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Foto portada: David Itano. Imagen submarina de un dispositivo concentrador de peces (FAD, del inglés *Fish Aggregating Device*). Se aprecia la parte flotante (en la zona superior) y la estructura subacuática, así como algunos peces agregados junto al objeto. © ISSF (2012)

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

Blanca Orúe[1]*, Jon Lopez[1,2], Gala Moreno[3], Josu Santiago[1], Guillermo Boyra[1], Maria Soto[4], Hilario Murua[1]

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.

Keywords: biomass, DFADs, echo-sounder buoys, non-tuna species, tuna

[1] *AZTI-Tecnalia, Herrera kaia portualdea z/g 20110 Pasaia (Gipuzkoa), Spain*
[2] *Inter-American Tropical Tuna Commission (IATTC) 8901 La Jolla Shores Drive, La Jolla CA 92037-1509*
[3] *International Seafood Sustainability Foundation (ISSF) 1440 G Street NW Washington DC 20005*
[4] *Instituto Español de Oceanografía, Corazón de María 8, 28002 Madrid, Spain*
[*] *corresponding author: borue@azti.es*

Introduction

Drifting fish aggregating devices (DFADs) are floating objects drifting in the surface of tropical waters, which attract numerous marine species (Castro *et al*., 2002), including main commercial tropical tuna species (i.e. skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*)) but also non-target species (e.g. rainbow runner (*Elagatis bipinnulata*), silky shark (*Carcharhinus falciformis*) or dolphinfish (*Coryphaena hippurus*)). Taking advantage of this associative behavior, fishers have been increasingly constructing and deploying artificial man-made DFADs since the 90s to facilitate the catch of tuna species (Fonteneau *et al*., 2013). In the Indian Ocean, more than 80% of the tuna purse-seine sets were made on DFAD by the Spanish fleet in the last years (Báez *et al*., 2018). The rest of the catch of the purse seine fishery comes from sets on unassociated tuna schools, also called free-swimming schools (FSC).

The most notable changes in the tropical tuna purse seine fishery in recent years have been particularly oriented to improve the efficiency of purse-seine fishing with DFADs (Lopez *et al*., 2014). Of special importance are the satellite linked echo-sounder buoys, which remotely inform fishers in near real-time about the accurate geolocation of the DFAD and also provide rough estimates of the fish biomass underneath them. The first buoys equipped with an echo-sounder appeared in the market in the 2000s (Lopez *et al*., 2014) and, today, they are used in most of DFADs used by tropical tuna purse seine fleets globally (Moreno *et al*., 2016).

Although DFAD fishing represent certain notorious advantages, like better ratio of positive sets on DFADs to FSC sets (Soto and Fernández, 2016) or the reduction of time devoted to search for tuna schools (Fonteneau *et al*., 2013; Lopez *et al*., 2014), DFADs may also have potential negative impacts on the ecosystem (Fonteneau *et al*., 2000; Marsac *et al*., 2000; Essington *et al*., 2002; Dagorn *et al*., 2012). Due to uncertainty about on their ecological and ecosystem impacts, DFAD fishing has become a concern for Regional Fisheries Management Organizations (RFMOs). As floating objects drift across the surface of the oceans for several months, being very temporary in time and space, the associated human and economic cost of investigating DFADs at large scale is certainly high. However, DFADs equipped with satellite linked echo-sounder buoys are continuously streaming information and, hence, have the potential to collect information in a cost-effective manner; being privileged observation platforms of the pelagic ecosystem (Moreno *et al*., 2015b). In recent years, the potential use of DFADs as scientific platforms has been highlighted by the scientific community (Dagorn *et al*., 2006; Moreno *et al*., 2015b; Lopez *et al*., 2016), with the aim to investigate several issues of scientific relevance, including fishery-independent abundance indices for tuna species (Santiago *et al*., 2017) and a variety of ecological and behavioral investigations of tunas and non-tuna species.

However, current echo-sounder buoys provide a single biomass value without determining species or size composition of the fish underneath the DFAD. Lopez *et al*. (2016) developed a model to improve the biomass estimates by group of using data from echo-sounder buoys at DFADs in the Atlantic Ocean. This model was based on the available knowledge of the vertical behavior of tuna and non-tuna species at DFADs and target strength (TS, dB re 1 m2; Maclennan *et al*. (2002)) and weight values for mixed species aggregations.

This paper aims to improve our understanding on the biomass estimates provided by fishers' echo-sounder buoys at DFADs and their associated uncertainty and variability sources, using as base model the one proposed Lopez *et al*. (2016). Aiming to this objective, we use a large number of fishing set information and their corresponding acoustic samples from echo-sounder buoys prior to the fishing set in the Indian Ocean, where the model was applied by areas, as species composition and associative behavior patterns may be region and environmental conditions-specific.

Materials and methods

Data collection

Echo-sounder buoy data, including tracks (location) and biomass information, was provided by the Spanish purse seine vessel company Echebastar. The buoy database includes information about DFAD-Buoy ownership, buoy ID (unique alphanumeric code provided by buoy manufacturers), buoy model (i.e. in this study we use a single buoy model), location (latitude and longitude), date, GMT time, speed, drift, and acoustic biomass records during its lifetime. The database contained information from January 2012 to May 2015.

Both fishing and FAD logbooks were also collected for the vessels and periods considered in the study. Fishing logbooks included information on fishing related activities of the vessels: fishing set mode (FAD/FSC), location, species and size composition of tuna catch. FAD logbooks provided information on the buoy ID, vessel, location, and the activity associated to the DFAD (i.e., deployment, visit, fishing, etc.) (De Molina *et al*., 2013), date and time of the activity, as well as information on the DFAD structure and materials. Information from both logbooks was used to match fishing sets information with their corresponding acoustic samples from echo-sounder buoys collected prior to the fishing set.

The buoy

The Satlink buoy (SATLINK, Madrid, Spain, www.satlink.es) was selected in the present study because (1) it was considered by interviewed fishers as the buoy that gave the most accurate biomass signal (Lopez *et al*., 2014) and because (2) it was the buoy with the most available technical information from manufacturers (i.e., algorithm to transform the acoustic sample into biomass). Besides, Lopez *et al*. (2016) developed a model for this particular buoy brand in the Atlantic Ocean. The buoy is equipped with a geolocation system and a Simrad ES12 echo-sounder and the information collected, including location, trajectories and the amount of biomass (in metric tons, t) underneath each DFAD is transmitted by satellite. The echo-sounder operates at a frequency of 190.5 kHz with a power of 120 W. Beam angle is 32^0 and the depth observation range extends from 3 to 115 m, which is split in ten homogeneous layers, each with a resolution of 11.2 m. The buoy has also a blanking zone (a data exclusion zone to eliminate the near-field effect of the transducer; Simmonds and MacLennan (2005)) between 0 and 3 m (**Figure 1**). The echo-sounder is programmed to operate for 40 seconds every time collects a sample. During this period, 32 pings are sent from the transducer and an average of the backscattered acoustic response is computed and stored in the memory of the buoy (hereafter called "acoustic sample"). Volume backscattering strength (S_v, dB re 1 m–1; Maclennan *et al*. (2002)) values smaller than –45 dB are automatically removed by the internal module of the buoy, as a precautionary measure to eliminate signals that likely corresponded to organisms smaller than tuna (i.e., organisms of the sound scattering layers; Josse *et al*. (1999); Josse and Bertrand (2000)).

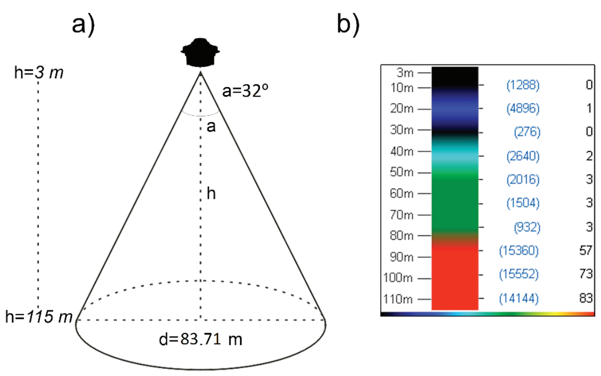

Figure 1. (a) Characteristics of the Satlink echo-sounder buoy: Beam angle (a), depth range (h), and diameter (d) at 115 m. (b) An example of the echogram display for the 10 depth layers (ranging from 3 m to 115 m) (modified from Lopez *et al*. (2016)).

Data analysis

Data cleansing process

The buoys used in the present study did not provide the position (latitude and longitude) and speed when biomass estimation is given. This information, however, is available from the buoy data before and after biomass signal is received. Thus, we use a linear interpolation program which calculates missing position and speed values using the nearest position, speed and drift data. Then, data cleaning was carried out following the next steps: i) remove data with invalid positions (e.g. positions on land or in another ocean) ii) remove duplicate records iii) remove data with speed values higher than 3 kn (likely representing onboard positions), iv) remove data located inside the continental shelf (i.e., shallower than 200 m) due to acoustic samples in < 200 m waters could give false positives.

Associating acoustic samples with fishing sets

Fishing sets and acoustic samples were linked using the information from both fishing and FAD logbooks with buoy position information. The fishing sets conducted by a given vessel on a particular DFAD were identified based on the information of buoy code, date, time and position recorded in the logbooks. Then, the acoustic sample for the same buoy code, location, day, and fishing set was related with the catch estimation from the logbook of the corresponding fishing set. Several options were considered for choosing the time at which acoustic signal is more representative of the biomass around the DFAD. The first option consisted in modelling the diel biomass estimated by the echo-sounder using general additive models (GAMs; Hastie and Tibshirani (1990), see Lopez *et al*. (2017) for details) and taking the maximum biomass value between the peak hours with maximum abundances. The second option consisted in taking the maximum value of the day, always before the set, but independently of the time of day. The third option consisted in 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 this is the time when tuna is observed to be more closely aggregated under the DFADs (Brill *et al*., 1999; Josse *et al*., 2000; Moreno *et al*., 2007a; Harley *et al*., 2009).

Improve biomass estimation accuracy

Manufacturer´s method converts raw acoustic backscatter (s_a, m2/m2; Maclennan *et al*. (2002)) into biomass in tons, using a depth layer echo-integration procedure based exclusively on an algorithm based on the TS and weight of skipjack tuna, which is the main target species of the DFADs purse seine fishery. Therefore, this method does not consider the different species and sizes aggregated around the DFAD. With the aim of improving the biomass estimates and species and sizes information provided by the manufacturer, we followed the model proposed by Lopez *et al*. (2016) for the Atlantic Ocean. This model was based on the best available knowledge on the vertical behavior of species and sizes at DFADs, and their corresponding TS and weight values by species group.

Following the steps indicated in the **Figure 2** we obtained corrected biomass estimations. First, we established a depth boundary limiting non-tuna from tuna species at 25 m, based on experimental evidences from tagging and acoustic surveys around DFADs (Matsumoto *et al*., 2006; Dagorn *et al*., 2007b; Moreno *et al*., 2007a; Moreno *et al*., 2007b; Taquet *et al*., 2007; Leroy *et al*., 2009; Govinden *et al*., 2010; Filmalter *et al*., 2011; Mitsunaga *et al*., 2012; Govinden *et al*., 2013; Schaefer and Fuller, 2013; Matsumoto *et al*., 2014; Forget *et al*., 2015). Second, we established a preliminary limit between small and large tuna at 80 m according to previous studies showing potential segregation of size with depth (Moreno *et al*., 2007a) (Figure 2, step 1). The next step was the election of the most appropriate TS and weight values for non-tuna species, small and large tuna (Figure 2, step 2). For non-tuna species biomass, a TS value of –42 dB was used based on previous field studies (Josse *et al*., 2000; Doray *et al*., 2006; 2007; Lopez *et al*., 2010). The mean weight used for the biomass characterization of this community was 1 kg ind^{-1}, which was estimated from the mean length of the most representative non-tuna species at DFADs, and their corresponding weights (Lopez *et al*., 2016). Because no consistent TS-length relationships exist for yellowfin and bigeye tuna, although it is known for skipjack (Boyra *et al*., 2018), and the 3 tuna species are usually mixed in similar depth ranges, difficulties exist to accurately know the acoustic backscatter contribution by each species (Josse and

Bertrand, 2000). Thus a TS corresponding to mixed species aggregations was chosen (Moreno *et al*., 2007a) to apply to the supposedly mixed tuna layers. These TS values were measured in situ at DFADs for thousands of acoustic shoals at different depth ranges using scientific echo-sounders in the Indian Ocean (Moreno *et al*., 2007a). These mixed species acoustic shoals showed the following TS values: (i) -35.1 dB for acoustic shoals found at shallower-medium depths (25-80 m), likely corresponding to small tuna and (ii) -29.9 dB for acoustic shoals occupying deepest layers (greater than 80 m), likely corresponding to large tunas. According to the most common tuna sizes caught at DFADs (Chassot *et al*., 2013; Fonteneau *et al*., 2013), the depth range for tuna shoals shallower in the water column was considered to be populated by skipjack, yellowfin and bigeye tuna of a mean mass of 2 kg ind^{-1}, whereas the depth for acoustic shoals found at greater depths was assumed to be occupied by larger yellowfin and bigeye tuna individuals with a mean weight of 21 kg ind^{-1}. Then, the predicted biomass is calculated using a depth layer eco-integration procedure (Maclennan *et al*., 2002), converting the backscatter into biomass per groups (Figure 2, step 3). The echo-integration procedure was conducted repeatedly by applying all possible combinations of depth limits between small and large tuna in the entire depth range (i.e., having the virtual limit in 25 m, 36m, 47m, 59m, 70m, 92m, 104m and 115m) (Figure 2, step 4). The selected depth limit was the one that had the best coefficients of correlation (r) and determination (r^2) between predicted biomass and real catch (Figure 2, step 5). Finally, in order to correct the predicted biomass, the error (in tons) of the uncorrected predicted biomass was modeled with different regression models (polynomials of order 2 (POL2) and 3 (POL3), generalized linear models (GLM), and generalized additive models (GAM) (Hastie and Tibshirani, 1990; Venables and Dichmont, 2004; Wood, 2006)) as a function of the uncorrected predicted biomass. Obtained functions by regression models were used to adjust biomass estimates and get final corrected biomass values (Figure 2, step 6) (see Lopez *et al*. (2016) for details).

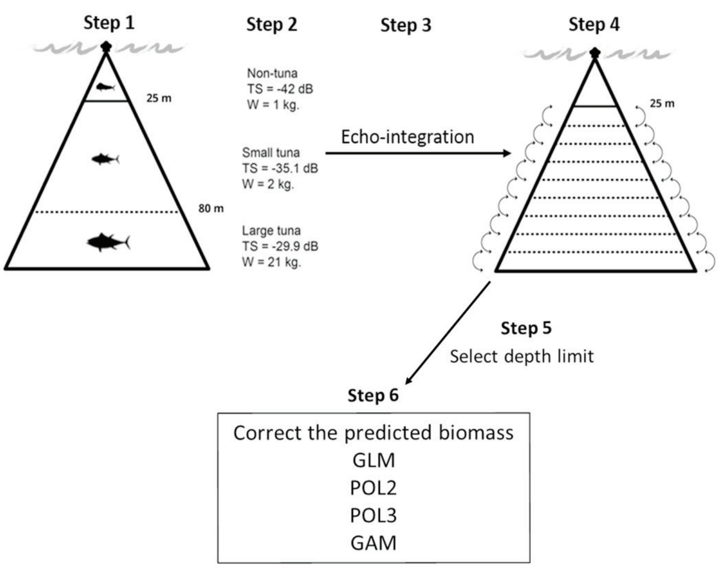

Figure 2. Steps of the model proposed by Lopez *et al*. (2016).

The method was implemented in the 287 sets related to acoustic data. Moreover, to account for potential spatial differences in species composition and vertical behavior we applied the method by areas. The regions were based on the ZET (zones d'echantillonnage thonière) areas defined by Petit *et al*. (2000).

Results

Data collection

The preliminary database contained information on 7514 buoys, with 3.7 million records of position and around 1 million records of biomass signals from echo-sounder buoys (**Table 1**).

Table 1. Description of buoy data.

	2012	2013	2014	2015	TOTAL
Buoys	574	1,578	2,930	2,432	7,514
Position records	316,096	980,332	1,555,738	818,491	3,670,657
Acoustic records	38,277	251,408	454,428	249,952	994,065

The number of buoys and acoustic records available after the cleaning process was 5,167 and 522,964, respectively. The echo-sounders provide an average of 2.2 acoustic record per day.

Associating acoustic samples with fishing sets

In order to select the time at which the acoustic sample must be taken, previous analysis using the three options proposed in section 2.3.2 were conducted. The dynamics of the diel biomass seem to be region specific according to the models, which showed peaks of abundance at different hours (Somalia 08h00-12h00; NW Seychelles 15h00-19h00; SE Seychelles 04h00-08h00; Mozambique Channel 10h00-15h00) (**Figure 3**). Because sampling frequency is not hourly, taking maximum values of abundance at these specific peaks limit the number of samples to be used in this study. On the other hand, using the maximum biomass value of the day, regardless of the time of day, we obtained poorer results when preliminarily compared to real catches. Finally, using the maximum value provided by the echo-sounder buoy at sunrise we obtained the best preliminary relationship with real catches. Based on this exploratory analysis, 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.), was chosen as the acoustic sample to be used in posterior stages of the study. If the acoustic record time is not close to the set, the catch could be not representative of the acoustic aggregation, so we select the records of the same day from half an hour before the set up to a maximum of 4 hours of difference. For sets where there was no acoustic record from the same day, the maximum biomass of the previous day at sunrise was selected.

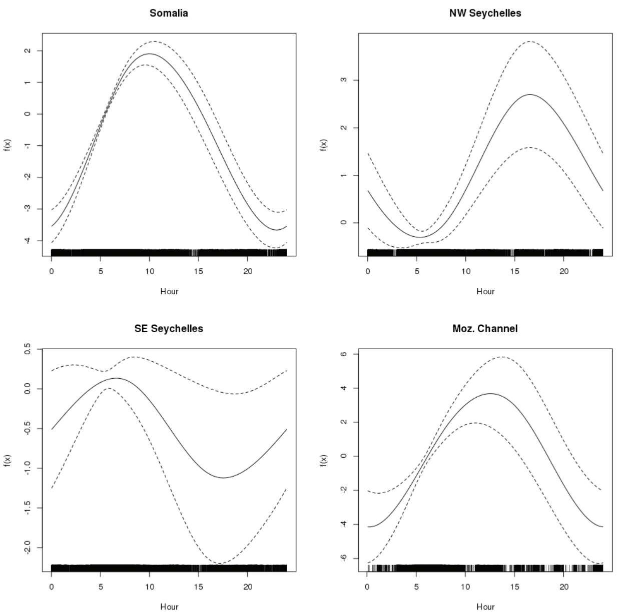

Figure 3. Smoothed fits of time of day modelling the tuna biomass abundance for different areas. Dashed lines indicate 95% confidence bounds.

From 651 fishing sets available, a total of 287 sets were identified using FAD logbooks, fishing logbooks and buoy data provided by the fishing company (**Figure 4**) for which acoustic information from echo-sounder buoy before the set was available. These sets occurred in four different ZET areas (**Table 2**).

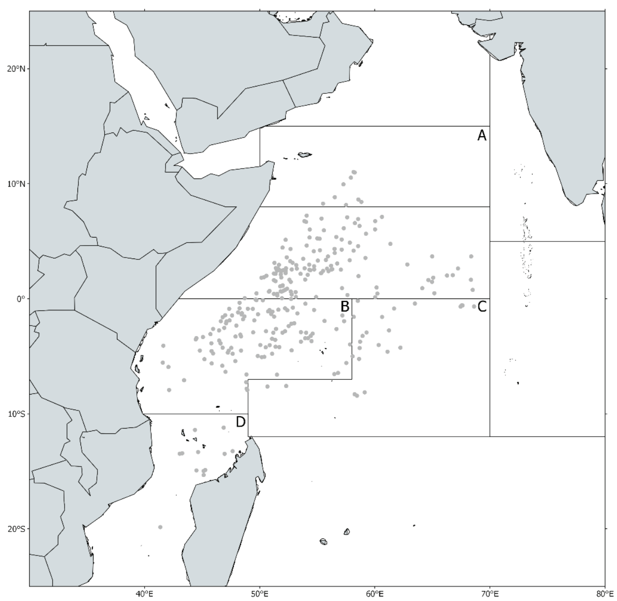

Figure 4. 287 sets identified in the Indian Ocean (A=Somalia, B=NW Seychelles, C= SE Seychelles, D= Mozambique Channel).

Table 2. Number of sets made in the four zones:

ZET	Number of sets
Somalia	138
Seychelles NW	110
Seychelles SE	27
Mozambique Channel	12

Improve the accuracy of biomass estimation

After applying all possible combinations of depth limits for tunas occupying shallow layers (likely being smaller) and tuna occupying deeper layers (likely being larger), we select the one with the best correlation and determination coefficients between the uncorrected predicted biomass and catch. For all the study area (i.e. 287 sets) the best correlation value corresponded to limit at 25m or 115m, which suggests that there is not a clear limit between small and large tunas. However, the application of the method by areas showed different potential depth limits between small and large tunas for each zone (Somalia 59 m, Seychelles NW 104 m, Seychelles SE 70 m and Mozambique Channel 104 m). Then, using these depth limits for each region and non-limit in all sets together, we corrected the predicted tuna biomass using four regression models. The corrected tuna biomass estimates using the different regression models and manufacturer biomass estimates were compared with catch of the same fishing set (**Table 3**).

Table 3. Coefficients of determination (r^2) between catch and biomass estimated (manufacturer biomass, Manuf.; predicted biomass, Before correction; and corrected biomass obtained after different model corrections (GLM=generalized linear model; POL2=polynomial of order 2; POL3=polynomial of order 3; GAM=generalized additive model)) for all sets and each region. The model selected is highlighted in bold.

Zone	Manuf.	Before correction	GLM	POL2	POL3	GAM
All sets	0.022	0.021	0.021	0.028	**0.03**	0.027
Somalia	0.025	0.025	0.025	0.026	**0.029**	0.025
Seychelles NW	0.047	0.050	0.050	0.158	**0.158**	0.159
Seychelles SE	0.065	0.073	0.073	0.093	**0.093**	0.073
Mozambique Channel	0.011	0.012	0.012	0.012	**0.084**	0.012

An improvement is observed when the biomass is corrected by polynomial regressions and GAMs. The corrected biomass obtained with the correction of the GLM model hardly improves, the biomass provided by the manufacturer. We selected polynomial of order 3 as the main model for all sets and regions. **Figure 5** shows the improvement over manufacturer estimation for all sets and regions. This improvement is larger in NW Seychelles and in Mozambique Channel.

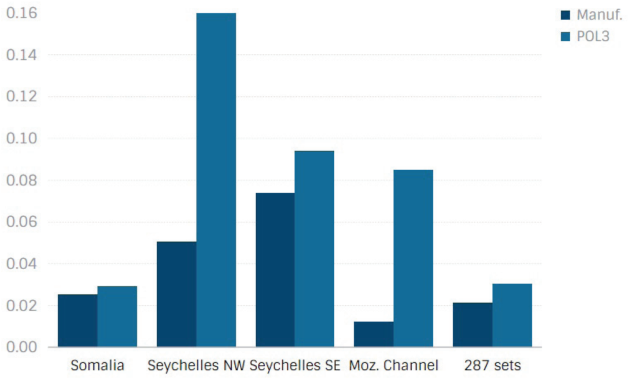

Figure 5. Coefficients of determination (r^2) between catch and biomass estimated by manufacturer (Manuf.) and between catch and final biomass estimations corrected by polynomial model of order 3 (POL3).

Figure 6 shows the boxplot of the distribution of the absolute errors, defined as the difference between the biomass estimations and the real catches, for the manufacturer´s method and the method corrected by polynomial of order 3 (POL3). It can be seen that in almost all cases the biomass estimation of the corrected method is closer to the catch estimation although the corrected method slightly overestimated the biomass underneath the DFAD, contrary to the uncorrected method where the biomass is underestimated. In addition, the error ranges are significantly reduced after applying the model.

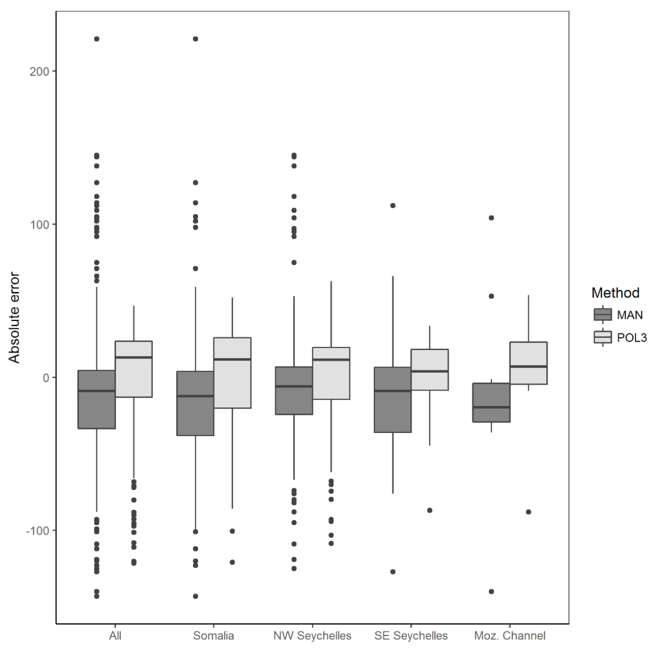

Figure 6. Boxplots of the absolute error (MAN= the error for the manufacturer´s method; POL3= the method corrected through polynomial of order 3) for all sets and each region.

Discussion

Results showed that the model used in this study, based on existing knowledge of the vertical distribution of non-tuna and tuna species at DFADs and mixed TS and weights, improves the biomass estimates provided by the manufacturer. This improvement varies by area, being highest in NW Seychelles and in Mozambique Channel, while the improvement is very slight in the Somalia area. However, the results obtained by Lopez *et al*. (2016) in the Atlantic Ocean are significantly better than those obtained in the current study, albeit the number of samples used for the analysis was much lower in that case (n=21). When the method has been applied to the Indian Ocean, the improvement of the biomass estimates is not as large as expected. Nevertheless, this issue leads us to better understand sources of variability and uncertainty in the echo-sounder buoy data. The reasons of the lower model performance could be various, for example:

Associating acoustic samples with fishing sets

One of the difficulties when building the database of the study was to assign an acoustic sample to a given fishing set. FAD logbooks have been a useful tool for the identification of sets and its associated acoustic sample. In 2011, the Spanish national administration established a FAD Management Plan for its global tropical purse-seine fleet, which has been and is being implemented to date (De Molina *et al*., 2013). In this plan, fishers are requested to conform to new FAD logbook format in order to harmonize the information. FAD logbooks provided information on all DFAD-related activities, spatio-temporal information of this activity as well as identification of associated buoy. The FAD-logbook also considers an inventory section, where the material and structure specifications and characteristics of each DFAD must be provided. This information allows identifying which buoy has been fished and link it with the associated acoustic sample in the database. However, the DFAD-form shows some typical errors in the data collection, such as wrongly typing the unique identification number of the buoy provided by the manufacturer. Fishers have historically marked the buoy with another identification and not the buoy ID and sometimes their marking code is included in the FAD logbook instead of the buoy code. This code will not match any code in the database and consequently the information to identify the set will be lost. In order to avoid the loss of data caused by this human error, it would be advisable to always collect the unique buoy identification number provided by the manufactured in the FAD logbooks by the fishers as requested by tuna RFMOs (Resolution 17/08 (IOTC, 2017); Resolution 16/01 (IATTC, 2016); Recommendation 16/01 (ICCAT, 2016)).

The time at which acoustic sample is available is key to select the more appropriate measurement to be used in the studies. Assuming that purse seiners' fishing strategy is optimized to catch tuna at DFADs (i.e. according to Cillaurren (1994), more than 95% of the biomass if within 500 m from the DFAD), then the acoustic sample should be received close to the peak of tuna aggregation (i.e. not dispersed around DFADs) or to the time at which signal is more representative of the biomass around the DFAD. In order to take into account diel tuna biomass variability at DFADs in a given area, the best option seem to be to model the diel biomass estimated by the echo-sounder and take the maximum biomass value between abundance peaks. In our case, however, taking maximum values of abundance at these peaks will greatly reduce the number of samples for the posterior phases of the analysis. Therefore, we chose the acoustic sample with maximum biomass value before the set in the same day or the day before, always around sunrise (i.e. between 3 a.m. and 8 a.m.) since, in addition to linking a large number of sets to apply the model, we obtained better relationships with the actual catches than using the maximum daily biomass without taking into account the time of day. These results are indicating that the time of day is very important in studies related to acoustic data provided by fishers' echo sounders buoys and therefore further research is needed. For example, in future studies, more fishing sets with their corresponding acoustic data should be linked to apply the model considering the specific daily behavior by region (Lopez *et al*., 2017).

It is also important to highlight the potential effect of the selection criteria for sets. Sets with very small catches may be due to the fish having been able to escape. For future work, it would be necessary to study what is the average catch per area and remove sets smaller than those catches.

Spatial and temporal variability

Tunas are well known to conduct both horizontal and vertical movements (Govinden *et al*., 2013; Schaefer and Fuller, 2013; Weng *et al*., 2013; Fuller *et al*., 2015). The approach presented in this paper sets virtual vertical separations between small and large tunas. Although overlap may exist between size categories, it is interesting to note that different depth limits have been identified by the model between small and large tuna by region. These differences can be explained by the fact that tuna vertical distribution at DFADs may vary depending on different factors, including oceanographic conditions (thermocline, currents…), total associated biomass or number and size of species present at DFADs. For example, in relation to environmental conditions, a variation in the thermocline may have direct implications on the vertical positioning of the species, since tuna distributions are strongly influenced by the local depth of the thermocline (Dagorn *et al*., 2007a; Schaefer and Fuller, 2013; Fuller *et al*., 2015). Moreover, 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) with the occurrence of winter monsoon (December-March), summer monsoon (June–September) and two intermonsoon periods (April-May and October-November). Jury *et al*. (2010) suggested that the seasonality of the Indian Ocean affects the marine ecology as well as the presence and relative species composition of an area. In this study, different improvements were obtained when the method is applied by areas which may be related to the species composition under the DFADs. In the case of Somalia, for example, the improvement of biomass estimates was less compared with the other regions considered in the study. This may be attributed to the issue that purse-seine catches in DFAD are dominated by skipjack in this area, being more than 65% of total compared to 50-60 % in other areas (2000-2015; IOTC official catches), and manufacturer model is based on TS and weight of skipjack. Although the depths are different between regions, all of them are distributed between 59-104 m, which is consistent with previous studies, where potential segregation between small and large tunas with depth were found (Moreno *et al*., 2007b).

It would also be desirable to use tagging experiments to improve our understanding on the diel behavior of species at DFADs by region and season, and their preferred use of the vertical habitat. This information would allow to better infer remotely species occurrences at DFADs, and hence, can provide interesting information to improve data interpretation and future applications.

Acoustic variability

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 may 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. Also, buoys may emit acoustic data while still onboard, providing false positives (i.e. although these errors can be eliminated using the proposed data cleansing in the section 2.3.1)

Currently, scientists are not able to discriminate between the three main tropical tuna species found at DFADs using echo-sounder buoys. This is partly due to the lack of fundamental knowledge of the acoustic properties of tropical tuna species and partly to relatively poor information (e.g. only one frequency) provided by the echo-sounder buoys at the moment. Regarding acoustic properties of tuna, only few studies have analyzed acoustic properties on aggregations around DFADs, most of them using a single acoustic frequency. 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 tuna at three frequencies (Boyra *et al*., 2018).

Recent acoustic research by ISSF (Moreno *et al*., 2015a) has found different frequency response for skipjack compared to bigeye and yellowfin tunas when analyzed simultaneously at multi-frequencies, because skipjack doesn´t have swimbladder while bigeye and yellowfin do. Bladder species normally produce a higher echo than bladderless ones since this hydrostatic organ, when present, is responsible for 90–95% of the backscattering energy (Foote, 1980). In addition, bladderless species tend to have stronger response at high frequencies (Gorska *et al*., 2005; Korneliussen, 2010) whereas bladder species have a flat or more response at low frequencies (Fernandes *et al*., 2006). Finding specific TS-frequency relationships for each tuna species could also improve the performance of the model used in this paper as well as to discriminate the acoustic signal by species. This would represent a potential for tuna species discrimination at DFADs that would require using multiple frequencies incorporated to DFADs echo-sounder buoys simultaneously.

This information, together with the TS for each tuna species, would allow significantly improving the accuracy of biomass estimates by tuna species and, in monospecific cases, even sizes before the fishing set. One of the most significant negative effect derived from the massive deployment of DFADs is the increase of catches of juvenile bigeye tuna (Leroy *et al*., 2012), being a particular management concern in the tuna RFMOs. Having a specific composition information before the fishing set could contribute to mitigate, for example, the catch of small bigeye and, hence, contributing to a more sustainable exploitation of the resources.

Moreover, the relation between the sampled area with buoys and vertical/horizontal dimensions of the fished schools could provide useful relations in order to correct estimates coming from echo-sounder buoys. This study could be carried out by measuring schools by scientific sonars and analyzing the relation between school axes and catches. All these corrections could be applied depending the study area.

Although in this study we used a specific buoy brand, the EU FAD-fishing fleet uses four brand echo-sounder buoys manufactured by different companies, which work with different frequencies, beam angle, ranges and other technical characteristics. Thus, an inter-calibration is necessary to understand inter-buoy variability and obtain comparable magnitudes and relative abundance signals per brand (Moreno *et al*., 2015b).

Conclusions

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.

The data collected by fishers' echo-sounder buoys are not originally intended to be used for scientific purposes but for fishing. Although this data may show certain limitations, they also offer large-scale interesting information that should not be ignored by scientist. In this paper it has been proven that the application of the model developed by Lopez *et al*. (2016) improves the biomass estimates provided originally by manufacturers in the Indian Ocean, though the improvement is not as large as expected. This could indicate that the large variability in these data is not easily considered with a single model. Throughout the work, different measures have been proposed to be taken into account in order to improve the current model in order to find a model that reflects the great variability of these data.

Thousands of DFADs with echo-sounder buoys are annually deployed by fleets targeting tropical tuna worldwide (Lopez *et al*., 2014). These DFADs may represents a powerful tool for the study of pelagic ecosystems (Moreno *et al*., 2015b), as they are continuously recording and providing information on the DFADs trajectories and biomass of fish aggregated underneath them in a non-invasive manner. Unlike with fisheries data, echo-sounder buoy data are less affected by fleet dynamics, effort, and spatio-temporal constraints, covering thousands of kilometers across the ocean for several months. Large-scale deployments of fishers' buoys could be used as lagrangian drifters covering most areas of the tropical oceans. Currently, floating objects provide almost real-time information of speed, surface drifts and sea surface temperature. Taking advantage of the DFAD use by fishers, new sensors may be installed following the needs of the scientists to serve as instrumented platforms that automatically obtain oceanographic observations. Some of these sensors could be recorders of salinity, oxygen, chlorophyll or even air pressure and wind speed. Moreover, the combined use of acoustics and visual system, already used in some fisheries (Macaulay *et al*., 2012; O'Driscoll *et al*., 2012), could be very useful to increase knowledge and understanding of the acoustic data, providing acoustic record and an image at the same time.

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References

Báez, J.C., Fernández, F., Pascual-Alayón, P.J., Ramos, M.L., Deniz, S., Abascal, F., 2018. Updating the statistics of the EU-Spain purse seine fleet in the Indian Ocean (1990-2017). IOTC-2018-WPTT20-15.

Boyra, G., Moreno, G., Sobradillo, B., Pérez-Arjona, I., Sancristobal, I., Demer, D.A., 2018. Target strength of skipjack tuna (Katsuwanus pelamis) associated with fish aggregating devices (FADs). ICES J Mar Sci.

Brill, R., Block, B., Boggs, C., Bigelow, K., Freund, E., Marcinek, D., 1999. Horizontal movements and depth distribution of large adult yellowfin tuna (Thunnus albacares) near the Hawaiian Islands, recorded using ultrasonic telemetry: implications for the physiological ecology of pelagic fishes. Mar. Biol. 133, 395-408.

Castro, J., Santiago, J., Santana-Ortega, A., 2002. A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. Rev. Fish Biol. Fish. 11, 255-277.

Cillaurren, E., 1994. Daily fluctuations in the presence of *Thunnus albacares* and *Katsuwonus pelamis* around fish aggregating devices anchored in Vanuatu, Oceania. Bull. Mar. Sci. 55.

Chassot, E., de Molina, A.D., Assan, C., Dewals, P., Cauquil, P., Areso, J., Rahombanjanaharyk, D., Floch, L., 2013. Statistics of the European Union and associated flags purse seine fishing fleet targeting tropical tunas in the Indian Ocean 1981–2012, IOTC-WPTT-13, 44pp.

Dagorn, L., Holland, K.N., Itano, D.G., 2006. Behavior of yellowfin (Thunnus albacares) and bigeye (T. obesus) tuna in a network of fish aggregating devices (FADs). Marine Biology 151, 595-606.

Dagorn, L., Holland, K.N., Itano, D.G., 2007a. Behavior of yellowfin (Thunnus albacares) and bigeye (T. obesus) tuna in a network of fish aggregating devices (FADs). Mar. Biol. 151, 595-606.

Dagorn, L., Holland, K.N., Restrepo, V., Moreno, G., 2012. Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? Fish and fisheries.

Dagorn, L., Pincock, D., Girard, C., Holland, K., Taquet, M., Sancho, G., Itano, D., Aumeeruddy, R., 2007b. Satellite-linked acoustic receivers to observe behavior of fish in remote areas. Aquat. Living Resour. 20, 307-312.

De Molina, A.D., Ariz, J., Santana, J., Rodriguez, S., 2013. EU/Spain Fish Aggregating Device Management Plan. SCRS/2013/029

Doray, M., Josse, E., Gervain, P., Reynal, L., Chantrel, J., 2006. Acoustic characterisation of pelagic fish aggregations around moored fish aggregating devices in Martinique (Lesser Antilles). Fish. Res. 82, 162-175.

Doray, M., Josse, E., Gervain, P., Reynal, L., Chantrel, J., 2007. Joint use of echosounding, fishing and video techniques to assess the structure of fish aggregations around moored Fish Aggregating Devices in Martinique (Lesser Antilles). Aquat. Living Resour. 20, 357-366.

Essington, T.E., Schindler, D.E., Olson, R.J., Kitchell, J.F., Boggs, C., Hilborn, R., 2002. Alternative fisheries and the predation rate of yellowfin tuna in the eastern Pacific Ocean. Ecol. Appl. 12, 724-734.

Fernandes, P., Korneliussen, R., Lebourges-Dhaussy, A., Masse, J., Iglesias, M., Diner, N., Ona, E., Knutsen, T., Gajate, J., Ponce, R., 2006. The SIMFAMI project: species identification methods from acoustic multifrequency information. Final Report to the EC, 02054.

Filmalter, J.D., Dagorn, L., Cowley, P.D., Taquet, M., 2011. First descriptions of the behavior of silky sharks, Carcharhinus falciformis, around drifting fish aggregating devices in the Indian Ocean. Bull. Mar. Sci. 87, 325-337.

Fonteneau, A., Chassot, E., Bodin, N., 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. Aquat. Living Resour. 26, 37-48.

Fonteneau, A., Pallares, P., Pianet, R., 2000. A worldwide review of purse seine fisheries on FADs, Proceedings of the Conference on Pêche thonière et dispositifs de concentration de poissons, Martinique, 15-19 October, Edited by J.Y Le Gall, P.Cayré and M.Taquet, IFREMER edition. pp. 15-35.

Foote, K.G., 1980. Importance of the swimbladder in acoustic scattering by fish: a comparison of gadoid and mackerel target strengths. J. Acoust. Soc. Am. 67, 2084-2089.

Forget, F.G., Capello, M., Filmalter, J.D., Govinden, R., Soria, M., Cowley, P.D., Dagorn, L., 2015. Behaviour and vulnerability of target and non-target species at drifting fish aggregating devices (FADs) in the tropical tuna purse seine fishery determined by acoustic telemetry. Can. J. Fish. Aquat. Sci. 72, 1398-1405.

Fuller, D.W., Schaefer, K.M., Hampton, J., Caillot, S., Leroy, B.M., Itano, D.G., 2015. Vertical movements, behavior, and habitat of bigeye tuna (Thunnus obesus) in the equatorial central Pacific Ocean. Fish. Res. 172, 57-70.

Gorska, N., Ona, E., Korneliussen, R., 2005. Acoustic backscattering by Atlantic mackerel as being representative of fish that lack a swimbladder. Backscattering by individual fish. ICES J Mar Sci. 62, 984-995.

Govinden, R., Dagorn, L., Filmalter, J., Soria, M., 2010. Behaviour of Tuna a ssociated with Drifting Fish Aggregating Devices (FADs) in the Mozambique Channel, IOTC-2010-WPTT-25.

Govinden, R., Jauhary, R., Filmalter, J., Forget, F., Soria, M., Adam, S., Dagorn, L., 2013. Movement behaviour of skipjack (Katsuwonus pelamis) and yellowfin (Thunnus albacares) tuna at anchored fish aggregating devices (FADs) in the Maldives, investigated by acoustic telemetry. Aquat. Living Resour. 26, 69-77.

Harley, S., Williams, P., Hampton, J., 2009. Analysis of purse seine set times for different school associations: a further tool to assist in compliance with FAD closures? Western and Central Pacific Fisheries Commission WCPFC-TCC5-2009/IP-02.

Hastie, T.J., Tibshirani, R.J., 1990. Generalized additive models. CRC press.

IATTC, I.-A.T.T.C., 2016. Amendment of resolution C-15-03 on the collection and analyses of data on Fish Aggregating Devices.

ICCAT, 2016. Recommendation by ICCAT on a multi-annual conservation and management programme for tropical tunas.

IOTC, 2017. Procedures on a Fish Aggregating Devices (FADs) management plan, including a limitation on the number of FADs, more detailed specifications of catch reporting from FAD sets and the development of improved FAD designs to reduce the incidence of entanglement of non-target species. IOTC-2017-WPDCS13-INF02.

Johannesson, K., Mitson, R., 1983. Fisheries acoustics: a practical manual for aquatic biomass estimation. Food and Agriculture Organization of the United Nations.

Josse, E., Bertrand, A., 2000. In situ acoustic target strength measurements of tuna associated with a fish aggregating device. ICES J Mar Sci. 57, 911.

Josse, E., Bertrand, A., Dagorn, L., 1999. An acoustic approach to study tuna aggregated around fish aggregating devices in French Polynesia: methods and validation. Aquat. Living Resour 12, 303-313.

Josse, E., Dagorn, L., Bertrand, A., 2000. Typology and behaviour of tuna aggregations around fish aggregating devices from acoustic surveys in French Polynesia. Aquat. Living Resour 13, 183-192.

Jury, M., McClanahan, T., Maina, J., 2010. West Indian ocean variability and east African fish catch. Mar. Environ. Res. 70, 162-170.

Korneliussen, R.J., 2010. The acoustic identification of Atlantic mackerel. ICES J Mar Sci. 67, 1749-1758.

Leroy, B., Itano, D.G., Usu, T., Nicol, S.J., Holland, K.N., Hampton, J., 2009. Vertical behavior and the observation of FAD effects on tropical tuna in the warm-pool of the western Pacific Ocean, Tagging and Tracking of Marine Animals with Electronic Devices, Springer, pp. 161-179.

Leroy, B., Phillips, J.S., Nicol, S., Pilling, G.M., Harley, S., Bromhead, D., Hoyle, S., Caillot, S., Allain, V., Hampton, J., 2012. A critique of the ecosystem impacts of drifting and anchored FADs use by purse-seine tuna fisheries in the Western and Central Pacific Ocean. Aquat. Living Resour. 26, 49-61.

Lopez, J., Moreno, G., Boyra, G., Dagorn, L., 2016. A model based on data from echosounder buoys to estimate biomass of fish species associated with fish aggregating devices. Fish. Bull. 114.

Lopez, J., Moreno, G., Ibaibarriaga, L., Dagorn, L., 2017. Diel behaviour of tuna and non-tuna species at drifting fish aggregating devices (DFADs) in the Western Indian Ocean, determined by fishers' echo-sounder buoys. Mar. Biol. 164, 44.

Lopez, J., Moreno, G., Sancristobal, I., Murua, J., 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fish. Res. 155.

Lopez, J., Moreno, G., Soria, M., Cotel, P., Dagorn, L., 2010. Remote discrimination of By-cath in purse seine fishery using fishers' echo-sounder buoys. IOTC-2010-WPEB-03.

Macaulay, G.J., Kloser, R.J., Ryan, T.E., 2012. In situ target strength estimates of visually verified orange roughy. ICES J Mar Sci. 70, 215-222.

Maclennan, D.N., Fernandes, P.G., Dalen, J., 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES J Mar Sci. 59, 365-369.

Marsac, F., Fonteneau, A., Menard, F., 2000. Drifting FADs used in tuna fisheries: an ecological trap?, Proceedings of the Conference on Pêche thonière et dispositifs de concentration de poissons, Martinique, 15-19 October, Edited by J.Y Le Gall, P. Cayré and M. Taquet, IFREMER, Actes de colloques. no. 28, pp. 537-552.

Matsumoto, T., Okamoto, H., Toyonaga, M., 2006. Behavioral study of small bigeye, yellowfin and skipjack tunas associated with drifting FADs using ultrasonic coded transmitter in the central Pacific Ocean. second regular session of the scientific committee, Western and Central Pacific Fisheries Commission. Information Paper 7.

Matsumoto, T., Satoh, K., Toyonaga, M., 2014. Behavior of skipjack tuna (Katsuwonus pelamis) associated with a drifting FAD monitored with ultrasonic transmitters in the equatorial central Pacific Ocean. Fish. Res. 157, 78-85.

Mitsunaga, Y., Endo, C., Anraku, K., Selorio Jr, C.M., Babaran, R.P., 2012. Association of early juvenile yellowfin tuna Thunnus albacares with a network of payaos in the Philippines. Fish. Sci. 78, 15-22.

Moreno, G., Boyra, G., Rico, I., Sancristobal, I., Filmater, J., Forget, F., Murua, J., Goñi, N., Murua, H., Ruiz, J., 2015a. Towards acoustic discrimination of tuna species at FADs. IATTC SAC-07-INF-C.

Moreno, G., Dagorn, L., Capello, M., Lopez, J., Filmalter, J., Forget, F., Sancristobal, I., Holland, K., 2015b. Fish aggregating devices (FADs) as scientific platforms. Fish. Res. 178, 122-129.

Moreno, G., Dagorn, L., Sancho, G., Itano, D., 2007a. Fish behaviour from fishers´ knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). Can. J. Fish. Aquat. Sci. 64.

Moreno, G., Josse, E., Brehmer, P., Nøttestad, L., 2007b. Echotrace classification and spatial distribution of pelagic fish aggregations around drifting fish aggregating devices (DFAD). Aquat. Living Resour. 20, 343-356.

Moreno, G., Murua, J., Restrepo, V., 2016. The use of echo-sounder buoys in purse seine fleets fishing with DFADs in the eastern Pacific Ocean. IATTC, SAC-07 INF- C (c).

O'Driscoll, R.L., De Joux, P., Nelson, R., Macaulay, G.J., Dunford, A.J., Marriott, P.M., Stewart, C., Miller, B.S., 2012. Species identification in seamount fish aggregations using moored underwater video. ICES J Mar Sci. 69, 648-659.

Petit, C., Pallarés, P., Pianet, R., 2000. New sampling and data processing strategy for estimating the composition of catches by species and sizes in the European purse seine tropical tuna fisheries.

Santiago, J., Murua, H., López, J., Quincoces, I., 2017. Buoy derived abundance indices of tropical tunas in the Indian Ocean. IOTC-2017-WGFAD01-13.

Schaefer, K.M., Fuller, D.W., 2013. Simultaneous behavior of skipjack (Katsuwonus pelamis), bigeye (Thunnus obsesus), and yellowfin (T. albacares) tunas, within large multi-species aggregations associated with drifting fish aggregating devices (FADs) in the equatorial eastern Pacific Ocean. Mar. Biol. 160, 3005-3014.

Schott, F.A., McCreary, J.P., 2001. The monsoon circulation of the Indian Ocean. Prog. Oceanogr. 51, 1-123.

Simmonds, J., MacLennan, D., 2005. Fishery acoustic theory and practice, Blackwell Scientific Publications, Oxford, UK.

Soto, M., Fernández, F., 2016. Statistics of the purse seine Spanish fleet in the Indian Ocean (1990-2015), IOTC-2016-WPDCS12-INF04.

Taquet, M., Dagorn, L., Gaertner, J.-C., Girard, C., Aumerruddy, R., Sancho, G., Itano, D., 2007. Behavior of dolphinfish (Coryphaena hippurus) around drifting FADs as observed from automated acoustic receivers. Aquat. Living Resour. 20, 323-330.

Venables, W.N., Dichmont, C.M., 2004. GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. Fish. Res. 70, 319-337.

Weng, J.S., Hung, M.K., Lai, C.C., Wu, L.J., Lee, M.A., Liu, K.M., 2013. Fine-scale vertical and horizontal movements of juvenile yellowfin tuna (Thunnus albacares) associated with a subsurface fish aggregating device (FAD) off southwestern Taiwan. J. Appl. Ichthyol. 29, 990-1000.

Wood, S., 2006. Generalized additive models: an introduction with R. CRC press.

DERIO

Astondo Bidea, Edificio 609
Parque Tecnológico de Bizkaia
48160 - Derio (Bizkaia)

SUKARRIETA

Txatxarramendi ugartea z/g
48395 - Sukarrieta (Bizkaia)

PASAIA

Herrera Kaia, Portualdea z/g
20110 - Pasaia (Gipuzkoa)

azti tecnalia