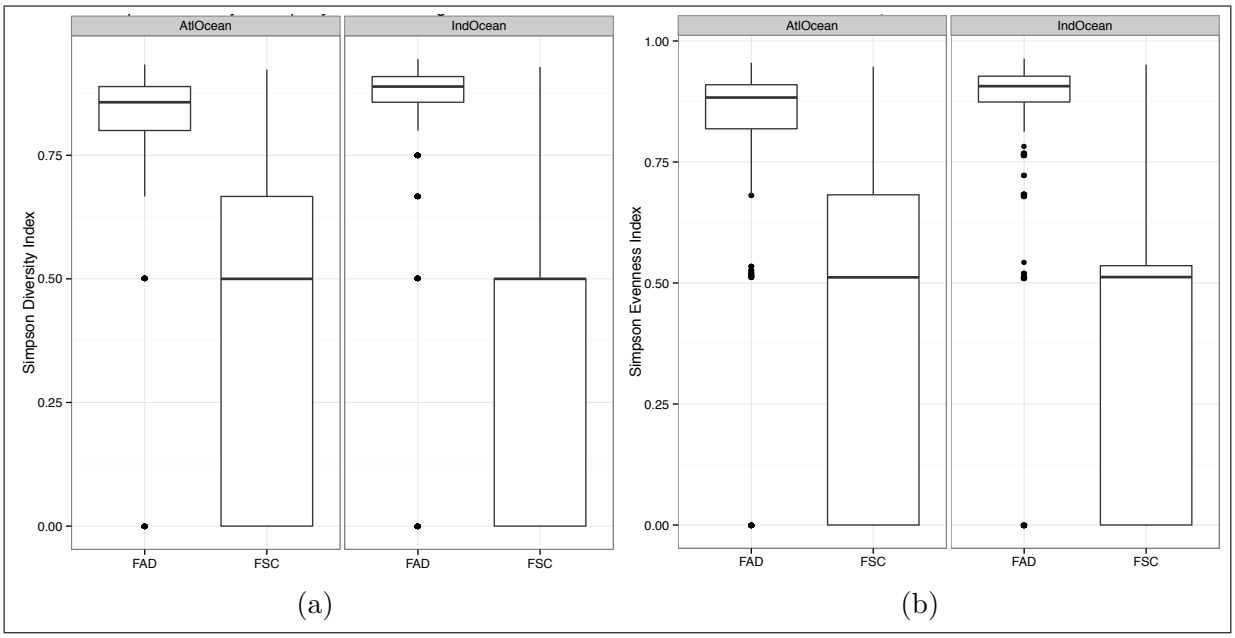


Figure 5: Simpson diversity index (a) and Simpson evenness index (b) in the Atlantic and Indian Ocean

Table 7: Estimated diversity and Evenness per oceans and fishing mode.

	Atlantic Ocean		Indian Ocean	
	FAD	FSC	FAD	FSC
Diversity	0.7814	0.3266	0.8363	0.3245
Evenness	0.8031	0.3376	0.8547	0.3358

2.1.4 Typical fishing set species composition profile

In terms of numbers of occurrences, the taxonomic composition reveals differences between oceans and fishing modes (table 8). Sailfishes are more present in FSC rather in FAD

contrary to marlins which occur more frequently under FAD. Rays are more frequently observed in FSC and sharks (miscellaneous and Silky sharks independently) under FAD.

Table 8: Group listing and occurrences per ocean and fishing mode (captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

Category	Group	Taxonomic groups	Atlantic Ocean FAD	Atlantic Ocean FSC	Indian Ocean FAD	Indian Ocean FSC
bycatch	Cetaceans	Whale	0	8	0	3
		Dolphins	0	1	1	0
	Turtles	Turtles	25	35	17	6
	Selachians	Rays	19	39	57	87
		Misc. sharks	47	36	68	20
		Silky sharks	118	43	647	57
	BillFishes	Marlins	94	44	161	82
		Sailfishes	34	158	28	21
		Swordfishes	5	3	9	3
	Fishes	Misc. Fishes	273	81	730	65
		Balistidae	368	42	753	49
		Molidae	13	28	4	9
		Carangidae	332	34	275	10
		Echeneidae	349	64	703	53
		Dorado	274	44	747	53
		Wahoo	310	42	640	39
		Misc. Scombridae	93	8	59	3
		Auxis spp.	164	15	428	44
Target spp.	Tuna	ALB	4	15	17	106
		YFT	317	597	875	594
		SKJ	498	149	922	150
		BET	163	94	388	138

Landings and discards data have been summarized by ocean, fishing method (FAD or FSC) and species or group of species. The amount and composition of catches vary among oceans and fishing methods. All the 22 species groups are caught in both oceans but most species caught are different. Catch per set and taxonomic group were plotted (Figure 6) among fishing methods, oceans. While considering a specific Ocean, some species groups are predominant in the catch depending on the fishing method. In the Atlantic Ocean, the most common groups encountered under FAD are: Auxis spp., Misc. Scombridae and various fishes such as Balistidae and Carangidae ; while under FSC, the main groups are: Auxis spp., misc. Scombridae, Sailfishes and Wahoo. In the Indian Ocean, under FAD it is common to observe more sharks and mesopelagic fishes like Balistidae, Echenidae and Dorado while under FSC there are more Billfishes, Misc. Scombridae, Carangidae and Rays. It is in accordance with the table 8 summarising the occurrences of each taxonomic groups.

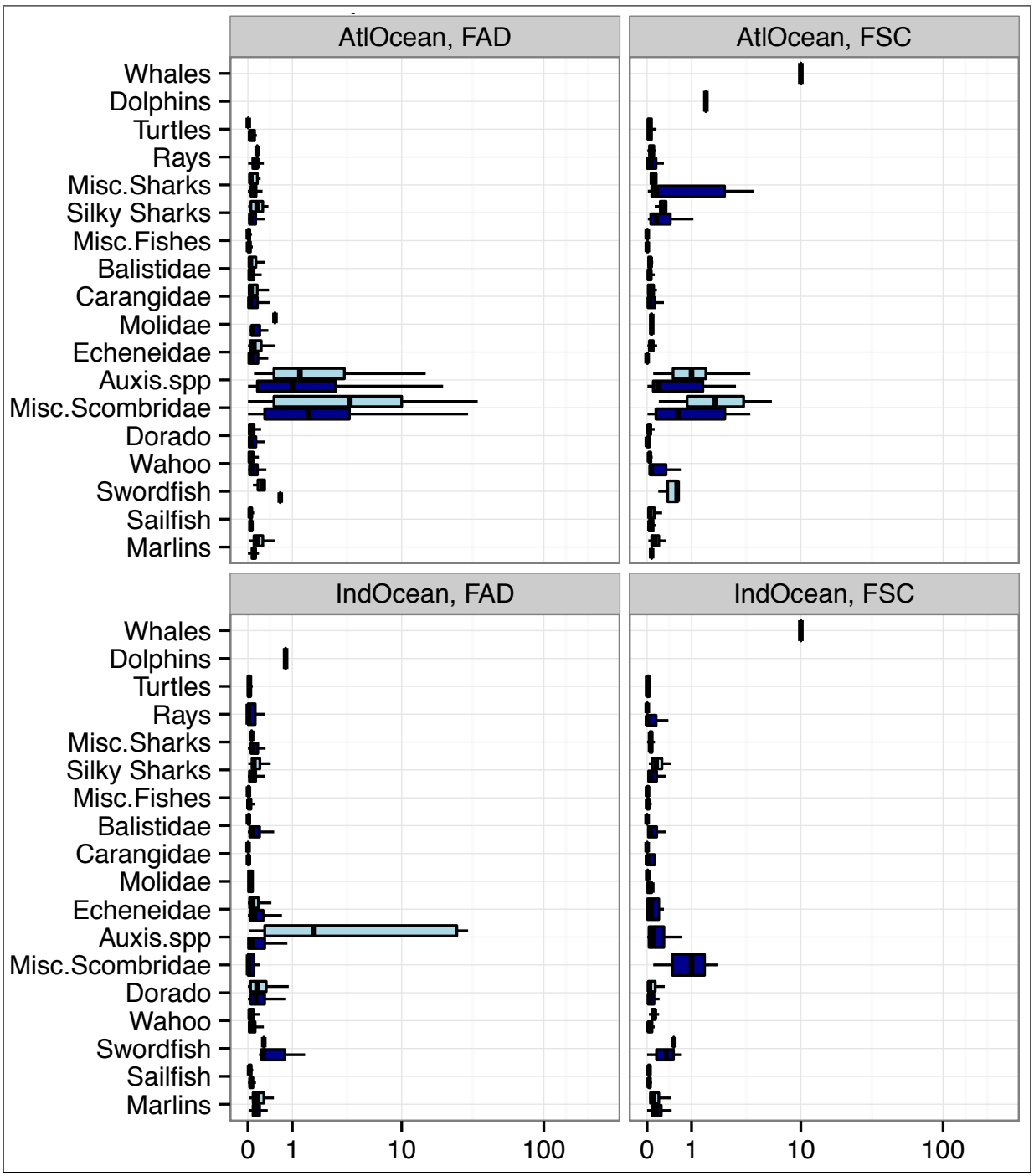


Figure 6: Purse-seine FAD and FSC catch (t/set) in the Atlantic and Indian Ocean per species group (*Discards in dark blue and landings in blue*)(captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

2.2 Indicators of the fishery impacts

2.2.1 Length-class distribution of the bycatch

The length class distribution of the bycatch community has been plotted (figure 7). There is no significant difference between oceans and fishing mode (p-value > 5%). But on FSC it seems that the length class distribution is slightly broken down in two modes: one around 50 cm and the second around 80 cm. On FAD the length class distribution is smoother and if two modes should be viewed, the first one is around 35 cm and the second around 70-80 cm. In short, therefore, it appears that, even if it is not significant, length class are shifted to smaller distributions under FAD.

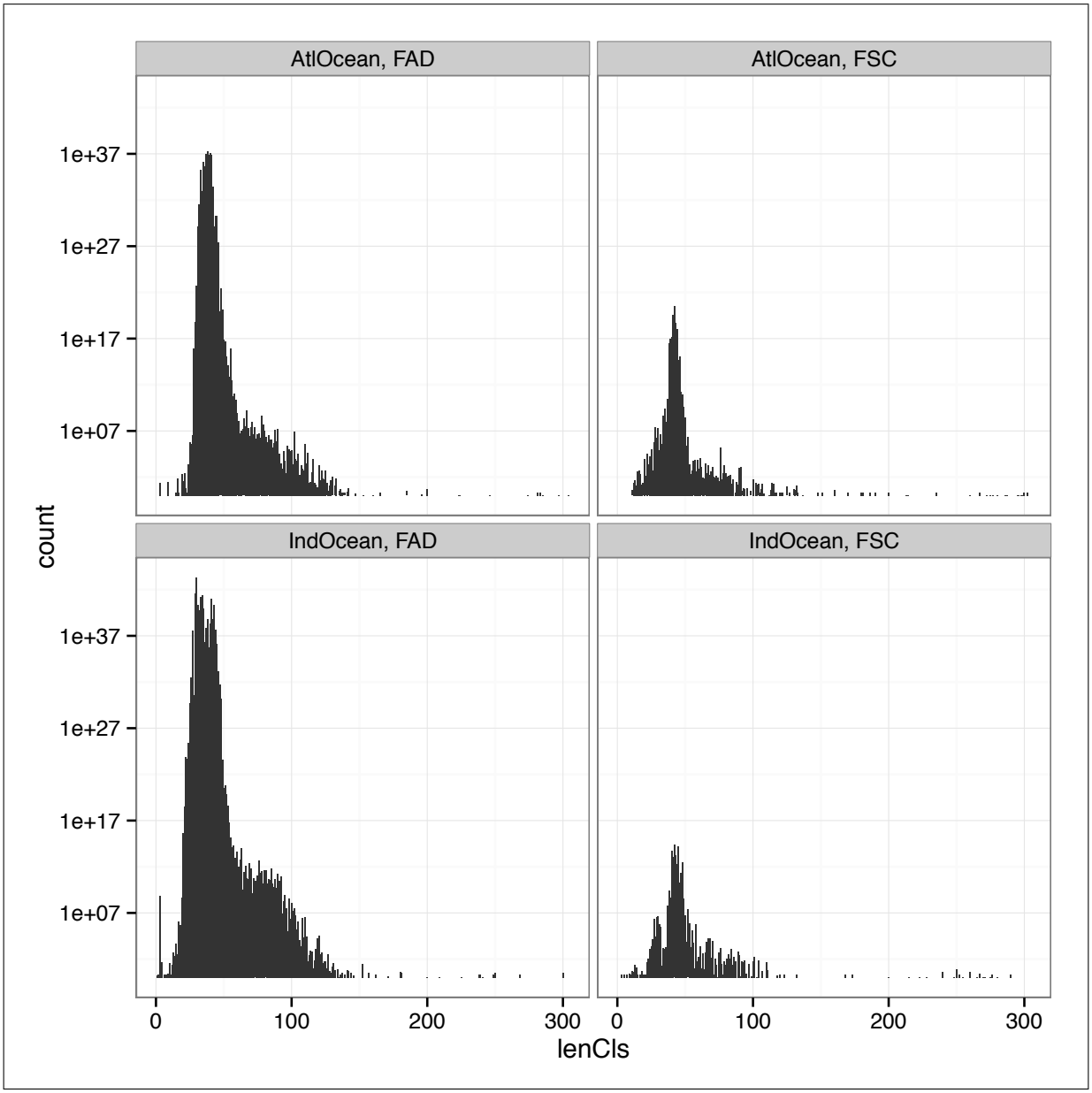


Figure 7: Length class spectrum of the bycatch under FAD and FSC in the Atlantic and Indian Ocean (captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

2.2.2 Mean Trophic Level of the bycatch

The mean trophic level appeared to be quite different from FAD to FSC (figure 8). Indeed, a Kruskal-Wallis test has been done and shows up significant difference between fishing mode for a given ocean (table 9). The median of trophic level in the Atlantic Ocean is 4.07 under FAD and 4.63 on FSC, where in the Indian Ocean the median trophic level is 4.29 under FAD and 4.33 on FSC.

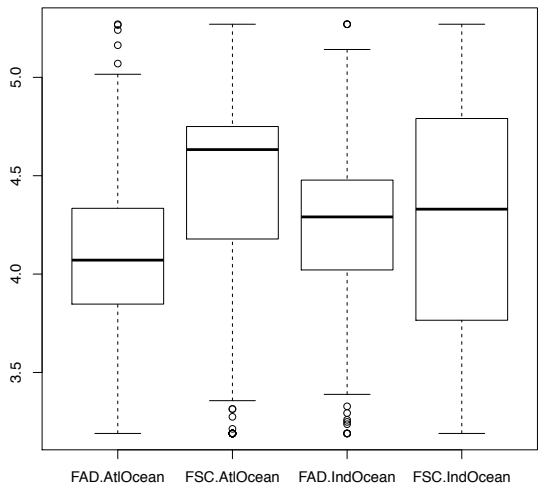


Figure 8: Mean trophic level per set for both oceans and fishing mode

The difference in mean trophic level between fishing mode is strongly significant in the Atlantic ocean but slightly significant in the Indian Ocean (table 9).

Table 9: Kruskal-Wallis test on trophic level.

	Atlantic Ocean		Indian Ocean	
	FAD	FSC	FAD	FSC
median trophic level	4.07±0.03	4.63±0.05	4.29±0.02	4.33±0.09
kruskal wallis test	$p\,value < 2.2e-16$		$p\,value = 0.01232$	

2.2.3 Biomass-size spectrum

Slopes of the biomass-size spectrum (figure 9) are always higher under FAD (slopes ranged from -12 to -15 for respectively the Atlantic and the Indian Ocean) than under FSC (slopes ranged from -6.5 to -9.9 for respectively the Atlantic and the Indian Ocean). The impact on the overall community size structure of a fishing mode appears to be mostly higher under FAD. Although the means of biomass-size distribution (intercepts) are higher under FAD too. It means that the amount of total accessible biomass is not the same depending on the fishing fishing mode (fishermen don't exploit the same part of the overall marine community).
The spectra in the Indian Ocean cross themselves for a log-length of 4.70 which corresponds to a length class of 109 cm. It could mean that the fishing pressure is mostly on fishes longer than 109 cm and that smaller fishes (under 109 cm) are mostly discarded or released. The spectra in the Atlantic Ocean cross themselves for a log-length of 5.05

which corresponds to a length class of 161 cm. It could mean that the fishing pressure is mostly on fishes longer than 161 cm and that smaller fishes (under 161 cm) are mostly discarded or released. The impact of the tuna purse-seine fishery seems to be higher in the Indian ocean than in the Atlantic ocean

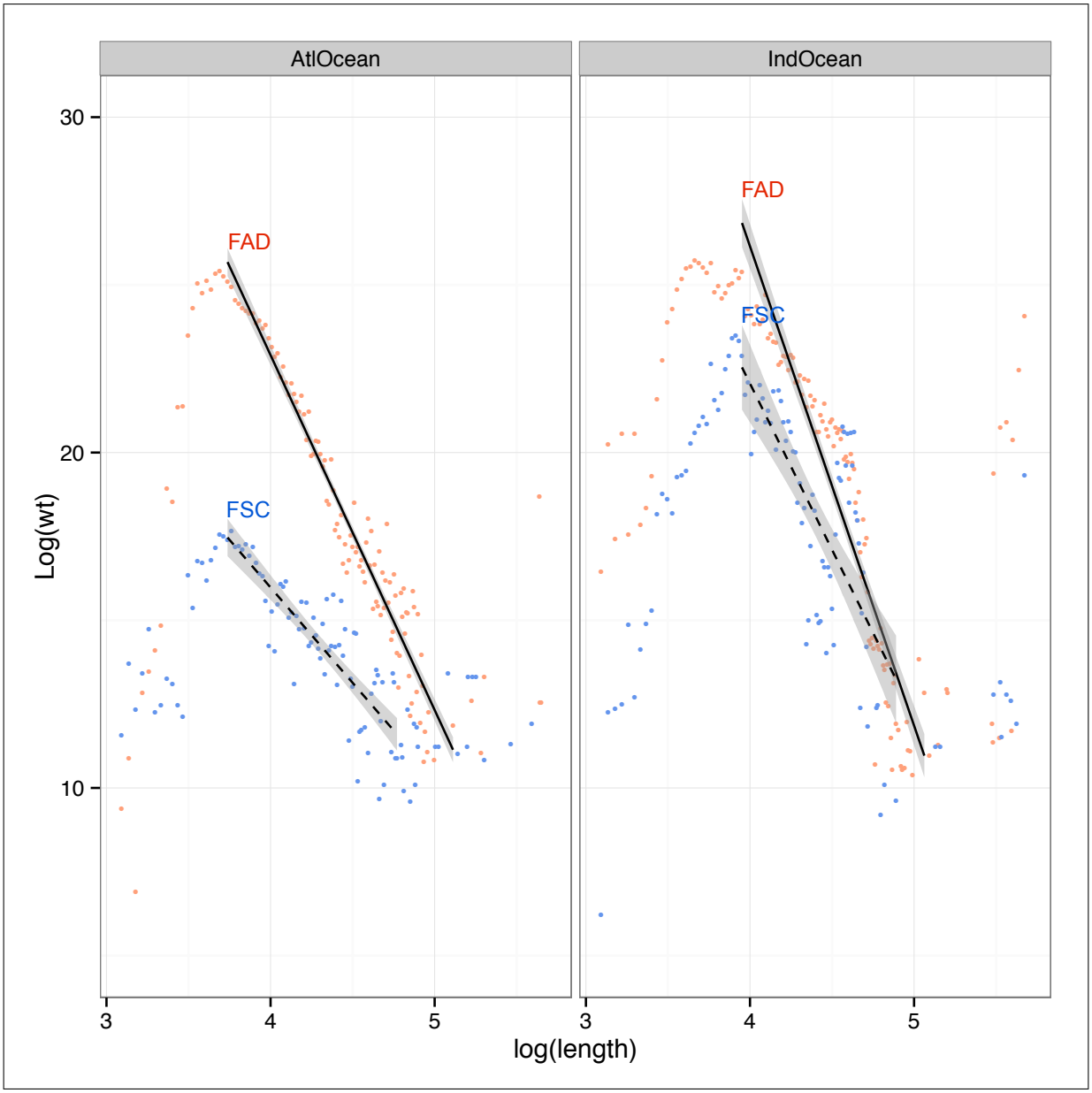


Figure 9: Biomass by length class spectrum (*FAD in red full line and FSC in blue dashed line*)(captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

Equations of the spectra are:

$$log(W_{FAD}^{Atl}) = 70 - 12.log(L_{FAD}^{Atl}); r^2 = 0,838 \textbf{ (8)}$$

$$log(W_{FSC}^{Atl}) = 42 - 6.5.log(L_{FSC}^{Atl}); r^2 = 0,549 \textbf{ (9)}$$

$$log(W_{FAD}^{Ind}) = 86 - 15log(L_{FAD}^{Ind}); r^2 = 0,825 \textbf{ (10)}$$

$$log(W_{FSC}^{Ind}) = 62 - 9.9.log(L_{FSC}^{Ind}); r^2 = 0,513 \textbf{ (11)}$$

2.3 Monospecific model on *Carcharhinus falciformis.*

2.3.1 Explicative model

A. Data exploration

Before the construction of the model, effects of various parameters on the amount of silky sharks caught (when they occur) were investigated. An effect of the fishing mode and the season (figure 10) and a spatial effect (figure 11) were observed.
Purse-seine fisheries fish more silky sharks on FAD sets during the warm season and on FSC during the cold season, in the Atlantic Ocean, even if levels of silky sharks caught are similar between fishing modes at that period of the year (figure 10 a). In the Indian Ocean, silky sharks are more caught on FAD regardless to the season, but FSC sets catches more silky sharks in the austral winter than in austral summer (figure 10 b).

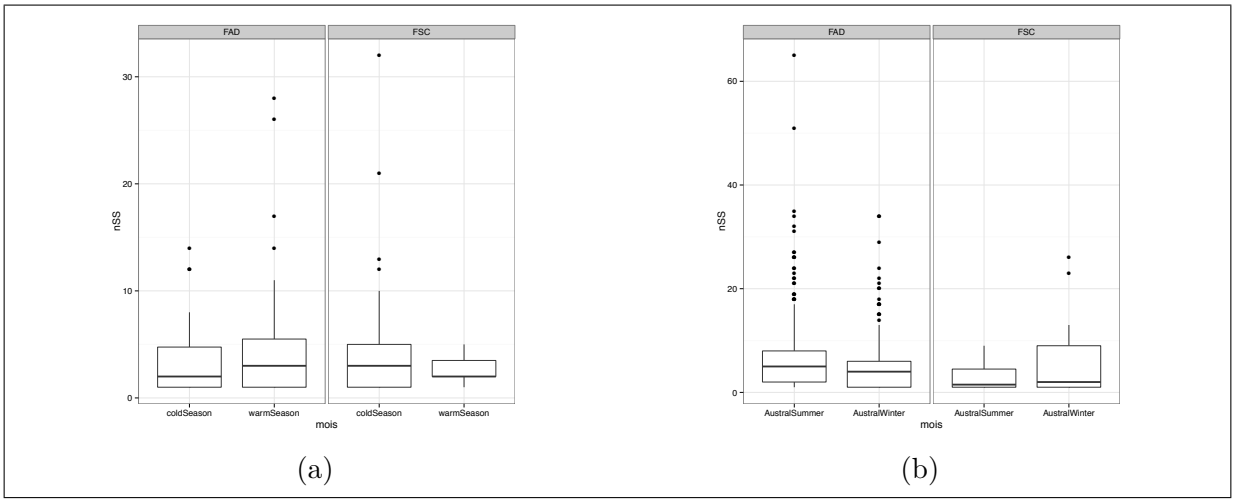


Figure 10: The number of silky sharks caught when they occur in the purse-seine sets per seasons in the Atlantic Ocean (a) and in the Indian Ocean (b).

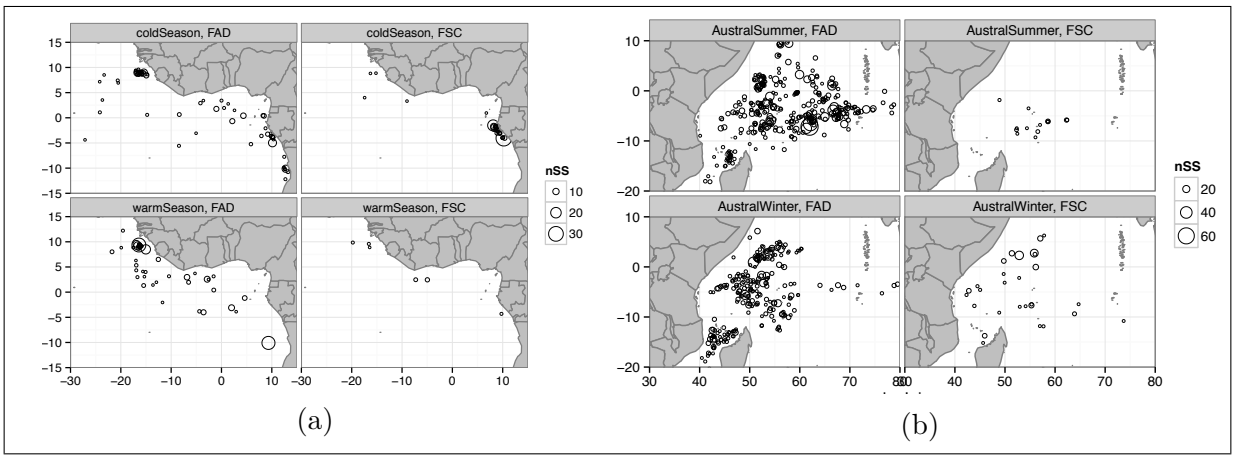


Figure 11: Mapping of the number of silky sharks caught in the Atlantic (a) and Indian (b) Ocean (captures are only from the french observers database and haven't been elevated to the whole tuna fishery).

Silky sharks are not fished in the same areas depending on the fishing mode and the season. In the Atlantic Ocean, under FAD, silky sharks captures reach their maximum level during the warm season in the Guinean Gulf and near the Guinea coast during the cold season. FSC sets catch more silky sharks during the cold season and near the Gabon

coast in the Guinean Gulf (figure 11 a). In the Indian Ocean, on FAD sets, silky sharks are mostly caught offshore of the Somalian coast during the austral winter and in the south east part of the studied area during the austral summer (figure 11 b).

B. Monospecific model in the Atlantic Ocean

Silky sharks occurred only in 161 sets on 1518 in the Atlantic ocean (11%). The model shows no significant difference of silky sharks capture level between the two fishing modes. There is a significant spatial effect (table 10) in the count model. However, even if the spatial effect is significant, its amplitude is not that high and the standard error around its estimation is itself high. It could limit the effect of these parameters on the prediction of occurrences and capture level. Furthermore, silky sharks appear to occur more often during the warm season (from December to may) than during the cold season (From June to November). The value of theta is slightly significant and shows a good fitting of the negative binomial probability density (cf. 1.4.1). A poisson density could be more adapted to this model.

Table 10: Zero-inflation model coefficients (binomial with logit link) and Count model coefficients (negbin with log link), in the Atlantic Ocean.

Zero-inflation model coefficients (binomial with logit link):

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	2.462291	0.301179	8.175	2.95e-16	***
latitude	-0.043201	0.043171	-1.001	0.316977	
longitude	-0.044301	0.024202	-1.830	0.067176	.
FSC	-1.207799	0.338272	-3.570	0.000356	***
warmSeason	0.401004	0.256519	1.563	0.117994	
latitude:longitude	0.005817	0.001963	2.964	0.003037	**
FSC:warmSeason	1.417381	0.637813	2.222	0.026266	*

Count model coefficients (negbin with log link):

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	0.620444	0.345052	1.798	0.07216	.
latitude	0.085667	0.048880	1.753	0.07967	.
longitude	0.084834	0.027478	3.087	0.86720	
FSC	-0.070573	0.422048	-0.167	0.44389	
warm season	0.701952	0.290041	2.420	0.01551	*
latitude:longitude	-0.002251	0.003014	-0.747	0.45522	
FSC:warmSeason	-0.995018	0.735228	-1.353	0.17594	
log(theta)	-0.761358	0.435806	-1.747	0.08064	.

- - -
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Theta = 0.467
log-likelihood: -871.4 on 15 Df

C. Monospecific model in the Indian Ocean

Silky sharks occurred only in 704 sets on 2153 in the Indian ocean(32%). The model shows a significant difference of silky sharks capture level between fishing modes. Indeed, silky sharks are caught in an higher proportion under FAD (table 11). Moreover, the level of the estimation of the effect of the fishing mode parameter is strongly different of zero.

There is no significant spatial effect in both the count model and the presence model. Furthermore, silky sharks appear to occur more often during austral summer (From October to march) than during austral winter (from April to September). Nevertheless, captures are significantly different from zero under FSC during the austral winter. This is probably due to the fishing strategy conducted in the Indian Ocean: tuna purse-seiners use to fish under FSC the first semester of the year and switch mostly to FAD-fishing for the rest of the year (so during austral summer).
The value of the estimation of theta shows a good fitting of the negative binomial probability density (cf. 1.4.1).

Table 11: Zero-inflation model coefficients (binomial with logit link) and Count model coefficients (negbin with log link), in the Indian Ocean.

Zero-inflation model coefficients (binomial with logit link):

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.674e+00	5.493e-01	3.047	0.00231	**
latitude	-1.391e-03	6.597e-02	-0.021	0.98318	
lonitude	8.044e-03	9.399e-03	0.856	0.39207	
FSC	-1.129e-01	3.443e-01	-0.328	0.74289	
moisAustralWinter	-1.272e-01	1.024e-01	-1.242	0.21418	
latitude:lonitude	-1.008e-05	1.277e-03	-0.008	0.99370	
FSC:AustralWinter	5.054e-01	4.096e-01	1.234	0.21730	

Count model coefficients (negbin with log link):

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.058843	0.705160	1.502	0.133210	
latitude	0.149833	0.080048	1.872	0.061234	.
longitude	0.009727	0.012105	0.804	0.421629	
FSC	-1.124336	0.384440	-2.925	0.003449	**
AustralWinter	-0.122051	0.128655	-0.949	0.342791	
latitude:longitude	-0.002458	0.001531	-1.605	0.108486	
FSC:AustralWinter	1.101460	0.469514	2.346	0.018978	*
Log(theta)	-0.518421	0.157345	-3.295	0.000985	***

- - -
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Theta = 0.5955
log-likelihood: -3770 on 15 Df

D. Residuals analysis

Estimation of each parameter effect is done within the link function environment and should be converted back in the "normal" environment to have the real effect of each parameter. Moreover, a look was given to the residuals of the model to verify the normality of the residual variation and confirm the fitting of the model (figure 11).
Gross residuals are the difference between observations and predictions. Residuals analysis is not that direct because we don't usually know the distribution law of the residuals. Residuals must furthermore, reflect the relation between the esperance and the variance of the model. We looked the standardised residuals of Pearson because of the variations are supposed to be normalised. The QQplot/QQline of the standardised residuals should help us to determine if the chosen model represents well the reality. We observe there that the tail of the loss estimates diverge from the normality: showing there an increase

of variability with higher value. The model predicts well the lower values but diverges when it predicts higher values of silky sharks caught.

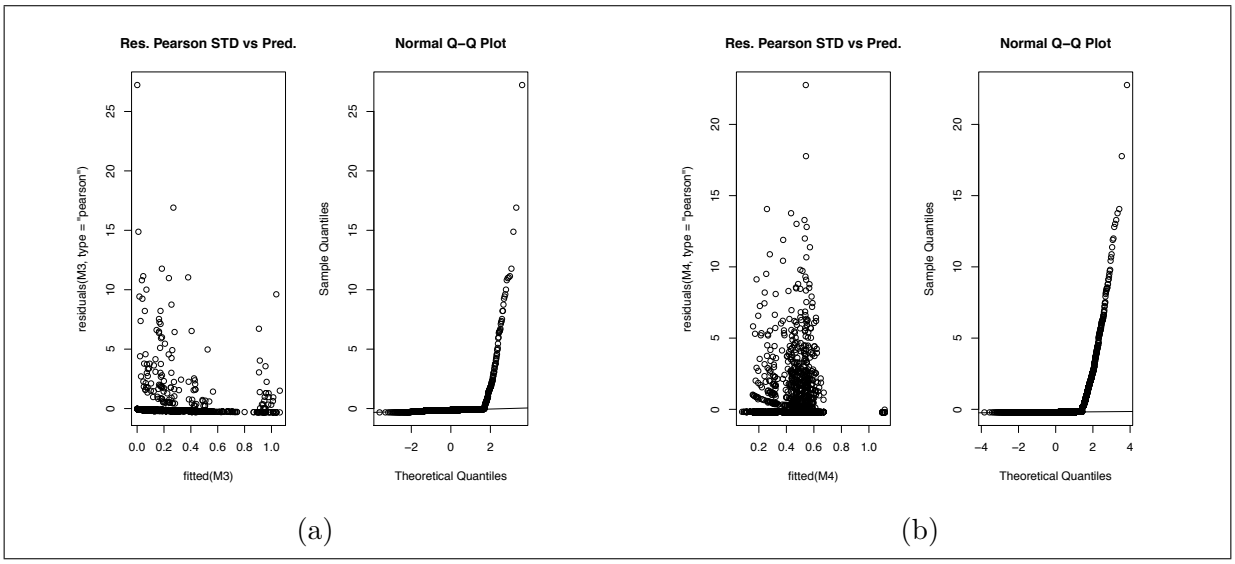


Figure 12: Standardised residuals versus fitted predictions and Normal Q-Q plot in the Atlantic Ocean (a) and in the Indian Ocean (b).

2.3.2 Prediction of the catch amount

A. Prediction in the Atlantic Ocean

After the fitting of the ZINB in the Atlantic Ocean, predictions on the number of silky sharks caught among seasons and fishing modes were computed (figure 13).
The ZINB model predicts higher level of silky sharks bycatch under FAD all over the seasons with similar capture level on FSC during the cold Season

Predictions were then mapped and reveal hotspot of captures in the Guinean Gulf (figure 14). However, levels of captures heavily depend on the season and the fishing mode (figure 13). Regardless to the season, FAD catch twice as much sharks as FSC do (5 to 7 silky sharks caught in the hotspot on FAD-fishing *versus* 2 to 3 on FSC-fishing).

B. Prediction in the Indian Ocean

After the fitting of the ZINB in the Indian Ocean, predictions on the number of silky sharks caught among seasons and fishing modes were computed. The model predicts more Silky sharks caught on FAD fishing regardless to the season (figure 15). However, captures during the austral winter are similar between FAD and FSC fishing. Predictions were then mapped and reveal hotspot of captures offshore the Somalian coast and the second in the south east of the studied area (figure 16). However, levels of captures depend on the season and the fishing mode (figure 15). On FAD, captures levels are similar in the austral summer and in the austral winter. Nevertheless, the highest captures on FAD are done in the austral summer (time of the year when FAD are used the most). On FSC in austral winter captures are twice as high as they in the austral summer.

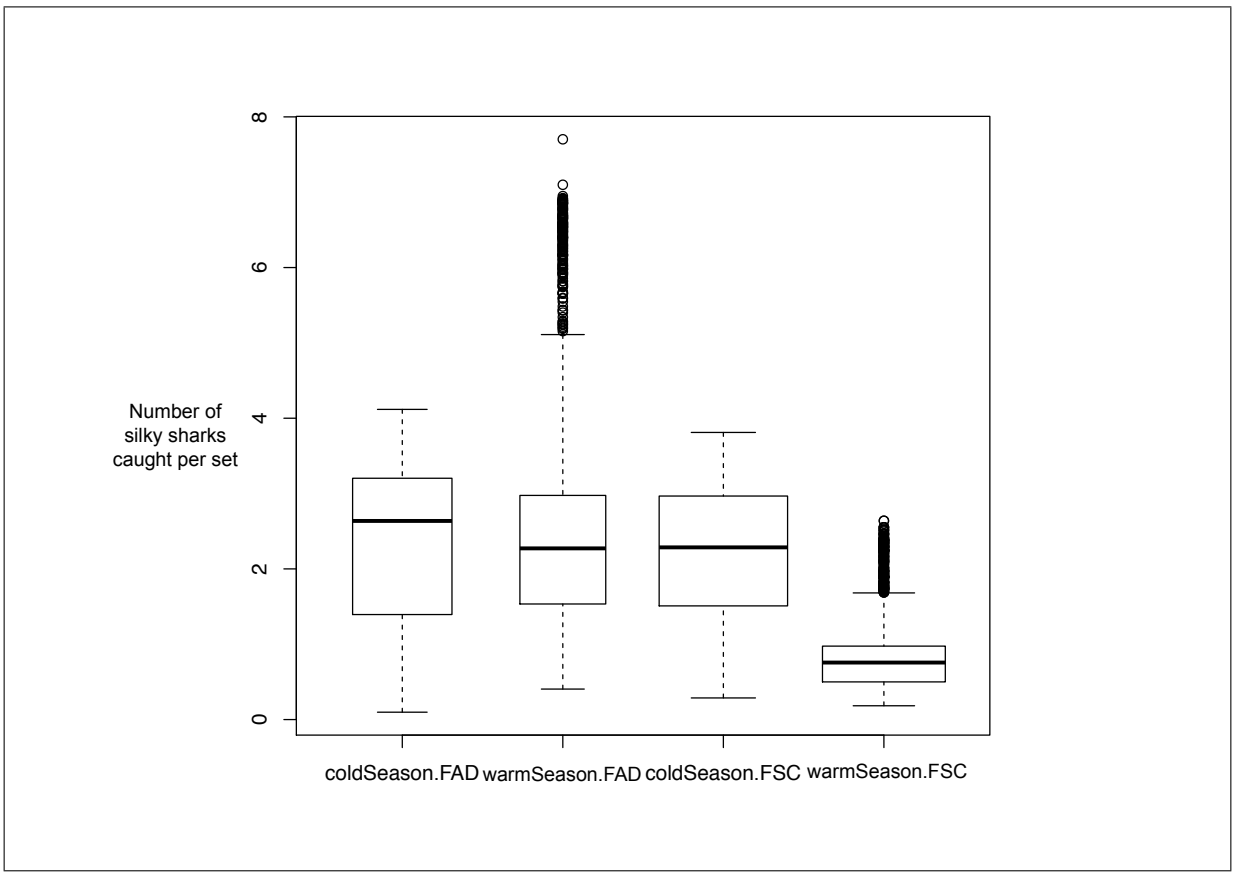


Figure 13: Predicted number of silky sharks caught in the Atlantic Ocean

2.4 Multi-specific models

2.4.1 Model on the Simpson diversity

A. Multispecific model in the Atlantic Ocean

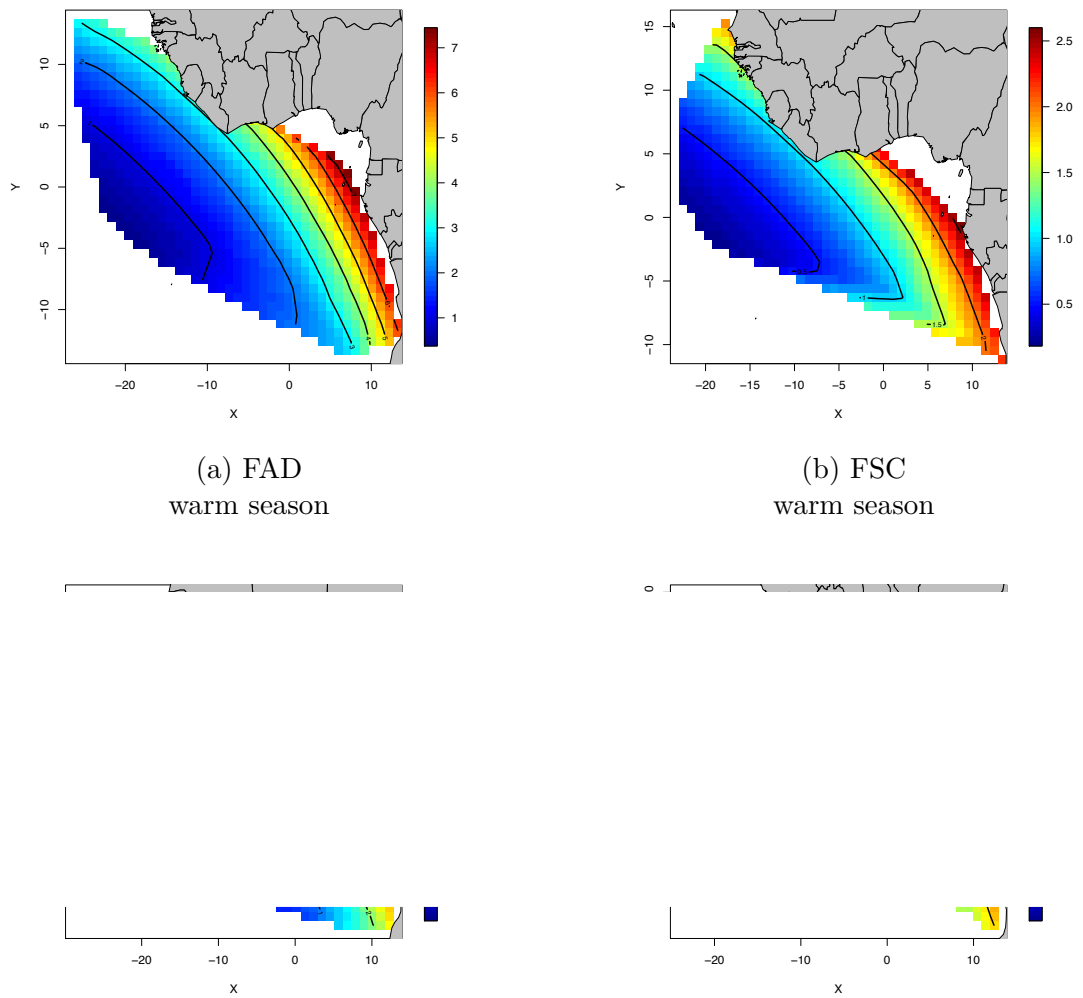
The $GAM_{binomial}$ in the Atlantic Ocean is adjusted with a $R^2 = 0.409$ and explains 34.4% of the variation observed (table 12). The fishing mode have a significant effect on the Simpson diversity index unlike the season which has no effect on the Simpson diversity index. The diversity is significantly lower under FSC as observed previously (see Part 2.1.4). The diversity was higher during the warm seasons.

The curve of the smoother may be useful as a broad summary of the pattern of change over latitude and longitude. Here (figure 17), the trend of the curves suggests an increase of the Simpson index with increased latitude and longitude.

B. Multispecific model in the Indian Ocean

The $GAM_{binomial}$ in the Indian Ocean is adjusted with a $R^2 = 0.528$ and explains 46.3% of the variation observed (table 13). All the parameters chosen have a significant effect on the Simpson diversity index. However, the fishing mode appears to be the more significant parameters : the diversity is significantly lower under FSC. The diversity was lower during the austral winter.

The trend of the curves (figure 18) suggests a reduction of the Simpson index in the middle of the ocean.



(a) FAD
warm season

(b) FSC
warm season

(c) FAD
cold season

(d) FSC
cold season

Figure 14: Mapping of the predicted number of silky sharks caught in the Atlantic Ocean

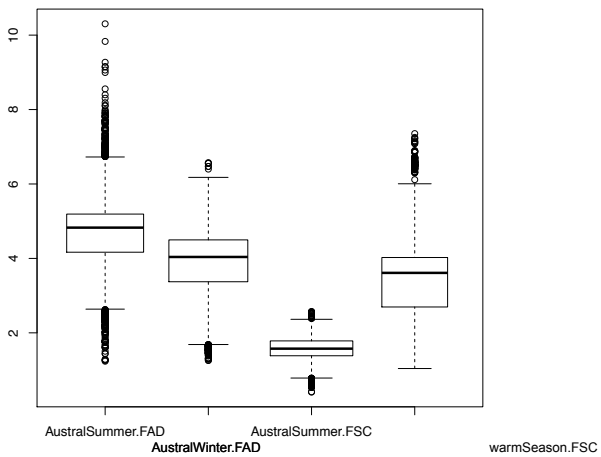
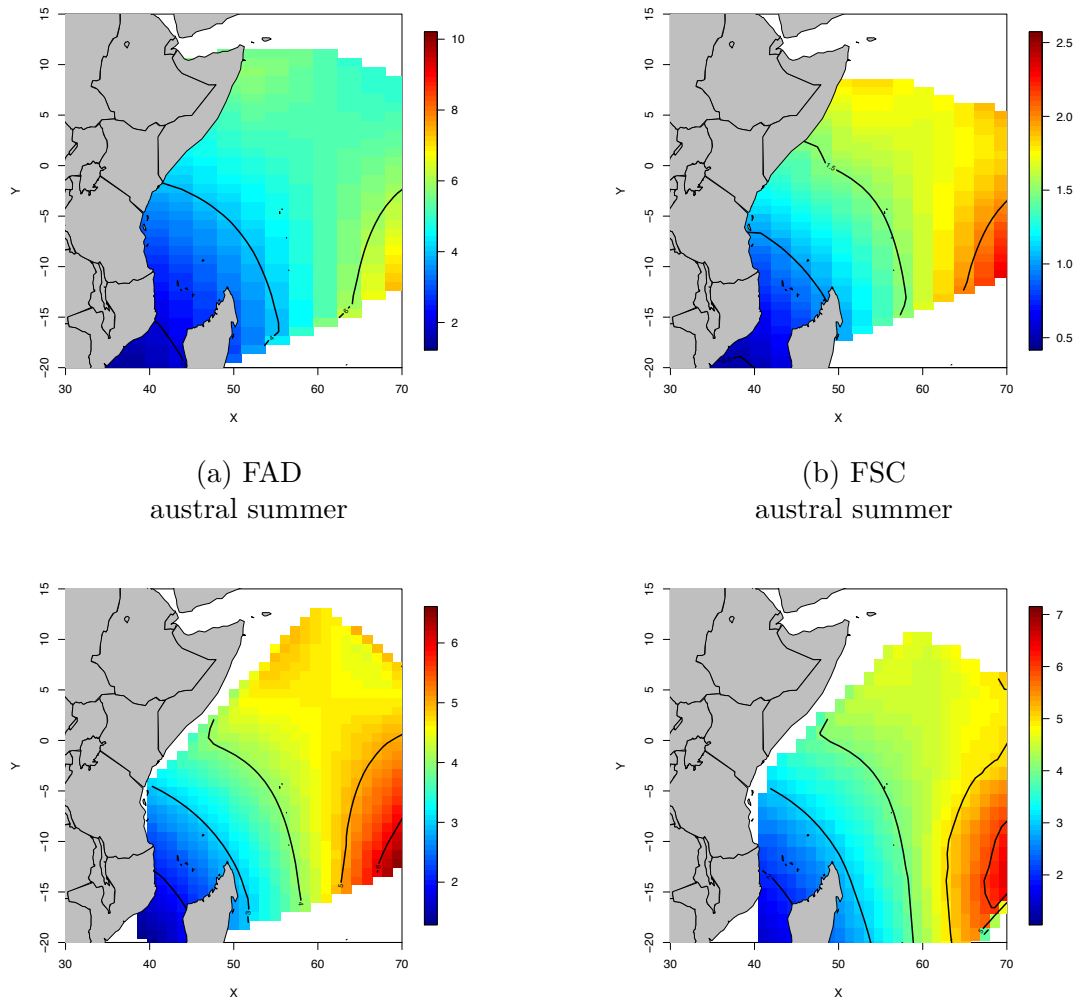


Figure 15: Predicted number of silky sharks caught in the Indian Ocean



(a) FAD
austral summer

(b) FSC
austral summer

(c) FAD
austral winter

(d) FSC
austral winter

Figure 16: Mapping of the predicted number of silky sharks caught in the Indian Ocean

Table 12: GAM model coefficients (binomial with logit link) in the Atlantic Ocean.

Parametric coefficients :

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.1976	0.1295	9.250	< 2e-16	***
warm season	0.1502	0.1542	0.974	0.33	
fishing mode FSC	-2.0038	0.1326	-15.117	< 2e-16	***

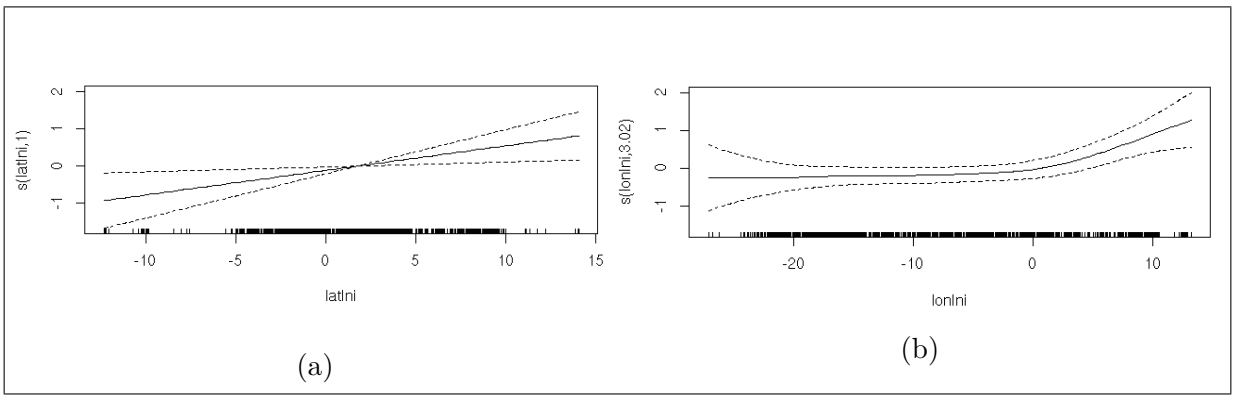
- - -
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms :

	edf	Ref. df	Chi. sq	p-value	
s(latitude)	1.000	1.001	3.738	0.05326	.
s(longitude)	3.571	4.447	16.560	0.00371	**

- - -
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq (adj) = 0.409 & Deviance explained = 34.4 %



(a) (b)

Figure 17: Smoothing curves of the smooth parameters latitude (a) and longitude (b) in the Atlantic Ocean

Table 13: GAM model coefficients (binomial with logit link) in the Indian Ocean.

Parametric coefficients :

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.48111	0.09962	14.867	< 2e-16	***
mois: austral winter	0.34496	0.12666	2.724	0.00646	**
fishing mode FSC	-2.35042	0.12521	-18.772	< 2e-16	***

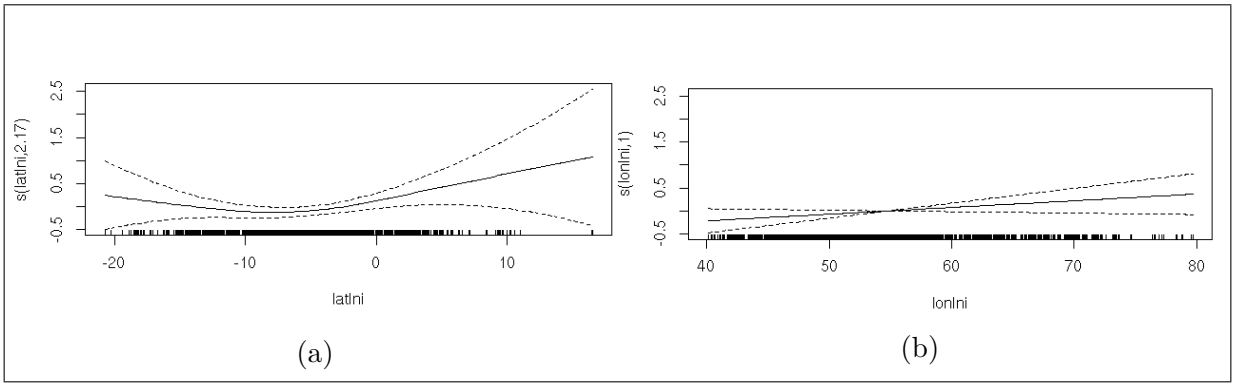
- - -
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms :

	edf	Ref. df	Chi. sq	p-value	
s(latitude)	2.291	2.961	8.420	0.0371	*
s(longitude)	1.001	1.001	4.131	0.0422	*

- - -
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq (adj) = 0.528 & Deviance explained = 46.3 %



(a) (b)

Figure 18: Smoothing curves of the smooth parameters latitude (a) and longitude (b) in the Indian Ocean

2.4.2 Predictions

A. Prediction in the Atlantic Ocean

The seasonal effect added in the model gave more contrast in the predicted values of the Simpson diversity index among fishing mode in the Atlantic Ocean (figure 19). These predicted values of Simpson index are in conformity with value observed in part 2.1.3.

Tho model predicts a diversity of 0.77±0.006 under FAD and of 0.30±0.008 on FSC. The diversity seems to reduce during the cold season. This loss is significant (under FAD: p-value = $5.184e^{-12}$. On FSC: p-value = $1.839e^{-09}$).

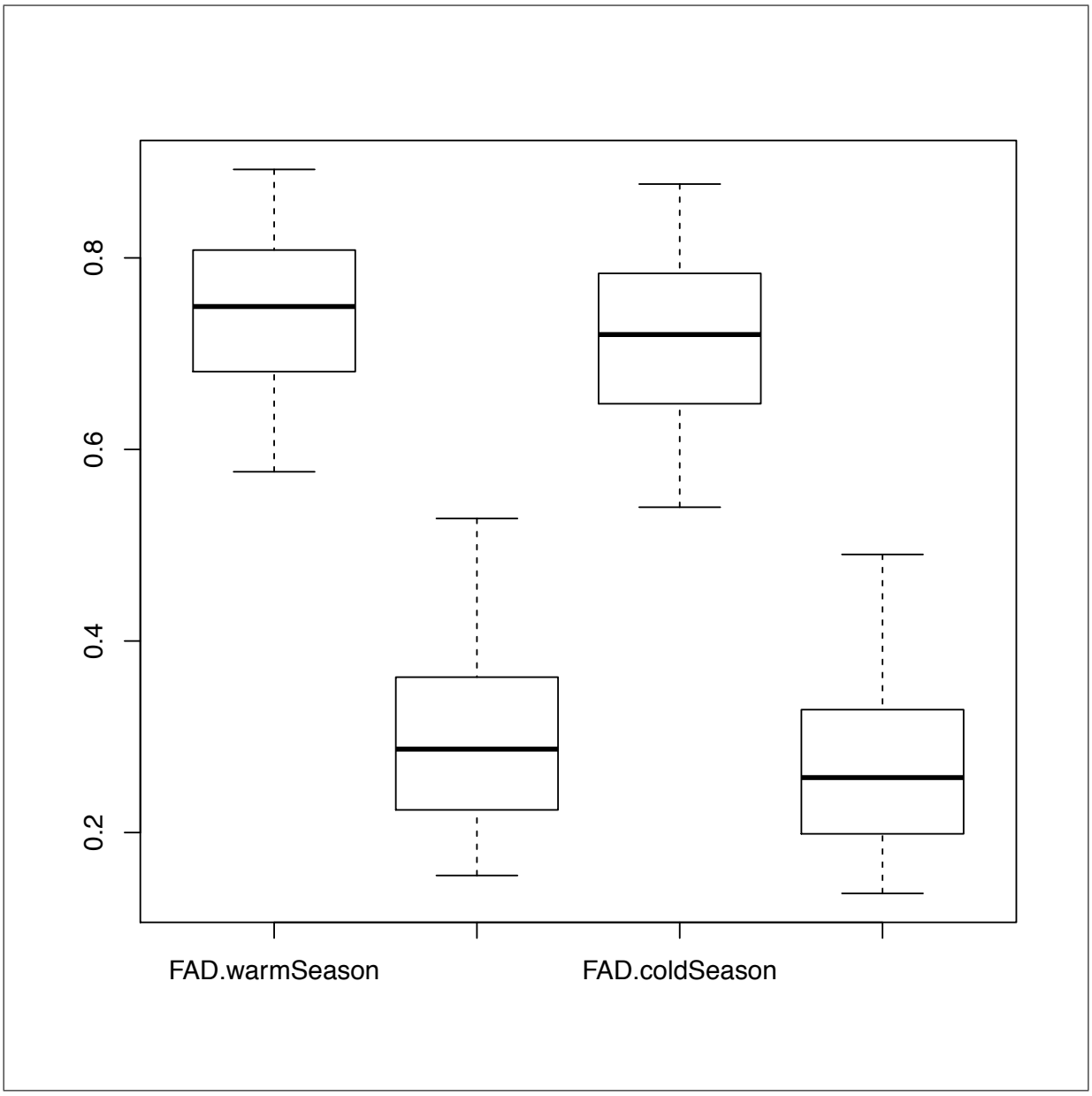


Figure 19: Predicted Simpson diversity index per fishing mode and season in the Atlantic Ocean.

B. Prediction in the Indian Ocean

The seasonal effect added in the model gave more contrast in the predicted value of the Simpson diversity index among fishing mode in the Atlantic Ocean (figure 10). These predicted value of Simpson index are in conformity with value observed in part 2.1.3. A diversity (or probability to observe two different species) around 0.85±0.003 under FAD and around 0.35±0.005 on FSC. The diversity seems to increase during the austral winter. This enhancement is significant (under FAD: p-value $< 2.2e^{-16}$. On FSC: p-value $< 2.2e^{-16}$).

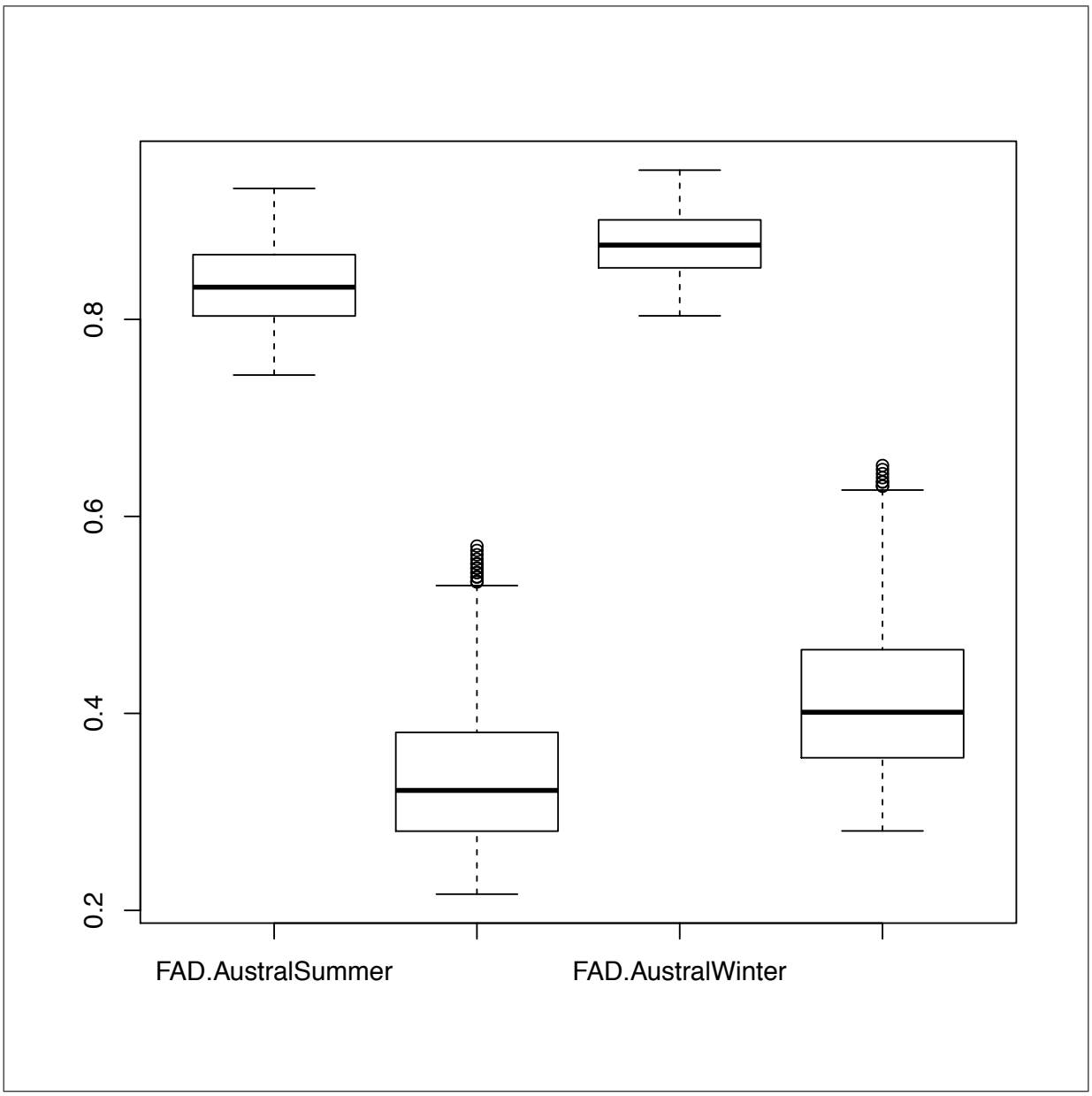


Figure 20: Predicted Simpson diversity index per fishing mode and season in the Indian Ocean.

3 Discussion

These results may be used to understand better tuna purse-seine fisheries conducted in the tropical Atlantic and Indian Oceans and more precisely, differences between FAD fishing and fishing on FSC. Using diversity indicators such as the taxonomic richness, the Simpson diversity index and the Simpson evenness index, a description of the overall catch has been done, giving some clue of understanding of what is caught under FAD and on FSC (Hortal et al. 2006, Magurran 1988). Results are based on the french observers data collected from 2006 to 2011. The Spanish data weren't available. This lack of data widely limits results because the Spanish fishery is about 50% bigger than the French fishery and covers different areas. An other limit of this study is the precision of species identification which depends on the qualifications of the observers. The short duration of the time series reduces the data usable and Somalian piracy reduces the coverage rate as pointed out by Chavance et al (2011) in their study of tuna purse seine bycatch and discards. Ours results showed that French tuna purse-seine fisheries generate higher level of bycatch and discards on FAD-fishing than on FSC-fishing.

Richness is higher under FAD due to the aggregating function of those devices. Diversity (the probability for drawing randomly two different species) is higher under FAD too. Evenness (the probability for drawing two different individuals) doesn't always follow the same trend than diversity but it is the case here. To summarize, there are more various species under FAD, the probability to observe two different species is increased by the using of FAD and the biomass is more equitably allocated between species under FAD rather than on FSC. It is in accordance with the results obtained by Lezama-Ochoa N. (2015) in her study of the Indian tuna purse-seine fishery. Indeed, even if it was Shannon diversity and evenness indexes which were used and not Simpson's, results she presented showed that the richness, the diversity and the evenness were higher under FAD than on FSC. It confirmed previous observations indicating that the fishing mode affects the taxonomic richness and diversity (Torres-Irineo et al 2013).

The most common groups encountered under FAD are: Auxis species, miscellaneous Scombridae and various fishes such as Balistidae and Carangidae. Those fishes are well known to aggregate under FAD as described by Prado (2001) and Deudero (1999): very close to the FAD, very small fishes and juveniles are feeding on molluscs and crustaceans fixed on the device a few meters away species found are mostly Carangidae, Echenidae and Balistidae. A few more meters away are found the predators like dorado, sharks, tuna. On FSC, the most common groups encountered are rather epipelagic species know for being solitary or forming small loose aggregations rather than compact schools such as billfishes, wahoo and some species of Auxis. Our results confirmed previous observations (Ariz et al. 1999, Chassot et al. 2009) indicating that the fishing mode affects the taxonomic composition of the capture (Amandé J. et al. 2010, Ariz et al 1999, Hallier and Parajua 1999, Fonteneau et al. 2000, Romanov 2002).

The length class distribution analysis conducted concerns only the bycatch and could inform on what size range is impacted by the fisheries. However, no significant conclusion could have been made on the base of the present data. Probably due to the lack of data assigned to the non-available Spanish data. According to Shin et al. (2005), size-base indicators can be used to evaluate the ecosystem effect of fishing. FAD-fishing catch smaller individuals than FSC-fishing and then have a stronger effect on fish communities. As described by Gascuel et al (2004) trophic spectra are based on aggregated data by species in combination with species trophic level and can be used as ecosystem indicator or to describe impact that fisheries can have on marine communities. The trophic level analysis conducted in this study concerns just the bycatch and could inform on what

preys tuna feed on and what part of the trophic spectrum is the more impacted by the fisheries. mostly the trophic level on FSC is higher meaning that on average, FAD catch more taxa with a lower trophic level than FSC (it could be different species or smaller individuals from the same species but with a lower trophic level). Diversity analysis in addition with trophic analysis give clues for better understanding of the overall capture and exploited ecosystem (Xianshi and Qisheng 1995)

As described by Benoît et al. (2003), in their continuous model of biomass size spectra governed by predation, linear size spectra are stationary solutions of this model. He found that realistic fishing effort should affect the curvature and stability of the size spectrum rather than its slope where a strong effect affect the curvature and the slope. Jul-Larsen et al. (2003) showed how the biomass-size spectrum is modified from an unexploited community, alters as a results of size-selective fishing, and potential prey release. Our results showed a stationary size-selective with prey release biomass-size spectrum under FAD with a high fishing effort. Results obtained by Sweeting et al. (2008) showed impacts on demersal fish communities of a trawling exclusion in Sicily. Their result can be used for ecosystemic tuna fisheries management in order to reduce bycatch and protect key areas

Carcharhinus falciformis is one of the three most common pelagic shark species with the *Carcharhinus longimanus* and the *Prionace glauca*. They are caught throughout the tropical and subtropical regions (Compagno 1984, Henderson et al. 2009, Gerrodette et al. 2011) and are a major component of tuna purse-seine fisheries bycatch (Amandé et al. 2008, Amandé et al. 2010, Romanov 2002, Watson et al. 2009). Filmalter et al. (2011), described for the first time the behaviour of silky sharks around drifting fish aggregating devices in the Indian Ocean. Their results showed a residency pattern of juvenile silky sharks around FAD. In their model, Amandé et al. (2011) wanted to explore effect of various parameters on the presence and amount of silky sharks caught in purse-seine net in the Indian Ocean. Our results are in accordance with theirs: most of silky sharks caught by the french tuna purse-seine fishery are captured under FAD and are mainly dominated by immature individuals (Amandé et al. 2008), a strong spatial and temporal effect have been showed too. In their model they used the richness as explicative parameter but because of a richness map of the studied area wasn't available it was impossible for us to use that parameter. However, these results may be used to determine key areas and seasons to protect in order to reduce the numbers of silky sharks caught around FAD in the Atlantic and Indian Ocean. The Somalian coast and the inner Guinean Gulf are hotspots of silky sharks bycatch and could be protected in order to reduce the capture of this species.

The results of our multispecific model have shown seasons and specific areas with high value of Simpson diversity index and could be used in the future for an ecosystem based fishery management for tuna purse-seine fisheries. Indeed, some areas like the inner Guinean Gulf and the Somalian coast could be protected to reduce bycatch of silky sharks and bycatch of several other species (richness, diversity and evenness high in those areas). At the same time, a reduction of the FADs using could be a way for reducing the impact of the tuna purse seine fisheries on fish communities.

Next objectives that could be implemented for future studies are first to collect more environmental data in order to have a better understanding of the marine communities physical environment and add more contrast in our model. This could help us to determine better areas to protect and to exploit if we find area with lower bycatch level and high tuna captures. However before that we need to have access to the Spanish data for a full coverage of the tuna purse-seine fishery, then we need to extend the time series for a smoothing of inter-annual variability.

Conclusion

The main purpose of our study was to extend previous assessments of tuna purse-seine fisheries by (1) quantifying the impact on targeted and bycatch species captured by purse-seine fishing for Tuna in the Atlantic and Indian Oceans, (2) using descriptors of the composition of total capture (catch and bycatch) in terms of species diversity, numbers of individuals, weight, etc. and through these previous goals (3) giving some help for an ecosystem approach to purse-seine fisheries management. Results of this study showed that FAD-fishing discards more biomass than FSC-fishing (10% *versus* 3%). In the 114 taxa observed between the Atlantic and the Indian ocean a total of 68 taxa were common to both oceans, 13 exclusive to the Atlantic and 34 to the Indian ocean. To avoid species identification issues, a total of 22 taxonomic groups were developed. The richness, the diversity and the equitability analysis conducted on those 22 groups showed that these index were higher under FAD and in the Indian ocean. The FAD-fishing impact a larger part of the marine community and especially fragile or delicate species such as Selachians (sharks and ray). At the same time, trophic and length class analysis revealed that the mean trophic level of the bycatch was higher on FSC than under FAD and length class were slightly smaller under FAD. FAD fishing catches smaller individual of a larger portion of ecosystem and as a consequence of that the trophic level of the bycatch is reduced in comparison with FSC-fishing capture which is more oligo-specific and composed by high trophic level individual such as Sailfishes. The biomass-size spectra constructed in this study were interesting for quantifying and describing the impact of FAD-fishing *versus* FSC-fishing. It revealed significant difference between fishing modes and oceans. Fishing under FAD impact more marine communities and a larger part of the ecosystem according to biomass-size spectra constructed. Most of silky sharks caught by the french tuna purse-seine fishery are captured under FAD and are mainly dominated by immature individuals. The model showed a strong spatial and temporal effect on the silky sharks bycatch level. These results may be used to determine key areas and seasons to protect in order to reduce the numbers of silky sharks caught around FAD in the Atlantic and Indian Ocean. The Somalian coast and the inner Guinean Gulf are hotspots of silky sharks bycatch and could be protected in order to reduce the capture of this species. The results of our multispecific model have shown seasons and specific areas with high value of Simpson diversity index and could be used in the future for an ecosystem based fishery management for tuna purse-seine fisheries. Indeed, some areas like the inner Guinean Gulf and the Somalian coast could be protected to reduce bycatch of silky sharks and bycatch of several other species (richness, diversity and evenness high in those areas). At the same time, a reduction of the FADs using could be a way for reducing the impact of the tuna purse seine fisheries on fish communities.

Acknowledgement:

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Résumé du rapport de fin d'études

Impact de la pêche thonière à la senne sur les communautés pélagiques de l'océan Atlantique tropical et de l'océan Indien : comparaison de la pêche sous dispositifs de concentration de poissons et sur bancs libres.

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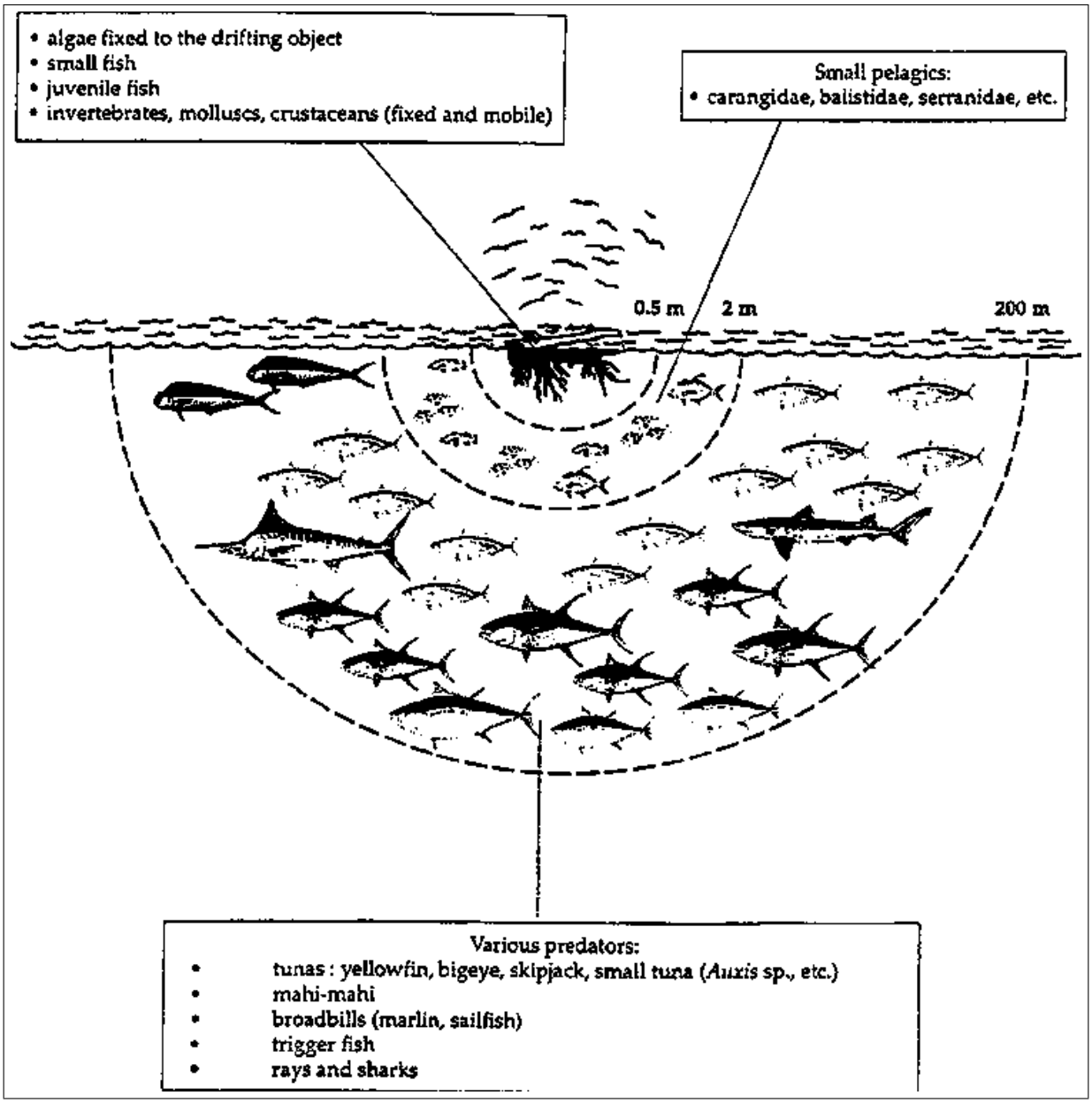
Les pêcheries thonières impactent non seulement les populations d'espèces cibles mais également la structure et la diversité des communautés associées par le prélèvement d'espèces non ciblées au travers des captures accessoires. En accord avec la réforme de la politique commune des pêches (politique du zéro rejet) et l'opinion publique, une gestion écosystémique des pêches thonières apparaît comme étant un objectif fortement recommandé (Pikitch et al. 2004; Levin et al.2009; Mc Leod and Leslie 2009). L'impact que peuvent avoir les pêcheries sur la structure et le fonctionnement des écosystèmes dépend de la biomasse, la composition, l'histoire de vie et du rôle écologique des différentes espèces capturées (Gerrodette et al. 2012). La pêche à la senne est réalisée dans l'océan Atlantique tropicale et l'océan Indien selon deux méthodes : en pêchant sur bancs libres (FSC) ou sur dispositifs de concentration de poissons (DCP). Les thons sont connus pour s'agréger à proximité d'objets flottants, tant naturels qu'artificiels. Plusieurs types de DCP peuvent être distingués : objets flottants naturels ou objets artificiels par exemple. La pêcherie thonnière tropicale est une pêcherie multispécifique ciblant *Thunnus albacares* (YFT), *Katsuwonus pelamis* (SKJ), *Thunnus obesus* (BET) et dans une moindre mesure, *Thunnus alalunga* (ALB). Un nombre non négligeable d'espèces non-ciblées telles que les

poissons porte-épées, les requins, raies et diverses espèces de poissons sont capturées. Les captures accessoires correspondent à la partie de la capture qui n'est pas ciblée par les pêcheurs (Kelleher 2005) et peuvent être rejetées (parce que les individus sont trop petits, abîmés ou n'ont aucune valeur marchande) ou retenues à bord (Hall 1996; Romagny et al. 2000). Les deux modes de pêche (DCP et FSC) capturent des prises accessoires mais dans des proportions différentes. La réduction des prises accessoires est un but explicite de l'Organisation des Nations Unies pour l'alimentation et l'agriculture (la FAO), les directives pour des plans de gestion de pêches responsables. Le projet européen 'Catch, Effort, and eCOsystem impacts of FAD-fishing' (CECOFAD) a pour objectif l'amélioration des connaissances sur les DCP et fournir des évaluations fiables d'indices d'abondance et d'indicateurs précis de l'impact de la pêche sous DCP sur les juvéniles de thons et sur l'espèces accessoires. Ce projet, cofinancé par la PCP européenne et la DG MARE est supervisé par l'IRD (Institut de Recherche pour le Développement) en collaboration avec AZTI et IEO (des instituts de recherches espagnols). Les données sur lesquelles s'appuie notre étude provienne du programme observateur mené de 2005 à 2014 dans l'océan Atlantic et l'océan Indien. Les captures accessoires sont plus élevées sous DCP qu'en bancs libres et nécessitent des mesures de gestion (Amandé et al 2008). C'est tout naturellement que la présente étude s'est fixé pour objectif d'étendre les précédentes évaluations des pêcheries à la senne en (1) quantifiant l'impact sur les espèces cibles et non-cibles capturées par les pêcheurs senneurs, (2) en utilisant entre autre des descripteurs de la composition des captures en termes de richesse, diversité et équitabilité spécifique,et de classes de taille ont révélé et enfin (3) de donner des pistes de réflexion pour une gestion écosystémique de ces pêcheries.
La pêche sous DCP rejette 10% de ses captures contre 3% en bancs libres. Sur les 114 taxa observés entre l'océan Atlantique et l'océan Indien un total de 68 taxa étaient communs aux deux océans, 13 exclusifs à l'océan Atlantique et 34 à l'océan Indien. Pour éviter des soucis d'identification d'espèces, un total de 22 groupes taxonomiques ont été développés. Les analyses de richesse, diversité et d'équitabilité conduites sur ces 22 groupes ont montré que ces indexes étaient plus élevés sous DCP et dans l'océan Indien. En même temps, les analyses de niveaux trophiques et de classe de taille ont révélés que le niveau trophique moyen des prises accessoires était plus haut sur bancs libres que sous DCP en même temps que les classes de taille étaient légèrement plus petites sous DCP. La pêche sous DCP capture des individus plus petits et de niveau trophique plus faible en plus grande proportion. Les spectres de biomasse-taille construit dans cette étude ont révélé des différences significatives entre les modes de pêche et les océans. LA pêche sous DCP impacte plus les communautés marines et une plus grosse part de l'écosystème. La majeure partie des requins soyeux attrapés par la pêche à seine française est capturée sous la DCP et est principalement caractérisée par des individus immatures. Le modèle a montré des effets spatiaux et temporels forts sur les niveaux de captures accessoires de requins soyeux. La côte somalienne et l'intérieur du Golfe de Guinée sont des zones fortement sujettes aux prises accessoires de requins soyeux et pourraient être protégées afin réduire les captures de cette espèce. Les résultats de notre modèle multispécifique ont révélé des effets spatiaux et temporels sur les valeurs de l'indice de diversité de Simpson qui pourraient être utilisés dans le cadre d'une gestion écosystémique des pêcheries thonières à la seine.

Annexes

Annex 1: Fishes Aggregating Devices



Fishes Aggregating Devices (*FAD*) are man-made floating object used to attract and aggregate ocean going pelagic fishes. They usually consist of buoys or floats. In the case of the tropical purse-seine tuna fisheries, FAD are floating rad equipped with GPS balise and sometimes more technologic apparats, amongst others, eco-sonar (to mesure the size of the tuna school) and lights (to improve the aggregating process during the night). Over 300 species of fish gather around FAD.

Annex 2: Entity diagram(*from the observers instructions manual*)

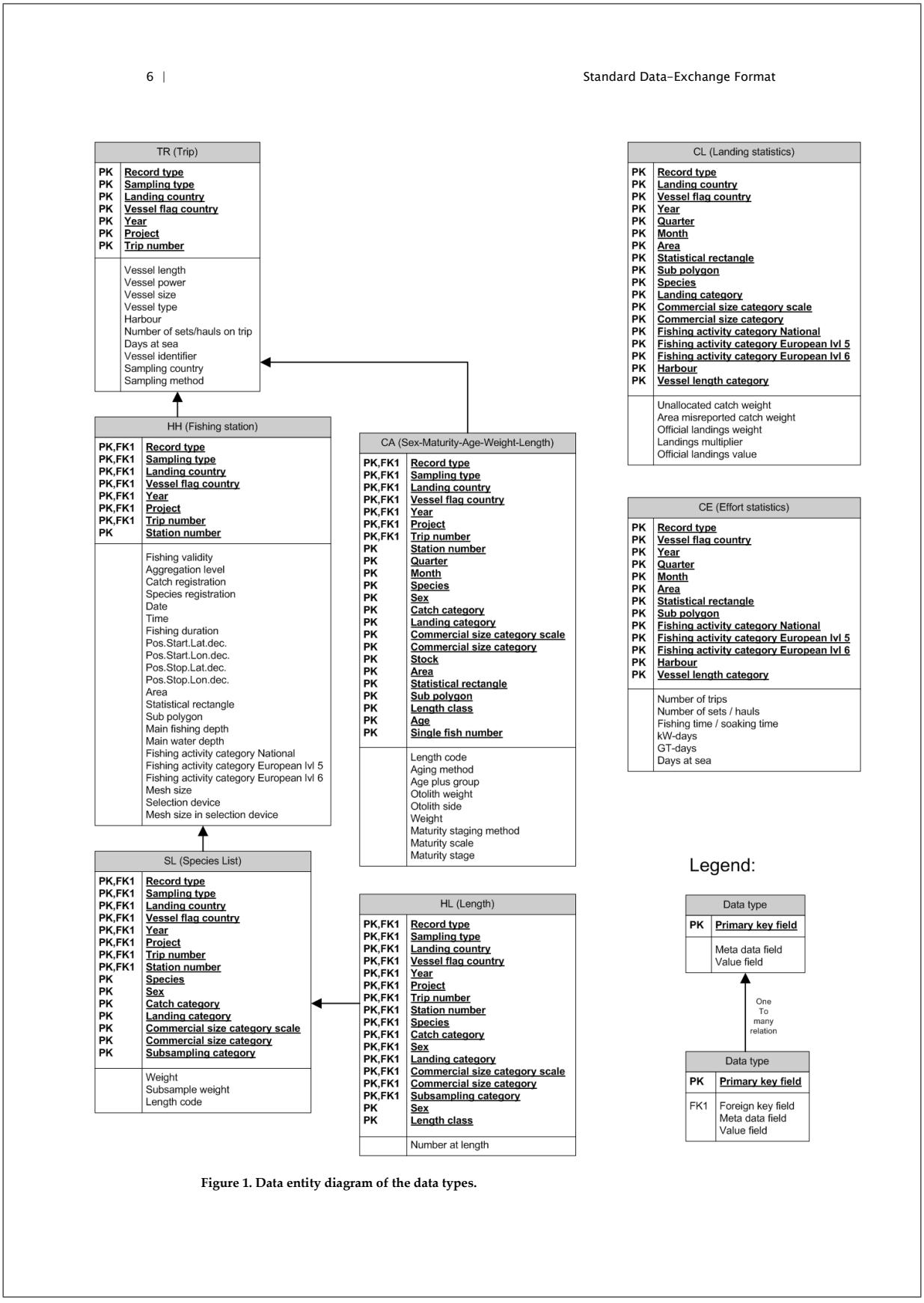


Figure 1. Data entity diagram of the data types.