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How many Fish Aggregating Devices are currently drifting in the Indian Ocean? Combining sources of information to provide a reliable estimate.

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Abstract

Since the mid 1990s, drifting Fish Aggregating Devices (dFADS), artificial objects specifically designed to aggregate fish, have become an important mean of catching tropical tunas in the Indian Ocean for the purse seine fleet. In recent years, the massive deployments of dFADs as well as the massive use of tracking GPS and echosounder buoys on dFADs and natural floating objects (logs) have raised serious concerns for tropical tuna stocks but also regarding the possible modifications in ecosystem functioning. However, relatively little remains known on the modalities of dFAD and tracking buoy use by purse seiners. These knowledge gaps render difficult the evaluation of the impacts of fishing practices with dFADs and logs. For the first time, the three French fishing companies operating or having operated in the Indian Ocean provided the GPS buoy tracks of a large proportion of the dFADs and logs monitored by the French fleet. Here, we combine this new source of information with observations of dFADs and logs by observers aboard French and Spanish purse seiners, quarterly French fishing companies orders of buoys, and interviews with purse seine skippers conducted in the port of Victoria. This allows us to identify 4 dFAD and log seasons, to understand the strategies of fishers regarding dFAD and tracking GPS buoy deployment, to extrapolate the total number of dFADs and GPS buoys used by all purse seine fleets and to examine some of the impacts of dFAD use in the Indian Ocean. The results we obtain are a first step for a better assessment and management of the purse seine dFAD fishery.

Keywords: dFAD, log, GPS buoy, purse seine, fisher strategies

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1. Introduction

During the early 1980s, several exploratory purse seine (PS) fishing cruises took place in the Indian Ocean (Hallier, 1988; Marsac and Stéquert, 1983, 1984). There, fishers and scientists arriving from the Atlantic Ocean realized the importance of natural floating objects (logs) to increase tropical tuna schools vulnerability to purse seine activities (Marsac *et al.*, 2014). At the same time, the success of anchored Fish Aggregating Devices (aFADs), man-made anchored floating objects specifically designed to aggregate fish that were in use in the Philippines since the 1960s encouraged purse seine fleets to deploy their own FADs, with the support of fishery scientists involved in tropical tuna fisheries (Bromhead *et al.*, 2000, Stretta and Slepoukha 1986, Moron et al. 2001). Deployments of drifting FADs (dFADs), generally consisting of a bamboo raft and pieces of net were proposed and studied as a viable solution to support the development of Floating Object (FOB, either logs or dFADs) purse seine fishery in the Indian Ocean and reach the full exploitation of stocks – notably the skipjack – and the profitability of the fishery. In the scientific literature, dFADs were often described as a solution to capture fast tuna schools (Bard *et al.*, 1985) and the cryptic fraction of skipjack stocks (Ariz Telleria *et al.*, 1999) that were problematic for purse seine fishing in all oceans.

During the 1990s, the intensive dFAD fishery really began. Radio range beacons introduced in the late 1980s and GPS buoys a decade later contributed to the improvement of the FOB fishery by offering the opportunity to locate dFADs and logs during their drift (Moron et al. 2001, ISSF 2012). In addition to these technological improvements, supply vessels were introduced to monitor purse seiners' FOB array and detecting associated schools (Fonteneau *et al.*, 2000). As the use of dFADs and tracking radio and GPS buoys increased, interest for dFADs, concerns for tuna stocks, bycatch species and ecosystem functioning grew among the scientific community (Fonteneau *et al.*, 2000; Hallier, 1988). The concept of dFADs acting as an ecological trap emerged (Hallier and Gaertner, 2008; Marsac *et al.*, 2000) due to the fast increase in dFAD use, tuna may remain trapped in areas that are suboptimal for their individual condition (Ménard *et al.*, 2000, Jaquemet et al. 2011) and their trophic migrations (Marsac *et al.*, 2000, Wang et al. 2014).

Despite these important concerns, almost three decades after the rapid mutation of the purse seine fishery towards a dFAD and log purse seine fishery, relatively little is known on the modalities of dFAD and GPS tracking buoy use. Many questions remain unanswered such as: where, when and how are dFADs and GPS tracking buoys deployed in the Indian Ocean? How many dFADs and GPS buoy tracked objects are currently drifting in the Indian Ocean? How does this affect purse seiner searching and fishing strategies and ultimately purse seine fishing effort in the Indian Ocean? As a better knowledge of the impacts of dFAD use is required (Dagorn et al. 2013, Fonteneau et al. 2013, ISSF 2014, Robert et al. 2014), the present analysis aims at filling some of these gaps. To address these questions, the three French fishing companies, operating or having operated in the Indian Ocean, agreed for the first time to provide detailed information on the positions of the GPS buoys used by the French PS fleet on logs and dFADs. Here, this new highly variable and complex source of information (Maufroy *et al.*, 2014) is used in combination with three other sources of information: logbook data, fisheries observer data and interviews with skippers. Our objectives are threefold (i) describe the strategies of the French fleet regarding dFAD and tracking GPS buoy deployment and (ii) provide an estimate of the daily number of dFADs drifting at sea and active tracking GPS buoys in the Indian Ocean over the period 2007-2013 (iii) understand the effects of FOB use on fishing activities. Our analysis complements the analysis of Chassot et al. (2014a) based on historical purchase orders buoys and declarations of activities related to dFAD activities to take into account the difference between types of FOBs (logs or dFADs), PS fleets (French, Spanish and others) as well as the spatial structure of the population of FOBs equipped with GPS buoys.

2. Material and Methods

2.1 dFAD and GPS buoy tracking data

"Classical" fishery data

The IRD (Institut de Recherche pour le Développement) and IEO (Instituto Español de Ocenaografia) have been in charge of monitoring the European purse seine fleet in the Indian Ocean since the 1980s. More recently, IEO with AZTI Tecnalia and IRD have been in charge of the European fisheries observer program aboard tropical tuna purse seiners since 2003 and 2005, respectively. For the present study, two complementary sources of information derived from declarations and observations at-sea covering the period 2007-2013 were made available by these institutes. Logbook data for the French component of the fleet provide information on the position and catch composition of fishing sets on dFADs and logs, with no possibility to distinguish from the two types of FOBs. In addition, observations of dFADs and logs equipped with GPS buoys collected by observers aboard French and Spanish purse seiners from 2006 to 2013 were used. They describe the type of activity on a FOB (deployment, visit without fishing, fishing set, retrieval without fishing), the type of FOB (dFAD or log), the type of activity on the GPS buoy (deployment, retrieval or visit) as well as the fleet of the owning vessel (French, Spanish or others) in about half of the cases. For the present study, 20,800observations of FOBs were available, covering a wide zone of the Western Indian Ocean (Figure 1), and a variable proportion of French and Spanish fishing trips (Table 1). Because of piracy threat in the late 2000s, no data was available for the Spanish fleet during 2011-2013 while the observer sampling design was unbalanced in favour of the second quarter (fishing grounds mainly located in the Mozambique Channel) during that period for the French PS fleet.

Table 1: *quarterly coverage (%) of French trips by onboard observers*

year	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
2007	5.1	10.3	10.3	9.8
2008	6.4	7.7	11.6	7.1
2009	7.5	6.5	3	-
2010	3.6	-	-	-
2011	3.3	20	7.1	5.3
2012	6.9	20	7.4	15.2
2013	12.1	20.7	7.7	14.7

Table 2: *quarterly coverage (%) of Spanish trips by onboard observers*

Year	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
2003	0.0	8.6	0.0	9.3
2004	2.0	3.0	15.9	6.8
2005	1.9	2.6	10.0	7.3
2006	3.5	5.0	6.3	9.4
2007	0.0	9.8	15.2	14.0
2008	5.0	7.0	10.0	12.2
2009	4.8	2.9	3.0	0.0
2010	0.0	0.0	0.0	0.0
2011	0.0	0.0	0.0	0.0
2012	0.0	0.0	0.0	0.0
2013	0.0	0.0	0.0	0.0

French GPS buoy tracks

For the first time, through an agreement with the 3 French fishing companies, positions of French GPS buoys equipping logs and dFADs were also available, with a varying coverage. We separated *onboard* and *at sea* positions (Maufroy *et al.*, 2014). This resulted in more than 2,000,000 *at sea* positions of 12,459 GPS buoys from November 2006 to December 2013, with varying times of emission of the GPS buoy signal (from a few minutes to more than 1 year). French GPS buoys were present in wider zones than those described by onboard observers, covering the entire tropical Indian Ocean (Figure 1).

The vessel coverage of the GPS dataset has gradually increased over time towards a yearly coverage of 100%. However, due to storage and exporting issue, data may be missing for some companies. Indeed, during several periods, no data was available for 2 of the 3 fishing companies. Besides, the last fishing company, only a fraction of the total number of GPS buoys was provided for 2007 and for the beginning of 2008 but the corresponding coverage was unknown. To solve this problem, fishing company 1 indicated that 100 buoys were in use per vessel in the Indian Ocean at that time. Using data available for this company over 2009-2013, we evaluated the expected number of GPS buoys for fishing company 1 as the mean ratio between buoys used each month and buoys used on a yearly basis. Combining this information with the number of purse seiners of company 1, we assumed that the coverage of this company was the ratio between provided buoys and expected buoys. Coverage of French fishing vessels and fishing company 1 GPS buoys were combined to provide a final coverage of all French GPS buoys each month of 2007-2013 (Figure 2).

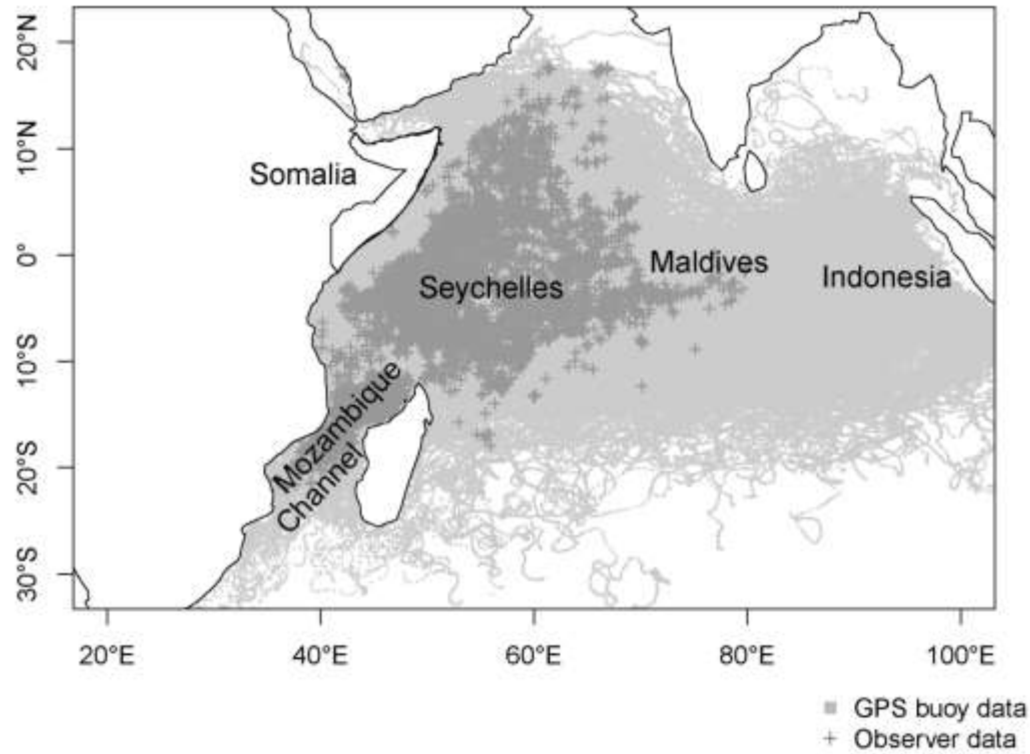

Figure 1: *positions of at sea French GPS buoys (pale grey) and observations of floating objects aboard French and Spanish vessels from 2007 to 2013 (dark grey)*

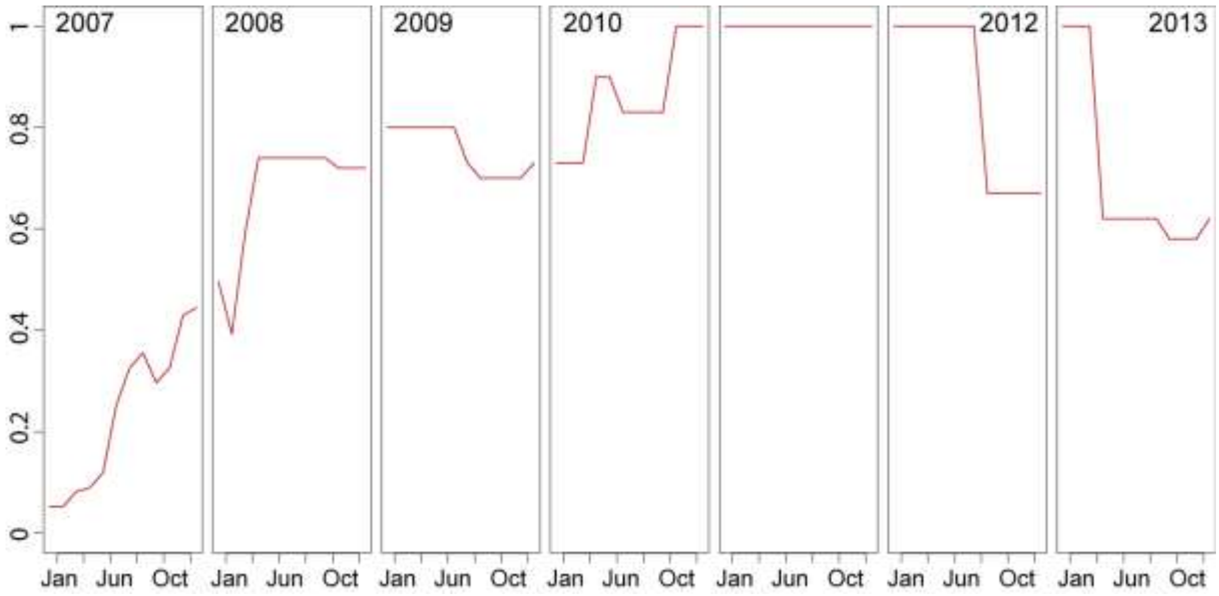

Figure 2: *coverage rate of French GPS buoys tracks*

2.2 Understanding purse seiners' strategy with dFADs and GPS buoys

When and where are GPS buoys deployed at sea?

Addressing the questions of understanding dFAD, log and GPS buoy use relied on the combination of a new, complex and variable source of information (GPS buoy trajectory data, Maufroy et al. 2014a) with multiple sources of information that had never been used for such a purpose (logbook and observer data) with detailed spatial and temporal scale. To overcome the inevitable uncertainties regarding the interpretation of these sources of information, 14 interviews with skippers were conducted in the port of Victoria from June to August 2013. These interviews, conducted as informal discussions with skippers, were used as a complementary source of qualitative information to guide statistical analyses (Chalmers and Fabricius, 2007; Johannes *et al.*, 2000; Moreno *et al.*, 2007a; Neis *et al.*, 1999). Among others, we discussed about their strategies regarding dFAD and GPS buoy deployment and identified the seasonality and the use of oceanic currents as key factors for these deployments (Maufroy et al. 2014b).

A deployment season was then defined as a group of successive months with similar deployment intensities on the same zones. Twofold Pearson correlations between monthly maps were calculated and used in a cluster analysis to obtain GPS buoy deployment seasons. A similar approach was then conducted on FOBs fishing sets derived from logbook data to compare FOB deployment and fishing seasons over 2007-2013. Finally, using speed vectors derived from French GPS buoy tracking data, seasonal maps of currents transporting GPS buoy tracked FOBs were obtained. At each time step, $\vec{u}$ and $\vec{v}$ components of speed vectors were computed at the scale of 5 degrees (chosen for representation purposes).

Individual components of speed vectors were then averaged to obtain seasonal mean speed vectors.

How do skippers organise their dFAD deployment activities?

Skippers also drew attention to the complex nature of dFAD and GPS buoy deployments by discussing of series of deployment (when a vessel dedicates from a few hours to a whole day to perform dFAD deployment activities only). Using available French and Spanish observer data, number, distance and time interval between dFADs of the same series of deployment were evaluated. Series of deployment were defined as successive deployments of dFADs with roughly equivalent times between consecutive deployments. Differences between seasons and years were tested through simple linear regression models and stepwise forward-backward selection of variables using AIC criterion. Due to piracy, no data was available to analyse series of deployment for the French fleet in 2010 and after 2010 for the Spanish fleet. Therefore, this analysis was only conducted over 2006-2009.

2.3 From French GPS buoys to a total number of monitored dFADs

What types of objects are equipped with GPS buoys?

To evaluate and manage the FOB fishery, it is necessary to know how many dFADs as well as how many GPS buoys are used on FOBs (Fonteneau and Chassot 2014). Some studies attempted to provide such estimates but they relied on a few information, did not separate dFADs and logs and did not account for spatio-temporal variability (Baske *et al.*, 2012; Ménard *et al.*, 2000; Moreno *et al.*, 2007a). Here, combining and comparing onboard observer data and French GPS buoy tracking data, we estimate the total number of dFADs and GPS buoys used in the Indian Ocean.

GPS buoy data available for this study consist of at sea positions of GPS buoys used by the French fleet and of purchase orders of GPS buoys by the French fleet, with no distinction between the type of FOB (dFAD or log) that these buoys are equipping. Evaluating the total number of dFADs and FOBs at sea requires the use of observer data to calculate the following proportions (Figure 2):

p_{fr}: proportion of French (associated flags) GPS buoys in the total population of GPS buoys
α_{fr}: proportion of dFADs in the French FOB population
p_{sp}: proportion of Spanish (associated flags) GPS buoys in the total population of GPS buoys
α_{sp}: proportion of dFADs in the Spanish FOB population
p_{oth}: proportion of other buoys in the total population of GPS buoys
α_{oth}: proportion of dFADs in FOB population of other fleets

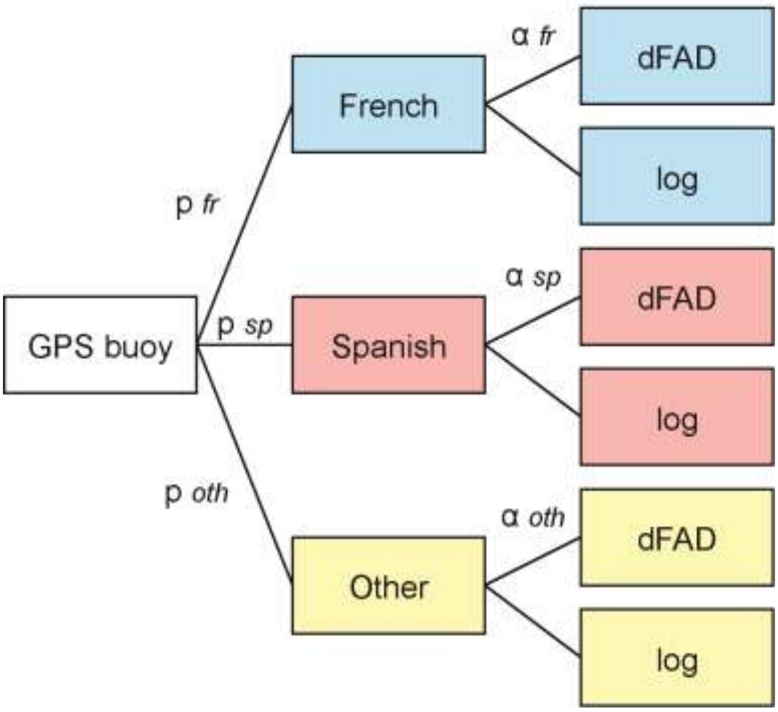

Figure 2: *types of GPS buoy-equipped objects and derived coefficients*

Purse seiners were considered as samplers of the FOB population. They use GPS buoys to monitor their FOBs and therefore know where to find them, and are also able to randomly find buoys and FOBs they do not own. Therefore, there is a preferential sampling of owned buoys among the total GPS buoy population while the sampling of non-owned buoys and FOBs was assumed to be random. To calculate the proportion α_{fr} (resp. α_{sp}) , GPS buoy deployments on logs and dFADs aboard French (resp. Spanish) vessels were used. Randomly found foreign buoys encountered aboard French and Spanish vessels were used to calculate α_{oth}. Non-owned buoys encountered aboard French and Spanish vessels were used to calculate the proportions p_{fr}, p_{sp} and $p_{oth.}$

How many dFADs and logs are monitored by the PS fleet?

The previous proportions were used to derive raising factors so as to calculate the total number of GPS buoys (N_b; Eq. 1) and the total number of dFADs equipped with buoys (N_d) (Eq. 2following:

$$N_b = \frac{N_{bfr}}{p_{fr} \times \varphi} \quad \text{(Eq. 1)}$$

$$N_d = \left(\frac{\alpha_{fr} \times p_{fr} + \alpha_{sp} \times p_{sp} + \alpha_{oth} \times p_{oth}}{p_{fr} \times \varphi} \right) N_{buoys,\ fr} \quad \text{(Eq. 2)}$$

Where φ represents the data coverage for the French buoys derived from GPS buoy and manufacturer data.

To account for variability in time and space in the deployment of dFADs and GPS buoys, a one degree gridded map was built and the values of each proportion α_i and p_i were calculated on cells of 9*9 degrees centered on each of the 1*1 degree cells. This method presents the advantage of smoothing and removing gaps in the calculated values that would be an artefact caused by too wide spatial strata. The number of French buoys $N_{buoys,fr}$ was calculated on a daily basis using GPS buoy trajectories interpolated to obtain a unique position each day at 00:00. This could only be done at the end of each month, as one of the French fishing companies deactivates GPS buoys of unused dFADs on a monthly basis.

2.3 Evaluating the impacts of dFADs in the Indian Ocean

How often do FOBs not contribute to fishing effort?

The total number of dFADs and GPS buoys can be considered as an index of nominal effort on FOBs but does not well take into account the true use of FOBs. Indeed, several reasons may render FOBs unavailable for fishing activities. This is the case of GPS buoy transfers (when a given vessel find a foreign GPS buoy and replaces the buoy with one of its own) and drift in inappropriate zones. In observer data, transfers of GPS were identified as sequences of GPS buoy retrieval immediately followed by a buoy deployment on a FOB that does not belong to the observed fishing vessel. We counted the occurrence of such events, taking into account possible changes over time from 2007 to 2013, seasonality and differences between fleets. These events were compared to the occurrence of random visits to GPS buoy-equipped objects that were not detained by observed fishing vessels. For this analysis, our objectives were both to detect changes in fishers' behaviour due to the increasing use of dFADs and GPS buoys and to evaluate the dynamics in dFAD ownership.

Due to the cost of acquiring GPS buoy signals, decided to deactivate GPS buoy that were not used by its skippers at the end of each month. These series of deactivations occurred for echosounder buoys from September to June 2013. In French GPS buoy tracking data, we detected such events as an important variation in the number of monitored FOBs at sea, between the last day and the day before the end of each month. We calculated the proportions of unused FOBs as the proportion of deactivated GPS buoys between these two days over 2011-2013.

How do GPS buoy-equipped FOBs influence PS fishing activities?

Finally, the associative behaviour of tunas with FOBs includes both environmental and social factors and remains poorly resolved (Fréon and Dagorn 2000; Castro et al. 2002; Robert et al. 2013). Modelling simulations of the social behaviour of tunas in arrays of FOBs suggest that tuna abundance could scatter for high FOB densities (Sempo et al. 2013). In such context and as preliminary analysed by Sempo et al. (2013), the increasing number of FOBs over time resulting from the massive deployment of dFADs is expected to result in an increasing number and proportion of FOBs without associated tuna. Additionally, the average catch of tuna by fishing set on FOBs is expected to decrease with the increasing number of FOBs, as associated schools may be fractionated between FOBs.

This hypothesis was tested over the period 2007-2013 for randomly found FOBs using observer data through the occurrence of visits that were not followed by a fishing set. In complement, the hypothesis of a saturation effect (“carrying capacity”) of the number of dFADs was tested. In this hypothesis, increasing the number of dFADs would not change the fraction of tuna available at FOBs, relative to tuna available at FSC. If it is the case, we should observe periods of higher proportions of FOB fishing sets compared to FSC sets, or of higher yield per FOB fishing sets. Using logbook data from 1982 to 2013, we calculated (1) the proportion of FOB vs FSC fishing sets per fishing trip, year and season (2) the ratio between the total catch on FOBs and the number of FOB fishing sets per fishing trip, year and season. The effects of year and season were tested through generalized linear models. 1982 and 1983 were excluded from these analyses, as mots of the data correspond to exploratory fishing campaigns.

3. Results

3.1 Strategies in dFADs and GPS buoy deployment

Seasonality in GPS buoy deployment and patterns of FOB drift

Most of skippers interviewed mentioned the importance of the knowledge of appropriate seasons and zones to make the decision of deploying dFADs and GPS buoys. In the Indian Ocean, 4 GPS deployment seasons were obtained: March to May, June-July, August to October and November to January. These seasonal deployment patterns were stable whatever the resolution (1, 2, or 5 degrees) but slightly varied between years. In this ocean, the variability seemed related to the beginning of a given season, that was found to occur earlier or later depending on the year. We obtained the same FOB fishing seasons, showing that activities of deployment and fishing on FOBs are correlated in time and space. Four different buoy deployment grounds could be identified in the Indian Ocean.

From March to May, over the period 2007-2012, GPS buoys were deployed in the Mozambique Channel area mainly between 12°S-18°S / 41°E-48°E (Figure 3). At this season, patterns in GPS buoy-equipped FOB drift were mainly eastward or North-Eastward at the scale of 5° (Figure 4). According to skippers, eddies that form in the Mozambique Channel at a finer scale “trap” GPS buoy-equipped FOBs in productive areas where they can rapidly attract fish. In June-July, GPS buoys were deployed on the West Seychelles deployment ground around 7°S-1°S/46°E-53°E. At this period of the year, FOB drift was mainly northward. FOBs were transported from the West of the Seychelles, to eastern coasts of Tanzania, Kenya and finally off Somalia. From August to October, GPS buoy deployments kept moving to the North West of the Indian Ocean to join the Somalia deployment ground around 3°N-12°N/50°E-60°E. August to October, FOBs reached the rich cold waters of the upwelling of Somalia. As the winter monsoon began, strong eastward patterns of drift of 0.5 $m.s^{-1}$ appeared during the season August to September and extended during the next season. Interviewed fishers considered that this drift pattern was responsible for a loss of up to 50% of their GPS buoy-equipped FOBs, as they reach the East of the Maldives-Chagos area that is too far from fishing grounds to be visited. From November to January, the French fleet deployed its GPS buoys around 5°S-10°S/51°E-62°E on the South Seychelles deployment ground. The strong eastward patterns in FOB drift were still active.

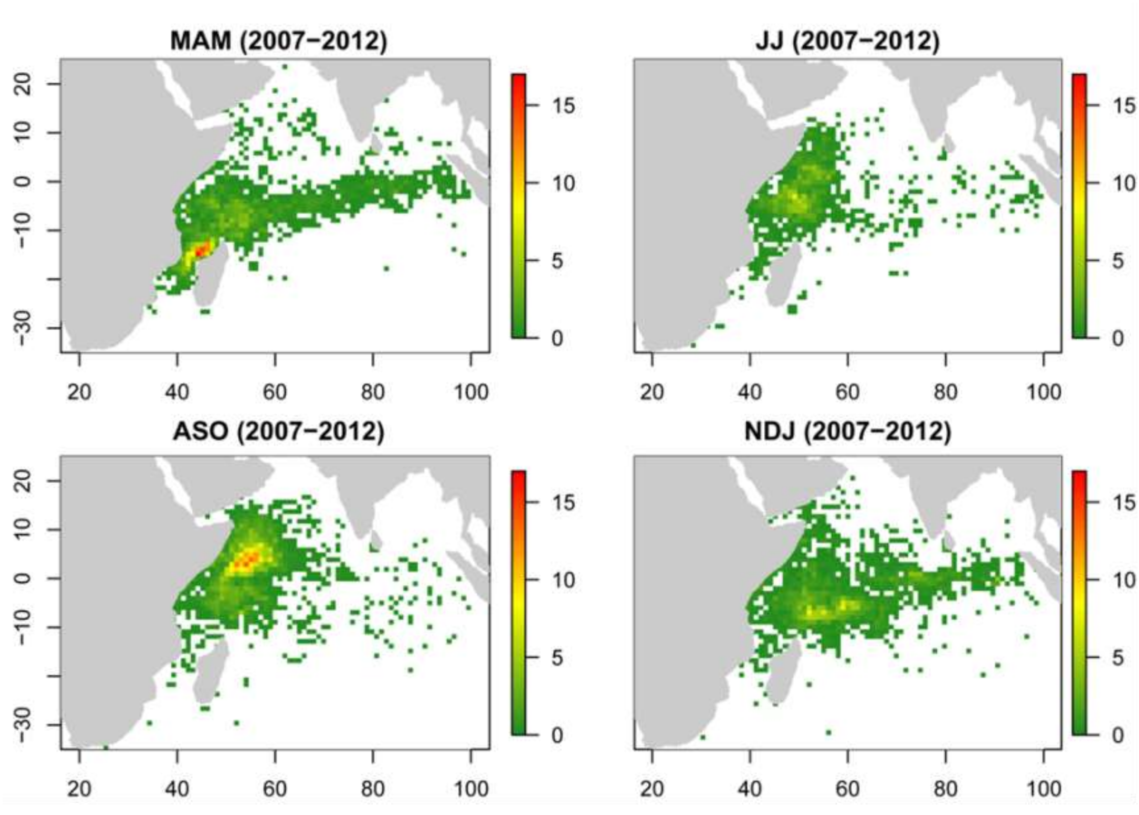

Figure 3: *GPS buoy deployment seasons*

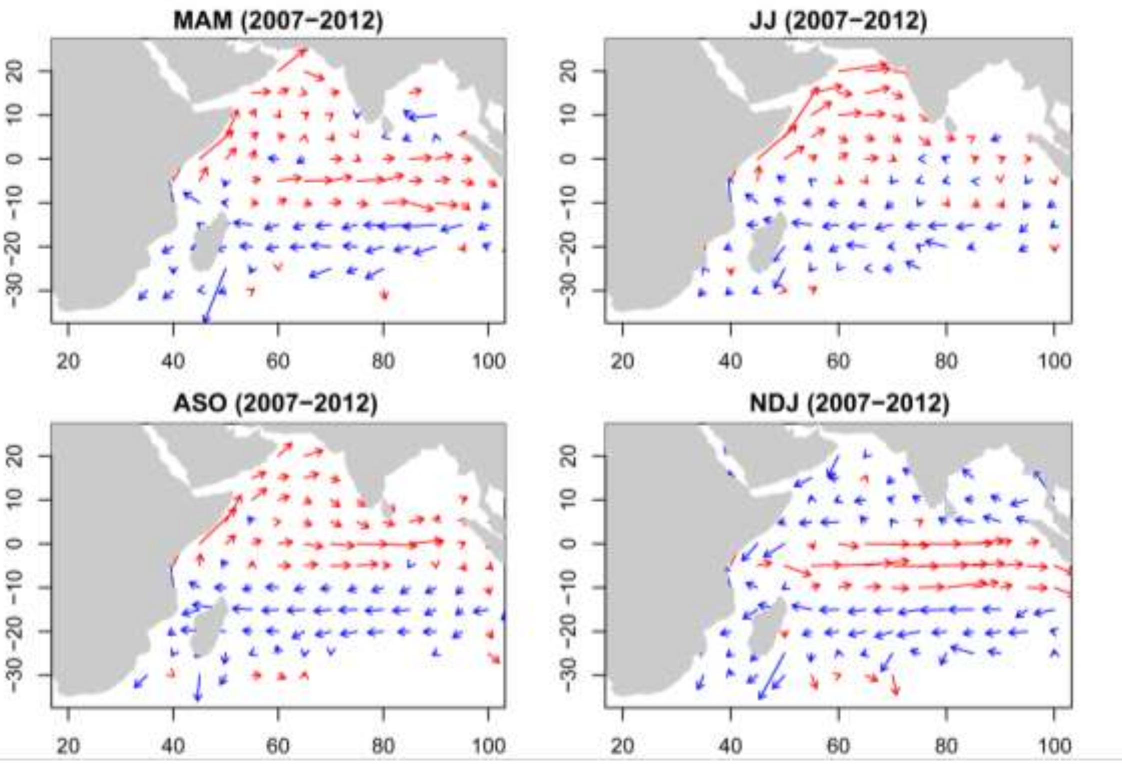

Figure 4: *seasonal patterns in GPS buoy-equipped FOB drift*

French and Spanish series of dFAD deployment

Over 2006-2009, the effects of year, fleet and interactions between fleet and season were significant on the time interval between deployments of dFADs of the same series. Only the effects of fleet (resp. year) explained the variance in distance between dFADs (resp. number of dFADs) in deployment series. No significant temporal trend in time between deployments could be detected over 2006-2009. Fitted linear regression models only explained respectively 32.3%, 9.6% and 18.1% of time, distance and number of dFADs variance in deployment series, underlying the complex nature of dFAD deployment decision making.

Time between consecutive dFAD deployments were generally lower for the Spanish fleet than for the French fleet (*p*-value = 1.1 10^{-3}) being respectively 63.2 min (SD = 26.6 min) and 82.4 min (SD = 41.2 min). This was also the case for distance between deployment, with a mean distance of 24.2 km (SD = 19.8 km) for the Spanish fleet and 57.1 km for the French fleet (SD = 398).

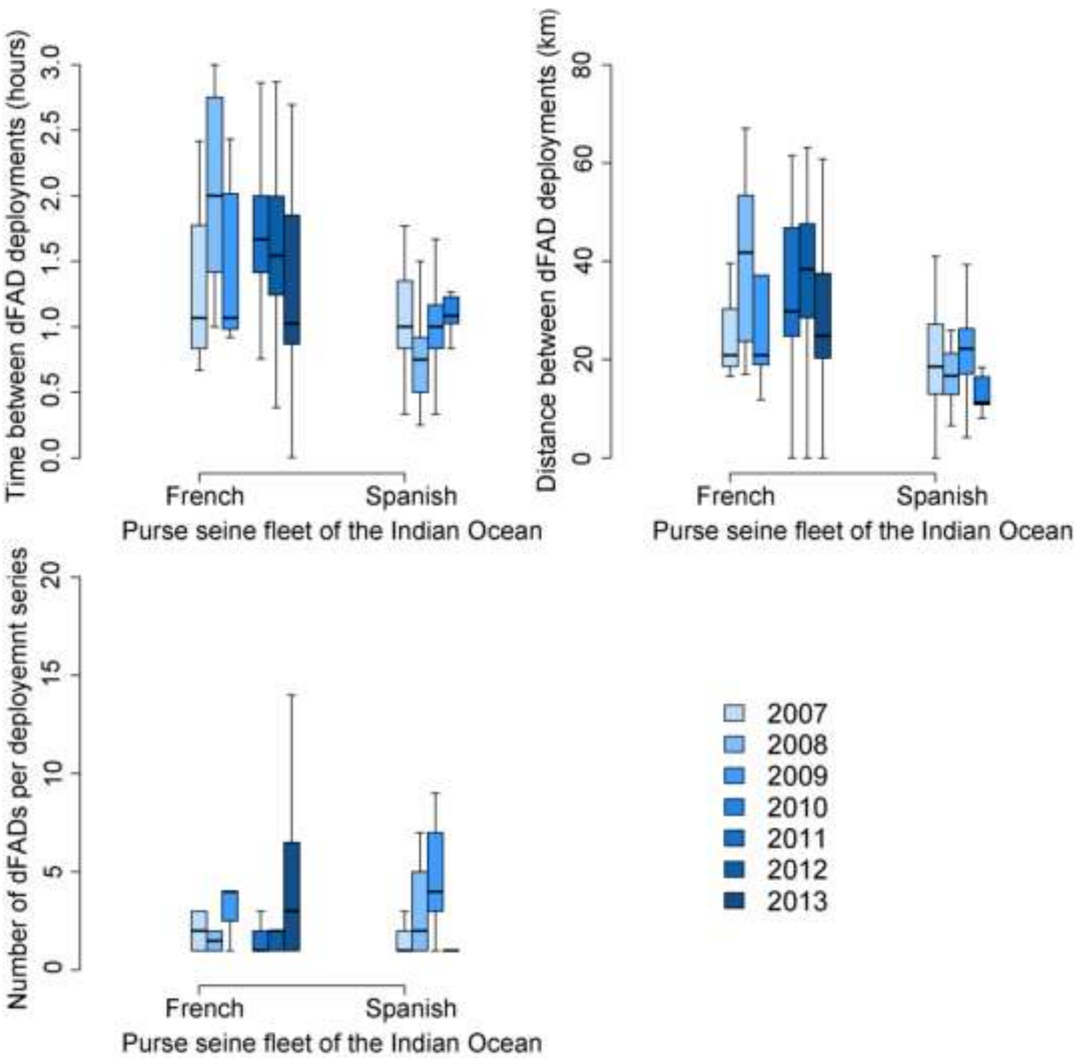

Figure 5: *yearly time, distance and number of dFAD deployments per series for the French and Spanish fleets*

3.2 Recent evolution of the number dFADs and GPS buoy-equipped objects in the IO

Types of objects equipped with GPS buoys

Over the period 2007-2013, the proportion of dFADs equipped with buoyss followed a decreasing gradient from the North-East to the South-West. Main log zones were the Mozambique Channel area with a proportion of logs reaching a maximum of 0.75 (around 25°S- 40°E) and the East of the Seychelles area reaching a maximum of 0.54 (around 3°S – 63°E). These trends tend to indicate that the choice of monitoring logs with GPS buoys relied on the oceanic circulation of the Indian Ocean, as the source of logs that are used for fishing activities.

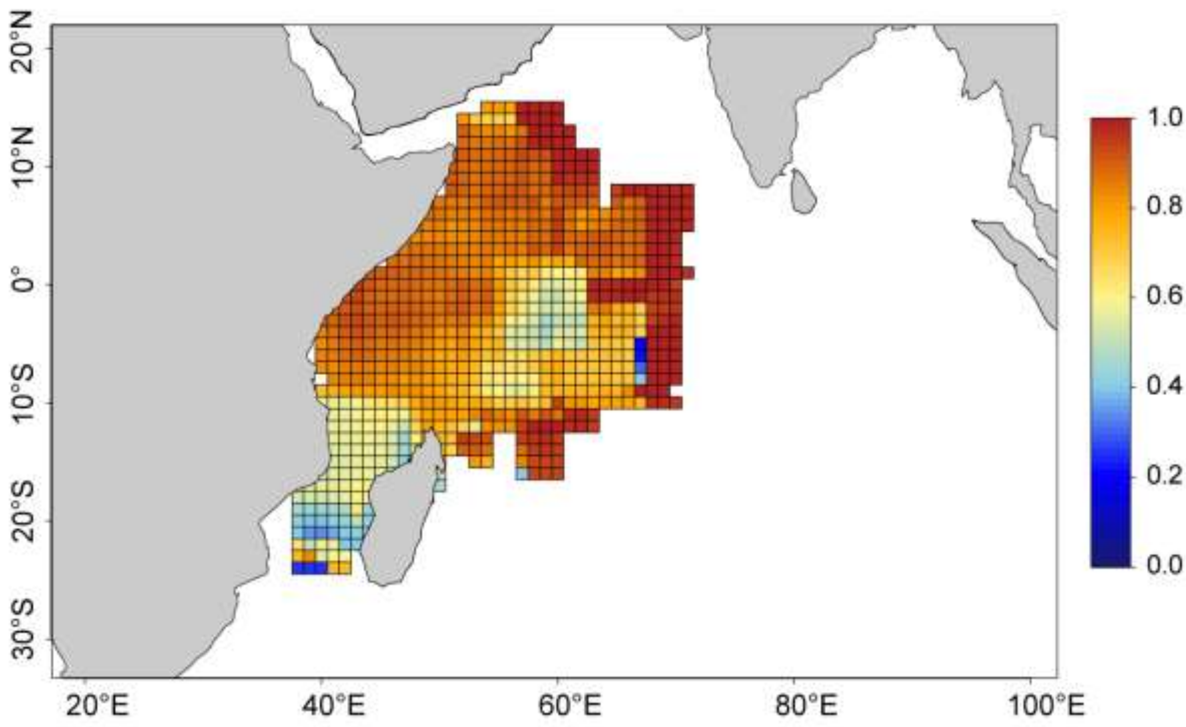

Figure 6: *proportion of dFADs among GPS buoy-equipped FOBs of all fleets (0 indicates that there are only logs – 1 that there are only dFADs on the zone)*

Recent evolution of the number of French GPS buoys

On a daily basis, GPS buoys equipping FOBs drifting at sea ranged from 13 at the end of January 2007 to 85 buoys per vessel at the end of September 2013. Through time, there was a strong increase in the use of GPS buoys on a daily basis that was almost multiplied by 8 between these two dates. As a result, the total number of French GPS buoys at sea on a daily basis increased from about 250 in January 2007 to about 1,100 in September 2013, corresponding to an increase of 360%. Also, variations between months of the same year became sharper as the total number of at sea GPS buoys per day increased in the Indian Ocean. However, periods such as March to May and August to September were constantly the most important for GPS buoy use by the French PS fleet.

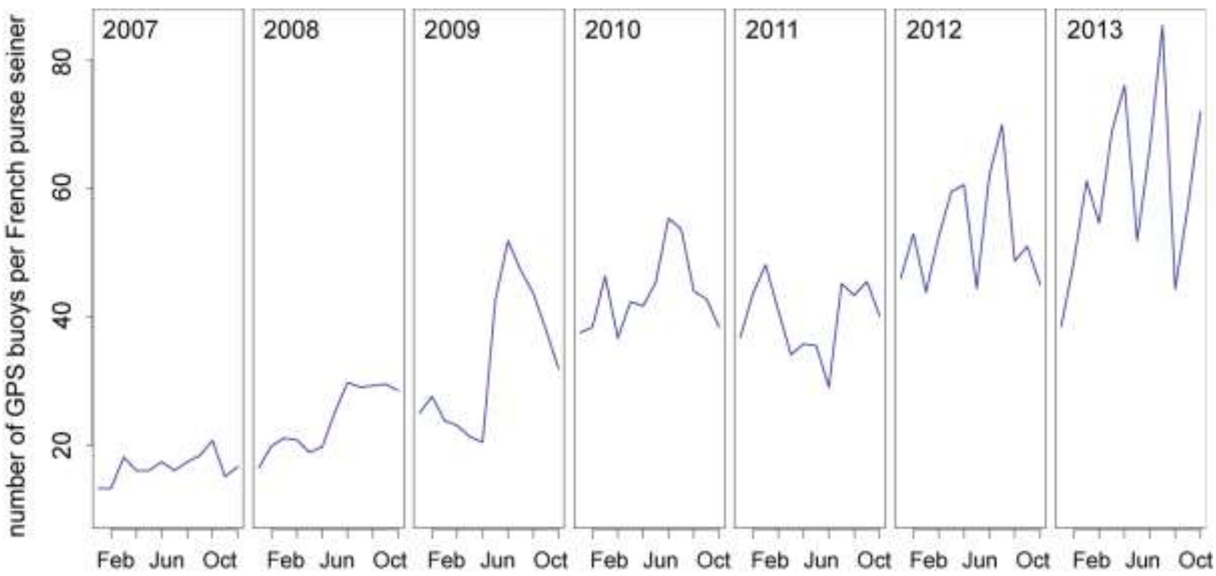

Figure 7: *daily number of French GPS buoys at sea at the end of each month, per French purse seiner*

Recent evolution of the number of dFADs on PS fishing grounds

Over 2007-2013, the estimated total number of dFADs and GPS buoy-equipped objects increased from 900 dFADs and 1,400 GPS buoy-equipped FOBs per day on Western Indian Ocean fishing grounds at the end of January 2007 to 2,700 dFADs and 4,000 buoy-equipped FOBs in December 2013 (Figure 8). From year to year, two distinct periods were important for monitoring dFADs and logs at sea: from the end of February to the end of June and from the end of July to the end of November. In 2010 for example, we estimated that 1,500 dFADs and 2,300 GPS buoy-equipped FOBs per day were drifting at sea at the end of March and 3,600 dFADs and 3,800 GPS buoy-equipped objects at the end of August. Some years, the peak end of July-end of November in dFAD and GPS buoy use was broken down into to peaks and a third season of dFAD and GPS buoy use occurred from the end of June to the end of September.

From December to February and from March to May, when European PS vessels concentrated their activities on their eastern fishing grounds and later in the Mozambique Channel, the relative proportions of logs in the population of GPS buoy-equipped objects seems was higher. At the end of April 2014, logs contributed to up to 46.2% of daily numbers GPS buoy-equipped FOBs. On the contrary, during the rest of the year, dFADs generally represented the majority of GPS buoy-equipped FOBs. This was particularly true from August to September when PS activities mainly occurred on the Somali fishing ground. In 2011, dFADs represented 76.2% of GPS buoy-equipped FOBs.

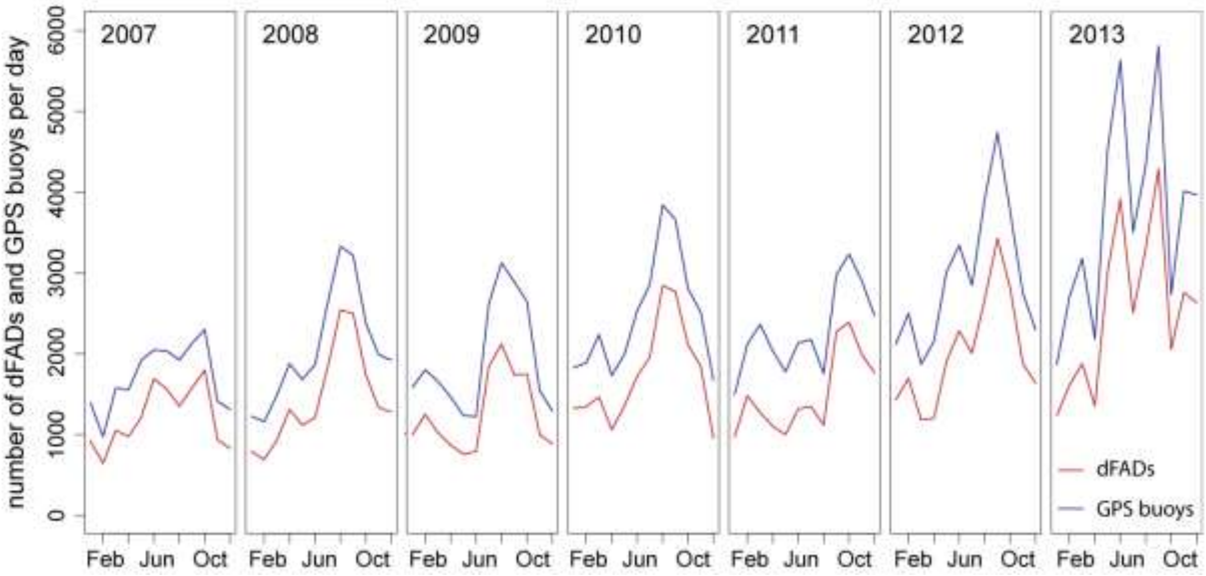

Figure 8: *estimation of the total number of dFADs and GPS buoy-equipped FOBs in the Indian Ocean per day, at the end of each month (2007-2013)*

All over the period 2007-2013, Spanish vessels used more GPS buoys than French purse seiners, with a ratio between estimated daily use of GPS buoy-equipped FOBs between these two fleets ranging from 2.1 at the end of February 2008 to 5.5 at the end of July 2013. This ratio was often lower when the PS fleet concentrate its activities in the Mozambique Channel around March to May than during the Somali season around August to September. For the two fleets, the number of GPS buoy-equipped FOBs increased from 250 French and 1,000 Spanish GPS buoys at the end January 2007 to 1,100 French and 4,600 Spanish GPS buoys at the end of September 2013 (Figure 9).

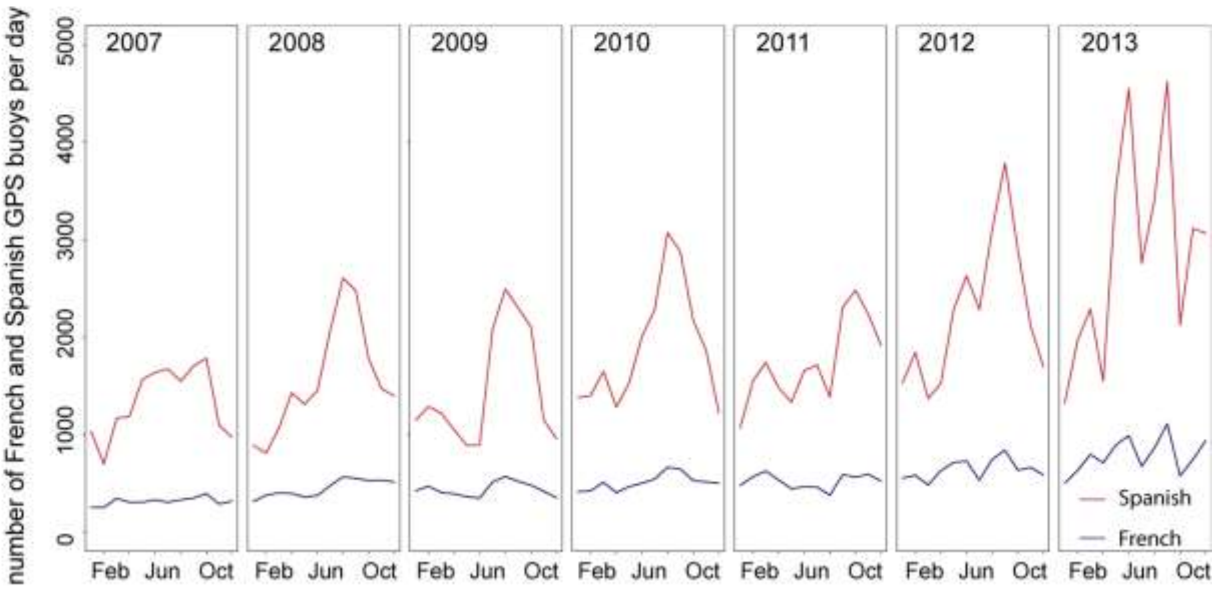

Figure 9: estimation of the total number of French and Spanish GPS buoys active in the Indian Ocean per day, at the end of each month (2007-2013)

3.3 Consequences of dFAD and GPS buoy use on FOB fishing

Transfers of GPS buoys

During 2006-2013, French and Spanish PS vessels replaced a proportion of 0.47 for the Spanish fleet from March to May to 0.72 for the French fleet from June to July. Interviews with fishers suggested that Spanish purse seiners would automatically transfer GPS buoys whereas French PS vessels would be more selective due their more limited number of GPS buoys available per vessel. This was the case from August to February but not from May to July partly due to missing information in observer data and partly to a lower occurrence of visits of non-owned for the Spanish PS fleet (Table 6). Also, the probability of a buoy being transferred greatly depended on the owner of the original buoy. Most of the time Spanish GPS buoys had a higher probability to be transferred than French GPS buoys (Table 7).

Table 6: *Proportions of GPS buoys transfers on randomly found FOBs, per fleet randomly finding FOBs and per season. Note that these rates may be underestimated, as some observers poorly report transfer events.*

Season/fleet	French	Spanish
Mar-Apr-May	0.57	0.47
Jun-Jul	0.72	0.67
Aug-Sep-Oct	0.64	0.67
Nov-Dec-Jan-Feb	0.54	0.62

Table 7: *Proportions of GPS buoys transfers on randomly found FOBs, per fleet owning FOBs and per season. As in Table 5, these rates may be underestimated.*

Season/fleet	French	Spanish
Mar-Apr-May	0.43	0.41
Jun-Jul	0.08	0.66
Aug-Sep-Oct	0.5	0.66
Nov-Dec-Jan-Feb	0.17	0.49

Deactivations of GPS buoys

Over September 2011-June 2013, 18 events of GPS buoy deactivations were detected on echosounder buoys. During such events, rate of deactivations varied from 19.0% in January 2013 to 53.7% in June 2013. Deactivated GPS buoys were most of the time equipping FOBs located outside or at the limit of FOB fishing grounds, where visiting these objects would probably have required too important cruising distance and time. Neither the year, nor the seasons were found to significantly influence these rates of deactivations.

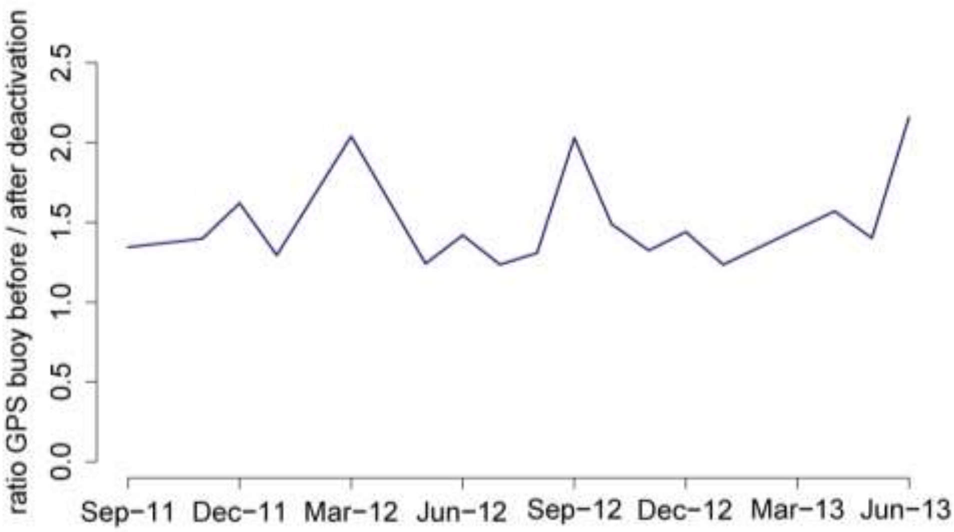

Figure 10: rate of GPS buoys deactivations

"Empty" FOBs

Over 2007-2013, the proportions visits of "empty" FOBs increased from 0.76 to 0.87 for the French fleet, suggesting that a higher proportion of visited FOBs had not aggregated sufficient levels of fish for undertaking a fishing set. However, the opposite was observed for the Spanish fleet, with a decreasing proportion of visits that were not followed by a fishing set, from 0.82 in 2007 to 0.75 in 2010. It is therefore not possible to conclude that the increase in dFAD and GPS buoy use has induced a fractionation of FOB schools over 2007-2013.

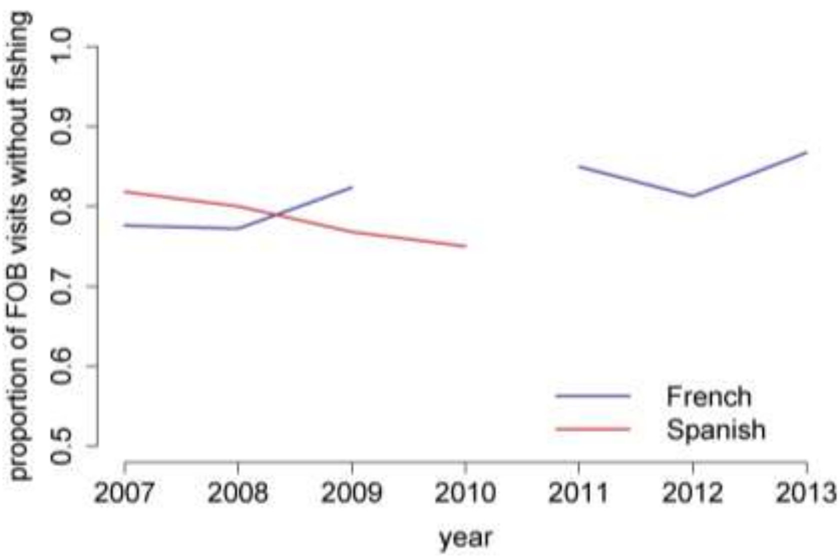

Figure 11: proportion of visits of GPS buoy-equipped FOBs that were not followed by a fishing set, per fleet and per year

Evolution of the PS fishing activities

Over 2007-2012, the effects of year, season and interactions between years and seasons were significant and explained 27.5% of deviance in the proportion of FOB fishing sets per fishing trip. The most important factor was the influence of the season, August from October being the season with the highest ratio FOB fishing sets / FSC fishing sets. June to July (p value=2 10^{-3}) and November to February (p value = 1.7 10^{-5}) were found to be significantly less important for FOB fishing than August to October. However, though it seemed to be case for the seasons June to July and November to February between 2007 and 2011 (Figure 12), we could not detect clear temporal patterns indicating whether the recent evolutions in the number of GPS buoy-equipped FOBs at a significant effect on the relative proportions of FOB and FSC fishing sets.

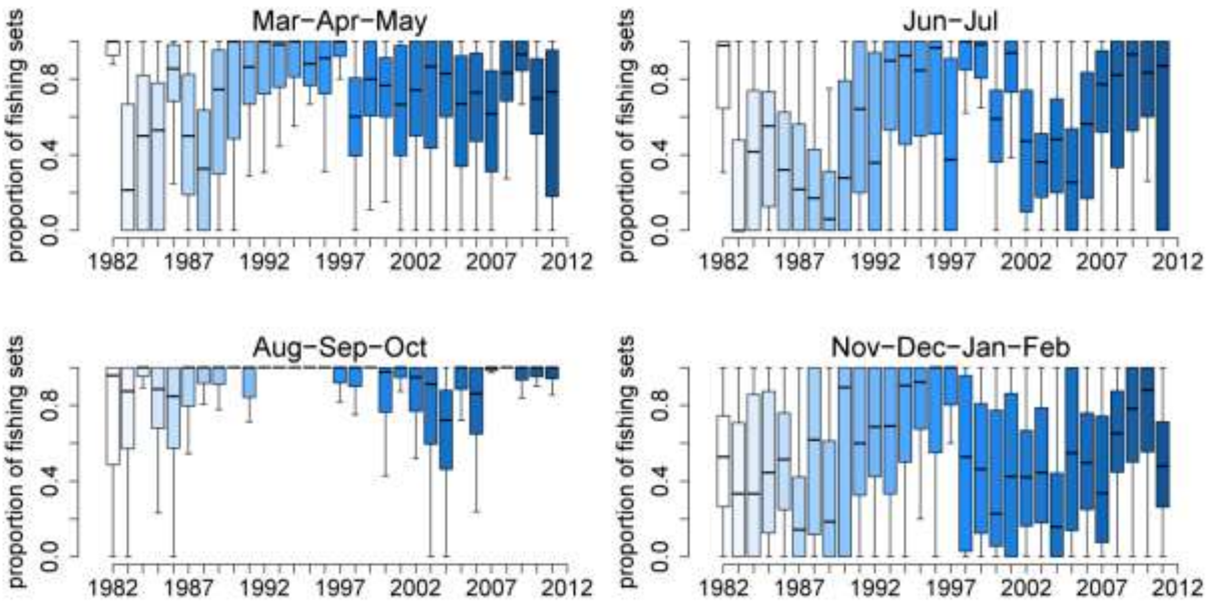

Figure 12: proportion of fishing sets on FOBs, per fishing trip, year and season for the French fleet from 1982 to 2013

As for the ratio between the amount of tuna catch at FOBs per fishing trip and the number of fishing sets, the effect of year, season and the combination of year and season explained 19% of the total deviance. Some periods such as 1999 to 2005 had constantly higher yields of catch per FOB fishing sets than 2012, suggesting that if a dFAD “carrying capacity” exists for the Indian Ocean, this capacity was probably reached during this period. Then, the yield per fishing sets tend to decrease over time. Figure 12 indicates that this was particularly true for the main dFAD fishing season, August to October.

Also, though the effect of year was not always significant between 1984 and 2013, our results tend to indicate the existence of 3 distinct periods. Between 1984 and 1998, a gradual increase occurred to reach a maximum in 1988 before declining. Similar “cycles” of increasing and decreasing yields occurred between 1999 and 2006 and between 2006 and 2013.

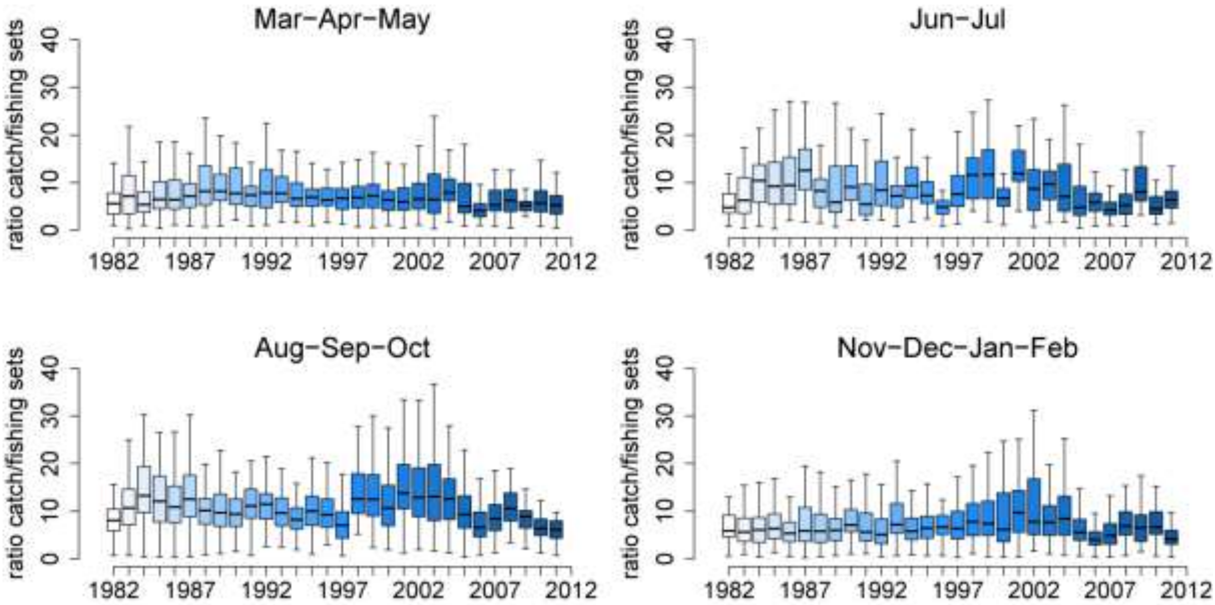

Figure 13: average yield of FOB fishing sets (in tons/fishing set) per fishing trip, year and season for the French fleet from 1982 to 2013

4. DISCUSSION

4.1 Separating logs and dFADs in GPS buoy counts

Using tuna aggregative behaviour for their fishing activities, purse seiners may impact tropical ecosystems by two means: (i) directly, through the deployment of dFADs that modify the environment of tuna and (ii) indirectly by increasing fishing capacity through the monitoring of dFADs and logs with GPS and echo-sounder buoys while they drift. As such, knowing the numbers of dFADs and GPS buoys in use appears essential for a better evaluation and management of tropical tuna fisheries. In tuna RFMOs however, the vocabulary in use to designate the different types of objects may not be adapted to these requirements. Often, the term “Fish Aggregating Device” confuses natural floating objects, debris of human activities (e.g. pieces of netting, plastic boxes) that were not intentionally left at sea by fishers/vessels and man-made artificial objects that have been specifically designed to aggregate tuna. For a better assessment of actual impacts of the fishery, a better choice of the terminology may be preferable. In this study, we made the choice to call dFAD man-made floating objects that were specifically been deployed at sea to aggregate tuna, logs floating objects that were randomly found by fishers but were not deployed specifically to aggregate tuna (this term can be refined in “natural log” and “artificial log”, to indicate if the object is a debris a human activities). dFADs and logs were then grouped under the term Floating Object (FOB) that also allows to count how many GPS buoys are in use. Our results indicate that this is important, as up to 23.8% of GPS buoys were deployed on logs in 2011.

4.2 Estimating the use of FOBs in the Indian Ocean

The results we obtain seem to greatly differ from previous estimates. In 2007, Moreno et al. estimated that there was approximately 2,100 FOBs at sea per day in the Indian Ocean (Moreno *et al.*, 2007b). These estimates are rather above ours. For example for 2007, we obtain a maximum of around 1,800 dFADs and 2,300 buoys per day on FOB activity grounds. Several reasons may explain the difference between these results. First of all, our methodology entirely relies on French GPS buoy tracks over 2007-2013. Because part of the information was missing due to lack of storage or export problems, this probably induced an underestimation of daily use of GPS buoy use by the French PS fleet. However, our results indicate strong changes for this fleet, as numbers of FOBs daily monitored may have been multiplied by about 6 in just 7 years, i.e. from about 10 in 2007 to about 60 in 2013. By contrast, information given through purchase orders of buoys by vessel indicates a less than twofold increase during the same period, i.e. from 100 buoys in 2007 to 190 in 2013. Such differences could result from the different temporal scales that are used to provide these estimates. In coming months, when a greater proportion of French GPS buoy tracks become available, it will be possible to confirm these trends for the French fleet.

Secondly, because no GPS buoy tracking data was available for other PS fleets of the Indian Ocean, we used observer data, covering between 5 to 10% of French and Spanish fleets. This was not an optimal solution, as this data required correction before use that relied on observers' comments on activities on FOBs. This low coverage of French and Spanish fleets prior to 2014, as well of the absence of observers aboard Spanish vessels in the Indian Ocean after 2010 due to piracy of Somalia, obliged us to use this information without consideration of the year and the season. If more data had been available, it would have been a better option to calculate the proportions α and p for each year, and at each FOB season. In particular, this can be a problem if, as suggested by skippers, the rate of increase in dFAD and GPS buoy use was higher for the Spanish than for the French PS fleet. If it is the case, our results underestimate the number of dFADs and GPS buoys in use in the Indian Ocean, at least for the Spanish PS fleet. Availability of Spanish GPS buoy tracking data would obviously greatly improve our estimates.

Finally, observer data is only available on zones where European purse seiners deploy, search and fish on FOBs. There is no information under 25°W and above 80°E, in zones were FOBs accumulate due to too strong eastern currents in the Indian Ocean. Interviews with skippers (e.g. one of them indicated a loss of up to 50% of dFADs to the East of the Indian Ocean), the intensity of GPS buoy use in 2007 could be higher than our estimate. Also, as our data is limited to the west of 80°E, we may not be able to correctly assess dFAD and GPS buoy use by non-European purse seine fleets such as Japan that mostly fish on FOBs.

Despite the possible limitations of our methodology, our results indicate that a strong increase in GPS buoy use has occurred over 2007-2013, for all fleets. Though our results tend to underestimate the real number of dFADs and GPS buoys currently in use in the Indian Ocean, our approach explicitly separates dFADs from GPS buoys and provides information on a daily basis, a scale that seems more appropriate than current quarterly declarations provided by European fleets. As such, our results can be considered as an index of FOB fishing effort or FOB fishing capacity. Therefore, the fast increase in FOB use may represent a strong increase in the PS fishing effort. However, this increase would be counterbalance with the decrease on the number of European PS due to piracy (IOTC, 2012). In any case, the potential impacts of FOB increase require a better monitoring of the number of dFADs and GPS buoys in use in the Indian Ocean which will allow assessing their effect on the population and putting the basis for a discussion on the management of FOB PS fishery (Fonteneau and Chassot 2014).

4.3 Assessing the effects of dFAD and GPS buoy use on fishing effort

Obviously, it is also important to take into account the effects of the seasonality and the differences between fleets on the interpretation of these changes in activities related to dFADs, logs and GPS buoys. For example, high seasonal rates of GPS buoy transfers may lower the effects of such an increase, as PS vessels may rapidly lose the ownership of a given dFAD or a given log. Also, it is important to underline that only a fraction of GPS buoy-equipped FOBs may be of interest for FOB fishing activities. Between 2011 and 2013, we could for instance estimate that between 19% and 53.7% GPS buoy-equipped FOBs would be abandoned by one the French fishing companies. These objects, if they are not retrieved, may contribute to a possible ecological trap (Hallier and Gaertner, 2008; Marsac *et al.*, 2000), dFAD ghost fishing (Filmalter *et al.*, 2013) though non-entangling dFADs may contribute to greatly reduce this problem for European PS fleets (Delgado-Molina et al., 2014) or damages to potentially fragile ecosystems through beaching of 10% of GPS buoy-equipped FOBs 10% (Maufroy et al. 2014a).

However, a large proportion of these GPS buoy-equipped FOBs contributes to FOB fishing capacity. This may induce long term changes in the structure of yellowfin, skipjack and bigeye tuna stocks. In particular, if as suggested by Sempo et al. 2013, when the number of dFADs increases too strongly, the size of associated fishing schools under each FOB is reduced. Our results tend to indicate the existence of such a “FOB carrying capacity” in the Indian Ocean, that may derived from periods of higher yield per FOB fishing sets such as 1999-2005 , These results suggest that the optimal number of dFADs can be determined by analyzing the information of logbooks, echosounder information and observer data. Yet, 3 distinct periods in yield per FOB fishing sets were identified in logbook data: 1984-1998, 1999-2005 and 2006-2013 and the probable existence of a dFAD “carrying capacity” may not be the only reason for observing such cycles on increasing-decreasing yield. Indeed, the end of the 1990s and 2006 correspond to two main technological improvements with the introduction of GPS buoys and echosounder buoys to monitor FOBs. Years immediately following these improvements may have benefited for an increased fishing efficiency. Finally, changes in skippers’ preference for smaller or larger schools over time may explain our results, through a detailed analysis of the distribution of catch per fishing set would be required.

To test these hypotheses and validate our results, collection of dFAD information through dFAD management plans should be reinforced and collaboration with fishermen would be required, as in this study, to provide echosounder buoy information. In the future this will allow to assess and manage a sustainable dFAD PS fishery.

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