Developing a science-based framework for the management of drifting Fishing Aggregating Devices

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Abstract

Fish Aggregating Devices (FADs) are man-made floating objects deployed by fishers to attract tuna and improve their catches. Currently, more than half of the global tropical tuna purse-seine catches occur at FADs. The fast development of the purse-seine fisheries operating on drifting FADs (DFADs) has raised concerns regarding their impacts on tuna populations, on non-target species like sharks, as well as on pelagic and coastal habitats. Consequently, the management of DFAD fisheries is a priority of all tuna regional fisheries management organizations. Limits on the number of DFADs have been set in all oceans, based on the precautionary approach, due to the little availability of science-based advice to support management decisions. This paper discusses a science-based framework for the management of DFADs, relying on indicators and operating models. A set of indicators and models related to the ecological impacts of DFADs is discussed, considering the case study of DFAD fisheries management in the Indian Ocean. The aim of this approach is assessing and predicting the effects of increasing numbers of DFADs on coastal and pelagic ecosystems, in order to support and/or evaluate past, present and future management actions.

1. Introduction

Tuna fisheries figure among the world's most important fisheries in terms of global yields (FAO, 2020). In 2020, the catch of major commercial tunas attained 4.9 million tonnes, of which around 95% correspond to tropical tuna catches (ISSF, 2022), with skipjack tuna (*Katsuwomus pelamis)* exceeding 2.8 millions tonnes in 2020 and being the third top marine species in terms of total yield, only after anchoveta and Alaska pollock (FAO, 2020). Tropical tuna species manifest an associative behavior with floating objects (FOBs), forming large multi-specific aggregations around them (Freon & Dagorn, 2000). Both artisanal and industrial fisheries worldwide exploit this associative behavior by deploying man-made floating objects, called Fish Aggregating Devices (FADs). Anchored FAD arrays (AFADs) are generally exploited by the artisanal/semi-industrial fisheries of coastal countries (e.g. trollers, handliners, small purse-seiners and pole-and-line vessels) (Jauharee et al., 2021; Macusi et al., 2017; Sadusky et al., 2018), whereas drifting FADs (DFADs) are deployed offshore by the industrial purse seiners in all oceans (Scott and Lopez, 2014). In recent years the catches of tropical tuna at DFADs have exceeded more than half of the global tropical tuna catches (Dagorn et al., 2013; ISSF, 2022; Scott and Lopez, 2014). The increasing DFAD-based fishing efficiency that characterizes the industrial purse-seine tuna fisheries is mainly due to the development of novel technologies that equip DFADs, such as GPS beacons and, more recently, echosounder buoys (Wain et al., 2021). These satellite-linked devices are deployed on DFADs to remotely locate them and to provide information on the associated tuna biomass beneath them (Baidai et al., 2020; Lopez et al., 2014; Moreno et al., 2016). The exploitation of DFADs by purse-seiners has direct effects on:

i. **Target species**, i.e. skipjack, yellowfin (*Thunnus albacares*) and bigeye tuna (*T. obesus*): by increasing their catchability and by shifting the purse-seine fishing effort on juveniles (for yellowfin and bigeye tuna) (Dagorn et al., 2013; Fonteneau et al., 2013; Griffiths et al., 2019);
ii. **Non-target (bycatch) species**: by increasing their catchability, with major concerns for some Endangered, Threatened and Protected (ETP) species, such as the silky shark (*Carcharhinus falciformis)* and the oceanic whitetip shark *(C. longimanus*) (Tolotti et al., 2015) but also through ghost fishing of DFADs when their design causes entanglements of sharks (Filmalter et al., 2013);
iii. **Habitats**: by increasing the number of floating objects at sea, leading to modifications of surface marine habitats, with unknown consequences on the fitness and physiological condition of tuna and associated species (Dupaix et al., 2021; Marsac et al., 2000), DFAD beaching on sensitive ecosystems (e.g. coral reefs) (Imzilen et al., 2021; Maufroy et al., 2015), and increased marine pollution when built up using plastic materials (Zudaire et al., 2021).

Accordingly, concerns were raised about the sustainability of DFAD fisheries (Dagorn et al., 2013; Fonteneau et al., 2013; Griffiths et al., 2019; Leroy et al., 2013), leading all tuna regional fisheries management organizations (RFMOs) to establish limits to the number of DFADs (see e.g.: Indian ocean: IOTC Res.19/02 (IOTC, 2019); Atlantic ocean: ICCAT Rec 21-01 (ICCAT, 2021); Eastern Pacific ocean: IATTC C-21-04 (IATTC, 2021); Western Pacific ocean: WCPFC CMM 2021-01 (WCPFC, 2021)). Other management measures were also adopted by tuna RFMOs, such as time-area closures specific to DFAD fishing (e.g., ICCAT Rec 21-01; WCPFC CMM 2021-01) and discard bans (e.g., IOTC Res.19/05). Furthermore, specific resolutions imposing the use of fully non-entangling FADs without netting material (IOTC Res. 19/02 (IOTC, 2019) or low-entanglement risk FADs have been adopted (ICCAT Rec.19-02 (ICCAT, 2020), IATTC Res. C-19-01 (IATTC, 2019), and WCPFC CMM 2021-01 (WCPFC, 2021)). Concomitant to these management measures, a series of mitigation measures to reduce the impacts of the use of DFADs was voluntarily adopted by some of the industrial purse-seine fleets, including changes in the design of DFADs to mitigate shark entanglements (ISSF, 2019), the transition towards biodegradable materials (ISSF, 2019; Zudaire et al., 2021) and best practices for releasing sharks and other bycatch species (Murua et al., 2021; Poisson et al., 2014).

Such management and mitigation measures are regularly discussed within dedicated RFMO technical FAD working groups, Scientific Committees and RFMOs annual Commission meetings, where ultimately management measures are adopted (see e.g. ICCAT, 2019). However, due to the lack of quantitative science-based advice for DFADs management and empirical evidences, it is difficult to ascertain the effectiveness of those adopted management measures. Similarly, the mitigation measures adopted by the fishing industries to reduce the impacts of DFADs are often questioned, because either the measures are not considered efficient enough or due to their lack of enforcement (Davies et al., 2014; Gershman et al., 2019; Gomez et al., 2020). More globally, the participation of increasingly diverse stakeholders in RFMO technical scientific working groups, where scientific advice for fisheries management is developed, can lead to deviate discussions from a scientific perspective towards a political angle. Therefore, it is paramount to clarify the role of scientific advice in the development of FAD management measures.

This study presents a framework for a science-based management of FAD fisheries, relying on indicators and operating models to support the development and implementation of management measures within tuna RFMOs. The main focus of this study are DFADs, although the same framework can also be applied to the management of AFAD fisheries.

2. Definition of a science-based FAD management framework

The conceptual framework of a science-based FAD management scheme proposed in this study consists in a feedback-loop process, going back and forth from stakeholders to policymakers (Figure 1). Similar to the process used in the Management Strategy Evaluation (MSE), the global aim of this scheme is to identify a management strategy that will allow achieving a set of candidate objectives (Punt et al., 2016). The role of scientists lies at the heart of this loop and aims to provide ecological knowledge and advice to: (i) support the formulation of novel management and mitigation measures, depending on the management objectives (ii) provide feedback information on the effectiveness of past management measures that may cause the management decisions/objectives to be revised.

This conceptual framework is headed by the definition of ***management objectives*** and Target Reference Points (TRPs) (Figure 1). Defining and prioritizing clear management objectives is an essential step for fisheries management (Su et al., 2021). Currently, management objectives driving the decision-making process, such as controlling the fishing capacity or reducing ecosystem impacts of FADs, have either not been set, or not been prioritized (Gershman et al., 2019). The same holds for the definition of specific Target Reference Points (TRPs), i.e., target indicators' levels to be achieved through management measures. The definition of management objectives and TRPs should be discussed by all stakeholders and, ultimately, agreed by fishery managers taking into account different considerations (e.g., socioeconomic impacts, sustainability, etc.). For example, management objectives and TRPs should be defined considering the ecological impacts of DFADs. In this respect, a clear management objective that has been recently identified by tuna RFMOs is reducing the risk of entanglement of sharks at DFADs, for which specific management measures have already been adopted. However, a TRP related to shark entanglement risks, such as attaining zero shark entanglement events or reducing them of a given percentage with respect to a reference year, has not been defined yet and the effectiveness of shark entanglement mitigation measures at DFADs is still largely debated. Management objectives and TRPs can also extend beyond the ecological dimension, according to the social, economic, and cultural priorities brought by stakeholders.

A clear definition of objectives and TRPs can guide the provision of scientific advice, the science underpinning management decisions and the adoption of novel management measures. Once management objectives and TRPs are agreed, scientists develop a set of ***indicators and performance metrics*** that allow evaluating quantitatively the management measure against the agreed management objectives and TRPs. For example, considering the previous example of a management objective and TRP aiming at mitigating shark entanglements at DFADs, relevant indicators that allow monitoring at which level this objective/TRP is attained correspond to monitoring individual shark entanglement rates or the number of entangled sharks per sampled DFAD (see (Filmalter et al., 2013) and section 2.1 for further details). Performance metrics would consist in analyzing the gap between these indicators and TRTs. Furthermore, other indicators than those specifically addressing the management objectives themselves can be produced by scientists, in order to evaluate potential indirect impacts of management decisions. Indeed, management measures can induce a change in fishing strategies, with unintended consequences on target species, non-target species and habitats. For example, a recent study (Tolotti et al., 2022) demonstrated that the rebuilding plan for yellowfin tuna adopted by the Indian Ocean Tuna Commission (IOTC Res. 16/01) was followed by an increase on the number of DFAD sets and an expansion of the fishing effort, resulting in higher by-catch of silky sharks (see more details in section 2.1). In summary, within the proposed science-based FAD management framework, the direct and indirect impacts of management decisions are assessed using multiple indicators.

Indicators alone often lack prediction capabilities to test candidate management options. Therefore, another important building block of the proposed science-based framework, consists in using ***operating models*** (OM). Numerical models constitute an essential, complementary tool to support decision-making. In fishery science, OMs simulate the past and future dynamics of the fish stocks and the fisheries to evaluate the consequences of different management procedures (MP, also referred to as harvest strategies) on exploited fish populations. As such, OMs can be employed using Management Strategy Evaluation

(MSE) to test different FAD management strategies and the resultant performance metrics for each management option will inform if the management objectives and TRPs are achieved. The use of OMs is widespread in fisheries management (Punt et al., 2016; Sharma et al., 2020) within the MSE framework. To date, most applications of MSE have focused on evaluating MPs that define catch and effort limits. As a consequence, within tuna RFMOs, the OMs considered in the MSE frameworks developed so far account for the population dynamics of tuna species and their associated fisheries (Punt et al., 2016). From a more general perspective, the main scope (and challenge) of an OM is to describe the main population and fisheries processes that are relevant to fisheries management. In the case of DFAD fisheries management, OMs certainly need to account for the *population dynamics* of target species, which allow understanding at which level the catches at DFADs are sustainable. However, other dimensions need to be considered. First, OMs accounting for the *association dynamics* of target and non-target species (i.e., accounting for the time spent associated with FADs or not associated, also referred to as associative behavior) constitute a key element of the approach, since such dynamics directly affect the catchability of associated species to the DFAD fisheries (Forget et al., 2015). Secondly, the DFAD catches of tuna and non-target species also depend on *fishers' behavior* (i.e., the number of DFAD sets) (Dagorn et al., 2012; Lennert-cody et al., 2018). These two additional components are therefore essential within the proposed science-based framework, where dedicated OMs can predict the trends of DFAD catches of tuna and non-target species as well as their sustainability according to different management measures. Finally, accounting for the spatio-temporal *dynamics of the DFADs* themselves (i.e., their drift speed and trajectories) is key to predict DFAD beaching and loss events, as well as changes in surface habitats (number of FOBs) according to different management strategies. Within such OM-based approach, the uncertainty related to the biology and behavior of target and non-target species can be characterized, providing a quantitative framework for the application of the precautionary approach (Garcia, 1994).

In summary, indicators and performance metrics will allow evaluating how well the different management options tested using the Operating Models perform, to achieve the agreed management objectives and TRPs. The development of OMs, as well as testing/evaluating candidate/past MPs through indicators and performance metrics, is carried out by scientists in technical scientific working groups. The performance of those candidate management options is then presented to the managers during joint dialogue meetings among scientists, stakeholders and managers. Ultimately, depending on the management objectives, managers will adopt a set of “best” FAD **management measures**, which are tailored to achieve the agreed objectives, during tuna RFMO Commission meetings. These management measures can also be complemented with **technical mitigation measures** developed by the fishery itself on a voluntary basis (ISSF, 2019; Murua et al., 2021; Poisson et al., 2014; Zudaire et al., 2021). The key aspect of a science-based management relies on the fact that the selection of management/mitigation measures, as well as the evaluation of their effectiveness and global impacts on marine ecosystems, can draw on indicators and OMs’ outputs provided by scientists separating clearly the role of science and managers.

In the following sections specific indicators and OMs focusing on the ecological impacts of DFADs are presented. The effect of past management decisions (e.g., total limits on the number of operational buoys, but also management measures that are not strictly related to DFADs, like the introduction of quotas) is discussed, by inspecting the trends of the indicators that can be built from the available information, considering the Indian ocean as a case study.

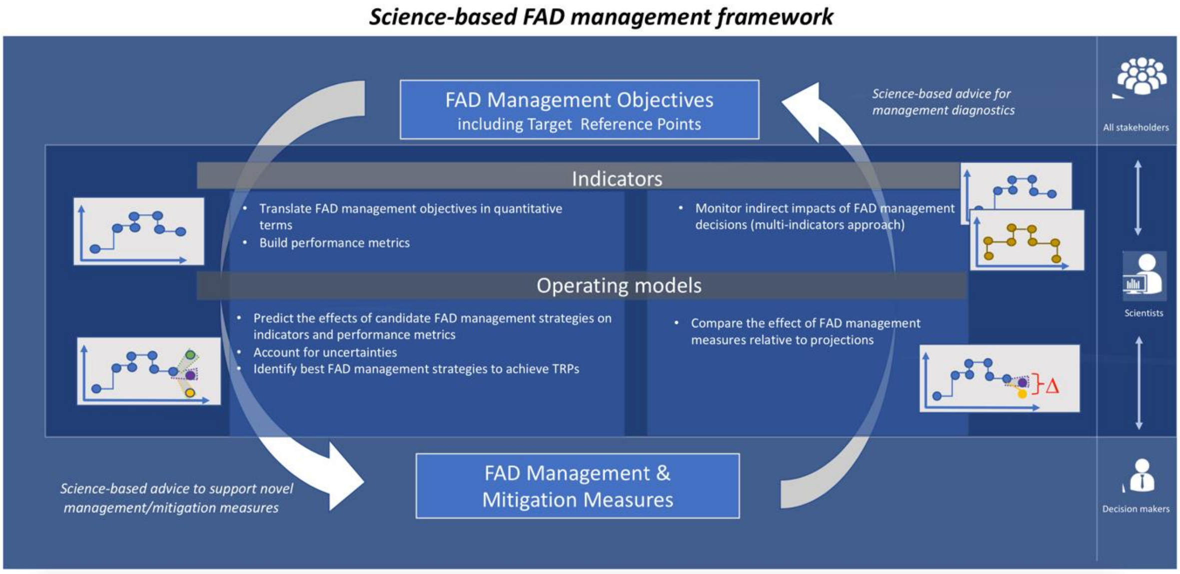

Figure 1: Schematic view of a science-based approach for FAD management relying on indicators and operating models.

2.1 Indicators

In order to quantitatively evaluate the ecological impacts of DFADs and support management decisions, a number of indicators can be set up considering (i) target species, (ii) non-target species and (iii) coastal and pelagic habitats (Table 1). In the following sections, for each set of indicators, an example describing the data requirements/availability and a rationale of their relevance for DFAD management is provided.

Table 1. Possible ecological indicators to monitor the impacts of DFADs on target tuna species, non-target species and coastal and pelagic habitats.

Category	Ecological Indicators	Data source
Target / Non-target species	Species-specific catches at DFADs	Logbook data Observers' data
	Species-specific physiological condition	Observers' data Scientific cruises
Non-target species	Entanglement rates of sharks at DFADs	Observers' data Scientific cruises
Habitats	Number of DFAD beaching events	Buoys data Logbook data
	Amount of plastics beached/sank	Buoys data Logbook data Observers' data
	Total number of DFADs relative to the number of natural floating objects (NLOGs)	Observers' data

2.1.1 Target tuna species

Tuna catches (by species) operated at DFADs by purse seiners can be obtained from logbook data and are generally available within all tuna RFMOs for stock assessments, where DFAD-related catches are globally referred to as "log-associated". This category encloses all tuna catches conducted around floating objects (both natural and artificial floating objects). Generally, the declared catches of tuna species found in the logbooks are corrected considering port sampling data (Duparc et al., 2018), in order to account for possible bias related to the logbook declarations made by the skippers. This correction is conducted separately for log-associated schools and free-swimming schools (not associated), because their corresponding species and size composition differ. In the case of the Indian Ocean, the timeline of total log-associated tuna catches obtained from the main purse-seine fleets that exploit DFADs (Figure 2) demonstrates increasing trends for skipjack tuna until 2018, with a clear decrease in 2019 and 2020. The catches of yellowfin and bigeye tuna followed similar trajectories but increased to a minor extent in the period prior to 2018. Because the tuna catches depend both on the tuna abundance, their catchability and the fishing effort, it is difficult to explain the trends of this indicator on the light of the adopted FAD management plans and establish straightforward cause-effect relationships. However, as a matter of fact, the first DFAD management plans adopted in the IOTC (Res. 15/08; Res. 17/08) limiting the number of DFADs that could be used by the purse seine fleet did not seem to alter the global increasing trends of log-associated catches. The most recent DFAD management plan (Res. 19/02), that entered into force in January 2020, occurred after a significant decrease in tuna catches, which could be explained by the entry into force of the new rebuilding plan for yellowfin tuna adopted in October 2018 (Res.18/01). In summary, even if discussing catch trends on the light of past management actions should be taken with precaution, catch trends still remain a straightforward indicator that can inform on the evolution of the fishery through time. Furthermore, this indicator can be used to feed OMs (see Section 2.2).

A second indicator related to target tuna species concerns their physiological conditions. More than twenty years ago, the so-called “ecological trap hypothesis” was formulated, considering that FADs can constitute ecological traps for tuna (Marsac et al., 2000). In order to evaluate to which extent the physiological condition of tuna has been affected by the increase on the number of DFADs deployments, it is necessary to elucidate the link between the number of FADs and biological information (e.g. development of gonads, weight, size etc.). So far, only ad-hoc studies, focusing on restricted zones and time periods, have tried to address this issue (Hallier & Gaertner, 2008; Jaquemet et al., 2011; Robert et al., 2014). Regular data collection should be conducted to provide temporal and spatial trends of tuna physiological indicators, considering the evolution of the number of DFADs as a co-variable. Regular samplings of tuna physiological condition would also allow evaluating the role of DFAD density relative to other environmental variables (e.g., sea-surface temperature and chlorophyll), which can also change through time and affect tuna physiology (Dueri et al., 2014).

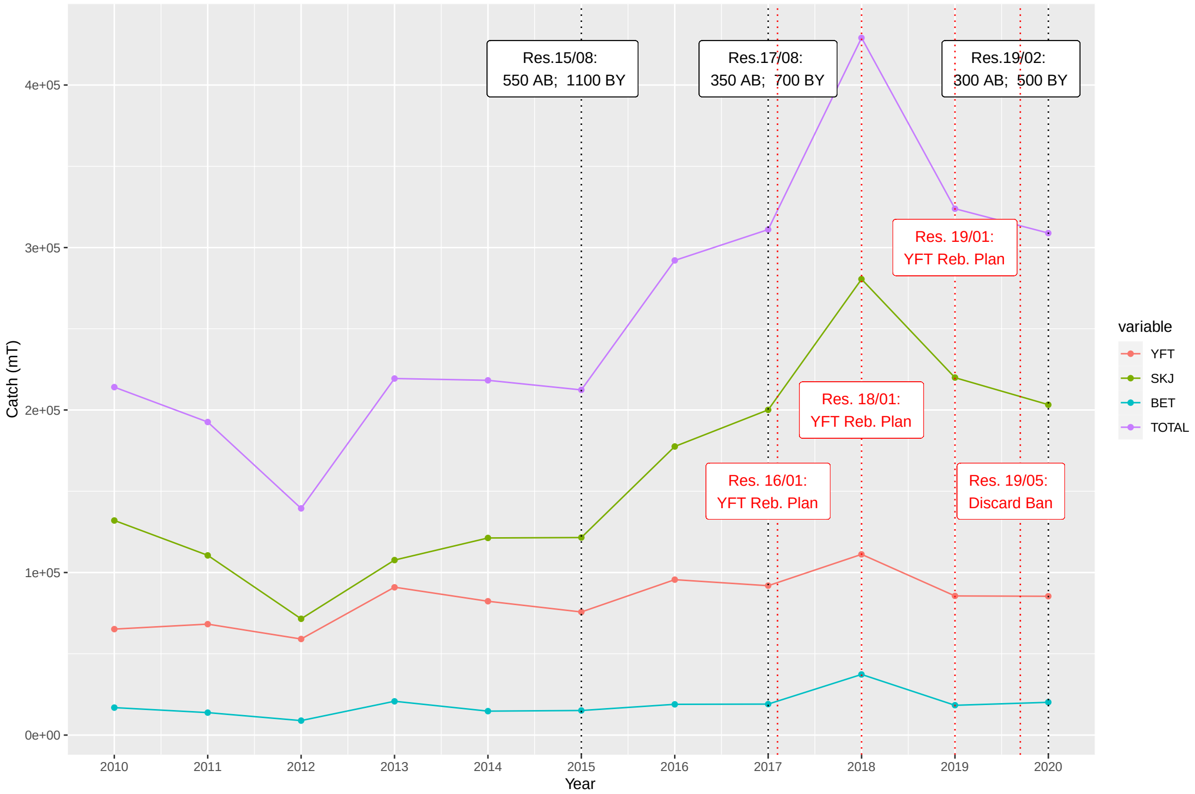

Figure 2. Timeline of purse seine catches of FOB-associated tuna in the Indian ocean (YFT: yellowfin tuna; BET: bigeye tuna; SKJ: Skipjack tuna; TOTAL: sum of the catches of the three species). Only the tuna catches for the main purse-seine fleets exploiting DFADs were considered: EU-Spain, EU-France, Seychelles, Mauritius and Korea. Resolutions related to DFAD management plans are indicated with black vertical dotted lines (AB= limit for the number of active buoys per vessel; BY= limit in the total number of buoys purchased yearly per vessel). Other relevant resolutions affecting the DFAD fisheries are indicated in red. All resolutions are indicated considering the year when they entered into force in the abscissa. Data source: Indian Ocean Tuna Commission (https://www.iotc.org/WPTT/23AS/Data/05-CESurface).

2.1.2 Non-target species

Indicators on non-target species should primarily focus on ETP of major concern such as the silky shark, which constitute the main shark bycatch species caught at DFADs, and the oceanic whitetip shark (Amandè et al., 2010; Gilman, 2011; Lezama-Ochoa et al., 2018; Tolotti et al., 2015; Torres-Irineo et al., 2014). Due to the paucity of data, stock assessments are lacking for both species in the Indian Ocean. Based on susceptibility and productivity analyses, Ecological Risk Assessments (ERA) were conducted in 2012 and 2018 (Murua et al. 2012; Murua et al. 2018). However, these assessments only provide relative measures of vulnerabilities of each species to the different fisheries rather than indicator trends. A preliminary abundance trend derived from the associative behavior of silky sharks with floating objects based on observer data has been proposed (Diallo et al. 2019). The results show a slight upward trend between 2006 and 2018, indicating that the local abundance has increased in both Seychelles and Mozambique Channel areas. Nevertheless, it is not possible to infer the significance of these increases, as the relationship between the abundance index and the actual population size is unknown. For the oceanic whitetip shark, a simple occurrence indicator estimated from the proportion of positive sets has been proposed (Tolotti et al. 2019). Oceanic whitetip sharks are much less frequent in DFAD sets than silky sharks, therefore, an abundance indicator based on its associative behavior still requires additional research. Generally, the sample size is not evenly distributed throughout the time series, as observer coverage varied, and a small sample size for relatively rare occurrences can be statistically problematic.

A straightforward way to evaluate the effectiveness of any management measures that aim to reduce shark bycatch would be to develop a timeline of the overall number of sharks caught at DFADs. The information on the catch per set of sharks originates from observers' data. Observations on purse seine sets inform on the number of sharks (and other by-catch species), their status (dead/alive) and their retention or release. The data is gathered by tuna RFMOs and can be made available to scientists, in aggregated forms. In order to build an indicator on the total number of sharks caught by purse seiners at DFADs, extrapolation factors should be applied in the case of partial observer's coverage, considering the shark catch per set of the observed DFAD sets and the overall number of purse seine sets operated on DFADs in the same period/region. From these total catch estimates, overall mortality should be estimated based on at-vessel and post-release mortality rates from dedicated studies. In the Indian Ocean, information on the number of DFAD sets can be obtained through IOTC 3FA forms, which are used to report mandatory information on DFAD activities (deployment, retrieval, encounter, loss at sea, etc.) as well as catch and effort on DFADs for all purse seine fleets operating in the IOTC area of competence (IOTC Resolution 19/02). However, due to gaps and inconsistencies on the way the forms are collected and submitted by CPCs, the information on the total number of DFAD sets is not readily available. Using alternative sources of verification, Tolotti et al. (2022) managed to collate information from the IOTC Form 3FA from most purse seine fleets operating in the western Indian Ocean (Spain, France, Seychelles, and Mauritius) but for the years 2016 and 2018 only. In order to build a timeline that would be more temporally representative, the total number of DFAD sets were collated from national reports presented in the 21st Working Party on Tropical Tuna (IOTC-2019-WPTT21-11_Rev1; IOTC-2019-WPTT21-12; IOTC-2019-WPTT21-14_Rev1). Then, total silky shark catches at DFADs were estimated following the methodology described in Tolotti et al. (2022) from 2014 to 2018. The reports were available for Spain, France and Seychelles, the main purse seine fleets operating in the western Indian Ocean. The proportions of DFAD sets with n silky sharks were obtained from French observer's data (Figure 3 – bottom panel). From these proportions, total silky shark catches were estimated considering the total number of DFAD sets declared in the IOTC reports for each year.

Figure 3 (top panel) shows an example of catch of silky sharks at DFADs. Catches of silky sharks attained a maximum in 2016 and remained relatively stable in the subsequent years. However, this indicator's trend should be considered with care. Indeed, one issue with using national reports is that the information on the number DFAD sets is not georeferenced. Therefore, total silky shark catches can only be derived globally and not by area as is in Tolotti et al. (2022). Furthermore, as mentioned above, trends on DFAD induced shark catch should be further refined to account for actual mortality. This could be done by considering at-vessel and post-release mortality rates from dedicated studies that also consider release practices. A few independent studies estimated mortality rates for silky sharks caught by purse seine vessels in the Pacific, Atlantic and Indian oceans (Eddy et al., 2016; Hutchinson et al., 2015; Poisson et al., 2014; Onandia et al., 2021). These studies estimate total mortality rates between 60% and 80%, even when individuals are released following good practices. This is mainly due to the high at-vessel mortality rate, as most silky sharks are already dead by the time they reach the deck. The best way to incorporate the results of the different studies into total mortality estimates needs to be discussed, since they vary depending on the implementation of good release practices, that could be vessel or fleet specific. Because these practices can also evolve with time, such dedicated studies should be periodically updated.

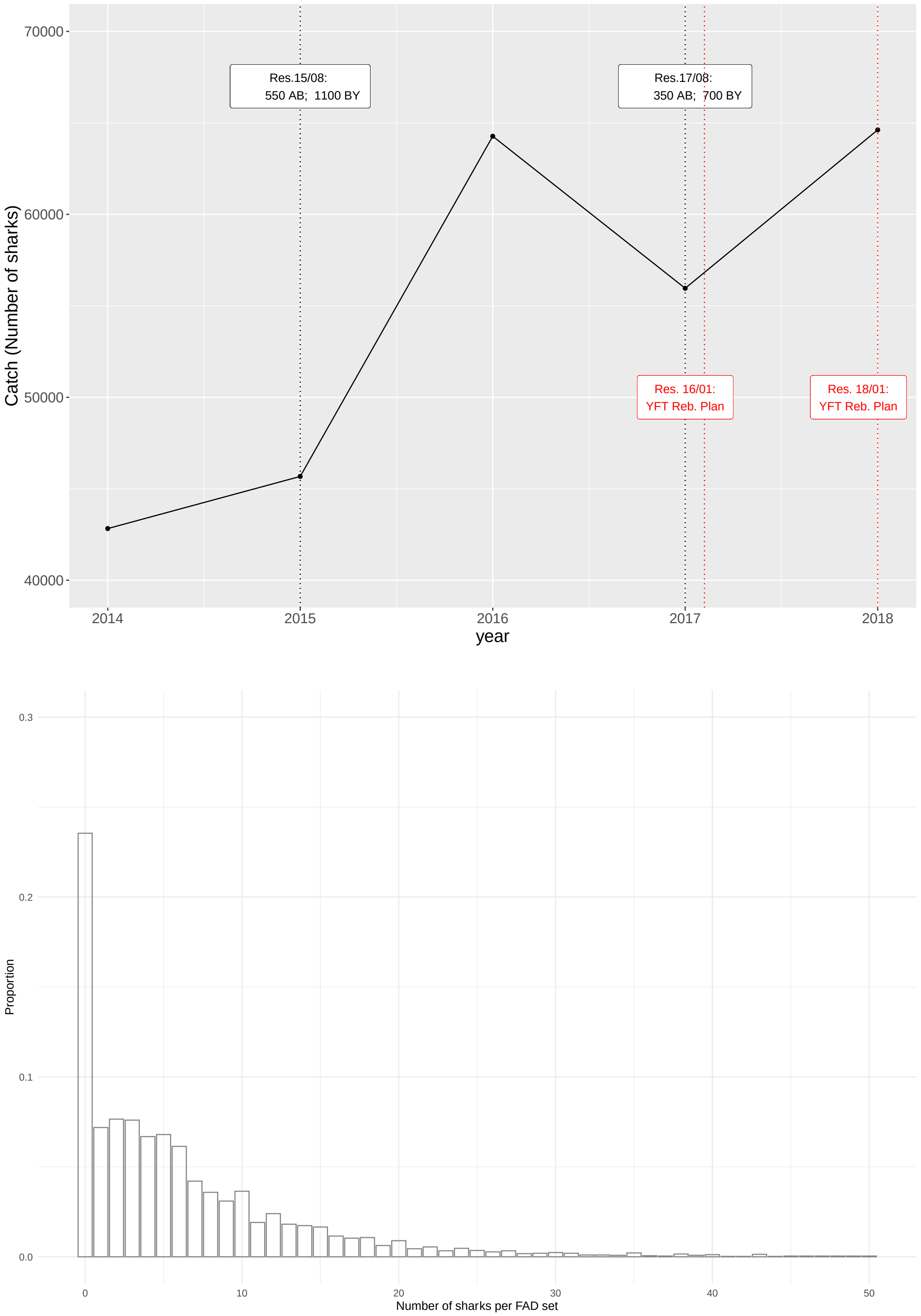

Figure 3. Estimated purse seine catches of silky sharks at DFADs (number of individuals) by the main fleets operating in the western Indian Ocean (Spain, France and Seychelles (top

panel). Bottom panel shows the proportion of silky shark catches (number of individuals) per DFAD set, including sets with 0 sharks. For visualization purposes, the histogram is truncated at sets with 50 sharks (the observed maximum number of sharks per set is 200). Resolutions related to FAD management plans are indicated with black vertical dotted lines (AB= limit for the number of active buoys per vessel; BY= limit in the total number of buoys purchased yearly per vessel). Other relevant resolutions affecting the DFAD fisheries are indicated in red. All resolutions are indicated considering the year when they entered into force in abscissa.

In addition to the indicator shown in Figure 3, a dedicated indicator providing the temporal evolution of shark entanglement risks should be produced to evaluate this additional source of mortality. A first study (Filmalter et al. 2013), quantified the extent of shark entanglement within the underwater structure of DFADs in the Indian Ocean. Since this study unveiled this issue, mitigation measures such as changes in the design of DFADs were voluntarily adopted by the purse seine fleets to reduce the risk of entanglement (Murua et al., 2017). Resolutions on the adoption of fully non-entangling DFADs without netting (IOTC Res. 19/02 (IOTC, 2019b)) and with low entanglement risk have also been adopted across RFMOs (ICCAT Rec.19-02 (ICCAT, 2020), IATTC Res. C-19-01 (IATTC, 2019), WCPFC CMM 2021-01 (WCPFC, 2021)) with the objective of reducing the risk of shark entanglement. The assessment of shark entanglement at DFADs relies on pop-up satellite electronic tags and observers'/scientific data that inform respectively on the vertical behavior of silky sharks (by which entanglement events can be detected) and on the number of sharks observed entangled in the DFADs' underwater structure (Filmalter et al., 2013; Hutchinson et al., 2015; Poisson et al., 2014). To the purpose of monitoring the temporal evolution of shark entanglement risks and the effectiveness of management measures, regular electronic tagging campaigns should be conducted by trained observers.

Finally, similar to tuna, the physiology of other associated species like sharks can also be affected by increasing DFAD densities. Recent electronic tagging studies conducted on both tuna and non-tuna species found around DFADs demonstrated that silky sharks spend significant amounts of time associated with FADs (Bonnin et al., 2020) with a similar associative dynamics as tunas (i.e., comparable residence times) (Tolotti et al., 2020).

Therefore, if the “ecological trap” scenario was proven, it could equally be applied for these species. Future data collection and research effort should be dedicated to evaluating their physiological condition and their trends relative to changes in the DFAD density. No data is currently available to build this indicator in the Indian Ocean.

2.1.3 Habitats

Indicators on the impacts of DFADs on coastal and pelagic habitats aim at assessing how management actions affect the number of DFAD beaching events, the amount of marine litter and pollution caused by DFADs, as well as changes in the number of floating objects found at the sea surface. The main data sources to build such indicators consist in GPS data transmitted by the satellite-linked buoys which equip all DFADs (Escalle et al., 2019; Imzilen et al., 2021, 2022; Maufroy et al., 2015) as well as observers’ and logbook data (Dupaix et al., 2021).

Beaching events correspond to DFADs stranded in coastal environments. Their impacts are particularly critical for coral reef areas, since the DFAD structure can damage these sensitive habitats (Gomez et al., 2020). In the Indian ocean, using satellite-linked buoys data provided by the French fleet, Imzilen et al. (2021) highlighted a steady increase in the percentage of DFAD beaching events (from 3.5% in 2008 to nearly 20% in 2013), followed by a stabilization (between 15-20% in the period 2013-2017). On the other hand, so far no study has been conducted for the other fishing fleets operating in the Indian Ocean, to evaluate whether similar trends could be globally observed over the same period. Furthermore, in order to evaluate the ecological impacts of DFADs on marine habitats, assessing the trends in the *total number of DFAD beaching events* is necessary. Namely, a stable percentage of DFAD beaching events can still imply higher/lower numbers of stranded DFADs (and therefore higher/lower ecological impacts) if the number of DFAD deployments increases/decreases through time. Currently, in the Indian ocean, the data on DFAD deployments is available through two forms: directly in Form 3FA (number of deployments) and indirectly in Form 3FD (only available for the period 2018-2019), which rely on FAD activity information (e.g., deployment) from FAD logbook data (IOTC, 2021). A detailed comparison of the data reported for these forms (IOTC, 2021) revealed that Form 3FA shows under-reported total number of DFAD deployments in comparison to the same data provided through Form 3FD, with a total of around 3,500 more

DFADs reported as deployed by the latter source for both 2018 and 2019. Therefore, the IOTC Secretariat recommends caution when analyzing DFAD deployment data provided through Form 3FA. Similarly, if the data quality appears to be higher when provided through Form 3FD, it is severely limited by the temporal coverage and resolution of the dataset (annual, limited to 2018 and 2019 only). Given these uncertainties and data limitations on the total number of DFADs deployed, to date, a reliable timeline of the number of DFAD beaching events cannot be built for the Indian ocean.

Furthermore, DFAD beaching events are not the only possible fate of DFADs. Indeed, FADs can also sink in the open ocean. Secondly, when a DFAD drifts out the fishing zones, its echosounder buoy can be deactivated by its owner and the DFAD lost and abandoned by the vessel. This practice can be encouraged by resolutions setting limits on the number of operational buoys: in order to comply with the authorized limits, purse-seiners can deactivate buoys that depart from their fishing grounds. Despite, in the case of the Indian Ocean, this practice can be restricted by the limits in the annual purchase of buoys and the total number of buoys in stock per vessel (Resolution 19/02), the actual effect of past management measures on this practice have never been assessed. Finally, the retrieval of the echosounder buoy by another fishing vessel, a common practice in all oceans, is another source of DFAD loss, as well as buoy GPS signal transmission issues (related to hardware/software failure of the buoy). In all those cases, the position of DFADs cannot be tracked anymore, and its fate is unknown. Indicators accounting for the number of DFAD beaching/sinking events should include this additional and unknown source of DFAD loss. Because DFADs also include non-biodegradable materials for the raft frames, floats, and subsurface structure, all these DFAD-loss events can be a source of marine pollution and should be monitored (Moreno et al., 2021). In this respect, the amount of plastics lost into the oceans should be quantified through a specific indicator accounting for the DFAD design (weight and composition of their constituent materials) (Zudaire et al., 2021). This indicator would also allow quantifying the effectiveness of management and mitigation measures promoting the shift towards biodegradable materials for some of the DFAD components (Moreno et al., 2021; Zudaire et al., 2021), as well as designing adequate DFAD recovery programs (Imzilen et al., 2022).

Finally, changes in the surface habitats induced by the deployment of DFADs can be monitored considering the temporal evolution of the number of DFADs relative to the number of natural floating objects (NLOGs), which constitute a natural component of the pelagic habitat (Dagorn et al., 2013; Dupaix et al., 2021). In the western Indian Ocean, such indicator is built from observers' data, which report the position and type of floating objects encountered by the fishing vessels. A recent study suggests that the ratios between the number of DFADs and the number of NLOGs have increased in the recent years (2014-2018) relative to 2007-2008. The entire western Indian Ocean is impacted, with FADs representing more than 85% of the overall FOBs for the period 2014-2018, NLOGs less than 10%, and objects originating from pollution 5% (Dupaix et al., 2021).

3. Operating models

An ensemble of operating models can be developed to support management decisions aiming at mitigating the ecological impacts of DFADs (Table 2).

Table 2. List of operating models focusing on target tuna species, non-target species and coastal and pelagic habitats.

Category	Operating model	Output/Prediction
Target species	Stocks dynamics	Optimal catch and catch-at-age options for maintaining the stock on the target reference points and rebuilding tuna stocks Fishery impact plots per fishing gear
Target/ non-target species	Catches at DFADs	Catch trends for variable DFAD densities
Habitats	FAD and NLOG drifts	Number of FAD beaching and sinking events Changes in the density of floating objects (DFADs and NLOG inside and outside the fishing grounds)

2.2.1 Population dynamics OM

The issue of the increased catch of juveniles of yellowfin and bigeye tuna on floating objects and the relative reduction of sets on free-swimming schools targeting adult individuals is a major concern of the DFAD fisheries (Fonteneau et al., 2013; Griffiths et al., 2019; Ménard et al., 2000). Understanding the consequences of this shift in the exploitation of the juvenile component of yellowfin and bigeye stocks on the yield-per-recruits is key to ensure the sustainability of the DFAD fisheries. This topic is particularly important in relation to the rebuilding plans of overfished stocks, such as the yellowfin tuna in the Indian ocean (IOTC Res. 16/01; Res. 18/01; Res. 19/01; Res. 21/01). However, considering the DFAD catches alone may not be sufficient to draw conclusions: it is necessary to account for the whole stocks and fisheries dynamics, including the catches of juveniles by other gears and adults from other fisheries (e.g., longline fisheries). To this purpose, OMs similar to those currently used in stock assessment and in the MSE framework, like Stock Synthesis (Methot & Wetzel, 2013; Sharma et al., 2020), should be used to quantify the impacts of increased fishing mortalities of juvenile yellowfin and bigeye tunas on the yield-per-recruit and stock biomass in conjunction with the impact on fishing in the adult component. These models can be run considering the main sources of uncertainty on tropical tuna stocks’ dynamics. Simulations can be conducted considering different fishing-mortalities-at-age to identify the best total-allowable-catch-at-age options for the stock rebuilding plans. However, this implies catch allocation rules between gears which are beyond the scientific discussion and involves managers' decisions. Fishery impact analysis (Murua et al., 2021) can be done by analyzing how the population spawning potential has been impacted, historically and at present, by major fishery types over years. Fishery impact analysis is done by estimating the spawning biomass dynamics over time that would have occurred in the absence of historical fishing. The reduction in spawning biomass potential induced by a particular fishing gear is estimated, so that the relative fishery impact on Spawning Stock Biomass (SSB) by major gear type can be compared (see figure 46 in (Ducharme-barth et al., 2020)). As such, fishery impact plots could inform managers on the relative contribution of each gear to the stock status..

2.2.2 DFAD Catches OM

Another ensemble of OMs is necessary to assess how increasing DFAD densities affect the catches of tuna and associated species, including ETP species such as silky sharks. Previous studies already demonstrated that increasing DFAD densities do not necessarily imply larger associated populations (Sempo et al., 2013) or a higher number of DFAD sets (Lennert-cody et al., 2018), revealing that the relationship between number of DFADs and tuna catches can be non-linear and/or non-monotonic. In order to provide scientific advice on DFAD MPs, operating models that can predict tuna and ETP species catch trends for variable DFAD densities should be developed. These models should account for both the associative dynamics of tuna/non-target species at DFADs and the purse seine fishing practices at DFADs (number of DFAD sets). Indeed, for a given DFAD density, the amount of catches of each species depends on both their associative dynamics (i.e. the proportion of time spent associates/not associated, which in turn affects the proportion of the population which is associated, i.e., vulnerable to the fishery (Capello et al., 2016)) and the fishers' behavior (which affects the number of DFAD sets) (Lennert-cody et al., 2018). Building and conditioning such models will require combining information from multiple data sources: logbook/observers' data (which inform on catches per set and number of DFAD sets), echosounder buoys data (which inform on the presence/absence of tuna at DFADs as well as on DFAD densities), and on electronic tagging data (which inform on the amount of time that tagged individuals spent at and away from DFADs), see supplementary Tables S1 and S2. Uncertainties related to the behavioral processes setting the aggregation dynamics (e.g., the role of schooling behavior (Capello et al., 2022)) could also be accounted for in these OM.

2.2.3 FOB drifts OM

Models of FOB drifts, capable of predicting the trajectories of FOBs from their release location and the local surface currents can be used to assess the risks of DFAD beaching (Curnick et al., 2020) and changes in the surface habitats (Dupaix et al., 2021). These models, building on previous results showing that FOBs drift similarly to oceanographic drifters (Imzilen et al., 2019) simulate FOB trajectories using Lagrangian simulations (Lett et al., 2008). Model inputs include (i) FOBs numbers and initial positions (ii) ocean surface currents (iii) the average lifetime of FOBs. To account for uncertainties in the modeled FOB trajectories, a random walk component of particles motion can be considered within the Lagrangian model (Curnick et al., 2020). FOB lifetimes also constitute a source of uncertainty and FOB drift OMs run considering different lifetimes allow to assess the sensitivity of results (Dupaix et al., 2021).

3. Discussion

This study proposes a science-based framework, based on an ensemble of indicators and OMs, to support the development of FAD-fisheries management plans. We show ways to evaluate the effectiveness of DFAD management measures by providing specific examples of indicators related to the ecological impacts of DFADs and their trends, considering the Indian Ocean as a case study.

Some of the indicators proposed in this study are available in the literature and have been presented to tuna RFMOs (Dagorn et al., 2013; Davies et al., 2014; Dupaix et al., 2021; Fonteneau et al., 2000; Imzilen et al., 2021; Lennert-cody et al., 2018; Maufroy et al., 2017). However, scientific studies generally provide a snapshot over a given time window where the studies were conducted or consist of one-time studies (Filmalter et al., 2013). Within the approach proposed in this study, a continuous monitoring of such indicators is proposed, in order to provide scientific advice. Depending on the management objectives, some indicators could be spatialized and considered on a quarterly basis to allow for spatio-temporal management decisions. Derived indicators, that are drawn from the former, can also be built (for example, the ratio between the DFAD catches of target and bycatch species), depending on the management objectives.

Other indicators which include data from other fishing gears and techniques should complement those currently proposed: indicators showing the target and non-target relative catch of DFADs compared to other gears, or, for the purse seine fisheries only, indicators comparing the catches conducted at DFADs and free schools. Global catches of bycatch species and discard rates could also be considered. Moreover, economic indicators would also be key to weight the interests of all parties and evaluate the impacts of management decisions beyond the ecological aspects. For example, the implications of total retention of bycatch species in coastal countries, where long-distance fisheries ports are based, could be measured by monitoring fish prices and sales in local markets, or indicators related to the creation of employment due to canneries. Moreover, indicators accounting for cultural, political and social implications of DFAD use could be defined. Finally, indicators monitoring how the carbon emissions associated to how the purse seine fishery evolves with time and are affected by management decisions could also be used (Chassot et al., 2021).

Due to the complexity of the relationship between number of DFADs, tuna abundance, tuna associative dynamics, the fishing strategies adopted by purse seiners, and the catches of target and non-target species, it is difficult to predict the effects of management measures from indicators alone. For this reason, the use of operating models should complement the proposed indicators. In the current framework, an ensemble of operating models is proposed, each aiming to provide science-based advice on a specific ecological impact of DFADs on target species, non-target species and habitats. Operating models are now widely used in the MSE context for testing harvest control rules of target species (Punt et al., 2016) and, more generally, for evaluating the robustness of multiple indicators within ecosystem-based fisheries management approaches (Fulton & Smith, 2005). So far, the MSE has been developed to support management decisions for single species stocks management (Merino et al., 2020). Remarkably, if the approach discussed in this paper follows the same spirit as the MSE, it substantially differs regarding its targets and objectives, since it is devoted for the management of a fishing tool rather than a fish stock. In conjunction with the management of other fishing tools/gears, this approach will contribute to the sustainable management of the tuna stocks and, more globally, marine ecosystems.

The scientific advice that can be produced through the proposed indicators and operating models is related to the ecosystem-based approach for fisheries management (EBFM). Several studies advocated the adoption of an integrated EBFM in RFMOs (Bard et al., 1985; Clarke et al., 2006; Huckstorf et al., 2009; Melnychuk et al., 2017; Patrick & Link, 2015; Pikitch et al., 2004; Pitcher et al., 2009). However, so far very little applications of an EBFM can be found within tuna RFMOs, where management decisions are most often taken considering single species management approaches. In the case of DFAD fisheries, similar to other fishing practices and gears, whose impacts involve not only target tuna species, but also non-target species, coastal and pelagic habitats, adopting an integrated EBFM and overcoming the limits of single-species management approaches is an essential step. In this respect, this study offers new pathways towards the implementation of an EBFM. Similarly, the use of OMs allows accounting for uncertainties on biological and behavioral processes, which is a pre-requisite of the Precautionary Approach framework (Garcia, 1994).

Both indicators and OMs rely on catch-dependent and independent data provided by fisheries monitoring programs, scientific surveys and stakeholders such as fishers. The synergy between data collection programs and the development of models and indicators is a key aspect of the proposed framework. In this respect the density of DFADs and the number of DFAD deployments are undoubtedly a key input for building and interpreting the proposed indicators for monitoring the ecological impacts of DFADs. Until recently, instrumented buoys data (buoy daily position data and/or echosounder raw acoustic biomass data) were provided to national scientists through specific agreements which concerned only national fleets. This data has certainly proven to be useful for scientists (Baidai et al., 2020; Moreno et al., 2016; Santiago et al., 2016), but its partial coverage has so far impended accurate estimations of total DFAD densities. Nowadays, specific resolutions have been adopted to provide, for all contracting parties using DFADs, buoys position data to tuna RFMOs (e.g. IOTC Res 19/02) and buoy daily position data and biomass data (IATTC CMM 21-04). These new datasets allow estimating the density of operational buoys (i.e., the buoys which are transmitting their data remotely), which can be used as a proxy of the DFAD density. However, as mentioned before, buoys can currently be deactivated or retrieved while at sea. As a result, the density of operational buoys can only be considered as a lower bound for the actual number of DFADs floating in the ocean. More importantly, depending on the buoy deactivation practices (which may change with time depending on the limits imposed on the maximum number of operational buoys allowed by tuna RFMOs) the gap between the number of operational buoys and DFADs could vary, further biasing the estimates of the total number of DFADs estimated based on buoy numbers. To cope with this issue, buoys data should be complemented with additional information allowing a higher traceability of the fate of DFADs. First, the information on the number of deactivated buoys should be made available at the same scale as the buoys’ position data. Second, the number of DFAD deployments and retrievals should accurately be provided to tuna RFMOs and scientists. Moreover, DFAD should be associated with unique identifiers and their encounters (since the time of deployment) should be recorded within dedicated DFAD logbooks.

Since January 2020, in the Indian ocean, due to the entry into force of IOTC resolution 19/02, the buoys GPS positions are provided to the secretariat at a daily scale by the buoy providers, to support the monitoring of compliance with the limitation established by the same resolution. The IOTC secretariat can currently deliver this data in an aggregated form, at a 1°/monthly scale. This novel data availability constitutes a big step forward, because the information on the overall density of echosounder buoys (and not only the buoys of a single purse-seine fleets delivered through specific agreements with national scientists) is key to evaluate DFAD densities and their ecological impacts. On the other hand, the unavailability of fine-scale buoy data (i.e., daily GPS positions of the buoys) still limits its exploitation for scientific purposes. Indeed, the operational information exploited by skippers has much higher resolutions with data being transmitted every few hours (e.g., 6 to 12 hours in default mode, depending on the buoy model). Similarly, both tuna and shark species respond to the local number of FADs at time scales of the order of few days (Tolotti et al., 2020). In order to build and condition operating models accounting for the behavior and catchability trends of tuna and associated species for variable FAD densities, making this data available to scientists at a finer scale (i.e., daily GPS positions transmitted by the buoys) will be key.

Finally, the data related to “log-associated catches” of tuna species provided by tuna RFMOs generally include the aggregated tuna catches conducted both on NLOGs, DFADs or other floating objects. Management decisions promoted by tuna RFMOs can set limits in the number of DFADs but cannot apply to other types of floating objects such as the NLOGs. However, the latter can also show variable densities through time, due to natural and anthropogenic factors, such as extreme weather events or climate change. Reporting separately the tuna catches conducted on NLOGs and DFADs is key to discern the specific effects of management decisions devoted to set DFADs limits from other sources of variabilities in the total number of FOBs that are independent from management.

Conclusions

This study presents a new science-based framework to evaluate options for the management of DFADs, relying on indicators and operating models. The operating models can support scientists and decision-makers alongside a set of indicators obtained from both fisheries-dependent and independent FAD-related data, towards a science-based approach for the management of FAD fisheries. The *operating models* and indicators proposed in this study can also be considered as part of adaptive management strategies. In this respect models and indicators can be used to build performance measures and to understand the effectiveness of past, present and future management actions. The same approach can be applied to other fisheries, including the science-based management of AFAD fisheries by coastal states. The use of DFADs is currently the source of conflicting debates. Recent discussions on FADs in tuna RFMOs have gone through at the point of turning scientific and technical groups into political debates. As a result, scientific evidence and advice has lost its importance to provide management advice and mainly the political position of interest groups have prevailed in the scientific groups. With the approach suggested here, science can be put back at the forefront of the subject to provide the DFAD fishery management advice.

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Supplementary Material

Category	Observable	Source
Tuna individuals	Time spent by tuna associated at FADs (residence time)	Electronic tagging
	Time spent by tuna unassociated (absence time)	
Tuna aggregations	Fraction of FADs occupied by a tuna aggregation Time spent by a FAD without tuna aggregations Time spent by a FAD with tuna aggregations	Echosounder buoys
FAD catches	Catch/set of tuna species	Logbook/observers'data
Environment	Local number of FOBs	Echosounder buoys + observers'data

Table S1. List of observables that are relevant for conditioning operating models that account for tuna associative dynamics.

Category	Observable	Data availability
FAD fishing	Fraction of followed FOBs (operational buoys) Number of FAD/NLOG sets per vessel	Echosounder buoys + logbook/observers'data
FAD catches	Catch/set of tuna species Catch/set of ETP species	Logbook/observers'data
Environment	Local number of FOBs	Echosounder buoys + observers'data

Table S1. List of observables that are relevant for conditioning operating models that account for the fishers' behavior.