Ecosystem Fisheries Overviews - Assessing the applicability of IOTC candidate ecoregions as a spatial framework for developing ecosystem-based advisory products

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Abstract

The Indian Ocean Tuna Commission (IOTC) is advancing the development of tools and products to support the implementation of the Ecosystem Approach to Fisheries Management (EAFM). A spatial framework has been developed comprising nine candidate ecoregions within the IOTC convention area to facilitate ecosystem-based planning and research, as well as the development 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 study aims to contribute to the development of a pilot advice product - regional Ecosystem-Fishery Overviews (EFOs) - to assess the feasibility and general applicability of the candidate ecoregions as a spatial framework to support the development of integrated and ecosystem-based advice products for IOTC. We successfully developed a preliminary EFO as a proof of concept, focusing on two key thematic sections: (i) who is fishing and (ii) what are they catching, for three selected candidate ecoregions (the Somali Current Ecoregion, the Indian Ocean Monsoon Gyre Ecoregion, and the Maldives Ecoregion). We also conducted a strengths, weaknesses, opportunities, and threats (SWOT) analysis to assess the potential usefulness and role of regional EFOs as advice products to complement existing advisory processes in IOTC. While the initial development of regional EFOs is promising, significant challenges remain, particularly related to the quality and spatial resolution of IOTC fishery statistics. These limitations hinder the characterization of fleet dynamics and their catch composition within ecoregions, indicating the need for improved data collection and reporting. The study also highlights the strengths of EFOs, including their capacity for cumulative assessments of fisheries and ecosystems, improved regional ecosystem planning, and enhanced integration of ecosystem considerations into management advice. However, further interdisciplinary research, collaborations, and consultative and interactive processes are necessary to further develop regional EFOs and fully embed them into the IOTC advisory framework.

1. Introduction

Currently, the Ecosystem Approach to Fisheries Management (EAFM) has become an essential element of fisheries management policies in many countries (e.g. USA, Australia) and is increasingly being recognized in international fisheries advisory and management bodies such as the tuna Regional Fisheries Management Organizations (RFMOs). The EAFM is a management framework that considers the complex interactions between species, as well as the combined effects of fishing, climate and environmental factors, and food availability on the species and the human communities that depend on fishing (Garcia et al., 2003). The operationalization of the EAFM seeks to maximize the ecological, economic, and social sustainability of fisheries and evaluate the trade-offs among multiple competing objectives.

Implementation of the EAFM requires the identification of a spatial extent within which different ecosystems can be characterized, monitored, and reported on (Garcia et al., 2003; Staples et al., 2014). Since 2018, the Indian Ocean Tuna Commission (IOTC) Working Party on Ecosystems and Bycatch (WPEB) has been developing a process to advance the identification of ecologically meaningful regions (ecoregions) within the IOTC convention area, yet large enough to be practical, to be used as a spatial framework to support the development of tools and products for guiding EAFM implementation (Juan-Jorda et al., 2018). The ecoregions aim to provide a spatial framework to support regional collaborative and cross-sectoral ecosystem planning and prioritization, incentivize ecosystem research, and the development of regional integrated ecosystem-based advice products to inform fisheries management decisions in IOTC (ICES, 2020; Rice et al., 2011; Zador et al., 2016). During the 1st IOTC Ecoregion Workshop in 2019, a total of seven candidate ecoregions were identified within the IOTC convention area (Juan-Jorda et al., 2019). The second IOTC Ecoregion Workshop took place in 2022, resulting in a refined process for guiding the delineation of ecoregions and a refined proposal of nine candidate ecoregions within the IOTC convention area (Juan-Jorda et al., 2022); Figure 1, Table 1). For delineating IOTC ecoregions, pre-established criteria were used to guide the underlying regionalization and expected qualities of the resultant ecoregions. The criteria were informed mainly by three thematic factors: (1) the main oceanographic patterns and biogeography of the pelagic ecosystem in the Indian Ocean; (2) the spatial patterns in the distributions of major IOTC species (Table 2) along with the ecological communities they form; and (3) the spatial patterns of the main IOTC fisheries (Table 3), their core fishing grounds, and the fisheries complex they form. 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 1). Therefore, the resultant ecoregions possess a degree of internal homogeneity and are distinct in terms of their oceanographic characteristics and composition of target tuna and billfish species and fisheries targeting them.

At this stage, the IOTC candidate ecoregions should be considered a working hypothesis to be tested, validated, and refined before they are used for resource planning, research, and management. Two approaches are generally used for testing and validating ecoregions (Bailey, 1983; Loveland & Merchant, 2004). One approach consists of statistically evaluating the hypothesis underlying the regionalization and the expected qualities of the resultant ecoregions (Table 4). This approach is chosen when the aim is to quantitatively evaluate and verify the results of the ecoregion mapping. However, this validation approach of statistically evaluating the hypothesis underlying the regionalization and the resultant ecoregion mapping is known to be challenging. This is because the ecoregion maps are a synthesis and a compromise of many components of thematic factors underlying the criteria, and they are the result of a process of generalization to reduce complexity to a manageable spatial framework for a particular purpose. In addition, the boundaries of the ecoregions are often considered gradients rather than sharp edges or “true” boundaries, which are considered transition zones. These characteristics do not lend ecoregion maps and their boundaries to easy verification using conventional statistical measures (Bailey, 1983; Loveland & Merchant, 2004). Therefore, it is advisable that when attempting to quantitatively evaluate the IOTC candidate ecoregions, to acknowledge (1) that the ecoregions are a compromise of three underlying thematic factors, and (2) that the homogeneity that distinguishes an ecoregion from another is most manifested at the core of the region, while distinguishable characteristics are less clear at the periphery (the regional edges).

A second approach for validating and verifying the ecoregion maps contends that the ultimate test of the utility of ecoregions as tools for resource planning, research, assessment, and provision of advice may be the extent to which they meet the end user needs (Bailey, 1983; Bryce & Clarke, 1996; Loveland & Merchant, 2004). Therefore, it consists of developing pilot products (e.g. Ecosystem-Fisheries Overviews, regional EcoCards, etc.) to test how the ecoregions support or affect the intended uses of the ecoregions. The IOTC ecoregions were delineated to be used as a spatial unit of analysis for supporting regional ecosystem planning, ecosystem research, and development of ecosystem-based advice products to complement the current single-species advice provided in IOTC with bycatch advice, ecosystem-based advice, and climate-based advice at the ecoregional level. Following these intended uses, the IOTC WPEB in 2022 endorsed the candidate ecoregions 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 (e.g. Ecosystem and Fisheries Overviews). A selection of case study ecoregions, including the Somali Current Ecoregion and the Indian Ocean Monsoon Gyre Ecoregion, were identified to demonstrate their applicability and intended use to the Commission (IOTC WPEB18, 2022).

Multiple ecosystem-based advice products (e.g. Fishery Overviews, Ecosystem Overviews, State of the Ocean Reports, State of the Ecosystem Report) are being developed at the ecoregion level in multiple organizations such as the International Council for the Exploration of the Sea (ICES) and the Northwest Atlantic Fisheries Organization (NAFO) (ICES, 2023; Koen-Alonso et al., 2019). In a nutshell, these types of advice products are used to provide a holistic narrative of each ecoregion, covering the ecosystems in general as well as focusing on the core species and fisheries under management within the ecoregion and their effects on the ecosystem. In the end, 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. Therefore, these types of ecosystem-advice products aim 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. These advice products are not meant to be catalogs of all available information on an ecoregion but synthesize science-based statements supported by quantitative (where possible) and qualitative data and research on relevant topics of interest to be used by the Commission and other stakeholders (ICES, 2023). Among others, these advice products may be used to synthesize key fisheries and relevant ecosystem information about the managed stocks in the region, their status, the gears catching them, and countries involved in the fisheries, as well as the effects of the main fisheries operating in the area on the ecosystem including bycatch and food web impacts. The role of environmental and climate effects of the managed stocks in the region can also be addressed in these types of products. In the end, these advice products are intended to advance the delivery of integrated advice, focusing on the core target and bycatch species and fisheries in a region, their impact on the ecosystems as well as the most influential environmental, climate, and ecosystem processes. These advice products are usually treated as living documents based on information provided by expert groups to be updated and further developed every year or few years.

Since an EFO is a holistic advice product, it 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 2). 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. 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 (SWOT) of such regional products in the context of IOTC standard procedures to produce scientific advice for the Commission.

The main objective of this study is to contribute to the development of a pilot product to assess the general applicability of ecoregions as a spatial framework for developing integrated and ecosystem-based advice products. Towards this aim, we started the development of EFOs for three contrasting ecoregions: the Somali Current Ecoregion (SCE), the Indian Ocean Monsoon Gyre Ecoregion (IOMGE), and the Maldives Ecoregion (ME) (Figure 1). Towards developing EFOs as a proof of concept for the three selected ecoregions, we developed the following two thematic sections of an EFO (Figure 2):

Task 1 – Who is fishing? We identify, map, and describe the most important fleets operating in each ecoregion, including the flag States, gears used, and their spatio-temporal patterns of activity using IOTC publicly available fishery statistics datasets. This provides an overview of the core fleets operating in each ecoregion and whether their fishing grounds are contained within a single ecoregion or over multiple ecoregions.

Task 2 – What are they catching? Based on the core fleets identified for each ecoregion under Task 1, we describe the spatio-temporal patterns of catches by species, gears, and fleets in each ecoregion using IOTC publicly available fishery statistics datasets. This provides an overview of what species are caught in each ecoregion and their catches over time.

Last, we conducted a strengths, weaknesses, opportunities, and threats (SWOT) analysis to assess the potential usefulness and role of EFOs as an advice product based on the ecoregions framework to complement the existing type of advice in IOTC. Specifically, we conducted a SWOT analysis of the EFO products with the purpose of (1) identifying the potential strengths of this type of advisory product to complement the existing type of advice in IOTC, (2) identifying any weaknesses or limitations of this advisory product as well as limitations and challenges in their practical development, (3) exploring opportunities to enhance this type of product and identify emerging developments of IOTC that could create opportunities for this product to have a greater impact, and (4) identifying potential threats or challenges that could affect its development and their effectiveness and relevance as an advisory product. This could be used to engage and communicate to the IOTC community the potential benefits of this product. Furthermore, we also hope that the SWOT analysis will provide valuable insights into the feasibility and effectiveness of using ecoregions as a spatial framework/basis for the development of EFO products within the IOTC framework.

2. Methods

2.1 Data sources

We used IOTC and CCSBT datasets to identify, map, and describe the most important fleets operating in each ecoregion (i.e., the core fleets) and characterize their main fishing gears and catch composition across each IOTC candidate ecoregion (Table 5). The IOTC 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. From the 1950s until 2022, the IOTC 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. The IOTC Raised Catch dataset is the best scientific estimate of the raised Nominal Catch data, which contains georeferenced (5° x 5°) live weight data. This dataset covers explicitly the five main tuna and billfish species managed by IOTC (albacore tuna -*Thunnus alalunga*, bigeye tuna - *Thunnus obesus*, skipjack tuna - *Katsuwonus pelamis*, yellowfin tuna -*Thunnus albacares*, and Swordfish - *Xiphias gladius*, Table 2, Figure 2). The IOTC Nominal Catch dataset is available on the IOTC website, whereas the IOTC Raised Catch dataset 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 5). One additional dataset utilized to complete this analysis was the catch data from the Commission for the Conservation of Southern Bluefin Tuna (CCSBT). The CCSBT 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*).

2.1 Task 1 – Who is fishing?

We used the two IOTC datasets and one CCSBT dataset (Table 5) to identify, map, and describe the most important fleets operating in each ecoregion (i.e., the core fleets). The IOTC Raised Catch dataset contains six gear groups and 132 fleets (fleet defined as the combination of GearGroup and FleetCode) reporting catches between 1950 and 2022 in the whole IOTC convention area. We examined the catches over the last 13 years (2010-2022) to provide a snapshot of the main fleets currently operating in the ecoregions. The identification of core fleets for each ecoregion relied on a comprehensive and iterative methodology, incorporating a series of ranking and sequential filtering steps. These filters were designed to encapsulate the broad spectrum of fleets that could be deemed representative of a particular ecoregion's dynamics. Core fleets were defined as distinct combinations of flag States and fishing gear types (Table 3), meeting stringent criteria related to their catch volume, operational range, and activity intensity within an ecoregion. This methodological approach was consistently applied to identify core fleets within the three selected ecoregions.

The initial step to identify core fleets involved identifying the total count of unique fleets from the IOTC Raised Catch dataset (SCE = 56 fleets, IOMGE = 64 fleets, ME = 30 fleets) that reported catches (between 2010-2022) in each ecoregion. Subsequently, a range of metrics and indicators were computed for each fleet to determine which fleets qualify as core fleets within each ecoregion. The initial indicators examined for each fleet using the Raised Catch dataset included:

- Indicator 1: The number of years with reported catches over the past 13 years for each fleet.
- Indicator 2: Presence of catch reporting in at least three out of the last six years for each fleet.

- Indicator 3: Percentage of the total catch of each fleet within the ecoregion relative to the total catch across the IOTC convention area for each fleet.
- Indicator 4: Percentage of the total fishing ground of each fleet within the ecoregion relative to the entire fishing ground across the IOTC area, measured in the number of pixels (5°x 5° degree squares) with reported catches.
- Indicator 5: Percentage of total catch of each fleet relative to the total catch of all fleets within an ecoregion.
- Indicator 6: Percentage of the fishing ground of each fleet relative to the ecoregion area, also measured in pixels (5°x 5° degree squares) with reported catches.

We applied three sequential filters to determine which fleets qualify as core fleets within each ecoregion (Figure 3). The first filter applied to the fleets within each ecoregion was temporal, utilizing the frequency of data reporting as a proxy for fleet activity. Fleets reporting data for at least three of the past six years (2016-2022) were retained, while the others were excluded. A second and third filter was applied to identify core fleets that are representative of only one ecoregion (termed regional fleet) and identify core fleets that can be representative of multiple ecoregions (termed as across-regions fleets). The second filter consisted of two criteria aimed at identifying fleets with strong ties to the ecoregion (regional fleets), even if their catch volumes were comparatively lower. To pass this filter, a fleet had to demonstrate that at least 55% of its catch originated from within the ecoregion, or that at least 55% of its fishing activity occurred within its boundaries. For the remaining of the fleets, the third filter was applied, with two criteria, to identify if the fleet had significant presence in the ecoregion in terms of catches and fishing activity (across-regions fleet). These across-region fleets had to capture in the ecoregion at least 1% of the total catch volume within the ecoregion over the past 13 years or conduct fishing operations across at least 40% of area of the ecoregion.

2.2 Task 2 – What are they catching?

Building upon the core fleets identified for each ecoregion, we conducted an analysis to characterize historical catches within each ecoregion, disaggregating them by major target taxa and gear groups. This analysis involved utilizing both the IOTC Nominal Catch dataset and the IOTC Raised Catch dataset (with the SBT georeferenced catches included), as the allocation of catch to a fleet depended on the spatial extent of their catches and fishing grounds within ecoregions. The IOTC Nominal Catch dataset offers a broad taxonomic coverage, encompassing reported nominal catches for tuna and tuna-like species and other species caught in IOTC fisheries by each fleet. However, these reported catches lack georeferencing at a spatial resolution enabling automatic assignment to specific ecoregions. Conversely, the IOTC Raised Catch dataset contains nominal catch data only for the five major commercial species, with georeferencing (5ºx 5º) facilitating direct assignment to ecoregions. Thus, catch data for each fleet were sourced from either the IOTC Nominal Catch dataset or the Raised Catch dataset, depending on the spatial distribution of catches and fishing grounds within the ecoregions. IOTC Nominal Catch data was attributed to a fleet when the majority of the catch and extension of fishing grounds occurred within the area of an ecoregion. Alternatively, the IOTC Raised Catch data was attributed to a fleet if its catches and fishing grounds spanned both inside and outside ecoregion areas, with only catches of the fleet within the ecoregion considered in such cases. This analysis offers a comprehensive overview of the species caught by the main core fleets in an ecoregion, along with their catch trends over time.

3. Results

3.1 Somali current ecoregion (SCE)

3.1.1 Task 1 – Who is fishing?

Out of 58 fishing fleets reporting catches within the SCE between 2010-2022, 28 qualified as core fleets, meeting the established criteria (Figure 5A). These fleets were selected based on their catches and spatial prevalence within the SCE. A detailed breakdown of which fleets met the criteria to be classified as core fleets of the SCE can be found in Appendix 1 (Appendix 1 – SM_Table 1). Together, the 28 fleets accounted for 95% of the total catch within the SCE. These fleets used six different major gear types (purse seine, longline, baitboat, gillnet, line, and others) and represented 12 unique flag States. When ranking these 28 core fleets based on their average annual catches since 2010 within the SCE, we find Iran, Pakistan, Oman, and Yemen gillnet fleets emerged as the most dominant gillnet fleets in the SCE (Figure 5 Panel A). The Iranian gillnet fleet, in particular, records an average catch of around 240.000 tonnes annually. The gillnet fisheries catch mostly neritic small tunas and seerfishes, followed by tropical skipjack and yellowfin tuna (Figure 5B). Among purse seiners, the European and Seychelles purse seine fleets are the most dominant in the ecoregion, with tropical tunas (skipjack, yellowfin, and bigeye tunas) making the bulk of the catches (Figure B5). Among line fisheries, Oman and Yemen line fleets are the most dominant in the ecoregion, mostly catching yellowfin tuna(Figure 5B). Other gears from Oman are also dominant in the ecoregion (Figure 5B). Last, the catches of the longline and baitboat fleets are negligible in this ecoregion (Figure 5).

The core fleets in the SCE comprise a combination of regional fleets (26 fleets) and across-regions fleets (2 fleets) (Figure 5, Appendix 1 – SM_Table 1). Most of the fleets in the SCE were categorized as regional, having the majority of their fishing grounds (average 90% of the area of the SCE) and their catches (96% on average) occurring within the ecoregion. All gillnet (10 fleets), line (8 fleets), other gears (2 fleets), baitboat (1 fleet), and longline (2 fleets) fleets operate predominantly within the SCE (regional fleets). Notably, 18 of the fleets have a value of 100% in the regional catch and presence indicators operating entirely within the ecoregion. The remaining two core fleets are across-regions industrial purse seine fleets (PS_EU and PS_SYC) with fishing grounds extending across multiple ecoregions in the Indian Ocean (Figure 5), yet a large amount of their catches occur within the SCE (on average, 14% of their catch) and their fishing grounds (40% on average) occupy a large surface area within the SCE.

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 (Figure 6). 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 IOMGE ecoregion (Figure 6E and G). The gillnet fleets primarily catch skipjack and yellowfin tuna, with minor albacore tuna catches, whereas the line fleets catch almost exclusively yellowfin tuna. 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 6C). 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 6K). The longline fleets (Kenya and Tanzania), although categorized as regional fleets, have a small proportion of catches that extend into other ecoregions (Figure 6A). Last, the purse seine across-regions fleets operate within the SCE and IOMGE (Figure 6I).

3.1.2 Task 2 – What are they catching?

Catches of tuna and tuna-like species, as well as other teleosts and sharks, have increased steadily since the 1950s in the SCE (Figure 7). Catches peaked in 2019 and 2022 at around 550.000 tonnes. Most of the catches (68% of the total catches) come from regional fleets operating within the SCE (Figure 7A). Using the IOTC Nominal Catch dataset to source catches of these regional fleets 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. From the 1950s until the 1990s, the catch was dominated by other sharks and neritic tunas and seerfishes, and since the 1990s, around half of the catch is made of tropical tunas (yellowfin tuna skipjack tuna), and the rest of neritic small tunas and seerfishes. Over the last five years, yellowfin tuna has constituted an average of 26% of the total catch. Skipjack tuna is the second most-caught species, averaging 17% of the catch. The third most-caught group comprises the small-tunas (bullet tuna, longtail tuna, frigate tuna, and kawakawa, 26% of the total catch on average). Teleost fishes and the seerfishes group (Indo-Pacific king mackerel, narrow-barred Spanish mackerel, and other seerfishes) average 22% of the catch. The historical catches in the region have been predominantly dominated by gillnet fisheries since 1950, followed by line and purse seine fisheries since the 1980s (Figure 7C). Over the last five years, the average catch in the SCE shows that the gillnet fisheries dominated the regional catches, accounting for 69% of the total catch, followed by line (18%), purse seine (18%), and other gears (2%).

3.2 Indian Ocean Monsoon Gyre Ecoregion (IOMGE)

3.1.1 Task 1 – Who is fishing?

Out of 63 fishing fleets reporting catches within the IOMGE between 2010-2022, 14 qualified as core fleets meeting the established criteria (Figure 8A). These fleets were selected based on their catches and spatial prevalence within the IOMGE. A detailed breakdown of which fleets met the criteria to be classified as core fleets of the IOMGE can be found in Appendix 1 (Appendix 1 – SM_Table 2). Together, the 14 fleets accounted for 87% of the total catch within the IOMGE. These fleets used four different major gear types (purse seine, longline, gillnet, and line) and represented 11 unique flag States. When ranking these 14 core fleets based on their average annual catches since 2010 within the IOMGE, we find the European, Seychelles, and Sri Lanka purse seine fleets emerged as the most dominant fleets in the region (Figure 8A). The European purse seine fleet, in particular, records an average catch of around 42.000 tonnes annually, with the majority of the bulk of the catches made of tropical tunas (skipjack, yellowfin, and bigeye tunas) (Figure 8B). Among gillnet fisheries, the Sri Lanka fleet is the most dominant in the ecoregion, catching mostly tropical tunas but also, in smaller proportions, some neritic tunas, seerfishes, swordfish, and shark species (Figure 8B). Lines from Sri Lanka are also dominant in the ecoregion. Among longliners, the Taiwan, India, and Sri Lanka fleets are the most dominant in the ecoregion, with tropical tuna species making the bulk of their catches (Figure 8B).

The core fleets in the IOMGE comprise a combination of regional fleets (11 fleets) and across-regions fleets (3 fleets) (Figure 8, Appendix 1 – SM_Table 2). Most of the fleets are categorized as regional, with the majority of their fishing grounds (average 35% of the area of the IOMGE) and their catches (81% on average) occurring within the ecoregion. All purse seine fleets (6 fleets), line (1 fleet Sri Lanka), and gillnet (1 fleet Sri Lanka) were considered regional. Longline fleets were categorized as regional (India, Sri Lanka, Seychelles) or across-regions fleets (China, Japan, Taiwan).

The spatial distribution of the catches by gear type shows that three out of the four types of gear primarily operate and have their fishing grounds within the IOMGE (Figure 9). The gillnet and line fleet have a more coastal distribution concentrating around Sri Lanka, yet a small proportion of their catches and fishing grounds extend into the IOMGE (Figure 9C and E). These fleets primarily catch skipjack and yellowfin tunas. The purse seine fleets are also categorized as regional fleets, having the majority of their fishing grounds (33% on average) and their catches (83% on average) occurring within the ecoregion, yet their fishing grounds also expand into the SCE and the northern area of the ACE. The longline fleets are a mix of regional and across-regions fleets; while some operate mostly within the IOMGE, others expand across multiple ecoregions (Figure 9A). While the fishing grounds of the across-regions longline fleets extended across multiple ecoregions in the Indian Ocean (Figure 9G), their catches within the IOMGE are made mostly of tropical tunas.

3.1.2 Task 2 – What are they catching?

The IOMGE is an oceanic ecoregion. Catches of tuna and tuna-like species have remained low until the early 1980s, and since then, they have increased steadily, peaking in 2004 at around 647.000 tonnes and again in 1999 at around 487.000 tonnes (Figure 10). Most of the catches (79% of the total catches) come from regional fleets operating largely within the IOMGE (Figure 10A). From the 1980s until now, the catch has been dominated by tropical tunas (yellowfin and skipjack tunas) and, to a lesser extent, bigeye tuna (Figure 10B). Over the last five years, skipjack tuna has constituted 45% of the total catch on average, followed by yellowfin tuna (averaging 28% of the catch), other teleosts (averaging 10% of the catch) and bigeye tuna (averaging 9% of the catch). Purse seine fisheries have predominantly dominated the historical catches in the region since the 1980s, while longline, gillnet, and line fleets have been present in the region since the 1950s and 1960s (Figure 10C). Over the last five years, the average catch in the IOMGE shows that the purse seine fisheries dominated the regional catches, accounting for 75% of the total catch, followed by longline (13%), gillnet (6%), and line (6%).

3.3 Maldives Ecoregion (ME)

3.1.1 Task 1 – Who is fishing?

Out of the 29 fleets reporting catches within the ME between 2010-2022, three qualified as core fleets meeting the established criteria (Figure 11). These fleets were selected based on their catches and spatial prevalence within the ME. A detailed breakdown of which fleets met the criteria to be classified as core fleets of the IOMGE can be found in Appendix 1 (Appendix 1 – SM_Table 3). Together, the three fleets accounted for 96% of the total catch within the ME. These fleets used two different major gear types (baitboat and line) and represented two unique flag States. When ranking these three core fleets based on their average annual catches since 2010 within the ME, we find the ME baitboat emerged as the most dominant fleet in the region, followed by the ME line and Indian baitboat (Figure 11A). The ME baitboat fleet, in particular, records an average catch of around 98.000 tonnes annually, with the majority of the bulk of the catches made of skipjack tuna (Figure 11B). The three core fleets in the ME are categorized as regional fleets, having the majority of their fishing grounds (average 39% of the area of the ME) and their catches (98% on average) occurring within the ecoregion.

The spatial distribution of the catches by gear type shows that two types of gear (lines and baitboat) primarily operate and have their fishing grounds within the ME (Figure 12). Both operate along the Maldives island chain, yet a small proportion of their catches and fishing grounds extend into the IOMGE (**Figure 12 A, C**). These fleets primarily catch skipjack and yellowfin tunas.

3.1.2 Task 2 – What are they catching?

The ME can be considered a tropical oceanic ecosystem, the open waters surrounding the Island Chain support oceanic tuna and tuna species. Since the 1950s, catches of mainly tropical tunas (skipjack and yellowfin tunas) have increased steadily, peaking at around 193.000 tonnes, stabilizing in catches in the last six years around 150.000 tonnes (Figure 13). 100% of the catches come from regional fleets operating largely within the ME (Figure 12A). Since the 1950s, the catch has been dominated entirely by skipjack (73% of catch over the last five years) and yellowfin (25% of catch over the last five years) tunas (Figure 12B). The historical catches in the region have been predominantly dominated by baitboat fisheries since the 1950s, while line fisheries have been present in the region since the 1970s, gaining importance in the last two decades (Figure 12C). Over the last five years, the average catch in the ME shows that the baitboat fisheries dominated the regional catches, accounting for 85% of the total catch, followed by line (15%).

4. Discussion

The primary aim of this study 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 study has developed two thematic sections of a pilot Ecosystem-Fishery Overview (EFO): (1) characterization of the core fleets and (2) characterization of the historical catches for the three selected ecoregions as a proof of concept. This pilot EFO is expected to serve as the foundation for further developing EFO advice products in IOTC. First, we discuss the challenges encountered to characterize the core fleets and historical catches in the selected ecoregions and assess the general use and applicability of the IOTC candidate ecoregions as a spatial framework to support the development of EFOs in the region. Then, we discuss the strengths, weaknesses, opportunities, and threats of the pilot EFO as an advice product to support EAFM implementation in IOTC.

4.1 Feasibility of IOTC ecoregions to support ecosystem-based tools and products to support EAFM implementation

Through the spatiotemporal analysis of fleet dynamics and their catches, we evaluated the feasibility of developing some thematic sections for a pilot EFO product across three selected ecoregions. Despite the inherent limitations on the IOTC fishery statistics, we were able to identify core fleets, exhibiting distinct operational footprints within each ecoregion, highlighting the uniqueness of each ecoregion. Additionally, we were able to distinguish between core regional fleets, characterized by a concentration of catches and fishing activities confined predominantly within a single ecoregion, and core across-regions fleets, which display relevant catches and spatial prevalence across multiple ecoregions. This allowed us to provide an overview of the core fleets operating within each ecoregion and whether their fishing grounds are confined to a single ecoregion or span multiple ecoregions. Furthermore, we were also capable of characterizing historical catches by major taxa and gear groups within each ecoregion, offering insights into the species targeted and the primary gears used over time. These findings demonstrate the feasibility and the potential of developing regional advice products, such as EFOs, at the ecoregion level, which could potentially complement the existing single species advice provided by the Scientific Committee to the IOTC commission. However, further research and work is needed to evaluate the feasibility of other potential sections of the EFO product (Figure 2) for these ecoregions and to extend the development of EFOs to remaining ecoregions.

While the IOTC fishery statistical datasets were not purposely designed to support ecosystem-based regional products such as an EFO, they have proven useful for developing these two thematic sections of a pilot EFO, albeit with inherent caveats and limitations. The two thematic sections of the EFO product rely on the fishery catch statistics reported to IOTC, primarily the IOTC Nominal Catch and Raised Catch datasets. However, these datasets exhibit known limitations such as underreporting of catches, and poor taxonomic, spatial, and temporal resolutions, as well as inconsistent and poor data quality submitted by some IOTC member states. For example, the IOTC Nominal Catch dataset reports certain taxa groups with poor taxonomic resolutions, particularly for shark and ray species (Heidrich et al., 2022). Although the proportion of shark and ray catches reported at the species level has improved over the last decades, significant gaps remain. Consequently, these two thematic sections should be interpreted with caution as they mostly provide information on target tuna commercial species, with an awareness of the inherent data limitations in fisheries statistics across the different regions.

The spatially explicit nature of the EFO product necessitates accurate knowledge of where fisheries operate and where catches are made, making it highly dependent on catch statistics reported with spatial information. However, georeferenced catch data remains limited in IOTC (Heidrich et al., 2022). Historically, only 64% of the reported catches to the IOTC secretariat have been submitted with spatial information, typically reported in 1x1 to 5x5 degree grids, depending on the gear type (Heidrich et al., 2022). As a result, the IOTC secretariat estimations for deriving the IOTC Raised Catch dataset with the georeferenced catches raised to the total nominal catch rely on numerous assumptions. The georeferenced catches reported for certain 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. Consequently, any analysis and results derived from the IOTC Raised Catch dataset require careful scrutiny. Furthermore, the taxonomic completeness in the IOTC Raised Catch data set is also limited, covering only five of the 16 tuna and tuna-like species included in the IOTC convention mandate. This introduces a bias towards the most commercially valuable species, excluding neritic tunas, Spanish mackerels, and subtropical billfish species, that may also be significant in some regions. To provide a more comprehensive understanding of the fishery impacts on the ecosystem and the catch and fishing trends by area, the IOTC should strive to increase the taxonomic completeness of this dataset to include a broader range of tuna and tuna-like species. Additionally, the spatial resolution of the IOTC Raised Catch data, typically reported at a 5x5 degree grid, presents challenges in accurately assigning catches to specific ecoregion boundaries or within coastal ecoregions confined to the continental shelf. This coarse resolution may result in misidentification of core fleets within certain ecoregions, potentially leading to inaccuracies in the spatial representation of fleet dynamics and catch composition and trends of the core fleets in the region.

4.2 Strengths, Weaknesses, Opportunities and challenges (SWOT) of an EFO product in the context of IOTC

Below we discuss potential strengths and weaknesses as well as identify opportunities and threats foreseen in the development and use of this type of product for strategic planning and decision-making in the context of IOTC.

Strengths of a EFO product and IOTC to support its development

The development and use of EFOs in IOTC as advisory products may offer several unique strengths and benefits to connect better bycatch, climate and ecosystem considerations spatially and thus complement single-species assessments and advice in multi-species fisheries. We highlight some potential strengths and benefits:

- **Holistic-interdisciplinary product -** An EFO product aims to characterize the interactions between multiple fisheries, species and environmental factors in a region (e.g. ecoregion level). Therefore, EFOs provide holistic assessments of the status and trends of marine ecosystems and fisheries in a region. EFOs may be used to communicate stakeholders relevant bycatch, climate and ecosystem indicators monitoring status and trends in the region. These indicators may provide valuable insights into fishing impacts on the ecosystems or the overall condition and productivity of the ecosystem and help identify areas of concern that may not be apparent from single-species assessments alone. This product may allow IOTC to assess the broader ecosystem and fleet-specific contexts and monitor potential ecosystem-wide impacts of fishing activities and the effect of ecosystems and climate on fisheries resources.

- **Incentivize ecosystem planning and prioritization -** The spatial-framework utilized in EFOs (i.e. using ecoregions as the spatial framework), enhances understanding of the main fisheries and fleets in a region, their dynamics and interactions with biodiversity and their associated socio-ecological system. By identifying critical gaps in the data, monitoring, research, and policy, these products might facilitate more effective ecosystem planning, especially when it comes to monitoring the impacts of fisheries on associated and dependent species, as mandated under IOTC mandate. Moreover, the EFO can also serve as a platform for communicating the identified gaps and needs to the Scientific Committee and Commission, thereby guiding targeted efforts to address them. Thus, in turn, it could inform prioritization efforts for strengthening fisheries management and conservation strategies in a region; thus becoming more efficient than suggesting advice for the entire IOTC convention area.

- **Incentivize integrated research and management strategies** - By recognizing interconnectedness of fisheries, species and associated socio-ecological systems in a region, the EFOs can incentivize the development of integrated assessments across specific fleets, for example to address cumulative impacts of fisheries, assess fisheries interactions and species interactions. EFOs could also facilitate the integration of bycatch, climate and ecosystems into management strategies to address multiple objectives and visualize trade-offs between competing objectives. The use of EFOs to complement single-species advice can lead to more effective and sustainable management strategies that consider the broader ecosystem context.

- **Communication and outreach platform -** EFOs can be used as a vehicle to strengthen efforts to effectively communicate the status and trends of key ecosystem components relevant to the fisheries being managed within the region, as well as to communicate scenarios of management strategies that consider the broader ecosystem context to the Commission and other stakeholders, facilitating their engagement and awareness.

- **Stakeholder engagement and multi-sector collaborations -** The development of EFOs at the ecoregion level requires collaborations across multiple disciplines, including fisheries science, ecology, oceanography, and socio-economics, depending on the sections and topics to be covered by the EFO product (Figure 2). This multidisciplinary approach can further foster collaborations and information sharing among scientists, managers and other stakeholders from the industry and local communities with fisheries' interest in the region that potentially can enhance the relevance and credibility of the advice provided in the EFOs.

The IOTC scientific community also possesses several strengths that enable them to develop EFOs for providing more integrated advice to the commission:

- **Technical expertise and experience -** The IOTC Secretariat and scientists within the Scientific Committee comprise experts in various fields, including fisheries, biology, ecology, and oceanography. Collectively they have recognized expertise and knowledge for conducting comprehensive assessments and support the development of this type of product. They can also ensure that the EFO product is directly applicable to address specific needs and priorities of the Commission.

- **Collaborative networks and coordinated data collection and research efforts -** The IOTC Secretariat and scientists within the Scientific Committee collaborate closely with each other and external partners for coordinating data collection efforts but also to support research and assessments of target species and vulnerable taxa. These collaborative approaches are already facilitating data sharing, knowledge exchange and interdisciplinary research, which could further bolster the development of EFOs. Capacity development and networking can take place more efficiently if the relevant CPCs with fisheries interest in an ecoregion are readily identifiable.

Weaknesses and limitation of a EFO product and IOTC impeding its development

The IOTC scientific community may face several weaknesses and limitations in the development and use of EFOs connected to a specific geographic area or ecoregion. Some of the weaknesses derive from the quality and spatial resolution of information collected by fleets on the composition of their catch and distribution of their operations, and the lack of adequate bycatch monitoring and reporting for many of the core fleets in a region. We highlight some potential weaknesses and limitations:

- **Ecosystem complexity and interdisciplinary challenges -** Marine ecosystems are inherently complex and dynamic, with numerous interacting components and feedback mechanisms. Simplifying these interactions into discrete geographic areas or ecoregions and then into useful narratives and advice in the EFOs may lead to an oversimplification of complex relationships. Furthermore, the integration of multidisciplinary data and knowledge from various disciplines (oceanography, fisheries, ecosystems, social sciences) is also challenging, requiring a large amount of expertise and resources. Integrating multidisciplinary data and knowledge from different sources and disciplines (e.g. oceanography, fisheries, ecosystems, social sciences) to develop EFOs connected to specific geographic areas or ecoregions could be challenging. Variations in data formats, methodologies, and quality standards across countries or fleets or regions may impede data harmonization and integration efforts.

- **Data availability and quality in IOTC fishery statistics and other sources of data** - The quality of EFOs and their advice rely heavily on the IOTC fishery statistics datasets and the quality of the available data may not always meet the desired standards for some fleets. The IOTC fishery statistics datasets do not have the adequate spatial resolution required to support the development of quality spatially-explicit EFOs and advice, in particular for other species than the six major tuna and billfish species covered in the IOTC Raised Catch dataset. There are also a large number of fleets with poor reporting records of fishery statistics in multiple regions. Furthermore, the limited publicly available bycatch information at the fleet level also poses a challenge for monitoring bycatch and conducting bycatch assessments for providing advice, although this may be overcomed with joint-collaborative efforts across interested CPCs. Also, the data availability and quality can be uneven across fleets and time periods within a region. The reliance on incomplete or limited data may affect the accuracy and comprehensiveness of the indicators and assessments that may be captured in an EFO, especially for less monitored fisheries or regions with poor monitoring. This could jeopardize the scientific rigor, reliability and credibility of the information and thematic sections included in an EFO. However, the IOTC fishery statistics are continuously being updated and improved so the expectation is that as the fishery statistics datasets improve the quality of the EFOS will also improve too.

- **Resource demanding and inadequate or asymmetric capacity -** Development and maintaining EFOs requires significant resources in terms of time, funding, and expertise. Data collation, integrated analysis and assessments, and synthesis of knowledge requires the involvement of groups of experts across multiple disciplines being involved in the development of the product, making it resource-demanding. There is the risk that limited investment in capacities including funding, expertise and human resources could hinder the development of the EFOs. Potentially expert groups could be created to lead the development of the EFOs for each specific region leading their own initiatives to attract funding to support the development of this product. There might also be limited capacity and expertise within some member states, hindering their ability to participate and contribute effectively in the development of EFO. Capacity-building initiatives will be necessary to address these gaps.

- **Management and policy relevance and integration -** There might be delays in data collection, updates of the assessments and analysis, and production of the EFO reports, which means that the EFOs might not always reflect the most current state of ecosystems or fisheries. In practice, this type of product would need to be updated every 3-5 years. This might create challenges to integrate finding of the EFO into policy and management decisions, requiring effective collaborations and coordination among stakeholders.

Opportunities to enhance the development and use of EFOs

Several opportunities are available or emerging to enhance the development and use of EFOs in IOTC connected to a geographic area or ecoregion. We highlight some opportunities:

- **Enhanced data collection and advances in technology** - Investing in improved data collection methods and rapid advances in technologies can provide more accurate and comprehensive fishery data and others (biology, ecology, etc.) for monitoring marine ecosystems and fisheries activities, and for supporting integrated assessments, which products can lead to more robust EFOs.

- **Integrating EFOs with ongoing initiatives -** There are ongoing initiatives lead within the Scientific Committee (e.g. EcoCard tool process) or external funded research projects (e.g. ECOTUN) which are producing new relevant information, knowledge and products that could feed relevant sections of the EFOs. For example, the ongoing development of an ecosystem model for the tropical Indian Ocean, using the ecopath with ecosystem modeling tool, could populate the section of “Climate and fishing effects in ecosystems” in the EFO for the IOMGE.

- **Policy alignment and coherence -** Emerging global policy trends (e.g. implementation of the global biodiversity framework and High Seas Treaty, UN SDGs) emphasize the importance of sustainable resource management and biodiversity conservation. IOTC has the opportunity to align its advisory products such as the EFOs with these policy goals, thereby enhancing their relevance and impacts, and also facilitating the integration of fisheries management with broader environmental and conservation IOTC policies and other international policies.

Threats and challenges affecting its development and use as an advisory products

Several threats and challenges may impede the development and use of EFOs in IOTC connected to a geographic area or ecoregion. We highlight some threats and challenges:

- **Institutional barrier -** The current structure of the Scientific Committee may not be well-suited to support the development of spatially-explicit products such as EFOs. The IOTC WPEB would need to establish a process to interact more effectively with the other Working Parties to populate the product.

- **Extra layer of complexity -** EFOs can be seen as an extra layer of complexity for the Commission. The role and purpose of EFOs as products to support EAFM implementation in the context of IOTC species and fisheries can be technical and difficult to understand for a non-specialist audience, bringing an extra layer of complexity for the managers.

- **Resistance to change -** The traditional fisheries management in IOTC is deeply ingrained in single species practices and advice. Therefore, the development of EFOs might face resistance from stakeholders including managers, industry and others accustomed to existing practices.

- **Not an official request from the Commission** - EFOs have not been formally requested by the Commission. Therefore it lacks clear objectives and directions to drive the process. Yet their development as a pilot product is contemplated in the work plan of the WPEB as a potential tool to support EAFM implementation in IOTC and it is being developed as part of adaptive process- doing by learning.

5. Conclusions

This study underscores the potential of employing IOTC ecoregions as a spatial framework for developing regional Ecosystem-Fishery Overviews (EFOs). Despite challenges related to the quality and spatial resolution of the IOTC fishery statistics datasets, this work successfully presents a preliminary EFO as a proof of concept, focusing on two key thematic sections: (i) who is fishing and (ii) what are they catching, for three selected candidate ecoregions. While the existing information is sufficient to demonstrate the fisheries and ecological distinctiveness of each ecoregion supporting the feasibility of creating regional ecosystem advice products, notable data deficiencies and challenges for refining and developing other regional EFO products persist. The development and integration of EFOs within IOTC's advisory framework present several key strengths, including the ability to conduct cumulative assessments of fisheries and ecosystem interactions, enhanced regional ecosystem planning, and the potential for more integrated management strategies. Nevertheless, addressing data limitations, strengthening collaboration, and effectively embedding these products into existing advisory processes within the IOTC remain critical. By capitalizing on emerging opportunities, such as technological advances in data collection and alignment with global policy trends, the IOTC can enhance the relevance and impact of EFOs, moving towards more integrated and ecosystem-based fisheries management advice for the management of IOTC fisheries.

6. References

Bailey, R. G. (1983). Delineation of ecosystem regions. *Environmental Management*, *7*(4), 365–373. https://doi.org/10.1007/BF01866919

Bryce, S. A., & Clarke, S. E. (1996). Landscape-level ecological regions: Linking state-level ecoregion frameworks with stream habitat classifications. *Environmental Management*, *20*(3), 297–311. https://doi.org/10.1007/BF01203839

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.

ICES. (2020). Definition and rationale for ICES ecoregions. In *Report of the ICES Advisory Committee, 2020* (ICES Advice 2020, pp. 1–12). International Council for the Exploration of the Sea (ICES). https://doi.org/10.17895/ices.advice.6014

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

IOTC WPEB18. (2022). *Report of the 18th Session of the IOTC Working Party on Ecosystems and Bycatch Assessment Meeting* (No. IOTC-2022-WPEB18-R[E]; p. 98). Indian Ocean Tuna Commission (IOTC).

Juan-Jorda, M. J., Murua, H., & Todorovic, S. (2018). *Selecting ecosystem indicators for fisheries targeting highly migratory species* (Report No. IOTC-2018-WPEB14-21_Rev1). Indian Ocean Tuna Commission (IOTC).

Juan-Jorda, M. J., Nieblas, A., Murua, H., de Bruyn, P., Bonhommeau, S., Dickey-Collas, M., Dalleau, M., Fiorellato, F., Hayes, D., Jatmiko, I., Koubbi, P., Koya, M., Kroese, M., Marsac, F., Pepin, P., Shahid, U., Thoya, P., Tsuji, S., & Wolfaardt, A. (2019). *Report of the IOTC workshop on Identification of regions in the IOTC Convention Area to Inform the Implementation of the Ecosystem Approach to Fisheries Management* (No. IOTC-2019-WPEB15-INF01). Indian Ocean Tuna Commission (IOTC).

Juan-Jorda, M., Nieblas, A., Tsuji, S., Marsac, F., Chasso, E., Hayes, D., Shahid, U., Khan, M., Andonegi, E., de Bruyn, P., Fiorellato, F., Thoya, P., Green, M., Kitakado, R., Nelson, L., Ramos-Alonso, L., Martin, S., Moss, J., Lopetegui-Eguren, L., … Murua, H. (2022). *Report of the Second IOTC Ecoregion Workshop on "The Identification of Regions in the IOTC Convention Area to Inform the Implementation of the Ecosystem Approach to Fisheries Management"* (No. IOTC-2022-WPEB18-22; pp. 1–34). Indian Ocean Tuna Commission (IOTC).

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

Loveland, T. R., & Merchant, J. M. (2004). Ecoregions and Ecoregionalization: Geographical and Ecological Perspectives. *Environmental Management*, *34*(S1), S1–S13. https://doi.org/10.1007/s00267-003-5181-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

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.

Zador, S., Holsman, K. K., Aydin, K. Y., & Gaichas, S. K. (2016). Ecosystem considerations in Alaska: The value of qualitative assessments. *ICES Journal of Marine Science*, *74*, 421–430.

7. Main Figures

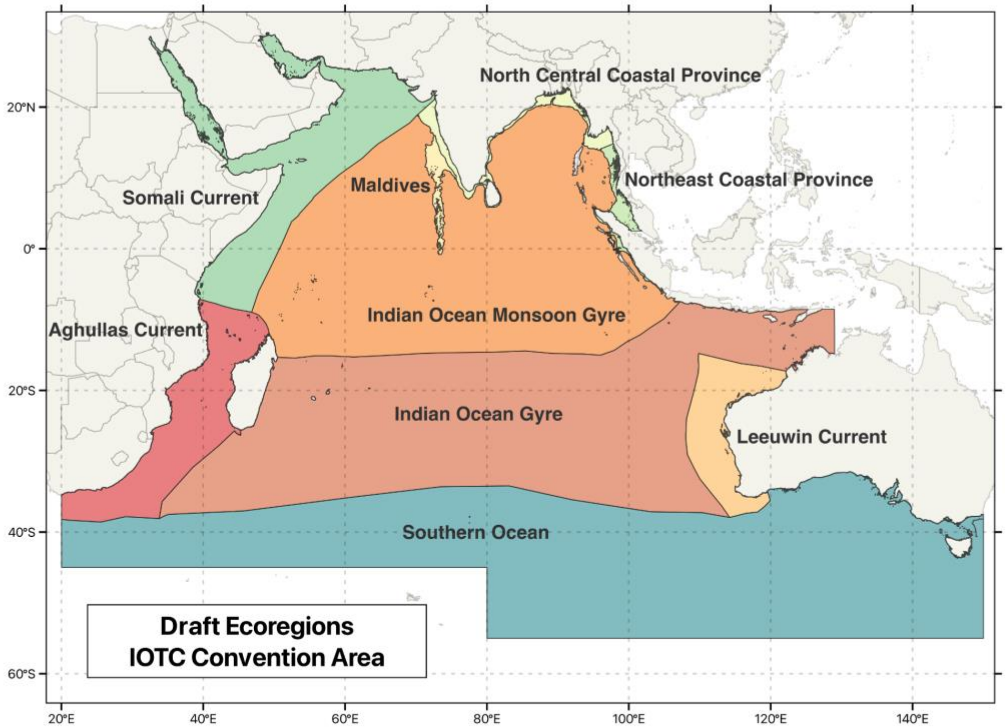


Figure 1 - Candidate ecoregions within the IOTC convention area refined during the second IOTC ecoregion workshop (Juan-Jorda et al., 2022).

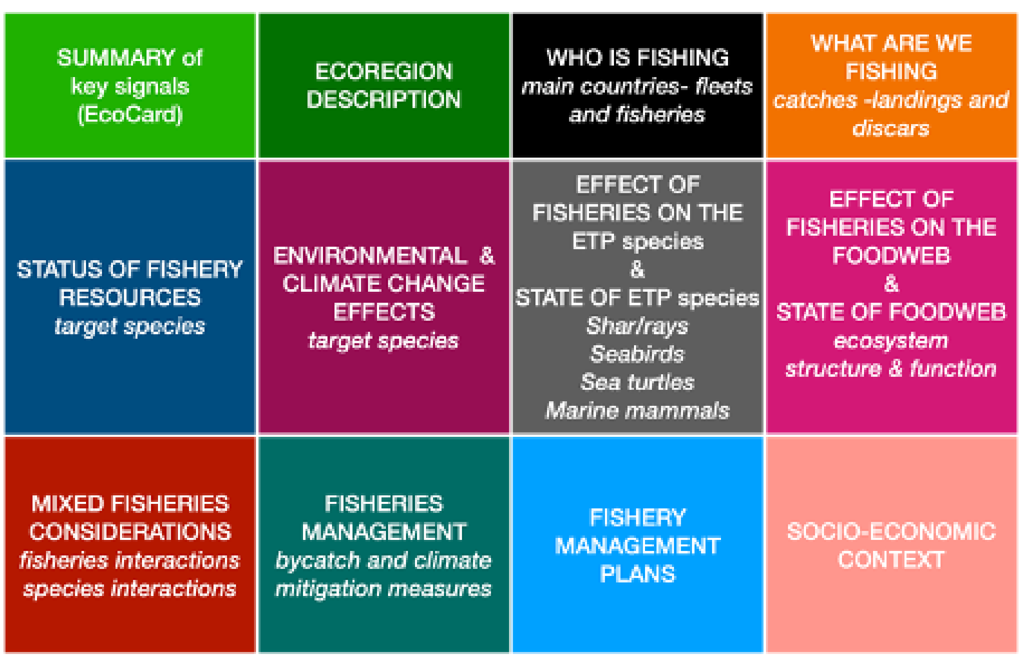


Figure 2. Potential sections that may be incorporated in an Ecosystem-Fishery Overview (EFO)

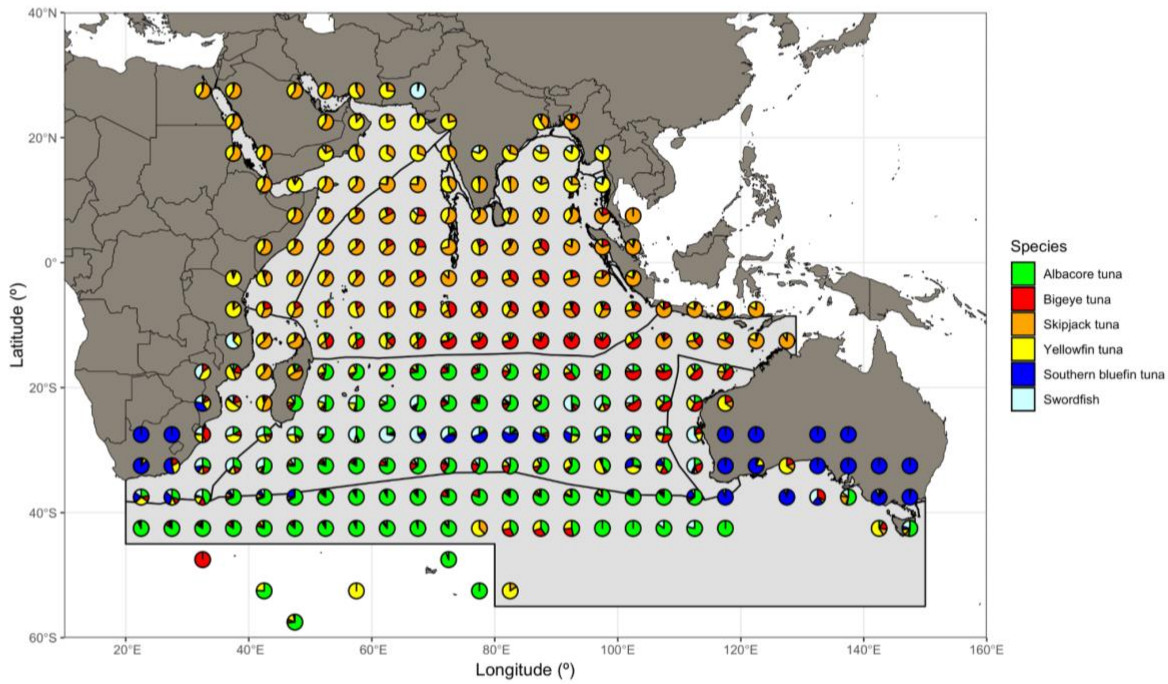


Figure 3 - Average catch composition (between 2010 - 2022) for the main IOTC species (six tuna and tuna-like species) across the 132 fleets operating in the IOTC convention area.

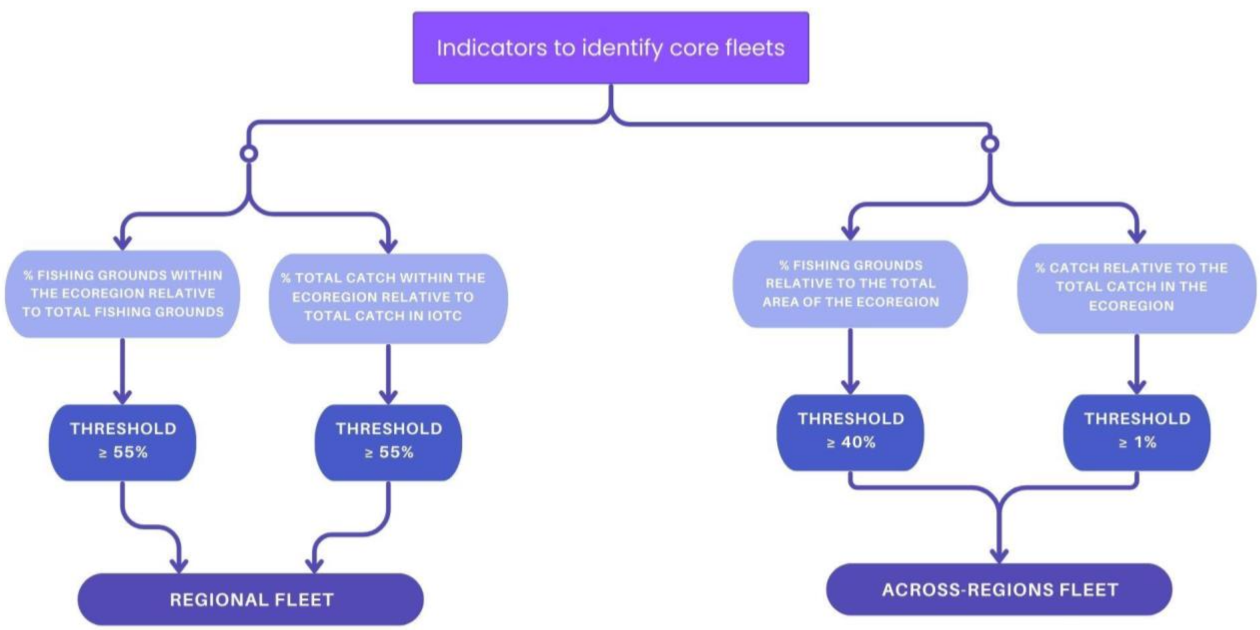


Figure 4 - Criteria and Indicators to identify core fleets within each ecoregion.

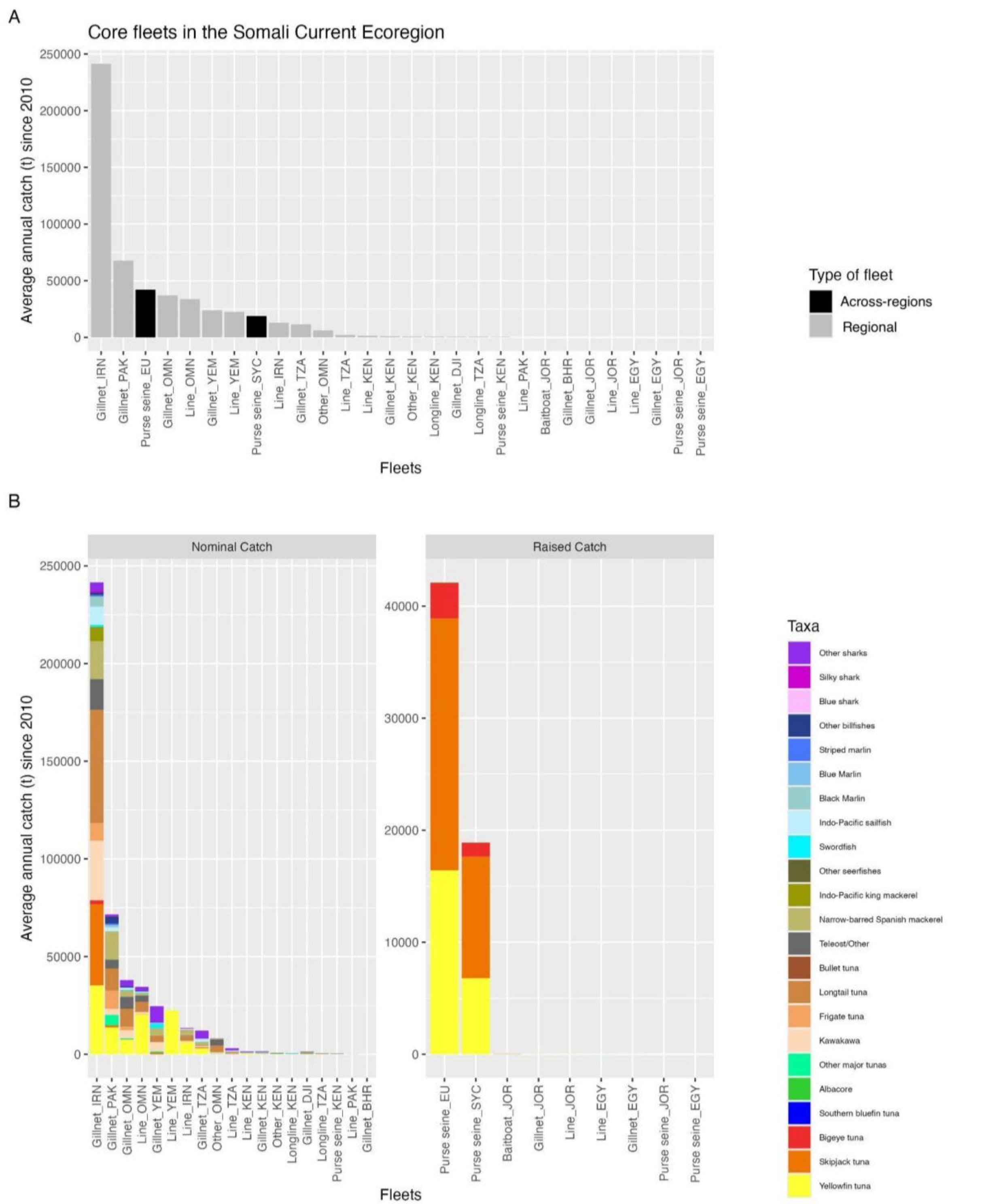
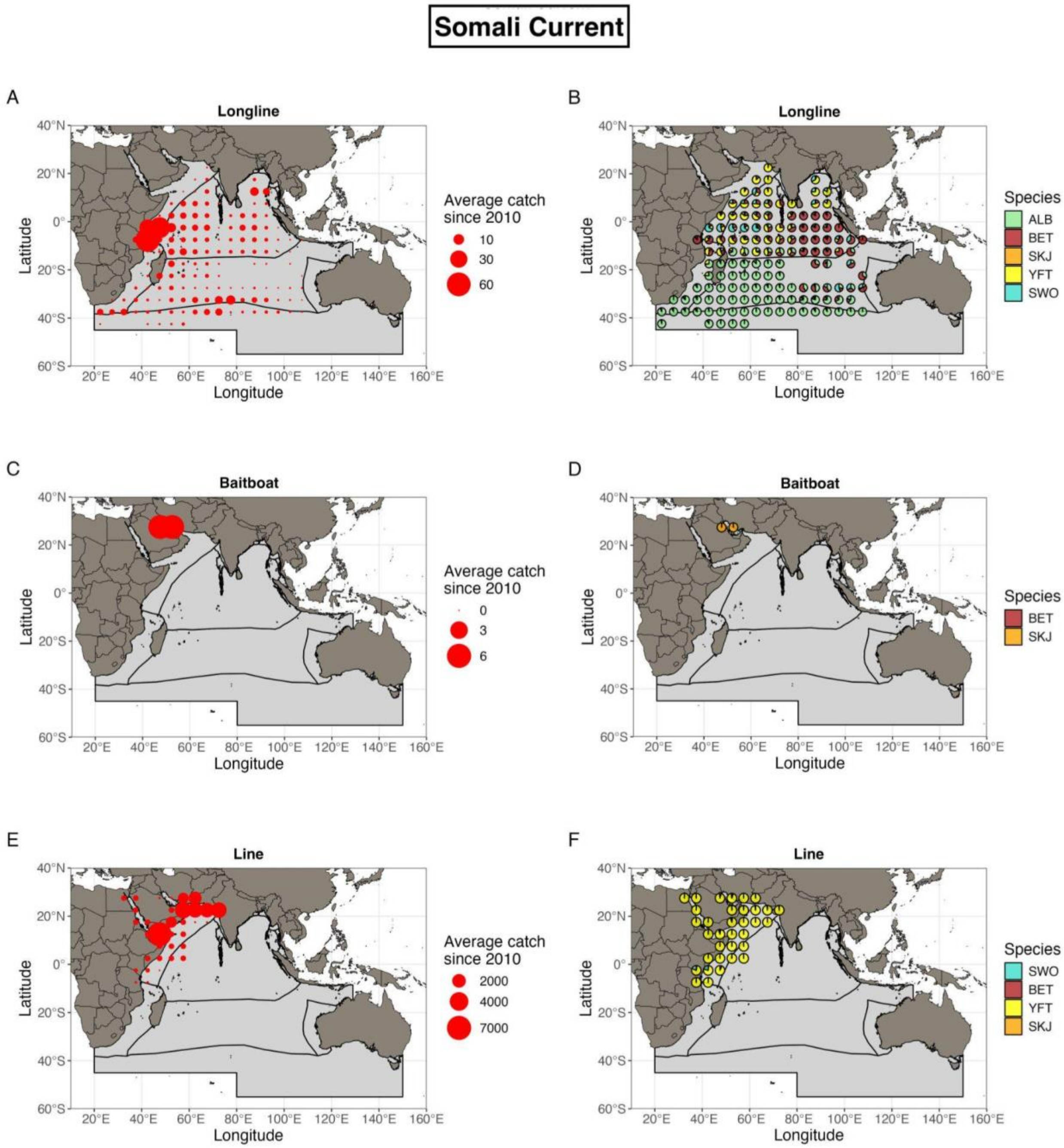


Figure 5 - Core fleets (28 fleets) identified in the SCE. (A) average annual catch (tonnes) since 2010. (B) Average annual catch composition (tonnes) since 2010. Catch data for each fleet are sourced either from the IOTC Nominal Catch dataset or the IOTC Raised Catch dataset, depending on the spatial extent of their catches and major fishing grounds of each fleet. Jordan and Egypt fleets do not appear in the IOTC nominal catch dataset and the raised catch dataset was used to characterize their catches.


Somali Current
A
Longline
Average catch since 2010
10
30
60
B
Longline
Species
ALB
BET
SKJ
YFT
SWO
C
Baitboat
Average catch since 2010
0
3
6
D
Baitboat
Species
BET
SKJ
E
Line
Average catch since 2010
2000
4000
7000
F
Line
Species
SWO
BET
YFT
SKJ
Latitude
Longitude
40°N
20°N
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120°E
140°E
160°E

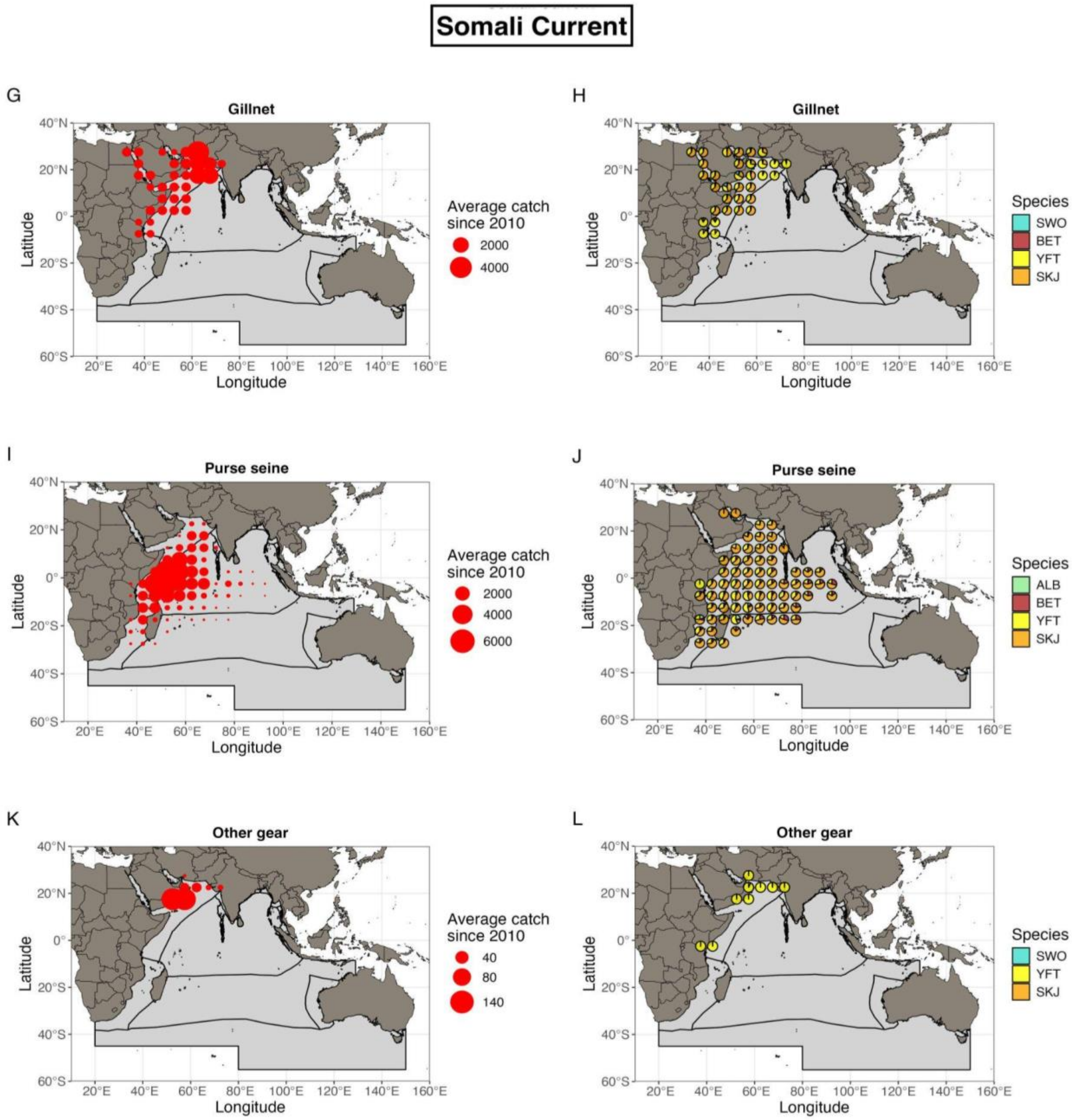


Figure 6 - Spatial distribution of catches and catch composition (average annual catch since 2010) of the 28 core fleets identified in the SCE disaggregated by major gear groups. List of core fleets within each gear group shown in SM Table 1.

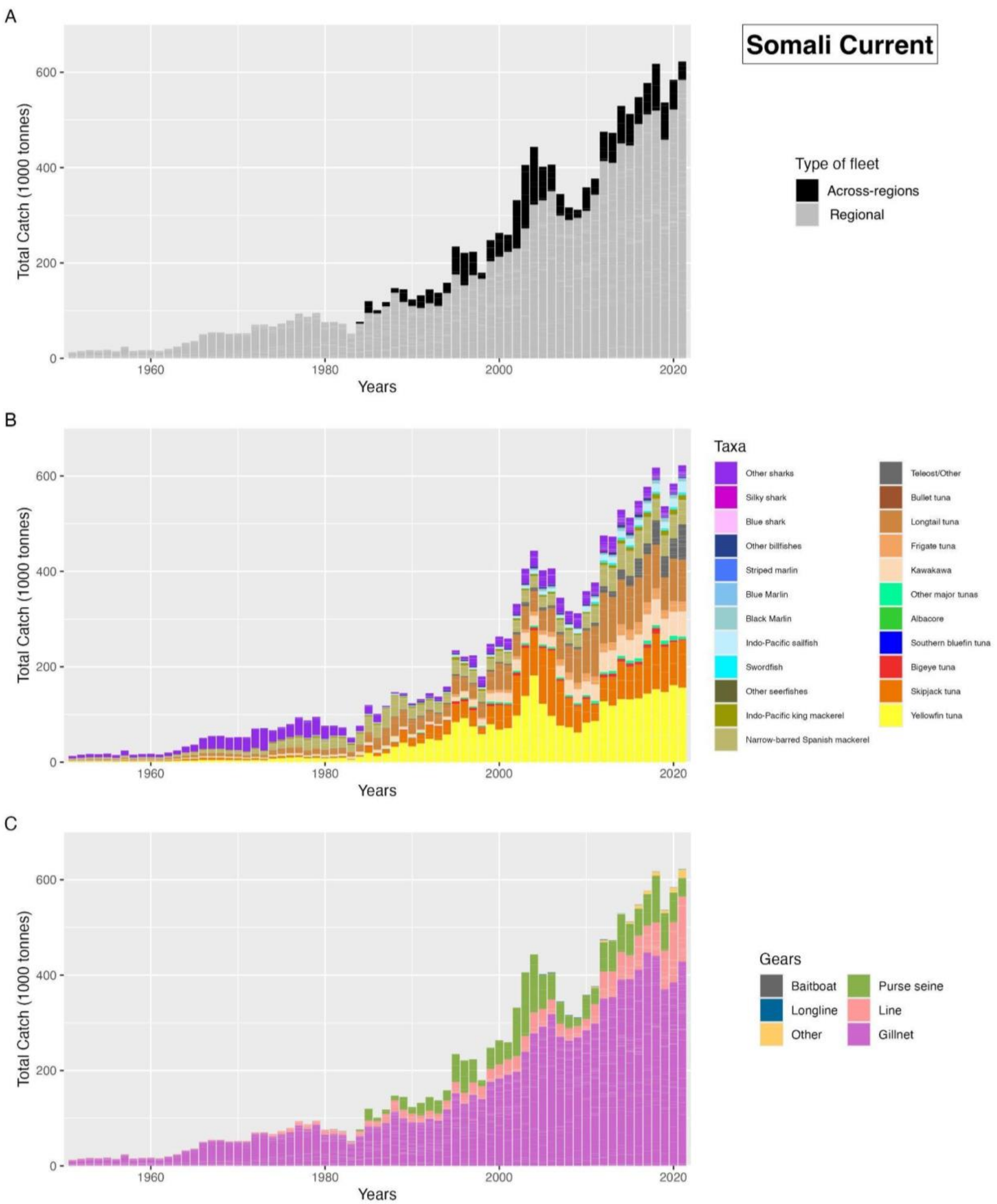


Figure 7 - Total catches of the 28 core fleets in the SCE between 1950 and 2022 disaggregated by (A) source of data, (B) major taxa, and (C) major gears.

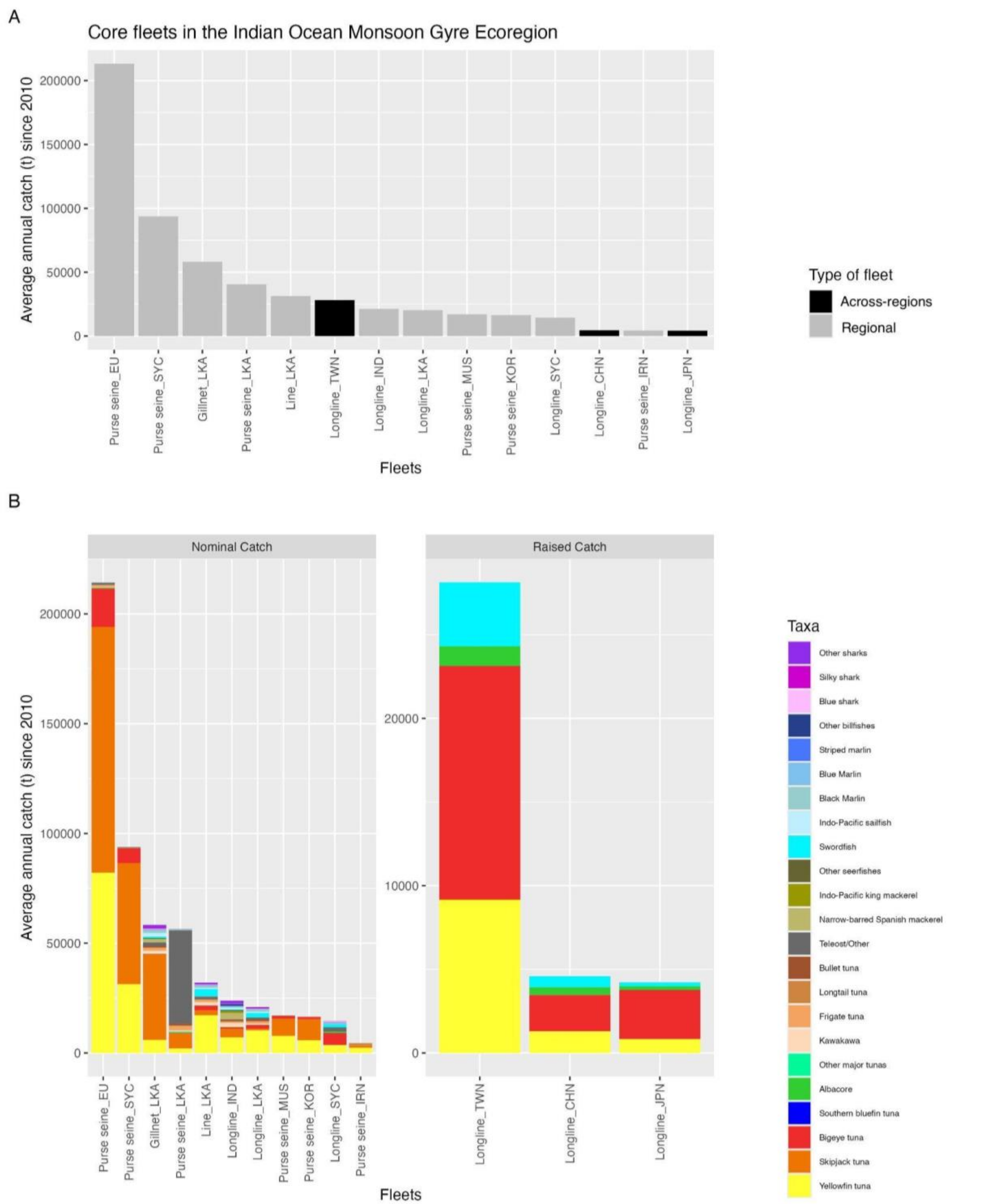
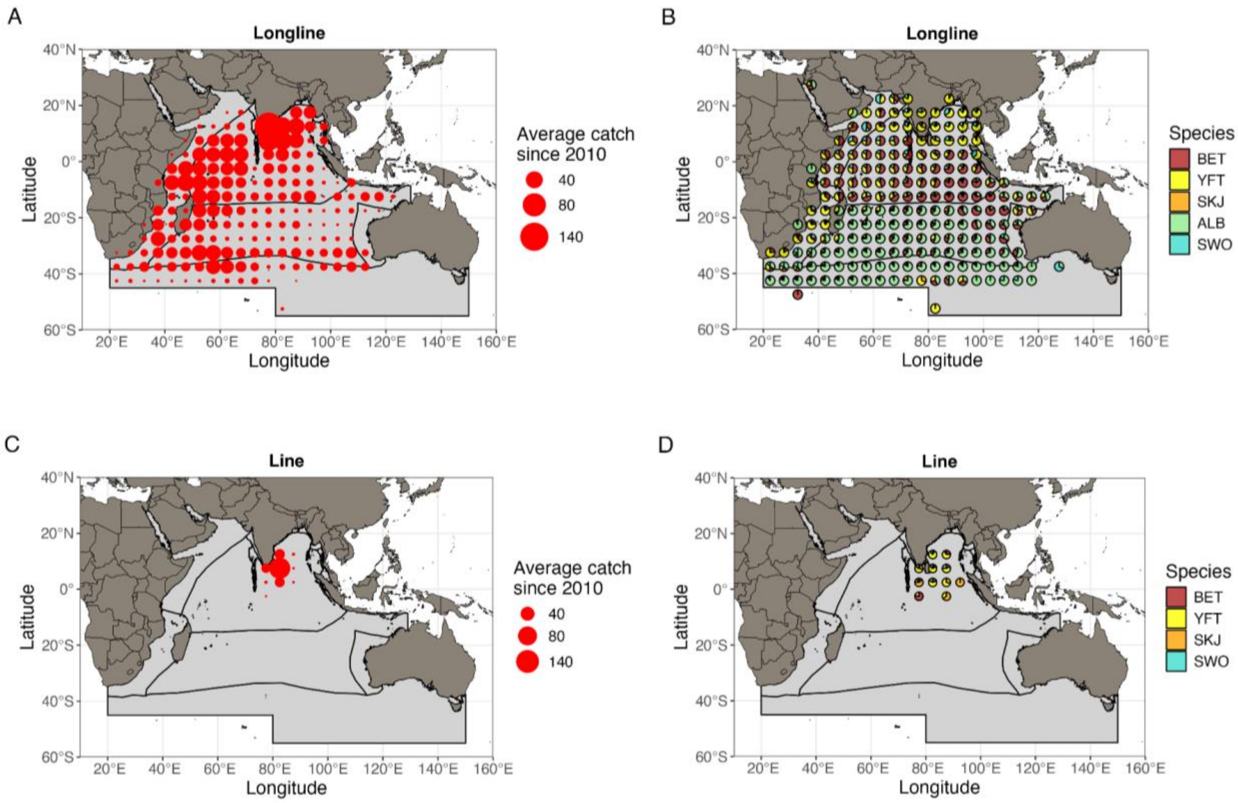


Figure 8 - Core fleets (14 fleets) identified in the IOMGE. (A) average annual catch (tonnes) since 2010. (B) Average annual catch composition (tonnes) since 2010. Catch data for each fleet are sourced either from the IOTC Nominal Catch dataset or the IOTC Raised Catch dataset, depending on the spatial extent of their catches and major fishing grounds of each fleet.

Indian Ocean Monsoon Gyre



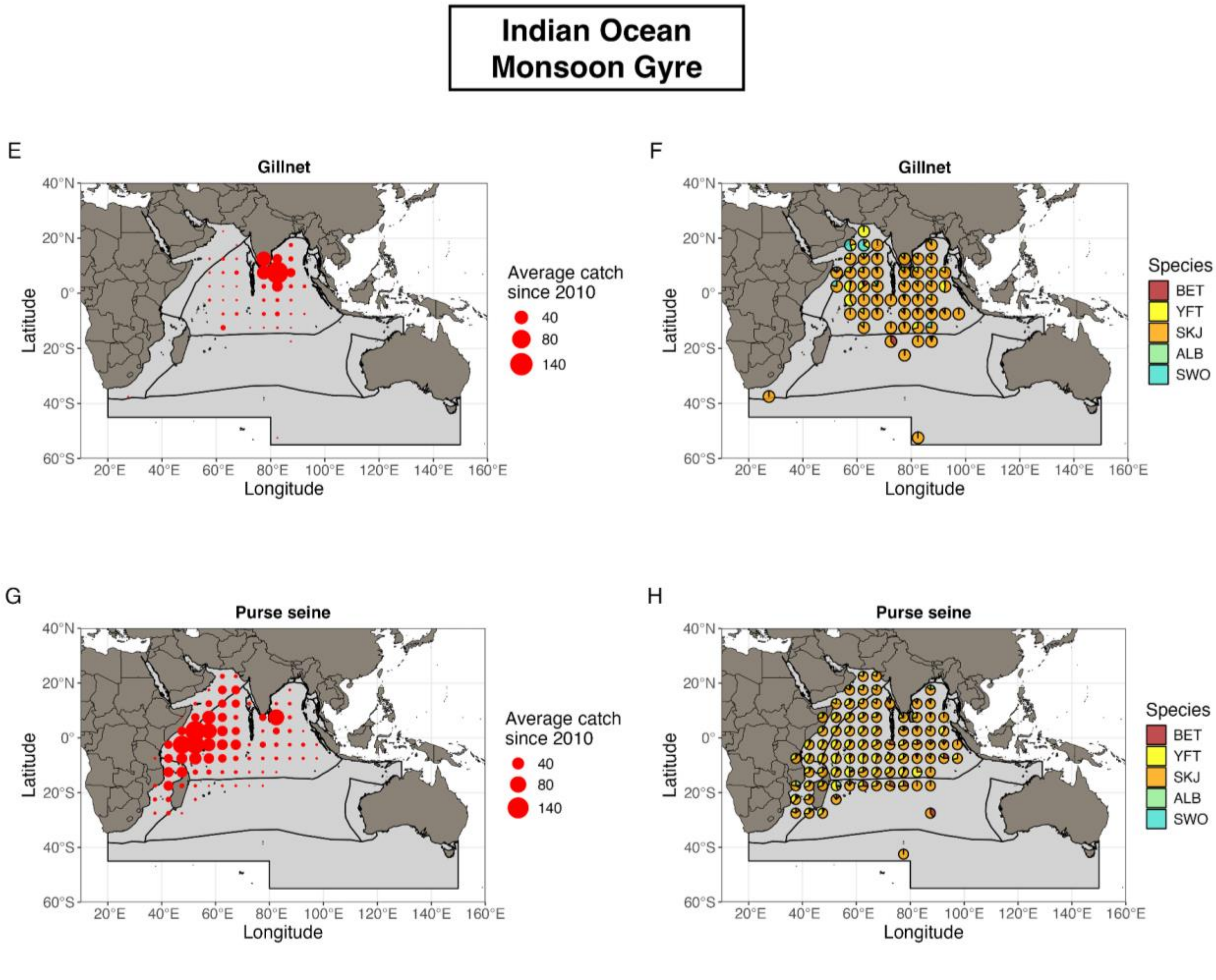


Figure 9 - Spatial distribution of catches and catch composition (average annual catch since 2010) of the 14 core fleets identified in the IOMGE disaggregated by major gear groups. List of core fleets within each gear group shown in SM Table 2.

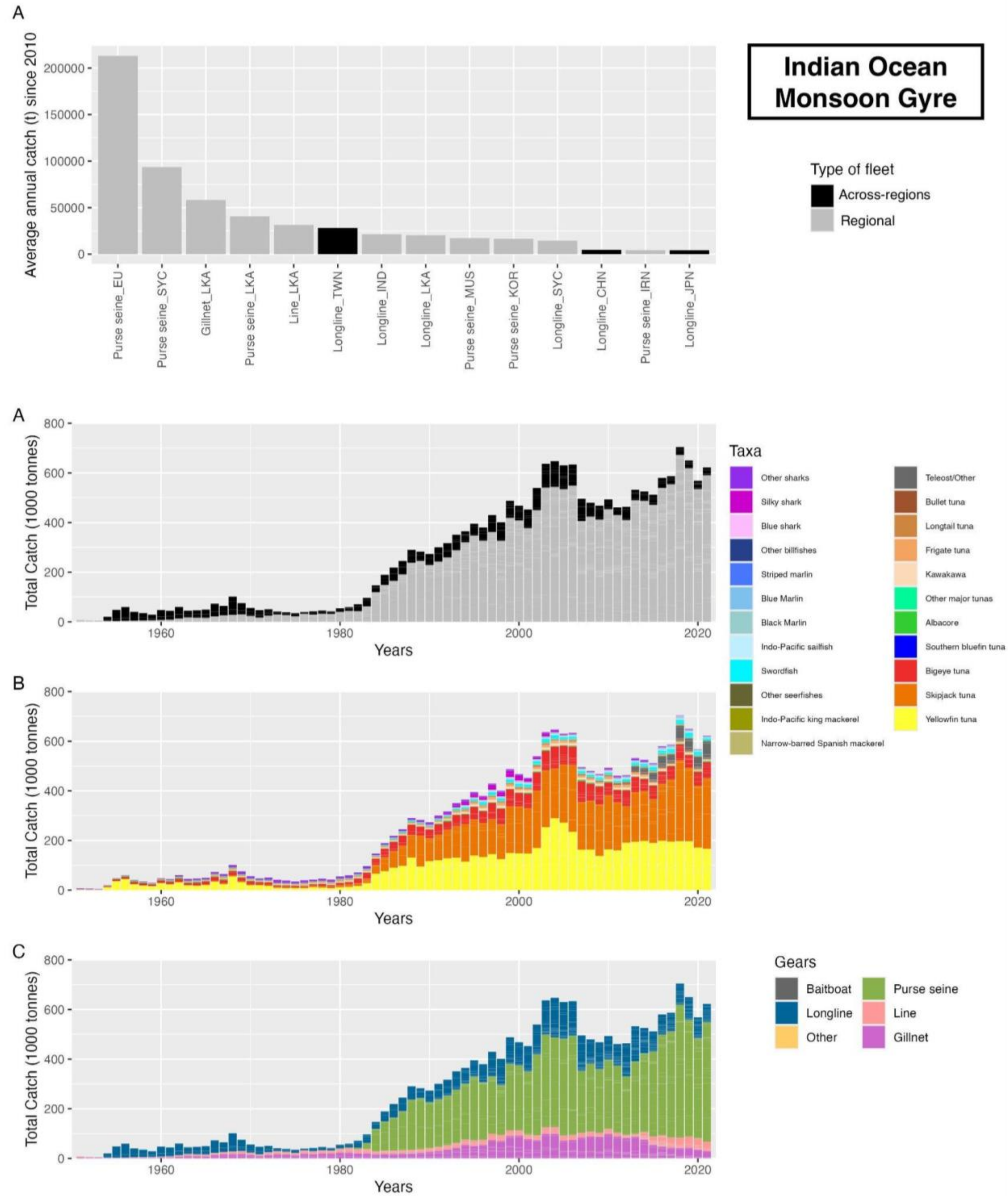


Figure 10 - Total catches of the 14 core fleets in the IOMGE between 1950 and 2021 disaggregated by (A) source of data, (B) major taxa, and (C) major gears.

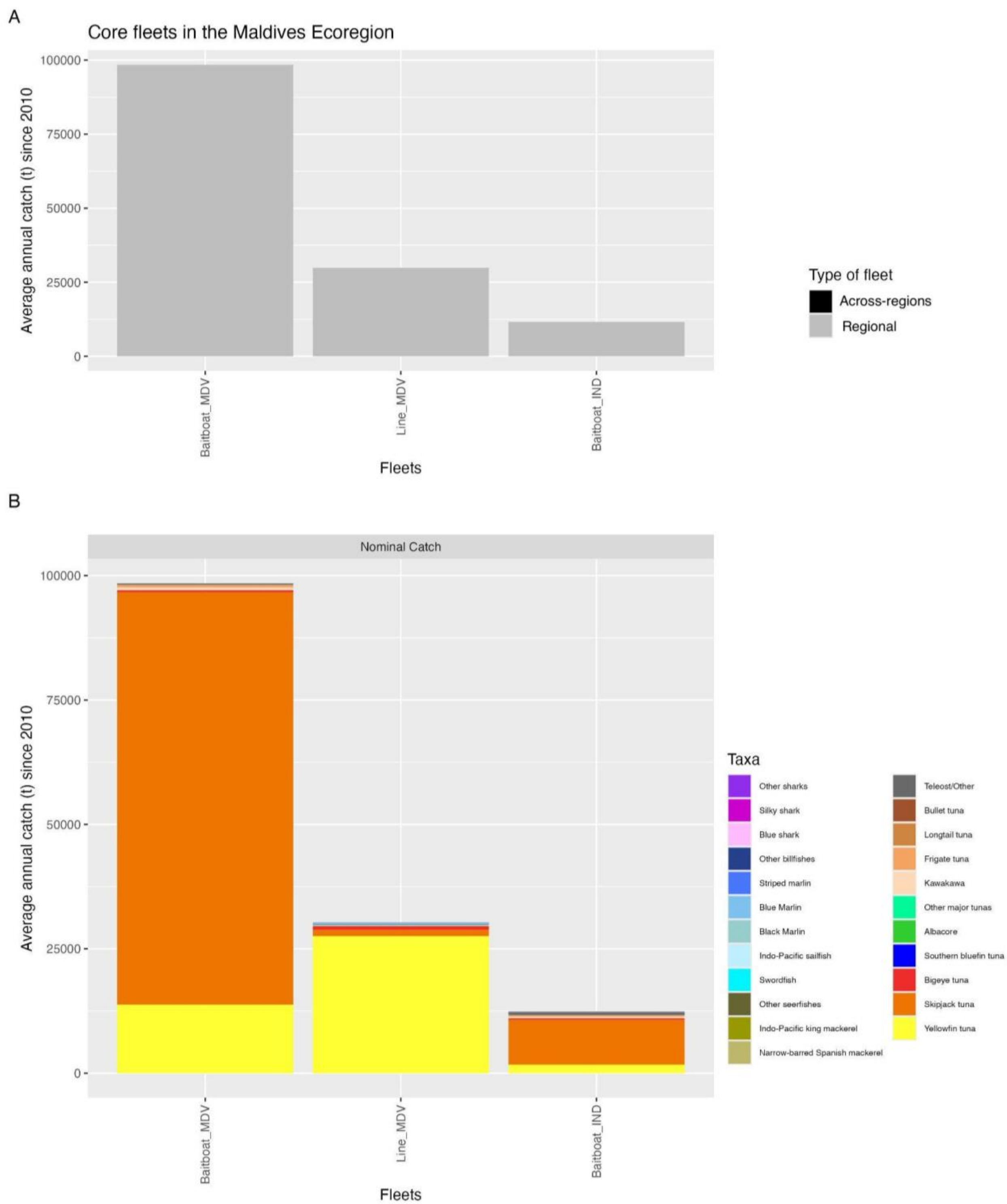


Figure 11 - Core fleets (3 fleets) identified in the ME. (A) average annual catch (tonnes) since 2010. (B) Average annual catch composition (tonnes) since 2010. Catch data for each fleet are sourced either from IOTC Nominal Catch dataset or IOTC Raised Catch dataset, depending on the spatial extent of their catches and major fishing grounds of each fleet.

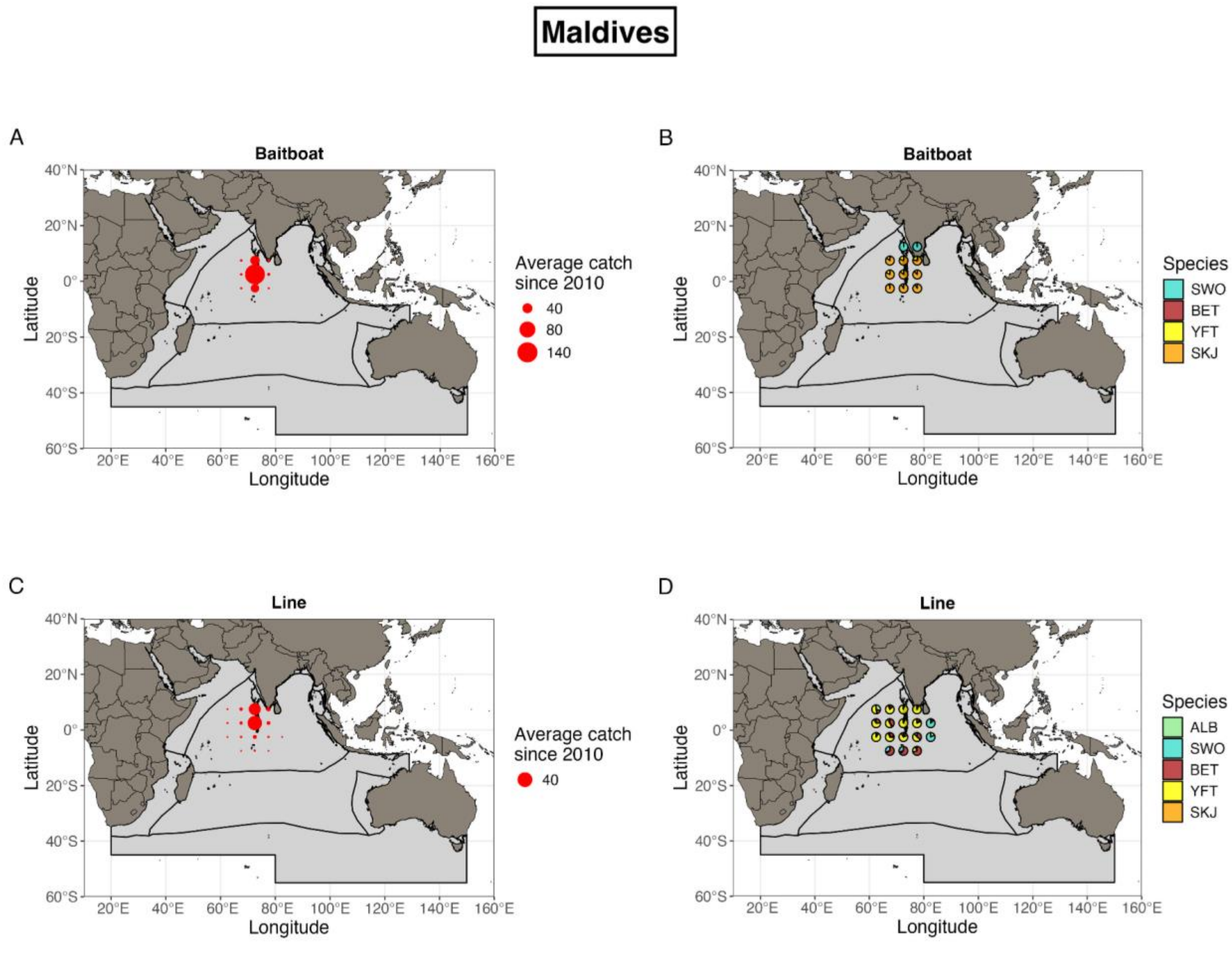


Figure 12 - Spatial distribution of catches and catch composition (average annual catch since 2010) of the 3 core fleets identified in the ME disaggregated by major gear groups. The list of core fleets within each gear group is shown in SM Table 3.

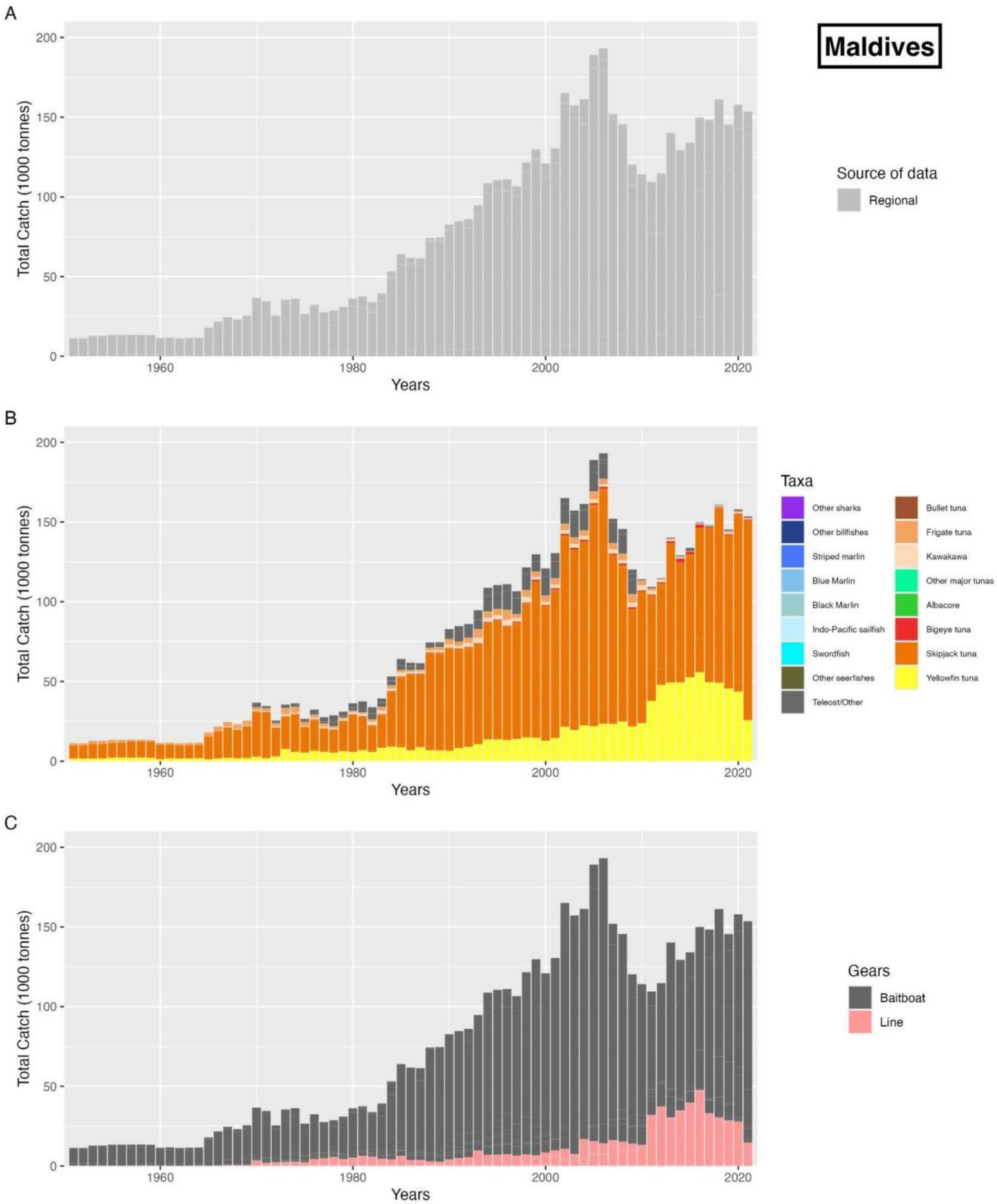


Figure 13 - Total catches of the 3 core fleets in the ME between 1950 and 2021 disaggregated by (A) source of data, (B) major taxa and (C) major gears

8. Main Tables

Table 1. IOTC candidate ecoregion (full names and acronyms).

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 2. IOTC major tuna and tuna-like species. *These are the five major species covered in the georeferenced Raised Catch dataset (see Table 5).

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

Table 3. Main fisheries 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**

Table 4. Core criteria establishing the main thematic factors used to guide the ecoregion delineation and the expected qualities of the ecoregion based on the chosen criteria.

Core thematic factors	**Expected qualities of the ecoregions**
The oceanography and biogeography of the water column: Rationale: Understanding the major oceanographic and biogeographic aspects of the water column offers valuable insights into the spatial distribution of marine species and ecological processes. Integrating knowledge of both the physical and biological aspects of the water column, particularly those related to lower trophic levels, into an ecological delineation helps identify ecologically meaningful units based on shared oceanographic characteristics.	•The boundaries of proposed ecoregions appropriately delineate areas with clear oceanographic and biogeographic justifications and are characterized by distinct oceanographic and biogeographic features. •Ecoregions characterized by similar oceanographic and biogeographic features are likely to exhibit comparable ecological communities and ecosystem processes, making them suitable units for informing EAFM implementation. •It should be feasible to establish connections between ecosystem planning and ecosystem research, as well as the development of ecosystem assessments and advice products to support the delivery of integrated fisheries management advice.
The core distribution of main IOTC targeted species: Rationale: Understanding the distribution of the main IOTC species (main targeted species) and species communities they form is crucial for characterizing the composition and structure of ecosystems within ecoregions. By identifying and characterizing species communities, insights into the ecological context of each ecoregion can be gained, including species interactions, trophic relationships, and ecosystem dynamics.	•The proposed ecoregions demarcate areas with a distinct community of tuna and tuna-like species (targeted IOTC species), thus, an ecoregion is likely to exhibit relatively homogenous ecological communities and ecosystem processes. •Incorporating information on species communities into ecoregion delineation supports integrated science and management approaches that consider the broader ecological context of fisheries management.

The spatial dynamics and core fishing grounds of main IOTC fisheries: Rationale: Identifying the primary fishing grounds of major IOTC fisheries, along with areas where a set of fisheries are targeting similar IOTC species, enables the development of region-wide products (e.g., bycatch assessments, ecosystem assessments). Additionally, fisheries activities can have cascading effects on marine ecosystems. Therefore, delineating ecoregions based on the spatial patterns of major fisheries facilitates the assessment of ecosystem-wide impacts and cumulative effects of multiple fisheries, supporting mixed fisheries and multi-species advice.	•The proposed ecoregions demarcate areas where a unique set of fisheries operate, targeting similar IOTC species, including both artisanal and commercial fisheries. •The proposed ecoregions are characterized by a distinct set of IOTC fisheries targeting similar IOTC species. •Since an ecoregion will encompass an area where multiple fisheries operate, leading to spatial overlap in fishing activities, it should allow for coordinated efforts to connect ecosystem planning and research, as well as the development of bycatch and ecosystem assessments to effectively provide integrated advice and support integrated management (e.g. mixed fisheries scenarios, cumulative impacts of fisheries).

Table 5. IOTC and CCSBT fishery statistics 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.
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.

Annex 1 - Supplement material tables

Supplementary table 1 - SCE core fleets

	Temporal filter		Indicators to identify regional fleets		Indicators to identify long-distance fleets		
Fleet name	Years with reported catch since 2010	Years with reported catch since 2016	% total catch within SCE relative to total catch in IOTC	%fishing grounds within SCE relative to total fishing grounds	% catch relative to the total catch in SCE	% fishing grounds in SCE relative to the total SCE area	Type of fleet
Baitboat_JOR	13	7	100	100	0,0094	6,25	Regional
Gillnet_BHR	11	7	100	100	0,0006	6,25	Regional
Gillnet_DJI	13	7	100	100	0,0229	3,12	Regional
Gillnet_EGY	6	5	100	100	0,001	6,25	Regional
Gillnet_IRN	13	7	91	88	32,7102	68,75	Regional
Gillnet_JOR	13	7	100	100	0,0048	6,25	Regional
Gillnet_KEN	13	7	100	100	0,1739	6,25	Regional
Gillnet_OMN	13	7	90,6	85,71	3,1965	18,75	Regional
Gillnet_PAK	13	7	100	100	7,6049	12,5	Regional
Gillnet_TZA	13	7	100	100	1,6556	12,5	Regional
Gillnet_YEM	13	7	100	100	0,9633	6,25	Regional
Line_EGY	6	5	100	100	0,0016	6,25	Regional
Line_IRN	13	7	97,4	88	2,6787	68,75	Regional
Line_JOR	13	7	100	100	0,0041	6,25	Regional
Line_KEN	13	7	100	100	0,2887	9,38	Regional
Line_OMN	13	7	79,8	83,33	7,4148	15,62	Regional
Line_PAK	3	3	100	100	0,0018	12,5	Regional
Line_TZA	13	7	100	100	0,0362	12,5	Regional
Line_YEM	13	7	100	100	10,6279	6,25	Regional
Longline_KEN	6	5	86,6	4,08	0,0985	6,25	Regional
Longline_TZA	11	5	62,4	7,19	0,105	31,25	Regional
Other_KEN	4	4	100	100	0	6,25	Regional
Other_OMN	9	5	93,5	85,71	0,0213	18,75	Regional
Purse seine_EGY	3	3		100	0	6,25	Regional
Purse seine_EU	13	7	19,6	20	19,004	40,62	Long-distance
Purse seine_JOR	7	7	100	100	0	6,25	Regional
Purse seine_KEN	4	4	100	100	0,0117	6,25	Regional
Purse seine_SYC	13	7	20,2	20,34	8,5242	37,5	Long-distance

Supplementary table 2 - IOMGE core fleets

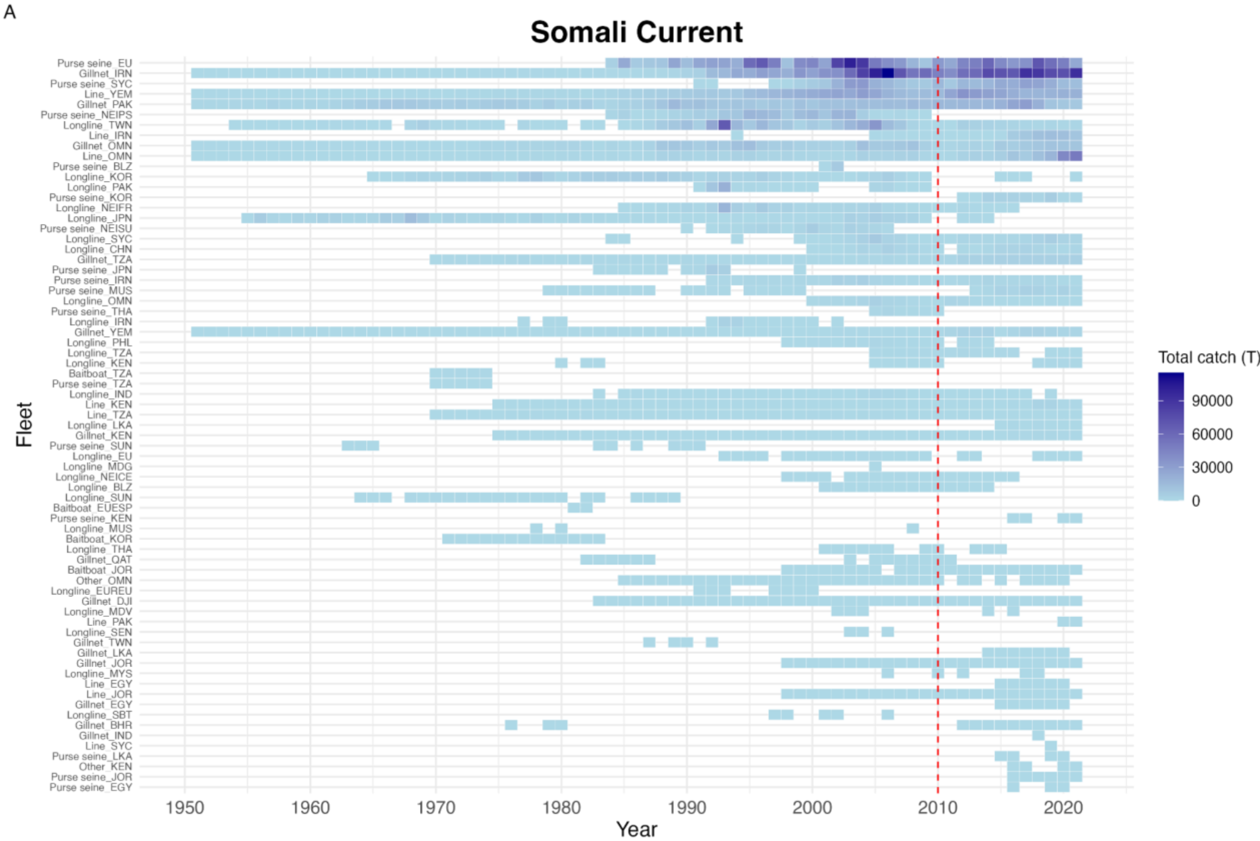
	Temporal filter		Indicators to identify regional fleets		Indicators to identify long-distance fleets		
Fleet name	Years with reported catch since 2010	Years with reported catch since 2016	% total catch within IOMGE relative to total catch in IOTC	%fishing grounds within IOMGE relative to total fishing grounds	% catch relative to the total catch in IOMGE	% fishing grounds in IOMGE relative to the total IOMGE area	Type of fleet
Gillnet_LKA	13	7	75,2	37	7,6716	66,07	Regional
Line_LKA	13	7	90,2	9	4,9907	16,07	Regional
Longline_CHN	13	7	48,5	48	1,0204	85,71	Long-distance
Longline_IND	12	6	86,3	52	0,2335	92,86	Regional
Longline_JPN	13	7	41,6	48	0,9399	85,71	Long-distance
Longline_LKA	13	7	72,2	39	2,3818	69,64	Regional
Longline_SYC	13	7	72,8	48	1,7886	85,71	Regional
Longline_TWN	13	7	52,1	54	6,2671	96,43	Long-distance
Purse seine_EU	13	7	80	38	38,3522	67,86	Regional
Purse seine_IRN	12	6	73,7	31	0,5044	55,36	Regional
Purse seine_KOR	11	7	85,3	37	2,6402	66,07	Regional
Purse seine_LKA	10	7	95,6	28	1,5432	50	Regional
Purse seine_MUS	10	7	86,8	29	2,5217	51,79	Regional
Purse seine_SYC	13	7	78,5	37	16,3397	66,07	Regional

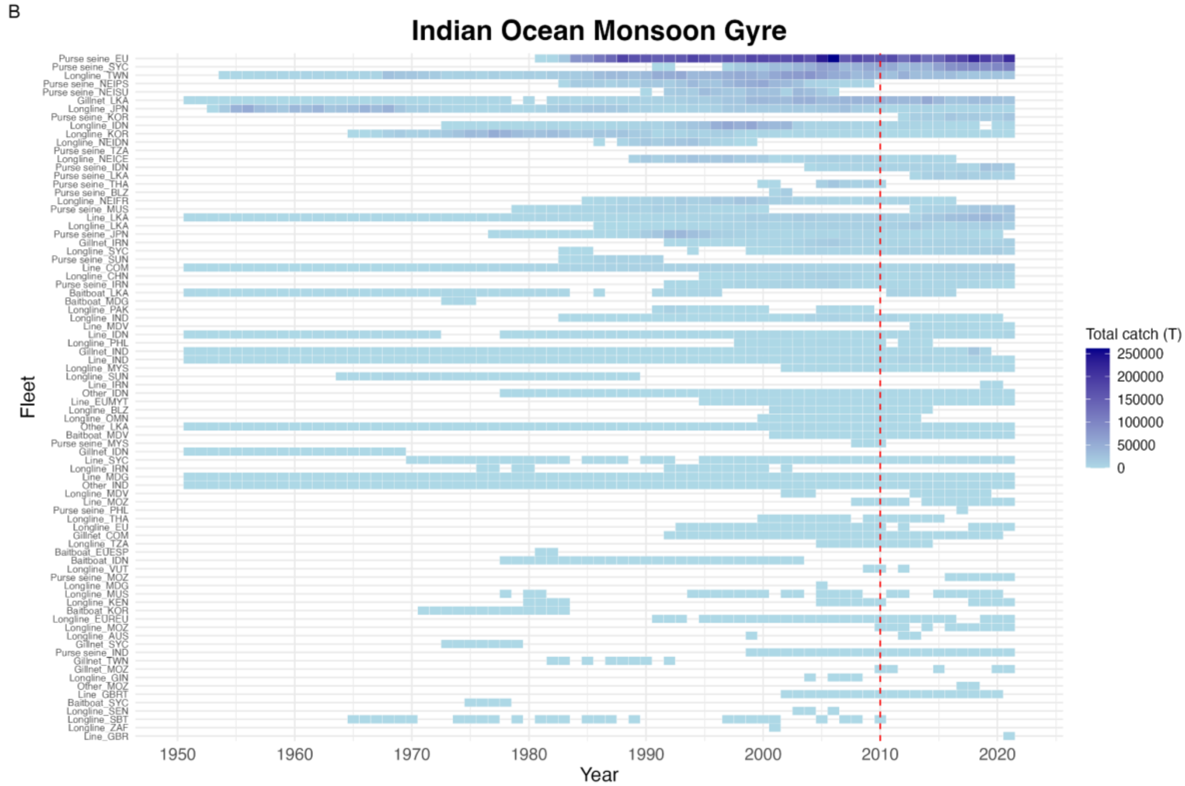
Supplementary table 3 - ME core fleets

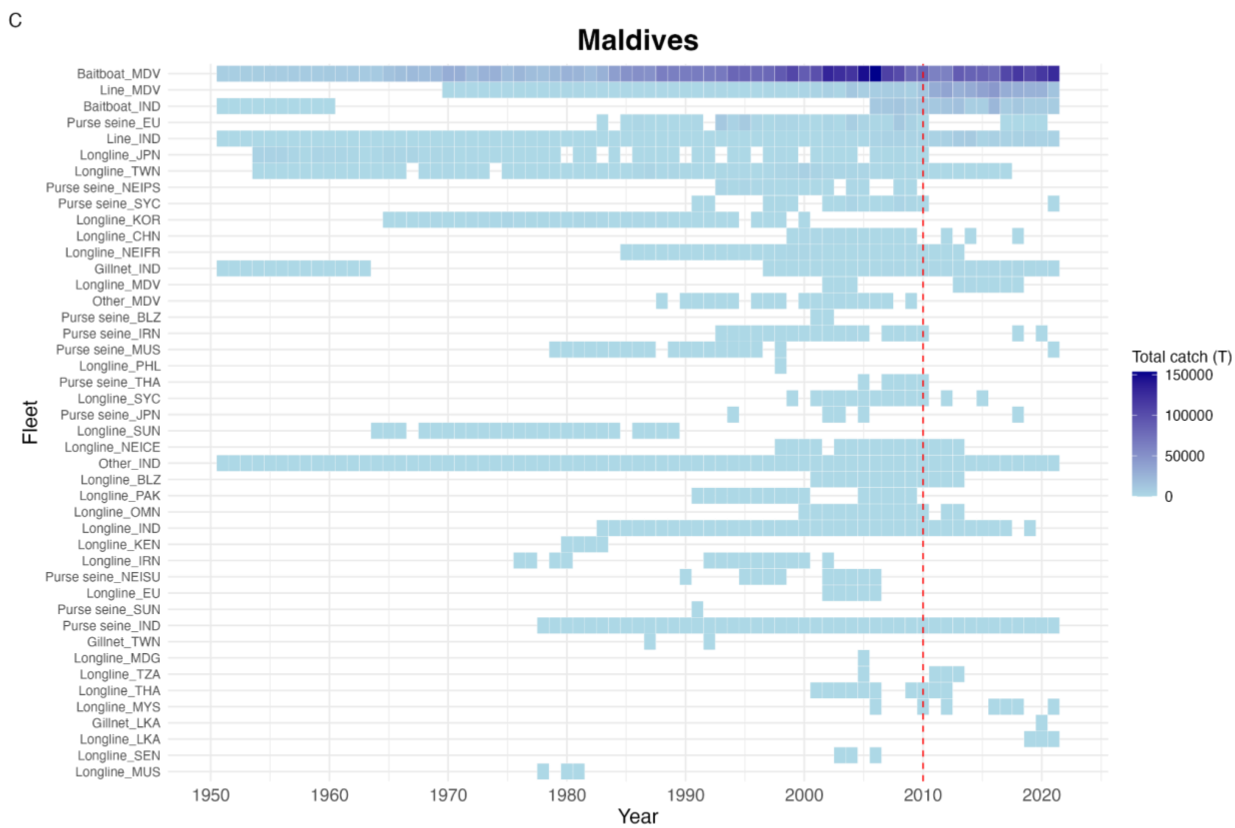
	Temporal filter		Indicators to identify regional fleets		Indicators to identify long-distance fleets		
Fleet name	Years with reported catch since 2010	Years with reported catch since 2016	% total catch within ME relative to total catch in IOTC	%fishing grounds within ME relative to total fishing grounds	% catch relative to the total catch in ME	% fishing grounds in ME relative to the total ME area	Type of fleet
Baitboat_IND	13	7	100	66,67	7,7413	50	Regional
Baitboat_MDV	13	7	99,1	33,33	68,0743	75	Regional
Line_MDV	13	7	95,3	17,65	19,8664	75	Regional

Annex 2 - Supplement material figures

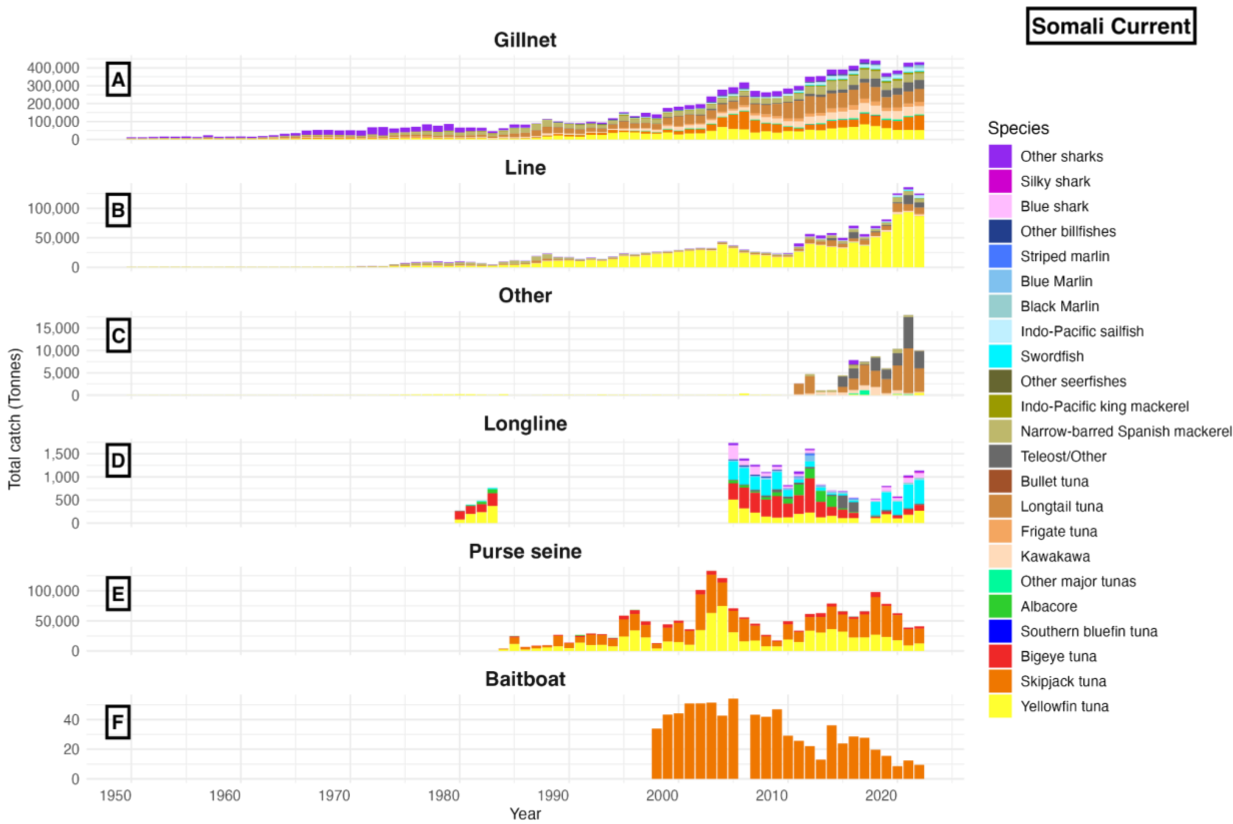
A



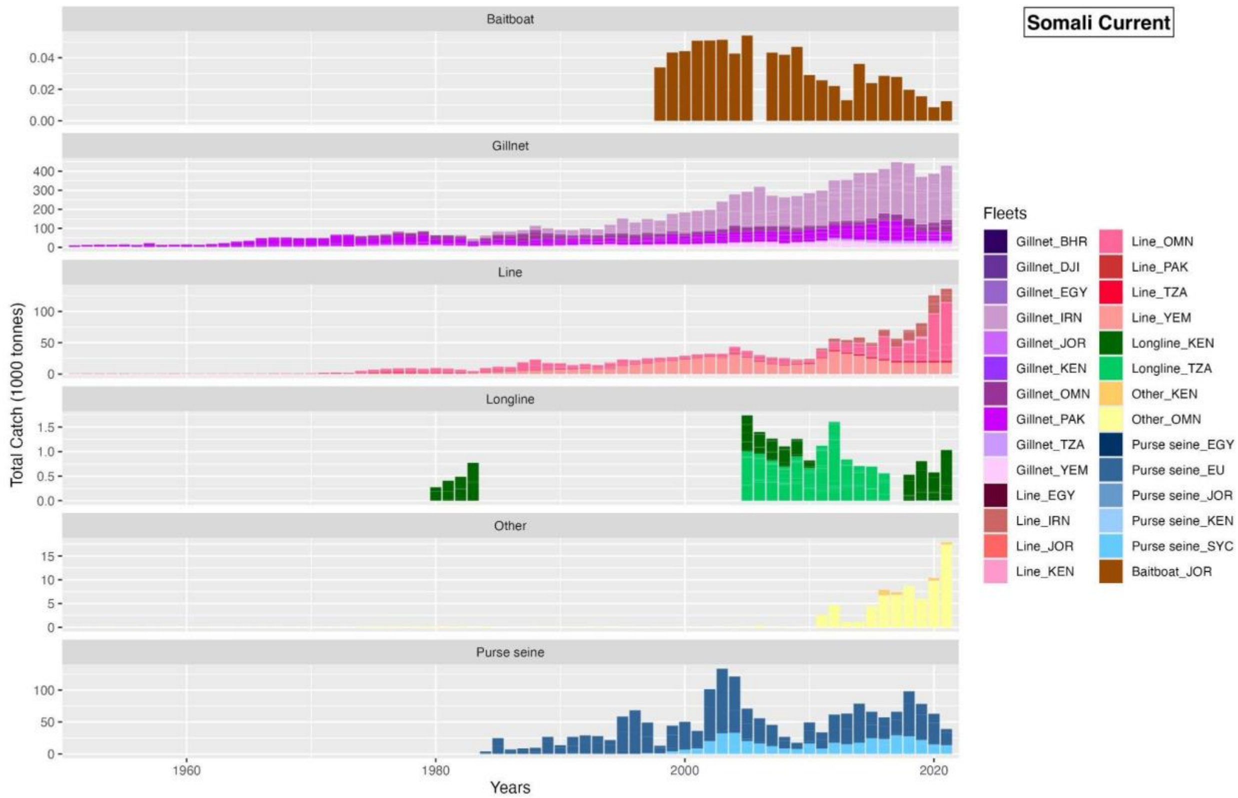




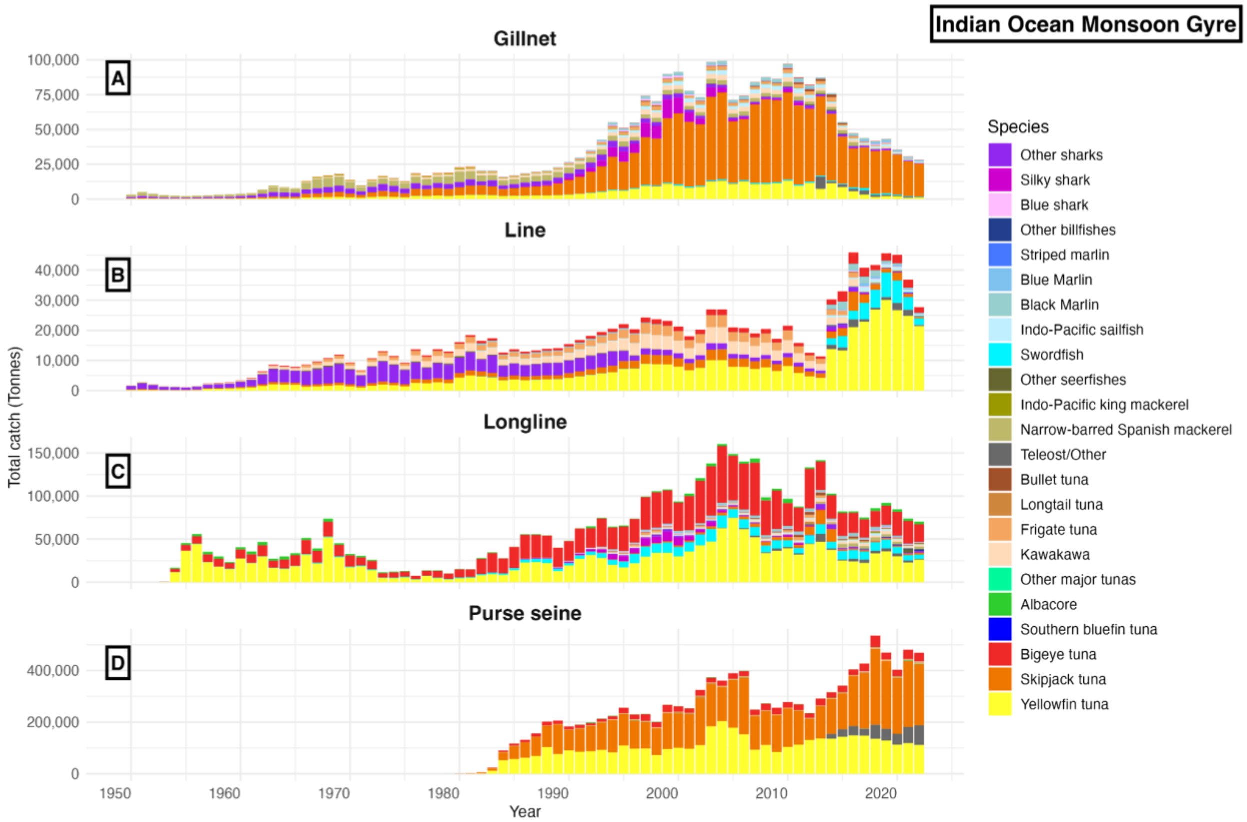
Supplementary figure 1 - Total annual catch of fleets reporting catches in each ecoregion between 1950 to 2022 (A) Somali Current Ecoregion, (B) Indian Ocean Monsoon Gyre and (C) Maldives.



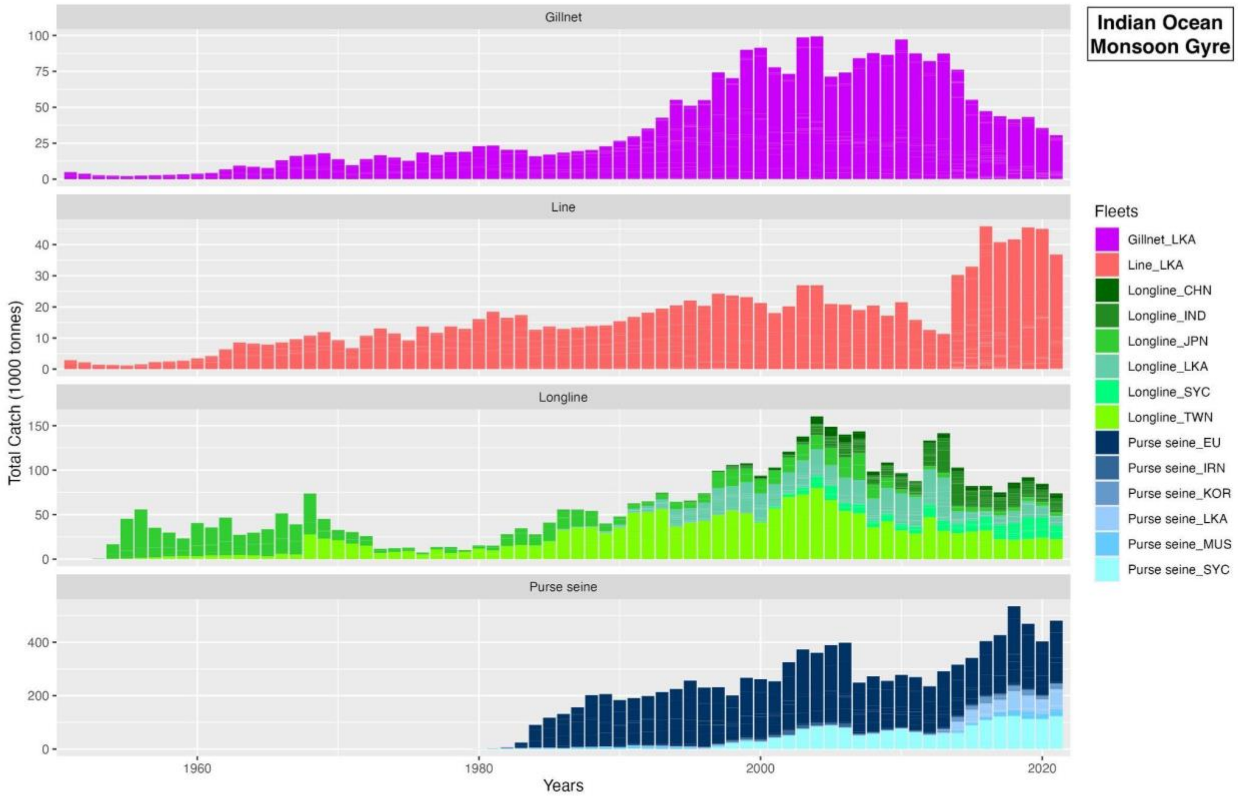
Supplementary figure 2 - Catch composition by gear type from the core fleets in the SCE



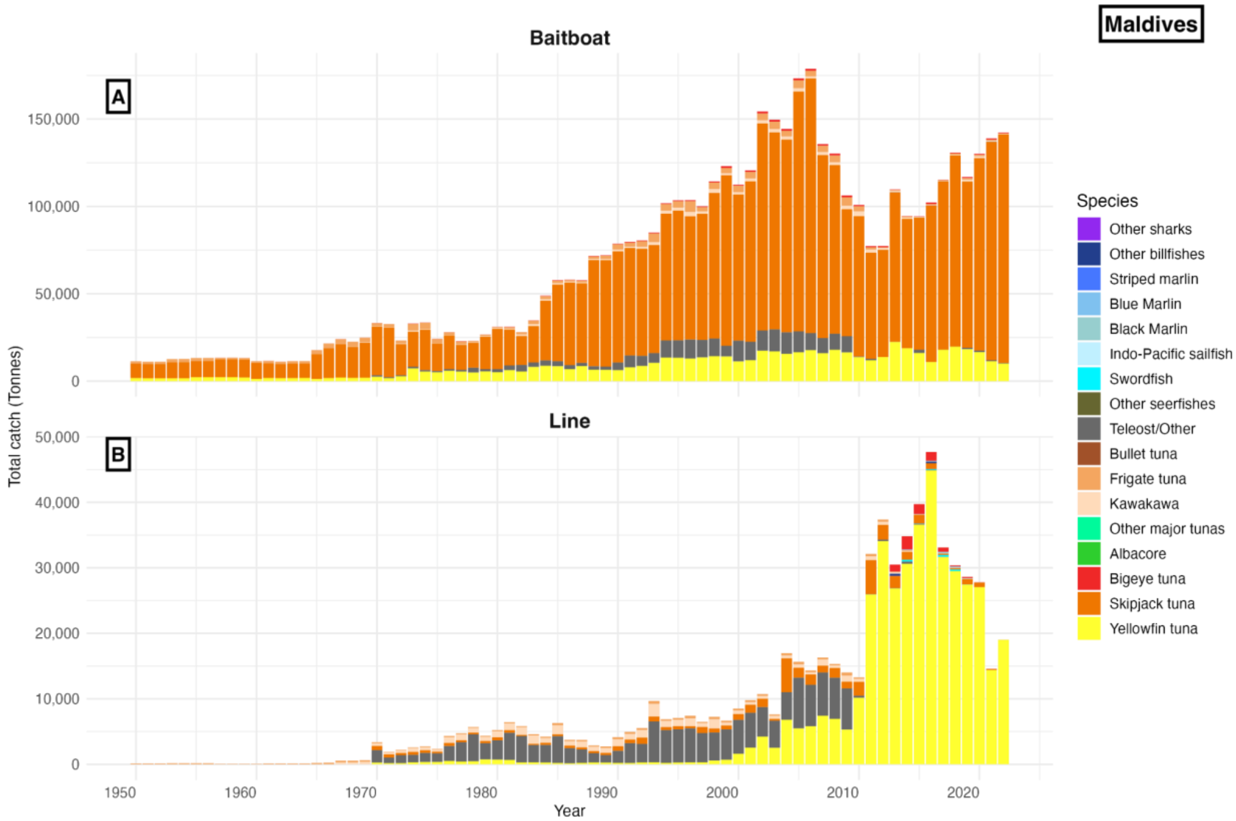
Supplementary figure 3 - Fleet composition by gear type from the core fleets in the SCE



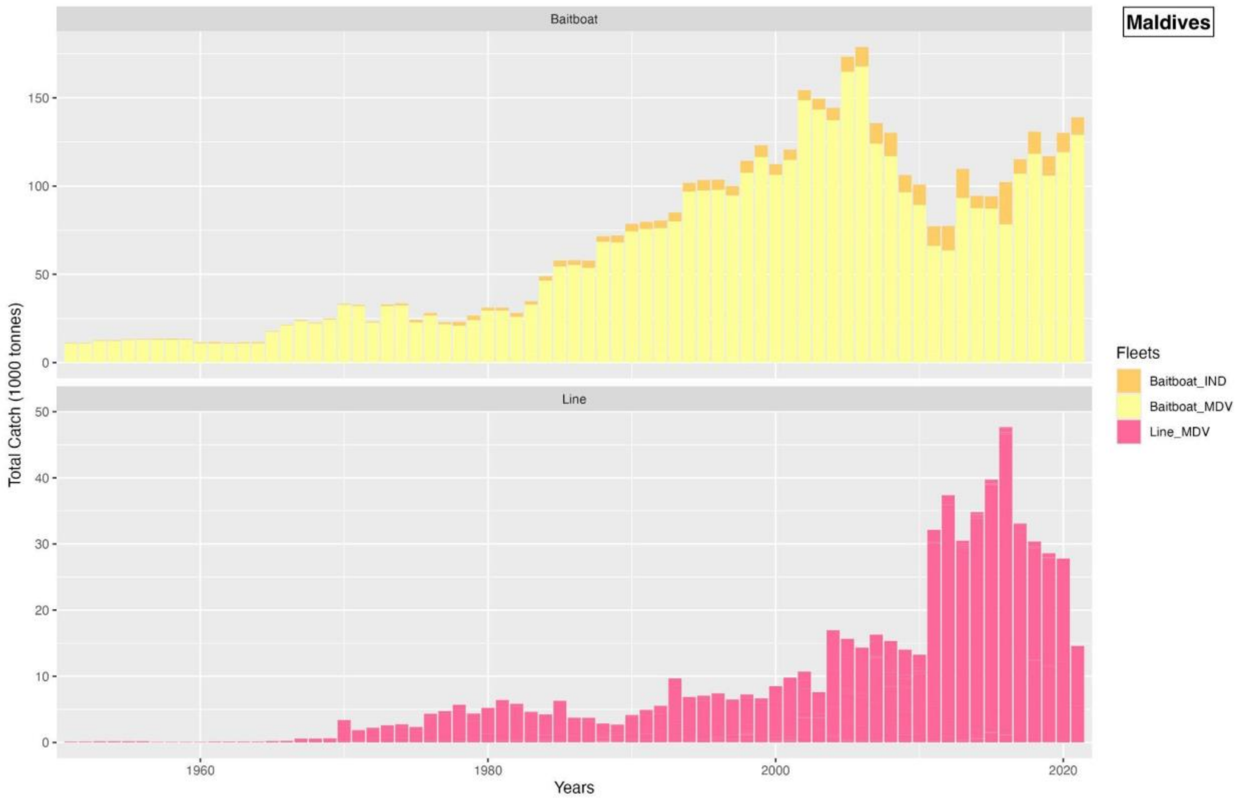
Supplementary figure 4 - Catch composition by gear type from the core fleets in the IOMGE.



Supplementary figure 5 - Fleet composition by gear type from the core fleets in the IOMGE.



Supplementary figure 6 - Catch composition by gear type from the core fleets in the ME



Supplementary figure 7 - Fleet composition by gear type from the core fleets in the ME