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Monitoring of Spanish flagged purse seine fishery targeting tropical tuna in the Indian ocean: Timeline and history

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ABSTRACT

The Spanish tuna purse seine freezer fleet targeting tropical tuna in the Indian Ocean is one of the most important fleets in the world. The present study firstly describes the history and evolution of this fishery (including its current status, following the economic crisis and the upsurge of Somali piracy of this last decade), and secondly describes the effort of Spanish scientific institutions to collect data (including estimates of catch, effort, and length-frequency distributions by species) from distant fisheries. This monitoring has been carried out in collaboration with stakeholders and other regional scientific organizations since its origins in the early 1980s. During this period the monitoring have been adapted to the change in the fishery, improving both the scientific estimates of the exploited species, as well as our knowledge of the impact of the fishery on the ecosystem, which in turn has served to improve the management and sustainability of the fishery. Although, in general, data quality has improved over time, there are periods with poor data quality. Currently, the priority is to eliminate possible biases from sampling at port. Finally, our general assessment of the adequacy of past and present monitoring systems, is that the current estimation system (called T3) is an important tool throughout the historical series to provide total tropical tuna catches, but in the new context of the TAC proposed for the yellowfin tuna, it is necessary to separate this scientific tool from others used for the flag state authorities to manage the TAC.

1. Introduction

Tuna and tuna-like species are one of the four most highly valuable commercial fish groups [1]. They are considered to be an important source of protein and a key component to ensure global food security [2]. The world record in total catches of tuna and tuna-like species was achieved in 2014 at almost 7.7 M tonnes [1]. Skipjack tuna (*Katsuwonus pelamis*) (SKJ) and yellowfin tuna (*Thunnus albacares*) (YFT) are among the eight marine species with the highest landings in the world [1]. Both species, together with bigeye tuna (*Thunnus obesus*) (BET) are the target catch of freezer tuna purse seiners operating in the tropical belt around the world [2]. Albacore tuna (*Thunnus alalunga*), together with several species of neritic tuna (mainly *Auxis* spp. And *Euthynnus* spp.), may also be caught on purse seine sets directed at tropical tunas, although they only represent a small fraction of total purse seine catches [3]. Global SKJ catches reached a maximum of around 3 M tonnes in 2014, while YFT catches were around 1.5 M tonnes [4].

In the Indian Ocean, the Indian Ocean Tuna Commission (IOTC)

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public authorized active vessel list [5] included 84 tropical tuna purse seine in 2017. Among them, 52 are large freezer tuna purse seines targeting tropical tuna from EU-Spain (14 vessels), Seychelles (13 vessels), EU-France (12 vessels), Republic of Korea (3 vessels), Iran (5 vessels), Mauritius (2 vessels), Japan (2 vessel), and EU-Italy (1 vessel) [5]; which vary in overall length (LOA) between about 60 and 116 m, with a LOA of 85 m on average. In 2019, the Spanish purse seiner freezer fleet targeting tropical tuna comprises a total of 15 fishing boats supported by 6 vessels not equipped with a fishing gear that mainly manage the floating objects stock (i.e. construction, deployment, monitoring and maintenance). The 15 industrial tropical tuna purse seiners operating under Spanish flag vary in overall length from about 80 to 116 m, with an average length of 97 m. As such, the Spanish purse seiner freezer fleet is one of the most important purse seiner fleet in the region. In 2014, when the global tropical tuna catch in the Indian Ocean reached its maximum, the Spanish fleet caught around 133,000 tonnes. This figure represents about 1.7% of the global catch of tuna and tuna-like species, of which 66,597 tonnes were SKJ (i.e. 2.18% of the global SKJ catch) and 57,892 tonnes were YFT (i.e. 3.95% of the global YFT catch) [3].

The IOTC is the Regional Fisheries Management Organizations responsible for the management of tuna stocks in the Indian Ocean. The IOTC agreement was signed on 1993 and entered into force in 1996. Before IOTC, the Indo-Pacific Tuna Development and Management Programme (IPTP) under Food and Agriculture Organization (FAO) was established in 1982 with the objective to develop a tuna data centre for the management and development of tuna fisheries. IPTP provided information and advice to the Indian Ocean Fishery Commission established in 1968 under FAO. Therefore, the history of the Spanish purse seine fleet is closely linked to the management measures that the IOFC, IPTP and IOTC have been introducing since its establishment. Since the beginning of the Spanish fishery at the beginning of the 1980s, Spain has been monitoring its activity and providing its fishery statistics, first to the Indo-Pacific Tuna Programme (IPTP) and then to the IOTC. The Instituto Español de Oceanografía (IEO: Spanish Oceanography Institute) has been the responsible institution to carry out the monitoring of the Spanish fleet with the collaboration, in recent years, of AZTI (a Research institution in the Basque Country, Spain). The IEO has provided the Spanish Government and the European Union (EU) – since it entered IOTC in 1995 - with scientific estimates of catches, effort, and other biological fisheries data for the Spanish fleet. Among others, the IEO provides scientific data and support to the Spanish Government, through the Fishery General Secretary (SGP -Secretaría General de Pesca), and the European Union (DGMARE), the later being the responsible organization to report the data to the IOTC. In addition to complying with IOTC mandatory fishery statistics requirement submission, which are established in several IOTC Resolutions, data on Spanish purse seine fleet activity regarding annual nominal catch estimates, catch and effort spatiotemporal distribution, catch-at-size, and others are submitted to the scientific stock assessment working groups (for the last report, see Ref. [3]).

The aim of the present study is firstly to describe the history and evolution of the Spanish purse seine fishery in the Indian Ocean and, more importantly, to describe the activities that Spanish scientific institutions have undertaken in the collection of fisheries data to monitor, since its beginnings in the early 1980s, the activity of the fleet contributing to the stock assessment and management process of the IOTC. During this period, continuous efforts have been made to obtain accurate estimates of nominal catch, catch and effort, and length-frequency distributions by species and fishing mode for the stock assessment process. In addition to the research effort and monitoring, this study also reviews the milestones of the Spanish purse seine fishery since its beginning in the Indian Ocean. We also include an overview of the current status of the fleet, following the economic crisis of this last decade and the upsurge of Somali piracy in the Western Indian Ocean. This timeline is of great relevance in understanding changes in the purse seine fleet and the fisheries statistics over the historical time series as well as current scenario under yellowfin quotas.

2. History of the Spanish tuna purse seine fishery in the Indian Ocean

2.1. Beginnings of the Spanish tuna purse seine fishery in the Indian Ocean

The Spanish tropical tuna purse seine fisheries started their activity at the end of the 1960s in the Atlantic Ocean. There are two key milestones in the evolution and dynamics of these fisheries: the first was the adoption of the 200 nautical mile Exclusive Economic Zone (EEZ), in 1977, this event triggered the displacement of the fleet to high seas and exploration of new agreements with coastal countries; and the second milestone was the decrease in YFT catch rates from 1983 to 1984 in the Atlantic Ocean due to a thermal anomaly in Gulf of Guinea (greater depth of the thermocline), which reduced the catchability of tuna schools [6,7]. Due to the latter, part of the fleet moved from the Atlantic Ocean into other areas. Both events led to the Spanish Fisheries Administration to seek for new fishing grounds away from the traditional fishing grounds closer to European coasts. For this reason, the Spanish government funded a fishing prospecting survey on 1981–82 in the Seychelles to explore new fishing grounds beyond the Atlantic Ocean. The epic history of the first survey (1981–1982) was conducted by two small bait boats that crossed from Algeciras (in the south of Spain) to the Seychelles via the Suez Canal [8]. The second Spanish prospecting survey was conducted by four purse seiners in 1984 [9]. At that time, French purse seine vessels also started moving from the Atlantic to the Indian Ocean, following a first fishing cruise by a French purse seiner, Yves de Kerguelen, which entered the EEZ of Seychelles on November 1981 [10]. A review of the French history of tuna industrial fisheries in the Indian Ocean is well described in Marsac et al. [10].

Diplomatic relations between Spain and the Seychelles were good at the time of the independence of the Seychelles in 1976, whose ceremony was attended by Spanish authorities [11]. On October 28, 1983, the governments of the Seychelles and Spain signed a fisheries agreement in Mahé, which granted Spain access to the Seychelles EEZ to fish highly migratory species. The first four purse seiners began their activities in March 1984 and the fleet gradually increased to 15 by December 1984 [9]. The agreement was regularly updated [12] until Spain entered the European Union in January 1986. Between 1984 and 2017, the number of Spanish vessels in the area has remained relatively stable with an average of 17 vessels per year (Table 1). Although new vessels have been built, the fleet has become older over time and the current average age is 19 years, however, the carrying capacity in tons has increased over time due to the construction of larger vessels (Table 2).

During the start of the fisheries, and due the monsoon period, some of the vessels operated in both the Atlantic and Indian oceans. The fishery has traditionally conducted its activities in the Western Indian Ocean, but exceptionally the fleet expanded its activity to the Eastern Indian Ocean, due to an oceanographic anomaly related to El Niño, in 1998. That year, it unloaded many catches in Phuket (Thailand) instead of other traditional ports. Currently, Port Victoria (Seychelles), Diego Suárez (Madagascar) and Mombasa (Kenia) are the most important landing ports (Table 3).

2.2. Development of fishing on floating objects

Traditionally, tropical tuna purse seiners in the Indian Ocean have used two main types of fishing sets: a) free school sets (where single schools of large YFT catch predominates); and b) school sets associated with floating objects (where mixed school of mainly SKJ with small YFT/BET are caught). Free school fishing involves the detection of freely swimming schools through signs in the surface of the ocean. This activity is conducted from the boats, through the use of binoculars set on structures such as the crow's nest, and devices such as the bird radar, or

Table 1
Number of ships per year with Spanish flag (SP-vessels), and ships with non-Spanish flag (Non SP-vessels) but Spanish owners. Key: *Data estimated from Pallares et al. [31]; for the rest of data estimated from Báez et al. [3].

Year	SP-vessels	Non SP-vessels	Total
1984	16	1	17
1985	17	1	18
1986	17	1	18
1987	14	1	15
1988*	16	1	17
1989*	20	4	24
1990*	20	5	25
1991*	17	5	22
1992*	18	5	23
1993*	19	7	26
1994*	18	7	25
1995*	19	7	26
1996*	22	10	32
1997*	23	10	33
1998*	20	10	30
1999*	20	11	31
2000	17	11	28
2001	17	11	28
2002	18	11	29
2003	18	15	33
2004	20	11	31
2005	20	9	29
2006	22	9	31
2007	21	9	30
2008	17	9	26
2009	15	10	25
2010	13	9	22
2011	13	7	20
2012	14	6	20
2013	14	7	21
2014	15	7	22
2015	17	7	24
2016	14	7	21
2017	14	5	19
2018	14	5	19

Table 2
Carrying capacity in tons, and number of supplies vessels. Key: *Data estimated from Pallares et al. [32]; for the rest of data estimated from Báez et al. [3].

Year	C.Cap.	Supp
1984*	5343	
1985*	9142	
1986*	8793	
1987*	10,504	
1988*	14,361	
1989*	20,050	
1990*	17,908	–
1991	16,568	–
1992	16,711	–
1993	18,953	–
1994	18,779	–
1995	20,908	–
1996	24,090	–
1997	26,128	–
1998	21,243	–
1999	20,260	6
2000	19,473	7
2001	20,479	5
2002	20,490	8
2003	21,007	8
2004	23,832	15
2005	29,052	13
2006	31,224	13
2007	29,438	13
2008	24,212	11
2009	20,805	11
2010	20,677	6
2011	20,458	7
2012	21,657	6
2013	22,056	4
2014	20,761	7
2015	23,251	10
2016	23,507	11
2017	22,811	10
2018	22,811	6

by sightings of bird flocks through binoculars set in different parts of the boat.

According to Hallier and Parajua [13] the association of tunas with floating objects was very well known by purse seine fishermen. Therefore, from the beginning of the 80's fishermen started to tie-up radio beacons to floating logs in order to track them at sea. Since 1984–85, this practice was widely used in this fishery, mainly in three areas: waters off Somalia, Mozambique Channel and western to Seychelles Islands. There were generally two peaks of log (land originated natural floating drifting objects from river runoffs, such as palm tree branch) school fishing, a smaller one in April/May and a main one in September/October [9,13]. These two fishing seasons for tuna schools associated to logs occur following changes in the Indian Ocean monsoon system. Soon after, in addition to natural logs, fishermen started building artificial floating objects, known as Fish Aggregating Devices (FADs), to take advantage of the associative behaviour of tuna.

The number of associated school sets (FAD and logs) has increased steadily from the early period (1984–1990), with 31.9% of the sets directed at associated schools, to more than 80% of the sets in recent years (2012–2018 period) (Fig. 1). Thus, the number of sets on free schools gradually decreased as the number of sets on floating objects increased [14]. Those changes were also driven by technological improvement, such as the use of echosounder buoys, which the fleet started using at the beginning of 2000s and has been widely used since 2010 [15,16]. A particular case in the past, was the use of sea mount where one support vessel acted as anchored floating objects (aFADs) over sea mounts (mainly the *Coco de Mer* seamount in the Indian Ocean), currently there is none. They attracted baitfish using lights which in turn brought tuna to the surface, thus allowing the purse seiners to catch them. However, this practice is forbidden since 2016 (IOTC Resolution

Table 3
Total tropical tuna landing (in tons, t) per main ports and years.

Years	Victoria (Seychelles) t	Diego Suarez (Madagascar) t	Mombasa (Kenia) t	Others t
1989	92,824	4933	0	5346
1990	68,086	20,768	0	1714
1991	87,926	120	105	0
1992	37,207	12,767	37,689	0
1993	50,388	28,794	25,006	0
1994	66,086	28,270	16,255	5237
1995	80,501	28,714	25,335	1332
1996	70,563	20,149	28,513	9722
1997	83,997	16,442	17,271	7381
1998	39,827	24,973	3969	6760
1999	107,854	13,604	5448	7141
2000	118,112	14,437	6399	69
2001	107,315	10,154	813	444
2002	132,716	12,030	6453	4365
2003	152,608	14,252	4887	34,912
2004	138,614	329	1392	1066
2005	160,260	993	10,547	1187
2006	194,115	2467	2367	2042
2007	101,235	10,027	0	1292
2008	109,963	11,173	1339	0
2009	91,314	17,452	2554	565
2010	117,233	19,545	1902	1088
2011	117,628	10,054	0	2522
2012	94,587	10,429	2869	340
2013	132,494	14,152	0	220
2014	124,814	3734	2739	2190
2015	112,294	4657	3796	0
2016	128,771	4346	0	3006
2017	142,091	9200	0	0

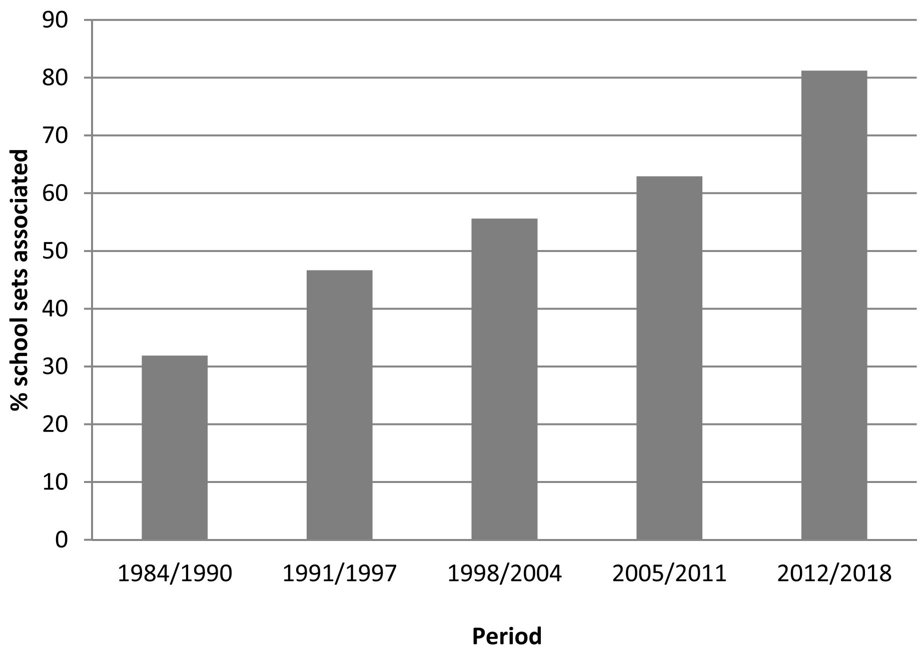

Fig. 1. Trend in the percentage of associated sets used by Spanish fleet per fishing year between 5 different periods. Data estimated from Báez et al. [3] and Hallier, J. I. Parajua [12].

16/07). The drifting FAD (dFAD) fishing strategy led to significant increases in catch of SKJ and small YFT and BET (with mean weights around 5 kg). The SKJ sizes are very similar for the FAD and for the free schools catches [3], and most of the individuals being larger than the maturity threshold [17].

Fishing on dFADs has led to significant increases in SKJ catch worldwide. However, it also has had an impact on BET and YFT, through an increase in the catches of small juvenile fish, and higher bycatch and impacts on the habitat. Some authors have suggested, that the increased use of dFADs could have lead to changes in behaviour of the species that tend to aggregate beneath them, altering their biology (e.g. movement patterns, feeding and condition factors, growth, and spawning) and habitat [18–20]. Regarding bycatch, purse seiners dFAD sets bycatch is composed of various species of billfish, small tuna (neritic tunas), and other marine fishes (e.g. triggerfish and rainbow runner). In addition, various species of sharks (mainly silky shark *Carcharhinus falciformis* and Oceanic whitetip shark *Carcharhinus longimanus*, and marine turtles may also be incidentally encircled by purse seine nets [20]. Moreover, there is another negative interaction component, mainly of sharks and marine turtles, associated to the entanglement of dFAD structures [21].

The structure of dFADs has not changed substantially since they were first used. They consist on a floating structure (raft), made of bamboo rafts plus an underwater component consisting on large net panels that hang underneath the raft and may go from 30 to 50 m dept in the particular case from Indian Ocean [22]. A large number of shark entanglement was estimated in 2013 (between 0.5 and 1 million of individuals) indicating a high mortality associated to entanglement in the FAD nets as a consequence of the large-mesh net panels used at the time [23]. The results of this study lead to the adoption of non-entangling FADs designs (net mesh-size less than 3 cm or if larger tightly tied into sausage-like bundles) by purse seiners under ANABAC and OPAGAC, which have been progressively deployed since 2013 as a results of IOTC Resolution 13–08. This resolution requested to deploy gradually non-entangling FADs as defined in the resolution and the use of non-entangling FADs was done mandatory in 2019 (Resolution 19–02). Thus, since 2020 all FAD should be non-entangling without the use of netting material [24]. The Spanish FAD logbook and scientific observer information were important to assist in the evaluation of FAD fishery impacts and to help finding solutions to mitigate those. Fig. 2, based on observer data, shows the evolution of the materials employed to build FADs.

In order to monitor and collect fishery associate information of the dFAD fishery, the Spanish Secretariat General for Fisheries (SGP) in close collaboration with the IEO and the Spanish tropical tuna purse seine fleet organizations ANABAC (National Association of Tuna Freezer Shipowners) and OPAGAC (Producers' Organization of Large Tuna Freezers) developed a Fish Aggregating Devices Management Plan (FADMP) for the Spanish fleet in 2010. The plan has been in force since then and is subject to constant review. It was a pioneering initiative in which a flag state part of one of the Contracting Parties (collectively known as CPC) of the *t*-RFMO introduced, among other things, a user-friendly data collection plan for the fleet to record FAD activities, based on previous experience [25,26]. Thus, skippers provide detailed information about FAD-related activities through a FAD-logbook. This logbook contains information on FAD activities at each visit (deployment, set, encounter, repairs, retrieval), structure (floating structure, hanging materials) and when a FAD set occurs information on target catch and bycatch. Under this plan, on average 14,834 annual deployments occurred between 2013 and 2018.

Since 2018, the EU fleet has been testing the use of biodegradable FADs in the Indian Ocean. This initiative was conducted within the framework of the BIOFAD [27] project, which was co-funded by the European Union, coordinated by AZTI (Spain) and participation of IEO (Spain) and IRD (*Institut de Recherche pour le Développement*, France), in collaboration with the ISSF (International Seafood Sustainability Foundation) and EU purse seine operators. The project builds upon the experience of purse seine skippers and addresses the problems associated with the synthetic materials and designs currently used in the construction of FADs (see IOTC resolution 18/04 for information on the BIOFAD experimental project). A total of 771 BIOFADs were deployed during the project, providing useful knowledge in terms of FAD lifespan, drift, materials' durability, catch and tuna aggregation in comparison to the regular non-entangling FADs [27]. The results of the BIOFAD Project will be instrumental in assisting future FAD biodegradable FAD designs as requested by IOTC Resolution 19–02; which promotes the use of biodegradable materials in FAD construction to reduce the amount of synthetic marine debris. Science – fishing industry – managers collaboration should be also promoted to find and agree on biodegradable

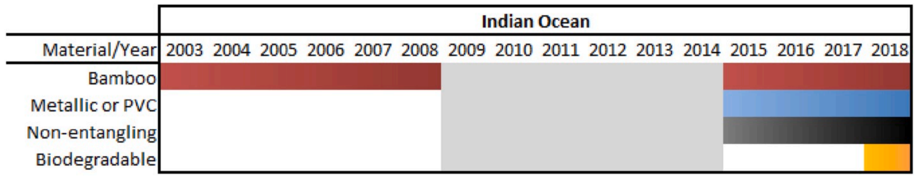

Fig. 2. Timeline of metallic/PVC FADs vs bamboo FADs deployments according to IEO observer data and the registration of non-entangling FADs seeding.

materials and FAD designs to reduce the impact of dFADs in the ecosystem.

2.3. Trends in the use of supply vessels

According to Pallarés et al. [28], the use of supply vessels in the Indian Ocean began in 1994. At that time, there was an average of five supply vessels per year assisting Spanish purse seiners. Its numbers increased significantly during the period 2004–2008, dropping as a consequence of Somali piracy (2009–2013), increasing again until 2017, from which numbers have declined substantially, following the implementation of Resolution 16/01 by the IOTC (Fig. 3). Supply vessels are those that work in association with the purse seiners on different activities, such as crew changes or the deployment of objects or provisions. The origin of these types of vessels lies in the “maciceros”, which are associated with tuna purse seiners by acting as FADs anchored to seamounts [28,29].

At the beginning of the purse seine fishery, the old “maciceros”, unlike the current support boats, threw bait from the boat to retain schools of fish. Currently, the support boats are in continuous movement and their activities are mainly related to the deployment and maintenance of FADs [28,29].

In the beginning of the FAD fishery, the increase in BET catch rates by Spanish tuna vessels could be related to the use of supply vessels, which help the deployment and monitoring of a greater number of FADs [30]. In those days, support vessels informed the purse seiners about the amount of tuna associated beneath a FAD. However, this activity has become less relevant nowadays because purse seiners can now directly obtain fish biomass information underneath of dFAD from satellite buoys equipped with echosounders. At present, supply vessels are mainly involved in FAD deployment and maintenance, although they also provide information on aggregations beneath the FADs when visiting them.

Noting that supply vessels contribute to increasing the effort and capacity of purse seiners and that the number of supply vessels had been increasing significantly over the years, in 2016 the IOTC adopted a first measure that limited the number of supply vessels to half the number of purse seine vessels reported per contracting parties members on the IOTC active list [5] for the same year (IOTC resolution 16/01: “on an interim plan for rebuilding the Indian ocean yellowfin tuna stock").

According to IOTC resolution 19/01 (i.e. “on an interim plan for rebuilding the Indian ocean yellowfin tuna stock in the IOTC area of competence”), supply vessels will be gradually reduced by December 31, 2022 with one supply vessel in support of no less than two purse seiners, all of the same flag State, between 2018 and 2019, and two supply vessels in support of no less than five purse seiners, all of the same flag State, between 2020 and 2022. Additionally, no CPC will be allowed to register any new and additional supply vessel on the “IOTC Record of Authorized Vessels” after December 31, 2017. The list of authorized Spanish supply vessels in the Indian Ocean was reduced to six ships in 2019. Unlike IOTC resolutions 16/01 and 18/01, Resolution 19/01 establish that a single purse seine vessel will not be supported by more than one supply vessel of the same flag State at any point in time.

2.4. FAD management history in the IOTC area

In 2013, the IOTC adopted Resolution 13/08, on a fish aggregating devices (FADs) management plan, that provides standards for the collection and reporting of data on fishing activities on drifting and anchored FADS undertaken by purse seine and pole-and-line fisheries. It also includes more detailed specifications on catch reporting from FAD sets and on the development of improved FAD designs to reduce the incidence of entanglement of non-target species (see above). This resolution has been reviewed on four occasions, with new resolutions adopted each time: 15/08, 17/08, 18/08 and, most recently, Resolution 19/02. This last resolution re-established procedures on a FADs management plan, the collection and submission of data on FADs to the IOTC, the obligation to use non-entangling FADs constructed with non-

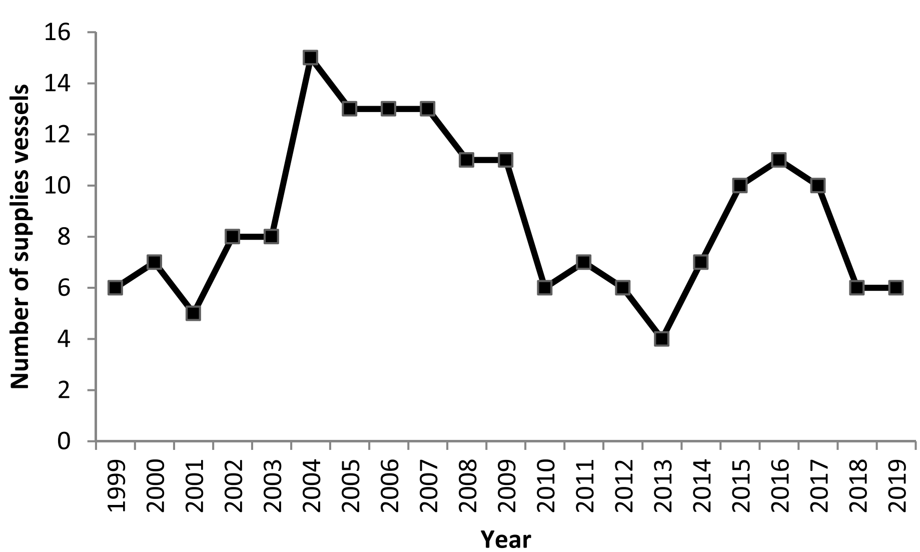

Fig. 3. Spanish supply vessels in the Indian Ocean: trend for the period 1999–2019.

mesh material, and promoting the use of biodegradable FADs by 2022. These also establish a limitation on the maximum number of operational buoys followed by any purse-seine vessel, and the number of instrumented buoys that may be acquired annually for each purse seine vessel or the number of instrumented buoys in stock. According to the current resolution (Resolution 19/02) the maximum number of operational buoys followed is 300, the number of instrumented buoys that may be acquired annually for each purse seine vessel is 500, and the maximum number of instrumented buoys in stock at any time is 500. Resolution 19/01 (on an interim plan for rebuilding the Indian Ocean yellowfin tuna stock in the IOTC area of competence) also limits the use of support vessels to 2 vessels in support of not less than 5 purse seiners all of the same flag state.

At present, IOTC CPC must provide catch-and-effort data in relation to: (i) the total number of FADs deployed by purse seiners and support vessels by FAD type, quarter, and fleet; (ii) effort data expressed as the total number of FAD visits per type of FAD, type of visit, 1° grid area, month, and FAD ownership (whether owned by the reporting contracting party member or not); and (iii) total catches of target IOTC species and bycatch species taken on FADs, at the same level of resolution (according to IOTC "form 3FA").

However, there is a lack of clarity regarding some of the requirements in IOTC resolution 19/02 and the data requested in "form 3FA" (e.g., spatial stratification or the interpretation of the types of FAD activities). Ambiguities in the interpretation of the FAD data requirements may lead to the development of FAD logbooks that fall short in producing the data required to be able to respond to the objectives set by the tRFMOs. IOTC Scientific Committee is working to clarify those issues so as the FAD requirements are harmonized and clarified in all IOTC Resolutions.

3. Scientific data collection

3.1. Main data sources

The primary data source is the logbook filled out by the skippers. From the beginning of the fishery, the purse seine fleet has maintained two logbook systems, a standard logbook designed by the IEO [31] for scientific purposes, and a logbook designed by the Spanish Secretariat General for Fisheries (SGP). This last SPG-logbook, currently is an electronic-logbook called Diario Electrónico Abordo (DEA by its Spanish acronym). The main fields included in the IEO-logbook are: searching effort, activity (FAD deployment, retrieval, visit, set on FAD, etc …), set, type of set (i.e. associated set or free school set), set and/or activity position (latitude and longitude), date and time; total retained catch by species and commercial category, besides some ancillary data (captain, port of entry and departure).

Direct information on discards of target and bycatch species (e.g. catch and by-catch species, number of individuals, size, and other biological data) is collected by scientific observers. Observer data are used to produce estimates of total bycatch and discards for the fishery, by species, area and season. Information about bycatch release practices and the fate of the species discarded is also collected for Endangered, Threatened and Protected species (ETP) such as sea turtles, sharks and marine mammals.

Observers also collect data on vessel activities, including activities on FADs, which is useful to cross-verify with the data provided by the IEO-logbooks filled by the skippers. Thus, this allows scientists to improve the logbooks that are provided by skippers.

The IEO-logbook together with port sampling are used to produce estimates of landings by species for main market species in the catch tropical tunas. Finally, this data source are used to produce global catch estimates by species for the whole fleet.

3.2. Port sampling and catch estimation procedures

The tropical tuna surface fisheries catch mainly YFT, SKJ and, to a lesser extent, BET. The species composition by set is reported in the logbooks (both in the IEO logbook and DEA), however the identification of species onboard is difficult for skippers and, hence, bias in logbooks on catch by species has been evidenced since the beginning of the tropical tuna purse seine fishery [32]. Fonteneau [32] discussed the difficulty experienced by skippers to correctly identifying the retained catch composition, through the analysis of data in fishing logbooks. Consequently, a correction procedure based on a multi-species sampling system in port was designed (a similar system to estimate catch by species is used in the InterAmerican Tropical Tuna Commission -IATTC-, International Commission for the Conservation of Atlantic tuna -ICCAT and IOTC). This data processing procedure in IOTC and ICCAT developed for the European fleet is called '*Traitements des Thons Tropicaux*' (T3) [32–35]. It has been used since 1980 in the Atlantic Ocean [33] and since 1985 in the Indian Ocean collecting port sampling data in the major unloading ports for the EU fleet [31,34]. The T3 procedure was created in order to provide scientific estimates of the species composition of the catch and the catch at size aggregated by area and quarter. Sampling operations are conducted during the unloading of the purse seiners, in port. The sampling unit is the fish well and the sampled is stratified by fishing mode, geographical area, quarter, and fish size category. Since the beginning of the activities of the purse seiners in the western Indian Ocean, the samples have been stratified according to the commercial categories of the fish (i.e. <10 kg, 10–30 kg and >30 kg). Based on extensive analyses on the best time-area stratification for the species composition of the main tuna species [35], quarter and areas were chosen. The areas selected were: Arabian sea, Somalia, North-West Seychelles, East-South Seychelles, Maldives-Chagos, South Indian Ocean, the Mozambique channel, India-Lakshadweep, Gulf of Bengal, and West Indonesia [35]. Currently, the same sampling protocols are used by Spain, France, and the Seychelles in the Indian Ocean. Samples are taken in ports, at unloading of selected fish wells, and the data are ultimately used to estimate both species composition and size frequency of the catch for each stratum. Port sampling information (length and species composition by stratum) is shared among the three institutes – the IEO, IRD and Seychelles Fishing Authority (SFA)–, which use the same T3 procedures to adjust catches and estimate catch-at-size for each species. They provide best scientific estimates of catch and size by species to be used in stock assessment. The management of raw data for the Indian Ocean purse seine fisheries is conducted using the AVDTH *('Acquisition et Validation des Données de Pêche au Thon Tropical')* software that was developed by the IRD in the mid-1990s [36]. AVDTH is a standalone application which connects to an MS Access database. The datasets are composed of (i) daily fishing activities and retained catches as recorded in logbooks, (ii) landing reports recorded per trip at unloading or transhipment at the ports of the principal tuna markets by commercial category, and (iii) the species composition and size-frequency by species measured at unloading.

During 1996 and 1997 a large scale research program, called ET, funded by the European Commission and coordinated by the IEO and ORSTOM (currently IRD), was conducted. At the end of this program new sampling and statistical procedures were adopted to improve the accuracy of catch and size estimates from the Atlantic and Indian Oceans [31]. In 1999, a new sampling strategy was implemented [34,35]. The correction of the species composition of the catches, as well as the estimation of their size distribution was performed using data from port sampling on French, Spanish and other purse seine fleets adhering to the system, since the statistical analysis made during the ET project showed that there was not a significant fleet effect.

However, Pallarés et al. [31] identified some issues following the inception of the new scheme: *" … the new sampling method has been applied in 1999 … The change of the old sampling method to the new one has produced several problems in the sampling process affecting the quality of the* *species composition and sizes distribution of the catch in 1999. For this reason the catch by species estimated for 1999 as well as the sizes distribution should be considered as provisional*". According to Fonteneau et al. [37], the quality of the sampling in Seychelles was very poor between 1998 and 2000, with a combination of errors in species identification, in the measurement and in the choice of the samples. Thus, during the period 1998–2000 there was a very low number of fish sampled (Fig. 4), mainly due to issues in the adoption of the new methodology and with samplers in Seychelles, not implementing the new standards properly. Therefore, catch and size composition over the period 1998–2000 shall be considered with caution. Institutional arrangements (IEO-IRD-SFA) led to improvements in the monitoring in the following years and better quality port sampling from 2000 onwards.

From the start of the fishery a bilateral agreement between Spain and Seychelles led to the formation of a Fisheries Office and the appointment of a Consultant to coordinate port sampling and monitoring activities on Spanish purse seiners. This situation continued until mid-2013 when, due to the economic crisis in Europe, the office was closed. It was not until 2015 that the SFA team, through an agreement with the Spanish IEO, resumed sampling. A new program coordinator was appointed in April 2019 and dispatched to the Seychelles. He works in close collaboration with the SFA since then.

Fig. 4 shows the number of fish sampled over the period 1990–2018. Although the number of specimens measured is usually very high, in 2013 was the suspension of in situ Spanish coordination of sampling at port in Port Victoria. Moreover, from 2013 onwards no sampling has been carried out outside Seychelles in other major unloading ports. In addition, the number of tunas measured in Port Victoria (Seychelles) between 2015 and 2018 decreased substantially, largely due to bureaucratic issues in Spain, related to the outsourcing of the sampling. Given that all the samplings collected on Spanish, French and Seychelles purse seiners are combined for the estimation of catch by species and catch at size, it is difficult to know in which way the poor sampling coverage of the Spanish fleet in those years has affected the catch composition estimates. According to Fonteneau et al. [38], this assumption may be valid when vessels of various flags are simultaneously fishing within a small area, but: "*this homogeneity in the species composition of the catch remains questionable when a component of the fleet operates in distinct and distant fishing grounds of the same T3 area than the other components, as often observed in the fishery*" [38].

Fig. 5 shows the corrected catch (using T3 procedure) by species and effort (searching days) of the purse seine Spanish fleet in the Indian Ocean from 1984 to 2018 (more information on supplementary material).

3.3. Spanish national observer program

In March and April 1986, the IEO participated in a purse seine observer training workshop funded by the FAO. Following the workshop, Spain initiated an observer program and the data collected onboard purse seiners was useful to improve fisheries statistics for the fleet and planning of future data collection activities.

The adoption of Data Collection Regulations (DCR) for fisheries data by the EU (see EU Council Regulation No. 1543/2000 of June 29, 2000 that established a Community framework for the collection and management of the data needed to conduct the EU Common Fisheries Policy) provide support to continue with the IEO Spanish observers for the collection of scientific data on Spanish purse seiners in the Indian Ocean. The main goal of the program was to facilitate the estimation of impacts from the purse seine fishery, with a focus on bycatch and discards. At present, the IEO and AZTI are responsible for the Fisheries Observer Sampling Program (IEO/AZTI FOSP thereafter) [39].

The IEO/AZTI-FOSP data collection and processing methodology has been developed co-ordinately by IRD, AZTI, IEO and SFA, and applies to Spanish and Seychelles flag purse seiners operating in the Indian Ocean [39]. Same protocol is also used in the Atlantic Ocean.

On average, between 2003 and 2018, Spain covered between 5 and 10% of the sets of Spanish purse seiners (with a gap between 2010 and 2013). Between 2003 and 2009 observer coverage levels were at around 5% of the total number of sets. The 5% observer coverage was also aligned with the coverage IOTC implemented in 2011, through the adoption of Resolution 11/04 ″on a regional observer scheme". During 2010–2013, due to increased insecurity, the observer program in the Indian Ocean was suspended. Somali piracy had also important impacts on the catch and effort levels of Spanish vessels. Between August 1996 and November 2005, the Spanish fleet fished within the EEZ of Somalia, through the adoption of various bilateral agreements involving the Spanish industry and the authorities of Somalia. However, since 2005,

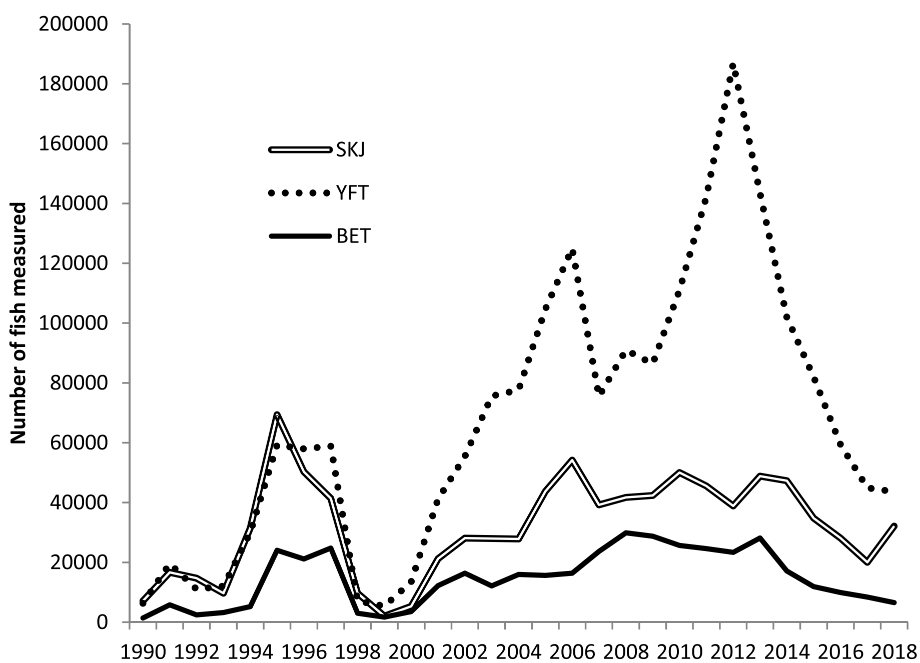

Fig. 4. Total number of tropical tunas fishes (SKJ, YFT and BET) sampled in Spanish flag fleet per year in the Indian ocean, mainly at Port Victoria (Seychelles).

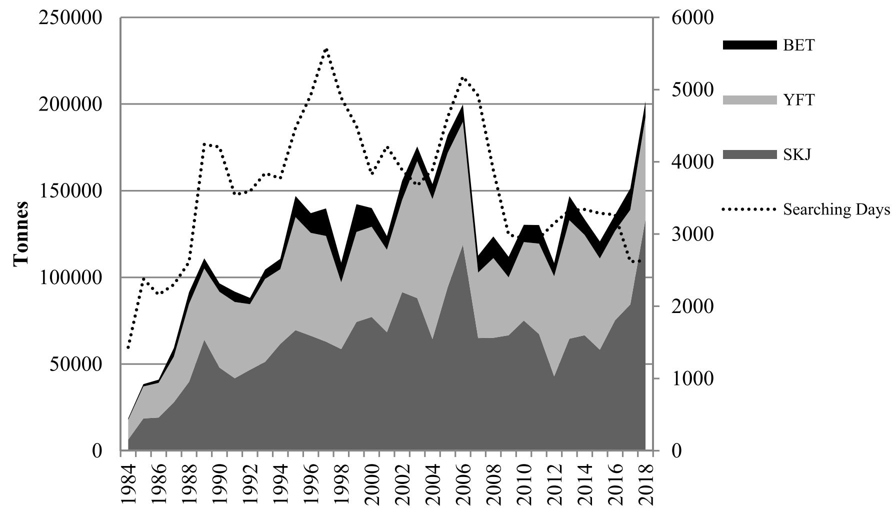

Fig. 5. Catch estimates by species and effort (searching days) of the purse seine Spanish fleet in the Indian Ocean in the period 1984–2018 using T3 procedure.

the increase of piracy in Somalia led to the kidnapping of two purse seiners (Playa de Bakio in 2008 and Alakrana in 2009) and the abandonment of fishing in waters anywhere near the Somali EEZ. The observer program was resumed in 2013 and during the period 2014–2018 observer coverage increased significantly, to attain 10% average levels of coverage of the total number of sets. In addition, private monitoring programs have recently increased the observers coverage significantly, thanks to a Memorandum of Understanding for the deployment of fisheries observers on the tuna purse-seine fleet signed in 2014 between the TAAF (*Terres Australes et Antarctiques Françaises*), the Mauritius Ministry of Fisheries, the Seychelles Fisheries Authority (SFA), and AZTI. This agreement has allowed the placement of local onboard observers under the same protocols as those developed under the EU observer program. Figs. 6 and 7 show the position of observed sets by scientific IEO/AZTI observers on board Spanish purse seiners by year separately for the period 2003–2018 or grouped by months (see Supplementary Material for greater detail).

4. Fisheries monitoring, control and surveillance

The General Secretariat for Fisheries (SGP) of the Ministry of Agriculture, Fisheries and Food of Spain (MAPAMA) is responsible for the Monitoring, Control, and Surveillance of the Spanish flagged fishing vessels. This responsibility includes the real-time monitoring of activities using a Vessel Monitoring System (VMS) and an Electronic Logbook System (known in Spain as DEA), as well as arrangements for the monitoring and control of the fleet in all the areas in which Spanish boats operate. Moreover, the SGP is the responsible ministry to control and enforcement of all IOTC Resolutions.

To address those IOTC resolutions in relation to fishery data collection and monitor (e.g. Res. 15/01 and 15/02), and following the start of Spanish tuna purse seiner activities in the Indian Ocean, the SGP made arrangements with IEO to ensure that fishing activities were correctly monitored with the aim of complying with national and international requirements, and in particular, measures promoted by the IOTC. This initiative involved outsourcing the monitoring of the fleet to an external consultant, and the setting up of bilateral agreements between the governments of Spain and the Republic of the Seychelles to facilitate this task. In addition, the consultant was responsible for arrangements in other ports were Spanish tuna purse seiners unloaded, mainly in Diego Suarez (Madagascar). The ports of Mombasa (Kenya), Dar Es Salaam (Tanzania), Port Louis (Mauritius), Gan (Maldives), Bandar-Abbas (Iran), and Phuket (Thailand) also registered some landings. Thereby, arrangements were established for port sampling during specific periods in some ports (e.g. Mombasa and Phuket).

5. Monitoring of the Code of Good Practices

The Code of Good Practices for Responsible Tuna Purse Seining is a set of Guidelines that were voluntarily adopted by the members of the two Spanish Producers' Organizations, ANABAC-OPTUC and OPAGAC-AGAC, which include the ship-owners of all Spanish-owned purse seiners [40,41]. The Code was adopted in 2012 and has been reviewed on several occasions to address recommendations originating from new research and the IOTC/ICCAT/IATTC/WCPFC management measures.

The Code has three main elements:

1. The design and use of FADs that do not entangle sensitive associated species (primarily turtles and sharks).
2. The development and application of releasing techniques that pose less risk to associated species and optimize those species' survival. This includes materials and equipment developed expressly for releasing associated species.
3. The application of a FAD management system through the implementation of a FAD logbook.

The Code of Good Practices is monitored through:

- *100% observer coverage, including support vessels, to monitor compliance with the Code.*
- *Training for fishing masters, crew, and scientific observers to improve data collection and monitoring compliance with the Code.*
- *Scientific verification of activities related with good practices and continuous monitoring of the programme by a steering committee.*

Since the adoption of the Code, AZTI has monitored its implementation in all oceans, through onboard monitoring conducted by a combination of human observers and electronic monitoring systems (EMS). In the case of the electronic monitoring, minimum standards for the purse seine fleet were adopted by the IOTC Scientific Committee in 2016, based on a document presented by the EU scientists and several EMS providers [42]. In conclusion, both human observers and EMSs are complementary each with their own weaknesses and strengths. EMSs are still limited for a purely scientific monitoring program, covering all observers' tasks, especially with the collection of biological samples as well as size measurement of target and bycatch species [43]. However,

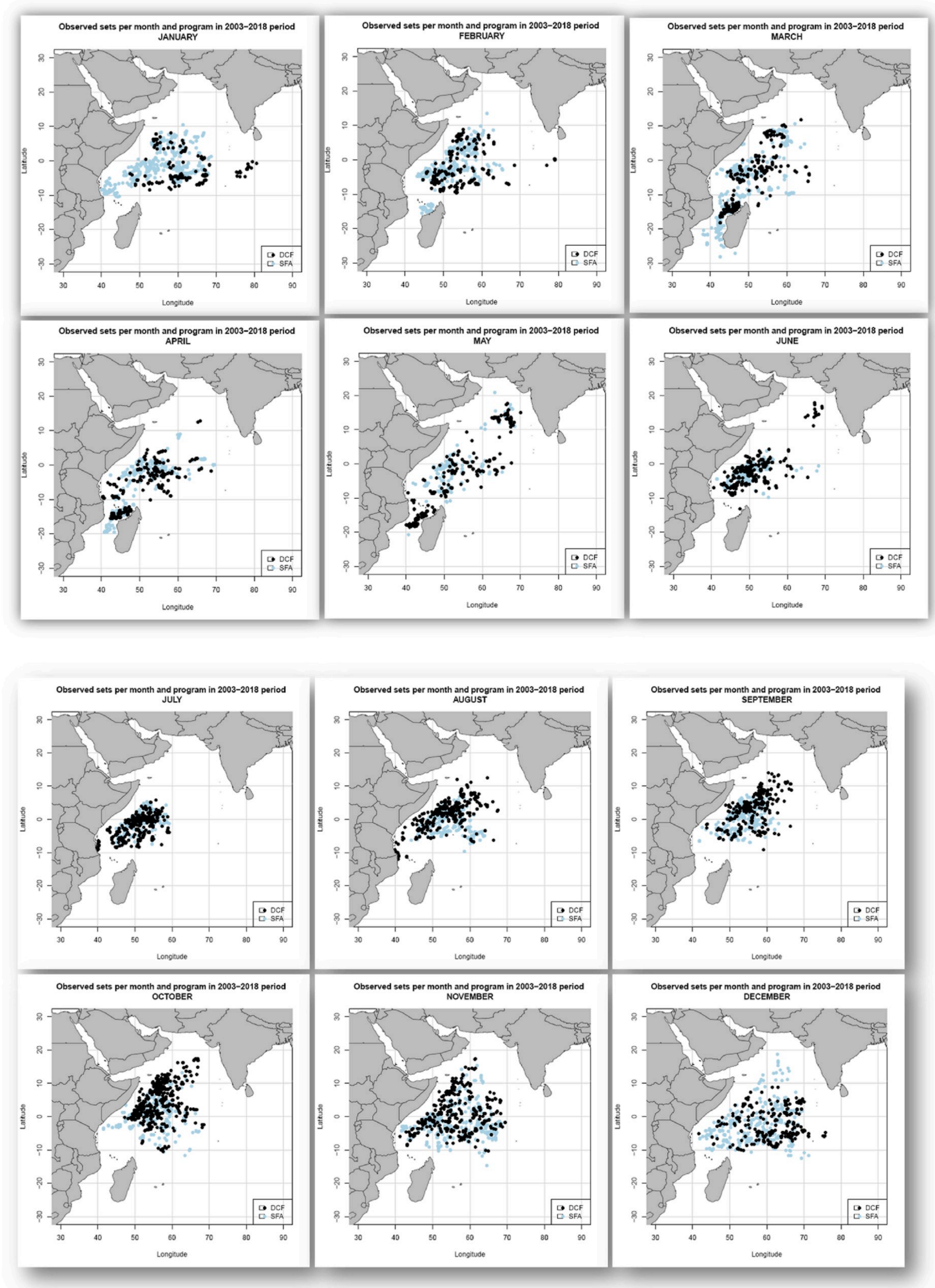

Fig. 6. Position of observed sets by scientific IEO/AZTI observers on board Spanish purse seiners in the period 2003–2018 including all observed sets per month (January to December). Each program (DCF or SFA) shown with a different colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

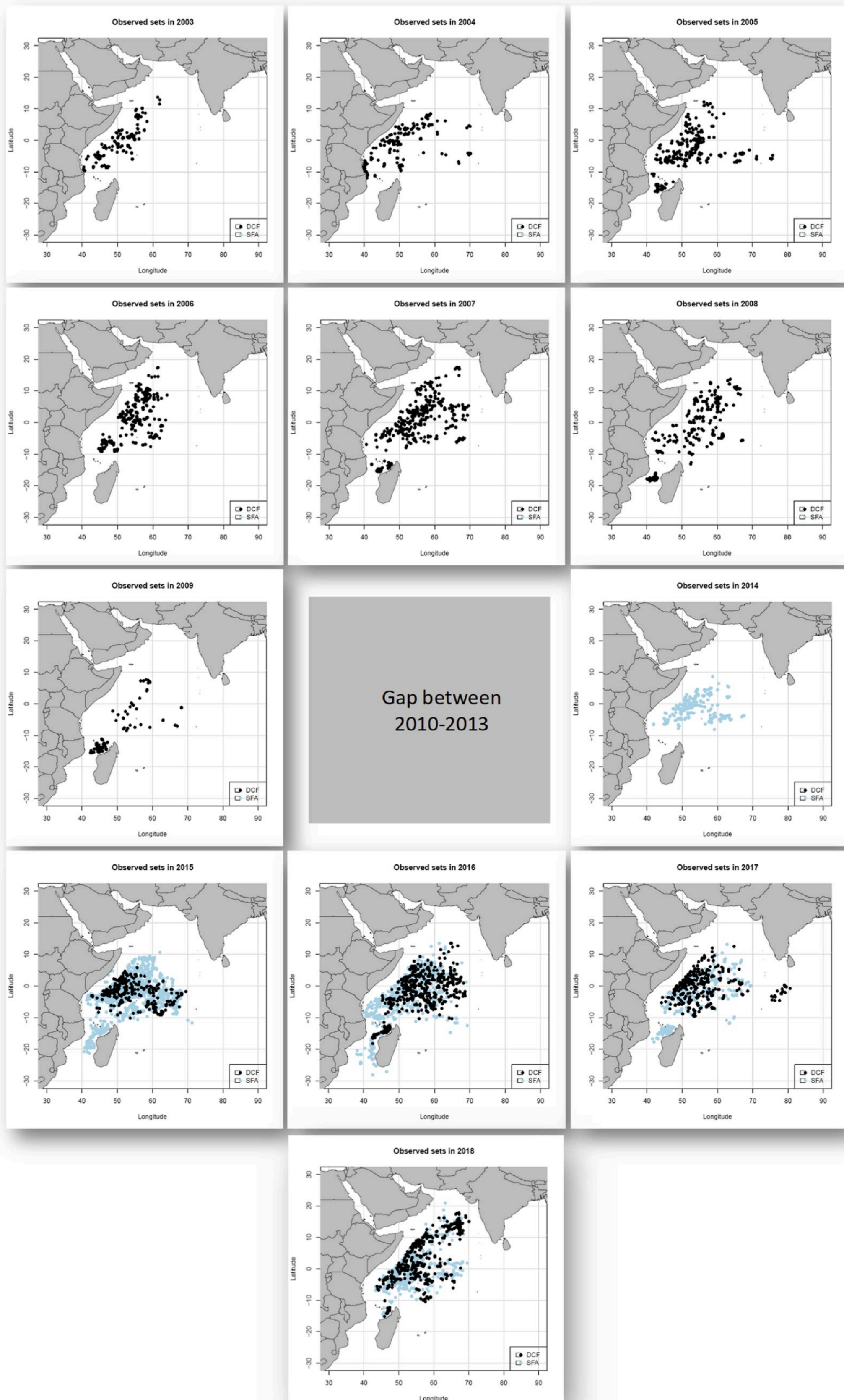

Fig. 7. Position of observed sets by scientific IEO/AZTI observers on board Spanish purse seiners by year separately for the period 2003–2018. Each program (DCF or SFA) shown with a different colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

EMS is valuable to complement and increase the coverage achieved by human observers. Thus, monitoring coverage reached 100% of the fishing trips s on the ANABAC and OPAGAC fleets under the Code of Good Practices since 2015.

6. Integrating the different scientific data sources

All this information from various monitoring data sources (i.e. observer data, FAD logbook, fishing logbook data, and sampling in port) work together to fulfil data requirements by the flag state, European Union and the RFMO, IOTC in this particular case (Fig. 8). For example, basic catch, catch and effort and catch at size data by area and season are estimated from logbooks and corrected with port sampling (using the T3 methodology as explained above), while observer data provide an estimation of bycatch for the fleet. From a scientific point of view these data helped to improve our knowledge about the impact of purse seine fisheries in the pelagic ecosystem of the Indian Ocean [44], or on catch levels of ETP species, and has been a key input to the assessments of stocks of tropical tuna species.

A more detailed information about the data monitoring sources and collected data is provided in supplementary information.

7. Discussion

7.1. Data quality and improvements

The statistics produced for EU purse seiners are among the best in the region. Although, in general, data quality has improved over time, there were periods in which data quality was poor. One of the issues remaining is that the statistics before 1990, which were produced using a different methodology, have never been reviewed or adjusted to account for the changes introduced in 1999, and therefore are likely to be inaccurate. In addition, during 2013–2014 due to the closure of the Fisheries Office in Seychelles there was a lack of sampling (see Appendix Supplementary material) for the Spanish component of the fishery while French component was continued to be monitored. From 2015 on, under an SFA – IEO agreement, sampling in port proceeded without an 'in situ' Spanish coordinator. On the other hand, due to the intensification of piracy there were no scientific observers onboard between 2010 and 2013.

Nevertheless, there are some issues that require further work to continue improving the monitoring system and analysis of data system from purse seiners. For example, the time-area stratification for the correction of catch composition by species and catch at size is based on the super-samplings conducted by Pallarés and Petit [34] during the period 1996 to 1997 (ET project, as explained above). This coincided with a longer period in which there were moderate La Niña events and strong El Niño events in the region [45]. For this reason, it would be advisable to repeat the super-samplings and adjust the protocols according to the prevailing oceanographic conditions or to use smaller mobile stratification areas taking advantage of the increased monitoring of the fleet in order to establish a more accurate area stratification [38,46–48]. Moreover, recent studies identified potential biases in estimates of catch by species obtained from T3; which probably originate from the use of outdated length-weight keys to estimate sampled weights, from an inappropriate reliability on fish category reported by the vessel skippers in the logbooks (which are part of the extrapolated strata) and/or misidentification of the species in port sampling [38,46,49–53]. Although these issues suggest that improvements in T3 are needed to obtain more accurate estimates of catch by species and size for the European purse seine fleet, T3 outputs are considered to be the best scientific estimates available for stock assessment.

With regard to the development and current capacity of the monitoring system to address fundamental monitoring objectives, such as on the use of drifting FADs, the monitoring system implemented by Spain is under constant review. This is done to incorporate new requirements adopted at the flag state and/or RFMO level, or recommendations from research institutions. The process involves consultation among the Secretariat of Fisheries of Spain, the IEO, AZTI, and the fishing industry. In recent years, the Spanish SGP has been working, with the collaboration of IEO, AZTI and the fishing industry; in the design and implementation of a Fishery Information System with the main objectives to consolidate all existing monitoring systems, procedures and databases into a unique server (i.e. merging different databases such as logbooks, observers, FAD logbooks into a unique interrelated database). This will facilitate the access to the system and the extraction of data through

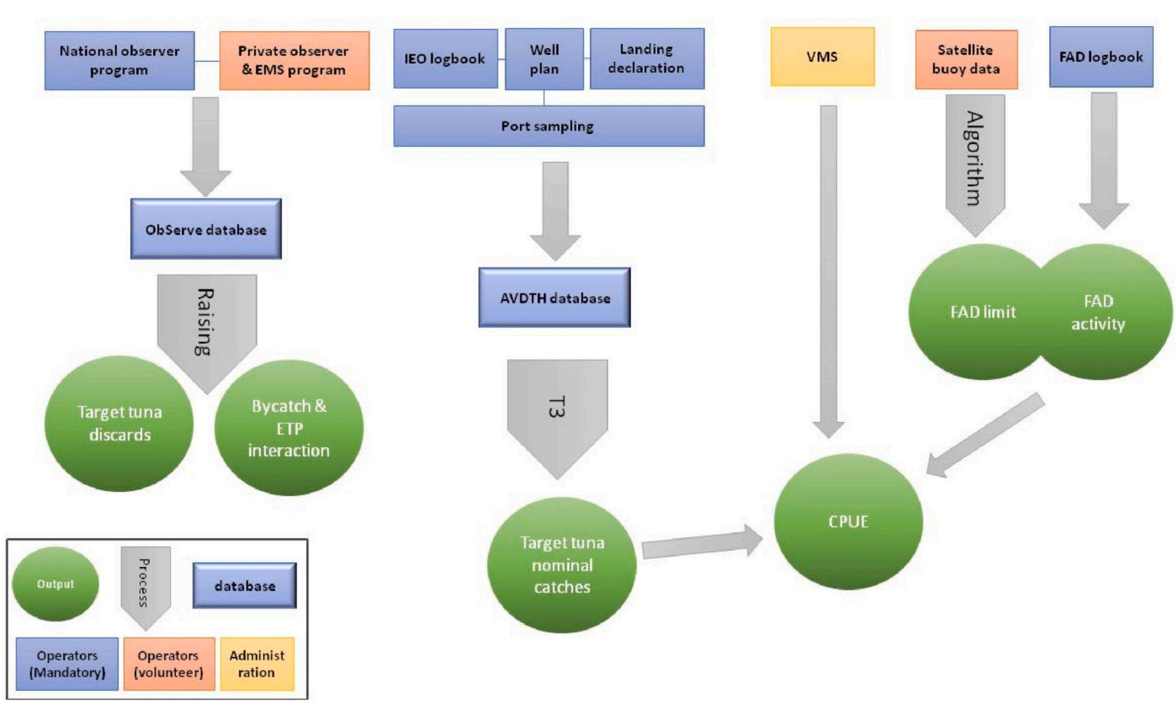

Fig. 8. Data flow of data sources and outputs.

better allocation of access rights and privileges to potential users. In this line, in 2017 a new improved FAD-logbook was introduced [54]. The main objective was to facilitate data input through a more user-friendly format as well as standardizing data entry procedures.

7.2. Monitoring of fishery for the production of scientific data

The General Secretariat of fisheries of Spain (SGP) is responsible for the monitoring of catches on all fishing vessels flagged in Spain, including those operating in the areas of competence of tuna Regional Fisheries Management Organizations such as the IOTC. In addition, the SGP is the national correspondent of official data for the IOTC via DG-Mare (European Union).

To monitor the compliance with the catch limits of YFT adopted in 2016 for 2017 fishing period, as adopted by the Spanish authorities, the program established for the scientific monitoring of catches (T3, see above) was used in 2017. However, while this system was designed to produce estimates of catch by species, size and spatiotemporal strata at fleet level, it was not developed to estimate catch by species at individual vessels. For the latter, an alternative mechanism might be required (e.g. a mechanism that allows for the monitoring of catches in [near] real-time or, alternatively, at the end of each trip, such as sale slips issued from canning factories). Therefore, the Spanish authorities may need to reconsider if the existing monitoring system is sufficiently effective to address monitoring and compliance with the YFT quota. In any case, a scientific monitoring system designed to provide best scientific fishery statistics to feed into stock assessment should be used to address original purposes as it may not suit for achieving other objectives (e.g. individual vessel quotas).

Until 2017, the Spanish Government provided to the EU as official data the scientific estimates obtained following the T3 procedure [33,34,55], i.e. catches for each individual purse seine set corrected using proportions originating from all available samples from vessels that operated in the same stratum (commercial category, area, quarter and set type), regardless of the flag of the vessel (Spain, France or Seychelles).

In 2018 the SGP adopted Individual Vessel Quotas to control the Spanish yellowfin tuna quota. The monitoring system implemented for estimating the catches by species (i.e. T3), for the reasons indicated in the previous paragraphs, were designed to estimate the catch by species at the fleet level and not at vessel level. Thus, the SGP decided to use the sale slips to control the quota utilization by individual vessel, in accordance with EU control procedures. Moreover, the SGP decided, for the first time since the beginning of the fishery, to submit to IOTC the sale slips information used for the control of quota utilization by Spanish purse seine vessels as an official nominal catch data for 2018. Upon receiving the data, the IOTC Secretariat and IOTC WPTT [56] identified potential biases in the proportions of YFT and BET (and SKJ), when comparing the new data reported with previous years' Spanish catch by species data and catch by species from other purse seine fleet in 2018. The increase in BET catches, originating from sale slips, was considered implausible and, therefore, the IOTC Working Party on Tropical Tunas decided to use alternative estimates, based on previous years species proportions in catches, in the assessment [57,58]. Moreover, this high proportion of BET declared has never been observed in the average scientific samples. In addition, the IOTC Scientific Committee recommended to further explore this issue and for the EU to consider introducing changes to its monitoring scheme to allow for a more precise estimation of catches by species and individual fishing set [59].

A "key" lesson emerges from this, the monitoring systems tailored to address specific goals (e.g. best scientific estimates to feed the stock assessment) should be used for its original purpose. The total catch per year, as scientific data is essential to help understanding the historical trends of catches. The reasons for the discrepancies between control and scientific data should be further explored, towards the implementation of a system that might satisfy the needs of both science and control. It is also important to note that the implementation of TACs usually leads to changes in the behaviour of fishers that in some cases are detrimental to the resources upon which the TACs are set or other target species. This has been the case in Indian Ocean purse seine fisheries, which have shifted effort from free school (large yellowfin) to FAD fishing (juvenile yellowfin) to avoid reaching the YFT quota too soon with a concomitant increase on juvenile yellowfin catches [58]. To avoid this unexpected changes, alternative management measures (such as effort control for purse seiners) to control fishing mortality and recover the stock could also be explored as in Sharma & Herrera [60]. Pros and cons of different management options should be investigated and discussed towards the adoption of the most effective management measure for a sustainable management of IOTC fisheries.

7.3. Final remarks

The dynamics of a fishery and the remoteness of fishing grounds from national territories increase the difficulty of monitoring and correctly collecting fishery statistics, which are needed for the assessment of resources. The experience described here has demonstrated the efficiency of a system implemented by Spain in close collaboration with IRD and SFA, to monitor and produce best scientific estimates of catch by species and size distribution of catches in the Indian Ocean. However, the constant events and changes during the period in which Spanish purse seiners have been active in these waters (see Appendix Supplementary material) should be taken into account when assessing the performance of the monitoring programme over this period. In spite of some of the issues described in the current document, the efforts devoted by Spain and the EU to implement such a monitoring scheme with the assistance of the SFA should be acknowledged. This has ensured that reliable fishery statistics are produced for stock assessment for the main tropical tuna species by the IOTC.

A cooperative fishing sector is also be very important. Thus, it is important to note the contribution of the Code of Good Practices, self-imposed by the fleet, which allowed to increase the observer coverage to 100% and, hence, to improve bycatch estimates in recent years [61], avoiding possible deviations in bycatch estimates due to poor coverage of scientific observation [62].

One of the main pending challenge is improving standardized Captures per Unit of Effort for purse seiners, and integrating FAD echosounder biomass estimation to obtain abundance indices. Moreover, it would be necessary to improve the monitoring of FAD loss and stranding events. This would be very relevant to analyze the impact of FADs on sensitive ecosystems [63], as well as determine the effect of FADs on the natural behaviour of tuna schools [64]. The evaluation of FAD loss requires that fine-scale FAD data are available from as many fleets as possible, in order to be able to discriminate third-party appropriations of FADs from real losses of FADs at sea (through sinking or stranding events). In this sense, as a proxy for this, it was used the number of active buoys with satellite communication system [65–69].

Finally, it is important to ensure continue funding for routine scientific monitoring of the fishery for a correct assessment and management of these important resources [70]. The data collected has proved instrumental to evaluate the impact of technological changes incorporated by the fisheries or any other changes that have occurred. Purse seine fisheries are highly dynamic and only their constant monitoring can ensure the sustainability of their target stocks in the long term, and reduce the impacts on other species and the habitat.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2020.104094.

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