Support for the development of an ecosystem approach to fisheries management for Indian Ocean tuna fisheries

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Abstract

The Sustainable Indian Ocean Tuna Initiative (SIOTI) is a large-scale FIP comprising the major purse seine fleets and tuna processors in the Indian Ocean. As part of its Action Plan, SIOTI supported this study with the overall objective of examining the core requirements of an ecosystem approach to fisheries management (EAFM) resulting from the ecosystem impacts of tuna purse seine fishing in the Indian Ocean. To do so, this study summarizes the current progress of IOTC in implementing the EAFM and proposes several research avenues and options to facilitate its operationalization. It also reviews the key risk areas associated with the ecosystem impact of purse seine fisheries on the foodweb structure and function, and identifies potential options to improve fisheries management that explicitly accounts for ecosystem impacts. Ultimately, this study aims to inform the actions and activities planned in the SIOTI Action Plan established under the three critical and non-critical Improved Performance Goals (IPG6, IPG15 and IPG16) related to the ecosystem impacts of purse seine tuna fishing.

KEYWORDS

Fishery Improvement Project, SIOTI, Ecosystem approach to fisheries management (EAFM), Improved Performance Goals, ecosystem impacts, purse seine fishery, ecosystem structure and function

1. Introduction

The increasing demand for sustainable seafood and emergence of market-driven mechanisms have put pressure on fisheries to improve their environmental sustainability. Under the Marine Stewardship Council (MSC) standard for responsible fisheries, fisheries can get certified and authorised to display the blue MSC ecolabel if they meet the MSC Standard. Fisheries Improvement Projects (FIPs) have emerged as multi-stakeholder initiatives with the objective of improving a fishery towards sustainability and MSC certification. The Sustainable Indian Ocean Tuna Initiative (SIOTI) is a large-scale FIP comprising the major purse seine fleets and tuna processors in the Indian Ocean (SIOTI action plan 2017). The FIP is supported by Seychelles and WWF, formalised the signing of a Memorandum of Understanding with industry representatives in October 2016, and followed by a partnership agreement signed by 17 industry partners in March 2017. The first Action Plan for the SIOTI FIP was adopted by partners in May 2017. The Action Plan establishes a set of actions linked to the MSC performance indicators. Those actions seek to close the gaps in the performance of the fishery towards MSC certification. The SIOTI Action Plan considers three 'potential Units of Certification (UoC)' for MSC certification, one for each of the three target tropical tuna species (skipjack, yellowfin and bigeye tunas). However, the Action Plan also recognises that there are two different fishing strategies – fishing on free schools and fishing on schools associated with floating objects (e.g. both FAD and natural objects) – and that different actions might be required to address both of these fishing strategies.

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Based on several MSC-related pre-assessments of several purse seine fleets in the Indian Ocean, and a scoping report for the OPAGAG's skipjack, yellowfin and bigeye tuna fishery, benchmarked to the MSC Standard, the SIOTI Action Plan identified a number of related critical and non-critical Improved Performance Goals (IPG), six critical IPG and twelve non-critical IPG (SIOTI action plan 2017). Three IPGs were identified relating to the ecosystem impacts of purse seine tuna fishing:

- Critical IPG6 - Ecosystem management (MSC PI 2.5.2): The goal is to ensure that there are measures in place to ensure the potential Unit of certification (UoC) does not pose a risk of serious or irreversible harm to ecosystem structure and function, and that by the end of the FIP, there is objective evidence that the ecosystem-based management strategy is working.
- Non-Critical IPG16 - Ecosystem information (MSC PI 2.5.3): The goal is to ensure that there is adequate knowledge of the impacts of the potential UoC on the ecosystem, with additional data and information gathering initiatives, if necessary, formally agreed and in place by the end of the FIP.
- Non-Critical IPG15 - Ecosystem outcome (MSC PI 2.5.1): The goal aims to ensure that the potential UoC does not cause serious or irreversible harm to the key elements of ecosystem structure and function, and that by the end of the FIP, key risks are identified and management measures, if necessary, are in place.

The overall objective of this study is to examine the core requirements of an ecosystem approach to fisheries management (EAFM) resulting from the ecosystem impacts of tuna purse seine fishing in the Indian Ocean. To do so, it summarizes the current progress of IOTC in implementing the EAFM and identified several research avenues and options that may facilitate its operationalization. It also reviews the key risk areas associated with the ecosystem impact of purse seine fisheries on the foodweb structure and function, and identifies potential options to improve fisheries management that explicitly accounts for ecosystem impacts. This study aims to inform the actions and activities established under the three critical and non-critical IPG (IPG6, IPG15 and IPG16) related to the ecosystem impacts of purse seine tuna fishing.

Addressing the core requirements of an EAFM requires at first to answer the simple question of what EAFM is and clarify how this term is used in this study. Here, the EAFM represents a policy-driven process that aims to expand traditional single species focus management to one that also considers the major components of an ecosystem and the social and economic benefits they can provide (Garcia et al. 2003). Such an approach and transition requires developing a more holistic view of the system, the creation of a management system that accounts for relevant ecosystem interactions (interactions among gears, species, the environment and socio-economic factors), and the generation of more integrated scientific advice in order to inform on what ecological, physical and socio-economic factors should be accounted in fisheries management decisions.

In practical terms, the implementation of the EAFM cannot be done as a single large action, it is a process which requires multiple supporting layers of implementation including comprehensive ecosystem planning, scoping and profiling the state of the ecosystem where fisheries operate, prioritizing high risk ecosystem issues, and building a management system that allows for ecosystem considerations (Fletcher and Bianchi 2014, NOAA 2017). By segmenting the EAFM process into a manageable number of steps, the operationalization can be tackled with a series of mixed activities and interventions over time. There is not one single large action that can solved the operationalization of the EAF process in the context of tuna fisheries in the Indian Ocean or anywhere else. The implementation of the EAFM is a heterogeneous process, that may only be addressed by a mix of manageable interventions and steps covering every step of the EAFM road map (Figure 1). It is important to keep in mind that these implementation layers may already be tackled and started using the available knowledge and ecosystem science in IOTC. The implementation of the EAFM does not required full knowledge of the ecosystem and understanding all the interactions within the ecosystem, it can be started with the knowledge at hand, which may be improved along the way as needed. However, it is considered a best practice to identify and establish science programs to improve understanding of ecosystem processes in order to facilitate EAFM implementation. Similarly, this process of EAFM implementation would also need to be highly consultative, interactive and participatory by involving the CPCs in IOTC and other interested stakeholders in all the layers of implementation.

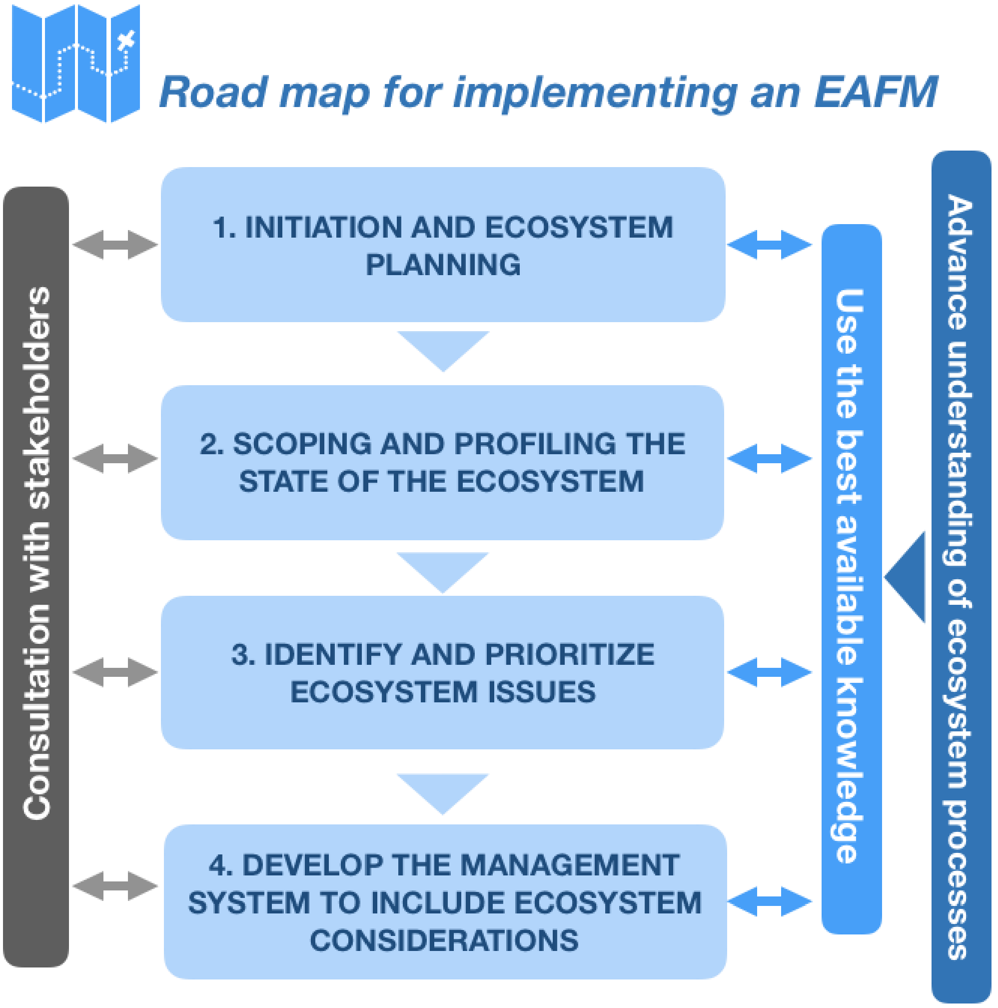

Figure1. Generalized road map illustrating the major steps required to implement an EAFM. Adapted from http://www.fao.org/fishery/eaf-net/en and Fletcher and Bianchi (2014).

Specifically, this study addresses the following main tasks:

- Revision of the development and implementation of an EAFM in other regional fisheries management bodies, identification of lessons learnt and transferability and applicability of EAFM approaches in the context of IOTC.
- Summary of the progress in preparing for EAFM implementation within IOTC, including inter-sessional work following the 2018 WPEB
- Synopsis of the main ecosystem impacts of tuna fisheries in the Indian Ocean, and assessment of the relative importance of impacts from tuna purse seine fishing relative to other major gears.
- Identification of core elements and requirements for EAFM implementation that stem from the ecosystem impacts of purse seine tuna fishing in the Indian Ocean. This includes a review of ecosystem indicator options.
- Identification of the key information gaps in enabling an ecosystem approach to tuna fisheries management in the Indian Ocean, with recommendations for addressing gaps through additional data and information gathering
- Outline of options for ecosystem-based management strategies for tuna fisheries in the Indian Ocean, specifically addressing measures specific to purse-seine gear as well as global measures, and including provisions for strategy evaluation

2. Revision of the development and implementation of EAFM in other regional fisheries management bodies, identification of lessons learnt, and transferability and applicability of EAFM approaches in the context of IOTC.

Several international legal agreements and guidelines, such as the Convention on Biological Diversity (CBD 2004), the UN Stock Agreement (United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks) and FAO Code of Conduct for Responsible Fisheries (FAO 1995) have set the standards and ecosystem principles to guide the implementation of an Ecosystem Approach to Fisheries Management (EAFM). Almost thirty years after these agreements and guidelines were established, the operationalization of an EAFM in marine areas beyond the limits of national jurisdictions, i.e., the high seas, is still in an early stage compared to national implementations. Yet significant progress towards implementing the EAFM has been made in several regions of the world from where best practices and lessons can be extracted and learnt. This revision picked and reviewed three case studies of fisheries management bodies (two international and one national) that have made considerable progress in operationalizing the EAFM with measurable actions in their respective management areas. In each case study region, progress was reviewed by examining what type of activities, programs and management actions have been put in place pertinent to each of the implementation layers in the EAFM road map (Figure 1) including activities relevant to ecosystem planning, scoping and profiling the state of the ecosystem where fisheries operate, prioritizing high risk ecosystem issues, and building a management system that allows for ecosystem considerations. The three case studies picked are at different stages of implementing an EAFM, which allows highlighting properties of success, best practices and lessons learnt from different states of the EAFM implementation process, so their transferability can be evaluated in the context of IOTC. This revision builds on an European project which also reviewed these three case studies to identify best practices of EAFM implementation and evaluate their transferability in the context of tuna RFMOs (Juan-Jordá et al. 2019).

The three case studies reviewed were:

Case study 1: The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). The CCAMLR was established by the Antarctic Treaty Consultative Parties to prevent over-exploitation of Antarctic krill which is a key prey species for other species in the region. When established, a number of other Antarctic species had already been overexploited including whale and seal populations that prey on krill. Therefore, taking action to ensure that exploitation of krill did not inhibit the recovery of those species was seen as necessary (Constable et al. 2000). CCAMLR has been a pioneer regional organization in incorporating ecosystem considerations into fisheries management. Their approach to account for ecosystem considerations in their fisheries management process has been relatively flexible and incremental but also effective enough to build consensus among all its members.

Case study 2: The Northwest Atlantic Fisheries Organisation (NAFO). NAFO is an intergovernmental fisheries science and management body, which overall objective is to contribute through consultation and cooperation to the optimum utilization, rational management and conservation of the fishery resources of the NAFO Convention Area. The fishery resources managed by NAFO are straddling stocks of demersal fish species such as cod, flounder, hake and halibut. The main issues in the NAFO area are related with recovery plans for many demersal stocks that experienced a steep decline during the 1980s-1990s and have not been yet recovered to their traditional high productivity, like the American plaice, cod and Greenland halibut. Since 2008 the Working Group on Ecosystem Studies and Assessment (WGESA) have worked to develop a roadmap for an EAF in NAFO. The NAFO EAF road map identifies what processes need to be incorporated to ensure sustainability at ecosystem level (Koen-Alonso et al. 2019).

Case study 3: The North Pacific Fishery Management Council (NPFMC) in the United States. The NPFMC is one of the eight regional Fisheries Management Councils in the USA established to manage fisheries within their Exclusive Economic Zone. The main commercial fisheries are comprised of groundfish fisheries, the halibut fishery, salmon fisheries and the crab and scallop fisheries (Zador et al. 2016). The most important and current fisheries issues in this region are bycatch control, discard policies, habitat protections, protected species, and catch share allocations. The NPFMC has also been a pioneer fisheries organization developing ecosystem information and products for managers to provide them with the ecosystem context to inform fisheries management decisions.

From these three world case studies, properties of success (Table 1) and best practices in developing useful ecosystem information, science and products to inform ecosystem-based fisheries management (Table 2) are summarized. The transferability of these best practices and lessons in the context of fisheries management of tuna and like species in the IOTC is also discussed. Lessons learnt along the way by these organization when linking their different ecosystem products and ecosystem advice into fisheries management are also highlighted which possibly could be taken into account when IOTC develops its ecosystem-related research and activities (Table 3).

When identifying properties of success, best practices and lessons from these three world case studies, the following elements were reviewed and considered in facilitating their EAFM implementation:

(i) The state and their progress in terms of ecosystem planning, including whether they had a clear overall vision and ecosystem objectives, and had ecosystem management plans in place.
(ii) The existence and use of sound scientific knowledge and ecosystem science to assess and characterise the state of the ecosystem and the impacts of fisheries (and other pressures such as climate change) on the state of the ecosystems,
(iii) Their progress in using ecosystem science and ecosystem principles in their fisheries management and advice.

Table 1. Properties of success in implementing the EAFM extracted from three world case studies and their applicability to IOTC. The three case study regions were the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the Northwest Atlantic Fisheries Organisation (NAFO) and the North Pacific Fishery Management Council (NPFMC) in the United States.

"Properties of success" facilitating the implementation of EAFM in the NPFMC, CCAMLR and NAFO.	**Potential transferability to IOTC**
Well-articulated needs and ecosystem vision – The adoption of the EAFM in the NPFMC, CCAMLR and NAFO has been supported by an explicit commitment to EAFM in their convention mandates. Agreed ecosystem principles underpinned the EAFM vision and objectives in the NPFMC, CCAMLR, and NAFO. A clear ecosystem vision and policy allows for long-term planning initiatives, fishery management actions, and science planning to support the implementation of EAFM.	The IOTC Convention Agreement does not make reference to the principles of the precautionary approach or principles governing the EAFM. The IOTC has not articulated an ecosystem vision and an ecosystem-based policy to allow for the long-term planning of activities, ecosystem science and fisheries management actions to support the implementation of the EAFM (see further details in section 3). IOTC may consider reviewing its convention mandate to explicitly address and commit to implement the EAFM in its convention area, as well as developing an ecosystem-based policy and vision to drive the work of the Commission and its Scientific Committee.
A clear and well-planned framework for guiding the implementation of the EAFM –The development of ecosystem plans in the NPFMC or an EAFM road map in NAFO has put in place a mechanism that facilitates the implementation of the EAFM in practical terms. The adoption of ecosystem plans in the NPFMC allow to formalize and strengthen the delivery of ecosystem information to the management body and provide a transparent tool for evaluating emergent trade-offs between conflicting management objectives. The EAFM road map developed in NAFO has allowed to identify and represent the processes and activities needed to incorporate sustainability at ecosystem level and to allow for consideration of trade-offs between fisheries and multispecies sustainability.	An EAFM road map or an ecosystem plan have not been formally developed in IOTC. However, the Scientific Committee has included the development of an EAFM plan into their work plan (see further details in section 3). IOTC may consider developing a EAFM framework and used it as tool to facilitate and make more efficient the implementation of EAFM in its convention area.

Transparent and trusted participatory and consultative process – All the case studies reviewed have stressed the importance of having a transparent and open process when defining the mechanisms to implement the EAFM. Access to the relevant ecosystem information, science, and the process itself to facilitate EAFM implementation, strengthens transparency and supports participation from a broader spectrum of stakeholders. An open and inclusive consultation process in all the layers of EAFM implementation helps to build trust among interested parties, improves consensus, and increases the support in the process. For example, in the NPFMC, the Council, its Ecosystem Advisory Panel, and its Scientific Committee all operate in an open forum where many other organizations, scientist, and stakeholders can participate, provide inputs and review the data and analytic methods in the science. NAFO has also recently established a joint Scientists -Managers working group (NAFO Joint Commission-Scientific Council Working Group on Ecosystem Approach Framework to Fisheries Management - WG-EAFFM) to increase the dialogue between the scientist and managers on ecosystem issues.	The IOTC has organized in the past several workshops to connect better IOTC science to the management process and increase the dialogue between scientists and managers. In addition, IOTC has established a dedicated Technical Committee of Management Procedures (TCMP) as a formal communication channel between science and management to enhance decision-making response of the Commission in relation to Management Procedures. While these initiatives facilitate the communication between science and management processes, to date they have focused on single species focus management, and there has been no dedicated time to address how ecosystem science can also be channeled into fisheries management decisions (see further details in section 3). IOTC may consider creating similar mechanism (or expand the existing mechanism) to enhance the dialogue between scientists and managers on ecosystem matters.

Table 2. Best scientific practices supporting the implementation of the EAFM extracted from three world case studies and their applicability to IOTC. The three case study regions were the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the Northwest Atlantic Fisheries Organisation (NAFO) and the North Pacific Fishery Management Council (NPFMC) in the United States.

"Best scientific practices" facilitating the implementation of EAFM in the NPFMC, CCAMLR and NAFO.	**Potential transferability to IOTC**
***Data collection and assessment processes that allow for estimation of cumulative impacts of fishing* –** A fundamental transition in data collection and analysis is needed to facilitate evaluation of impacts of different gears and species in an ecosystem in cumulative terms. The NPFMC, NAFO and CCAMLR have some of the following element in place to allow for the assessment of cumulative impacts of fishing: a well-established ecosystem monitory program, extensive observer coverage and collection of data that cover a range of ecosystem aspects (species biology, bycatch, stock structure, food web structure and dynamics), which aim to build the evidence basis for understanding ecosystem impacts. For example, the NPFMC mandates 100% observer coverage for larger vessels (> 125 feet) and 30% coverage for medium size vessels (60-124ft) to monitor all the removals by fisheries including both target and incidentally caught species. The CCAMLR has an ecosystem monitoring programme which monitors prey and predator species interactions to be accounted in fisheries management.	IOTC has not a well-established ecosystem monitory program, does not mandate an extensive observer coverage to its fisheries/fleets, and the collection of data by its CPCs do not always ensure or cover a wide range of ecosystem aspects (see further details in section 4-5-6) to inform ecosystem assessments of the cumulative impacts of fishing. The adoption of a Regional Observer Scheme in IOTC is considered a positive step towards improving the data collection relevant to support the development of ecosystem indicators and assessments of the impacts of fisheries in cumulative terms. The IOTC Regional Observer Scheme sets the standards for the collection and reporting of observer data including the levels of observer coverage required and reporting deadline. However, its success is based entirely on national implementation, and to date the majority of the IOTC CPCs have not complied with this minimum requirement (IOTC 2018a).
***Setting area-based assessment units (or ecoregions) to inform ecosystem research activities and ecosystem-based management advice* –** The NPFMC has divided its area of competence into four ecoregions which are used to guide ecosystem research and assessments ultimately to provide better ecosystem advice to inform fisheries management (Zador et al. 2016). NAFO has also delimitated several area-based ecosystem production units to better capture	IOTC has not examined the potential use of having well defined ecoregions within its convention area to structure its ecosystem research and assessments, and ultimately to provide more structured ecosystem context and advice to inform fisheries management decisions. The potential use and benefits of having well stablished ecoregions within IOTC need to be further examined and analysed.

ecosystem processes. They serve as the basis for ecosystem productivity estimates and can also set the spatial level at which management approaches are evaluated (NAFO 2017). The CCAMLR has also worked on developing methodology for defining bioregions in the Southern Ocean and mapping and identifying information to support such regionalisation and its use for management (Constable 2016).	The WPEB14 recommended a workshop should be organized to provide advice on the identification of candidate ecologically meaningful regions that could serve as a basis to support the operationalization of the EAFM in IOTC (IOTC–WPEB14 2018). This workshop will take place in August 2019 prior to the WPEB15 meeting where the outcomes of the workshop will be presented (see more details in section 3).
***Monitoring selected ecosystem indicators to track the impacts of pressures (fishing and climate) on the state of the ecosystems* –** All the case studies reviewed highlight that there is a need to focus efforts on a manageable number of ecosystem indicators to achieve efficiency both in analysis and communication. The NPFMC uses an indicator-based ecosystem report card to summarize the status of top ecological indicators for each ecoregion which are supported by well-established ecosystem assessments. The top indicators monitored on an annual basis have been selected by a team of ecosystem experts that best describes the ecological status of each ecoregion. Each ecoregion has its own list of ecosystem indicators, as selected by the ecosystem experts, to provide ecosystem the context on an area basis to support fisheries management decisions (Zador et al. 2015).	The IOTC WPEB has included in its workplan the task of developing an ecosystem report card with the objective of assessing the state of the IOTC ecosystem and the impacts of its fisheries on the ecosystem by monitoring a set of selected ecosystem indicators (see more details in section 3).
***Quantification of ecosystem production and thresholds* –** This approach is being used to provide a broader context within which management decisions for the exploitation of single species or groups of species are taken. Total ecosystem production estimates or total caps for catches could be the outcome of multispecies /ecosystem models, empirical studies, or both. For example, the NPFMC has adopted a total cap for groundfish catches based on the productivity of the region to provide a precautionary limit on the total harvest (NPFMC 2014).	The quantification of a total cap for catches in the IOTC area based on the productivity of the region and its application would require a change in mind set and the way how the science and management process operate in IOTC.

***Development of ecosystem risk assessments* –** This process examines the ecological, social and economic risks of the different pressures including fishing and climate change. It can identify priority issues and areas that deserve further management attention, but it also can be used as a tool to highlight research needs. This approach is used extensively in the NPFMC, CCAMLR and NAFO, but also all around the world. For example, CCAMLR requires that an ecosystem risk assessment be undertaken before any new fishing activities can be authorised. The NPFMC has conducted comprehensive ecosystem risk assessments for each of its ecoregions to identify the most pressing ecosystem issues and prioritize actions on an area basis.	The development of ecosystem and ecological risk assessments is a common practice in many areas of the world including IOTC. While some ecological risk assessments (which focus on a particular taxonomic groups and fishing gears) have been conducted in IOTC, further work is needed to conduct comprehensive ecosystem risk assessment to understand what ecological, physical and socio-economic elements and risk factors may be used to drive fisheries management (see more details in section 3).
***Processes to support the establishment of bycatch-reduction* –** The NPFMC, CCAMLR and NAFO have adopted gear modifications or restrictions such as time/area closures to minimise impact of fisheries on vulnerable and threatened species. The NPFMC has also bycatch limits for vulnerable species and juveniles of commercial stocks, and a fishery may be closed when the total allowable catch for one of the by-catch species is reached.	IOTC has adopted an extensive list of conservation and management measures (non-binding recommendations and binding resolutions) for bycatch species, including some species of billfishes, sharks, seabirds, sea turtles, marine mammals. Overall the adopted measures have the main purpose to minimize the effects of fishing on by-catch species with the modification of gears to avoid catching them or by prohibiting their retention. The current adopted measures do not include time/area closures or total bycatch limits as a bycatch reduction tool. The state of bycatch species, particularly those species threatened, has not been taken into account to evaluate the robustness of harvest strategies of main IOTC species. IOTC may consider the use of time/area closures and total bycatch limits as an additional bycatch reduction tool to minimize the impact of fisheries on vulnerable and threatened species, and link them to the harvest strategies of main IOTC species.

***Processes to support protection of habitats of ecological concern to fishing impacts* –** The NPFMC, CCAMLR and NAFO have identified vulnerable marine ecosystems (VME) and have established time/area closures or bottom trawl restrictions to protect them. There are also programs in the NPFMC to remove lost fishing gear from the beaches where it can entangle seabirds and marine mammals. CCAMLR has adopted conservation measures to protect VME, underpinned by methods for identifying VMEs and protocols that govern vessels actions once they encounter them. NAFO has also designed and adopted move on rules to reduce encounters with VME.	IOTC has not adopted conservation and management measures to explicitly protect habitats of special concern for relevant IOTC species or threatened species interacting with IOTC species. Knowledge of habitats of special concern and habitat preferences for IOTC species is relatively scarce. This type of knowledge is not currently used to inform decision-making in IOTC. There is not a formal mechanism to accommodate minimum habitat needs and habitat protection into the current management or management decisions, and it is not under discussion by the Scientific Committee. This type of information has not been taken into account to evaluate the robustness of harvest strategies of main IOTC species. IOTC may consider improving its science-based knowledge about habitats of ecological concern for IOTC species and threatened species interacting with IOTC species and make use of time/area closures as a tool to minimize the impact of fisheries on critical habitats.
***Processes to support protection of foodweb structure and function to fishing impacts* –** The NPFMC has adopted several measures designed to prevent the depletion of prey needed by marine mammals and seabirds. In the NPFMC, quota calculations explicitly account for the need to ensure that food availability for predators is not compromised. The CCMALR has developed decision rules that account for the needs of predators and are part of the generalised yield model that is used for setting quotas. The decision rules adjust the allowable catches to ensure that fishing does not compromise ecosystem functioning; i.e. there is enough prey left to support predators after the catches have been taken.	IOTC has not adopted conservation and management measures to explicitly account for the impacts of fishing on trophic interactions and the food web in order to maintain the structure and functioning of marine ecosystems. Knowledge on the trophic ecology for many IOTC species is scarce, and the use and development of ecosystem models or multispecies models to understand food web dynamics, species interactions and their ecological role in the food web has been slow. There is not a formal mechanism to accommodate multispecies and food web interactions and ecosystem modelling into the current management and conservation of target or bycatch species and associated ecosystems. This type of information has not been taken into account to evaluate the robustness of harvest strategies of main IOTC species. IOTC may consider improving its science-based knowledge on the

	trophic ecology of IOTC species and support the development of tools such as ecosystem models or multispecies models to investigate the potential impacts of fishing (and effects of climate) on the structure and function of the ecosystem.
Incorporation of knowledge on environmental processes and climate change into fisheries management – The NPFMC has invested in research to improve understanding of climate effects on fish stocks and ecosystems, and it has proven record of incorporating this knowledge into their management system. For example, the stock assessment of halibut incorporates information on the phase of the Pacific Decadal Oscillation to evaluate the robustness of the harvest strategy.	Focused research to understand the effects of climate and environmental variability on the abundance, recruitment and productivity of IOTC species has been relatively scarce. This type of information has not been taken into account to evaluate the robustness of harvest strategies of main IOTC species.

Table 3. Summarizes the lessons learned from CCAMLR, NPFMC and NAFO implementing the EAFM in their convention areas.

Useful lessons extracted from the three case studies reviewed that could be considered in the context of EAFM implementation in IOTC
Ecosystem-focused fisheries management can be done without full knowledge of the ecosystem, but making use of all knowledge available is crucial. This lends support to iterative, adaptive processes and recognises that not all ecosystem components or challenges can be addressed at the same time. In the case of the CCAMLR, its ecosystem approach relied on very little existing knowledge when it was first introduced. Their adoption of ecosystem principles was incremental and was underpinned by a precautionary approach that was built into the assessment models and also supported by the collection of data.
Good knowledge of the annual management cycle helped in the identification of opportunities for incorporating ecosystem information into management decisions. Strengthening engagement between scientists and managers as well as making timely and tailored scientific contributions along the management cycle are some of the critical features that has been highlighted as important for progressing EAFM. In the case of the NPFMO, an ecosystem considerations report, which includes the ecosystem status of several components of the ecosystem as well as potential concerns, is prepared and presented every year at the annual Council meeting. This report is presented strategically prior to the stock assessment harvest and quota recommendations to allow for the opportunity to consider the ecosystem context into management decisions. Therefore, the NPFMC learnt the “lessons” that scientists need to structure the ecosystem information to best fit the management cycle, and not the other way around.
The process of selecting ecosystem indicators needs to be flexible and adaptive to identify a small number of key indicators. For example, in the NPFMC, the process of developing ecosystem indicators and ecosystem report cards highlighted the need to have a flexible process and adaptive products fitted to the needs of specific regions. An adaptive process helps to deal with challenges relating to data gaps and resources and recognises that not all ecosystem issues could be identified at the start of the EAFM process and that ecosystem issues might differ by area.
Stakeholders need to be involved in the development of ecosystem products from the beginning through transparent processes and tailored communication. For example, the NPFMC had a well-established mechanisms to set broad consultations using workshops and formal meetings for discussing and setting ecosystem objectives and priorities, as well as to ensure participation of managers and scientists with a broad range of expertise in the selection of ecosystem indicators and subsequent development of the ecosystem report cards. The creation of a “team of ecosystem experts” representing multiple stakeholders worked really well for the process of selecting relevant ecosystem indicators and developing the indicator-based report cards which had the support of the Council. These has ensured that the ecosystem products are tailored to the needs and requests of managers.

Development of ecosystem indicators and assessments can provide an opportunity for stronger regional collaboration. Sharing data and knowledge is emerging as a key action for making best use of resources and provides a further incentive for collaboration. Adoption of standardised guidelines for data collection and estimation of indicators (and to override data confidentiality issues), as it is done in the CCAMLR, will support stronger outputs and can increase participation and regional collaborations.
***Digital tools to visualize indicators and integrate information in support of ecosystem assessments* –** The three case studies highlighted that the use of visualisation and other digital tools can increase outreach and help inform fisheries scientists, policy makers, and the public about the status of marine ecosystems and their response to fishing. The frequent use of visual communication tools with managers and other stakeholders allows for adaptive products that are more useful at the end.

3. Summary of progress in preparing for EAFM implementation within IOTC, including inter-sessional work following the 2018 WPEB

The implementation of the EAFM cannot be done as a single large action, it is a process that requires multiple supporting layers of implementation (Figure 1). Progress by IOTC within each layer of implementation is summarized below which includes the main activities and work carried out by the IOTC WPEB and the Scientific Committee.

3.1 Progress in IOTC in terms of ecosystem planning

The ecosystem planning step is mostly about identifying and setting the high-level ecosystem vision and objectives that will drive the whole process implementation process. It is also important here to establish whether ecosystem plans will be needed and conducted to structure and guide the whole process. Furthermore, it is also a common practice to define the management units to be managed, and whether area-based management units (or ecoregions) are needed to structure the process. Ideally every layer of implementation requires stakeholder involvement, therefore the identification of the main stakeholders to be involved at each step in the whole process as well as the establishment of a communication channel should be done at the initial planning stages of the process too (Fletcher and Bianchi 2014).

IOTC has done limited progress in terms of effective ecosystem planning to make the implementation of the EAFM more operative in IOTC. With respect the establishment of high-level ecosystem objectives, the IOTC Convention Agreement does not make reference to the principles of the precautionary approach or main ecosystem principles. IOTC has not drafted or adopted an ecosystem policy with a clear ecosystem vision and objectives to inform and guide the Commission or the work of the Scientific Committee. Not having a well-established ecosystem vision and objectives of what the EAFM entails and is striving to achieve may create unnecessary confusion in the IOTC community about what EAFM is in terms of concept and practice in the context of tuna fisheries. Adopting common terminology and definitions for the most commonly used terms, tools and ecosystem products is highly advisable as this would facilitate communication within the IOTC community. In addition, the EAFM cannot be successfully implemented without clear definitions and goals. In order to solve this issue, a better dialogue between the IOTC Scientific Committee and the Commission may be advisable to address this.

The existence of a clear entity to be responsible and in charge of planning, advising and coordinating EAFM relevant entities is recognized as a best practice. In IOTC, the Working Party on Bycatch was created in 2005, and in 2007 this Working Party was renamed as the WP on Ecosystem and Bycatch and expanded its terms of reference to coordinate and integrate ecosystem and bycatch monitoring, research, modeling and advice activities to facilitate the incorporation of ecosystem considerations into management decisions (IOTC 2007). The Working Party on Ecosystems and Bycatch is a scientific working group, which meets every year to tackle ecosystem and bycatch related research and associated activities as required by the Scientific Committee to fulfill its advisory role to the Commission. The work conducted depends on the priorities set by the Commission, which until now has focused only on estimating fisheries interactions with bycatch species and providing guidance on mitigation measures to reduce bycatch (IOTC 2014b), leaving in a second place in most years, other ecosystem related activities. The creation of an additional Working Group, a Ecosystem Plan Team or Advisory Team made with a wide range of expertise in natural and social sciences and the policy, science and management interface, including scientist and managers and other interested stakeholders, could facilitate and make more efficient the implementation of EAFM in IOTC. The role of this newly created Working Group could be task to oversee ecosystem related planning and scientific activities carried out by the WPEG but also other scientific Working Groups in IOTC doing relevant ecosystem related work (e.g. the neritic working group) and find ways to integrate and connect better all these work with fisheries management to provide guidance to the Scientific Committee and the Commission.

IOTC has not formally developed and adopted an operational ecosystem plan, which is a tool that aims to link higher level policies and objectives into actions (Staples et al. 2014). Ecosystem plans provide a framework of strategic planning to guide and prioritise fishery and ecosystem research, modelling and monitoring needs, and facilitates the integration of information and knowledge from different fisheries operating in a region and their cumulative impact on the ecosystem into the management system. However, since 2015 the work plan of the WPEB includes the task of developing an ecosystem plan to address the EAFM in the IOTC area as a high priority to guide the development of ecosystem research or ecosystem considerations and ecosystem management advice to ensure it remains responsive to the Commission needs (IOTC–WPEB11 2015). However, there has not been progress on this matter in the WPEB and what actions or research activities need to take place have not been established yet with specific deadlines.

In 2011, IOTC agreed to further support capacity building activities, including activities to improve the level of comprehension among IOTC member on how the scientific process informs management and increase communication between scientist and managers to inform the process. Since then, the IOTC has organized several workshops to connect better IOTC science to the management process and increase the dialogue between scientists and managers. The last workshop "Workshop on Connecting the IOTC Science and Management Processes" occurred in 2015. In addition, IOTC has also established a dedicated Technical Committee of Management Procedures (TCMP) as a formal communication channel between science and management to enhance decision-making response of the Commission in relation to Management Procedures. While these initiatives facilitate the communication between science and management processes, to date they have focused on single species focus management, and there has been no dedicated time to address how ecosystem science can also be channeled into fisheries management decisions. The IOTC may consider creating similar mechanism (or expand the existing mechanism) to enhance the dialogue between scientists and managers on ecosystem matters and how best to integrate them in the policy, science and management interface in IOTC.

Last, the identification of spatial units or regions that make ecological sense can be also an important element of effective ecosystem planning and one of the starting points when operationalizing the EAFM process in a region (Fletcher et al. 2010, Staples et al. 2014). IOTC has not explored yet the potential use and the benefits of having well established regions within the IOTC contention area, which may contribute to achieve a range of scientific, management and conservation objectives including the development of integrated ecosystem assessments and report cards, inform large-scale ecological modelling and guide ecosystem-based management (Grant et al. 2006, Zador et al. 2017). In 2017 an EU funded project undertook some of the initial work towards a broad-scale regionalization of the IOTC convention areas (Juan-Jordá et al. 2019). This project developed and tested an evaluation criterion to inform the identification of regions within the IOTC convention area. The candidate criteria developed were mainly based on (1) the biogeography of the pelagic waters in the Indian Ocean, (2) the spatial distributions of major IOTC tuna and billfish species, (3) and the spatial dynamics of major IOTC fleets operating the IOTC area. Based on these preliminary evaluation criteria, two candidate broad regions were proposed within the IOTC convention area, a tropical region and a temperate region (Juan-Jordá et al. 2018). In 2018 this initial work was presented at the Working Party on Ecosystems and Bycatch 14 (WPEB14) as a conceptual scientific exercise to discuss its potential utility and explore venues for future work. The WPEB14 discussed that the two candidate regions proposed by the EU project did not reflect adequately the characteristics of the IOTC region in part because it did not entirely account for some of the main fisheries in the region, in particular the most coastal fisheries (IOTC–WPEB14 2018). The WPEB14 recommended that the criteria to inform boundaries of the ecoregions need to be revised and should account for a larger number of factors and characteristics of the region. The WPEB14 recommended to convene a workshop in 2019 to delineate candidate regions based on a revised criteria to foster further discussions about their potential use to inform the implementation of EAFM in the IOTC region (IOTC–WPEB14 2018). This workshop will take place the 30th and 31st of August and 1st of September prior to the WPEB15 meeting which will take place the following week in La Reunion/

3.2 Progress in IOTC in terms of scoping and profiling the state and health of the ecosystem relevant to IOTC fisheries

WHERE IOTC IS KNOW?

2. SCOPING AND PROFILING THE STATE OF THE ECOSYSTEM

What is the state and health of the ecosystem relevant to IOTC fisheries?
What are the main pressures on the ecosystem?
Does IOTC has the science to understand the main ecosystem processes, threats, status and trends of major ecosystem components?

The scoping and profiling step are mostly about identifying what it is to be managed and assessed, what species, area, fleets, fishing communities, and synthesizing current knowledge on the main pressures on and the state of the ecosystem relevant to IOTC fisheries, and addressing data gaps and knowledge. At this stage is important to identify relevant interactions among gears, species, the environment and socio-economic factors, so it can be used to generate more integrated scientific advice in order to inform on what ecological, physical and socio-economic factors should be accounted in fisheries management decisions. And most important, how to channel this information to the Scientific Committee and the IOTC Commission so it can inform the management process.

Since its creation in 2005, the Working Party on Bycatch, later renamed as the Working Party on Ecosystem and Bycatch, works under the terms of reference of coordinating and integrating ecosystem and bycatch monitoring, research, modeling and advice activities to facilitate the incorporation of ecosystem considerations into management decisions (IOTC 2007). The Working Party on Ecosystems and Bycatch meets every year to tackle ecosystem and bycatch related research and associated activities as required by the Scientific Committee to fulfill its advisory role to the Commission. Every year, the Working Party on Ecosystems and Bycatch prepares a report summarizing the main research activities conducted and reviewed during the year and prepares a series of recommendations for the Scientific Committee regarding bycatch and ecosystem issues and progress in implementing EBFM.

There are multiple tools available to enhance communication and link better ecosystem information into fisheries management and advice. One of the available tools is the development of ecosystem report card (and the supporting ecosystem assessments). The WPEB Program of Work (2019-2013) includes the development of an indicator-based ecosystem report card and assessments for the IOTC region (IOTC–WPEB14 2018). The main purpose of the ecosystem report card is to improve the link between ecosystem science and fisheries management to support the implementation of the EAFM in the IOTC region. Potentially, it could be an effective communication tool to increase the awareness, communication and reporting of the state of IOTC’s different ecosystem components to the Commission, since it can be used to synthesize large and often complex amount of information into a succinct and visual product. Ultimately the ecosystem report card aims to report on the relevant pressures affecting the state of the pelagic ecosystem, and report on the ecological state of the pelagic ecosystem interacting with IOTC fisheries.

The WPEB14 drafted a workplan to support the development of an indicator-based ecosystem report card for the IOTC region (IOTC–WPEB14 2018). The workplan presented a reporting framework to monitor the full range of interactions between IOTC fisheries and the different components of the pelagic ecosystem (Figure 2). This reporting framework presents different ecosystem components as key areas that would be required for monitoring the overall health of the ecosystem surrounding and supporting species under IOTC management responsibility.

The workplan also identified the teams of individuals that have volunteered their time to develop indicators and indicator-based assessments for each ecosystem component in the reporting framework. IOTC scientist are working intersessional to develop and present at the next WPEB15 meeting some indicator-based assessments for each ecosystem component in the reporting framework. Each team is expected to propose and develop some candidate indicators that would be the most suitable and representative for monitoring the status of each component, and document their process towards their development of an ecosystem assessment report which will be used to inform the ecosystem report card for the IOTC region. All the assessment reports reviewed by the WPEB15 will be used to inform the development of the first ecosystem report card in IOTC. It is expected this will be an iterative and collaborative process which will require multiple iterations and multiple years before a robust ecosystem report card is produced. The ultimate goal is to create a robust product in order to provide better ecosystem advise to the Commission.

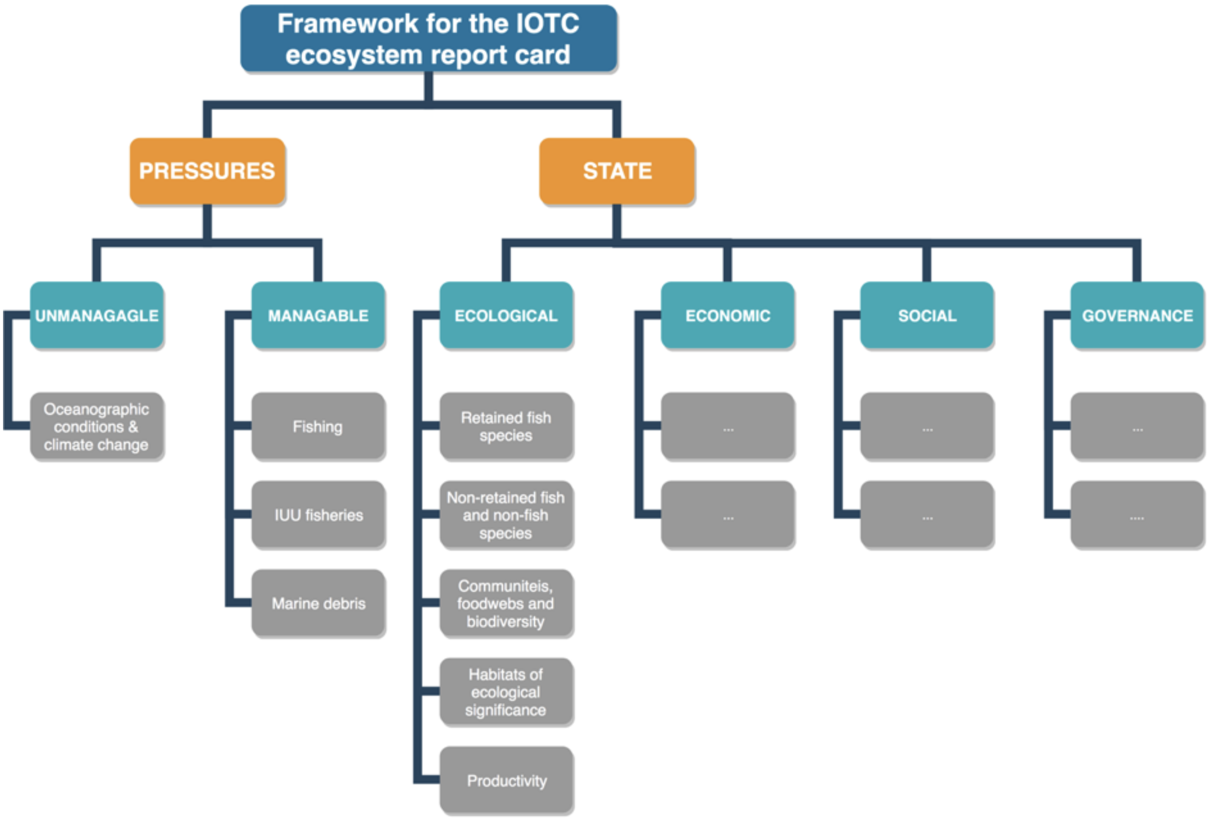

Figure 2. Framework for the IOTC ecosystem report card (IOTC–WPEB14 2018).

The robustness and quality the ecosystem report cards will depend on the quality of each of its ecosystem components (Figure 2), and how the WPEB makes progress on each of the areas of research to monitor each ecosystem component. The reality is that the work conducted by the WPEB depends on the priorities set by the Commission. Responding to Commission requests, the WPEB has until now focused on conducting stock assessments for some sharks species, estimating fisheries interactions with other bycatch species (sea turtles, seabirds, marine mammals) and providing guidance on mitigation measures to reduce bycatch interaction and bycatch mortality (IOTC 2014b). Currently, the WPEB is prioritizing the development of indicators of stock status for three species of sharks (blue shark, oceanic white tip shark and shortfin mako). The development of the 2014 Multiyear Shark Research Program, initiated by the IOTC Scientific Committee and shark experts in the Working Party on Ecosystems and Bycatch, is facilitating the development of stock assessments and status indicators for shark species caught by IOTC fisheries and improving the collaboration and cooperation among IOTC researchers (IOTC 2014a). Regarding bycatch species including endangered, threatened and protected species, the poor reporting levels of bycatch data and very low levels of observer coverage in most IOTC CPCs have hinder any attempt to conduct joint analysis to quantify overall levels of bycatch rates and bycatch mortality in the Indian Ocean and quantify the contributions of each fishery and fleets to those overall levels of bycatch. (IOTC–WPEB14 2018). Furthermore, very few research studies are presented at the WPEB meeting regarding habitats of special concern and habitat preferences for IOTC species, on the trophic ecology for IOTC species, ecosystem modelling or multispecies models to understand food web dynamics, species interactions and their ecological role in the food web similarly. Focused research to understand the effects of climate and environmental variability on the abundance, recruitment and productivity of IOTC species has also been relatively scarce.

3.3 *Progress in IOTC in terms of identifying and prioritizing issues*

WHERE IOTC IS GOING?
3. IDENTIFY AND PRIORITIZE ECOSYSTEM ISSUES

What are the main threats and issues?
What are the risks and should be IOTC priorities?

The identification and prioritization steps are mostly about identifying those relevant issues specific IOTC fisheries and species before being assessed for risks. For practical reasons, issues can be broken down into (1) ecological assets (e.g. species, threatened species, trophic relationships, habitats) relevant to the IOTC fisheries, (2) social and economic outcomes being generated by the fishery (e.g. food security, jobs, working conditions), and (3) the management and institutional system in place to deliver "outcomes" (e.g. compliance, conflict resolution) (Fletcher and Bianchi 2014). Traditionally the Scientific Committee in IOTC has mostly focused its work to address the ecological assets, to provide advice to the Commission mostly about the impact of fishing on the ecological component of the EAFM, leaving in a second place, those social and economic analysis and factors that might be relevant to take into account in fisheries management decision. How to incorporate social and economic information, analysis and factors into fisheries management decisions remains underdeveloped and unexplored in IOTC. A recent scoping study of socio-economic data and indicators of IOTC fisheries has been conducted for the IOTC Commission for its consideration and prospective actions (Poseidon Aquatic Resource Management 2019).

In this step it is also critical to identify relevant risks to allow managers to prioritize risks as well as explore multiple pressures to better understand cumulative effects on the ecosystems. The level of risk will determine what level of managed response is required (Fletcher and Bianchi 2014). Risk analysis and assessments can be used to determine the level of risk, which will inform if the current management system in place is sufficient and is working at the right level. Risk assessments can include climate vulnerability assessments, community vulnerability assessment to system changes, habitat risk assessments and the traditional ecological risk assessments focused on specific taxonomic group of species and gears.

IOTC has a long record in conducting ecological risk assessments (ERAs) on specific taxonomic group of species and fishing gears. In 2012 the Scientific Committee conducted a preliminary ecological risk assessment for shark species, as determined by a susceptibility and productivity analysis (Murua et al. 2012), in order to rank their relative vulnerability to logline and purse fisheries in the IOTC area. An ecological risk assessment for sharks in gillnet fisheries is still missing driven by a lack of data availability. In 2010, a preliminary level 1 ecological risk assessment was conducted for seabirds to evaluate the risk of seabirds from bycatch in longline fisheries in the IOTC area (IOTC–WPEB06 2010). This assessment was considered preliminary and it has not been used to provide management advice to the Commission. The Scientific Committee recommended to undertake a level 2 ecological risk assessment for those species identified as high priority, and to conduct a level 3 assessment for a smaller number of species where data availability permits it. These assessments have not been undertaken or reviewed by the Scientific Committee yet. In 2018, a risk assessment of the vulnerability of sea turtles to IOTC fisheries including longline, purse seine and gillnet fisheries (Williams et al. 2018). An comprehensive ERA has not been developed yet to assess the vulnerability of marine mammals to IOTC fisheries, yet the Scientific Committee has noted that gillnets are a major impact on marine mammals in certain areas of the Convention, which still needs to be addressed in order to determine if this bycatch is sustainable.

To date, the WPEB and IOTC community has focused on developing ERAs on specific taxonomic group of species and gears to prioritize their work, and while these remains an important tool, the other type of risk assessment focusing on habitat risks, climate risks and others ecosystem risks remain underused and underexplored in IOTC.

3.4 Progress in IOTC in terms of developing a management system that includes ecosystem considerations

The prioritizing step allows to identify what issues are most at risk and that require direct intervention. The next step requires to develop a response in the management system that will address those high-risk issues. The management system needs to link ecosystem information into fisheries management and to balance the trade-offs between achieving ecological, social and economic objectives. It is clear that accounting for gear interactions, species interactions and climate interaction in the management context requires that harvest strategies are planned and chosen making explicit connection to the interconnectedness of gears, species and climate.

IOTC has made some progress with the development and adoption of harvest strategies, which are pre-agreed rules for the management of fisheries (IOTC–SC21 2018). IOTC has adopted a harvest strategy for skipjack, it is working on harvest strategies for yellowfin, bigeye and albacore tunas, and for swordfish, and has not started the process the rest of species such as neritic tunas. A harvest strategy usually includes target and limit reference points and associated harvest control rules, that outline the data requirements needed to manage that particular stock, and the pre-agreed actions to be taken in the stock falls below the prescribed biological levels. Until now the harvest strategies developed or under development in IOTC are focused on the management of a single stock (accounting for its biology, ecology and social and economic conditions relevant to that stock), but they are not designed or planned to make explicit connection to the interconnectedness of gears, species and climate. For example, the state of a bycatch species, particularly a species threatened, has not been taken into account to evaluate the robustness of the harvest strategies being developed for the main IOTC species. Furthermore, there is not a formal mechanism to accommodate multispecies, food web interactions, ecosystem modelling, knowledge of habitats of special concern into the current management and conservation of IOTC targeted or bycatch species and associated ecosystems. This type of information has not been taken into account to evaluate the robustness of harvest strategies of main IOTC species. Similarly, relevant environmental and climatic indices have not been accounted to evaluate the robustness of harvest strategies of main IOTC species. Robust harvest strategies that make explicit connection to the interconnectedness of gears, species and climate (in the case those connections were deemed of high risk) will require significant time and resources to evaluate the data, identify and evaluate the various management strategies, explore the trade-offs among multiple management objectives, agreeing on acceptable levels of risks and model potential harvest scenarios. At this stage, perhaps a more pragmatic way to advance this process would be supporting the development of ecosystem indicators and ecosystem models and used them to assist in the modelling of different potential harvest scenarios accounting under different ecosystem-driven objectives to inform harvest strategies and inform strategic ecosystem-based management (Griffiths et al. 2019).

4. Synopsis of the main ecosystem impacts of tuna fisheries in the Indian Ocean, and assessment of the relative importance of impacts from tuna purse seine fishing relative to other major gears.

Multiple fisheries, including purse seine, longline, gillnets, and pole and line fisheries, operate in the Indian Ocean within the IOTC convention area. During the last decade, purse seine gears have reported over 26% of the total catches of IOTC species in the Indian Ocean, pole-and-line fisheries reported 7%, gillnets 32%, longline 13% and the rest of the gears combined (hand-line, trolling and other small-scale fisheries) 21% of the total catches (IOTC 2018a). Fishing is an extractive activity, and potentially every fishery can have direct and indirect negative impacts on the marine ecosystem. Furthermore, some of these major fisheries, at least the purse seine and longline fisheries, also use different fishing strategies (e.g. different depth for setting the gear, day vs night setting, setting purse seine nets on floating objects vs swimming schools of tuna) depending on what species are being targeted. The different fishing strategies can determine the way the fishery and gear interact with the marine environment and consequently their potential ecosystem impacts. In the case of the purse seiners, purse seiners catch tuna species using two different fishing strategies, either setting their nets on free-swimming schools of tuna or setting on drifting floating objects where tunas and other fish and non-fish species aggregate. The floating objects can be natural drifting floating objects such as logs, or man-made artificial drifting objects known as Fish Aggregating Devices (FADs). Tuna species (including juveniles of tuna) and other species aggregate around the floating objects which makes them easier to spot and catch, making the fishing operation more successful and the catch rates higher for the target species but also incidentally catching a larger diversity of species than when setting on free-swimming schools of tunas. Consequently, the ecosystem impacts of these two different purse seine fishing strategies or operations are different (Dagorn et al. 2013). Pelagic longliners can also use varying fishing strategies. For example, pelagic longline fisheries can set their hooks relatively deep (between 100 and 400 meters deep) during the day to target bigeye tunas, but can also set the hooks at relatively shallower depths (less than 100 meters deep) during the nighttime to target swordfish. Each longline fishery strategy is expected to interact and incidentally catch a different range of species with distinct impacts on the ecosystem. For example, the number of interactions with sea turtles and mortality rates will vary between the shallow set and deep set longline fisheries (Clarke et al. 2014). It is important to bear in mind that while fishery impacts should be investigated for each major fisheries and gears individually, the cumulative impacts across all the fisheries and gears operating on a regional basis can only provide a true understanding of the extent of the fishing impacts on the ecosystem.

The ecological impacts of fisheries on marine ecosystems can be broadly categorized as:
(1) impacts on the individual targeted species;
(2) impacts on the individual non-targeted species including endangered, threatened and protected (ETP) species;
(3) impact on habitats of ecological significance; and
(4) impacts on the structure and function of marine ecosystems.

Each of these broad impacts are briefly summarized below, yet this section focuses on reviewing and summarizing the existing evidence on changes in food web structure and ecosystem level changes in response to tuna fisheries. This section together with sections 5-7 aim to inform the actions established under the three critical and non-critical IPG (IPG6, IPG15 and IPG16) related to the ecosystem impacts of purse seine tuna fishing identified in the SIOTI FIO Action Plan.

4.1 Fishing impacts on the individual targeted species

Fishing irrespective of the gear used reduces the biomass and alters the size structure of the targeted species. When fisheries (all fisheries combined) catch too many fish of a particular species it impairs the reproductive potential of the species leading to recruitment overfishing. Additional, when all fisheries combined are catching too many small fish that have the potential to grow to a much larger size, if they were to survive, it can lead to a loss of potential yield known as growth overfishing. There are some concerns that there has been an increase in the purse seine FAD effort in all the oceans, including the Indian Ocean, resulting in further increase in catches for the targeted tuna species (skipjack, yellowfin and bigeye tunas). There are also concerns on the increases of catches for juvenile of yellowfin and bigeye tuna as juveniles aggregate around FADs (Dagorn et al. 2013). These increasing trend in FAD effort may lead to overfishing of the stocks without the appropriate management capacity.

In the Indian Ocean, yellowfin tuna is currently the only major targeted tuna species considered overfished and subject to overfishing. The increase in catches of yellowfin tuna in recent years has substantially increased the pressure on this species resulting in fishing mortality exceeding the maximum sustainable yield related levels (IOTC–SC21 2018). Between 2013-2016, purse seine contributed to 35% of the total yellowfin catches (23% in FAD associated schools, 12% in free swimming schools), longlines to 16%, gillnets to 17% and all the other minor coastal gears combined to 31% of the total catches. At the end, for managing impacts on the targeted species IOTC needs to ensure that the targeted species are around target levels, and when overfished as it is the case of yellowfin tuna, it needs a rebuilding plan in place to rebuild the stock around the target level in an established timeframe. These needs to be done by managing all fisheries combined, not just purse fisheries and FAD effort, but also the effort exerted by the rest of fisheries. This will require to agree on clear management objectives for all the target species and decisions about allocations, both among all gears targeting the species, as well as within the purse seine fishery given its two fishing strategies (Hampton et al. 2017).

4.2 Fishing impacts on the individual non-targeted species including endangered, threatened and protected (ETP) species.

Non selective gears also capture accidentally unwanted or non-targeted species, which might include endangered, threatened and protected species such as some sharks and sea turtles. In this study, the catch of non-targeted species, which can be either landed because of their commercial value or discarded at sea because of their low commercial value or the non-retention measures in place, is referred as bycatch. In the same way as the targeted species, fishing can alter their biomasses and size structures of bycatch species, and if exploited beyond safe biological limits, their reproductive capabilities might be impaired endangering them.

Globally tropical purse seine tuna fisheries have relatively low bycatch rates compared to the other pelagic gears such as longliners and gillnets (Gilman 2011, Justel-Rubio and Restrepo 2017). Tropical purse seine tuna fisheries have an overall bycatch rate of non-target fish (small tunas, other teleost, sharks, rays) of 1.4% (Justel-Rubio and Restrepo 2017). These means that for every 1000 tonnes of the targeted tunas (skipjack, yellowfin and bigeye tunas landed and discarded), 14 tonnes of non-targeted fish are caught. These bycatch rates for non-targeted fish vary by ocean, 0.57 in the West and Central Pacific Ocean, 0.61% in the Eastern Pacific Ocean, 2.42 in the Atlantic Ocean, and 2.15 in the Indian Ocean (Justel-Rubio and Restrepo 2017). Among the non-targeted fish caught, shark species are the most vulnerable to purse seine fisheries due to their slow life histories (slow growth and low reproductive rates). Silky and oceanic whitetip sharks are the most caught species of sharks, and are listed as Near-Threatened and Vulnerable in the IUCN Red List of Endangered Species, respectively. Turtles are also caught in purse seiners but in small numbers are released alive relatively easily (Amande et al. 2008, Ruiz et al. 2018). Sea

While the purse seine bycatch rates are relatively low, the large scale of the global purse seine fishery may lead to measurable impacts on the non targeted species, for these reason management measures need to ensure that bycatch rates continue to be monitored and reduced to the extent possible to ensure species are not endangered. IOTC has adopted through several recommendations or resolutions, several measures to reduce purse seine impacts, including bycatch rates. These include requirements to use non-entangling FAD designs, encouragement to use biodegradable FADs, a limit on the active FADs and/or FAD sets (350 active FAD limit per vessel), the use of safe handling and release practices for sharks, rays and turtles, and a prohibition of intentional setting on whale sharks and cetaceans. In addition, the European Union (EU), Seychelles and Mauritius-flagged purse seine vessels fishing for pelagic tunas and under the SIOTI FIP, which constitute the majority of the purse catches in the IOTC convention area, have put forward various additional activities to reduce the mortality by entangling or by incidental catch of FAD-associated vulnerable species (sharks, rays, mantas, whale sharks and sea turtles). The good practices adopted by these fleets include the use of non-entangling FADs as well as the application of release operations for FAD-associated vulnerable fauna. A recent study has estimated that the purse seine fishery in the Indian Ocean is responsible for just 0.15% of the fishing mortality of sharks, 0.16% of whale sharks, nil of marine mammals, and 0.3% of marine turtles. On the contrary, gillnet, driftnet, longline fisheries are responsible for most of the bycatch mortality of sharks, marine mammals and marine turtles (Garcia and Herrera 2018). This study also highlighted that the uncertainty of estimates for the longline and gillnet fisheries remains very high due to the low levels of coverage, poor data quality and little information available and reported to IOTC. IOTC needs to address these limitations in data quality and availability if reasonable assessments of bycatch across the different gears and species groups are to be made to inform management decisions.

4.3 Fishing impact on habitats of ecological significance

Identifying habitats of ecological significance for species and how fisheries might interact and affect them is also an important element to consider when trying to understand the broad ecosystem impacts of fishing. Habitats of ecological significance might include areas used by species for spawning grounds and migration corridors, productive areas for feeding, or areas of high biodiversity where multiple species aggregate in a particular time. Consequently, it is important to support research to further our understanding of the environmental preferences of tuna and related species, how they utilize the pelagic habitat, as well as what other biotic factor such as prey preferences, determine their habitat use (Harrison et al. 2017).

There has been some concerns and discussions that the increase in the use of FADs in purse seine fisheries might be changing the natural habitat of tunas and how tunas interact and use the pelagic habitat. Tunas naturally have always aggregated around logs and natural debris. Now, the FADs used by the purse seiners to attract fish add additional opportunities for species to aggregate in the vast featureless oceanic waters, by increasing the number of floating objects where natural logs already occur, and by appearing in areas where natural logs would not normally occur. It has been hypothesized that FADs can alter the natural habitat of tuna species by providing more opportunities for shelters, “meeting points” and feeding opportunities (Dagorn and Fréon 1999, Dagorn et al. 2013). Tunas are not the only species being aggregated around the FADs, but also a diverse range of species (fish and non-fish species) are attracted to them. It has been suggested that these FADs may act as “ecological traps” for species as they aggregate biomass of a wide range of species up to several kilometers which would not be aggregated if they were not present. If FADs were to act as ecological traps it has been hypothesized that they may have potential consequences to the behavior, movements and biology of those species aggregating around them (Marsac et al. 2000, Hallier and Gaertner 2008). FADs might retain tuna species and other species or carry them into locations that were not part of their original migrations, and also might affect their diet, condition, growth and reproductive success. There has been considerable work on this subject but with conflicting interpretation and results on both the behavioral and biological impacts of FADs on tunas (Dagorn et al. 2013, ISSF 2014). To test whether FADs may affect the behaviour and large-scale movements of tunas, the large-scale movements would need to be compared before and after the period of the large-scale deployment of FADs. The current data and available research are not suitable to test this (ISSF 2014). There have also been some studies that show differences in the condition of tunas between free swimming schools and those associated with floating objects, but with varying results depending on the study area. Furthermore, it is not clear how the condition of fish may impact the growth and reproduction of these species (ISSF 2014). Therefore, there is a general consensus among the scientific community that more research is needed to investigate this topic and determine whether and how FADs act or not as ecological traps for tunas and other species.

Additionally, fishing gears might be abandoned, lost or discarded on the marine environment, which could also potentially impact and cause ecological problems for marine species and sensitive habitats as well as socio-economic problems for the fishing fleets (Gilman 2015). One ecological problem derived from these abandoned, lost or discarded fishing gears is that lost floating gears may continue to catch organisms (known as ghost fishing). Not accounting for the mortality due to ghost fishing in stock assessment models has the potential to make less effective the harvest strategies of managed targeted species as well as affect the population viability of the most vulnerable species such as sea turtles, marine mammals, seabirds and some sharks and bony fishes (Coggins et al. 2007, Gilman et al. 2013).

Furthermore, the abandoned, lost and discarded fishing gear and in general marine debris can also end up stranded on beaches and sensitive coastal areas such as coral reefs (Maufroy et al. 2015, Zudaire et al. 2018b). Over the last decades the amount of marine debris including abandoned, lost and discarded fishing gear has increased substantially globally with the expansion of fishing effort and with the transition to more durable and more buoyant fishing materials (Gilman 2015). The extent and magnitude of the marine debris derived from fisheries in the Indian Ocean and elsewhere is unknown or poorly known. Some studies have tried to estimate the number of FADs that might be lost and that might be reaching the coast. It has been estimated that the French fleet in the period between 2007 and 2011 may have been lost onshore and stranded on the coast each year between 1500-2000 GPS buoys associated to the FADs in the Atlantic and Indian Ocean combined contributing to coastal marine debris (Maufroy et al. 2015). In the Indian Ocean, beaching of buoys tends to concentrate off the Somalia, Kenya and Tanzania and only a small proportion of them reach the Mozambique channel and the northern coasts of Madagascar. These beaching events may be potentially occurring in sensitive areas such as coral reefs, beaches, estuaries and mangroves. Mitigating the impacts of lost drifting FADs and lost buoys may be possible by avoiding deployment zones and time periods that increases the probability of losing leading to an increase in beaching events (Maufroy et al. 2015). IOTC has adopted measures for the use of non-entangling FADs and promotes the use of sustainable materials to construct them such as biodegradable FADs. There are also private actions, for example the FAD Watch program, led by the private sector, industry and the government of Seychelles, to prevent and mitigate FAD beaching in the Seychelles islands (Zudaire et al. 2018a). The contribution of other fisheries such as the longline and gillnet fisheries to the total amount of abandoned, lost or discarded fishing gears in the Indian ocean remains unknown.

4.4 Fishing impacts on the ecosystem function and structure of marine ecosystems

There is increasing evidence that the abundance and composition of the targeted and non-targeted species is changing as a result of fishing. Fishing by removing large amounts of biomass and reducing the abundance of multiple species in the foodweb can alter a wide range of biological interaction causing changes in the predatory-prey interactions and cascading effects in the foodweb (National Research Council 2006). In some cases, fishing has led to alternative ecosystem states, a state with different species composition or productivity relative to the pre-fishing condition. A classic example of large-scale system changes is the overexploitation and depletion of cod as well as other high trophic levels species in the Northwest Atlantic, which has led to a drastic restructuring of the entire food web, attributed in part to trophic cascades by the removal of top predators (Frank et al. 2005).

In the context of tuna fisheries, there is also a growing body of literature providing evidence of the impacts of industrial fishing on the structure and function of marine ecosystems (Cox et al. 2002a, Polovina and Woodworth-Jefcoats 2013, Griffiths et al. 2019). However, assessing the impact of fishing on the broader structure and function of marine ecosystems in the open ocean where most tuna fisheries operate is not an easy task. Additionally, there are also significant difficulties in understanding the impacts of the total removals of biomass from the different fisheries and gears operating in an area, and detecting changes in the relative abundance of species and reliable assigning those changes to specific fisheries and gears (Allain V. et al. 2015). In the open-ocean ecosystems, where most of the tuna fisheries operate, multispecies models and ecosystem models are emerging as effective tools to understand the impacts of multiple gears and multiple harvest strategies on the structure and dynamics of marine ecosystems and to compare the possible outcomes of the different fishery management options (National Research Council 2006, Griffiths et al. 2019). Trophic based and size based ecosystem models are increasingly being used to explore specific hypothesis because they allow representing the complex ecological interaction and trophic (feeding) relationships or size based relationships across a wide range of species in the ecosystem and their interactions with different fishing gears (and harvest strategies) and other external factors such as major features of the environment and climate change (Polovina and Woodworth-Jefcoats 2013, Allain V. et al. 2015). Therefore, ecosystem models are useful for exploring the consequences of alternative fisheries management scenarios on economically important species, but also to understand how fishing impacts may propagate to other species and through the wider pelagic ecosystem.

Over time there has been multiple working hypothesis to explain how fishing affects food webs. First, the decline in the mean trophic level of the catches, resulting from fisheries gradually changing their target species towards smaller species as the abundance of the larger species decreases, has been described as “fishing down the food web” (Christensen 1996, Pauly et al. 1998). Second, it has also been observed the phenomenon of “fishing through the food web" (Essington 2006, Branch et al. 2010), which indicates that multiple trophic levels (high and low trophic levels species) are being fished simultaneously. Catches of high-trophic level species can stay high and increase but fishing also expands on lower trophic species. Third, the phenomenon of "fishing up the food web" has also been documented. This occur when fishing targets low trophic level species and the shifts to larger even higher trophic level species (Essington 2006, Erlandson et al. 2009, Litzow and Urban 2009). In the context of tuna fisheries, the phenomenon of "fishing down the food web" has been documented in the subtropical North Pacific Ocean with a decline in the mean trophic level of the catches from 3.85 to 3.66 by the Hawaiian longline fishery (Polovina et al. 2009b). The observed declines of the bigeye and albacore tunas, shortbill spearfish, striped marlin, and blue shark catches resulted in the proliferation of mid-trophic level species such as mahi mahi, sickle pomfret, scolar and snake mackerel. In contrast, a recent study in the western Pacific Ocean showed that the phenomena of "fishing up the foodweb" is occurring there (Griffiths et al. 2019). This study documented a gradual increase in the mean trophic level of the catches from 4.21 in 1980 to 4.28 in 2010. While there has been strong declines in biomass in several high-trophic level target species and bycatch species such as yellowfin and bigeye tunas, striped marlin and silky and oceanic sharks in the western tropical Pacific Ocean, the increase in the mean trophic level of the catches results from a combination of declining catches of the traditionally high-trophic level targeted species and an increase of catches of other purse seine FAD-associated species that also occupy similar high trophic levels (Griffiths et al. 2019). In order to observe the ecological change of a "fishing down effect" being reflected in the mean trophic level of the catches, the biomasses for the majority of species in high trophic levels (above 4) would need to be severely depleted, which is not the case in the western and central Pacific Ocean. In the Indian Ocean, the fishing impacts of tuna fisheries on the foodweb structure and function have been poorly examined, and therefore, there are no documented large-scale changes in the foodweb structure in this Ocean.

In the Indian Ocean research activities and practices to address the importance of trophic interactions, food-web analysis, diet analysis and the development of ecosystem indicators and models to track ecosystem changes in response to fishing have been relatively rare (IOTC–WPEB08 2012, IOTC–WPEB09 2013, IOTC–WPEB14 2018). Nevertheless, the IOTC Scientific Committee and the IOTC WPEB encourages research on ecosystem approaches, on diet studies to investigate the trophic interactions among predators and prey species interacting with IOTC fisheries, and multi-species and ecosystem modelling to understand potential changes at the ecosystem level of alternative management strategies (IOTC–WPEB07 2011, IOTC–WPEB14 2018). Furthermore, the Scientific Committee also encourages the development of mechanisms to better integrate ecosystem considerations into the scientific advice provided by the Scientific Committee to the Commission (IOTC–SC21 2018).

While there are not reliable studies and documented large scale changes of the impacts of fishing on the foodweb structure and function in the Indian Ocean, several ecosystem indicators, food web and ecosystem models have been developed and tested in the Pacific Ocean and disused in the WCPFC and IATTC which provide useful insights to understand the ecosystem level changes from tuna fisheries and the environment in general. Below the most relevant studies conducted in the Pacific Ocean are summarized to provide some insights about what it is known and not known on the impacts of tuna fisheries on the structure and function of marine ecosystems with the aim to provide some ideas of research analysis and avenues that could also be developed or further develop in the Indian Ocean in the near future.

Several studies in the North Pacific subtropical gyre have suggested possible ecosystem impacts from fishing tunas, billfishes and sharks. A study comparing a scientific research survey in the 1950s when industrial fishing commenced with more recent data collected by observers on longline fishing vessels suggested a substantial decline in the abundance of large predators (large tunas and billfishes), and the mean body mass of these predators (Ward and Myers 2005). By contrast, there was some evidence of an increased abundance of some formerly rare species such as the pelagic stingray. Another study compared the catch rates for the 13 most abundant species caught in the deep-set longline fishery off Hawaii between 1996 and 2006 (Polovina et al. 2009a). This study suggested the catch rates for the top predatory species (bigeye and albacore tuna, blue shark, shortbill spearfish and striped marlin) declined between 3% and 6% per year, while catch rates for some mid-trophic species (mahi mahi, sickle pomfret, scolar and snake mackerel) increased by 6% to 18% per year. This study suggested a change in the ecosystem structure from high-trophic predatory species towards mid-trophic level faster-growing and shorter-lived species. Furthermore, several trophic-based ecosystem models, Ecopath with Ecosym model, have also been built in the North Pacific subtropical gyre to investigate the existence of any keystone species and examine the evidence of trophic cascades based on the decline of tunas and billfishes of the region(Kitchell et al. 1999, Cox et al. 2002b, Kitchell et al. 2002). These modelling exercises suggested there was not a single species (or functional group) that functioned as keystone species, and these models suggested there was limited evidence of trophic cascades or other ecosystem impacts based on the declines of tunas, billfishes and sharks in the region. A more recent family of ecosystem models, the size-based ecosystem models, have also started to be used to investigate ecosystem changes from fisheries in the marine system, and in open-water ecosystems, where there is increasing evidence that predation is more strongly driven by body size than species. A study in the North Pacific examined ecosystem changes in the subtropical gyre from a size-based perspective using both the observations from the Hawaii longline fishery with simulations from a size-based ecosystem model (Polovina and Woodworth-Jefcoats 2013). This study further supported the previous evidence (Polovina et al. 2009a) of an increased in the relative abundance of mid-trophic level fishes concurrent with declines in top predatory tunas, billfishes and sharks between 1950s to 2011 in the North Pacific subtropical gyre. In addition, this size-based ecosystem model suggested that size-predation is the dominant mechanism in structuring the foodweb in the North Pacific subtropical gyre.

Several studies using the Ecopath with Ecosim (EwE) ecosystem models have also been developed in the western and central tropical Pacific (Allain V. et al. 2015, Griffiths et al. 2019)and the eastern and central Pacific Ocean(Olson and Watters 2003, Griffiths and Fuller 2019) suggesting a significant change in ecosystem structure since the 1980s from heavy exploitation of top predators such as tunas, billfishes and sharks. These studies went a step further and explored the potential ecological impacts of decades of industrial fisheries on the ecosystem structure and the biomass of individual species (targeted, non-targeted species) and the plausible ecological impacts of future alternative efforts regimes with a focus on exploring alternative FAD efforts (hypothetical increasing and decreasing FAD efforts) in purse seine fisheries (Griffiths et al. 2019, Griffiths and Fuller 2019).

In the western Pacific Ocean, simulations with a reduction of FAD effort by at least 50% predicted to increase the biomass of tuna species including bigeye tuna, and vulnerable sharks, a current concern in the WCPFC, and returning the ecosystem structure to a pre-industrial fishing state within 10 years. In contrast, simulations with an increase in FAD effort from current levels suggested that it is an unlikely viable measure, as it decreases the sustainability of the tuna species directly targeted (yellowfin and bigeye tunas), and decreases the sustainability of the vulnerable-long-lived bycatch species (silky, oceanic whitetip, and mako sharks and blue marlin), whose biomass were predicted to decline by 43%. Yet, an increase in the FAD effort also resulted in increased up to 30% the biomasses of FAD-associated species such as wahoo, mahi mahi and rainbow runner, which is a trophic response from decreasing their natural predators. From an ecosystem perspective, the simulations carried out in Griffiths et al., 2019 study did not predict a substantial change in the structure and function of the marine ecosystem or any substantial trophic cascades after decades of industrial fishing. Furthermore, the simulations also showed that the ecosystem structure appeared to be resilient to the simulated fishing perturbations and to the substantial changes in biomass of many of the high-trophic level target and bycatch species. This resilience appeared to be driven by the high diversity of highly productive fishes in the upper trophic levels in oceanic waters that are generally opportunistic predators and consume a wide variety of prey (Griffiths et al. 2019). Under this circumstances, trophic cascades are harder to follow, since biomass declines from the targeted species are quickly buffered by small changes in biomass in a wide range of opportunistic predators. This indicates that the high-trophic level species (targeted and non-targeted) species are exerting only a weak tow-down regulation. Griffith et al. 2019 recommended that the combined fishing efforts from the three major gears (purse seine, longline and pole and line) in the region need to be monitored in combination (not in isolation) and ensure that if they are increased they did not eventually drive the ecosystem to a tipping point of no return where the altered ecosystem dynamics could no longer be reversed by any level of management intervention. Griffith et al. 2019 focused simulation of increasing or reducing FAD efforts, but future studies could also simulate effort scenarios for the long line fisheries and their interactions with the other gears (purse seine, and pole and line) to explore potential harvest strategies to assist managers in exploring trade-offs and finding optimal economic and ecological outcomes on which to base their management decisions.

In the eastern Pacific Ocean, several trophic-based ecological indicators also suggest a significant change in ecosystem structure over the last 50 years from the exploitation of top predators such as tunas, billfishes and sharks (Griffiths and Fuller 2019). The biomass of the high trophic level species (above 4 trophic levels) has declined steadily from the 1970s to 2014, furthermore, as a response from lowering predation pressure on the lower trophic levels, there has also been a steadily increase in the community biomass of the trophic levels (less than 4). Simulations with an increase of FAD effort predicted a further reduction on the biomass of all target tuna species (yellowfin, bigeye and skipjack tuna) and other vulnerable bycatch species (sharks and rays), while simulation with a decrease of FAD effort predicted an increase in biomass for the target tunas, but not for the larger bigeye tuna, which predicted a decline. These scenarios which are considered preliminary need to be further examined, but this result may be due the impact of longline effort on bigeye tuna in the area which has also been increasing in the region (Griffiths and Fuller 2019). Simulations also suggested that a substantial reduction in purse-seine effort, but also longline effort, is required to restore the ecosystem structure back to 2010 level when the effort of purse and longline were around half of what it is today. However, this study also discussed that the patterns observed are not considered detrimental to the structure and function of the ecosystems, but that these changes warrant continuing monitoring.

5. Identification of core elements and requirements for EAFM implementation that stem from the ecosystem impacts of purse seine tuna fishing in the Indian Ocean, including a review of ecosystem indicator options.

There is increasing evidence that fishing is changing species relationships and foodweb connections in the context of tuna fisheries. At the individual species level, overfished tuna and billfish stocks have recovered when fishing pressure has been reduced. However, whether the impacts of tuna fishing on food webs is leading to unwanted ecosystem states remains poorly known and monitored. Furthermore, whether the productivity and resilience of the ecosystem might cross a certain thresholds and what thresholds that might be, and whether the observed ecosystem impacts are reversible remains also elusive and poorly understood in all the oceans where tuna fisheries operate including the Indian Ocean.

Whether the observed foodweb impacts are leading or not to unwanted states, at the very least the risks of no monitoring potential ecosystem impacts need to be contemplated and accounted, and tools to monitor changes in the ecosystem and their underlying causes need to be put in place. It is important that fishery impacts are investigated by major fisheries and gears as well as their cumulative impacts on a regional basis, since cumulative impacts can only provide a true understanding of the extent of the fishing impacts on the ecosystem. Below, three core elements to support EAFM implementation that stem from the impacts of fisheries, including purse seiners and others, are briefly presented. First, the potential risks of not monitoring the wider ecosystem impacts are described, which need to be identified and recognized in order to inform ecosystem-level objectives. Second, the use of ecosystem indicators for monitoring ecosystem changes and the potential impacts of fishing are also presented, with a focus on those indicators that can be developed in the context of tuna fisheries. Third, the use of models, including ecosystem models and multispecies model, to support indicator development, but also as tools for exploring the consequences of alternative fisheries management scenarios on the state of the ecosystem are presented. In the broader road map for implementing the EAFM in IOTC, these three core elements can be considered key elements in the scoping and profiling step (Step 2 in the EAFM road map in Figure 1) since they facilitate the synthesis and integration of knowledge to characterize the main pressures on and the state of the ecosystem relevant to IOTC fisheries. Furthermore, the development of indicators and ecosystem models are also key tools to inform strategic management and the development of a management system that accounts for ecosystem information and that acknowledges and balances the trade-offs between achieving ecological, social and economic objectives (Step 4 in the EAFM road map in Figure 1).

5.1 Risks of not monitoring ecosystem impacts

Fishing by removing large amounts of biomass and reducing the abundance and altering the size of multiple species in the foodweb can alter the species composition in food webs and a wide range of biological interaction. These alterations can cause changes in the predatory-prey interaction and cascading effects in the foodweb. Cascading effects are often unforeseen, which might result in unexpected results when implementing a management actions at the species level, especially if the focus species in the management action is playing a critical role in the ecosystem (National Research Council 2006).

There are few documented cases, not in the context of tuna fisheries, where fishing has led to alternative ecosystem states, a state with different species composition or productivity relative to the pre-fishing condition. While regime shifts and alternative ecosystem states have not been observed in open-ocean ecosystems where tuna fisheries operate, a global fisheries multispecies maximum sustainable yield analysis suggested that the exploitation rates of individual species that achieves maximum sustainable yield should be considered an upper management limit rather than a management target in order to minimize the risk of low-productive species to collapse and reduce the impacts on ecosystem structure and function (Worm et al. 2009).

5.2 Ecosystem indicators for monitoring ecosystem changes and the potential impacts of fisheries in the context of tuna fisheries

Ecosystem indicators have been mostly used in two ways in terms of monitoring and ultimately managing the impacts of fishing on the broader ecosystem. First, indicators have been used to monitor ecosystem changes and track how well the ecosystem-level objectives are met. Second, and most challenging, ecosystems can be linked to the management system and can be used as part of decision rules to determine if management strategies are addressing those impacts(Fulton et al. 2005). Multiple ecosystem indicators are used to quantify and monitor the structural changes that may occur in the marine food web and the ecosystem resulting from fishing or environmental changes (Fulton et al. 2005, Shin and Shannon 2010, Coll et al. 2016). At glance, ecosystem indicators can be estimated using three sources of data: independent fisheries data obtained from biological surveys, fisheries dependent data obtained from fishing vessels (logbooks) and fisheries observer programs, and last, they can be model-derived when ecosystem models are available. In the open ocean where most tuna fisheries operate the paucity or non-existence of fishery independent data has been identified as a major impediment to properly analyze the current state of fisheries and ecosystem (National Research Council 2006). In these systems, fisheries dependent data is more readily available to support the developing and testing of ecosystem indicators. Computer simulation and ecosystem models also provide an alternative tool to study the system and derive model-derived ecosystem indicators to understand the properties of the ecosystem and its responses to fishing pressure (Fulton et al. 2005). However, it is important to bear in mind that the fishery dependent data complemented with data derived from dedicated research studies (e.g. trophic ecology of species) also remains the main source of data to feed the ecosystem models in the open-ocean. Therefore, any ecosystem study or analysis using fishery-dependent data can be subject to various interpretations since fisheries can change their fishing location and target species in response to many factors other than the abundance of fish species (e.g. markets, management, technology etc..), yet these are the most readily available data today in oceanic systems.

Multiple ecosystem indicators have been identified, developed and tested in the literature and put forward as candidate indicators to detect and monitor the effects of fishing on marine ecosystems (Fulton et al. 2005, Shin and Shannon 2010, Coll et al. 2016). The numerous ecosystem indicators available are used to describe and capture changes in multiple attributes of the ecosystem including, biomass, size structure, spatial structure, diversity, trophic level, and energy flows. Attributes are features of the ecosystem that society might be interested to capture and protect and are usually liked to common ecosystem level objectives such as maintaining ecosystem health, integrity or resilience (Fulton et al. 2005). Furthermore, it is widely recognized that no single or type of indicators is able to provide a complete picture of the ecosystem state. The natural complexities of marine ecosystem and ecological process requires to use a suite of indicators to provide a complete picture of the impacts of fishing on the ecosystem. The suite of indicators chosen need to be able to monitor and highlight changes in the system structure, help to diagnose the causes of those changes in the system, and last monitor the recovery of lost properties in the system(Fulton et al. 2005).

Table 4 provides a summary of ecosystem indicators that could be estimated (or are commonly estimated) to capture and describe changes in multiple attributes of the open ocean ecosystems derived from the impacts of tuna fishing. A brief description is provided for each indicator with a reference to the type of attribute it tries to capture and describe of the ecosystem. A distinction is also made whether the indicator can be empirically estimated using regularly collected fisheries dependent data, or whether it necessarily needs to be derived from ecosystem models.

None of the community- and ecosystem-level indicators presented in Table 4 are routinely estimated and monitored by IOTC in any tuna fishery in the Indian Ocean, yet some of the indicators presented might be under development now driven by the IOTC WPEB initiative to develop an ecosystem report card for the IOTC region. For example, European scientists (IEO, AZTI, IRD) are using the available data (logbook fisheries data and observer data) from the European purse seine fishery catching tropical tunas in the tropical Indian Ocean to examine the potential ecological effects of this fishery on the foodweb structure and functioning. This on-going analysis is comparing the total biomass removed by the fishery in terms of weight, trophic level and replacement time among each purse seine fishing method (sets on floating objects-FOBs and sets on free schools-FSCs). These indicators collectively try to understand the ecological effects of removing all animals through fishing, not only the bycatch or discards. In addition to the monitoring of the total biomass removed, they also monitor changes in the species composition of the total catch (whether they are retained or not), and use information of the life histories of species and their ecological role in the foodweb to understand fishing impacts. A similar analysis was conducted in the Atlantic Ocean and presented in the ICCAT SubCommittee on Ecosystems meeting (Juan Jorda et al. 2019). By examining the temporal trends of several ecosystem indicators based on the total removals by the fishery and the trophic level and life history traits of the species removed, this type of studies aims to support the on-going IOTC initiative to develop ecosystem status assessments and ecosystem report cards to monitor the effects of fisheries and climate in the Indian pelagic ecosystem.

Table 4. A summary of ecosystem indicators to capture and describe changes in multiple attributes of open ocean ecosystems derived from the impacts of tuna fishing. A brief description is provided for each indicator with a reference to the type of attribute it tries to capture of the ecosystem. A distinction is also made whether the indicator can be empirically estimated using regularly collected fisheries dependent data, or whether it necessarily needs to be derived from ecosystem models.

Indicator type	**Attributes measured**	**Brief description and rationale**	**Potential data sources**
Community-level pressure indicators. For example: -Catch rates -Discards rates or proportion of discards in the fishery (discards/landings)	Pressure on the ecosystem, also uses as proxy of community abundance changes	Logbook records with total catches and effort for the commercially valuable species are widely reported in fisheries statistics. In addition, a portion of the fisheries may also carry observers. From these, catch-per-unit-of-effort CPUE over time can be estimated, at least for the most common species, to monitor changes in catch rates over time. CPUE indicators are commonly used as an indicator of stock health in single species fisheries assessments, but they can also be used to monitor community-level changes in CPUE rates, yet they are not so easily obtained as it will depend on the quality of the fishery data sets(Fulton et al. 2004). Community and population-level discards rates can be used to monitor what it is actually landed versus what it is actually caught in total. It is used to provide insights about the pressures on the entire community exposed to fishing and it is important to estimate them at the fishery levels as each fishery and gear type can have very different discards rate and therefore distinct ecological effects. These indicators rely on fisheries dependent data, and its interpretation can be masked by a wider range of confounding factors (changes in gear type, targeting and effort) (Fulton et al. 2004).	-Empirically estimated using fisheries dependent data -Model-derived
Community level biomass-based indicators. For example: -Total biomass -Biomass by taxa groups	Biomass	Community-level or population level biomass indicators are commonly used to assess the impacts of fisheries on ecosystem and track the state of key functional groups in the system. Easy to understand but also subject to natural environmental variation. Direct independent measures are not available to derive them, stock-level and ecosystem models are required to obtain estimates of abundance and biomass.	Model-derived
Community level size-based indicators. For example: - Mean size of predefined groups from catch data or biomass estimates - 95% percentile (or others) of the size distribution of predefined groups from catch data or biomass estimates	Size structure	Size data is the most commonly and easily collected type of fishery data. Aside from supporting the fisheries assessments at the population level, it can also server to assess the changes in size structure at the community and ecosystem level. Fish size generally decreases under fishing pressure as high-value target species are generally lager, fishing gears are also size-selective often designed to target the larger fish, and larger fish also tend to be more vulnerable to fishing because of their life history traits (Shin and Shannon 2010). These size-based indicators can be derived using catch data or biomass estimates from ecosystem models.	-Empirically estimated using fisheries dependent data -Model-derived

-Proportion of large fish (proportion of fish catches or fish biomass larger than a specific size value) - The slope and intercept of the biomass size spectra of the marine community		In the case of the biomass size spectra, this indicator could be only estimated from size-based ecosystem models (Shin et al. 2005). The biomass size spectra indicators while they are also commonly estimated using data from independent-surveys, these data are not available in open-ocean ecosystems.	
Community level age-based indicators. For example: - Average age of predefined groups from catch data or biomass estimates - 95% percentile (or others) of the age distribution of predefined groups from catch data or biomass estimates -Proportion of older fish (proportion of fish catches or fish biomass larger than a specific age value).	Age structure	The increasing reliability of aging techniques has increased the number and use of age-based indicators. The means and tails of age distributions data at the species and community level can be informative about fishing effects as fisheries usually target the larger and older individuals. Yet the collection and estimation of age structure data remains more costly than collecting size data. Aside from supporting the fisheries assessments at the population level, age data can also server to assess the changes in age structure at the community and ecosystem level (Fulton et al. 2004). These indicators can be derived using catch data or biomass estimates from ecosystem models.	-Empirically estimated using fisheries dependent data -Model-derived
Trophic-based indicators. For example: -Mean trophic level of the catch by fisheries -Mean Trophic Index (the same as the mean trophic level of catches but includes only catches of species with trophic levels above 4) -Mean trophic level of the community (derived with biomass estimates from ecosystem models). -Proportion of predatory fishes in the ecosystem	Trophodynamics	Trophic-based indicators have been used to identify shifts in community and ecosystem structure. There are multiple forms and variations of these indicators and depending on the way they are estimated (based on catches, or based on the estimates of biomass from models) different interpretations and uses can be made. In general terms, they allow monitoring the species composition (in the catch or in the ecosystem) in terms of trophic positioning. The mean trophic level when derived using catch data from the fisheries (Pauly and Watson 2005) can be a useful metric to monitor ecosystem change. Generally, it is expected to decrease in response to fishing because fisheries tend to target species at higher trophic levels first. But other patterns (increases in the trophic level of catches) have also been observed, and therefore this indicator can also provide information on the changes of fishing and targeting practices in response to changes in fish abundances or market drivers. The mean trophic level of the community-level biomass can be derived with the biomass estimates from ecosystem models (Shannon et al. 2014). This indicator can be used to monitor the mean trophic level of different functional groups in the ecosystem (categorized in different trophic levels ranges, e.g. trophic level 3.0-3.25, 3.25-5, >4), and allows to identify changes in the ecosystem structure after the biomass removals from fisheries. These model-derived indicators across different trophic level groups can be used in combination to detect trophic cascades.	-Empirically estimated using fisheries dependent data -Model-derived

- Fishing in Balance (FIB) index. It relates the catches and the average trophic level in a given year to the catches and trophic level of an initial year, and the determines if the change in the mean trophic level is compatible with the trophic efficiency of the region.		The proportion of predatory fish measured as the estimated biomass of predatory functional groups is also used to monitor the potential effects of fishing on the functioning of marine foodwebs as their depletion can lead to trophic cascades (Shin and Shannon 2010). The FIB index provides indication whether fisheries are balance in ecological terms and not causing disruption to the functionality of the ecosystem (Pauly et al. 2000). When the FIP is constant (equal to zero) provides that a fishery is balanced, which means that all trophic level changes are matched by ecological equivalent changes in the catches. When FIP is <0 provides an indication that the effects of fishing, by the removal of excessive levels of biomass, are sufficient to compromise the functionality of the system, and a FIB >0 indicates either a bottom-up effect (e.g. increase in primary productivity) or an expansion of the fishery (increase in the diversity of species caught and or biomass of bycatch species) (Kleisner and Pauly 2011, Pauly and Lam 2016). All trophic based indicators rely heavily on diet analysis and modelling to determine the trophic level of the species. The collection of diet data can be expensive, and it is not collected as frequent as the catch or biomass data.	
Diversity based indicators. For example: -Shannon's index -Kempton's Q index adapted for ecosystem models	Diversity	Diversity-based indicators to monitor fishing impacts at the community and ecosystem level might be difficult to be applied as they are highly susceptible to sampling problems. Simple biodiversity indicators are preferred. For example, the Shannon's index is widely used as a measure of species diversity based on species richness and the relative proportions of species in a community (evenness), generally measures in terms of biomass(Shannon 1948). A decrease in the index indicates a decrease in evenness and richness. Kempton's Q index adapted for ecosystem models is a diversity-based index for assessing changes in the diversity and biomass of high trophic level species (trophic level >3) (Ainsworth and Pitcher 2006). A decrease in the index indicates a decrease in upper level evenness and richness.	-Empirically estimated using fisheries dependent data -Model-derived

5.3 Models to support the development of ecosystem indicators and exploring the consequences of alternative fisheries management scenarios to understand fishing impacts on the ecosystem

Compare to the ongoing development of empirically-based ecosystem indicators as part of the ongoing work of the IOTC SC, ecosystem models still need to be developed and matured as an additional tool for informing on the state of the ecosystem and inform potential fisheries management strategies in IOTC. Although some ecosystem-level goals could be in principle monitored using empirically driven indicators, without the need for models, the use of appropriate models is seen by many as an additional core tool to inform the implementation of the EAFM (Plagányi et al. 2012). The development and use of ecosystem models in the Indian Ocean to examine fishing effects on the ecosystem and explore the different harvest strategies and fisheries management options for tuna fisheries has been underused, and still needs to mature as a potential tool to be used in IOTC. The increasing use of these tools in the other tuna RFMOs (e.g. WCPFC and IOTC) (Allain V. et al. 2015, Griffiths et al. 2019) can serve as an example to incentivise this type of modelling work and further development of ecosystem models in IOTC.

Ecosystem models, of the type Ecopath with Ecosism or other size-based ecosystem models, continue to be used to inform “strategic” fisheries management. Ecosystem models are used as tools to provide insights about the larger picture of fisheries interacting with different components of the ecosystem, and used to provide context and direction to support fisheries management decision. This is in larger contrast with the more traditional single-species fisheries models which are developed with the precise role to provide tactical advice on specific management actions on a shorter time scale. In between these two tools, multi-species models are also being increasingly used as a tool to support both strategic and tactical fisheries decision making that accounts for ecosystem considerations (Hollowed et al. 2000, Plagányi et al. 2012). Multi-species models tend to focus on a limited number of species of the ecosystem, most likely target species and species interacting with the target species. In this way, they only include those components of the ecosystems needed to address management in question reducing the complexity of the ecosystem models. Multispecies models can provide multiple benefits including better estimates of natural mortality and recruitment, better understanding of variability in growth rates and the spawner-recruit relationships, alternative ways to formulate and evaluate biological reference points, and provide a framework for evaluating ecosystem properties (Hollowed et al. 2000).

Multispecies models also allow to address tactical management questions by connecting the species of interest and estimating their current abundances, exploitation rates and reference points for those set of connected species. Other emergent applications of these models include the prediction of future recruitment rates, which allow to estimate sustainable catches and the potential of rebuilding for overfished stocks, given different scenarios (changes in environmental factors or temperature, impact of closed areas on yield), as well as understand the impact of protecting a vulnerable species in the yield of others (Plagányi et al. 2012). The development and use of multispecies models and its multiple application in the context of tuna fisheries have also been poorly explored and are underdeveloped in all the tuna RFMOs including IOTC.

6. Identification of the key information gaps in enabling an ecosystem approach to tuna fisheries management in the Indian Ocean, including recommendations for addressing gaps through additional data and information gathering

The previous section identified the development of ecosystem indicators and models as two core requirements to inform several layers of the EAFM road map to operationalize this approach in the context of tuna fisheries. It also highlighted how their development and use as well as their multiple applications in the context of tuna fisheries have been poorly explored and are underdeveloped in IOTC. The few attempts to build ecosystem indicators and models in the Indian Ocean can be explained in part because they require and rely on a large number of fisheries, biological and ecological data, but also in part because until today IOTC has focused its vision and work on the conservation and management of species under its mandate (mostly tuna and tuna-like species) and rather from a single species perspective(Juan-Jordá et al. 2017).

Next, the data requirements to develop these tools with the goal of elucidating current data gaps in IOTC are briefly explained; and when relevant, what additional data and research are needed to develop these tools in IOTC are also highlighted.

Fishing impacts on the structure and dynamics of marine ecosystems are commonly described using ecological indicators that describe the total removals of fisheries in the ecosystem based on several metrics or attributes: removals in terms of weights, sizes, species composition and trophic levels (Table 4). Examining the total removals require reporting (or estimating) the landings and discards of each fishery by fleet, gear, species, year (or finer resolution) and area (the finer the resolution the better). It is of foremost important to monitor the total removals for each fishery individually and then combined across fisheries to examine the cumulative extents of the impacts. Logbook records from fishing vessels complemented with the observer programs are critical to get accurate estimates of total removals in terms of weights, numbers, sizes and species composition. Understanding the total removals in terms of trophic levels also requires knowing the trophic position of the species in the food web derived from diet analyses.

IOTC has a series of data collection and reporting requirements, through the adoption of several resolutions, for species under the IOTC agreement (major tuna species, billfishes and some neritic fish species) and other species not in the IOTC agreement (such as sharks, marine mammals, sea turtles, seabirds) that interact with IOTC fisheries. Of all the IOTC data requirements, the following list of data requirements are pivotal to develop many of the ecosystem indicators and models proposed in Table 4, and their reporting levels, completeness and quality will determine whether these core activities can be supported or not.

Main IOTC data requirement relevant for the development of ecosystem indicators and models proposed in Table 4:

- **Nominal catches for IOTC species and sharks.** These are highly aggregated nominal catches (in weight) including discards for all IOTC species and some pelagic sharks, disaggregated by species, fleet, gear, year and area (large areas).
- **Total bycatch for seabirds, marine turtles, marine mammals.** These data are highly aggregated statistics for all species combined or, where available, by species, estimated per fleet, gear and year for the whole IOTC area.
- **Catch-and-effort data for IOTC species and non-IOTC species.** These refers to the finer-scale data, usually from logbooks, reported by fleet, gear, species, year, month, and area (1^{o} grid areas for surface fishery, 5^{o} grid areas for longline

fisheries, and most convenient resolution for coastal fisheries). Information on the use of FADs and supply vessels is also collected.

- **Size data for IOTC species and sharks.** Individual body lengths of species sampled by the fishery, by fleet, gear, species, year, month and area (5 ^{o} grid areas).
- **Scientific observer data.** These include samples of the catches at-sea covering at least 5% of the fishing operations. IOTC has adopted a Regional Observer Scheme setting out the minimum recording requirements and timing for implementation and reporting by the CPCs.

The quality and completeness of these datasets vary greatly by fleet, species, area and time period. In a nutshell, for the species under the IOTC mandate (major tuna species, billfishes and some neritic fish species), the reporting coverage tends to be higher for nominal catch, followed by catch-and-effort, while size data reporting levels are way below the levels of the nominal and catch-and-effort data sets (IOTC Secretariat 2018). Overall, the nominal catches recorded by purse seine fisheries (which contribute to 26% of the catches of IOTC species), and pole and line fisheries (which contribute 7% to the total catch) in the IOTC database are considered of fair to good quality, particularly for the tropical and temperate tuna species. The nominal catches recorded by gillnet fisheries (which contribute 32% to the total catch) are considered of poor to fair quality, and the nominal catches recorded for longline fisheries (which contribute 13% to the total catch) were considered of good quality until the late 1980s but since then of fair quality. The catches of other gears such as handline, trolling, coastal gillnets and other minor artisanal fisheries (which contribute 21% to the total catch) are considered of poor quality (IOTC Secretariat 2018). The current areas used for reporting the nominal catches are very coarse (broadly by two areas: East and West Indian Ocean). This spatial resolution in the nominal catches hinders the development of ecosystem indicators that require more detail spatial resolutions. The discards levels are also very poorly reported in most fisheries and fleets (IOTC Secretariat 2018). The discards are believed to be high for fisheries using longlines and oceanic gillnets, moderate for purse seine fisheries (mainly setting on FADs) and low in pole and line fisheries. In addition, the coverage of the nominal catch, catch-effort and size datasets varies by species groups. The catch-and-effort and size data is particularly poor for the neritic species and billfishes (IOTC Secretariat 2018).

For the species not under the IOTC mandate (sharks, seabirds, marine mammals, sea turtles, and some teleost fishes), the reporting is very low and of poor quality, compared to the levels reported for the IOTC species (IOTC 2018b, IOTC Secretariat 2018). Few useful statistics exist for sharks, seabirds, sea turtles, and other non-IOTC species caught by IOTC fleets targeting tuna or tuna-like species. The nominal catch data for sharks has been historically low, discards are rarely reported, catches are aggregated to family or higher taxonomic level, distribution of catches are unknown, effort levels unknown, just to name a few of the main issues. The reporting rates for sharks have increased in recent years following the adoption of new measures, as well as the resolution of the data (e.g. increased proportion of reported shark catches are now provided at the species/genus level), but the overall quality of the statistics remain still poor even hindering the fishery stock assessments for the most caught shark species or most vulnerable species (IOTC 2018b, IOTC Secretariat 2018). It is very similar for marine mammal, marine turtles and seabirds. Data reports for these taxonomic groups are very poor, information is too patchy, lacking temporal and spatial resolution, or basically not submitted at all to the IOTC Secretariat following reporting standards. Complicating matters, the data collection and reporting requirements for non-IOTC species, through the adoption of resolutions (in particular Resolution 15-01) can vary by gear (Garcia and Herrera 2018). For example, the reporting of one species may be required by one gear, and not by other, and if required might be voluntary for one gear and an obligation for another. Although the current resolutions do not preclude IOTC CPCs from collecting complete information across all gears and species, this is rarely the case. These fragmented resolutions in terms of species coverage and CPCs responsibilities results in that there is not a single non-IOTC species or species group for which all the fisheries are obliged to report catches and discards (Garcia and Herrera 2018). Furthermore, estimation of many of the proposed ecosystem indicators rely on fisheries data that have explicit spatial information to support area-based ecosystem indicators and the regionalization of ecosystem assessments and models. The spatial resolution for the large majority of IOTC and non-IOTC species is incomplete or of poor quality hampering any area-based integrated ecosystem assessments.

Furthermore, despite the Regional Observer Scheme is in place since 2011, most IOTC CPCs have failed systematically to provide to the IOTC Secretariat with observers reports from which catch levels of the non-IOTC species can be properly assessed and evaluated to estimate total bycatch and total bycatch rates in the IOTC convention area (IOTC 2018b, IOTC Secretariat 2018). Regardless the detailed data that might be collected by observer programs by each individual CPCs, the data reported to the IOTC Secretariat for the Regional Observer Scheme remains poor and lacks the scientific rigor to be used in any type of bycatch or ecosystem assessments (Garcia and Herrera 2018). Furthermore, most IOTC fleets not even comply with the minima levels (5% observer coverage) adopted by IOTC, and the 5% level of coverage is below the minimum level recommended by the scientific community, which recommends at least 20% coverage (Wolfaardt 2016). Not all fisheries fail to collect or report data requirement at levels or above those required by IOTC. In 2016, the fleets under the SIOTI FIP, including the majority of European Union (EU), Seychelles and Mauritius-flagged purse seine vessels fishing for pelagic tunas in the Indian Ocean had on average a 27% of observer coverage, which is above the minimum level adopted by IOTC. However, as 2018, the only observer data held by the IOTC Secretariat consisted of datasets for the EU purse seiners and Japanese longliners, yet these datasets covered a limited number of years (Garcia and Herrera 2018). The poor reporting levels and very low levels of observer coverage implemented by IOTC CPS is hampering any attempt to use the observer data under the Regional Observer Scheme to estimate bycatch levels or contribute to the estimations of total removals of any fisheries (or all fisheries combined), thus hindering the development of ecosystem indicators, ecosystem models and ecosystem assessments in the IOTC convention area.

Despite IOTC adopting multiple resolutions stablishing the data collection and reporting requirements of both the IOTC and non-IOTC species, the reported data for the main IOTC species is considered of fair to good quality (greatly varying by gear, fleet, species and area), and for the non-IOTC species remains of poor to fair quality (greatly varying by gear, fleet, species and area). Despite the good practices of some fleets, the overall poor reporting by the large majority of the fleets and the resultant incompleteness and poor quality of the data hampers the work of IOTC to estimate total removals (retained and discarded levels of catches) of both the IOTC and non-IOTC species across fisheries using the current data available in support of developing ecosystem indicators and robust ecosystem models and assessments.

The development of robust ecosystem models, such as the trophic-based Ecopath with Ecosym mode or other ecosystem models (e.g. size-based ecosystem model), requires feeding them with a large number of biological, ecological and fisheries datasets. Here, the Ecopath and Ecosim models are used as an example to highlight the type of biological, ecological and fisheries data that are usually needed to build these models. The Ecopath model, which provides a static representation of energy flows in a food web, first, it requires to establish the main ecosystem components or functional groups in the ecosystem, and second for each of them it requires values for three of the four following basic parameters: biomass across the model region, production/biomass ratio, consumption/biomass ratio (describing the energy requirements of predators and the standing biomass of their pray) or ecotrophic efficiency (fraction of the total production of the functional group utilized by the systems) (Heymans et al. 2016). Generally, the biomass estimates for the exploited species in the model can be obtained from the existing single specie stock assessment models and for the other un-exploited groups from independent surveys. The production/biomass ratio and the cosumption/biomass ratio can be obtained from bioenergetic models and laboratory experiments, and if not available there are some indirect proxies that can be obtained from established empirical equations (Heymans et al. 2016). The total catch (retained and discarded) of the fisheries accounted in the ecosystem model is also a critical data input, which further emphasizes the value of the observer data, which unlike the more commonly collected logbook data, provides information on bycatch and discarded species, thus contributing to a more complete understanding of ecosystem dynamics. Furthermore, a diet matrix is also a critical input in the ecosystem models in order to establish the trophic linkages for all predatory-prey interactions or functional groups included in the model. Furthermore, the Ecosim model, which allows forecasting of ecosystem responses to perturbations (fishing effort or climate perturbations) over time, also requires to be calibrated using time series data consisting of biomass and/or fishing mortality and/or catch for all functional groups included in the model. This time series can be obtained from the existing single stock assessment models or other the more traditional fishery statistics collected by IOTC (catches, discards). Again, it further scores the value of having quality fisheries data to build and run these ecosystem models. It is not surprising, a common shortcoming of these models has been the insufficient or unreliable fisheries and biological data for parameterizing and calibrating the models, which at the end it can compromise their usefulness for ecological and tactical fisheries application (Plagányi et al. 2012).

The advances done in ecosystem modelling in the Pacific Ocean (in the WCPFC and IATTC) are the result of decades of region-specific biological, ecological and fisheries research data which now are being used to build ecosystem models to examine the impacts of fisheries and multiple harvest strategies on the structure and dynamics of marine ecosystems (Allain V. et al. 2015, Griffiths et al. 2019, Griffiths and Fuller 2019). The existing ecosystem models have been supported by a combination of high-quality stock assessment model out data for many of the targeted and bycatch species, reliable catch time series for non-targeted species and reliable estimates for forage species and large phytoplankton. The well-designed observer programmes to monitor catches (and discards) for a wide range of species caught in the WCPFC and IATTC pelagic fisheries (at least for some of their fisheries) have also been crucial to inform these ecosystem models. All the fisheries included in the ecosystem models developed in the Pacific Ocean (Allain V. et al. 2015, Griffiths et al. 2019, Griffiths and Fuller 2019) have relatively good estimates of the annual landings and discards for the most important species, usually derived from vessel logbook, and validated or estimated using the relatively good scientific observer data collected in these regions. The Pacific Ocean has also a relatively robust history of trophic level studies needed to construct the diet matrix to establish the trophic linkages for all predatory-prey interactions or functional groups established in the models (Olson et al. 2016).

In comparison, the research on the trophic ecology of IOTC species and others relevant species in the Indian Ocean still needs to provide the detail that exist for the Pacific Ocean (Olson et al. 2016). The IOTC would need to invest into a more comprehensive approach, combining stomach contents data, trophic tracers such as stable isotopic analysis and genetic studies to get a better understanding of the trophic pathways that support commercially important IOTC species, and provide the trophic knowledge to support the development of ecosystem studies (Olson et al. 2016). There is a critical need to conduct trophic studies for not only the commercially important IOTC species (mostly tunas and billfishes) but also on other species such as sharks, neritic tuna species, and their preys. The collection of trophic samples to support these analyses could be done by observers and the collaboration with IOTC CPCs.

If robust ecosystem models were to be developed in the Indian Ocean, they would need to be supported by the combination and the improvement of the following data and research avenues in IOTC: (1) high-quality stock assessment model output data for the exploited fish species (the targeted species and if possible the most relevant bycatch species); (2) reliable catch (retained catches and discards) time series for non-targeted species for each major fishery; (3) reliable estimates for forage species and large phytoplankton; (4) a comprehensive research program to improve the knowledge on the trophic ecology of key species as needed included in the model; (5) experimental studies for some of the large pelagic fishes to determine the consumption/biomass ratio (Q/B), which is one of the most influential parameters in ecosystem models (at least the ecopath models).

This study also stresses the need for IOTC CPCs to improve data collection and reporting for both IOTC species (mostly large tunas, billfishes and some neritic species) and non-IOTC species considered bycatch species of tuna fisheries (sharks, sea turtles, marine mammals, seabirds and other teleost fishes). Among the four major fisheries in IOTC, the paucity of data from gillnet fisheries is greatly impacting the rigor of all the work of the Scientific committee from single stock assessments, to bycatch analysis and the development of ecosystem indicators and models. Gillnet fisheries remain inadequately monitored despite its large contribution to the total IOTC catches, and like the rest of fisheries, gillnet fisheries need to be effectively managed and monitored.

IOTC also needs to improve the data reporting requirement and dissemination standards to allow for joint analysis across fisheries, fleets and species which are necessary to get a broader integrative picture of ecosystem impacts from the cumulative and individual impacts of each fishery. There is wide consensus that the observer programs are crucial to provide information on bycatch and discarded species, unlike the more commonly collected logbook data, thus contributing to a more complete understanding of ecosystem dynamics. It is important that IOTC works towards ensuring that at least the minimum requirements, especially the minimum observer coverage level (5%), are fulfilled by all IOTC CPCs, and in addition, contemplate to increase these minimum standards to at least 20% following scientific advice. Unless the core data collection are improved (nominal catch including discards, catch and effort, size data and observer data), the IOTC Scientific Committee will be unable to respond to Commission requests and work on the development of ecosystem indicators and ecosystem models to inform integrative ecosystem assessments of the overall state of the ecosystem, thus limiting the quality and robustness of its ecosystem advice regarding ecosystem impacts on the food web for the Commission.

7. Outline of options for ecosystem-based management strategies for tuna fisheries in the Indian Ocean, specifically addressing measures specific to purse-seine gear as well as global measures, and including provisions for strategy evaluation

Accounting for gear interactions, species interactions and climate interactions in a tactical fisheries management context requires that harvest strategies are planned and chosen making explicit connection to the interconnectedness of gears, species and climate in marine ecosystems. Until recently these connections with the harvest strategies and the management system in general have been relatively rare (Plagányi et al. 2012, Kvamsdal et al. 2016). Yet, as most fisheries are approaching their theoretical sustainable limits, as it is the case of tuna fisheries under the five tuna RFMOS with most stocks being fished at maximum sustainable levels (Juan-Jordá et al. 2011, ISSF 2018), and recognizing that there are not many unexplored fisheries to be developed, interactions among species, gears and climate will be increasingly recognized as an important element to take into account in future fisheries management decisions (National Research Council 2006).

In the context of tuna fisheries where multiple gears catch a mixed of tunas, billfishes, shark and other bycatch species, the harvest strategies chosen would need to recognize at least these gear and species interconnectedness. Management strategy evaluation, which in the broad sense involves assessing the consequences of multiple harvest strategies, can be important to elucidate the options, provide the choices and layout the trade-offs across a range of management objectives, but at the end the allocation of trade-offs and choice of the most optimum harvest strategy will be a multilateral policy decision. Ecosystem-driven scientific research and knowledge can only inform the process to achieve optimum solutions.

Next, a list of actions and research activities is proposed that may facilitate ecosystem based management in tuna fisheries in IOTC. These list of actions and research activities aim to advance our understanding of ecosystem processes and basic ecosystem science, as well as to support the improvement of methods and tools to design ecosystem-based harvest strategies to support ecosystem based strategic and tactical fisheries management.

- **Enhance fishery data collection.** IOTC should ensure compliance, and enhance the minimum requirements, in the collection of basic fisheries statistics (catch, effort and size data). Multiple data gaps exist especially for gillnet fisheries.
- **Enhance spatially explicit fishery data collection.** The fishery statistics reported to IOTC should be spatially explicit for IOTC species and other species interacting with IOTC fisheries (whether retained and non-retained by the fisheries). Currently catch, effort and size data with explicit spatial information (5^o x 5^o grid) of relatively good quality is only available for five IOTC fish species (4 tuna species and one billfish).
- **Enhance research studies to elucidate the spatial dynamics of the marine ecosystem.** The strength of interactions among species (but also gears) may vary in space. Research is needed to identify ecologically relevant ecosystem boundaries in the pelagic environment that can be used to set the boundaries to inform ecosystem assessments and modelling and structure ecosystem information and advice.
- **Enhance data collection and research on the basic biology and trophic ecology of species to monitor fishing impacts on foodwebs.** Research on specific life history traits such as growth and age and the life history strategies of species interacting with IOTC species is crucial information to support the development of ecosystem models. Furthermore, studies on fish diet, feeding ecology and food habits are also needed to

support the development of ecosystem models and better understand trophic interactions and foodweb dynamics in marine ecosystems.

- **Enhance FAD research and management in purse seine fisheries.** More data needs to be collected on FAD types and structure and usage patterns to better understand changes in fishing capacity of purse seiners, and the likely impacts of FADs on major targeted and non-targeted species incidentally caught, and likely impacts on the broader ecosystem structure and function. Promote research on procedures to mitigate the impacts of FAD, e.g. build effective biodegradable FADs and support their uses to reduce incidental catches.
- **Further support the development of empirically based ecosystem indicators relying on fisheries dependent data.** Empirically-based ecosystem indicators rely on fisheries statistics derived from logbooks and observer programs. Fisheries data, and more specifically the observer data collected by IOTC CPCs have been mostly used to quantify and monitory bycatch rates in their fisheries. IOTC scientific community could further explore the use of observer data to support the development of ecosystem indicators (as proposed in Table 4), as well as find ways to support joint collaborative analysis among CPCs to share confidential data, and thus develop ecosystem indicators and assessments to monitor the cumulative impacts of fisheries on different components of ecosystem.
- **Further support the development of multispecies, food web and ecosystem models and their use to evaluate alternative management scenarios.** Ecosystem model outputs can also be used to develop model-derived ecosystem indicators to monitor and assess the past and current state of the ecosystem, elucidate potential regime shifts, and also evaluate the effectiveness of previous management actions and evaluate future management scenarios.
- **Support the creation of interdisciplinary working groups to inform and develop the scenarios needed to test the proposed management actions.** Building multispecies and ecosystem models and setting realistic scenarios for testing fisheries management actions will require interdisciplinary working groups experts on the fisheries, gears, species and area on question, and the integration and synthesis of information from many sources. These interdisciplinary working group would also need to communicate effectively with fisheries managers to identify important trade-offs that should be considered when creating the models and the scenarios.
- **Invest in research to find better ways and tools to visualize trade-offs and different scenarios as decision support tools.** For example, ecosystem models can be used to evaluate alternative management scenarios. In principle, the impact of different effort and catch quotas or limits for the different fishing gears (not just purse seine fisheries), the effect of different temporal and spatial closures, the interactions among gear types, all these elements could be tested for their potential impacts on the ecosystems. There is a need for better visualization tools to visualize these different options and scenarios so managers can discuss and understand the management implications and the trade-offs involved.
- **Develop multi-species and multi-gear harvest strategies that account for gear and species interactions and food web dynamics.** The management scenarios developed in the multispecies and ecosystem models may be used to inform the choice of multi-species and multi-gear harvest strategies since the different management scenarios can elucidate the trade-offs emerging in a multi-species and gear context. The challenge for

managers will be to assign different probabilities and weights to the range of scenarios to capture existing uncertainties about foodweb dynamics and responses of the food webs to various fishing strategies (National Research Council 2006).

- **The adoption of ecosystem-level management objectives**. It is essential IOTC adopts clear ecosystem-based objectives that are operational. For example, a management strategy evaluation needs to have pre-established management objectives in order to evaluate the performance of multiple ecosystem-based harvest strategies relative to those predefined ecosystem-level objectives. This emphasizes the need to manage fisheries holistically focusing on key gear interactions, species interaction and climate interaction when or if deem relevant. Ecosystem risk assessments can be used to identify those high-risk gears, species, and climate interactions that may deserve further attention and that may need to be connected better to the management system.

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