AGGREGATION PROCESSES OF TUNA UNDER DRIFTING FISH AGGREGATING DEVICES (DFADS) ASSESSED THROUGH FISHER'S ECHOSOUNDER BUOY IN THE INDIAN OCEAN

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SUMMARY

The aggregative behavior of tuna around floating object is widely exploited by the industrial purse-seine fishery, which deploy thousands of floating objects each year in all oceans in order to improve their catches. These fish aggregating devices (FADs) are generally equipped with echosounder buoys that can collect acoustic data, conferring to these devices the status of privileged observation platforms for the fish communities that aggregate. Using a classification model based on supervised learning algorithms trained on M3I buoy data, we were able to translate the acoustic data collected along the trajectories of 5748 drifting FADs newly deployed between 2016 and 2018 in the Indian Ocean into presence or absence of tuna aggregation. Analysis of the resulting time series indicated that drifting FADs are colonized by tuna aggregation over an average of 39 days. The results also revealed, for the first time, that the residence time of a tuna aggregation around a single DFAD is about 6 days and that DFADs spend on average 9 days without tuna. After colonization, DFADs appear to be occupied by tuna aggregation about 43 % of their soaking time. Finally, we showed that these metrics can manifest spatial and temporal variations.

KEYWORDS

Echosounders, Drifting fish aggregating devices (FAD), Tropical tunas, Behaviour

1. Introduction

Understanding the mechanisms underlying tuna aggregation processes around floating objects currently constitutes an undeniable requirement for the development of sustainable conservation and management measures for tropical tuna fisheries. Indeed, the majority of the world's tuna catches are ensured by purse seine fishing (Galland et al., 2016), which is itself largely based on the use of fish aggregating devices (Fonteneau et al., 2013; Miyake et al., 2010). This effectiveness is a result of the several advantages offered by fishing under drifting fish aggregating devices (DFADs) compared to that targeting school of free-swimming tunas. DFADs can significantly increase the proportion of successful sets or purse seiners (Fonteneau et al., 2000). For instance, during the period from 1990 to 2015, less than 10 % of fishing operations carried out on DFADs by Spanish purse seiners fleet in Indian ocean, resulted in null sets (unsuccessful attempts in capturing), against 42% for sets on free-schools (Soto and Fernandez, 2016). DFADs are also equipped with technological instruments to locate them and

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detect the possible presence of fish (Lopez et al., 2014). By providing purse seiners with this real-time remote information, they allow the elaboration of more productive exploration pathways, thus contributing to an increase in fishing efficiency (Suuronen et al., 2012).

DFADs technology exploits a peculiar behavioural trait of pelagic marine species (including the three main tropical tuna species), which leads them to gather in mass around floating objects at sea. However, although several studies have addressed this topic, the mechanisms behind this aggregation processes are still poorly understood (Fréon and Dagorn, 2000). The low accessibility on information directly collected on DFADs, represents one of the main causes of shortcomings. The recent availability of location and acoustic data collected by the echosounder buoys that equip most of the deployed DFADs represents an unprecedented opportunity to study the different aspects of the ecology and behaviour of fish associated with floating objects. The present paper examines the colonisation and aggregation processes of tuna around floating objects, based on the analysis of acoustic data provided by commercial echosounder buoys that equip DFADs. Different metrics describing the aggregation process of DFADs by tuna species are estimated: colonization time, lifetime of a tuna aggregation, time between two tuna aggregations, as well as their spatial and temporal variability. These metrics constitute a novel contribution to the understanding of the aggregation processes and a key step towards the exploitation of echosounder buoys data for tuna resource management.

2. Material and methods

2.1. Data Collection

We considered the data collected by Marine Instruments[3] buoys (Marine Instruments, Nigrán, Spain, www.marineinstruments.es) instrumenting the DFADs of the French fleet, hosted by Ob7/IRD. The study focused on acoustic data collected on DFADs by the M3I buoy model, from 2016 to 2018, in the Indian Ocean. This buoy is equipped with GPS positioning device, and an echosounder powered by solar panels, operating at a frequency of 50 kHz, with a power of 500 W, and a beam angle of 36° (**Figure 1**). It provides acoustic information recorded in layers of 3 m, over a detection depth of 150 m (50 layers, the first two corresponding to the transducer blank zone). The acoustic data is processed by the buoy into discrete indices ranging from 0 to 7, basically intended for visual interpretation by fishermen (Figure 1). For each acoustic sample, the data are also processed by an internal buoy algorithm to provide an abundance index of the sampled biomass.

2.2. Data cleansing process

Data were first pre-processed according to the procedure described by Baidai et al. (2017) and Orue et al. (2019a). Duplicated rows, aberrant and erroneous location data (related to failures in satellite communication), data recorded under low voltage conditions, data on land or at shallow positions (depth less than 150 meter, the echosounder detection range) have been discarded from the dataset. Then, a simple-rule based algorithm using buoy speed and its variations as main classifiers (Baidai et al., 2017) was applied to discriminate acoustic data recorded when the buoy is on board a ship from those actually recorded on the water.

[3] The mention of trade names or companies is for identification purposes only and does not imply any commercial interest of the authors.

2.3. Classification of tuna presence-absence

The absence or presence of tuna under DFADs was assessed from acoustic data, using the methodology described by Baidai et al. (2018). This approach is based on a preliminary processing of the acoustic data recorded during a full day (24 hours) of sampling, followed by a classification based on the random forest algorithm. Data preliminary processing consists of clustering the acoustic data sampled by the buoy over 6 temporal bins of 4-hours and 6 aggregated-depth layers, which summarize the daily acoustic information into a 6 × 6 matrix referred to as "daily acoustic matrix". The classification of tuna presence/absence was then carried out on a daily basis, using random forest algorithms trained from acoustic data recorded on DFAD deployments and visits without fishing sets (labelled as tuna absence), and positive fishing sets (labelled as tuna presence). The strong performance in characterizing aggregations under DFADs (with overall accuracy of 87 % in the Indian Ocean, see Baidai et al, 2018), supported the use of this classification method.

Finally, a post-processing step to improve the predictions made by the classification models on the DFAD trajectories was applied. To this purpose, short-term predictions (isolated single days of presence or absence) were considered unlikely, attributed rather to misclassification, and corrected with the previous or next prediction value. This stage allowed the revision of 7.41 % of the initial predictions made by the classification model.

2.4. DFAD deployments dataset

Virgin DFAD deployments were identified from two datasets: fishing logbooks and observers on-board purse-seine fishing vessels of the French fleet, between 2016 and 2018 in the Indian Ocean. To ensure that they truly corresponded to newly deployed DFADs, data for which fishing sets were reported during the week following the deployment were removed from the dataset. This dataset was combined with the echosounder database, using the unique buoy identification code and the deployment date.
Furthermore, the following cleansing operations were applied to the dataset in order to:

(i) Discard data with inconsistent positions between the location of DFAD deployment registered in logbook or observer database, and the actual position recorded by the buoy.
(ii) Exclude time series of acoustic data, where gains different from 1 were used, since classification models were only calibrated for acoustic data recorded on gain equal to 1;
(iii) Consider only time series with a minimal length of 30 days.

The final dataset consisted in 5748 newly deployed DFADs in the Indian Ocean (**Table 1**). The tuna presence/absence time series were obtained for each DFAD by applying the classification algorithm on the echosounder data explained above.

2.5. Soak Time and Colonization time

Soak time is here defined as the number of days at sea between the deployment of a pair DFAD-buoy, and the first operation reported on it (fishing sets or buoy retrieval from sea). Tuna colonization time refers to the number of days between the deployment of a virgin DFAD and the first day of presence of a tuna aggregation.
Variability of DFAD soak times in the dataset constituted a bias for directly estimating the average value of tuna colonization time. Namely, since the number of available DFADs-buoy

pairs at sea strongly decreases in time (due to fishing and buoy retrievals), longer colonization times are less likely to be observed (**Figure 2**). This results in underestimating the colonization time using a simple arithmetic average. To overcome this bias, we estimated daily colonization times based on the daily colonization rates, considering the daily fraction r_i of DFADs colonized relative to the available DFADs for each day *i* after deployment, see (**Eq.1**):

$$r_i = \frac{colonized\_DFAD_i}{colonized\_DFAD_i + not\_colonized\_DFAD_i} \qquad \text{(Eq.1)}$$

Where, $colonized\_DFAD_i$ and $not\_colonized\_DFAD_i$ respectively denote for a day *i*, the number of DFADs colonized (after deployment), and the number of DFADs not colonized (namely, the DFADs not yet colonized, nor retrieved from the water). The mean colonization time ($\bar{t}$) was then estimated as the inverse average colonization rate $\bar{r}$:

$$\bar{t} = \frac{1}{\bar{r}} \qquad \text{(Eq.2)}$$

Where $\bar{r}$ denotes the average daily colonization rate estimated according to the following equation:

$$\bar{r} = \frac{1}{D}\sum_{i=1}^{D} r_i \qquad \text{(Eq.3)}$$

Where D represents the number of days at which 30 DFADs are still available (i.e., not colonized and not retrieved). This threshold was based upon a preliminary sensitivity analysis that demonstrated that for too low numbers of available DFADs, the rate of (**Eq.1**) becomes less reliable. In our estimates, D corresponded to 120 days.

2.6. Aggregation metrics

In the FAD literature "Continuous residence times" (CRT) are commonly referred to as the duration of residency of tagged tuna individuals at FADs without day scale (>24h) absences (Ohta and Kakuma, 2005, Capello et al. 2015). This metric was adapted at the scale of the aggregation to assess the residence times of tuna aggregations at DFAD. Accordingly, we considered *aggregation continuous residence times* (aCRT) as the time during which tuna aggregations are continuously detected at the DFAD without day scale (>24h) absence. In a similar way, we also considered *aggregation continuous absence times* (aCAT) as the continuous period of time that a DFAD spends without tuna aggregation (**Figure 3**). Values located immediately at the start (corresponding to colonization times) and the end of the trajectories (potentially truncated by the activity on the DFAD or the buoy), were excluded from the analysis. A total of 12 962 aCATs and 14 934 aCRTs were measured along the trajectories of the newly deployed DFADs (**Table 2** and **Table 3**). Finally, the proportion of tuna occupancy time was calculated as the ratio of the sum of all aCRTs measured under a DFAD, relative to its total soak time, after the colonization period.

2.7. Influence of spatio-temporal factors

To account for potential seasonal differences in the aggregation process around FADs, deployment data were grouped according to the seasonality in DFAD deployments, highlighted by Maufroy et al. (2017): from November to February, March to May, June to July and August to October. We also explored the possibility of spatial patterns, dividing the initial deployment sites based on the biogeographic partition of the global ocean proposed by Longhurst (2007). DFAD deployments considered in the study covered mainly three Longhurst provinces: the

Indian South subtropical gyre (ISSG), the Eastern India coast (EAFR), the Northwest Arabian Sea upwelling (ARAB) and the Indian monsoon gyre (MONS) with respectively 0.33 %, 0.43 %, 5.25 % and 93.98 % of the dataset (see **Table 1** and **Figure 4**). Due to their limited number, deployment data located in ISSG and EAFR were not analyzed. The MONS province constituted the zone with the highest number of DFAD deployments, covering regularly all seasons. aCRT, aCAT and proportion of occupation time were assessed and compared through the Kruskal-Wallis tests, by seasons and the Mann-Whitney test, by deployment areas.

3. Results

3.1. Colonization times

Daily colonization rates exhibited a stable trend (see **Figure 5**). The average colonization time of a DFAD by tuna in the Indian Ocean was estimated through **Eqs. (1-3)** at 38.98 days (SD 14.09) (**Table 4**). Northwest Arabian Sea upwelling (ARAB) province was characterized by a longer colonization time (mean 41.49 SD 39.27) than Indian Monsoon gyre province (mean 36.44 SD 18.87) – see **Table 5**. On the other hand, excepted the November-February seasons, which were marked by faster colonization of FADs by tuna aggregations, the other seasons were characterized by relatively close values of colonization time (**Table 6**).

3.2. Aggregation continuous residence (aCRT) and absence times (aCAT)

The distributions found for both aCAT and aCRT are shown in **Figure 6**. In average, tuna aggregations continuously stayed at the DFADs (aCRT) during 6 days (SD 6.62), with a maximum value recorded at 109 days under the same DFAD. The average time spent by a DFAD without tuna aggregation (aCAT) was estimated at 9.68 days (SD 12.07), with a maximum value of 120 days. No significant influence of the deployment locations or seasons were found on these two metrics (**Figure 7**).

3.3. Proportion of tuna occupancy

After being colonized, newly deployed DFADs in the Indian Ocean remained occupied by tuna aggregations on average 43.34 % (SD 22.17 %) of their soak time, with little spatial and seasonal differences (**Figure 8).**

4. Discussion

4.1. Colonisation process of DFADs

Previous studies on colonization time of DFAD by tuna have yielded a wide range of results. Very fast colonization of DFADs by tuna (ranging from 1 hour to 6 days) has been reported in the Atlantic Ocean, by Bard et al. (1985). Recently, in the Indian Ocean, Orue et al. (2019b) have found that tuna arrive under DFAD around 12 days after their deployment. More generally, fishermen consider that the waiting time for the first tuna school around a FAD would generally be in the range of 22 days (Macusi et al., 2017), to around one month (Moreno et al., 2007). Our work, using data collected on DFADs by a widely used buoy model, estimated average colonization times of 39 days in the Indian Ocean. This discrepancy with previous results could rely on the new methodology used for estimating colonization times, that avoid the possible bias (underestimation) due to the decreasing number of DFADs available as a function of time. It could also derive from sensitivity of the buoy model used in the detection of tuna aggregation. Indeed, acoustic data from this device were translated into presence or absence of tuna aggregation, using a classification method based on a supervised learning. The algorithm was trained from acoustic data sampled on purse seine catches under DFADs (considered as presence of tuna aggregation) and deployments as well as DFADs visits without fishing set (considered as tuna absence). The term aggregation refers here to the minimum value of the tuna biomass of the model's learning data set (1 ton). Supplementary analyses assessing the accuracy of detection of the presence of different aggregation sizes of tuna under FADs revealed that the buoy model used was less accurate in distinguishing the presence of tuna for small tuna schools under FADs (**Figure 9**). This may be related to several factors such as the position of the school in relation to the measuring instrument, the intrinsic sensitivity of the detection of the buoy itself (which may vary depending on the depth of the acoustic target), environmental characteristics, etc. This detection bias could therefore be likely to overestimate the colonization times. Further studies using other buoy models will be required to confirm these results

4.2. Aggregation stability

This work is the first to exploit the potential of echosounder buoys in the assessment of key metrics that describe the behaviour of tuna around drifting FADs at the scale of the aggregation. It introduces two new metrics into the study of tuna aggregation dynamics around the DFAD. The first describes the time during which a FAD does not host any tuna aggregation after being colonized: aCAT (aggregation continuous absence time). This parameter was estimated at about 9 days in the Indian Ocean. The second was adapted from the concept of continuous residence time of tuna individuals around FADs (CRT) first defined by Ohta and Kakuma (2005). It measures the continuous amount of time that tuna aggregations spent around a DFAD : aCRT (aggregation continuous residence time), estimated around 6 days in the Indian Ocean. Despite the fact that it is not yet possible to determine the tuna species constituting the detected aggregation, our findings remain consistent with those of previous tagging studies (Ohta and Kakuma, 2005; Dagorn et al., 2007; Robert et al., 2012; Matsumoto et al., 2014; Matsumoto et al., 2016; Rodriguez-Tress et al., 2017). These studies evidenced that tuna departures from FADs were usually not all simultaneous (Dagorn et al., 2007; Weng et al., 2013), and that some fish can replace others (Matsumoto et al., 2014). This would imply that the continuous time during which a FAD is occupied by a tuna aggregation should therefore be longer than the time spent by a single tuna individual under a FAD. Incidentally, similarly to the colonization times, it is possible that the estimated aCRT and aCAT may depend on the buoy sensitivity to detect smaller aggregation, which would result in underestimating the aCRT and overestimating the aCAT.

5. Conclusion

This study highlights the potential of echosounder buoys data for characterizing the tuna dynamics around drifting FADs. Although these data may have some limitations, they have enabled in the present work, to measure for the first time different metrics that characterize tuna aggregations under floating objects. Integrating these metrics into population assessment models that account for the associative behaviour of tuna, will allow deriving fisheries-independent abundance indices for tropical tuna and also to construct reliable scenarios on the impacts of FADs on tuna populations.

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TABLES

Table 1. Number of deployment per locations and seasons in Indian Ocean (ISSG: Indian South subtropical gyre, EAFR: Eastern India coast, ARAB: Northwest Arabian Sea upwelling, MONS: Indian monsoon gyre).

	Nov.-Feb.	Mar.-May	June-July	Aug.-Oct.	Total
ISSG	5	9	5	0	19
EAFR	0	13	12	0	25
ARAB	50	53	67	132	302
MONS	1208	1596	963	1635	5402
Total	1263	1671	1047	1767	5748

Table 2. Number of aCRT measured per deployment locations and seasons in Indian Ocean

	Nov.-Feb.	Mar.-May	June-July	Aug.-Oct.	Total
ARAB	85	142	167	208	695
MONS	3218	4524	1682	2854	14145

Table 3. Number of aCAT measured per deployment locations and seasons in Indian Ocean

	Jan-Fev	Mar-May	Juin-Sept	Oct-Dec	Total
ARAB	91	164	189	251	602
MONS	3642	5129	1956	3418	12278

Table 4. Summary of tuna aggregations metrics measured in Indian Ocean

	Min.	Max.	Median	Mean	Standard deviation
DFAD Soak time	30	363	68	77.84	42.01
Daily colonization rate	0	0.087	0.025	0.026	0.011
Tuna colonization time	-	-	-	38.98	14.09
aCAT	2	120	5	9.68	12.07
aCRT	2	109	4	6.00	6.62
Proportion of occupation time	2.02	98.08	41.67	43.34	22.17

Table 5. Mean and standard deviation (into brackets) of aggregation metrics per deployment locations (MONS: Indian monsoon gyre; ARAB: Northwest Arabian Sea upwelling).

Deployment locations	Colonization time	aCAT	aCRT	Proportion of occupation time
MONS	36.44 (18.87)	9.52 (11.92)	6.32 (8.06)	43.36 (22.13)
ARAB	41.49 (39.27)	9.68 (12.09)	5.98 (6.56)	43.16 (2329)

Table 6. Mean and standard deviation (into brackets) of aggregation metrics per deployment seasons

Deployment seasons	Colonization time	aCAT	aCRT	Proportion of occupation time
Nov.-Feb.	27.72 (17.00)	8.49 (10.60)	6.76 (7.98)	47.19 (22.47)
Mar.-May	39.20 (24.15)	9.93 (12.36)	5.89 (5.93)	42.90 (21.74)
Jun.-Jul.	41.35 (25.19)	10.47 (13.54)	5.83 (7.06)	41.97 (22.23)
Aug.-Oct	40.63 (27.51)	10.09 (12.07)	5.48 (5.66)	41.69 (22.08)

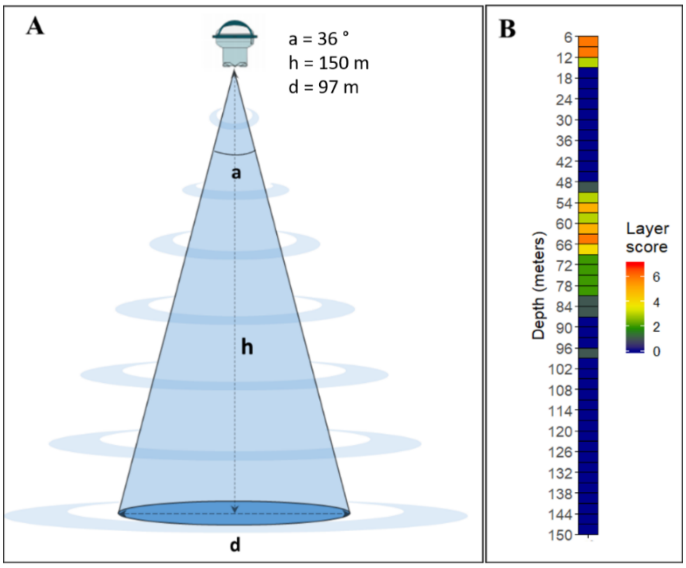

Figure 1. Technical specifications of M3I marine instruments buoys

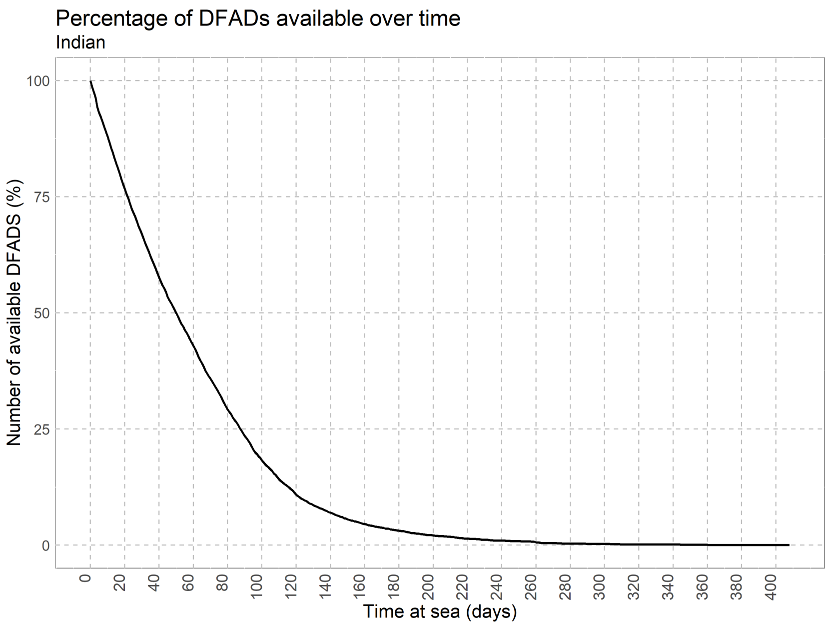

Figure 2. Percentage of DFAD-M3I buoy pairs available over time in Indian Ocean

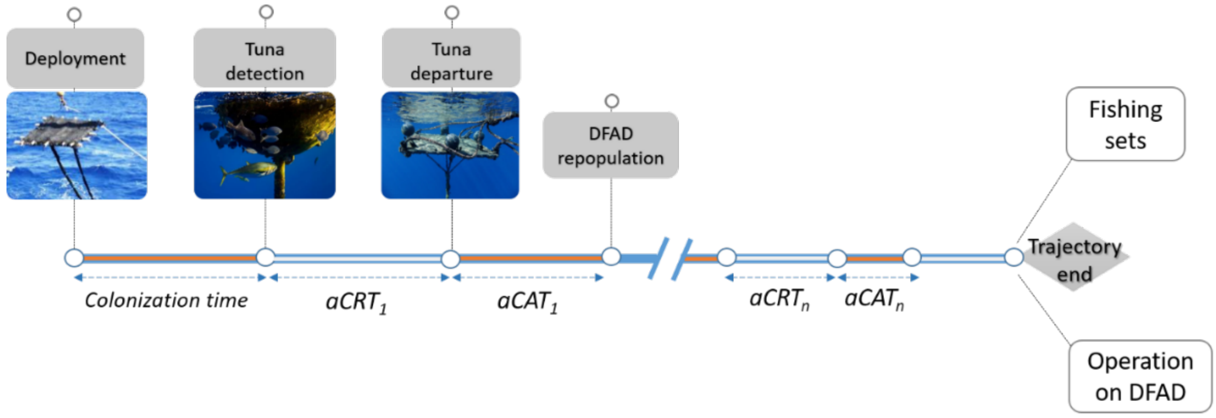

Figure 3. Schematic representation of aggregation process under DFAD

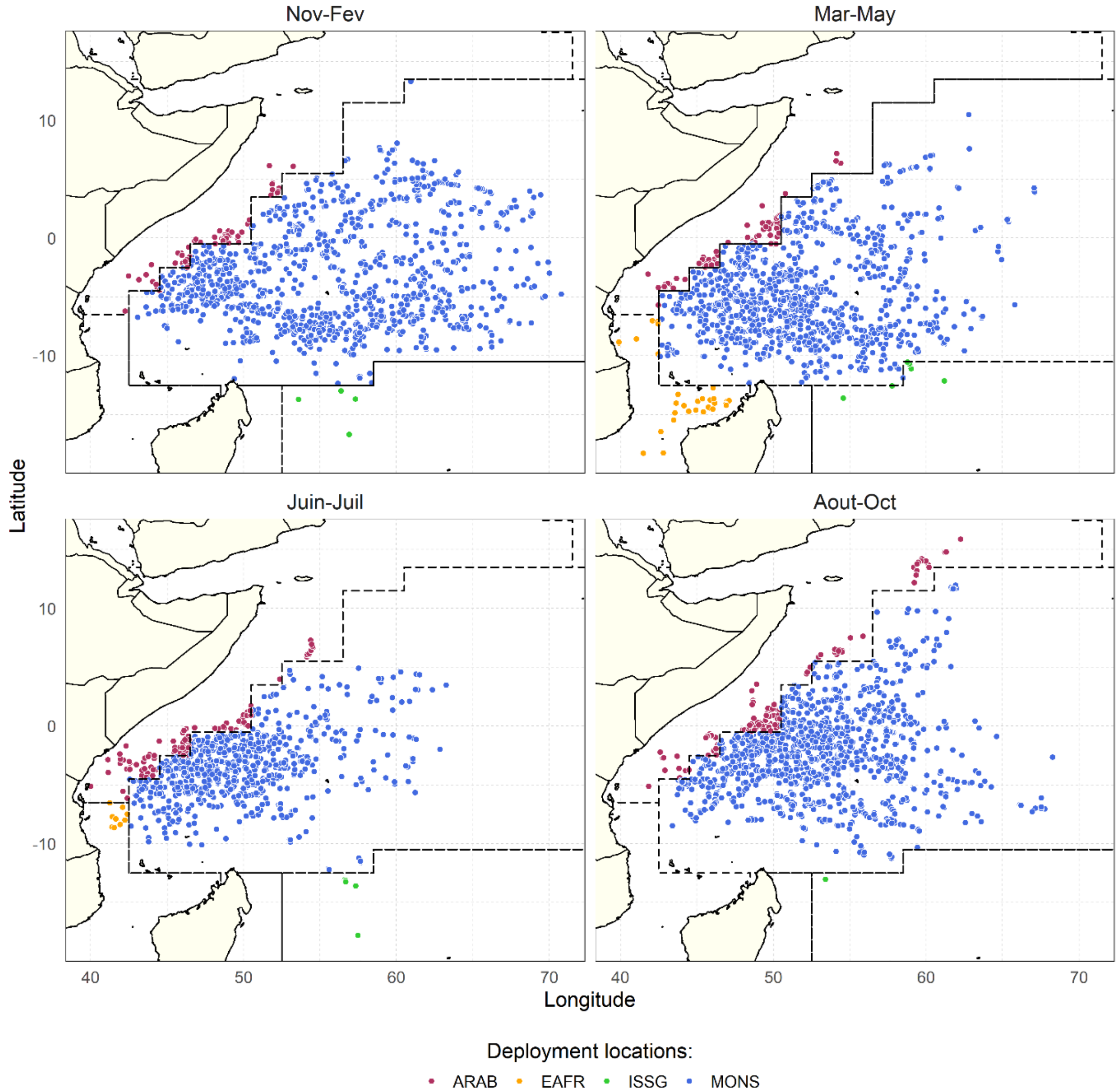

Figure 4. Spatial and seasonal distribution of deployment of French DFADs equipped with M3I echosounder buoys over 2013-2018.

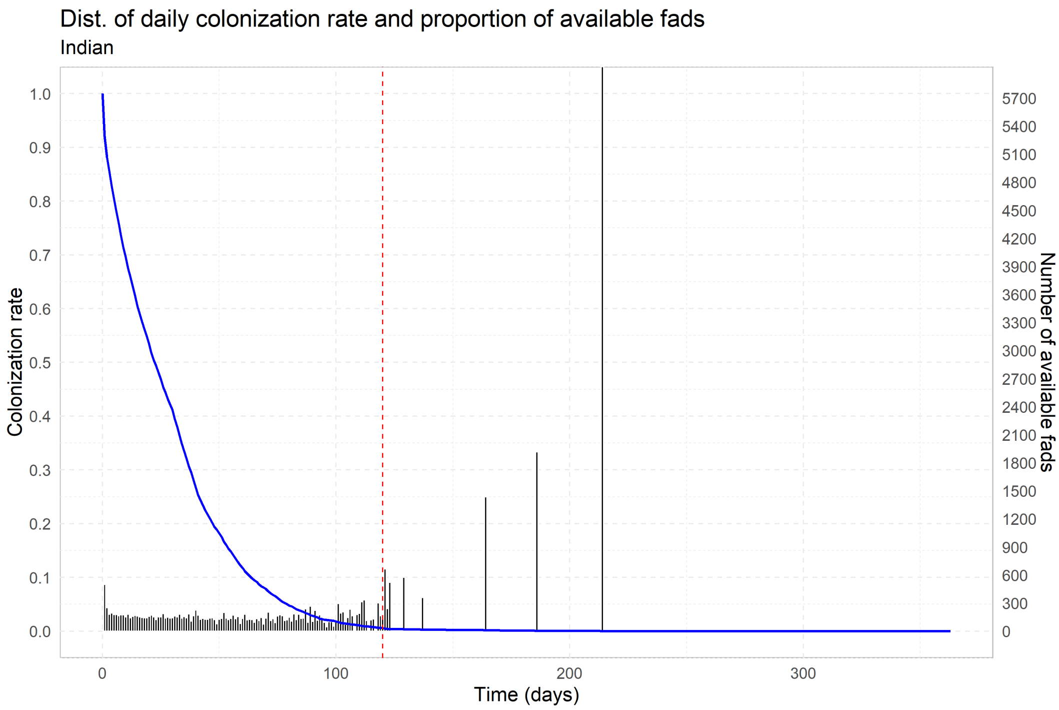

Figure 5. Daily colonization rate (bars) and number of available DFADS (line) over time in the Indian Ocean.

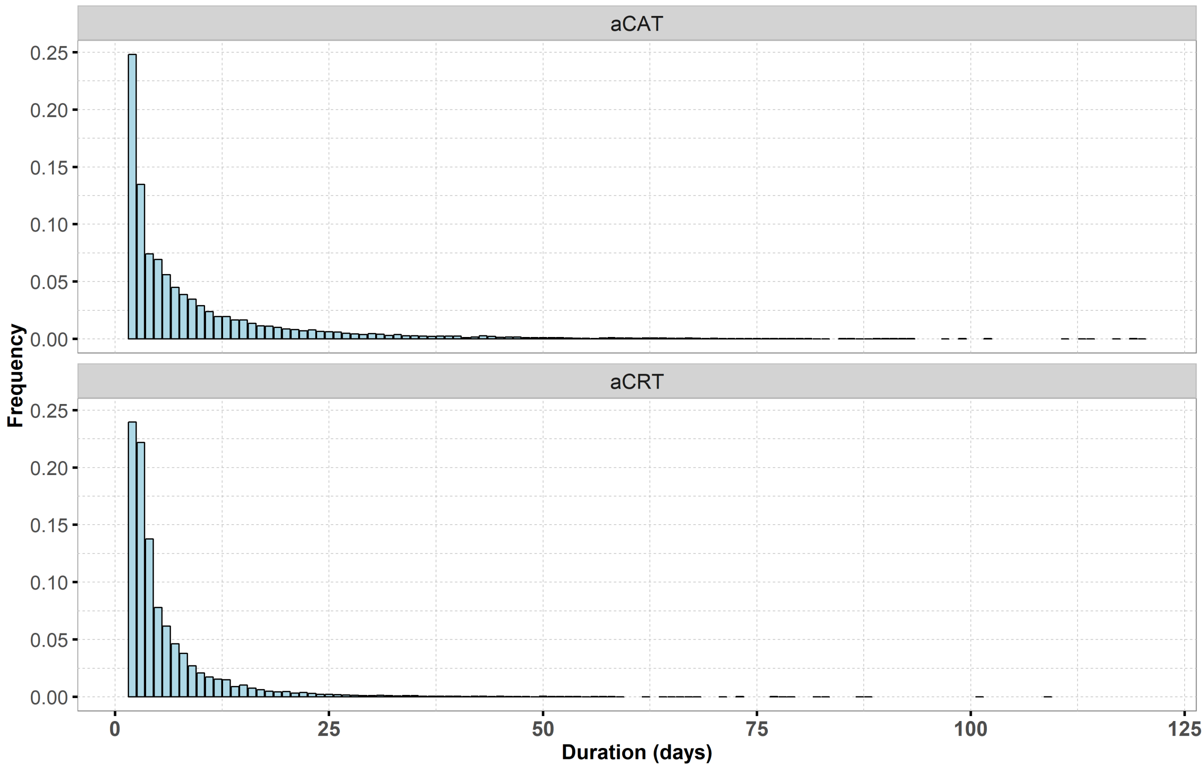

Figure 6. Distribution of aggregation continuous absence times (aCAT) and aggregation continuous residence times (aCRT).

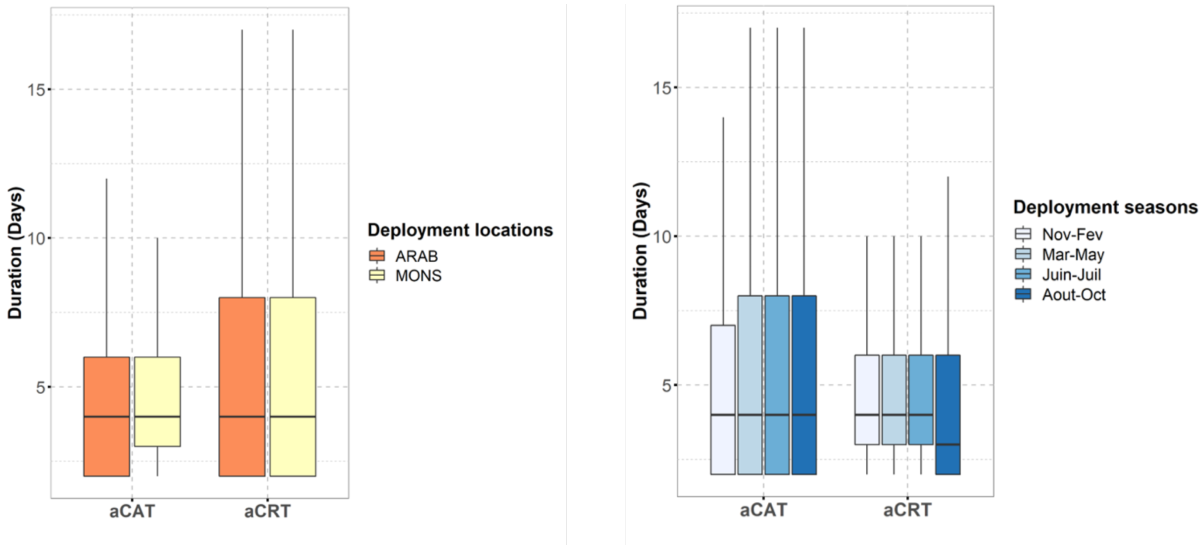

Figure 7. Boxplots of aggregation continuous absence times (aCAT) and aggregation continuous residence times (aCRT) by deployment locations (A), and seasons (B).

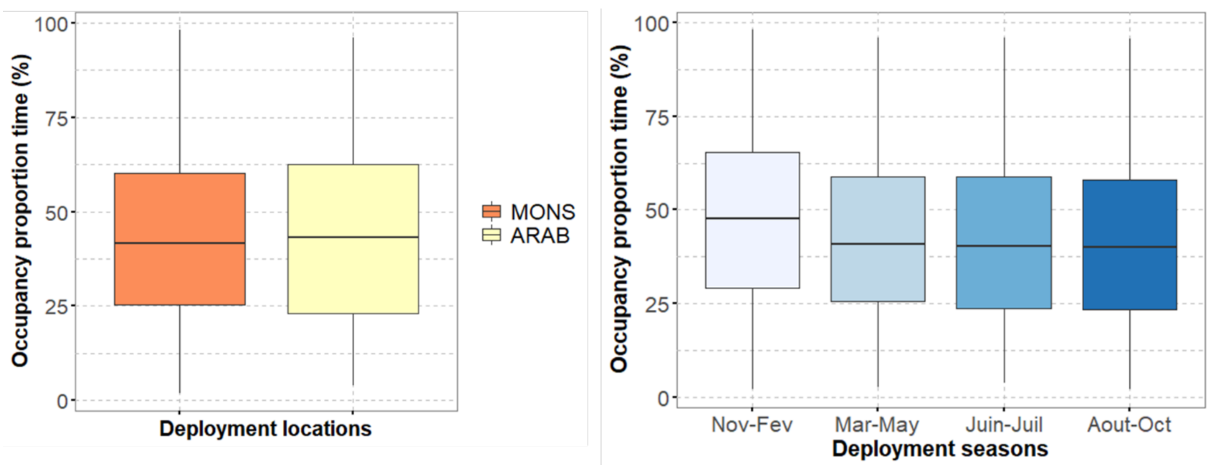

Figure 8. Boxplots of proportion of occupation time by deployment locations (A), and seasons (B)

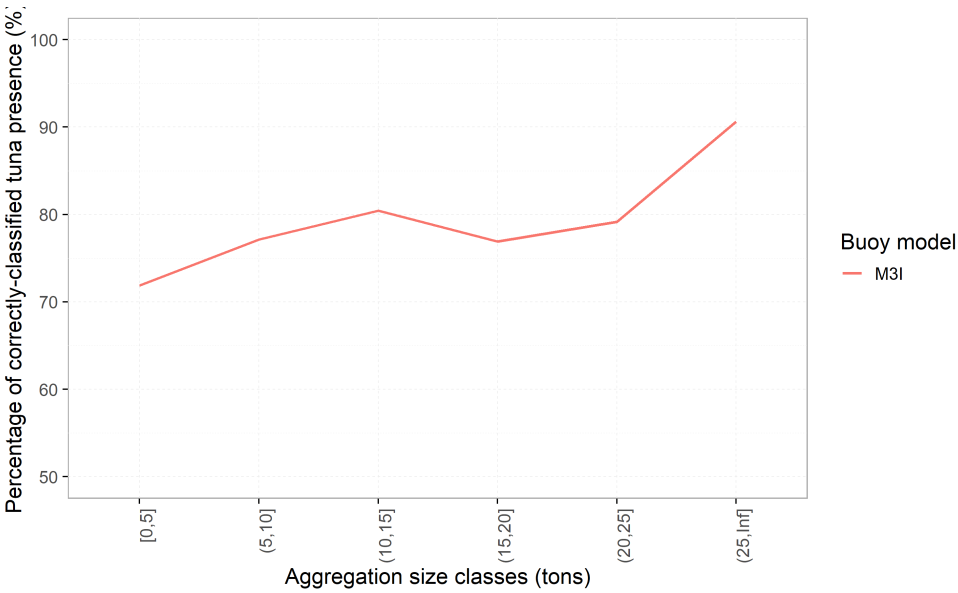

Figure 9: Sensitivity of buoy detection performance according to different aggregation size classes in Indian Ocean. The classification model trained with data from 2016 to 2018, data was tested on acoustic data recorded on the 2019 catches.