Ecology and behavior of tuna and non-tuna species at drifting fish aggregating devices (DFADs) in the Indian Ocean using fishers' echo-sounder buoys

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PhD Thesis 2019
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PhD Thesis

"Ecology and behavior of tuna and non-tuna species at drifting fish aggregating devices (DFADs) in the Indian Ocean using fishers' echo-sounder buoys"

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July 2019

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Resumen

Los objetos que flotan a la deriva en la superficie de los océanos tropicales, también conocidos como dispositivos concentradores de peces a la deriva (DCPs), atraen a cientos de especies marinas, entre ellas las principales especies de túnidos tropicales comerciales, así como también otras especies no atuneras. Actualmente, los DCPs son utilizados casi exclusivamente por las flotas industriales de cerco, donde los pescadores aprovechan este comportamiento asociativo para incrementar sus capturas (Castro et al. 2002; Fonteneau et al. 2013). Generalmente, los DCPs se componen de una estructura flotante (por ejemplo, balsas de bambú con corchos) y una parte submarina suspendida debajo del objeto (por ejemplo, redes atadas en "salchichas", cuerdas, hojas de palma, pesos). Hoy en día, la gran mayoría de las flotas de cerco de todo el mundo utilizan DCPs equipados con boyas con ecosonda conectadas por satélite (Lopez et al. 2014; Moreno et al. 2016b), las cuales proporcionan a los pescadores la localización precisa del objeto y una estimación aproximada de la biomasa que se encuentra debajo, de forma remota y en tiempo casi real.

La pesca con DCPs ofrece grandes ventajas cuando se compara con la pesca en cardúmenes no asociados (también llamados de banco libre), como por ejemplo la reducción en el tiempo de búsqueda (Fonteneau et al. 2013; Lopez et al. 2014), reducción del tiempo de viaje y del coste operativo para encontrar bancos de atunes (Guillotreau et al., 2011; Davies et al., 2014) o el éxito de los lances a objeto frente a los de banco libre (Fonteneau et al. 2000). A pesar de todas estas ventajas, el uso creciente de DCPs podría tener consecuencias negativas en el ecosistema (Fonteneau et al. 2000; Marsac et al. 2000; Essington et al. 2002), como el aumento de la captura de juvenil de patudo y rabil (Leroy et al. 2012), mayores tasas de captura incidental (Castro et al. 2002; Romanov 2008; Amandè et al. 2010; Amande et al. 2012) y la posible alteración de los movimientos naturales de las especies asociadas, así como su comportamiento y biología (Marsac et al. 2000; Hallier and Gaertner 2008; Dagorn et al. 2012b). Debido al uso masivo de DCPs en las pesquerías de cerco industrial de todo el mundo, el valor de esta pesquería y los posibles impactos negativos es realmente necesario mejorar el conocimiento sobre la ecología y el comportamiento de las especies asociadas con DCPs

para desarrollar un asesoramiento científico adecuado para las Organizaciones Regionales de Ordenación Pesquera (OROP).

Actualmente, el conocimiento científico sobre el comportamiento y la ecología de las especies asociadas a los DCPs es bastante limitado, debido principalmente al alto coste económico y humano asociado a la investigación de los DCPs a gran escala, ya que estos objetos derivan por la superficie de los océanos durante varios meses. Un proyecto de investigación sobre la dinámica y distribución espacial de especies asociadas con DCPs requiere la recolección de datos a gran escala, lo cual es casi imposible llevar acabo con un solo programa científico debido a que el acceso y el trabajo en los DCPs remotos es poco práctico, tanto desde el punto de vista económico como logístico. Aunque en los últimos años ha aumentado la investigación relacionada con los DCPs, queda mucho por hacer e investigar.

En los últimos años, varios estudios han destacado la importancia que tienen los datos acústicos proporcionados por las antes mencionadas boyas con ecosondas en la investigación de varios temas de relevancia científica (Santiago et al. 2015; Lopez et al. 2016; Moreno et al. 2016a), incluyendo la investigación sobre la ecología y el comportamiento de las especies asociadas, ya que recogen información del ecosistema pelágico de una manera económicamente rentable (Moreno et al. 2016a). A diferencia de los datos basados en las capturas, las boyas con ecosonda proporcionan datos acústicos menos afectados por la dinámica relacionada con la pesca, el comportamiento de la flota, el esfuerzo y las limitaciones espacio-temporales. Además, los DCPs cubren miles de kilómetros a través del océano durante varios meses, recogiendo automáticamente una gran cantidad de información sobre la biomasa asociada bajo ellos.

El objetivo de esta tesis es describir el proceso de agregación, investigar la distribución espacio-temporal y las preferencias ambientales de los túnidos y otras especies asociadas a DCPs, usando datos acústicos proporcionados por las boyas con ecosonda de los pescadores. Esto contribuirá a la evaluación y ordenación de los atunes tropicales en el Océano Índico, ya que proporcionará una mejora en los conocimientos sobre la ecología y el comportamiento de los atunes y otras especies no atuneras asociadas con los DCPs. Para lograr este objetivo se recopilaron, procesaron y analizaron datos acústicos proporcionados por más de 7500 boyas con ecosonda utilizadas por los pescadores en el Océano Índico entre 2012 y 2015. Esta tesis se ha dividido en cinco capítulos, presentados como un trabajo científico individual, con su propia introducción, material, resultados y discusión. De esta manera, se ha incluido inevitablemente información redundante sobre la introducción y las secciones de materiales y métodos.

El **Capítulo 1** presenta un análisis en profundidad de los datos acústicos proporcionados por los pescadores y establece un protocolo estandarizado para procesar los datos acústicos de las boyas con ecosondas con fines científicos. Además, este trabajo contribuye a la mejor comprensión de las fuentes de variabilidad e incertidumbre de los datos.

Las boyas con ecosonda utilizadas actualmente no proporcionan información sobre la composición por especies o tamaño bajo los DCPs. El objetivo del **Capítulo 2** es mejorar las estimaciones de biomasa proporcionadas por los ecosondas usadas por la flota, utilizando modelos propuestos anteriormente basados en el conocimiento existente de la distribución vertical, pesos y *target strength* (TS) de las especies asociadas a los DCPs.

El **Capítulo 3** describe el proceso de agregación de DCPs vírgenes en el Océano Índico Occidental, usando la información acústica de boyas con ecosonda proporcionadas por los pescadores. Este capítulo estudia el día de llegada al objeto (a partir de la fecha de despliegue de un DCP virgen) de las especies atuneras y no atuneras, así como los procesos de agregación de ambos grupos de especies usando modelos aditivos generalizados mixtos. Además, en el análisis se consideran diferentes temporadas, áreas y profundidades de la estructura subacuática del DCP para tener en cuenta las posibles diferencias espacio-temporales y estructurales. Este trabajo contribuirá a ayudar en la sostenibilidad de las pesquerías atuneras, proporcionando información para ayudar a diseñar medidas de ordenación específicas para mitigar la captura incidental y reducir los posibles efectos negativos asociados a la pesca en DCPs.

El **Capítulo 4** investiga las preferencias de hábitat y la distribución de los atunes y especies no atuneras asociadas con los DCPs en el Océano Índico, utilizando modelos espaciales jerárquicos bayesianos basados en datos acústicos, información ambiental (e.g. temperatura de la superficie del mar, clorofila, salinidad…) y variables del DCP (e.g. identificación del DCP y días en el agua). Los resultados de este estudio podrían contribuir al diseño de medidas de ordenación como, por ejemplo, vedas espacio-temporales para reducir el impacto de las pesquerías de cerco con DCPs sobre las poblaciones de atún y especies asociadas.

El **Capítulo 5** presenta, por primera vez, una comparación de la distribución espacio-temporal de los atunes tropicales agregados bajo los DCPs, usando diferentes fuentes de datos. Para ello se utilizaron modelos espaciales jerárquicos bayesianos usando datos dependientes (datos de captura) e independientes (datos acústicos) de la pesca. Los resultados permitirán analizar las ventajas y desventajas de ambas fuentes de datos, así como determinar la validez de los datos acústicos proporcionados por las boyas con ecosonda de los pescadores para fines científicos. Además, los resultados contribuirán a la mejora del conocimiento de la dinámica espacial y la distribución de los túnidos en el Océano Índico occidental y ayudarán al asesoramiento científico de las OROP.

Finalmente, se presenta una discusión y conclusiones generales para analizar los principales resultados y conclusiones obtenidos en esta tesis doctoral, incluyendo la tesis que responde a la hipótesis de trabajo del estudio.

Summary

Floating objects drifting in the surface of tropical waters, also known as drifting fish aggregating devices (DFADs) when they are built for fishing purposes, attract hundreds of marine species, including tuna and non-tuna species. DFADs are used almost exclusively by industrial tuna purse seine fleets throughout the world´s tropical oceans, where the fishers take advantage of this associative behavior in order to increase their catches (Castro et al. 2002; Fonteneau et al. 2013). DFADs are generally composed by a floating structure (e.g. bamboo rafts with purse seiner corks) and an underwater part suspended below the floating object (e.g. nets tied in “sausages”, ropes, palm leaves, weights). Today, the vast majority of the purse seine fleets ocean wide use DFADs equipped with satellite linked echo-sounder buoys (Lopez et al. 2014; Moreno et al. 2016b), which remotely provide fishers in near real time with accurate geolocation of the object and a rough estimate of the biomass underneath.

DFAD fishing represent certain notorious advantages when comparing with fishing on unassociated schools (also called free-swimming schools, FSC), such as the reduction in search time (Fonteneau et al. 2013; Lopez et al. 2014), traveling time and operating cost for finding tuna schools (Guillotreau et al. 2011; Davies et al. 2014b) or the success of DFAD sets against the free-school sets (Fonteneau et al. 2000). Despite these advantages, the increasing number of DFAD deployments could bring negative consequences (Fonteneau et al. 2000; Marsac et al. 2000; Essington et al. 2002), such as the increase of small bigeye and yellowfin tuna catch (Leroy et al. 2012), higher bycatch ratios of certain species (Castro et al. 2002; Romanov 2008; Amandè et al. 2010; Amande et al. 2012) and potential alteration of the natural movements of the species and their behavior and biology (Marsac et al. 2000; Hallier and Gaertner 2008; Dagorn et al. 2012b). Due to the massive use of DFADs in tuna fisheries, the value of this fishery and the potential negative impacts, increasing knowledge of the ecology and behavior of tuna and non-tuna species associated with DFADs is key to develop adequate scientific advice for tuna Regional Fisheries Management Organizations (RFMOs).

Scientific knowledge on the behavior and ecology of DFAD associated aggregations is currently limited, mainly due to the high human and economic cost associated to

investigating DFADs at large scale. As floating objects drift across the surface of the oceans for several months, they are temporary in time and space. Thus, the establishment of a research project on species associated with DFADs requires the collection of large-scale data on their dynamics and spatial distribution. A single scientific program alone could not achieve such spatio-temporal coverage, as accessing and working on remote DFADs will be impractical and unrealistic, both economically and logistically. As such, few direct observations of tuna behavior and dynamics at FADs have been made using active and passive acoustic tracking (Taquet et al. 2007a; Filmalter et al. 2011; Schaefer and Fuller 2013; Matsumoto et al. 2014; Filmalter et al. 2015), scientific acoustic surveys (Moreno et al. 2007b; Boyra et al. 2018), and underwater visual census (Taquet et al. 2007b). Although in recent years, research related to DFADs has increased, much remains to be done and investigated.

Recent studies have noted the importance that acoustic data provided by the echo-sounders buoys attached to the DFADs have addressing several issues of scientific relevance (Santiago et al. 2015; Lopez et al. 2016; Moreno et al. 2016a), including the investigation of the ecology and behavior of associated species, as they collect catch-independent information of the pelagic ecosystem in a privileged cost-effective manner (Moreno et al. 2016a). Unlike catch-based data, echo-sounder buoys provide acoustic data that is less affected by fisheries-related dynamics, such as fleet behavior, effort, and spatio-temporal constraints. Furthermore, DFADs cover thousands of kilometers across the ocean for several months, collecting automatically a huge amount of acoustic biomass information.

The aim of this thesis is to describe the aggregation process, investigate the spatio-temporal distribution and environment preferences of tuna and non-tuna species aggregated with DFADs, using acoustic data provided by fishers´ echo-sounder buoys. This will contribute to the assessment and management of tropical tunas in the Western Indian Ocean as the will require knowledge about the ecology and behavior of tuna and non-tuna species associated with DFADs.

For achieving the aim of this PhD, acoustic data provided by more than 7500 echo-sounder buoys used by fishers in the Indian Ocean was collected, processed and analyzed for 2012-2015. This thesis has been divided in five chapters, presented as an individual scientific paper, with its own introduction, material, results and discussion. In this manner, some redundant information has been inevitably included regarding introduction and materials and methods sections.

Chapter 1 provides an in-depth analysis of the acoustic data provided by fishers and establishes a standardized protocol to process the biomass gathered by echo-sounder buoys to be used with scientific purposes. In addition, this work contributes to the understanding of variability sources and uncertainty in the data.

Current echo-sounder buoys do not provide information on species or size composition under the DFADs. The aim of the **Chapter 2** is to progress towards improved remote biomass estimates using the previous models to convert biomass from echosounder acoustic signal available in the field, based on existing knowledge of the vertical distribution of non-tuna and tuna species at DFADs and mixed species target strengths (TS) and weights.

Chapter 3 describes the aggregation process of virgin DFADs in the Western Indian Ocean, ascertained through using fishers' echo-sounder buoys information. This chapter studies the arrival day (from the date of deployment of a virgin DFAD) of tuna and non-tuna species and investigates the aggregation processes of the two species group using Generalize Additive Mixed Models. Moreover, different seasons, areas and depths of the underwater structure of the DFAD is considered in the analysis to account for potential spatio-temporal and DFAD design differences. This work will contribute to assist on the sustainability of tuna fisheries, helping to design mitigation conservation management measures for tuna and non-tuna species, such as reducing the undesired bycatch.

Chapter 4 investigates the habitat preferences and distribution of tuna and non-tuna species associated with DFADs in the Indian Ocean. This study implemented Bayesian Hierarchical spatial habitat models based on catch independent data derived from fishers' echo-sounder buoys, environmental information (Sea Surface Temperature, Chlorophyll, Salinity, Eddy Kinetic Energy, Oxygen concentration, Sea Surface height and

Heading) and DFAD variables (DFAD identification, days at sea). The results of his study could contribute to design spatio-temporal conservation management measures (e.g. area closures) for both target and non-target species.

Chapter 5 presents, for the first time, the comparison of spatio-temporal distribution of tropical tuna aggregated under the DFADs, using observations from different data sources. The aim of this chapter is to investigate tuna distribution in the Indian Ocean implementing Hierarchical Bayesian spatial habitat models using fisheries dependent (i.e. catch data) and independent (i.e. acoustic data from fishers´ echo-sounder buoys) data in order to compare the results obtained. The results will make it possible to analyze the advantages and disadvantages of both data sources, as well as will allow determining the suitability of using fishers´ echo-sounders buoys acoustic data for species distribution models, and more generally, their validity for scientific purposes. Moreover, results of this exercise will contribute to increase the knowledge of the spatial dynamics and distribution of tuna in the Western Indian Ocean and assist the scientific-advice of t-RFMOs.

Finally, general discussion and general conclusions are presented to analyze the main results and conclusions of this thesis dissertation, including the thesis answering to the working hypothesis of the study.

GENERAL INTRODUCTION

1. Tuna world fisheries

Global capture fisheries production was 90.9 million tons in 2016, of which 87.2 percent of the total was fishing in marine waters (FAO 2018). Tunas are of great importance because of their high economic value and extensive international trade, representing a significant part of the global fish economy with an annual value of USD 42.2 billion (Galland et al. 2016).

Although the term tuna includes 15 species divided into 5 genus (Graham and Dickson 2004) (*Allothunnus, Auxis, Katsuwonus, Euthynnus* and *Thunnus*), seven are of major commercial importance (i.e. skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), bluefin (*Thunnus thynnus*, *Thunnus maccoyii*, *Thunnus orientalis*) and albacore (*Thunnus alalunga*)). The total landings of the principal market tuna species have showed a continuous increasing trend since 1950, reaching 4.8 million tons in 2017 (ISSF 2019) (**Figure I.1**).

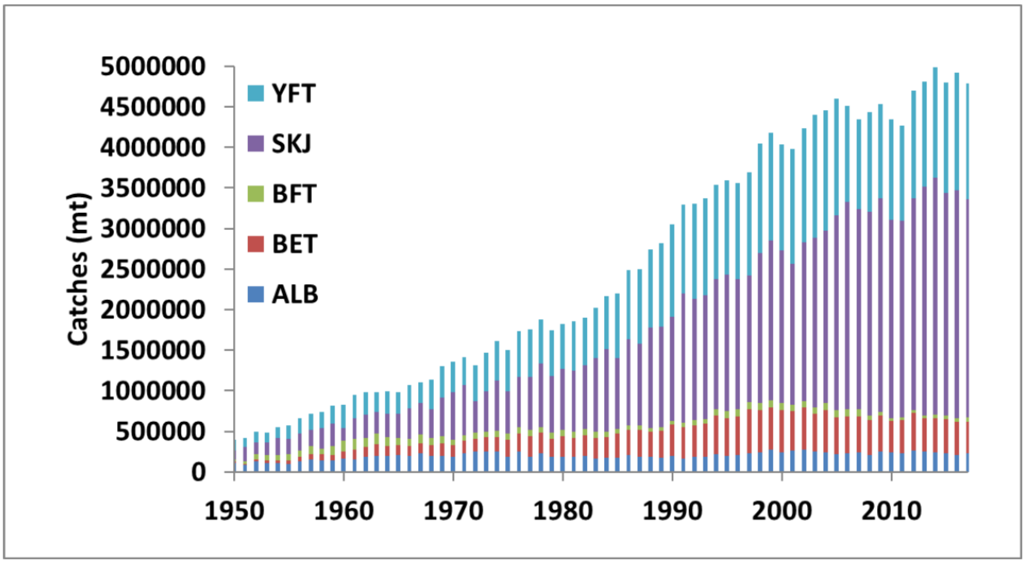


Figure I.1. *Global trends in catch (tons) of major commercial tunas by species. Source: ISSF (2019)*

Tuna fisheries are among the oldest in the world. One of the first evidences of tuna fishing was Phoenician trap fisheries for bluefin tuna occurring around 2000 *Before Christ* (BC) (Ravier and Fromentin 2001). Since then, traditional tuna fishing has been carried out in various parts of the world, generally locally and near the coasts but written documents have been scarce till the 19th century. As a result of increasing demand for canned tuna, industrial fisheries started during the 1940s and 1950s (Majkowski 2007). Since then, the number of vessels has been continuously increasing in parallel with the use of diverse types of fishing gears, and many countries have begun to participate in tuna fisheries.

From the 1950s to the mid-1970s, longline fishery and pole-and-line fishery were the main fishing gears involved in the tuna fisheries worldwide. The relative importance of these fishing gears decreased with the fast development and expansion of the purse seine fishery in the early 1980s. Since the 1980s, global purse seine catches continuously increase, being currently the major gear capturing tropical tunas worldwide (**Figure I.2**).

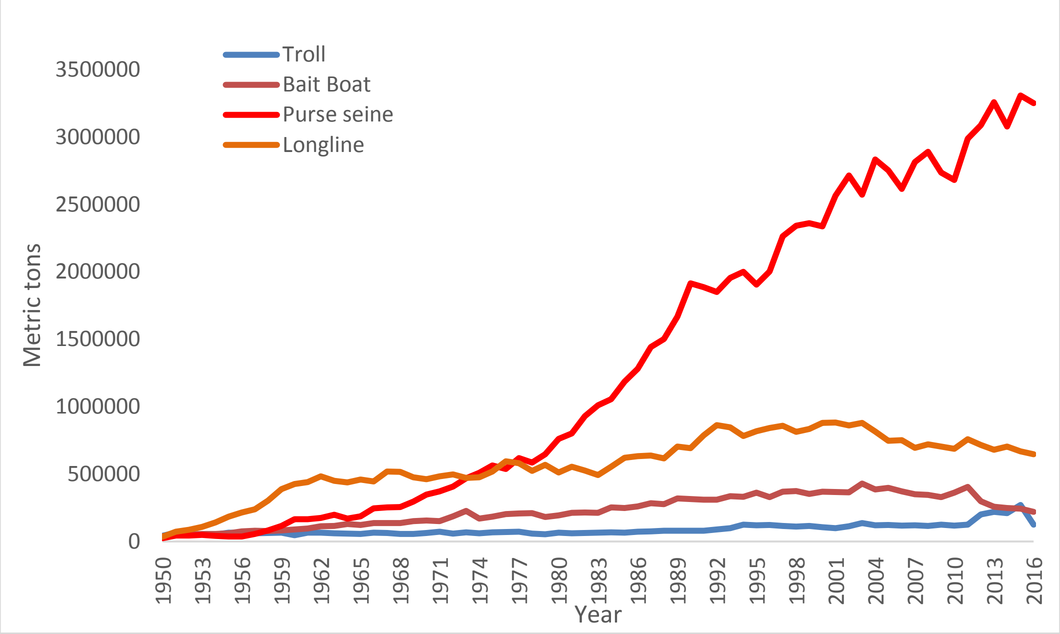


Figure 2. *World Major Tuna Catch by Fishing Gears (1950-2017). Data collected from the RFMOs databases*

2. Tuna purse seine fishery

Nowadays, the tuna purse seine fishery accounts for approximately 65% of the world tuna catches (**Figure I.3**) (ISSF 2019), representing nearly USD 26 billion of tuna´s total end value (Galland et al. 2016).

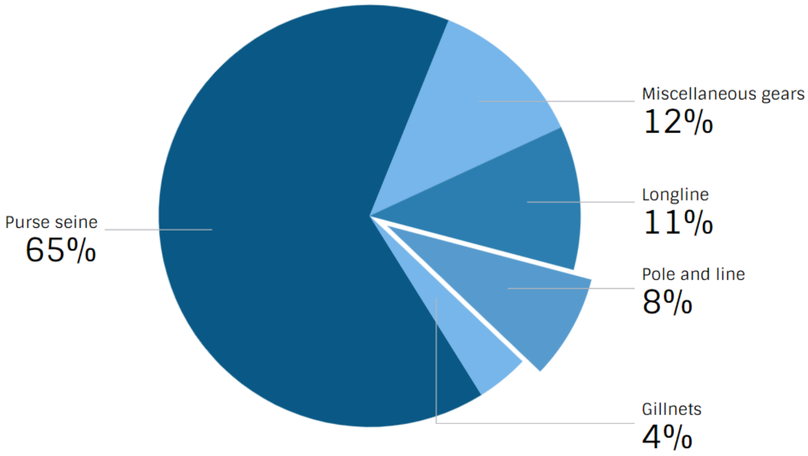


Figure I.3. *Percentage of tuna catches by fishing gear. Source: ISSF (2019)*

The industrial purse seine gear uses a large net which encircles the school of tunas and is closed at the bottom to entrap the tuna school. The fishing operation consists in several steps (**Figure I.4**). Once a tuna school is detected, the vessel chases the school until is placed next to it to deploy the net. The net is deployed by an auxiliary boat called “panga”, encircling the school. During the set, the purse seiner is responsible for describing the circle that will form the purse seine, while the "panga" approaches one end of the net to the bow of the vessel, moving in the opposite direction to the movement of the vessel until the purse seine is closed. Then, the net is closed through the bottom along a seine or steel cable, catching the fish. Fish are harvested with the vessel’s gear and winches, using a large scoop net called the “braile”. Finally, the tunas are stored in wells, first in brine and once is cold, frozen dry at -20ºC.

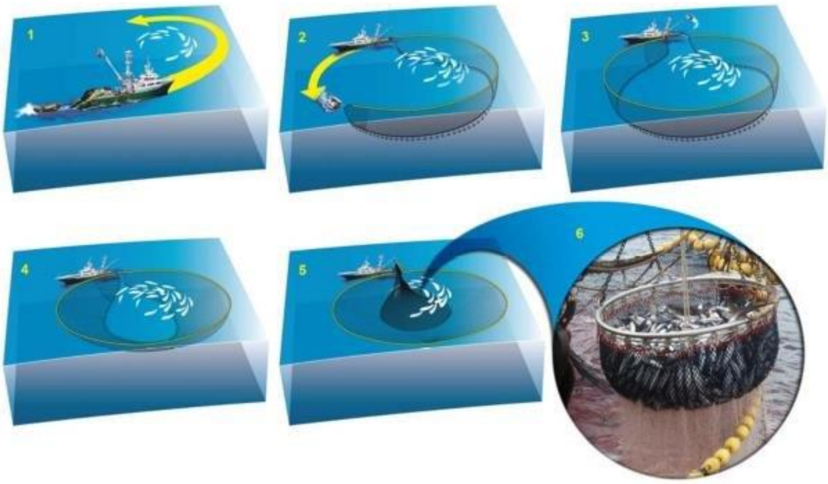


Figure I.4. *Different phases in the deployment of a purse seine. Source: IRD, EME*

2.1 Composition of fishery

The tropical tuna purse seine fishery targets skipjack and yellowfin, and in lesser extend the bigeye depending on the fishing mode (see section 2.3), as it exploits their surface schooling behavior. Nevertheless, this fishery also catch non-target species, which include the incidental catch of non-target marine animals and undersized individuals of target species (Davies et al. 2009).

Tunas

Skipjack tuna (*Katsuwonus pelamis*) (**Figure I.5, A**), which is the most important captured tuna species and mostly used in cans for consumption, is an epipelagic fish distributed in the three tropical oceans (**Figure I.5, B**), confined to waters with temperatures above 15ºC (overall temperature range of recurrence is 14.7° to 30°C) (Barkley et al. 1978; Collette and Nauen 1983). The depth distribution range of skipjack tuna is from the surface to about 260 m during the day (Collette and Nauen 1983). Previous studies have indicated that skipjack tuna inhabit predominantly the mixed layer, but occasionally could be found below the thermocline for short periods (Schaefer and Fuller 2005; Matsumoto et al. 2006). Adult skipjack tuna feed on fish, crustaceans, cephalopods and molluscs (Matsumoto et al. 1984). Skipjack is the fastest growing tuna species (Froese and Pauly 2009), with a maximum fork length of about 108 cm, which corresponds to a weight of 32.5 to 34.5 kg (Collette and Nauen 1983), although the typical capture size is between 40 and 70 cm fork length. As a result of the high growth rate until the onset of maturation, together with a young age at maturity, year-round spawning season (Hunter et al. 1986; Schaefer and Fuller 2019), high spawning potential of young age classes and high fecundity, Skipjack tuna is a resilient species (Stéquert et al. 2001; Grande et al. 2014; Eveson et al. 2015). The maximum age of skipjack tunas is not known but is relatively short, living between 3 and 4 years (Murua et al. 2017).

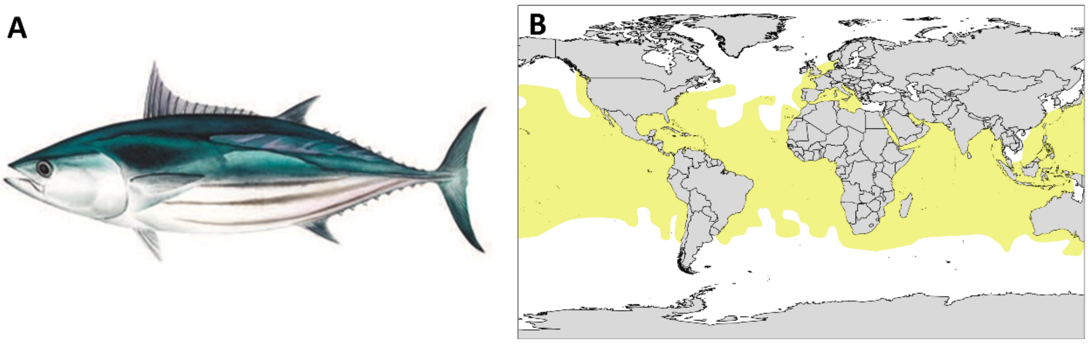


Figure I.5. *Skipjack tuna (Katsuwonus pelamis, Linnaeus 1758) (A) and its spatial distribution (B)*

Yellowfin tuna (*Thunnus albacares*) (***Figure* I.6, *A***) is a highly migratory mid-sized tuna, widely distributed in tropical and sub-tropical waters of the Atlantic, Pacific and Indian Oceans (Collette and Nauen 1983) (**Figure I.6, B**). The temperature boundaries of occurrence for yellowfin tuna are roughly 18° and 31°C (Collette and Nauen 1983). Yellowfin tuna is basically limited to depths of the mixed layer or at the top of the thermocline (Holland 1990; Brill et al. 1999; Dagorn et al. 2006), but occasionally make deep dives for short durations (e.g. 460 m) (Carey 1982). The relationship between yellowfin tuna and thermocline indicates that temperature is the major limiting factor in their vertical distribution (Sund et al. 1981; Brill 1994). Yellowfin tuna is a relatively large tuna, being the most common size of the catch between 40 and 150 cm fork length and a weight of 1.3 to 70 Kg (Collette and Nauen 1983). This specie reach the status of mature by the time they reach a length of 100 cm in fork length at an age of about 3 to 5 years (Zhu et al. 2008; Froese and Pauly 2009) being a multiple egg batch-spawner, spawning over a vast areas of the tropical zone throughout the year (Schaefer 2001). Yellowfin tuna has a lifespan of up to 6.5 years (Lehodey and Leroy 1999).

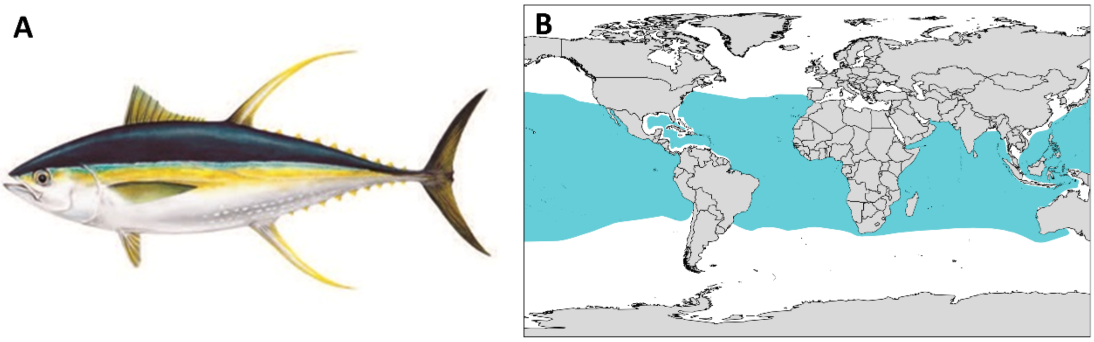


Figure I.6. Yellowfin tuna (*Thunnus albacares, Bonaterre 1788) (A) and its spatial distribution (B)*

Bigeye tuna (*Thunnus obesus) (**Figure** **I.7, A)*** is an epipelagic and mesopelagic species, which live in the tropical and warm temperate waters of the three tropical oceans (**Figure I.7, B**), however, they occupy deeper, cooler waters compared to other tropical tunas. Bigeye tuna is distributed in a temperature range from 13° to 29° C, with an optimal range of between 17° and 22° C (Collette and Nauen 1983). Bigeye tuna are known to occupy depths below the thermocline (Schaefer and Fuller 2002; Olson et al. 2016), as they can dive into deeper and cooler waters due to its heat exchange system. Tunas have an specific vascular heat exchange system by counter current circulation, called "rete mirabile" (Barrett and Hester 1964; Carey and Teal 1966), which allows to conserve heat produced by metabolism. The degree of development of this system is different among tuna species and influences their vertical distribution. As bigeye has a more sophisticated heat exchange system (i.e. visceral heat exchange system), which is the main factor driving the vertical distribution of the species, they can explore deeper and colder waters (Holland and Sibert 1994; Graham and Dickson 2001). Bigeye tuna is one of the largest species of tuna, normally weighing between 20 and 80 Kg and reaching lengths up to 180 cm, and have a longer lifespan than either yellowfin or skipjack, which is estimated to be about 12 years at least (Murua et al. 2017).

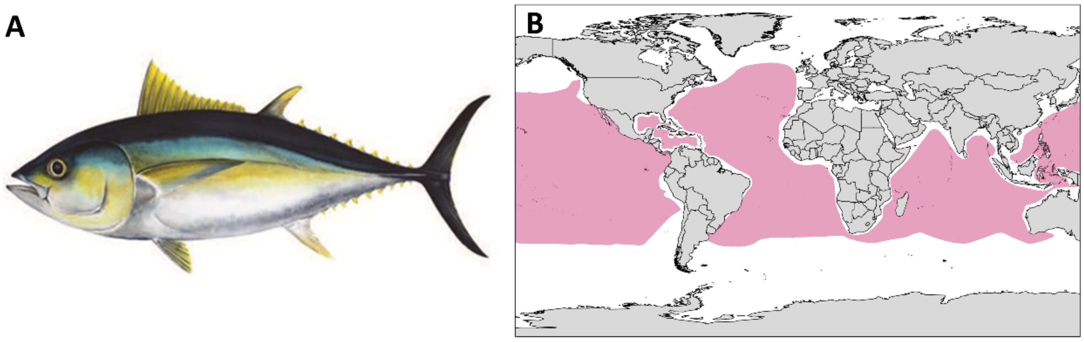


Figure* I.*7. Bigeye tuna (*Thunnus obesus, Lowe 1839) (A) and its spatial distribution (B)*

Compared to the small, fast growing and fecund skipjack tuna (Grande et al. 2014), yellowfin and bigeye tunas have higher length at maturity at around 100–110 cm fork length (Sun et al. 2013; Zudaire et al. 2013) and a lower growth rate (Murua et al. 2017).

They are therefore considered to be more sensitive to exploitation than skipjack tuna (Juan-Jordá et al. 2015).

Non-tuna species

The capture and mortality of non-target species has become a major issue in global fisheries management and conservation (Kelleher 2005; Zeller et al. 2018). Although tuna purse seine fisheries have been shown to be selective, leading to lower levels of bycatch than other fisheries (Hall and Roman 2013), several species can be incidentally caught, including sea turtles, marine mammals, rays, sharks, and other bony fish.

The most frequently found non-target species are triggerfish (*Canthidermis maculata*), wahoo (*Acanthocybium solandri*), dolphinfish (*Coryphaena hippurus*), rainbow runner (*Elegatis bipinnulata*) and billfishes (*Istiophorus platypterus* and *Makaira indica*) (Hall and Roman 2013; Torres-Irineo et al. 2014; Ruiz et al. 2018) (**Figure I.8**). Purse seine fishing operations also catch several species of sharks and rays, such as Oceanic White Tip sharks (*Carcharhinus longimanus*), silky sharks (*Carcharhinus falciformis*), Giant Devil Ray (*Mobula mobular*) and, in much lesser extent interact as well with whale sharks (*Rhincodon typus*) being most of them release from the net alive (Capietto et al. 2014; Escalle et al. 2019)**.** The most frequently species of turtles found are green turtle (*Chelonia mydas*), olive ridley (*Lepidochelys olivacea)* and loggerhead turtle (*Caretta caretta*) (Bourjea et al. 2014), although the majority of captured turtles are released alive into the sea (Amandè et al. 2010). In the case of marine mammals, accidental encirclement by the purse seiner are very infrequent, although it is documented in all three tropical oceans (Scott et al. 2012; Escalle et al. 2015).

Figure I.8. *Examples of purse seine by-catch species. Source: Nerea Leazama*

In the Atlantic Ocean, the bycatch of the purse seine fishery is currently retained and sell as “Faux poisson” (false fish) as an important by-product in West Africa, mainly in Abidjan (Ivory Coast). It shows also a growing importance in the Western Indian ocean in places like Antsiranana (Madagascar) (Chavance et al. 2011). It is made up of a mix of damaged or undersized target tunas, minor tuna species, and associated species, like billfish, sharks, and various bony fish, that are sold on the local market (Romagny et al. 2000; Chavance et al. 2015).

2.2 State of the stocks

Assessing the state of the tuna stocks is key for the provision of scientific advice for fisheries management in tuna Regional Fisheries Management Organizations (RFMOs) with the aim to ensure long-term sustainable exploitation and conservation of the stocks, while maximizing the catch. Currently, of the total tropical tuna catch (i.e. skipjack, yellowfin and bigeye), 86% comes from stocks at “healthy” levels in terms of abundance, 4% from stocks at an intermediate level of abundance and 10% from stocks in need of stronger management (ISSF 2019). However, when analyzing the same information by species the picture is different, as skipjack stocks contribute more than one half of the global catch of tunas, and they are all in a healthy situation. However, 26% and 20% of the yellowfin and bigeye tuna catches, respectively, come from overexploited stocks (**Figure I.9**).

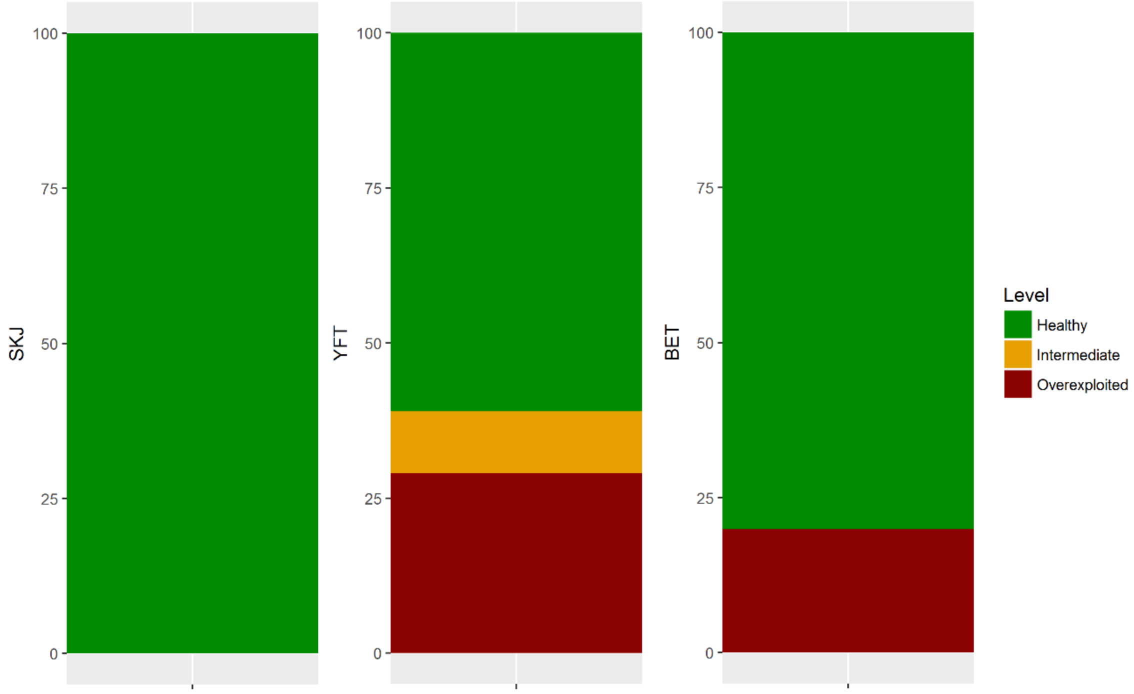


Figure I.9. *Distribution of catch of major commercial tunas according to their stock status. The percentages correspond to the total catch of all stocks with a given ranking. Source: ISSF (2019)*

2.3 Tuna purse seine's fishing modes

Tropical tuna purse seining operations, fishing sets, are different depending on the way in which tunas are detected and encircled. In fishing on **free school sets (FSC)**, schools of tuna are visually detected on the sea surface through the observation of breezes, jumps, boilers or foamers. The typical tuna catch in FSC consists of a monospecific school of large adult yellowfin tuna (>30 kg) **(Figure 10)** and generally have a very low bycatch rate (Amandè et al. 2010). Sets made in the vicinity of whales, which are also used as indicators of the presence of tuna schools, are also considered free school sets, due to their same species and size composition of the fish (Pallarés and Petit 1998). **Dolphin sets (DOL)** occurs when tunas are associated with groups of dolphins (Hall 1998) and this type of fishing is exclusive of the Eastern Pacific Ocean (EPO). The associated catch in this type of sets is constituted of large yellowfin tuna with very few bycatch other than dolphins (Hall 1998; Scott et al. 2012). The last type is the **fish aggregating devices (FADs) sets**, where the fishers take advantage of the associative behavior of tuna and non-tuna species with floating objects in order to facilitate their catches (Biais and Taquet 1991; Fonteneau et al. 2013). FAD-associated catches contain typically smaller sizes of the three major tropical tuna species compared to FSC and DOL associated catches. Catches with FADs are usually made of a majority of adult skipjack, but also small juvenile yellowfin and bigeye tunas (**Figure I.10**). Moreover, fishing in FADs produces more bycatch than FSC sets (Romanov 2002; Amande et al. 2012).

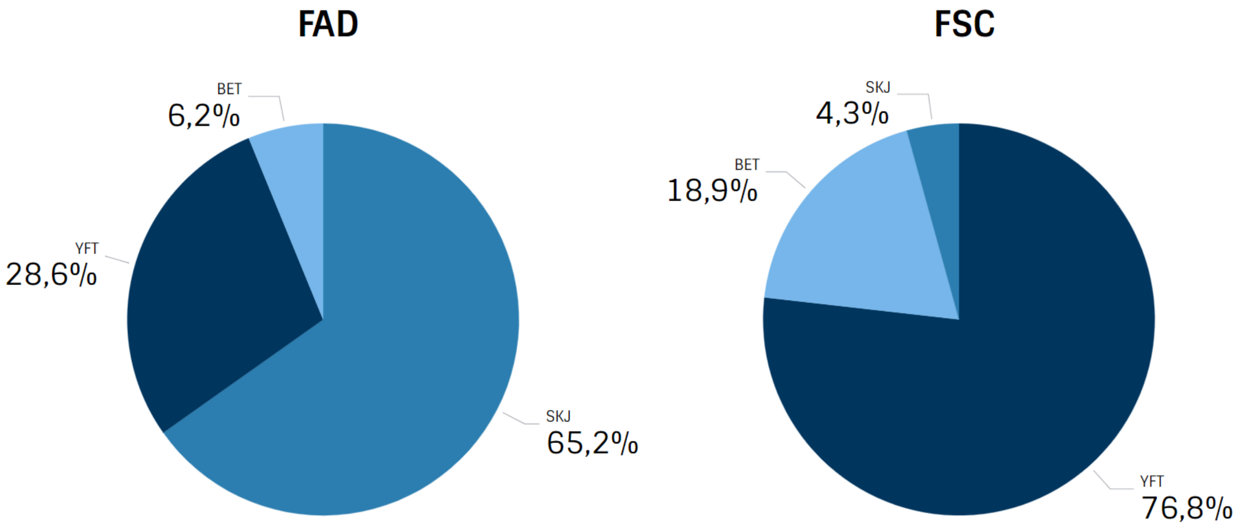


Figure I.10. *Example of Spanish purse seiners species composition of the catch on FADs and FSC in 2017 in the Indian Ocean. Source: Báez et al. (2018)*

2.3.1 What are fish aggregating devices?

Fish aggregating devices are floating objects found in the tropical and subtropical oceans that tend to aggregate pelagic species underneath. These objects attract hundreds of marine species, for example around 333 fish species belonging to 96 families have been observed around floating structures (Castro et al. 2002), including the three main commercial tropical tuna species, but also non-target species. The first reference to this associative behavior with floating objects dates back to the VIII century BC, observed in a painted Greek vase found on the Island of Ischia, Italy (Viñuales-Solé 1996) (**Figure I.11**).

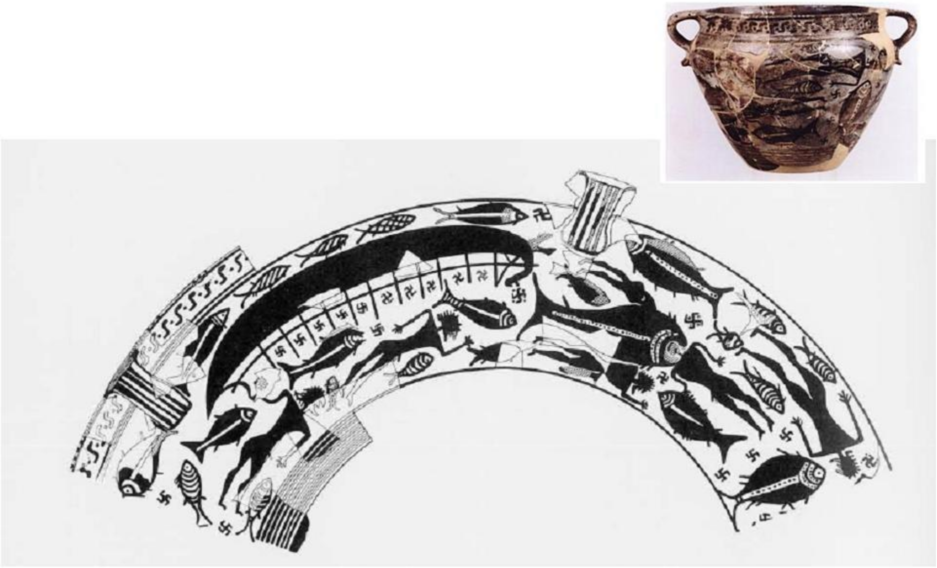


Figure I.11. *The shipwreck of Pitecusa. On the rigth side, aggregated fish can be seen under a floating body*

2.3.2 Types of FADs

In broad terms, FAD describes any type of floating object used to attract and aggregate fish which resulted in increasing fish catchability. In the past, the majority of floating objects used by fishers were natural floating objects (e.g. driftwood, trees, logs, seaweed or coconuts) encountered by chance. Traditionally, these natural objects have been called “logs”. Over time, the objects began to be modified by fishers and, thus, an operational definition was adopted for them (i.e. man-made FADs) to separate from natural floating objects. There are two basic categories of FADs according to their design: moored to the sea-floor, called anchored FADs (AFADs) (**Figure I.12.A**), and objects that drift freely on the surface of the oceans, called drifting FADs (DFADs) (**Figure I.12.B**).

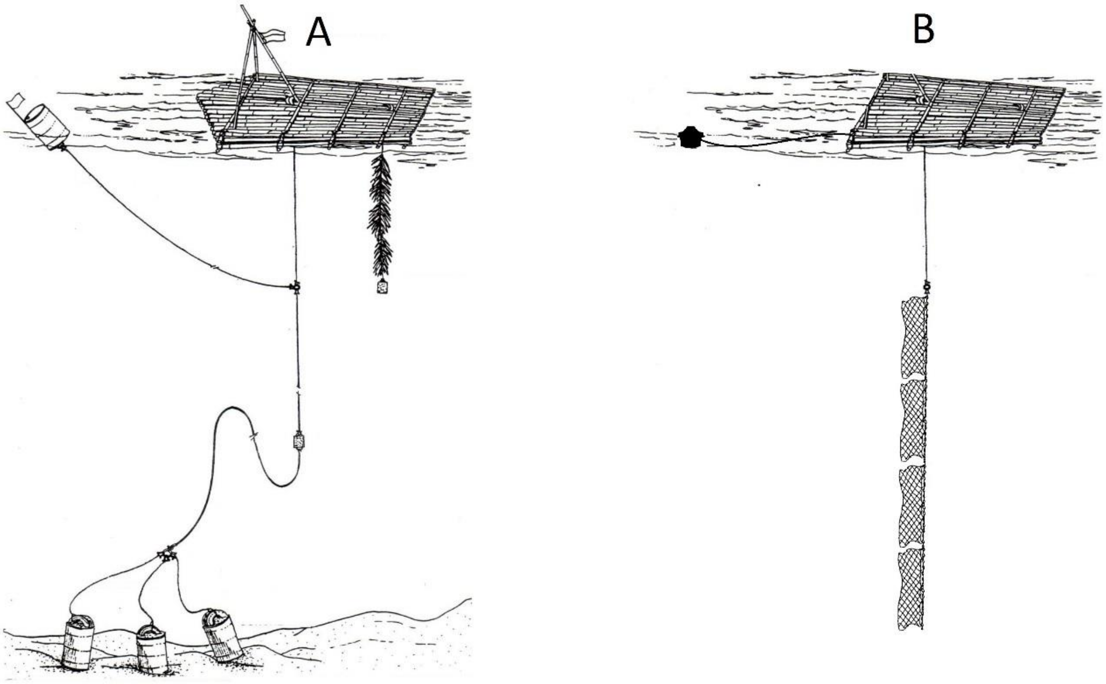


Figure I.12. *Design of anchored FADs anchored to the bottom (A) and design of a drifting FAD (B)*

The majority of AFADs have long been used in coastal areas by artisanal and recreational fisheries. These anchored objects are usually made of raft anchored with cement blocks attached to ropes of several hundred meters to up to 5000 m long (Scott and Lopez 2014b; Gervain et al. 2015).

On the other hand, DFADs are most widespread in industrial tuna fisheries. In the late 1950s, fishers took advantage of encounters with natural objects, such as terrestrial wooden debris entering the ocean from river run-offs. In the 1990s, fishers began to build and use DFADs to aggregate pelagic fish and increase fishing efficiency and catch rates (Hall and Roman 2013). Man-made DFADs are composed of rafts, which are constructed with different material (e.g. bamboo or metal), and an underwater part hanging off to depths between 5 and 80-100 meters. The length of the underwater structure is ocean-specific (5-20 m or 60-80 m depending on the region in the Indian Ocean, 80-100 m in the Atlantic Ocean and around 30 m in the Eastern Pacific Ocean) (Scott and Lopez 2014b; Murua et al. 2019). The underwater structure of DFADs is used to reduce the drifting speed of the DFAD and is thought to act as a shelter for some of the associated non-tuna species (Murua et al. 2016). DFADs are used almost exclusively by industrial tuna purse seine fleets throughout the world´s tropical oceans and currently it is roughly estimated that ~100,000 DFADs are deployed annually worldwide (Scott and Lopez 2014b; Gershman et al. 2015b).

Due to the extensive use of FADs around the world and the different names given to them according to the area, a classification to unify all the definitions of FADs were proposed. Following the definitions provided by CECOFAD project (Catch, effort, and ecosystem impacts of FAD-fishing, EU MARE/2012/24 project), the International Commission for the Conservation of Atlantic Tunas (ICCAT) has adopted a more detailed classification of floating objects (**Figure I.13**), taking into account the construction materials or whether the objects were created for fishing or not.

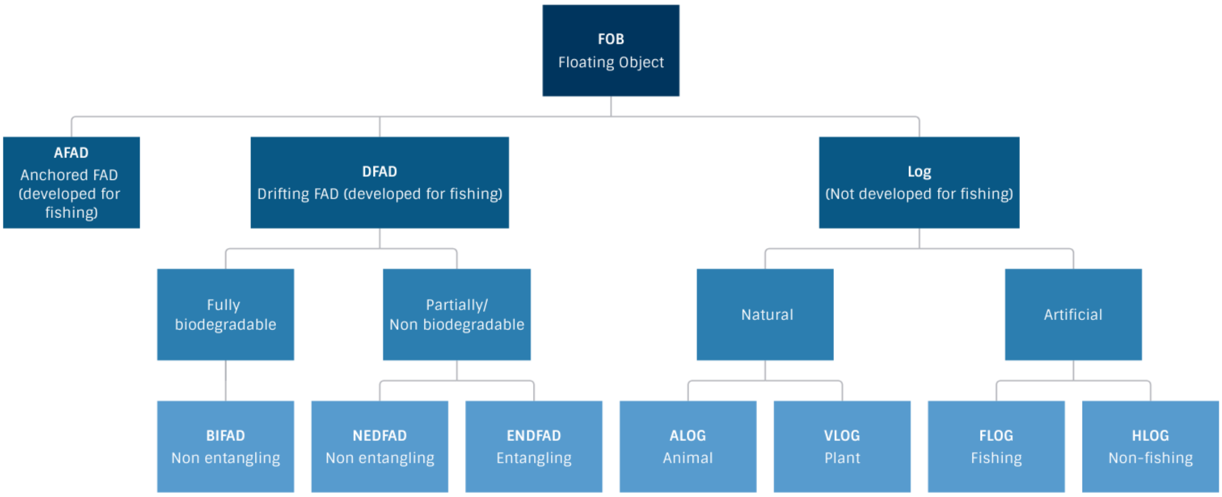


Figure I.13. *New classification of Floating Objects (FOBs) proposed in the framework of the CECOFAD project*

2.3.3 What are the reasons driving this associative behavior?

Although fishers have been using FADs for nearly a century to increase their catches, the reasons driving this associative behavior are not fully understood. The reasons of this behavior may be diverse in nature, as shown by the high number of hypotheses proposed to explain the reasons for pelagic fish to associate with floating objects (Castro et al. 2002). The first one was briefly mentioned by Suyehiro (1951), and proposes that the objects act as a shelter from predators. Although this hypothesis might be feasible for non-tuna species, it is unlikely for large predators such as tuna, as tuna schools are too big to hide under small objects. Another hypothesis is that FADs may be an indicator of food (Bard et al. 1985). This hypothesis suggests that floating objects aggregate small fish in their vicinity, on which large fish could prey. However, no strong evidence has been found to support the presence of a sufficient amount of small fish near floating object to sustain tunas, as tunas need to eat approximately 5% of their weight each day (Olson and Boggs 1986). Klima and Wickham (1971) proposed that floating objects could provide spatial references around which fish can orient in unstructured pelagic environment, but this hypothesis could not explain the aggregative behavior towards moving floating objects such as DFADs (Freon and Dagorn 2000). Another hypothesis proposed primarily for solitary predators and then for tuna, was comfortability stipulation hypothesis (Batalyants 1992). It suggests that fish remain close to floating objects to rest and recover energy after feeding in the area. However, the author conceded that stomach content of tuna was difficult to study due to regurgitation of the fish when caught and does not explain why a tuna would choose to rest near a DFAD instead of elsewhere.

Currently, the two most accepted hypothesis for tuna aggregation behavior around DFADs are the indicator-log (Hall et al. 1992) and the meeting point hypothesis (Dagorn and Freon 1999). The first is based on the assumption that tunas may use floating objects as a result of an evolutionary process, since natural objects could be an indicator of productive areas, either because most natural floating objects originate in rich areas (e.g., river mouth, mangrove swamp) and remain within these rich bodies of water, or because they aggregate in rich frontal zones (Dagorn et al. 2013). Therefore, tunas could use these indicators to find or stay in rich waters. The meeting point hypothesis was first advanced by Dagorn (1994) and successfully simulated by Dagorn and Freon (1999). This hypothesis relies on the social behavior of tunas and suggests that floating objects could act as meeting points in a vast visually-void environment to form and re-structure schools of tunas. The benefits of large school are well known (Rieucau et al. 2015), such as the reduction of the risk of predation (i.e. to aid in predator avoidance) (Pitcher and Parrish 1993; Parrish et al. 2002), the increase of hunting efficiency (i.e. larger schools of predators are more effective at quickly breaking up schools of prey, resulting in faster food finding by isolating more prey (Pitcher et al. 1982)) or social benefits (i.e. information transfer, and opportunity for learning by social facilitation (Pitcher and Parrish 1993; Fréon and Misund 1999; Karplus et al. 2006)). Moreover, acoustic telemetry experiments endorse the hypothesis that fish more likely arrive as individuals or small groups and leave the DFAD in larger schools (Soria et al. 2009). These hypotheses may not mutually exclusive, and it is possible that predatory fish such as tunas will be attracted to DFADs for several reasons.

2.3.4 Behavior of fish associated to floating objects

The fish species associated to DFADs are classified in different groups according to their distance to the floating object (Parin and Fedoryako 1999). The fish community around DFADs is subdivided into "intranatant species" (e.g. sergeant major damselfish, Abudefduf sp.), which remain within 0.5 m of the floating object, "extranatant species" (0.5–2 m) (e.g. White-spotted triggerfish, *Canthidermis maculatus*) and "circumnatant species" (2m- several nmi) (e.g. oceanic whitetip shark, *Carcharhinus longimanus*), which are loosely associated with the object. Freon and Dagorn (2000) proposed different distances: 2 m for the intranatants/ extranatants, and up to 10–50 m for the extranatants/circumnatants, considering that there is a substantial overlap between the distributions of these three communities.

In addition to the difference in groups according to their distance to the DFADs, there is a clear vertical separation between tuna and non-tuna species under the floating objects. Although overlap may exist between tuna and non-tuna species, a vertical separation have been identified in previous studies conducted in the Indian Ocean using a variety of information sources (i.e. tagging, scientific acoustic surveys, visual surveys) (Moreno et al. 2007b; Taquet et al. 2007b; Forget et al. 2015). In the research carried out by Forget et al. (2015), where tuna and non-tuna species were tagged at DFADs, a significant separation at around 25 m was observed between tuna and non-tuna species (**Figure I.14**). This is consistent with the vertical behavior observed by using visual surveys (Taquet et al. 2007b) and using scientific echo-sounders (Moreno et al. 2007b), where more than 2000 aggregations were analyzed.

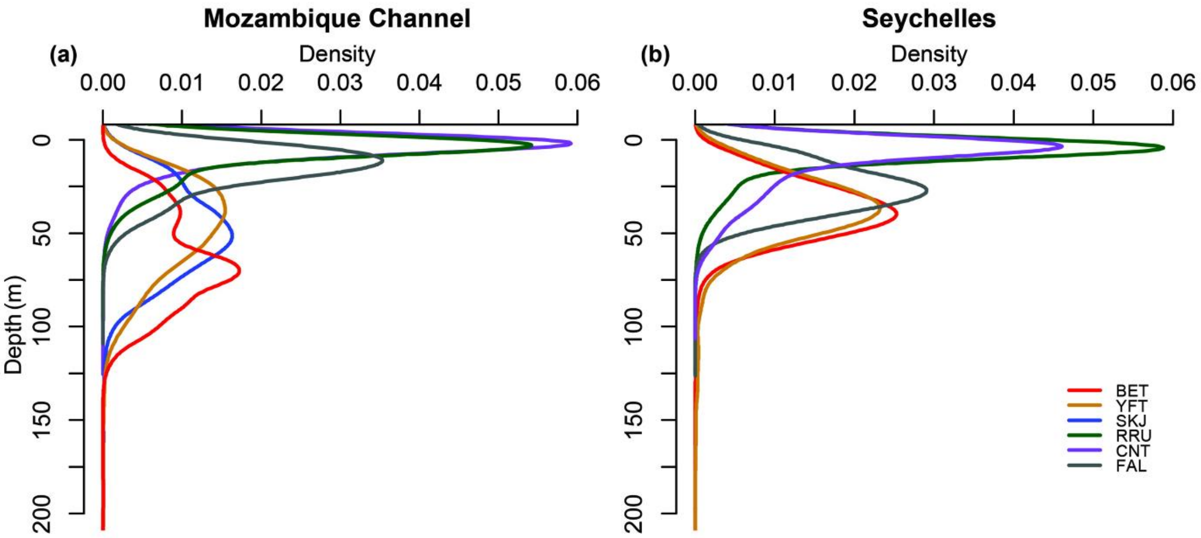


Figure I.14. *Vertical distributions by species in the Mozambique Channel (a) and the Seychelles (b. Species code: bigeye tuna (BET), yellowfin tuna (YFT), skipjack tuna (SKJ), rainbow runner (RRU), oceanic triggerfish (CNT), silky sharks (FAL). Source: Forget et al. (2015)*

Moreover, tagging and acoustic data suggest differences in depth preferences between the species and the different sizes of tuna (Moreno et al. 2007b; Matsumoto et al. 2016), although overlap may exist in the vertical range of the three species of tuna. Skipjack tuna schools tend to remain in shallower waters, as do small yellowfin and bigeye tuna that are found occupying similar depth ranges as skipjack. However large individuals of bigeye and yellowfin tuna are found at greater depths. In addition to this segregation by species and sizes, the vertical distribution of tuna at DFADs may vary depending on different factors, such as total biomass associated, species and sizes composition (Robert et al. 2013) and oceanographic conditions (e.g. thermocline depth or surface and subsurface currents) (Schaefer and Fuller 2013; Fuller et al. 2015).

In relation to associative behavior, non-tuna species are strongly and tightly associated with DFADs (Parin and Fedoryako 1999) showing less frequent excursions out of DFAD (Moreno et al. 2007a; Dagorn et al. 2012a; Forget et al. 2015; Lopez et al. 2017a). On the other hand, tuna are well known to engage in both horizontal and vertical movements around DFADs (Govinden et al. 2013; Schaefer and Fuller 2013; Weng et al. 2013; Fuller et al. 2015), including diel excursions (Govinden et al. 2010; Schaefer and Fuller 2013; Matsumoto et al. 2014; Matsumoto et al. 2016; Lopez et al. 2017a), where the tuna is supposed to be more distanced from the object during day and night and closer to DFAD at dawn (Josse et al. 2000; Moreno et al. 2007a; Harley et al. 2009).

2.4 Fishing technology development: from free school to DFAD fishing

Changes in fishing technology and operations have allowed improving the fishing strategy and increase catches. Two periods of technological breakthrough could be distinguished in the tropical tuna purse seiner fishery worldwide. The first period occurred before the widespread use of DFADs (1980-1995) (Scott and Lopez 2014b), where innovations were focused on improving the success rate of free school fishing and increasing the ability and diminishing the time to load and store the large catches (Itano 1998). In the second period, and with the introduction of the DFAD fishery over the past 25 years, most of the changes occurring in the tropical tuna purse seine fishery have been oriented towards the improvement of purse seine DFAD fishing efficiency (Lopez et al. 2014). This change over time from FSC fishing to DFADs fishing, is due to the fact that the aggregation behavior of tunas around DFADs facilitates the purse seiner set and tuna catch in comparison to FSCs, because the school remains relatively fixed in space. The success rate of the purse seine on DFADs is much higher than in FSC, for example in 2017 the proportion of success on DFAD-sets was 95% while the proportion of successful FSC sets was 52% for the Spanish fleet in the Indian Ocean (Báez et al. 2018).

In the first period, different elements of the vessels were modified which increased fishing efficiency. For example, during the mid-1980s the hydraulic power systems of the purse seiners were modified, helping to reduce the time needed for a fishing set and increase the capacity of hauling larger free school sets (Scott and Lopez 2014b). The most important changes in that period were related to increasing the size and the capacity of vessels to refrigerate large catches (Itano 1998). The average size of purse seiners increased from about 42 m length overall for those built during the 60s to more than 90 m in the 2000s (Maufroy 2016). Regarding capacity, the tuna seiners can nowadays freeze and store up to 200-400 t/day in a series of tanks of up to 3,000 m^3 total capacity. Purse seiners also began to introduce electronics devices into their fishing operations (e.g. bird radar, navigation radar, underwater current meters, sonar, etc.).

This technological development was highly focused on improving catches of free schools (Itano 2003), such as bird radars used to detect flocks of birds, indicators of tuna schools.

In the second period, the most significant improvement incorporated into the tropical tuna purse seine fishery was the use of DFADs. Since the early 1990s, the use of DFADs for tuna fishing has widely and rapidly expanded, largely improving the searching efficiency of purse seiners (Miyake et al. 2010; Davies et al. 2014b). The development of highly efficient purse seining on DFADs was also accompanied by the incorporation of support vessels, which invest their time in activities related to DFAD fishing (e.g. deployment, visiting, etc.) aimed at increasing the efficiency of tuna vessels they support (Itano et al. 2004). Although support vessels do not carry out fishing activities, they collaborate with the construction and deployment of DFADs, retrieving DFADs when they drift off or too far from the area of fishing interest, or visiting DFADs owned by the purse seiners they assist (Arrizabalaga et al. 2001). Support vessels are forbidden in the Eastern Pacific Ocean (IATTC resolution C-99-07) and limitations on their numbers have been established in the Indian Ocean (IOTC resolution 18/01).

The implementation of tracking buoys to DFADs is probably the most significant technological development that has occurred in the last 20-30 years to increase the efficiency of tuna fishing with DFADs (Scott and Lopez 2014b). In the mid-'80s fishers began attaching radio beacons to objects so they could monitor and relocate them, with signals ranging from 500 to 1,000 nautical miles. In the 90's they started to attach the first satellite GPS beacons to DFADs that could be tracked by the vessels in real time providing remotely the accurate geolocation of the DFAD. Over time, their emission distance and battery autonomy improved and, at the beginning of the 2000s, solar panels were included to ensure a virtually limitless duration of emission of the buoys signal (Itano et al. 2004).

The first buoys equipped with an echo-sounder appeared in the market in the 2000, but fishers did not began using them regularly until mid-2000’s (Lopez et al. 2014). These devices, in addition to geolocate the DFAD, provide rough estimates of the abundance of fish underneath (**Figure I.15**). The echo-sounder provide a single biomass estimation which does not comprise information on the species composition nor the size distribution of the aggregation. Fishers use the biomass estimates from the buoys, along with other information (e.g. environmental conditions, catches in the same area, etc.), to decide on the best DFAD to visit, avoiding DFADs that have not aggregated sufficient biomass to undertake a fishing set (Lopez et al. 2014). Therefore, echo-sounder buoys facilitate route decisions and reduce search time between two successful DFAD sets.

Figure I.15. *Echo-sounder buoys on the deck of a purse seine vessel. Source: Francisco Blaha*

From the first echo-sounder buoy, there has been a continuous development in buoy technology, with notable advances in the detection zone of the acoustic signal, biomass estimation and the battery life. Their use has rapidly spread and, today, the vast majority of the purse seine fleets oceanwide use DFADs equipped with satellite linked echo-sounder buoys (Moreno et al. 2016b) (**Figure I.16**).

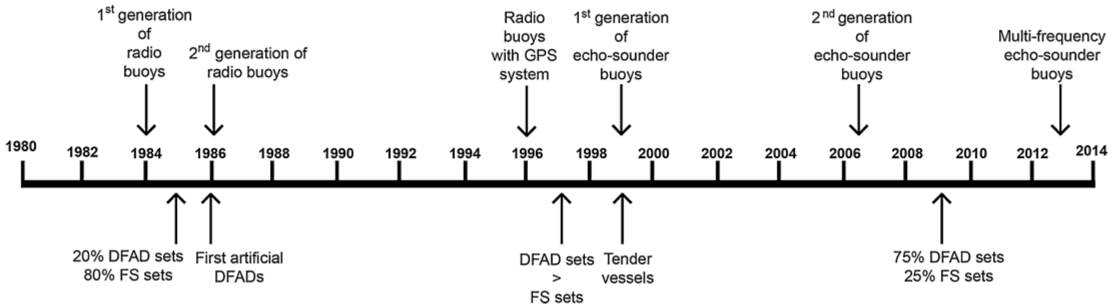


Figure I.16. *Timeline of the most important events that occurred in the development of buoys technology in the Spanish tropical purse seine DFAD fishery in the Indian Ocean for the last 30 years. Source: Lopez et al (2014)*

Currently, there are 3 different echo-sounder buoy brands widely used in the tuna purse seine fishery worldwide (i.e. Zunibal, Satlink and Marine Instruments). These buoys operate with lower frequencies of 38 kHz in some buoys and up to 200 kHz in others, with a maximum depth range at which biomass is recorded ranging from 115 to 150. At this time, none of the echo-sounders have the capability to directly identify fish size and species since, although buoy companies are working towards acoustic discrimination of tuna and have improved the hardware for that, discrimination is not possible yet. If echo-sounder buoys had the ability to discriminate the species and sizes of tunas found at DFADs, fishers could avoid navigating to areas where non-desired species and sizes of tunas represent the majority of the catch. Likewise, the use of onboard sonar and echo-sounders capable of tuna discrimination would allow more accurate evaluation of the species and sizes present at DFADs, allowing fishers making more sustainable decisions. The acoustic data needed to discriminate tuna species using acoustic gear is not yet available, as few studies have addressed acoustic properties of tropical tunas. This may be due to the fact that tropical tunas are usually found in offshore fishing grounds and DFAD aggregations are ephemeral, making the research expensive and logistically difficult.

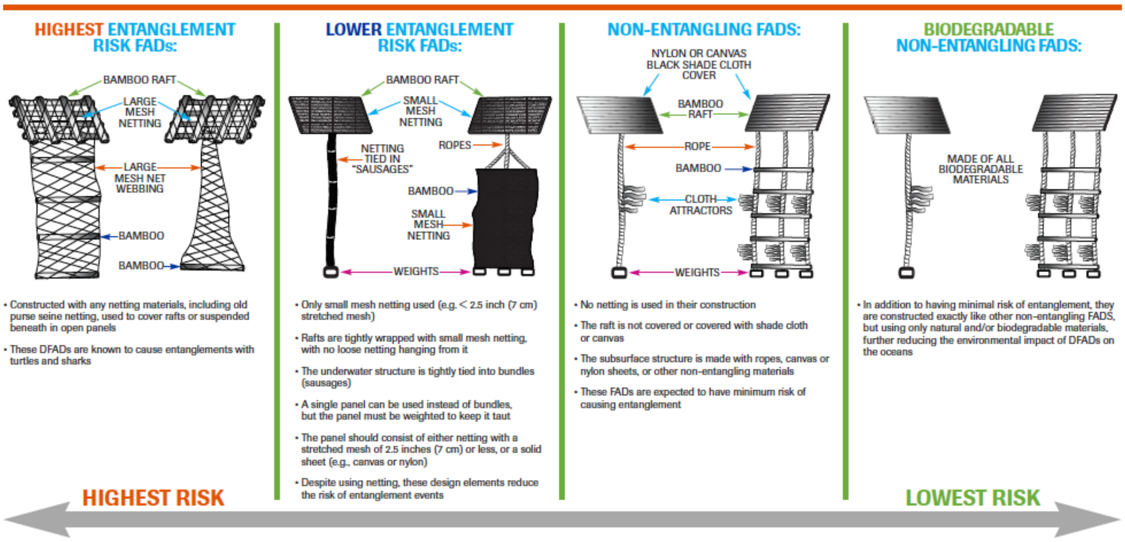
3. Impacts of DFADs

The widespread use of DFADs in tuna fisheries has become an increasingly important management concern for the four tropical tuna-RFMOs: the Indian Ocean Tuna Commission (IOTC, www.iotc.org), the International Commission for the Conservation of Atlantic Tunas (ICCAT, www.iccat.int), the Western and Central Pacific Fisheries

Commission (WCPFC, www.wcpfc.int) and the Inter-American Tropical Tuna Commission (IATTC, http://www.iattc.org). Although the use of objects has positive consequences for purse seine fishing, such as the reduction in search time (Fonteneau et al. 2013; Lopez et al. 2014), traveling time and operating cost for finding tuna schools (Guillotreau et al. 2011; Davies et al. 2014b) or the success of DFAD sets against the free-school sets (Fonteneau et al. 2000), the increasing number of DFAD deployments could also bring negative consequences (Fonteneau et al. 2000; Marsac et al. 2000; Essington et al. 2002; Dagorn et al. 2012b).

One of these negative effects is the increase in by-catch levels (Castro et al. 2002; Romanov 2008; Amandè et al. 2010; Amande et al. 2012). Although tuna purse seine DFAD fisheries have lower levels of by-catch than other fisheries (Alverson et al. 1994; Kelleher 2005), several non-target species can be incidentally caught. DFAD fishing generates approximately three to five times more bycatch per ton of tuna than fishing on FSC (Romanov 2002; Amandè et al. 2010; Kaplan et al. 2014). Romanov (2002) found by-catch in 93% of the sets made around DFADs in the western Indian Ocean.

The use of netting material in the construction of DFADs, both in the raft and underwater part, could result in entanglement of sensitive species such as turtles and sharks (Anderson et al. 2009; Filmalter et al. 2013). For example, Filmalter et al. (2013) estimated that between 480 000 and 960 000 silky sharks could be entangled and dead in the Indian Ocean due to the netting used to build DFADs. However, this mortality would be very easily avoided by modifying the design of the DFADs to make them non-entangling. Nowadays, most of the fleets worldwide have moved towards the use of either DFADs that present low entanglement risk (netting tied into “sausages” or mesh size of less than 7 cm) or are non-entangling (no netting present) (**Figure I.17**) (Franco et al. 2012; Murua et al. 2016; IOTC 2017; Moreno et al. 2018). The obligation to use low risk entanglement DFADs or non-entangling DFADs are being adopted by the different tuna-RFMOs (IOTC Res. 18/08, IATTC Res. C-17-02, ICCAT Rec. 16-01 and WCPFC CMM-2013-05).



- Constructed with any netting materials, including old purse seine netting, used to cover rafts or suspended beneath in open panels
- These DFADs are known to cause entanglements with turtles and sharks

- Only small mesh netting used (e.g. < 2.5 inch (7 cm) stretched mesh)
- Rafts are tightly wrapped with small mesh netting, with no loose netting hanging from it
- The underwater structure is tightly tied into bundles (sausages)
- A single panel can be used instead of bundles, but the panel must be weighted to keep it taut
- The panel should consist of either netting with a stretched mesh of 2.5 inches (7 cm) or less, or a solid sheet (e.g., canvas or nylon)
- Despite using netting, these design elements reduce the risk of entanglement events

- No netting is used in their construction
- The raft is not covered or covered with shade cloth or canvas
- The subsurface structure is made with ropes, canvas or nylon sheets, or other non-entangling materials
- These FADs are expected to have minimum risk of causing entanglement

- In addition to having minimal risk of entanglement, they are constructed exactly like other non-entangling FADS, but using only natural and/or biodegradable materials, further reducing the environmental impact of DFADs on the oceans

Figure 17. *DFAD categories based on entanglement and environmental impact. Source: ISSF, 2015*

Another ecological concerns include the increase catch of small yellowfin and bigeye tuna (Fonteneau et al. 2000; Miyake et al. 2010; Leroy et al. 2012). Associated school around DFADs has much higher proportion of small yellowfin and bigeye tuna compared to FSC. As a result of the increased use of DFADs, the exploitation patterns of tropical tuna have been modified with a decrease in the mean weight of yellowfin and bigeye tuna (Chassot et al. 2015). Most of these two species are caught under DFADs between lengths of 40 to 60 cm (Fonteneau et al. 2013), while the size at which they reach maturity is between 80-100 cm (Sun et al. 2013; Zudaire et al. 2013). Therefore, large catches of small juveniles may threaten the viability of the tuna stocks and decrease the yield per recruit and Maximum Sustainable Yield (MSY) (Fonteneau et al. 2000).

Another concern on using DFADs is the alteration of the natural movements of the species associated to DFADs modifying their behavior and biology (Marsac et al. 2000; Bromhead et al. 2003; Hallier and Gaertner 2008; Dagorn et al. 2012b; Sempo et al. 2013). Marsac et al. (2000) proposed the "ecological trap" hypothesis, which suggest that DFADs could entrain tunas to biologically unsuitable locations, having a detrimental effect on the health of the stock (e.g. condition, natural mortality) and alter the spatio-temporal dynamics of fish that are strongly associated with floating objects. Some evidence has been observed that shows significant differences in many biological and ecological characteristics of tunas associated with DFADs as opposed to those in free-swimming schools, such as lower growth rates and poorer body condition (Marsac et al. 2000; Ménard et al. 2000; Hallier and Gaertner 2008; Jaquemet et al. 2011). However, these results have been questioned (Dagorn et al. 2013) and there is still a limited understanding of the possible long-term effects of DFADs on tuna stocks and pelagic ecosystems (Fonteneau et al. 2000; Bromhead et al. 2003).

One of the biggest concerns of tuna-RFMOs is the damage to marine habitats due to the debris resulting from the loss or abandonment of DFADs and the beaching events when abandoned DFADs reached sensitive areas (Maufroy et al. 2015; Maufroy et al. 2016; Davies et al. 2017). The material used by purse seine fleets to construct DFADs (i.e. the nylon fishing nets, the plastic covers of rafts or the plastic floats) increase the lifetime of DFADs at sea and therefore increase the marine litter as well as the risk of habitat destruction when the object end up stranding in sensitive habitats (Maufroy et al. 2017). DFADs used by fleets may drift to land, becoming stuck in a wide range of habitats, being coral reefs the most impacted habitat (Balderson and Martin 2015). For example, Maufroy et al. (2015) estimated that almost 10% of all DFADs deployed by French vessels in the Indian and Atlantic Oceans ultimately became beached. Therefore, reducing the amount of synthetic material in the construction of DFADs, by promoting the use of environmentally friendly DFADs (i.e. natural or biodegradable materials), will automatically reduce the production of marine debris and the impact of the DFAD structure in sensitive habitats. The challenge of developing a fully biodegradable DFAD constructed with natural materials which will have less impact on coastal sensitive areas when stranding, has become one of the key objectives of tuna-RFMOs in relation to DFAD fisheries. In that sense, different initiatives have been conducted by both the scientific community and the fishing industry to find an efficient DFAD that is composed, as much as possible, by biodegradable materials (Franco et al. 2009; Goujon et al. 2012; Moreno et al. 2017). In addition, there are other projects being carried out to avoid DFAD stranding events, such as FAD-Watch program (Zudaire et al. 2018). This project is a first multi-sectorial initiative developed to prevent and mitigate DFAD beaching across islands in Seychelles, in which the coastal recovery is applied as a mitigation measure. DFADs crossing exclusive economic zone of Seychelles and the beaching events have been reduced on 20% and 41% respectively, during 2016 to 2017 period, showing how the FAD-Watch initiative in combination with other mitigation options could add great value to the package of mitigation measures on the reduction of DFADs impacts on vulnerable coastal and pelagic habitats .

Due to all these negative effects, increase knowledge about the processes that operate in the attraction and aggregation of tropical tuna and non-tuna species and a good scientific understanding of the different ecological impacts of the DFADS are essential for the provision of best scientific advice to tuna-RFMOs to ensure a proper management of the resources. It is therefore necessary to implement management measures towards the minimization of the impact of DFAD fishing strategy and ensure a sustainable long-term fishery. Currently, several options for managing tropical tuna purse seine fisheries are being implemented to reduce the negative impacts of DFAD fishing, including the limitation of the number of DFADs, limitation of the use of support vessels, time and area closures, application of “best practices” for DFAD use and sensitive species safe-release from the deck.

4. Importance of DFADs research

Considering the value of the fishery, the lack of knowledge regarding the associative behavior of the species around objects and the possible impacts that DFADs could produce on the marine ecosystem is striking, as one could have thought that thousands of studies related to the topic would be available in the literature. Although in recent years, DFAD-related research has increased, there are still few studies on the subject. For example, doing a simple search on Science Direct (www.sciencedirect.com) we find 5 to 10 papers per year with the keyword "fish aggregating device" versus 100-150 per year with the keyword "tuna". Therefore, few studies related to fish aggregation at DFADs have been published focused on active and passive acoustic tracking (Taquet et al. 2007a; Filmalter et al. 2011; Schaefer and Fuller 2013; Matsumoto et al. 2014; Filmalter et al. 2015), scientific acoustic surveys (Moreno et al. 2007b), and underwater visual census (Taquet et al. 2007b). Clearly, scientific knowledge on the behavior and ecology of DFAD associated aggregations is currently limited and much remains to be done and investigated.

One of the main causes of this lack of research is because the associated human and economic cost of investigating DFADs at large scale is certainly high, as floating objects drift across the surface of the oceans for several months, being temporary in time and space. For this reason, the vast majority of research on associate behavior of fish around objects has been performed on AFADs, because the associated cost is lower, as they are fixed to the bottom and closer to the coastal areas (Ohta and Kakuma 2005; Mitsunaga et al. 2012; Govinden et al. 2013; Rodriguez-Tress et al. 2017). However, it is not clear whether pelagic fish behave differently in anchored and drifting FADs (Holland 1990; Freon and Dagorn 2000) and, therefore, it is preferable to develop investigation for improving our understanding of the ecological mechanisms in DFADs.

Nevertheless, establishment of research program to tackle those scientific questions above (e.g. associative behavior around DFADs, ecological impacts, etc.), which will inform management measures and conservation strategies for tuna and non-tuna species associated to DFADs, require the collection of large-scale data on their spatial dynamics and distribution. A single scientific program alone could not achieve such spatio-temporal coverage as accessing and working on remote DFADs will be impractical and unrealistic, botch economically and logistically.

4.1 Use of echo-sounders as scientific platforms

Today, DFADs are equipped with satellite linked echo-sounder buoys (Lopez et al. 2014) and they are used by the whole purse seine fleets globally (Moreno et al., 2016). Considering that around 100,000 objects may be deployed annually worldwide (Scott and Lopez 2014b; Gershman et al. 2015b), these devices could provide invaluable and continuous information to researchers about the rough estimate of the biomass of tuna and non-tuna aggregations under the objects along its trajectory, almost in real time, in a regular and effective basis, representing a powerful tool for the study of pelagic ecosystems (Moreno et al. 2016a). In recent years the potential use of DFADs as scientific platforms has been highlighted by the scientific community (Santiago et al. 2015; Lopez et al. 2016; Moreno et al. 2016a), with the aim to investigate several issues of scientific relevance as they collect fishery-independent information of the pelagic ecosystem in a privileged cost-effective manner (Moreno et al. 2016a). In these studies, its use has been proposed for different investigations, including fishery-independent abundance indices for stock assessment and a variety of ecological and behavioral investigations of tunas and accompanying species.

In contrast to fisheries-dependant data, echo-sounder buoys provide data less affected by fisheries, such as fleet dynamics, effort, and spatio-temporal constraints. Furthermore, DFADs cover thousands of kilometers across the ocean for several months, collecting automatically biomass information in a non-invasive manner with high spatio-temporal resolution. Yet, despite these obvious advantages, very few studies have been done using data provided by fishers' echo-sounder buoys (Robert et al. 2013; Lopez et al. 2017a; Lopez et al. 2017b). This is because the data collected by fishers' echo-sounder buoys are not originally intended for scientific purposes but for fishing. Therefore, prior to its scientific use, there is a need to carefully refine the data acquisition process (time, acoustic sample coverage, etc.) as well as to understand the representativeness of the resulting echo-sounder biomass information and explore the different sources of uncertainty associated to their use.

5. Hypothesis and objectives

5.1 Working hypothesis

The working hypothesis is a provisional statement that can be composed of activities involving the "technique and organs of operation" and that functions as a guide to progress in the research (Dewey, 1938; Shields and Tajalli, 2006). As such, the working hypothesis helps to establish the connection between the research questions and the observed evidences. The working hypothesis is the following:

"The assessment and management of the tropical tuna purse-seine fishery requires information about the ecology and behavior of tuna and non-tuna species associated with DFADs.

Describing the aggregation process, investigating the spatio-temporal distribution and environment preferences of those species, using acoustic data provided by fishers´

echo-sounder data, will contribute to the assessment and tropical tuna fishery management of tropical tunas in the Western Indian Ocean”.

5.2 Objectives

Taken the above-mentioned working hypothesis into account, the overarching aim of this thesis is to investigate the aggregation dynamics and spatio-temporal distribution of tunas and non-tunas associated with DFADs using acoustic data provided by fishers’ echo-sounder buoys in the Indian Ocean.

In order to investigate the behavior and ecology of tuna and non-tuna species associated with DFADs, specific research objectives were defined as follows:

1. To establish standardized protocols to process fishers echo-sounders´ acoustic raw biomass estimates in order to use them for scientific purposes (**Chapter 1**).
2. To progress towards improved remote biomass estimates by the echo-sounders equipping DFADs, following previous analysis proposed in the field, based on existing knowledge of the vertical distribution of non-tuna and tuna species at DFADs and mixed species target strengths (TS) and weights (**Chapter 2**).
3. To investigate the aggregation process of virgin (i.e. newly deployed) DFADs in the Western Indian Ocean using the acoustic records provided by fishers’ echo-sounder buoys, determining the first detection day of tuna and non-tuna species at DFAD and identifying the potential differences in the spatio-temporal dynamics of the aggregations (**Chapter 3**).
4. To investigate the habitat preferences and distribution of tuna and non-tuna species associated with DFADs and environmental conditions in the Indian Ocean implementing Bayesian Hierarchical spatial models (**Chapter 4**).
5. To compare the spatio-temporal distribution of tuna in the Western Indian Ocean resulted from both fisheries-dependent (i.e. nominal catch data) and independent (i.e. acoustic data from fishers´ echo-sounder buoys) data using spatially-explicit Bayesian Hierarchical spatial models (**Chapter 5**).

Chapter 1. From fisheries to scientific data: A protocol to process information from fishers' echo-sounder buoys

Abstract

Most of the drifting fish aggregating devices (DFADs) used by the industrial tropical tuna purse seine fishery are deployed with satellite linked echo-sounder buoys. These buoys provide information on the accurate geo-location of the floating object and estimates of fish biomass aggregated along the trajectory of the DFAD. This huge amount of information is provided in large and complex datasets consisting in rough estimations of biomass, which are not originally intended to be used for scientific purposes but for fishing. This study establishes a standardized protocol for cleaning raw data from fishers' echo-sounders buoys prior to their use for scientific purposes, in which potential errors are eliminated. In addition, the main advantages and limitations of the data are analyzed and discussed. This paper provides the first step towards the use and better understanding of fishers' echo-sounder buoys for scientific research.

Published as:

Orue, B., Lopez, J., Moreno, G., Santiago, J., Boyra, G., Uranga, J., Murua, H., 2019.From fisheries to scientific data: A protocol to process information from fishers’ echo-sounder buoys. Fish. Res. 215, 38-43.

Chapter 2. Using fishers' echo-sounder buoys to estimate biomass of fish species associated with drifting fish aggregating devices in the Indian Ocean

Abstract

The majority of the drifting fish aggregating devices (DFADs) used by the industrial tropical tuna purse seine fishery are deployed with satellite linked echo-sounder buoys. These buoys provide information on the accurate geo-location of the floating object and estimates of fish biomass underneath the DFAD. However, current echo-sounder buoys do not provide information on species or size composition under the DFADs. The aim of this study is to progress towards improved remote biomass estimates using the previous models proposed in the field, based on existing knowledge of the vertical distribution of non-tuna and tuna species at DFADs and mixed species target strengths (TS) and weights. Aiming to this objective, we use 287 fishing set information and their corresponding acoustic samples from echo-sounder buoys prior to the fishing set in the Indian Ocean. Results show that manufacturer's biomass estimates generally improve, being this improvement more pronounced in NW Seychelles and in Mozambique Channel. However, the improvement of the biomass estimates is not as large as expected, so it can be further improved, indicating that the large spatio-temporal variability in the Indian Ocean is not easily considered with a single model. Potential reasons driving echo-sounder buoy estimates variability, as well as the limitations encountered with these devices are discussed, including the lack of consistent TS values for tropical tunas, among others.

Published as:

Orue, B., Lopez, J., Moreno, G., Santiago, J., Boyra, G., Soto, M., Murua, H., (2019). Using fishers' echo-sounder buoys to estimate biomass of fish species associated with drifting fish aggregating devices in the Indian Ocean. Revista de Investigación Marina, AZTI 26(1), 1-13

Chapter 3. Aggregation process of drifting fish aggregating devices (DFADs) in the Western Indian Ocean: Who arrives first, tuna or non-tuna species?

Abstract

Industrial tropical purse seiners have been increasingly deploying artificial man-made DFADs equipped with satellite linked echo-sounder buoys, which provide fishers with information on the accurate geo-location of the object and rough estimates of the biomass aggregated underneath, to facilitate the catch of tuna. Although several hypotheses are under consideration to explain the aggregation and retention processes of pelagic species around DFADs, the reasons driving this associative behavior are uncertain. This study uses information from 962 echo-sounder buoys attached to virgin (i.e. newly deployed) DFADs deployed in the Western Indian Ocean between 2012 and 2015 by the Spanish fleet (42,322 days observations) to determine the first detection day of tuna and non-tuna species at DFAD and to model the aggregation processes of both species group using Generalize Additive Mixed Models. Moreover, different seasons, areas and depths of the DFAD underwater structure were considered in the analysis to account for potential spatio-temporal and structure differences. Results show that tuna species arrive at DFADs before non-tuna species (13.5±8.4 and 21.7±15.1 days, respectively), and provide evidence of the significant relationship between DFAD depth and detection time for tuna, suggesting faster tuna colonization in deeper objects. For non-tuna species, this relationship appeared to be not significant. The study also reveals both seasonal and spatial differences in the aggregation patterns for different species groups, suggesting that tuna and non-tuna species may have different aggregative behaviors depending on the spatio-temporal dynamic of DFADs. This work will contribute to the understanding of the fine and mesoscale ecology and behavior of target and non-target species around DFADs and will assist managers on the sustainability of exploited resources, helping to design spatio-temporal conservation management measures for tuna and non-tuna species.

Published as:

Orue, B., Lopez, J., Moreno, G., Santiago, J., Soto, M., Murua, H., 2019b. Aggregation process of drifting fish aggregating devices (DFADs) in the Western Indian Ocean: Who arrives first, tuna or non-tuna species? PloS one 14, e0210435.

Chapter 4. Seasonal distribution of tuna and non-tuna species associated with Drifting Fish Aggregating Devices (DFADs) in the Western Indian Ocean using fishery-independent data

Abstract

Man-made floating objects in the surface of tropical oceans, also called drifting fish aggregating devices (DFADs), attract tens of marine species, including tuna and non-tuna species. In the Indian Ocean, around 80% of the sets currently made by the EU purse-seine fleet are on DFADs. Due to the importance and value of this fishery, understanding the habitat characteristics and dynamics of pelagic species aggregated under DFADs is key to improve fishery management and fishing practices. This study implements Bayesian hierarchical spatial models to investigate tuna and non-tuna species seasonal distribution, based on fisheries-independent data derived from fishers' echo-sounder buoys, environmental information (Sea Surface Temperature, Chlorophyll, Salinity, Eddie Kinetic Energy, Oxygen concentration, Sea Surface Height, Velocity and Heading) and DFAD variables (DFAD identification, days at sea). Results highlighted group-specific spatial distributions and habitat preferences, finding higher probability of tuna presence in warmer waters, with higher sea surface height and low eddy kinetic energy values. In contrast, highest probabilities of non-tuna species were found in colder and productive waters. Days at sea were relevant for both groups, with higher probabilities at objects with higher soak time. Our results also showed species-specific temporal distributions, suggesting that both tuna and non-tuna species may have different habitat preferences depending on the monsoon period. The new findings provided by this study will contribute to the understanding of the ecology and behavior of target and non-target species and their sustainable management.

Submitted as:

Orue, B., Pennino, M.G, Lopez, J., Moreno, G., Santiago, J., Ramos, L., Murua, H., (Under review). Seasonal distribution of tuna and non-tuna species associated with Drifting Fish Aggregating Devices (DFADs) in the Western Indian Ocean using fishery-independent data. Frontiers in Marine Science.

Chapter 5. Modelling tropical tuna distribution: do fisheries dependent and independent data provide comparable results?

Abstract

Species distribution models (SDMs) are used for a variety of scientific and management applications. For species associated with drifting fish aggregating devices (DFADs), such as tuna, spatial models can help tuna Regional Fisheries Management Organizations (t-RFMOs) understand their habitat characteristics and dynamics. DFADs are monitored and tracked with satellite linked echo-sounder buoys, which remotely provide fishers rough estimates of the abundance of fish underneath them. Although this type of fishery-independent data has been recently used in scientific studies, SDMs using this data have never been compared with models using fishery-dependent data (i.e. nominal catch data). This study investigates the results obtained with both data sources using Bayesian Hierarchical spatio-temporal models, allowing to analyze their advantages and disadvantages, as well as compare the predicted distributions. Although the two model outputs show, in general, similar areas of tuna presence under the DFADs, the most remarkable result of the comparison between the models derived from the two different data sources is the precision of the hotspots identified in the prediction maps. The maps obtained with acoustic data allow identifying areas of high probability of tuna presence under the DFADs with greater precision, whereas the maps derived from catch data do not allow observing any variation on a finer scale. The application of spatio-temporal models of tuna associated with DFADs using acoustic data provided by fishers´ echo-sounder buoys appears promising to identify the distribution dynamics of the species in a cost-effective way and may help designing integrated spatial programs for more efficient fishery management.

Submitted as:

Orue, B., Lopez, J., Pennino, M.G, Moreno, G., Santiago, J., Murua, H., (Under review). Modelling tropical tuna distribution: do fisheries dependent and independent data provide comparable results? Deep-Sea Research Part II.

General discussion

General discussion

Tropical tuna purse seine fisheries have increased the use of DFADs in the last 20 years (Scott and Lopez 2014a), generating a need for knowledge on DFADs fisheries which has not improved at the same pace as their use. Understanding the impacts of DFADs on the ecosystem and the ecology and behavior of marine species associated with floating objects, with the aim of providing the best scientific advice in support of the management of tropical tuna species is, thus, needed. The lack of knowledge and sound science to manage DFAD fisheries, in conjunction with their potential impacts on the ecosystem, has increased the criticism of DFAD use worldwide. Until recently, most studies related to tuna behavior and dynamics at DFADs have been made using active and passive acoustic tracking (Taquet et al. 2007a; Filmalter et al. 2011; Schaefer and Fuller 2013; Matsumoto et al. 2014; Filmalter et al. 2015), scientific acoustic surveys (Moreno et al. 2007b; Boyra et al. 2018), and underwater visual census (Taquet et al. 2007b). However, these studies on the associated behavior of species with the DFADs were quite limited, due basically to the great economic and human cost involved in the research of the drifting objects, as they are very temporary in time and space.

Currently, DFADs equipped with satellite linked echo-sounder buoys are a privileged observation platform of the pelagic ecosystem (Moreno et al. 2016a; Brehmer et al. 2018), as they are continuously providing information on DFAD position and biomass underneath the DFAD, and, hence, have the potential to collect a vast amount of information in a cost-effective manner. This PhD investigates the behavior and ecology of tuna and non-tuna species associated with floating objects at different spatial-temporal scales in the Indian Ocean based upon the acoustic data automatically collected by the echo-sounder buoys attached to DFADs. For that purpose, we use acoustic data provided by fishers' echo-sounder buoys, which provide information on the geo-location of the object and rough estimates of fish biomass aggregated underneath along the trajectory of the DFAD. In particular, along this PhD dissertation we intend to respond several questions related to the behavior and ecology of the species associated to DFADS using acoustic data from fisher´s echo-sounder buoys: Could we improve the current biomass estimates provided by echo-sounders? How is the aggregation process of tuna and non-tuna species towards DFADs? Where and when are the species associated with DFADs distributed in the Indian Ocean? Are the results of species spatial and temporal distribution obtained using fishers' echo-sounder biomass data similar to the results using fishery statistics data?

For this thesis we use data from Satlink echo-sounders buoys (SATLINK, Madrid, Spain, www.satlink.es) for three and a half years in the Indian Ocean provided by a Spanish fishing company (Echebastar S.A., Bermeo, Spain, www.echebastar.com). Recent works noted the importance that these devices may have to investigate several issues of scientific relevance, including a variety of ecological and behavioral investigations of tunas and accompanying species (Moreno et al. 2016a), and other potential applications, such as the development of a fisheries-independent tuna abundance index (Capello et al. 2016; Santiago et al. 2017; Santiago et al. 2019). However, prior to the use of echo-sounder buoy biomass estimates for scientific purposes, there is a need to carefully refine the data acquisition process (e.g. time, acoustic sample coverage, etc.) as well as to understand the representativeness of the resulting echo-sounder biomass information as a proxy of tuna and non-tuna abundance around DFADs. This is particularly important when data is recorded by tools that are not originally developed for scientific purposes, implying that data needs to be pre-processed and adapted to the requirements of the end-user (Lopez et al. 2014; Baidai et al. 2018). Therefore, the first step taken in this investigation was to create a protocol (**Chapter 1**) that allows cleansing and pre-processing the integration of the information provided by fisher's echo-sounders and to understand in depth these novel data (**Chapter 2**) before its use with the aim of addressing scientific questions posed in **Chapter 3**, **Chapter 4**, and **Chapter 5** **(Figure D.1)**.

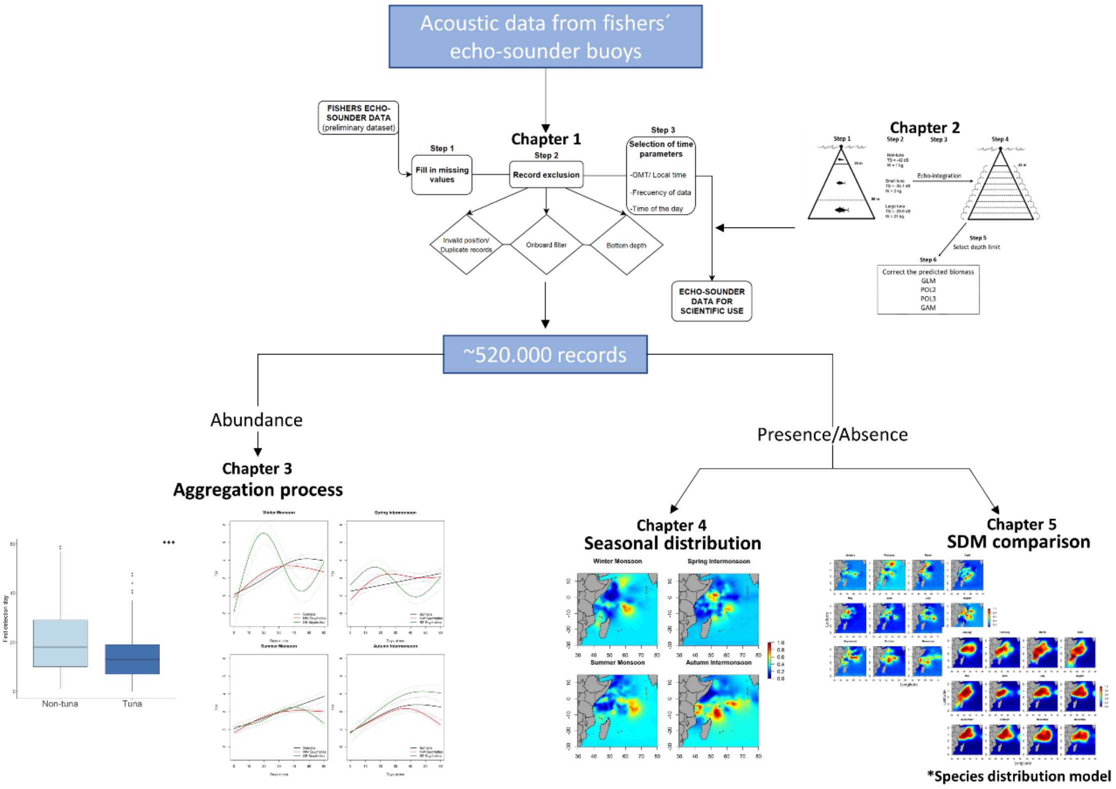


Figure D.1. *Outline of the research carried out in this thesis*

Making data operational: From fishers to scientific data

The first step taken in **Chapter 1** and **Chapter 2** represents a significant effort to understand the large amount of data available in this research and its variability. In **Chapter 1**, a deep exploratory analysis of the raw data highlighted the main sources of error present in the acoustic measurements provided by the echo-sounders. In **Chapter 2,** we analyzed the possibility of improving the estimation of biomass made by current echo-sounders, using models previously proposed by Lopez et al. (2016). In this case, the improvement of the biomass estimates was not as good as expected. Nevertheless, this chapter leads us to better understand sources of variability and uncertainty in the echo-sounder buoy data.

Among the biggest challenges we face when working with data from echo-sounder buoys are (i) the differentiation of acoustic data provided by buoys onboard and buoys at-sea and, (ii) as multiple acoustic measurements per day are available, the identification of the acoustic sample that provides a better proxy of the biomass underneath DFADs. The first issue comes from the fact that the fishers usually turn on the buoys minutes or hours prior to their deployment at sea and are switched off after an uncertain period of time (usually when are retrieved from the sea or taken by other vessels), therefore some of their acoustic samples may correspond to onboard positions. To address this issue, two filters were proposed in **Chapter 1**: a simpler one based on DFAD speed (i.e. <3 knts) and a more complex one based on a Random Forest (RF) classification model. The RF identifies 4% more data onboard and, as it included more information and it is a more comprehensive model, we believe it is the filter that should be used to discern between at sea and onboard data. However, in this thesis we used the speed filter, since the necessary data for the creation of the RF model were obtained from another brand of echo-sounder buoys in the last months of the study when most of the analysis were completed. However, this has not affected the results of the PhD as in **Chapters 3, 4** and **5** we only selected the buoys for which the time and position of deployment was known (i.e. their first day in the water) using information from FAD logbooks. As such, any buoy data onboard previous to the deployment that was classified at-sea with the speed filter was eliminated.

Another important aspect to consider when working with acoustic data from buoys is the time at which acoustic samples are recorded by the buoys and how to deal with its variability. As there is more than one acoustic record per day, it is necessary to consider the echo-sounder biomass signal that better represents the abundance of fish under the DFAD, given that fish may conduct excursions from and to DFADs at diel scale (Govinden et al. 2010; Forget et al. 2015; Lopez et al. 2017a). Depending on the objective of the study, different options could be explored. In this thesis we have used different approaches regarding the time at which the acoustic sample should be taken for the analyses (**Table D.1**). Although in a preliminary analysis (**Chapter 2, Figure 2.3**) we observed that the maximum daily biomass pattern was different according to the area in the Indian Ocean, taking values of abundance at the time of these specific maximum peaks limit the number of samples to be used for the posterior phases of the analysis in Chapter 2, due to the fact that sampling frequency is not hourly. Therefore, in **Chapter 2**, where the objective was to improve the estimation of biomass made by echo-sounders comparing the acoustic data with catch of the set, and taking into account that most sets are made at dawn as this is the time when tuna is assumed to be more closely aggregated under the DFADs (Brill et al. 1999; Josse et al. 2000; Moreno et al. 2007a; Harley et al. 2009), we selected the maximum acoustic biomass value around sunrise (i.e. between 3 a.m. and 8 a.m.). On the other hand, to study the process of aggregation of species associated with DFADs (**Chapter 3**), we use the maximum daily biomass provided by the acoustic signal from the buoy to avoid possible measurement variability and sampling constraints as well as obtain the best representation of daily community size. In **Chapters 4** and **5**, presence/absence models were used, so if the buoy emitted a non-zero signal throughout a day, it was considered as presence of tuna, regardless of the time of the day.

Table D.1. *Options explored and used in this thesis to take into account the time at which the acoustic sample should be taken for the different objectives*

	What was done?	Why it was done?	Where was it applied?
Option 1	Modelling the diel biomass estimated by the echo-sounder for different areas, using general additive models (GAMs) and taking the maximum biomass value between the peak hours with maximum abundances	In order to take into account diel tuna biomass variability at DFADs in a given area	This option was not used, as taking maximum values of abundance at these specific peaks limit the number of samples to be used in this study, due to sampling frequency is not hourly
Option 2	Choosing the echo-sounder sample with maximum biomass value before the set in the same day or the day before, always around sunrise (between 3 a.m. and 8 a.m.)	As it was necessary to compare the acoustic data with catch of the set, and taking into account that most sets are made at dawn which is the time when tuna is assumed to be more closely aggregated under the DFADs	Chapter 2
Option 3	Use the maximum daily biomass provided by the acoustic signal from the buoy	To avoid possible measuring variability and sampling constraints as well as obtain the best representation of daily community size	Chapter 3
Option 4	If the buoy emitted a non-zero signal throughout a day, it was considered as presence, regardless of the time of the day	Because only presence and absence data are used	Chapter 4 and Chapter 5

In this PhD, we propose the data cleansing protocol for a specific buoy brand in order to establish the basis of its use for science. The EU FAD-fishing fleet uses four echo-sounder buoy brands manufactured by different companies, which work with different frequencies, beam angle, ranges and other technical characteristics. Future studies should generate brand-specific protocols for cleaning raw acoustic data prior to their use for scientific purposes, due to the different technical specifications mentioned above. Currently, studies are being conducted with another brand of buoys than the one used in this study to evaluate the accuracy of biomass estimates obtained through echo-sounder buoys and to improve the current algorithms used for estimating the associated biomass (Baidai et al. 2018). In addition to the need for brand-specific protocols, each company provides a non-comparable pool of acoustic measurements because each buoy has specific data processing and echo-integration procedures. Thus, an inter-calibration is also necessary to understand inter-buoy variability and obtain comparable abundance signals per brand (Moreno et al. 2016a).

In previous works carried out with the same buoy brand, a model capable of improving the estimation of the biomass provided by the echo-sounder was described (Lopez et al. 2016). This model was based on the available knowledge of the vertical behavior of tuna and non-tuna species at DFADs and target strength and size/weight values for mixed species aggregations under DFADs (Josse and Bertrand 2000; Doray et al. 2006; Doray et al. 2007; Moreno et al. 2007b; Fonteneau et al. 2013; Chassot et al. 2015). The study developed by Lopez et al. (2016) was conducted in the Atlantic Ocean comparing a small sample of acoustic data and catches, exactly 21 fishing sets associated with their acoustic data taken previous to the set. The results were good, reducing the error variability in biomass estimates by 60%. In **Chapter 2** we apply the same model to a large number of fishing sets (i.e. 287 sets associated with their previous acoustic data) in the Indian Ocean. In this case, although the model improves the biomass provided by the manufacturer, the improvement is not as large as observed by Lopez et al. (2016). Therefore, in order to not introduce more variability in the data, in **Chapter 3** the biomass provided by the echo-sounder buoy was used directly, without applying the model explored in **Chapter 2**. The results indicate that the large spatio-temporal variability in the Indian Ocean cannot easily be considered with a single model, so the model can be further improved. One of the great advances to improve the biomass provided by buoys, would be to apply specific TS values of the associated species measured *in situ*. As there were no consistent TS-length relationship for the three tuna species when the buoy algorithm to convert acoustic signal in biomass was developed, a TS corresponding to mixed species aggregations was chosen to apply to the assumed mixed tuna layers (Moreno et al. 2007b). A series of recent studies measured TS-length relationship of skipjack and bigeye tuna at three frequencies (Boyra et al. 2018; Boyra et al. Under review), which could considerably improve the biomass estimate from acoustic tools (both, used onboard vessels or equipping buoys used to track DFADs). Another option would be to include the species composition and size by area and season in an algorithm to convert acoustic signal into biomass. The Indian Ocean is characterized by experiencing strong environmental fluctuations associated to monsoon regimes that affect ocean circulation and biological production (Schott and McCreary 2001; Wiggert et al. 2006), the marine ecology as well as the presence and relative species composition of an area (Jury et al. 2010). Therefore, using fishery statistics it would be possible to obtain the percentage and size of the different tuna species according to the area and season, and introduce this information in the conversion algorithm of the model, in order to further improve the biomass estimate provided by the fishers' echo-sounder buoys.

The first two chapters of this thesis allowed us to know in depth these novel data in order to exploit them correctly. In addition, through the protocol, we obtain clean data ready to use in different investigations related to the ecology and behavior of tuna and non-tuna aggregations around DFADs at different spatial and temporal scales. These investigations could provide an important opportunity to advance in the understanding of the aggregation mechanisms (**Chapter 3**) as well as to investigate the distribution of species associated with DFADs (**Chapter 4, Chapter 5**).

Understanding the aggregation process of virgin DFADs

In **Chapter 3** we investigate the aggregation process of new DFADs in the Western Indian Ocean using the acoustic biomass provided by fishers' echo-sounder buoys. We obtained results on tuna and non-tuna first day of arrival to the DFADs as well as trends in the aggregation process of tuna and non-tuna during the first 60 days of the DFAD at sea.

Contrary to what it has been published up to now (Hunter and Mitchell 1967; Moreno et al. 2007a) we found that tuna arrived earlier at DFADs than non-tuna species. Masters of the purse-seine fleets working in the Western Indian Ocean were interviewed and they suggested that non-tuna species took less time than tunas to colonize floating objects (i.e. 1-3 weeks for non-tuna species and one month for tuna) (Moreno et al. 2007a). This study was more than 10 years ago (i.e. 2007) and they had just started working extensively with DFADs equipped with echo-sounders, so it would be necessary to consult fishers again to determine whether their beliefs have changed over time due to the extensive use of these technological devices. Another possible explanation is that non-tuna species may be easier to observe than tuna when fishers approach the object, as non-tuna species are strongly associated with DFADs (Parin and Fedoryako 1999) showing less frequent excursions out of DFAD (Moreno et al. 2007a; Dagorn et al. 2012a; Forget et al. 2015; Lopez et al. 2017a). If a significant time gap between the arrival of two groups is confirmed, a potential fisheries management measure to reduce the amount of bycatch in the studied region would be to propose sets to be made between the tuna arrival and the arrival of the non-tuna species. Although the buoy internal detection threshold of 1 ton could affect the results, as arrivals of tuna and non-tuna in lower quantities than one ton would not be detected, we do not believe that this limitation is a major problem. This is because one ton of the current skipjack-based algorithm biomass of Satlink buoy may not necessarily represent the same amount of non-target species, but probably less, and thus the threshold may not weaken the results and conclusions of later arrival of non-tuna, as explained in **Chapter 3**. Yet, it would be advisable to work with echo-sounder data without this detection threshold. Thus, future research is necessary to verify which group of species arrives first at the object, for example using remote underwater video cameras or satellite/archival tagging information. The use of video cameras to study marine life has increased over the past twenty years, and a variety of video survey techniques are now commonly used for sampling marine populations (Cappo et al. 2006; Mallet and Pelletier 2014; Stobart et al. 2015), including colonization research (Jan et al. 2007; Flopp et al. 2011). We believe that the implementation of video cameras in the underwater structure of the DFADs at different depths could provide a very clear view of the colonization process at DFADs. In addition, this would contribute to the knowledge about the behavior of the different associated species, as well as to throw light on the reasons why they are aggregated.

In **Chapter 3** we found a significant relationship between the depth of the underwater structure of DFADs (i.e. < and > 20 meters) and colonization of tuna, suggesting a faster tuna colonization for deeper objects. For non-tuna species this relationship appeared to be not significant. It is possible that these differences may be related to the vertical distribution of the species under DFADs. As non-tuna species usually occupy shallower waters (i.e. <25 m) (Forget et al. 2015), the depth of the underwater part may not affect their aggregation ability. By contrast, tunas are usually found in deeper waters (i.e. > 25 m) (Dagorn et al. 2000b; Schaefer et al. 2009; Schaefer and Fuller 2013; Matsumoto et al. 2014; Forget et al. 2015), and thus, deeper objects might be easier to detect visually, if this is the sensory cue used. If the attraction of the underwater part (i.e. >20m) for tunas is stronger in longer DFAD tails, which in turn would produce an increase in the difference on arrival time between tuna and non-tuna species (i.e. since tuna would arrive earlier and non-tuna species would continue to arrive later without the influence of the underwater part), it could be used as a potential bycatch mitigation strategy. As such, the time between the arrivals of each group to the DFADs with a deep tail should be analyzed and, if significant, this could potentially be applied as a mitigation measure to reduce the catch of non-tuna species. It should be taken into account, however, that these results are applicable to the Indian Ocean, but may not be extrapolated to other oceans as (i) the aggregation process could be ocean-specific and (ii) the length of the underwater structure varies from the different oceans (5-20 m or 60-80 m depending on the region in the Indian Ocean, 80-100 m in the Atlantic Ocean and around 30 m in the Eastern Pacific Ocean) (Scott and Lopez 2014a; Murua et al. 2019). Therefore, future work is needed to confirm whether the relationship between tuna arrival day and the depth of the DFAD underwater part also occurs in other oceans. With these results, specific management measures could be designed for each RFMO, such as the adoption of underwater parts larger than 20 meters in the Indian Ocean for the mitigation of incidental catches. However, this could also lead to more marine debris and more impact on beaching events and, therefore, before implemented a risk assessment should be done to investigate collateral possible negative effects. Alternatively, the measure could be potentially applied in conjunction with other measures such as the use of biodegradable materials, when developed and available, for the construction of the DFADs.

The aggregation process (i.e. the biomass trend over 60 days) was analyzed spatially and temporally and they differed between monsoon periods and areas in both tuna and non-tuna species. However, these variations were greater between periods than between areas. The differences between monsoons could be explained by changes in the biophysical environment associated with seasons. The ocean circulation in the Indian Ocean is strongly influenced by the marked monsoon system, which greatly affects the oceanography and production in the area (Schott and McCreary 2001; Wiggert et al. 2006; Schott et al. 2009). The atmospheric Hadley cells, which meet at the Intertropical Convergence Zone (ITCZ), play critical roles in transporting heat, driving ocean circulation and precipitations. The ITCZ location changes through the year, which induces regime fluctuations (Green and Marshall 2017). In the Northern Hemisphere, the trade winds move in a southwestern direction from the northeast, while in the Southern Hemisphere, they move northwestward from the southeast (Wyrtki 1973). The drastic changes in circulation of the surface currents induced by the monsoon affect biophysical factors and productivity (i.e. chlorophyll, temperature, salinity, dissolved oxygen) (Tomczak and Godfrey 2013) and, thus, could also affect the presence and relative species composition in an area (Jury et al. 2010) as well as the abundance and distribution of several species (Heinrich 2010; Anderson et al. 2011; Escalle et al. 2016; Sasikumar et al. 2018). In addition to the aggregation process (**Chapter 3**), seasonal differences were also found in the distribution of tuna around the DFADs in the Indian Ocean (**Chapter 4**), suggesting that monsoon periods greatly influence the behavior and ecology of tunas aggregated to DFADs.

Habitat preferences and distribution of tuna and non-tuna species associated with DFADs

Species distribution modeling methods combine known location of a species and environmental data to produce a model of species occurrence and distribution patterns (Elith and Leathwick 2009). Understanding the habitat characteristics and dynamics of pelagic species aggregated under DFADs would contribute to the management and design conservation measures of these valuable fishery resources, such as provide a base for the design of area closures, especially in a changing ocean. In **Chapter 4**, results highlighted group-specific spatial and temporal distributions and habitat preferences under DFADs, suggesting that both tuna and non-tuna species may have different habitat preferences depending on the monsoon period. This study represents the first investigation of spatial and temporal distribution of tropical tuna and non-tuna species aggregated under DFADs in the Indian Ocean using fishery-independent data collected by fishers' echo-sounder buoys.

The results suggested that part of the variability of the habitat distribution of tuna and non-tuna under DFADs is not explained by the selected variables, meaning that other ecological processes not considered in this study may also be involved at different scales on the aggregation process of the species at DFADs (e.g. social behavior of tuna at DFADs, DFAD densities in the area, dispersal or the patterns of aggregative species). This is consistent with previous studies, where environmental variables were seen to play a more important role in free schools than in DFAD communities in the Indian Ocean (Lezama-Ochoa et al. 2015). Therefore, we could hypothesize that for small tuna, that usually are aggregated to DFADs, the environmental conditions might be confounded with the motivation to remain aggregated with DFADs, which to some extend is related to the ecological trap hypothesis (Marsac et al. 2000). The ecological trap concept was developed by Dwernychuk and Boag (1972) and is assumed to arise when formerly adaptive habitat preferences become maladaptive because the cues individuals preferentially use in selecting habitats lead to lower fitness than other available alternatives (Dwernychuk and Boag 1972; Schlaepfer et al. 2002; Fletcher et al. 2012; Robertson et al. 2013). Marsac et al. (2000) were the first to propose the possibility that the DFADs might act as an ecological trap for tunas, suggesting that DFADs could entrain tunas to biologically unsuitable locations, having a detrimental effect on the health of the stock (e.g. condition, natural mortality) and alter the spatio-temporal dynamics of fish that strongly associate with floating objects. The majority of studies related to ecological traps have been conducted in terrestrial systems (Robertson and Hutto 2006), as for example the studies conducted with insects (Ries and Fagan 2003; Duchet et al. 2018), reptiles (Rotem et al. 2013) or birds (Dwernychuk and Boag 1972; Shochat et al. 2005; Santangeli et al. 2018). On the contrary, few studies have addressed ecological traps in marine environments (Hallier and Gaertner 2008; Dempster et al. 2011; Reubens et al. 2013; Gutzler et al. 2015). The demonstration of the existence of an ecological trap in fishery studies is difficult because preference for habitat and individual choices driving to a poor condition and higher mortality are difficult to detect using most of fisheries data (Hallier and Gaertner 2008). Moreover, working with DFADs requires major financial cost and logistical support, as they drift through the open sea for several months (Dagorn et al. 2010). In order to shed light on the ecological trap hypothesis, further research should be carried out using acoustic data provided by echo-sounder buoys to model the biomass aggregation/decrease around the DFAD and compare it with preferential/non-preferential areas found in **Chapter 4** and with the condition of tuna, which could inform the effect of the DFADs on the movements of tunas and their habitat.

Effective fisheries management is increasingly important, as overfishing threatens fish stocks globally, reduces biodiversity and alters ecosystem functioning (Jackson et al. 2001; Pauly et al. 2005). Currently, the vast majority of spatial management measures for marine species, such as Marine Protected Areas (MPA), often set fixed boundaries around mobile species (Hyrenbach et al. 2000; Norse et al. 2005; Crowder and Norse 2008), which is not very adequate due to the ocean itself being highly dynamic. Fixed MPAs may not be also adequate for highly mobile species like tuna, which the United Nations Convention on the Law of the Sea (UNCLOS) includes as one of the main migratory marine species (Article 64 and Annex 1) (Maguire 2006), due to their large migratory nature. In recent years, the concept of dynamic ocean management has been defined as “management that changes in space and time in response to the shifting nature of the ocean and its users based on the integration of new biological, oceanographic, social and/or economic data in near real-time” (Maxwell et al. 2015). This concept requires more precise data and faster collection, processing and analysis to enable near real-time responses (Wilson et al. 2018). Data collection for fish such like tunas is difficult, time-consuming and costly because of their wide distribution and large mobility, and the complex interactions within marine ecosystems and the physical environment (Bradley et al. 2019).

The approach used in this study could be the first steps towards the design, in the near future, of spatial-temporal conservation management measures (e.g. area closures) for both target and non-target species, using near real-time habitat predictions based on acoustic data provided by fishers' echo-sounders and remote sensing systems (**Figure D.2**). Nevertheless, much work remains to be done, especially related to the improvement of biomass estimation by echo-sounders buoys. Moreover, none of the echo-sounders used at this time have the capability to directly identify fish size and species, since these buoys operate with a single frequency. If echo-sounder buoys had the ability to discriminate the species and sizes of tunas found at DFADs, these real-time habitat predictions could provide specific management measures for certain species or sizes. Moreover, it would be necessary to develop initiatives of data-exchange between fishers and scientific organizations, which allow the transmission of echo-sounder buoy data to scientists in near real-time following strict confidentiality rules. As the fishing fleet has to transfer the data, for this data-exchange to take place efficiently, the fishers should understand and be part of the management measures proposed. If the results have no value to fishers or cannot benefit their fishing operation, then participation in data collection programs will be met with resistance. Therefore, a collaborative process is needed to ensure that results are shared with fishers to guide management decisions made at sea (Neitzel et al. 2017) and to move towards a co-management system (Jentoft 2005; Stephenson et al. 2016).

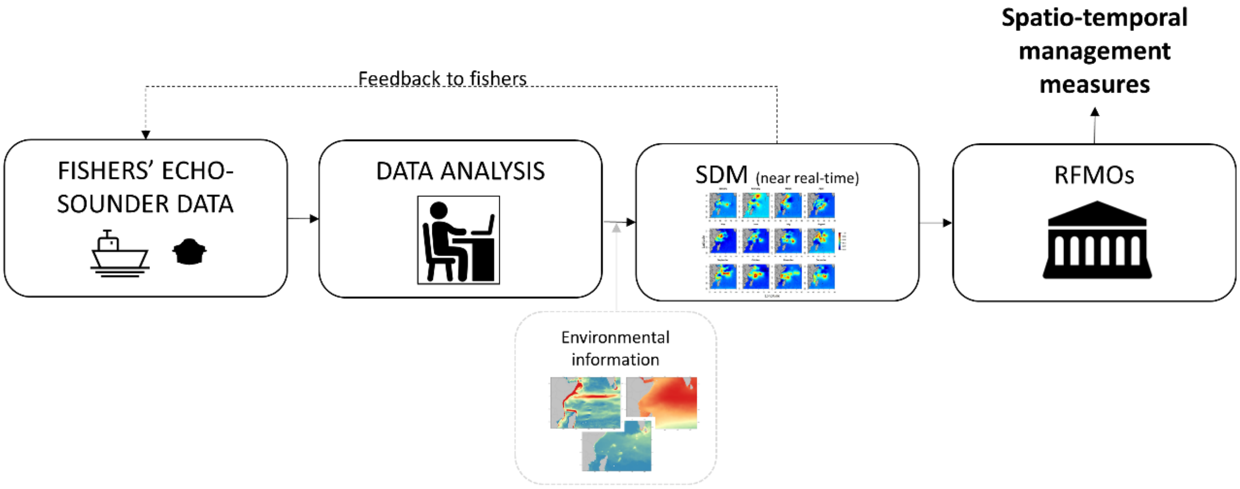


Figure D.2. *A conceptual diagram of a hypothetical future process of dynamic ocean management using fishers' echo-sounder buoys*

Fisheries-dependent vs fisheries-independent data: Advantages of using echo-sounders buoys

Chapter 5 focuses on evaluating whether two different data sources (i.e. fishery information as fisheries-dependent data and acoustic information as fisheries-independent data) produce similar, different or comparable habitat distribution results using the same spatio-temporal models of **Chapter 4**. The most remarkable result of the comparison between the models derived from the two different data sources is the precision of the hotspots identified in the prediction maps (**Figure D.3**). In the maps derived from catch data we obtain a large hotspot that covers practically the entire fishing area without major changes during the year, but that does not allow observing any variation on a finer scale (**Figure D.3, B**). On the other hand, the maps obtained with acoustic data allow identifying areas of high probability of tuna presence under the DFADs with greater precision (**Figure D.3, A**). It is possible that the differences found between models are related to the characteristics of the data (i.e. the spatial and temporal resolution of the data) and data processing (e.g. aggregated or fine scale environmental data). Moreover, the prediction maps obtained with catch data indicate zero probability of finding tuna near the horn of Somalia since there are no observations to build SDMs due to the large exclusion zone off the Somali coast due to piracy problems (Chassot et al. 2010) in the study period. In contrast, echo-sounder buoys continuously record and provide information in areas and seasons where catch data is not available. Maps illustrating the distribution of tuna associated with DFADs are fundamental sources to help design management and conservation measures, so it is very useful to obtain maps as much detailed as possible within the large area occupied by tropical purse-seine fisheries. With the availability of high-resolution data of tuna presence derived from fishers' echo-sounder buoys and environmental variables from satellite data, broad-scale studies can be made to estimate tuna distribution at fine resolutions.

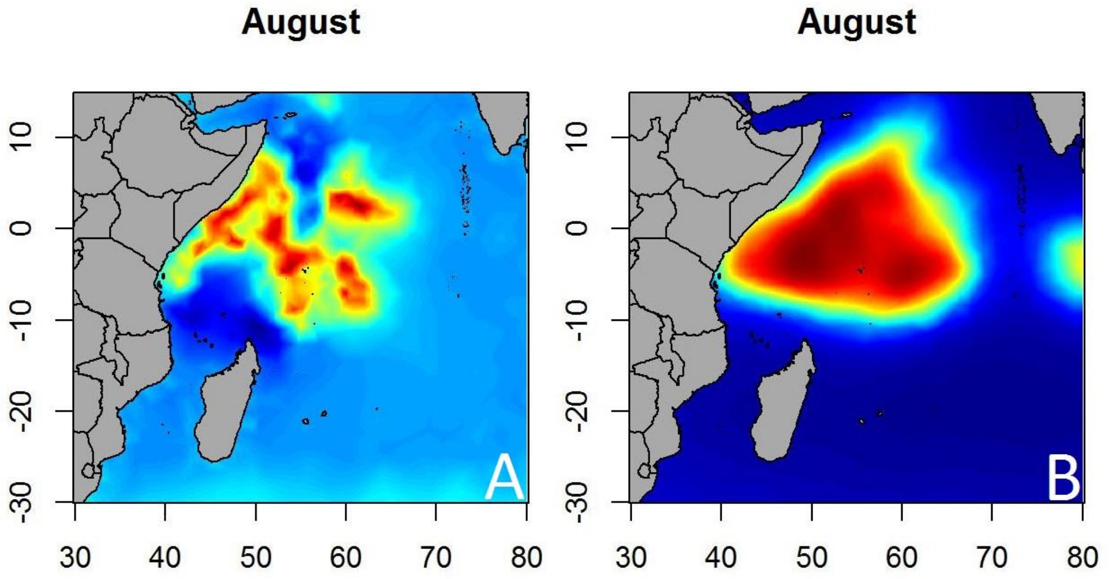


Figure D.3. *Maps of the posterior mean of tuna occurrence probability in august using fishery- independent (A) and dependent data (B).*

As discussed extensively in **Chapter 5**, fisheries-dependent and independent data have different advantages and limitations (**Table D.2**). Although ideally the use of scientific data specifically designed for each study would be best, this is often difficult in large-scale studies due to the high economic cost of these surveys (e.g. ocean research vessels cost ranging from $10,000 to more than $40,000 per day (Valdés 2017)). Having a large amount of data with high spatial and temporal resolution is essential to scientific studies and to effectively manage the fishery. However, oceans are a three-dimensional habitat, that forms over seventy percent of the surface area of the earth, in constant flux affecting the species and resource users which are being managed (Maxwell et al. 2015). In that sense, DFADs appear as a valuable tool for obtaining huge amounts of information in a very cost-effective manner and with a high spatio-temporal resolution, presenting clear advantages for broad-scale ecological analyses. For information purposes, if the acoustic data used in this thesis were collected with a scientific acoustic survey, it would have cost more than 710 million euros (i.e. assuming that a scientific acoustic survey costs around 10 euros per square nautical mile per year (G. Boyra, pers. comm.)). **Chapter 5** highlights the great potential fishers´ echo-sounder buoys have for undertaking studies to address sound scientific questions, including those related to the ecology and behavior of tuna species associated with DFADs. The integration of these novel sources of information in science and management are a valuable tool that should not be undervalued and dismissed.

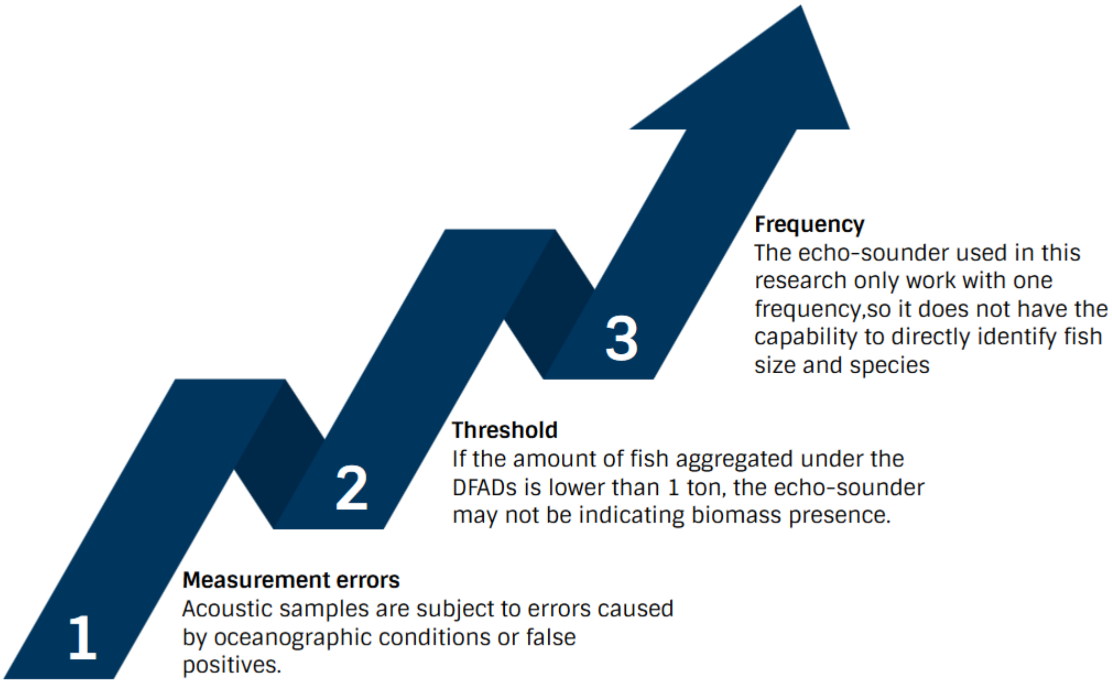
Table D.2. *Main characteristics of catch data, scientific fishery-independent data and echo-sounder data, as well as their major limitations and advantages.*

	Catch data (Fishery-dependent data)	**Scientific surveys (Fishery-independent data)**	**Echo-sounder buoys (Fishery-independent data)**
Economic cost	Low-cost	High-cost	Low-cost
Spatial coverage	1ºx1º or 5ºx5º	Samples that generally cover specific areas and relatively short periods of time	Fine scale (latitude, longitude)
Temporal coverage	Monthly		Daily
Bias sources	-Preferential sampling -Data constrained to the areas where fishing occurs -Others: aggregation of species into generic groups, transcription errors and misreporting of catches	-Limited amount of data can be collected -Limited coverage in space and time (in terms of seasonality or the number of years of available data)	-Not originally developed for scientific purposes -Echo-sounder buoys are switched off when they move away from the fishing zone - Others: aggregation of species into groups (tuna and non-tuna), no size information, measurement errors
Advantages	-Long time series -Wide spatial coverage	-Less bias: Survey data are considered to be of higher quality because sampling	-Echo-sounders buoys are continuously recording information on the DFADs

	and collection are scientifically designed and standardized	trajectories and biomass of fish aggregated underneath in a non-invasive manner, covering areas and seasons where catch data are not available - Wide spatial/temporal coverage

Main limitations of fishers´ echo-sounder buoys

Despite the advantages, the novel acoustic data used in this thesis has some limitations **(Figure D.4**), however, this thesis has shown that acoustic data provided by fishers' echo-sounders buoys can be used knowing how to interpret the information and being aware of their limitations.



Frequency
The echo-sounder used in this research only work with one frequency,so it does not have the capability to directly identify fish size and species

Threshold
If the amount of fish aggregated under the DFADs is lower than 1 ton, the echo-sounder may not be indicating biomass presence.

Measurement errors
Acoustic samples are subject to errors caused by oceanographic conditions or false positives.

Figure D.4. *Main limitations of acoustic data provided by fishers' echo-sounder buoys*

The first limitation is related to the measurement errors of the echo-sounder buoy. Acoustic samples are subject to errors caused by the nature of the physical measurement (Johannesson and Mitson 1983). In addition, oceanographic conditions, like wind induced bubbles, can produce attenuation of acoustic waves and therefore affect buoys' movement and subsequently, negatively bias the acoustic signal and sampling. Another source of noise may occur when underwater part of the DFAD gets under the echo-sounder, so the echo will be integrated as a false fish echo. However, when this occurs the echo-sounder signal give the maximum value in several layers (i.e 63 tons), which is very easy to recognize and, therefore, to remove from the analysis. In addition, duplicate data or seabed reverberation (i.e. biomass signals reflecting the seafloor) are also part of these measurement errors. Thanks to the in-depth data analysis carried out in **Chapter 1**, the latter measurement errors (i.e. false positives due to underwater part of DFAD) were identified and removed from the database. Another aspect to take into account is the beam angle of the echo-sounder, since it has a certain aperture (i.e. 32º), which probably does not allow to collect the information of the whole aggregation. Moreover, the position of the fish in relation to the echo-sounder beam and its detectability is something to be considered. Some bycatch species are known to be more strongly and tightly attached to the DFAD (intranatant/extranatant species, see Freon and Dagorn (2000)) than tuna species (circumnatant) and thus, may be more easily detected. Besides, some species like tuna make longer excursions out of the DFAD when compared to most non-tuna species (Govinden et al. 2010; Forget et al. 2015; Lopez et al. 2017a). However, the cone shape of the beam of the echo-sounder, covering a larger area with increasing depth, compensates the detectability of tuna individuals. Future studies should combine echo-sounder buoy sampling around DFADs with dedicated tagging and monitoring of fauna surveys to infer detectability rates per size and species to assist in acoustic signal interpretation.

One of the major limitations of the data used in this thesis is that the buoys have an internal detection threshold of 1 ton of estimated tuna biomass. If the amount of fish aggregated under the DFADs is lower than one ton (as for the conversion done by the manufacturer) during the first few days the object is at sea, the echo-sounder may not be indicating biomass presence, potentially biasing the analysis. This limitation may be significant in the case of non-tuna species, since bycatch species are normally found in lower amounts than tuna species at DFADs (i.e. in a range between 1-5 tons (Romanov 2002; Romanov 2008; Dagorn et al. 2012a)). Satlink buoys use a method that converts raw acoustic backscatter into biomass using an empiric algorithm based on the target strength and weight of skipjack tuna, which is the main target species of purse seine fishery using DFADs. Whereas the skipjack tuna does not have a swimbladder, the majority of bycatch species do (e.g. wahoo (*Acanthocybium solandri*), rainbow runner (*Elegatis bipinnulata*) or trigger fish (*Canthidermis maculatus*). Swimbladdered species normally produce a much higher echo than bladderless since this hydrostatic organ, when present, is responsible for 90–95% of the backscattering energy (Foote 1980). Accordingly, one ton of the skipjack-based algorithm non-tuna biomass may not necessarily represent the same biomass of non-target species, but probably less, and therefore the threshold of one ton may not be as important as would be expected for first detection of non-tuna in DFADs. Nevertheless, it is important to take into account this limitation for the use of these data for scientific purposes. Yet, it would be very useful to work without this detection threshold which could be solved by buoy providers very easily. Access to these raw data would provide scientists information without the threshold limitation, which could help in the investigation of sustainability and the management of the exploited resources.

The echo-sounder used in this research only works with one frequency, so it is not possible to discriminate between the three main species and sizes of tropical tuna found in the DFADs. One of the prerequisites to discriminate tuna species and asses their biomass is knowing the target strength (TS; dB re 1 m), TS-length (L; cm) and TS-frequency (f; kHz) for the 3 species found at DFADs. An acoustic research conducted by ISSF (Moreno et al. 2015; Moreno et al. in press) found different frequency response for skipjack compared to bigeye and yellowfin tunas when analyzed simultaneously with multi-frequency echo-sounder, because skipjack doesn´t have swim bladder while bigeye and yellowfin do. Given that the highest contribution to the TS is given by the swim bladder, there is normally a contrasting different frequency response between swim bladdered and non-swim bladdered species (Gorska et al. 2005; Fernandes et al. 2006). This source of discrimination between species could be applied to distinguish skipjack from bigeye and yellowfin, as it has already been applied in other cases (Logerwell and Wilson 2004; Korneliussen 2010). Unfortunately, only few studies have analyzed acoustic properties on aggregations around DFADs, most of them using a single acoustic frequency, probably due to the fact that DFAD aggregations are ephemeral in time and space making the research expensive and logistically difficult. *In situ* TS measurements for bigeye and yellowfin are only available at 38 kHz (Josse and Bertrand 2000; Doray et al. 2006; Moreno et al. 2007b), whereas a recent study measured TS-length relationship of skipjack and bigeye tuna at three frequencies (Boyra et al. 2018; Boyra et al. Under review). Finding specific TS-frequency relationships for each tuna species would allow significantly improving the accuracy of biomass estimates by tuna species and, in monospecific aggregations, even tuna sizes before the fishing set.

Future perspectives using fishers' echo-sounder buoys data

This thesis represents the first steps towards understanding and use of acoustic data provided by fishers' echo-sounder buoys for scientific purposes.

One of the most promising and innovative research areas is to derive fishery-independent abundance indices of tunas based on acoustic samples of echo-sounder buoys. Fisheries stock assessment models are the basis to evaluate and assess the condition of a population and a fishery, and to establish a scientifically sound management measures (Hilborn and Walters 2001). The vast majority of stock assessment models require some index of abundance. In tuna stocks, the use of fisheries-independent abundance indices is rare due to the migratory nature of the species and, hence, the difficulty to carry out dedicated scientific surveys covering the whole spatio-temporal distribution of the species. Currently, the majority of abundance indices used in the stock assessment models for highly migratory species are based on fisheries-dependent catch-and-effort analysis (Catch per Unit of Effort, CPUE) (Maunder and Punt 2004). The CPUE of the tropical tuna purse seine fishery is typically standardized using fishing time, searching time or the number of positive fishing sets as fishing effort unit, without considering technological creep or fishing strategy changes that may affect catchability (i.e. the parameter relating catch and effort with stock abundance) (Fonteneau et al. 2013; Katara et al. 2017). The introduction of DFADs, and the associated rapid technological development, make it difficult to evaluate the effective effort of the purse seine fisheries and have therefore hindered the reliable estimation of standardized purse seine CPUE indices (Maunder et al. 2006; Gaertner et al. 2015). Alternatively, several authors have proposed the use of fisheries-independent data to develop relative abundance indices of tuna species. Capello et al. (2016) proposed a method to estimate species abundance using data obtained through acoustic tagging at DFADs and DFAD densities. Furthermore, several studies (Santiago et al. 2017; Santiago et al. 2019) proposed to use the biomass estimated from acoustic samples provided by echo-sounders buoys on DFADs to develop a tuna abundance index, based on the assumption that the signal from the echo-sounder is proportional to the abundance of fish:

$$BAI_t = \varphi \,.B_t$$

where BAI_t is the Buoy-derived Abundance Index, φ is the coefficient of proportionality and B_t is the biomass in time t. The results derived from this tuna BAI could provide significant information to further complement current stock assessments of tropical tuna fisheries that only rely on fisheries-dependent data, particularly for this fleet, where changes in technology may imply significant changes in fleet behavior, effort and catchability of the species.

Another major development for the future of echo-sounders related to both research and conservation, is the integration of different frequencies. The data provided by buoys equipped with multi-frequency echo-sounders could be very useful for informing species specific BAI indices (above) but also in developing science-based regulatory measures to minimize bycatch and catches of vulnerable species (Moreno et al. in press). For example, the over-exploitation of bigeye tuna is in part due to the catch of small bigeye at DFADs, that simultaneously aggregate the three species (Leroy et al. 2012; Pons et al. 2017). Having a specific composition information before the fishing set could contribute to mitigate the catches of small bigeye individuals, avoiding their fishing, and, hence, contributing to a more sustainable exploitation of the resources. Moreover, acoustic discrimination of different species associated with DFADs could contribute to increase knowledge on their ecology and behavior. The availability of acoustic data by species would make it possible to conduct the analyses carried out in **Chapter 3**, obtaining the aggregation dynamics for the three tuna species separately, as well as obtaining maps of preferential habitats for each species, such as those obtained in **Chapter 4** and **Chapter 5**.

This thesis focuses on the ecology and behavior of tuna and non-tuna species associated with DFADs in the Indian Ocean. Since each ocean has unique oceanographic characteristics and the fleet makes different use of DFADs depending on the ocean (i.e. deployment strategy, length of the underwater structure, etc…), it could be very useful to expand the different analysis performed in this thesis to other oceans. This could allow a general comparison of all these aspects (i.e. aggregation process, spatio-temporal distribution and environmental preferences) by ocean basins.

Throughout this thesis, we highlight the importance of the acoustic data provided by fishers' echo-sounder buoys for scientific analysis. Considering this, there is a need to propose collaborations between buoy companies, fishers and scientists to develop a process for a routine, continuous, confidential and RFMO-supported raw data transfer between the purse seine industry and research centers.

Main contributions

The main contributions of this thesis are, on the one hand, to detail the management of acoustic data provided by fishers' echo-sounder buoys for scientific purposes and, on the other hand, to increase knowledge about the ecology and behavior of tuna and non-tuna species associated with DFAD, analyzing the aggregation process as well as the habitat distribution and preferences of both species groups. The scientific advances in this knowledge could contribute to the scientific basis for DFAD management measures (e.g. dynamic spatial management on real time), supporting tuna RFMOs in decision-making for a more sustainable management of the species and fishery under their mandate. Overall our findings show that acoustic data provided by fishers' echo-sounders buoys can be used in scientific research, especially in large-scale studies where data accessibility is limited. Fine-scale extended open-ocean data allow us to have a large spatial-temporal coverage for diverse investigations related to the species associated to floating objects.

Conclusions and thesis

Conclusions and thesis

The conclusion of the first chapter with the aim "*to establish standardized protocols to process fishers echo-sounders´ acoustic raw biomass estimates in order to use them for scientific purposes*" is:

1. The implementation of the proposed standardized protocol eliminates errors and false positives found in data provided by fishers' echo-sounder buoys and allows the collection of clean acoustic data useful for scientific purposes.

The conclusion of the second chapter with the aim *"to progress towards improved remote biomass estimates by the echo-sounders equipping DFADs, following previous analysis proposed in the field, based on existing knowledge of the vertical distribution of non-tuna and tuna species at DFADs and mixed species target strengths (TS) and weights*" is:

2. Although the application of behavior/size-based model improves acoustic biomass estimates provided originally by manufacturers, the improvement of the biomass estimates is not as large as expected; which suggest that a single model to convert acoustic signal into biomass is not enough to explain the large variability in these data and further improvements are needed.

The conclusions of the third chapter with the aim "*to investigate the aggregation process of virgin (i.e. newly deployed) DFADs in the Western Indian Ocean using the acoustic records provided by fishers' echo-sounder buoys, determining the first detection day of tuna and non-tuna species at DFAD and identifying the potential differences in the spatio-temporal dynamics of the aggregations*" are:

3. The average period for the arrival of fishes to the DFADs (i.e. first day that the echo-sounder detected biomass) is 13.5±8.4 days for tuna and 21.7±15.1 days for non-tuna species; which indicates that tuna arrive at DFADs before non-tuna species.
4. The analysis shows a significant relationship between DFAD depth and detection time of tuna, suggesting a faster tuna colonization for deeper objects. For non-

tuna species this relationship appears to be not significant. The influence of underwater structure on the aggregation process may be related to the vertical distribution of the species under DFADs.

5. The aggregation dynamics differ between area and monsoon periods in both tuna and non-tuna species. These differences could be explained by changes in the biophysical environment associated with seasonality, although there may be other social factors affecting the aggregation process of tuna and non-tuna species at DFADs, such as the density and abundance of the local tuna population or DFADs.
6. The results of this research could be used as a tool to assist on the sustainability of tuna fisheries, helping to design conservation measures for tuna and non-tuna species management, such as reducing the undesired catch.

The conclusions of the fourth chapter with the aim “*to investigate the habitat preferences and distribution of tuna and non-tuna species associated with DFADs and environmental conditions in the Indian Ocean implementing Bayesian Hierarchical spatial models*” are:

7. Results highlight species-specific spatial and temporal distributions as well as different relevant environmental factors for tuna and non-tuna species presence associated with DFADs, which suggest that both species group may have different habitat preferences.
8. The highest probabilities for tuna presence are found in warmer waters, with larger sea surface height and low eddy kinetic energy. In the case of non-tuna species presence on DFADs, the highest probabilities are found in colder and productive waters. For both groups, days at sea is relevant, with a higher probability of tuna and non-tuna presence on DFADS when the object stays longer at sea.
9. The relevance of buoy random effect and the spatial effect could indicate that there must be other ecological processes behind this associative behavior of tuna and non-tuna species at DFADs that are not being taken into account in this study (e.g. social behavior of tuna at DFADs or DFAD densities in the area).

10. The results of his study could contribute to design spatio-temporal conservation management measures (e.g. dynamic area closures) for both target and non-target species, using near real-time habitat predictions based on acoustic data provided by fishers' echo-sounders and remote sensing systems.

The conclusions of the fifth chapter with the aim "*to compare the spatio-temporal distribution of tuna in the Western Indian Ocean resulted from both fisheries-dependent (i.e. nominal catch data) and independent (i.e. acoustic data from fishers´ echo-sounder buoys) data using spatially-explicit Bayesian Hierarchical spatial models*" are:

11. The predicted probability of occurrence for tuna developed using fisheries-dependent and fisheries-independent data show, in general, similar areas of tuna presence under the DFADs, however, some fine-scale differences are observed. The good level of overlap in the predictions indicate by the similarity statistics, considering the low correlation values, are most likely due to the fact that the large-scale habitat preference predictions considered in this study have very low probabilities outside the main fishing area, which may result in misleading similarity statistics.
12. The maps obtained with acoustic data allow identifying areas of high probability of tuna presence at DFADs with greater precision, whereas the maps derived from catch data do not indicate any variation of tuna distribution on a finer scale.
13. Results of monthly specific tuna distribution patterns under DFADs suggest that tuna species may have different habitat preferences depending on the season.
14. The results of this research highlight the great potential fishers´ echo-sounder buoys have for addressing key scientific questions on tuna ecology and behavior. Furthermore, these data could significantly contribute to the development of possible management measures, for example time–area closures, in which, by having greater precision in the spatio-temporal distribution of tuna associated with DFADs, management measures could be more efficient.

Finally, considering all these conclusions, the working hypothesis has been confirmed:

Results on the aggregation process, spatio-temporal distribution and environmental preferences of species associated with DFADs in the Indian Ocean, using acoustic data provided by fishers' echo-sounder buoys, contribute to increase the knowledge of ecology and behavior of tuna and non-tuna species associated with DFADs, which could advice the scientific basis for DFAD fishery management, supporting tuna RFMOs in decision-making for a more sustainable management of the species and the fishery.

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