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

Maria José Juan-Jordá[1]

Abstract

The Sustainable Indian Ocean Tuna Initiative (SIOTI) is a large-scale Fishery Improvement Project 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 reviews the key risk areas associated with the impact of purse seine fisheries on the marine ecosystems (including impacts on non-targeted species, habitats and the structure and function of ecosystems) in the Indian Ocean. Specifically, it focuses on the role of ecosystem indicators and ecosystem models as tools to monitor the impacts of fisheries on the structure and function of marine ecosystems, and identifying the key information gaps hindering the development of these tools. It also provides recommendations, options for progress, and highlights relevant ongoing activities to better account for the impacts of purse seine tuna fishing on marine ecosystems and provides an outline of options for supporting the development of ecosystem-based management strategies for tuna fisheries in the Indian Ocean. Ultimately, this study aims to inform 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, bycatch, habitats. ecosystem structure and function, risk assessments, ecosystem models, ecosystem indicators, stakeholder participation, ecosystem-based management strategies

[1] Consultant, Madrid, SPAIN. Email address of corresponding author: mjuanjorda@gmail.com

Table of contents

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 authorized 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, formalized 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 recognizes 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.

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.

1.1. Objectives

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 identifies several research avenues and options that may facilitate its operationalization. It reviews the key risk areas associated with the impact of purse seine fisheries on the marine ecosystems (including impacts on non-targeted species, habitats and the structure and function of ecosystems) in the Indian Ocean, and identifies potential options to improve fisheries management that explicitly accounts for impacts of fisheries on the structure and function of marine ecosystems. Ultimately, it 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.

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 on the structure and function of marine ecosystem in the Indian Ocean. This includes a review of ecosystem indicator options.
- Identification of the key information gaps in enabling the development of tools such as ecosystem indicators and ecosystem models in the Indian Ocean, with recommendations for addressing gaps through additional data and information gathering.
- Final recommendations, options for progress, and relevant ongoing activities to support EAFM implementation in IOTC.
- Final recommendations, options for progress and relevant ongoing activities to better account for the impacts of purse seine tuna fishing on marine ecosystems, including on (a) non-targeted species, (b) habitats and (c) the structure and function of ecosystems.
- Final recommendations and options for supporting the development of ecosystem-based management strategies for tuna fisheries in the Indian Ocean, specifically addressing measures specific to purse-seine gear as well as global measures, including provisions for strategy evaluation.

1.2. What is EAFM implementation in the context of tuna RFMOs?

Addressing the core requirements of an EAFM requires at first to answer the simple question of what EAFM means in the context of tuna RFMOs, and clarify how this term is going to be 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, including relevant ecosystem interactions

(interactions among gears, species, the environment and socio-economic factors) (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 EAFM 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 EAFM implementation layers may already be tackled and started using the available knowledge and ecosystem science in IOTC. In fact, partial EAFM implementation is already happening in IOTC (see Section 3 in this report). 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 research programs to improve understanding of ecosystem processes in order to facilitate EAFM implementation (e.g. program to understand impacts of climate change on species of interest, program to identify habitats of ecological significance for species of interest). Similarly, this process of EAFM implementation would also need to be highly consultative, interactive and participatory by involving the Member States in IOTC and other interested stakeholders such as the private sector in all the layers of implementation.

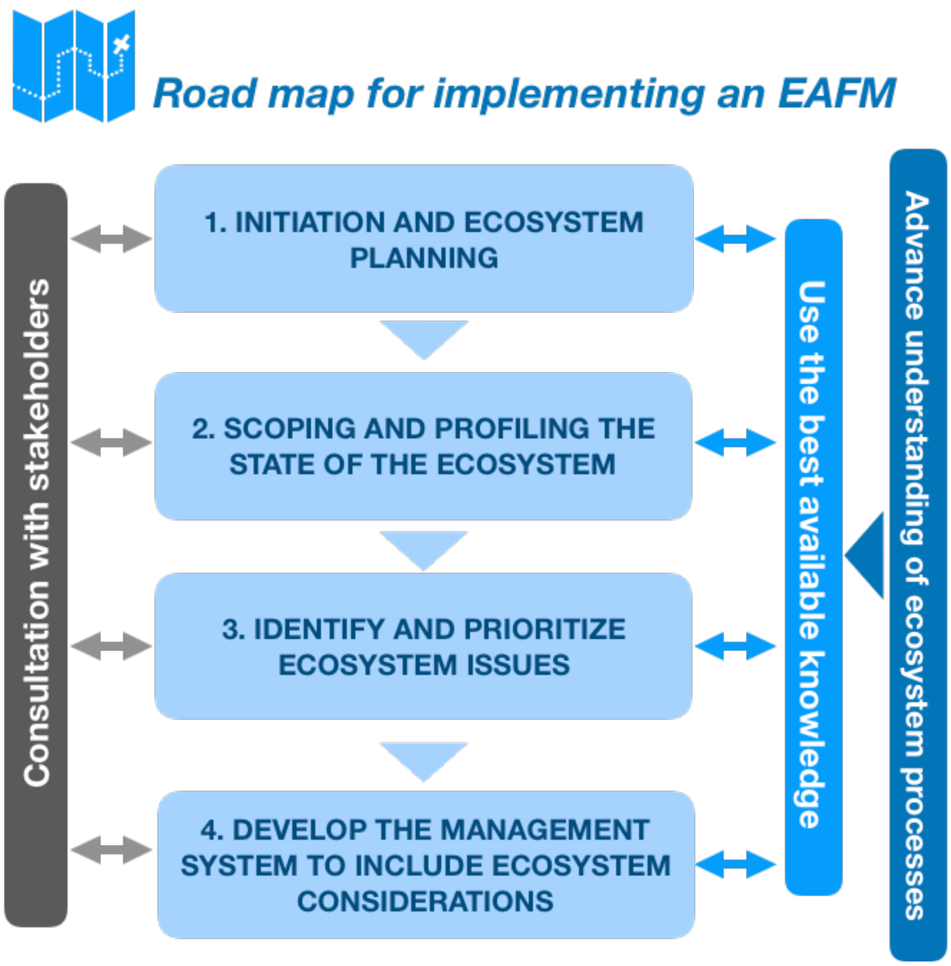


Figure1. Generalized road map illustrating the major steps required to implement an EAFM. Adapted from http://www.fao.org/fishery/eaf-net/en and Fletcher and Bianchi (2014).

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.

EAFM Implementation in the open oceans lags behind national implementations - Several international legal agreements and guidelines, such as the Convention on Biological Diversity (CBD 2004), the UN Fish Stocks Agreement (United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks), Reykjavik declaration on Responsible Fisheries in the Marine Ecosystem (2001), and FAO Code of Conduct for Responsible Fisheries (FAO 1995) have set the standards and ecosystem principles to guide the implementation of an 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.

Three case studies with proven progress in implementing EAFM - 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 (Table 2) in developing useful ecosystem information, science and products to inform ecosystem-based fisheries management were summarized. The transferability of these best practices and lessons in the context of fisheries management of tuna and like species in the IOTC was also discussed. Lessons learnt (Table 3) along the way by these organizations when linking their different ecosystem products and ecosystem advice into fisheries management were also highlighted which possibly could be taken into account when IOTC develops its ecosystem-related research and activities.

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:

(1) 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.
(2) The existence and use of sound scientific knowledge and ecosystem science to assess and characterize the state of the ecosystem and the impacts of fisheries (and other pressures such as climate change) on the state of the ecosystems,
(3) 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 explicit reference to the principles of the precautionary approach or principles governing the EAFM. The IOTC has not articulated an EAFM vision and an EAFM 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 EAFM 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 plan has 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 plan 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 been focused on addressing single species science and management needs, 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 mechanisms (or expand the existing mechanism) to enhance the dialogue between scientists and managers, as well as the private sector, 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 Member States do not always ensure or cover a wide range of ecosystem aspects (see further details in section 4-5-6 of this report) 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 Member States have not complied with this minimum requirement (IOTC 2018a). IOTC may consider increasing the level of observer coverage to 100% (using a combination of human observers and electronic monitoring system -EMS) in all IOTC fisheries as part of its Regional Observer Scheme. The adoption of a high observer coverage would allow more precise estimates of ecosystem impacts by type of fisheries, as well as the assessment of cumulative impacts.

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 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).	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. 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 IOTC Ecoregion workshop took place in August 2019 prior to the WPEB15 meeting where the outcomes of the workshop were presented (see more details in Section 3). Following the advice of the Ecoregion workshop, IOTC may consider using and testing the usefulness of the IOTC draft ecoregions to structure and provide integrated ecosystem-based advice.
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 main pressures on and the state of the IOTC ecosystem components relevant to tuna fisheries, by monitoring a set of selected ecosystem indicators (see more details in Section 3). The IOTC may continue supporting the development of the IOTC ecosystem report card.

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 quantification of total ecosystem production 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 and are typically based on a productivity-susceptibility analysis) 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 prioritized to inform fisheries management (see more details in Section 3). IOTC may consider using a broader range of risk assessments including EASI-Fish type ERAs, climate risk assessments on species and fishing communities, habitat risk assessments, social vulnerability analysis, among others.
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 improving its science-based knowledge and use other management tools such as 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 significance and of potential concern for IOTC species and threatened species interacting with IOTC fisheries, 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	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

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.	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. IOTC may consider to support the proposal for the development of a ocean-climate web page (Marsac, 2018). The proposal is being subject to a scoping study, to assess its feasibility, under the supervision of the IOTC secretariat.

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 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 and mapping of the main stakeholders to be involved at each step in the whole process, as well as the establishment of a communication channel, should also be done at the initial planning stages of the process (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 explicit reference to the main principles of the EAFM. IOTC has not drafted or adopted an EAFM 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 EAFM 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 scientific community and between Scientific Committee and the Commission. 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.

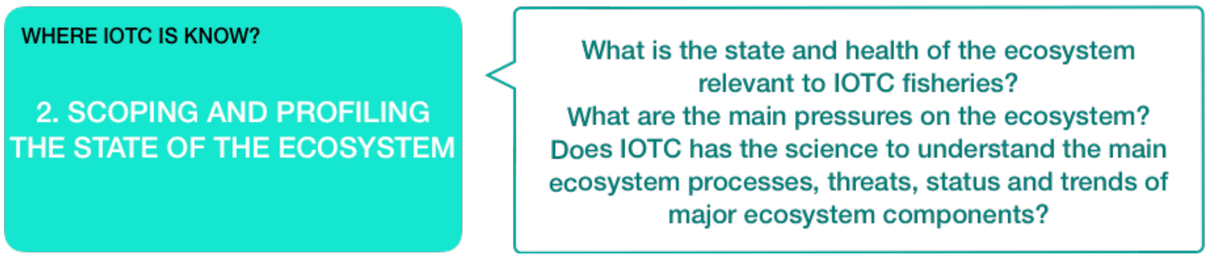
The existence of a clear entity to be responsible and in charge of planning, advising and coordinating EAFM relevant entities is recognized as a best practice. In IOTC, the Working Party on Bycatch was created in 2005, and in 2007 this Working Party was renamed as the WP on Ecosystem and Bycatch and 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 IOTC Working Group (as an Ecosystem Plan Team or Advisory Team) composed of a wide range of experts with expertise in natural and social sciences and the policy, science and management interface, including scientists and managers, could have the role of guiding the EAFM process, and facilitate and make more efficient the implementation of EAFM in IOTC. The role of this newly created Working Group could be tasked 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 finding ways to integrate and connect better all these existing research and advice with fisheries management to provide guidance to the Commission.

IOTC has not formally developed and adopted an operational EAFM plan, which is a tool that aims to link higher level EAFM policies and objectives into actions (Staples et al. 2014). EAFM plans can 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 EAFM plan in the IOTC area as a high priority to guide the development of ecosystem research or ecosystem considerations and ecosystem management advice to address 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 this 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 addressing single species research and management for main IOTC targeted species, and there has been no dedicated time to address other issues such as bycatch, or other relevant EAFM related research and advice can also be channeled into fisheries management decisions. The IOTC may consider creating similar mechanisms (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.

Furthermore the identification of spatial units or regions that make ecological sense can be also an important element of effective ecosystem planning to support the production of better integrated advice. The identification of spatial units that make ecological sense is 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 ecosystem report cards, inform large-scale ecological modelling and guide ecosystem-based advice (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 area (Juan-Jordá et al. 2019). This project developed and tested an evaluation criteria 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 in 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 also 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). The IOTC ecoregion workshop took place the 30th of August- 1st of September prior to the WPEB15 meeting in La Reunion. The ecoregion final workshop report is under preparation.

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



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 it 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, has worked 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 integrated 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 a better 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 worked intersessional to develop and present at the WPEB15 meeting some indicator-based assessments for each ecosystem component in the reporting framework. At the WPEB15 meeting, each team proposed some candidate indicators that would be the most suitable and representative for monitoring the status of each component, and documented their process towards their development of an ecosystem assessment report which will be used to inform the ecosystem report card for the IOTC region. The teams will continue working intersessional and present their progress at the WPEB16. All the assessment reports reviewed by the WPEB 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.

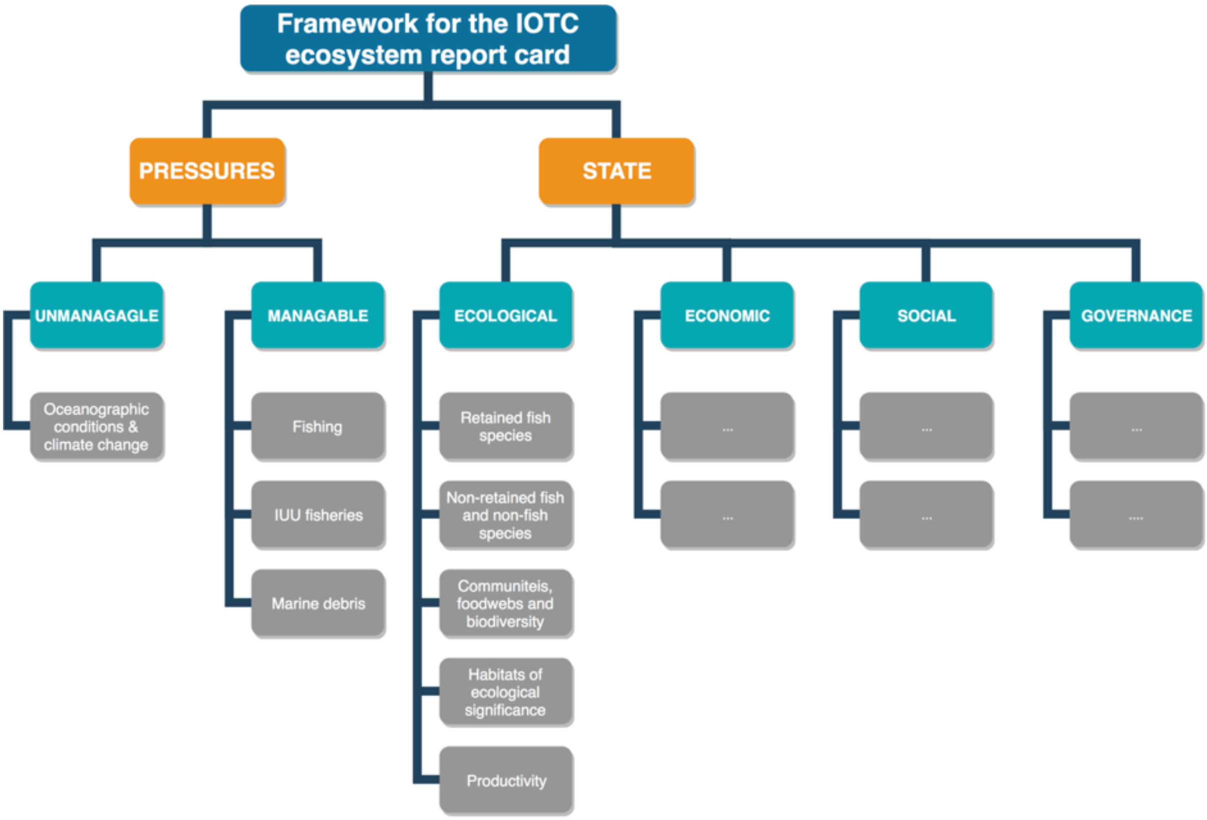


Figure 2. Framework for the IOTC ecosystem report card (IOTC–WPEB14 2018).

The robustness and quality the ecosystem report cards will depend on the quality of the assessments produced for each of its ecosystem components (Figure 2), and how the WPEB makes progress on selecting, developing and monitoring indicators for each ecosystem component. The reality is that the work conducted by the WPEB depends on its own priorities and 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 Member States have hindered any attempts 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 ecological significance of species or 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?

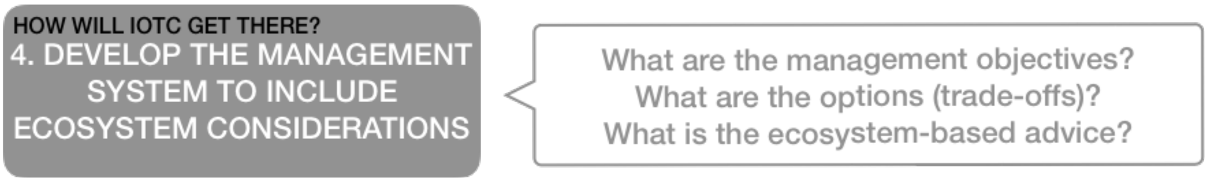
The identification and prioritization implementation step is mostly about identifying those relevant issues specific to IOTC fisheries and species to inform the risk assessments. For practical reasons, issues can be broken down into (1) ecological assets (e.g. species, threatened species, trophic relationships, 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). Yet, it remains to be seen how the Commission will proceed in developing the social and economic aspects of IOTC fisheries.

In this implementation 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 may include climate vulnerability assessments, fishing community vulnerability assessment to system changes, habitat risk assessments and the most traditional ecological risk assessments which focus 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 was conducted (Williams et al. 2018). A comprehensive ecological risk assessment 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 scientific community has focused on developing ecological risk assessments 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 to species and fishing communities, and others type of 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 implementation step allows to identify what issues are most at risk and that require direct intervention. The next implementation 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 in 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 of the main IOTC species. 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 (if 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 (as part of the IOTC ecosystem report card) as well as support the development of 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.

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 different type of species and have 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 in four types of impacts:
(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
(4) impacts on the structure and function of marine ecosystems.

This section briefly summarizes each of these four broad impacts in the context of IOTC fisheries, and in particular purse seine fisheries, yet it focuses on reviewing and summarizing the existing evidence on the impact of IOTC tuna fisheries on the structure and function of marine ecosystems (the fourth type of impact). An attempt is also made to link these four broad impacts of fishing to the MSC Fisheries Standard and its performance indicators. 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

The impact of a fishery on the target stocks/species is covered under P1 of the MSC Fishery Standard.

Fishing irrespective of the gear used reduces the biomass and alters the size structure of the targeted species. When a fishery (or all fisheries combined) catches too many fish of a particular species it can impair the reproductive potential of the species leading to recruitment overfishing. Additional, when a fishery (or all fisheries combined) catches 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.

The not-targeted species caught by a fishery are covered under P2 of the MSC Fishery Standard under the component of Primary Species (P2.1), Secondary Species (P2.2) and Endangered, threatened or Protected (ETP) Species (P2.3).

Fishing gears may capture accidentally unwanted or non-targeted species, which can include species that might be or not already fishery assessed or species that are considered endangered, threatened and protected species such as some sharks and sea turtles. In this study, the catch of non-targeted species is broadly referred as bycatch. This bycatch 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. In the same way as the targeted species, fishing can alter the biomass and size structure 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, and are released alive relatively easily (Amande et al. 2008, Ruiz et al. 2018).

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 the catches of non-target species remain sustainable . 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, some of the fleets 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). For example, many of the SIOTI partners comply with the aspects of the Code of Good Practices for Responsible Tuna Purse Seining, developed and agreed by OPAGAC and ANAVAC. SIOTI partners would benefit from having a share code of good practices that it could be applied by all the partners (Nieblas and SIOTI, 2019). The good practices used by some of the SIOTI fleets include the use of non-entangling FADs as well as the application of release operations for FAD-associated vulnerable fauna.

It is also important to monitor the contribution of each fishery to the overall levels of bycatch mortality. 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 relative to the other major fishing gears (gillnet, longline, driftnet). 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

Fishing impacts on habitats are covered under P2 of the MSC Fishery Standard under the component of Habitats (P2.4). The component of Habitat under the MSC Fishery Standard refers to the impacts of a fishery on the "habitat structure, biological diversity and function". It is not clear under the MSC Fishery Standard and Guidance whether this habitat component is only restricted to cover the impact of fisheries on the demersal and coastal habitats (e.g. seamounts, coral reefs) or if also covers the impacts of fisheries on the pelagic habitats of the species which might be used as essential habitats for reproduction, feeding grounds or migratory corridors. Understanding the meaning of the component of Habitat (P2.4), and its practice, is important particularly in the context of tuna fisheries.

Impacts of fisheries on habitats of ecological significance for species - Understanding better habitat utilization and identifying habitats of ecological significance for species and how fisheries might interact and affect them is 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 impacting their natural habitats, 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 and habitat utilization 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.

It is not entirely clear whether the potential impact of FADs on the behavior and large-scale movements and habitat utilization of tunas, as well as their diet, condition, growth and reproductive success should be reviewed under the component of Habitats (P2.4) or Ecosystems (P2.5) of the MSC Fishery Standard remains unclear. Although the impact of FAD fishing on the behavior and large-scale movements and habitat utilization of tunas, have often been reviewed under the component of Ecosystem (P2.5) of the MSC Fishery Standard, it might fit better under the component of Habitats (PI2.4) given the broad definition of the term “habitat” in the MSC Fishery Standard. This would leave the component of Ecosystem (P2.5) to be focused on understanding the Outcome, Management and Information regarding the impacts of fisheries on the “structure and function of marine ecosystems”.

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). In the MSC fishery standards, the impacts of ghost fishing on species (target or non-target) would be covered under P1 (regarding target species) or under P2 (P2.1,2.2 or 2.3) depending if the species are considered primary, secondary or ETP species.

Impacts of marine debris on habitats - In addition, 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). This impact of fisheries on the demersal habitats or coastal habitats of ecological significance are clearly covered under the component of Habitats (P2.4) of the MSC Fishery Standard.

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

Fishing can also have an impact on the "function and structure of marine ecosystems", which is covered under the component of Ecosystem (P2.5) of the MSC Fishery Standards.

There is increasing evidence that the abundance and composition of species (both targeted and non-targeted species of a fishery) is changing as a result of fishing. Fishing by removing large amounts of biomass and reducing the abundance of multiple species in the food web can alter a wide range of biological interaction causing changes in the predatory-prey interactions and cascading effects in the food web (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 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 reliably 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.

Three working hypotheses of how fishing may affect food webs - Over time there has been three working hypothesis to explain how fishing affects food webs:

(1) The decline in the mean trophic level of the catches, resulting from fisheries gradually changing their target larger 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).

(2) 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.

(3) 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 Hawaian 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.

Documented large scale changes of the impacts of fishing on the food web structure and function in the Indian 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.

Documented large scale changes of the impacts of fishing on the food web structure and function in the North Pacific Ocean - 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.

Documented large scale changes of the impacts of fishing on the food web structure and function in the West and Central Tropical Pacific - 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.

Documented large scale changes of the impacts of fishing on the food web structure and function in the Eastern Tropical Pacific - 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 impacts of purse seine tuna fishing on the structure and function of marine ecosystems in the Indian Ocean, including a review of ecosystem indicator options.

There is increasing evidence that fishing is changing species relationships and food web 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 food web 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.

Core elements to better monitor impacts of fisheries on the structure and function of marine ecosystem - Below, three core elements to support EAFM implementation that stem from the impacts of fisheries, including purse seiners and others, on the structure and function of marine ecosystems are briefly presented:

(1) 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.
(2) 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.
(3) 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 (Implementation 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 (Implementation 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 food web 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 food web. 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

Why ecosystem indicators are needed? - 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, indicators 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).

Sources of data to estimate ecosystem indicators - 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:

(1) independent fisheries data obtained from biological surveys,

(2) fisheries dependent data obtained from fishing vessels (logbooks) and fisheries observer programs, and

(3) 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.

Types of ecosystem indicators - 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.

Are ecosystem indicators monitored in IOTC? 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 Atlantic and Indian Ocean to examine the potential ecological effects of this fishery on the food web structure and functioning (Juan Jorda et al. 2019). 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 food web to understand fishing impacts.

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.

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 -Proportion of large fish (proportion of fish catches or fish biomass larger than a specific size value)	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. 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.	-Empirically estimated using fisheries dependent data -Model-derived

- The slope and intercept of the biomass size spectra of the marine community			
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 - 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	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. 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).	-Empirically estimated using fisheries dependent data -Model-derived

compatible with the trophic efficiency of the region.		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

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 ecosystem 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 IATTC, see section 4.4 of this report) can serve as an example to incentivize 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" and not "tactical" 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 strategic 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.

Furthermore, there is an emerging use of multi-species models 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 other few other 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.

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).

6. Identification of the key information gaps in enabling the development of tools such as ecosystem indicators and ecosystem models in the Indian Ocean, with recommendations for addressing gaps through additional data and information gathering

Identification of the key information gaps in enabling the development of tools such as ecosystem indicators and ecosystem models, with 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. 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.

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 Member States.

The quality and completeness of these datasets vary greatly by fleet, species, area and time period, which is briefly summarized below:

- **Quality of datasets for major IOTC species -** 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).
- **Quality of datasets for IOTC species by major fisheries -** 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).
- **Spatial resolution of nominal catches -**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.
- **Quality of datasets on discards -** 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.
- **Quality of data sets for neritic and billfish species -** The coverage of the nominal catch, catch-effort and size datasets varies by species groups within the major IOTC species. The catch-and-effort and size data is particularly poor for the neritic species and billfishes (IOTC Secretariat 2018).
- **Quality of data sets for non-IOTC species -** 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. 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 Member States from collecting complete information across all gears and species, this is rarely the case. These fragmented resolutions in terms of species coverage and Member States 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).
- **Quality of data sets for sharks -**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).

- **Quality of data sets for marine mammals, 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.
- **Spatial resolution of data sets for IOTC and non-IOTC species -** The 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.

The role and quality of the observer data to support the development of ecosystem indicators and ecosystem models - Despite the Regional Observer Scheme is in place since 2011, most IOTC Member States 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 Member States, 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 Member States 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.

What type of data is needed to support the development of ecosystem models? - 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: (1) biomass across the model region, (2) production/biomass ratio, (3) consumption/biomass ratio (describing the energy requirements of predators and the standing biomass of their pray) or (4) 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.

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).

Why ecosystem models have been developed in the Pacific Ocean and not in the Indian Ocean? - 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 Member States.

What is needed to support the development of ecosystem models in the Indian Ocean? - 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).

The importance of understanding the contribution of each fishery to the overall ecosystem impacts - 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. This study stresses the need for IOTC Member States 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 Member States, and in addition, contemplate to increase these minimum standards to 100 % observer coverage, or at least to 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. Final recommendations, options for progress, and relevant ongoing activities to support comprehensive EAFM implementation in IOTC

SIOTI may consider supporting the following initiatives and activities:

- **Support the development of an EAFM implementation plan** - Promote change at the national and regional level to support the development of an IOTC EAFM policy and vision and an EAFM implementation plan. A commission-mandated EAFM plan would provide step-by-step guidance, including what activities, timelines and roles, on how EAFM could be further implemented in the context of IOTC fisheries. The recent joint tuna RFMO EAFM workshop (organized by the FAO Common Oceans ABNJ Tuna Project on the 17-19 September 2019) established as one of its major course of actions the development and adoption of commission-mandated EAFM plans to legitimise EAFM activities, ecosystem research, identify gaps and prioritise actions to ensuring that time and resources will be applied effectively in management areas where they are most needed (final report being prepared).

- **Support EAFM-related communication and building capacity activities -** Support national and regional activities, ranging from formal regional meetings such as the IOTC TCMP to specialized workshops and building capacity activities, to enhance the communication and dialogue between scientists, managers and the private sector, and other relevant stakeholders on how ecosystem science and EAFM related activities (regarding bycatch, habitat and ecosystems) can be better addressed in fisheries management decisions.

- **Support the production of integrated advice** - Support activities such as a specialized technical workshop for testing the usefulness of the IOTC candidate ecoregions, which is a tool that aims to be used structure and provide better integrated ecosystem-based advice (e.g. gear, species, climate interactions) and evaluate ecosystem-based management actions on a regional basis with the participation of relevant stakeholders including scientist, managers and other relevant stakeholders.

- **Support higher observer coverage -** Promote change at the national and regional level to support the adoption of a high observer coverage (ideally 100% observer coverage using a combination of human observers and electronic monitoring) in all IOTC fisheries as part of the IOTC Regional Observing Scheme. This would allow more precise estimates of ecosystem impacts by major types of IOTC fisheries, as well as the assessment of cumulative impacts across all fisheries.

- **Support the development of ecosystem indicators -** Support activities such as specialized technical workshops for selecting, developing and testing ecosystem indicators to monitor the impacts of IOTC of fisheries on the broader ecosystems with the participation of relevant stakeholders including scientist, managers and principal data collectors.

- **Support the development comprehensive ecosystem risk assessments -** Support activities such as specialized technical workshops to conduct a comprehensive range of ecosystem risk assessment to understand what ecological, physical and socio-economic elements and risk factors may be prioritized to inform fisheries management. Risk assessments not being yet explored within IOTC include the use of EASI-Fish type ecological risk assessment for bycatch species, the use of climate risk assessments on species and associated fisheries/fishing communities, habitat risk assessments, social and economic vulnerability analysis, among others.

- **Examine time area closures and bycatch limits** - Support activities and enforce research actions to further explore the use of time/area closures and total bycatch limits as additional bycatch reduction tools to minimize the impact of fisheries on vulnerable and threatened species, and use this knowledge to explore ways of linking bycatch areas and limits to the harvest strategies of main IOTC species.

- **Identify and protect habitats of ecological significance -** Support activities and enforce research actions to identify habitats of ecological significance and potential concern and to further explore the use of time/area closures as an additional management tool to minimize the impacts of fisheries on habitats of ecological significance and of potential concern for IOTC species and threatened species interacting with IOTC fisheries.

- **Support the development of ecosystem models and multispecies models -** Support activities and enforce research actions to improve the knowledge on the trophic ecology of IOTC species and associated 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 and test alternative ecosystem-based harvest strategies.

- **Support the development of an IOTC ocean-climate web** - Support and promote the proposal for the development of an IOTC ocean-climate web, which will encourage further research and studies on the role and influence of climate and environment, including climate change on the population dynamics, movement, abundance of main IOTC species.

- All the above activities acknowledge the value of collaborations between scientists, managers and private sectors and others in the developing of new tools to assist in the provision of better integrated ecosystem-based advice and the evaluation of management actions.

8. Final recommendations, options for progress, and relevant ongoing activities to better account for the impacts of purse seine tuna fishing on marine ecosystems, including on (a) non-targeted species, (b) habitats and (c) the structure and function of ecosystems

SIOTI may consider supporting the following initiatives and activities:

- **MSC Fishery Standard P2.4 Habitats and P2.4 Ecosystems need to be clarified for the context of tuna fisheries -** Engage with the MSC to clarify better the MSC Fishery Standard and Guidance in relation to what type of fishery impacts need to be reviewed under the component of Habitats (P2.4) and the component of Ecosystem (P2.5) in the context of tuna fisheries.

- **Enhance fishery data collection and support other fisheries (e.g. gillnets) with poor reporting -** Promote change at the national and regional level to enhance fishery data collection and ensure compliance with IOTC data requirements, enhancing the minimum requirements in the collection of basic fisheries statistics (catch, effort and size data). Multiple data gaps exist especially for gillnet fisheries. Continue ongoing collaborative projects with WWF Pakistan and other partners to improve data collection from gillnet fisheries.

- **Enhance spatially explicit fishery data collection -** Promote change at the national and regional level to enhance spatially explicit fishery data collection. The spatial resolution of the fishery statistics reported to IOTC are poor or very incomplete, which hinders many of the research activities conducted by the IOTC Scientific Committee. 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), and is not requested or available for the rest of species interacting with IOTC fisheries.

- **Enhance the collection of size-based data in the observer programs -** The observer programs in the SIOTI fleet provide information about all the species in the catch and that are discarded, which underpin and support many of the bycatch and ecosystem studies, including the development of indicators in Table 4. During the observer trips, there is size sampling for tunas and for the accompanying fauna, yet the size sampling for the bycatch species is focused on rays, sharks, cetaceans and turtles when possible.

It is recommended the size sampling is extended to all the species (fish and non-fish species) being caught in order to support the development of size based indicators and size-based ecosystem models.

- **Advance knowledge of the impacts of purse seine tuna fishing on non-targeted species including vulnerable and threatened species.**
    - o SIOTI partners would benefit from having a **shared Code of Good Practices for Responsible Tuna Purse Seining** similar to the one developed by OPAGAC and ANABAC to minimize and reduce the mortality of bycatch species (Nieblas and SIOTI, 2019).
    - o Continue supporting ongoing research and SIOTI studies aiming to estimate the **contribution of each major fishery to the overall levels of bycatch mortality**, with a focus on vulnerable and threatened taxa. The study of Garcia and Herrera 2018 could be updated and extended to get better estimates of the uncertainty for all major taxa groups (and at the species level to the extent possible) and all gears, especially longline and gillnet fisheries.
    - o Enhance **FAD research and management** in purse seine fisheries and support research to mitigate the impacts of FAD, e.g. build effective biodegradable FADs.

- **Advance knowledge of the impacts of purse seine tuna fishing on habitats.**
    - o Support research to increase understanding of the environmental preferences and **habitat utilization** (e.g. spawning grounds, feeding grounds, migration corridors) of tuna species and associated species.
    - o Enhance **FAD research and management** in purse seine fisheries and support research to further investigate whether and how FADs act or not as ecological traps for tunas and other species.
    - o Support research similar to the **FAD Watch program**, led by the private sector and the government of Seychelles, to prevent FAD losses and mitigate FAD beaching in coastal habitats of ecological concern.

- **Advance knowledge of the impacts of purse seine tuna fishing on the structure and function of marine ecosystems.**
    - o **Enhance data collection and research on the basic biology and trophic ecology of species to monitor fishing impacts on food webs.** 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.
    - o **Support the development of empirically based ecosystem indicators using fisheries dependent data.** Empirically-based ecosystem indicators rely on fisheries data from fishing vessels and observer programs. Fisheries data, and more specifically the observer data collected by IOTC Member States have been mostly used to quantify and monitory bycatch rates in their fisheries. IOTC should further explore the use of observer data to support the development of ecosystem indicators (as proposed in Table 4), as well as support specialised technical workshops and joint collaborative analysis among Member States to share confidential data, and thus develop ecosystem indicators and ecosystem

assessments to monitor the cumulative impacts of fisheries on different components of ecosystem on an area basis.

- **Support the development of multispecies and ecosystem models, and their use to estimate ecosystem indicators and 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 (ecosystem structure and function), elucidate potential ecosystem regime shifts, and also evaluate the effectiveness of previous management actions and evaluate future management scenarios (see section 9 of this report).

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

The design of ecosystem-based management strategies requires to understand gear interactions, species interactions and climate interactions, so they can be used to inform strategic and tactical fisheries management. Alternative harvest strategies would need to be planned and chosen making explicit connection to the interconnectedness of gears, species and climate in marine ecosystems, focusing on those interactions that are relevant. 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 tuna fisheries are approaching their theoretical sustainable limits (Juan-Jordá et al. 2011, ISSF 2018), 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.

A list of actions and research activities is proposed next that may facilitate the process of developing ecosystem-based management option in tuna fisheries in IOTC. These list of actions and research activities aim to support the improvement of methods and tools to design and test alternative ecosystem-based harvest strategies to support ecosystem based strategic and tactical fisheries management.

- **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 of 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 off 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 (e.g. bycatch, ecosystem structure and function, habitats of ecological significance). 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 should 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 bycatch rates, food web 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 EAFM objectives including 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 assessment can be used to identify those high-risk gear, species, and climate interactions on an regional basis (based on large scale ecoregions) that deserve further attention and that should be connected to the management system.

10. Acknowledgements

Many thanks to Jan Robinson for his support throughout this study and to the SIOTI partners for providing useful comments on early versions of the manuscript which have greatly improved the study.

11.References

Ainsworth, C. H., and T. J. Pitcher. 2006. Modifying Kempton's species diversity index for use with ecosystem simulation models. Ecological Indicators 6:623-630.

Allain V., Griffiths S., B. J., and N. S. 2015. Monitoring the pelagic ecosystem effects of different levels of fishing effort on the western Pacific Ocean warm pool. Issue-specific national report. Oceanic Fisheries Programme, Secretariat of the Pacific Community, Nouméa, New Caledonia.

Amande, J. M., J. Ariz, E. Chassot, P. Chavance, d. M. A. Delgado, D. Gaertner, H. Murua, R. Pianet, and J. Ruiz. 2008. By-catch and discards of the european purse tuna fishery in the Indian Ocean. Estimation and characteristics for the 2003-2007 period. IOTC-2008-WPEB-12.

Branch, T. A., R. Watson, E. A. Fulton, S. Jennings, C. R. McGilliard, G. T. Pablico, D. Ricard, and S. R. Tracey. 2010. The trophic fingerprint of marine fisheries. Nature 468:431–435.

CBD. 2004. The Ecosystem Approach, (CBD Guidelines) Montreal: Secretariat of the Convention on Biological Diversity 50 p.

Christensen, V. 1996. Managing fisheries involving predator and prey species. Reviews in Fish Biology and Fisheries 6:417–442.

Clarke, S., M. Sato, C. Small, B. Sullivan, Y. Inoue, and D. Ochi. 2014. Bycatch in Longline Fisheries for Tuna and Tuna-like Species: a Global Review of Status and Mitigation Measures. FAO Fisheries and Aquaculture Technical Paper No. 588. Food and Agriculture Organization of the United Nations, Rome.

Coggins, L., M. Catalano, M. Allen, W. Pine, and C. Walter. 2007. Effects of cryptic mortality on fishery sustainability and performance. Fish and Fisheries 8 8:1-15.

Coll, M., L. J. Shannon, K. M. Kleisner, M. J. Juan-Jordá, A. Bundy, A. G. Akoglu, D. Banaru, J. L. Boldt, M. F. Borges, A. Cook, I. Diallo, C. Fu, C. Fox, D. Gascuel, L. J. Gurney, T. Hattab, J. J. Heymans, D. Jouffre, B. R. Knight, S. Kucukavsar, S. I. Large, C. Lynam, A. Machias, K. N. Marshall, H. Masski, H. Ojaveer, C. Piroddi, J. Tam, D. Thiao, M. Thiaw, M. A. Torres, M. Travers-Trolet, K. Tsagarakis, I. Tuck, G. I. van der Meeren, D. Yemane, S. G. Zador, and Y. J. Shin. 2016. Ecological indicators to capture the effects of fishing on biodiversity and conservation status of marine ecosystems. Ecological Indicators 60:947-962.

Constable, A. 2016. SC-CAMLR work on Climate Change (Paper XP19 to CEP–SC-CAMLR Workshop 2016), WG-EMM-16/71.

Constable, A. J., W. K. de la Mare, D. J. Agnew, I. Everson, and D. Miller. 2000. Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). ICES Journal of Marine Science 57:778-791.

Cox, S. P., T. E. Essington, J. F. Kitchell, S. J. D. Martell, C. J. Walters, C. Boggs, and I. Kaplan. 2002a. Reconstructing ecosystem dynamics in the central Pacific Ocean, 1952–1998. II. A preliminary assessment of the trophic impacts of fishing and effects on tuna dynamics. Canadian Journal of Fisheries and Aquatic Sciences 59:1736-1747.

Cox, S. P., T. E. Essington, J. F. Kitchell, S. J. D. Martell, C. J. Walters, C. Boggs, and I. Kaplan. 2002b. Reconstructing ecosystem dynamics in the central Pacific Ocean, 1952–1998. II. A preliminary assessment of the trophic impacts of fishing and effects on tuna dynamics. Canadian Journal of Fisheries and Aquatic Sciences 59:1736-1747.

Dagorn, L., and P. Fréon. 1999. Tropical tuna associated with floating objects: a simulation study of the meeting point hypothesis. Canadian Journal of Fisheries & Aquatic Sciences 56:984–993.

Dagorn, L., K. N. Holland, V. Restrepo, and G. Moreno. 2013. Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? Fish and Fisheries 14:391-415.

Erlandson, J., M. Rick, T. C. , and T. J. Braje. 2009. Fishing up the food web?: 12,000 years of maritime subsistence and adaptive adjustments on California's Channel Islands. Pacific Science 63:711– 724.

Essington, T. E. 2006. Fishing through marine food webs. Proceedings of the National Academy of Sciences 103:3171-3175.

FAO. 1995. Code of Conduct for Responsible Fisheries, Food and Agriculture Organization of the United Nations, FAO, Rome.

Fletcher, W. J., and G. Bianchi. 2014. The FAO – EAF toolbox: Making the ecosystem approach accessible to all fisheries. Ocean & Coastal Management 90:20-26.

Fletcher, W. J., J. Shaw, S. J. Metcalf, and D. J. Gaughan. 2010. An ecosystem based fisheries management framework: the efficient, regional-level planning tools for management agencies. Marine Policy 34:1226-1238.

Frank, K., B. Petrie, J. Choi, and W. Leggett. 2005. Trophic Cascades in a Formerly Cod-dominated Ecosystem. Science 308:1621–1623.

Fulton, E. A., M. Fuller, A. D. M. Smith, and A. E. Punt. 2004. Ecological Indicators of the Ecosystem Effects of Fishing: Final Report. Report Number R99/1546. Camberra, Australia: Australian Fisheries Management Authority.

Fulton, E. A., A. D. M. Smith, and A. E. Punt. 2005. Which ecological indicators can robustly detect effects of fishing? ICES Journal of Marine Science 62:540-551.

Garcia, A., and M. Herrera. 2018. Assessing the Contribution of Purse Seine Fisheries to Overall Levels of Bycatch in the Indian Ocean. IOTC-2018-WPDCS14-26_Rev1.

Garcia, S. M., A. Zerbi, C. Aliaume, T. Do Chi, and G. Lasserre. 2003. The Ecosystem Approach to Fisheries. Issues, Terminology, Principles, Institutional Foundations, Implementation and Outlook. FAO Fisheries Technical Paper. No 443, FAO, Rome.

Gilman, E. 2015. Status of international monitoring and management of abandoned, lost and discarded fishing gear and ghost fishing. Marine Policy 60:225-239.

Gilman, E., P. Suuronen, M. Hall, and S. Kennelly. 2013. Causes and methods to estimate cryptic sources of fishing mortality. Journal of Fish Biology 83:766–803.

Gilman, E. L. 2011. Bycatch governance and best practice mitigation technology in global tuna fisheries. Marine Policy 35:590-609.

Grant, S., A. Constable, B. Raymond, and S. Doust. 2006. Bioregionalisation of the Southern Ocean: Report of Experts Workshop, Hobart, September 2006. WWF-Australia and ACE CRC.

Griffiths, S. P., V. Allain, S. D. Hoyle, T. A. Lawson, and S. J. Nicol. 2019. Just a FAD? Ecosystem impacts of tuna purse-seine fishing associated with fish aggregating devices in the western Pacific Warm Pool Province. Fisheries Oceanography 28:94-112.

Griffiths, S. P., and L. Fuller. 2019. An updated ecosystem model of the Eastern Tropical Pacific Ocean: analysis of ecological indicators and the potential impacts of FAD fishing on ecosystem dynamics. IATTC Scientific Advisory Committee, Tenth Meeting, San Diego, California, USA. 13-17 May 2019.

Hallier, J. P., and D. Gaertner. 2008. Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. Marine Ecology Progress Series 353:255-264.

Hampton, J., G. Leape, A. Nickson, V. Restrepo, J. Santiago, J. Amande, R. Banks, M. Brownjohn, E. Chassot, R. Clarke, T. Davies, D. Die, D. Gaertner, G. Galland, D. Gershman, M. Goujon, M. Hall, M. Herrera, K. Holland, D. Itano, T. Kawamoto, B. Kumasi, A. Maufroy, G. Moreno, H. Murua, J. Murua, G. Pilling, K. Schaefer, J. Scutt Phillips, and M. Taquet. 2017. What does well-managed FAD use look like within a tropical purse seine fishery? WCPFC-SC13-2017/ MI-WP-06, SCIENTIFIC COMMITTEE THIRTEENTH REGULAR SESSION
Rarotonga, Cook Islands 9 – 17 August 2017.

Harrison, D. P., M. G. Hinton, S. Kohin, E. M. Armstrong, S. Snyder, F. O'Brien, and D. K. Kiefer. 2017. The pelagic habitat analysis module for ecosystem-based fisheries science and management. Fisheries Oceanography:1-20.

Heymans, J. J., M. Coll, J. S. Link, S. Mackinson, J. Steenbeek, C. Walters, and V. Christensen. 2016. Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. Ecological Modelling 331:173-184.

Hollowed, A. B., N. Bax, R. Beamish, J. Collie, M. Fogarty, P. Livingston, J. Pope, and J. C. Rice. 2000. Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? ICES Journal of Marine Science 57:707-719.

IOTC. 2007. Report of the Third Session of the IOTC Working Party on Ecosystems and Bycatch (previously the Working Party on Bycatch). Seychelles, 11-13 July 2007. IOTC-2007-WPEB-R[E]. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC. 2014a. Draft: Indian Ocean Multi-Year Shark Research Program. IOTC-2014-WPEB10-11. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC. 2014b. Program of Work (2015-2019) for the Working Party on Ecosystems and Bycatch. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC. 2018a. Report on IOTC data collection and statistics. IOTC–2018–WPDCS14–07.

IOTC. 2018b. Review of the statistical data available for bycatch species. IOTC-2018-WPEB14-07.

IOTC Secretariat. 2018. Report on IOTC data collection and statistics. IOTC–2018–WPDCS14–07.

IOTC–SC21. 2018. Report of the 21st Session of the IOTC Scientific Committee. Seychelles, 3 – 7 December 2018. IOTC–2018–SC21–R[E]: 250 pp.

IOTC–WPEB06. 2010. Report of the Sixth Session of the IOTC Working Party on Ecosystems and Bycatch. Victoria, Seychelles, 27-30 October 2010. IOTC–2010–WPEB–R[E]. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC–WPEB07. 2011. Report of the Seventh Session of the IOTC Working Party on Ecosystems and Bycatch. Lankanfinolhu, North Malé Atoll, Republic of Maldives, 24–27 October 2011. IOTC–2011–WPEB07–R[E]. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC–WPEB08. 2012. Report of the Eighth Session of the IOTC Working Party on Ecosystems and Bycatch. Cape Town, South Africa, 17–19 September, 2012. IOTC–2012–WPEB08–R[E]. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC–WPEB09. 2013. Report of the Ninth Session of the IOTC Working Party on Ecosystems and Bycatch. La Réunion, France, 12–16 September, 2013. IOTC– 2013–WPEB09–R[E]. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC–WPEB11. 2015. Report of the 11th Session of the IOTC Working Party on Ecosystems and Bycatch. Olhao, Portugal, 7-11 September, 2015. IOTC– 2015–WPEB11–R[E]. Indian Ocean Tuna Commission, Mahé, Seychelles.

IOTC–WPEB14. 2018. Report of the 14th Session of the IOTC Working Party on Ecosystems and Bycatch. Cape Town, South Africa 10 – 14 September 2018 IOTC–2018–WPEB14–R[E]: 106pp.

ISSF. 2014. Report of the ISSF Workshop on FADs as ecological traps. 29-31 January 2014 - Sete, France. ISSF Technical Report 2014-03.

ISSF. 2018. Status of the world fisheries for tuna. Oct. 2018. ISSF Technical Report 2018-21. International Seafood Sustainability Foundation, Washington, D.C., USA.

Juan Jorda, M. J., E. Andonegi, M. H, R. J, M. Lourdes Ramos, P. S. Sabarros, F. J. Abascal, and P. Bach. 2019. In support of the ICCAT ecosystem report card: three ecosystem indicators to monitor the ecological impacts of purse seine fisheries in the tropical atlantic ecoregion. SCRS 2019/051.

Juan-Jordá, M. J., I. Mosqueira, A. B. Cooper, and N. K. Dulvy. 2011. Global population trajectories of tunas and their relatives. Proceedings of the National Academy of Sciences of the United States of America 51:20650-20655.

Juan-Jordá, M. J., H. Murua, P. Apostolaki, C. Lynam, A. Perez-Rodriguez, J. C. Baez-Barrionuevo, F. J. Abascal, R. Coelho, S. Todorovic, M. Uyarra, E. Andonegi, and J. Lopez. 2019. Selecting ecosystem indicators for fisheries targeting highly migratory species. Final Report. European Commission. Specific Contract No. 2 EASME/EMFF/2015/1.3.2.3/02/SI2.744915 under Framework Contract No. EASME/EMFF/2016/008. pp. 1 - 395.

Juan-Jordá, M. J., H. Murua, H. Arrizabalaga, N. K. Dulvy, and V. Restrepo. 2017. Report card on ecosystem-based fisheries management in tuna regional fisheries management organizations Fish and Fisheries 19:321-339.

Juan-Jordá, M. J., H. Murua, and S. Todorovic. 2018. Selecting ecosystem indicators for fisheries targeting highly migratory species. IOTC-2018-WPEB14-21_Rev1.

Justel-Rubio, A., and V. Restrepo. 2017. Justel-Rubio, A., Restrepo, V., 2017. Computing a Global Rate of Non-Target Species Catch (Bycatch) in Tropical Tuna Purse Seine Fisheries, ISSF Technical Report 2017-01. International Seafood Sustainability Foundation, Washington, D.C., USA. .

Kitchell, J., C. Boggs, X. He, and C. Walters. 1999. Keystone predators in the Central Pacific. Page 665−683 Ecosystem approaches to fisheries management. University of Alaska Sea Grant, AL-SG-99-01, Fairbanks, AK.

Kitchell, J., T. Essington, C. Boggs, D. Schindler, and C. Walters. 2002. The role of sharks and longline fisheries in a pelagic ecosystem of the central Pacific. Ecosystems 5: 202–216. Ecosystems 5:202–216.

Kleisner, K., and D. b. Pauly. 2011. The Marine Trophic Index (MTI), the Fishing in Balance (FiB) Index and the spatial expansion of fisheries. In The state of biodiversity and fisheries in Regional Seas (eds. Christensen, V., Lai, S., Palomares, M.L.D. and others). Fisheries Centre Research Reports 19(3), 41-44. Fisheries Centre, University of British Columbia.

Koen-Alonso, M., P. Pepin, M. J. Fogarty, A. Kenny, and E. Kenchington. 2019. The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges. Marine Policy 100:342-352.

Kvamsdal, S. F., A. Eide, N.-A. Ekerhovd, K. Enberg, A. Gudmundsdottir, A. H. Hoel, K. E. Mills, F. J. Mueter, L. Ravn-Jonsen, L. K. Sandal, J. E. Stiansen, and N. Vestergaard, 2016. Harvest control rules in modern fisheries management. Elem Sci Anth, 4, p.000114. DOI: http://doi.org/10.12952/journal.elementa.000114. 2016. Harvest control rules in modern fisheries management. Elementa Science of the Anthropocene 1:000114.

Litzow, M. A., and D. Urban. 2009. Fishing through (and up) Alaskan food webs. . Canadian Journal of Fisheries and Aquatic Sciences 66:201–211.

Marsac, F., A. Fonteneau, and F. Menard. 2000. Drifting FADs used in tuna fisheries: an ecological trap? Biology and behaviour of pelagic fish aggregations.

Marsac, F. 2018. Proposal for the development of an ocean-climate web page for the IOTC. 14th session of the Working Party on Data Collection and Statistics, Mahe, Seychelles, 29 Nov-1 Dec 2018. IOTC-2018- WPDCS14-36, 9 p.

Maufroy, A., E. Chassot, R. Joo, and D. Kaplan. 2015. Large-Scale Examination of Spatio-Temporal Patterns of Drifting Fish Aggregating Devices (dFADs) from Tropical Tuna Fisheries of the Indian and Atlantic Oceans. PLoS ONE 10(5): e0128023 10:e0128023.

Murua, H., R. Coelho, M. N. Santos, H. Arrizabalaga, K. Yokawa, E. Romanov, J. F. Zhu, Z. G. Kim, P. Bach, P. Chavance, A. Delgado de Molina, and J. Ruiz. 2012. Preliminary Ecological Risk Assessment (ERA) for Shark Species Caught in Fisheries Managed by the Indian Ocean Tuna Commission (IOTC). IOTC-2012-SC-nº XX revision 1. Indian Ocean Tuna Commission, Mahé, Seychelles.

NAFO. 2017. Report of the 10th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). Dartmouth, Nova Scotia, Canada.

National Research Council. 2006. Dynamic Changes in Marine Ecosystems: Fishing, Food Webs, and Future Options. Washington, DC: The National Academies Press. https://doi.org/10.17226/11608.

Nieblas, A., E. SIOTI, 2019. Towards improvement in monitoring, reporting and management of Fish Aggregating Devices in the Indian Ocean Purse Seine Tuna Fishery. IOTC-2019-WPEB15-37.

NOAA. 2017. NOAA Fisheries Ecosystem-Based Fisheries Management Road Map. http://www.nmfs.noaa.gov/op/pds/index.html.

NPFMC. 2014. North Pacific Fishery Management Council Status of Ecosystem Based Fishery Management (EBFM) development process and actions, May 2014.

Olson, R. J., and G. M. Watters. 2003. A model of the pelagic ecosystem in the eastern tropical Pacific Ocean. Inter-American Tropical Tuna Commission, Bulletin 22:133-218.

Olson, R. J., J. W. Young, F. Ménard, M. Potier, V. Allain, N. Goñi, J. M. Logan, and F. Galván-Magaña. 2016. Bioenergetics, trophic ecology, and niche separation of tunas. Advances of Marine Biology 74:199-344.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. J. Torres. 1998. Fishing down marine food webs. Science 279:860-863.

Pauly, D., V. Christensen, and C. Walters. 2000. Ecopath, Ecosim and Ecospace as tools for evaluating ecosystem impact of fisheries. ICES Journal of Marine Science 57:697-706.

Pauly, D., and V. W. Y. Lam. 2016. Chapter 6.1: The status of fisheries in large marine ecosystems, 1950-2010. In IOC-UNESCO and UNEP (2016). Large Marine Ecosystems: Status and Trends. United Nations Environment Programme, Nairobi, pp 113-137.

Pauly, D., and R. Watson. 2005. Background and interpretation of the 'Marine Trophic Index' as a measure of biodiversity. . The Royal Society 360:415–423.

Plagányi, E. E., A. E. Punt, R. Hillary, E. B. Morello, O. Thébaud, T. Hutton, R. D. Pillans, J. T. Thorson, E. A. Fulton, A. D. M. Smith, F. Smith, P. Bayliss, M. Haywood, V. Lyne, and P. C. Rothlisberg. 2012. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity. Fish and Fisheries 15:1-22.

Polovina, J., M. Abecassis, E. A. Howell, and P. Woodworth. 2009a. Increases in the relative abundance of mid-trophic level fishes concurrent with declines in apex predators in the subtropical North Pacific, 1996-2006. Fishery Bulletin 107:523-531.

Polovina, J. J., M. Abecassis, E. A. Howell, and P. Woodworth. 2009b. Increases in the relative abundance of mid-trophic level fishes concurrent with declines in apex predators in the subtropical North Pacific, 1996–2006. Fishery Bulletin 107:523-531.

Polovina, J. J., and P. A. Woodworth-Jefcoats. 2013. Fishery-Induced Changes in the Subtropical Pacific Pelagic Ecosystem Size Structure: Observations and Theory. PLoS ONE 8:e62341.

Poseidon Aquatic Resource Management. 2019. Scoping study of socio-economic data and indicators of IOTC fisheries. IOTc-2019-S23-13[E]_Rev1.

Ruiz, J., F. J. Abascal, P. Bach, J. C. Baez, P. Cauquil, M. Grande, I. Krug, J. Lucas, H. Murua, M. Ramos-Alonso, and P. S. Sabarros. 2018. Bycatch of the European and associated flad, purse-seine tuna fishery in the Indian Ocean for the period 2008-2017. IOTC-2018-WPEB14-15.

Shannon, C. E. 1948. A mathematical theory of communication. Bell System Technical Journal 27:379-423.

Shannon, L., M. Coll, A. Bundy, D. Gascuel, J. J. Heymans, K. Kleisner, C. P. Lynam, C. Piroddi, J. Tam, M. Travers-Trolet, and Y. Shin. 2014. Trophic level-based indicators to track fishing impacts across marine ecosystems. Marine Ecology Progress Series 512:115-140.

Shin, Y.-J., M.-J. Rochet, S. Jennings, J. G. Field, and H. Gislason. 2005. Using size-based indicators to evaluate the ecosystem effects of fishing. ICES Journal of Marine Science 62:384-396.

Shin, Y.-J., and L. J. Shannon. 2010. Using indicators for evaluating, comparing and communicating the ecological status of exploited marine ecosystems. 1. The IndiSeas project. ICES Journal of Marine Science 67:686–691.

SIOTI action plan. 2017. https://fisheryprogress.org/fip-profile/indian-ocean-tuna-purse-seine-sioti.

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

Regional Office for Asia and the Pacific, Bangkok, Thailand, RAP Publication 2014/13.

United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks. July 24–Aug. 4, 1995, Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, U.N. DOCA/Conf. 164/37.

Ward, P., and R. A. Myers. 2005. Shifts in open-ocean fish communities coinciding with the commencement of commercial fishing. Ecology 86:835-847.

Williams, A. J., L. Georgeson, R. Summerson, A. Hobday, J. Hartog, M. Fuller, Y. Swimmer, B. Wallace, and S. J. Nicol. 2018. Assessment of the vulnerability of sea turtles to IOTC tuna fisheries. IOTC-2018-WPEB14-40.

Wolfaardt, A. 2016. Data collection requirements for observer programmes to improve knowledge of fishery impacs on seabirds. Collective Volume of Scientific Papers - ICCAT 72:1975-1983.

Worm, B., R. Hilborn, J. K. Baum, T. A. Branch, J. S. Collie, C. Costello, M. J. Fogarty, E. A. Fulton, J. A. Hutchings, S. Jennings, O. P. Jensen, H. K. Lotze, P. M. Mace, T. R. McClanahan, C. Minto, S. R. Palumbi, A. M. Parma, D. Ricard, A. A. Rosenberg, R. Watson, and D. Zeller. 2009. Rebuilding global fisheries. Science 325:578-585.

Zador, S., K. Aydin, S. Batten, N. Bond, K. Cieciel, A. Dougherty, M. Doyle, E. Farley, E. Fergusson, N. Ferm, L. Fritz, J. Gann, A. Greig, C. Harpold, A. Hermann, K. Holsman, J. Ianelli, J. Joyce, K. Kuletz, E. Labunski, C. Ladd, B. Lauth, J. Lee, M. Litzow, A. Matarese, K. Mier, J. Moss, F. Mueter, J. Murphy, J. Olson, J. Orsi, I. Ortiz, J. Overland, K. Shotwell, E. Siddon, W. Stockhausen, K. Sweeney, S. Vulstek, M. Wang, A. Wertheimer, A. Whitehouse, T. Wilderbuer, M. Wilson, E. Yasumi-, and S. Zador. 2015. Ecosystem Considerations 2015: Status of Alaska's Marine Ecosystems. NPFMC Ecosystems Considerations. Anchorage, Alaska. 297 p.

Zador, S., K. K. Holsman, K. Y. Aydin, and S. K. Gaichas. 2016. Ecosystem considerations in Alaska: the value of qualitative assessments. ICES Journal of Marine Science 74:421-430.

Zador, S. G., K. K. Holsman, K. Y. Aydin, and S. K. Gaichas. 2017. Ecosystem considerations in Alaska: the value of qualitative assessments. ICES Journal of Marine Science 74:421-430.

Zudaire, I., J. Santiago, M. Grande, H. Murua, P. A. Adam, P. Nogués, T. Collier, M. Morgan, N. Khan, F. Baguette, J. Moron, I. Moniz, and M. Herrera. 2018a. FAD Watch: a collaborative initiative to minimize the impact of FADs in coastal ecosystems. IOTC-2018-WPEB14-12.

Zudaire, I., J. Santiago, M. Grande, H. Murua, P. A. Adam, P. Nogués, T. Collier, M. Morgan, N. Khan, F. Baguette, J. Moron, I. Moniz, and M. Herrera. 2018b. FAD Watch: a collaborative initiative to minimize the impact of FADs in coastal ecosystems. IOTC-2018-WPEB14-12.