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Original Article

Massive increase in the use of drifting Fish Aggregating Devices (dFADs) by tropical tuna purse seine fisheries in the Atlantic and Indian oceans

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Since the mid-1990s, drifting Fish Aggregating Devices (dFADs), artificial floating objects designed to aggregate fish, have become an important mean by which purse seine fleets catch tropical tunas. Mass deployment of dFADs, as well as the massive use of GPS buoys to track dFADs and natural floating objects, has raised serious concerns for the state of tropical tuna stocks and ecosystem functioning. Here, we combine tracks from a large proportion of the French GPS buoys from the Indian and Atlantic oceans with data from observers aboard French and Spanish purse seiners and French logbook data to estimate the total number of dFADs and GPS buoys used within the main fishing grounds of these two oceans over the period 2007–2013. In the Atlantic Ocean, the total number of dFADs increased from 1175 dFADs active in January 2007 to 8575 dFADs in August 2013. In the Indian Ocean, this number increased from 2250 dFADs in October 2007 to 10 300 dFADs in September 2013. In both oceans, at least a fourfold increase in the number of dFADs was observed over the 7-year study period. Though the relative proportion of natural to artificial floating objects varied over space, with some areas such as the Mozambique Channel and areas adjacent to the mouths of the Niger and Congo rivers being characterized by a relatively high percentage of natural objects, in no region do dFADs represent <50% of the floating objects and the proportion of natural objects has dropped over time as dFAD deployments have increased. Globally, this increased dFAD use represents a major change to the pelagic ecosystem that needs to be closely followed in order to assess its impacts and avoid negative ecosystem consequences.

Keywords: fish aggregating device, fishing effort, fishing strategy, GPS buoys, observers' data.

Introduction

Tropical tunas skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye (*Thunnus obesus*) tend to associate with objects floating at the surface of the ocean (Kingsford, 1993; Fonteneau *et al.*, 2000b; Castro *et al.*, 2002). When tropical tuna purse seiners (PS) began to operate in the Atlantic and Indian Oceans in the early 1960s and 1980s, respectively, they fished on a combination of Free Swimming Schools (FSC) and schools associated with natural floating objects (hereafter termed "logs"). At that time, logs, originating from natural sources, such as river mouths, constituted the main source of Floating OBjects (FOBs) (Greenblatt, 1979). They could be either strict natural floating objects (e.g. wooden debris or marine mammals) or debris of human activities (e.g. pieces of fishing net) (Hallier and Parajua, 1999). During the 1990s, fishers began to deploy large numbers of their own FOBs. These man-made drifting Fish Aggregating Devices (dFADs) generally consist of a bamboo raft covered by old pieces of purse seine net. Support vessels were also introduced into the fishery to assist PS in building, deploying, and monitoring dFADs, and also in searching for FSC (Ariz *et al.*, 1999; Ramos *et al.*, 2010). Throughout the 2000s, several technological improvements occurred in the purse seine fishery (Torres-Irineo *et al.*, 2014), including the use of GPS buoys to more accurately locate dFADs and logs, and the introduction of echosounder buoys to monitor the amount of biomass aggregated under FOBs (Lopez *et al.*, 2014).

The development of dFAD-fishing has had several consequences (Dagorn *et al.*, 2013b; Fonteneau *et al.*, 2013). First, this increased fishing effort and overall capacity of the fishery by (i) enhancing the aggregation of tropical tunas, including juveniles of yellowfin and bigeye tuna; (ii) reducing search time dedicated to locating tuna schools; and (iii) increasing the fraction of sets with non-zero catch (Ariz *et al.*, 1999). Secondly, dFADs may have modified the natural habitat of tropical tunas and other species. There are concerns that the increased use of dFADs has modified the dynamics and structure of tuna schools, their feeding ecology and movements (Fonteneau *et al.*, 2000a; Marsac *et al.*, 2000; Ménard *et al.*, 2000; Hallier and Gaertner, 2008). It has been hypothesized that dFADs act as an "ecological trap" by maintaining tunas in suboptimal areas and/or reducing school size (Marsac *et al.*, 2000; Hallier and Gaertner, 2008; Sempo *et al.*, 2013), though evidence for such effects remains limited (ISSF, 2014). In addition, FOB fisheries have potential to severely negatively impact coastal and pelagic ecosystems via increased levels of bycatch and discarding (Amandè *et al.*, 2010, 2012; Hall and Roman, 2013), ghost fishing of sensitive species (Filmalter *et al.*, 2013), and potential damage to fragile ecosystems when lost FOBs end up beaching on coral reefs (Balderson and Martin, 2015; Maufroy *et al.*, 2015).

Though FOB fishing for tropical tunas has existed since at least the 1990s, it is generally believed that dFAD and GPS buoy use has significantly increased in recent years with potentially adverse effects on pelagic habitats (Hallier and Gaertner, 2008). Despite the recent implementation of dFAD management plans by tuna RFMOs to collect data on dFADs and GPS buoy use (ICCAT Recommandation 14/01; IOTC Resolution 13/08), it is still difficult to evaluate the magnitude and ecological impacts of dFAD use. In this context of growing concerns for tropical tunas and pelagic ecosystems, it is necessary to evaluate how many dFADs are currently drifting at sea and how many dFADs and logs are equipped with GPS buoys (Fonteneau and Chassot, 2014).

Prior studies have attempted to provide such estimates, but they were on basis of limited information, did not separate dFADs from logs, and did not account for spatio-temporal variability in FOB use (Ménard *et al.*, 2000; Moreno *et al.*, 2007; Baske *et al.*, 2012). Furthermore, previous descriptions of dFAD deployment strategies and seasonality in the Indian and Atlantic Oceans date from the beginning of the 1990s (Hallier and Parajua, 1999; Ariz *et al.*, 1999). It is therefore necessary to improve our understanding of the use of dFADs and GPS buoy-equipped FOBs in order to properly manage their use and mitigate their ecosystem and fishery impacts.

Our objectives here are to describe when, where and how many dFADs are deployed by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. We use position records from the period 2007 to 2013 of GPS buoys used by the French PS fleet on logs and dFADs, in combination with logbook and observer data, to quantify the number of French GPS buoys, as well as the portion of the entire FOB "population" that French objects represent. From this, we extrapolate the total number of GPS-equipped FOBs by season, fishing area, fleet, and FOB type.

Material and methods

Hereafter, the term "drifting FAD" (dFAD) will be used to describe any drifting object that has been built and deployed at sea by fishing vessels to aggregate tropical tuna. The term "log" will be used in opposition to "dFAD" to designate any floating object that is not a dFAD (Table 1). Though logs are generally randomly found by tropical tuna PS, once found, they can be used similarly to dFADs to detect the presence of tuna schools and increase the success of fishing sets. This includes the potential attachment of a GPS buoy to a log or the deployment of a dFAD on a log to enhance its floatability. The term "FOB" will be used to refer to dFADs or logs, without specifying the nature of the floating object (Table 1).

When a FOB is equipped with a GPS buoy, we will refer to the object as a "GPS buoy-equipped FOB" (Table 1). GPS buoys can be deployed either during the deployment of a new dFAD, or as a result of a random encounter with a FOB that was not previously equipped with a GPS buoy (e.g. unaltered log) or was equipped with a GPS buoy belonging to another vessel (in which case the finding vessel generally replaces the GPS buoy with one of its own GPS buoys). Three main groups of PS operate in the Atlantic and Indian Oceans (French, Spanish, and Other), each maintaining a certain number of GPS-equipped FOBs (Table 1). In this paper, we will quantify the number and type of GPS-equipped FOBs maintained by each fleet over time and space.

Data sources

Three major data sources were used: French logbooks, French and Spanish onboard observer data, and GPS positions for French GPS-buoys attached to FOBs. French logbook data provided positions for the 17 914 FOB fishing sets carried out by French PS over the period 2007–2013. Similar data were not available for this study for Spanish and other non-French PS. For a subset of French and Spanish PS fishing trips, onboard observers were present and collected additional, detailed information on FOB activities, including position, the type of FOB (dFAD or log), the type of activity on the FOB (deployment, visit, fishing, or retrieval) and the type of activity on the attached GPS buoy (deployment, retrieval or visit). In addition, observers have the possibility to provide more detailed information on FOB activities, such as the fleet (French, Spanish, or other) of the vessel owning the GPS buoy. This information was available for 66.7% of the 20 800 distinct activities on GPS buoy-equipped FOBs noted by observers. Observer data were available for ∼5–10% of French and Spanish PS fishing trips (Supplementary Material S1, Supplementary Tables S1.1 and S1.2) and covered a substantial part of the Eastern Atlantic Ocean and Western Indian Ocean (Figure 1). During 2010–2013, problems of piracy off Somalia in

Table 1. Typology of Floating OBjects (FOBs) used by tropical tuna purse seine fleets depending on the origin of the object (log or dFAD) and of the presence of a GPS buoy.

		GPS buoy-equipped FOB		
FOB type	**Free FOB (no GPS buoy)**	**French +assoc. flags (e.g. Mauritius)**	**Spanish +assoc. flags (e.g. Seychelles)**	**Other Asian PS fleets other gears (baitboat)**
Natural log e.g. marine mammal, tree or Artificial log e.g. debris of human activities	*Free-LOG*	LOG_{fr}	LOG_{sp}	LOG_{oth}
dFAD e.g. bamboo or metallic raft	*Free-FAD*	FAD_{fr}	FAD_{sp}	FAD_{oth}
FOBs = logs + dFADs	*Free-FOB*	FOB_{fr}	FOB_{sp}	FOB_{oth}

Data were only available for GPS buoy-equipped FOBs. Numbers of Free-Floating FOBs were therefore not estimated in this study. dFAD, man-made drifting Fish Aggregating Device; LOG, any floating object that is not a dFAD.

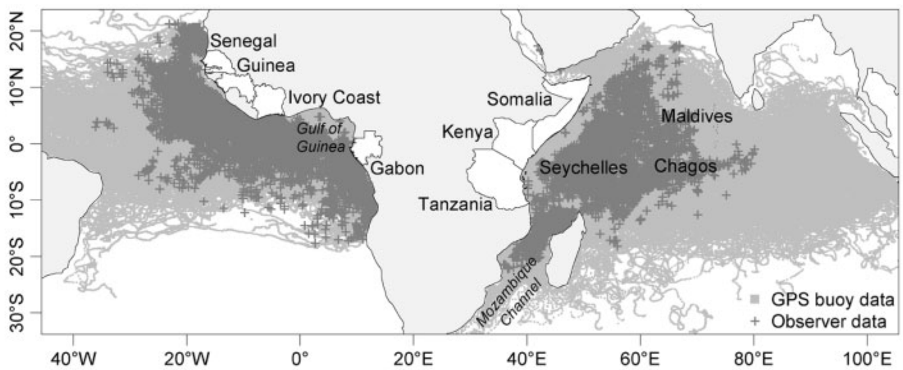

Figure 1. French GPS buoy data (pale grey) and observer data collected onboard French and Spanish vessels from 2007 to 2013 (dark grey).

the Indian Ocean (Chassot *et al.*, 2010) prevented the boarding of observers on Spanish vessels for security reasons and restricted observers on French PS to safer fishing grounds, such as the Mozambique Channel.

Finally, the positions of FOBs equipped with French GPS buoys were available for the Atlantic and Indian oceans. A detailed description of the data coverage and the methodology used to filter and process the data can be found in Maufroy *et al.* (2015) and in Supplementary Material S1. FOB position data used for this study included more than 2 490 000 drifting positions from 14 415 distinct GPS buoys covering the period January 2007 to December 2013. GPS buoy trajectories varied in time length from less than a day to more than a year, with periodicity of position data also varying, but typically being hourly or daily. French GPS buoy positions covered the entire Atlantic and Indian oceans, extending beyond typical tropical tuna fishing grounds (Figure 1). However, as observer data were restricted to fishing grounds, French GPS buoy data were only used within these areas and, therefore, our estimates of GPS-equipped dFADs and logs are limited to purse-seine fishing grounds of the Indian and Atlantic Oceans.

Seasonal trends in dFAD and GPS buoy deployment strategy

French GPS buoy positions data were used to assess seasonal trends in FOB use. We assumed that seasonality in use of GPS buoys by French PS is also representative of other PS fleets, i.e. that French PS deploy GPS buoys in the same areas and with the same seasonality as other PS fleets, though not necessarily in equal numbers or with the same relative spatial distribution. This assumption is supported by similar overall spatial extents of FOB fishing sets for the three fleet types, though Spanish fishing grounds extend beyond French fishing grounds in certain areas (e.g. off Mauritania in the Atlantic Ocean or in the north of Somalia in the Indian Ocean, Delgado de Molina *et al.*, 2014; Chassot *et al.*, 2015).

Seasonal trends in GPS buoy deployment were assessed on basis of the starting positions of at sea trajectories of French GPS buoys. A deployment season was defined as a group of successive months with similar relative spatial patterns of GPS buoy deployments (i.e. density maps of positions where GPS buoys entered the water). Only one of the three French fishing companies provided data for each month of the entire period 2007–2013. To avoid bias, one degree gridded mean monthly density maps of deployments were built using only data from this fishing company. Twofold Pearson correlations between these monthly maps were used in a cluster analysis to determine GPS buoy deployment seasons. Calculations were carried out using the cor and hclust (with Ward clustering) functions in R (Murtagh and Legendre, 2014; R Core Team, 2015). A similar approach was used on densities of FOB fishing sets derived from French logbook data over 2007–2013 to define FOB fishing seasonality. The correlation between French FOB deployment and French FOB fishing was measured using the Pearson correlation coefficient, at the scale of the year

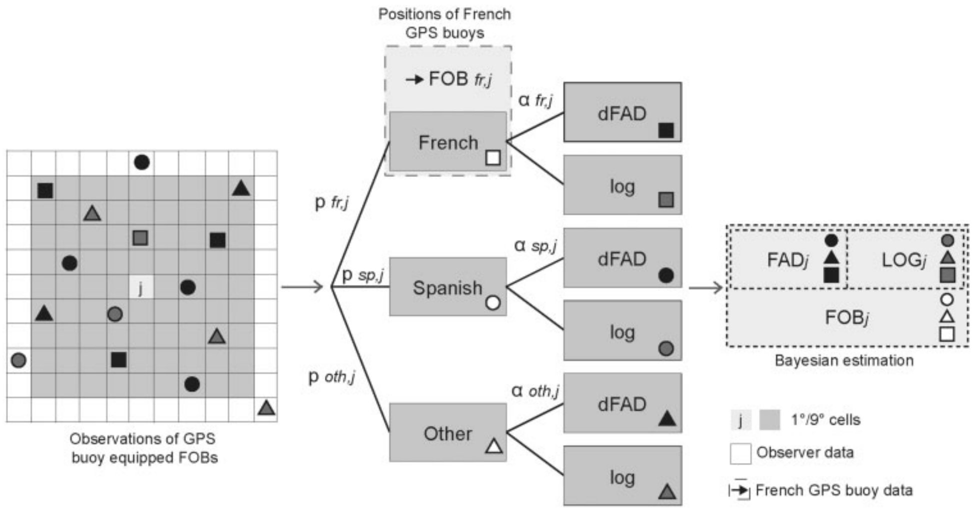

Figure 2. Types of GPS buoy-equipped objects and extrapolation procedure. French GPS buoy data were used to estimate the number of French GPS buoys ($N_{b,fr,i}$) in each 1 × 1 degree cell *i* (dark grey). French and Spanish observer data were used to estimate the proportions of the different types of FOBs in cells of 9 × 9 degrees (pale grey).

and at the scale of the season. Autocorrelograms were calculated on the basis of one degree gridded maps of both FOB deployment and FOB fishing using R package "RGeostats" (Renard *et al.*, 2016). FOB deployment and FOB fishing maps were restricted to areas of activity of PS that is to say to one degree grid cells with observer data. Effective sample size accounting for spatial autocorrelation structures was calculated (Clifford and Richardson, 1985) and used to test the significance of the correlation between FOB deployment and FOB fishing (Dale and Fortin, 2009) under the null hypothesis of correlation ($\alpha = 5\%$). Finally, mean seasonal speed vectors of GPS buoys were represented at the scale of 5° (Supplementary Material S2).

From French GPS buoys to a total number of monitored dFADs

French GPS buoy tracking data only provide information on the number of buoys at sea deployed by French PS (FOB_{fr}) and their location (cell *j*). Therefore, the total number of FOBs can only be calculated from French data if we also know the proportion of all FOBs that are French in each space-time stratum. Observer data from random FOB encounters within fishing grounds provide information on the relative proportion of French ($p_{fr,j}$), Spanish ($p_{sp,j}$), and Other ($p_{oth,j}$) GPS buoys (these proportions satisfying the condition $p_{fr,j}+p_{sp,j}+p_{oth,j}=1$ in cell *j*) through the flag of the buoy reported by observers, and on the proportion of GPS buoy-equipped FOBs from each fleet that are dFADs, as opposed to logs($\alpha_{fr,j}$, $\alpha_{sp,j}$, $\alpha_{oth,j}$). These fleet and FOB type proportions from observer data were combined with French GPS buoy positions data, accounting for spatio-temporal strata, to estimate the total number of GPS buoy-equipped dFADs (*FAD*) and GPS buoy-equipped FOBs (*FOB*) in use in the Atlantic and Indian Oceans during 2007–2013. A detailed, step-by-step presentation of this methodology is provided below.

French GPS buoy tracking data were used to estimate the number of French buoys in a given one degree cell ($FOB_{fr,j}$) at the end of each month or on an annual basis (Figure 2 and Table 2). French GPS buoy trajectories were first linearly interpolated between successive GPS positions to obtain a unique position each day at 00:00 GMT. These positions were aggregated on a 1° grid, and then a density map of French GPS buoys was generated from the number of GPS-buoys in each grid cell *j* on the last day of each month. The last day of the month was used because one of the three French fishing companies deactivated GPS buoys that had been flagged as "lost" by boat captains (i.e. onboard another vessel, beached or outside of fishing grounds) on the first day of each month from December 2011 onward (Sarah Le Couls, CFTO, personal communication). Therefore, using the last day of the month provided a better upper bound for the number of French buoys active within fishing grounds. For simplicity, we will refer to this as the "number of GPS buoys in a given month" even though it really corresponds to the number of active buoys at a precise moment during the month. Though we believe this to be the most accurate methodology, the magnitude of any potential bias in our results because of using the end as opposed to the beginning of each month was estimated by considering the percent decrease in the total number of GPS buoys at the end of the month. The number of buoys in our database decreased on average by 8.6% (s.d. 17.5%) at the end of each month. This decrease had no apparent spatial or temporal trend, and, therefore, would represent an average 8.6% decrease in the total number of estimated buoys if all buoys turned off were classified as in the water at the time they were turned off. This potential overestimation in our FOB counts is likely smaller than the underestimation in the total number of GPS-equipped FOBs caused by being limited to only estimating within fishing grounds given that on average 19.2% of all French "water" GPS-buoy positions during the study period occurred outside of fishing grounds (17.9% in the Atlantic Ocean and 19.8% in the Indian Ocean).

Annual estimates of $FOB_{fr,j}$ in each 1° square were computed as the sum of all French GPS buoys having passed through the 1° cell *j* at some point during the year, with each buoy's contribution to the sum being inversely weighted by the number of cells it visited during the year (so that the total contribution of each buoy to the density map for the year is 1).

Observer data were then used to derive the relative proportions of FOBs of each PS fleet $p_{i,j}$ ($i=$ French, Spanish, and Other) and

Table 2. Data and methodology to estimate the total number of GPS buoy-equipped dFADs (FAD) and GPS buoy-equipped FOBs (FOB).

Step	Data	Spatio-temporal strata	Method and variables
1	French GPS buoy data	1° 1 month/1 year	Total number of French GPS buoys $FOB_{fr,j}$
2	Observer data	9° 2007–2009/2010–2013	Bayesian estimation of the distribution of $p_{i,j}$ and $\alpha_{i,j}$
3	$FOB_{fr,j}$ $p_{i,j}$ and $\alpha_{i,j}$ distributions	whole ocean 1 month/1 year	Raising factor to estimate *FAD* and *FOB numbers*

p is the relative proportion of GPS buoys; α is the relative proportion of GPS buoy-equipped FOBs. *i* and *j* indicate fleet (i.e. French, Spanish, and Other) and spatial cell, respectively.

their relative use of dFADs and logs ($\alpha_{i,j}$) in a given spatio-temporal stratum (Figure 2). Because of the relatively low coverage of French and Spanish fishing trips in observer data and to the lack of observer data for the Spanish PS fleet in the Indian Ocean since 2010, observer data were aggregated over several years so as to have sufficient data in each stratum. The proportions $p_{i,j}$ and $\alpha_{i,j}$ were computed for two distinct periods: 2007–2009 and 2010–2013. The relative proportions of GPS buoys belonging to each fleet were estimated based on observations of GPS buoy-equipped FOBs pertaining to other vessels that were randomly encountered at sea by PS. For example, if two French, two Spanish, and one other GPS buoy-equipped FOBs (not belonging to the observing vessel) were noted by observers in a given spatio-temporal stratum, then the most likely composition of FOBs in that strata was 2/5 = 40% French, 2/5 = 40% Spanish, and 1/5 = 20% Other (see below for how this "most likely" estimate is translated into a probabilistic framework).

Similarly, the relative proportions of dFADs ($\alpha_{i,j}$) versus logs ($1 - \alpha_{i,j}$) equipped with GPS-buoys by the French and Spanish PS fleets were derived from deployments of GPS buoys on new dFADs or FOBs found at sea. This procedure had to be modified for Other PS fleets and for the Spanish PS fleet in the Indian Ocean for the period 2010–2013 because of the absence of onboard observers. In this case, random encounters of non-owned dFADs and logs were used to calculate the proportions $\alpha_{sp,j}$ and $\alpha_{oth,j}$ instead of using deployments.

To avoid spatial gaps and unrealistic spatial gradients, all proportions were calculated over 9 × 9 degree grid cells centred on each of the 1 × 1 cells. Using smaller grid cells led to significantly reduced spatial coverage of observer data and high-spatial variability of the proportions, whereas larger grid cells could mask the spatial variability in the distribution of dFADs and logs (Dagorn *et al.*, 2013a).

Uncertainty in estimates of FOB_j and FAD_j was assessed through a Bayesian procedure to propagate uncertainty in $p_{i,j}$ and $\alpha_{i,j}$ estimates to total numbers of GPS buoy-equipped FOBs and dFADs (see Supplementary Material S3 for details on the procedure and priors). For each period 2007–2009 and 2010–2013 and in each 9 × 9 degree cell, observations of French, Spanish and Other GPS buoys were assumed to follow a multinomial distribution. Bayesian posterior distributions for the parameters (i.e. proportions $p_{i,j}$ and $\alpha_{i,j}$) of multinomial distributions were estimated using the Metropolis–Hastings Markov Chain Monte Carlo (MCMC) algorithm implemented in the function metrop of R package "mcmc" (Geyer and Johnson, 2015) assuming uninformative prior distributions. Convergence of the MCMC algorithm to a stationary posterior distribution was visually evaluated through trace plots and autocorrelation diagnostics. To improve mixing, 4 separate MCMC chains, each with 2500 steps, were used for parameter estimations on each spatio-temporal stratum, so as to obtain 10 000 values of proportions $p_{i,j}$ and $\alpha_{i,j}$. Further details of the estimation procedure can be found in Supplementary Material S3.

The total number of GPS-equipped FOBs in each cell of the grid was finally calculated as follows:

$$FOB_j = \frac{FOB_{fr,j}}{p_{fr,j} \times \varphi} \qquad \text{(Eq. 1)}$$

where φ represents the coverage of French GPS vessels in GPS-buoy tracking data (Supplementary Material S1), $p_{fr,j}$ the relative proportion of French buoys in cell *j* derived fromthe Bayesian estimation procedure, and $FOB_{fr,j}$ the number of French GPS buoys in a given 1 × 1 degree cell *j*. Average values and confidence intervals (CI) (95%) for the total number of GPS buoys were calculated on basis of ensemble averaging over individual proportion estimates from the Bayesian MCMC algorithm described above.

The number of dFADs in a given cell was calculated by multiplying the total number of FOBs by the weighted average (among the different fleets) proportion of dFADs among all FOBs estimated using the Bayesian approach described above:

$$FAD_j = \left(\alpha_{fr,j} \times p_{fr,j} + \alpha_{sp,j} \times p_{sp,j} + \alpha_{oth,j} \times p_{oth}\right) \times FOB_j \qquad \text{(Eq. 2)}$$

The total number of GPS-buoy equipped FOBs (FOB_j) and dFADs (FAD_j) was summed to obtain an estimate per ocean.

Results

Strategies in dFADs and GPS buoy deployment

In the Atlantic and Indian Ocean, the clustering procedure of mean monthly density maps of GPS buoy deployments over 2007–2013 produced four deployment seasons in each ocean (Figure 3). The different seasons were generally more distinct from each other in the Indian Ocean than in the Atlantic Ocean as evidenced by the separations between groups of months in dendogram plots occurring at greater heights in the Indian than in the Atlantic Ocean (Figure 3). Similar seasons were obtained with densities of fishing sets on FOBs, showing that activities of deployment and fishing on FOBs were correlated in time and space (Supplementary Material S2). Correlation between these two types of activity was generally higher in the Indian Ocean (Pearson correlation coefficient of 0.85 at the scale of the year, p-value <0.001) than in the Atlantic Ocean and varied slightly from season to season (Supplementary Material S2 and Supplementary Table S2.1). For example in the Indian Ocean, the

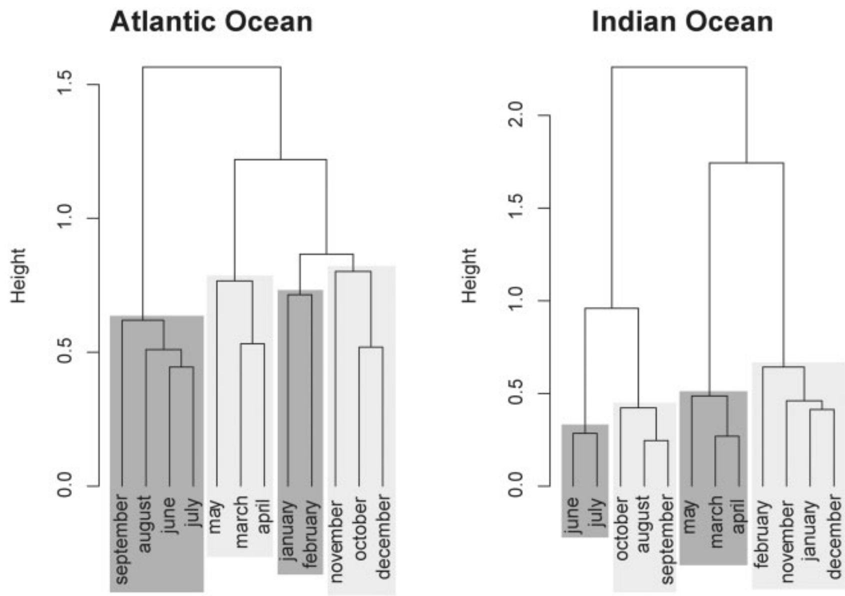

Figure 3. Clusters of months of GPS buoy deployments by the French PS fleet. In each ocean, four different clusters are identified, allowing the detection of four distinct seasons of GPS buoy deployments.

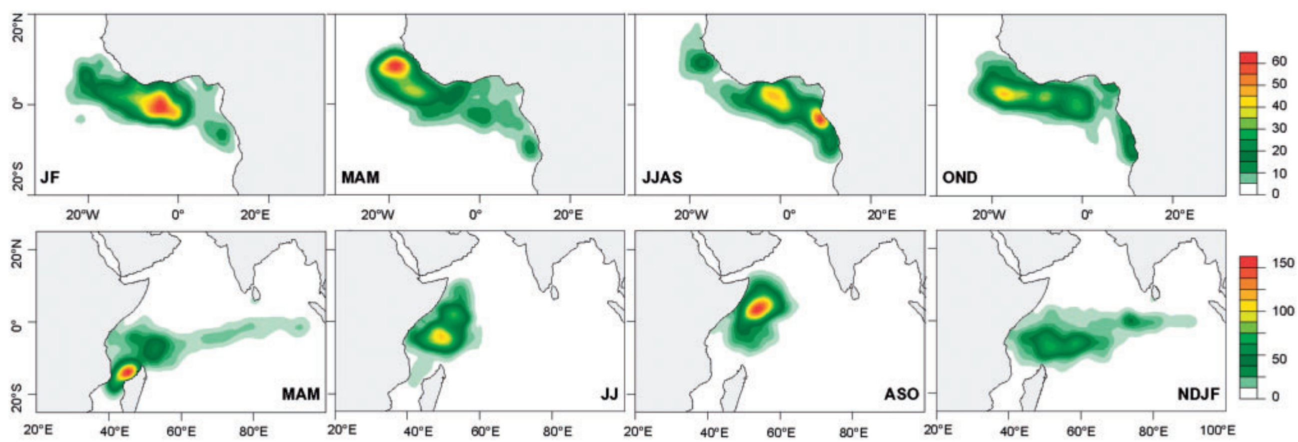

Figure 4. Seasonal density of GPS buoy deployments on dFADs and logs. Maps were smoothed using kde2d function of R MASS package. Top panel: in the Atlantic Ocean. JF, January–February; MAM, March–May; JJAS, June–September; OND, October–December. Bottom panel: in the Indian Ocean. MAM, March–May; JJ, June–July; ASO, August–September; NDJF, November–February.

correlation between deployment and fishing activities was lower during June–July than during any other season. Seasonal deployment patterns were stable whatever the resolution of the analysis (1°, 2°, or 5°), but varied between years (Supplementary Material S2), suggesting that a given deployment season could occur earlier or later depending on the year.

In the Atlantic Ocean, the season June–July–August–September (JJAS) was most distinct (height = 1.56). January–February (JF) and October–November–December (OND) were separated at a relatively low height of 0.83, indicating that these two seasons share common areas of GPS buoy deployments (Figure 3). During the four seasons, French deployments of GPS buoys on FOBs mainly occurred in three areas (Figure 4): Senegal (centered around 9°N, 18°W), Gulf of Guinea (1°N, 2°W), and Gabon (1°S, 7°E). The relative densities of deployments, as well as the extent of these deployment grounds varied from season to season over 2007–2013. From January to March, PS progressively moved from the Gulf of Guinea (2°N, 3°S/18°W, 2°E) northwest to deployment grounds off Senegal (11°N, 6°S/22°W, 16°W). From June to September, GPS buoy deployments were relocated to the southeast and mainly occurred off Gabon (2°S, 8°S/4°W, 4°E). Finally, from October to December, they covered the whole Gulf of Guinea and extended westward along the Equator. Throughout the year, these deployments of GPS buoys occurred relatively close the Western Coast of Africa.

In the Indian Ocean, four seasons were detected: March–April–May (MAM), June–July (JJ), August–September–October (ASO), and November–December–January–February (NDJF). During these four seasons, GPS buoy deployments moved clockwise on four distinct deployment grounds: the Mozambique Channel area from March to May (12°S, 18°S/41°E, 48°E), the West Seychelles deployment ground from June to July (7°S, 1°S/

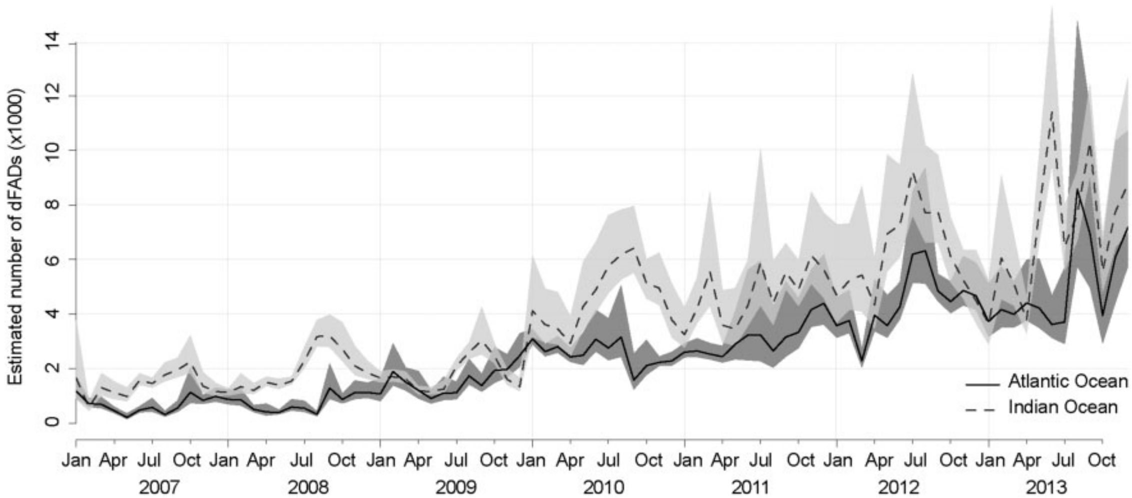

Figure 5. Estimation of the total number of GPS buoy-equipped dFADs in the main purse seine fishing grounds of the Atlantic (solid line) and Indian (dashed line) oceans, at the end of each month (2007–2013).

46°E, 53°E), the Somalia deployment ground (3°N, 12°N/50°E, 60°E) from August to October and finally the Southeast Seychelles deployment ground (5°S, 10°S/51°E, 62°E) from November to February (Figure 4). Though these GPS buoy deployment grounds were more distinct than those of the Atlantic Ocean, secondary zones of deployment also appeared in some seasons (e.g. North West Seychelles from March to May).

In both oceans, GPS buoys available to PS to monitor FOBs were mainly used to track dFADs as indicated by the proportions of dFADs versus logs among GPS buoy-equipped FOBs over 2007–2013. The proportion of dFADs increased over time in both oceans, suggesting that fewer logs or more dFADs were being equipped with GPS buoys. The dFAD proportion was somewhat higher for Spanish and Other fleets than for the French fleet [0.95, 95% CI (0.90; 0.98) for the Spanish PS fleet and 0.88, CI (0.77; 0.95) for the French PS fleet after 2010] and in the Atlantic Ocean [0.95, CI (0.94; 0.97) in the Atlantic Ocean and 0.91, CI (0.87; 0.95) in the Indian Ocean after 2010]. In the Indian Ocean, there was a generally decreasing gradient of dFAD proportion among buoy-equipped FOBs from the North to the South and the East to the West of the ocean that followed main paths of oceanic currents. The Mozambique Channel area has a relatively high proportion of logs, with an average proportion of logs of 0.46 [CI (0.17; 0.65)] over 2007–2009 and 35% logs [CI (0.18; 0.66)] over 2010–2013. This was also the case around the Chagos Archipelago and the Maldives. In the Atlantic Ocean, two zones with a relatively higher prevalence of logs were observed in the area of influence of the Niger (around 8°N–18°W) and the Congo (around 2°S–7°E) rivers. In these zones, the proportions of logs averaged 0.14 [CI (0.03; 0.42)] and 0.09 [CI (0.02; 0.27)] over 2010–2013.

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

In both oceans, the number of GPS buoys per French vessel continuously increased over 2007–2013. In the Atlantic Ocean, August 2007 was the month with the lowest use of GPS buoys with 14 GPS buoys per vessel. These numbers reached 65 GPS buoys per French purse seiner in December 2013. French PS of the Atlantic Ocean have increased their use of GPS buoys by a factor of 5.5 (s.d. 2.8) over the period 2007–2013. In the Indian Ocean, the use of GPS buoys by the French fleet ranged from 14.2 GPS buoys in February 2007 to a maximum of 80.5 GPS buoys per vessel in September 2013. On average over 2007–2013, French PS of the Indian Ocean have multiplied their use of GPS buoys by a factor of 5.8 (s.d. 1.2).

The strong observed increase in French use of GPS buoys is mirrored in our estimate of the number of GPS buoys used by all fleets (Figure 5; Supplementary Material S3, Supplementary Table S3.1). In the Atlantic Ocean, it is estimated that 1174 dFADs [CI (909; 1692)] and 1289 GPS buoys [CI (1001; 1852)] were in use in January 2007. In 2013, these numbers reached maximums of 8575 dFADs [CI (5748; 14 110)] and 8856 GPS buoys [CI (5964; 14 487)] at the end of August. On average, the monthly use of dFADs by all fleets was multiplied by 7.0 [CI (2.65; 12.5)]. Though the seasonality was less obvious than in the Indian Ocean, there was generally a low season in the use of dFADs by all fleets from May to August and a higher level of use during the rest of the year. Estimated numbers of dFADs were generally higher for the Spanish fleet than for all other fleets. For example, during 2013, the Spanish, French, and Others PS fleets are estimated to have accounted for 74.3, 8.3, and 17.4% of the dFADs drifting in the Atlantic Ocean.

In the Indian Ocean, October was the main month of FOB use in 2007 with 2252 dFADs [CI (1840; 3138)] and 2679 GPS buoys [CI (2165; 3820)]. This number increased to reach 10 307 dFADs [CI (9083; 12 444)] and 10 929 GPS-buoy equipped FOBs [CI (9631; 13 234)] at the end of September 2013. On average, this represented an increase of a factor 4.2 [CI (1.6; 8.92)] in the use of dFADs by all PS fleets. There was a stronger seasonality in the use of dFADs in the Indian Ocean than in the Atlantic Ocean. A primary peak in the use of dFADs was generally observed from August to September, when PS fleets concentrate their activities off the coast of Somalia. During certain years, this peak began earlier in the year (e.g. June-July in 2012 and 2013, Figure 5) as PS prepared for the Somalia season by deploying new dFADs and new GPS buoys off the coasts of Kenya and Tanzania. A secondary peak was also observed from March to May, as PS operate mostly in the Mozambique Channel area. Again, the Spanish PS fleet used more dFADs (87.5% in 2013) than the French fleet (10.2%) and non-European PS fleets (2.3%).

Discussion

In recent years, because of growing concern regarding the state of tropical tuna stocks and pelagic ecosystems, tuna RFMOs have implemented dFAD management plans. However, because of missing exhaustive information on dFAD and GPS buoy use, it is still difficult to identify changes in FOB fisheries and to measure their magnitude. Here, for the first time, spatially explicit time-varying estimates of the total number of FOBs used by all fleets, as well as the uncertainty in this estimate, have been obtained via an extrapolation based on combining information from multiple datasets. Results indicate that the number of dFADs deployed in the Atlantic and Indian Oceans increased by factors of 7.0 and 4.2, respectively, over the period 2007–2013. This major increase in dFAD use over the last decade has been previously hypothesized (Davies *et al.*, 2014; Fonteneau and Chassot, 2014), but not verified until now. The present study underlines the need for detailed information on dFAD use of all fleets for improved evaluation of the impacts of dFADs and management of tropical tuna fisheries.

Strategies in dFAD and GPS buoy deployment

Seasons of GPS buoy deployment identified here are consistent with previous studies of FOB deployment and fishing (Hallier and Parajua, 1999; Ariz *et al.*, 1999; Ménard *et al.*, 2000; Kaplan *et al.*, 2014; Torres-Irineo *et al.*, 2014). For the French fleet, deployment and fishing on FOBs were correlated in time and space, indicating that PS deploy dFADs and GPS buoys where they are actively fishing, with a few exceptions. In the Indian Ocean for instance, the correlation is lower during June-July, when fishers deploy dFADs and GPS buoys off Tanzania and Kenya to use them later off Somalia. A large proportion of these deployments may occur during GPS buoy transfers (i.e. replacements of foreign GPS buoys), except for PS benefiting from a support vessel, which may be able to anticipate French GPS buoy deployment seasons by a few weeks. Preliminary information on GPS buoy deployments available from Seychelles support vessels suggests a separation in space and time between PS and their associated support vessels (Assan *et al.*, 2015). Future estimates of dFAD use should include information from support vessels when it becomes available to complement the data used in the present study.

Spatio-temporal patterns of GPS buoy deployments also allow us to draw inferences regarding how fishers use oceanic currents to deploy new dFADs and GPS buoys (Supplementary Material S2). In the Atlantic Ocean, GPS buoys were generally deployed east of 20°W in the South Equatorial Current, closer to the coast than in the Indian Ocean. The strong westward currents that are active throughout the year in the Atlantic (Ariz *et al.*, 1999; Philander, 2001) were probably avoided to reduce the risk of losing dFADs and GPS buoys (Maufroy *et al.*, 2015). In the Indian Ocean, a similar behaviour was observed during the season NDJF with respect to the eastward South Eastern Counter Current (Schott *et al.*, 2009), which is capable of rapidly transporting FOBs to the east of the Indian Ocean, where they may beach on the coasts of the Maldives, Chagos, or Indonesia (Maufroy *et al.*, 2015). During the rest of the year, Indian Ocean PS targeted the rich waters of the eddies of the Mozambique Channel (Sætre and Da Silva, 1984) and of the upwelling zone off Somalia (Sætre and Da Silva, 1984; Shankar *et al.*, 2002). In this study, because of data availability, the use of currents for GPS buoy deployments could only be examined with data aggregated on 2007–2013, and at the scale of 5°. In the future, FOB drift could be modelled using ocean surface currents and used in Lagrangian numerical simulations (e.g. Ichthyop, Lett *et al.* 2008) to understand how skippers anticipate the drift of their FOBs.

Estimating the use of FOBs in the Atlantic and Indian oceans

Our estimates for the total number of dFADs are generally consistent with previous estimates of dFAD and GPS buoy use for specific years and oceans. In the Indian Ocean, Moreno *et al.* (2007) estimated that there were approximately 2100 dFADs at sea in 2007 at any given moment. For 2007, our monthly estimates for the Indian Ocean ranged from 590 in February [CI (455; 808)] to 2252 in October [CI (1840; 3138)]. At the annual scale, we estimated the number of dFADs and GPS buoy-equipped FOBs used to be 7050 and 8550, respectively, in 2009 (Supplementary Material S3), when Baske *et al.* (2012) estimated that there were 7600 dFAD deployments for the same year. In the Atlantic Ocean, Ménard *et al.* (2000) suggested that more than 3000 radio buoys could have been used in 1998. If this is the case, our estimate of 2600 dFADs and 2700 GPS buoys in 2007 is consistent with the decrease in the number of PS in the Atlantic that occurred between 1998 and 2007 (Delgado de Molina *et al.*, 2014). Furthermore, it was estimated that 9000 dFADs were deployed in the Atlantic Ocean in 2010 (Baske *et al.*, 2012), which is close to the 9500 dFADs and 9800 GPS buoys we estimated for the same year (Supplementary Material S3). However, any comparisons between our results and other estimates should be considered cautiously as they often do not represent equivalent measurements. For example, the number of "dFAD deployments" estimated by Baske *et al.* (2012) is not precisely equivalent to our annual or monthly instantaneous estimates of the number of active dFADs.

Though these estimates are consistent with previous knowledge, the use of observer data, covering 3–45% of French and Spanish fleets (Supplementary Material S1) and the absence of observers aboard Spanish vessels in the Indian Ocean after 2010 because of piracy off Somalia (Chassot *et al.*, 2010), limited the number of observations of GPS buoy-equipped FOBs. This explains to a large extent the relatively high level of variability and uncertainty in our estimates. In particular, the amount and the quality of the information available in observer data varied between observed fishing trips, either because of a lack of experience of the observer or because of few detections of FOBs by the vessel. As there was no reason to believe that some vessels are more skilled at finding dFADs from one fleet than another or log vs dFADs, this should only affect the level of uncertainty in our estimates, because of reduced number of observations. Furthermore, data limitations prevented assessment of possible inter-annual changes in the relative proportions of GPS buoys of each fleet, as well as intra-annual variability in the amount of logs introduced to the ocean because of seasonality in river discharge (Ariz *et al.*, 1999). Finally, PS of one of the French fishing companies have been remotely deactivating GPS buoys drifting too far from fishing grounds, onboard another vessel or otherwise inaccessible to the fishery on the last day of each month since December 2011. In each ocean, this produced considerable fluctuations in the total number of French GPS buoys between the end of a given month and the beginning of the next month (on average 8.6%, s.d. of 17.5%). Therefore, we used French GPS buoy data at the end of each month as a reasonable proxy for the number of French buoys inside fishing grounds although this choice might result in some overestimation. However, to put this potential bias in perspective, note that our results do not account for those GPS-buoy equipped FOBs that drift outside the main purse seine fishing grounds. On average 19.2% of French GPS-buoy "water" positions during 2007–2013 were outside fishing grounds, suggesting that our "fishing grounds" calculations underestimate the total number of GPS-equipped FOBs in both oceans by a similar percentage. These FOBs outside fishing grounds generally do not contribute to overall fishing effort of the fleet, but they still have potential to negatively impact marine ecosystems (see below).

Assessing the impacts of dFAD and GPS buoy use

Our results demonstrate that dFADs are now the dominant form of FOB in all PS fishing areas of the Atlantic and Indian Oceans. Even in relatively "dFAD-free" zones, the level of habitat modification through the use of dFADs is high and increasing in recent years. For example, in the Mozambique Channel of the Indian Ocean, the introduction of dFADs may have increased the numbers of FOBs by 110% (Dagorn *et al.*, 2013a, b) to 270% (our results). dFADs may impact coastal and pelagic ecosystems via a number of mechanisms, such as overfishing (Dagorn *et al.*, 2013b; Fonteneau *et al.*, 2013), ghost fishing (Filmalter *et al.*, 2013; though non-entangling dFADs are increasingly used by the European PS fishery, e.g., Franco *et al.*, 2012; Goñi *et al.*, 2015), coastal habitat destruction if they become marine debris (Balderson and Martin, 2015; Maufroy *et al.*, 2015), disturbance to tuna spatial distributions (Marsac *et al.*, 2000; Hallier and Gaertner, 2008) and alteration of schooling behaviour (Sempo *et al.*, 2013). Combined with bycatch, ghost-fishing and/or echo-sounder buoy data, our estimated densities of FOBs could be used to assess these potential dFAD impacts. This would represent a considerable improvement over the extensive speculation, but little concrete evidence, surrounding a number of these impacts (e.g. the potential for an ecological trap effect).

Finally, purse-seine fishing effort in the Atlantic and Indian Oceans has been modified by not only the increasing number of GPS-buoy equipped FOBs, but also the increasingly sophisticated technological means aboard tuna PS (Torres-Irineo *et al.*, 2014), the introduction of echosounder GPS buoys capable of assessing FOB-associated tuna aggregations in real time (Lopez *et al.*, 2014), and the increasing use of support vessels (Chassot *et al.*, 2015). For a better evaluation and management of the tropical tuna PS fisheries, the collection of dFAD information through dFAD management plans should be reinforced and collaboration with fishermen would be required, as in this study. In particular, detailed information on the use of FOBs by all purse seine fleets would be necessary for a precise evaluation of the contribution of GPS buoy-equipped FOBs to overall fishing effort and fishing capacity of tropical tuna PS.

Supplementary data

Supplementary material is available at the ICESJMS online version of the manuscript.

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