First look at the distribution of deactivated dFADs used by the French Indian Ocean tropical tuna purse-seine fishery

Wencheng Lau-Medrano, Daniel Gaertner, Francis Marsac, Loreleï Guéry, David M Kaplan

ICES Journal of Marine Science, 2024, Vol. 0, Issue 0, 1–8
https://doi.org/10.1093/icesjms/fsae104
Received: 6 March 2024; **revised:** 11 July 2024; **accepted:** 12 July 2024
Food for Thought

ICES CIEM
International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

First look at the distribution of deactivated dFADs used by the French Indian Ocean tropical tuna purse-seine fishery

Wencheng Lau-Medrano [1,2,*], **Daniel Gaertner** [1,2], **Francis Marsac** [1,2], **Loreleï Guéry** [3,4], **David M. Kaplan** [1,2]

[1]MARBEC, University of Montpellier, CNRS, Ifremer, IRD, 34203 Sète, France
[2]Institut de Recherche pour le Développement (IRD), Av. Jean Monnet, 34203 Sète, France
[3]CIRAD, UMR PHIM, 34394 Montpellier, France
[4]PHIM, University of Montpellier, CIRAD, INRAE, Institut Agro, IRD, 34394 Montpellier, France
*Corresponding author. UMR MARBEC, Institut de Recherche pour le Développement (IRD), av. Jean Monnet, CS3017, 34203 Sète Cédex, France. E-mail: luis.laum@gmail.com

Abstract

The presence of abandoned, lost or otherwise discarded fishing gears, including drifting fish aggregating devices (dFADs), in marine ecosystems poses significant ecological and socioeconomic concerns. The estimation of the number of dFADs in the marine environment is challenging due to the loss of tracking information when dFAD tracking buoys are remotely deactivated. For the first time, a data set of dFADs buoy positions, including those that had previously been remotely deactivated, has been made available for the period July–August 2020. Data from this period provide valuable insights into the life expectancy, spatial distribution, and status of deactivated dFAD buoys, enabling a more accurate assessment of dFAD presence and impacts. Deactivated buoys represented a 17.2% increase in the total number of tracked objects, and we estimate the in-water half-life of deactivated dFAD tracking buoys to be 101 days. Including deactivated buoys increases the number of strandings during the SP by 23.7%. Nevertheless, the representativity of these results is unknown given the limited spatio-temporal and numerical extent of our data, highlighting the importance of availability of comprehensive data on dFADs to effectively estimate their total numbers and mitigate their environmental impacts.

Keywords: distributions; deactivated; dFADs; Indian Ocean; marine litter; floating objects; industrial fishery; skipjack tuna

Introduction

There is considerable concern regarding abandoned, lost or otherwise discarded fishing gears (ALDFGs) due to their potential for negative ecological and socioeconomic impacts (Gilman 2015). As a result, there are a number of continuing efforts to estimate their amount and their impacts on various marine and coastal ecosystems (Wang et al. 2014, FAO 2019a), as well as to reduce their numbers in aquatic environments (FAO 2019b). In this regard, the work of Gilman et al. (2021) lists the main sources of ALDFG with respect to their relative risk score, noting that the third most important is drifting fish aggregating devices (hereafter dFADs). DFADs are typically constructed of bamboo, canvas, or metal rafts, subsurface netting and/or ropes, and plastic floats or balsa wood for added flotation (Imzilen et al. 2022), and they are deployed very extensively by tropical tuna purse seine fisheries, in order to take advantage of the natural aggregation behavior of marine fish species around floating objects (Hallier and Parajua 1992, Escalle et al. 2021). A GPS-tracking buoy/beacon is attached to each dFAD, sending with an ∼hourly to daily periodicity GPS position information and other buoy data via satellite to the buoy manufacturing company, which in turn organizes and distributes this information to vessels and/or fishing companies tracking the dFAD (Zudaire et al. 2023). These devices are actively used in tropical tuna fisheries globally to facilitate catch of object-associated tuna schools and have impacts on marine ecosystems (Gaertner et al. 2016, Pons et al. 2023), such as high catch of juvenile yellowfin and bigeye tunas, higher bycatch rates of non-target species compared to fishing on free-swimming schools (i.e. fish schools not associated with any floating object), potential for habitat perturbation or creation of an ecological trap (Marsac et al. 2000, Hallier and Gaertner 2008, Dupaix et al. 2024), and risk of dFAD stranding on beaches or shallow sensitive marine environments like sea grasses and coral reefs (Imzilen et al. 2021, MacMillan et al. 2022). dFAD use has also recently been the subject of extremely contentious debates at the Indian Ocean Tuna Commission (IOTC) due to environmental concerns, growth overfishing issues, and competition for access and harvest of tuna resources among different fishing fleets and gears (Pons et al. 2023).

One major challenge is to estimate the number of dFADs. In this regard, several studies have estimated the number of deployed (Fonteneau et al. 2015, Maufroy et al. 2017, Lennert-Cody et al. 2018, Escalle et al. 2021), lost and abandoned (Escalle et al. 2021, Imzilen et al. 2022), and stranded dFADs (Zudaire et al. 2018, Imzilen et al. 2021) worldwide. Although the estimation methods are varied and use different sources of information and statistical approaches, most of them suffer from an important weakness: estimates are incomplete as they do not include information on dFAD tracking buoys remotely deactivated by fishers. GPS-equipped, satellite-transmitting buoys are attached to deployed dFADs, and data provided by these buoys allow fishers to track their position and scientists to quantify their distribution and impacts. These buoys can be remotely deactivated by fishers for a number of reasons, including (i) when the dFAD is no longer in a fishing zone of interest, (ii) when it has been recovered by another fishing vessel, (iii) immediately before or after stranding, or (iv) post location data loss, e.g. due to sinking of the dFAD or malfunction of the buoy. Deactivation stops the communication via satellite of position and other information normally transmitted by tracking buoys to the buoy owners and, indirectly, scientists and others monitoring dFAD distributions. This action of de-registering the buoy from the satellite system does not stop the buoy from transmitting data to the satellite network as long as the buoy has not been physically switched off, which can only happen through a direct physical interaction with the buoy. Due to this information loss, most studies counting numbers of dFADs must acknowledge that the estimates are minima, potentially biased due to underestimation in certain spatio-temporal zones and/or only correspond to "active" dFADs. As remote reactivation of tracking buoys is prohibited by most or all tuna regional fisheries management organizations (IOTC 2017, IATTC 2021), these deactivated dFADs are generally permanently lost from the tracking database. In this context, any information that can be obtained on the number, distribution, and life cycle of deactivated dFADs' buoys is extremely important for understanding the accuracy of dFAD counting exercises and fully quantifying a variety of dFAD impacts.

Between 18 July and 7 August 2020, one of the main suppliers of dFAD tracking buoys temporarily allowed transmission of dFAD positions from all their turned-on buoys for the French fleet in the Indian Ocean, even those that had been previously deactivated. Though the position data of these deactivated buoys were not transmitted to any purse seine vessels, they were included in the data provided to scientists. This specific time interval is hereafter referred to as the "special period" (SP) due to the appearance of (deactivated) buoy tracking data not transmitted to any fishing vessels. This data set provides a unique, though short-lived and partial, view of the life expectancy, spatial distribution, and status of deactivated dFAD buoys, essential information for quantifying the true total prevalence of dFADs in the marine environment.

The aim of the present work is 3-fold: (i) to assess the numbers of deactivated buoys within the Indian Ocean between January 2020 and the end of the SP (7 August 2020), (ii) to understand the fate of deactivated dFADs and the reasons for their deactivation, and (iii) to estimate in water dFAD life expectancy after deactivation (i.e. until permanent loss due to sinking or equipment failure). These analyses provide essential baseline information for correcting estimates of dFAD use, strandings, and loss statistics for the effects of remote deactivation and point toward the value of wider access to tracking data from deactivated dFAD buoys.

Methods

Available data

DFAD tracking data in this paper correspond to tracking buoys from one of the buoy manufacturers used by the French tropical tuna purse seine fleet in the Indian Ocean from January to August 2020. Position data for 2019 are not available, though 2020 data at times include buoy deactivation dates from 2019.

The tracking buoy attached to the dFADs allows the owner to perform some actions remotely, such as modulating the signal transmission periodicity or deactivating signal transmission, which implies that vessels tracking the dFAD no longer receive buoy location information. During the SP (18 July 2020–7 August 2020), dFAD position information included not only the positions of active buoys, but also those for which vessels had previously requested the end of transmission of buoy information to them.

To analyze these deactivated buoy positions, we assembled three complementary data sets:

- **Buoy position data for 2020:** GPS coordinates (buoy ID, longitude, latitude, and date–time) for all transmitting buoys from the buoy manufacturer used by the French purse seine fleet in the Indian Ocean from 1 January 2020 to 7 August 2020 (end of the SP). Position records are often spaced at regular intervals (e.g. one position per hour); however, there are records with irregular intervals that may extend from a few minutes up to a day. All position records were classified as on board a vessel or in the water using the classification algorithm detailed in the supplementary material of Imzilen et al. (2021).
- **Stranded buoys:** A list of stranding events for each buoy is included in the previous data set. This data set includes reference information of time and position of the start and end of every stranding event. The stranding periods were estimated based on the classification model developed by Imzilen et al. (2021), although without including a filter that did not consider those buoys lacking (in water) position data prior to the start of the stranding period as this filter would remove all deactivated buoys only observed to be stranded during the SP.
- **SP buoys:** A list of the buoys that were previously deactivated, but nevertheless reported position information during the SP that was not transmitted to any fishing vessel. This data set includes details regarding the deactivation event (date–time, position) and its stranding status before and during the SP.

Data filtering

The first set of analyses focused on counting the number of buoys that were classified as either SP buoys (i.e. buoys that logged position information during the SP that was not transmitted to any fishing vessel) or stranded buoys (buoys that had stranding events either at the time of their deactivation or at the start of the SP if they were SP buoys). Buoys that were deactivated before the start of the SP were analyzed, and a distinction was made between buoys that were deactivated "on board" a vessel and those that were deactivated remotely (i.e. when the buoy was "in the water"). For the survival analyses, we only considered buoys that were deactivated while in the water, did not reactivate after they were deactivated (which would indicate an interaction with a fishing vessel), and that met exactly the theoretical categories proposed and described in the next section.

Survival analysis and half-life

From the information on buoy deactivations and their reappearance or not in the SP, an analysis was carried out to estimate the in water life expectancy of dFADs tracking buoys after deactivation, the interest being in understanding how long these objects remain in the surface marine environment, representing a risk for stranding and/or other environmental

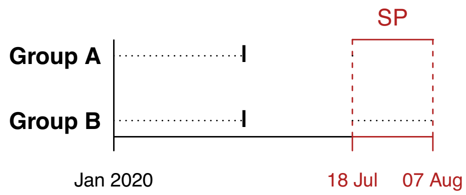

Figure 1. Two distinct groups of dFAD buoy timestamp history, each representing a scenario employed in the survival analysis. The *X*-axis denotes the timeline from January 2020 to the end of the SP (7 August), while the *Y*-axis presents a hypothetical example for each group, with each small dot representing a GPS recording. For Group A, no records were observed during the SP (expressed in red on the figure), implying that their disappearance occurred between their deactivation date (represented as small and vertical bold lines, "|") and the start of the SP. In contrast, Group B dFADs have position information not transmitted to any fishing vessel during some part or the entirety of the SP.

impacts and having the potential to transmit their position information for scientific and/or clean-up purposes. The analysis was carried out using the formalism of a simple Cormack–Jolly–Seber mark-recapture model (Schwarz 2001, Kaplan et al. 2017), where the marking date for each buoy corresponded to that of its deactivation and the SP served as the recapture period. It was observed that each individual deactivated buoy could be categorized into one of the following two groups (Fig. 1):

- **Group A**: Those buoys that did not have position information during the SP, so it was assumed that they sank or the tracking buoy stopped functioning for some reason (e.g. buoy equipment failure or being physically turned off by a vessel recovering the buoy) sometime between deactivation and the start of the SP.
- **Group B**: Those buoys that either (i) have position information during the SP, but this data stops before the end of the SP period, so it was assumed that they disappeared at a specific time in the SP and therefore their date of "death" is known, or that (ii) kept emitting signal (position information) during the entire SP, so it was assumed that their sinking or stranding occurred after the end of the SP.

Based on these two scenarios, we calculated the mean life expectancy of dFADs tracking buoys post deactivation based on survival (Group B) or not (Group A) of tracking buoys from deactivation to the start of the SP. A table was prepared with one row for each day between 1 January 2020 and the start of the SP (18 July 2020), and columns containing the total number of buoys deactivated on the given day, the proportion of survivors (i.e. the number of buoys that started providing position information again during the SP with respect to all that were deactivated on a given day), and the difference (in days) between the given day and the start of the SP. Subsequently, a binomial GLM (Generalized Linear Model) was applied considering the proportion of survivors as the response variable, the number of days as the predictor variable, and the total number of buoys per day as the offset. The *y*-intercept of the model was set to zero, and the link function was set to "log" so that the model represents pure exponential decay of the number of survivors.

The concept of half-life refers to the amount of time it takes for the probability of an event (such as "death") to reach 50%. It is a measure of the median time it takes for a certain event to occur in a population under study, and it is commonly used to examine the decay or duration of a certain condition or phenomenon. Based on our exponential decay model for deactivated dFAD tracking buoy survival, we calculated the half-life of these objects in the marine environment.

It is important to note that the term "death" in the context of this work refers to when a buoy stops emitting GPS signals by natural forcing, i.e. without human intervention (direct or remote) from a deactivation event. Though the survival analyses in this paper assume an absolute relationship between the "death" of a buoy and its associated dFAD, in practice, this is not entirely true for multiple reasons. First of all, there are cases where a buoy may be separated from its associated dFAD by external fishers and subsequently brought ashore, who may decide to turn it off manually (if they know how to do it) or leave it on and bring it ashore so that its owner or someone from the same company can reclaim it and use it again. Also, fishers from the same fishing company who deployed the dFAD buoy may take it and place it on another dFAD so that the buoy's GPS signal can continue to function (emitting) even though the original associated dFAD is no longer the same. On the other hand, there is also the possibility that due to natural causes a buoy becomes separated from its dFAD. At present, there is no documented estimate of the amount of the proportion of each of these cases, so for the present work, it has been assumed that the buoy-dFAD association is fully maintained, and the word "death" refers to the sinking and/or degradation of individual buoy-dFADs.

Deactivations and stranding events

One objective of our analysis is to understand why buoys are deactivated and to what extent deactivations are related to stranding events preceding or shortly after deactivation, the latter potentially biasing estimation of the number of dFAD strandings. For this analysis, only buoys classified as stranded whether at deactivation or at the first records within the SP, were selected. In addition, a comparative analysis of the distance to the coast between on-board and in water deactivated buoys was made, for which the variable Distance to Nearest Coastline was obtained from the PacIOOS project (OBPG and Stumpf 2012). To determine the possible motivations for deactivation events and the association between seabed depth and stranding periods, an assignment of bathymetry values to each buoy position was made using the GEBCO global bathymetry data set (GEBCO Bathymetric Compilation Group 2023).

Numerical tools

All analyses were performed using R version 4.4.0 (R Core Team 2024) with the *dplyr* (Wickham et al. 2023) and *tidyr* (Wickham et al. 2024) packages for data pre-processing and sorting, the (default) *stats* package for fitting GLMs, the *survival* (Therneau 2024) package for fitting survival curves and *ggplot2* (Wickham 2016) and *graphics* packages for plotting results. The GIS analyses were carried out using the tools of the *terra* (Hijmans 2024) and *sf* (Pebesma and Bivand 2023) packages.

Results

From the beginning of 2020 to the end of the SP, 1717 buoys were recorded in our data set. Of these, 387 (22.5%) were in the deactivated state at the start of the SP and 228 (13.3%)

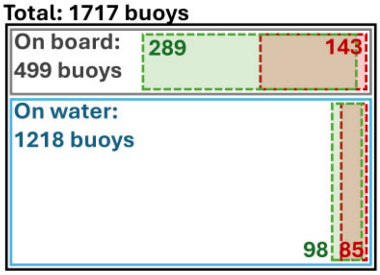

Figure 2. Comparison between the number of total buoys available (1717) and those that were classified as being in the water at the start of the SP and immediately before their final deactivation preceding the SP (1218). The green polygons and numbers represent those buoys that were deactivated at the start of the SP, while for each group, the red ones are those that were identified as SP buoys. Note that it is possible for SP buoys to not be in the deactivated state at the start of the SP if they were deactivated during the SP.

were identified as SP buoys (Fig. 2). SP buoys represented on average a 17.2% increase in the daily number of transmitting buoys during the SP.

If we consider only buoys that were classified as being in the water at the start of the SP and immediately before their final deactivation preceding the SP (if any) so as to exclude all buoys that had signs of interacting with fishing vessels shortly before deactivation or during the SP, we have 1218 buoys in our data set from the beginning of 2020 to the end of the SP, of which 98 (8.0%) were deactivated at the start of the SP. Of these, 85 (7.0% of all in water buoys) were identified as SP buoys (Fig. 2), representing an average daily increase of 11.8% in the number of in water transmitting buoys during the SP.

Of the 387 buoys that were deactivated between January 2020 and the start of the SP, 90 (23.3%) of them were deactivated in water, and 39 (43.3%) of them ended up stranded (the other 51 buoys not appearing during the SP, found drifting during the SP, or found to be onboard a vessel).

The median distance to the coast of the deactivations that occurred on board was 238 km, while the median of the deactivations that occurred in water was only 10.5 km (Fig. 3). Within this last group, it was observed that 54.4% of the deactivations were <20 km, particularly in the vicinity of Seychelles and its surrounding islands and the east coast of Africa. The distance between the last location of a SP buoy before it was deactivated and its initial position within the SP ranged from 0 to 4283 km, with an average distance of 256.1 km.

Mean lifetime

The half-life of deactivated in water dFAD tracking buoys was estimated to be 101.3 days (Fig. 4). Overall, the exponential decay model is a reasonable representation of the empirical cumulative distribution function of the data, though there are discrepancies between the data and the model for survival times >180 days.

Deactivations and stranding events

Analysis of deactivated buoys for evidence of strandings identified 78 stranded buoys, although in 4 of them, the periods of stranding were short, transient, and significantly prior to deactivation. Out of the remaining buoys (73), the stranding

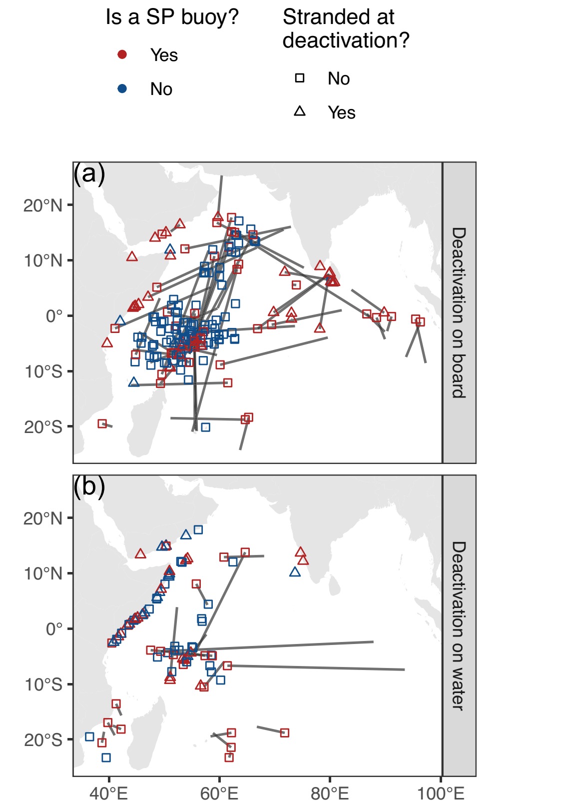

Figure 3. Map of deactivation locations for buoys that were in the deactivated state as the start of the SP (July 18) and for which we have position information at the time of deactivation (i.e. the deactivation occurred in 2020). The top panel (a) shows locations of buoys that were classified to be on board at time of deactivation ($n = 184$), whereas the bottom panel (b) shows buoys classified as in water at time of deactivation ($n = 90$). The shape of the dots indicates if the buoy were tagged as stranded (triangles) or not (squares) at time of deactivation, and the color indicates whether the buoy was tagged as a SP buoy (blue) or not (red). The dark gray lines join the locations of deactivation and the first record in the SP, if available.

periods occurred before or even at the time of their deactivation in 59 of them. For the remaining 14 cases, stranding was only observed post-deactivation during the SP. Therefore, we were able to detect 23.7% more stranding cases by including deactivated SP buoys. Finally, it was observed that 51 (86.4%) buoys were deactivated less than a month after stranding, suggesting that stranding or potential for stranding in the near future is a strong motivation for deactivating buoys (Fig. 5).

Discussion and recommendations

Our study provides the first tantalizing glimpse into what happens to dFADs after they are remotely deactivated by fishing vessels, key information for accurately estimating the true total impact of dFADs on marine ecosystems, and identifying effective clean-up methods for the ALDFG created by dFADs. Though our data set is clearly limited both in numbers and in temporal extent, these data are unique and highlight the potential value of continuing to record dFAD position information after fishing fleets no longer see value in them as indicated by remote deactivation. Continued tracking of dFADs post-deactivation, even with a considerably reduced temporal periodicity (e.g. one position per 1–3 days) would allow not

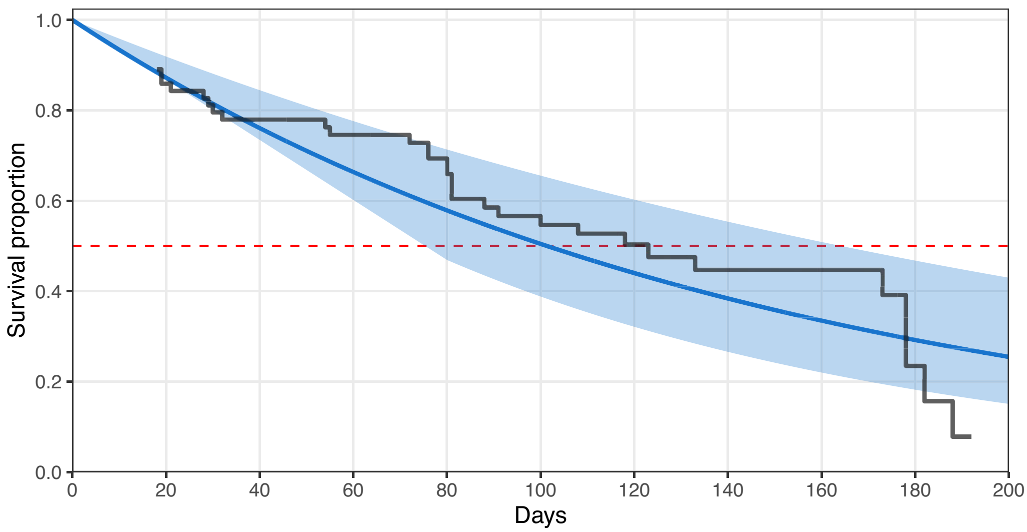

Figure 4. Fitted in water dFAD tracking buoy survival curve in blue, and the observed survival proportion (Empirical Cumulative Distribution Function) in gray. The estimated half-life is the intersection between the curve and the horizontal red dashed line at survival proportion 0.5.

only accurately quantifying dFAD life expectancy, loss rates, and stranding rates and locations, but also would be essential to designing effective dFAD recovery programs to reduce marine litter. As remote reactivation is generally not permitted by tuna RFMOs, remote deactivation of in water dFAD tracking buoys typically indicates permanent abandonment of a dFAD by a fishing vessel (unless the dFAD tracking buoy is serendipitously encountered and picked up by another vessel and returned to port for later redeployment by the owning vessel). Given this abandonment, there would seem to be little privacy concern with making subsequent dFAD tracking information publicly available in real time so that other vessels could potentially make use of or recover the dFADs and so that coastal communities could organize removal of dFADs from the environment (potentially with financial or other support from the fishing industry itself, for example via a polluter-payer program). Such satellite transmission of position information would involve a monetary cost, but costs could be reduced via less frequent transmission of position information and non-transmission of additional data, such as echosounder information, and these costs could be financed by a number of different mechanisms, including, but not limited to, an industry-paid fee associated with each new dFAD deployment. We strongly feel that, in the future, this critical information for reducing the impact of dFADs on marine ecosystems should be made universally available by all fleets and in all oceans.

The SP provides baseline estimates of the percentage of untracked dFADs in the environment and the length of time they could be tracked if position information continued to be recorded post-deactivation. Understanding the length of time dFAD tracking buoys continue to transmit position information after deactivation is essential for developing effective dFAD recovery plans and optimizing retrieval efforts, thus reducing marine pollution and associated ecological damage (Restrepo et al. 2017). For example, our half-life estimates could be used to identify key time periods for recovering deactivated buoys before sinking and to develop management procedures that account for the full life-cycle of dFADs. The number of buoys transmitting position information increased by ~17.2% during the SP, and we estimate a mean in water lifetime of deactivated buoys of ~3 months. This life expectancy is of the same order of magnitude as previous estimates of dFAD trajectory duration prior to deactivation or loss. Maufroy et al. (2015) estimated mean in-water trajectory duration of 47 days with duration ranging from less than a day to more than 2 years, whereas Zudaire et al. (2023) estimate the average lifetime of a dFAD to be between 6 and 12 months (from its deployment in the water until its deactivation). Our post-deactivation life expectancy estimates are within this overall range, suggesting both their plausibility and that the trackable time post-deactivation represents a non-negligible portion of the overall dFAD life expectancy. Given the small size of our data set and its particular geographic and temporal context, it is, however, difficult to assess the extent to which our life expectancy estimates are representative of other regions, fishing fleets, fishing companies, dFAD designs, and buoy manufacturers. There is real potential for important differences across tropical tuna PS fisheries worldwide, emphasizing the value of making post-deactivation tracking information universally available.

Among the 14 cases where there was a deactivation event before a stranding was identified during the SP, in 50.0% of the cases, the buoys were found to be in shallow water (<50 m depth) immediately prior to deactivation. Furthermore, of the 30 in water deactivations that were neither SP buoys nor associated with a stranding, 8 were in shallow water. Both these results suggest that potential for stranding due to presence in a shallow-water environment is an important motivation for remote deactivation. Overall, estimates of the number of strandings increased by 23.7% by including buoys deactivated before stranding identified in the SP, a non-negligible increase in stranding rates that should be taken into account when assessing published dFAD stranding rates (e.g. Imzilen et al. 2021). For future confirmation of this result, in addition to post-deactivation tracking information, it would be extremely useful to have vessel logbook information regarding motivations for remote deactivation of dFADs, information that will hopefully be included in ongoing improvements to recording of dFAD operations in vessel logbooks.

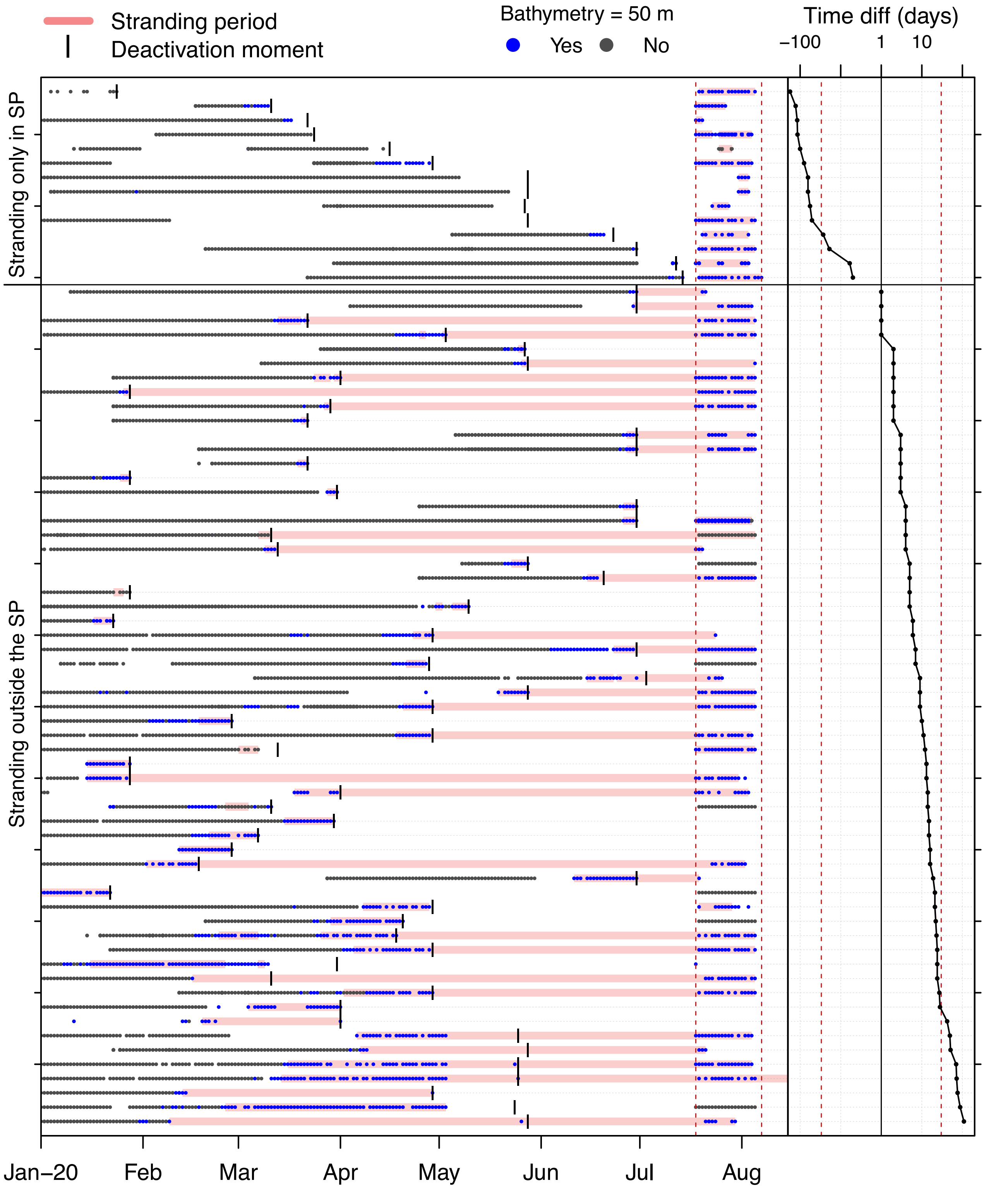

Figure 5. Left panel: time history of buoys ($n = 73$) that were stranded, whether at their deactivation or at the initial position within the SP. Within every row representing one buoy record history, the small dots represent tracking buoy position timestamps, with blue color indicating that the bathymetry at the position was <50 m, horizontal semi-transparent red ribbons represent the stranding period, and small black vertical lines (|) indicate the deactivation event for each buoy. Red dashed vertical lines delineate the SP (from 18 July to 7 August). Right panel: time difference for each buoy between the starting date of their last stranding period and their deactivation. Positive values indicate that the deactivation occurred after the stranding. Time differences are presented on a log scale with ±30 days indicated by a red-dash vertical line. From top to bottom, the buoys were sorted in two groups: (i) 14 buoys whose stranding periods occurred only during the SP and (ii) 59 buoys whose stranding periods started on or before their deactivation date.

Overall, our results provide to our knowledge a unique window into the life of dFADs after they are no longer actively tracked by fishing vessels. It is our hope that this limited data set provides incentive to fishers, industry representatives, buoy manufacturers, managers, scientists, and politicians to make tracking information spanning the full lifetime of dFADs used by all fleets and in all oceans widely available for scientific, management, and conservation purposes.

Acknowledgements

We express our sincere thanks to ORTHONGEL for making their dFAD tracking data available and providing feedback on a draft of this article and to the Ob7 for data management and preparation, including, but not limited to, Taha Imzilen. We thank the handling editor and two anonymous reviewers for their insightful comments that significantly improved our article. All data analyses and visualization scripts are available as a Quarto document by request to the corresponding author.

Author contributions

W.L.M.: Data curation, Formal Analysis, Software, Visualization, Writing – original draft. D.G: Supervision, Writing – review & editing. F.M.: Supervision, Writing – review & editing. L.G.: Supervision, Writing – review & editing. D.M.K.: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work is part of the DYNASTIA project funded by the Occitanie Region of France [grant number 21012994] and the Ob7 pelagic ecosystem observatory based at the UMR MARBEC in Sète, France. The work also received support from the REDUCE project funded by Horizon Europe [grant agreement no. 101135583].

Data availability

Given the confidential nature of the dFAD trajectory data used in this paper, requests for data access should be addressed directly to the Ob7 (https://www.ob7.ird.fr/) pelagic ecosystem observatory using the email address: adm-dblp@ird.fr.

References

Dupaix A, Ménard F, Filmalter JD *et al.* The challenge of assessing the effects of drifting fish aggregating devices on the behaviour and biology of tropical tuna. *Fish Fish* 2024;**25**:381–400. https://onlinelibrary.wiley.com/doi/10.1111/faf.12813 (26 April 2024, date last accessed).

Escalle L, Hare SR, Vidal T *et al.* Quantifying drifting fish aggregating device use by the world's largest tuna fishery. *ICES J Mar Sci* 2021;**78**:2432–47. https://academic.oup.com/icesjms/article/78/7/2432/6307380 (28 April 2023, date last accessed).

FAO. *Report of the Thirty-third Session of the Committee on Fisheries: Rome, Italy 9-13 July 2018, 1249*. FAO, Rome, 2019a.

FAO. 2019b. Voluntary Guidelines on the Marking of Fishing Gear. Directives Volontaires Sur Le Marquage Des Engins de Pêche. Directrices Voluntarias sobre el Marcado de Las Artes de pesca. Rome: FAO. https://www.fao.org/documents/card/en/c/CA3546T/ (28 April 2023, date last accessed).

Fonteneau A, Chassot E, Gaertner D. Managing tropical tuna purse seine fisheries through limiting the number of drifting fish aggregating devices in the Indian Ocean: food for thought. *Collect. Vol. Sci. Pap.*, 2015, **71**, ICCAT. https://www.semanticscholar.org/paper/MANAGING-TROPICAL-TUNA-PURSE-SEINE-FISHERIES-THE-OF-Fonteneau-Chassot/36767a2aee6b886d8c18de5d5fbed3d620bd5ac9

Gaertner D, Ariz J, Bez N *et al.* Results achieved within the framework of the EU research project: catch, effort, and ecosystem impacts of FAD-fishing (CECOFAD), IOTC, 2016. https://iotc.org/documents/results-achieved-within-framework-eu-research-project-catch-effort-and-ecosystem-impacts (8 December 2023, date last accessed).

GEBCO Bathymetric Compilation Group 2023. The GEBCO_2023 Grid—a continuous terrain model of the global oceans and land [object Object]. 2023. https://www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b/ (14 May 2024, date last accessed).

Gilman E. Status of international monitoring and management of abandoned, lost and discarded fishing gear and ghost fishing. *Mar Policy* 2015;**60**:225–39. https://linkinghub.elsevier.com/retrieve/pii/S0308597×1500175X (25 April 2023, date last accessed).

Gilman E, Musyl M, Suuronen P *et al.* Highest risk abandoned, lost and discarded fishing gear. *Sci Rep* 2021;**11**:7195. https://www.nature.com/articles/s41598-021-86123-3. (26 April 2023, date last accessed).

Hallier J, Gaertner D. Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. *Mar Ecol Prog Ser* 2008;**353**:255–64. http://www.int-res.com/abstracts/meps/v353/p255-264/ (6 October 2022, date last accessed).

Hallier J-P, Parajua JI. Review of tuna fisheries on floating objects in the Indian Ocean. In: *Proceedings of the International Workshop on the Ecology and Fisheries for tunas Associated with Floating Objects*, 1992, pp. 354–70. La Jolla, California, USA: NOAA Technical Report NMFS-SEFSC-334.

Hijmans RJ. Terra: spatial data analysis. 2024. https://CRAN.R-project.org/package=terra (25 July 2024, date last accessed).

IATTC. Resolution C-21-04, Conservation measures for tropical tunas in the Eastern Pacific Ocean suring 2022-2024. Inter-American Tropical Tuna Commission. 2021.

Imzilen T, Lett C, Chassot E *et al.* Spatial management can significantly reduce dFAD beachings in Indian and Atlantic Ocean tropical tuna purse seine fisheries. *Biol Conserv* 2021;**254**:108939. http://www.sciencedirect.com/science/article/pii/S0006320720309976. (12 January 2021, date last accessed).

Imzilen T, Lett C, Chassot E *et al.* Recovery at sea of abandoned, lost or discarded drifting fish aggregating devices. *Nat Sustain* 2022;**5**:593–602. https://www.nature.com/articles/s41893-022-00883-y (7 March 2023, date last accessed).

IOTC. Resolution 17/08: procedures on a Fish Aggregating Devices (FADs) management plan, including a limitation on the number of FADs, more detailed significations of catch reporting from FAD sets, and the development of improved FAD designs to reduce the incidence of entanglement of non-target species. 2017.

Kaplan DM, Cuif M, Fauvelot C *et al.* Uncertainty in empirical estimates of marine larval connectivity. *ICES J Mar Sci* 2017;**74**:1723–34. https://academic.oup.com/icesjms/article/74/6/1723/2741993 (27 September 2023, date last accessed).

Lennert-Cody CE, Moreno G, Restrepo V *et al.* Recent purse-seine FAD fishing strategies in the eastern Pacific Ocean: what is the appropriate number of FADs at sea? *ICES J Mar Sci* 2018;**75**:1748–57. https://academic.oup.com/icesjms/article/75/5/1748/4976455 (24 October 2022, date last accessed).

MacMillan I, Attrill MJ, Imzilen T *et al.* Spatio-temporal variability in drifting fish aggregating Device (dFAD) beaching events in the Seychelles Archipelago. *ICES J Mar Sci* 2022;**79**:1687–700. https://academic.oup.com/icesjms/article/79/5/1687/6591913 (6 March 2023, date last accessed).

Marsac F, Fonteneau A, Ménard F. 2000. Drifting FADs used in tuna fisheries: an ecological trap?. *Pêche Thonière et Dispositifs de Concentration de Poissons* 537–52.

Maufroy A, Chassot E, Joo R *et al*. Large-scale examination of spatio-temporal patterns of drifting fish aggregating devices (dFADs) from tropical tuna fisheries of the Indian and Atlantic oceans. *PLoS One* 2015;**10**:e0128023. https://dx.plos.org/10.1371/journal.pone.0128023 (5 October 2022, date last accessed).

Maufroy A, Kaplan DM, Bez N *et al*. Massive increase in the use of drifting fish aggregating devices (dFADs) by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. *ICES J Mar Sci* 2017;**74**:215–25. https://academic.oup.com/icesjms/article-abstract/74/1/215/2418180/Massive-increase-in-the-use-of-drifting-Fish (9 March 2017, date last accessed).

OBPGand Stumpf RP. Distance to nearest coastline: 0.01-degree grid. Distributed by the Pacific Islands Ocean Observing System (PacIOOS). 2012. https://www.pacioos.hawaii.edu/metadata/dist2coast_1 deg.html (16 January 2024, date last accessed).

Pebesma E, Bivand R. *Spatial Data Science: With Applications in R*. Chapman and Hall/CRC. 2023. https://r-spatial.org/book/

Pons M, Kaplan D, Moreno G *et al*. Benefits, concerns, and solutions of fishing for tunas with drifting fish aggregation devices. *Fish Fish* 2023;**24**:979–1002. https://onlinelibrary.wiley.com/doi/10.1111/faf.12780 (31 July 2023, date last accessed).

R Core Team. *R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing*. Vienna, Austria. 2024. https://www.R-project.org/ (25 July 2024, date last accessed).

Restrepo V, Dagorn L, Itano D *et al*. A summary of bycatch issues and ISSF mitigation initiatives to-date in purse seine fisheries, with emphasis on FADs. *lSSF Technical Report, 2017-06*. International Seafood Sustainability Foundation, Washington, D.C, USA, 2017.

Schwarz CJ. The Jolly-Seber model: more than just abundance. *J Agric Biol Environ Stat* 2001;**6**:195–205. http://link.springer.com/10.1198/108571101750524706 (27 September 2023, date last accessed).

Therneau TM. A package for survival analysis in r. 2024. https://CRAN.R-project.org/package=survival (25 July 2024, date last accessed).

Wang X, Chen Y, Truesdell S *et al*. The large-scale deployment of fish aggregation devices alters environmentally-based migratory behavior of skipjack tuna in the Western Pacific Ocean. *PLoS One* 2014;**9**:e98226. https://dx.plos.org/10.1371/journal.pone.0098226 (31 July 2023, date last accessed).

Wickham H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. New York: Springer. https://ggplot2.tidyverse.org.

Wickham H, François R, Henry L *et al*. Dplyr: a grammar of data manipulation. 2023. https://CRAN.R-project.org/package=dplyr (25 July 2024, date last accessed).

Wickham H, Vaughan D, Girlich M. Tidyr: tidy messy data. 2024. https://CRAN.R-project.org/package=tidyr (25 July 2024, date last accessed).

Zudaire I, Moreno G, Murua J *et al*. Biodegradable drifting fish aggregating devices: current status and future prospects. *Mar Policy* 2023;**153**:105659. https://linkinghub.elsevier.com/retrieve/pii/S0308597×23001860 (21 July 2023, date last accessed).

Zudaire I, Santiago J, Grande M *et al*. FAD watch: a collaborative initiative to minimize the impact of FADs in coastal ecosystems. *IOTC-2018-WPEB14-12. IOTC*, 2018.

Handling Editor: Michael Pol