Draft ecoregions for the IOTC convention area in preparation for the 2019 IOTC Workshop:

"Identification of regions in the IOTC convention area to inform the implementation of the ecosystem approach to fisheries management"

La Saline, La Réunion, France, 30 August to 1 September 2019

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EXECUTIVE SUMMARY

The ecosystem approach to fisheries management (EAFM) is a spatially-explicit approach to fisheries management that incorporates ecosystem knowledge and uncertainties, considers multiple external influences and endeavors to account for diverse societal objectives. One of the fundamental requirements for the effective operationalisation of the EAFM is the identification of area-based units with ecologically-meaningful boundaries, or "ecoregions", that can be used to plan and structure ecosystem-based integrated advice to inform fisheries management. In practical terms, ecoregions can be used to produce integrated ecosystem and fisheries overviews to report on the status and trends of fisheries resources, on mixed fisheries considerations of relevance to the management of fisheries, and on the impacts of fisheries on ecosystems in terms of bycatch of endangered and threatened species. Ecoregions can also be used as a framework for research purposes, for example, to frame ecosystem models and habitat modelling, and the development of integrated ecosystem assessment. Ecoregions are not currently in use nor adopted by the IOTC or any other tuna RFMO to structure ecosystem advice and inform EAFM implementation, though recent efforts have been made.

Two candidate ecoregions within the Indian Ocean were proposed to the 14th session of the Working Party for Ecosystems and Bycatch (WPEB14) based on a preliminary study derived from a European project. The WPEB14 noted that the two candidate ecoregions did not adequately reflect the characteristics of the IOTC convention area and suggested that additional ecological and socio-political factors and expert knowledge from IOTC CPCs could be accounted for when delineating the boundaries of ecoregions. Ensuing discussion led to the recommendation that a workshop be convened in 2019 to review criteria for evaluating candidate ecoregions and propose revised candidate ecoregions in an interactive and collaborative workshop setting.

The current work has been performed in preparation for the **2019 IOTC Ecoregions workshop, "Identification of regions in the IOTC convention area to inform the implementation of the ecosystem approach to fisheries management",** to be held in La Saline, La Réunion from 30 August to 1 September 2019. This work addresses the recommendations made by the WPEB14 with the final aim to propose draft ecoregions to inform the implementation of EAFM in the IOTC Convention Area. The draft of candidate ecoregions are intended to foster discussion at the workshop and it is expected they will be further informed and refined by the expert knowledge of the participants.

The main tasks performed in this work, which lead to the proposal of candidate ecoregions, are briefly summarized:

Task1 - Lessons learned from global examples using ecoregions to inform EAFM implementation

In Section 2 we reviewed previous experiences of national and international bodies that are implementing the EAFM in their convention areas and are using spatially-explicit units (i.e. ecoregions) to guide their ecosystem planning and structure their ecosystem advice (i.e., NAFO, ICES, NPFMC in the USA, and CCAMLR). We synthesized their approaches to extract their best practices for informing ecoregion delineation, which includes defining a clear set of criteria, engaging all stakeholders early in an inclusive process, encouraging an iterative process to refine ecoregion boundaries, and the use of both quantitative and qualitative (i.e.

expert advice) methods for their delineation. Several presentations were also planned at the workshop to share further their insights and views on this topic.

Task 2 - Acknowledging existing marine pelagic biogeographic classifications
In Section 3, we reviewed existing marine pelagic biogeographic classifications relevant for the Indian Ocean and assessed their relevance for tuna and tuna-like species. The reviewed biogeographic classifications include Longhurst Biogeochemical Provinces, Large Marine Ecosystems (LMEs), Marine Ecosystems of the World (MEOW), Pelagic Provinces of the World (PPOW), Tuna Biogeographical Provinces, the GOBI/CSIRO bioregionalisation project of the Indian Ocean, and the global Dynamic Biogeochemical Provinces.

Based on the review of these existing classifications, we developed a list of expected qualities that should be accounted for when deriving the draft of candidate ecoregions. Draft ecoregions for the IOTC would ideally include coastal and oceanic pelagic waters to cover the distribution of neritic and oceanic species under IOTC mandate. The data used to inform the delineation of ecoregion boundaries would also need to be examined carefully to assess their quality, completeness, and availability. Ecoregion boundaries should be derived using a quantitative statistical method informed mainly by criteria based on ecological processes (e.g. species distributions), and then further refined by expert opinion following socio-political criteria. The spatial scale at which ecoregions are made can also have an important impact on their potential uses, therefore the ideal versus practical number of ecoregions, and whether they should have hierarchical subdivisions, should also be examined. The ecoregion boundaries should be static and relatively few in number to make them practical for informing EAFM implementation.

Task 3 - A revised criteria for evaluating the expected qualities of ecoregions
In Section 4, we proposed a revised evaluation criteria, which is important to define prior to start the process of ecoregion delineation. The criteria allows setting the core principles to define the ecoregions and the expected qualities of ecoregions that would be appropriate to inform EAFM implementation. The proposed revised criteria are based on the ICES ecoregion criteria that guided the regionalization of European waters, adapted to the context of the IOTC species and its fisheries. The revised criteria covered both ecological and socio-political processes following the recommendations of the WPEB14. A core set of criteria was developed based on ecological processes which included the following core principles: oceanography, the spatial distribution of main IOTC species and the spatial distribution of main IOTC fisheries. A secondary set of criteria covering some social and political factors was also developed to be used as additional considerations when defining the ecoregions. These included compatibility with other regional initiatives, socio-economic factors, geopolitical factors and management factors. For each subcriterion, we outlined the expected qualities of ecoregions that would be appropriate for the implementation of the EAFM in the IOTC. The evaluation criteria were then used to guide the data selection and spatial analysis for deriving a proposal of draft ecoregions for IOTC.

***Task 4 - An overview of potential ecological data layers* with potential to inform the delineation of draft ecoregions**
In Section 5, we reviewed the available data layers covering the ecological processes described in the revised criteria that could be used to derive the draft ecoregions. Data were sourced mainly in consultation with the IOTC Secretariat and we also searched published

literature and global online databases. The data layers were evaluated based on their quality, completeness, and availability as to whether they could be included in subsequent spatial analyses. We expected missing or inadequate data layers to be further informed by expert contributions at the workshop.

First, we pre-selected those biogeographic classifications to be used in subsequent spatial analyses that were most relevant to inform candidate draft ecoregions (Section 5.1). The Longhurst, PPOW, and MEOW biogeographic classifications were selected as they include both coastal and pelagic provinces (pelagic PPOWs and coastal MEOWs complement one another), capture well the main oceanographic features of the Indian Ocean, have fixed spatial boundaries and a hierarchical classification structure.

Second, we examined the distribution and co-occurrence in space of the main IOTC species, including tunas, billfish, and neritic species using the spatial distributions of their catch to infer species distributions (Section 5.2). We also examined the distribution of shark species caught by IOTC fisheries, and investigated possible data sources for turtles, seabirds and marine mammals. Among all the datasets examined, the estimated raised catch data for the five main oceanic IOTC species (i.e. albacore, *Thunnus alalunga*, ALB; yellowfin tuna, *Thunnus albacares,* YFT; bigeye tuna, *Thunnus obesus*, BET; skipjack tuna, *Katsuwonus pelamis*, SKJ; and swordfish, *Xiphias gladius*, SWO) were only considered to be of good quality and had a high degree of completeness, and therefore, they were used for subsequent spatial analyses. The catch data available for neritic tunas and shark species were found to be of low quality and had a low degree of completeness, and therefore were not included in subsequent spatial analysis. The IOTC regional observer data set administered by the IOTC secretariat was available, but considered of low quality and had a low degree of completeness in terms of capturing the spatial distribution and the extent of interactions of bycatch species with IOTC fisheries and was not included in subsequent spatial analysis. Online databases with information on marine turtles, sea birds, and marine mammals had biased distributions of observations or access to relevant datasets was restricted. We expect the data layers that were classified as low quality to be informed by expert advice at the workshop.

Third, we examined the spatial distribution of the different life history stages of selected species (i.e., juvenile versus adult distribution) by investigating size frequency data for the oceanic IOTC tunas, swordfish and blue shark (Section 5.3). We found the data were often biased by the different selectivity of the gears or it did not adequately reflect 'true' spatial distributions of the different size classes, e.g. catches mostly of juveniles, or catches mostly of adults. Thus, these data were not included in subsequent spatial analyses. We performed a literature search of the limited information on spawning regions of the five oceanic IOTC species, and we expect these data layers to be further informed by expert advice at the workshop.

Finally, we also examined the spatial distribution of the main IOTC fisheries, including purse seines, longlines, gillnets, and other major coastal and high seas fisheries, using estimated IOTC raised catches as a proxy to determine the main fishing grounds of each fishery (Section 5.4). These data were made available by the IOTC, were considered to have good quality and a high degree of completeness, and therefore, they were included in subsequent spatial analyses.

***Task 5 - An overview of potential socio-political data layers* to be used to inform the delineation of draft ecoregions**

In Section 6, we reviewed potential data layers covering relevant socio-political processes corresponding to the evaluation criteria that can inform discussion at the workshop of whether these processes should be used or not to inform the boundaries of ecoregions. First, we mapped the convention areas of the other regional fisheries management organisations (RFMOs) in the Indian Ocean, i.e. the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), and the Southern Indian Ocean Fisheries Agreement (SIOFA), and the regional fisheries body, the Southwest Indian Ocean Fisheries Commission (SWIOFC). We also mapped the no-take and the partial-take marine protected areas (MPAs) of the Indian Ocean and the Ecologically or Biologically Significant Areas (EBSAs) relevant to IOTC species in the Indian Ocean (i.e. not benthic or deep sea). These EBSAs have been identified by expert advice to be important for the healthy functioning of ocean ecosystems. We expect workshop discussions to assess the relevance and compatibility of these other regional initiatives when revising the draft ecoregions.

Second, we considered the recommendation by the WPEB14 that socio-economic factors may also need to be accounted for when deriving the draft ecoregions. A program to collect socio-economic data is currently underway at the IOTC; however these data were not available when conducting this study, so its potential usefulness for this work could not be evaluated.

We note that the inclusion of diverse fishing gears that represent a mix of industrial, semi-industrial, and artisanal fisheries as part of the core ecological criteria already incorporates to some extent some of the diversity of the socio-economics of the IOTC fleets.

Finally, we also investigated examples of geopolitical information, noting that the Indian Ocean comprises many different countries with complex interactions, translating to large variations in marine protection and management. We presented examples of armed conflict activities, and territorial disputes in the western Indian Ocean. While these socio-economic and political data layers were not included in subsequent spatial analysis, we expect discussions at the workshop to examine what type of socio-economic and geopolitical information should or should not be considered in these type of analysis, and how this information, if relevant, could be used to inform and refine the delineation of draft ecoregions.

Task 6 - Spatial analyses to derive a draft proposal of ecoregions for IOTC

In Section 7, we performed several spatial analyses to derive a draft proposal of ecoregions for the IOTC convention area. The spatial analyses were divided into three major steps: 1) a spatial overlapping analysis with the purpose of selecting a final biogeographic classification to base all subsequent spatial analysis, 2) a specificity and fidelity indicator analysis that measures the association of individual species and fisheries with provinces in the selected biogeographic classification, and 3) a statistical hierarchical clustering analysis to cluster biogeographic provinces according to their degree of similarity based on the species and fishery based indicators. Each of these spatial analyses were based on the ecological data layers identified to have "good" quality, and high completeness and availability in Section 5.

First, we conducted the spatial overlapping analysis to examine the degree of overlap between pre-selected biogeographic classifications (i.e., Longhurst, PPOWs, and MEOWs) and the spatial distribution of the five IOTC oceanic tuna and billfish species and the fisheries targeting them. The distribution of neritic species is implicitly represented by the inclusion the coastal biogeographic classification. We qualitatively examined the species data layers and their overlap with the pre-selected biogeographic classifications and selected a combination of PPOWs and MEOWs classifications as they best represent and cover the distribution of coastal and oceanic IOTC species and the fisheries targeting them. The combined classification was also selected because MEOWs specifically include the central and western Indian Ocean islands, unique in terms of both species and fisheries compositions, and they are not considered in other biogeographic classifications. The combined MEOW and PEOW classification scheme resolve to 24 provinces in the IOTC convention area.

Second, we used the combined MEOW and PEOW classification and calculated an indicator that characterizes the association of each species and type of fishery to each biogeographic province, following methods in Dufrene and Legendre (1998) and Reygondeau et al. (2012). This indicator is the product of two indices: specificity and fidelity, and we hereafter refer to it as the SF Indicator. Specificity is a measure of how much a species associates with a province, or a representation of its “preference” of one province over others. Fidelity is a measure of how broadly a species is found (caught) within a province. The product of specificity and fidelity gives the SF Indicator of the community and fisheries makeup of that province in terms of its species or fisheries. Each of the MEOW-PPOW provinces show different patterns in their SF Indicators, but some clear groupings can be made. A quantification of the extent of these similarities can be used to reduce the final number of provinces in the IOTC convention area to a practical number of ecoregions.

Third, we performed a hierarchical clustering algorithm on the SF Indicators for each province based on 1) their species composition, 2) fisheries composition and 3) species and fisheries composition combined. The resulting clusters were used to delineate the draft ecoregions for IOTC proposed to the workshop participants for discussion and further refinement.

Overall, we found that the first-order clustering of the provinces based on their species composition, fisheries composition, and a combination of both species and fisheries composition all gave roughly similar results indicating three major groupings: a large northern oceanic cluster of provinces with the inclusion of the western Indian Ocean islands, a large southern oceanic cluster with the inclusion of some bordering coastal provinces, and a smaller central coastal cluster including coastal areas bordering the northern Indian Ocean. The second-order clusters were more variable across the analyses performed in how the coastal areas were subdivided. In general, we find that the large northern oceanic cluster is primarily dominated by purse seine fisheries catching tropical tunas (SKJ, YFT and BET) and secondarily dominated by longline fisheries catching also tropical tunas (BET and YFT) and some SWO, the southern oceanic cluster is dominated by longline activity catching temperate ALB and SWO, and the coastal clusters represent a diverse mix of both fisheries activities and species communities.

Conclusions

The draft ecoregions will be presented at the upcoming IOTC ecoregion workshop, where expert advice will be solicited. Workshop participants will review the analyses leading to the proposed draft ecoregions and will assess the draft ecoregions against the proposed evaluation criteria to provide a final ecoregion proposal refined by expert knowledge. This final ecoregion proposal will also be delivered to the IOTC WPEB15 meeting for further input. We remind participants that the development of ecoregions is an iterative process. It is important to design an iterative and consultative process within the IOTC Scientific Committee and Commission to ensure the criteria for defining ecoregions consider both ecological and socio (political) processes relevant to the IOTC context and ensure that resultant ecoregions are fit for purpose. Ultimately, ecoregions can be used to plan and structure ecosystem-based integrated advice to inform fisheries management, solve challenges that are region specific and inform regionalized fisheries conservation and management measures.

1 Introduction

Several binding and non-binding international instruments encourage the implementation of the ecosystem approach to fisheries management (EAFM), including the 1995 Fish Stocks Agreement, 1995 Code of Conduct for Responsible Fisheries of the Food and Agriculture Organization (FAO) and the 2001 Reykjavik declaration on Responsible Fisheries in the Marine Ecosystem. Regional fisheries management organisations (RFMOs; of which the Indian Ocean Tuna Commission (IOTC) is one) are advised to implement an EAFM to account for the impacts of fisheries on marine ecosystems and the effects of marine ecosystems on fisheries (FAO 2002, FAO 2003). The EAFM has many definitions, but in general, it is a spatially-explicit approach to fisheries management that incorporates ecosystem knowledge and uncertainties, considers multiple external influences and endeavours to account for diverse societal objectives (NOAA 2004). It attempts to account for the connectivity between species, their habitats and the physical environment, and their connection with multiple fisheries and humans (Rice et al 2011). IOTC has the mandate to manage 16 species (Table 1), among which are three species of tropical tuna, two species of temperate tuna (though in practice *Thunnus maccoyii* is managed by the Convention for the Conservation of Southern Bluefin Tuna (CCSBT), six species of neritic tuna, and five species of billfishes. In the IOTC, single-species stock assessments are performed every two to three years to provide fisheries management advice on major IOTC species to the Commission. Management advice on bycatch species (e.g. seabirds, turtles) is also regularly provided to the Commission. Yet there is not effective implementation of an EAFM within the IOTC convention area (Figure 1).

Table 1. Species under the management of the IOTC (taken from https://iotc.org/about-iotc/competence).

FAO English name	FAO French name	Scientific name	FAO Code	Habitat type
Yellowfin tuna	Albacore	Thunnus albacares	YFT	Tropical open ocean
Skipjack	Listao; Bonite à ventre rayé	Katsuwonus pelamis	SKJ	Tropical open ocean
Bigeye tuna	Patudo; Thon obèse	Thunnus obesus	BET	Tropical open ocean
Albacore tuna	Germon	Thunnus alalunga	ALB	Temperate open ocean
Southern bluefin tuna	Thon rouge du sud	Thunnus maccoyii	SBT	Temperate open ocean
Longtail tuna	Thon mignon	Thunnus tonggol	LOT	Neritic
Kawakawa	Thonine orientale	Euthynnus affinis	KAW	Neritic
Frigate tuna	Auxide	Auxis thazard	FRI	Neritic
Bullet tuna	Bonitou	Auxis rochei	BLT	Neritic
Narrow barred Spanish Mackerel	Thazard rayé	Scomberomorus commerson	COM	Neritic
Indo-Pacific king mackerel	Thazard ponctué	Scomberomorus guttatus	GUT	Neritic
Blue Marlin	Makaire bleu	Makaira nigricans	BUM	Tropical open ocean
Black Marlin	Makaire noir	Makaira indica	BLM	Tropical open ocean
Striped Marlin	Marlin rayé	Tetrapturus audax	MLS	Tropical open ocean
Indo-Pacific Sailfish	Voilier de l'Indo-Pacifique	Istiophorus platypterus	SFA	Tropical open ocean
Swordfish	Espadon	Xiphias gladius	SWO	Open ocean

One of the fundamental requirements to an effective operationalisation of EAFM is the identification of area-based units with ecologically-meaningful boundaries, or "ecoregions" (Vierros et al 2006, Rice et al 2011, Todorovic et al *in press*). Ecoregions are useful for the implementation of the EAFM because at the scale at which they are defined, they would ideally capture the core of a functional ecosystem, and most species within an ecoregion would be expected to respond to similar environmental drivers and management actions (Waltner-Toews et al 2008). Within these ecoregions, a fisheries management body can assess and report on the status and trends of fisheries resources, on considerations of mixed fisheries relevant to the management of fisheries, and on the impacts of fisheries on ecosystems in terms of bycatch of endangered and threatened species. As such, ecoregions are being used to plan and structure ecosystem-based fisheries advice, solve challenges that are region specific and inform regionalised fisheries conservation and management measures (Rice et al 2011, ICES 2018). Furthermore, ecoregions can also be used as a framework for research purposes, for example, to inform ecosystem and habitat modelling, and the development of integrated ecosystem assessments.

Ecoregions are generally proposed based on oceanographic features and biogeographic classifications, sometimes also taking into account other political, social and economic considerations. Biogeographical classification as one of the main features informing the delineation of ecoregion boundaries, is a method that uses biological and physical characteristics of the marine environment to identify broad patterns of co-occurrence of species, habitat and ecosystem processes (Spalding et al 2007). These are then used to delineate geographically distinct units of homogenous ecological characteristics at a specified scale that are relatively distinct from adjacent areas (UNEP-WCMC 2006). There are several national and international case studies with the practical use of operational ecoregions (also referred as ecologically-meaningful area-based geographical units) to structure ecosystem advice and inform the implementation of EAFM (e.g. North Atlantic Fisheries Management Organization (NAFO), the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), International Council for the Exploration of the Sea (ICES), the North Pacific Fisheries Management Council in the USA), yet regions with ecologically-meaningful boundaries are not currently in use or adopted by the IOTC (Figure 1) or any other tuna RFMO to inform EAFM implementation.

Though highly migratory with wide spatial distributions, tuna and tuna-like species have been shown to have distinct, geographical assemblages (Reygondeau et al 2012); and thus, ecoregions with distinct assemblages of tuna and tuna-like species and associated fisheries targeting them may play an important role in structuring ecosystem advice and the identification of regional challenges to provide evidence for implementing the EAFM.

1.1 Overview of IOTC paper "IOTC-2018-WPEB14-21_Rev1" and WPEB14 discussions leading to the recommendation of convening an IOTC ecoregion workshop in 2019

Recent efforts have been made to identify candidate ecoregions for the IOTC convention area. The paper IOTC-2018-WPEB14-21_Rev1, presented at the 14th session of the Working Party for Ecosystems and Bycatch (WPEB14) in 2018, summarized the main outputs of an EU project entitled "Selecting ecosystem indicators for fisheries targeting highly migratory species" (Juan-Jordá et al 2018). This work was funded under the Framework Contract -

EASME/EMFF/2016/008 provisions of Scientific Advice for Fisheries Beyond EU Waters (hereafter "the EU project"). This EU project included partnerships between AZTI, CEFAS, IEO, WMR, IPMA, IRD, and MRAG and addressed several scientific challenges hampering EAFM implementation in ICCAT and IOTC. Among its tasks, the EU project identified and proposed two candidate ecoregions within the IOTC convention area, namely a northern tropical region and a southern temperate region divided at about 15°S (Figure 1). These ecoregions were based on spatial analysis of three main data layers, including the biogeography of the region, the spatial distribution of the main IOTC target species (i.e., albacore tuna, yellowfin tuna, bigeye tuna, skipjack tuna, and swordfish), and the spatial distribution of the industrial fisheries (purse seine and longline fisheries). The spatial distributions of the main species were examined based on georeferenced raised catches, which were provided by the IOTC at 5°x5° and were averaged over a period of 15 years (2001-2016). Fidelity and specificity indicators were calculated following Dufrêne & Legendre (1997) and Reygondeau et al. (2012), to examine the association and dominance of each species to biogeographic provinces, for which the Spalding's Pelagic Provinces of the World were used (PPOW, Spalding et al 2012). Ecoregion boundaries were assessed against selected criteria (see Section 3.1 for more details) to identify whether the boundaries were both ecologically-meaningful and managerially-practical. Final decisions on the ecoregion boundaries were based on expert opinion (Figure 1). The EU-project candidate ecoregions were noted by the authors to be preliminary and required adaptation to the needs of the IOTC community.

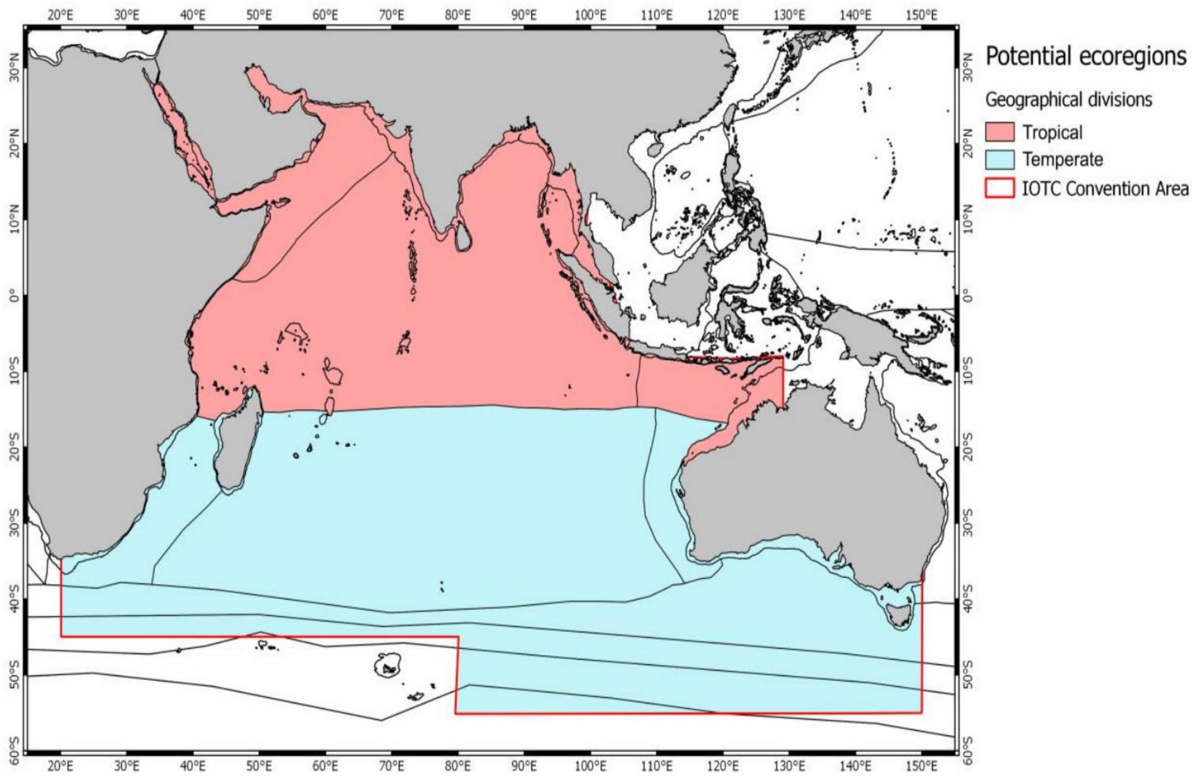

Figure 1. The IOTC convention area (red line) and the candidate ecoregions proposed by Juan-Jordá et al. 2018. Black poligon lines correspond to the Spalding's Pelagic Provinces of the World (PPOW).

Regarding the EU-project, the WPEB14 noted that the operationalisation of the ecosystem approach to fisheries is widely discussed, but its implementation is often challenging from a management point of view (IOTC 2018). They noted; however, that there is an increasing number of examples where the operationalisation of the EAFM shows progress, including e.g., the NPFMC in the USA, NAFO and CCAMLR; and they noted that lessons should be learned from the previous experiences of these international bodies. Furthermore, the WPEB14 suggested that future work also explore the designation of Ecologically or Biologically Significant Marine Areas by the Convention on Biological Diversity in terms of its utility in informing any potential IOTC ecoregions.

Furthermore, the WPEB14 also noted that the process of implementing EAFM is similar to the process of implementing Management Strategy Evaluation, and that the EAFM could follow a similar approach, e.g. outlining clear objectives and expectations. They noted that any EAFM-related activity should be implemented with the involvement and feedback from managers of Contracting Parties or Cooperating non-Contracting Parties, Entity or Fishing Entities (CPCs) at all steps of the process from development to implementation. They suggested that ecosystem experts and fisheries managers should also be consulted to help establish the criteria to evaluate ecoregions and the expected qualities of ecoregions as well as inform the delineation of any proposed ecoregions.

The WPEB14 also noted that the data needed to monitor the broader impacts of fisheries on bycatch species and ecosystem structure and function are severely limited in the IOTC convention area, potentially hindering EAFM implementation. However, they noted that the process of implementing EAFM could help identify key datasets needed and gaps to inform ecosystem indicators, thus streamlining the data collection process and identifying research priorities.

Regarding the two ecoregions propoed by the EU project, the WPEB14 noted that these two ecoregions did not adequately reflect the characteristics of the IOTC convention area, and made specific suggestions of further criteria by which to inform any future ecoregions. An intersessional working group meeting during the WPEB14 suggested that ecoregion boundaries must make ecological sense, but also need to strive to be practical for informing fisheries management. They suggested that any future proposal should include coastal fisheries in addition to the industrial fisheries analyzed in the current proposal of the EU project. Furthermore, the WPEB14 suggested that more factors could be accounted for when characterising the boundaries of ecoregions, and should include at least the biogeography of the region, species distributions and their co-occurrence, fisheries knowledge (coastal artisanal, semi-industrial, and industrial), their dynamics and their overlap, socio-economic and geopolitical factors, compatibility with other regional initiatives (e.g. SWIOFC, IUCN, RFMOs, etc.), and expert knowledge from CPCs for each of these factors.

The WPEB14 discussions led to the recommendation that a workshop be convened in 2019 to review criteria for evaluating candidate ecoregions and propose revised candidate ecoregions in an interactive and collaborative workshop setting (IOTC 2018). The WPEB15 highlighted the importance of defining clear criteria for evaluating the expected qualities of ecoregions, for informing the delineation of the ecoregions prior to the workshop, and to foster discussion on their use to support the operationalisation of the EAFM in the IOTC convention area.

1.2 Objectives

The current work has been performed in preparation for the **2019 IOTC Ecoregions workshop, "Identification of regions in the IOTC convention area to inform the implementation of the ecosystem approach to fisheries management",** to be held in La Saline, La Réunion from 30 August to 1 September 2019. This work addresses the recommendations made by the WPEB14 with the final aim to propose draft ecoregions to inform the implementation of EAFM in the IOTC Convention Area.

Specifically, this work addresses the following tasks:

- Task1 - Reviews several case studies using area-based units or ecoregions in support of EAFM implementation and summarizes their benefits, uses and lessons learned
- Task 2 - Reviews existing marine pelagic biogeographic classifications in the Indian Ocean relevant to tuna and tuna-like species
- Task 3 - Provides revised criteria for evaluating ecoregions for IOTC and the expected qualities of ecoregions that would be appropriate for EAFM implementation in IOTC
- Task 4 - Provides an overview of the current available knowledge and data layers covering ecological processes covered in the criteria, which could be used to inform the delineation of draft ecoregions
- Task 5 - Provides an overview of the current available knowledge and data layers covering socio-political processes covered in the criteria, which could be used to inform the delineation of draft ecoregions
- Task 6 - Conducts a spatial analysis to derive a draft proposal of ecoregions for IOTC. The draft ecoregions produced by this work are intended to foster discussion at the workshop, to be further informed and refined by the expert knowledge of the participants.

2 Lessons learned from global examples using area-based units or ecoregions in support of EAFM implementation

As noted by the WPEB14, an increasing number of national and international bodies are implementing the EAFM in their convention areas using spatially-explicit units to guide ecosystem planning, research and assessments, ultimately to structure their ecosystem-based advice to inform fisheries management. Here, we investigated the examples provided by NAFO, ICES, NPFMC in the USA, and CCAMLR and provide a brief summary of each approach. These are then synthesized to extract the best practices and lessons in their venture to identify area-based units or ecoregions and their use in informing EAFM implementation.

2.1 Northwest Atlantic Fisheries Organization (NAFO)

A "Roadmap for the development of an ecosystem approach to fisheries (EAF) for NAFO" was launched in 2010, and the full operationalisation of EAF is still in development. This approach comprises a three-tiered hierarchical process to define sustainable exploitation levels within the NAFO convention area (i.e. FAO major fishing area 21, outside the EEZs of the United States, Canada and Greenland in the Northwest Atlantic Ocean), including Tier 1: ecosystem sustainability, Tier 2: multispecies sustainability, Tier 3: stock sustainability (Kenchington et al 2015). As part of this process, efforts were made to delineate ecoregions based on dominant ecological function, using multivariate analysis of both physical and biological data (Koen-Alonso et al 2019; Table 1). Specifically, principal components analysis (PCA) was used to reduce the dimensionality of the data layers and k-means clustering analysis was used to define the spatial boundaries of each homogenous ecoregion, following Pepin et al (2010).

NAFO plans to incorporate these ecoregions as spatially-explicit representations of benthic ecological function into assessments of the state of the ecosystem (NAFO 2014).

Table 2. Data layers used to inform ecoregions from global examples. Information is taken from NAFO (2014), ICES (2004), NPFMC (Eagleton and Evans 2015), CCAMLR (Grant et al 2006), and EU project (Juan-Jordá et al 2018). ICES used bathymetry in its decision-making process but the data source was not stated. CCAMLR divided its data into "primary inputs" (1°) or "secondary inputs" (2°) for its non/hierarchical statistical model (see text for details).

Data layer	NAFO 2014	ICES	NPFMC	CCAMLR	EU project
Delineation method	PCA/Kmeans	Expert decisions	Expert decisions	Mixed Non/ Hierarchical statistical model	Expert decisions
Bathymetry	GEBCO	x		1°	
Sea surface temperature	AVHRR 4km			1°	
Bottom temperature	Temperature at fishing		Surveys		
Chlorophyll-a	SeaWiFS (4 km)			2°	
Primary production	SeaWiFS (1.5 km)				
Species biomass	Demersal fish surveys				
Species diversity	Demersal fish surveys				
Nitrate (NOx) concentration				1°	
Silicate (Si) concentration				1°	
Sea ice				2°	
Existing management boundaries		OSPAR, ICES, Regional Advisory Council			IOTC convention area
Existing biogeography		LME, Longhurst, Dinter	LME		Longhurst, PPOW
Species distributions		Stock distribution	Surveys, observer reports of target and bycatch species		Catch of target species, fidelity* specificity index
Species densities			Surveys		
Growth, reproduction, survival rates			By habitats		

2.2 International Council for the Exploration of the Sea (ICES)

ICES integrates an 'Ecosystem Approach' to their advice in response to several political declarations advising the approach (e.g. the Reykjavik Declaration (FAO 2002), Bergen 2002 (NSC 2002), and the World Summit on Sustainable Development, Johannesburg, 2003). For ICES, an Ecosystem Approach in terms of management advice includes a multi-step process to identify ecosystems, identify the relevant ecosystem components, and then link these to human impacts on the ecosystems (ICES 2004).

As a first step towards the Ecosystem Approach for fisheries advice, ICES was requested by the European Commission to recommend ecoregions for European waters that incorporated appropriate oceanographic, biogeographic, and managerial characteristics, including information on human activities and land-sea interactions. In 2004, ICES recommended a set of ecoregions for European waters that integrated stock distributions, existing oceanographic/biogeographical/management classifications (e.g. Longhurst provinces, Large Marine Ecosystems, Dinter biogeographical regions; OSPAR regions, ICES areas, Regional Advisory Council areas), and stakeholder advice. This set of information was evaluated in a qualitative four-step process that resulted in ecoregion recommendations for European waters.

The qualitative step-wise assessment used by ICES was to 1) gather the data layers, i.e. oceanographic/biogeographic/management considerations; 2) identify clear decision-making criteria and their resulting expectations (e.g. Table 3), 3) evaluate the data layers against the criteria, and 4) adjust existing boundaries (or propose new ones) using expert and stakeholder opinions to improve their evaluation against the criteria. From this fourth step, the final ICES ecoregions were proposed (ICES 2004). ICES acknowledges that ecoregions, especially in marine systems will be subject to a changing climate and they recommend that ecoregion boundaries are reassessed at least every 20 years.

In 2015, ICES re-evaluated the boundaries of the ecoregions to incorporate further policy changes, including realignment with the EU Marine Strategy Framework Directive ecoregions, and adjustments to the Arctic zone based on recommendations by national scientists (ICES 2015). ICES notes that bioregionalisations are often iterative and boundaries should be regularly reassessed to incorporate changing policy and management approaches.

2.3 North Pacific Fisheries Management Council (NPFMC), USA

The NPFMC is a body that manages groundfish fisheries in the exclusive economic zone (EEZ) off Alaska in the USA. There is a wide-range of scientific research, information, and tools that have been developed to support the implementation of EBFM in the Alaska region. This includes the designation of well-established ecoregions, the establishment of optimum yields limits for the groundfish fisheries to avoid ecosystem overfishing, the identification of vulnerable habitats and species, the management of Essential Fish Habitat (EFH), the development of ecosystem indicators and indicator-based report cards, and the development of ecosystem, multispecies and climate models to provide context for fisheries management decisions.

Within the Alaska EEZ four ecoregions have been designated. These regions are distinct and diverse in ecosystem structure and function as well as in terms of the range of human pressures (NOAA, 2016). Every year, an indicator-based report card is presented by the

Ecosystem Committee to the Council which summarizes the status of top indicators selected by a team of ecosystem experts that best describes the ecological status of the four ecoregions. Each ecoregion has its own list of ecosystem indicators, as selected by the ecosystem experts, to provide ecosystem the context to support management decisions (Zador *et al.*, 2015). The indicator-based report card consists of a set of multi-year indicators with the objectives of illustrating their long- and short-term trends, and current status of different components of the ecosystem. The ecosystem report cards are also supplemented by a short bullet list with a small description of the ecosystem and a detailed ecosystem assessment. The ecosystem report cards in each region have been structured under different themes (e.g. variability theme to highlight the high variability of the region) and therefore are based on different indicators, driven mostly by the characteristics of the region, availability of data and knowledge of the team of experts involved in their development. Their development was the result of a long adaptive process and multiple versions as they were adapted to fit the management needs of the NPFMC (Zador *et al.*, 2016).

2.4 Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR)

CCAMLR has implemented an EAFM using biogeographical boundaries as the basis of its commitment to a precautionary, ecosystem-based approach to management. As such, they have defined and divided their convention area on the basis of biogeographical classification (Grant et al 2006). The biogeographical classification was performed using a mix of hierarchical and non-hierarchical statistical clustering models. Species distribution and abundance data are limited in most of the Southern Ocean; therefore, CCAMLR biogeographical classifications were developed based on satellite observations as proxies for ecosystem information, including physical processes, primary productivity, and habitat type. Data were partitioned into a primary set of environmental variables to identify the larger convention area, and a secondary set to define the smaller statistical units (Table 2).

This scheme allowed CCAMLR to define the border of their convention area largely on the limits of the Antarctic Circumpolar Current. This current acts as a natural biological barrier between polar species in the south and temperate species in the north. Furthermore, within their hierarchical scheme the larger convention area is divided into smaller, biogeographically-distinct statistical units, within which regionally-specific fishery statistical reporting is mandated and management measures are applied.

2.5 Best practices to identify ecoregions as part of EAFM implementation

Based on the review of the case studies above, we draw several conclusions as to the best practices used to identify area-based units with ecological meaningful boundaries to facilitate the provision of ecosystem advice and support the implementation of EAFM.

Identify a set of criteria for ecoregion evaluation and the expected qualities of the ecoregions

In all aspects of the bioregionalisations, a clearly-defined set of objectives and expectations should be established to develop and evaluate any proposed ecoregion. It is important to identify early a set of evaluation criteria and the expected qualities of the ecoregions to guide the delineation process. The criteria for defining ecoregions should consider ecological as well as socio-political processes.

Engage early and be inclusive in the regionalization process

Effective EAFM requires an integrated management approach to incorporate the views of all users in order to reach a shared agreement on the conservation, sustainable resource use and economic development goals for marine systems. Stakeholders should be included in the bioregionalisation process from the beginning to incorporate a diverse array of expertise. The engagement of key stakeholders in the establishment of the evaluation criteria as well as the data and methods used to delineate the final proposal of candidate ecoregion is also advisable.

Be flexible for future refinements of ecoregions as data improve or as management approaches are updated

All case studies note that biological data to inform the boundaries of ecoregions are limited, especially in terms of species diversity, distribution, and abundance. Several authors note that regionalizations do not have to be perfect to be useful in structuring ecosystem advice to inform EAFM implementation (e.g. Rice et al 2011), and therefore regionalizations should be started with the best data available, noting the limitations of the data. As noted by ICES and concluded by the EU project, it is important to plan for an iterative process from the beginning of the regionalization. Thus any ecoregion proposal can be refined step-by-step, as the process is shared across the different users and stakeholders, as improved data becomes available, and with stakeholder feedback.

Value of quantitative methodologies coupled to expert advice to delineate the boundaries of ecoregions

Half of the examples reviewed here used quantitative methodologies to define their ecoregions and the other half were based on qualitative expert advice. The use of quantitative methodologies enables an objective, statistical approach to delineating boundaries of biogeographically homogenous spatial units at multiple spatial scales. While quantitative methodologies are a good basis for proposing boundaries, we note that expert advice was essential in the other half of the case studies to incorporate practical management aspects when informing the final boundaries of the ecoregions. We suggest that a good practice is to couple the two methodologies, by proposing draft boundaries using statistical means and refining the boundaries using expert advice.

3 A review of existing biogeographic classifications relevant to the Indian Ocean and for tuna and tuna-like species

Several different strategies have been employed to biogeographically classify the global and Indian oceans, e.g. Longhurst Biogeochemical Provinces, Large Marine Ecosystems (LMEs), Marine Ecosystems of the World (MEOW), Pelagic Provinces of the World (PPOW), Tuna Biogeographical Provinces (TBP), the CSIRO bioregionalisation of the Indian Ocean, and

Dynamic Biogeochemical Provinces. We briefly review these examples here, noting their relevance in the context of tuna and tuna-like species of the IOTC convention area. Catches of tuna and tuna-like species in the Indian Ocean occur in both coastal areas and the high seas; therefore, we consider here biogeographic classifications that include coastal areas. Finally, we revise the properties and basic principles for a classification system of marine waters to inform the expected characteristics of the draft ecoregions to be proposed here.

3.1 Longhurst Biogeochemical Provinces

Developed by Sathyendranath and Platt (1993) and implemented by Longhurst (1995, 1998), the Longhurst biogeochemical provinces are a hierarchical scheme whereby the world is divided into four primary "biomes" into which 57 secondary "provinces" are further subdivided. The four biomes (polar, temperate, subtropical and tropical) were divided based on the oceanographic processes that make up their vertical density structure. The 57 provinces were then delineated based on models of primary productivity and related processes (e.g., Sverdrup 1953), coupled with *in situ* chlorophyll profiles, surface chlorophyll concentration (i.e. coastal zone colour scanner), mixed layer depths, and other oceanographic variables. Longhurst (1998) noted that the Indian Ocean is strongly influenced by the seasonal monsoon. However, while it is noted that the boundaries of the biomes and provinces vary seasonally and inter-annually, it is also noted that shifting boundaries are impractical for management, and they are thus deliberately fixed in space. While Longhurst provinces extend to the coastal regions, some authors note that the provinces have not been sufficiently subdivided near the coast (Watson et al 2003).

The Indian Ocean includes two Longhurst biomes and twelve provinces (Figure 2A).

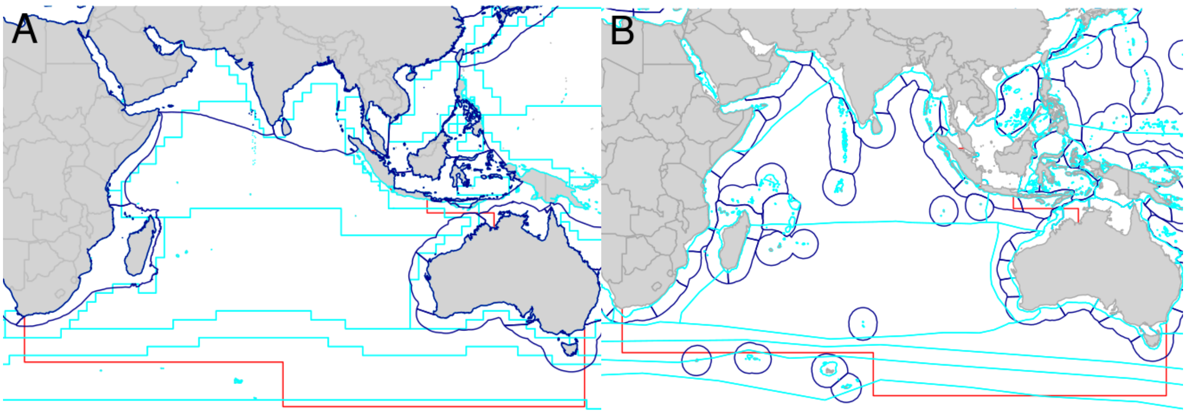

Figure 2. The IOTC convention area (red) overlaid with (A) the Longhurst biogeochemical provinces (cyan), the Large Marine Ecosystems (dark blue), and (B) the Marine Ecosystems of the World ecoregions (dark blue) and the Pelagic Provinces of the World (cyan).

3.2 Large Marine Ecosystems (LMEs)

LMEs are 66 relatively large coastal areas of about 200,000 km^2 based on distinct topography, hydrography, and productivity and incorporating trophically-coupled populations (Sherman et al 2004). They were developed through the cooperation of the National Oceanic and Atmospheric Administration (NOAA), the Global Environment Facility (GEF), the International Union for Conservation of Nature (IUCN), and several UN agencies in order to assist developing countries to implement an EAFM within their waters (Sherman and Duda 1999). The boundaries of LMEs roughly correspond to the margins of continental shelves, and an important component to their delineation is the incorporation of the trophic and life history linkages for commercial fish populations. Within the boundaries of LMEs 90% of the world's fisheries productivity occurs, as well as the majority of ocean pollution, exploitation, and habitat alteration (Watson et al 2003). Therefore, LMEs are viewed as appropriate EAFM management units for many marine activities and fisheries; however some authors note that they are neither large enough nor pelagic enough to be useful for highly migratory fish stocks (Sibert 2005).

There are ten LMEs of the Indian Ocean (Figure 2A).

3.3 Marine Ecosystems of the World (MEOW)

MEOW are a hierarchical classification scheme of the world's coasts and shelves developed by Spalding et al (2007), and includes 12 realms, 62 provinces and 232 ecoregions. This scheme was designed to streamline planning and priority setting, threat analysis, policy development and active management for marine coastal systems. MEOW ecoregions are the smallest scale of the classification scheme and include relatively homogeneous compositions of both benthic and neritic species and distinct oceanographic and topographic features. The delineations of the boundaries were based on strong biogeographic basis, using a diverse array of data. Expert opinions were also a key component in making decisions on boundary delineations, and these were influenced by the boundaries of existing political and biogeographical classifications.

The IOTC convention area includes four partial MEOW realms, 17 coastal provinces and 43 ecoregions (in hierarchical order) (Figure 2B).

3.4 Pelagic Provinces of the World (PPOW)

PPOW were developed for the world's off-shelf waters (< 200 m) (Spalding et al 2012). They were made to complement the MEOW coastal and shelf ecoregions. Similar to MEOW, PPOW is a hierarchical classification scheme based on existing biogeographical information and expert knowledge of pelagic biota. In hierarchical order, this scheme includes four realms, seven biomes, and 37 pelagic provinces. Spalding et al (2012) note that species distribution data, especially in the global pelagic zone is patchy and biased, and a quantitative approach would lead to false confidence in the resulting recommendations. Therefore, for the PPOWs, they followed a qualitative approach, employing expert knowledge to inform the delineation of boundaries. PPOW provinces, the smallest scale of the PPOW scheme, are large areas of epipelagic ocean that are based on large-scale, spatio-temporally-stable (i.e. seasonally recurrent) oceanographic processes. PPOW provinces comprise relatively homogeneous compositions of pelagic species and large-scale oceanographic features, such as ocean gyres, equatorial upwelling, basin-edge upwelling, semi-enclosed pelagic zones, and large-scale transition zones.

The IOTC convention area contains two PPOW realms, six biomes, and ten provinces (Figure 2B).

3.5 Tuna biogeographic provinces (TBP)

Reygondeau et al. (2012) developed nine global provinces of tuna biogeography based on the catch-per-unit-effort (CPUE) of major commercial species caught by Japanese and Korean longline fleets. These provinces were delineated using a quantitative statistical model that incorporated the distribution of the species and biophysical ocean features. They found that despite the highly-migratory nature of tuna and billfish, these species make up distinct communities that can be partitioned in space. Provinces are thus defined by single or multi-species dominances, or by diversified communities with no dominant species.

The IOTC convention area includes seven TBPs (Figure 3), including one with a high diversity of species (Indo-Pacific and Arabian Seas), one where bigeye tuna dominates (Tropical I), one where yellowfin tuna dominates (Tropical II), one where southern bluefin tuna dominates (Western Australian CS), one with a mixed community with swordfish and bigeye, but where albacore dominates (Seasonal Extent of Gyre), one with a mixed community with striped marlin and skipjack, but where albacore dominates (Core of Gyre), and one with a mixed community with swordfish and albacore, but where southern bluefin tuna dominates (Temperate).

While this study used the CPUE of major commercial species caught by Japanese and Korean longline fleets as a proxy to infer fish abundances and inform the global provinces of tuna biogeography, it should be noted that the CPUE of longlines excludes some commercial species important in the IOTC convention area, such as skipjack, which are not captured by longline due to low catchability, and neritic species, which are not targeted by industrial longlines. Restricting the analysis to CPUEs of a few selective gears may lead to a poor representation of tuna and billfish communities.

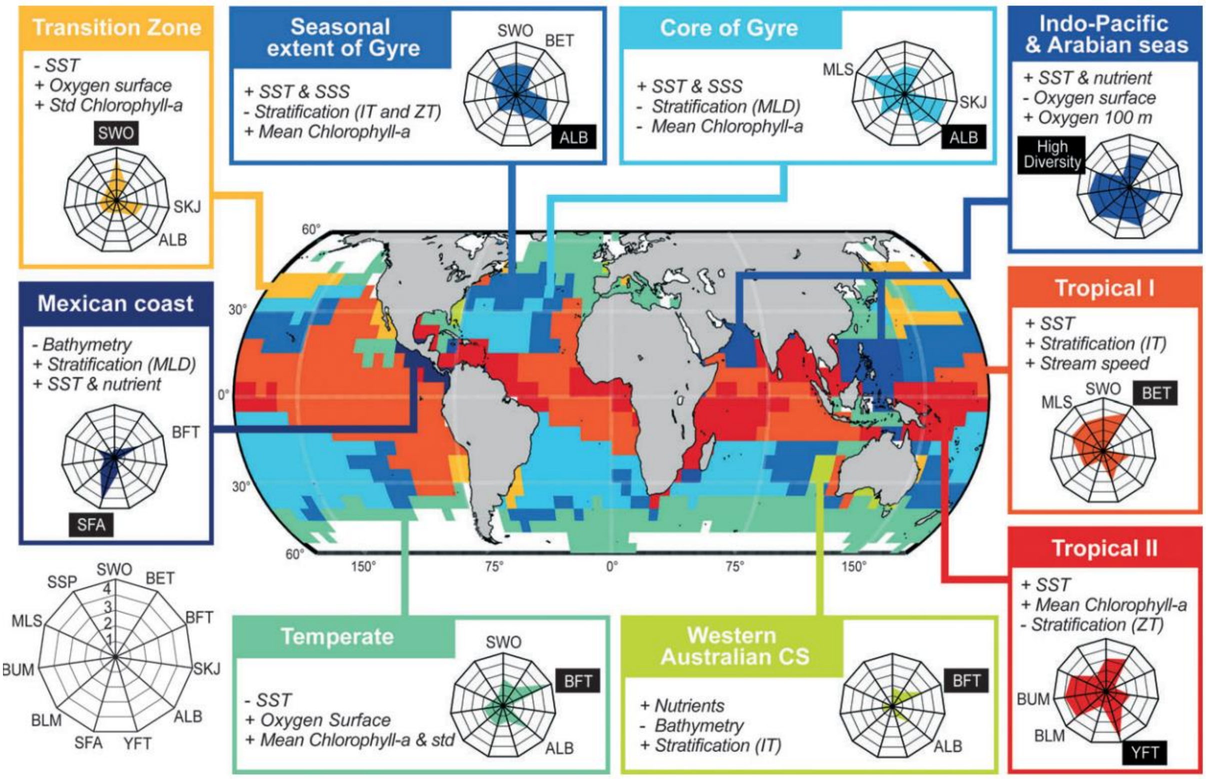

Figure 3. Tuna biogeographical provinces of the world (taken from Reygondeau et al 2012).

3.6 GOBI/CSIRO bioregionalisation of the Indian Ocean

Though the final report is not yet published, a recent expert-based bioregionalisation of the benthic, pelagic and mesopelagic Indian Ocean was completed, led by the CSIRO of Australia (Dunstan et al 2018). The boundaries of the two-scale hierarchical regionalisation were delineated at two participatory workshops whereby expert knowledge was extracted from participants to map the physical environment, habitat, and species distributions. These data were then used to delineate preliminary boundaries, which were then refined by applying expert knowledge at the second workshop to account for missing information, ensure consistent definitions, describe linkages between provinces and identify and facilitate transboundary issues.

The Large Marine Regions then, were defined based on relationships between physical, geological, evolutionary, and ecological processes that should encompass the ecosystems and patterns of biodiversity of the Indian Ocean. The smaller-scale provinces were defined based on major species groups and ecosystems, and informed by data from the Biologically Significant Marine Areas (EBSA) and existing classification schemes (Figure 4).

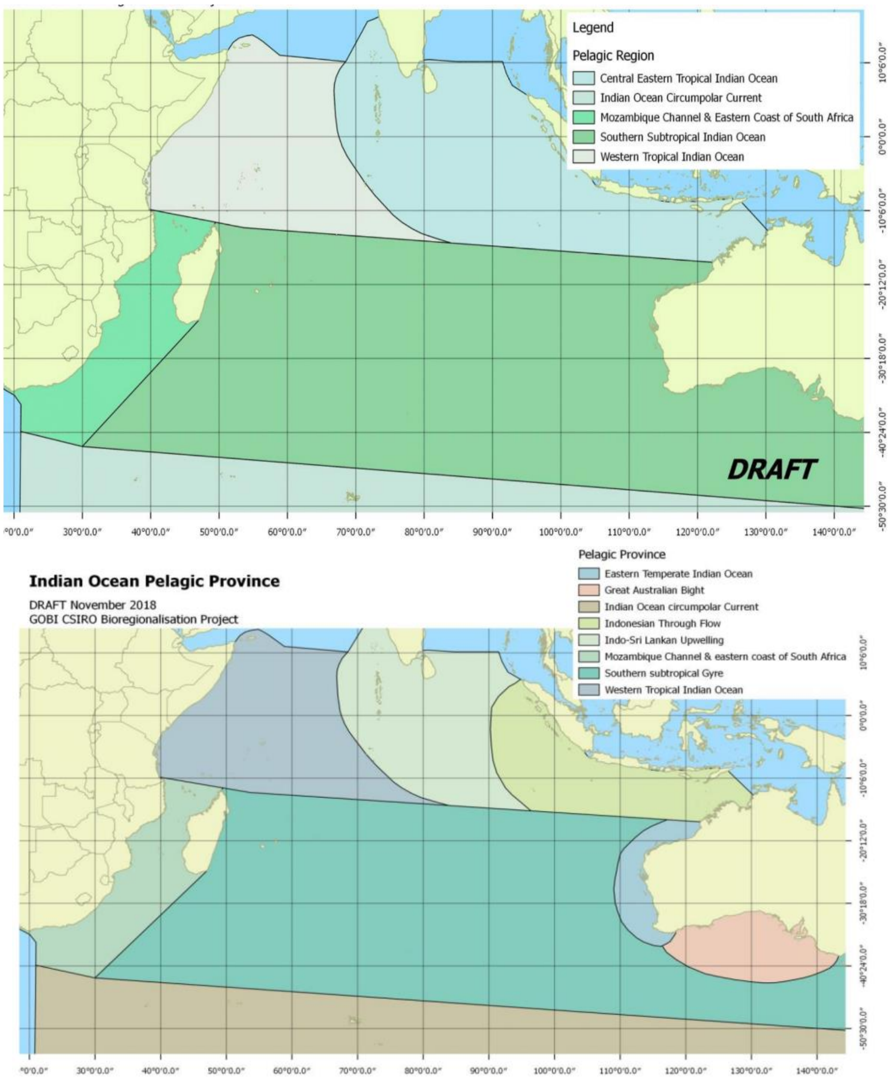

Figure 4. The draft hierarchical pelagic provinces as recently delineated for the Indian Ocean, led by CSIRO (taken from Dunstan et al 2018). The top panel shows the Large Marine Regions, i.e. the highest-order provinces, and the bottom panel shows the second-order provinces.

3.7 Dynamic biogeochemical provinces

Reygondeau et al (2013) explored the seasonal and interannual variability of Longhurst biogeochemical provinces (Figure 5). Employing a Non-Parametric Probabilistic Ecological Niche Model, they reclassified the global ocean with updated data and dynamic borders. They found that while static classifications schemes should take into account seasonal and interannual variability, this is often not the case, and large shifts of the boundaries occur. They found seasonally poleward displacements of up to 18° for subtropical provinces, and longitudinal shifts of up to 27°. In the Indian Ocean, these longitudinal displacements are attributed to the seasonal monsoon. They noted that at multi-annual climate scales, the eastern Indian Ocean provinces respond to El Nino by extending their southern boundaries further south. The authors noted that dynamic boundaries can be used to monitor, study, and forecast the dynamics of ecosystem composition at each trophic level.

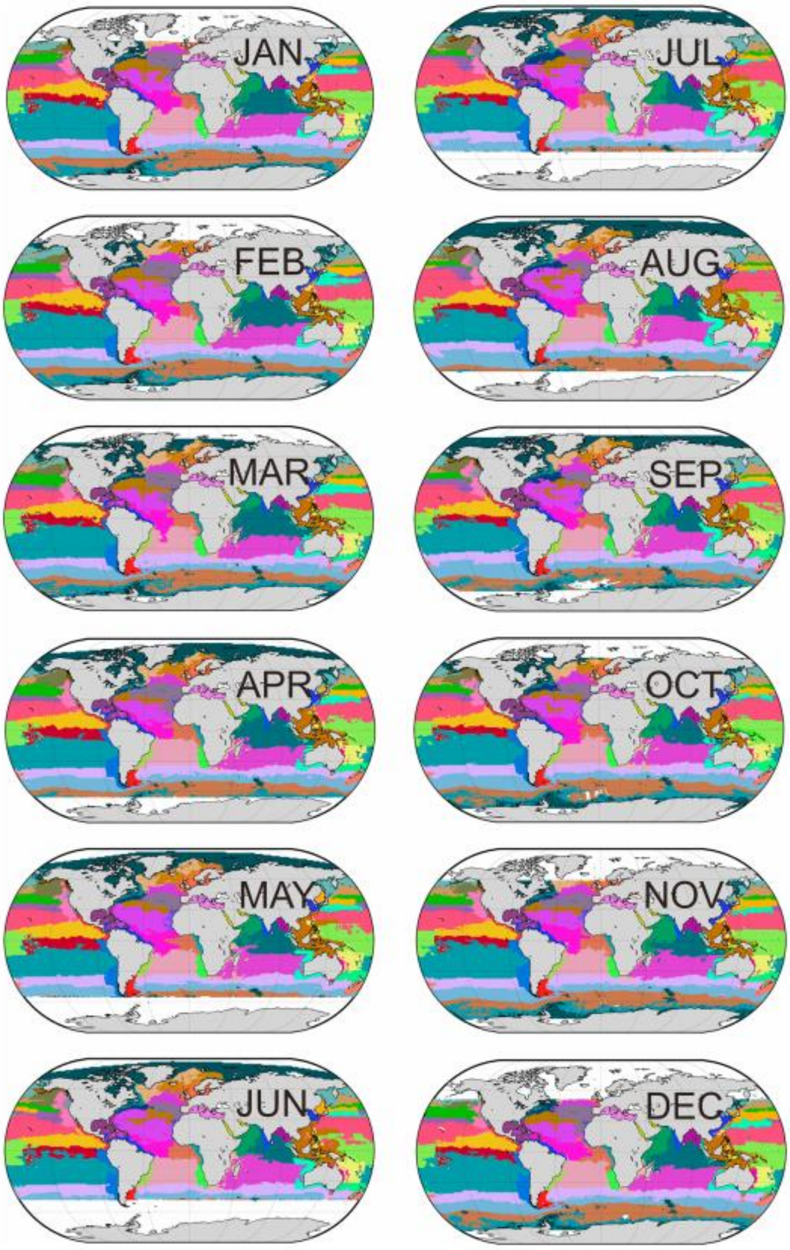

Figure 5. Monthly climatologies of dynamic Longhurst biogeochemical provinces (taken from Reygondeau et al 2013).

3.8 Basic properties of the biogeographic classifications reviewed

Below we list properties and basic principles for a classification system of marine waters to inform the expected characteristics of the draft ecoregions.

Coastal versus open ocean

The biogeographic classification schemes reviewed here classify either coastal waters (i.e. LMEs, MEOW) or the open ocean (i.e., Longhurst, PPOW, TBP). This division is due to the major differences in habitat and human impacts between coastal and open ocean zones. Coastal zones are shallow, and their oceanography is heavily influenced by topography. In contrast, the open ocean is generally divided into layers depending on their depth and dynamism, i.e., the epipelagic, mesopelagic, and bathypelagic zones. Furthermore, biogeographical classifications of the coastal zone often incorporate human-influenced boundaries, such as EEZs.

Main data layers

The main data layers that are employed in biogeographical classifications are physical, incorporating biological data to a lesser extent. This is because physical data is readily available with good spatial and temporal coverage (especially with the advent of satellite remote sensing). Physical variables generally include sea surface temperature, water column stratification, mixed layer depth, ocean circulation and bathymetry. Unbiased biological data with good spatial and temporal coverage are more difficult to obtain, and the most common biological input is sea surface chlorophyll concentration and primary productivity. Species distributions and abundance are also commonly used, but they are often severely biased, especially at the global scale (e.g., more data in areas where there are more scientific activities (Spalding et al 2012), and data are often fisheries-dependent. Moreover, the availability of species distribution data and fishery-dependent statistics by species are different between areas (e.g. coastal vs. open ocean), which make their use for biogeographical classification more challenging.

Quantitative versus qualitative

An ideal biogeographical classification scheme would employ objective statistical algorithms on fine-scale spatial data, resolved to the level of the species (Spalding et al 2012). This would enable a consistent standard by which to assess the resulting ecoregions and replicate the classification process. However, as noted above, there is often a lack of good biological data, and there is concern that with a quantitative classification, the biases in the data will dominate the results. For example, Reygondeau et al 2012 used longline catch and effort data but the catchability of the neritic tunas and skipjack of longline gear is very low and, thus, these species did not influence in the resulting classification. Thus, many classification schemes incorporate expert advice to address these deficiencies in biological data sets.

Static versus dynamic

Most biogeographical classification schemes reviewed here have static borders that the authors note should account for the seasonal and interannual dynamics of each biogeographically-homogenous province. In addition, ICES (2004) note that ecoregion boundaries should be relatively static in space over the time scale of management decisions (i.e. decades or more). However, in reality, due to the fluid nature of the marine environment, the boundaries of these provinces are constantly shifting and these shifts can be significant (Reygondeau et al 2013). Any ecoregion delineation must acknowledge that boundaries of homogenous ecosystem function must fluctuate in space through time and a key point in defining marine ecoregions is to quantify and capture these dynamics (Strayer et al 2003). However, for a practical implementation of the EAFM, static bioregions are favoured that will allow the development of ecoregion-tailored ecosystem planning activities, ecosystem-based assessments and ecosystem advice to inform management actions. In any case, to resolve the need for practical static management boundaries in a variable environment, interannual and multi-annual variability can be accounted for by a regular reassessment of boundaries.

Spatial scales

Physical and biological processes of the ocean occur at several different spatial scales, which are reflected in the differences between coastal and open ocean classification schemes. Coastal classifications generally include numerous smaller ecoregions whereas open ocean classifications are generally fewer in number and larger in size. The scale of the classifications can have a large impact on their practical usage. Rice et al (2011) noted that classification at different scales is essential for allowing management measures to be developed at both an ecologically-meaningful and managerially-practical scale. They noted that biogeographical classifications will only be effective for management if the effects of management measures can be identified and implemented at regional scales. In order to ensure this, the biogeographical classification must then accurately reflect the dominant ecological processes of the region upon which the ecosystem planning and assessment activities, and resulting ecosystem-based management advice could be applied. Hierarchical classification can thus be particularly useful for planning and management purposes, as goals are often set at the basin scale in the context of tuna RFMOs, but implementation often occurs at more regional or local scales.

3.9 Relevance of the reviewed biogeographic classifications for tuna and tuna-like species of the IOTC

Coastal classifications

Though the main target species of the IOTC include the highly-migratory tunas and billfishes, IOTC also manages neritic species such as bullet tuna, frigate tuna, kawakawa, and Spanish mackerel. Therefore, both coastal and open ocean classifications are considered in our review. Furthermore, the WPEB14 noted that the IOTC convention area is complex, with diverse socio-economics and geopolitics.

Both LMEs and MEOW ecoregions are coastal and based strongly on biogeography (Figure 2). However, LMEs do not specifically delineate ecoregions around many of the island nations in the western Indian Ocean (e.g., Maldives, Seychelles, Mauritius, La Réunion), many of which have complex geopolitical histories that have the potential to influence management decisions (e.g. disputed areas). In contrast, MEOW ecoregions have been specifically designed to incorporate political boundaries.

Considered in the scope of the IOTC convention area, the large size of the LMEs and the fact that they are relatively few in number in the Indian Ocean can be considered ecologically-meaningful even for neritic species and practical from a management point of view. MEOW ecoregions, on the other hand are numerous, which could be impractical for any development of ecosystem plans and integrated assessments of status, and resulting management implementations. However, MEOW ecoregions are also hierarchical (including 43 ecoregions in 17 coastal provinces in the Indian Ocean), meaning that different spatial scales could be used to represent species distributions and management.

Open ocean classifications

The open ocean classifications that were considered in this review, the Longhurst biogeographic classification with its resulting provinces and the PPOW biogeographic classification with its resulting provinces, are particularly relevant for the main IOTC species (i.e., albacore, yellowfin, bigeye, skipjack and swordfish) due to their highly-migratory behaviour and wide distribution. The Longhurst provinces include both coastal and open water regions, while PPOW only cover open water as the PPOW are a complementary scheme to the MEOW coastal classification by the same author (Spalding et al 2007, Spalding et al 2012). Longhurst provinces are based on patterns of primary productivity and the physical properties of the water columns, while the PPOW classification also incorporate higher-order species distributions and communities. Similar to MEOW, the PPOW classification scheme includes expert knowledge to account for existing biogeographical and political boundaries.

Both Longhurst and PPOW classifications are hierarchical with approximately the same number of divisions in the Indian Ocean at each spatial scale. As noted, hierarchical classifications are particularly useful in a management context for wide-ranging species to incorporate both the spatial distribution of the species and more precise management units.

Tuna biogeographical provinces

Though Reygondeau et al (2012) used a limited number of species and gear types in their analysis, their conclusion that highly-migratory and widely distributed species, such as tuna and billfish, show distinct spatial distributions is important. This analysis proves that biogeographical classification can be useful for these types of species, and a similar exercise that expanded the number of species and gears included in the analysis could be informative in the IOTC convention area.

Dynamic biogeographical provinces

As noted previously, boundaries of regions of homogenous biogeographical characteristics are dynamic in a marine environment. We note that the application of dynamic boundaries for management purposes is possible. For example, southern bluefin tuna off the east coast of Australia are dynamically managed based on their shifting habitat as defined by sea surface temperature (Hobday et al. 2014). However, the practical application of dynamic boundaries is complicated and requires capacity and cooperation across science, technology, management, legal, and policy fields. Moreover, the application of dynamic boundaries in large bioregions could be very challenging. For a region as complex and diverse as the IOTC convention area, static boundaries are preferable and could even be considered a required feature of any biogeographical classification.

CSIRO biogeographical classification of the Indian Ocean

The expert-based bioregionalisation of the Indian Ocean led by CSIRO last year resulted in a hierarchical set of bioregions based on physical processes, species assemblages, and included transboundary issues. The preliminary regions and provinces are relatively few in number and are hierarchical, making them pragmatic for management. In addition, the spatial distribution and catch of tuna and tuna-like species are considered within each province based on expert knowledge, though the data sets used to inform decisions were not expressly included/described. Though these regions are still considered preliminary and further information is required, they are potentially very interesting as a basis to inform potential ecoregions within the IOTC convention area.

3.10 Proposed qualities of ecoregions

Finally, based on the review of the international case studies that use ecoregions to inform EAFM implementation and the review of existing biogeographic classifications, we identified the following best practices and qualities to derive the boundaries of the draft ecoregions for the IOTC :

1) The draft ecoregion will incorporate coastal and pelagic biogeography to account for the life histories and the spatial distribution of neritic and open ocean species under IOTC mandate;
2) Draft boundaries will be derived using a quantitative statistical methods informed mainly by the ecological data. It is also expected that expert opinion will inform and refine the draft boundaries following the socio-political information, and potentially examining hierarchical subdivisions;
3) The draft boundaries of the ecoregion will be static, while encouraging these to be are reviewed at regular intervals to account for changes in data availability and quality, changes in management approaches, and the effects of climate change and variability;
4) The proposed draft ecoregions should be relatively few in number to make them practical for informing EAFM implementation.

4 Evaluation criteria to inform the delineation of IOTC ecoregions

4.1 EU project criteria and factors

The EU project developed a set of evaluation criteria, similar to those developed by ICES (see Table 3) to inform the delineation of ecoregion boundaries that are both ecologically-meaningful and practical from a management point of view. Evaluation criteria were defined to assess whether boundaries of proposed regions matched the spatial scales of the main oceanographic features, the core distribution of the main IOTC species, and whether they reflected the spatial dynamics of the main IOTC fisheries and fleets (Juan-Jordá et al 2019).

Final decisions of the ecoregion boundaries were determined based on these evaluation criteria.

4.2 Revised evaluation criteria

Noting that the WPEB14 found that the ecoregions proposed by the EU project did not adequately reflect the complexities of the IOTC fish communities or fisheries, and noting as well that the WPEB14 suggested that any future ecoregion proposal include clear objectives and expectations; here, we review and examine further the evaluation criteria and the expected qualities of ecoregions that would be appropriate for the implementation of the EAFM in the IOTC, and use it to inform the next proposal of draft ecoregions.

Here, we adapt ICES (2004) evaluation criteria used to delineate ecoregion boundaries in EU waters and other relevant criteria to the context of the IOTC species and its fisheries, and use it to guide our proposals of ecoregions within the IOTC convention area. We have organised the evaluation criteria (and subcriteria) to address the specific recommendations of the WPEB14 that requested that future ecoregions proposals were based on criteria that considered both ecological and socio-political processes by accounting for

1. the biogeography of the region,
2. the knowledge of the spatial distributions and co-occurrence of main IOTC species (tuna, billfishes, and other bycatch species),
3. the spatial dynamics of the main fisheries (including coastal artisanal, semi-industrial and industrial fleets) and their spatial overlaps,
4. relevant socio-economic and geopolitical factors, and
5. compatibility with other regional initiatives (e.g. SWIOFC).

The WPEB14 also requested that future ecoregions proposals were also informed by expert knowledge from CPCs in all the above criteria.

Based on the WPEB14 recommendations above, we propose the following revised evaluation criteria (Table 3 and Table 4). The evaluation criteria presented in Table 3 covers criteria 1-3, which account mostly for ecological processes, and these will be used to guide the first-order delineation of ecoregion boundaries (hereafter, the 'ecological criteria'). In addition, Table 4 considers other criteria recommended by WPEB14, including relevant socio-economic and geopolitical criteria and criteria relevant to the compatibility with other regional initiatives (hereafter, the 'socio-political criteria'). These criteria are expected to be informed in a large part by expert advice. The socio-political criteria (Table 4) can be used to refine the boundaries of the draft ecoregions that were developed using the ecological criteria (Table 3).

Table 3. The ecological evaluation criteria used to evaluate ecoregions and the expected qualities of ecoregions corresponding to these criteria were mainly derived from ICES (2004). These criteria were used to inform the delineation of ecoregion boundaries that would be appropriate for implementing the EAFM in IOTC. The ecological criteria were adapted for the context of IOTC species and fisheries within the IOTC convention area following the recommendations of the WPEB14. A proposal of data layers and methodologies that may be used to address each criterion are also included.

No.	Criteria	Expectations of appropriate ecoregions	Potential data layers/methodology to be used in the evaluation of ecoregions
	1. Oceanography/Biogeography		
1.1	Do the boundaries of existing or proposed ecoregions appropriately demarcate areas with identifiable oceanographic characteristics?	Boundaries should have clear oceanographic justification for demarcation	Data layer: Existing biogeographical classifications (i.e., Longhurst, PPOW, MEOW, LME, TBP, CSIRO regionalization project)
1.2	If there are subregions within the ecoregion (oceanographically/ biogeographically identifiable regions that do not meet the criteria for ecoregions), do they nest within ecoregions without gaps or inefficiencies?	If divided, ecoregion should divide clearly and completely into a small number (≤ 3) of sub-regions	Methodology: Exploration of a hierarchical classification delineated either quantitatively or via expert knowledge
1.3	Would there be significant spatial variation in the response of existing or proposed ecoregions physical characteristics, species and communities to climate variability and climate change?	Spatial variation in response to climate variability and climate change should be relatively slow.	Methodology: Ecoregions should be reassessed at regular intervals by the IOTC group (e.g. 15-20 years).
1.4	Is the oceanographic and biological variability within the existing or proposed ecoregion smaller than variability between ecoregions?	Variability within ecoregions should be smaller than variability among ecoregions	Methodology: Statistical classification to quantify the variability
	2. Spatial distributions of main IOTC species		
2.1	Do the boundaries of existing or proposed ecoregions appropriately demarcate the distribution of main oceanic IOTC tuna and billfish species and distinct tuna and billfish communities inhabiting the pelagic zone?	Boundaries should demarcate the core distribution of main IOTC tuna and billfish species and distinct fish communities	Data layer: Spatial distributions of IOTC species (2002-2017) within the IOTC convention area and co-occurence of species

2.2	Are ecoregions representative of spatial distributions of main neritic species?	Boundaries should demarcated core spatial distribution of IOTC neritic tuna	Data layer: Bathymetry, IUCN habitat distributions
2.3	Do the boundaries of existing or proposed ecoregions incorporate the different life history stages of the main IOTC tuna and billfish species? ?	Boundaries should incorporate the main life history stages of species, including core adult and juvenile distributions, and spawning areas.	Data layer: Size-frequency data of main IOTC tuna species (2002-2017) within the IOTC convention area. Presumed reproductive zones of major species should be considered.
3. Spatial distribution of main IOTC fisheries			
3.1	Do the boundaries of existing or proposed ecoregions appropriately demarcate the distribution of IOTC fleets and fisheries operating in the IOTC convention area?	Boundaries should demarcate the core fishing grounds for main IOTC fleets and fisheries.	Data layer: Core spatial distribution of the fisheries and fleets within the IOTC convention area, including artisanal and industrial fishing fleets.

Table 4. The socio-political evaluation criteria used to evaluate ecoregions and the expected qualities of ecoregions corresponding to these criteria were mainly derived from ICES (2004). These criteria can be used to inform and refine the delineation of ecoregion boundaries that would be appropriate for implementing the EAFM in IOTC. The socio-political criteria were adapted for the context of IOTC and following the recommendations of the WPEB14. Proposed data layers and methodologies that may be used to address each criterion are also included.

No.	Criteria	Expectations	Data layer/Methodology
4. Compatibility with other regional initiatives			
4.1	Are the boundaries of existing or proposed ecoregions compatible with those of other existing or proposed regional initiatives?	Compatibility should be high and used to identify potential synergies and ecological linkages relevant to tuna and billfish species and their fisheries, e.g., interactions with other fisheries' gear, effects of fishing prey species (e.g. small pelagics) on IOTC species.	Expert advice can be used to inform this criterion. Data layer: Management unit maps, other RFMO/RFB convention areas (SIOFA, CCSBT, SWIOFC), MPAs, EBSAs
5. Socioeconomic factors			
5.1	Do the proposed ecoregions consider and incorporate relevant socioeconomic factors and processes?	Boundaries should address relevant socioeconomic factors and processes.	Expert advice can be used to inform this criterion. Data layer: Currently, IOTC data are not available, though data collection is ongoing on a voluntary basis.

6. Geopolitical factors			
6.1	Are the boundaries of the existing or proposed ecoregion compatible with the provisions of UNCLOS and other relevant international conventions?	Ecoregion boundaries should be compatible with the provisions of UNCLOS and other relevant international conventions	Expert advice : UNCLOS units - e.g., EEZ, territorial seas, high seas
7. Management factors			
7.1	Can research, assessment and monitoring of marine impacts and resulting advice be effectively linked at the scale of the existing or proposed ecoregion?	It should be possible to link research, assessment and monitoring of marine impacts to effectively support the delivery of integrated advice to inform fisheries management	Expert advice can be used to inform this criterion.
7.2	Do the boundaries of existing or proposed ecoregions create any known impediments to effective fisheries management in IOTC?	Boundaries should not create impediments to effective management in IOTC	Expert advice can be used to inform this criterion.

5 An overview of the available knowledge and data layers covering ecological processes to inform the delineation of draft ecoregions

Here we present an overview of the different data layers that could be used to derive the draft ecoregions in line with the evaluation criteria in Table 3 and Table 4. In this section (5), we present those data layers that will be used to delineate the draft ecoregions in line with the ecological evaluation criteria presented in Table 3, and in Section 6, we present those data layers covering socio-political processes that are to inform discussion at the workshop to further refine the draft boundaries of ecoregions as aligns with the criteria presented in Table 4.

In the ToRs of this study, data were recommended to be sourced mainly in consultation with the IOTC Secretariat to the extent possible. We have also searched for additional data sources in the published literature and global online databases.

Following the recommendations from the WPEB14 and the ToRs of this study, we first reviewed the biogeographic classifications for pelagic waters in the Indian ocean and examine their relevance for tuna and tuna-like species (Section 3). Here, we pre-selected those biogeographic classification most relevant to inform the candidate draft ecoregions (Section 5.1). Second, we examined the distribution and co-occurrence in space of the main IOTC species, including tunas, billfish, and neritic species, and also considered this as one of the primary layers to inform the boundaries of candidate ecoregions (Section 5.2). We examined the spatial distributions of IOTC catches for each species to infer their distributions. We also examine the distribution of some bycatch species of IOTC fisheries such as sharks, turtles, seabirds and marine mammals, and their relevance for informing the boundaries of ecoregions will be further discussed during the workshop.

Consideration of the spatial distribution of species should include the spatial distribution of all stages of its life cycle, as identified in criterion 2.3 (Table 3). Therefore, we investigated size data to identify juvenile versus adult ranges for the main IOTC species, and we performed a literature search to identify the spawning regions of the different species (Section 5.3).

Finally, to inform the delineation of draft ecoregions we also examined the spatial distribution of the main IOTC fisheries, including purse seine, longlines, gillnets, and other major coastal and high seas fisheries, using IOTC catches by each major fishery and fleet as a proxy to determine the main fishing grounds of each fishery (Section 5.4).

Next, we provide an overview and describe each of the data layers that could be used to inform the delineation of ecoregions in line with the ecological evaluation criteria outlined in Table 3. We note that not all data reviewed here could be included in the spatial analyses (Section 7) due to deficiencies in availability, quality and completeness, as summarised in Table 5. We expect missing or inadequate data layers to be further informed by expert contributions at the workshop.

Table 5. Data layers explored during the course of this study. Data that were considered 'good' in terms of quality, completeness and availability were retained as inputs in the final statistical spatial analysis (green rows) in Section 7.

Data layers	**Data type**	**Data quality and completeness**	**Time range of dataset**	**Included in statistical spatial analysis**	**Data source**	**Reference**
			Existing biogeographic classification			
Longhurst provinces	Shapefile	Good		Yes	http://www.marineregions.org/download_file.php?name=longhurst_v4_2010.zip	Longhurst 1995, 1998
Large Marine Ecosystems	Shapefile	Good		No	http://lme.edc.uri.edu/index.php/digital-data	Sherman et al. 2004
MEOW	Shapefile	Good		Yes	http://data.unep-wcmc.org/datasets/38	Spalding et al. 2007
PPOW	Shapefile	Good		Yes	http://data.unep-wcmc.org/datasets/38	Spalding et al. 2012
			Spatial distribution			
IOTC target species: open ocean	Raised catch	Good	2000-2017	Yes	Official IOTC data request	IOTC Secretariat
IOTC target species: neritic	Catch	Low	1952-2017	No	https://www.iotc.org/WPB/17/Data/07-CEAll	IOTC Secretariat
IOTC target species: neritic	IUCN habitat distribution	Good	-	Implicit	https://data.nodc.noaa.gov/cg	NOAA ETOPO1

					i-bin/iso?id=gov.noaa.ngdc.mgg.dem:316	
IOTC bycatch species: sharks	Catch	Medium	1952-2017	No	https://www.iotc.org/WPB/17/Data/07-CEAll	IOTC Secretariat
IOTC bycatch species	Observer data	Unknown	Unknown	No	IOTC public domain	IOTC Secretariat
Bycatch species: turtles, seabirds, marine mammals	Visual sightings, telemetry, acoustics	Spatially-biased	1978-2018	No	OBIS-SEAMAP	Halpin et al. 2009
Bycatch species: seabirds (albatross, petrels)	GLS, GPS, PTT	Data unavailable	Unknown	No	Bird Life International Sea Bird Tracking Database	
			Size distribution			
IOTC target species: ALB	Size frequency	Good	1952-2017	No	https://www.iotc.org/documents/WPTmT/07/DP/DATA/09-SFALB	IOTC Secretariat
IOTC target species: BET	Size frequency	Biased according to gear	1952-2017	No	https://www.iotc.org/documents/size-frequency-data-bigeye-tuna-bet-0	IOTC Secretariat
IOTC target species: YFT	Size frequency	Biased according to gear	1952-2017	No	https://www.iotc.org/documents/size-frequency-data-yellowfin-tuna-yft-0	IOTC Secretariat
IOTC target species: SKJ	Size frequency	Biased according to gear	1952-2017	No	https://www.iotc.org/documents/size-frequency-data-skipjack-tuna-skj-0	IOTC Secretariat
IOTC target species: SWO	Size frequency	Only juveniles caught according to LatM	1952-2017	No	https://www.iotc.org/WPB/17/Data/09-SFData	IOTC Secretariat
IOTC target species: neritic	Size frequency	Low	1952-2017	No	https://www.iotc.org/WPNT/09/Data/09-SFData	IOTC Secretariat
IOTC bycatch species: other billfish	Size frequency	Low	1952-2017	No	https://www.iotc.org/WPB/17/Data/09-	IOTC Secretariat

					SFData	
IOTC bycatch species: sharks	Size frequency	Low	1952-2017	No	https://www.iotc.org/WPEB/15/Data/09-SFData	IOTC Secretariat
Spawning regions						
IOTC target species: ALB	Spawning/Feeding/Migration	Discussion criteria		No	IOTC WPTMT reports	Nikolic et al 2014, Nishida and Tanaka 2004
IOTC target species: BET		Discussion criteria		No		
IOTC target species: YFT		Discussion criteria		No		
IOTC target species: SKJ		Discussion criteria		No		
IOTC target species: SWO		Discussion criteria		No		
IOTC target species: neritics		Discussion criteria		No		
IOTC bycatch species: sharks		Discussion criteria		No		
Spatial distribution of fisheries						
IOTC fisheries (gears)	Raised catch data	Good	1952-2017	Yes	Official IOTC data request	IOTC Secretariat
Existing management initiatives						
Marine Protected Areas (MPAs)	Shapefile	Good		No	https://www.protectedplanet.net/marine	*UNEP-WCMC WPDA*
IOTC convention area	Shapefile	Good		Yes	http://www.fao.org/geonetwork/srv/en/resources.get?id=31675&fname=indian_ocean.zip&access=private	FAO
SIOFA convention area	Shapefile	Good		No	http://www.fao.org/geonetwork/srv/en/resources.get?id=31675&fname=indian_ocean.zip&access=private	FAO
SWIOFC convention area	Shapefile	Medium		No	http://www.fao.org/geonetwork/srv/en/resources.get?id=31675&fname=indian_ocean.zip&access=private	FAO
Ecologically or	Shapefile	Good		No	See Table 8.	

Biologically Significant Areas (EBSAs)						
Socioeconomics						
Fleet, market information	Voluntary data collection scheme	Not available	Recent	No	Not available	IOTC Secretariat
Geopolitics						
UNCLOS: EEZ, high seas	Shapefile via the MEOW classification scheme	Good		Yes	http://data.unep-wcmc.org/datasets/38	Spalding et al. 2007
Anti-shipping activities	Literature	Discussion criteria	1968-2017	No		Levin et al. 2018
Disputed areas of the western Indian Ocean	Literature	Discussion criteria		No		Levin et al. 2018

5.1 Existing biogeography

The biogeography and oceanography of the Indian Ocean have been previously investigated and defined in several studies as reviewed in this report (Section 3). We believe both coastal classification and oceanic classification are crucial to representing the full range of IOTC target species (including neritic and oceanic species). Though the LME biogeographic classification incorporates coastal features important to neritic species distribution, we decided not to further investigate LMEs as 1) they do not include pelagic oceanic provinces important to the main IOTC species, and 2) these ecoregions do not sufficiently represent the island nations of the Indian Ocean basin (e.g. the Maldives, Chagos, Mascarenes, Seychelles). Therefore, we retained for further analysis only the Longhurst biogeographic classification, which include oceanic and coastal provinces, the PPOW biogeographic classification, which are oceanic provinces delineated up to the continental shelf, and we also retained for further analysis a combination of the complementary PPOW and MEOW provinces that cover both the coastal and oceanic pelagic waters.

5.2 Spatial distribution and abundance of species

Oceanic tunas and swordfish species distribution inferred from raised catch data

IOTC estimated georeferenced raised catch data for the main IOTC tuna species and swordfish, and these were used to infer their spatial distribution and abundance. Catch data were used instead of catch per unit effort as this analysis aimed to include diverse species caught from diverse gear types. Combining catch per unit effort indices across the numerous different gear types included here is a difficult task, and not within the scope of this study. We note that these data are fisheries dependent, and thus may not be the ideal for inferring ecological processes (Reygondeau et al 2012). However, as fisheries-independent data are few, we believe that catch data can be useful in inferring patterns of species distributions and co-occurrence of species to inform ecoregion delineation.
We requested raised catches of the main target species, including albacore, yellowfin, bigeye, skipjack and swordfish from the IOTC Secretariat. The Secretariat estimates the raised catch data using a combination of different techniques, mostly involving proxy fleets / gears to fill the

gaps where catch and effort data are not reported, or are reported with very coarse spatial resolution (e.g. at the level of the CPC's EEZ). These data were available from 1952 to 2017, and are a mix of 1°x1° and 5°x5° resolutions, which is due to the reporting requirements of the different fisheries in the IOTC. For this study, we regridded the data to 5°x5° in correspondence with the official 5°x5° IOTC reporting grids (shapefile) and used an average of the last 15 years of data (2003-2017), in accordance with the EU project. To avoid biasing distributions toward extreme high catches, data were filtered to remove catches greater than the 95th percentile. Data were further filtered to remove potentially erroneous reporting errors, specifically catches of tropical tuna (SKJ, YFT, BET) captured below 45°S. Raised catch data for oceanic tuna and swordfish species are considered "good" in terms of data quality and completeness (Table 5).

The majority of the raised catch of the main target IOTC oceanic species are in the northern and western Indian Ocean basin (Figure 6, Figure 7). Large catches elsewhere may be influenced by the substantial catches from a few number of observations in these regions (Figure 8). Catch and the number of observations are both high in the western Indian Ocean north of the Seychelles and west of Somalia (Figure 6, Figure 7, Figure 8). Substantial catch occurs south of India, in Maldivian and Sri Lankan waters and off Indonesia. We find that in general, the tropical species YFT, BET and SKJ are primarily found north of 20°S and that the subtropical and temperate species (ALB and SWO) are found primarily south of 20°S (Figure 9).

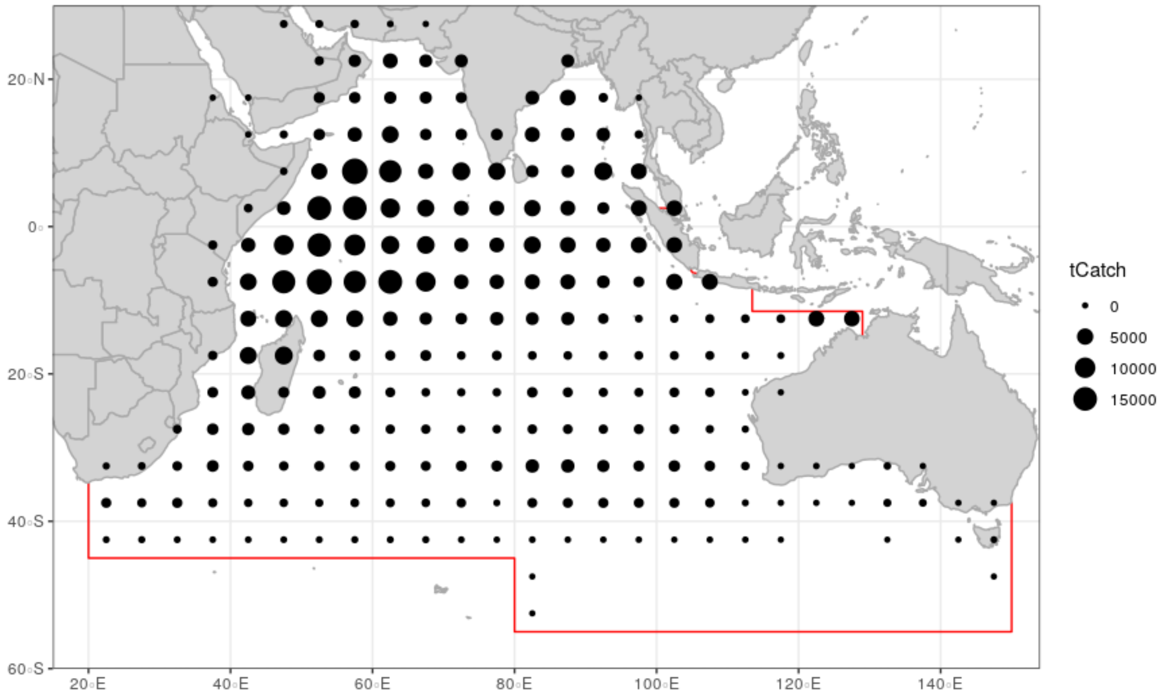

Figure 6. The spatial distribution and quantity of median annual raised catch (MT; 2003-2017) of the main IOTC pelagic species combined including ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) in the IOTC convention area. Circles are proportional to the average quantity of the catch in each grid cell over the period.

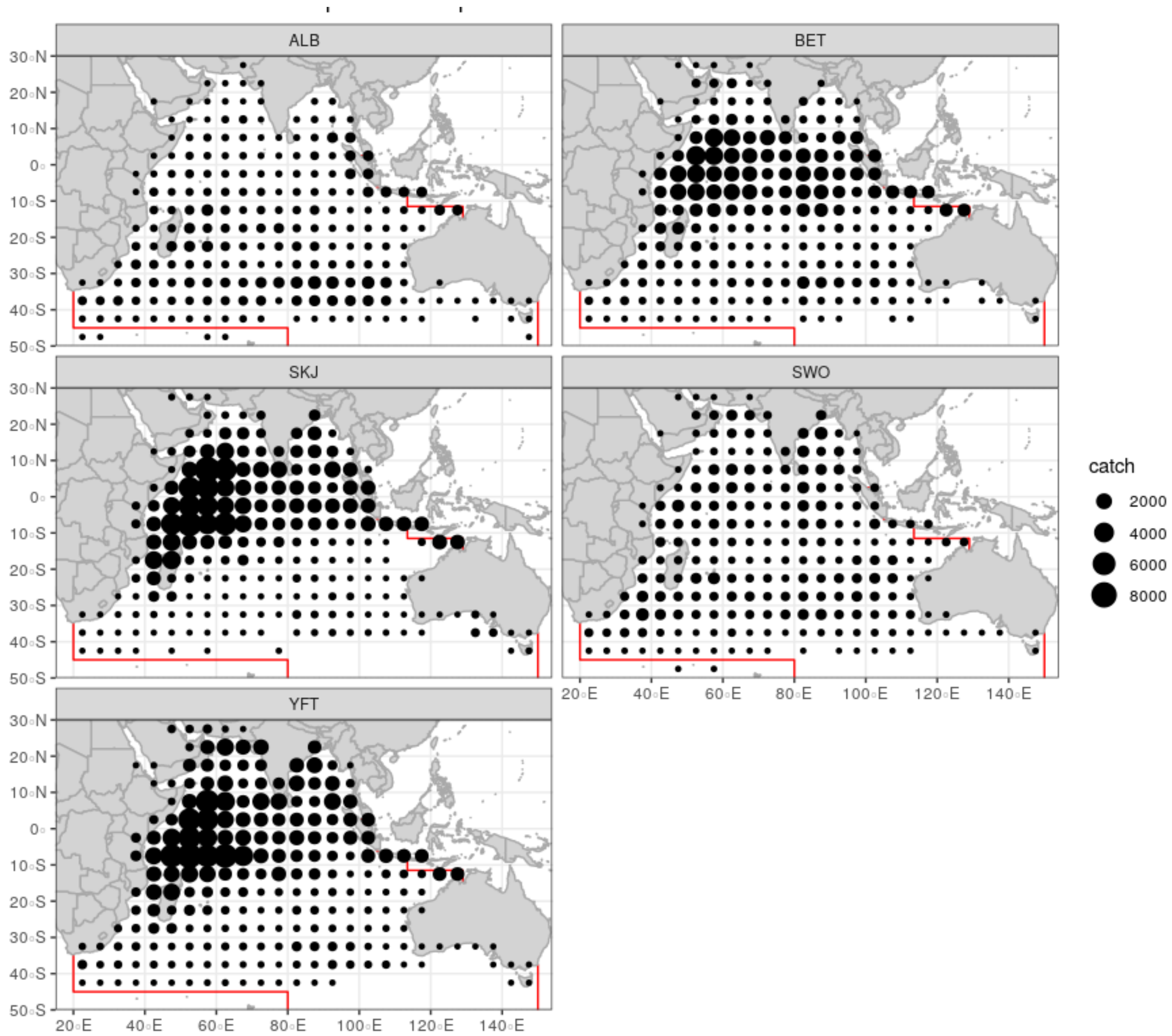

Figure 7 The spatial distribution and quantity of annual raised catch (MT) of each of the main IOTC pelagic species, including ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) in the IOTC convention area averaged over 2003-2017. Circles are proportional to the average quantity of the catch in each grid cell over the period.

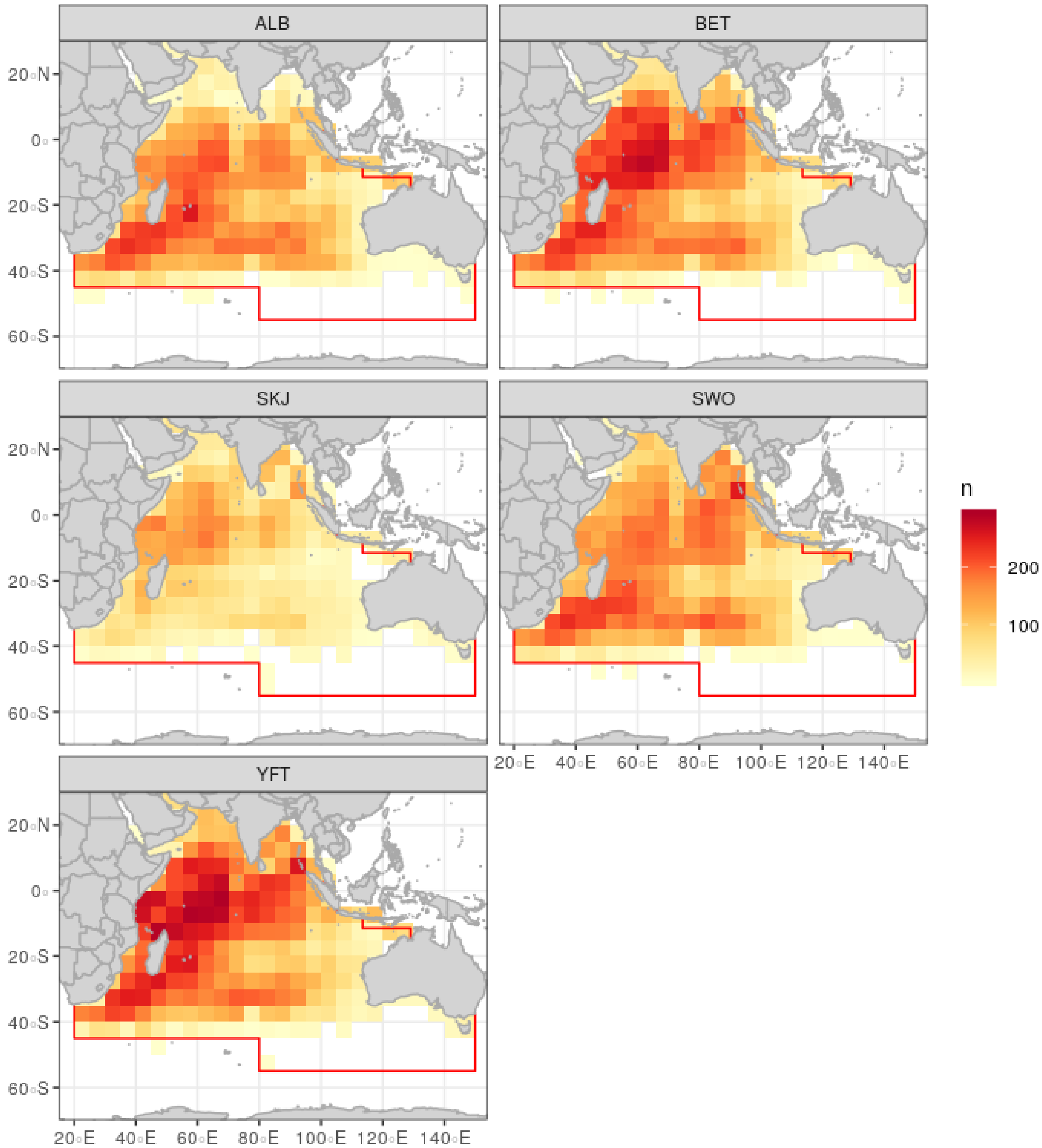

Figure 8 The total number of observations in each grid cell by species for the period 2003-2017 derived from the IOTC raised catch data of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

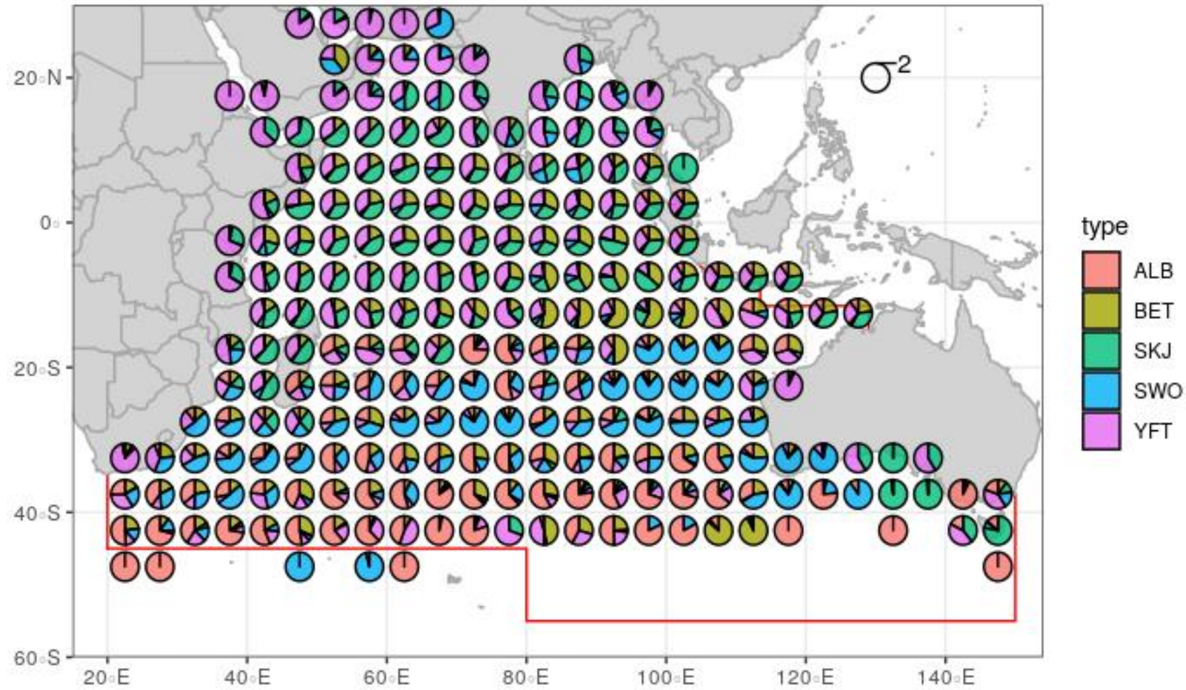

Figure 9. The spatial distribution of annual raised catch of the main IOTC pelagic species, including ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) in the IOTC convention area averaged over 2003-2017. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species in each grid cell.

Neritic species distribution inferred from catch data

Some publicly-available IOTC catch data exist for neritic tuna in the IOTC convention area. Note that these data are not raised and underreporting may be significant. These data were downloaded from the IOTC website (Table 5), regridded to 5°x5°, and averaged over the last 15 years to be consistent with the raised catch data of the pelagic species. Catch data for neritic species are considered "low" in terms of data quality and completeness (Table 5), especially for time-area catches (CE data). However, we note that the georeferenced catch data available show few catches in the coastal regions where neritic species are known to inhabit and sustain coastal fisheries (Figure 10, Figure 11, Figure 12), and in fact, most CE data for neritics are reported in non-regular areas. Much of the georeferenced catch that is reported is located in the Gulf of Aden, the Persian Gulf, south of India in Maldivian and Sri Lankan waters, and in northern Indonesia.

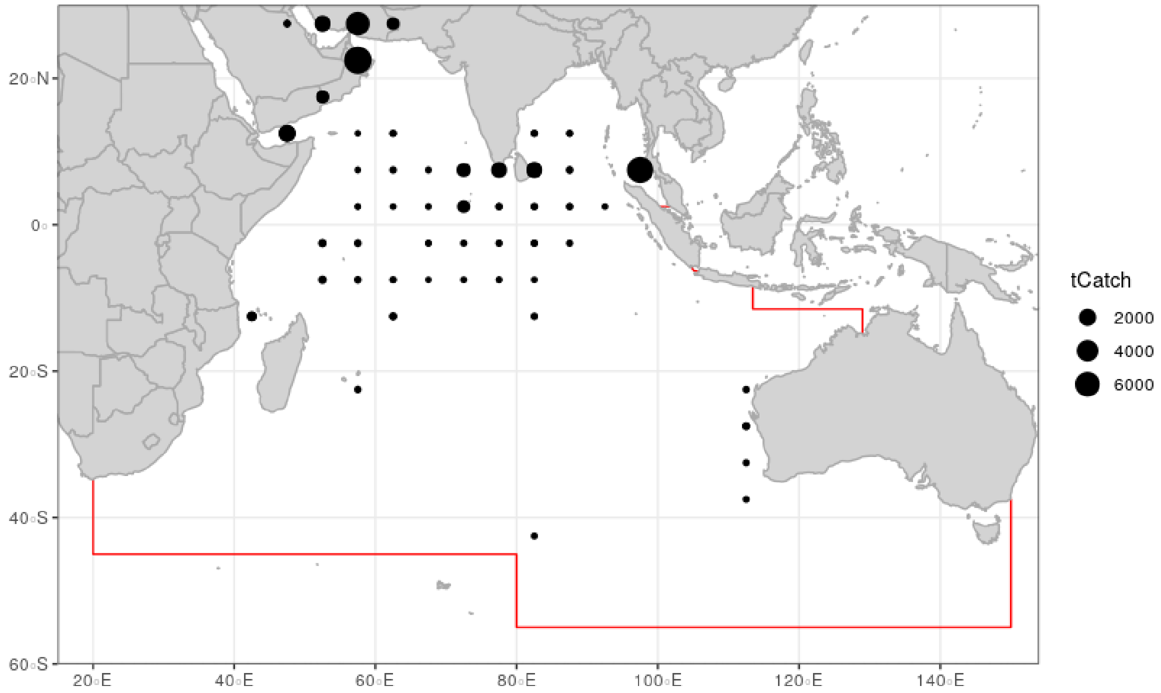

Figure 10. The spatial distribution and quantity of median annual catch (MT) as reported for the IOTC neritic species (see Table 1) in the IOTC convention area averaged over 2003-2017 for each 5°x5° grid cell. Circles are proportional to the catch.

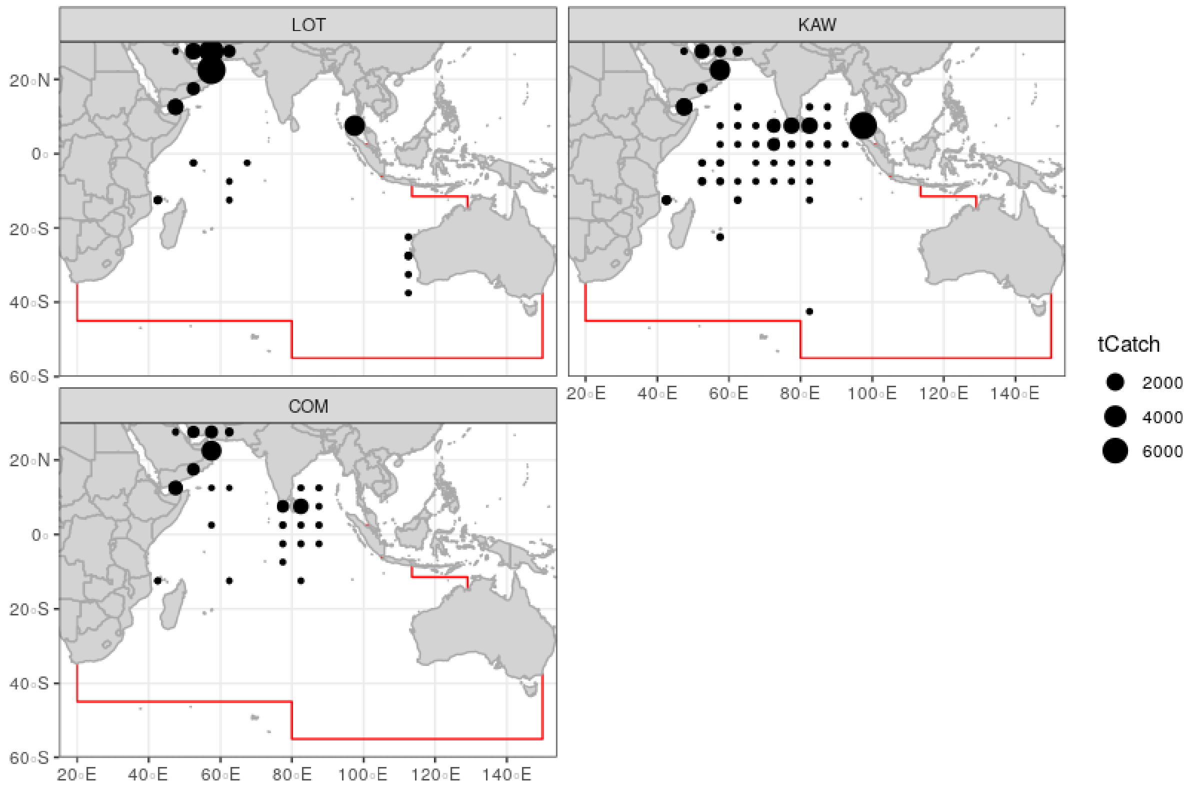

Figure 11. The spatial distribution and quantity of the median annual catch (MT) for each of the three neritic species found in the IOTC online database (Table 5 for data information, Table 1 for species codes).

Reports of high seas catch correspond primarily to kawakawa and longtail tuna, and the narrow-barred Spanish mackerel (Figure 11). These species generally inhabit waters close to the shoreline <200 m in depth (Collette et al. 2001). The neritic species of this dataset are caught primarily by coastal and offshore gillnets, handlines, baitboats, and coastal purse seines, with some catch by beach seines, troll, coastal longline, and there are catches reported by purse seiners (Figure 13).

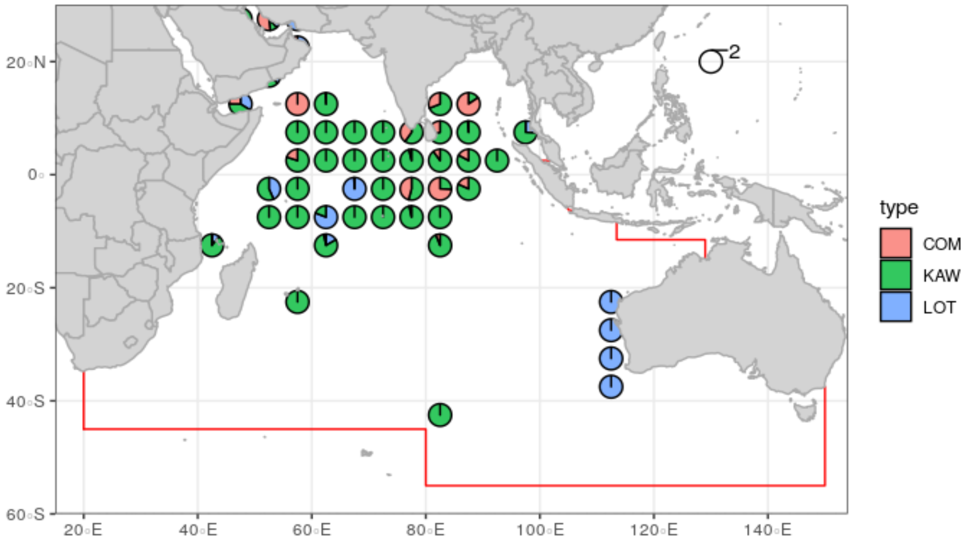

Figure 12. The spatial distribution of annual median catch of IOTC neritic species (see Table 1) in the IOTC convention area averaged over 2003-2017. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell.

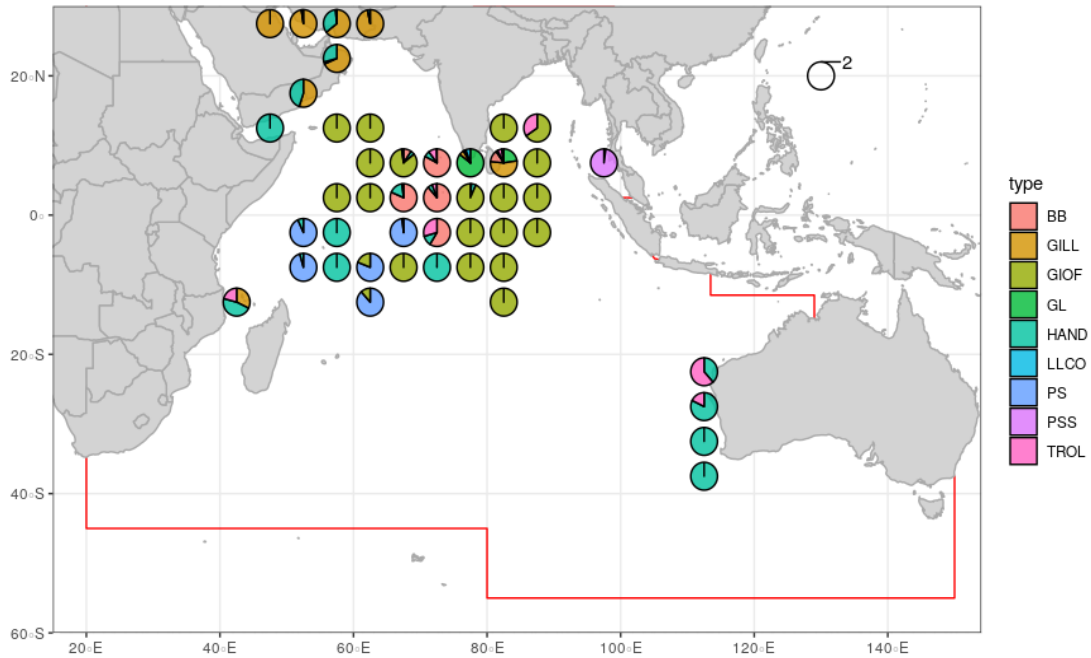

Figure 13. The spatial distribution of the catch of neritic species attributed to each fishery (see Table 7 for gear code) in the IOTC convention area averaged over 2003-2017. Pie sizes are not representative of the quantity of catch, but display the proportion of the catch attributed to each fishery for each grid cell.

Neritic species distribution inferred from IUCN habitat distribution

Neritic species are a critical part of the IOTC fisheries, but there is a substantial lack of information about their catches, spatial distributions and abundance. We account for this deficiency in distribution data by investigating habitat distributions of the three main neritic species using data sourced from the IUCN. We find that these species are primarily found over the continental shelf (~200 m depth) and slope (~1000 m depth), but are known to be present further offshore as well (Figure 14). These data are not explicitly used in the spatial analysis in Section 7, but were used to infer the potential habitat of these species in terms of selecting appropriate biogeographic classifications.

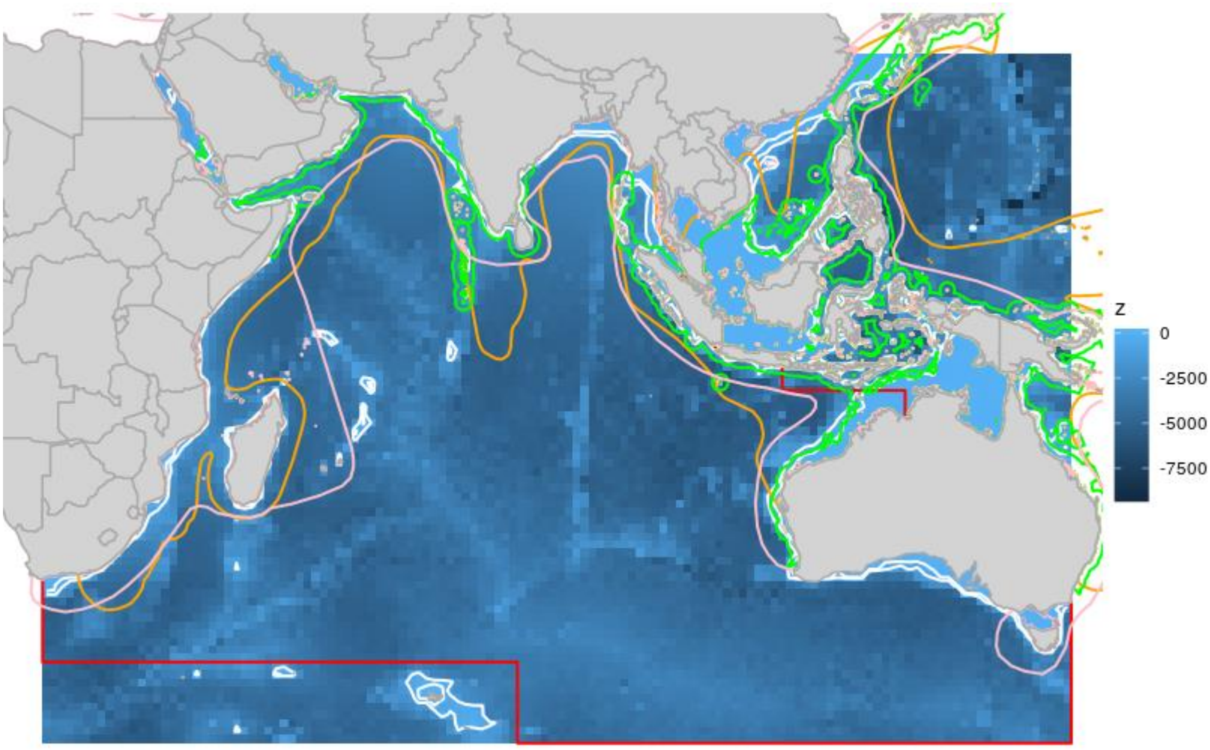

Figure 14. Bathymetry at 5°x5° resolution as sourced from NOAA's ETOPO1 database. The IOTC convention area is delineated by the red line. Habitat distribution of the three main neritic species LOT (green polygon), COM (pink polygon), and KAW (orange polygon) are sourced from the IUCN. Species codes as in Table 1.

Shark distribution inferred from catch data

Some publicly-available IOTC catch data exist for sharks in the IOTC convention area. Note that these data are not raised and underreporting may be significant. These data were downloaded from the IOTC website (Table 5), regridded to 5°x5°, and averaged over the last 15 years as consistent with the raised catch data of the open ocean species. The quality and completeness of these data are of medium quality (Figure 15, Table 5).

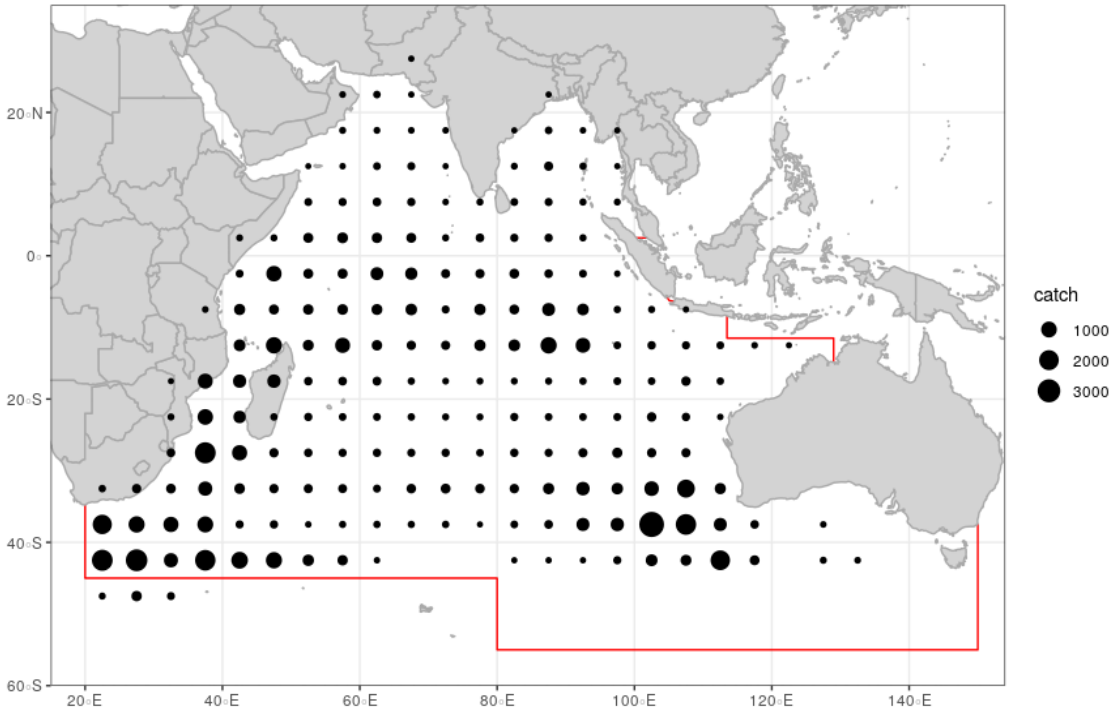

Figure 15. The spatial distribution and quantity of median annual catch (MT) of the sharks in the IOTC convention area averaged over 2003-2017.

The top shark species according to the reported catches are blue (*Prionace glauca,* BSH), silky (*Carcharhinus falciformis,* FAL), oceanic whitetip (*Carcharhinus longimanus,* OCS), and porbeagle (*Lamna nasus,* POR) sharks (Figure 16, Figure 18). Blue sharks are perhaps the widest-ranging shark species with circumglobal distribution in tropical and temperate waters (FAO 1994). We find that spatial catch data reported for the blue shark represents reasonably well the distribution of this species (Figure 19); however, these data show some spatial bias in the southeast and southwest of the IOTC convention area (Figure 16), probably due to reporting issues (Figure 17). Silky sharks have circumtropical distributions that extend to the South Africa (Figure 19; Compagno et al 1989), which is consistent with our findings that show catches of silky sharks are primarily in the northern basin though they are reported as far as 35°S. Porbeagle appear to be caught most frequently south of South Africa, which is in keeping with their known circumglobal distribution in temperate waters of the southern hemisphere (Figure 19; Compagno 1984). However, we find it unlikely that these temperate species would be caught in the northern Indian Ocean as appears in the IOTC catch data (Figure 16). Oceanic whitetip are known to have circumglobal distribution in tropical to subtropical waters (FAO 1994), and we find that the patchy distribution of catch throughout the IOTC convention area reflects its distribution (Figure 16, Figure 18).

Catches of sharks are reported for the different longline fisheries, and some are reported in the coastal purse seine fishery (Figure 20).

Catch distribution data are patchy in terms of representing the spatial distribution of these species and unlikely to reflect their true spatial density (using catch as a proxy). In addition, there appear to be underreporting issues of shark catches for fisheries other than longline. Thus, we have labeled these data layers as ‘medium’ in terms of quality and completeness (Table 5) and have not included them in the spatial analysis in Section 7.

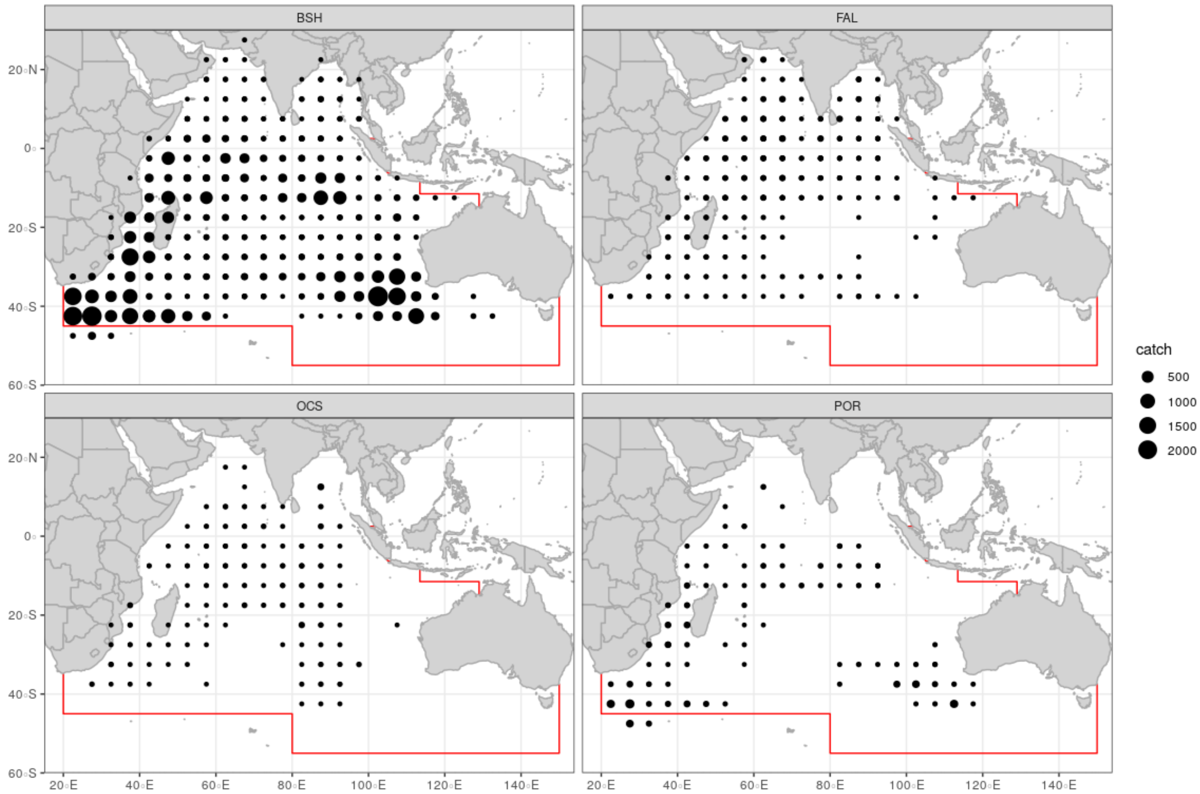

Figure 16. The spatial distribution and quantity of median annual catch (MT) for each of the shark species found in the IOTC online database (Table 5 for data information, Table 1 for species codes).

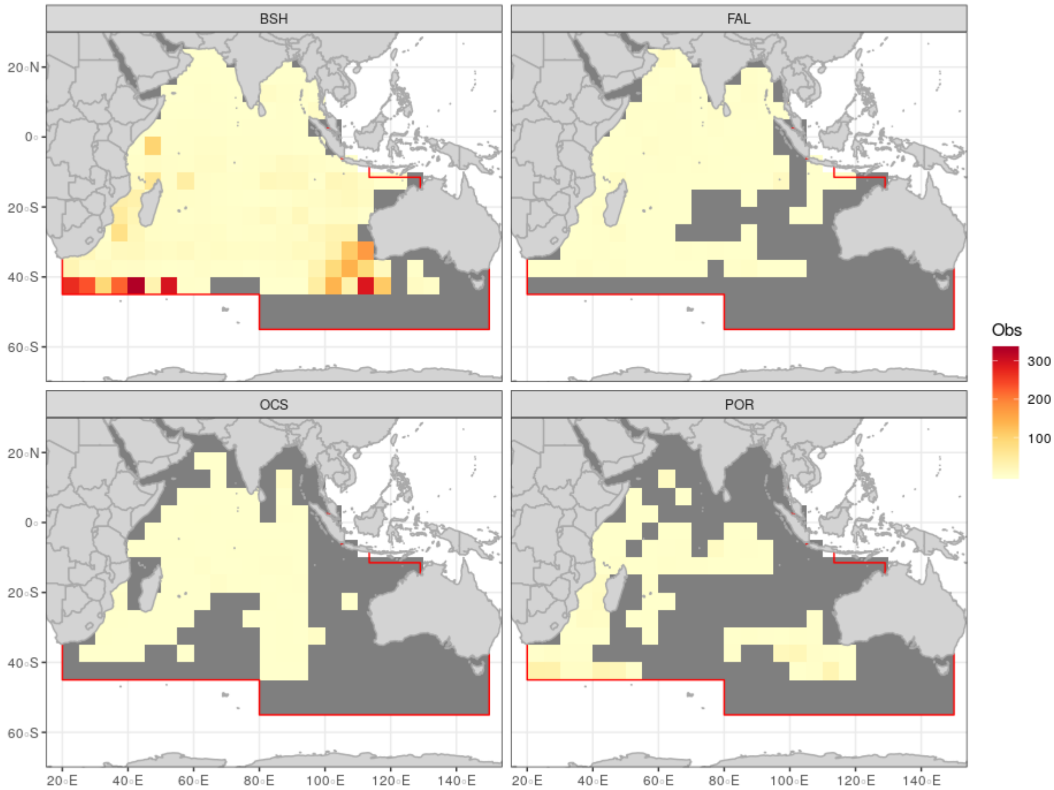

Figure 17. The total number of observations for each of the shark species found in the IOTC online database from 2003-2017.

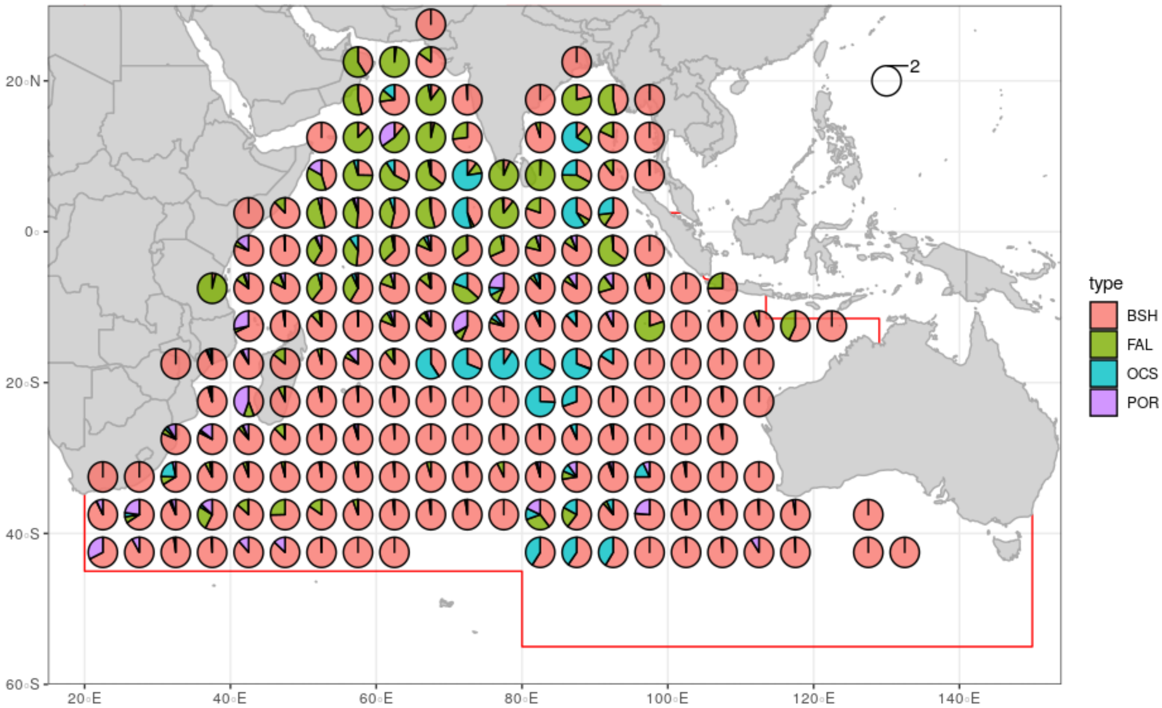

Figure 18. The spatial distribution of median annual catch of sharks by species (see Table 1 for species codes) in the IOTC convention area averaged over 2003-2017. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. The IOTC convention area is indicated by the red polygon.

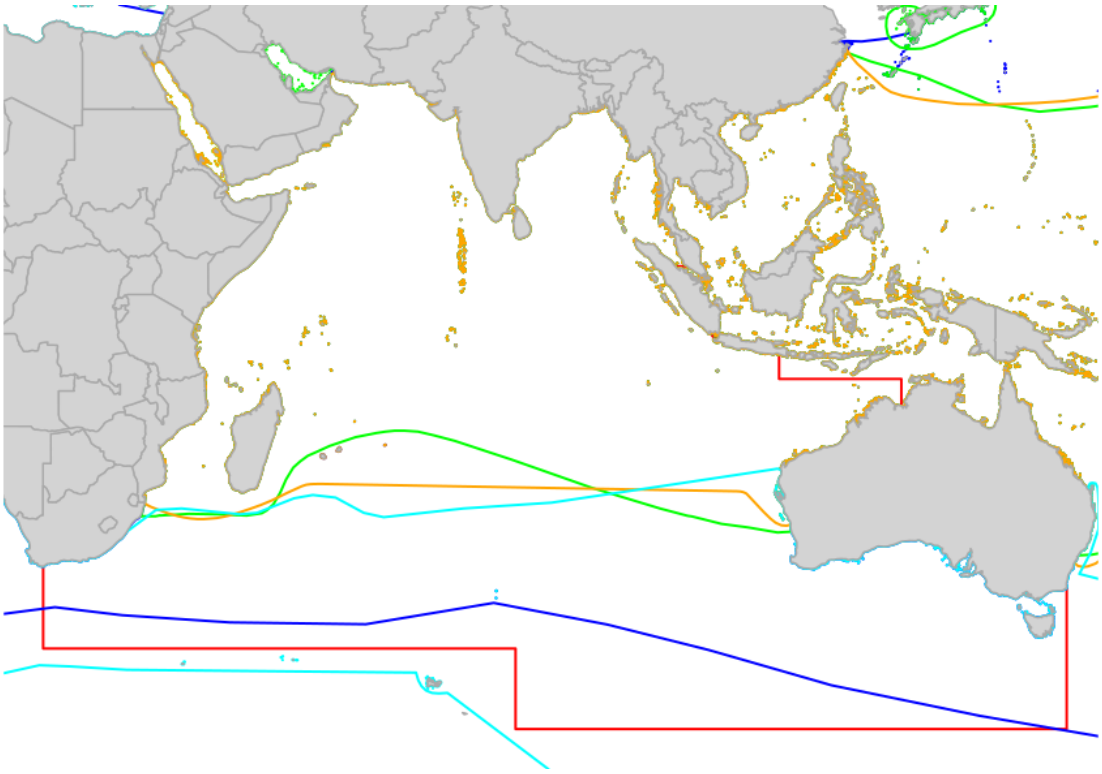

Figure 19. The habitat distribution of BSH (blue polygon), FAL (green polygon), and OCS (orange polygon) and POR (cyan polygon) sourced from the IUCN. The IOTC convention area is indicated by the red polygon.

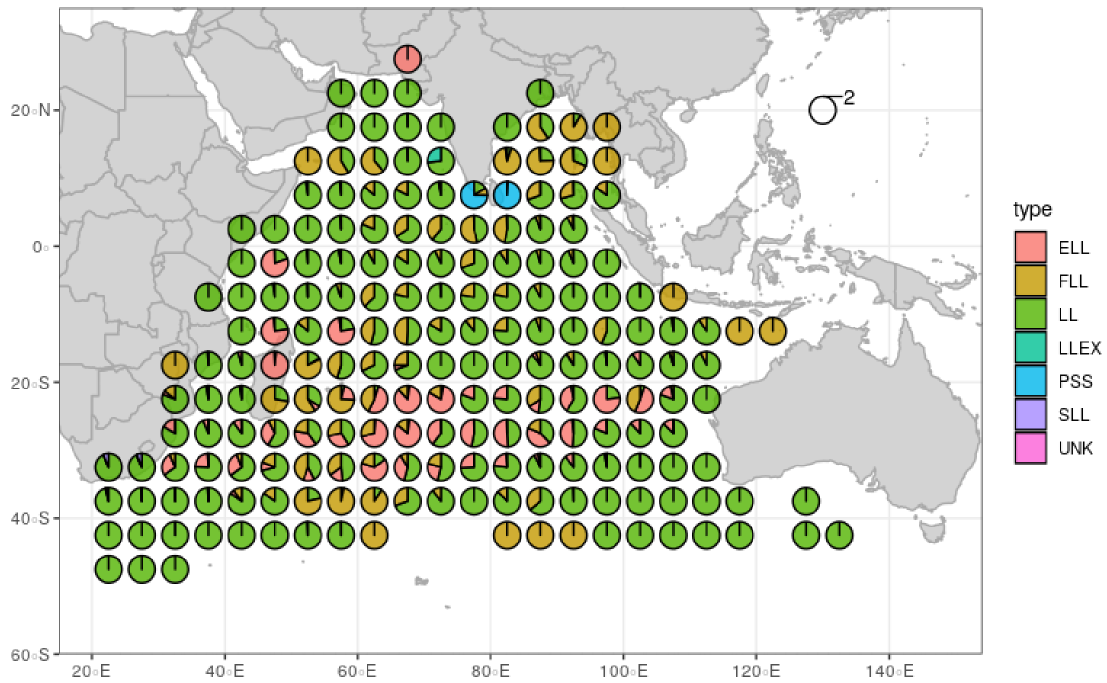

Figure 20. The spatial distribution of the catch of sharks by fishery (see Table 7 for gear codes). Circles are not proportional to catch but instead display the proportion of the catch attributed to each gear type for each grid square.

Other bycatch species

The IOTC regional observer datasets are of low quality and completeness in terms of capturing the spatial distribution and the extent of interactions of bycatch species with IOTC fisheries. These data include some information on marine turtles, sea birds, and marine mammals, but were not included as a spatial layer for analysis (Table 5). Alternatively, we investigated Duke University's Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP; Table 5), which is an online database of spatially-aggregated marine mammal, seabird, sea turtle and shark and ray data (Halpin et al 2009). These data are sourced from global observations and we note that data availability in the Indian Ocean is limited, with most observations along the edges of the basin and little to no observations in the center of the basin. As such, we believe that the distribution of observations is biased and inclusion of these data into a quantitative analysis may lead to biased results. Therefore, we did not further consider these layers of information for later spatial analysis.

We also explored BirdLife International Seabird Tracking Database for observations of 19 species of albatross and petrels (the species thought to be most impacted by IOTC fisheries). These data appear to be widely spread throughout the Indian Ocean basin (except over northern Australia and Indonesia), though their resolution of data discovery is limited in scale due to proprietary restrictions of their datasets. The data are derived from numerous different individual contributors, and special requests are required prior to being granted data access. Unfortunately, access to these data has not currently been granted, and thus we cannot include these data in this study (Table 5).

5.3 Spatial distribution of different life history stages

Size distribution

The spatial distribution of size data can give an indication of any spatial ontogenetic shift during the life cycle of each species by showing for example differences in distributions between adults and juveniles. Size frequency data are publicly-available from the IOTC for many of the species of this study including the main pelagic target species (ALB, YFT, BET, SKJ, and SWO), neritic tuna, several billfish species, and sharks. Data for the main pelagic species are ranked 'good' in terms of quality and completeness, and were further investigated as to their utility as data layers in the spatial analysis (Table 5). We also investigated spatial distributions of size for blue sharks. Following Nikolic et al. 2014, we use length at maturity as derived from the literature and the size at maturity used by IOTC stock assessments (Table 6), and defined juveniles as all those individuals less than the length-at-maturity, and adults were defined as individuals greater than or equal to the length-at-maturity. We then found the median number of individuals from 1980-2017 and across all gears that were below the size-at-maturity (Table 6), and defined these as juveniles, and those that were above the size-at-maturity, are used to separate juveniles from adults when investigating their distributions.

Table 6. Length at maturity (cm) of the main IOTC species where size frequency data are 'good' or 'medium', as is the case for BSH (blue shark, *Prionace glauca*). Other species codes as in Table 1.

Species	Size at maturity (cm)	Source
ALB	85	FishBase
YFT	100	IOTC
BET	100	IOTC
SKJ	42	IOTC
SWO	145	IOTC
BSH	198	IOTC

We find that ALB has a distinct pattern in the spatial distribution of juveniles, with the majority of juveniles found south of 20°S and the adults found overlapping to 30°S and the majority of their distribution in north of 30°S over the basin until 15°S, and then primarily in the western Indian Ocean fishing grounds (Figure 21). This pattern has an overall coherence with previous studies that indicate a north-south divide between adults and juveniles of ALB (i.e. Nikolic et al. 2014).

The majority of the YFT and BET are fished in the western Indian Ocean, which is also where almost all their juveniles are caught (Figure 20, 22). This pattern of juvenile distribution is likely due to the fact that purse seines in the western Indian Ocean catch juvenile BET and YFT; and the likely true distribution of juvenile BET and YFT is likely much wider than found from these size data. The majority of SKJ caught are adults with catches primarily in the western Indian Ocean and across the basin between 0° and 15°S (Figure 23). The few juveniles that are caught are in the north western Indian Ocean, corresponding to the distribution of the industrial purse seine fishing grounds (see Figure 29).

SWO spatial distribution of size shows that almost all of the individuals caught are juveniles, distributed throughout the basin, but primarily south of 20°S (Figure 24). Likewise, we find that the spatial distribution of blue shark size classes indicate that almost all individuals caught are juveniles (<214 cm, Table 6, Figure 25).

We find that with the exception of ALB, the spatial distribution of size is not likely to meaningfully contribute to the spatial analysis in Section 7. For BET, YFT, and SKJ, the differentiation between the spatial distribution of juveniles to adults is biased by the fishing gear, i.e. purse seines in the western Indian Ocean. For SWO and blue sharks, no adult distribution is represented in the data, thus as an input these data would be repetitive to the species distribution data as in Figure 7. As such, these data are not considered further (Table 5).

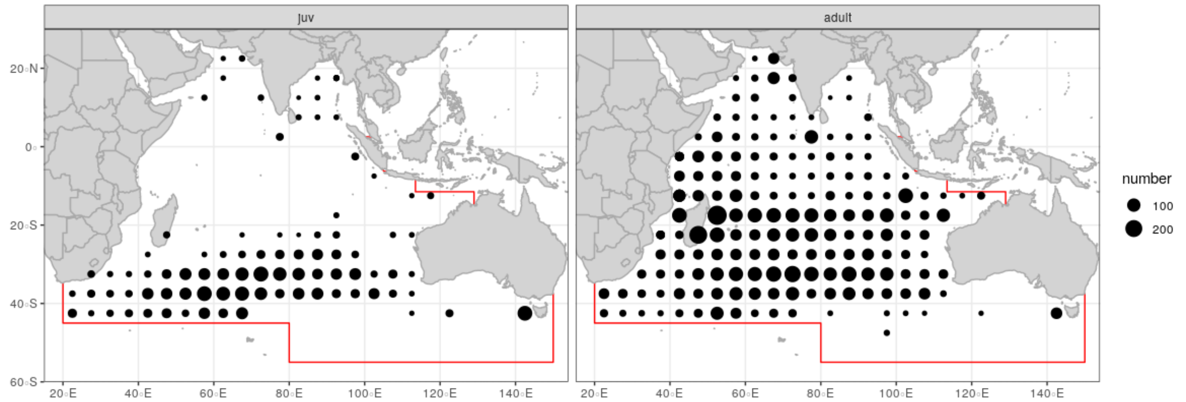

Figure 21. Distribution using the number of juveniles (left panel) and adults (right panel) for ALB as determined by their size-at-maturity (Table 6). Data are from 1980-2017 and include all gear types. Species codes as in Table 1.

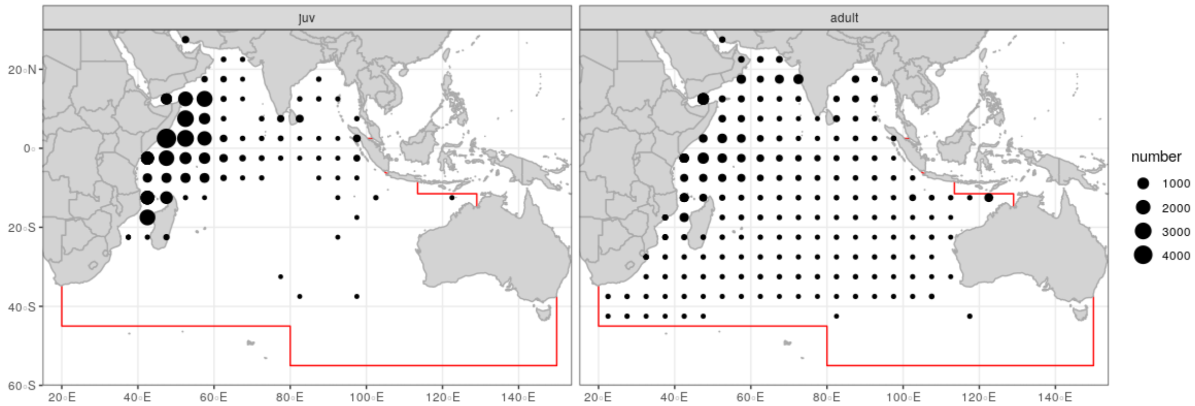

Figure 20. Distribution using the number of juveniles (left panel) and adults (right panel) of YFT as determined by their size-at-maturity (Table 6). Data are from 1980-2017 and include all gear types. Species codes as in Table 1.

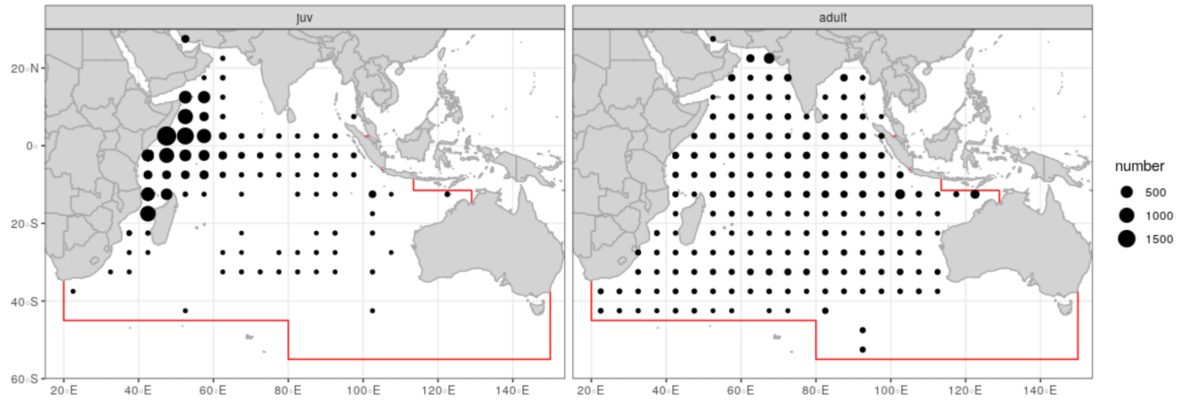

Figure 22. Distribution using the annual median number of juveniles (left panel) and adults (right panel) for BET as determined by their size-at-maturity (Table 6). Data are from 1980-2017 and include all gear types. Species codes as in Table 1.

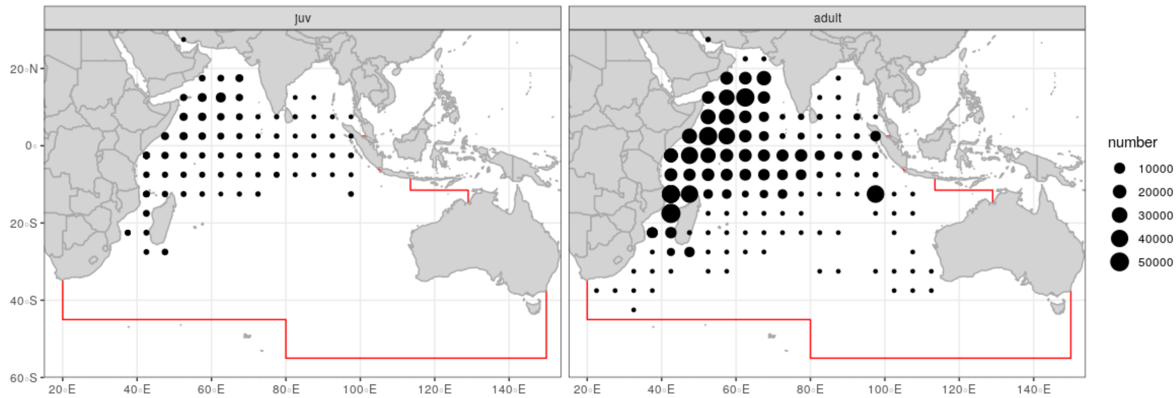

Figure 23. Distribution using the annual median number of juveniles (left panel) and adults (right panel) for SKJ as determined by their size-at-maturity (Table 6). Data are from 1980-2017 and include all gear types. Species codes as in Table 1.

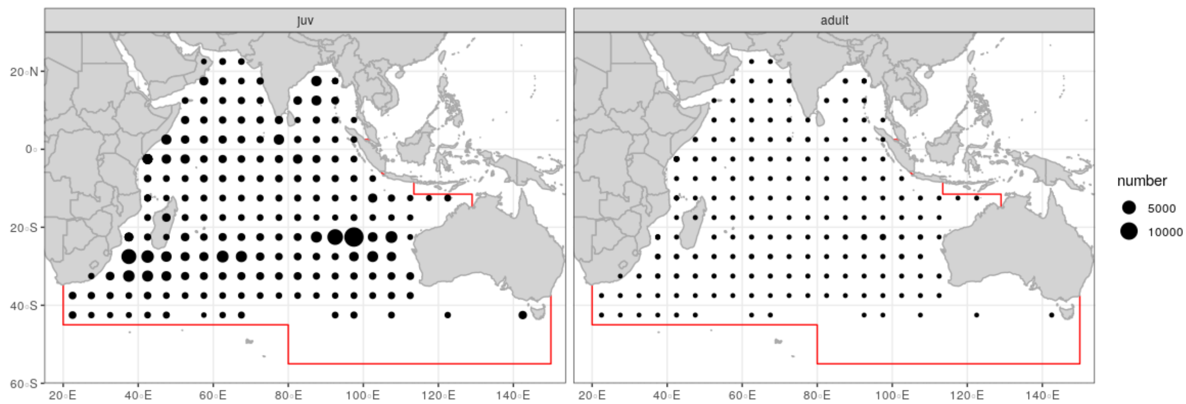

Figure 24. Distribution using the annual median number of juveniles (left panel) and adults (right panel) for SWO as determined by their size-at-maturity (Table 6). Data are from 1980-2017 and include all gear types. Species codes as in Table 1.

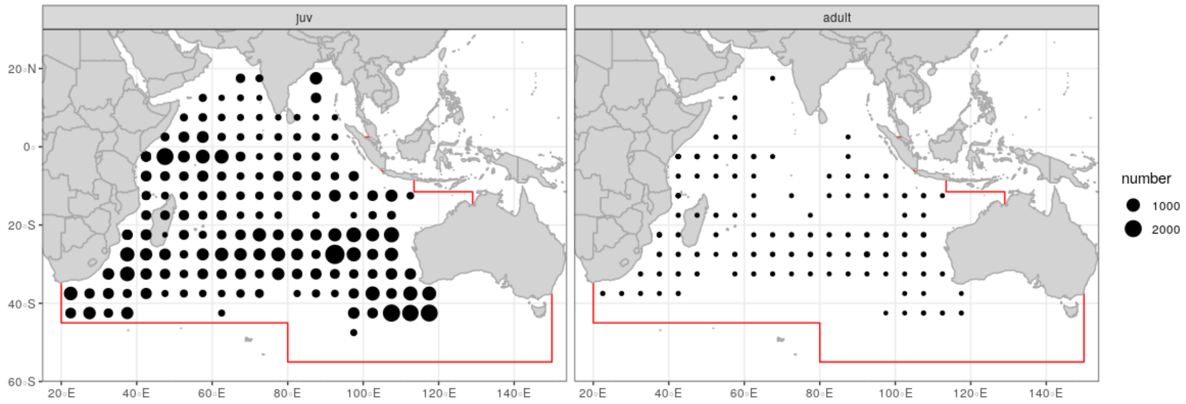

Figure 25. Distribution using the annual median number of juveniles (left panel) and adults (right panel) for blue sharks as determined by their size-at-maturity (Table 6). Data are from 1980-2017 and include all gear types. Species codes as in Table 1.

Presumed spawning regions

Relatively little is known about the spawning distributions of the main species of the IOTC, and one of the highest priorities of the IOTC Working Party for Tropical Tuna and the Working Party for Billfish was to expend more effort to identify biological information on maturity, fecundity, and spawning season and location. Here, we present the little that is known of the presumed spawning regions of the main IOTC species (Table 5). These spawning regions are presented in a qualitative manner and are meant to inform discussion and to invite advice from the experts at the workshop. Where possible, information on distribution according to species-specific behaviour (e.g., feeding grounds, migration pathways) is also included.

Albacore, Thunnus alalunga (ALB)

Albacore are thought to spawn in the tropical band of the Indian Ocean between 10°S and 30°S (Nikolic et al. 2014), and including the Indo-Australian Bight in the pathway of the Indonesian Throughflow (Figure 26). The feeding region of the adults is located in the western Indian Ocean and the Mozambique Channel. Albacore are thought to segregate by size and age with juveniles found primarily south of 20°S, and adults found in the north and west (Figure 26).

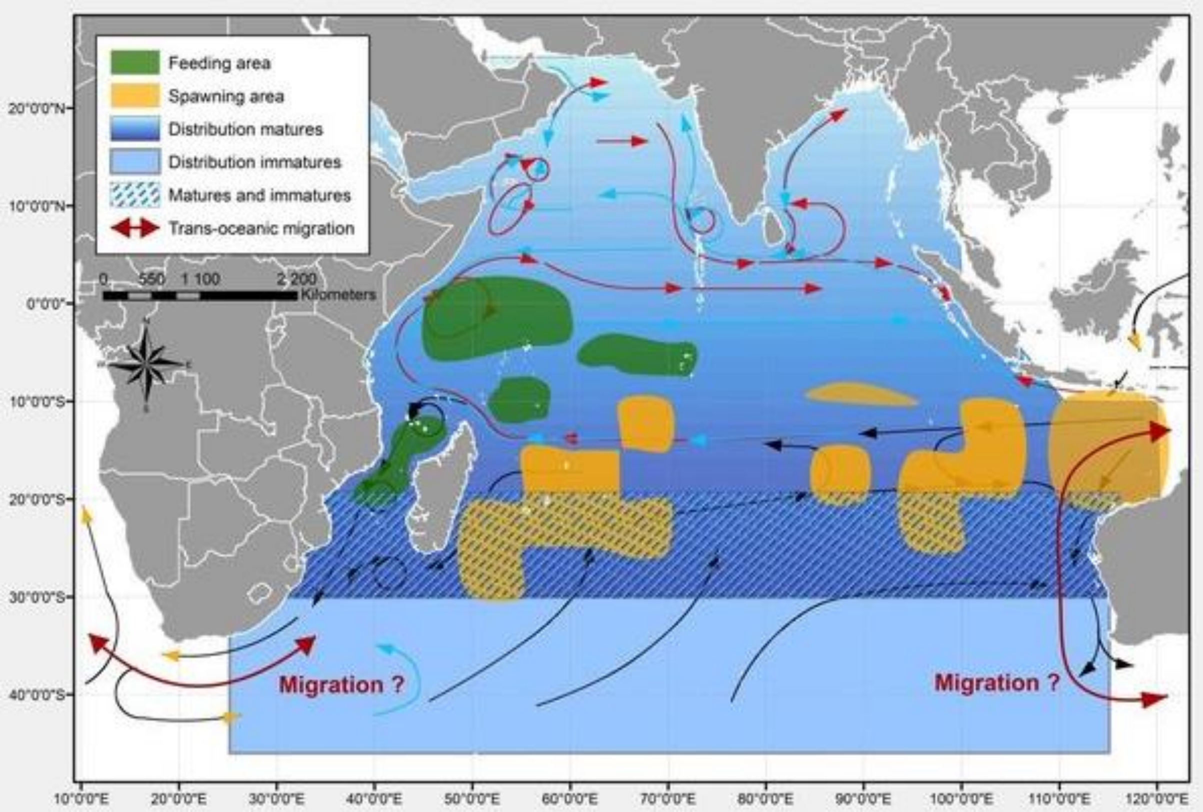

Figure 26. Distribution of albacore in the Indian Ocean throughout its life history, including presumed spawning regions, juvenile and adult distributions, and potential migration pathways taken from Nikolic et al. 2014.

Yellowfin, Thunnus albacares (YFT)

Yellowfin spawning occurs from December to March in the longitudinal band from 0° to 10°S, with the primary spawning grounds west of 75°E. Secondary spawning grounds are found off Sri Lanka, in the Mozambique Channel, and off Australia (IOTC 2016a).

Bigeye, Thunnus obesus (BET)

Bigeye spawning in the Indian Ocean occurs from December to January, and in June in the eastern Indian Ocean (IOTC 2016b).

Skipjack, Katsuwonus pelamis (SKJ)

Skipjack are thought to spawn opportunistically year round. They are considered income breeding species, meaning that they require an external food source very soon after hatching. This tends to concentrate spawning near regions of high productivity, which in the Indian Ocean can include the Mozambique Channel and the Somali Upwelling (Druon et al. 2016; Chassot et al 2019).

Swordfish, Xiphias gladius (SWO)

Some studies have suggested potential locations of swordfish spawning grounds in the Indian Ocean (i.e Mejuto et al. 2006, Poisson and Fauvel 2009). These presumed spawning grounds are located along the Somali coast, potentially around Reunion Island, and in the Bay of Bengal (Figure 27).

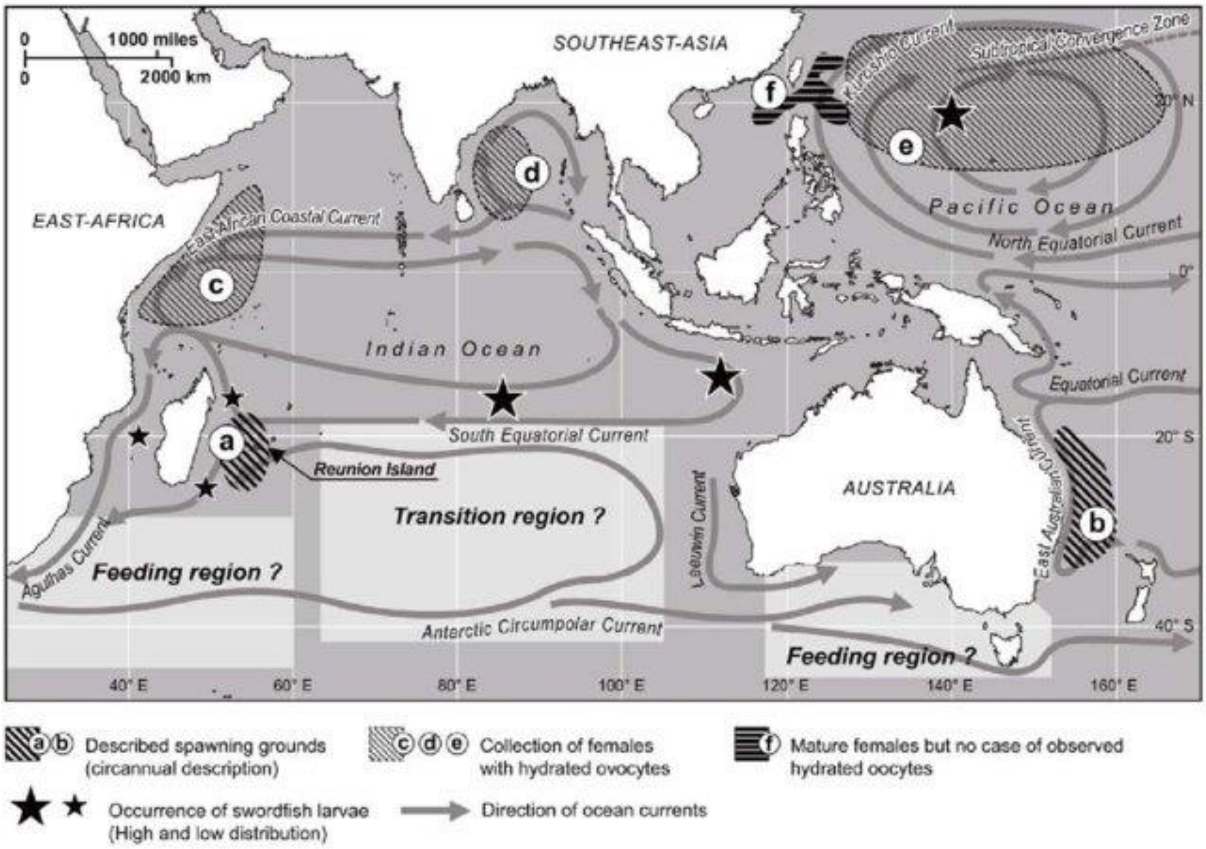

Figure 27. The described and potential spawning grounds of swordfish in the Indian and western Pacific Oceans (taken from Poisson and Fauvel 2009).

5.4 Spatial distribution of the main IOTC fisheries

The spatial distribution of the main IOTC fisheries were inferred by plotting the estimated raised catch data for the main IOTC oceanic species (ALB, YFT, BET, SKJ, SWO) by gear type (Table 7, Figure 28).

High seas purse seiners dominate the catch, followed by longline fisheries (Figure 28). Several different types of longline fisheries are important in terms of catch in the IOTC. These longline types are split based on the species they target (i.e. swordfish versus tuna, ELL), how they store their catch (deep freezing versus fresh, FLL), and where they operate (high seas versus coastal; Table 7). A variety of other gear types, often operating in coastal areas account for much of the rest of the catch (Table 7).

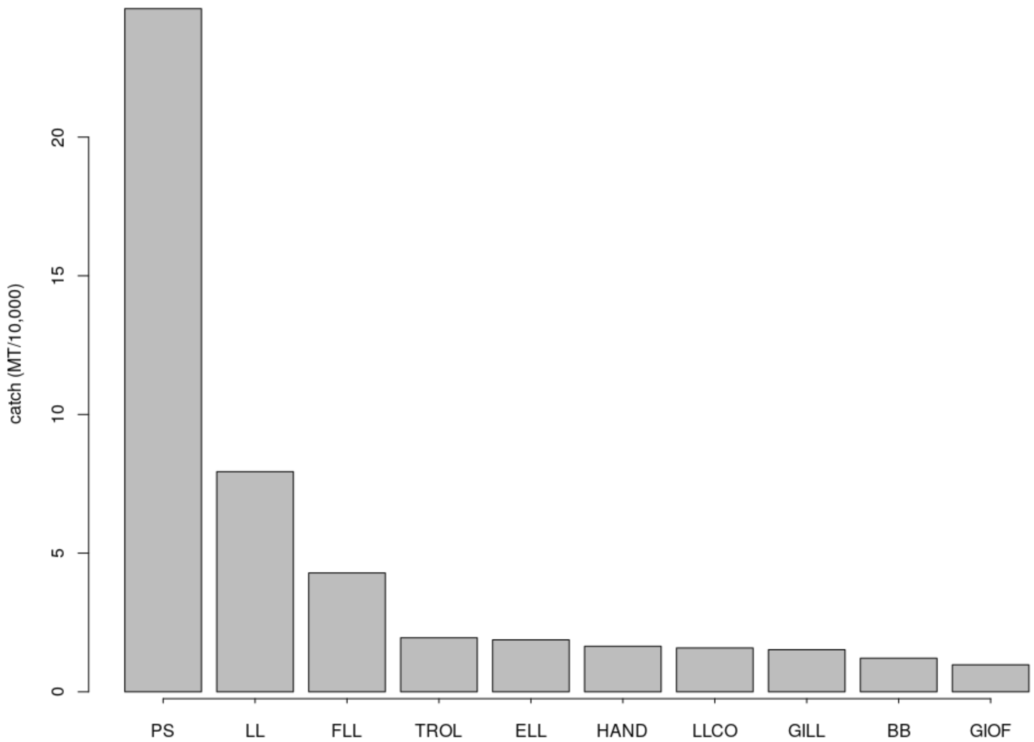

Figure 28. Median annual catch between 2003-2017 by the main gear types of the main target species in the IOTC convention area: ALB, BET, YFT, SKJ, and SWO (see Table 1 for species codes). Gear codes are as in Table 7.

Table 7. The main IOTC fisheries (see Figure 28) in the IOTC convention area.

Major fishery	Habitat type		IOTC fishery codes
Purse seine	High seas	Purse seine high seas	PS
Longline	High seas	Long line high seas deep-freezing tuna	LL
Longline	High seas	Long line high seas fresh-tuna	FLL
Longline	High seas	Longline high seas targeting swordfish	ELL
Longline	Coastal	Longline coastal	LLCO
Gillnet	Coastal	Coastal gillnet	GILL
Gillnet	High seas	High seas gillnet	GIOF
Baitboat	Coastal	Baitboat	BB
Line	Coastal	Handline	HAND
Line	Coastal	Trolling	TROL

The main fisheries operating in the high seas are the longline and purse seine fisheries, with purse seine vessels operating primarily in the northwest (Figure 30), and longlines operating throughout the Indian Ocean (Figure 29), though these fisheries dominate the catch south of 20°S and in southeast (Figure 33). The coastal regions of continents and around island nations are more complex in their gear use, which is divided between gillnet, baitboat, handline, and trolling fisheries (Figure 31, Figure 32, and Figure 33). Longlines targeting swordfish (ELL) operate in a longitudinal band mainly between 20°S and 30°S. Baitboats and handlines are particularly important in Maldivian waters south of India. Both coastal and offshore gillnets, trolling, and longline (LL) are the main gears in the northern Arabian Sea, while fresh-storage longliners (FLL) operate mostly due south of the Bay of Bengal and in the eastern basin. Fisheries are diverse along Indonesia's coastline, and coastal longline, trolling, baitboat, and handlines make up a large proportion of the catch.

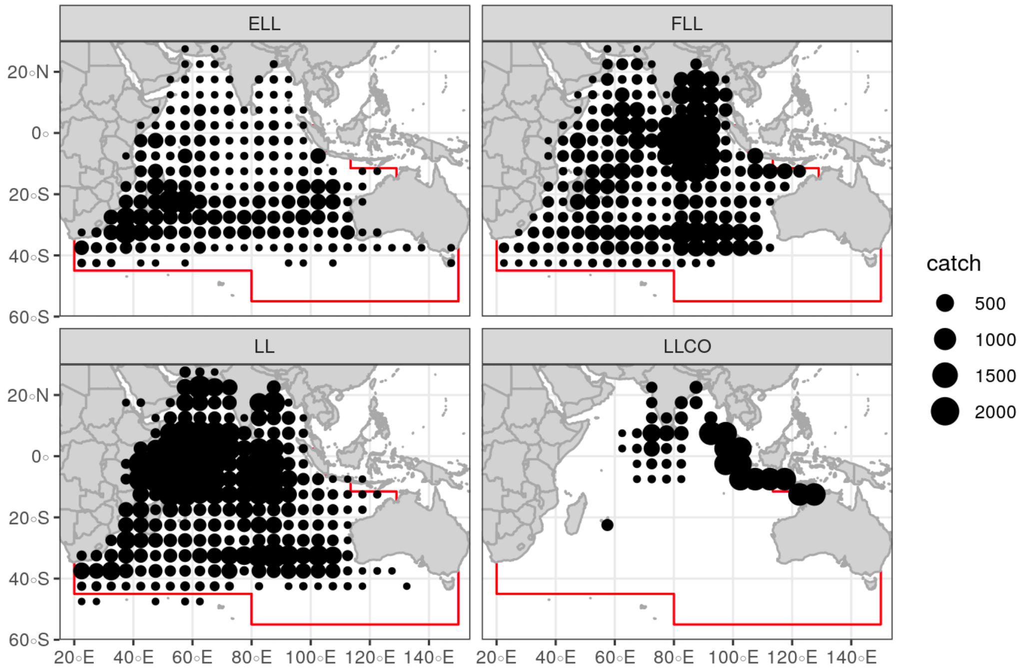

Figure 29. Spatial distribution of the longline IOTC fisheries (i.e., ELL, FLL, LL, and LLCO; see Table 7) as inferred from median catch per grid cell of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) between 2003-2017.

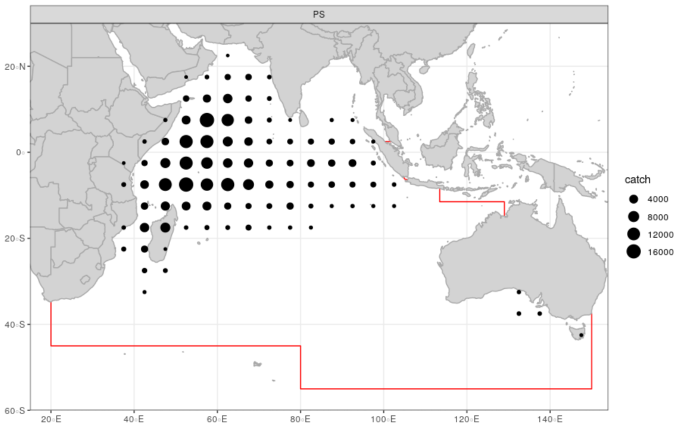

Figure 30. Spatial distribution of the industrial purse seine IOTC fisheries (PS; see Table 7) as inferred from median catch per grid cell of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) between 2003-2017.

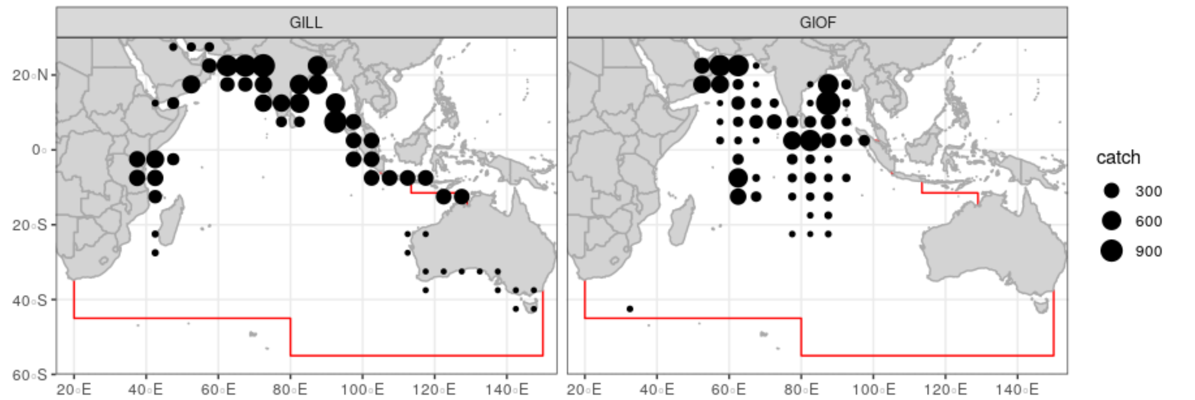

Figure 31. Spatial distribution of the gillnet IOTC fisheries (i.e., GILL, GIOF, and GL; see Table 7) as inferred from median catch per grid cell of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) between 2003-2017.

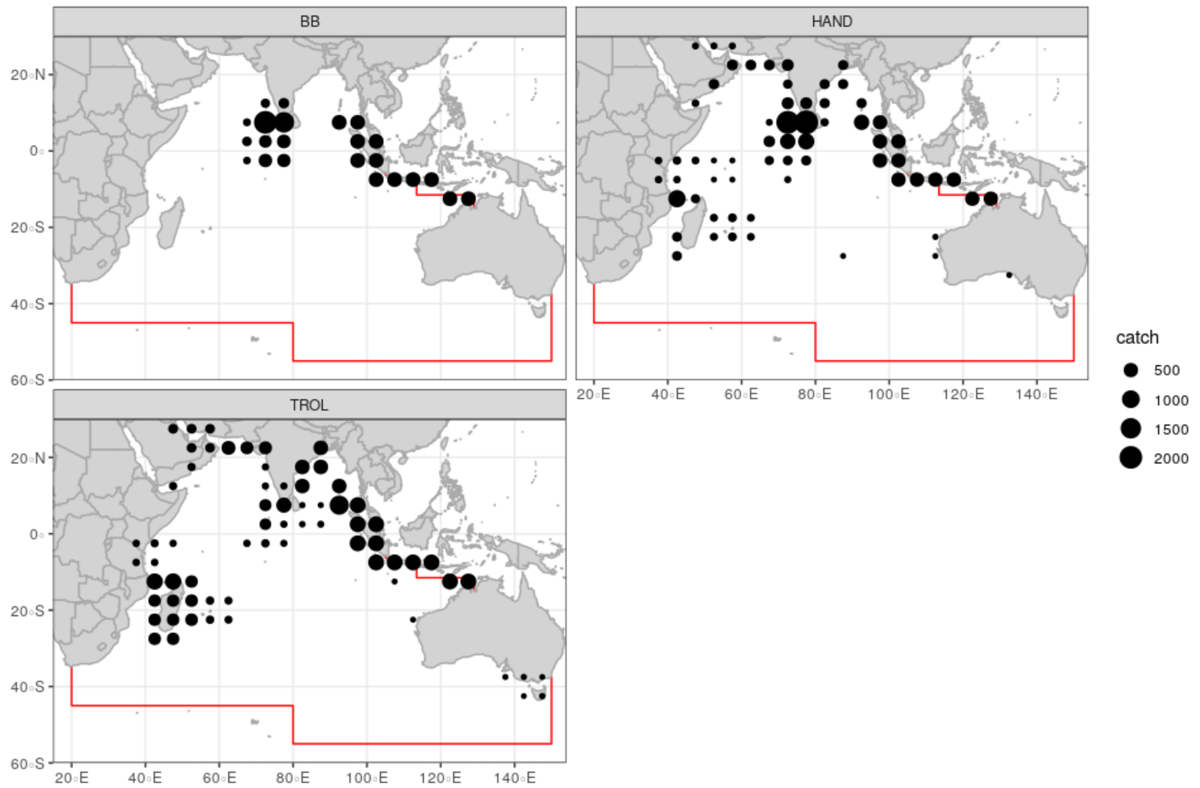

Figure 32. Spatial distribution of the other coastal IOTC fisheries (i.e., BB, HAND, and TROL; see Table 7) as inferred from median catch per grid cell of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes) between 2003-2017.

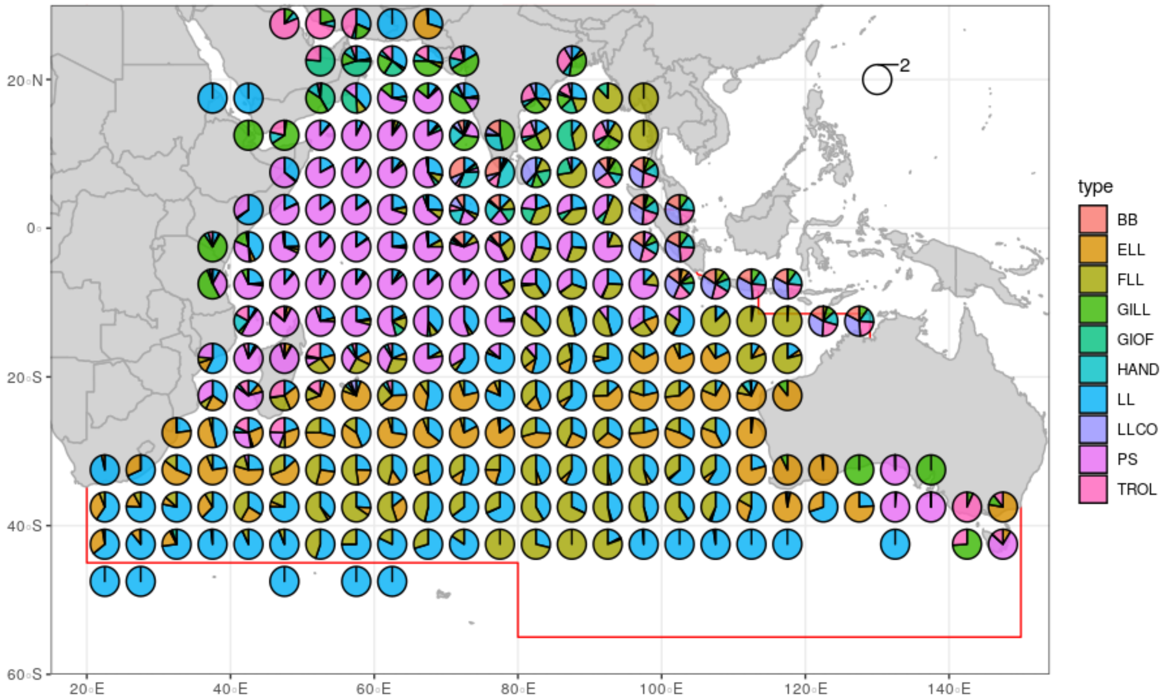

Figure 33. Spatial distribution of the main IOTC fisheries as inferred from catch. Gear codes are as in Table 7. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are derived from an average over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

Industrial purse seine (PS), whose catches are the largest relative to all other fisheries, have catch made up mostly of SKJ and YFT, with some BET (Figure 34). Industrial longlines (LL, ELL, and FLL) show diverse catch with YFT caught mostly in the northern basin, a mix of BET, SWO, and YFT caught in the middle-north and western basin, and ALB and SWO making up the majority of the catch in the southern basin (Figure 35). The catch of offshore gillnets (GIOF) is mostly SKJ with some YFT catches as well (Figure 36). Coastal gillnets (GILL) primarily report catches of YFT and SKJ in the western Indian Ocean and around Australia (Figure 37). A large proportion of the gillnet catch around India appears to be SWO, while the majority of catch along Indonesia is reported to be BET (Figure 37). The catch of coastal longlines (LLCO) are diverse and are shared between YFT, SWO, and SKJ, with some catch of ALB reported along Indonesia (Figure 39). The other major coastal fisheries, including HAND, TROL, and BB (see Table 7 for gear codes) operate along the coasts of the continents, but also around the island nations of the central and western Indian Ocean. Their catches are primarily made up of YFT and SKJ, though ALB are reported in the catches around the Mascarene Islands and in southern Australia (Figure 40).

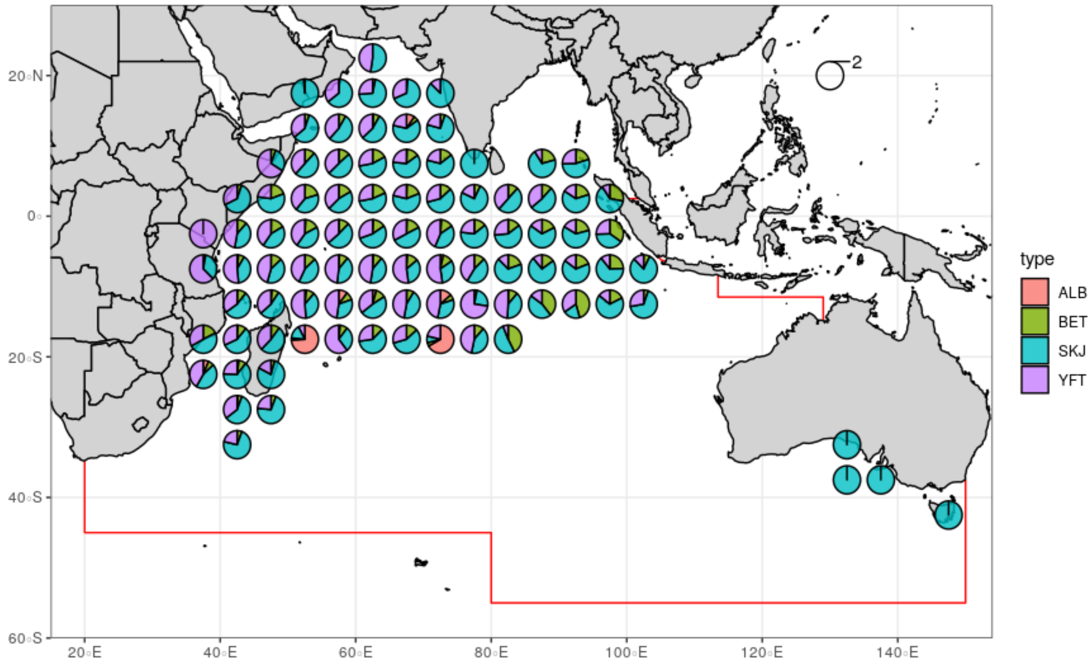

Figure 34. Spatial distribution of the main IOTC target species caught by industrial purse seiners (PS) in the IOTC convention area. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are derived from the annual median over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

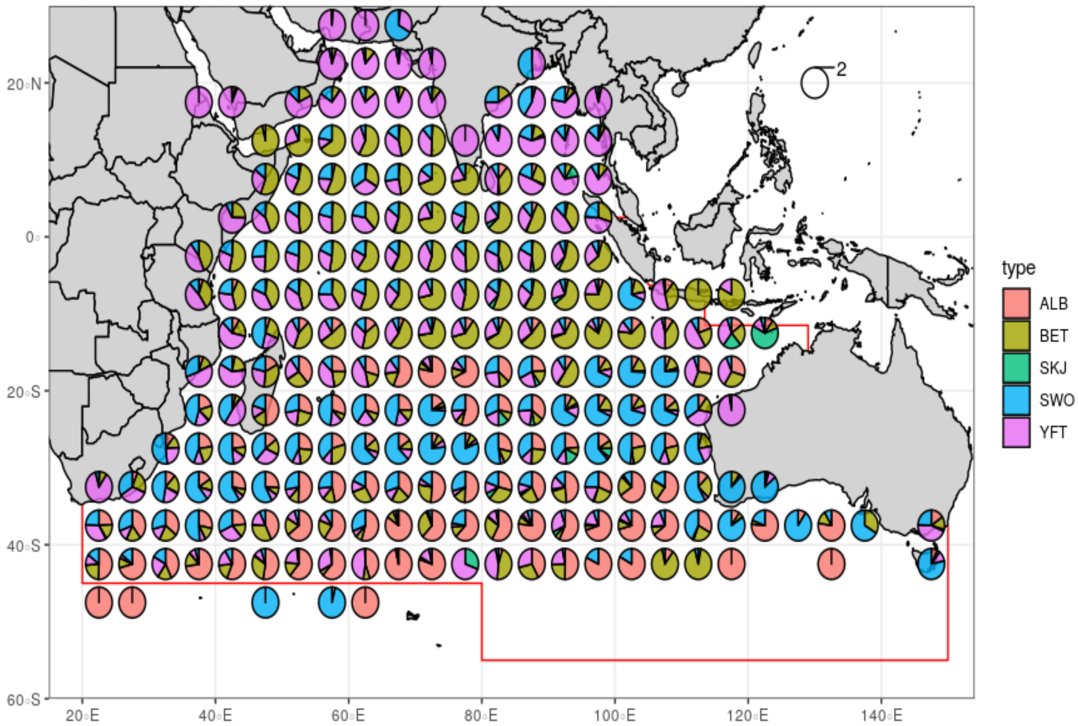

Figure 35. Spatial distribution of the main IOTC target species caught by industrial longliners (LL, ELL, FLL; see Table 7 for gear codes) in the IOTC convention area. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are derived from the annual median over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

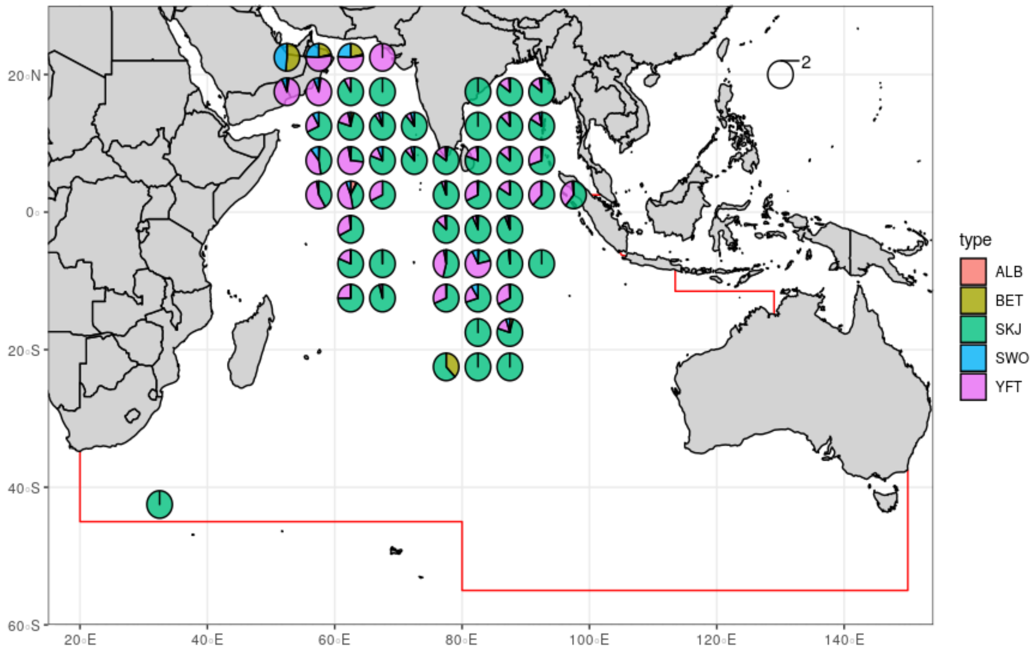

Figure 36. Spatial distribution of the main IOTC target species caught by high seas gillnets (GIOF) in the IOTC convention area. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are derived from the annual median over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

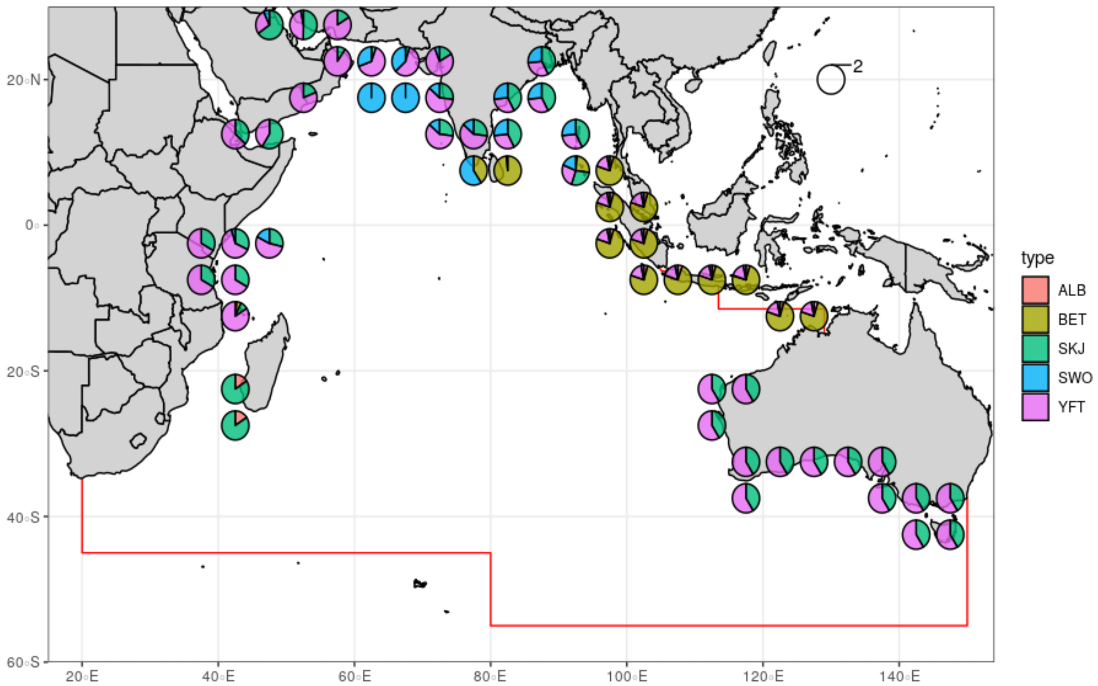

Figure 37. Spatial distribution of the main IOTC target species caught by coastal gillnets (GILL; see Table 7 for gear codes) in the IOTC convention area. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are derived from the annual median over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

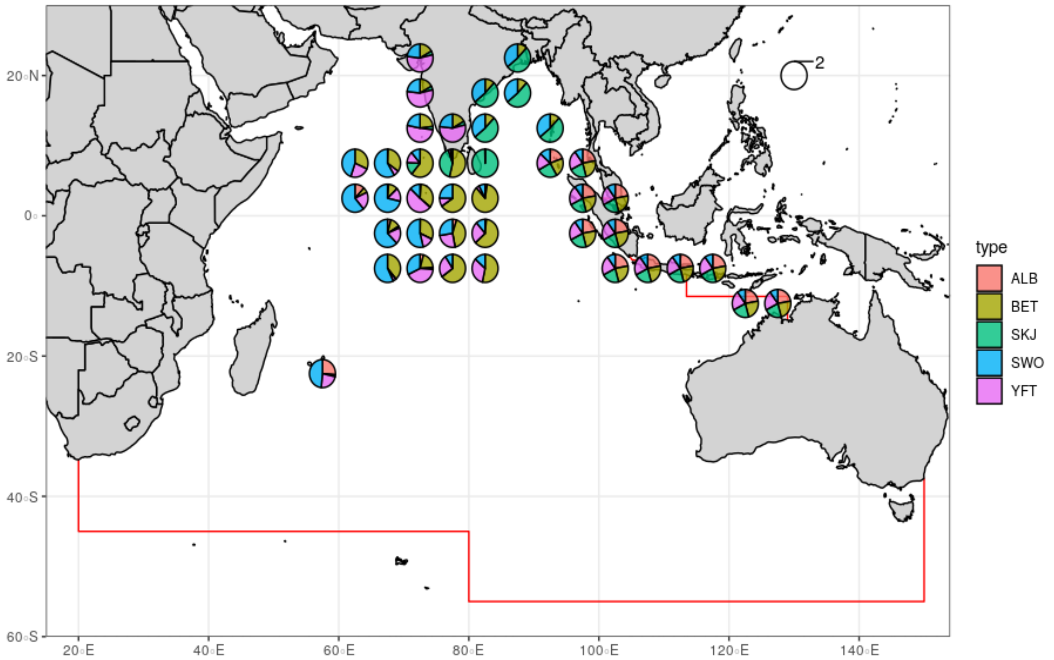

Figure 39. Spatial distribution of the main IOTC target species caught by coastal longliners (LLCO; see Table 7 for gear codes) in the IOTC convention area. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are derived from the annual median over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

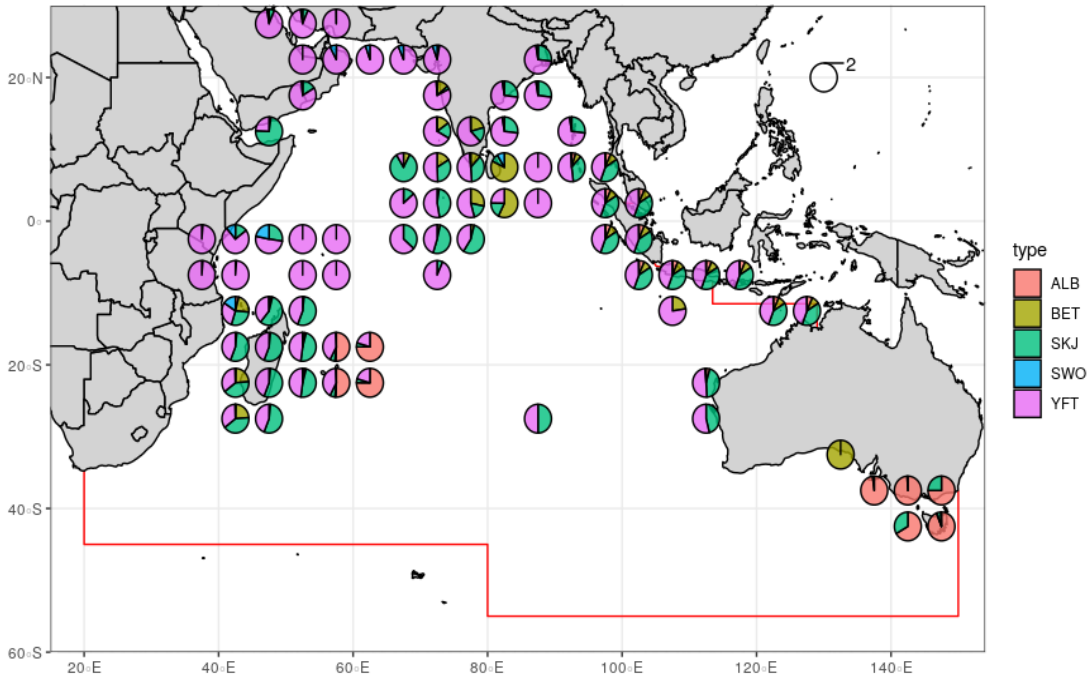

Figure 40. Spatial distribution of the main IOTC target species caught by other major fisheries (i.e., HAND, BB, and TROL; see Table 7 for gear codes) in the IOTC convention area. Pie chart sizes are not proportional to the quantity of catch (MT), but rather are meant to display the proportion of the catch that was due to each gear type for each grid cell. Catch data are

derived from the annual median over 2003-2017 of ALB, YFT, BET, SKJ, and SWO (see Table 1 for species codes).

6 An overview of the available knowledge and data layers covering socio-political processes to refine the delineation of draft ecoregions

The following section gives an overview of the data layers that are proposed to inform discussion at the workshop in line with the socio-political criteria to refine the boundaries of the draft ecoregions. The data reviewed in this section are not included in the spatial analyses (Section 7).

6.1 Compatibility with other regional initiatives

One of the recommendations by the WPEB14 and in line with criterion 4.1 from Table 4 was to investigate the compatibility of the draft ecoregions with other regional initiatives. Here, we propose several data layers that map regional spatial management initiatives that may be relevant to IOTC species and fisheries. We believe these data layers can be a basis for discussion at the workshop to decide whether this type of information should be considered, and how to use it to inform the delineation of draft ecoregions.

Overlap with other Regional Fisheries Management Organisations (RFMOs) or Regional Fisheries Bodies (RFBs)

We mapped the convention areas of the other regional fisheries management organisations (RFMOs) in the Indian Ocean, i.e. the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), the Southern Indian Ocean Fisheries Agreement (SIOFA), as well as the regional fisheries body, the Southwest Indian Ocean Fisheries Commission (SWIOFC).

CCSBT

As noted, the IOTC has the mandate to manage 16 species (Table 1), but in practice CCSBT manages SBT. The CCSBT has no geographically definitive convention area, and its management applies wherever SBT are found. The distribution of SBT highly overlaps with the southern edge of the IOTC convention area (Figure 41). We note that the overlap of this convention area with the IOTC convention area indicates interactions between the SBT fishery and other IOTC species and fisheries.

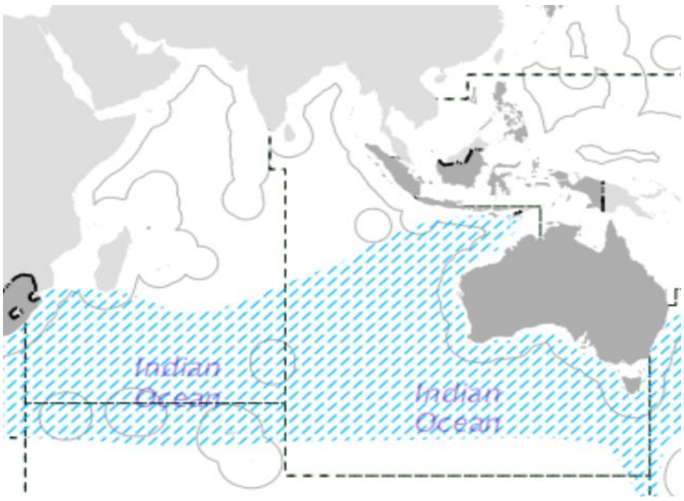

Figure 41. The CCSBT area of competence (blue hash), whose geographical limits correspond to anywhere that *Thunnus maccoyii* is present, and overlaps with the IOTC convention area (black dashed lines in the Indian Ocean).

SWIOFC

The SWIOFC convention area is in the western Indian Ocean and includes both national waters and high seas waters within the boundaries as displayed in Figure 42. The species and stocks covered by SWIOFC include all living marine resources, including IOTC species, their competitors and prey of the species. SWIOFC often provides advice and coordination on institutional and organizational matters, needs and processes, including methods and protocols, for data collection, analyses and reporting by member States at the country level. Unlike other Regional Fisheries Bodies, SWIOFC does not usually do assessments of the stocks covered by its mandate. Instead, these are undertaken nationally with the support of regional Projects. IOTC cooperates with SWIOFC, but there is little overlap in activities.

SIOFA

The SIOFA convention area includes the high seas areas of FAO Major Fishing Area 51 and 57 (Figure 42). National waters are not under SIOFA management. Though SIOFA manages demersal fish species that do not overlap in habitat with IOTC species, there may be some interaction with their gears.

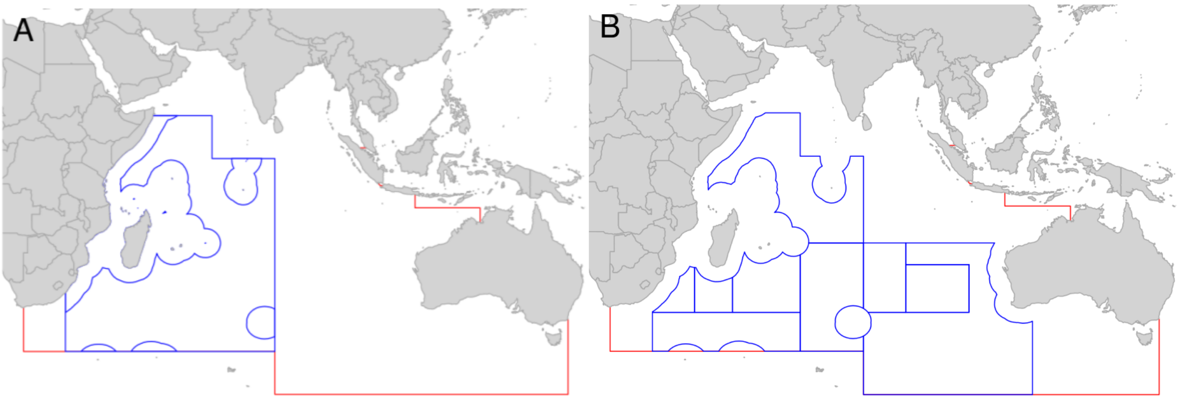

Figure 42. The regional fisheries body (blue), SWIOFC (A) and the regional fisheries management organisation (blue) SIOFA (B) whose convention areas have boundaries overlapping with the IOTC convention area (red). The SIOFA convention area (B) is plotted with its official management subareas.

Marine Protected Areas (MPA)

There are several Marine Protected Areas (MPAs) declared in the Indian Ocean (Figure 43), the largest of which is the Chagos no-take area, effectively bounded by its EEZ. The potential effects of the Chagos MPA on tuna populations are debatable, considering the wide-ranging behaviours of these species (Dueri and Maury 2012; Kaplan et al 2014). Though we present all the Indian Ocean MPAs here, we expect that only the large MPAs will have substantial impacts on the populations of IOTC species or fishing activities (Hernandez et al. 2019).

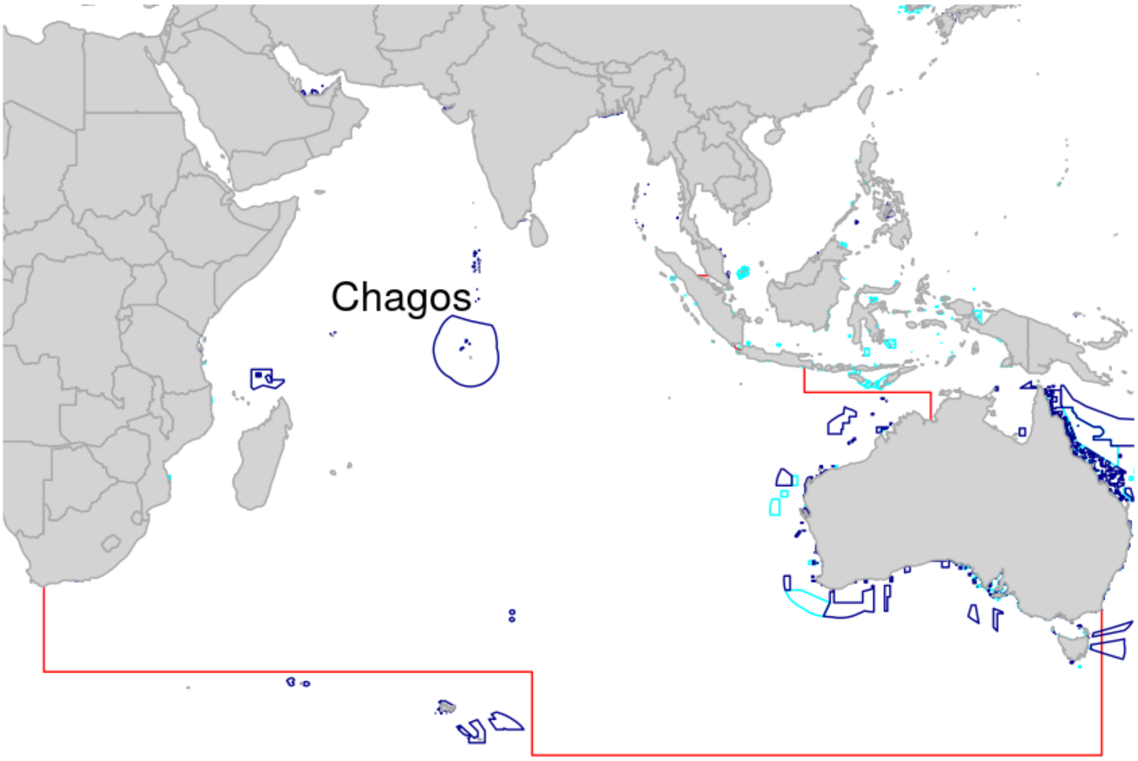

Figure 43. The no-take (dark blue) and partial no-take (cyan) Marine Protected Areas (MPAs) of the Indian Ocean with the Chagos no-take MPA is identified by name. The IOTC convention area is demarcated by the red polygon.

Ecologically or Biologically Significant Areas (EBSAs)

Ecologically or Biologically Significant Areas (EBSAs) are important areas in the ocean that support its healthy functioning. These areas have been defined based on a set of scientific criteria to identify regions that require protection in open ocean and deep sea habitats, i.e.,

C1. Uniqueness or Rarity
C2. Special importance for life history stages of species
C3. Importance for threatened, endangered or declining species and/or habitats
C4. Vulnerability, Fragility, Sensitivity, or Slow recovery
C5. Biological Productivity
C6. Biological Diversity
C7. Naturalness

Each EBSA was derived using these seven criteria, which are ranked as “High”, “Medium”, “Low”, or “No information” by the scientific panel of each EBSA. Here, we have summarised a selection of EBSAs in the Indian Ocean that are relatively large and/or particularly relevant to IOTC target and bycatch species, their prey, and their habitat (e.g. not benthic or deep sea) (Figure 43 and Table 8).

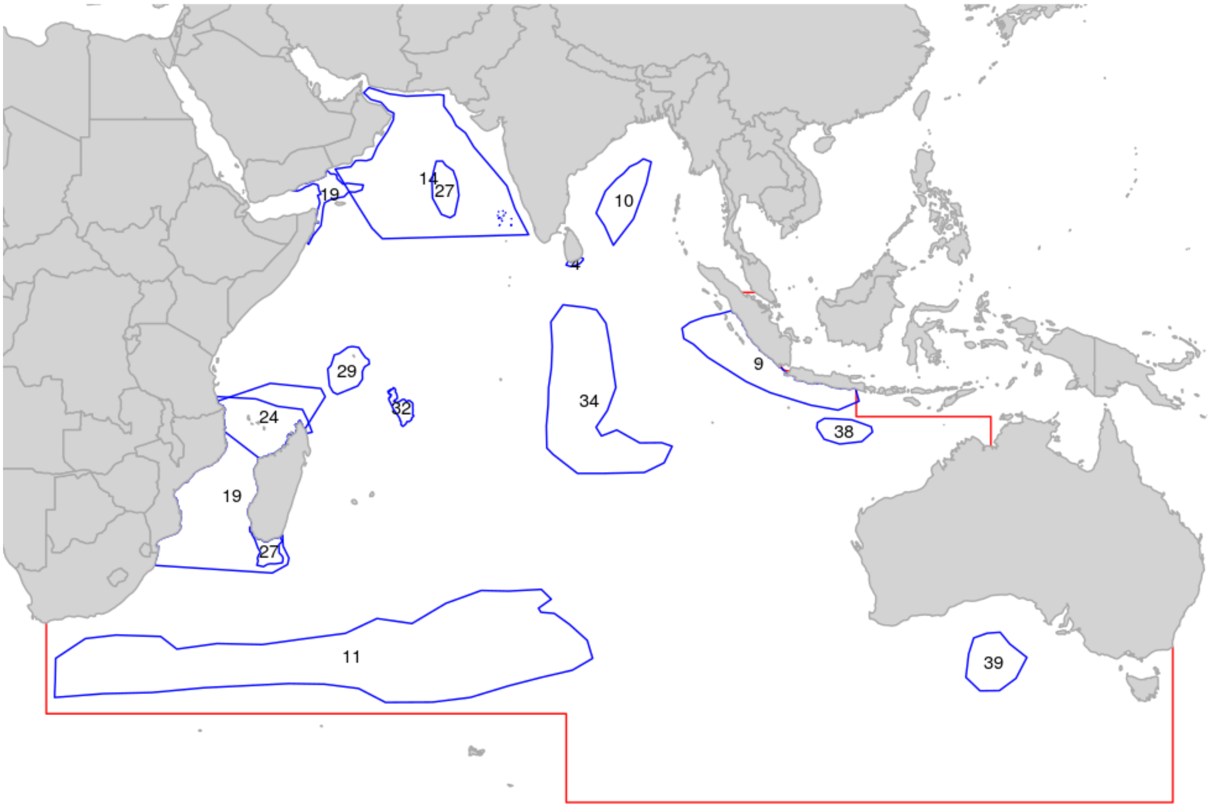

Figure 44. A selection of the Ecologically or Biologically Significant Areas (EBSAs) of the Indian Ocean (blue) (see Table 8 for EBSA codes). The IOTC convention area is demarcated by the red polygon.

Table 8. A selection of Ecologically or Biologically Significant Areas (EBSAs) in the Indian Ocean based on criteria C1-C7 as outlined in the text and the species groups relevant to IOTC fisheries including target and bycatch species that are described in each EBSA. H=High, M=Medium, L=Low, NA=No information. Species codes are as in Table 1.

Label	EBSA	C1	C2	C3	C4	C5	C6	C7	Species	Shapefile
11	Agulhas Front	H	H	H	M	H	M	L	SBT	SIO_11_EBSA-GIS_shapefile.zip
19	Mozambique Channel	H	H	H	H	H	H	M	Turtles, mammals, seabirds, fish	SIO_19_EBSA-GIS shapefile.zip
24	Northern Mozambique Channel	H	H	H	H	H	H	L	Sharks, turtles, mammals, seabirds	SIO_24_EBSA-GIS shapefile.zip
27	Southern Madagascar (part of the Mozambique Channel)	H	H	H	M	H	H	H	Cetaceans, turtles, birds	SIO_27_EBSA-GIS shapefile.zip
29	Mahe, Alphonse and Amirantes Plateau	H	H	H	M	H	M	L	Pelagic fish, turtles, seabirds, cetaceans	SIO_29_EBSA-GIS shapefile.zip

32	Saya de Malha Bank	H	H	NA	NA	H	NA	H	Cetaceans, turtles, birds	SIO_32_EBSA-GIS shapefile.zip
19	The Great Whirl and Gulf of Aden Upwelling Ecosystem	H	H	H	M	H	M	M	YFT, SKJ, SWO, marlin, neritic tuna, sharks, turtles, mammals, seabirds	NWIO_19_EBSA.zip
14	Arabian Sea Oxygen Minimum Zone	H	NA	L	L	H	M	H	Prey species of top predators	NWIO_14_EBSA.zip
27	Arabian Basin	H	H	H	M	M	M	M	Seabirds, turtles, mammals	NWIO_27_EBSA.zip
10	Olive Ridley Sea Turtle Migratory Corridor in the Bay of Bengal	H	H	H	H	NA	L	M	Olive Ridley turtles	NEIO_10_EBSA.zip
34	Central Indian Ocean Basin	L	H	M	L	L	M	NA	Seabirds	SIO_34_EBSA-GIS shapefile.zip
9	Upwelling Zone of the Sumatra-Java Coast	H	H	M	H	M	M	H	Tuna, shark	NEIO_9_EBSA.zip
38	South of Java Island	M	H	H	NA	H	NA	NA	SBT, BET, YFT, SWO, ALB	SIO_38_EBSA-GIS shapefile.zip
39	Due South of Great Australian Bight	NA	H	H	M	L	NA	NA	SBT, seabirds	SIO_39_EBSA-GIS shapefile.zip
4	The Southern Coastal and Offshore Waters between Galle and Yala National Park	H	H	H	M	H	M	NA	YFT, SKJ, SWO, billfish, sharks, turtles, mammals	NEIO_4_EBSA.zip

6.2 Socio-economic data

One of the recommendations from the WPEB14 and corresponding to criterion 5.1 of Table 4 was that the delineation of candidate ecoregions should consider the socio-economics of this diverse area, without specifying what those might be. A program to collect socio-economic data is currently underway at the IOTC; however these data are not currently available. Furthermore, the collection of socio-economic data is voluntary and at the national level. Therefore, it remains to be seen whether they can provide valuable information at the scale of the IOTC convention area.

We note that though specific socio-economic data are not available, we believe that the inclusion of diverse gears that represent a mix of industrial, semi-industrial, and artisanal fisheries, can incorporate some of the diversity of the socio-economics of the IOTC fleets.

We expect discussions at the workshop to examine what type of information should be considered and how this information can be used to inform the delineation of draft ecoregions.

6.3 Geopolitical data

A 2018 study investigated the economic and socio-political interactions amongst countries in the western Indian Ocean (Levin et al 2018). Their analysis describes the complex interactions between countries in this region, which translates to large variation in marine protection and management. Though these analyses focus only on the western Indian Ocean, we believe that the topics presented can be a basis for discussion at the workshop to expand the information to the rest of the Indian Ocean. We expect discussions at the workshop to examine what type of information should be considered and how this information can be used to inform the delineation of draft ecoregions.

Levin et al. (2018) have investigated all data points where armed conflict and anti-shipping activity took place in the western Indian Ocean from 1978. These were mainly related to piracy events in the within the Somali EEZ (Figure 45). Kaplan et al (2014) argued that the Somali EEZ was an effective no-take zone due to political instability from 2009. Piracy activity in the area forced changes in fishing activity (Chassot et al 2012); however, the political situation in this region is gradually improving.

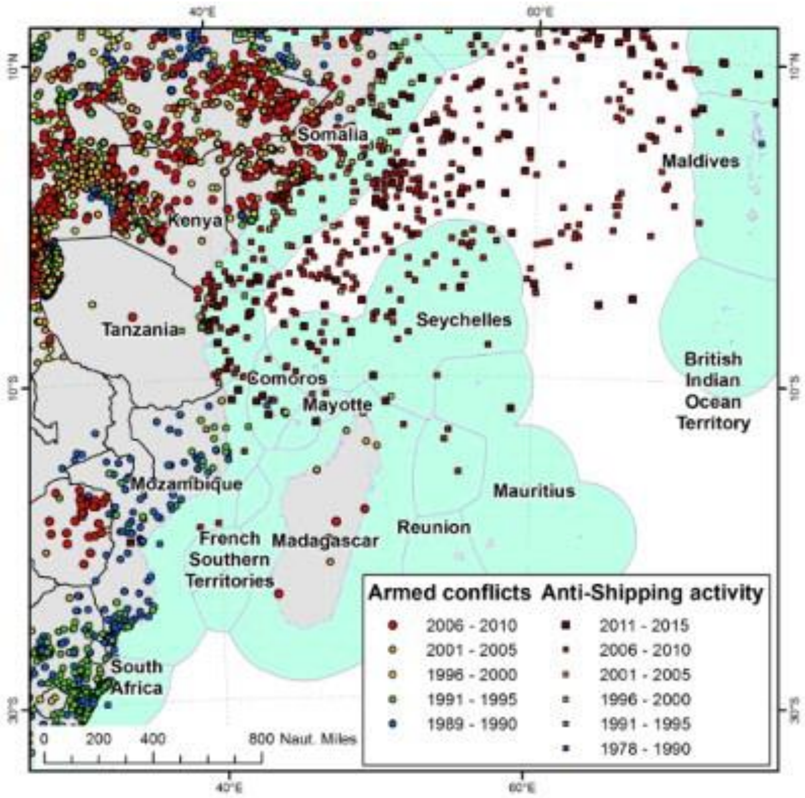

Figure 45. Armed conflicts in the western Indian Ocean between 1978-2015 (taken from Levin et al 2018).

The western Indian Ocean is a complex area in terms of sovereignty and disputes over marine jurisdictions, for example between Mauritius and France over the control of Tromelin, and Mauritius and the UK over the control of the Chagos, or British Indian Ocean Territory (Figure 46). These disputes can potentially lead to major management implications.

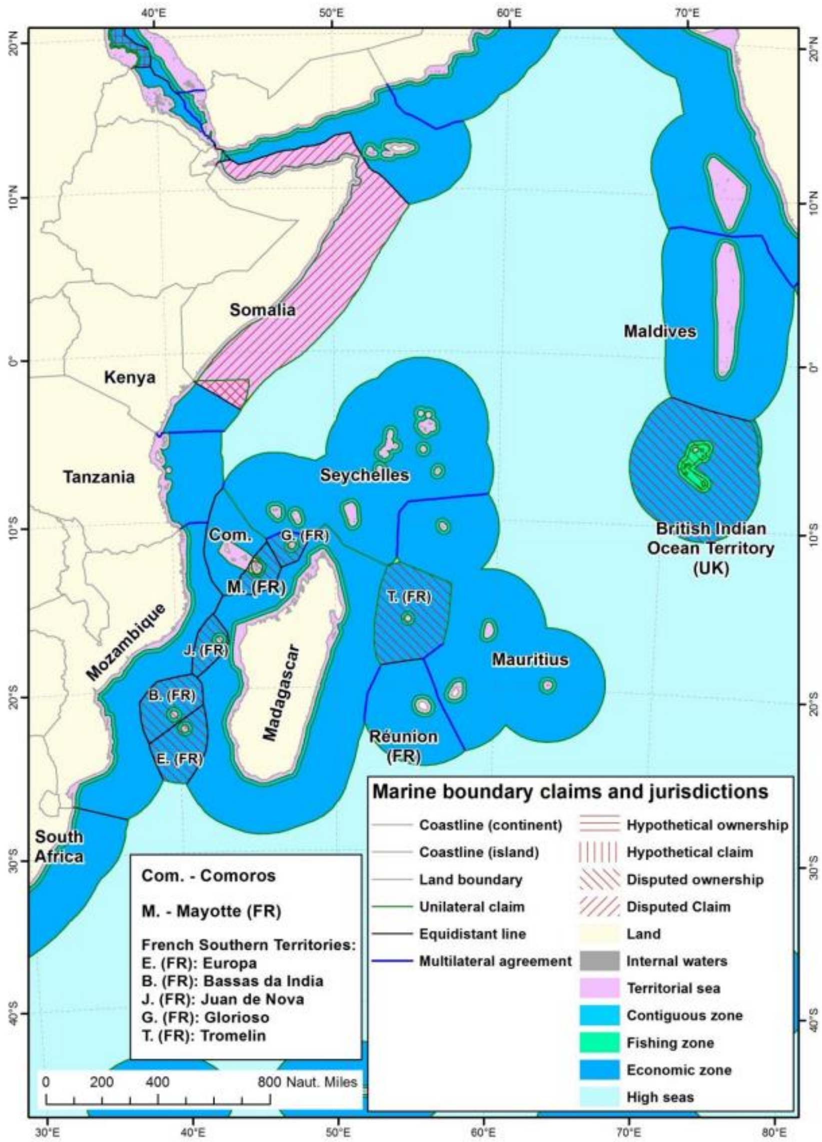

Figure 46. Marine boundaries, jurisdictions and disputes in the western Indian Ocean (figure taken from Levin et al. 2018).

Though these data layers are presented for discussion purposes, we consider that several of the data layers that were presented in the previous section (Section 5) and that will be used in the spatial analysis to delineate ecoregions, inherently incorporate some of these additional socio-political factors. For example, the choice of a biogeographic classification that specifically includes coasts (LMEs) and EEZs (MEOWs) takes into account some of the geopolitical issues occurring in the Indian Ocean.

7 Spatial analysis to derive a draft proposal of ecoregions for IOTC

7.1 Methodology

Based on the best practices reviewed in Section 2.5, we used a statistical hierarchical spatial approach to derive draft ecoregions that would be appropriate for the implementation of the EAFM in the IOTC convention area. The draft ecoregions will be presented at the upcoming IOTC ecoregion workshop, where expert advice will be solicited. Workshop participants will assess the draft ecoregions against the evaluation criteria presented in Table 3 and Table 4 to provide a final ecoregion proposal refined by expert knowledge. This final ecoregion proposal will also be delivered to the IOTC WPEB15 meeting for further input.

The statistical hierarchical spatial approach performed to derive draft ecoregions can be divided into three major steps: 1) a basic spatial overlapping analysis with the purpose of selecting a final biogeographic classification to base all subsequent spatial analysis, 2) a specificity and fidelity indicator analysis that measures the association of individual species and fisheries with the selected biogeographic classification, and 3) a hierarchical clustering analysis to cluster biogeographic provinces according to their degree of similarity based on the species and fishery based indicators. Each of these spatial analyses were based on those data layers which were classified as "good" quality under Section 5 (Table 5), so the interpretation of the results should be made in conjunction with the inherent strengths and weaknesses of each of the data layers.

The basic spatial overlapping analysis followed the methods of the EU project and investigated the degree of overlap between existing biogeographic classifications and the spatial distribution of major IOTC species (ALB, YFT, BET, SKJ, and SWO) and the fisheries targeting them. The distribution of neritic species is implicitly represented by the inclusion of biogeographic classifications of the coastal zone. We examined these data layers and their overlap with the selected existing biogeographic classifications outlined in Section 5.1, i.e. Longhurst provinces, PPOWs, and a combination of PPOWs and MEOWs. This spatial analysis allowed us to select a final biogeographic classification to base all subsequent spatial analyses. This was done by overlapping the species and fisheries distribution layers with each classification scheme and determining qualitatively which scheme best represented the important patterns in the data.

We then used the selected biogeographic classification and calculated an indicator that characterizes the association of each species and type of fishery to each biogeographic province, following Dufrene and Legendre (1998) and Reygondeau et al. (2012). This indicator is the product of two indices: specificity and fidelity, and we hereafter refer to it as the SF Indicator. The specificity, $A_{i,j}$ of a species or fishery i to a province j is the ratio of the mean abundance N (here estimated using catch in MT) to the sum of the mean abundance of the species in all the provinces N_i. Specificity is thus a measure of how much a species associates with a province, or a representation of its "preference" of one province over others. The fidelity $B_{i,j}$ of a species or fishery i for a province j is the ratio of the number of geographical cells where the species is present in province j to the total number of cells of the province S_j. Thus, fidelity is a measure of how broadly a species is found (caught) within a province. The product of specificity and fidelity gives the SF Indicator of the community makeup of that province in terms of its species or fishery.

Finally, we performed a hierarchical clustering algorithm on the SF Indicators for each province based on 1) their species composition, 2) fisheries composition and 3) species and fisheries composition combined. Clustering is performed first on each data layer separately to identify any major drivers of spatial patterns, and then on the combination of data layers for an integrative analysis. The resulting clusters are used to delineate the draft ecoregions proposed to the workshop participants for discussion and further refinement.

7.2 Overlapping biogeographic classifications with the spatial distributions of the main IOTC species

Overlapping with the Longhurst classification

Catch distribution overlaid on the Longhurst biogeographic classification

The Longhurst biogeographic classification was retained for further investigation because this scheme is representative of the main oceanographic patterns of the Indian Ocean and it incorporates coastal zones, though the classification near the coast has been noted to be "fuzzy" (Watson et al. 2003). We find that the low resolution of the catch data and the 5°x5° IOTC gridding scheme match well with the boundaries of the Longhurst provinces for the majority of the basin (Figure 39); however, due to this low resolution of the catch data (5°x5°), the Longhurst provinces miss most of the very coastal pixels (i.e. note the NAs in Figure 47, which are the grid cells nearest the coast) and make up a large proportion of the overall catch (Figure 49). We note that these very coastal pixels could be forced to take the value of their nearest neighboring Longhurst province. However, we find the Longhurst provinces lacking in terms of classifications for the island nations in the central and western Indian Ocean.

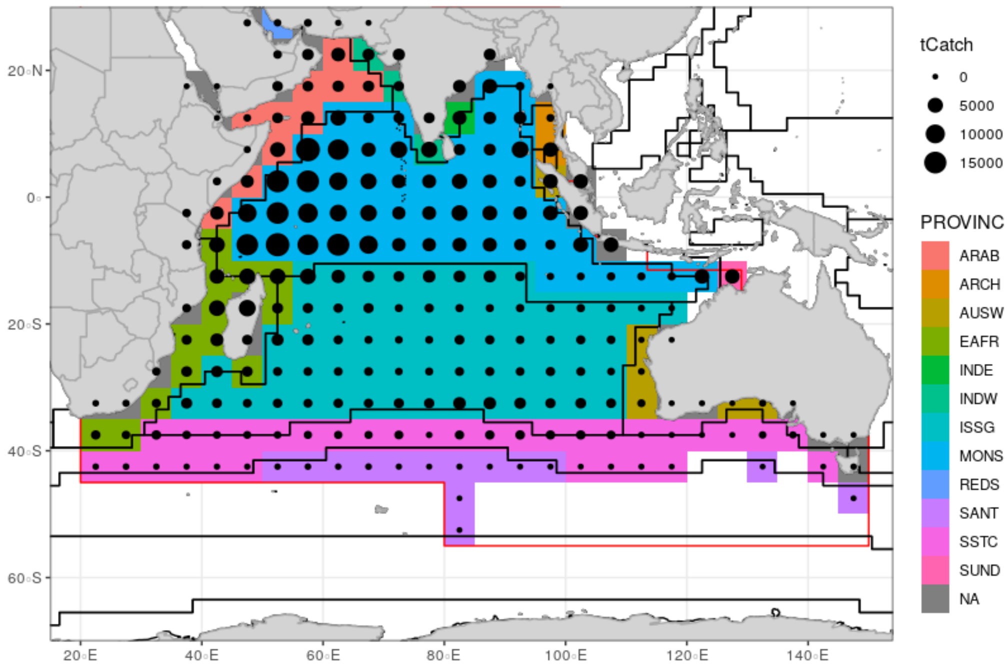

Figure 47. The raised median annual catch (MT) of the main IOTC species (YFT, SKJ, BET, ALB, SWO) distribution overlaid on Longhurst provinces. NAs represent the coastal regions where Longhurst provinces do not extend. The boundaries of the Longhurst provinces are outlined in black and the IOTC convention area is outlined in red.

Species distributions overlaid with the Longhurst biogeographic classification

We find that the Longhurst provinces represent well the distribution of species in large latitudinal bands across the Indian Ocean (Figure 48). For example, the MONS province of the northern basin (see Figure 47 for province codes) encompasses a majority of the distribution of the tropical species YFT, BET, and SKJ; however it does not capture the differences between the species distribution in the east and west of the northern basin. The spatial distribution of SWO overlaps well with the ISSG province of the southern basin, and ALB are coincident with the SSTC province. We find that tropical tuna (BET, SKJ, and YFT) are caught primarily in the MONS province (Figure 50), and captures of ALB and SWO are in the ISSF, with predominantly ALB in the SUND and SSTC.

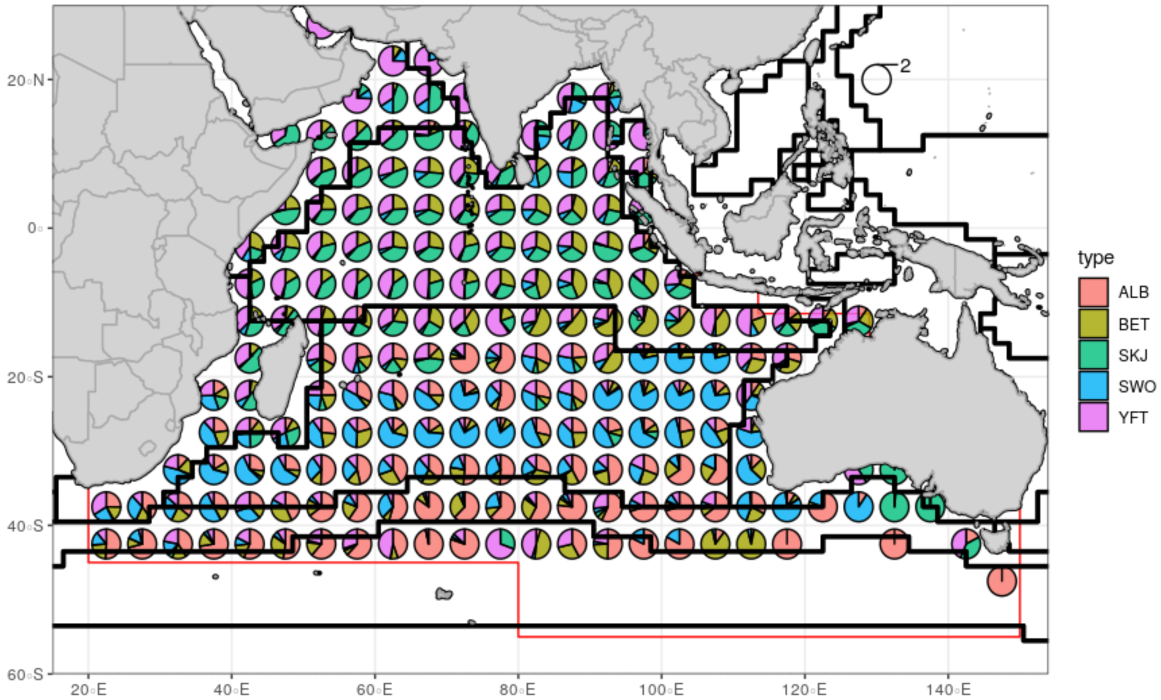

Figure 48. The spatial distribution of the raised median annual catch (2003-2017) of the main IOTC species (see Table 1 for species codes) in the IOTC convention area. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. Longhurst provinces are in black and the IOTC convention area is outlined in red.

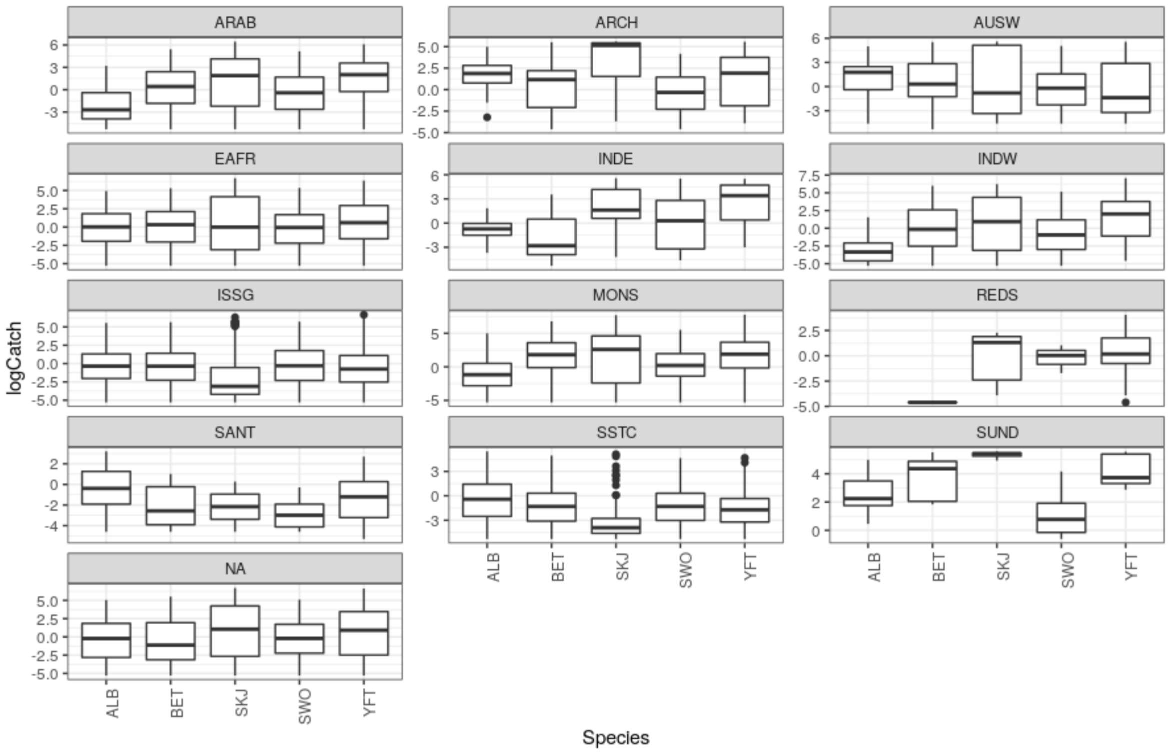

Figure 49. Median annual log catch (2003-2017) by species (MT) within each of the Longhurst provinces of the IOTC convention area. The 'NA' panel notes the coastal pixels where Longhurst provinces do not overlap without forcing due to the spatial resolution of the data in this study. See Figure 47 for Longhurst provinces. See Table 1 for species codes.

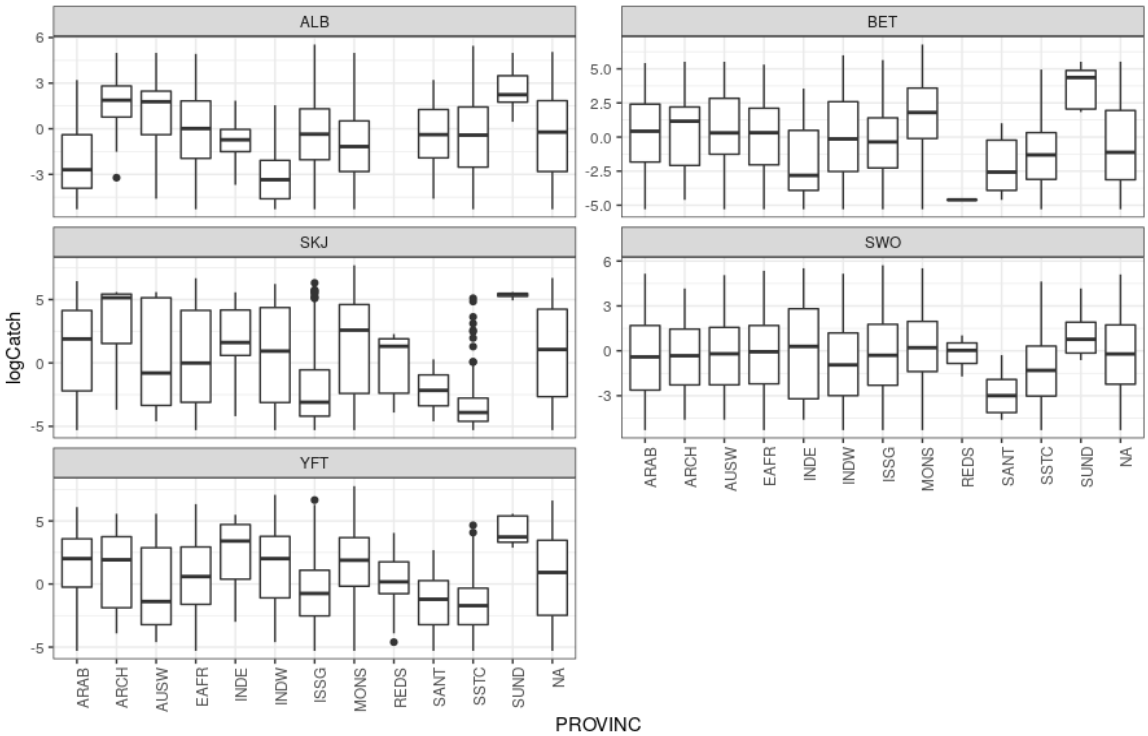

Figure 50. Median annual log catch (MT; 2003-2017) for each species for each of the Longhurst provinces of the IOTC convention area. The 'NA' panel notes the coastal pixels where Longhurst provinces do not overlap without forcing due to the spatial resolution of the data in this study. See Figure 47 for Longhurst provinces. See Table 1 for species codes.

Fisheries distributions overlaid with the Longhurst biogeographic classification

As described in Table 7 and Figure 28, there are 10 gear types that make up the majority of the total catch in the IOTC. Similar to species distributions, we find that the Longhurst provinces overlap with fisheries in broad longitudinal bands, matching to a large degree the range of the industrial purse seiners in the northern MONS province, and broadly capturing the range of the industrial longliners in the southern ISSG province (Figure 51). However, the closest Longhurst boundary to capture the divide between the northern and southern basin appears to be about 10° too far north (Figure 51). In addition, we find that the areas with the highest diversity of fisheries are along the coasts and around the central and western Indian Ocean islands. Coastal diversity appears to be captured somewhat within the INDE, ARCH, and AUSW provinces (Figure 52), but the diversity in fisheries of the central and western Indian Ocean are not captured well by the Longhurst provinces.

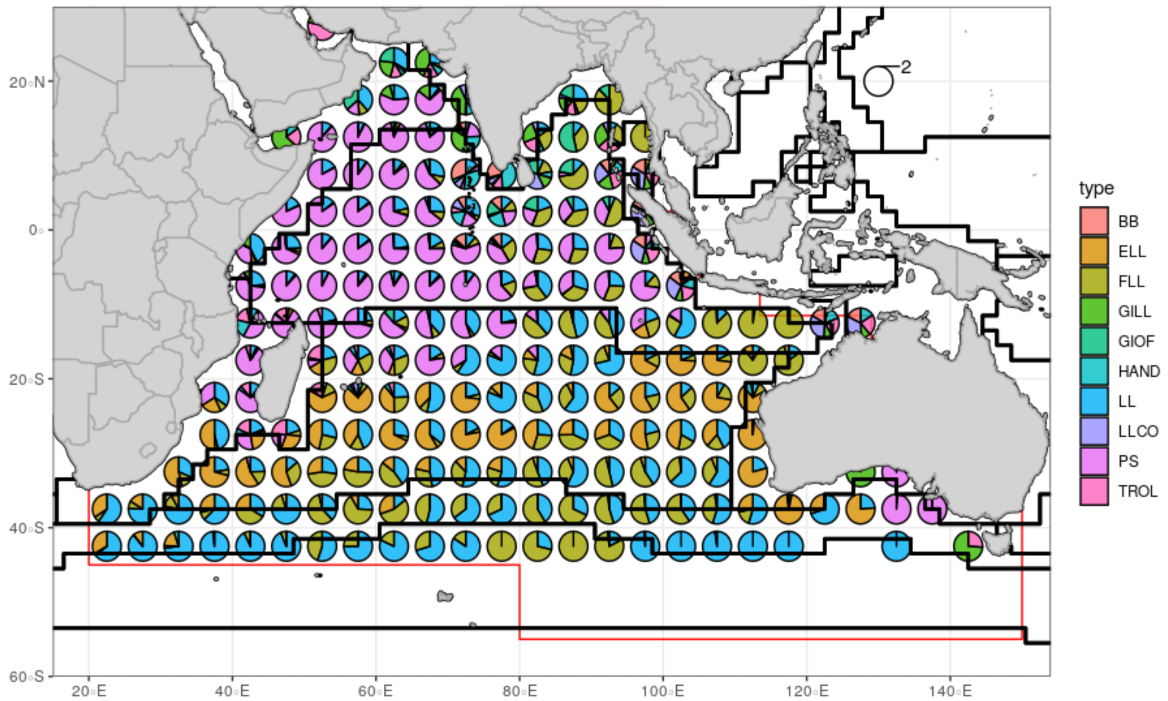

Figure 51. The spatial distribution of the main IOTC fisheries (see Table 7 for fishery codes) in the IOTC convention area as inferred from median annual catch from 2003-2017. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. Longhurst provinces are in black and the IOTC convention area is outlined in red.

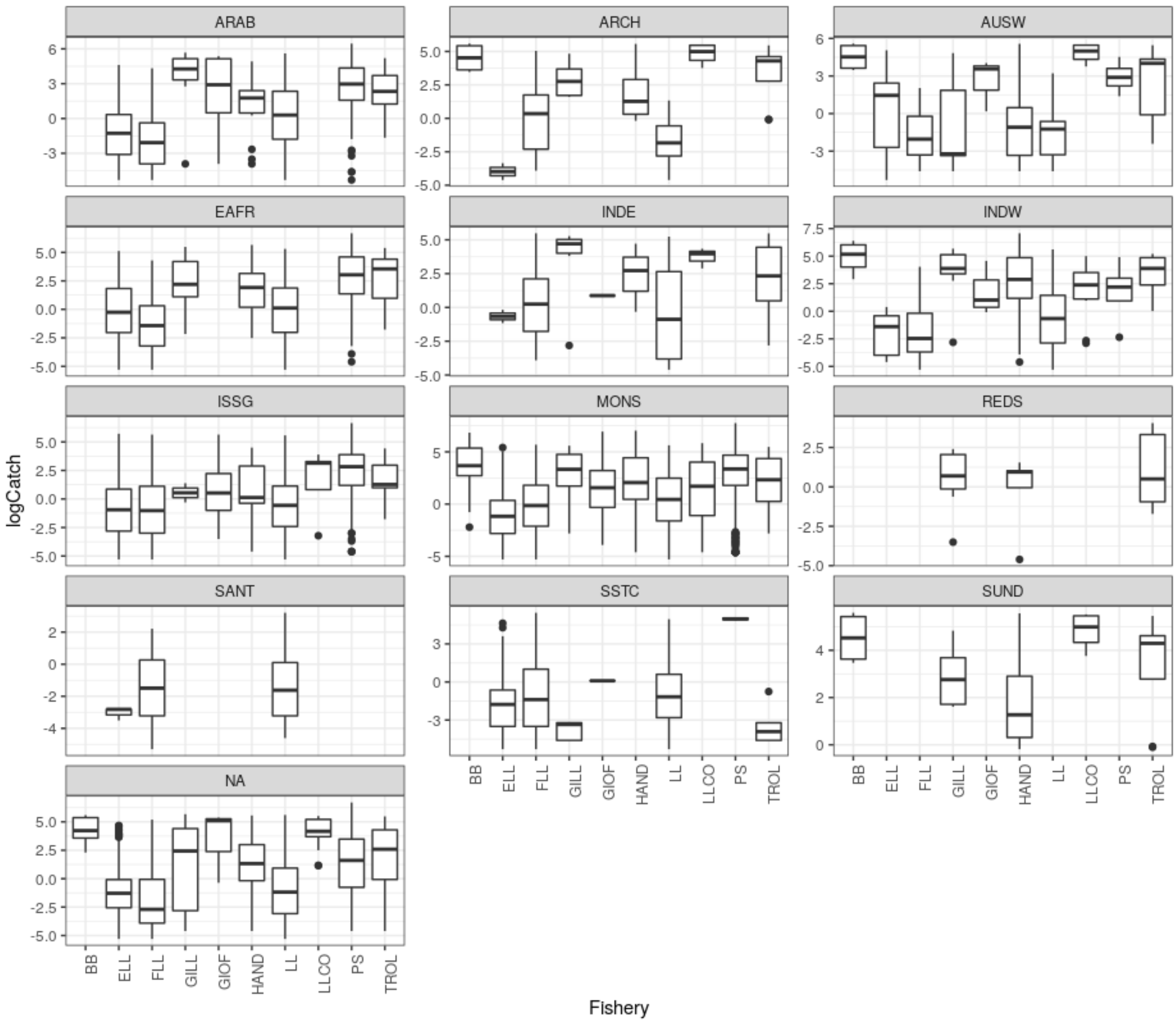

Figure 52. Median annual catch (2003-2017) by fishery (MT) within each of the Longhurst provinces (see Table 7 for fishery codes and Figure 47 for provinces). The "NA" province represents the coastal pixels that are not captured by the Longhurst provinces boundaries due to the spatial scale of the data of our study.

Overlapping with PPOW classification

Catch distribution overlaid on the PPOW classification

There are 11 PPOW provinces within the IOTC convention area (Figure 53). The shapefiles provided by WWF and Spalding (Table 5) include the PPOW provinces up to the continental shelf, and the MEOW provinces within the continental shelf. For this overlap study, we have specifically excluded the MEOW provinces, which are examined in conjunction with PPOW provinces in the next section. The PPOW provinces overlap well with the pelagic catches; however, the coastal catches are not represented by this classification scheme (Figure 55, Panel 'NA'), and would instead be represented by a MEOW province, if they were included.

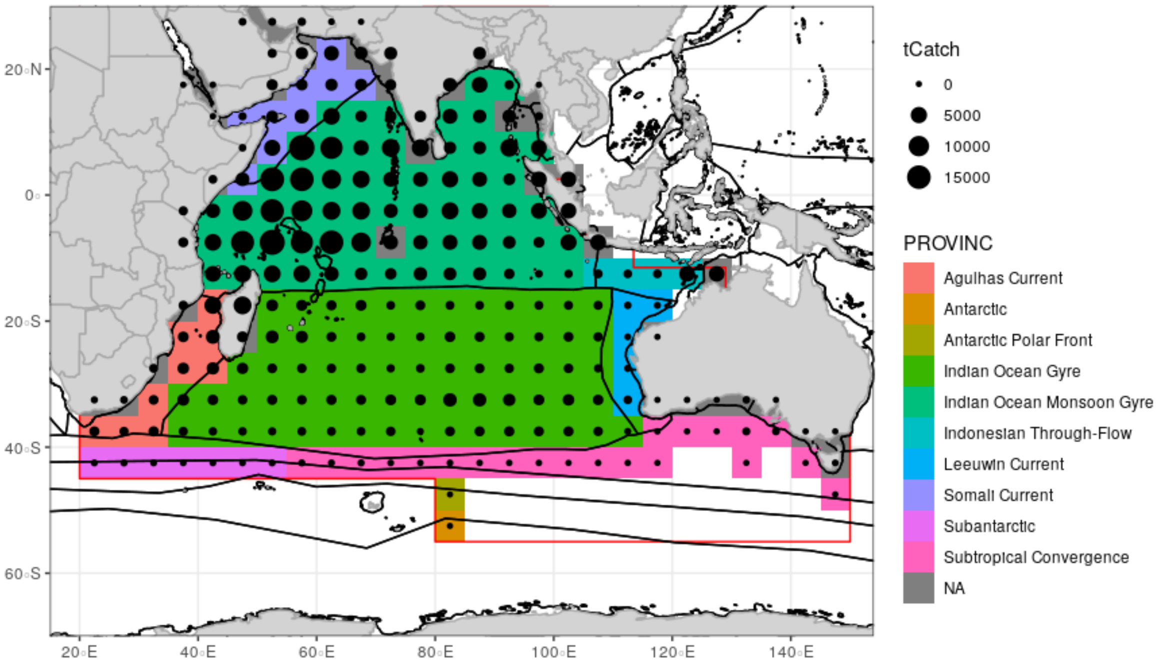

Figure 53. The raised total catch (MT) of the main IOTC species (YFT, SKJ, BET, ALB, SWO) distribution overlaid on PPOW provinces (black lines). NAs represent the coastal regions where the PPOW provinces do not extend. Note that NAs relate to provinces classified by MEOW that are not included in this figure. IOTC convention area is outlined in red.

Species distributions overlaid on the PPOW classification

We note that the PPOW appear to catch the divide between the north and south basin reasonably well in terms of species distributions, with the boundary delineation at about 15°S (Figure 54). However, the difference in species distributions between the eastern and western side of the northern basin are not represented by this classification scheme. We find that tropical tuna (BET, SKJ, and YFT) are mostly caught in the Indian Ocean Monsoon Gyre (Figure 56), ALB are caught mostly in the Indian Ocean Gyre to the south with substantial catch as well in the Agulhas Current, the Indian Ocean Monsoon Gyre, and in the coastal regions. SWO are caught in similar provinces to ALB, and as well in the Somali Current.

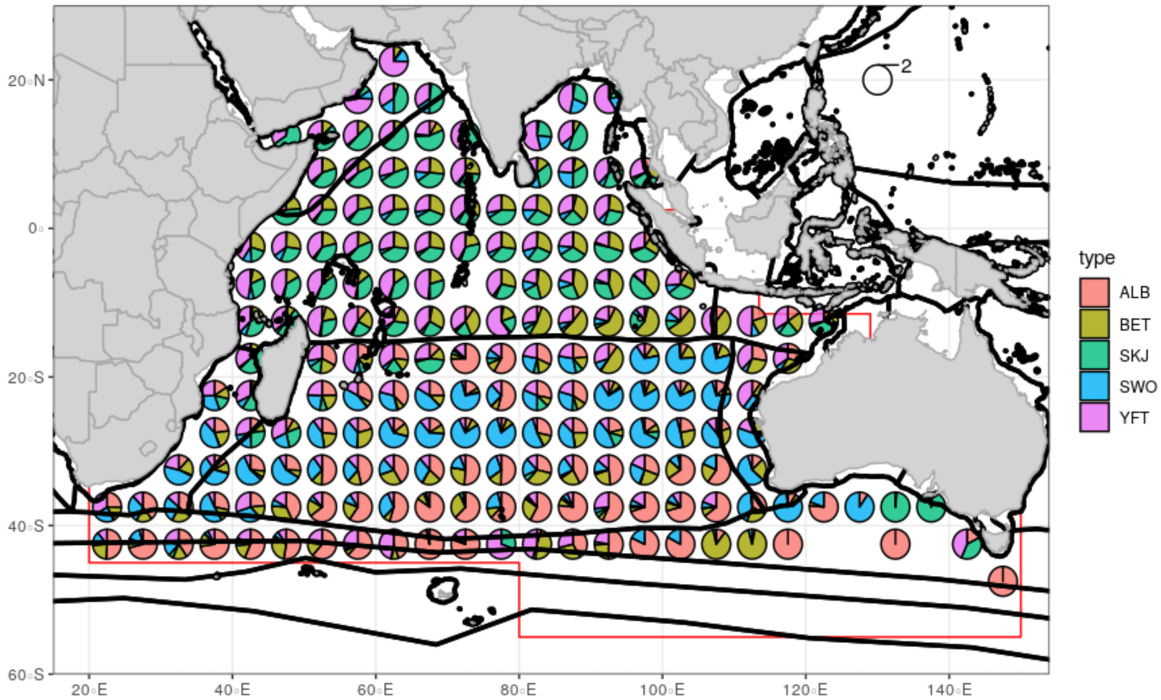

Figure 54. The spatial distribution of the raised median annual catch (2003-2017) of the main IOTC species (see Table 1 for species codes) in the IOTC convention area. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. PPOW provinces are in black and the IOTC convention area is outlined in red.

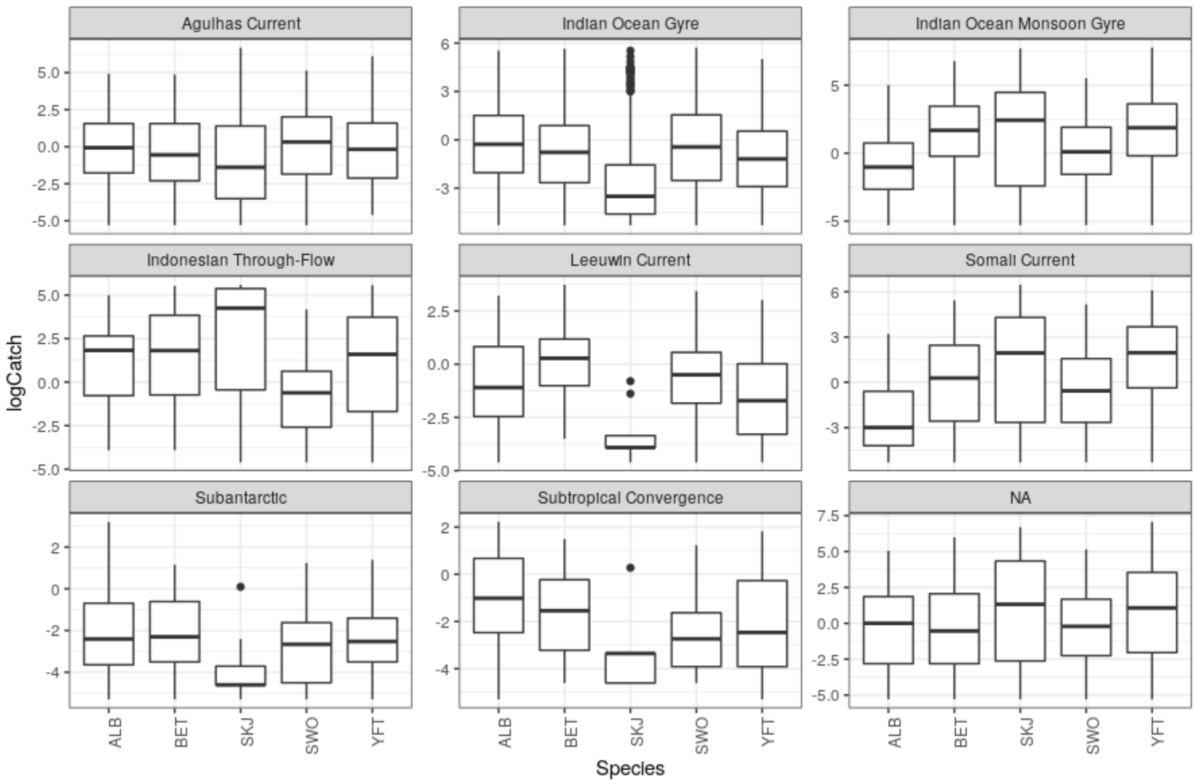

Figure 55. Raised median log annual catch (MT; 2003-2017) by species in each PPOW province (see Table 1 for species codes and Figure 53 for provinces). Note that the 'NA' plot refers to MEOW coastal regions to which the PPOW provinces do not extend.

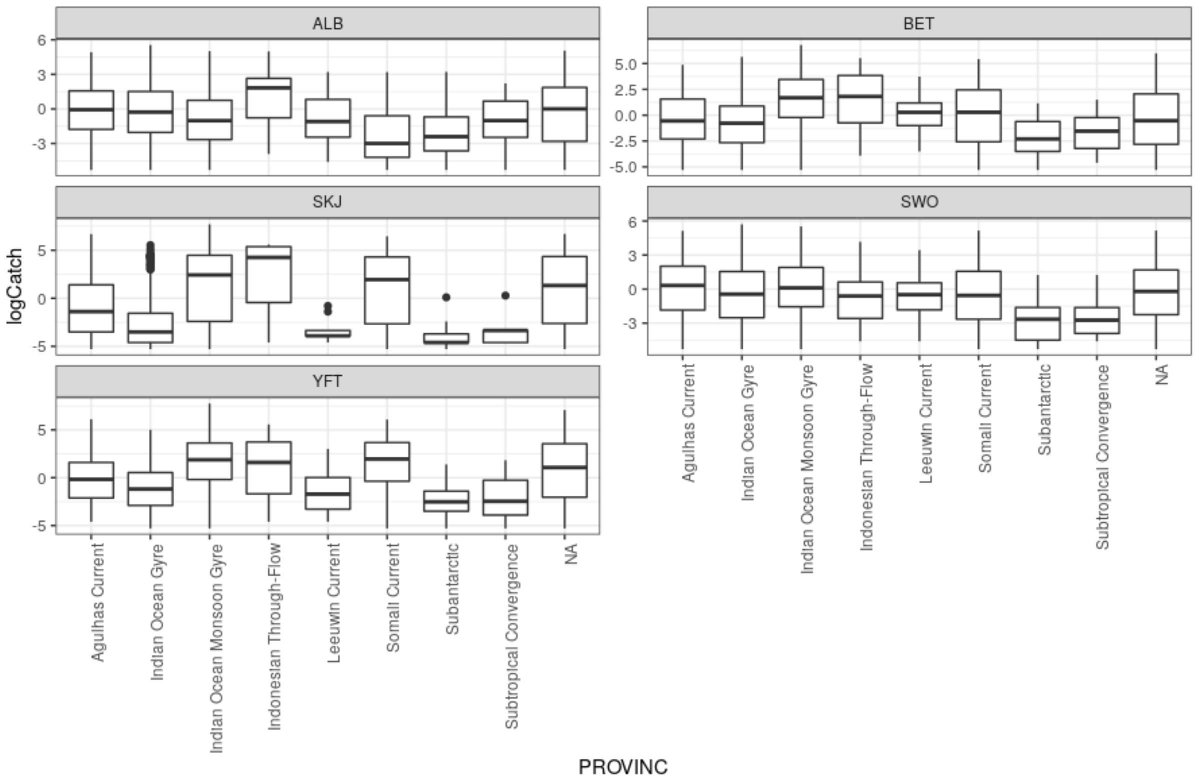

Figure 56. Raised median log annual catch (MT; 2003-2017) for each species in each PPOW province (see Table 1 for species codes and Figure 53 for provinces). Note that the 'NA' plot refers to MEOW coastal regions to which the PPOW provinces do not extend.

Fisheries distributions overlaid on the PPOW classification

We note that much of the diversity in gear is removed when the coasts are not considered (note the NA/coastal subplot of Figure 58). Thus, the pelagic provinces of the PPOW classification have no specific overlap with, for example, the diversity of fisheries in the northern basin, especially along Indonesia, the Bay of Bengal, South India, the Maldives, and Chagos. Likewise, some fisheries diversity is apparent in the western Indian Ocean south of Madagascar and around the Mascarene Islands that is not characterised by any PPOW province (Figure 57). In the Spalding classification schemes (i.e. PPOW and MEOW), much of the coastal pixels are represented by MEOW provinces and these could easily be attributed to the nearest neighbouring PPOW. However, oceanic islands (e.g. Maldives, Chagos, Mascarenes) are not differentiated from the greater pelagic province in the PPOW classification.

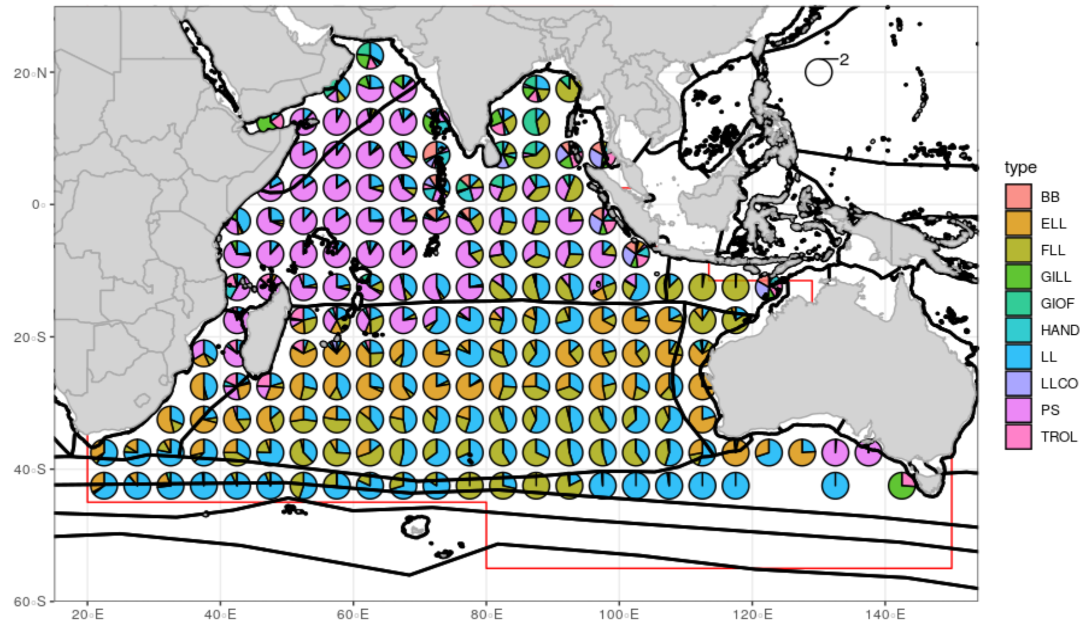

Figure 57.The spatial distribution of the main IOTC fisheries (see Table 7 for fishery codes) in the IOTC convention area as inferred from median annual catch from 2003-2017. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. PPOWs are in black and the IOTC convention area is outlined in red.

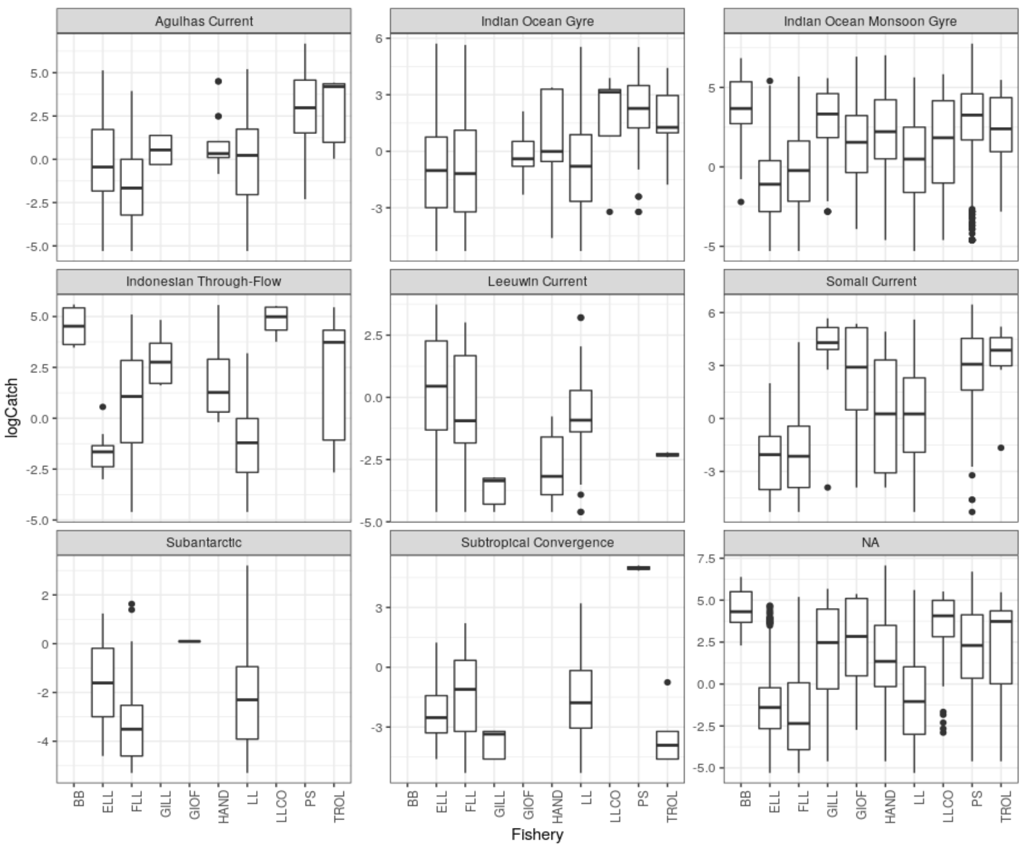

Figure 58. Raised median annual catch (MT; 2003-2017) by fishery in each PPOW province (see Table 7 for fishery codes and Figure 53 for provinces). Note that the 'NA' plot refers to MEOW coastal regions to which the PPOW provinces do not extend.

Overlapping with combined MEOW and PPOW classifications

Catch distribution overlaid on the MEOW and PPOW classifications

We note that due to their oceanic pelagic focus, both the Longhurst and PPOW classifications miss a significant portion of the overall catch in the IOTC region due to their lack of coverage in the most coastal regions (Figure 49 and Figure 55). In addition, they miss the diversity of fisheries in the central and western islands (Figure 51 and Figure 57). Although we note that the coastal pixels that fall outside the Longhurst and PPOW classifications could be reassigned to the nearest neighbouring province; we note as well that the MEOW classification incorporates both the coastal areas and the oceanic islands. Therefore, we examine the combined MEOW and PPOW classifications. In terms of province boundaries, note that there are some areas where PPOWs and MEOWs overlap spatially. In these cases, we gave preference to the MEOW classification, i.e. selecting MEOW provinces first, and then assigning PPOW provinces for any remaining pixels with catch information (Figure 59).

We note that the full quantity of IOTC catch is attributed in the provinces of this combined classification scheme (Figure 59 and Figure 61) and they are representative of the full spatial distribution of each species in the IOTC convention area (Figure 60), especially in the western Indian Ocean and eastern Bay of Bengal (Andaman province). We find that the overlap between the combined MEOW-PPOW classifications fits best with the diversity of fisheries in the coastal and island regions, as well as capturing the broad patterns of the central basin (Figure 63). We note that similar to both the Longhurst and PPOW classifications, the east/west divide in the species and fisheries distributions in the northern basin is not captured by this classification (Figure 60, Figure 63).

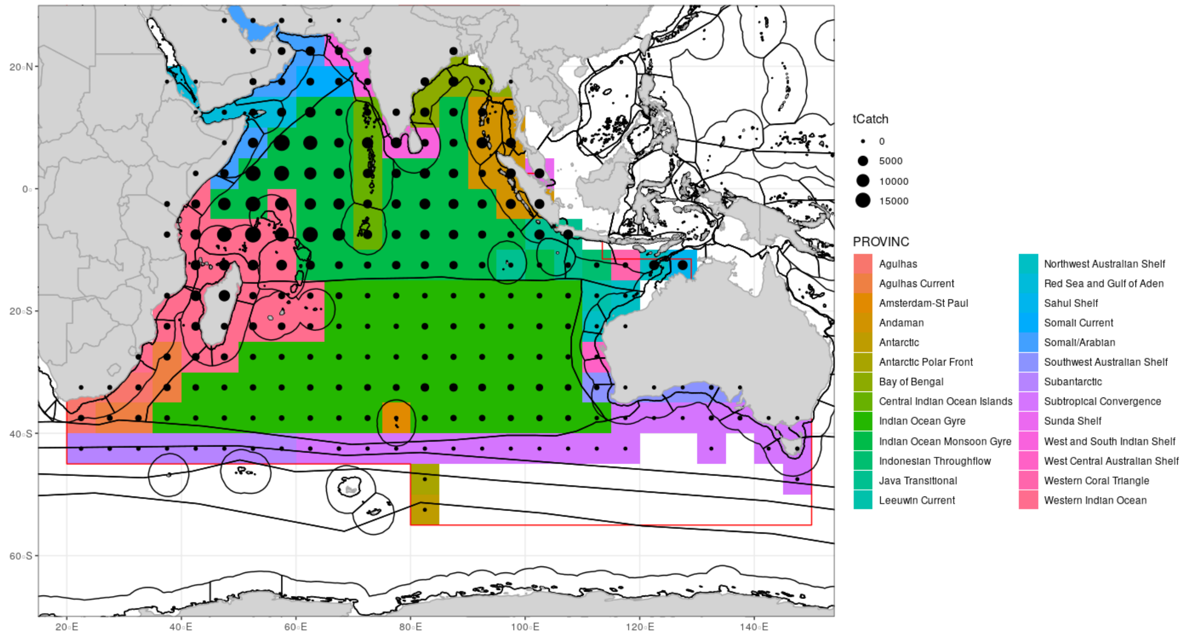

Figure 59. The raised total catch (MT) of the main IOTC species (YFT, SKJ, BET, ALB, SWO) distribution overlaid on merged MEOW-PPOW provinces (black lines). IOTC convention area is outlined in red.

Species distributions overlaid on the MEOW and PPOW classifications

Similar to the PPOW classification, the merged MEOW-PPOW classification represents well the divide between the north and south basin in terms of tropical and temperate species distributions (Figure 60). Furthermore, the diversity of species found near the coast are captured with the MEOW provinces, especially near the central Indian Ocean islands, and along the Indonesian and Australian coasts (Figure 60 and Figure 61). We find that for all species, the western Indian Ocean is an important province for catch (Figure 62). For the tropical species (YFT, BET, and SKJ), the majority of catches occur in the Indian Ocean Monsoon Gyre and the western Indian Ocean, for ALB, the majority of catches occur in the Indian Ocean Gyre and the western Indian Ocean, and SWO are caught more evenly across the provinces (Figure 62).

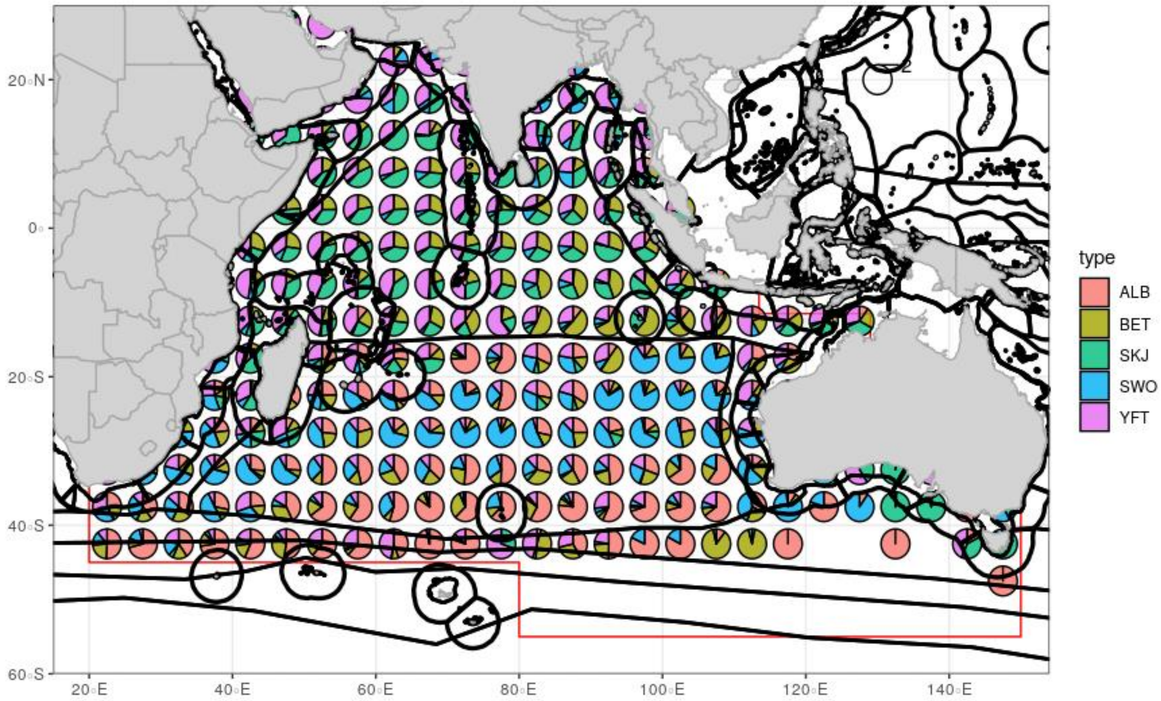

Figure 60. The spatial distribution of the raised median annual catch (2003-2017) of the main IOTC species (see Table 1 for species codes) in the IOTC convention area. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. MEOW and PPOW provinces are in black and the IOTC convention area is outlined in red.

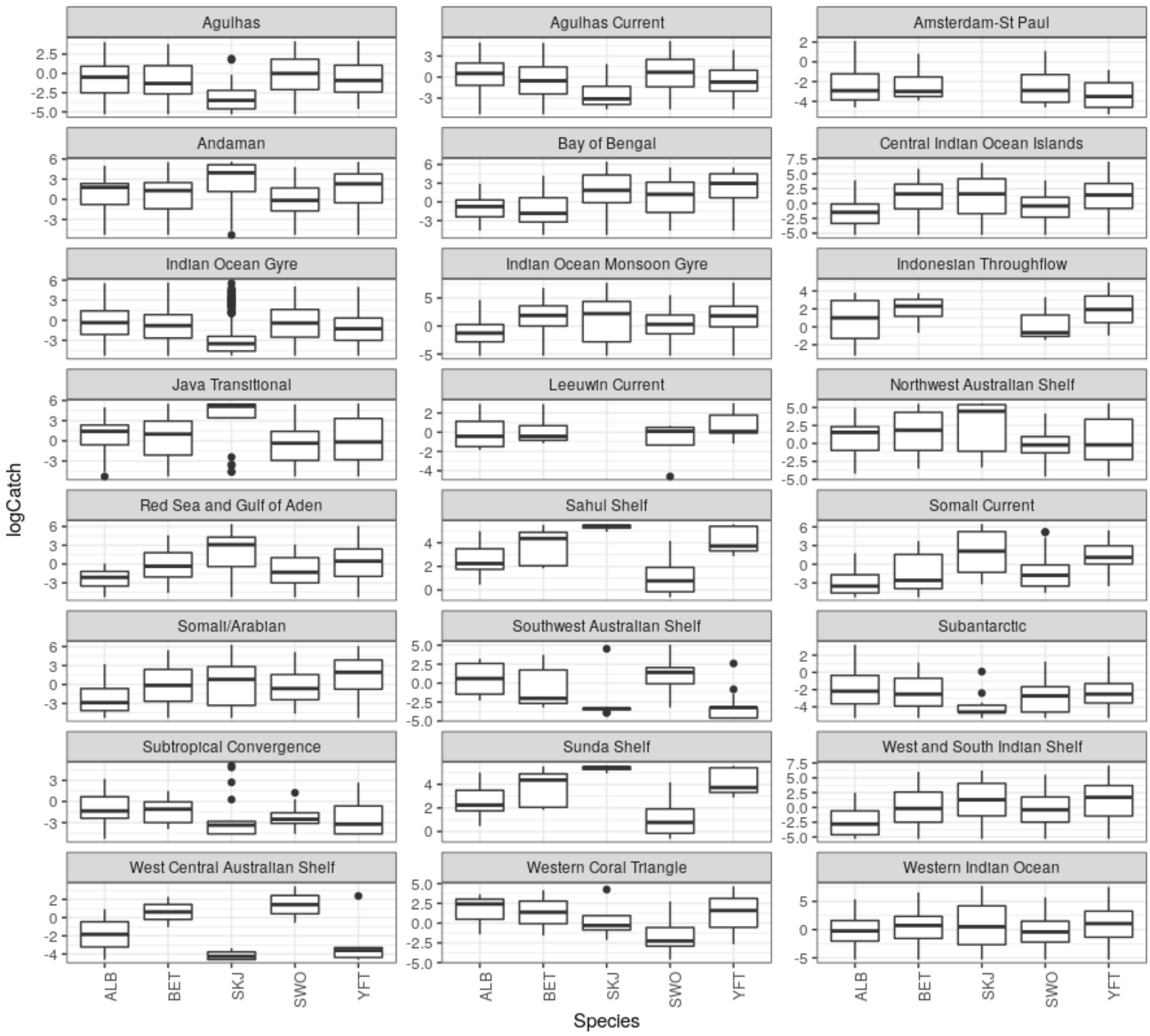

Figure 61. Raised median annual catch (MT; 2003-2017) by species in each MEOW and PPOW province (see Table 1 for species codes and Figure 59 for provinces).

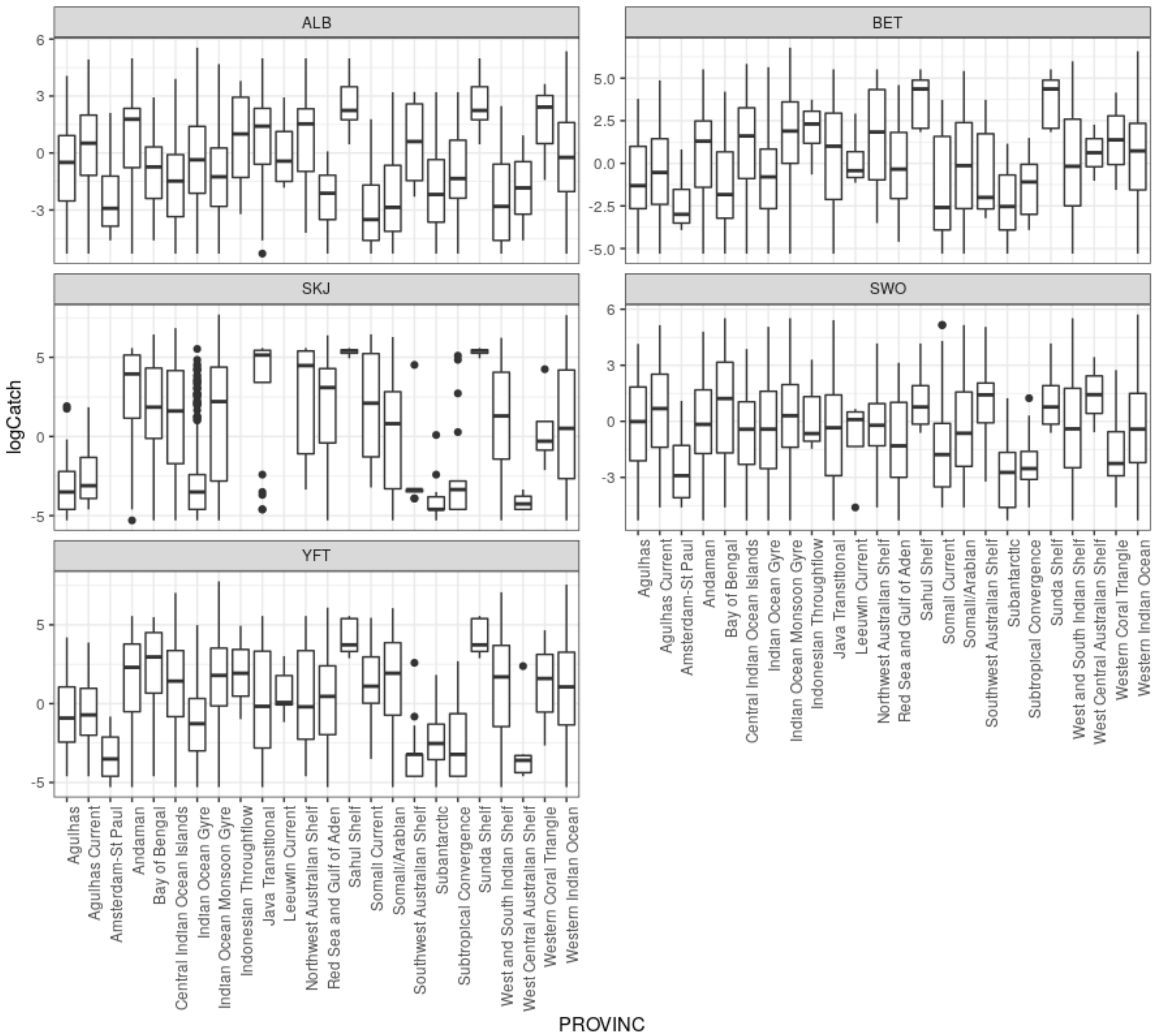

Figure 62. Raised median annual catch (MT; 2003-2017) of each species in each MEOW and PPOW province (see Table 1 for species codes and Figure 59 for provinces).

Fisheries distributions overlaid on the MEOW and PPOW provinces

In addition to the good representation by the PPOW provinces of the major fisheries patterns (i.e. the north-south divide between industrial purse seine activity and industrial longline activity), we find the MEOW-PPOW classification scheme does especially well at capturing the coastal diversity in fisheries. This is especially true along the northern Indonesian coast (i.e. Andaman province), the Bay of Bengal, and the central and western Indian Ocean islands, which are well represented by specific MEOW provinces (Figure 63 and Figure 64).

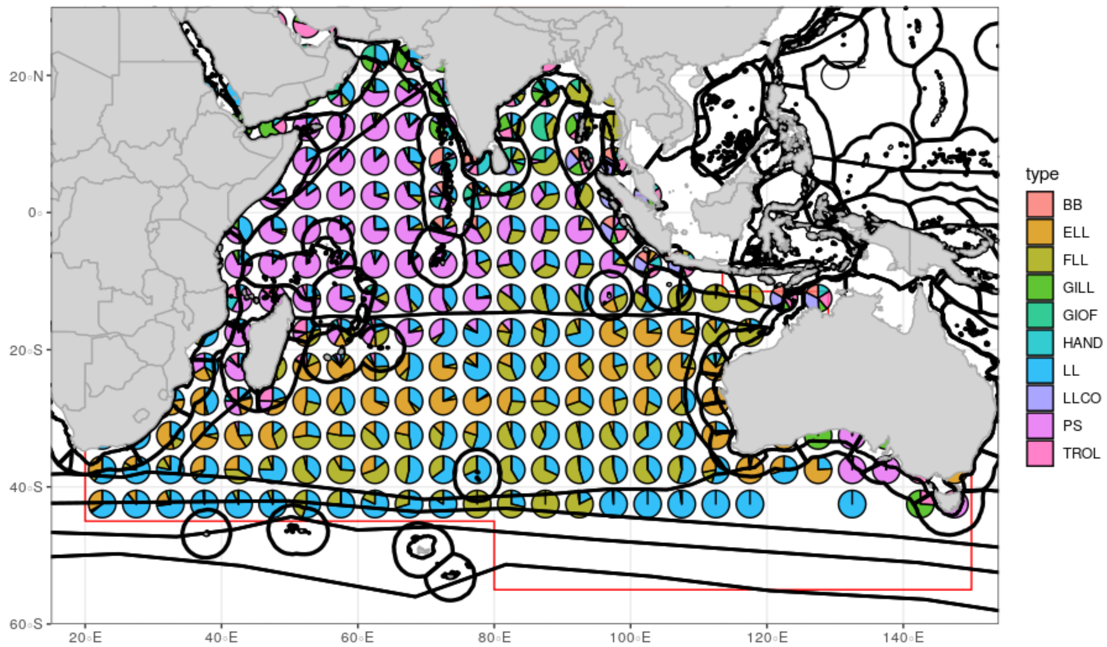

Figure 63. The spatial distribution of the main IOTC fisheries (see [Table 7](#) for fishery codes) in the IOTC convention area as inferred from median annual catch from 2003-2017. Pie chart sizes are not representative of the quantity of catch, but display the proportion of the total catch of each species per grid cell. MEOW-PPOWs are in black and the IOTC convention area is outlined in red.

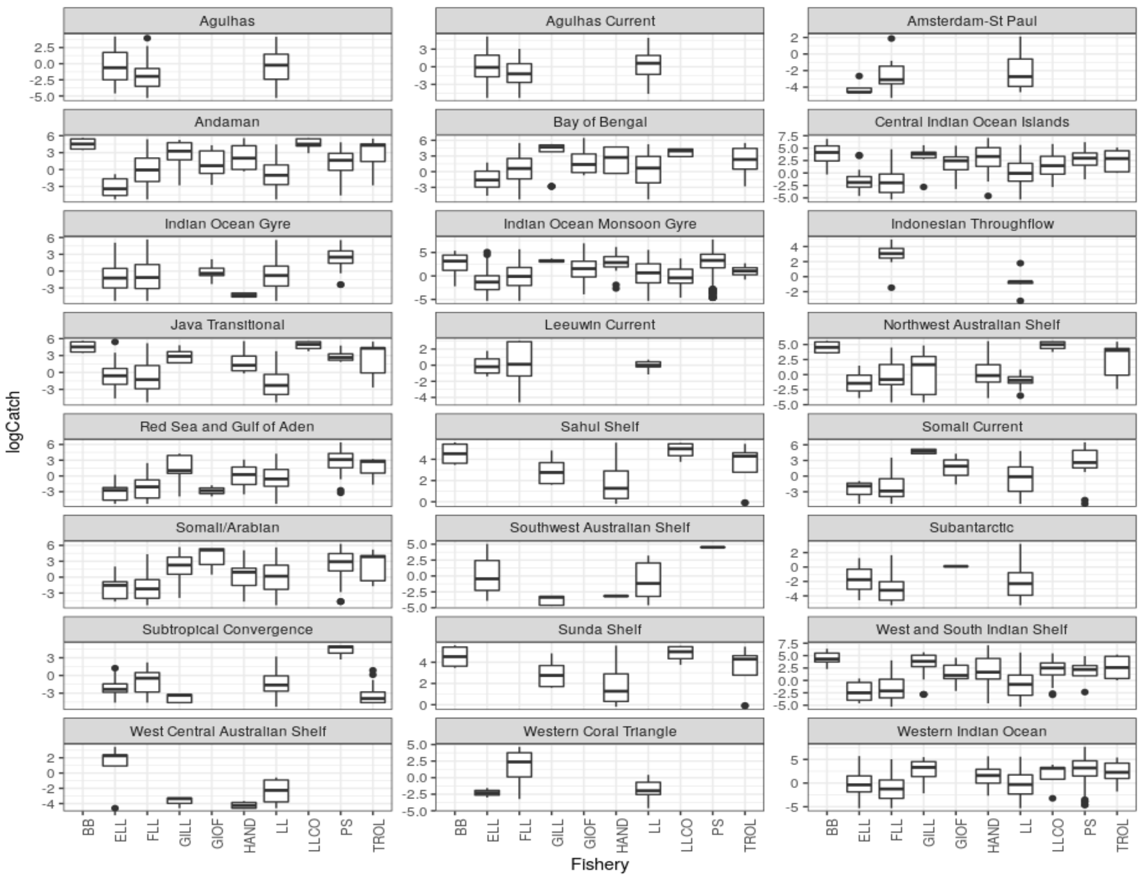

Figure 64. Raised median annual catch (MT; 2003-2017) by fishery in each MEOW-PPOW province (see [Table 7](#) for fishery codes and [Figure 59](#) for provinces).

Synthesis of overlapping spatial analysis

After investigating the overlap of the different biogeographic classification schemes with the different species and fisheries data layers, we decided that the combined MEOW and PPOW classification scheme was the most appropriate for capturing the diversity of species and fisheries in our dataset, as the inclusion of coastal provinces and oceanic island EEZs is a necessary feature to incorporate the distribution of neritic fish and coastal fisheries. The addition of the MEOW layers also clearly reflects the distribution of gears throughout the basin, i.e. large areas in the central basin dominated by few industrial fisheries and gears, and smaller areas closer to the coast that represent a diversity of small-scale fisheries and gears. Furthermore, the MEOW provinces incorporate many of the socio-economic and geopolitical data layers that were discussed previously, e.g. EEZs and the Chagos MPA.

7.3 Specificity and fidelity of species and fisheries within PPOW and MEOW classifications

We note that in terms of practicality for management, the number of provinces of the combined PPOW and MEOW classifications are too many (n=24). Thus, we performed a hierarchical clustering algorithm on the SF indicator for both species and fishery distribution data. The calculation and interpretation of the SF indicator analysis is presented in this Section 7.3, and the clustering analysis on the SF indicators for each biogeographic province is presented in the next Section 7.4. The SF indicator analysis can help determine the structure of the species communities and the diversity of gears within each province. It gives a good indication of the variability within and between provinces, and how similar provinces can be grouped. The clustering analysis provides at the same time an objective quantitative classification of ecoregions based on the species and fisheries communities of the Indian Ocean and a reduction in the number of biogeographic provinces by combining similar provinces into larger ones. We also note that the hierarchical scheme allows a nested set of smaller regions within a larger ecoregion.

Here, we present the results of the SF Indicator for species and fisheries distributions, presenting the overall SF Indicator (i.e. the product of specificity and fidelity) as a quantitative representation of species and fisheries communities within each province.

Specificity-fidelity Indicator based on the spatial distributions of species

The different provinces have different species communities, as indicated both by the differences in the absolute values of the indicators (Figure 65), and the patterns of the indicator within each province (Figure 66). We find that in terms of abundance (inferred from catches), the northern Indian Ocean Monsoon Gyre (IOMG) and the southern Indian Ocean Gyre (IOG) dominate. These provinces have diverse species compositions with tropical tuna in the IOMG and ALB and SWO in the IOG.

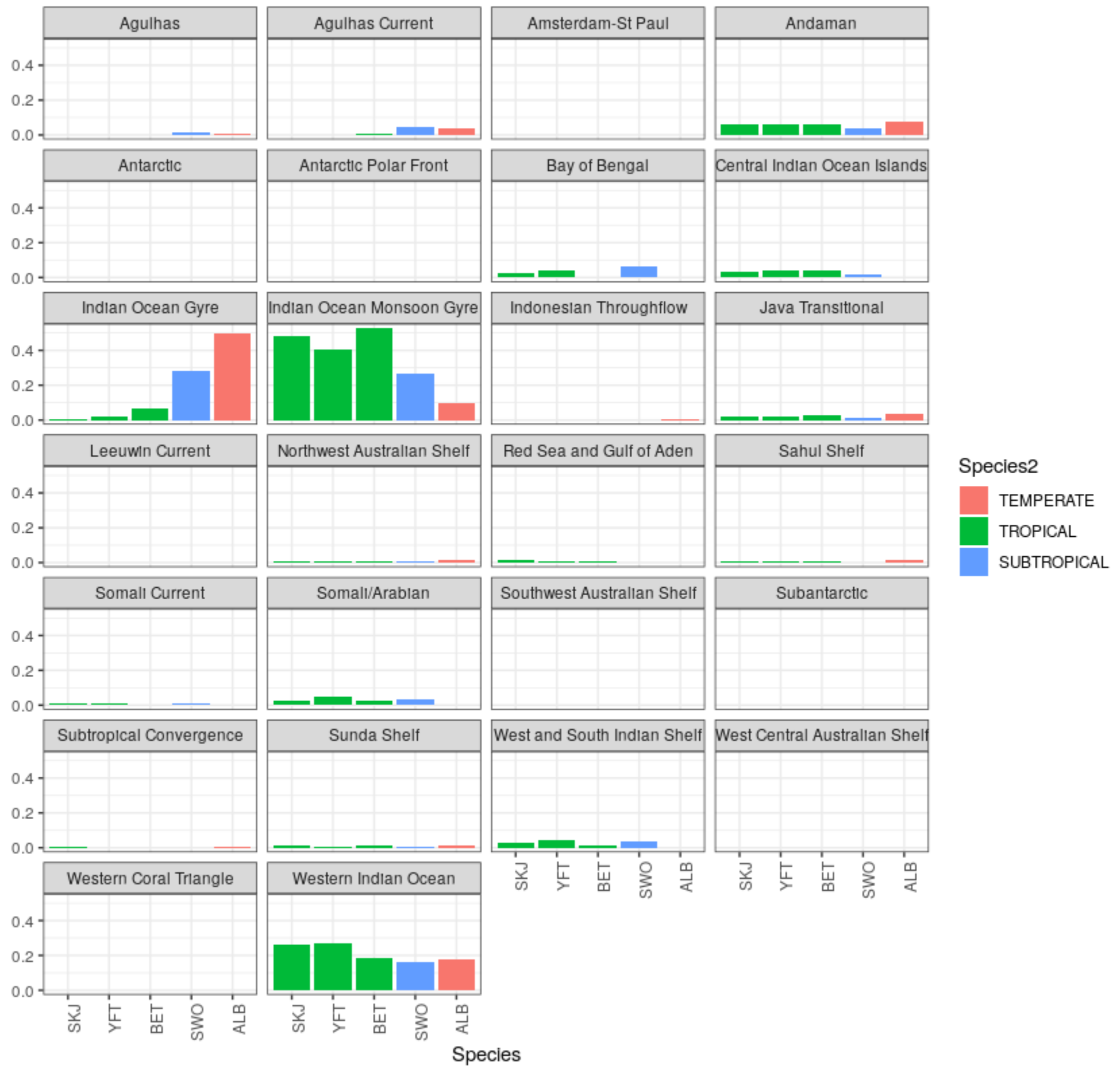

Figure 65. The specificity-fidelity indicator for the combined MEOW-PPOW provinces (see Figure 59) calculated from the species distribution of the main IOTC species (see Table 1 for species codes). The colors of the bars indicate whether a species is tropical (green), subtropical (blue), or temperate (red).

The third most abundant province is the Western Indian Ocean, which has similar species compositions to IOMG. The other provinces indicate low abundance relative to the IOMG, IOG and the Western Indian Ocean. However, we note as well similarities in their species patterns when looking at a relative scale (Figure 66), upon which we suggest higher-order groupings can be made. The IOMG and the Central Indian Ocean Islands show similar species compositions with high catches of tropical tuna, some catch of SWO, and low catches of ALB, as does the Western Indian Ocean, though with higher abundance of ALB. The Andaman, Java Transitional, Sahul Shelf, Sunda Shelf, and Western Coral Triangle indicate the full diversity of species, with some dominance by ALB. The West and South Indian Shelf, Somali Current, Somali/Arabian, Bay of Bengal, Red Sea and Gulf of Aden, diversity of species show very low catch of ALB, relatively high catch of SWO, and high catches of tropical tuna. The Indian Ocean Gyre, the Agulhas and the Agulhas Current indicate high SWO and ALB and low abundance of the tropical species. The Subantarctic, Amsterdam St Paul, Leeuwin Current, and Indonesian Throughflow show low tropical tuna catches and no SKJ, high catches of ALB, and some catch of SWO.

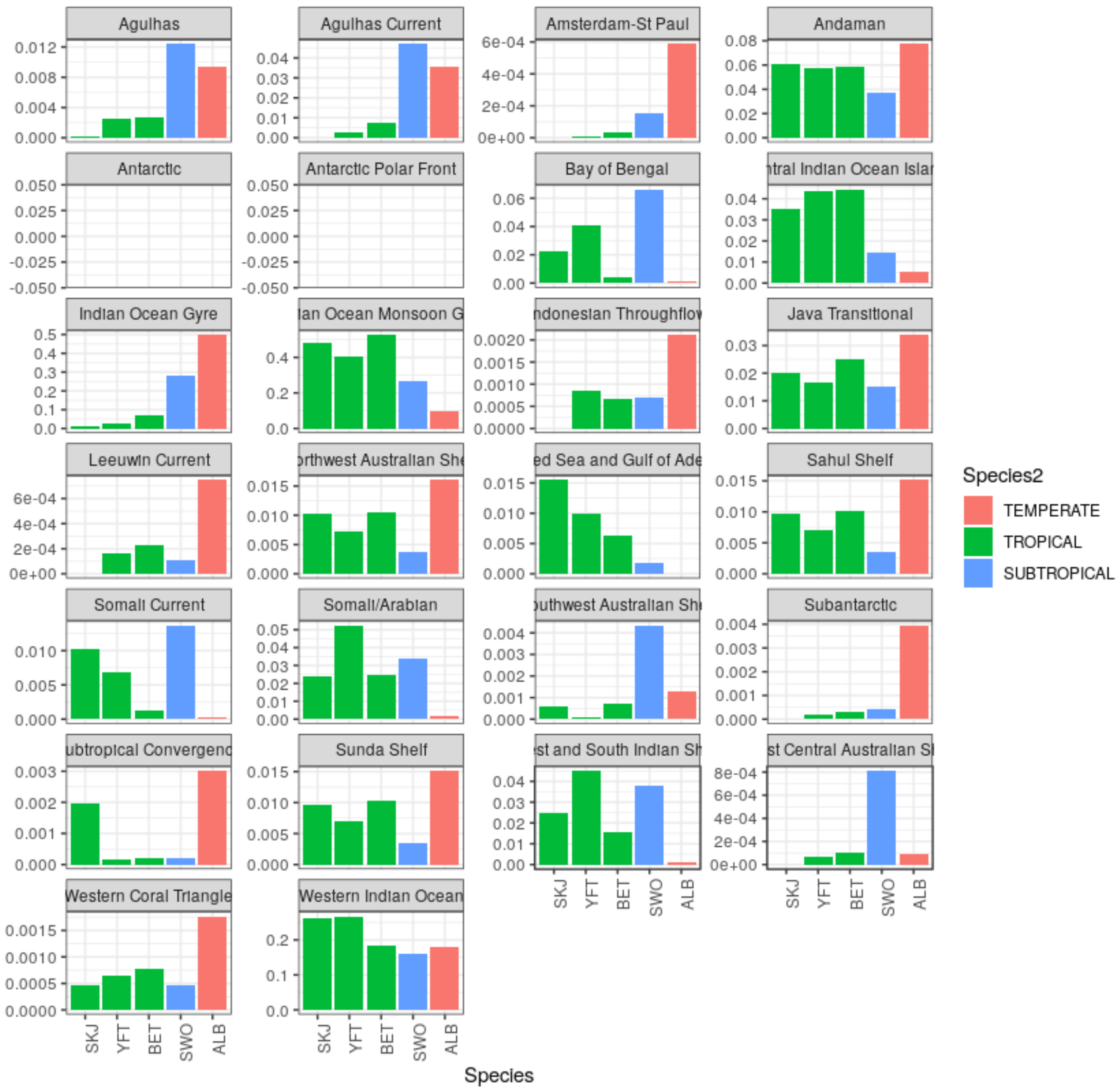

Figure 66. The specificity-fidelity indicator for the combined MEOW-PPOW provinces (see Figure 59) calculated from the species distribution of the main IOTC species (see Table 1 for species codes). The colors of the bars indicate whether a species is tropical (green), subtropical (blue), or temperate (red).

Specificity-fidelity indicator based on the spatial distributions of fisheries

The SF Indicator for fisheries indicates that the Andaman province, IOMG, IOG, and Western Indian Ocean have the most abundant catches (Figure 67), as is consistent with the analyses above (Figure 65, Figure 66). The diversity of fisheries within the IOMG and Western Indian Ocean is great relative to the IOG, which is mostly dominated by longline fisheries (LL, ELL, FLL). When examining the SF Indicator for fisheries qualitatively, we find that the fisheries in the northern basin of the Indian Ocean and the coastal areas are represent a diversity of fisheries, and the southern provinces in the southern basin of the Indian Ocean are dominated by the different longline fisheries (Figure 68). We find it qualitatively difficult to distinguish between the relative patterns of fisheries across the provinces.

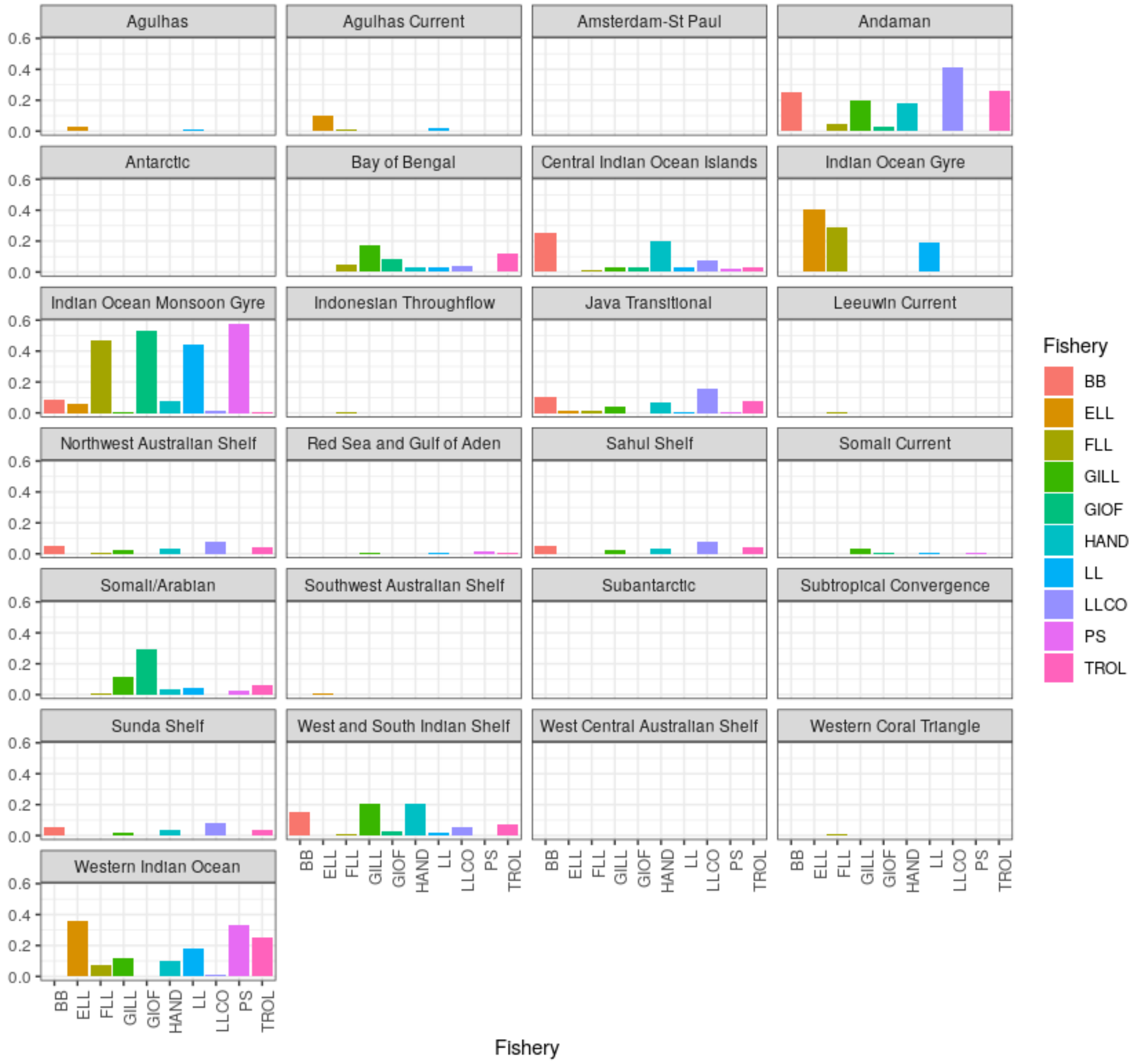

Figure 67. The specificity-fidelity indicator for the combined MEOW-PPOW provinces according to fisheries distribution of the main IOTC species (see Table 7 for gear codes).

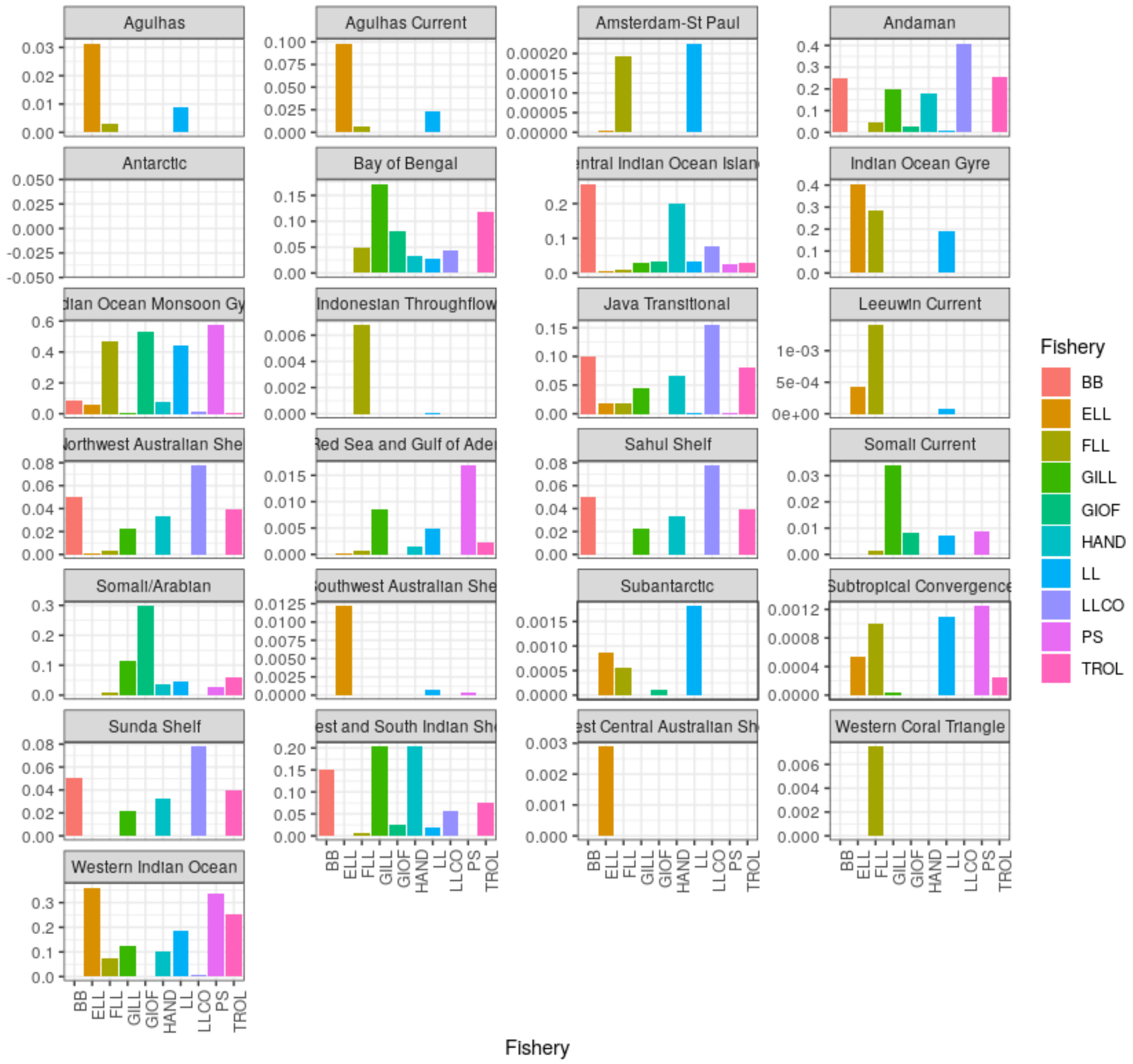

Figure 68. The specificity-fidelity indicator for the combined MEOW-PPOW provinces according to fisheries distribution of the main IOTC species (see Table 7 for gear codes).

7.4 Hierarchical clustering on the SF Indicators based on species and fisheries distributions to identify candidate draft ecoregions

We employed a statistical hierarchical clustering algorithm (hclust function from the R “stats” package) to group the different provinces (MEOWs and PPOWs) based on their similarities in terms of species and fisheries composition. The clustering was performed on the SF Indicators of the MEOW and PPOW provinces calculated in the previous section (Section 7.3).

For each MEOW and PPOW, we derived clusters based on 1) species composition, 2) fisheries composition, and finally 3) both species and fisheries composition combined. Data were scaled. We calculated a distance matrix between pairs of values using euclidean distances, and finally, we applied the hierarchical clustering algorithm using the single linkage method.

The cutoffs of the dendrogram used to define the clusters were subjectively assigned with the aim to minimise the number of higher-order clusters for practicality in terms of the number of ecoregions. SF Indicators (Figures 65 and Figure 67) were used as a guide in deciding the cutoff points between dissimilar provinces. However, we note that the hierarchical nature of this clustering method allows multiple levels to be nested within.

The results of our clustering analysis are presented here to inform the delineation of the draft ecoregions. We expect these proposals to be discussed and refined by workshop participants, particularly to incorporate their expert knowledge to address the impacts of inadequate and low quality data layers on the analysis. We invite participants to review these different proposals and suggest ways that they can be combined and refined.

Clusters of provinces based on species composition

The hierarchical clustering dendrogram using the SF indicators based on the species distributions breaks into the three first-order clusters: two that are made up of one to two provinces, and a third large grouping that is made up of all the other provinces (Figure 69). When plotted, the first cluster correspond to the northern IOMG basin with the Western Indian Ocean islands, the second cluster to the the southern IOG, and the third cluster with the rest of the other provinces. The northern and southern clusters are well explained by species distributions as above (Figure 65, Figure 66). The third cluster appears to represent the provinces where relatively little catch is found, regardless of the species composition within each of these provinces.

A second-order clustering was therefore performed to differentiate the third cluster (Figure 71), which clustered into separate three additional groupings. A group comprised of the northern coastal provinces (e.g. Central Indian Ocean Islands, Bay of Bengal) with a mix of tropical tuna species and swordfish catches, and the other two groups with the rest of provinces with dominant catches of Albacore (Figure 72). There are some clusterings across wide geographic distances, and these groupings should be considered by the workshop participants.

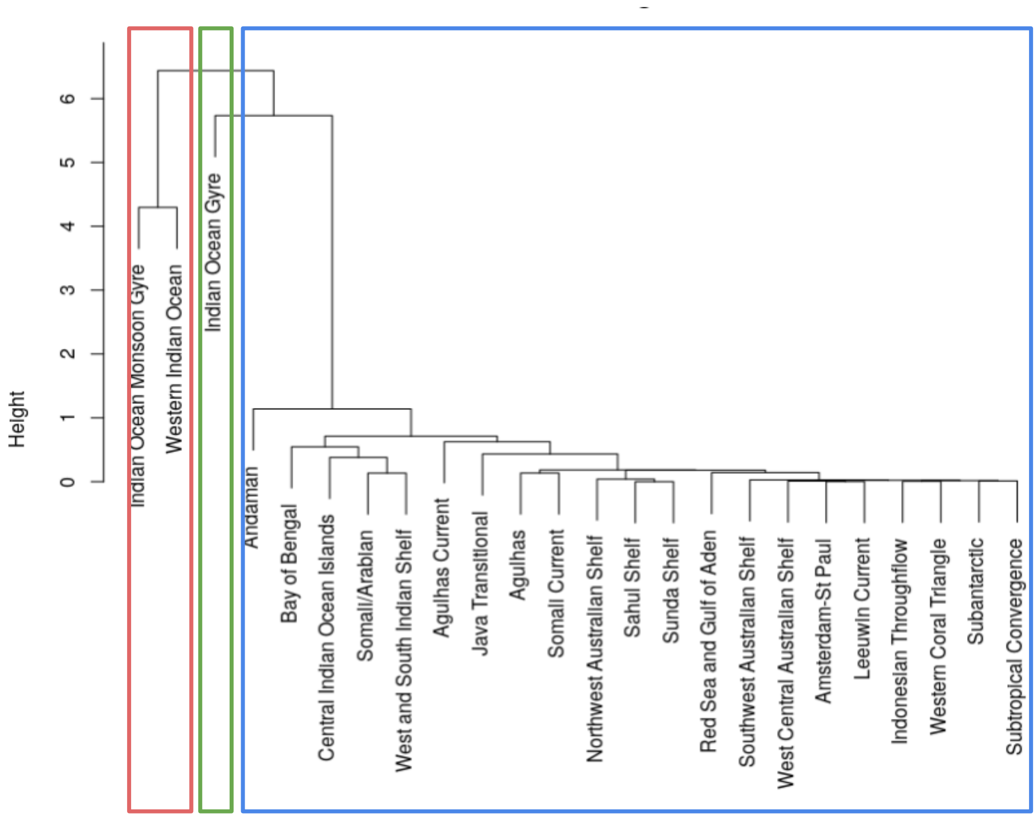

Figure 69. Dendrogram of first order hierarchical clustering on the combined MEOW and PPOW classification calculated from SF Indicators based on species distributions of the main IOTC species (2003-2017) in the IOTC convention area. The coloured boxes indicate the first-order clusters as in Figure 70.

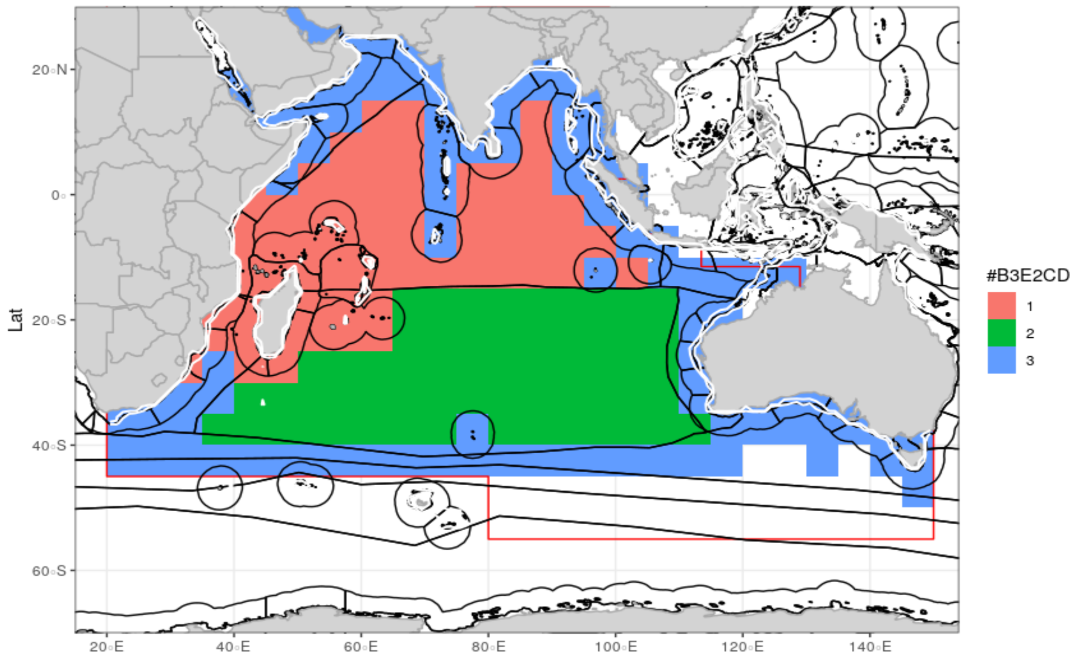

Figure 70. First order hierarchical clusters of the MEOW and PPOW provinces of the IOTC convention area as derived from the dendrogram in Figure 69, using specificity-fidelity indicators calculated from the species distributions of the 2003-2017 raised catch data of the main IOTC species. Provinces and their associated clusters can be found in Table 9. The 200 m and 1000 m isobaths are demarcated by the white polygons.

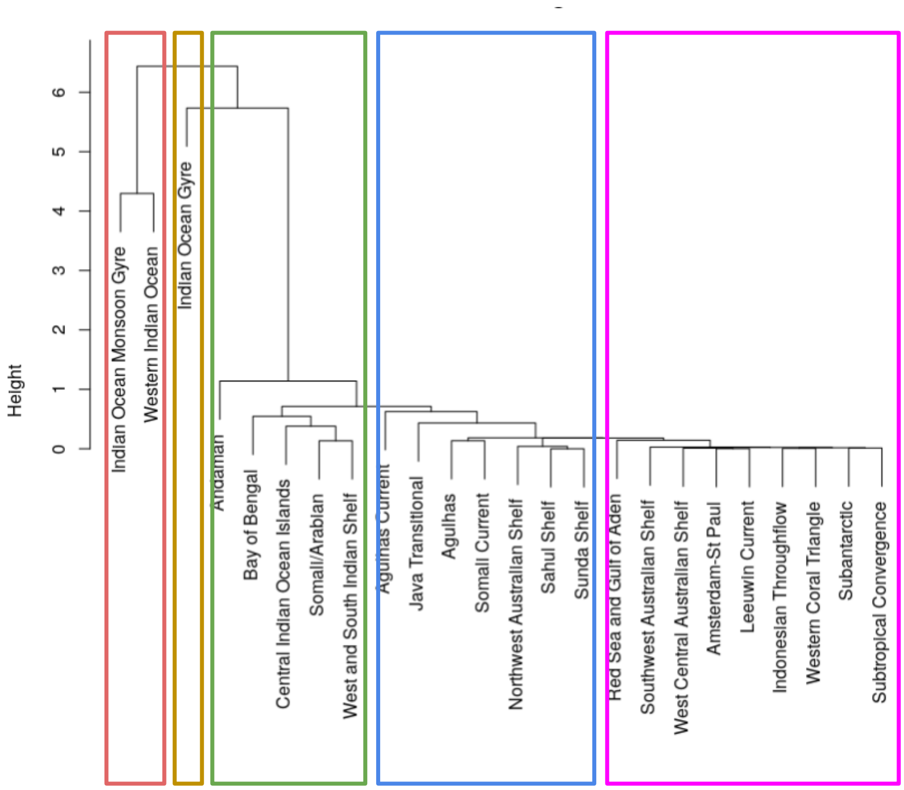

Figure 71. Hierarchical clustering dendrogram, clustering the MEOW and PPOW provinces of the IOTC convention area, using specificity-fidelity indicators calculated from the species distributions of the 2003-2017 raised catch data of the main IOTC species. The coloured boxes represent the second-order clusters as in Figure 72.

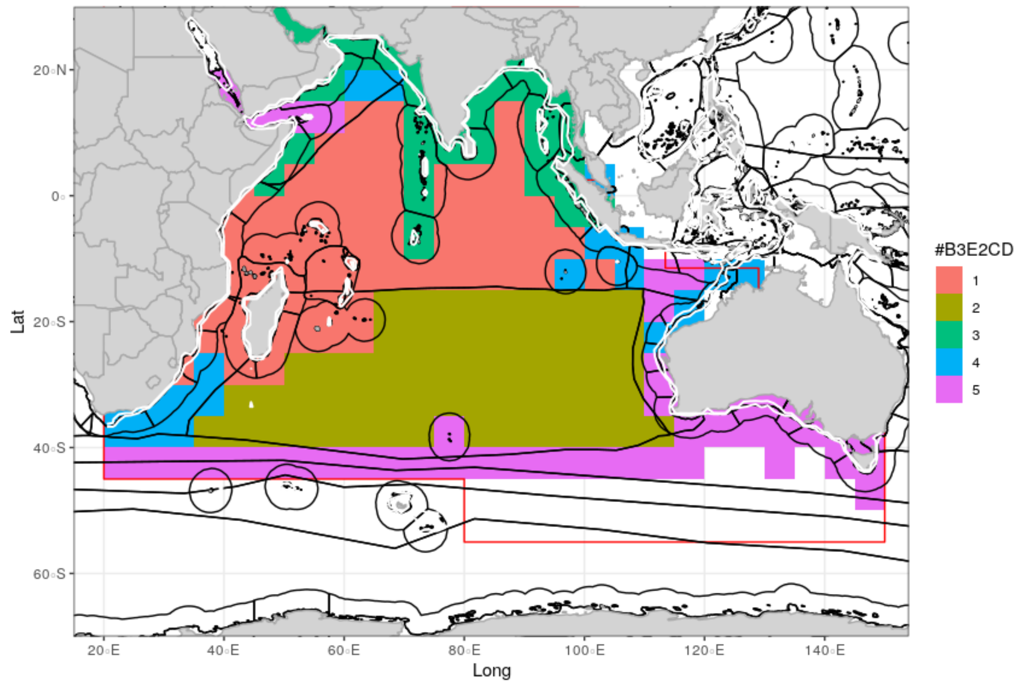

Figure 72. Second-order hierarchical clusters of the MEOW and PPOW provinces of the IOTC convention area as derived from the dendrogram in Figure 71, using specificity-fidelity indicators calculated from the species distributions of the 2003-2017 raised catch data of the main IOTC species. Provinces and their associated clusters can be found in Table 9. The 200 m and 1000 m isobaths are demarcated by the white polygons.

Table 9. The PPOW and MEOW provinces as identified in the dendrograms of the clustering analysis, and the cluster that they are assigned to depending on the data used for the analysis (i.e. Species, Fishery, or Combined).

Province type	Province	Species cluster		Fisheries cluster	Combined cluster
		1st order	2nd order	1st order	1st order
MEOW	Agulhas	3	4	2	4
PPOW	Agulhas Current	3	4	2	4
MEOW	Amsterdam-St Paul	3	5	2	4
MEOW	Andaman	3	3	4	3
MEOW	Bay of Bengal	3	3	2	4
MEOW	Central Indian Ocean Islands	3	3	4	5
PPOW	Indian Ocean Gyre	2	2	3	2
PPOW	Indian Ocean Monsoon Gyre	1	1	1	1
PPOW	Indonesian Throughflow	3	5	2	4
MEOW	Java Transitional	3	4	2	4
PPOW	Leeuwin Current	3	5	2	4
MEOW	Northwest Australian Shelf	3	4	2	4
MEWO	Red Sea and Gulf of Aden	3	5	2	4
MEOW	Sahul Shelf	3	4	2	4
PPOW	Somali Current	3	4	2	4
MEOW	Somali/Arabian	3	3	2	4
MEOW	Southwest Australian Shelf	3	5	2	4
PPOW	Subantarctic	3	5	2	4
MEOW	Subtropical Convergence	3	5	2	4
MEOW	Sunda Shelf	3	4	2	4
MEOW	West and South Indian Shelf	3	3	4	5
MEOW	West Central Australian Shelf	3	5	2	4
MEOW	Western Coral Triangle	3	5	2	4
MEOW	Western Indian Ocean	1	1	3	2

Clusters of provinces based on their fisheries composition

The hierarchical clustering dendrogram using the SF indicators based on fisheries distribution can be broken down into four first-order clusters (Figure 73). These clusters correspond roughly to a northern cluster of the IOMG, a southern cluster of the IOG and including the western Indian Ocean islands, a central and eastern coastal cluster including the Central Indian Ocean islands, and all the other provinces in a fourth cluster (Figure 74).

These patterns are similar to what is found when clustering on species distributions; however the Western Indian Ocean changes from clustering with the IOMG to clustering with the IOG. The IOG is dominated by catches made of longlines, the IOMG is dominated by catches made by purse seines, followed by longline catches, while the Western Indian Ocean province is dominated by both, purse seiners and longliners (Figure 68). The purse seine fisheries are active mostly in the northern part of the Western Indian Ocean Province, and they are coded as one type of fishery (the “PS”), whereas longline fisheries are active throughout the entire province and are categorized as different types of longline fisheries (the “LL”, “ELL”, “FLL”), potentially why this province groups with the IOG when based on fisheries.

The central and eastern coastal provinces show a distinct grouping that is based on relatively high abundance (Figure 67), and a high diversity of fisheries (Figure 68), with high catches by baitboats and handlines.

The fourth cluster is based on the relatively low catches found throughout these provinces (Figure 67, Figure 68). No further delineation of this cluster is imposed as it is expected that workshop participants will aid in the definition of these boundaries.

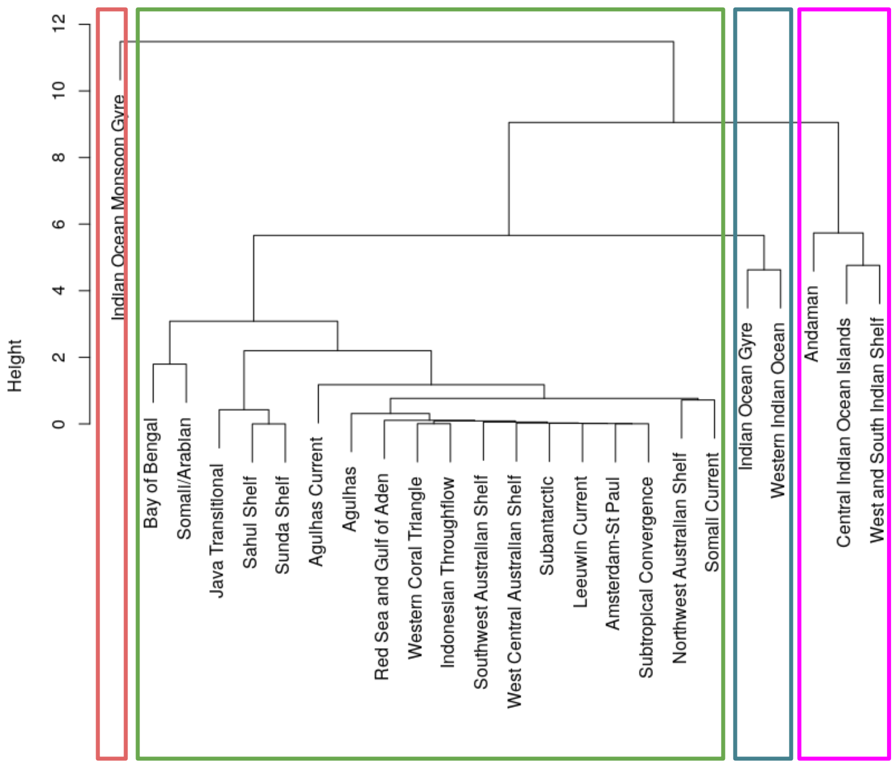

Figure 73. Hierarchical clustering dendrogram, clustering the MEOW and PPOW provinces of the IOTC convention area, using specificity-fidelity indicators calculated from the fisheries distributions of the 2003-2017 raised catch data of the main IOTC species. The coloured boxes indicate the first-order clusters as in Figure 74.

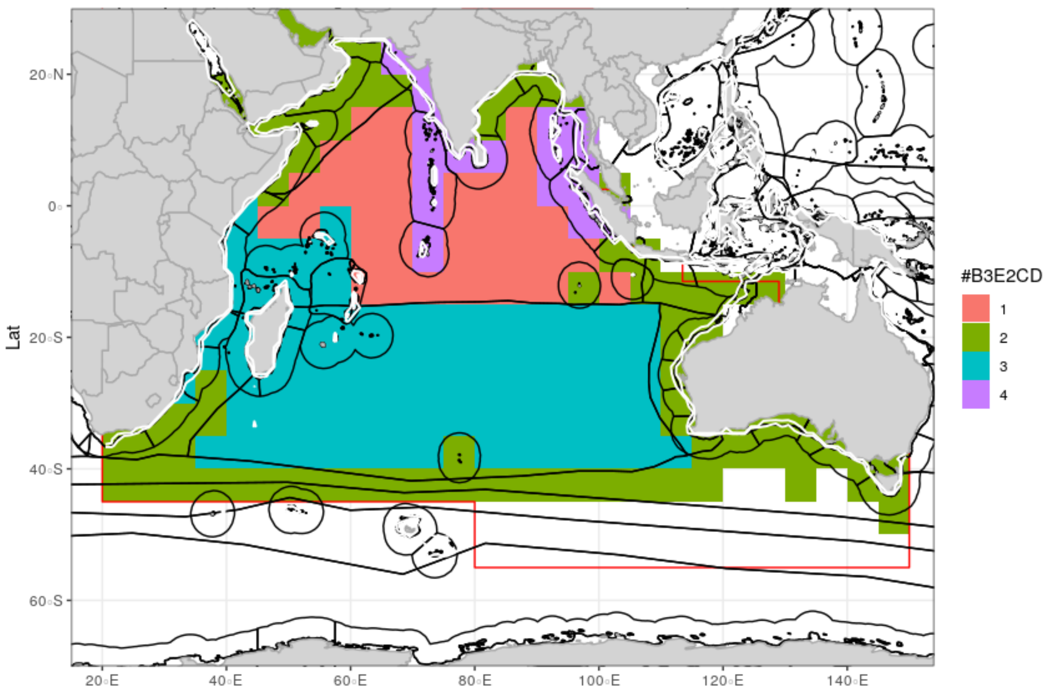

Figure 74. The highest-order clusters indicated by the coloured polygons and resulting from the hierarchical cluster analysis (Figure 73) of the MEOW and PPOW provinces of the IOTC convention area (black lines), using specificity-fidelity indicators calculated from the fisheries distributions of the 2003-2017 raised median annual catch data of the main IOTC species. Details on provinces and their associated clusters can be found in Table 9. The 200 m and 1000 m isobaths are demarcated by the white polygons.

Clusters of provinces based on both species and fisheries composition

The hierarchical clustering dendrogram using the SF indicators based on both the species and fisheries distributions can be broken down into five first-order clusters (Figure 75). These clusters correspond roughly to a northern cluster based on the IOMG, a southern cluster based on the IOG with the Western Indian Ocean islands, an eastern coastal cluster based on the Andaman province, a central coastal cluster, and a highly spread and diverse cluster composed of all the other provinces (Figure 76). These combined clusters correspond to high purse seine activity and catches of tropical tuna (BET, SKJ, YFT) in the northern cluster (the IOMG), a high longline activity and catches of temperate ALB and subtropical SWO in the southern cluster (IOG and Western Indian Ocean provinces), and a high diversity of fisheries and species in the test of the coastal clusters (Figure 65; Figure 66, Figure 67, Figure 68). The grouping of the Western Indian Ocean with the southern cluster appears again to be driven by the distribution of fisheries in this region, rather than the distribution of species. This might be confounded by the fact that whole the logline fisheries widely operate in the Western Indian Ocean province, the longline fisheries operating in the northern areas of this province are mainly targeting topical tuna species, while the longline fisheries operating in the souther areas of this province are targeting mostly temperate species.

The fifth cluster can likely be further differentiated, but no further delineation of this cluster is imposed as it is expected that workshop participants will aid in the definition of these boundaries.

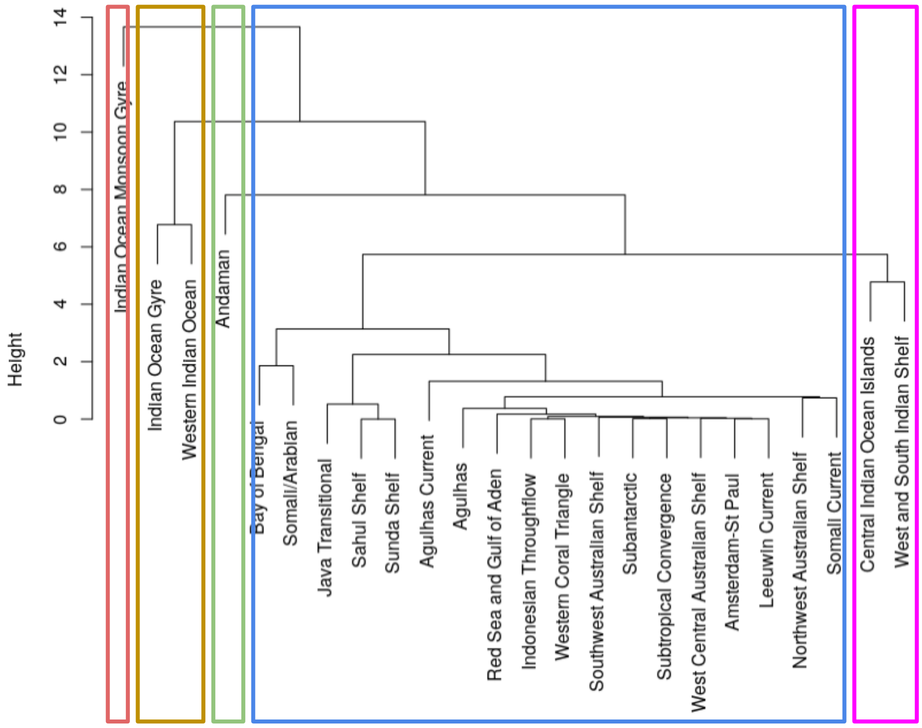

Figure 75. Hierarchical clustering dendrogram, clustering the MEOW and PPOW provinces of the IOTC convention area, using specificity-fidelity indicators calculated from both the species distributions and the fisheries distributions of the 2003-2017 raised median annual catch data of the main IOTC species. The colored boxes represent the first-order clusters as in Figure 76.

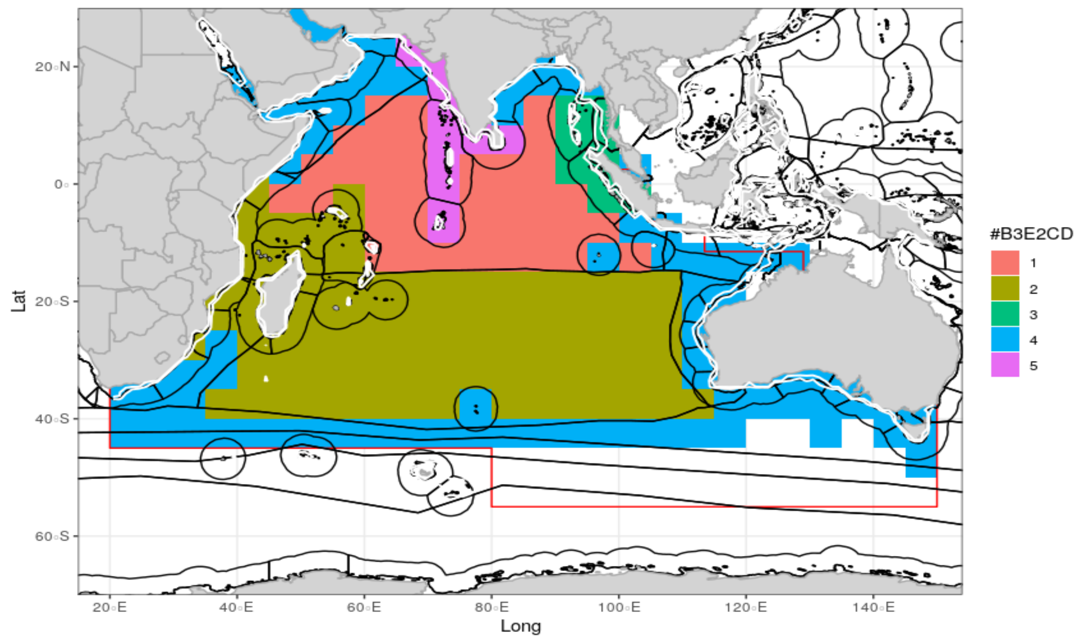

Figure 76. The highest-order clusters indicated by the coloured polygons and resulting from the hierarchical cluster analysis of the MEOW and PPOW provinces of the IOTC convention area (black lines), using specificity-fidelity indicators calculated from both the species distributions and the fisheries distributions of the 2003-2017 raised median annual catch data of the main IOTC species. Details on provinces and their associated clusters can be found in Table 9. The 200 m and 1000 m isobaths are demarcated by the white polygons

7.5 Conclusions spatial analysis

Overall, we found that the first-order clustering of the provinces based on their species composition, fisheries composition, and a combination of both species and fisheries composition all gave roughly similar results indicating three major groupings: a large northern oceanic cluster of provinces with the inclusion of the western Indian Ocean islands, a large southern oceanic cluster with the inclusion of some bordering coastal provinces, and a smaller central coastal cluster including coastal areas bordering the northern Indian Ocean. The second-order clusters were more variable across the analyses performed in how the coastal areas were subdivided. In general, we find that the large northern oceanic cluster is primarily dominated by purse seine fisheries catching tropical tunas (SKJ, YFT and BET) and secondarily dominated by longline fisheries catching also tropical tunas (BET and YFT) and some SWO, the southern oceanic cluster is dominated by longline activity catching temperate ALB and SWO, and the coastal clusters represent a diverse mix of both fisheries activities and species communities.

8 Points for workshop discussion

This work will be presented at the upcoming IOTC ecoregion workshop, where expert advice will be solicited. Workshop participants will review the analyses leading to the cluster groups which will be used to inform draft ecoregions. It is also expected that draft ecoregion will also be assessed against the proposed evaluation criteria in Table 3 to provide a final ecoregion proposal refined by expert knowledge.

Using the ecological evaluation criteria in Table 3, we preliminary evaluated the cluster groups in Figure 76 (derived from the species and fisheries distributions) to assess whether these cluster groups meet the expected qualities of ecoregions appropriate for implementing an EAFM in the IOTC (Table 10). We expect this preliminary evaluation will inform discussions at the workshop.

Preliminary evaluation points:

- Criterion 1.1 aims to ensure that the boundaries of ecoregions have clear biogeographic and oceanographic justification and these expectations were met as the ecoregion boundaries represent characteristic biogeography and oceanographic features. We accounted for this criterion by including a combined version of the MEOWs and the PPOWs, which by definition incorporate the biogeography and oceanography of the Indian Ocean.

- We addressed criterion 2.1 and criterion 3.1 by including the main IOTC species and fisheries specifically as data layers in the statistical spatial analysis. We find that expectations are met fairly well as each of the draft ecoregions are characterized by distinct species and fisheries compositions.

- Criterion 2.2 aims to ensure that the distribution of neritic tunas are also accounted for in the derivation of ecoregions. The spatial distribution of neritic species was indirectly accounted for by implicitly incorporating a coastal biogeographic classification (the MEOW provinces) into the statistical spatial analysis.

- We also expect that the spatial variation of the ecoregions in response to climate variability and climate change is relatively slow (criterion 1.3). We suggest that the boundaries of ecoregions could be reassessed at regular intervals (every 10-15 years) to address management adaptation to climate change if required.

- The hierarchical clustering that we performed gives a quantitative measure of the similarities within ecoregions and the differences between ecoregions, ensuring that there is greater similarity within than between (criterion 1.4).

- Expert knowledge will be required to refine the boundaries of the proposed draft ecoregions to ensure that the final candidate ecoregions comply with the remaining ecological criteria, specifically that there are no gaps between ecoregions in geographical space (criterion 1.2) and that they cover the main life history stages of species (criterion 2.3).

- Expert knowledge will also be required to evaluate the draft ecoregions against the socio-political criteria (Table 4). Discussion on other management initiatives, socioeconomic, and geopolitical considerations are expected to take place during the coming workshop.

Table 10. An evaluation of the draft ecoregions proposed in Figure 76 against the core criteria outlined in Table 3. Green rows indicate where the proposed ecoregion adequately meets the expectations set by the core criteria.

No.	Criteria	Expectations in appropriate ecoregion	Do the draft ecoregions meet the expectations?
	1. Oceanography/Biogeography		
1.1	Do the boundaries of existing or proposed ecoregions appropriately demarcate areas with identifiable oceanographic characteristics?	Boundaries should have clear oceanographic justification for demarcation	Yes : Using the combined MEOW-PPOW biogeographic classification ensures boundaries have clear oceanographic justifications
1.2	If there are subregions within the ecoregion (oceanographically/ biogeographically identifiable regions that do not meet the criteria for ecoregions), do they nest within ecoregions without gaps or inefficiencies?	Ecoregion may divide clearly and completely into a small number (≤ 3) of sub-regions	Partially: It requires further discussion and expert advice
1.3	Would there be significant spatial variation in the response of existing or proposed ecoregions physical characteristics, species and communities to climate variability and climate change?	Spatial variation in response to climate variability and climate change should be relatively slow.	Partially: Ecoregions can be reassessed at regular intervals to address management adaptation to climate change if needed.
1.4	Is the oceanographic and biological variability within the existing or proposed ecoregion smaller than variability between ecoregions?	Variability within ecoregions should be smaller than variability among ecoregions	Yes : By clustering provinces with similar species and fisheries composition, we ensure the variability within

			ecoregions is smaller than among ecoregions. The quantification of variability can be found in dendrogram in Figure 75.
2.Spatial distributions of main IOTC species			
2.1	Do the boundaries of existing or proposed ecoregions appropriately demarcate the distribution of the main IOTC tuna and billfish species and distinct tuna and billfish communities inhabiting the pelagic zone?	Boundaries should demarcate the core distribution of main IOTC tuna and billfish species and distinct fish communities	Yes : Draft ecoregions have distinct species composition and some of them include the core distributions of some species.
2.2	Do the boundaries of existing or proposed ecoregions include the contiguous shelf areas and the slope to a depth of at least 1000m fall into the same ecoregion?	The shelf and slope to a depth of at least 1000m should fall within the same ecoregion as fishing has increasingly spread from shelf to slope regions, and these regions are important to describe the spatial distribution of neritic tuna important for artisanal catches in the IOTC region.	Yes : Using the MEOW coastal classification, which includes the continental shelf, slope and ensures that most of the known habitat and distribution of neritic species is represented in the draft ecoregions (Figure 14).
2.3	Do the boundaries of existing or proposed ecoregions incorporate the different life history stages of the main IOTC tuna and billfish species?	Boundaries should incorporate the main life history stages characteristics of species, including core adult and juvenile distributions, and spawning areas.	No data layer were incorporated in the statistical analysis. Expert advice required.
3.Spatial distribution of main IOTC fisheries			
3.1	Do the boundaries of existing or proposed ecoregions appropriately demarcate the distribution of IOTC fleets and fisheries operating in the IOTC convention area?	Boundaries should demarcate the core fishing grounds for main IOTC fleets and fisheries.	Yes : Draft ecoregions have distinct fisheries composition and some of them include the core distributions of some fisheries.

We expect the final ecoregion proposal derived in the workshop will also be delivered to the IOTC WPEB15 meeting for further input.

We remind participants that the development of ecoregions is an iterative process. It is important to design an iterative and consultative process within the IOTC Scientific Committee and Commission to ensure the criteria for defining ecoregions consider both ecological and socio-political processes relevant for the IOTC context and to ensure that resultant ecoregions are fit for their purpose. Ultimately, ecoregions could be used to plan and structure ecosystem-based integrated fisheries advice to inform fisheries management, solve region-specific challenges and inform regionalized fisheries conservation and management measures (ICES 2018).

9 Acknowledgements

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