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DRIFTING FISH AGGREGATING DEVICES (dFADs) BEACHING IN THE ATLANTIC OCEAN: AN ESTIMATE FOR THE FRENCH PURSE SEINE FLEET (2007-2015)

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SUMMARY

In recent years, the increasing deployments of drifting Fish Aggregating Devices (dFADs) have raised serious concerns for tropical tuna stocks, bycatch species and marine ecosystems. In particular, considerable attention has been drawn on the negative impacts of lost dFADs on coastal and pelagic ecosystems in terms of pollution and habitat destruction. Using GPS buoy tracks of Floating OBjects (FOBs) for French purse seiners operating in the Atlantic Ocean over 2007-2015, we identify potential dFAD beaching events, estimate the beaching risk of dFADs and determine the main dFAD beaching areas depending on the dFAD deployment season and location. The results we obtain are used to discuss potential mitigation solutions for dFAD beaching in the Atlantic Ocean including the use of biodegradable dFADs, limitations of dFAD deployment or use and the recovery of lost dFADs (at sea or on land).

RÉSUMÉ

Ces dernières années, les déploiements croissants de dispositifs de concentration de poissons dérivants (DCPd) ont soulevé de vives inquiétudes pour les stocks de thonidés tropicaux, les espèces accessoires et les écosystèmes marins. En particulier, on a attiré l'attention sur les impacts négatifs des DCPd perdus sur les écosystèmes côtiers et pélagiques en termes de pollution et de destruction de l'habitat. Au moyen du suivi avec des bouées GPS des objets flottants (FOB) pour les senneurs français opérant dans l'océan Atlantique entre 2007 et 2015, nous identifions d'éventuels échouages de DCPd, évaluons le risque d'échouage des DCPd et déterminons les principales zones d'échouage des DCPd en fonction de la saison et de la localisation du déploiement des DCPd. Les résultats que nous obtenons sont utilisés afin de discuter de possibles solutions d'atténuation pour l'échouage des DCPd dans l'océan Atlantique, y compris l'utilisation de DCPd biodégradables, les limitations du déploiement des DCPd ou l'utilisation et la récupération des DCPd perdus (en mer ou à terre).

RESUMEN

En años recientes, el número creciente de dispositivos de concentración de peces a la deriva (DCPD) ha suscitado graves inquietudes respecto a los stocks de túnidos tropicales, a las especies de captura fortuita y a los ecosistemas marinos. En particular, se ha prestado una atención considerable al impacto negativo de los DCPD perdidos en los ecosistemas pelágicos y costeros en términos de contaminación y destrucción de hábitats. Mediante el seguimiento con boyas GPS de objetos flotantes (FOB) para los cerqueros franceses que operaron en el Atlántico entre 2007-2015, hemos identificado posibles casos de varamiento de DCPD, hemos estimado el riesgo de varamiento de los DCPD y hemos determinado las principales zonas de varamiento de DCPD dependiendo de la temporada y ubicación del plantado de los DCPD. Los resultados obtenidos se utilizan para discutir posibles soluciones en materia de mitigación para el varamiento de los DCPD en el océano Atlántico, lo que incluye el uso de DCPD biodegradables, las limitaciones al plantado de DCPD o el uso y la recuperación de DCPD perdidos (en mar o en tierra).

KEYWORDS

FADs, FAD loss, ecosystem impacts, pollution, management

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1. Introduction

Since the end of the 1990s, drifting Fish Aggregating Devices (dFADs), artificial Floating Objects (FOBs) designed by fishers to aggregate fish, have become an important mean of catching skipjack, yellowfin and bigeye tuna by tropical tuna purse seiners (Fonteneau *et al.*, 2000). These objects, that mimic the natural aggregative behaviour of fish with the objects floating at the surface of the ocean, are widely used to improve the detectability and the catchability of tropical tunas (Hall 1992, Fréon & Dagorn 2000, Castro et al 2002). Over time, increasing numbers of dFADs have been deployed in the world oceans and FOB-related technology has improved. Tracking devices such as GPS buoys providing the position of the FOB, echosounder buoys providing an estimate of the amount of biomass aggregated under the FOB and support vessels assisting purse seiners in their dFAD deployment and searching activities have been introduced (Fonteneau *et al.*, 2000; Arrizabalaga *et al.*, 2001; Castro *et al.*, 2002; Dagorn *et al.*, 2013; Fonteneau *et al.*, 2013; Lopez *et al.*, 2014).

In recent years, though dFAD use has been self-limited by the French fleet since 2012 and limited by ICCAT for all purse seine fleets since 2016 in the Atlantic Ocean, the increasing deployments of dFADs, as well as the increasing use of tracking devices on dFADs and natural floating objects, have raised serious concerns for tropical tuna stocks, bycatch species and marine ecosystems. Among others, considerable attention has been drawn by scientists and NGOs on the contribution of dFADs to increased catches of juveniles of yellowfin and bigeye tuna (Fonteneau *et al.*, 2000), increased fishing pressure on tropical tuna stocks (Hallier *et al.*, 1992; Ariz Telleria *et al.*, 1999; Fonteneau *et al.*, 2000; Maufroy *et al.*, in preparation), modifications of the natural behaviour of tropical tunas (Marsac *et al.*, 2000; Hallier and Gaertner, 2008; Sempo *et al.*, 2013), increased levels of bycatch and discards (Amandè *et al.*, 2011, 2012; Hall and Roman, 2013), ghost fishing of fragile species (entanglements of sea turtles and sharks; Anderson *et al.*, 2009; Filmalter *et al.*, 2013) and potential damages to vulnerable habitats due to dFAD loss onshore (dFAD beaching; Balderson and Martin 2015; Maufroy *et al.* 2015; Davies *et al.* 2017).

In the Atlantic Ocean, despite the recent adoption of FOB regulatory measures by ICCAT such as the implementation of "FAD management plans" that should improve data collection on FOB use by purse seine fleets and render purse seine fleets responsible for the management of their FOBs (ICCAT Recommendation 16-01), very little information is available on dFAD loss, its potential consequences as well as the potential management of this issue. This question was first examined when the French purse seine fleet voluntarily provided an exhaustive dataset of the positions of their GPS buoy equipped FOBs to the French Institute of Research for Development (IRD). A preliminary examination of these data in the Atlantic and the Indian oceans revealed that about 10% of French GPS buoy tracks had ended with a beaching event over 2007-2011 (Maufroy *et al.*, 2015a). Two additional studies have examined the case of the Indian Ocean either providing information on beaching events occurring in the Seychelles (Balderson and Martin, 2015) or discussing the potential causes, impacts and management of dFAD beaching in the whole Indian Ocean (Davies *et al.*, 2017).

In the present study, as the number of GPS buoy-equipped FOBs used by all fleets as kept increasing since 2011 (Maufroy *et al.*, 2017) and mitigation measures have not been discussed in the particular case of the Atlantic Ocean, the results obtained by Maufroy et al. (2015) are updated. Here, using GPS buoy tracks of French FOBs over 2007-2015, our objectives are threefold (i) estimate the risk of dFAD beaching in the Atlantic Ocean (ii) identify the main zones for dFAD beaching and their corresponding deployment areas (iii) discuss potential mitigation solution for dFAD beaching that would account for the specificities of dFAD use by tropical tuna purse seine fleets in the Atlantic Ocean.

2. Detection of beaching events for the French fleet in the Atlantic Ocean

2.1 Material and methods

French tuna purse seine fishing companies voluntarily provide the GPS tracks of their FOBs on a quarterly basis to the "Institut de Recherche pour le Développement (IRD)" through an agreement between their Producer Organisation ORTHONGEL and IRD. These data are routinely processed and stored in a dedicated database by the IRD with the methodology developed by Maufroy et al. (2015) to identify periods when FOBs are drifting at sea with a tracking device (either a GPS buoy or a GPS and echosounder buoy). For the present study, 2 000 917 drifting positions of 8 674 tracked FOBs were used to detect potential FOB beaching events in the Atlantic Ocean over 2007-2015 (**Figure 1**).

Potential FOB beaching events were detected as repeated positions (i.e. positions distant from less than 100 m) of the same GPS buoy, occurring close to land (less than 5 km from the nearest coast) and far from port (more than 10 km from the nearest port) and the FOB beaching risk was calculated as the percentage of GPS buoy tracks presenting a potential beaching event. When the same GPS buoy presented more than repeated position close to land and far from port, only the first repeated position was treated as a potential beaching event.

Spatio-temporal patterns of FOB beaching and corresponding deployment positions were represented on a seasonal basis using the four FOB seasons defined in (Maufroy *et al.*, 2017): January-February (JF), March-May (MAM), June-July-August-September (JJAS) and October-November-December (OND).

Finally, as purse seiners can remotely deactivate the tracking buoys of FOBs that are lost outside fishing grounds, not all FOB beaching events may be detected with such a methodology. Pre-beaching deactivations were detected as the last position of GPS buoy tracks ending “at sea” 5 to 100 km from the nearest coast.

2.2 Results

2.2.1 dFAD beaching risk and zones

Over 2007-2015, 8.8% of GPS French GPS buoy tracks (762 GPS buoy-equipped FOBs) presented a potential beaching event. Beaching events occurred on average 158.6 days (SD 125.2) after the deployment of the GPS buoy on the FOB and the average distance between the deployment and the beaching position reached 1881.4 km (S.D. 1894.8). Most beaching events (76,2%) occurred along the Western African coast and concentrated from Guinea to Cameroun (**Figure 2**, right panel). The rest of beached buoy equipped FOBs crossed the entire Atlantic Ocean to beach from Florida to Brazil.

The number of beaching events increased over time in relation with the increasing use of FOBs in the Atlantic Ocean, though the French purse seine fleet limited its use of GPS buoys since 2012. In 2007, a minimum of 7 beaching events were detected for the 276 active French GPS buoys. In 2015, a maximum of 232 beaching events were detected for the 2429 active French GPS buoys. The number of beaching events also varied from season to season with higher numbers of beaching events occurring from July to September (33.4% of all beaching events detected over 2007-2015) and lower numbers occurring from February to April (14.2% of all beaching events detected over 2007-2015).

2.2.2. Pre-beaching deactivations of GPS buoys

Part of beaching events may not have been detected with repeated positions occurring close to land and far from port. Over 2007-2015, a total of 910 GPS buoy trajectories (10.5%) ended with a position at sea 5 to 100 km from the nearest coast. As for potential dFAD beaching events, the number of potential pre-beaching deactivations of GPS buoys increased over time with 19 potential pre-beaching deactivations of GPS buoys in 2007 and 215 in 2015. Potential pre-beaching deactivations of GPS buoys also mainly occurred along the western coast of Africa (89.1%) while lower numbers of pre-beaching deactivations occurred along the southern American coast. However, in this area, potential pre-beaching deactivations mainly occurred off Brazil though potential beaching events were also detected from Florida to French Guiana. There was also a difference in the seasonality between pre-beaching GPS buoy deactivations and dFAD beaching events with more potential pre-deactivations of GPS buoys from August to October (37.4% of all pre-beaching deactivation events) and less potential pre-deactivations of GPS buoys in January and February (8.9% of all pre-beaching deactivation events).

2.2.3. Deployment zones contributing to dFAD beaching events

Three main zones of deployment for beached FOBs were detected (i) Gabon (centered around 3°S-8°W, **Figures 2 and 4**, left panels) (ii) Sierra Leone-Liberia (15°W-2°S) and (iii) Guinea (20°W-8°N). The main areas contributing to beaching events corresponded to the main seasonal FOB activity zones (**Figure 4**, Maufroy *et al.*, 2017): the western part of the Gulf of Guinea from January to February, Senegal from March to May, Gabon from June to August and finally the Gulf of Guinea and the area East of 20°W along the Equator from October to November. The number of FOB beaching events occurring in the Gulf of Guinea was higher from June to September when the main deployment zone corresponded to the area of influence of the eastward North Equatorial Counter Current (Ariz Telleria *et al.*, 1999; Philander, 2001). On the contrary, the number of FOB beaching events occurring on the South American coast was higher for the seasons January-February, March-May and October-December when the main deployment zones were located within the areas of influence of the westward North Equatorial and South Equatorial currents.

2.3 Implications and limitations of the results

In this study, GPS buoy tracks of FOBs voluntarily provided by the French fleet were used over 2007-2015 to detect potential dFAD beaching events and pre-deactivations of GPS buoys. Results indicate that approximately 8.7% of GPS buoys tracks presented a potential beaching event and 10.5% presented a potential pre-beaching deactivation of the GPS buoy. These numbers do not necessarily indicate that a total of 1672 GPS buoy equipped dFADs (762 GPS buoys with repeated positions and 910 GPS buoy tracks ending at sea) have beached in the Atlantic Ocean from 2007 to 2015 as various events may end the emission of the GPS signal, in particular when local fishing vessels find dFADs and their tracking GPS buoys drifting at sea.

In addition, the results we present here may overestimate the real number of dFAD beaching events, at least for the eastern Atlantic Ocean where small-scale fishing ports occur in the numerous branches of river. As a consequence, some of the repeated positions detected close to land may correspond to dFADs and/or GPS buoys found by local fishers and stored in local fishing ports. However, our results may also underestimate the number of beaching events occurring along the southern American coast. In the Atlantic Ocean, strong westward currents are active all year long (Ariz Telleria *et al.*, 1999; Philander, 2001) and dFAD trajectories present intense westward patterns of drift during all seasons (Maufroy *et al.*, 2015b). This could lead to more frequent dFAD beaching events than those detected in this study if purse seiners remotely deactivate the GPS buoys of their dFADs as soon as they leave fishing grounds.

Finally, the results we obtain may have different implications that would depend on (i) the nature of the impact of the dFAD beaching event (and more generally of dFAD loss) (ii) the nature of the habitat where the dFAD beaching or pre-beaching GPS buoy deactivation occurred. The impacts of dFAD loss can be classified in two categories: habitat modification or habitat destruction. One of the potential consequences dFAD loss is a risk of pollution as dFADs and their tracking buoys are made of plastics, metal and electronic components (see section 3.1). This issue would in theory impact all types of habitats, regardless of their nature. Another potential consequence is that beached dFADs may contribute to ghost fishing of sensitive species such as sea turtles if “sausage nets” of non-entangling dFADs become entangling again (Balderson and Martin, 2015). This second problem would occur if the underwater sausage net of non-entangling dFADs unravel when entangled on coral reefs or rocky bottoms close the coast. Finally, dFAD beaching may lead to the destruction of fragile habitats such as coral reefs. This issue has been described in the Indian Ocean (Balderson and Martin, 2015) but may be of lesser importance in the Atlantic Ocean where coral reefs are mainly located in the Gulf of Mexico and the Caribbean Sea (http://data.unep-wcmc.org/datasets/1) while more dFAD beaching events are detected on the Brazilian coast (**Figure 2**).

3. Potential mitigation measures for dFAD beaching in the Atlantic Ocean

A wide range of mitigation measures could be implemented to limit the number of dFAD beaching events and their negative consequences in the Atlantic Ocean. Different solutions may be considered from the building of dFADs to their loss (**Figure 5**). In this section, various solutions including changes in the design of dFADs, limitations in the use of dFADs and tracking buoys as well as the recovery of dFADs on land or at sea are discussed in the particular case of the Atlantic Ocean.

3.1 Improving dFAD design

During the two last decades, various projects involving fishing companies and scientific institutes have aimed at improving the structure of dFADs to reduce their impacts on sensitive species and ecosystems (Franco *et al.*, 2012). In particular, important progress was made by European tuna purse seine fleets (France, Spain and associated flags) to reduce the risk of sea turtle entanglement in the old pieces of fishing nets that were used to cover dFADs (Anderson *et al.*, 2009) and shark entanglement in the old pieces of fishing nets that were used as a subsurface drogue to anchor dFADs in oceanic currents (Filmalter *et al.*, 2013). During the 2010s, these fleets have progressively replaced their entangling dFADs by “lower entanglement risk” new designs (Goujon and Vernet, 2012; Murua *et al.*, 2017). In the case of the French fleet, the collaboration between ORTHONGEL and the IRD during the Tuna Contract for the Future (TCF) “ecoFAD” allowed developing a new design of dFAD that has replaced 100% of conventional dFADs since 2013 in the Atlantic Ocean (ORTHONGEL decision n°11 from the 23st November 2011). The different layers of old pieces of fishing nets with large mesh recovering dFADs to make them as invisible as possible (and reduce the risk that other vessels find and appropriate the dFAD) have been replaced with small mesh fishing nets. The sections of net of the part submerged of dFADs have been replaced by “sausage nets” used to anchor the dFAD in oceanic currents and panels of small mesh fishing nets to slow down the drift of dFADs in the strong westward currents of the Atlantic Ocean (Figure 6). Such dFADs are delivered by a building facility based in the port of Abidjan to ensure the reliability of non-entangling dFADs during their whole time at sea.

Though these new designs of dFADs contribute to a significant reduction of the entanglement risk for sharks and sea turtles (except when the sausage net unravels), non-entangling dFADs do not allow to solve the problems caused by lost or abandoned dFADs of tropical tuna purse seine fleets that become a source of pollution and habitat destruction when they are washed ashore (Balderson and Martin, 2015; Maufroy *et al.*, 2015a; Davies *et al.*, 2017). The metal or plastic rafts used by some purse seine fleets, the nylon fishing nets or the plastic covers of rafts, the plastic floats, the sections of nylon fishing nets of the subsurface structure of dFADs, the plastic and electronic components of GPS and echosounder buoys are all potential sources of pollution in coastal and pelagic environments. These non-biodegradable materials also increase the lifetime of dFADs and therefore the risk of habitat destruction when dFADs beach in sensitive habitats.

The development of non-entangling and non-polluting dFADs (thereafter termed "biodegradable dFADs") therefore becomes necessary. This would reduce the residence time of dFADs in pelagic and coastal environment and consequently reduce the risk of habitat pollution and habitat destruction due to dFAD beaching and dFAD loss (e.g. when dFADs sink). In addition, in the case of the Atlantic Ocean where strong westward currents extract dFADs from the eastern fishing grounds of tropical tuna purse seiners, the use of biodegradable dFADs, that would avoid recovering lost dFADs outside fishing grounds seems a promising solution. Though the initial objective was to conduct research to replace current non-entangling with biodegradable dFAD designs by 2018 in the Atlantic Ocean (ICCAT Rec 16-01), there are a number of technical challenges for biodegradable dFADs that should at the same time have a reduced lifetime in the environment, last long enough to allow fishing activities (approximately one year), be as efficient as current non-entangling dFADs for tuna aggregation, should not be too expensive or too complex to build and should not degrade into polluting particles that could be ingested by marine animals (Derraik, 2002; Andrady, 2011). To date, various "biodegradable" materials have been tested or are currently tested for dFAD construction including for instance cotton ropes to replace nylon "sausage nets" and cotton covers to replace the nylon fishing nets or the plastic covers of rafts (Lopez *et al.*, 2016; Moreno *et al.*, 2016).

Efforts are being made by all European purse seine fleets through various initiatives (the French fleet is for example using cotton ropes since 2016 in the Atlantic Ocean) such as the European project "BIOFAD" in the Indian Ocean or the collaboration between the French purse seine fleet and industrials in the starting ORTHONGEL Tuna Contract for the Future "ecoFAD 2". However, building entirely biodegradable dFADs is a difficult task for several reasons. First, the concept of "biodegradability" is often poorly defined and some plastic materials that are labelled as "biodegradable" either do not degrade in real conditions or break apart into polluting microparticles of plastics (Kershaw, 2015). Replacing plastic elements such as the floats of the surface structure of dFADs in a near future will be difficult, as many industrial solutions are still in development. Second, using biodegradable dFADs would not solve the problem of lost GPS buoys that are made of plastics but also of electronic components and can therefore not be made of biodegradable materials. Finally, testing the biodegradability of potential designs of dFADs would require the participation of all tropical tuna purse seine fleets to be able to follow prototypes of dFADs during their whole lifetime (Moreno *et al.*, 2016). However, this would also require the participation of other fishing fleets operating in the western part of the tropical Atlantic Ocean to monitor the fate of dFAD prototypes in this area.

3.2 Controlling dFAD deployment

As expected, the results we obtained in this study indicated that the number of beaching events increased with the number of FADs drifting at sea (see section 2.2). As a consequence, one of the simplest solutions to reduce dFAD beaching would be to reduce the number of dFADs and/or the number of active FOB tracking buoys used in the Atlantic Ocean. From 2012 to 2015, this limitation has already been implemented by the French purse seine fleet that decided to voluntarily limit their use of FOB tracking buoys to 150 buoys active at all times. In 2015, the ICCAT adopted a similar regulation for all purse seine fleets to 500 active tracking buoys per vessel (ICCAT Rec 15-01). This limitation applied for the first time in 2016, though the FAD management plan for the French purse seine fleet in 2016 and 2017 still limits the use of GPS buoys for the French fleet to 150 active GPS buoys per vessel.

In order to be efficient, such a limitation requires a unified, transparent and independent control of the number of active tracking buoys of all tropical tuna purse seine fleets. In addition, data reported to ICCAT should not consist of a count of dFAD deployments as such numbers are different from the number of tracking buoys that are actively monitored at sea (due to the deployment of active GPS buoys on natural FOBs, frequent changes in FOB ownership or to lost and abandoned FOBs). A solution would be to provide the number of active GPS buoys through activations/deactivations reports of GPS buoys provided by buoy manufacturers with a small delay of a few weeks or a few months. This would avoid confidentiality issues related to the provision of exhaustive positions of GPS buoy tracks to ICCAT and, in the case of the French purse seine fleet, this solution has been adopted by ORTHONGEL since 2010. However, it should be noted that limiting the use of tracking buoys without limiting the number of fishing vessels is unlikely to reduce the number of FADs drifting in the Atlantic Ocean.

Other studies have also proposed dFAD time-area deployment limits as a mitigation solution for dFAD beaching events (Maufroy *et al.*, 2015a; Davies *et al.*, 2017). Such a tool would only be adapted if some particular areas were responsible for the majority of dFAD beaching events. In the Atlantic Ocean, the deployment areas of Senegal, Ivory Coast and Gabon was one of the major deployment areas contributing to beaching of French dFADs over 2007-2015. However, these areas are also those that contribute to the majority of dFAD fishing sets in the Atlantic Ocean (Ariz Telleria *et al.*, 1999; Maufroy *et al.*, 2017) and reducing dFAD deployments would greatly affect fishing activities of purse seine fleets. Though fishing vessels should report the list of deployed dFADs in their dFAD logbooks (ICCAT Rec 16-01). This solution is clearly less suitable than a limitation of the use of tracking buoys as it is more complex and requires the use of human or electronic observers to control the time-area deployments of dFADs.

3.3 Avoiding dFAD loss and beaching in sensitive areas

Another approach to reduce the impacts of dFAD beaching would be to avoid dFAD loss or to recover lost dFADs at sea or on land. Potential solutions include the recovery of dFADs by purse seiners or by their support vessels when the dFAD is clearly exiting purse seine fishing grounds with very few chances to re-enter fishing grounds. This solution could be organised by fishing companies themselves without providing any confidential data on the position of their FOBs. In the Atlantic Ocean, this may be useful for FADs that begin drifting west of 20°W in westward currents. This would allow to avoid beaching events occurring on the coral reefs of the Gulf of Mexico or the Caribbean Sea for example. However, this solution will not feasible because operational and cost limitations for fishing companies as purse seiners and support vessels would be obliged to travel long distances only to retrieve potentially lost dFADs.

Lost dFADs could also be retrieved at sea before they beach or soon after the beaching event. This solution would require a real-time monitoring of GPS buoy tracked dFADs and a system of “beaching alert” when the dFAD enters a sensitive area (e.g. a few nautical miles from the nearest coast or the nearest coral reef). This option has already been examined for the coral reefs of Seychelles in the Indian Ocean through a “FAD Watch” (for the Spanish fleet: see Davies *et al.*, 2017; for the French fleet a similar project is discussed with the Seychelles Fishing Authority since 2016) but has also a number of potential limitations. First, the size of recovery areas may be large in the Atlantic Ocean as they extend from Florida to Brazil on the southern American coast and from Senegal to Namibia on the western African coast. Of course, it would be possible to prioritize the areas where lost dFADs could be retrieved by selecting the most sensitives habitats (e.g. coral reefs) but this would not be satisfying to reduce the risk of pollution. Second, the size of recovery areas may vary due to annual and seasonal oceanic conditions and remain difficult to evaluate, in particular if false detections of lost dFADs occur in numerous small scale fishing ports. Third, implementing a “FAD Watch” requires involving the appropriate local partners that could either be NGOs, local fishers or dedicated dFAD recovery vessels. The most suitable solution would depend on the area where lost dFADs should be retrieved, the cost of recovering dFADs with the chosen solution (for example, using dedicated dFAD recovery vessels is likely to be too costly), the means available for local the partners to retrieve lost dFADs, the availability of a disposal facility locally etc. Finally, the time dedicated to travelling towards dFADs pre or post beaching and the time dedicated to recovering dFADs entangled in coral reefs and rocky bottoms may increase the cost of retrieval operations.

Losses of dFADs could also be avoided through the development of dFADs with remotely controlled trajectories (Global FAD Science Symposium, 2017). This solution is likely to greatly increase the cost of dFADs compared to current non-entangling designs that use recycled (e.g. pieces of old fishing nets, used plastic floats) or cheap (e.g. bamboo) materials. This solution would only be interesting if the additional cost of such dFADs compensate the cost of constantly replacing the numerous dFADs and tracking buoys that are lost at sea.

To conclude, several potential solutions could be implemented to reduce the impacts of lost and beached dFADs in terms of pollution and habitat destruction. Each of these solutions has potential advantages and drawbacks, related to the cost of the solution, the provision of sensitive information, issues of control, the lack of technical solutions or the size of areas where beaching events occur. As a unique solution is unlikely to solve the issues related to dFAD beaching, the combination the use of biodegradable dFADs and the limitation of the number of active buoys used by individual purse seiners seems promising. In any case, the implication of fishing companies and their producer organization is required to identify the best adapted solutions.

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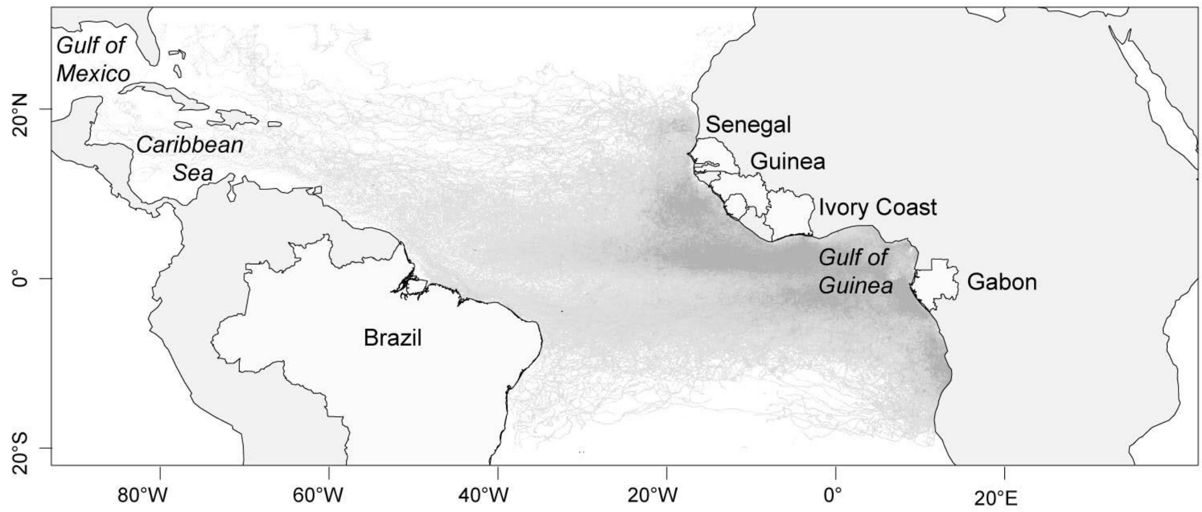

Figure 1. Positions of French GPS buoy equipped FOBs in the Atlantic Ocean from 2007 to 2015.

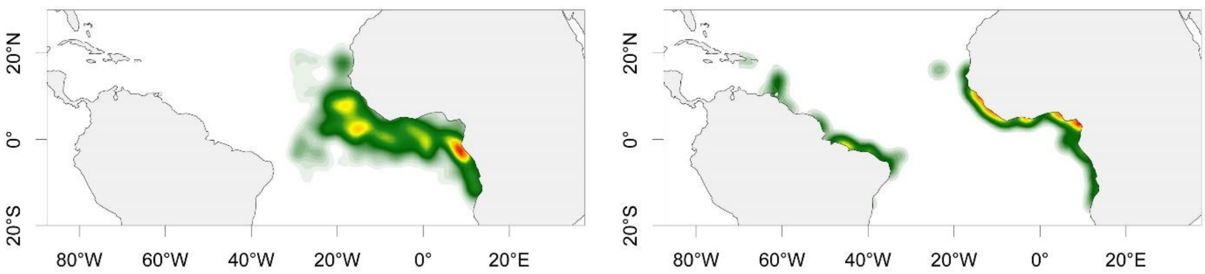

Figure 2. Smoothed densities of dFAD beaching events for the French purse seine fleet over 2007-2015 (right panel) and their corresponding deployment positions (left panel). Maps were smoothed using function kde2d of R MASS package.

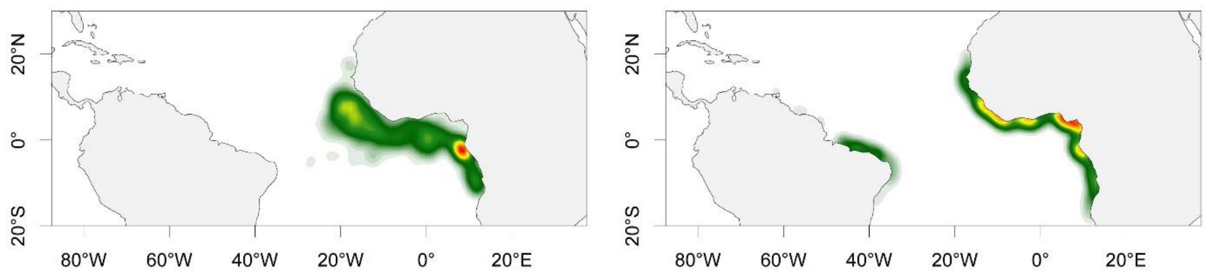

Figure 3. Smoothed densities of dFAD pre-beaching deactivation of GPS buoys for the French purse seine fleet over 2007-2015 (right panel) and their corresponding deployment positions (left panel). Maps were smoothed using function kde2d of R MASS package.

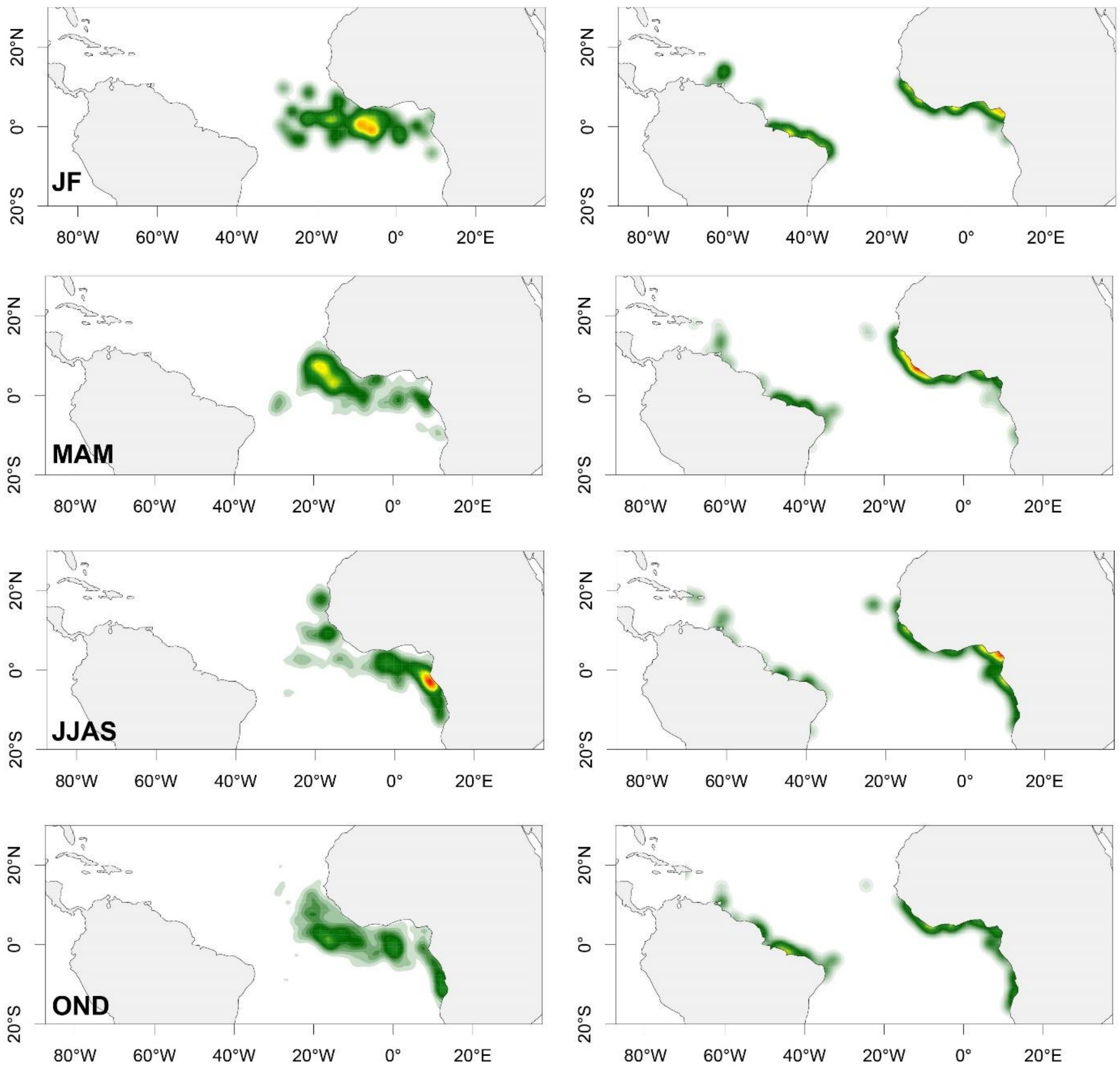

Figure 4. Smoothed densities of dFAD beaching events for the French purse seine fleet (right panel) and their corresponding deployment positions (left panel) depending on their deployment season. JF: January-February, MAM: March-May, JJAS: July-August, OND: October-November. Maps were smoothed using function kde2d of R MASS package.

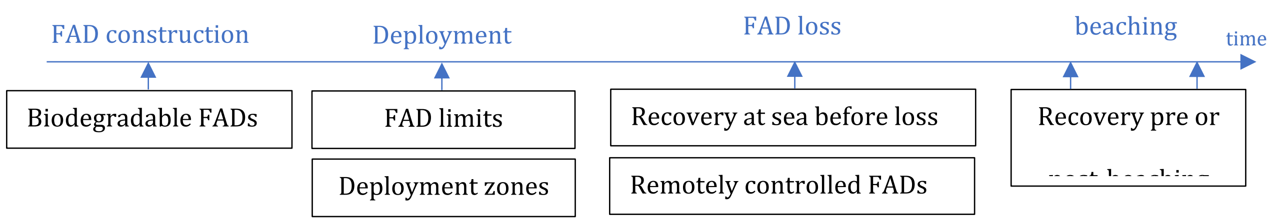

Figure 5. Potential mitigation solutions for dFAD beaching.

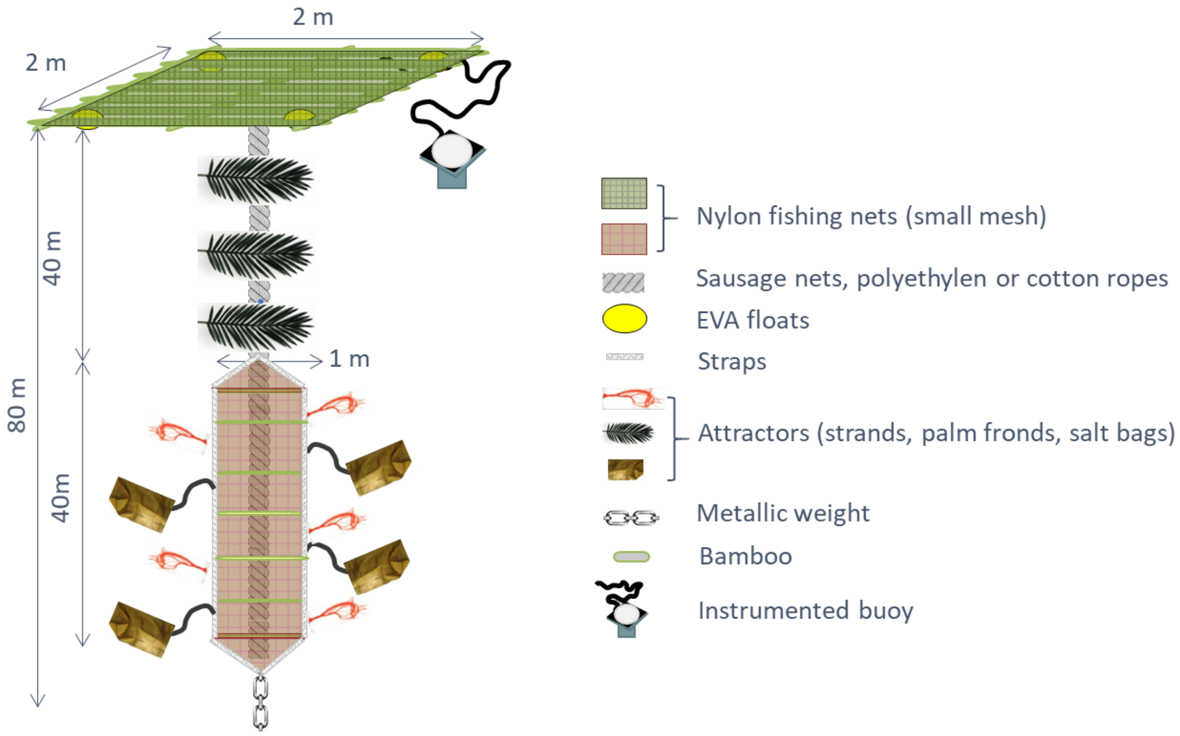

Figure 6. Design of non-entangling FADs used in 2017 by the purse seine fleet in the Atlantic Ocean.