UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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The spatial and temporal distribution of fishing effort for major tuna fisheries in the Indian Ocean

Master's Thesis

Master's Degree in Assessment and Environmental Monitoring of Marine and Coastal Ecosystems

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ABSTRACT

Tuna fisheries are among the largest and most valuable fisheries in the world. These fisheries can have a large impact on incidentally caught species, many of them considered vulnerable taxa and threatened species. The purpose of this study is to develop the spatially gridded fishing effort maps for major fisheries in the Indian Ocean (IO) under the management of the Indian Ocean Tuna Commission (IOTC). This study shows that only two of the main fishing gears targeting tuna fisheries in the IOTC, purse seine and longline fisheries, report sufficient spatially gridded catch and effort data to produce maps of fishing effort. The fishing effort maps for the purse seine fishery show that during the last decades has expanded around the IO, especially during the last decade in the western part. The long line fishing effort maps also show the same expanding patterns since the 1950s, covering the IO, decreasing over the last decade. The member countries of IOTC prioritize the collection and reporting of high-quality georeferenced catch and effort data for their fisheries, especially gillnet and line fisheries. In this manner, support the development of spatially explicit assessments of the stock status, for data-poor threatened species caught in tuna fisheries.

Keywords: tuna fisheries, IOTC, fishing effort, threatened species

RESUMEN

Las pesquerías de atún se encuentran entre las pesquerías más grandes y valiosas del mundo. Estas pesquerías pueden tener un gran impacto en las especies capturadas incidentalmente, muchas de ellas consideradas taxones vulnerables y especies amenazadas. El propósito de este estudio es desarrollar mapas de esfuerzo de pesca cuadriculados espacialmente para las principales pesquerías en el Océano Índico (OI), bajo la gestión de la Comisión del Atún del Océano Índico (IOTC). Este estudio muestra que solo dos de las principales artes de pesca dirigidas a las pesquerías de túnidos en IOTC, las pesquerías de cerco y de palangre, reportan suficientes datos de captura y esfuerzo cuadriculados espacialmente para producir mapas de esfuerzo de pesca. Los mapas de esfuerzo pesquero para la pesquería de cerco muestran que, durante las últimas décadas se ha expandido en todo el OI, especialmente durante la última década en la parte occidental. Los mapas de esfuerzo de pesca con palangre también muestran los mismos patrones de expansión desde la década de 1950, cubriendo el OI, pero decreciendo durante la última década. Los países miembros de la IOTC priorizan que la recopilación y el informe de datos de captura y esfuerzo de sus pesquerías, estén georreferenciados y de alta calidad, especialmente redes de enmalle y de línea. De esta manera, apoyar el desarrollo de evaluaciones espacialmente explícitas del estado de las poblaciones de especies amenazadas capturadas en las pesquerías de túnidos, que tienen pocos datos.

Palabras clave: Pesquerías de túnidos, IOTC, esfuerzo pesquero, especies amenazadas.

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1.Introduction

The incidental catch in fisheries, referred here as bycatch, continues to drive the decline of many threatened marine species such as seabirds, sharks, marine mammals, and sea turtles around the world (Carpenteri P. et al., 2021). Fisheries bycatch remains a significant conservation and management issue to be tackled in many fisheries, including tuna fisheries worldwide. Bycatch management is an important element to support the implementation of the Ecosystem-approach to Fisheries Management (EAFM) in tuna Regional Fisheries Management Organizations (RFMOs) (IOTC, 2015). Tuna RFMOs are intergovernmental organisations responsible for the management of tuna and billfishes in all the oceans. They are also responsible for the monitoring and management of species being incidentally-captured in tuna and billfish fisheries operating in their convention areas. They seek to achieve this by promoting cooperation among its Contracting Parties and Cooperating Noncontracting Parties (CPCs) to ensure the conservation and appropriate utilisation of fish stocks and encouraging the sustainable development of fisheries. The management of these fisheries has usually focused on ensuring the sustainable management of the targeted species of economic importance (e.g. principal market tunas) while monitoring the ecological impact of fisheries on bycatch species and the broader ecosystems remains a lesser priority (Juan-Jordà, 2019). A larger effort is required to address the impacts and consequences of major tuna and billfish fisheries on the state of threatened and vulnerable species caught in these fisheries and the structure and functioning of marine ecosystems (IOTC, 2018).

There are multiple assessment tools to monitor the impacts of fisheries on species and ecosystems and address simultaneously the economic and ecological objectives of fisheries and their trade-offs (FAO, 1997). Yet these are often difficult to implement in practical settings and are not often integrated in the decision-making process of fisheries management. One impediment to their practical implementation is the poor spatial and temporal resolution of the fishery data collected by many CPCs in tuna RFMOs for bycatch species. Fisheries data (catch, effort, size composition) underpins the fishery and impact assessments for all species (targeted and bycatch species) and the poor reporting fisheries data in part explains the small number of bycatch species properly assessed by tuna RFMOs worldwide (Juan-Jordà et al., 2015). An analytical tool has recently been developed to identify and prioritize species at risk, which can be applied to species in data-limited settings. This tool is a flexible spatially-explicit quantitative ecological risk assessment approach—called **E**cological **A**ssessment of **S**ustainable **I**mpacts of **Fish**eries (EASI-Fish)—which has been specifically designed to quantify the cumulative impacts of multiple fisheries for data-limited species (Griffiths et al. 2019). This new method has the advantage of calculating the cumulative impacts of multiple fisheries by producing estimates of conventional fisheries reference points, with reference to fishing mortalities and biomass, to assess the vulnerability status of species. This tool requires at least two main inputs of data, a habitat distribution model of the species and the spatial overlap of fisheries (spatial maps of fishing effort) on the species being assessed.

The main fisheries managed by the Indian Ocean Tuna Commission (IOTC), the tuna RFMO in the Indian Ocean, would benefit from a spatially-explicit approach to prioritize the vulnerability of bycatch species caught by IOTC tuna and billfish fisheries, then to inform and evaluate the efficacy of potential Conservation and Management Measures (CMMs). To support the development of spatially-explicit ecological risk assessments such as EASI-Fish, this study focuses on examining the effort data of the main tuna fisheries operating in the Indian Ocean being reported by CPCs to IOTC and also assessing the temporal and spatial patterns in fishing effort since the 1950s until today. FAO (1997) claims that the fishing effort is the amount of fishing gear of a specific type used on the fishing grounds over a given unit of time, for example, the number of hours in a day being trawled, the number of hooks in a set, or the number of hauls of a beach seine. FAO considers fishing effort a function of production unit, so management actions may involve direct action on these units, either altering the number or influencing their mode of operation. Understanding the spatial-temporal dynamics of fishing effort of major gears would allow the identification of the high-risk areas where species distributions overlap with high fishing effort. This can be achieved by mapping fishing effort at high spatial resolutions. IOTC has been collecting data on catches and fishing effort since the 50s which are useful to explore and map the spatial-temporal dynamics of the major fisheries operation in IOTC.

The IOTC has the mandate to manage sixteen fish species, among which are three species of tropical tuna (TROP), two species of temperate tuna (TEMP), six species of neritic tuna (NERI) and five species of billfishes (BILL) (Figure 1a). Since the 1950s CPCs report fishery statistics for the main mandate species to the IOTC secretariat but also for other species caught in tuna and billfish fisheries (BYCT-bycatch, UNCL-unclassified catch) (Figure 1a, Table 1a). The main fisheries operating in IOTC are gillnet, purse seine, longline, line and baitboat (Figure 1b).

Figure 1. Annual nominal catches (x1000 metric tonnes (MT)), (1950-2019). a) by group of species, b) by fisheries.

The total catch of tuna and tuna-like species has been steadily increasing yearly from the 1950s with longline fisheries catch being predominant in the early period, reaching a maximum of more than 2.1 million metric tonnes in 2018 (Figure 1b). From the 1980s the increase in catches in all the species groups is more marked, just after the introduction of the purse seine fishery in the Indian Ocean. The increase in catches is mainly reflected by the tropical tuna species (TROP), that under the IOTC mandate, are, the bigeye tuna (*Thunnus obesus*), skipjack tuna (*Kastuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*). The other group that represents a relevant amount of the total catch are the six neritic species (NERI), composed by six neritic tunas, bonitos, and Spanish mackerels, represented by bullet tuna (*Auxis rochei*), frigate tuna (*Auxis thazard*), kawakawa (*Euthynnus affinis*), longtail tuna (*Thunnus tonggol*), Indo-Pacific king mackerel (*Scomberomorus guttatus*) and narrow-barred Spanish mackerel (*Scomberomorus commerson*). The billfish species (BILL) is composed by five species that are black marlin (*Makaira indica*), blue marlin (*Makaira nigricans*), striped marlin (*Tetrapturus audax*), swordfish (*Xiphias gladius*) and Indo-Pacific sailfish (*Istiophorus platypterus*). The temperate tuna species (TEMP) are composed by albacore (*Thunnus alalunga*) and southern bluefin tuna (*Thunnus maccoyii*). The bycatch species (BYCT) are the incidental fish species caught by IOTC fisheries for tuna and tuna-like species, which are mostly sharks and other non-tuna teleost fishes.

2.Objective

The main aim of this study is to assist in the development of the spatially gridded fishing effort maps for major fishing gears in the Indian Ocean. These fishing effort maps will be used in future studies to estimate the volumetric overlap of each fishery with the distribution of vulnerable species caught in tuna and billfish species operating in IOTC. Specifically, this study has the following main objectives:

- Describe the major fishing gears operating in the Indian Ocean targeting tuna and tuna-like species under the purview of the Indian Ocean Tuna Commission.
- Develop spatially gridded fishing effort maps for each major fishery/fishing gear in the Indian Ocean.
- Describe the spatial and temporal evolution of fishing effort for major fishing gears.
- Identify major strengths and gaps and limitations in the current publicly available datasets.

3. Methods

3.1. Study Area

The convention area of the IOTC is considered the study area for this study (Figure 2). These include FAO statistical areas 51 and 57 and adjacent seas. It is necessary to cover such seas for the purpose of conserving and managing stocks that migrate into or out of the Indian Ocean (IOTC, 2021).

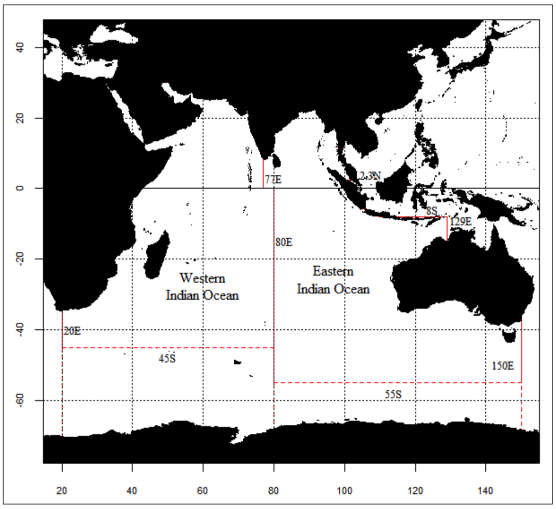

Figure 2. Area of Competence. Western IO (51), Eastern IO (57), IOTC. 2021.

3.2. Compilation of catch and effort data sets

Two publicly available IOTC datasets were analyzed on the present study: the nominal catch dataset and the catch and effort dataset (Table 1). These were downloaded from the IOTC website (IOTC, 2021).

Table 1. Summary of data sets. a) Nominal catch, b) Catch and effort.

a. Nominal Catch	- IOTC-LATEST-NC-ALL-1950-2019_2021_05_21	Annual report of total catches (in weights) (including discards), disaggregated by taxon (IOTC and non-IOTC species), fleet, gear and major Indian Ocean areas (East and West).
b. Catch and Effort	- IOTC-2020-WPTT22-DATA05-CESurface - IOTC-2020-WPTT22-DATA04-CELongline - IOTC-2020-WPTT22-DATA06-CEOther - IOTC-2020-WPTT22-DATA08-CEref	Annual report of catches (in weight or number) and effort, preferably raised to the nominal catch and fishing effort by month, fleet, gear, taxon (IOTC and non-IOTC species) and geographic grid cells. The spatial resolution of the grids ranges from purse seine (1°x1°) to longline (5°x5°) to coastal fisheries (10°x10°, 10°x20°, 20°x20°).

The nominal catch dataset corresponds to the latest version of the annual catches in live weight equivalent of all species (tuna and tuna-like species, including also non-target / by-catch species), aggregated by year, IOTC statistical area (East and West), species, and reporting country flag. Data are reported by calendar year and extend back to 1950s when industrial longlining started in the Indian Ocean (Table 1a).

The catch and effort dataset contains the catch in weight (purse seine) and/or the numbers of fish (longline) of tuna and tuna-like species and fishing effort by month, species, vessel flag and gear (Table 1b). The minimum spatial aggregation is 1°x1° grid area for purse seine and 5°x5° grid area for longline, and the catch and effort data recorded for most artisanal fleets is recorded using irregular gridded areas (IOTC, 2021). The size of the grids in Figure 3 represents the rectangle size used as unit of area. The data obtained from the catch and effort dataset (Table1b) was used for the mapping and analyses of fishing effort.

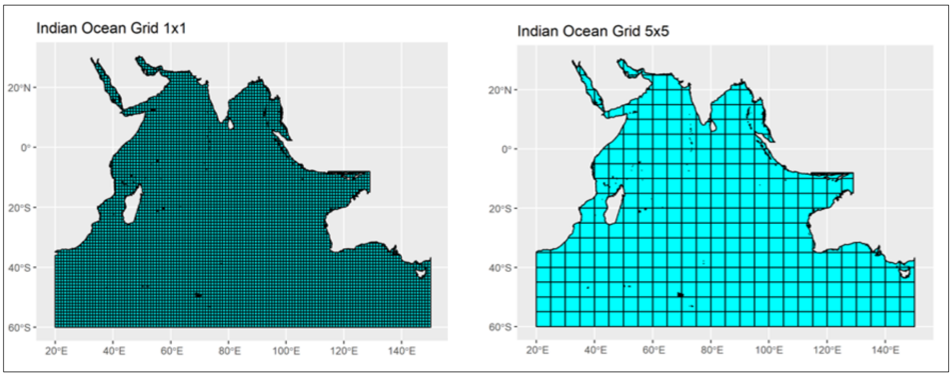

Figure 3. Grid Size 5 (1ºx1º) Purse seine, and Grid Size 6 (5ºx5º) Long line.

3.3. Data selection in the catch and effort-dataset

The fishing effort in the catch and effort dataset (Table1b) is reported in different units (Table2).

Table 2. Effort units reported in the catch and effort dataset with the name description.

EFFORT UNITS	DESCRIPTION	EFFORT UNITS	DESCRIPTION
FHOURS	Number of hours fishing	HOOKS	Number of hooks
HRSRH	Number of hours searching	NETS	Net-days
FDAYS	Number of fishing days	MD	Men-days
DAYS	Number of days at sea	SETS	Number of sets
TRIPS	Number of trips	STDHR	Hours fishing standard
BOATS	Number of boats	LINES	Number of lines (poles)

In general terms, different effort units are being reported for each major fishery gear type which in part depends on the preferences of each fleet (Table 3). The way effort units are reported can also change over time within major fishery gears and fleets, as it is explained on the following part of the study. Below, Table 3 summarises the type of effort units reported by each major IOTC fishery.

Table 3. Gears, Effort Units and Codes for the different datasets.

Dataset Catch and Effort	FISHERY GEAR	EFFORT UNITS	CATCH Effort CODE	Nominal CATCH CODE	SPECIFIC TYPE OF GEAR
IOTC-2020-WPTT22-DATA05-CESurface	**PURSE SEINE**	SETS FHOURS HOURS FDAYS DAYS TRIPS HRSRH STDHR	PS	PS	Purse seine
			PSS	PSS	Small purse seine
			RIN	PSS	Ring net
			RNOF	PSS	Ring net (offshore)
	BAITBOAT	FHOURS HRSRH FDAYS DAYS TRIPS	BB	BB	Baitboat
			BBM	BB	Baitboat mechanized
			BBN	BB	Baitboat non-mechanized
			BBOF	BB	Baitboat (OFFSHORE)
			BBPS	BB	Baitboat and purse seine
IOTC-2020-WPTT22-DATA04-CELongline	**LONGLINE**	HOOKS FDAYS DAYS BOATS TRIPS SETS	ELL	LL	Longline targeting swordfish
			FLL	LL	Longline Fresh
			LL	LL	Longline
			LLEX	LL	Exploratory longline
			SLL	LL	Longline targeting sharks
IOTC-2020-WPTT22-DATA06-CEOther	**LINE**	FDAYS DAYS MD FHOURS TRIPS BOATS HOOKS LINES	HABBTR	LINE	Handline, Pole line,Troll line
			HAND	HAND	Handline
			HATR	LINE	Handline and Troll line
			HLOF	HAND	Handline (offshore)
			HOOK	LINE	Hook and line
			LLCO	HAND	Coastal longline
			SPOR	TROL	Sport fishing
			TROL	TROL	Troll line
			TROLM	TROL	Trolling mechanized
			TROLN	TROL	Trolling non-mechanized
	OTHER	TRIPS BOATS FDAYS DAYS	BS	OTHER	Beach seine
			CN	OTHER	Cast net
			FN	OTHER	Fish net
			LIFT	OTHER	Liftnet
			TRAP	OTHER	Trap
			TRAW	OTHER	Trawl
			UNCL	OTHER	Unclassified
	GILLNET	NETS, FDAYS DAYS, TRIPS BOATS	G/L	GILL	Gillnet and Longline combination
			GIHA	GILL	Gillnet and hand line
			GILL	GILL	Gillnet
			GIOF	GILL	Offshore gillnet

It is important to understand how effort units of fisheries are reported to IOTC (Table 3) in order to choose what effort units best represent each fishery, and then examine temporal and spatial patters of effort in each fishery. In addition, it is also important to examine what and how each different fleet (CPCs) report effort and its units within the IOTC area of competence (Table 4). Table 4 shows the major fleets (CPCs) fishing in the Indian Ocean. During the analysis it was important to understand which fleets are reporting the catch and effort data and its effort units to inform of future recommendations for improving data reporting of fishery statistics.

Table 4. Major IOTC fleets operating in the Indian Ocean that are reporting Catch and Effort.

FLEET	NAME	FLEET	NAME
AUS	AUSTRALIA	MYS	MALAYSIA
CHN	CHINA	MUS	MAURITIUS
TWN	TAIWAN-, CHINA	MOZ	MOZAMBIQUE
COM	COMOROS	OMN	OMAN
EUFRA	EU. FRANCE	PAK	PAKISTAN
EUMYT	EU. FRANCE.MAYOTTE	PHL	PHILIPPINES
EUREU	EU. FRANCE.REUNION	SEN	SENEGAL
EUITA	EU. ITALY	SYC	SEYCHELLES
EUESP	EU. SPAIN	ZAF	SOUTH AFRICA
EUGBR	EU.UK	SUN	SOVIET UNION
GIN	GUINEA	LKA	SRI LANKA
IND	INDIA	THA	THAILAND
IDN	INDONESIA	GBRT	UK. TERRITORIES
IRN	IRAN ISLAMIC REP.	YEM	YEMEN
JPN	JAPAN	NEICE	NEI.FRESH
KEN	KENYA	NEIFR	NEI.FROZEN
KOR	KOREA REP.	NEIPS	NEI.OTHER
MDG	MADAGASCAR	NEISU	NEI.EXSOVIET

Next the temporal distribution of fishing effort for each major fishery by fleet and by type of effort units is described including: (1) surface fisheries, (2) longline fisheries and (3) other gears, with the objective of selecting the effort units most representative of each fishery.

3.3.1. Surface fisheries.

The surface fishery targeting tuna and tuna-like species in the Indian ocean include the purse seine and bait boat fisheries.

The purse seine fishery started to operate in the Indian Ocean around the 1980s. There was a remarkable increase in catches until the lates 2000s, where a significant drop occurred due to the piracy period effect or other factors such as the development of gillnet fisheries also targeting the same species (Figure 4) (IOTC, 2020). Catches increased again from 2015 onwards. The following minor purse fisheries including the purse seine (PS), small purse seine (PSS), ring net (RIN) and ring net offshore (RNOF) were selected for analysis. Throughout the years, the purse seine fleets that reported data (Figure 4a) were mainly the European fleets, with more than 50% of the catches, and Seychelles together with Japan and others, made up the rest of the catches. The effort units reported for these purse seine fisheries are diverse, with mainly fishing hours (FHOURS) and fishing days (FDAYS) being used to report the catch and effort across all fleets (Figure 4b). For this reason, the effort unit selected to represent purse seine fishing effort and to proceed with the analysis are FDAYS and FHOURS. Even though a major part of the data is represented in fishing hours FHOURS as it is reflected in the figure 4b, FHOURS was converted into FDAYS to aggregate both fishing units into one. In the Indian Ocean, the maximum duration of a fishing day for purse seiners targeting tropical tunas is 13 hours (Chassot, et al., 2019). Therefore, the total of FHOURS were divided by 13 to obtain the FDAYS (FHOURS/13=FDAYS). After the conversion of FHOURS to FDAYS, fishing days represents almost the totality of the total catch of purse seine (Figure 4b).

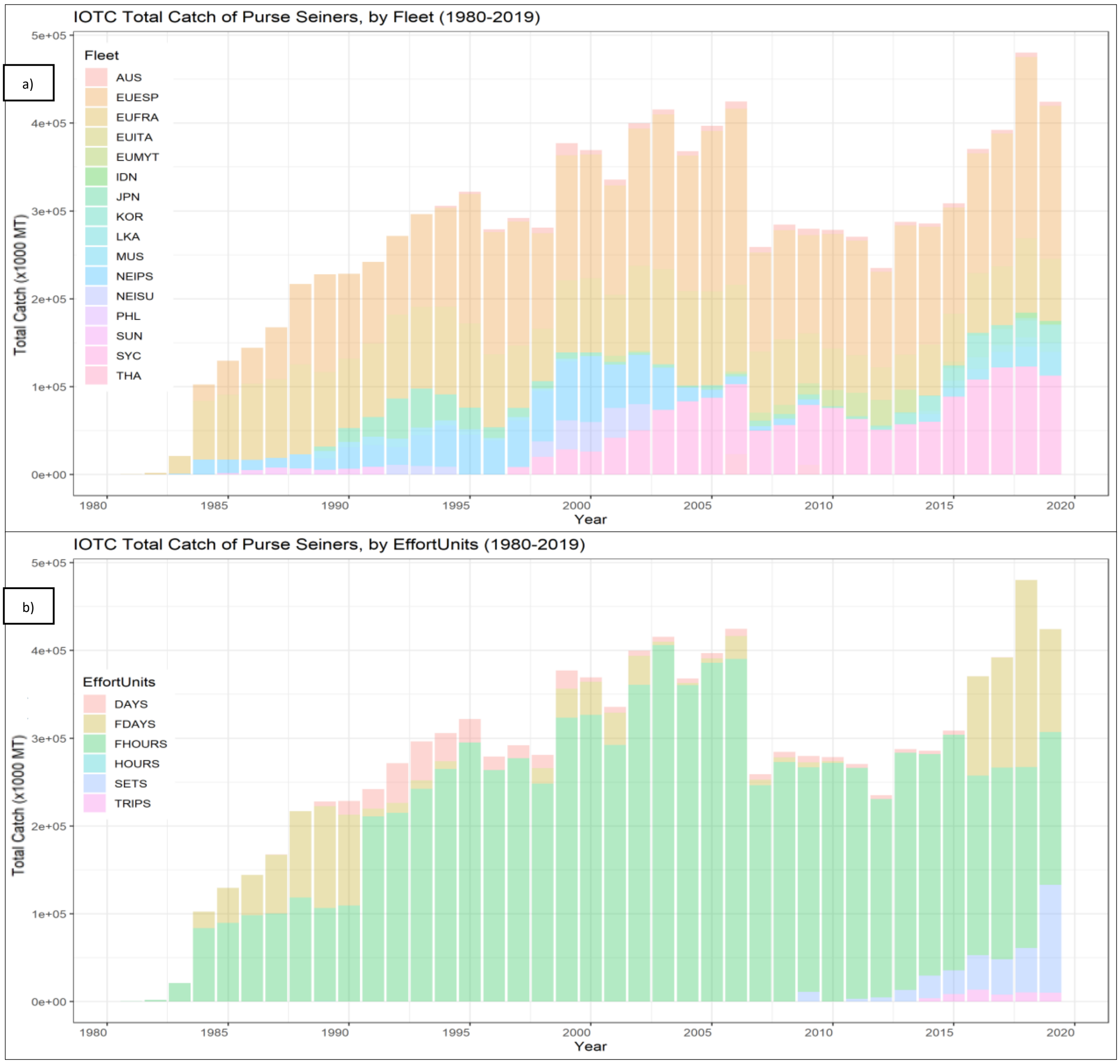

Figure 4. Total Catch of Purse seine (x1000 metric tonnes (MT), (1980-2019). a) By fleet. b) By effort units.

However, in the last decade there has been an increase of reporting catch and effort data as number of sets (SETS). It is an inconvenience, because when representing effort data spatially, those effort units that are not reported as FDAYS, as e.g., SETS, will not be analysed. It is necessary to have a standardized effort units reporting, to evaluate the real fishing effort in this fishery.

The baitboat fishery has been reporting fishing effort data since the 1970s, where the main baitboat fleet reporting catch and effort data is Maldives (MDV) (Figure 5a), which reported effort in TRIPS until 2012 and after started reporting in FDAYS (Figure 5b). The following minor baitboat fisheries including baitboat (BB), baitboat mechanized (BBM), baitboat non-mechanized (BBN), baitboat operating offshore (BBOF) and the combined baitboat and purse seine (BBPS) were selected for analysis (Table 3). The effort units reported by baitboat fisheries are also diverse (Figure 5b). The catch and effort of baitboat fisheries are mainly reported in fishing days (FDAYS), trips (TRIPS) and a small part in days (DAYS). Due to the high underreporting of catch and effort data by CPCs in IOTC baitboat fishery data was not further analysed in this study.

Figure 5. Total catch of Bait boat (x1000 metric tonnes (MT), (1970-2019). a) By fleet. b) By effort units.

3.3.2. Longline fishery.

The longline fishery started to operate in the IOTC convention area in the early 1950s soon expanding throughout the Indian Ocean, targeting several tuna and tuna-like species including the main target species of yellowfin tuna and bigeye tunas.

The longline fishery is divided into a deep-freezing longline component formed by Japan, Korea and Taiwan that mainly operate on the high seas. The other division of the longline fishery is the fresh-tuna longline component, that are considered, small to medium scale fresh tuna longlines operated by Indonesia and Taiwan (IOTC, 2020). The following longline minor gears including longline targeting swordfish (ELL), longline fresh (FLL), longline (LL), Exploratory longline (LLEX), and longline targeting sharks (SLL) were selected for the analysis (Table 3).

Throughout the years, the longline fleets reporting catch and effort data (Figure 6a), and mostly using hooks as effort units (Figure 6b), are mainly Japan, Taiwan and Indonesia. The European fleets just started operating in the Indian Ocean in the last decades, making up a small proportional of the total catches. The main effort units reported by longline fisheries are numbers of HOOKS, FDAYS, DAYS, BOATS, TRIPS and SETS (Figure 6b). The effort unit selected to represent longline fishing effort and to proceed with the analysis is number of HOOKs as most of the catch and effort data is reported in number of HOOKs.

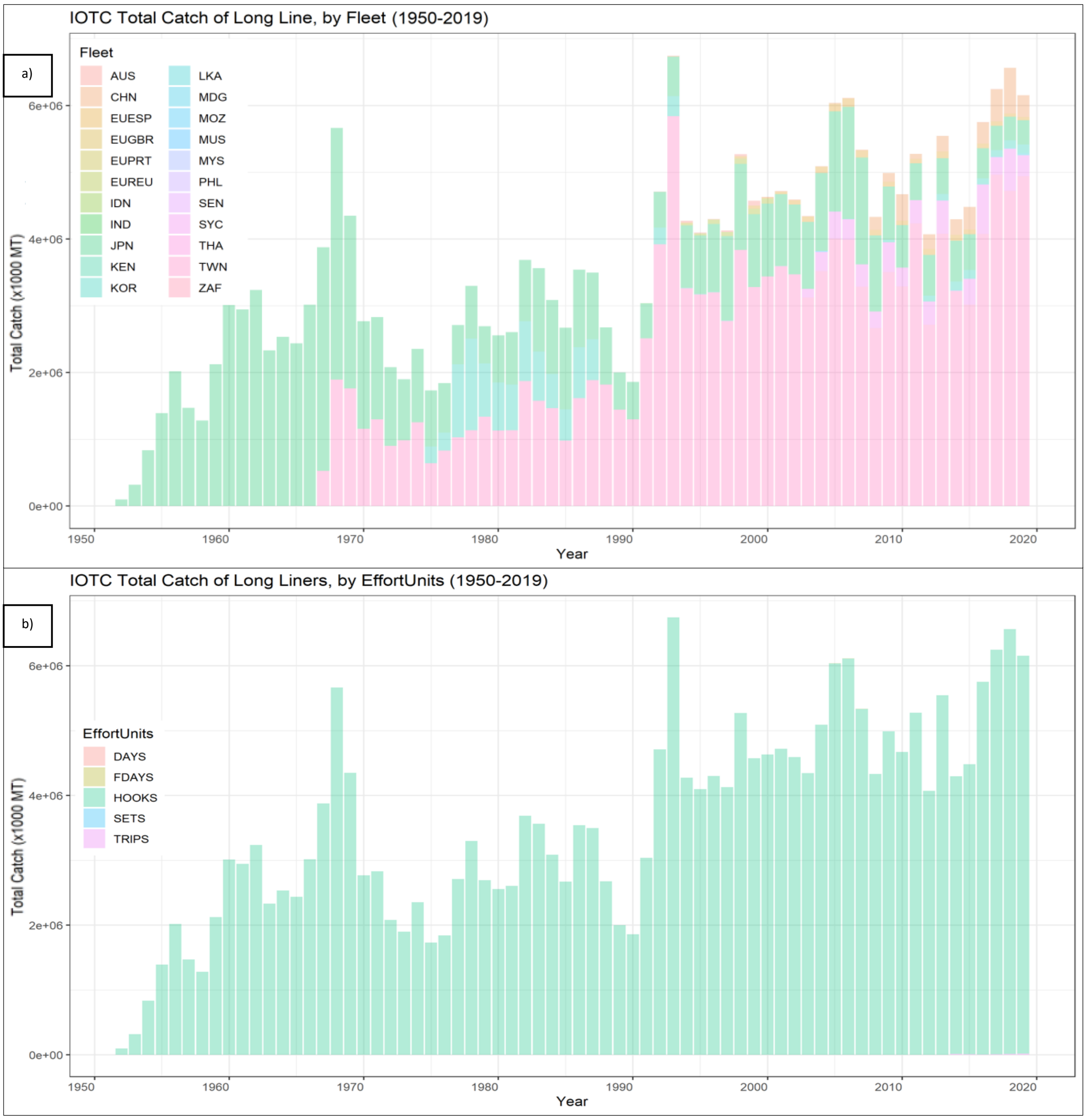

Figure 6. Total catch of Longline, (x1000 metric tonnes (MT), (1950-2019). a) By fleet. b) By effort units

3.3.3. Other fisheries.

The rest of gears reporting catch and effort data in the IOTC area are the line, gillnet, and other fisheries, which were all grouped as "Other fisheries" (Figure 7 and 8).

The main gears considered line fisheries (Table 3), are diverse, e.g., hand line, troll line (HABBTR), hand line and troll line (HATR), hook and line (HOOK), hand line (HAND), handline offshore (HLOF), and coastal longline (LLCO), sport fishing (SPOR), troll line (TROL), trolling mechanized (TROLM) and trolling non-mechanized (TROLN). The gears considered gillnet fisheries are gillnet and longline-gillnet combination (G/L), gillnet and hand line (GIHA), gillnet (GILL) and offshore gillnet (GIOF). And last for the other fisheries, the gears that are being used are beach seine (BS), cast net (CN), fish net (FN), liftnet (LIFT), trap

(TRAP), trawl (TRAW) and unclassified (UNCL). The majority of these fisheries and gears are considered artisanal fisheries operating mostly in coastal areas.

The other fisheries grouping comprehend a diversity of fisheries all together, where some of them report catch and effort data with a spatial resolution of 5°x5° (Figure 7) and others of 1°x1° (Figure 8).

Figure 7. Total catch of other fisheries (with grid 5 x 5), a) By gear. b) By fleet.

It is important to distinguish by size of grid (spatial resolution) that is reported to examine how the different countries/fleets are reporting the catch and effort data for the different gears used. The different catch and effort datasets available include data that is not standardised at the same spatial resolution, so it is difficult to merge information. These inconsistencies emerge because of the diverse range of artisanal coastal fleets fishing and reporting data at irregular areas. The different countries and fleets are also reporting the catch and effort data for each gear using different effort units, that are difficult to combine and understand the effect of the fishing effort all together. Due to the diversity of gears, mixed reporting of effort units and the relatively small proportion of catches reported, these data were not considered for the analysis.

Figure 8. Total catch of other fisheries (with grid 1 x 1), a) By gear. b) By fleet.

3.4. Mapping fishing effort

Spatially gridded fishing effort maps were produced for the two main fishing gears with the most complete catch and effort dataset, the purse seine and longline fishery. These maps were obtained after combining the total fishing effort and aggregating all the data from the catch and effort dataset across all countries and fleets (Table 1b).

3.5. R for data manipulation, synthesis, and mapping

The software used for all the data analyses and mapping was R, which is an integrated suite of software, that facilities data manipulation, calculation, and graphical display (Rstudio, 2013). The present study mainly used the packages of “readxl”, “rnaturalearth”, “dplyr” and “ggplot” for the analyses. The package “readxl” assisted in reading the datasets (Wickham H, Bryan J., 2022). “rnaturalearth” assisted in the mapping of the data (Andy South, 2017). “dplyr” assisted in the data manipulation , and “ggplot2” assisted in the data visualization (Wickham H., 2016).

4. Results

Next the spatially gridded fishing effort maps for the two main fishing gears targeting tuna and tuna-like species in IOTC, the purse seine (Figure 9) and longline (Figure 10) fisheries are shown.

4.1. Spatio-temporal distribution of fishing effort for purse seine fisheries

The spatial distribution of fishing effort for the purse seine fishery (Figure 9) by decade from 1980 to 2019 show the evolution of the spatio-temporal distribution in this fishery.

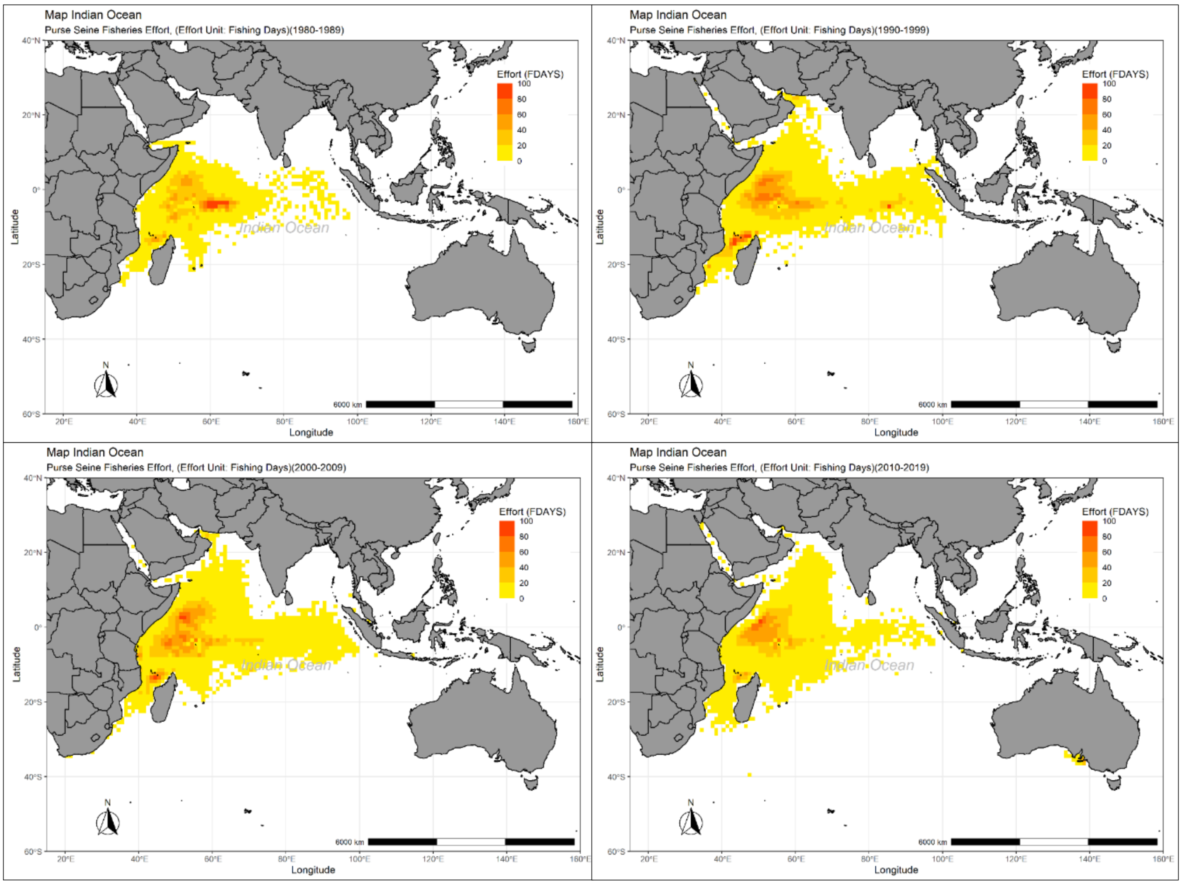

Figure 9. Purse seine fisheries effort in fishing days. Right-to-left, top-to-bottom. Period by decade, between 1980-2019.

During the first decade represented, 1980-1989, the purse seine fishery operated in the northeast of the Indian Ocean and concentrated the fishing effort around Seychelles and west of Seychelles off the coast of Somalia. During the 1990-1999 decade, the fishery spread northwards to the Arabian Sea, Red Sea, Gulf of Aden, Gold of Oman and Arabian Gulf, westwards reaching the Indonesian coast and southwards reaching the Mozambique Channel. The fishing effort still was concentrated western Seychelles and in the Mozambique Channel. During this period, the fishing effort increased up to 60 FDAYS. The following decade 2000-2009, it is still focused specially on the west of the IO, reaching a fishing effort of 80 FDAYS during the decade 2000-2009. During the last decade 2010-1019, the fishing effort starts increasing also in the Great Australian Bight.

Also, the results show the spread of the effort activity to the East part of the IO reaching Southeast of the Asian sea. As the graphs shows spread of fisheries surface and fisheries effort in all the IO.

4.2. Spatio-temporal distribution of fishing effort for longline fisheries

The spatial distribution of fishing effort for the longline fisheries (Figure 10) by decades.

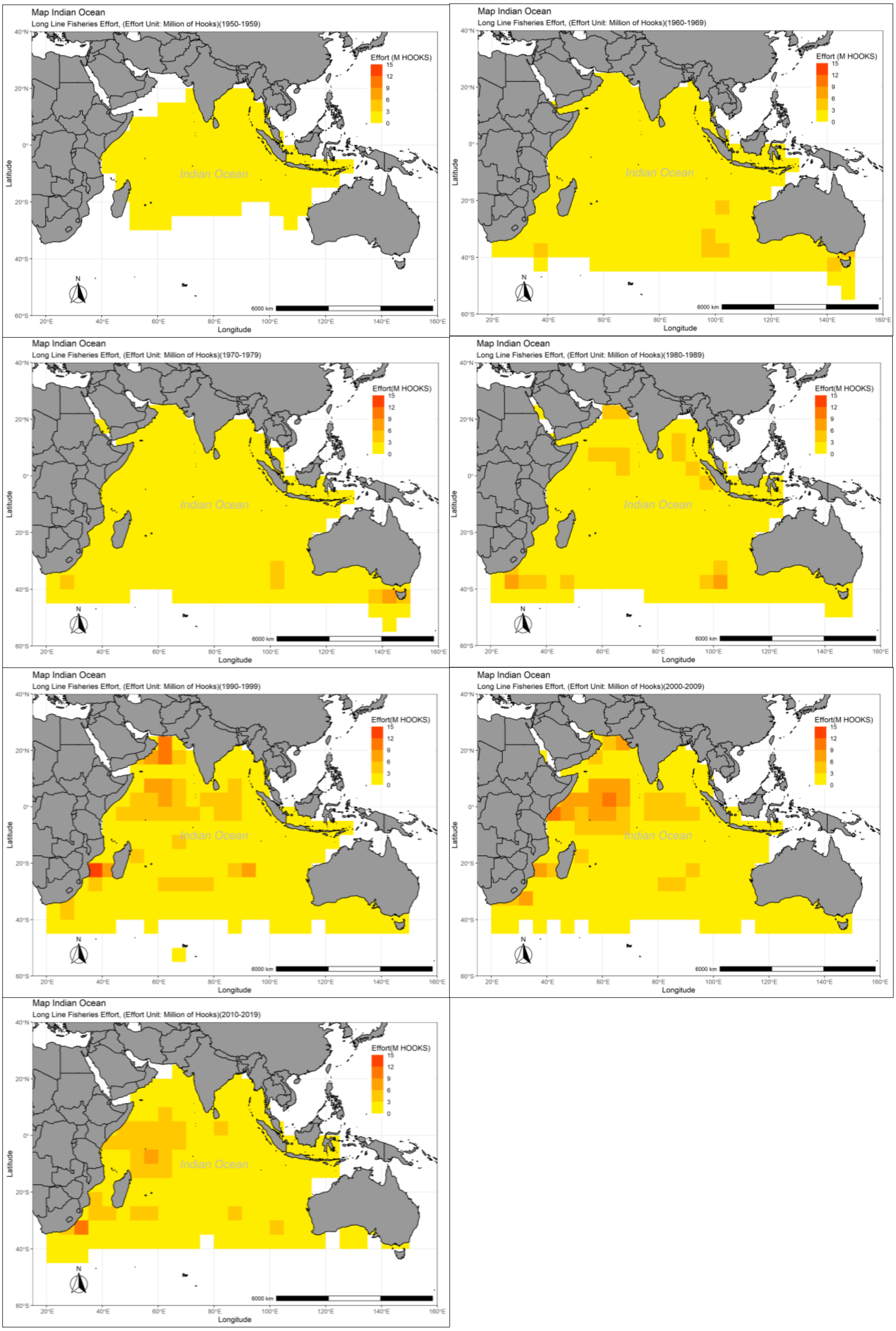

Figure 10. Longline fisheries effort in million of hooks. Right-to-left, top-to-bottom. Period by decade, between 1950-2019.

Over the decades, the fishing effort of longliners are covering almost all the surface of the IO. During the decade 1960-1969 the fisheries surfaces were totally covered by the longliners effort activity (see Figure 10). During the 1970-1979 period, the fishing effort remains similar to the previous decade. For the period 1980-1989 the fishing effort starts increasing mostly around the Arabian Sea. Also, the fishing effort started to increase in some areas around the Arabic Sea, the eastern and western part of the IO, with an increase through the decade that reached for the first time 6-9 million hooks. During the following decade, 1990-1999 period, the fishing effort reached 12-15 million hooks, and more millions of hooks spread around all the IO. Really similar scenario for the following period between 2000-2009. The last decade, 2010-2019 period, a small decrease of the fishing effort is observed, only on the southwest where in a small area is reaching 9-12 million hooks.

5. Discussion

Overall, we find the effort units reported by all the fisheries are diverse which makes it challenging to combine them for analyzing overall temporal and spatial patterns of fishing effort across the IOTC convention area. Yet, the industrial purse seine and longline fisheries reports relatively good spatially gridded catch and effort data and it was sufficient for producing spatiotemporal maps of fishing effort. While the spatial resolution of the reported catch and effort for the rest of the gears, mostly artisanal and operating in more coastal areas, was insufficient to produce spatial maps of fishing effort.

The spatio-temporal distribution of the fishing effort for purse seine fisheries, has increase throughout the decades and mostly concentrated in the western Indian Ocean. Yet it seems that after the decade 2000-2009, new fleets started to operate in other areas of the south eastern IO, such as the south of Australia. IOTC is composed of 30 contracting parties, member states with free access to tuna and tuna-like fishery resources in areas beyond national jurisdiction, which can lead to overcapacity in fishing effort and overexploitation of resources if increasing fishing effort is not controlled well (Scholaert, F. 2021).

The purse seine fishery started to operate in the Indian Ocean around the 1980s when the EU fleet moved from the Atlantic Ocean due to overcapacity to the Indian Ocean to exploit relatively new fishing grounds (Majkowski, J., 2007). The spatio-temporal distribution of the fishing effort for purse seine fisheries targeting mostly tropical tuna species has been increasing throughout the decades, with a remarkable increase in catches into the lates 2000s and contributing to a large proportion of the total catch in the area. Then a significant drop in purse seine catches occurred due to the piracy period effect or other factors such as the development of gillnet fisheries also targeting the same species (IOTC, 2020). Currently gillnet fisheries as well as other coastal gears such as artisanal longline, handline and others, make half of the catches of tropical tuna species as well as other neritic tuna species in the Indian Ocean. Yet, these fisheries poorly report their georeferenced catches and effort, making difficult the assessment of species and determining their exploitation status with certainty (Chassot, E. 2012).

On the other hand, the spatio-temporal distribution of the fishing effort for longline fisheries, starts from the 1950s increasing the fishing effort decade by decade, reaching approximately 15 million of hooks during the decade 1990-1999. After the 2000s there is decrease on the longline fishing effort, in part because the largest longline nation, Japan, started to decrease its presence in the Indian Ocean, while other longline fishing nation such as China and Taiwan started to develop their longline fleets (Majkowski, J., 2007). After the 1970s the introduction of fishing practices that improved catches, and the emergence of a sashimi market, resulted in an increase pressure on the principal market tunas species (IOTC, 2020). Currently there are two distinct longline fisheries operating in the IOTC area. The longline fishery is divided into a deep-freezing longline component formed by Japan, Korea and Taiwan which are the industrial fleets, and the fresh-tuna longline component, considered a small-medium scale fresh tuna longlines operated by Indonesia and Taiwan (IOTC, 2020). These fisheries target a wide range of species from tropical tuna species to the most temperate tunas and swordfish in the Southern Ocean. Since the 1990s, the industrial

European fleets (Spain and Portugal) also started operating in the Indian Ocean targeting swordfish and blue shark in the most temperate waters, making up a small proportional of the total catches. Our results show how the industrial longline fleets have been reporting with better success the mandatory fishery statistics of georeferenced catch and effort to IOTC, yet the artisanal longline component is lagging in the mandatory reporting because of lack of resources, planning and political will. Therefore, the current data gaps that are present in monitoring fishing effort is a big impediment to undertake quality fishery assessment and produce robust fisheries advise to the IOTC commission. Despite the poor fishery statistics reported in some fisheries, the quality and quantity of the fishery statistics in IOTC has been increasing over time. The number of species being reported in the fisheries statistics as well as the taxonomic and spatial resolution of the fisheries catch data and the catch and effort data has increased over time in IOTC (Heidrich, K. et al, 2022). Yet, the fishing effort is not being reported to be analysed or is incomplete for some of the fisheries that the fishing activity on the IOTC area, such as gillnet or line fisheries. These two fishing gears are representing a relevant effect on stock of the area studied and due to the lack or diverse data reported, e.g., the different fishing effort units making it impossible to be analysed. On the other hand, the effort units reported by the purse seine fishery, are also diverse but after combining some of the different effort units, it was possible to analyse the overall temporal and spatial patterns of fishing effort.

In addition, since 2013 IOTC is implementing a Regional Observer Scheme that will contribute to the better monitoring of fisheries in the area (Ewel, C. et al. 2020). However, in order to monitor effort effectively, the reporting of catch and effort data could be standardized better within and across fleets and fisheries, so their integration and aggregation to support regional studies can be done. Further efforts to standardize distinct units of efforts within the same type of fisheries and better reporting of effort is recommended.

In conclusion, this study enabled description of the general pattern and brought several new results to better understand the spatial distribution of the fishing effort of major fishing gears in the IOTC convention area. These will be used to inform the volumetric overlap of fisheries with the distribution of vulnerable species caught by tuna fisheries in the IOTC convention area in EASI-Fish assessments.

6. References

1. Carpentieri, P., Nastasi, A., Sessa, M. & Srour, A. E. Studies and Reviews 2011-21. 2021. 2015 p.
2. Auger L, Trombetta T, Sabarros PS, Rabearisoa N, Romanov E V, Bach P. Optimal fishing time window : an approach to mitigate bycatch in longline fisheries. Iotc–2015–Wpeb11–15. 2015;(August):1–12.
3. Juan-jordá MJ. IOTC-2019-WPEB15-31 Support for the development of an ecosystem approach to fisheries management for Indian Ocean tuna fisheries Maria José Juan-Jordá 1. IOTC-WPEB15-31, 2019. 2019;1–53.
4. IOTC-WPEB 14. Report of the Fourteenth Session of the IOTC Working Party on Ecosystems and Bycatch. Iotc-2018-Wpdcs14-R. 2018;(September):10–4.
5. FAO. Fisheries Management. Encycl Ecol Five-Volume Set. 1997;1572–82.
6. Juan-jordá MJ, Arrizabalaga H, Restrepo V, Dulvy NK, Cooper AB, Murua H. in Applying Ecosystem Based Fisheries Management. 2015;(August):1–70.
7. Griffiths SP, Lezama-Ochoa N, Roman M. Moving Towards Quantitative Ecological Risk Assessment for Data- Limited Tuna Fishery Bycatch : Application of “ Easi-Fish ” To the Spinetail Devil Ray (Mobula mobular). Vol. 0, IATTC. 2019.
8. IOTC. Area of Competence. 2021.
9. IOTC. NC-ALL @ www.iotc.org [Internet]. 2021. Available from: https://www.iotc.org/data/datasets/latest/NC-ALL
10. IOTC Secretariat. Review of the statistical data and fishery trends for tropical tunas. Vol. 22. 2020.
11. Chassot E, Floch L, Dewals P, Terrier I, Chavance P. Statistics of the French purse seine fishing fleet targeting tropical tunas in the Indian Ocean (1981-2011). IOTC Proc. 2012;68(3):1–29.
12. R Core Team. About @ Www.R-Project.Org. 1993.
13. Readxl @ readxl.tidyverse.org. 2013.
14. Rnaturalearth @ naturalearthdata.com. 2017.
15. Wickham H. Index @ Ggplot2.Tidyverse.Org. 2016.
16. Scholaert F. Tuna fisheries management in the Indian Ocean. 2021;
17. Majkowski J. Global fishery resources of tuna and tuna-like species. 2007;
18. Heidrich, K., M. J. Juan-Jorda, H. Murua, C. D. H. Thompson, J. J. Meeuwig, and D. Zeller. 2022. Assessing progress in data reporting by tuna Regional Fisheries Management Organizations. Fish and Fisheries.
19. Ewell C, Hocevar J, Mitchell E, Snowden S, Jacquet J. An evaluation of Regional Fisheries Management Organization at-sea compliance monitoring and observer programs. Mar Policy. 2020;115(August 2019):103842.