PRELIMINARY STEPS TOWARDS ASSESSING THE ECOSYSTEM IMPACTS OF FISHING IN THE TROPICAL INDIAN OCEAN THROUGH A TROPHIC MODELLING APPROACH

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SUMMARY

An Ecopath model of the Tropical Indian Ocean (TIO) pelagic ecosystem has been built to enhance the understanding of its structure, functioning, and to assess the ecosystem impacts of fishing. The model represents the pelagic oceanic ecosystem of the early 2000s, covering an area of over 21 million km^2, from the surface to a depth of 500m. It comprises 35 functional groups, ranging from primary producers to top predators. For ecological and fisheries considerations, the tropical tuna species (bigeye, yellowfin, and skipjack) are categorized into two life stages or stanzas (juveniles and adults). Additionally, the model includes 13 fishing fleets, differentiating between operations on free schools and on FAD-associated tuna schools for the purse seine fleets. Input data such as biomass, catches, diets, and production and consumption rates came from visual surveys, stock assessments, IOTC fishery statistics databases, empirical equations and published and unpublished literature. Results showed important impacts of fisheries on tuna and tuna-like species and vulnerable species caught in tuna fisheries such as pelagic sharks, with significant differences between fleets. This preliminary Ecopath model forms the basis for further analysis to assess the historical dynamics of the ecosystem and the cumulative impacts of fishing and climate change using the temporal module Ecosim. Ultimately, the aim is to use this modelling tool to complement single-species fisheries management advise, providing managers with a broader ecological context for managing tropical tuna species and associated ecosystems.

KEYWORDS

EAFM, Ecopath, food web model, tuna, FAD, ecological indicators, Indian Ocean

1. Introduction

In recent years some tuna and billfish populations have recovered globally reaching sustainable levels, yet some populations remain overfished[1]. In addition, climate change represents one of the main threats to marine ecosystems and fisheries by changing primary productivity, increasing acidification, raising temperatures, and causing deoxygenation[2]. These changes are already impacting marine species with direct consequences to fishing opportunities and communities that depend on marine resources[3].

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Within this context, tuna Regional Fisheries Management Organizations (RFMOs) have committed to operationalize the ecosystem approach to fisheries management (EAFM)[4,5]. The EAFM is a holistic framework that aims to incorporate climate and ecosystem considerations into fisheries management advice. Marine ecosystem models (MEMs) are recognized as powerful tools because they provide a framework to integrate available information on ecosystem components, processes and anthropogenic activities, as well as to assist decision-making processes[6]. The Ecopath with Ecosim (EwE) modelling framework has been widely applied to model aquatic ecosystems[7] including large oceanic areas and tuna fisheries, particularly in the Pacific Ocean[8-10]. However, an ecosystem model specific to the tropical Indian Ocean has not been developed to support decision-making processes within the Indian Ocean Tuna Commission (IOTC).

The primary objective of this study is to improve the knowledge about the structure and the functioning of the Tropical Indian Ocean (TIO) pelagic ecosystem and to assess the cumulative ecosystem impacts of all fleets catching tuna and tuna-like species, particularly tropical tunas (bigeye – *Thunnus obesus*; yellowfin – *Thunnus albacares*; and skipjack – *Katsuwonus pelamis*). The ultimate goal is to develop a modelling tool to assess past, present and future cumulative impacts of fishing and climate change on the TIO pelagic ecosystem and use this modelling tool to complement single-species fisheries management advise, providing managers with a broader ecological context for managing tropical tuna species and associated ecosystems.

2. Methods

The static Ecopath model was used to provide a quantitative representation of the food web in terms of biomass and energy flows for the early 2000s. The food web is modelled using functional groups, which can consist of single species, ontogenic fractions of a species, or groups of species that share a common ecological traits, as well as the fleets operating within the ecosystem[11,12].

The Ecopath assumes mass-balance over a specific period of time, and is parameterized by two master equations: one describing the production of biomass and the other describing the energy balance of each functional group[11,13]. For each functional group, input information for three of the four basic parameters — biomass (B), production rate (P/B), consumption rate (Q/B), or ecotrophic efficiency (EE) — is required, while the fourth parameter is estimated by the model. The model also requires data on the diets of all the functional groups to be able to define prey-predator relationships and the catches made by each fleet to represent the impacts of fishing. A detailed explanation of the algorithms, the equations of the approach and its main advantages and limitations are described in Christensen & Walters (2004) and Heymans (2016).

The model estimates average conditions of the oceanic ecosystem between 2000 and 2003, covering more than 21M km^2 between 0 and 500m deep, from the border of the continental shelf to the open ocean. The continental shelf was excluded from the model as it holds an area of minor importance for tropical tuna fisheries and its inclusion would necessitate modelling the demersal/benthic ecosystem and artisanal fleets, which would add unnecessary complexity to the model.

The model follows a similar structure to previously developed oceanic models with a focus on tuna and tuna-like fisheries[9,10,14]. It comprises 35 functional groups defined based on the commercial importance of the species, data availability and ecological characteristics of the species such as diet composition and depth ranges (Table 1). It includes nine functional groups of vulnerable species including one functional group of seabirds, two of cetaceans, five of elasmobranchs and one of sea turtles (Table 1). Each of the three tropical tunas caught in the model area (bigeye, yellowfin, and skipjack) were categorized into two life stages or age groups (following multi-stanza life-history criteria) according to their maturity[15-17], due to fisheries and ecological reasons. The swordfish (*Xiphias gladius*) and albacore (*Thunnus alalunga*) were also modelled as separate functional groups. The model also includes functional groups representing major taxa groups observed in offshore tuna fisheries, including other billfishes, small tunas and other scombrids, jacks, mackerels, runners and other carangids, triggerfishes, epipelagic fishes I and epipelagic fishes II (Table 1 and Annex – Table 1). Similarly, based on ecological and dietary considerations of higher trophic levels, the following functional groups were also created: one functional group of small epipelagic fishes; one of mesopelagic fishes; four of pelagic invertebrates; three zooplanktonic groups; one group of phytoplankton; one group of detritus; and one of discards (Table 1).

Thirteen fishing fleets are represented in the model, which were defined based on the characteristics of fishing gears and the flag (i.e., Spain, France, Seychelles or other countries). To define fishing fleets and estimate their catches within the model area three databases from IOTC were used:

- Nominal retained catch database which contains annual total catch disaggregated by taxon (IOTC and non-IOTC species, gear and vessel flag reporting country between 1950 and 2022 (https://iotc.org/data/datasets/latest/NC/ALL).
- Catch and effort database which contains georeferenced catch-and-effort data for all fisheries by month, year, taxon, gear, and vessel flag reporting country between 1950 and 2022 (https://iotc.org/data/datasets/latest/CE/All); The spatial resolution of the grids ranges from purse seine (1º x 1º) to longline, pole and line and driftnet (5º x 5º).
- Raised catch database, which was requested to the IOTC secretariat and contains the raised georeferenced catches (5º x 5º) for the 5 main IOTC species (bigeye, yellowfin, skipjack, albacore and swordfish) between 1950 and 2022.

The main fishing gears in the model area are purse seine, longline, gillnet, baitboat, line, and other gears (inc.: trawl, liftnet, danish seine and others). Purse seine fishing sets were separated into two fishing modes: fish aggregating devices (FAD) and free schools (FSC) to capture the differences in catch composition. Specifically, the purse seine fleets were categorized into the following groups: Spain, France (inc.: France, Mayotte and Mauritius), Seychelles, and other PS-fleets, which includes all the other purse seine fleets. The rest of the fleets were aggregated according to the fishing gear used (Table 3). Details on the calculations of landings can be found in the Annex – Table 2 and in Annex – Figure 2.

Input parameters include biomass obtained locally from visual surveys[18-20] or IOTC fishery stock assessments[15-17,21-27], catch data from official IOTC fishery statistics (https://iotc.org/data/browser), published diet data from stomach content analyses, as well as estimates of consumption and production rates using empirical equations[28-31]. To achieve the mass-balance conditions, we applied a manual procedure following best practice guidelines[12] and employed a top-down strategy, starting with groups with higher trophic levels. Within this context, the pre-balance (PREBAL) diagnostics were used to identify issues with input values before balancing[32] to ensure that the input data adhered to general ecological principles. Along the PREBAL analysis, the pedigree index, which consists of assigning a quantification between 0 (low certainty) and 1 (high certainty) and a confidence interval of the parameter certainty tied to the parameter's origin under different predefined categories, helped to prioritize and justify modifications of initial input values during the balancing procedure. The input parameters of the balanced model can be found in Table 1.

To analyse the food-web structure of the TIO model, biomass, trophic flows and trophic levels (TL) were visualized using the flow diagram. We also used several ecological indicators related to the development and maturity of ecosystems according to Odum (1969): total primary production/total respiration (Pp/R), total primary production/total biomass (Pp/B), net system production, system omnivory index (SOI) and Finn's mean path length (PL). We estimated the mean transfer efficiency (TE), which represents the average energy transferred to higher trophic levels through consumption or exported out of the ecosystem (e.g., by the fishery). Lastly, we also calculated the mean trophic level of the community (mTLco) by weighting the TL of each functional group by its relative contribution to the total consumer biomass in the system excluding the TL = 1 (primary producers and detritus).

To assess the ecological role of the functional groups we used the TL and the Mixed Trophic Impacts (MTI) analysis. The TL assess the ecological position of the functional groups of the TIO model while the MTI assess the effect of biomass changes in one group (impacting group) on the biomass of the other groups (impacted group) in the ecosystem. This indicator should be interpreted as a tool for indicating possible interactions (including competition) in a steady-state system, rather than as a tool for making predictions of what will happen in the future if certain interaction terms are changed[14].

To assess the impact of fishing, we calculated the mean trophic level of the catch (mTLc) by weighting the TL of each functional group by its relative contribution to the total catch for each fleet. In addition, we have calculated the mTLc of each fleet. The exploitation rate (F/Z), which is the proportion of the total mortality (Z) that is induced by fishing mortality (F), was also calculated by functional group. Lastly, the MTI was used to quantify the direct and indirect impacts of each fishing fleet on the functional groups, as well as the potential competition among fleets.

Table 1. Input data and outputs of the TIO model. Parameters estimated by the model are highlighted in bold. B = final biomass ($t{\cdot}km^{-2}$); P/B = production/biomass ($year^{-1}$); Q/B = consumption/ biomass ($year^{-1}$); P/Q = production/consumption ratio; EE = ecotrophic efficiency; TL = trophic level; F = fishing mortality; F/Z=exploitation rate.

	Functional group	B	P/B	Q/B	P/Q	EE	TL	F	F/Z
1	Seabirds	0.0005	0.12	77.62	**0.00**	**0.00**	**4.08**	-	-
2	Baleen whales	0.0002	0.05	3.98	**0.01**	**0.30**	**3.64**	**0.005**	**0.099**
3	Toothed whales	0.0047	0.08	8.16	**0.01**	**0.42**	**4.26**	**0.013**	**0.156**
4	Blue shark	0.0249	0.22	2.35	**0.09**	**0.60**	**4.32**	**0.125**	**0.579**
5	Silky shark	**0.0190**	**0.24**	2.44	0.10	0.50	**4.02**	**0.122**	**0.500**
6	Other sharks	**0.0710**	**0.24**	2.44	0.10	0.50	**4.43**	**0.117**	**0.482**
7	Whale shark	0.0067	0.04	1.38	**0.03**	**0.31**	**3.24**	**0.012**	**0.313**
8	Sea turtles	0.0017	0.19	3.03	**0.06**	**0.21**	**3.49**	**0.037**	**0.202**
9	Rays	0.0095	0.20	2.07	**0.10**	**0.20**	**3.47**	**0.025**	**0.120**
10	Other billfishes	0.0170	0.30	2.75	**0.11**	**0.33**	**4.36**	**0.081**	**0.272**
11	Swordfish	0.0099	0.27	2.13	**0.13**	**0.48**	**4.12**	**0.103**	**0.377**
12	Bigeye adult	0.0264	0.28	2.53	**0.11**	**0.84**	**4.36**	**0.205**	**0.732**
13	Bigeye juvenile	0.0130	0.55	4.20	**0.13**	**0.62**	**4.32**	**0.114**	**0.206**
14	Yellowfin adult	0.0798	0.37	3.51	**0.11**	**0.45**	**3.98**	**0.157**	**0.423**
15	Yellowfin juvenile	0.0310	0.68	5.20	**0.13**	**0.49**	**3.87**	**0.119**	**0.175**
16	Skipjack adult	0.0777	0.52	3.33	**0.16**	**0.85**	**3.68**	**0.247**	**0.476**
17	Skipjack juvenile	0.0023	1.04	7.70	**0.14**	**0.97**	**3.65**	**0.263**	**0.253**
18	Albacore	0.0027	0.54	4.52	**0.12**	**0.87**	**4.02**	**0.097**	**0.179**
19	Small tunas and other scombrids	**0.1808**	0.73	5.93	**0.12**	0.70	**3.75**	**0.071**	**0.097**
20	Jacks, mackerels, runners and other carangids	**0.2094**	0.92	6.99	**0.13**	0.80	**3.46**	**0.002**	**0.002**
21	Triggerfishes	**0.0291**	1.20	8.64	**0.14**	0.80	**3.53**	**0.015**	**0.012**
22	Epipelagic fishes I	**0.2162**	0.63	4.99	**0.13**	0.70	**3.81**	**0.001**	**0.001**
23	Epipelagic fishes II	**0.2666**	0.94	6.90	**0.14**	0.80	**3.53**	**0.000**	**0.000**
24	Small epipelagic fishes	0.5530	2.08	12.16	**0.17**	**0.96**	**3.11**	-	-
25	Mesopelagic fishes	2.6800	2.30	11.61	**0.20**	**0.48**	**2.71**	-	-
26	Pelagic cephalopods	**0.3076**	1.80	11.70	**0.15**	0.95	**3.51**	-	-
27	Pelagic crustaceans	**0.7710**	5.00	17.00	**0.29**	0.95	**2.49**	-	-
28	Pelagic molluscs	**0.2794**	4.46	13.84	**0.32**	0.95	**2.32**	-	-
29	Gelatinous plankton	**0.5254**	4.74	23.70	**0.20**	0.80	**2.45**	-	-
30	Macrozooplankton	1.4030	16.09	57.57	**0.28**	**0.29**	**2.47**	-	-
31	Mesozooplankton	2.4920	30.95	111.91	**0.28**	**0.64**	**2.18**	-	-
32	Microzooplankton	3.6770	56.06	186.81	**0.30**	**0.34**	**2.02**	-	-
33	Phytoplankton	11.658	205.0	-	-	**0.29**	**1.00**	-	-
34	Detritus	238.88	-	-	-	**0.12**	**1.00**	-	-
35	Discards	0.0010	-	-	-	**0.31**	**1.00**	-	-

3. Preliminary results and discussion

The functional groups are distributed across 4 TL, ranging from TL=1 for primary producers (f.g. 33) and detritus (f.g. 34) to TL=4.428 for other sharks (f.g. 6) (Table 1, Figure 1). The flow diagram highlights that zooplanktonic groups (f.g. 30-32), pelagic invertebrates (f.g. 26-29), mesopelagic fishes (f.g. 25) and the small epipelagic fishes (f.g. 24) play an important role in transferring energy from low to higher trophic levels. Furthermore, the detritus group (f.g. 34) constitutes an important source of energy into the ecosystem through its consumption.

To analyze the food web structure and functioning we have used some ecological indicators based on Odum's theory[33] of ecosystems (Table 2). The total primary production to total respiration (Pp/R) is expected to approach one as an ecosystem matures, Pp/R is higher in the TIO, which indicates that more energy is produced than respired within the ecosystem. In addition, both the net system production and the ratio of total primary production to total biomass (Pp/B) are also high, meaning that the ecosystem produces more than what is utilized within and that it has low levels of biomass accumulations. The Finns Cycling Index (FCI), which represents the proportion of the total flows that are recycled and tends to increase as the system matures, has a low value, suggesting a low energy recycling in the ecosystem. In addition, the system omnivory index (SOI) and the Finn's mean path length (PL) display relatively low values indicating that the food web is more chain-like (more linear and less complex) than web-like.

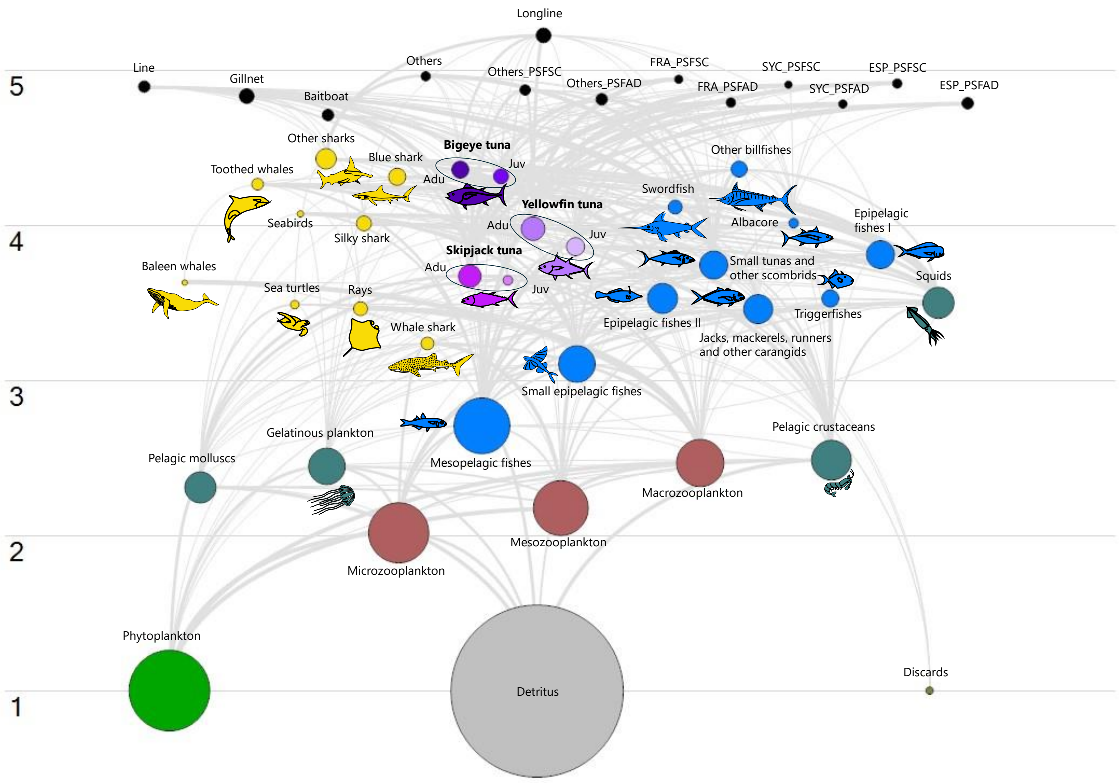

Figure 1. Flow diagram of the TIO model. The fleets are represented in black at the top arranged accordingly to their trophic level calculated based on the mean trophic level of their catch. Purple: tropical tunas; yellow: vulnerable species or taxa groups; blue: other fishes; green: invertebrates; brown: zooplankton. The size of each circle is proportional to the biomass of the functional group and the width of the lines are proportional to the magnitude of the flow represented.

Table 2. Summary statistics and ecological indicators for the tropical Indian Ocean pelagic ecosystem.

Statistics and ecological indicators of the ecosystem	**Value**	**Units**
Total primary production/total respiration (Pp/R)	6.493	
Net system production	2021.884	$t \cdot km^{-2} \cdot y^{-1}$
Total primary production/total biomass (Pp/B)	93.181	
System omnivory index (SOI)	0.234	
Finn's cycling index (FCI)	4.259	%
Finn's mean path length (PL)	2.437	
Total biomass (excluding detritus)	25.649	$t \cdot km^{-2}$
Mean trophic level of the community (mTLco, without TL=1)	2.510	
Total catches	0.074	$t \cdot km^{-2} \cdot y^{-1}$
Total landings	0.064	$t \cdot km^{-2} \cdot y^{-1}$
Total discards	0.010	$t \cdot km^{-2} \cdot y^{-1}$
Mean trophic level of the catch (mTLc)	3.965	
Primary production required to sustain the fisheries (from primary producers) (%PPR)	3.490	%
Mean transfer efficiency	12.60	%

The top predators (TL > 3.95) of the ecosystem are other sharks (f.g. 6), other billfishes (f.g. 10), bigeye adult (f.g. 12), bigeye juvenile (f.g. 13), blue shark (f.g. 4), toothed whales (f.g. 3), swordfish (f.g. 11), albacore (f.g. 18), silky shark (f.g. 5) and yellowfin adult (f.g. 14) (Table 1). Invertebrates' groups displayed TLs between 2.02 and 2.48, except for cephalopods (f.g. 26), which presented higher trophic levels (Table 1). TLs of fish ranged between 2.7 for mesopelagic fishes (f.g. 25) and 4.51 for other sharks (f.g. 6).

Toothed whales (f.g. 3), blue shark (f.g. 4), silky shark (f.g. 5), other sharks (f.g. 6) and small tunas and other scombrids (f.g. 19), are identified as potential keystone functional groups in the TIO model (Annex – Figure 2), playing a critical and disproportionate role relative to its abundance in maintaining the structure and function of the ecosystem. In addition, other groups were suggested to play an important role within the ecosystem (e.g., pelagic cephalopods (f.g. 26), pelagic crustaceans (f.g. 27) and macrozooplankton (f.g 30)) are also (Annex – Figure 2) but it is due their high abundance, and therefore they could be identified as dominant/structural groups within the ecosystem [34,35].

The MTI analysis highlights that groups at the base of the food web (e.g., discards, detritus, phytoplankton and zooplankton groups) and intermediate groups (e.g., pelagic molluscs, pelagic crustaceans, pelagic cephalopods, mesopelagic fishes and small epipelagic fishes) may have large impacts across the food web, indicating their importance within the system and suggesting possible bottom-up effects (Figure 2). This analysis also highlighted strong impacts (both positive and negative) of intermediate groups (e.g., pelagic molluscs, pelagic crustaceans, pelagic cephalopods, mesopelagic fishes and small epipelagic fishes) on lower and higher TL, highlighting their important role in transferring energy and suggesting a possible wasp-waist control of these organisms in the system. Lastly, this analysis also pointed out a strong negative impact of top predators on their preys (especially sharks (f.g. 4-6)). Remarkably, other sharks (f.g. 6) presented strong impacts on other high trophic level groups ((f.g. 4-18) mainly on albacore and juveniles of bigeye and yellowfin), either through direct predation or competition for the resources, including intra-group competition (Figure 2).

Total catches were 0.074t $km^{-2}\cdot year^{-1}$, with landings and discards representing 86.5% and 13.5% of the total catch, respectively. Sharks (f.g. 4-6) and adults of bigeye, yellowfin and skipjack (f.g. 12,14,16) exhibit high exploitation rates (Table 1). The percentage of primary production required to sustain the fisheries (%PPR) is 3.49% (Table 2), which is quite low compared with the global mean, but high compared with other oceanic areas[36]. The analysis of the total catch by fleet indicated that gillnet and longline fleets (fleets 4,5) have the highest catches in the area, followed by the baitboat and line fleets, and the Spanish purse seine fleet setting on FADs (Table 3). Fleets play the role of an apex predator in the ecosystem. The mTLc for all fleets is 3.965 (Table 2), which indicates that fleets catch high TLs. The baitboat fleet has the lowest mTLc (3.710) while the longline fleet has the highest mTLc (4.227) (Figure 1, Table 3).

Table 3. Catch ($t\cdot km^{-2}\cdot year^{-1}$) and mean trophic level of the catch (mTLc) of the fleets of the TIO model

	Fleet	Catch	mTLc
1	Baitboat	0.006	3.708
2	Others	0.002	3.993
3	Line	0.006	3.916
4	Gillnet	0.018	3.889
5	Longline	0.020	4.294
6	ESP_PSFSC	0.002	3.918
7	FRA_PSFSC	0.002	3.942
8	Others_PSFSC	0.003	3.823
9	SYC_PSFSC	0.001	3.904
10	ESP_PSFAD	0.005	3.780
11	FRA_PSFAD	0.003	3.791
12	Others_PSFAD	0.005	3.775
13	SYC_PSFAD	0.002	3.779

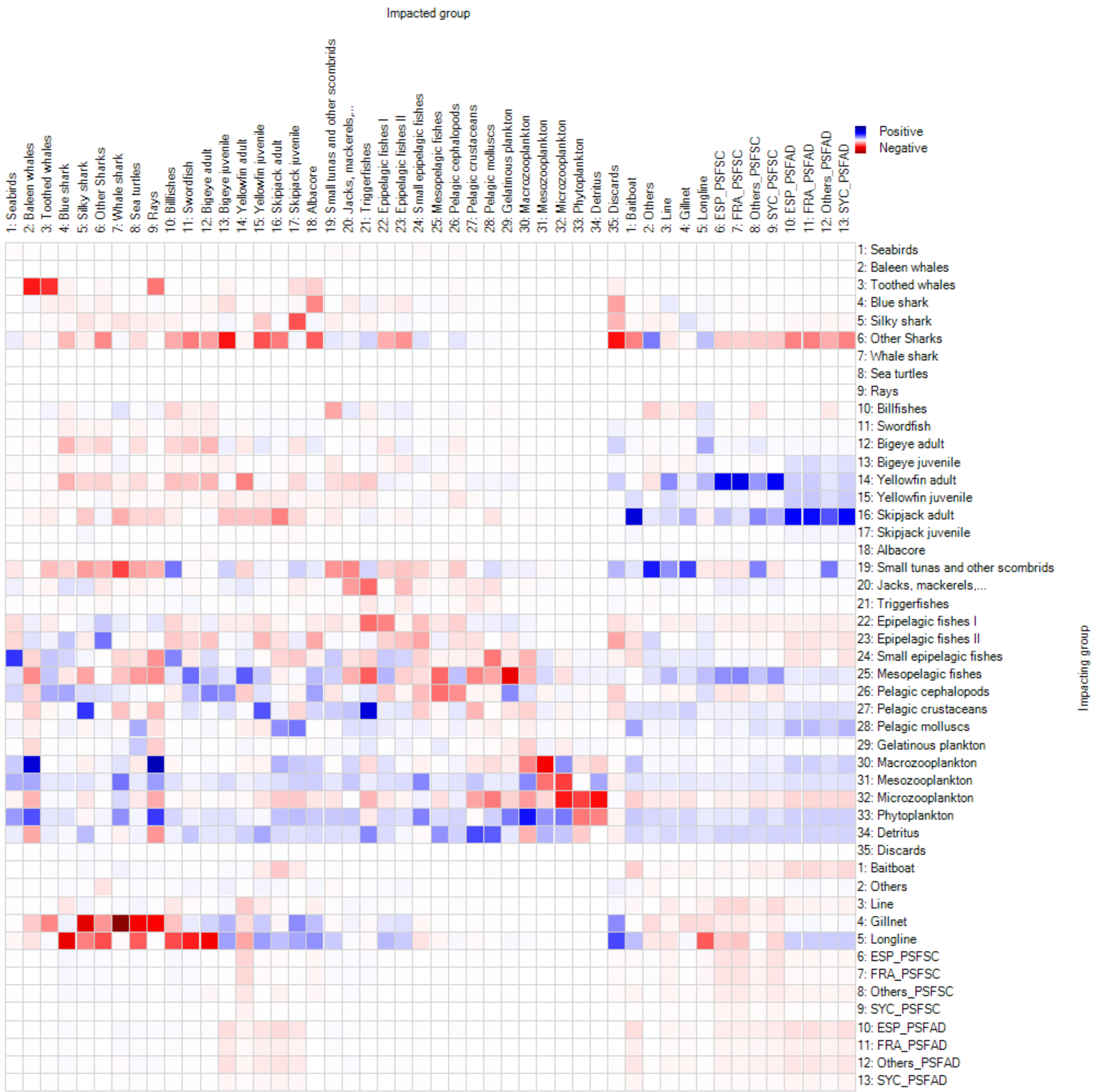

Figure 2. Mixed Trophic Impact (MTI) analysis of the TIO ecosystem for early 2000s. Negative (red) and positive (blue) impacts are represented.

The MTI also provides key insights into the main interactions between the fishing fleets and the species functional groups (Figure 2). The analysis shows that the 13 fishing fleets exert negative impacts on themselves due to intrafleet competition, as well as on the rest of the fleets through interfleet competition. However, there are indirect positives impacts observed from the longline fleet to the baitboat and the purse seine setting on FADs fleets (Figure 2). This positive impact arises because the longline fleet primarily targets adults of bigeye (f.g. 12) and sharks (f.g. 4-6), which are competitors and consumers of the main species targeted by these other two fleets, which catch juveniles of bigeye, yellowfin and skipjack (f.g., 13,15,17), and adults of skipjack (f.g. 16). The gillnet and longline fleets exhibit the most widespread impacts on vulnerable species. The gillnet fleet has strong negative impacts on toothed whales (f.g. 3), silky shark (f.g. 5), whale shark (f.g. 7), sea turtles (f.g. 8) and rays (f.g. 9), while the longline fleet has strong negative impacts on blue shark (f.g. 4), other sharks (f.g. 6) and sea turtles (f.g. 8). Additionally, the longline fleet has also a strong negative impact on some of its targeted species including other billfishes (f.g. 10), swordfish (f.g. 11), bigeye adult (f.g. 12) and yellowfin adult (f.g. 14) (Figure 2). Conversely, the longline and gillnet fleets have generalized positive impacts on the species that compete with or are predated upon by the species that they target. For example, these fleets positively influence the functional groups of juveniles of bigeye, yellowfin and skipjack (f.g. 13,15,17) and albacore (f.g. 18) (Figure 2). Regarding purse seiners, when setting on free schools (FSC) they have a negative impact mainly on adults of yellowfin (f.g. 14), while when setting on FADs, they have negative impacts on juveniles of bigeye, yellowfin and skipjack (f.g. 13,15,17), as well as on adults of skipjack (f.g. 16). The baitboat fleet, along with the line and the others fleets, have a negative impact on adults of skipjack (f.g.17) but in general they do not have strong positive nor negative impacts on the functional groups (Figure 2).

4. Conclusions and future steps

The present study represents the first ecosystem model of the Tropical Indian Ocean (TIO) and allowed to characterize the structure and functioning of the ecosystem and assess the impact of fishing. Therefore, the TIO model represents an important step towards the operationalization of the EAFM in the area by providing a complementary tool. However, the present model represents a preliminary model due to data availability.

Although the most updated and accurate available data was used to build the Ecopath module, substantial uncertainty exists due to data limitations. During the development of this model, we have identified several data gaps that should inform future scientific research objectives in the area. Addressing these gaps will enhance the robustness and applicability of the model. Below, we outline specific steps for future research:

1. A significant data gap has been identified related to the biomass estimation of specific species within the Indian Ocean (e.g., non-targeted large pelagic fishes, pelagic invertebrates and some vulnerable species). Further research is essential to accurately quantify and understand the population dynamics, distribution, and ecological role of these species.
2. Diet information of non-targeted species was scarce. Further studies on trophic ecology at all trophic levels are needed to better know the ecological role of the species, their predator-prey relationships, energy flows, and nutrient cycling. Furthermore, considering spatiotemporal studies would be particularly valuable for tracking dietary changes over time and space. As ocean conditions change, species may alter their diets. Long-term data can reveal shifts due to climate-related factors.
3. A significant data gap has been encountered due to incomplete reporting by certain fishing fleets. Without detailed information on their landings, accurately characterizing their impacts on species and the ecosystem becomes challenging. Future efforts should focus on improving reporting mechanisms and encouraging transparency to enhance our understanding of these ecological interactions.
4. Further improvements on discard reporting are crucial for characterizing the impact of the various fishing fleets on the ecosystem. Improving the information of discards would help on assessing the ecological consequences of fishing practices, assess the effectiveness of fisheries management measures, and design more sustainable fishing practices. Inconsistent reporting, lack of standardization, underreporting and missing species information need to be corrected by improving or implementing onboard or digital observer programs to collect real-time or near-real time discard data.

Therefore, future efforts will focus on enhancing the Ecopath model. A more detailed characterization of the discards for the Spanish and French purse seine fleets will be done by analysing observer data and applying post-release survival estimates. The trophic ecology of multiple species will undergo expert reviews to refine the dietary matrix of the model, ensuring it reflects the most accurate and current knowledge.

Once the preliminary Ecopath model is thoroughly parametrized, the temporal dynamic model, Ecosim, will be used to fit to time series data from 2003 to 2022 considering the impact of fishing and the environment. The adjusted Ecosim model will then be used to assess the historical dynamics of the TIO ecosystem and to evaluate potential fishing and climate change scenarios to understand how key drivers may interact and affect the ecosystem in the future and to analyse plausible conservation and management options that have the potential to meet preferred fishery and conservation objectives. The ultimate goal is to identify management measures that have the potential to ensure fishing yields while maintaining a good ecosystem status under a global change context.

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Annex

Annex – Table 1. Species composition of each functional group

Species composition of each functional group of the TIO model
1. Seabirds: *Puffinus lherminieri, Sterna fuscata, Oceanites oceanicus, Anous tenuirostris, Puffinus carneipes, Puffinus persicus, Anous stolidus, Bulweria fallax, Sterna anaethetus, Ardenna pacifica, Phalaropus lobatus, Pterodroma baraui, Gygis alba, Sula dactylatra, Oceanodroma monorhis, Phaethon aethereus, Fregetta tropica, Pelagodroma marina, Sula sula, Phaethon lepturus, Anous sp., Larus hemprichii, Stercorarius parasiticus, Fregata sp., Sula leucogaster, Stercorarius pomarinus, Sterna bergii, Calonectris diomedea, Stercorarius longicaudus, Fregetta sp., Oceanodroma matsudairae, Fregata ariel, Puffinus griseus*
2. Baleen whales: *Balaenoptera edeni, Balaenoptera musculus, Balaenoptera acustorostrata, Balaenoptera sp.*
3. Toothed whales: *Peponocephala electra, Globicephala macrorhynchus, Steno bredanensis, Lagenodelphis hosei, Feresa attenuata, Kogia sima, Kogia breviceps, Physeter macrocephalus, Indopacetus pacificus, Mesoplodon densirostris, Ziphius cavirostris, Delphinus capensis, Delphinus delphis, Grampus griseus, Orcinus orca, Pseudorca crassidens, Stenella attenuata, Stenella longirostris, Tursiops aduncus, Tursiops truncates, Stenella coeruleoalba*
4. Blue shark: *Prionace glauca*
5. Silky sharks: *Carcharhinus falciformis*
6. Other sharks: *Alopias superciliosus, Alopias pelagicus, Carcharhinus leucas, Lamna nasus, Carcharodon carcharias, Carcharhinus longimanus, Galeocerdo cuvier, Sphyrna lewini, Sphyrna zygaena, Isurus oxyrinchus*
7. Whale shark: *Rhincodon typus*
8. Sea turtles: *Chelonia mydas, Eretmochelys imbricata, Dermochelys coriacea, Caretta caretta, Lepidochelys olivacea*
9. Rays: *Mobula Japanica, Mobula mobular, Mobula birostris, Pteroplatytrygon violácea*
10. Other billfishes: *Istiompax indica, Tetrapturus angustirostris, Makaira nigricans, Istiophorus platypterus, Kajikia audax*
11. Swordfish: *Xiphias gladius*
12. Adult Bigeye tuna: *Thunnus obesus (>=110cm)*
13. Juvenile Bigeye tuna: *Thunnus obesus (<110cm)*
14. Adult Yellowfin tuna: *Thunnus albacares (>=75cm)*
15. Juvenile Yellowfin tuna: *Thunnus albacares (<75cm)*
16. Adult Skipjack tuna: *Katsuwonus pelamis (>=38cm)*
17. Juvenile Skipjack tuna: *Katsuwonus pelamis (<38cm)*
18. Albacore tuna: *Thunnus alalunga*
19. Small tunas and other scombrids: *Auxis rochei, Auxis thazard, Scomberomorus guttatus, Sarda orientalis, Euthynnus affinis, Acanthocybium solandri, Thunnus tonggol, Scomberomorus commerson*
20. Jacks, mackerels, runners and other carangids: *Elagatis bipinnulata, Seriola rivoliana, Caranx sexfasciatus, Neucrates ductor, Uraspis secunda, Uraspis helvola, Uraspis uraspis, Decapterus macrosoma, Ferdauia orthogrammus, Decapterus macarellus*
21. Triggerfishes: *Abalistes stellatus, Canthidermis maculata*

22. Epipelagic fishes I: *Alepisaurus ferox, Ablennes hians, Coryphaena equiselis, Brama brama, Ruvettus pretiosus, Lampris guttatus, Coryphaena hippurus, Tylosurus crocodilus, Lobotes surinamensis, Sphyraena barracuda, Lepidocybium flaobrunneum*
23. Epipelagic fishes II: *Diodon hystrix, Lagocephalus lagocephalus, Kyphosus vaigiensis, Kyphosus cinerascens, Platax teira, Masturus lanceolatus, Mola mola, Aluterus monoceros, Aluterus scriptus*
24. Small epipelagic fishes: *Exocoetus monocirrhus, Exocoetus volitans, Hirundichthys coromandelensis, Hirundichthys speculiger, Prognichthys sealei, Parexocoetus mento, Cheilopogon suttoni, Cheilopogon cyanopterus, Cheilopogon nigricans, Cheilopogon atrisignis , Cheilopogon furcatus*
25. Mesopelagic fishes: *Vinciguerria nimbaria, Sigmops elongatus, Cubiceps pauciradiatus, Myctophuidae sp.,*
26. Pelagic cephalopods: *Sthenoteuthis oualaniensis, Onychoteuthis banksii, Ornithoteuthis volatilis, Cranchiidae sp., Ctenopteryx sicula, Grimalditeuthis bonplandi, Mastigoteuthidae sp., Lycotheuthis lorigera*
27. Pelagic crustaceans: *Charybdis smithii, Oplophorus typus, Lysiosquilla tredecimdentata, Odontodactylus scyllarus, Brachyscelus crusculum, Platyscelus ovoides, Phrosina semilunata, Neoanchisquilla tuberculata, Natosquilla investigatoris*
28. Pelagic molluscs: *Argonauta sp., Carinaria sp., Cavolinia sp.,*
29. Gelatinous plankton: *Salpidae, Scyphozoa, Cubozoa, Hidrozoa*
30. Macrozooplankton (>2000 µm): *Oplophoridae, Mysidae, Phorosinidae, Euphausiidae, Fish larvae*
31. Mesozooplankton (<2000 and >1000 µm): Copepods, large crustaceans' larvae;
32. Microzooplankton (<1000 µm): Protozoans, Ciliates, Flagelates

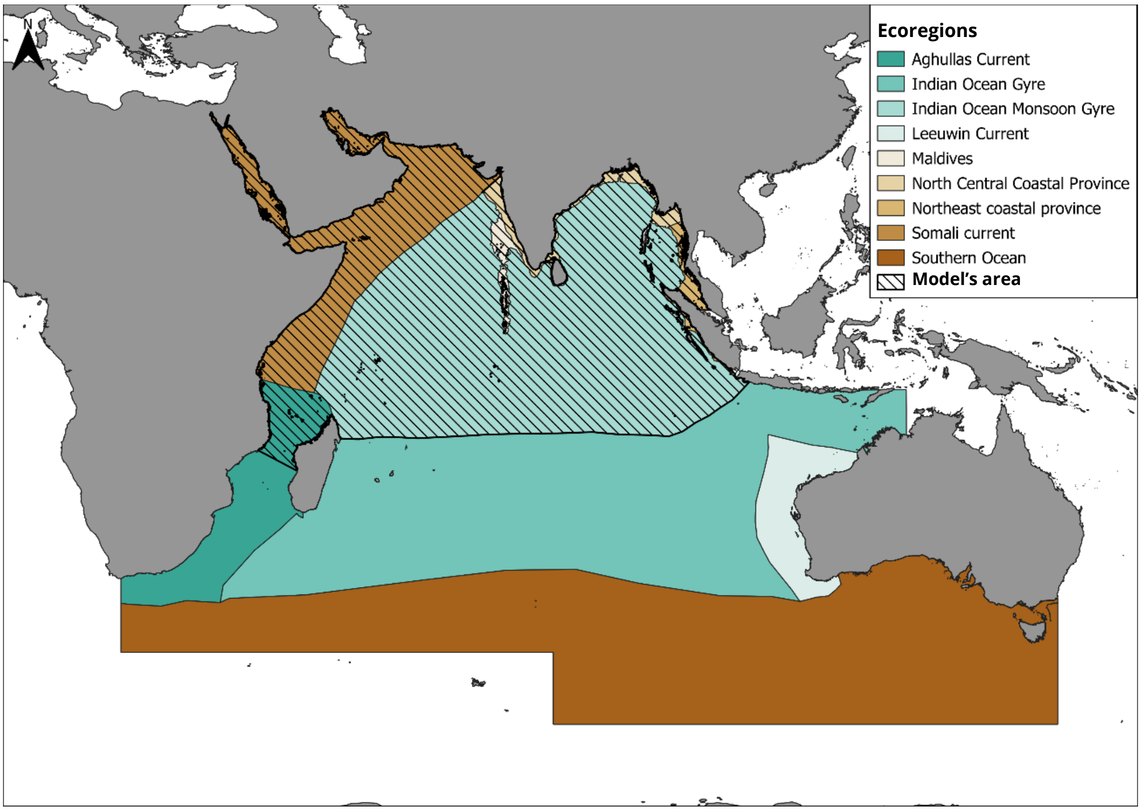

Figure 1. Map of the area modelled (diagonal lines) with the different ecoregions of the Indian Ocean.

Annex - Table 2. Official landings by fleet and functional group in the TIO model (t·km^{-2}·year^{-1}).

F.G./Fleet	NonEU_BB	NonEU_Oth	NonEU_LI	NonEU_GN	NonEU_PSFS	NonEU_PSLS	NonEU_LL	EUESP_PSFS	EUESP_PSLS	EUFRA_PSFS	EUFRA_PSLS	SYC_PSFS	SYC_PSLS	Total
1														
2														
3														
4														
5			0.00000	0.00113			0.00039							0.00152
6		0.00060	0.00025	0.00093			0.00362							0.00541
7														
8														
9				0.00001										0.00001
10		0.00000	0.00011	0.00030	0.00030	0.00030	0.00030							0.00132
11		0.00000	0.00005	0.00007	0.00000	0.00000	0.00081							0.00093
12	0.00000	0.00003	0.00017	0.00000	0.00016	0.00002	0.00321	0.00008	0.00002	0.00008	0.00001	0.00002	0.00001	0.00380
13	0.00004	0.00001	0.00002	0.00000	0.00003	0.00028	0.00040	0.00002	0.00033	0.00002	0.00021	0.00000	0.00010	0.00146
14	0.00011	0.00003	0.00181	0.00151	0.00088	0.00046	0.00363	0.00134	0.00059	0.00123	0.00032	0.00045	0.00018	0.01254
15	0.00056	0.00003	0.00049	0.00069	0.00005	0.00047	0.00001	0.00008	0.00063	0.00007	0.00034	0.00003	0.00020	0.00366
16	0.00462	0.00015	0.00090	0.00351	0.00106	0.00232	0.00008	0.00048	0.00315	0.00029	0.00158	0.00019	0.00097	0.01931
17	0.00012	0.00000	0.00004	0.00005	0.00002	0.00010	0.00000	0.00001	0.00013	0.00001	0.00006	0.00000	0.00004	0.00058
18	0.00000	0.00000	0.00006	0.00000	0.00002	0.00000	0.00013	0.00002	0.00000	0.00002	0.00000	0.00000	0.00000	0.00026
19	0.00026	0.00111	0.00163	0.00703	0.00092	0.00152	0.00009	0.00000	0.00001	0.00000	0.00000	0.00001	0.00001	0.01259
20														
21														
22							0.00014							0.00014
23														
24														
25														
26														
27														
28														
29														
30														
31														
32														
33														
34														
35														
Sum	0.00571	0.00196	0.00553	0.01525	0.00344	0.00547	0.01282	0.00202	0.00487	0.00171	0.00253	0.00072	0.00150	0.06353

*Annex - Table 3. Final diet matrix of the TIO model. The number in each box represents the proportion of a prey (rows) in the diet of a predator (columns). *: >0.0005*

Prey/ Pred	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1																																
2			0.0001																													
3			0.005	0.000																												
4			0.003																													
5																																
6			0.005			0.001																										
7																																
8						0.000																0.000										
9			0.004																													
10						0.002																										
11						0.002																0.000										
12						0.004																										
13			0.005	0.005		0.014																										
14						0.005																										
15			0.005	0.005	0.025	0.029																										
16			0.004	0.004		0.082						0.01																				
17			0.006	0.001	0.020	0.001						0.003		0.002	0.000																	
18			0.005	0.005		0.005																										
19	0.025		0.01	0.020	0.090	0.043				0.400	0.014	0.050	0.1	0.040	0.020	0.024	0.024		0.010	0.000		0.005										
20	0.058		0.01	0.120	0.110	0.009				0.026	0.009	0.020	0.050	0.089	0.043	0.023	0.023	0.005	0.050	0.020		0.010										
21	0.001				0.020					0.011	0.020	0.007	0	0.017	0.007				0.001	0.005		0.010										
22	0.009		0.01	0.080	0.044	0.155				0.014	0.072	0.150	0.070	0.010	0.004	0.010	0.001	0.050	0.014			0.020										
23	0.004	0.088	0.100	0.200	0.026	0.336		0.015		0.006	0.030	0.004	0.2	0.047	0.019	0.039	0.040	0.010	0.041	0.020	0.031	0.002										
24	0.425	0.114	0.200	0.120	0.070	0.001		0.030	0.000	0.241	0.003	0.100	0.001	0.073	0.020	0.022	0.020	0.045	0.200	0.050	0.010	0.200	0.130		0	0.060	0.010					
25	0.122	0.004	0.220	0.05		0.088		0.001		0.149	0.443	0.200	0.070	0.587	0.239	0.146	0.150	0.200	0.294	0.05		0.340			0.020	0.35						
26	0.193		0.400	0.325	0.125	0.173		0.020	0.002	0.126	0.355	0.450	0.350	0.097	0.210	0.088	0.090	0.390	0.081	0.010	0.019	0.060	0.020		0.001	0.020						
27	0.025		0.003	0.005	0.450	0.001		0.058	0.004	0.019	0.055	0.006	0.040	0.036	0.412	0.088	0.090	0.090	0.181	0.240	0.774	0.110	0.160	0.03	0.040	0.150	0.030					
28	0.006			0.005			0.04	0.176		0.010		0.000	0.02	0.000	0.000	0.280	0.280	0.005	0.006	0.080	0.093	0.050	0.040	0.050	0.010	0.05						
29	0.009			0.005			0.05	0.110				0.000	0.004	0.001	0.004	0.022	0.020	0.005	0.008	0.044	0.057	0.000	0.040	0.020	0.050	0	0.01					
30	0.124	0.7950					0.300	0.030	0.978				0.05	0.002	0.022	0.257	0.200	0.150	0.023	0.200	0.016	0.113	0.090	0.200	0.080	0.1	0.070	0.050	0.05			
31							0.4	0.060	0.015				0.045				0.061	0.05		0.15		0.000	0.07	0.4	0.120	0.12	0.150	0.120	0.150	0.400	0.02	
32							0.2													0.13			0.03	0.2	0.22	0.15	0.130	0.100	0.195		0.150	0.02
33							0.01												0.091	0.001			0.02	0.100	0.1		0.100	0.3	0.355	0.600	0.680	0.650
34																									0.289		0.500	0.43	0.250		0.150	0.330
35			0.005	0.05	0.02	0.048																										
Imports								0.500														0.08	0.400		0.071							

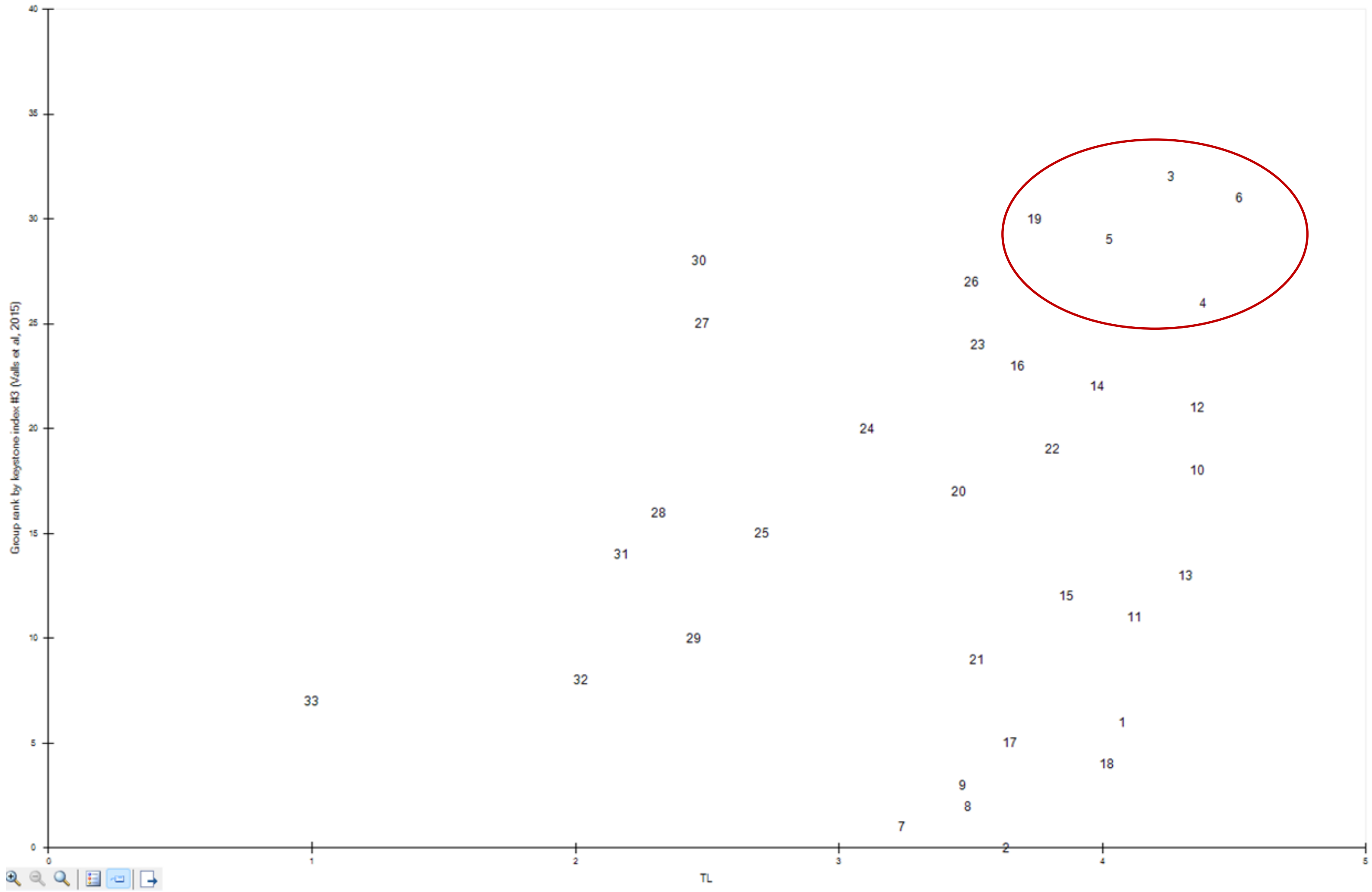

Figure 2. Keystoness index of Valls et al., 2015. Functional groups (represented by their number in the model) that are identified as keystone groups are encircled inside the red line which are: Toothed whales (f.g. 3), blue shark (f.g. 4), silky shark (f.g.5), other sharks (f.g. 6) and small tunas and other scombrids (f.g. 19).

Proceeding for the calculation of landings for the Ecopath model

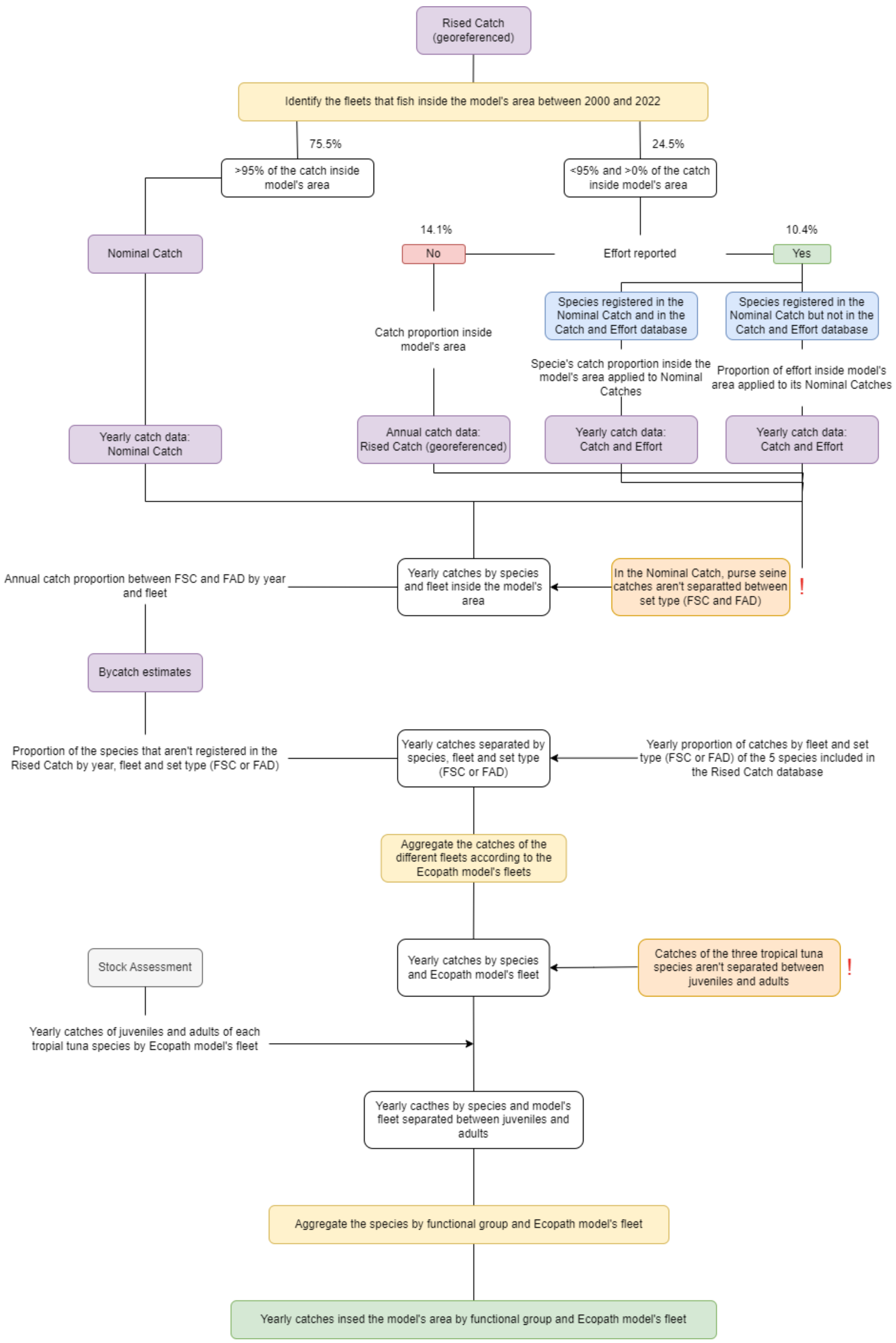

Figure 2. Methodology used to calculate the landings by functional group and Ecopath model's fleet. The percentages at the top indicate the percentage of the total catches that are calculated following each path. The three IOTC databases (Nominal Catch, Rised Catch, and Catch and Effort) used for these calculations can be found in: https://iotc.org/data/browser

**The numbers, countries and species mentioned in the examples of this document are only for example purposes.*

First, we need to identify the core fishing ground of each fleet using the IOTC Rised catch database (https://iotc.org/data/browser), as it has the catch of the 3 tropical tunas, albacore, and swordfish georeferenced by year, flag and fishing gear and type of set for purse seine.

- **>95%** of the catches inside model's area → Use **Nominal Catch** database to calculate the yearly total catches of each fleet.
- **<95% and >0%** of catches inside model's area → Use **Catch & Effort** or **Rised Catch** database to calculate the yearly total catches of each fleet.
- **0%** of catches inside the model's area → Discard the fleet as it does not fish inside our model area.

Check if there's effort data for the fleets with **<95% and >0%** of catches inside model's area.

- If there's **no effort data** of the fleet → Calculate yearly proportion of catches inside model's area from the **Rised Catch** and apply this proportions to the catches in the **Nominal Catch** database.
- If there's **effort data** → Calculate the catches using the **Catch & Effort** database following 3 conditions

<u>Species that appear in the Nominal Catch but not in the Catch & Effort</u> – Calculate yearly proportion of effort inside the model area and apply this proportion to this species that only appear in the Nominal Catch (e.g. if Mahi-Mahi catches for the Taiwanese fleet appear in the nominal catch but not in the Catch & Effort, and from the 100,000,000 hooks used by this fleet in 2003, 20,000,000 where set in the model's area, I will multiply the catches of Mahi-Mahi by the Taiwanese fleet in 2003 by 0.2 to obtain its catches inside the model area).

<u>Species that appear in the Nominal Catch and in the Catch & Effort</u> – In most cases not for all the catches, effort is registered. Therefore, calculate yearly proportion of species catches inside the model's area from the Catch & Effort and apply it to the Nominal Catch (e.g. Using the Catch & Effort database I calculate that in 2003, the Chinese longline fleet has caught 50,000 tons of Mahi-Mahi, 25,000 inside the model's area. But in the Nominal Catch the catches of Mahi-Mahi by the Chinese fleet in 2003 are 150,000 tons. Therefore, I do a simple rising applying the proportion of catches calculated using with the Catch & Effort database to calculate the most realistic value of total catches, in this case 75,000 tons (150,000 · (25,000/50,000))).

<u>Species that appear in the Catch & Effort but not in the Nominal Catch</u> – Divide the catches of the unclassified (UNCL) of the Nominal Catch database by the yearly

proportion of species that appear in the CE (e.g. the Korean longline fleet has registers of catches of CCP (sandbar shark) and LAG (Opah), but this species are not included in the Nominal Catch. According to the data in the Catch & Effort, in 2003, the proportion of catches between these two species was 0.3-0.7 respectively. In the registers of Korean catches of 2003 in the Nominal Catch, the unclassified catches are 120 tons, so then I apply the previous proportions to the unclassified group obtaining 36 tons of CCP and 84 tons of LAG. These are the total catches, to calculate the catches inside the model area, I multiply this value by the proportion of catches of these species inside the model's area previously calculated using the Catch & Effort database).

Aggregate the three previous calculations to obtain the yearly total catches by species and fleet inside model's area for the fleets with **<95% and >0%** of catches inside model's area

Then sum the catches of all the fleets by the Ecopath fleets (e.g. sum all the catches of the fleets that compose the Other_PS,…)

One limitation of the Nominal Catch database is that the purse seine catches aren't separated between catches at free or log school. To separate the catches of purse seine fleets between free and log school we calculate the yearly proportion of free school and log school catches for each fleet using the Rised Catch database and apply it to the total catches of the Ecopath fleet previously weighting their value by the catch volume (e.g. the Other_PS fleet is composed by the Thai and Japanese fleets. Using the Rised Catch database we calculate that in 2003, from the 1,000,000 tons of yellowfin caught by the Thai fleet, 40% was free school and 60% log-associated schools. The Japanese fleet caught 5,000,000 tons of yellowfin, 90% free school and 10% log associated schools. Then to calculate the proportion of yellowfin catches of the Other_PS fleet at free school in 2003 we do ((5,000,000*0.9+1,000,000*0.4)/(5,000,000+1,000,000)) which is 0.8167. Then I multiply this proportion to the total catches of this Ecopath fleet to obtain the yearly catches of yellowfin in the model area of the Other_PSFS fleet, and the resting catches correspond to the Other_PSLS fleet. The results of this method can only be applied to the 5 species included in the Rised Catch database. Regarding the rest of the species, the separation between free and log-associated schools must be done using estimates found in the literature or data from onboard observers.

At this point we have the catches of each Ecopath fleet inside the model by year, species and purse seine set type.

However, we need to separate the three tropical tuna catches between the two stanzas: adults and juveniles. To do so, we use the data from the latest stock assessment of each species. Using the dataset of the stock assessment that contains the information of catch at age, We can calculate for each fishing method (PSFS, PSLS, LL, GN,…) the total catches of juveniles and adults each year. With this, we calculate the proportion of juvenile and adult catches of the evaluated species that each fleet made each year. Multiplying these proportions to each fleet's total catch obtain the yearly catches of juveniles and adults by each Ecopath fleet in the model area.

If we look now at the list of species of which we have catches we would observe that there are not only species, but also groups of species, as a group called sharks. In this case we have two types of groups:

- Groups that include multiple species, but all the species are included in the same functional group of the Ecopath model. The value of catches of this group will be summed entirely to the catches of the corresponding functional group (e.g. I have a group called "Rays". I can't identify which species and in which proportion are included in this group, but it isn't a problem because all the catches of this group even if I could differentiate at species level, at the end, they would be summed to compose the catches of the rays' functional group of the model.
- Groups that include species which are an individual functional group in the Ecopath model. In this case I will calculate the proportion of the species catches' I want to extract from the group, with respect to the total catches of the species that would be included in that group but that their catches are at species level (e.g. I have a group called "Billfishes", however, in my model I have two functional groups, "Other billfishes" and "Swordfish". In the catch data apart from this group of billfishes which can include catches of swordfish not identified at species level, I also have the values of catches of different billfish species at species level, swordfish, black marlin, blue marlin,…To calculate how much of the catches of "Billfishes" correspond to Swordfish, I calculate for every year swordfish's catches proportion against all billfishes at species level including its own catches. So, if in 2003 the Spanish purse seine fleet caught 3 tons of swordfish, 5 tons of black marlin, 2 tons of blue marlin, and 40 tons of billfishes. When calculating the catches of the functional groups I will assume that the catches of swordfish are 15 tons ((3+(40*0.3)), and the catches of billfishes are 35 tons (40-12+5+2)). In this model case, the same happens with the "Other sharks" group, for which we extract the proportion of catches for the blue and the silky shark.

Finally, what we need to do is to sum all the catches at species and group level according to the functional group where they belong to obtain:

<u>Yearly catches of the functional group by each model's fleet inside model area differentiating school type, and the stanza for the three tropical tunas</u>