UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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Characterization of main tuna and tuna-like species and major fishing fleets in the Somali Current Ecoregion of the Indian Ocean Tuna Commission

Master's Thesis

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

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ABSTRACT:

The Indian Ocean Tuna Commission (IOTC) is advancing the development of tools to support the implementation of the Ecosystem Approach to Fisheries Management (EAFM). Within the IOTC convention area, a spatial framework comprising nine candidate ecoregions has been developed to facilitate ecosystem planning and the creation of ecosystem-based advice products to complement single-species fisheries management advice. However, validating these candidate ecoregions is essential before their application in resource planning, research, and management. This thesis contributes to the development of a pilot product aimed at evaluating the general applicability of the IOTC candidate ecoregions as a spatial framework for the creation of integrated and ecosystem-based advice products. Towards this aim, it focuses on creating a pilot Ecosystem Fishery Overview (EFO) for one IOTC ecoregion: the Somali Current (SCE). This pilot EFO addresses two questions: Who fishes in the SCE, and what species are being caught in the SCE? By analyzing IOTC catch data from 1950 to 2022, several indicators were used to identify the main fleets with major fishing grounds within the ecoregion and to characterize their historical catches. Of 62 fishing fleets reporting catches within the SCE from 2010 to 2022, 32 were identified as core fleets utilizing six different gear types (baitboat, gillnet, line, longline, purse seine, and other gear). These 32 fleets accounted for 95% of the total catch within the SCE. The core fleets in the SCE can be classified as either "regional" (24 fleets with the majority of catches and fishing grounds within the SCE) or "long-distance" (8 fleets with relevant catches and presence in the SCE but with extended distributions across the Indian Ocean). The most relevant regional fleets were gillnets and lines, while the most relevant long-distance fleets were longlines and purse seiners. In terms of species composition, Yellowfin tuna dominated with 37% of the total catches within the ecoregion, followed by Skipjack tuna at 20% and Longtail tuna at 11%. These findings are crucial for understanding the dynamics and spatial boundaries of the ecoregion. It can be concluded that the SCE has a unique set of core fleets, underscoring the distinctiveness of this ecoregion. Despite notable data deficiencies and challenges using the IOTC fishery statistic datasets, this study underscores the potential for developing EFOs as complementary advice products to those currently existing in IOTC to inform fisheries management decisions.

KEYWORDS: The Indian Ocean Tuna Commission (IOTC), ecoregions, Ecosystem Approach to Fisheries Management (EAFM), indicators, ecosystem-based research.

PALABRAS CLAVE: Comisión del Atún del Océano Índico, ecorregiones, enfoque ecosistémico para la pesca, indicadores, investigación ecosistémica.

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1. Introduction

1.1 Background

The Indian Ocean Tuna Commission (IOTC) was created in 1993 under Article XIV of the Food and Agriculture Organization (FAO) Constitution (International Seafood Sustainability Foundation, 2024). IOTC is one of the five Regional Fisheries Management Organizations (RFMO) that manage tuna and tuna-like species, as well as increasingly oceanic sharks and rays worldwide. The other four RFMOs are the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), the Inter-American Tropical Tuna Commission (IATTC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), and the Western and Central Pacific Fisheries Commission (WCPFC). These international organizations establish measures for the sustainable management and conservation of highly migratory fish species through international cooperation (Directorate-General for Maritime Affairs and Fisheries, 2024; NOAA Fisheries, 2023). Specifically, the IOTC manages 16 tuna and tuna-like species (tunas, bonitos, Spanish mackerels, mackerels, and billfishes, **Table 1**) in the Indian Ocean and adjacent seas. The IOTC convention area is subdivided into two areas: The Western and Eastern Indian Ocean (**Figure 1**). The main functions of IOTC are the conservation, management, and coordination of research of IOTC tuna and tuna-like species, their associated ecosystems, and the economic and social aspects of the fisheries. This includes estimating and overseeing the fishery stock status of IOTC species and monitoring the impacts of IOTC fleets on the ecosystem. IOTC also has a crucial role in collecting fishery statistics (e.g., catch, effort, size frequencies, etc...) of the fisheries under its purview to monitor the target and non-target species (bycatch species) caught in the IOTC fleets. This Commission consists of 29 Contracting Parties (CPC) and Cooperating Non-Contracting Parties (CNCP) that have established fisheries targeting tuna and tuna-like species in the Indian Ocean (IOTC, 2023).

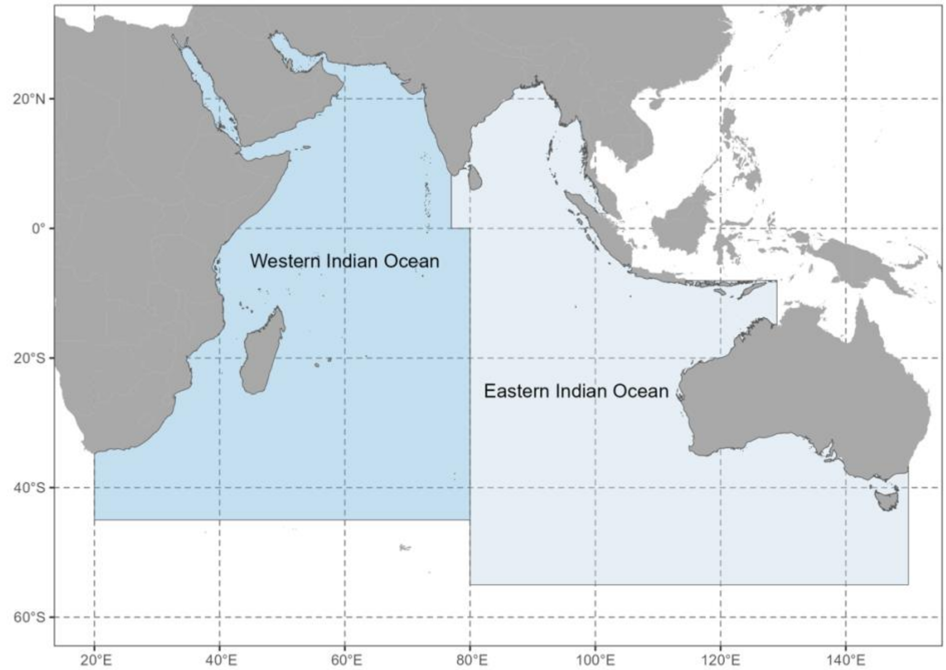


Figure 1. IOTC convention area with its two subdivisions. Obtained from the IOTC website (https://iotc.org/about-iotc/competence).

Table 1. IOTC major tuna and tuna-like species. *These are the five major species covered in the georeferenced Raised Catch dataset (see Table 4).

Taxa group	Common name	Acronym	Latin name	Climate
Billfishes	Black marlin	**BLM**	*Istiompax indica*	Subtropical
	Blue marlin	**BUM**	*Makaira nigricans*	Subtropical
	Striped marlin	**MLS**	*Kajikia audax*	Subtropical
	*Swordfish	**SWO**	*Xiphias gladius*	Subtropical
	Indo-Pacific sailfish	**SFA**	*Istiophorus platypterus*	Subtropical
Neritic tunas	Bullet tuna	**BLT**	*Auxis rochel*	Subtropical

	Frigate tuna	**FRI**	*Auxis thazard*	Subtropical
	Kawakawa	**KAW**	*Euthynnus affinis*	Subtropical
	Longtail tuna	**LOT**	*Thunnus tonggol*	Subtropical
	Indo-Pacific king mackerel	**GUT**	*Scomberomorus guttatus*	Subtropical
	Narrow-barred Spanish mackerel	**COM**	*Scomberomorus commerson*	Subtropical
Temperate tunas	*Albacore	**ALB**	*Thunnus alalunga*	Temperate
	Southern Bluefin tuna	**SBT**	*Thunnus maccoyii*	Temperate
Tropical tunas	*Bigeye tuna	**BET**	*Thunnus obesus*	Tropical
	*Skipjack	**SKJ**	*Katsuwonus pelamis*	Tropical
	*Yellowfin tuna	**YFT**	*Thunnus albacares*	Tropical

All tuna RFMOs have started to discuss how to implement an Ecosystem Approach to Fisheries Management (EAFM) according to internationally agreed standards (Juan-Jordá et al., 2018). EAFM emerged in response to the limitations of traditional fisheries management, which often focused narrowly on single species and has failed to consider the broader ecosystem context (Link, 2010). The EAFM is a spatially-explicit approach to the integrated management of fisheries that incorporates ecosystem knowledge and uncertainties, considers multiple external influences, and accounts for diverse societal objectives and their trade-offs (FAO, 2003; Garcia et al., 2003). It strives to account for the connectivity between species, their habitats, physical environments, and their connection with humans and fishing communities (Fogarty, 2014; Rice et al., 2011). The FAO adopted this ecosystem-based approach since it is an extension of conventional management, highlighting the need to maintain and ensure ecosystem health and productivity for future generations through a policy-driven process (Garcia et al., 2003).

Due to the challenges in implementing an EAFM in the context of international fisheries, the implementation of EAFM in tuna RFMOs has been slow (Juan-Jordá et al., 2018). Although most tuna RFMOs have this management strategy endorsed in their convention mandates or Scientific Committee Strategic Science Work Plans, there is a need to improve the base knowledge and develop new supporting integrated tools to better account for and monitor the fishing impacts of fisheries on bycatch and ecosystems, as well as the climate change effects on fisheries resources (Ortuño Crespo, 2019). Additionally, developing and implementing an EAFM road map in tuna RFMOs should be highly consultative, involving different supporting layers, including ecosystem planning and stakeholder participation.

Since 2015, the EAFM has been partially incorporated into IOTC's policies through the Working Party on Ecosystems and Bycatch (WPEB) (IOTC–WPEB11, 2015). Nevertheless, IOTC has made little progress in implementing the EAFM, particularly in monitoring the impacts of fishing on bycatch species and the structure and function of marine ecosystems (Juan-Jordá, 2018). The exploitation or conservation state of bycatch species, particularly endangered, threatened, and protected species, remains poorly known. Additionally, the understanding of the combined impacts of climate change and fishing activities on target and bycatch species and the broader community and ecosystem is incomplete. To advance EAFM implementation, there is a need to link better bycatch, ecosystem, and climate considerations into the more traditional fisheries management advice. This creates the need to think, plan, and act regarding ecosystems, requiring a spatial context within which ecosystems can be described, monitored, and reported (Fogarty, 2014). IOTC has yet to adopt an EAFM implementation roadmap, which is highly recommended for setting goals for ecosystem-based planning and research and developing advice products to complement the more traditional fisheries management advice.

One of the starting points and critical elements to inform EAFM implementation is identifying spatial units or spatial frameworks (ecoregions) that make ecological sense yet are practical for developing ecosystem-based research and advising products (Staples et al., 2014). Ecoregions are geographically defined areas exhibiting reasonably homogeneous ecosystems designed to be units of analysis to support ecosystem planning, incentivize ecosystem research, and the development of advice products for the integrated management of fisheries resources (Nieblas et al., 2022; Omernik, 2004). In recent years, the IOTC WPEB has been developing a process to advance the identification of ecologically meaningful regions (ecoregions) to be used as a spatial framework for guiding EAFM implementation in IOTC (**Figure 2**, **Table 2**) (Juan-Jordá et al., 2020). The delineation of ecoregions in IOTC was guided by preestablished criteria, which included three main guiding factors: (1) the main oceanographic patterns and biogeography of the pelagic ecosystem in the Indian Ocean. Two biogeochemical classifications, the Pelagic Provinces of the World (PPOW) and the coastal Marine Ecosystems Of the World (MEOW), were used to describe the major oceanographic patterns and features of the Indian Ocean pelagic ecosystem (Juan-Jordá et al., 2020). (2) the spatial patterns in the distributions of IOTC species along with the ecological communities they form. Georeferenced catches of major IOTC species were used to infer their distributions and the communities they form within the Indian Ocean. (3) The spatial patterns of the main IOTC fisheries (**Table 3**), their core fishing grounds, and the fisheries complex they form. Georeferenced catches of major IOTC fisheries were utilized to infer the spatial distribution of these fishing grounds and the resultant fisheries complexes within the Indian Ocean. These three thematic factors collectively (oceanography, species communities, and fishing grounds of major fisheries) contributed to guiding the ecoregion delineation and potential boundaries in IOTC (**Figure 2**). Distinct oceanographic characteristics, core species, and fisheries characterize the resultant ecoregions.

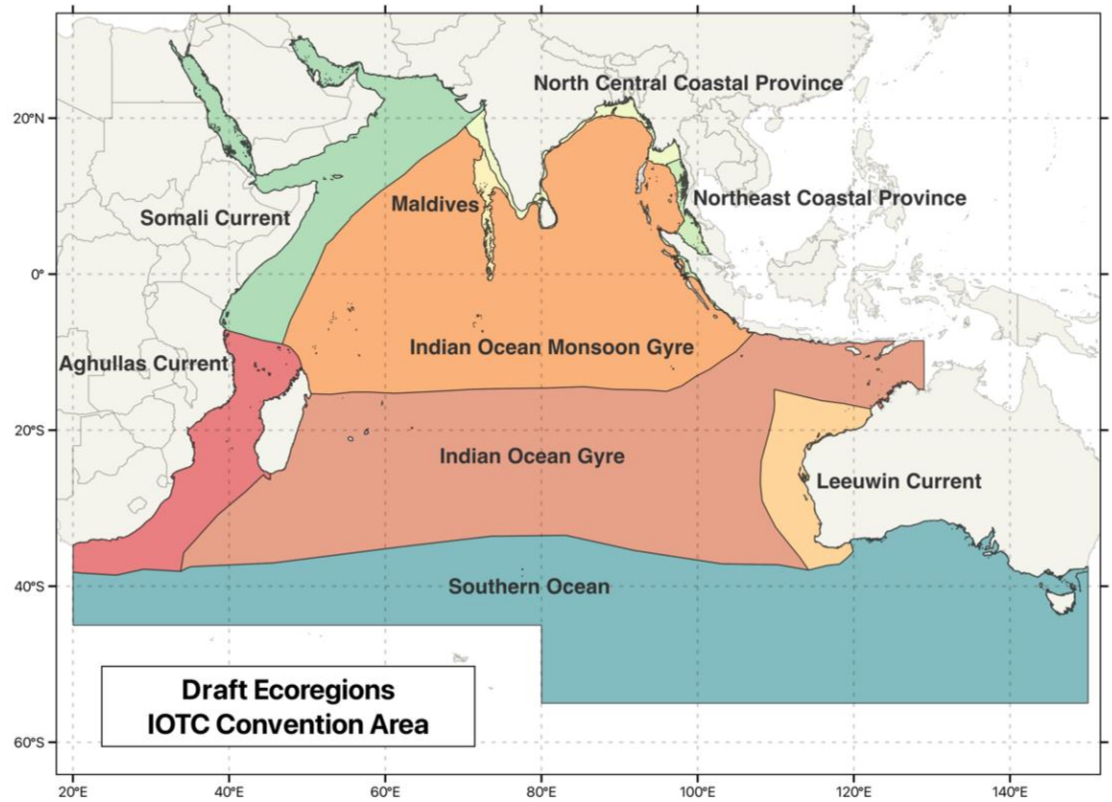


Figure 2. IOTC candidate ecoregions (Juan-Jordá et al., 2020; Nieblas et al., 2022).

During the second IOTC Ecoregion workshop in 2022, nine candidate ecoregions were identified within the IOTC convention area (**Figure 2**). At this stage, the IOTC ecoregions must be considered working hypotheses to be tested for their benefits and potential uses to inform EAFM implementation in IOTC. The IOTC WPEB endorsed the candidate ecoregion and recommended the development of pilot studies and example products to test their usefulness and feasibility as a spatial framework to support ecosystem-based planning and research products in IOTC (Nieblas et al., 2022). The candidate ecoregions have the potential to be used as spatial frameworks to support the development of ecosystem-based research and advise products (e.g., regional indicator-based ecosystem cards, ecosystem models, integrated ecosystem assessments, ecosystem-fisheries overviews, etc..) to complement existing fisheries management advice for informing EAFM implementation in IOTC. A trophic mass-balance ecosystem model to describe the dynamics of the tropical pelagic ecosystem using Ecopath with Ecosim is currently underway in the Indian Ocean. The WPEB has also been developing an indicator-based Ecocard for IOTC since 2018, yet the COVID-19 pandemic has hindered the progression of this initiative (Fuller et al., 2024). However, there are plans underway to resume the process and secure support. Additionally, the WPEB recommended the development of Ecosystem-Fisheries Overviews for two selected IOTC ecoregions to start the integration and synthesis of existing knowledge at the ecoregion level and assess the applicability of the ecoregions as spatial units to support the development of these products. It is important to emphasize that ecoregions, as a spatial tool, are not intended to be a management tool to apply spatial management or develop conservation and management measures at the ecoregion level. Instead, they intend to be a planning, research, and advice tool to assist the WPEB and Scientific Committee of IOTC in providing ecosystem-based advice to the Commission.

Table 2. IOTC candidate ecoregions (full names and their acronym).

Ecoregion name	Acronym
Somali Current Ecoregion	SCE
Maldives Ecoregion	ME
North Central Coastal Province Ecoregion	NCCPE
Northeast Coastal Province Ecoregion	NECPE
Indian Ocean Monsoon Gyre Ecoregion	IOMGE
Agulhas Current Ecoregion	ACE
Indian Ocean Gyre Ecoregion	IOGE
Leewin Current Ecoregion	LCE
Southern Ocean Ecoregion	SOE

Table 3. Main gear groups operating in the IOTC convention area.

Main gears	Acronym
Baitboat	BB
Gillnet	GL
Line	LI
Longline	LL
Other gear	OT
Purse seine	PS

1.2 Objectives

The primary goal of this thesis is to help develop a pilot product to assess the general applicability of the IOTC ecoregions as a spatial framework for developing integrated and ecosystem-based advice products to support the management of IOTC tuna and tuna-like species and associated ecosystems. To do so, I specifically contributed to developing an Ecosystem Fisheries Overview (EFO) in the IOTC convention area for a selected ecoregion – the Somali Current Ecoregion (SCE). An EFO is an advice product aiming to provide a holistic narrative of an ecoregion, covering the ecosystems in general and focusing on the core species and fisheries under management within the ecoregion and their effects on the ecosystem. They aim to provide fisheries and ecosystem context for decision-makers to make informed decisions on fisheries management based on regional bycatch, ecosystem, and climate considerations (ICES, 2023; Koen-Alonso et al., 2019). Therefore, an EFO is a type of ecosystem advice product aiming to complement the single-species advice already provided for the species under management in the ecoregion, allowing users to understand the implications of decisions tailored for the management of single stocks in an ecosystem context. At this stage, the development of a pilot Ecosystem-Fishery Overviews (EFO) product in the context of IOTC could have multiple aims: (1) testing the general applicability and uses of an ecoregion framework as "units of analysis" for the development of regional advice products, and (2) identifying the strengths, weaknesses, opportunities, and threats of such regional products in the context of IOTC standard procedures to produce scientific advice for the Commission.

An EFO is a holistic advice product that could potentially be composed of multiple sections covering a large number of topics to support the management of fisheries in an area accounting for bycatch, ecosystem, and climate considerations (**Figure 3**). The potential sections and topics to be included in an EFO product at the end will depend on the interest of the end-users (the IOTC commission), the capacity of the IOTC scientific committee and experts to produce the EFO product and update it regularly, available funds and resources, among other factors (ICES, 2024).

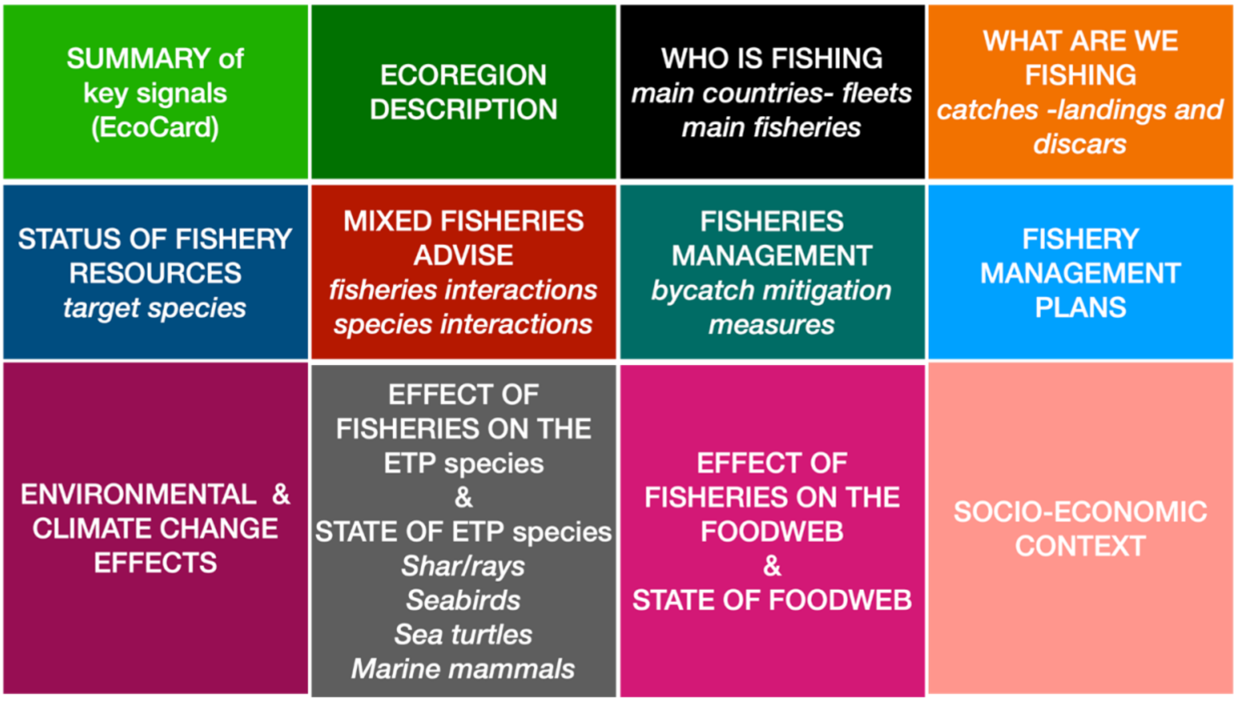


Figure 3. Potential sections to be incorporated in an Ecosystem Fisheries Overview (EFO).

Towards developing an EAF product for the Somali Current Ecoregion, the specific objectives of this thesis are to answer two research questions that will allow the development of two sections in the EFO advice product: (1) Who is fishing in the Somali Current Ecoregion and (2) What species are being caught in the Somali Current Ecoregion?

Objective 1: Who is fishing? This objective aims to identify, map, and describe the main fleets operating in the SCE, including the flag states, gears used, and their spatio-temporal activity patterns using the IOTC public datasets. This analysis provides an overview of the core IOTC fleets operating in the Somali Current Ecoregion.

Objective 2: What species are being caught? Based on the main fleets identified in Objective 1, Objective 2 aims to describe the historical catches of these fleets between 1950 and 2002 using the IOTC public fishery datasets. The fleet's historical data are described by taxa groups and gear types. This analysis provides a better understanding of the most caught and reported species in IOTC fisheries throughout the years within the ecoregion.

2. Methodology

2.1 Area of study

The Somali Current Ecoregion is one of the nine candidate ecoregions proposed by the IOTC Working Party on Ecosystems and Bycatch (WPEB) (Nieblas et al., 2022). This coastal ecoregion shares its boundaries with three other ecoregions: the Agulhas Current Ecoregion on the southwest, the Indian Ocean Monsoon Gyre Ecoregion on the southeast, and the North Central Coastal Province Ecoregion on the northeast (**Figure 2**). In the classification analysis leading to the nine ecoregion proposals (Juan-Jordá et al., 2018; Nieblas et al., 2022), the Somali Current Ecoregion was first classified as a Tropical Ecoregion alongside its adjacent province, The Indian Ocean Monsoon Gyre Ecoregion. Both ecoregions are characterized by monsoon winds, which create a rich environment for tropical tuna species (Juan-Jordá et al., 2018; Nieblas et al., 2022). A vital feature of the Somali Current ecoregion's oceanography is the coastal upwelling, which occurs in the area from June through September. Because of the influence of the East African Coastal Current (EACC) and the South Equatorial Current (SEC), nutrient-rich waters rise to the surface during the monsoon season, increasing fishing yields and marine productivity. In contrast, the winter monsoon causes a reversal in wind direction, altering current patterns and affecting the upwelling dynamics (Schott et al., 2002; Schott & McCreary, 2001).

Despite being a seasonal event, coastal upwelling plays a crucial role in sustaining the livelihoods of millions of people through small-scale fisheries (Hammond et al., 2022). Tropical tunas, such as Yellowfin (*Thunnus albacares*) and Skipjack tuna (*Katsuwonus pelamis*), as well as other tuna-like species, such as neritic tunas and mackerels, are the prominent species in this coastal ecosystem, primarily fished by gillnet fisheries.

2.2 Data sources

In this study, I analyzed primarily two IOTC datasets (**Table 4**). The first dataset, the Nominal Catch dataset, provides comprehensive information on the Nominal Catch for all species by year, IOTC area, fishery, fleet, and vessel flag, including species targeted and non-targeted (considered bycatch) by fleet[1]. From the 1950s until 2022, the Nominal Catch dataset aggregates the annual catches in live weight of all tuna and tuna-like species and other species caught by tuna and tuna-like fisheries by year and IOTC statistical area (**Figure 1**). The second dataset, the Raised Catch dataset, is the best scientific estimate of the raised Nominal Catch data, which contains georeferenced live weight data. This dataset covers explicitly the five main tuna and billfish species managed by IOTC (Albacore tuna, Bigeye tuna, Skipjack tuna, Yellowfin tuna, and Swordfish, **Table 1**). Nominal Catch is available on the IOTC website, whereas Raised Catch is available through request to IOTC's secretariat. The primary distinction between the Nominal Catch dataset and the Raised Catch dataset is whether the catches are georeferenced and the taxonomic completeness in the catch composition (**Table 4**). One additional dataset utilized to complete this analysis was the catch data from the Commission for the Conservation of Southern Bluefin Tuna (CCSBT)[2]. The catch dataset provides information on the catch by weight of Southern Bluefin tuna by year, month, gear, ocean, and 5-degree grid. CCSBT is the only tuna RFMO managing one tuna species, the Southern Bluefin tuna (*Thunnus maccoyii*).

Table 4. IOTC fishery statistical datasets used in the analyses.

Name	Description	Advantages	Disadvantages
Nominal Catch dataset	Nominal Catches by year (1950 to 2022), IOTC area, fleet, fishery, gear and species including bycatch species.	Better taxonomic resolution and completeness. 214 different taxa reported. Publicly available.	Catch data not georeferenced.

[1]https://iotc.org/data/datasets/latest/NC/ALL
[2] https://www.ccsbt.org/en/content/sbt-data

Raised Catch dataset	Estimated, raised georeferenced catches (weight and number) for main species by year (1950 to 2022), quarter, 5x5 degree grid, fleet, fishery and species.	Catch data georeferenced.	Poor taxonomic completeness since catch only available for five tuna and tuna-like species. Only available through request.
CCSBT catch dataset	Estimated georeferenced catches (weight) for SBT by year (1965 to 2022), month, gear, ocean and 5x5 degree grid.	Catch data georeferenced. Publicly available.	Difficulties integrating the dataset with IOTC data.

The data analysis was performed using the statistical software "R*: A Language and Environment for Statistical Computing*" (Wickham et al., 2023). Different R packages were utilized to accomplish this analysis. The most relevant R packages include: dplyr, a package for data manipulation and transformation (Wickham, 2016); ggplot2, a package for data visualization (Bivand et al., 2023); rgdal, a package for geographic data abstraction library (Pebesma & Bivand, 2023); and sf, used for handling and analyzing spatial data (Pebesma & Bivand, 2023). The R scripts used to identify the core fleets and create the figures for their analysis are available in Annex 1 and 2.

2.3 Identification of Operating Core Fleets in the Somali Current Ecoregion (SCE)

Using the georeferenced Raised Catch dataset, I examined the spatio-temporal dynamics of the IOTC fleets and their catches to identify the main fleets or core fleets operating in the Somali Current Ecoregion. IOTC defines fleet as:

> "A fishing fleet is a group of fishing vessels that may operate in the IOTC area of competence and whose fishing operations and catches of tuna and tuna-like species

are under the responsibility of a political entity or sub-entity recognized by the IOTC. The fishing fleet is derived from the combination of the flag state and reporting entity. (IOTC Secretariat, n.d.)".

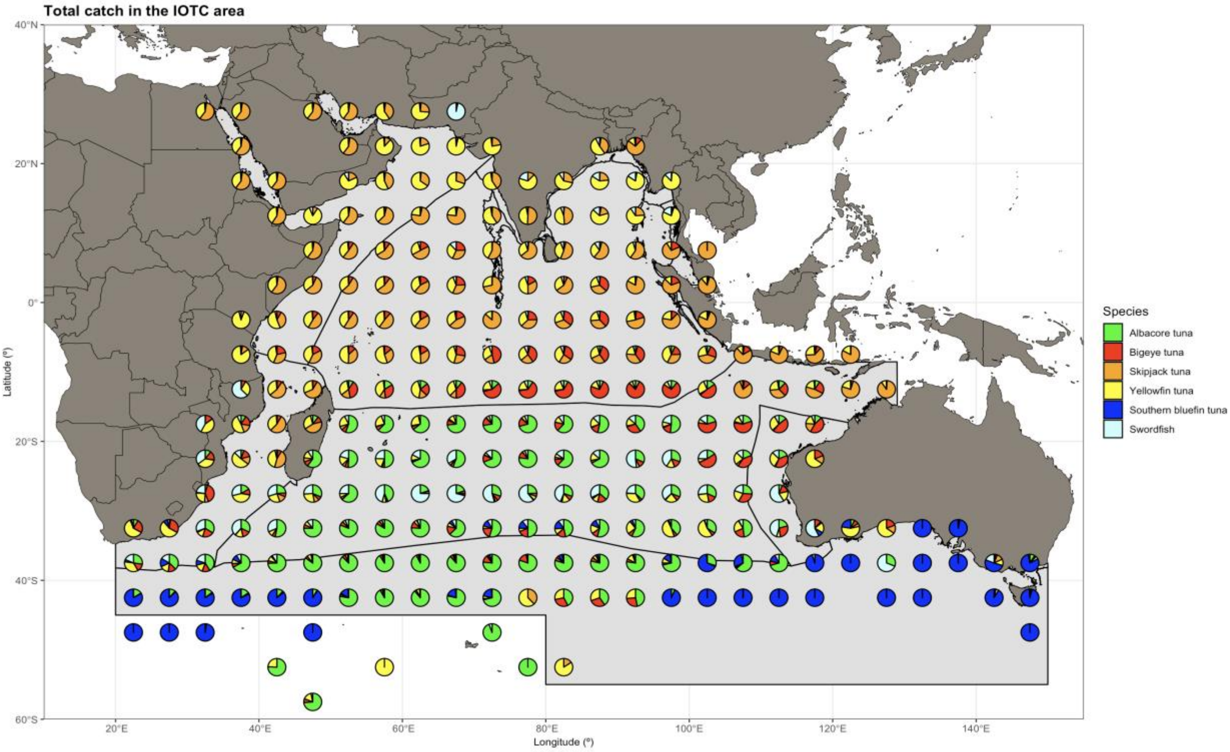


Figure 4. Average catch composition of six tuna and tuna-like species across the 118 fleets in the IOTC area. **S**ource of data: Raised Catch dataset.

When characterizing the main fleets in the IOTC region, a fleet was considered the combination of flag state information and gear type (**Table 3**). There are 118 IOTC fleets targeting tuna and tuna-like species in the Indian Ocean (**Figure 4**, **Figure 5**).

I identified core fleets operating in the Somali Current ecoregion following a series of steps. First, I selected fleets reporting catch data to IOTC from 2010 to 2022 to characterize fleets currently operating in the area **(Figure 5).**

Second, I selected only those fleets that were present and reporting catches in the SCE. Of the 118 fleets operating in the IOTC area, 62 reported catches between 2010 and 2022 in the Somali Current Ecoregion. For practical reasons, we combined several European purse seine fleets (PS_EUESP, PS_EUFRA, PS_EUITA, PS_EUMYT) as one EU fleet (PS_EU), resulting in 58 operating fleets in the SCE.

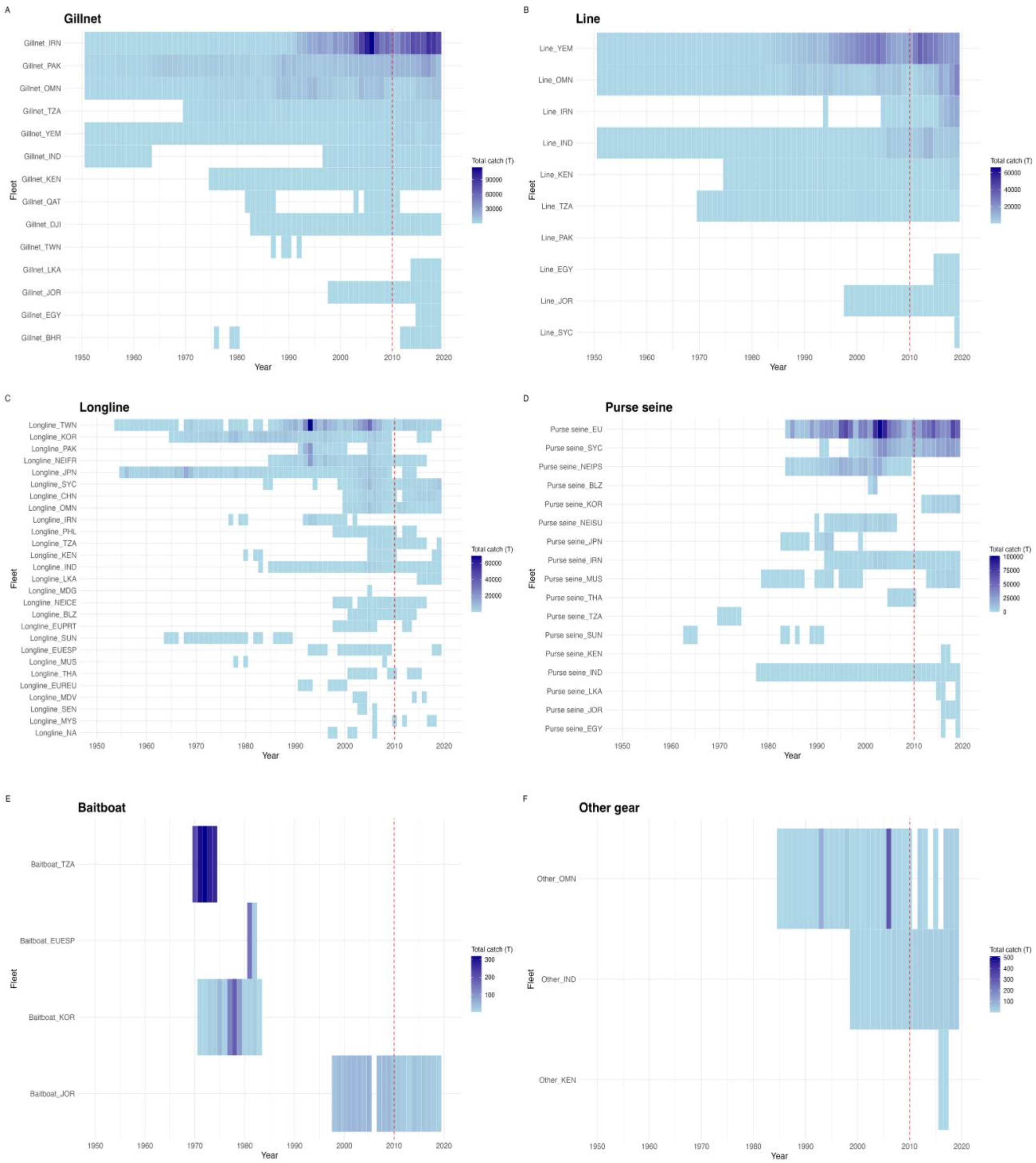


Figure 5. Tile plot displaying the results of the reported catches from fleets in the SCE between 1950 and 2022 by major gear types. The reported catches from 2010 onwards are marked with a red dashed line.

Third, I calculated a set of indicators for each fleet to facilitate the identification of core fleets within the SCE (Annex 3). These included:

Indicator 1 – The number of years each fleet report catches in the SCE. The number of historical reported years and the number of reported years between 2010 and 2022 allows monitoring of the reporting levels of each fleet within SCE fleets to determine whether they are currently operating in the region.

Indicator 2 – The dominance and prevalence of the fleets in the SCE. The dominance of the fleets in terms of catches (specificity indicator) and their spatial prevalence in terms of number of pixels (5x5) present (fidelity indicator) in the SCE allows to disentangle the relative importance of fleets in a region. The Specificity and Fidelity indicators were calculated following Dufrêne and Legendre's (1997) methodology. The **Specificity** of a fleet for a particular ecoregion was calculated as the ratio of the mean catch of the fleet in each ecoregion to the sum of the mean catch of the fleet throughout all the ecoregions. The **Fidelity** of a fleet for a particular ecoregion was calculated as the ratio of the number of geographical cells where the fleet is present to the total number of geographical cells in the ecoregion. To the Fidelity indicator, I applied two catch thresholds to ensure only the core fishing grounds of each fleet were accounted for in the indicator calculation by ensuring rare or unrepresentative pixels were excluded from the analysis. The first threshold controls the total number of years a fleet is found in a particular pixel or geographical cell, excluding the pixels where the fleets reported catches in a small number of years (the threshold applied is **at least five years of catch reporting)**. The second threshold controlled the relative catches of the fleets in each pixel *relative to the catches in the entire IOTC area,* **excluding the pixels with no significant catch** (the threshold applied – at least the pixel had reported catches above the 3rd percentile of catch).

Indicator 3 – Total catches of the fleets at different spatial scales. The total catch in tonnes of each fleet within the Somali Current Ecoregion, outside the SCE, and in IOTC allowed to quantify the extent of catches of each fleet at different spatial scales. Knowing the spatial extent of the catches within the SCE and in IOTC, it is possible to calculate the percentage of the catch done within the SCE. This shows whether a fleet is regional to the SCE or not.

Indicator 4 – Extent of the footprint of the fishing grounds of each fleet. The footprint of the fishing grounds by fleet in the SCE and IOTC allowed to quantify the spatial prevalence of the fleets at different spatial scales. The footprint is measured as the total number of pixels where each fleet operates and reports catches. The percentage of the total fishing ground within the SCE for each fleet was calculated, identifying whether a fleet is regional to the SCE or, if instead, is considered a long-distance fleet operating across a much larger scale within the IOTC region.

Indicator 5 – The dominant species in the catch for each fleet at different spatial scales. Calculating the dominant species in the catch for each fleet and their average catch in the SCE, outside the SCE, and in IOTC allowed to understand what species was targeted by each fleet in each region.

Indicator 6: Temporal and spatial analysis of the catches for each fleet. Individual fleet maps were created to illustrate the mean catch of each fleet and the species composition of the catches between 2010 and 2022. Visualizing the spatial catches of each fleet facilitated the identification of core fleets, yet the individual fleet maps are not shown here as the fleet-level spatial catch information is considered confidential data. ***Figure 4*****Error! Reference source not found.**Together, these indicators facilitated the understanding of the fleet dynamics, the catch composition of the fleets, their spatial extent, the number of years of reporting, and the contribution to the total catch within the SCE or relative to other fleets, among others.

Fourth, based on the descriptive indicators calculated in step 3, I applied criteria to determine which fleets qualify as core within the SCE. The selected criteria are informed by two composite indicators: (1) the composite indicator including the specificity and fidelity of a fleet to an ecoregion, and (2) the composite indicator including the percentage of the catch of a fleet within the SCE and the percentage of the total fishing ground of a fleet within the SCE (**Figure 6**).

The composite **Specificity-Fidelity** (Specificity x Fidelity x 100) for each fleet is based on their dominance and prevalence in the ecoregion regarding their catches (Dufrêne & Legendre, 1997; Reygondeau et al., 2012; Todorović et al., 2019). The Specificity-Fidelity allowed me to identify active fleets in the Somali Current, especially the long-distance fleets in the ecoregion. A fleet is classified as a "long-distance fleet" when its catches and fishing grounds extend inside and outside the area of the SCE. Based on this indicator, fleets with a Specificity-Fidelity value higher than two were considered core fleets of the SCE.

The composite indicator **Regional Catch and Footprint** indicator is based on two indicators: (1) the percentage of catch of a fleet within the SCE compared to the total catch of the fleet in the entire IOTC area, and (2) the percentage of the total fishing ground within the SCE measured as the total number of pixels (each one 5 x 5 degrees) where a fleet is present within the ecoregion relative to the total number of pixels present across the entire IOTC area This indicator highlights the regionality of the fleets, allowing the identification of regional small-scale fleets they are relevant and unique to the ecoregion. A fleet is considered a core "regional fleet" when the majority of its catch (at least 85% of its catches) and the majority of the extension of its fishing grounds (at least 90% of the fishing grounds in pixels) occurs within the area of the SCE.

Fleets were identified as core fleets if they met the criteria (1) the Specificity-Fidelity indicator ≥2) the Regional Catch and Footprint indicator (catch in the SCE and footprint in the SCE ≥ 90). This identification allows for a deeper understanding of the ecoregion's dynamics since the fleets identified play a crucial role in the ecosystem's balance.

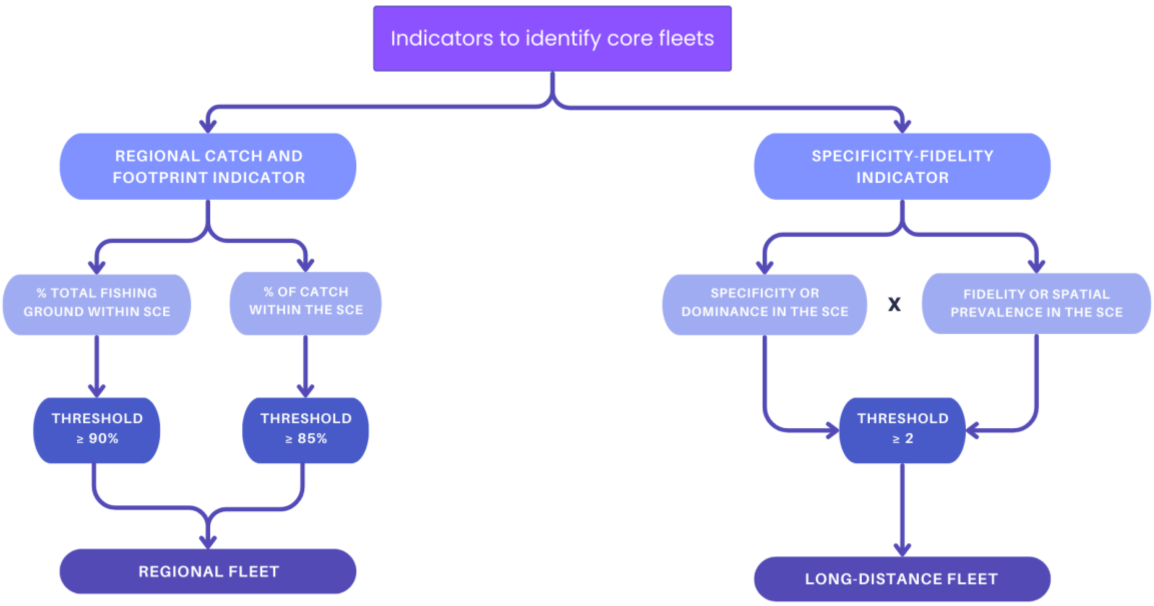


Figure 6. Decision tree of the indicators used to determine the regional and migrant long-distance core fleets.

2.4 Characterization of Historical Catches in the Somali Current Ecoregion (SCE)

Alongside identifying the core fleets operating in the SCE, I conducted an analysis to characterize the historical catches of these core fleets in the SCE. I disaggregated the historical catches by major taxa groups, gear types, fleets, and data source types to gain insights into the historical trends of the fishing activities, the species catch volume, and the predominant gears in this region. This analysis involved utilizing the IOTC Nominal Catch dataset and the IOTC Raised Catch dataset, as the catch allocation to a fleet depended on the spatial extent of its catches and fishing grounds within the SCE. The IOTC Nominal Catch dataset had detailed catch data offering broad taxonomic coverage of tuna and tuna-like species and other fish species caught in IOTC fisheries. However, these reported catches lack georeferencing at a scale enabling automatic assessment of the catches to a specific ecoregion. Hence, if a fleet has a high regionality in the ecoregion, it is possible to use Nominal Catch data as the primary source of catch information. Nominal Catch is the database with the most comprehensive catch information since it has 214 different entries of species, covering species such as temperate and tropical tunas, small tunas, seerfishes, billfishes, sharks, and teleost fishes, amongst others.

Conversely, the IOTC Raised Catch dataset contained georeferenced Raised Catch data for the five main tuna and tuna-like species, facilitating the assignment of catches to a specific ecoregion. The IOTC Nominal Catches (of all species reported in the catch) were attributed to the core "regional fleets". The IOTC Raised Catches for the five major tuna and tuna-like species were attributed to migrant long-distance fleets. I relied on the previously applied indicators to select to which fleets what type of catch dataset could be applied. This detailed characterization of the historical catches and fleet activities provides a comprehensive understanding of the ecoregion's fishing dynamics by gear and fleet.

3. Results

3.1 Core Fleets of the Somali Current Ecoregion (SCE)

Of the 58 IOTC fleets reporting catches in the Somali Current Ecoregion between 2010 and 2022, 32 qualified as core fleets (**Table 5, Figure 7**). These fleets were selected based on their temporal and spatial dominance and prevalence within the SCE. Together, the 32 fleets accounted for 95% of the total catch within the SCE. The predominant fisheries in the region are gillnet fleets (11 fleets, 34% of the core fleets), followed by line fleets (8 fleets, 25%), purse seine fleets (5 fleets, 16%), longline fleets (5 fleets, 16%), other gears (2 fleets, 6%) and baitboat (1 fleet, 3%) (**Figure 7)**. Together, the 32 fleets represented 29 unique flag states.

The most relevant fleets for the SCE are the Iranian gillnet and the Omani gillnet and line fleets. These fleets rank the highest in the Specificity-Fidelity and Regional Catch and Footprint indicators (**Figure 7A-B**). The average catch over the past 13 years (**Figure 7C**) shows that the Irani and Pakistani gillnet fleets stand out as the highest-catching fleets in the SCE.

Table 5. Thirty-two core fleets of the Somali Current Ecoregion. This includes indicators used to determine what qualifies as core fleets, the categorization of fleets into regional and long-distance fleets, and the type of IOTC dataset used to source the catch composition of each fleet.

Indicators to identify core fleets of the Somali Current Ecoregion								
	Indicators to identify core long-distance fleets			Indicators to identify core regional fleets				
Fleet name	**Specificity Indicator** Dominance of the catch in the SCE relative to total catch in IOTC	**Fidelity indicator** Spatial prevalence in the SCE	**SF [specificty x fidelity] Inicator** Dominace and spatial prevalence in the SCE	**SCE catch indicator** % of the total catch within the SCE	**SCE footprint indicator** % of the total fishing ground within the SCE	**Regional catch and footprint indicator:** % of total catch x % of total fishing ground within the SCE	**Fleet type**	**IOTC catch datasets used**
Baitboat_JOR	1	NA	NA	100	100	100	Regional	Nominal Catch
Gillnet_DJI	1	NA	NA	100	100	100	Regional	Nominal Catch
Gillnet_EGY	1	NA	NA	100	100	100	Regional	Nominal Catch
Gillnet_QAT	1	NA	NA	100	100	100	Regional	Nominal Catch
Line_PAK	1	NA	NA	100	100	100	Regional	Nominal Catch
Other_KEN	1	NA	NA	100	100	100	Regional	Nominal Catch
Purse seine_JOR	1	NA	NA	100	100	100	Regional	Nominal Catch
Purse seine_KEN	1	NA	NA	100	100	100	Regional	Nominal Catch
Gillnet_OMN	1	0,19	18,75	100	100	100	Regional	Nominal Catch
Line_OMN	1	0,16	15,63	100	100	100	Regional	Nominal Catch
Gillnet_TZA	1	0,06	6,25	100	100	100	Regional	Nominal Catch
Line_TZA	1	0,06	6,25	100	100	100	Regional	Nominal Catch
Gillnet_BHR	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Gillnet_JOR	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Gillnet_KEN	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Gillnet_PAK	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Gillnet_YEM	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Line_EGY	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Line_JOR	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Line_KEN	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Line_YEM	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Other_OMN	1	0,03	3,13	100	100	100	Regional	Nominal Catch
Line_IRN	0,97	0,06	6,06	97	88	92	Regional	Nominal Catch
Gillnet_IRN	0,91	0,28	25,59	91	88	90	Regional	Nominal Catch
Longline_KEN	0,87	0,03	2,72	87	4,08	46	Long-distance	Raised Catch
Longline_OMN	0,73	0,03	2,28	73	12,12	43	Long-distance	Raised Catch
Longline_TZA	0,62	0,06	3,88	62	7,19	35	Long-distance	Raised Catch
Purse seine_IRN	0,26	0,22	5,69	26	23,64	25	Long-distance	Raised Catch
Purse seine_EU	0,2	0,22	4,38	20	20	20	Long-distance	Raised Catch
Purse seine_SYC	0,2	0,22	4,38	20	20,34	20	Long-distance	Raised Catch
Longline_SYC	0,15	0,19	2,81	15	9,85	12	Long-distance	Raised Catch
Longline_CHN	0,15	0,16	2,34	15	8,09	12	Long-distance	Raised Catch

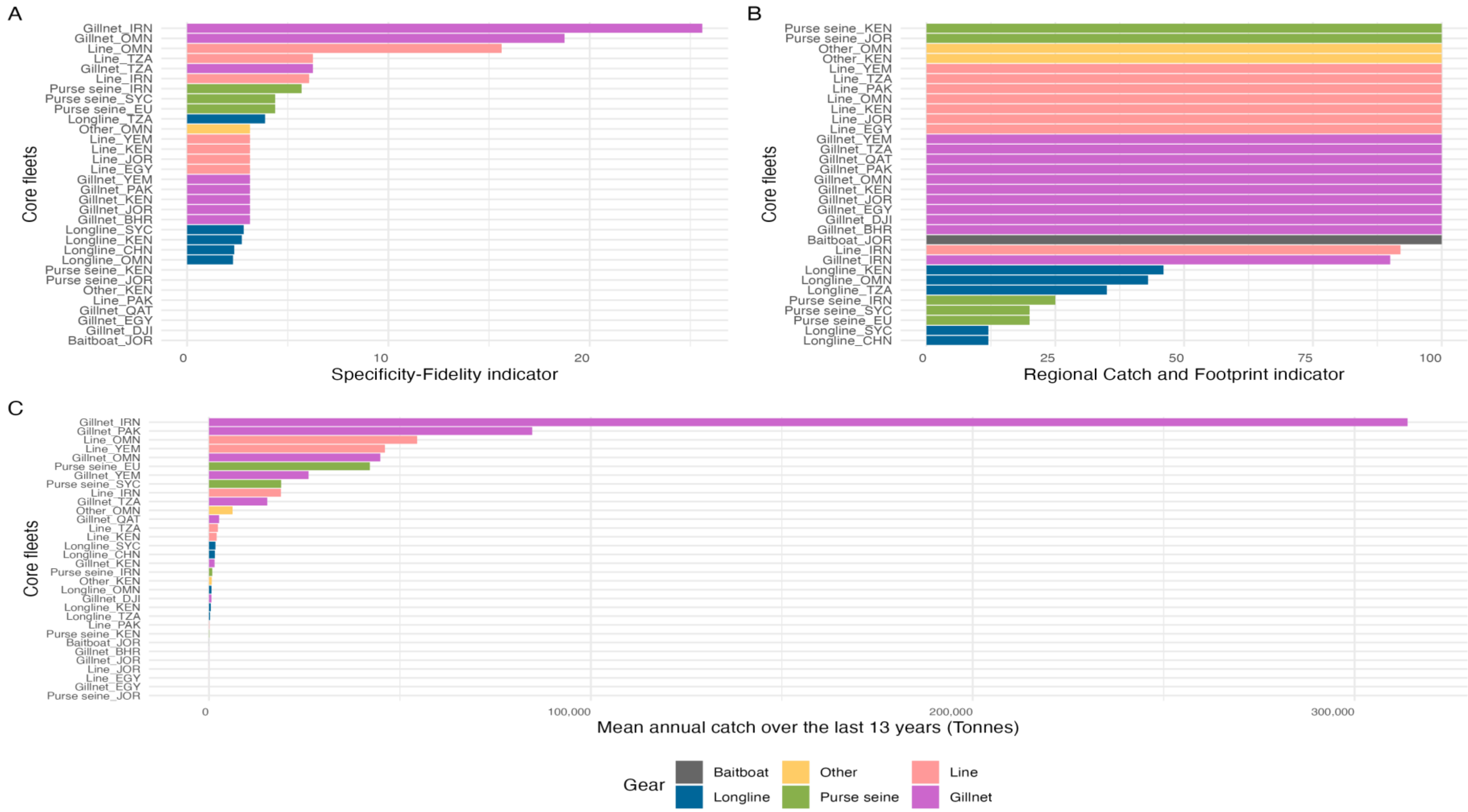
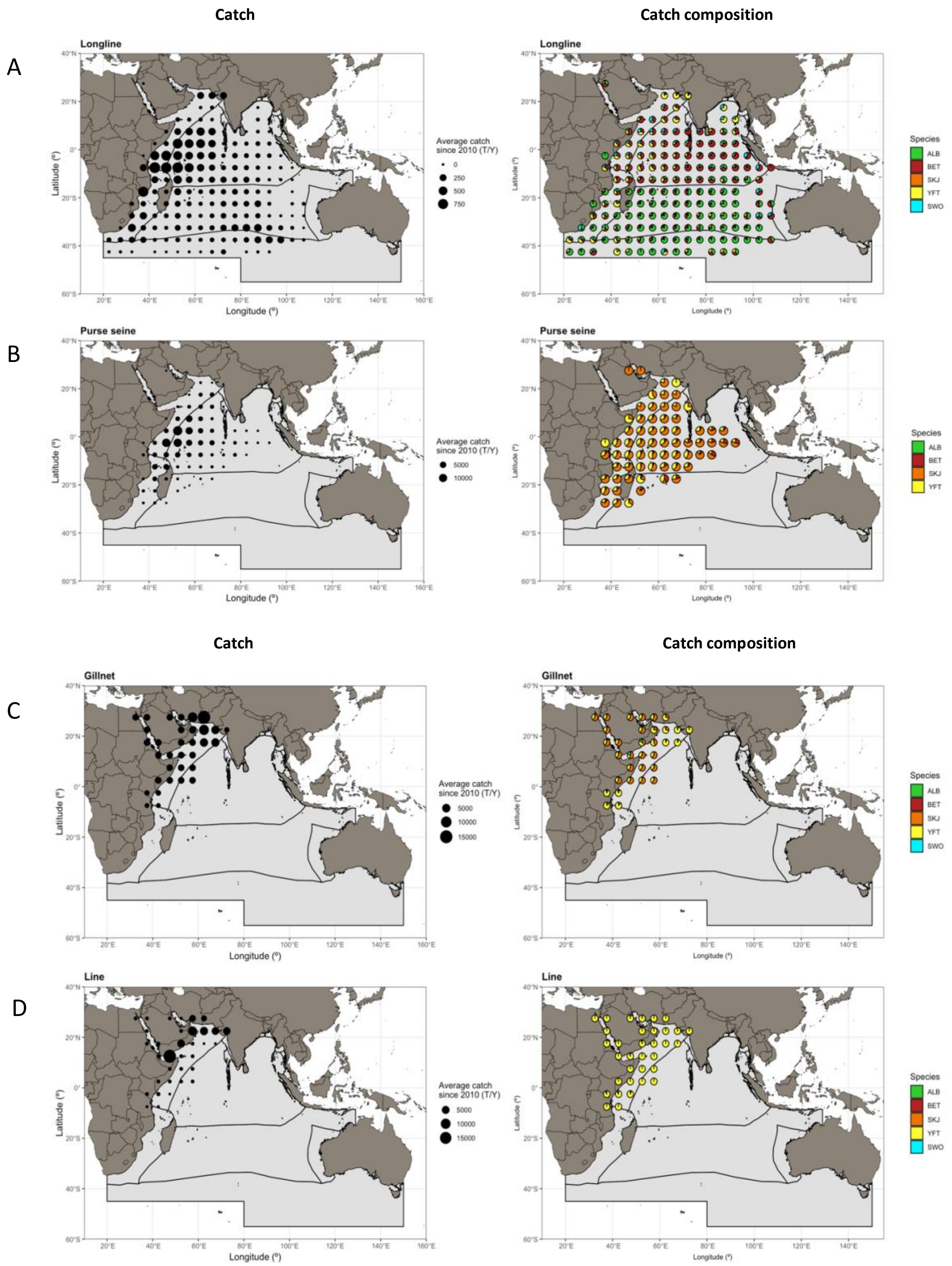


Figure 7. Set of indicators to identify core fleets of the Somali Current ecoregions. (A) Specificity-Fidelity indicator for each fleet. (B) Regional catch and footprint indicator for each fleet. (C) Mean annual catch over the last 13 years for each fleet. Fleets are colored by gear type.

The core fleets in the SCE comprise a combination of regional fleets (24 fleets) and long-distance fleets (8 fleets) (**Table 5**). Most of the fleets are regional, with 24 of the 32 fleets having their fishing grounds in at least 85% of the area of the SCE and at least 90% of their catch occurring within the ecoregion. Notably, 23 of the fleets have a value of 100% in the Regional Catch and Footprint indicator. Most of the gillnet and line fleets have a value of 100% in this indicator (**Figure 7B**). When ranking these 24 regional core fleets based on their average catch over the past 13 years, the Irani and Pakistani gillnet fleets emerge as the highest catching fleets, followed by the Omani and Yemeni line fleets (**Figure 7C**). The Iranian gillnet fleet, in particular, records an average catch of more than 300.000 tonnes annually. In contrast, the rest of the fleets have an average annual catch below 100.000 tonnes, highlighting a significant disparity in fishing trends within the ecoregion.

The spatial distribution of the catches by gear type shows that four out of the six types of gear primarily operate and have their fishing grounds within the SCE. The gillnet and line fleets have a similar spatial distribution, mainly within the SCE, with a small proportion of their fishing grounds extending into the border of the Indian Ocean Monsoon Gyre ecoregion (**Figure 8C-D**). The gillnet fleets primarily catch Skipjack and Yellowfin tunas, with minor Albacore tuna catches, whereas the line fleets catch almost exclusively Yellowfin tuna. Nevertheless, both gears catchall the five main tuna species of IOTC. The baitboat fishing fleet consists of only one fleet, the Jordanian. The Jordanian fleet has its fishing grounds confined in a small section of the ecoregion, the Persian Gulf. This fleet is a small-scale fishery; its average catch since 2010 has been 10 tonnes per year, mainly catching Skipjack tuna (**Figure 8E**). Other gear types are utilized by two distinct fleets. The Omani fleet operates in the northern part of the ecoregion, collecting most of the catch from the two fleets using other gear. The Kenyan fleet is a small-scale fishery with its fishing grounds off the coast of Kenya, with both fisheries catching Yellowfin tuna (**Figure 8F**).


Catch
Catch composition
A
B
C
D
Longline
Purse seine
Gillnet
Line
Average catch since 2010 (T/Y)
0
250
500
750
5000
10000
15000
Species
ALB
BET
SKJ
YFT
SWO
Latitude (°)
Longitude (°)

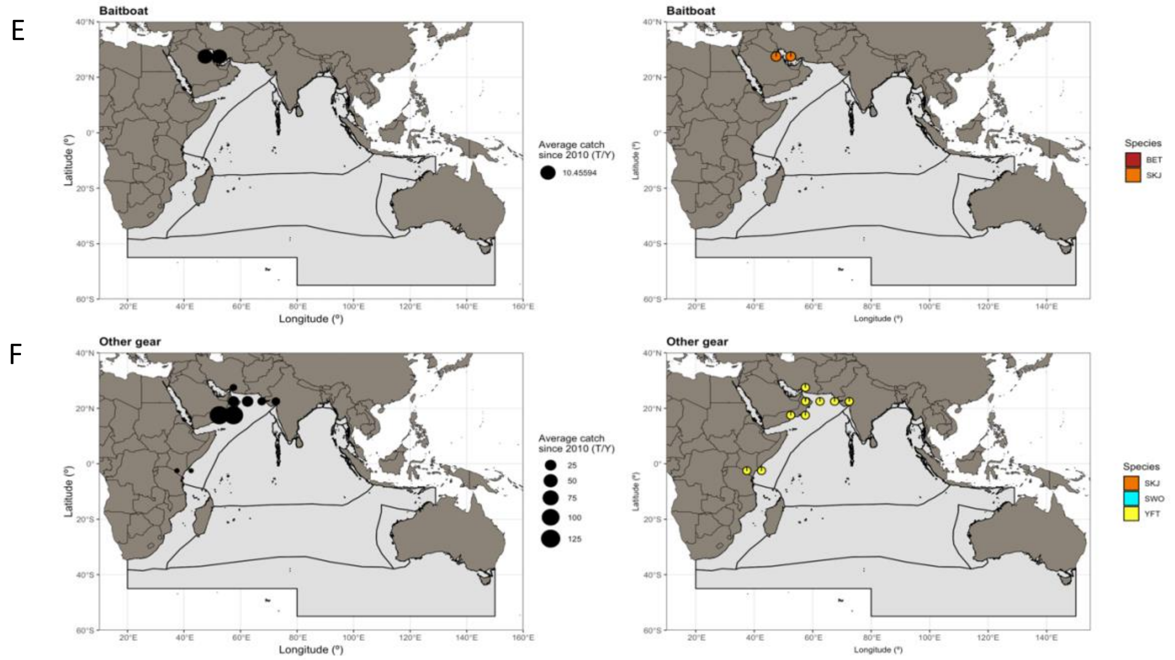


Figure 8. Spatial catches and species composition for the 32 core fleets of the SCE grouped by gear type. (A) longline, (B) purse seine, (C) gillnet, (D) line, (E) baitboat, (F) other gear. The average catch composition from 2010 to 2022 in tonnes is shown. The species composition of each fleet has been sourced from the IOTC Raised Catch dataset.

The long-distance fleets have relevant catches and spatial presence in the SCE, although their operations extend widely across the IOTC area. Their relevance to the ecoregion is underscored by their performance on the Specificity-Fidelity indicator, with all eight long-distance fleets overcoming the indicator thresholds (**Figure 7A**). Amongst the six gear types operating in the SCE, only longline and purse seine fleets operate extensively outside the ecoregion, reflected in their lower scores on the Regional Catch and Footprint indicator (**Figures 7B and 8A-B**). Whereas the purse seine fleets target mainly Yellowfin and Skipjack tunas, longline fleets target temperate and tropical tunas, showing a clear trend distinction at the 20ºS latitude. The European and Seychelles purse seine fleets are the most relevant among the long-distance fleets, ranking within the top highest-catching fleets based on the mean annual catch of the last 13 years (**Figure 7C**).

The 32 core fleets comprising regional and long-distance fleets in the SCE account for 95% of the total catch within the SCE (**Figure 9**). The catch composition of the regional fleets was sourced from the IOTC Nominal Catch dataset, as their fishing grounds operate largely within the SCE. Sourcing their catches from the IOTC Nominal Catch dataset provides a more comprehensive view of their catch composition beyond the major five tuna and tuna-like species in the IOTC Raised Catch dataset.

All five longline fleets (LL_CHN, LL_KEN, LL_OMN, LL_TZA, LL_SYC) and three purse seines (PS_EU, PS_IRN, PS_SYC) were sourced from the IOTC Raised Catch dataset due to their classification as long-distance fleets. Regarding their mean catch composition over the last 13 years, the European purse seine has been the dominant fleet with more than 40.000 tonnes annually, followed by the Seychelles purse seine with almost 20.000 tonnes on average per year. Both fleets catch mainly Skipjack, Yellowfin, and Bigeye tunas. Meanwhile, the other fleets have an average catch lower than 2.500 tonnes yearly. Yellowfin tuna is the most caught species by the smaller fleets, followed by Albacore and Swordfish.

Regarding the regional fleets (with catches sourced from the IOTC Nominal Catch dataset), the Iranian gillnet has the largest catches. This fleet's average catch composition is mostly Yellowfin, Skipjack, and Longtail tuna, followed by other small tunas (Frigate tuna and Kawakawa) and seerfishes for the 2010 to 2022 period. Alternatively, the fleets with lower average catches per year catch mainly Yellowfin tuna, followed by the small tunas group, and Skipjack tuna.

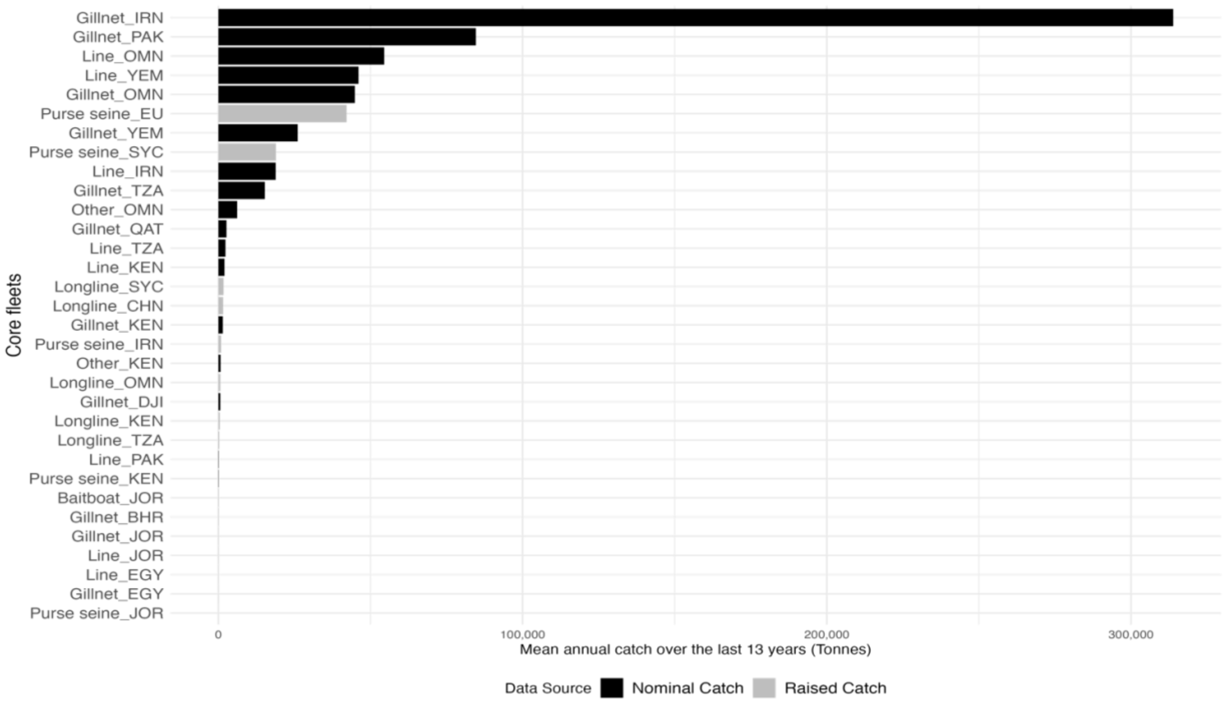


Figure 9. Thirty-two core fleets in the Somali Current Ecoregion ranked based on their mean annual catch over the last 13 years (2010-2022). The catch of each fleet has been sourced from either the IOTC Nominal Catch or IOTC Raised Catch datasets.

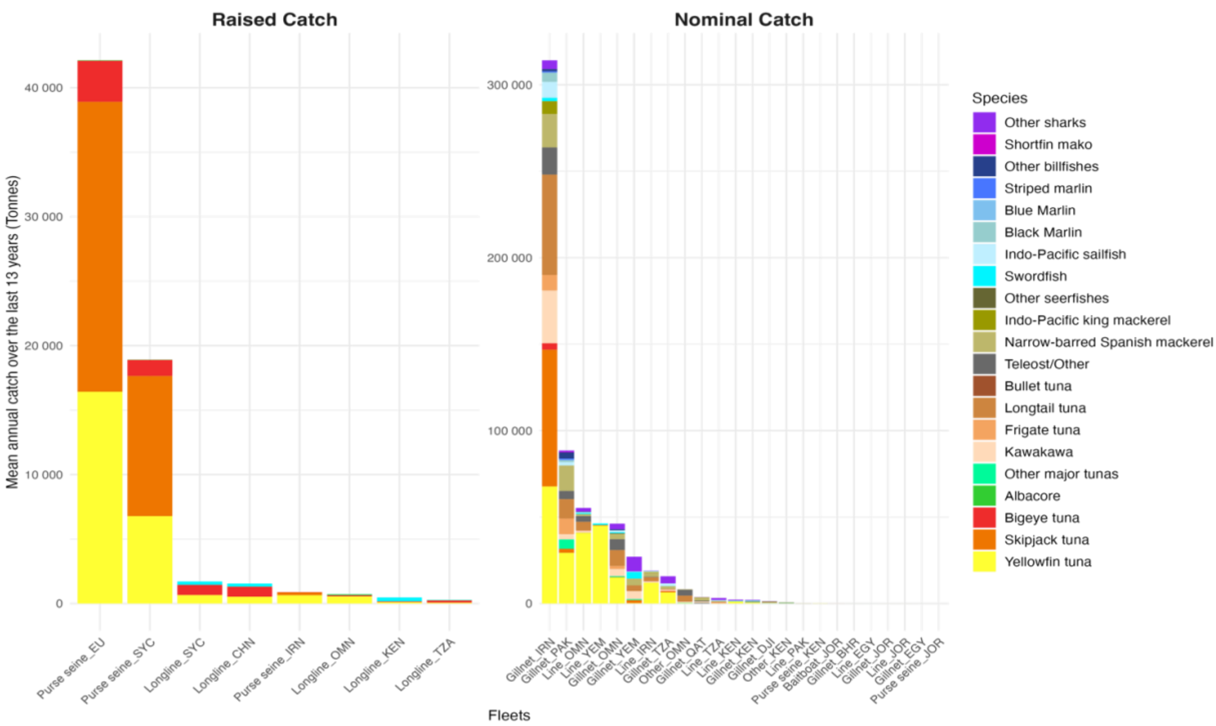


Figure 10. Mean annual catch composition over the last 13 years (2010-2022) of the 32 core fleets in the Somali Current Ecoregion grouped by data source. (A) Catch data source from the IOTC Raised Catch database. (B) Catch sourced from the IOTC Nominal Catch database.

3.2 Historical Catches in the Somali Current Ecoregion (SCE)

The historical catches of tuna and tuna-like species and other teleost species and sharks in the 32 core fleets of the SCE have increased steadily since the 1950s (**Figure 11**). Most of the catches in this region (95% of the total catches) come from regional fleets operating entirely within the SCE (**Figure 12**). Using the IOTC Nominal Catch dataset to source these regional fleet catches provides a more comprehensive view of the historical catches in the SCE, extending beyond the major five tuna and tuna-like species included in the IOTC Raised Catch dataset. Until the 1980s, the total catch slightly exceeded 100.000 tonnes, with the highest catch recorded in 1977 at 108.671 tonnes. From the late 1980s onwards, there has been steady growth, with a slight decrease in 1998 to 242.087 tonnes compared to the 300.000 tonnes caught in previous years. Subsequently, the increase has been almost exponential since the late 2000s, having a noticeable peak in 2004 at 611.914 tonnes. After this peak, there was a decrease, reaching the lowest point at 410.659 tonnes in 2009, followed by a quick recovery. Since 2016, the annual catch has been at least 700.000 tonnes, topping at 8.444.598 tonnes in 2021.

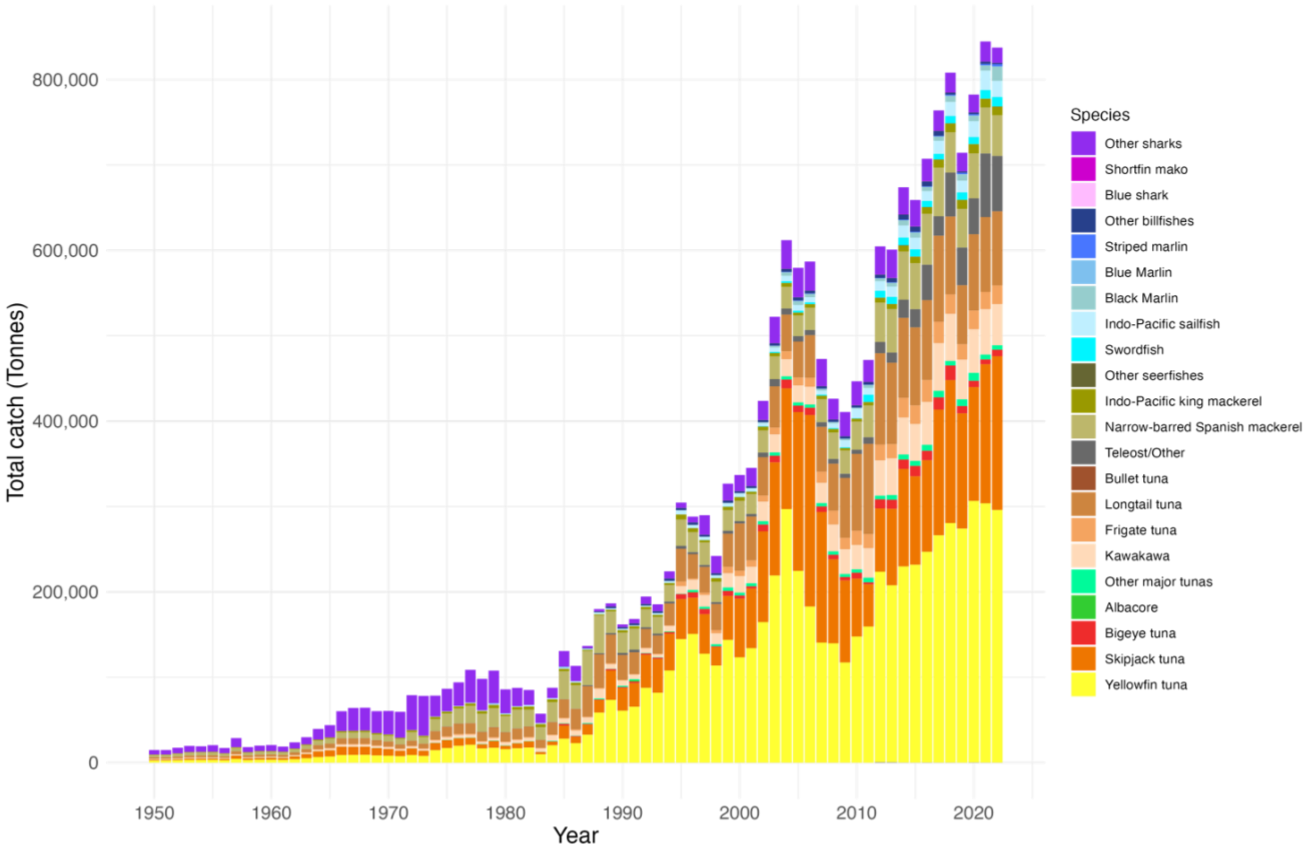


Figure 11. Total catches grouped by major species and taxa groups for the 32 Somali Current core fleets between 1950 and 2022.

Historically, the catch has been dominated by Yellowfin tuna, with a significant increase starting in the early 1990s (**Figure 11**). Over the last five years, Yellowfin tuna has constituted 37% of the total catch on average. Skipjack tuna is the second most-caught species, with its catches increasing since the early 2000s and averaging 20% of the catch in the last five years. The third most-caught group comprises the small-tunas (Bullet tuna, Longtail tuna, Frigate tuna, and Kawakawa), with a growing trend since the mid-1990s. Longtail tuna has been the third most relevant small tuna species over the last five years, making up 11% of the average total catch. Teleost fishes and the seerfishes group (Indo-Pacific king mackerel, Narrow-barred Spanish mackerel, and other seerfishes) have grown slowly but steadily since the late 1970s, with a marked upsurge in catches since 2010. The number of sharks caught has been relatively small but significant since 1950, experiencing a decline in the late 1980s and only recovering in the early 2000s.

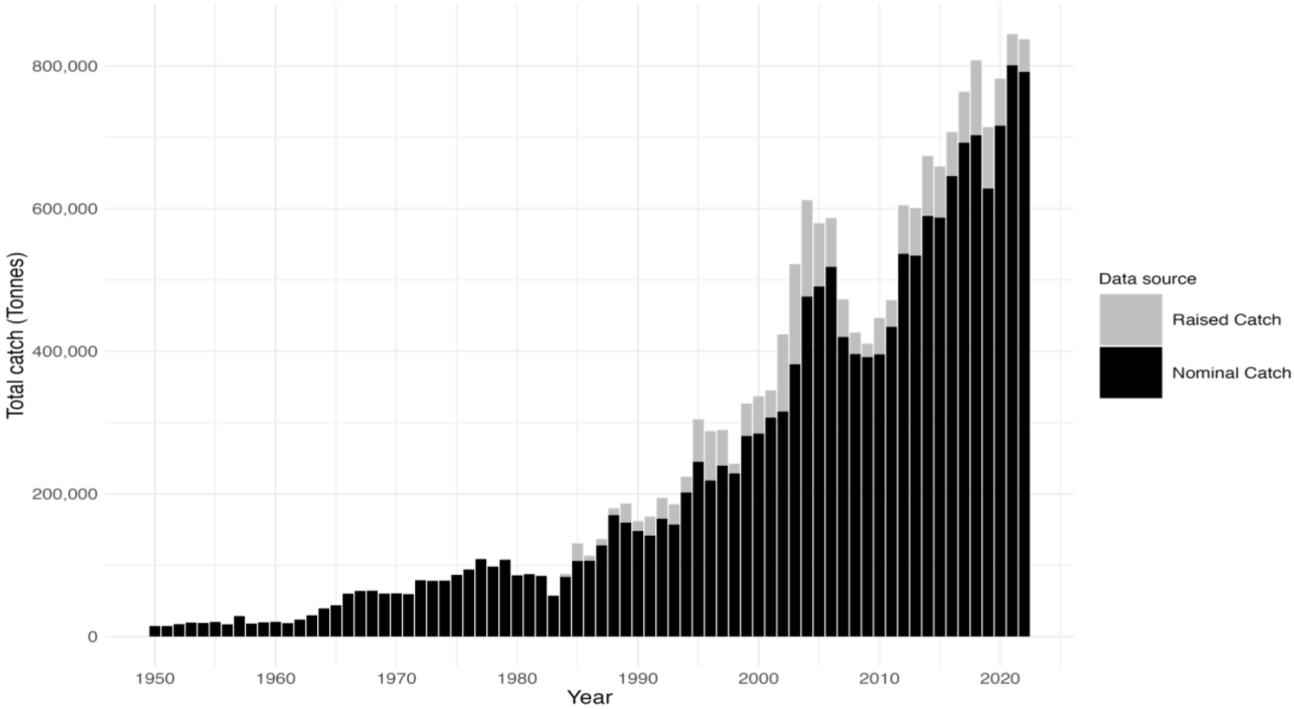


Figure 12. Total catches of the 32 core fleets of the SCE between 1950 and 2022, grouped by type of data source. Catch data for each fleet are sourced either from either the IOTC Nominal Catch dataset or the Raised Catch dataset, depending on the spatial extent of their catches and major fishing grounds of each fleet.

The historical catches in the region have been predominantly dominated by gillnet fisheries since 1950, followed by line and purse seine fisheries (**Figure 13).** Gillnet, line, and other gear fisheries have been present since 1950, showing different catch trends. The gillnet industry has shown significant activity since 1950, peaking at over 60.000 tonnes in 1967, before gradual decline and subsequent recovery in the mid-1970s. Following this recovery, the catch of the gillnet fleets grew annually, reaching a record catch of 591.330 tonnes in 2018. Over the past ten years, the catch has consistently been at least 435.000 tonnes annually. Line fleets began to expand significantly in the mid-1970s, with a notable peak after 2010, reaching its maximum catch in 2021 at 232.674 tonnes. In contrast, other gear fleets have historically had lower catches, not exceeding 35 tonnes until 1973. However, after 1973, these fisheries saw an increase in the catch, surpassing 100 tonnes. Their catch peaked after 2011, reaching 2.650 tonnes from just 11 tonnes the previous year. This fishery has continued to grow remarkably, striking its record in catch in 2021 with 17.914 tonnes.

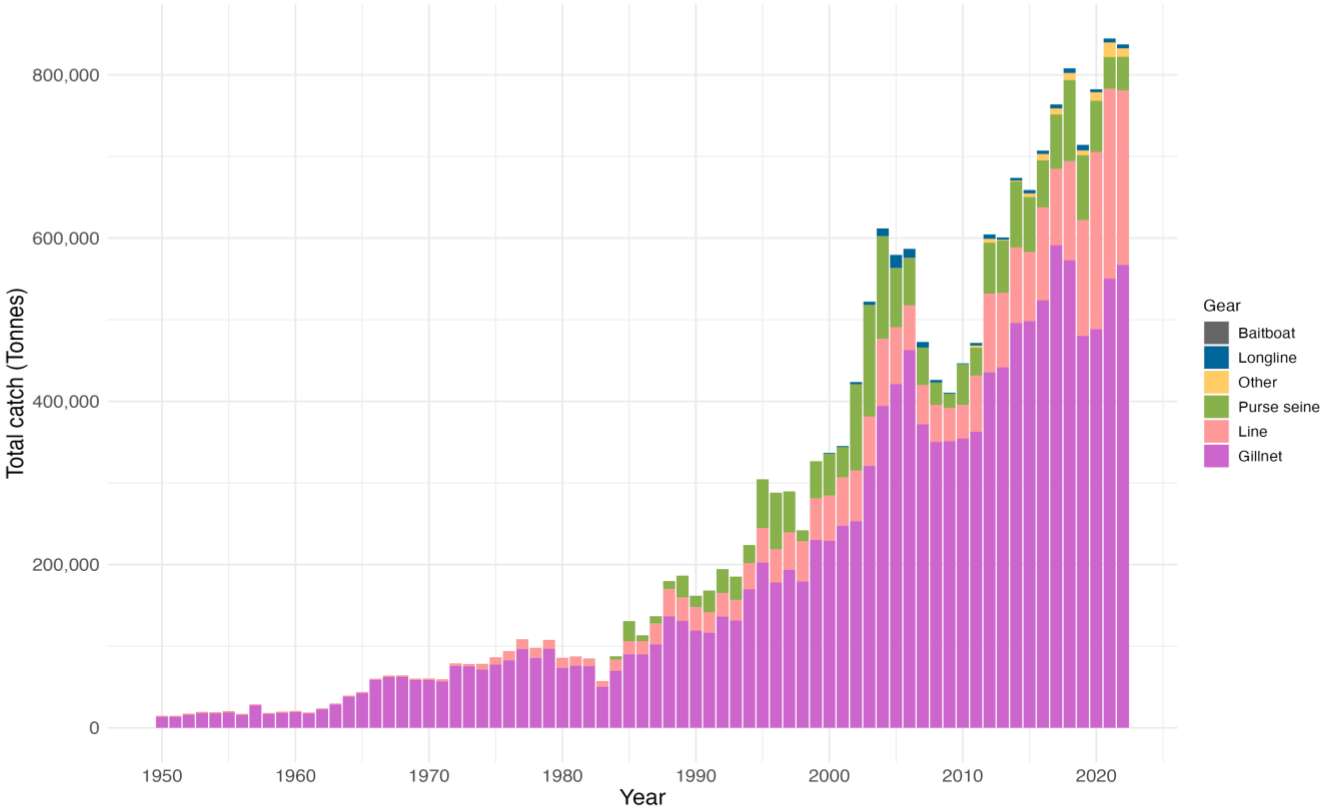


Figure 13. Total catches by gear type for the 32 Somali Current core fleets between 1950 and 2022.

In the decade of 1980, the longline and purse seine fleets started to operate in the Somali Current Ecoregion. Initially, both gears had small and irregular catches over the years. The longline sector saw a significant rise in the early 2000s, quickly increasing and reaching its maximum catch at 15.958 tonnes in 2005. However, after this peak, the longline industry's catch levels decreased to around 45.000 tonnes in recent years. The purse seine fishery began to increase noticeably in the mid-1980s, with a significant peak in catches in 2003 with 136.459

tonnes. Following this peak, catch levels decreased, dropping from 99.380 tonnes in 2018 to less than 40.000 tonnes in the last two years. The baitboat industry, represented solely by the Jordanian fleet, has been active since 1998. It peaked in the early 2000s with an annual catch of around 50 tonnes. However, since 2005, its catch has gradually decreased, falling to less than 15 tonnes annually since 2019. Over the last five years, the average catch in the SCE shows that the gillnet fleets dominate the regional catches, accounting for 67% of the total catch. The line fleets follow, contributing 23% of the catch, while purse seines comprise 8%.

The composition of the catches differs by fishery type (**Figure 14**). The gillnet fleets show the most remarkable taxonomic diversity in catches, primarily targeting Yellowfin tuna (22%) and Skipjack (21%). It also captures a significant proportion of small tunas (13% of Longtail tuna catches) and teleost fishes (9%) (**Figure 14A**). In recent years, catches of Swordfish and other billfishes have increased, though they constitute less than 5% of the total catch. Shark catches were higher throughout the 1970s and 1980s but decreased until the late 1990s. Following this reduction, shark catches have steadily increased, accounting for 3% of the total catch over the last five years.

The line fleets primarily catch Yellowfin tuna (82%), with minimal catches of other species (**Figure 14B**). Nonetheless, since 2010, there has been an increase in catches of other species, including Longtail tuna (5%), Narrow-barred Spanish mackerel (5%), teleost fishes (3%), and sharks (2%). The purse seine fleets primarily catch Skipjack tuna (65%), while the second most-caught species is Yellowfin tuna (29%), followed by Bigeye tuna (7%) (**Figure 14C**). Meanwhile, the longline fleets primarily catch Yellowfin tuna (46%), Bigeye (31%), and Swordfish (21%) (**Figure 14D**).

Lastly, the baitboat fleet catches Skipjack tuna, with no reported catches of other species (**Figure 14AE**). In contrast, the other gear fleets mainly catch Longtail tuna (51%), teleost fishes (35%), and Kawakawa (6%), whereas it was catching Yellowfin tuna exclusively until 2010 (**Figure 14F)**.

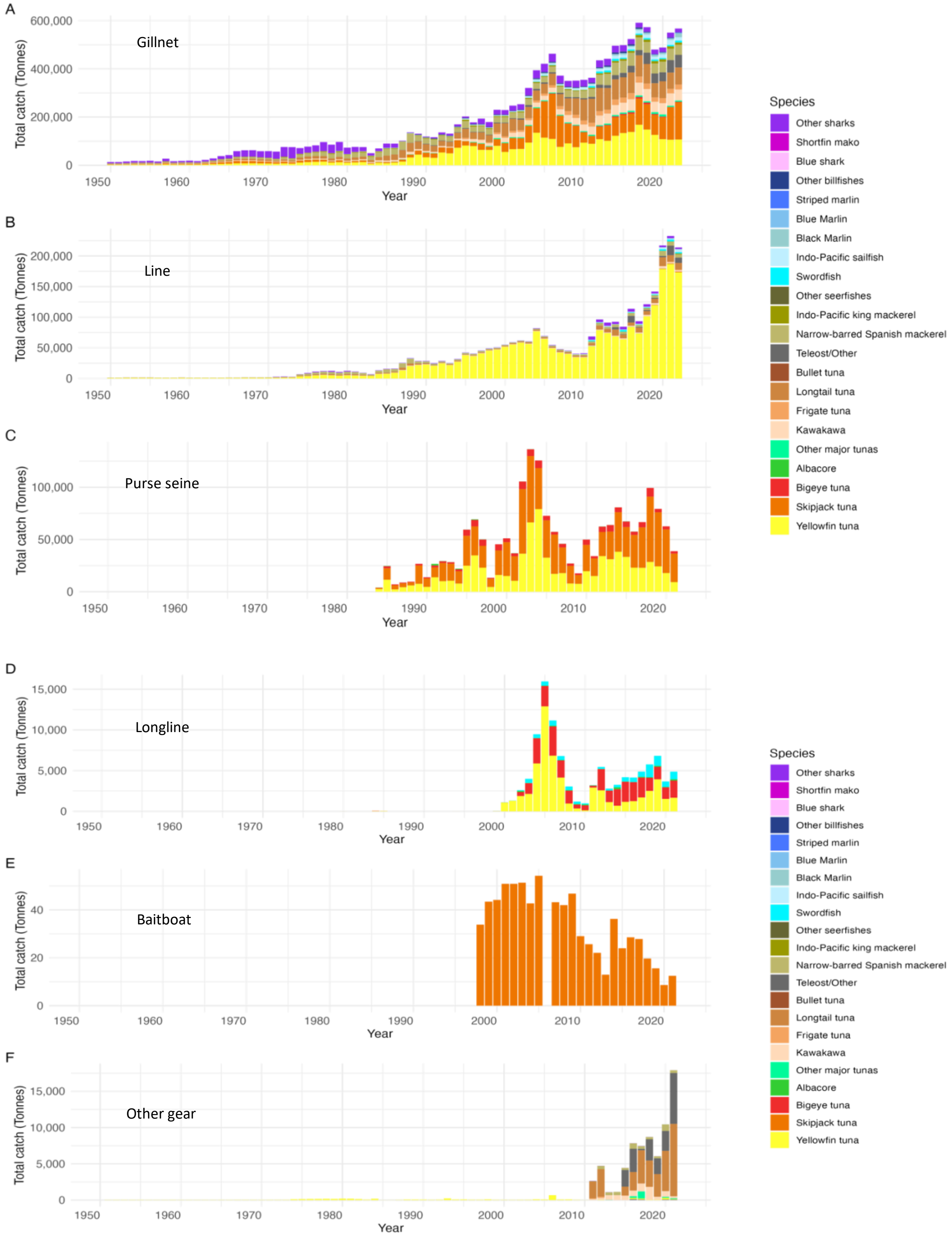


Figure 14. Total catches of the 32 core fleets of the Somali Current ecoregion between 1950 and 2022 grouped by major species and taxa groups and gear types. (A) gillnet, (B) line, (C) purse seine, (D) longline, (E) baitboat, and (F) other gear.

The fleet composition in the Somali Current has undergone significant changes over the years, with the gillnet gear emerging as the predominant method in the ecoregion, represented by 11 fleets (**Figure 15A**). In terms of total catches over the last five years, the Iranian gillnet accounts for 45% of the catches from the ecoregion, followed by the Omani line fleet with 13% of the catches, the Omani and Pakistani gillnet with 8% of the catches, and the European purse seine 6% of the total catches.

The gillnet fishery dominates the catches in the ecoregion, with the Iranian fleet reaching up to 591.330 tonnes (67%), followed by the Pakistani (12%) and Omani (12%) fleets (**Figure 15B**). Along the Yemeni (4%), these three fleets are amongst the oldest in the ecoregion. The second most prevalent gear in the ecoregion is the line fishery (**Figure 15C**), historically dominated by the Yemeni fleet until recent years. The Omani line fleet has grown exponentially in the last few years, with the Yemeni and Omani fleets being present since 1950. The Yemeni fleet experienced significant growth from the 1990s until the mid-2010s but has remained below 50.000 tonnes since 2017. In contrast, the Omani fleet has grown remarkably over the past ten years. Over the last five years, the Omani line fleet has accounted for 57% of the line catch, followed by the Yemeni fleet at 20%, the Iranian fleet at 19%, and the Kenyan fleet at 2%.

Regarding the longline fishery, the Seychelles fleet leads with the highest catch share at (50%), followed by the Chinese (33%) and Kenyan (11%) fleets (**Figure 15D**). This fishery gained relevance in the 2000s, with annual catches remaining below 10.000 tonnes in recent years. The purse seine fleet composition is dominated mainly by the European fleets, with 70% of the catch over the last five years, followed by the Seychelles fleet with 29% (**Figure 15E**). The temporal distribution of the purse seiners has been quite irregular, gaining continuity in the mid-1980s up until now.

Lastly, the baitboat fishery is exclusively represented by the Jordanian fleet, a small-scale fishery active since the late 1980s (**Figure 15F**). This fishery has shown declining catches in recent years. In contrast, the other gear fleets generally maintain catches below 10.000 tonnes, except for 2021, when the catches surpassed 15.000 tonnes, primarily attributed to the Omani fleet (**Figure 15G**). The Kenyan fleet catches, also a small-scale fishery, averages 1.2 tonnes annually. In the last five years, the Omani fleet accounted for 98% of the total catch amount, while the Kenyan fishery caught 2%.

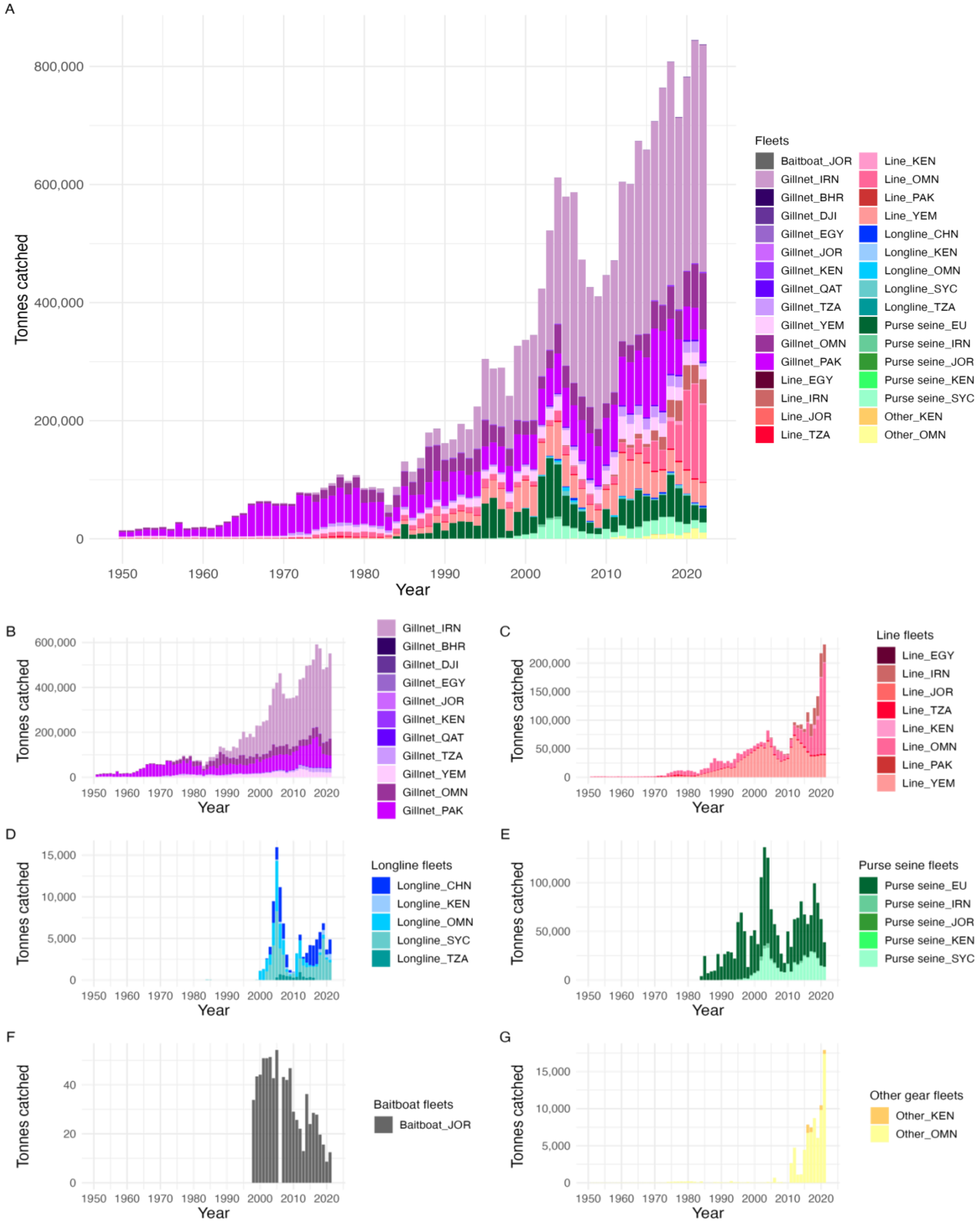


Figure 15. Total catches of the 32 core fleets of the Somali Current Ecoregion between 1950 and 2022 grouped by fleet composition. (A) Including the 32 fleets (B) gillnet, (C) line, (D) longline, (E) purse seine, (F) baitboat, (G) other gear.

4. Discussion

The primary aim of this thesis was to test the general applicability of the IOTC ecoregions as a spatial framework to support the development of advice products to inform EAFM implementation in IOTC. Specifically, this thesis has developed two thematic sections: (1) characterization of the core fleets and (2) characterization of the historical catches of a pilot Ecosystem-Fishery Overview (EFO) for the Somali Current Ecoregion. This pilot EFO is expected to be the basis for further implementing EFO advice products in IOTC. This section first explores the challenges encountered while utilizing public IOTC fishery statistical datasets to identify and characterize the core fleets and historical catches of the Somali Current Ecoregion. Second, it assesses the general use and applicability of the IOTC candidate ecoregions as a spatial framework to support the development of EFOs in the region, and third, it discusses the strengths and challenges of the pilot EFO as an advice product to support EAFM implementation in IOTC.

4.1 Challenges and difficulties faced using publicly available IOTC fishery statistical datasets to describe main fleets and their historical catches in the Somali Current Ecoregion (SCE)

This pilot EFO advice product relies on two public IOTC fishery statistical datasets: the Nominal Catch and Raised Catch datasets. The collection of catch data, including discards, catch and effort, and size frequency, is done by the IOTC member states. The fishery data reporting to IOTC has been primarily designed to support single species analysis and stock assessment so the IOTC Scientific Committee can advise the Commission on fishing opportunities for major IOTC species (IOTC Secretariat, 2018). These IOTC fishery statistical datasets have inherent caveats and limitations such as underreporting of catches, poor taxonomic, spatial, and temporal resolution, as well as poor quality submission of data by some IOTC member states. The IOTC Nominal Catch dataset reports a wide range of taxa groups with poor taxonomic resolutions for some groups, particularly for shark and ray species (Heidrich et al., 2022). However, the percentage of shark and ray catches reported at the species level has improved over the last decades. Furthermore, the total reported catch with georeferenced catches remains low in IOTC (Heidrich et al., 2022). Only 64% of the reported catches have been reported with spatial information typically ranging from 1x1 to 5x5 degree grids, depending on the gear type. Therefore, the IOTC secretariat estimations to derive the Raised Catch dataset with the georeferenced catches rely on many assumptions. Consequently, any analysis and results using the Raised Catch dataset needs to be scrutinized. Another central issue with reporting fishery statistical data is that each IOTC member state often uses its own formatting when filling the reports following standard adopted protocols, which may lead to data incompleteness and poor data-quality standards (IOTC Secretariat, 2018).

While the IOTC fishery statistical datasets were not purposely designed to support ecosystem-based products such as an EFO, these datasets have proven helpful for developing the pilot EFOs with some inherent caveats and limitations. Developing the two thematic sections of the pilot EFO requires knowing where the fisheries operate and where the catches occur. Therefore, they rely heavily on the quality of the IOTC Raised Catch dataset. As mentioned previously, the georeferenced Raised Catches for some IOTC member states and fleets are highly uncertain as these are reported with poor temporal and spatial resolution or simply not reported with any spatial information. In this study, some errors were observed in the IOTC fishery statistical datasets that needed correcting. An example of some identified errors was encountering georeferenced catches on land when plotting due to a lack of detailed spatial data or fleets consistently reporting zero tonnes but having georeferenced catch data, such as Purse seine_EGY.

It is important to note that better quality and detailed spatial and temporal fishery data are needed to support the development of advice products to support EAFM implementation in IOTC. The taxonomic completeness in the IOTC Raised Catch data set is also low since it only includes five of the 16 tuna and tuna-like species included in the IOTC convention mandate (Albacore tuna, Bigeye tuna, Skipjack tuna, Yellowfin tuna, and Swordfish). Therefore, this data set is biased towards the most commercial and economic species since it does not include any of the neritic tunas, Spanish mackerels, and subtropical billfish species caught in IOTC fisheries. The IOTC should strive to increase the taxonomic completeness of this dataset for a broader range of tuna-like species, as it would provide a more comprehensive understanding of the fishery impacts on the ecosystem and the catch and fishing trends per area.

One potential solution to these issues is to use and implement standardized forms for collecting fishery statistics as mandated by IOTC. Currently, CPCs can report data using their forms and templates since using IOTC's forms is not mandatory (IOTC Secretariat, 2018). More capacity building and resources are needed for better monitoring of fisheries in order to improve the quality of the fishery statistical datasets reported to IOTC. New technologies (e.g., electronic monitoring systems) offer an opportunity to improve fishery statistics. However, it is important to note that these options have limitations, as some fisheries may require more qualified personnel to complete the mandated form. Some countries might benefit from more capacity-building activities and a reinforcement of the resources needed to support monitoring their fisheries.

4.2 Applicability of IOTC ecoregions to support ecosystem-based tools and products for the delimitation of the Somali Current Ecoregion (SCE)

Through the spatiotemporal analysis of fleets and their catches, I assessed the feasibility of developing the pilot EFO product for the SCE. Thirty-two core fleets were identified in the SCE, providing a first picture of main fleets capturing tuna and tuna-like species in this region. The analyses showed that 78% of the core fleets (24 of the 32 fleets) are regional fleets with a large percent of their catches (more than 90% of their total catch) and extent of their fishing grounds (more than 85%) within the Somali Current Ecoregion. The spatial distribution of the catches for these 32 fleets maps also showed that all the gillnet, line, baitboat, and other gear fleets stay within the boundaries of the Somali Current Ecoregion. While some of the purse seine and longline fleets were considered regional, most are long-distance fleets with fishing grounds extending across the Indian Ocean, yet with significant presence and catches with the SCE. Therefore, it can be concluded that the SCE has a unique set of core fleets, underscoring the distinctiveness of this ecoregion. These findings support the feasibility and the potential of developing regional advice products such as EFOs at the ecoregion level to complement the existing single species advice already provided by the Scientific Committee to the IOTC commission. However, further research and work is needed to develop other potential sections of the EFO product (**Figure 3**) for the SCE as well as to develop other EFOs for the remaining ecoregions, as other ecoregions must be further examined to test their feasibility to develop regional advise ecosystem-based products and assess if the proposed IOTC candidate ecoregions (**Figure 2**) need further boundary modifications.

4.3 Strengths and challenges of using Ecoregions and Fisheries Overviews as ecosystem-based advice products and their contribution to implementing the EAFM in IOTC

The idea of developing ecosystem-based advice products to complement single-species advice products is new in IOTC. It is the first time the IOTC candidate ecoregions are used to create a pilot EFO as an ecosystem-based advice product at the ecoregion level. An EFO aims to be a synthetic integrated product aiming to provide a deeper understanding of the region's core fleets and fisheries and their fishing dynamic, providing a valuable regional framework for assessing the status of fisheries resources and their impacts on the ecosystems, for complimenting single species advice with a better understanding of fleets and species interactions (Nieblas et al., 2022). EFOs might be used to provide insight into each region's ecosystem status and trends and provide a foundation for informing EAFM implementation. Developing ecosystem-based advice and research products (EFOs, integrated assessments, ecosystem models) requires the delineation of ecologically meaningful ecoregions (Nieblas et al., 2022; Rice et al., 2011).

While an EFO product is a new concept in IOTC, several international organizations have successfully developed and currently use such products to guide ecosystem-based advice, planning, management, and research supporting EAFM implementation. Some of these organizations are the North Atlantic Fisheries Management Organization (NAFO), the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the International Council for the Exploration of the Sea (ICES), the North Pacific Fisheries Management Council in Alaska (NPFMC), and ICCAT have experiences developing and using them to provide ecosystem-based advice (Juan-Jordá et al., 2020; Nieblas et al., 2022). However, their development and use vary a lot among organizations; while ICES has a long record of developing and using Ecosystem and Fisheries overviews in all the ICES ecoregions, the concept and potential use of EFOs in ICCAT is still being discussed in the ICCAT subcommittee on ecosystems (Juan-Jordá et al., 2022).

EFOs are research products that may be used to inform and complement other types of advice, to provide supporting context to understand the implications of sectoral decisions and impacts in an ecosystem context (ICES, 2024), and to better inform fisheries management decisions within IOTC. Through EFOs, it is possible to transform different data obtained from IOTC's datasets into integrated information sections (**Figure 3**) to monitor fisheries' impacts on the ecosystem better. The multi-sector collaboration of experts creates a platform to communicate the gaps and threats identified. Thanks to this knowledge, it is possible to incorporate ecosystem indicators to monitor bycatch, biodiversity, and climate. With different perspectives on the data collected, it is possible to guide targeted efforts to address the issues encountered and to create further collaboration between stakeholders, the fishing industry, and local communities. EFOs also aim towards better regionalized ecosystem-based advice since focusing on conservation strategies in a region is more efficient than advising the complete IOTC area, incentivizing ecosystem planning.

Nevertheless, the use of ecoregions may be affected by the need for a clear justification for their need and a strong foundation linked to their management objectives, as well as outdated and incomplete data affecting their spatial delimitation. Implementing this research product requires time and funding to create an expert group to gather the knowledge needed to develop an EFO, which might be challenging to the Commission. Additionally, integrating multidisciplinary data might be challenging and create issues affecting the coherence of the EFOs. These matters may lead to in-depth discussions, which the governing bodies may prefer to avoid addressing. Moreover, the data quality and availability from IOTC fishery datasets may not have the necessary spatial and temporal resolution to create reliable advice. The lack of adequate monitoring and observer programs impedes quality data generation. Currently, only five species managed by IOTC have georeferenced data, which is insufficient to develop spatially explicit advice through EFOs (Ortuño Crespo et al., 2024). Changing the single-species management to ecosystem-based management would change traditional fisheries management, and the industry and the Commission might be reluctant to this change. These issues, alongside a changing geopolitical scene, might also result in an institutional barrier from the Commission since EFOs involve many different sociopolitical factors.

Early commission and stakeholder consultation and engagement into the development of regional EFOs at the ecoregion level and their potential role in complementing the advice provided by the Scientific Committee to the Commission would facilitate a more effective pathway for their development and use, potentially facilitating a smoother implementation of the EAFM into IOTC.

5. Conclusions

Nine candidate ecoregions have been delineated in the IOTC convention area as a spatial framework for informing EAFM implementation. For the first time, this work uses the ecoregions as a partial framework to create a pilot product: an EFO. By developing two pilot EFO sections, this thesis aims to characterize the core fleets and their historical catches in the SCE. Through a spatio-temporal analysis using two publicly available IOTC datasets (Nominal and Raised Catch dataset), I answered the following questions: Who is fishing, and what is being caught in the SCE?

The initial findings show that 58 fleets using six different gears operate in the SCE. After the indicator analysis, this number was refined to 32 core fleets. These core fleets were categorized into 24 regional and eight long-distance fleets, collectively accounting for 95% of the total catches in the ecoregion. The historical catch characterization shows that the dominating gear in the ecoregion is gillnet (67%), which has been widely active since the 1950s, followed by line (23%). Regarding catch composition, the most caught species are Yellowfin tuna (37%) and Skipjack tuna (20%) on average over the last five years. Additionally, the highest catching fleet is the Iranian gillnet, accounting for 45% of the total catch in the SCE, followed by the Omani line at 13%.

This preliminary pilot EFO demonstrates the feasibility of using ecoregions as a spatial framework to develop ecosystem-based tools and products. The development of ecosystem-based advice products such as the EFOs aims to improve the current single-species fisheries advice. The strong regionality of the fleets in the Somali Current Ecoregion supports its distinctiveness as a meaningful ecological region. Nevertheless, to better assess the fisheries resources and the state of the ecosystem, fisheries statistics must improve in spatial and temporal resolution and expand to include a broader range of species with georeferenced catch data. Enhancing the resolution and scope of fisheries data will enable a more comprehensive understanding of catch and fishing trends within specific areas. Future work will contribute to the further development of EFOs, a promising tool for advancing the implementation of EAFM within IOTC.

6. Sustainable Development Goals

The Sustainable Development Goals (SDGs) are integral to the 2030 Agenda, which represents an urgent call for a global partnership aimed at achieving peace and prosperity. The SDGs establish a critical connection among the three pillars of sustainable development: economic growth, social prosperity, and environmental protection (United Nations, 2015). These goals are interconnected and crucial for the well-being of individuals and societies.

This thesis contributes to multiple Sustainable Development Goals (**Table 6**). Next, I unpack how this thesis contributes to each of the SDGs.

Understanding the catch composition, historical trends, spatial distribution, and the performances of the core fleets is essential to understanding the fishing dynamics in the SCE, allowing for better-tailored advice on managing marine resources. This knowledge will provide advice on sustainable fisheries practices to maintain the stocks and reduce overfishing practices, contributing to **Responsible Consumption and Production**. This ecosystem-based advice aligns with **Zero Hunger** since better resource management contributes to food security.

Through the identification of regional core fleets, it is possible to highlight the relevance of small-scale fisheries and their contribution to the SCE, **Reducing Inequalities.** Small-scale fisheries are essential to the economic growth of some developing countries, and allowing them fair access to marine resources supports the **Decent Work and Economic Growth** as well as the **No Poverty** SDGs since preserving coastal fisheries sustains the livelihoods of millions of people (Hammond et al., 2022). This also aligns with **Sustainable Cities and Communities**, ensuring sustainable resource access that benefits developing communities' growth.

Improved management of the resources also ensures a healthy ecosystem and sustainable fishing trends, which addresses the connection between maintaining a healthy ecosystem and **Climate Action** since fishing trends have been affected by climate change. Understanding the ecosystem and fishing dynamics makes it possible to recognize the threats to a healthy ecosystem, creating advice to maintain a healthy ecosystem, which aligns with **Life Below Water**.

Calling for better ecosystem-based management for the RFMOs (IOTC in this case) contributes to **Peace, Justice, and Strong Institutions** as it aims toward better governance and **Partnership for the Goals** since it improves many ecological and societal aspects that align with the SDGs.

Table 6. Relevance level of the Sustainable Development Goals with the thesis.

Sustainable Development Goal	**Relevance level**			
	High	Medium	Low	Does not apply
1. No Poverty		X		
2. Zero Hunger		X		
3. Good Health and Wellbeing			X	
4. Quality Education				X
5. Gender Equality				X
6. Clean Water and Sanitation				X
7. Affordable and Clean Energy				X
8. Decent work and Economic Growth			X	
9. Industry Innovation and Infrastructure				X
10. Reduced Inequalities			X	
11. Sustainable Cities and Communities			X	
12. Responsible Consumption and Production	X			

13. Climate Action		X		
14. Life Below Water	X			
15. Life on Land				X
16. Peace, Justice and Strong Institutions			X	
17. Partnerships for the Goals		X		

7. References

Bivand, R., Keitt, T., & Rowlingson, B. (2023). *rgdal: Bindings for the 'Geospatial' Data Abstraction Library*. https://CRAN.R-project.org/package=rgdal

Directorate-General for Maritime Affairs and Fisheries. (2024). *Regional Fisheries Management Organisations (RFMOs)*. https://oceans-and-fisheries.ec.europa.eu/fisheries/international-agreements/regional-fisheries-management-organisations-rfmos_en#rfmos-managing-highly-migratory-species-mainly-tuna

Dufrêne, M., & Legendre, P. (1997). Species Assemblages and Indicator Species: The Need for a Flexible Asymmetrical Approach. *Ecological Monographs*, *67*(3), 345–366. https://doi.org/10.1890/0012-9615(1997)067[0345:SAAIST]2.0.CO;2

Fogarty, M. J. (2014). The art of ecosystem-based fishery management. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(3), 479–490. https://doi.org/10.1139/cjfas-2013-0203

Food and Agriculture Organization of the United Nations (Ed.). (2003). *Fisheries management. 2: The ecosystem approach to fisheries*. Food and Agriculture Organization of the United Nations.

Fuller, L., Lopez, J., Griffiths, S., Crear, D., Aires-da-silva, A., Juan-jordá, M. J., Allain, V., & Murua, H. (2024). *Review of t-RFMO ecosystem research to inform a workplan on ecocards for the EPO* (Document No. WGEB-02-02). Inter-American Tropical Tuna Commission.

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., & Lasserre, G. (2003). *The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook*. FAO.

Hammond, M. L., Jebri, F., Srokosz, M., & Popova, E. (2022). Automated detection of coastal upwelling in the Western Indian Ocean: Towards an operational "Upwelling Watch" system. *Frontiers in Marine Science*, *9*, 950733. https://doi.org/10.3389/fmars.2022.950733

Heidrich, K. N., Juan-Jordá, M. J., Murua, H., Thompson, C. D. H., Meeuwig, J. J., & Zeller, D. (2022). Assessing progress in data reporting by tuna Regional Fisheries Management Organizations. *Fish and Fisheries*, *23*(6), 1264–1281. https://doi.org/10.1111/faf.12687

ICES. (2023). *Guide to ICES advisory framework and principles*. https://doi.org/10.17895/ices.advice.22116890

ICES. (2024). *ICES Ecosystem Overviews Technical Guidelines*. ICES Technical Guidelines. https://doi.org/10.17895/ICES.PUB.22059803

International Seafood Sustainability Foundation. (2024). *Indian Ocean Tuna Commission (IOTC)*. https://www.iss-foundation.org/tuna-stocks-and-management/fisheries-management/regional-fisheries-management-organizations-rfmos/indian-ocean-tuna-commission-iotc/#

IOTC. (2023). *Structure of the Commission*. https://iotc.org/about-iotc/structure-commission

IOTC Secretariat. (n.d.). *Guidelines for the reporting of fisheries statistics to the IOTC*. https://data.iotc.org/reference/latest/guidelines/#

IOTC Secretariat. (2018). *IOTC Overview of fisheries data reporting and management processes*. https://www.fao.org/fi/static-media/MeetingDocuments/cwp/ReferenceHarmonization/2018/S1_4.pdf

IOTC–WPEB11. (2015). *Report of the 11th Session of the IOTC Working Party on Ecosystems and Bycatch*. Indian Ocean Tuna Commission.

Juan-Jordá, M. J., Murua, H., Arrizabalaga, H., Dulvy, N. K., & Restrepo, V. (2018). Report card on ecosystem-based fisheries management in tuna regional fisheries management organizations. *Fish and Fisheries*, *19*(2), 321–339. https://doi.org/10.1111/faf.12256

Juan-Jordá, M. J., Murua, H., & Todorovic, S. (2018). *Selecting ecosystem indicators for fisheries targeting highly migratory species*. https://iotc.org/sites/default/files/documents/2018/09/IOTC-2018-WPEB14-21_Rev1.pdf

Juan-Jordá, M. J., Nieblas, A. E., Hanke, A., Tsuji, S., Andonegi, E., Di Natale, A., Kell, L., Diaz, G., Alvarez Berastegui, D., Brown, C., Die, D., Arrizabalaga, H., Yates, O., Gianuca, D., Niemeyer Fiedler, F., Luckhurst, B., Coelho, R., Zador, S., Dickey-Collas, M., … Murua, H. (2022). Report of the ICCAT Workshop on the Identification of Regions in the ICCAT Convention Area for Supporting the Implementation of the Ecosystem Approach to Fisheries Management. *Collect. Vol. Sci. Pap. ICCAT*, *79*(5), 178–211.

Juan-Jordá, M. J., Nieblas, A.-E., Murua, H., de Bruyn, P., Bonhommeau, S., Dickey Collas, M., Dalleau, M., Fiorello, F., Hayes, D., Jatmiko, I., Koubbi, P., Koya, M., Kroese, M., Marsac, F., Pepin, P., Shahid, U., Thoya, P., Tsuji, S., & Wolfaardt, A. (2020). Identification of Regions in the IOTC Convention Area to Inform the Implementation of the Ecosystem Approach to Fisheries Management. In *WPNT10—10th Working Party on Neritic Tunas. 6-8/07/2020, Virtual meeting Documents. IOTC-2020-WPNT10-09, 30p.* https://archimer.ifremer.fr/doc/00734/84590/

Koen-Alonso, M., Pepin, P., Fogarty, M. J., Kenny, A., & Kenchington, E. (2019). The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: Structure, state of development, and challenges. *Marine Policy*, *100*, 342–352. https://doi.org/10.1016/j.marpol.2018.11.025

Link, J. S. (2010). *Ecosystem-based fisheries management: Confronting tradeoffs*. Cambridge University Press.

Nieblas, A.-E., Murua, H., Bruyn, P. D., Chassot, E., Fiorellato, F., & Jorda, M.-J. J. (2022). *Pre-workshop analysis in preparation for the 2022 IOTC Ecoregions Workshop: 'Identification of regions in the IOTC convention area to inform the implementation of the ecosystem approach to fisheries management'*. https://iotc.org/sites/default/files/documents/2023/01/IOTC-2022-WPEB18-INF14.pdf

NOAA Fisheries. (2023). *International and Regional Fisheries Management Organizations*. https://www.fisheries.noaa.gov/international-affairs/international-and-regional-fisheries-management-organizations

Omernik, J. M. (2004). Perspectives on the Nature and Definition of Ecological Regions. *Environmental Management*, *34*(S1), S27–S38. https://doi.org/10.1007/s00267-003-5197-2

Ortuño Crespo, G. (2019). The road to implementing an ecosystem-based approach to high seas fisheries management. In *Predicting Future Oceans* (pp. 483–493). Elsevier. https://doi.org/10.1016/B978-0-12-817945-1.00045-9

Ortuño Crespo, G., Andonegi, E., Murua, H., & Juan-Jordá, M.J. (2024). *Pilot Product to Test the Utility of ICCAT Ecoregions for Supporting the Development of Ecosystem-Based Advice Products*.

Pebesma, E., & Bivand, R. (2023). *Spatial Data Science: With Applications in R* (1st ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9780429459016

Posit team. (2024). *RStudio: Integrated Development Environment for R*. Posit Software, PBC. http://www.posit.co/

Reygondeau, G., Maury, O., Beaugrand, G., Fromentin, J. M., Fonteneau, A., & Cury, P. (2012). Biogeography of tuna and billfish communities. *Journal of Biogeography*, *39*(1), 114–129. https://doi.org/10.1111/j.1365-2699.2011.02582.x

Rice, J., Gjerde, K. M., Ardron, J., Arico, S., Cresswell, I., Escobar, E., Grant, S., & Vierros, M. (2011). Policy relevance of biogeographic classification for conservation and management of marine biodiversity beyond national jurisdiction, and the GOODS biogeographic classification. *Ocean & Coastal Management*, *54*(2), 110–122. https://doi.org/10.1016/j.ocecoaman.2010.10.010

Schott, F. A., Dengler, M., & Schoenefeldt, R. (2002). The shallow overturning circulation of the Indian Ocean. *Progress in Oceanography*, *53*(1), 57–103. https://doi.org/10.1016/S0079-6611(02)00039-3

Schott, F. A., & McCreary, J. P. (2001). The monsoon circulation of the Indian Ocean. *Progress in Oceanography*, *51*(1), 1–123. https://doi.org/10.1016/S0079-6611(01)00083-0

Staples, D., Brainard, R., Capezzuoli, S., Funge-Smith, S., Grose, C., Heenan, A., Hermes, R., Maurin, P., Moews, M., O'Brien, C., & Pomeroy, R. (2014). *Essential EAFM. Ecosystem Approach to Fisheries Management Training Course. Volume 1 – For Trainees*. FAO Regional Office for Asia and the Pacific.

Todorović, S., Juan-Jordá, M. J., Arrizabalaga, H., & Murua, H. (2019). Pelagic ecoregions: Operationalizing an ecosystem approach to fisheries management in the Atlantic Ocean. *Marine Policy*, *109*, 103700. https://doi.org/10.1016/j.marpol.2019.103700

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. United Nations. https://www.un.org/en/exhibits/page/sdgs-17-goals-transform-world

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). *dplyr: A Grammar of Data Manipulation*. https://CRAN.R-project.org/package=dplyr