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Lessons learnt from the first large-scale biodegradable FAD research experiment to mitigate drifting FADs impacts on the ecosystem

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ABSTRACT

Drifting Fish Aggregating Devices (dFADs) are currently made with synthetic and non-biodegradable materials contributing to the increase of marine litter and other potential ecosystem impacts. Tuna RFMOs have promoted the research and progressive replacement of existing FADs by non-entangling biodegradable FADs (bioFADs). Here, we present the results of the first large-scale biodegradable FAD project in the Indian Ocean to develop and implement the use of non-entangling biodegradable dFADs. The bioFAD tested were fully non-entangling without netting minimizing completely the risk of entanglement. Tested bioFADs significantly contribute to the reduction of the synthetic plastic-based materials, increase the use of biodegradable materials and reduce the total material weight used in FADs, reducing their overall ecosystem impacts. The results of testing 771 bioFADs in real fishing conditions, showed that the fishing performance regarding presence/absence of tuna around dFADs, first day of tuna detection, proportion of FADs occupied by tuna, biomass aggregation underneath the FADs and catch per set between bioFADs and conventional dFADs were similar. This provides support for the efficacy of bioFADs regardless of the degradation experienced by the biodegradable materials tested. Although some bioFADs lasted up to one year, the degradation of the biodegradable material was important and some bioFADs lost their original structure after the study period, suggesting the need to find alternative designs for bioFADs that will suffer less structural stress than those bioFADs made of biodegradable material but with conventional design. The lessons learnt in this large-scale trial will contribute to refining the future designs of biodegradable FADs.

1. Introduction

Tropical tuna purse seine fisheries fishing with drifting Fish Aggregating Devices (dFADs) catches around 60% of total 5 million tons of the tropical tuna catches worldwide [1], which underlines the importance of the dFAD fishery. Drifting FADs can be freely drifting in the ocean, and are usually constructed to have a surface structure (e.g., bamboo rafts and/or metal raft) and a submerged appendage or tail (traditionally, old nets hanging underneath; more recently, ropes or other non-entangling materials) that can reach 100 m depth globally, despite the size of the dFAD appendages are smaller in the Indian Ocean (e.g., 4–5 m on 60 % of the FADs while up to 50 m on 40 % of FADs) [2]. Currently, dFADs are usually constructed using plastic-derived materials (e.g., nylon nets, buoys and polypropylene ropes) and are equipped with satellite echosounder buoys which provide an estimate of the tuna biomass aggregated around the FAD and allow geolocating dFADs [3]. Although dFADs are not considered extractive fishing gears, they aggregate tunas and facilitate industrial tuna purse-seine operations increasing its

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efficiency. Globally, it is estimated that around ~100,000 dFADs are deployed every year [4]. Tuna Regional Fishery Management Organizations (RFMOs) have very large convention areas and, therefore, many FADs drift outside fishing grounds and are then lost. The dFAD loss rate is estimated to be around 44 %, which can be potentially increased to up to 90 %, as the fate of 46 % of FADs is unknown, in the Western and Central Pacific Ocean [5] and a minimum of 20% in the Atlantic and Indian Ocean [6,7]. There are three primary impacts associated with the structure of dFADs and lost and abandoned FADs, namely (a) entanglement associated with the use of wide mesh netting capable of enmeshing animals [8], (b) marine pollution related with the use of plastics and other non-degradable materials in their construction, and (c) other ecosystem impacts such as FADs stranding events in sensitive habitats (e.g., coral reefs) [9].

Drifting Fish Aggregating Devices were first introduced in the Indian Ocean in the early 90s [10]. Since then, the use of dFADs by the tropical tuna purse seine fishery has been progressively increasing up to 2015 [11] when FAD limitations started to be implemented in the region (IOT Resolutions 15/08, 16/01, 17/08). In the last decade, the Indian Ocean Tuna Commission (IOTC) has made efforts to eliminate dFADs with high entanglement risk characteristics, as this may negatively affect sensitive species like marine turtles and sharks [8], and other associated non-target species. The IOTC first defined procedures on FAD Management Plans through resolution 13/08, where Annex III called for the reduction of synthetic marine debris, by promoting the use of natural or biodegradable materials for FADs. In 2019, IOTC was the first tuna RFMO to adopt fully non-entangling dFAD design which prohibits the use of any netting material in its construction from 2020 onwards (Resolution 19/08). Similarly, tuna RFMOs in other oceans have also addressed these impacts and adopted several recommendations and resolutions to gradually replace existing FADs with non-entangling FADs and promote research on biodegradable FADs (ICCAT Recommendation 21–01, IATTC C-19–01, WCPFC CMM 2021–01).

FADs can be classified according to the type of materials and the configuration of the components used in their construction, and several FAD definitions have been proposed. For example, the International Seafood Sustainability Foundation (ISSF) defines four different FAD types [12]. The first three refer to their entanglement risk, focusing on the absence (i.e., Non-Entangling -NEFAD) or presence of netting material and mesh size (i.e., stretched mesh > or < 7 cm) in the FAD (i.e., High Entanglement Risk -HERFAD- and Low Entanglement Risk -LERFAD, respectively), while the fourth one (i.e., Biodegradable FAD) classifies FADs based on the use of natural or biodegradable materials (ISSF, 2019). The use of the terms natural or biodegradable to refer to those FADs is widely accepted by tuna RFMOs (IOTC Res. 19/08; ICCAT Rec. 21–01; IATTC C-19–01; and WCPFC CMM 21–01), and the definition of "biodegradable" materials for FAD construction is being discussed and preliminary adopted by some tuna RFMOs [13,14]. Moreover, different categories from 100 % biodegradable FADs to non-biodegradable FADs have also been adopted in the IATTC and the WCPFC [13,14]. Thus, the construction of biodegradable FADs is not straightforward, as biodegradable materials are subject to certain preconditions and there are different biodegradable FAD (bioFADs thereafter) definitions and categories in tuna RFMOs.

Although efforts were initially focused on eliminating the entangling features of dFADs, most of current floating objects are still made of synthetic and non-biodegradable materials (e.g., PVC, nylon ropes and small mesh pelagic fishing nets) contributing significantly to the increase of marine litter [15] and aggravating other potential impacts for the ecosystem, such as FADs beaching [16,17]. Thus, to address those impacts, tuna RFMOs have promoted the research and replacement of existing FADs with NEFADs that are made of biodegradable materials. As such, most RFMO FAD management measures encourage vessels to use biodegradable FADs [18]. For example, IOTC Resolution 19/02 encourages CPCs to transitioning to biodegradable FADs from 1 January 2022 and encourages their flag vessels to remove from the water, retain onboard and dispose of in port, all conventional FADs encountered (e.g., those made of entangling materials or designs).

However, an effective replacement of non-biodegradable FADs by those fully/partly biodegradable still requires investigation to solve important practical/technical aspects for the operationalization of the construction of these bioFADs, including the selection of appropriate biodegradable materials taking into account their durability, which for dFADs is at least one year [2]. Moreover, it requires key information on bioFADs behavior regarding their capacity for tuna aggregation, drifting performance, and their efficiency for fishing. Besides, the implementation of bioFADs is challenging as these biodegradable materials following international standards are subject to certain preconditions (e.g., ASTM Standard D6400, D6691, and EN13432 International Standard) [19]. Thus, tunaRFMOs should agree on useful biodegradable definitions to ensure harmonization of the term biodegradable to define the materials used for FAD construction [19].

In this process, IOTC adopted *Resolution 18/04 on biodegradable FAD experimental project*, which supported a large-scale biodegradable scientific research project to test the use of biodegradable materials and designs for the construction of drifting FADs in at-sea conditions. Thus, the European Union launched, in collaboration with IOTC, the project "Testing designs and identify options to mitigate impacts of drifting FADs on the Ecosystem (the bioFAD project)" to address current impediments and to support the implementation of non-entangling and biodegradable dFADs in the IOTC Convention Area. This project had the collaboration of all tropical industrial tuna purse seine fleets operating in the Indian Ocean (EU, Seychelles, Mauritius, and Korean fleets). The 28-month project addressed the problems associated to the current plastic-based FADs with the main purpose of testing biodegradable materials, designs, and their performance through the construction of bioFADs deployed in natural open ocean conditions. Ultimately, the project aimed to suggest potential biodegradable materials and designs providing recommendations to foster the implementation of bioFADs.

And to achieve those objectives, the project intended to:

(i) review the state of the art regarding the use of "conventional FADs" (i.e., entangling and non-biodegradable), "NEFADs" (i.e. non-entangling and non-biodegradable) and "bioFADs" (i.e., non-entangling and biodegradable),

(ii) evaluate the performance (e.g., lifetime and tuna aggregation behavior) of specific biodegradable materials and designs for the construction of FADs in real fishing conditions,

(iii) test, compare and measure the efficiency of bioFADs against current conventional NEFADs to aggregate tuna and non-tuna species at sea in "real" commercial fishing conditions,

(iv) assess the feasibility of using new biodegradable materials by the purse seine fleet and recommendation of an optimum bioFAD prototype.

The aim of this document is to present the results obtained at sea trials and discuss the lessons learnt and conclusions to inform on the possible transition to implement bioFADs in the IOTC region as requested by IOTC Resolutions 18/04 and 19/02.

2. Material and methods

2.1. Overall strategy

The objective of this large-scale experiment was to deploy 1000 bioFADs. The strategy was to deploy bioFADs in pairs along with conventional NEFADs currently being used for comparitive purposes. The deployment of bioFADs started in April 2018, followed by a quarterly organization of the seedings, and concluded in June 2019 (14 months). The project had the active assistance of 44 purse seiner vessels and several supply vessels operating in the Indian Ocean. In total, each purse seine vessel planned to deploy around 24 bioFADs and 24 conventional FADs (i.e., 6 + 6 by quarter).

2.2. BioFAD construction, deployment, data collection and comparison to NEFADs

2.2.1. Materials and prototypes for bioFADs construction

The methodology used for bioFAD construction, selection of biodegradable materials, design of prototypes, deployment strategy, comparison with NEFADs, as well as bioFAD and conventional FAD monitoring, data collection and reporting were agreed during a 2-day workshop with fishers. Information from previous workshops and studies examining the feasibility of different natural plant fibers for biodegradable dFAD construction were also used [20–23].

Several plant fibers such as cotton, sisal, hemp and linen were analyzed for the construction of ropes, and parameters like potential biodegradation, resistance, reproducibility, and availability in the market were assessed [20]. Previously, some small-scale trials were conducted by purse seine companies, ISSF and research institutes to test some of these plant fibers in bioFAD construction under real sea conditions in the Atlantic [24,25], Indian [26,27] and Pacific Oceans (pers. comm. M. Hall). Although some of these studies did not end with a clear recommendation of a particular biodegradable material, others have shown cotton ropes as one of the best options, as they retained a breaking strength of over 1000 kg. after 6 months [20]. Based on those results, it was decided to use 100 % cotton as the principal biodegradable material for both twined rope for the tail and canvas to cover the raft.

Three bioFAD prototypes (Fig. 1) were designed based on fisher's requirements and needs for FADs construction covering the different drifting performance characteristics that fishers seek with their conventional NEFADs in the Indian Ocean: superficial FADs (bioFAD prototype C), superficial FAD with medium-deep tail (bioFAD prototypes A1 and A2), and submerged high-deep tail and cage type submerged FAD (bioFAD prototypes B1 and B2, respectively).

2.2.2. Identification and deployment strategy for bioFADs and pairing conventional NEFADs

Traceability of bioFADs and their NEFADs pairs during their entire lifecycle was ensured by an identification system and deployment strategy. Experimental FADs were monitored through a specific FADs identification system. Each bioFAD had a unique double tag identification number (e.g., bioFAD 0001) for its entire lifetime. One tag was attached on the main structure (commonly named as raft) and the other on the echo-sounder buoy (Fig. 2), which tracks the position and amount of tuna schools aggregated underneath the FAD via satellite. This procedure ensured bioFAD traceability. In the Indian Ocean, FADs change ownership very often by changing the attached buoy (i.e., fishers

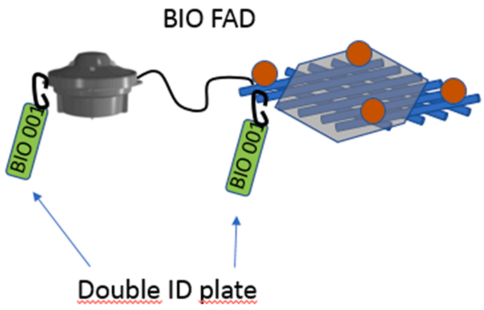
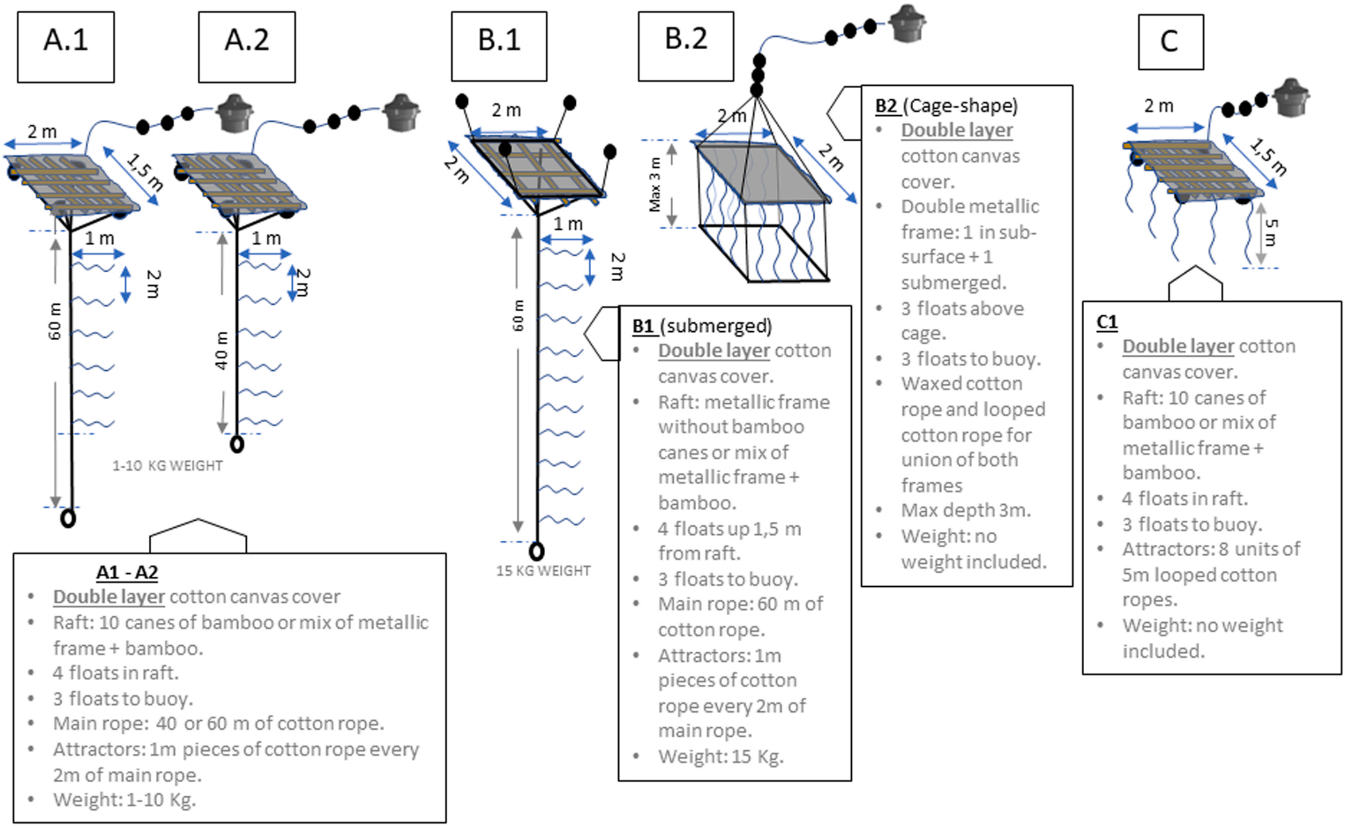


Fig. 2. Procedure to attach ID number plate to the bioFAD raft and to the echo-sounder buoy attached to the bioFAD.



A1 - A2

- Double layer cotton canvas cover
- Raft: 10 canes of bamboo or mix of metallic frame + bamboo.
- 4 floats in raft.
- 3 floats to buoy.
- Main rope: 40 or 60 m of cotton rope.
- Attractors: 1m pieces of cotton rope every 2m of main rope.
- Weight: 1-10 Kg.

B1 (submerged)

- Double layer cotton canvas cover.
- Raft: metallic frame without bamboo canes or mix of metallic frame + bamboo.
- 4 floats up 1,5 m from raft.
- 3 floats to buoy.
- Main rope: 60 m of cotton rope.
- Attractors: 1m pieces of cotton rope every 2m of main rope.
- Weight: 15 Kg.

B2 (Cage-shape)

- Double layer cotton canvas cover.
- Double metallic frame: 1 in sub-surface + 1 submerged.
- 3 floats above cage.
- 3 floats to buoy.
- Waxed cotton rope and looped cotton rope for union of both frames
- Max depth 3m.
- Weight: no weight included.

C1

- Double layer cotton canvas cover.
- Raft: 10 canes of bamboo or mix of metallic frame + bamboo.
- 4 floats in raft.
- 3 floats to buoy.
- Attractors: 8 units of 5m looped cotton ropes.
- Weight: no weight included.

Fig. 1. BioFAD prototypes designs and the details of materials and dimensions for each of them.

intercept and appropriate other vessels' FADs by changing the old echo-sounder buoy for their own buoy), and thus, the correct monitoring and traceability was difficult. To avoid the loss of traceability when FAD ownership was changed, every time there was a buoy replacement on a particular marked bioFAD, the plate with the ID number attached to the buoy was changed from the "old" buoy to the newly attached buoy, and the new buoy ID was noted accordingly.

To test, compare and measure the efficiency of new bioFADs in terms of aggregating tuna and non-tuna species against conventional NEFADs designs, each bioFAD deployment was accompanied by a deployment of a conventional NEFAD. Both deployments were conducted within a distance lower than 2 miles, following fleet's regular FAD deploying strategies. The deployed pair of bioFAD and conventional NEFAD were of similar design (i.e., same prototype) and both carried out an identification plate with the same number for their traceability to allow comparison among both FAD types (Fig. 3). The comparison of the efficiency of new FAD prototypes was done by using the same model of echo-sounder buoy attached to bioFADs and its pairing conventional NEFADs, as well as with the data collected in the logbooks (i.e., catches). Similar to the bioFADs, every time there was a buoy replacement in NEFADs, the plate with NEFAD ID number attached to the buoy was changed from the "old" buoy to the newly attached buoy, and the new buoy ID was noted accordingly.

2.2.3. Procedures for data collection and reporting

All the information related to the activities with the experimental FADs (i.e., new deployment, visit, buoy exchange, set, recovery, modification, and redeployment) were collected by the fleet and onboard scientific human observers (when present). All this information was reported using an email template and a dedicatedly designed form for skipper and observers, which was submitted to scientist as quickly as possible. These forms were also used to gather the information regarding bioFAD and NEFAD structure degradation status, using a simple value scale to assign the stage of degradation to each of FAD components.

Each time there was a new deployment or an encounter with a bioFAD or its conventional NEFAD pair, the following information was collected by the fleet and/or observers:

- ID number of bioFAD or conventional NEFAD.
- Echo-sounder buoy code number.
- When buoy replacement occurs, the new echo-sounder buoy ID code attached.
- FAD degradation information of bioFAD and conventional NEFAD pair.
- Pictures of newly deployed or encountered bioFAD and NEFAD, when possible.

The information regarding bioFAD and NEFAD degradation status was gathered using the criteria described in Table 1. Data collection followed the following procedure:

(i) Every time the net was set around a bioFAD or conventional NEFADs, the structure was lifted out of the water, when possible, to carry out the assessment of the status of degradation of the whole structure.
(ii) The degradation status was determined by the observer, when present. Otherwise, it was done by the skipper or captain.
(iii) All parts of the FAD structure were checked and described in the form (Table 1). A scale from 1 to 4 was applied to evaluate the degradation status of the FADs (1 = Very good, not damaged; 2 = Good, a bit damaged; 3 = Bad, quite damaged; 4 = Very bad, close to sinking; 5 = Missing-absent).
(iv) Every time there was a replacement of any part of the bioFAD and conventional NEFAD pair, this was also reported in the form.
(v) In the case of bioFADs, any damaged parts susceptible of replacement were replaced by agreed biodegradable materials and structures.

2.2.4. Procedures for comparing bioFAD and NEFAD efficiency

BioFAD efficiency was assessed by analyzing and comparing different parameters between experimental FADs (bioFADs vs. NEFADs): drifting patterns, lifespan, tuna presence/absence and biomass indicators given by echo-sounder buoys, and catch data.

BioFAD and NEFADs drifting patterns and lifespan were analysed using FAD buoy echo-sounder position data. Tuna presence and absence were estimated using a supervised classification of acoustic data from FAD buoy echo-sounder biomass data [28], but only employing one buoy model (i.e., M3i) for which the supervised classification was available. The data filtering process followed the protocols defined in [28,29]. Echo-sounder buoy data was also used to estimate the tuna biomass aggregation around FADs from acoustic energy values [30].

3. Results

3.1. Experimental FAD deployments and degradation of FAD materials

A total of 771 bioFADs were deployed together with their conventional NEFADs pairs by the participating fleets in the Indian Ocean. This represented 77 % of the initially planned goal of 1000 bioFAD deployments. From the total of 771 bioFADs deployed, 71 % corresponded to A1 prototype, 18 % to A2, 4 % to B1, 2 % to B2, and 5 % to C1. Fig. 4 shows the deployment effort which was not homogeneous throughout the experimental period. For example, during the first months few bioFADs were deployed by the fleet for different reasons, including reparation at dry dock, stop of fishing activity due to yellowfin (*Thunnus albacares*) quota limitation, or delay in the coordination of fishing companies involved in the construction of the experimental FADs. Afterwards, during the second quarter, the deployment ratio increased up to 87 % of programmed experimental FAD deployment. In the following quarters the deployment effort decreased again to 65 %, 47 % and 50 % respectively of the planned FAD seeding. Some vessels kept deploying bioFADs beyond the established period to recover accumulated delays in

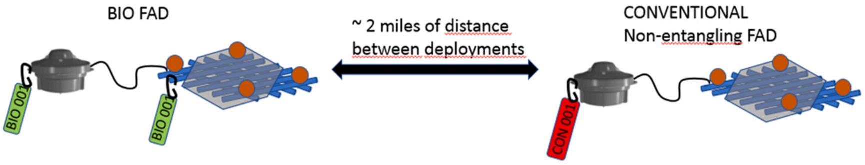
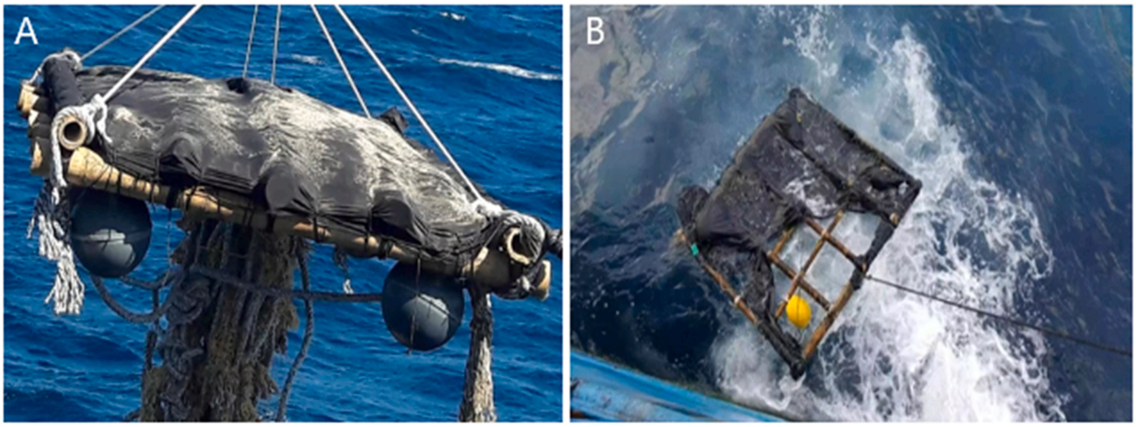


Fig. 3. Deployment and monitoring strategy for the bioFAD and its NEFAD experimental pair.

Table 1

Degradation status information of bioFAD and conventional NEFAD pair. This information was collected to assess the status of bioFAD and NEFAD structures included in an email template provided to the fishing fleet. Two illustrative photographs of the bioFAD flotation structure degradation stage 1 and 3 are included in the table.

BioFAD/NEFAd degradation stages classification						
Floating part	**FAD structure**	**1**	**2**	**3**	**4**	**5**
	Floats	Brand-new. No signs of damage	It shows certain damage	It shows clear damage affecting its floatation	Float damaged, not providing floatability. Replacement required	Component is missing
	Bamboo	Brand-new. No signs of damage	Bamboo cane shows certain damage. There are small cracks visible	Bamboo cane shows clear damage affecting flotation. Cracks clearly visible	Bamboo canes damaged, they do not fulfill their flotation function. Replacement required	Component is missing
	Pallet/ Metallic frame	Brand-new. No signs of damage	It shows certain damage	It shows clear damage affecting its structure and flotation	Pallet damaged, wooden plank broken or loose, not providing stiffness nor floatability. Replacement required	Component is missing
	Cover/ Canvas	Brand-new. No signs of damage (figure A)	It shows certain damage. There are breaks in the tissue	It shows clear damage, cover is ripped affecting to the shadow (figure B)	Cover damaged, it does not fulfill its function of covering FAD and shade. Replacement required	Component is missing
Hanging part	**Main rope**	Brand-new. No signs of damage	It shows certain damage	It shows clear damage affecting to its strength	Main rope damaged, it does not do its function. Replacement required	Component is missing
	Looped rope/ Attractor	Brand-new. No signs of damage	It shows certain damage	It shows clear damage affecting to its function as attractor	Rope damaged, it does not do its function as attractor. Replacement required	Component is missing
	Weight	Brand-new. No signs of damage	It shows certain damage	It shows clear damage affecting to its function as weight	Weight damaged, it does not do its function. Replacement required	Component is missing



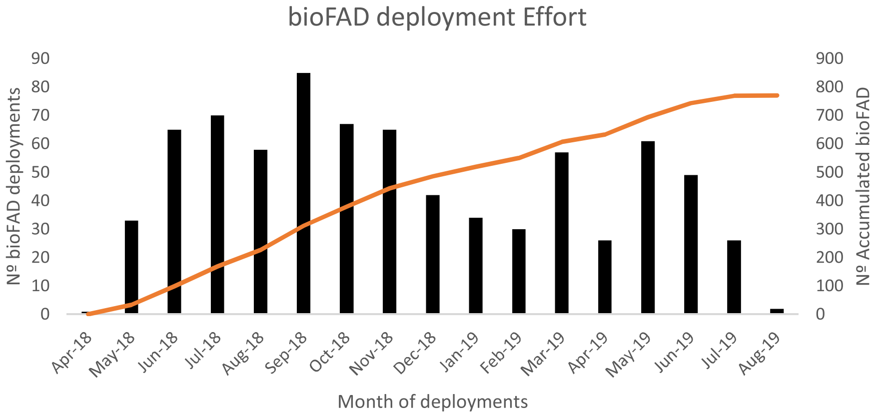


Fig. 4. The number of bioFADs deployed by month (bars) and accumulated number of deployments (red line).

previous months (deployments in July and August 2019).

The spatial distribution of bioFADs, and NEFADs pairs, deployments between April 2018 and August 2019, covered the principal fishing regions of the western Indian Ocean and followed a seasonally balanced deployment strategy covering all quarters (Fig. 5).

The total biodegradable and synthetic materials used for bioFAD and their equivalent NEFADs construction by FAD prototype was also assessed. For that, both bioFAD and their equivalent NEFAD prototypes were characterized, describing the type of material and dimensions for each FAD component (Annex I). As shown in Table 2, bioFAD prototypes

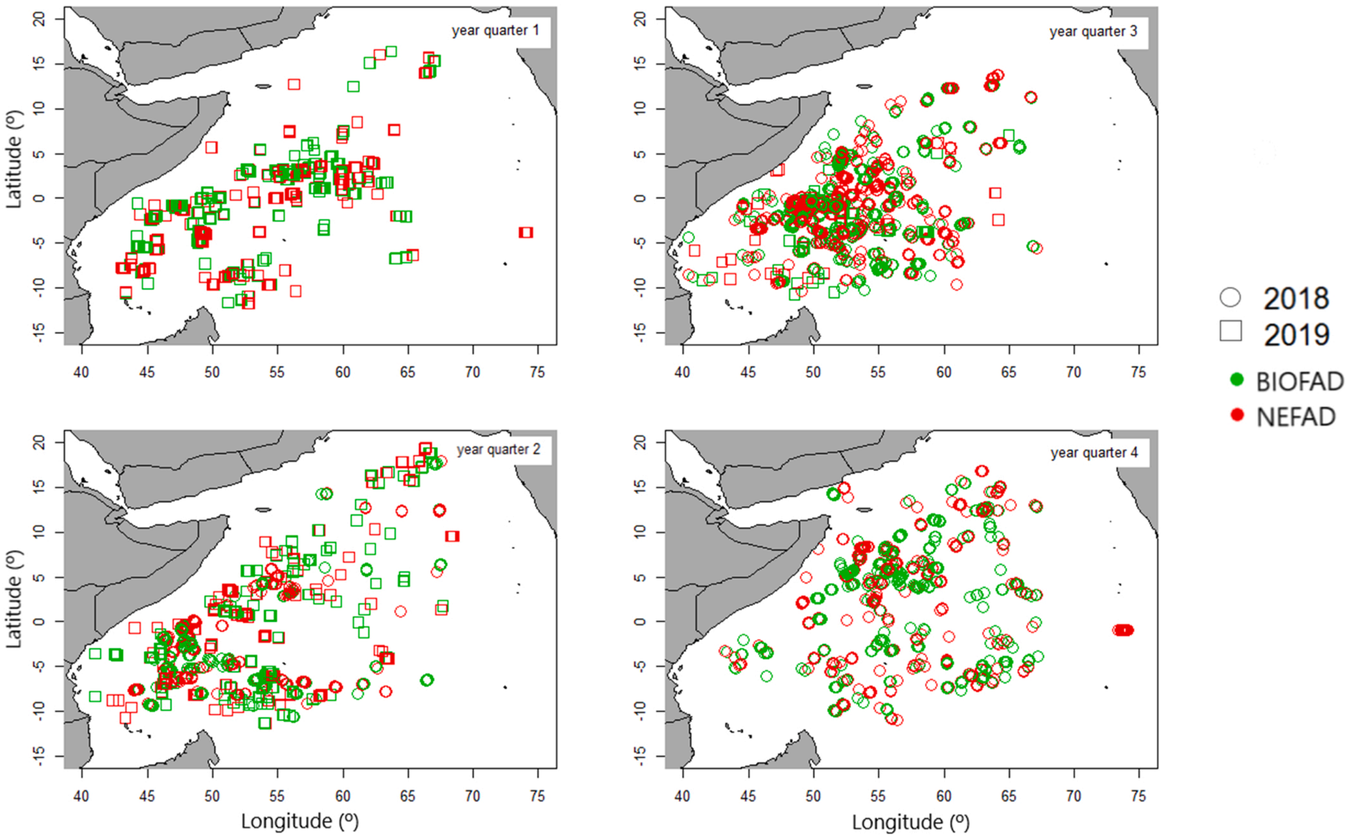


Fig. 5. Spatial distribution of new deployments of bioFADs (green) and conventional NEFADs pairs (red) by quarter.

Table 2
Data on total weight of material used for bioFAD and equivalent NEFAD construction. Weight of biodegradable and synthetic materials used in both types of FAD construction. Comparison (in percentual variation) between bioFAD and equivalent NEFAD in terms of total and synthetic materials.

FAD material	FAD prototype	Total weight (kg)	Biodegradable material (kg)	Synthetic material (kg)	Change of weight bioFAD/ NEFAD (%)	Change of synthetic material weight bioFAD/NEFAD (%)
BioFAD	A1	67,6	47,1	20,5	-44 %	-81 %
NEFAD		121,4	12	109,4		
BioFAD	A2	60,1	39,6	20,5	-50 %	-81 %
NEFAD		121,4	12	109,4		
BioFAD	B1	79,4	48,9	30,5	+ 27 %	-51 %
NEFAD		62,6	0	62,6		
BioFAD	B2	48,4	15,9	32,5	-11 %	-40 %
NEFAD		54,4	0	54,4		
BioFAD	C1	46,4	30,9	15,5	+ 1 %	-54 %
NEFAD		45,9	12	33,9		

A1, A2 and B2 required less material (in kg) for their construction in comparison to their equivalent NEFADs, with a reduction of 44 %, 50 % and 11 %, respectively. In the case of bioFAD prototypes B1 and C1, an increase in total material weight (27 % and 1 %, respectively) was observed in comparison with their equivalent NEFADs. However, all bioFAD prototypes reduced the amount of synthetic materials used for their construction. For instance, prototype A1, the one most used by the fleet, required 81 % less synthetic materials than its equivalent NEFAD.

To identify the pros and cons of each biodegradable material (i.e., cotton canvas of the raft, and two type of cotton ropes of the tail), and to compare them with their synthetic equivalents, the degradation status for each FAD component (e.g., surface, tail, etc.) was used. A small number of degradation status were submitted by the fleet, which could be due to the usual fishing strategy in which visited FADs are rarely lifted out of the water. This has limited the material degradation assessment, particularly in those months when observations were especially low. Fig. 6 shows the stage of degradation of the cotton canvas (i.e., the component used to cover the raft as an alternative to netting materials or synthetic raffia) started to suffer significant degradation already in the first and second months at sea. This degradation further increased in the third and fourth months, when more than 50 % of the observations estimated that the cotton canvas of bioFADs were in a “bad”, “very bad” or “missing/absent” stages. Similar high degradation patterns were also observed in the fifth and sixth months at sea. Contrarily, the synthetic material used to cover the raft in NEFADs, showed better performance than the biodegradable material and kept in good condition at least until the sixth month at sea. Afterwards, the number of observations sharply decreased and was too low to

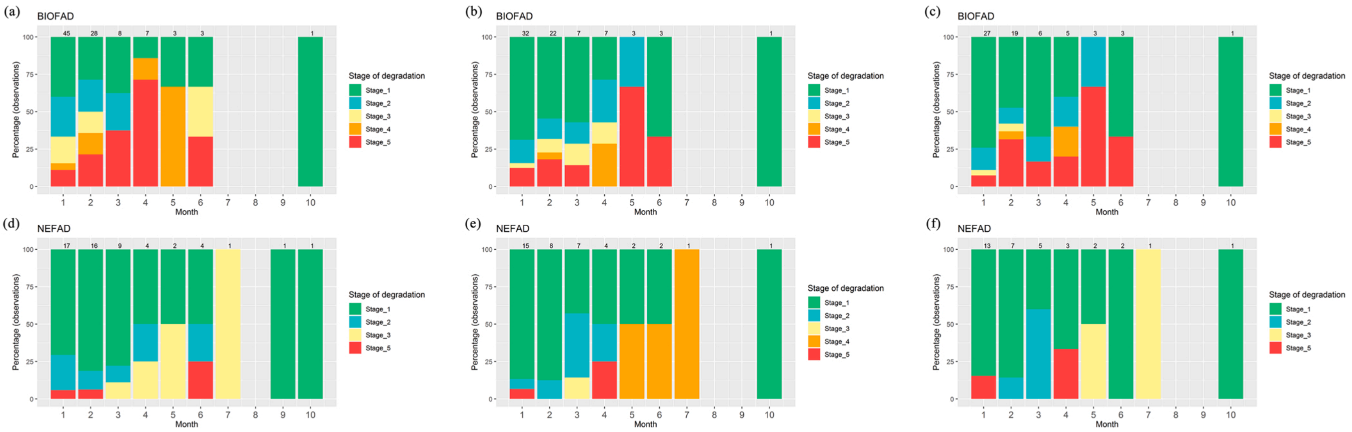


Fig. 6. Degradation status for the cotton canvas used in the raft (A), main cotton rope of the tail (B) and the cotton rope used as attractors (C) for bioFAD (upper panels) and synthetic material used as cover (D), tail (E) and attractors (F) for NEFAD (bottom panels). Stage 1 =Very good; Stage 2 = Good; Stage 3 = Bad; Stage 4 = Very bad; and Stage 5 = Missing-absent. The number of observation in each FAD component by month are provided on top of each bar.

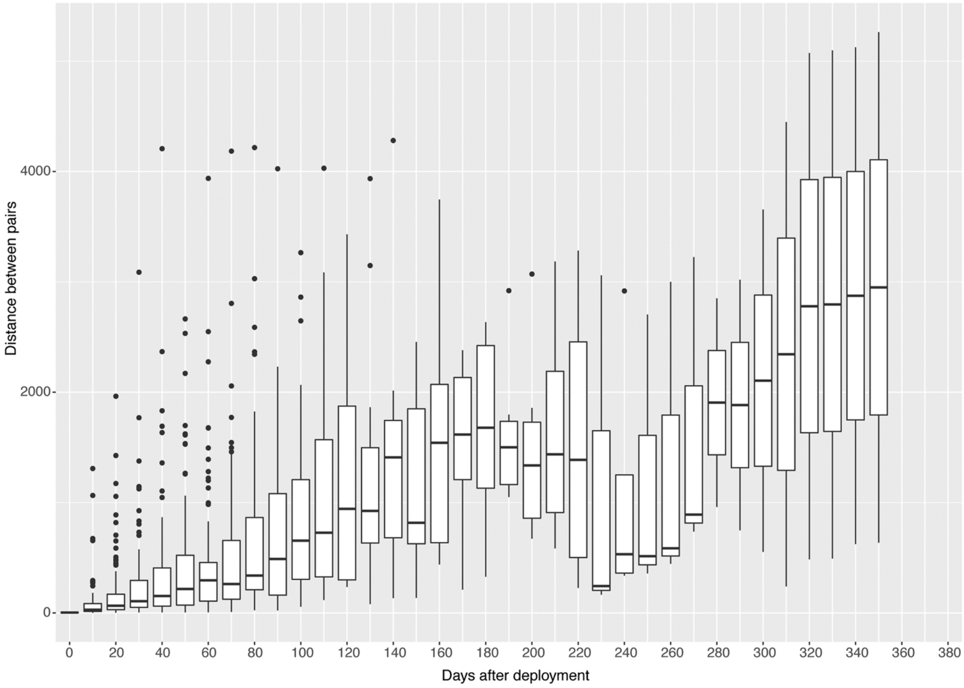


Fig. 7. Distance between bioFAD and NEFAD pairs (in nautical miles; y-axis) relative to the time after deployment (in days; x-axis).

adequately infer degradation status.

The degradation of the cotton rope (i.e., principal component of the submerged part of the FAD's tail) was less pronounced compared to the cotton canvas of the raft (Fig. 6). The degradation status for the cotton rope was "very good" or "good" quality until the fourth month at sea. However, in 10–20 % of the observations the "absence" of this material was reported during the first, second and third months at sea. By the fifth month the "absence" stage increased up to 70 %. Contrary to what was expected, the synthetic plastic alternative used as the tail in NEFADs, was also reported to be in "very bad" condition by the sixth month at sea. Similar results were observed for the looped cotton rope segments (i.e., components used as attractors tied to the main tail rope). The degradation status for this secondary rope was estimated to be in "very good" or "good" quality until the fifth month at sea. However, this component also showed in some cases high percentages of "absence" during the initial months at sea, especially during the fifth month when values increased up to 70% of the observations.

3.2. BioFAD efficiency: Drifting patterns, lifespan, tuna presence/absence, biomass aggregation underneath, and catch data

3.2.1. BioFAD vs NEFAD drifting pattern

The drifting pattern of experimental FADs was assessed by pairs (bioFADs vs NEFADs) without considering the effect of area, season of deployment or prototype. High variability in the drifting patterns was observed with (i) pairs following totally different drifts, (ii) pairs following partly similar drifts, and (iii) pairs following very similar drift patterns. Fig. 7 shows the distance (nautical miles) between pairs of

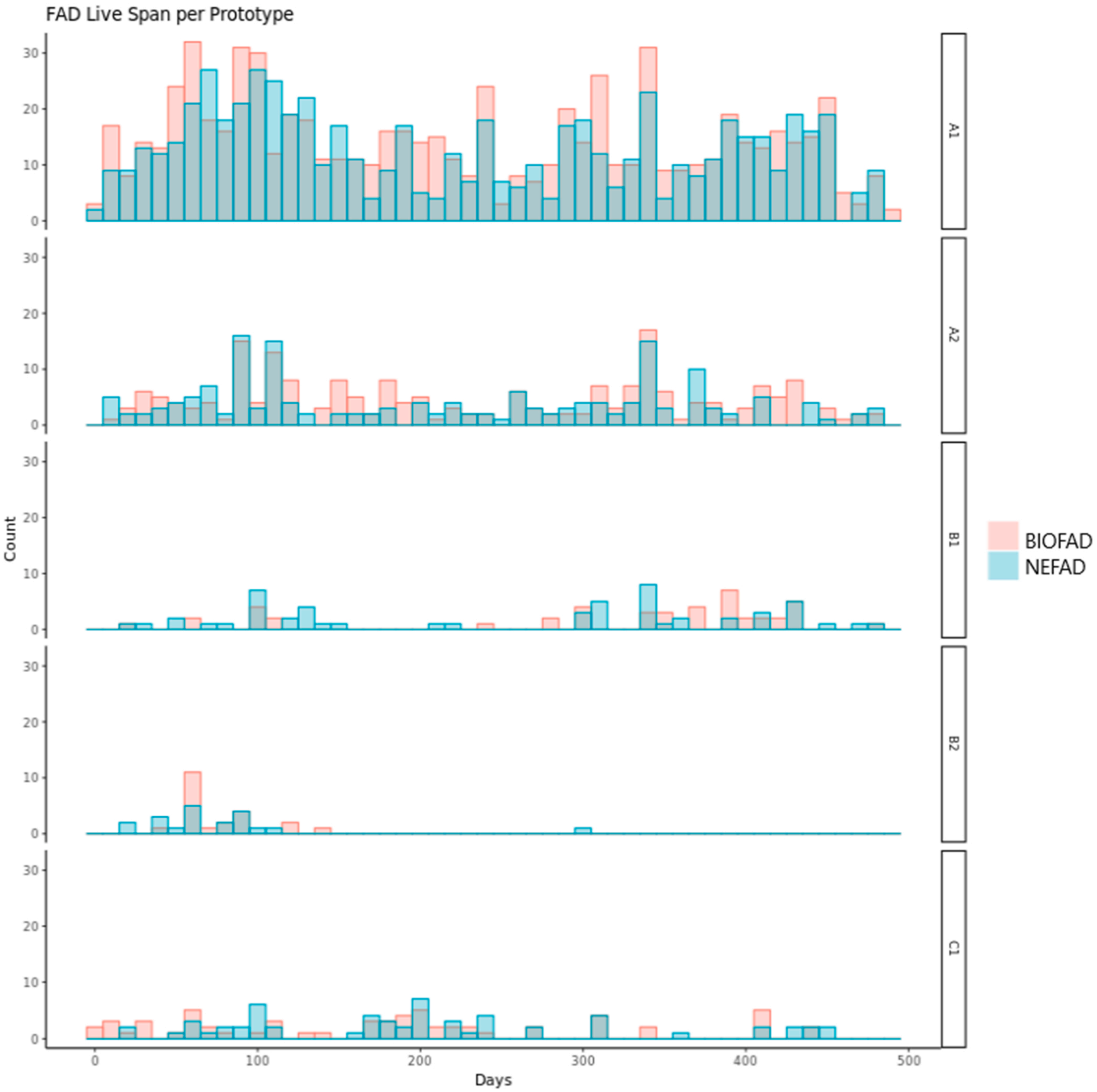


Fig. 8. Lifespan of bioFADs (red) NEFADs (green) by prototype.

Table 3
Lifespan data by FAD type (bioFAD and NEFAD) and prototypes.

FAD type	Prototype	Mean (days)	Min	Max	± SD
BioFAD	A1	191	1	483	145
BioFAD	A2	151	1	472	119
BioFAD	B1	242	15	432	166
BioFAD	B2	70	37	139	24
BioFAD	C1	161	3	436	146
NEFAD	A1	209	1	493	146
NEFAD	A2	177	5	483	132
NEFAD	B1	180	15	432	147
NEFAD	B2	75	22	139	31
NEFAD	C1	182	16	448	135

experimental FADs (bioFADs vs NEFADs) after the deployment. The distance of bioFAD and NEFAD pairs increased and then decreased during their lifecycle at sea, although an overall increase of distance between pairs with days after deployment was observed.

3.2.2. BioFAD vs NEFAD lifespan

The lifespan of experimental FADs (bioFADs and NEFADs) was defined as the period (in days) between the day of initial deployment and the day when the FAD was considered no longer active. The latter was estimated as the day when the FAD was eliminated/retrieved and/or the attached buoy was deactivated and no longer tracked. This information was provided by the vessel and/or buoy suppliers interacting with a particular marked FAD. All prototypes, for both FAD types, showed a maximum lifespan longer than 1 year (maximum lifespans

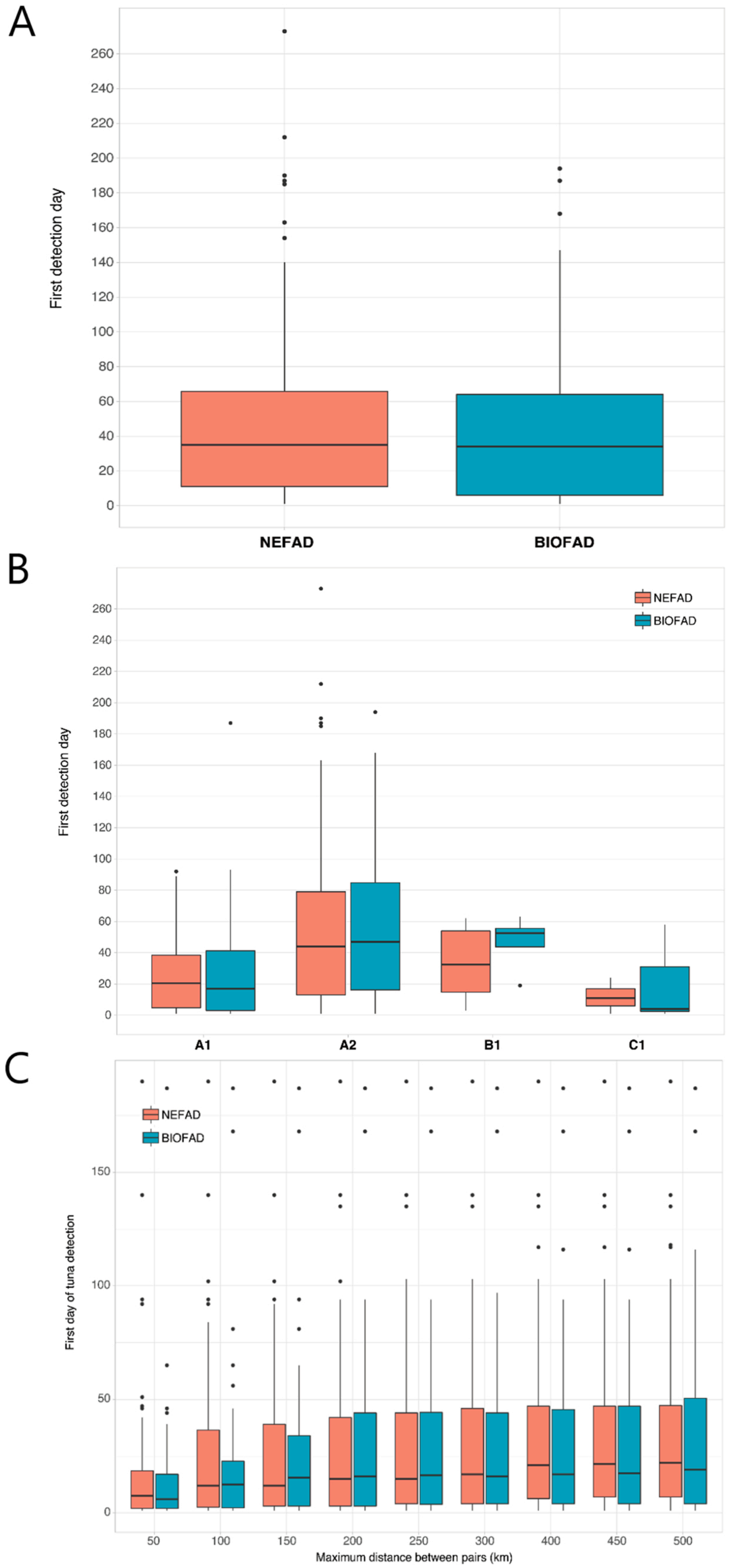


Fig. 9. First day of tuna detection: (a) by type of FADs (upper panel), (b) by FAD type and prototype (middle panel), and (c) by type of FADs (bioFAD and NEFAD) and distance between pairs (bottom panel).

were 483 days and 493 days for a bioFAD and a NEFAD, respectively), except for the prototype B2 which had a very limited number of deployments during the experiment (Fig. 8).

Highest mean lifespan values were observed in bioFADs B1 and A1, with 242 and 191 days, respectively (Table 3). In the case of NEFADs, prototype A1 and C1 showed the highest mean lifespan values with 209 and 182 days, respectively (Table 3). This analysis did not consider the degradation process of each FAD components, as the assessment of the final condition of those FADs lasting over a year was not always possible. In addition, the differences of number of FADs observed by prototype are in some cases important and, thus, comparisons between FAD prototypes should be considered with caution.

3.2.3. *Tuna presence/absence*

Tuna presence/absence assessment [28,31] to study the colonization time and lifetime of the fish aggregation underneath FADs was conducted by pairs (bioFADs and its NEFADs pair). The information available in the database, once filtered, resulted in 202 comparable pairs (A2 = 123; A1 = 62; B1 = 7 and C1 = 10). The pairs were compared by the distance between both pairs at a given time and the estimated distance was then grouped in predetermined distance ranges, such as less than 50 km, 100 km, 150 km, and so on, being the successive ranges accumulative, i.e., the next larger distance group includes the previous ones.

3.2.3.1. First day of tuna detection on FADs. Fig. 9a shows the values of first tuna detection day among FAD types. Although similar patterns of first tuna detection were observed in both FAD types (bioFADs and NEFADs), presence of tuna appeared to be slightly faster in NEFADs than in bioFADs (Fig. 9a). However, no statistically significant differences were found between both FAD types (Kruskal-Wallis chi-squared = 0.14349, df = 1, p-value = 0.7048). More variability was observed when this indicator was assessed by FAD type and prototype (Fig. 9b). Nevertheless, when statistical tests were applied to observed differences between prototypes (only A1 and A2 were considered for the test, for the rest of prototypes there were not enough data) no statistically significant differences were found between FAD types by prototype (prototype A1: Kruskal-Wallis chi-squared = 0.23799, df = 1, p-value = 0.6257; prototype A2: Kruskal-Wallis chi-squared = 0.073504, df = 1, p-value = 0.7863). First tuna detection was also considered according to FAD type and the distance between pairs and the results showed a similar but slightly faster presence of tuna, measured in days after deployment, in bioFADs than NEFADs. This pattern was kept until 250 km-s, from that distance onwards a slightly faster tuna presence was observed in NEFADs than bioFADs (Fig. 9c).

3.2.3.2. Proportion of FAD occupation by tuna. Presence/absence data were also analyzed to estimate the proportion of FADs occupied by tunas, considering the FAD type and prototypes. In terms of FAD occupation by tuna aggregation, the percentage of NEFADs occupied by tunas surpassed the percentage of bioFAD with tunas (Fig. 10). Similar to previous results, NEFADs showed higher proportions of FAD occupation by tunas, being this difference statistically significant (Kruskal-Wallis chi-squared = 6.5734, df = 1, p-value = 0.01035) (Fig. 10a). Differences were also observed when FAD occupation was assessed by FAD type and prototype. In this case, NEFADs prototypes A2 and B1 showed higher tuna occupancy values than bioFAD counterparts, but not for prototypes A1 and C1, which showed similar patterns (Fig. 10b). However, the statistical test applied to prototype A1 and A2 showed no significant differences between FAD type and prototypes (prototype A1: Kruskal-Wallis chi-squared = 3.5805, df = 1, p-value = 0.05846; prototype A2: Kruskal-Wallis chi-squared = 0.47523, df = 1, p-value = 0.4906). Prototypes B and C had unbalanced sample sizes and, therefore, were not considered for this analysis.

Finally, pairs were compared regarding the distance between both FAD types at a given time. Estimated distance differences were grouped in determined distance ranges, such as less than 50 km, 100 km, 150 km etc. being the successive ranges accumulative, i.e., the next larger distance group includes the previous ones. In Fig. 11 higher proportions of FADs occupied by tunas are observed for NEFADs in comparison with bioFADs as the distance between pairs increases. The proportion tended to increase when the distance between pairs was higher than 150 km, which is consistent with previously results on the first day of tuna detection according to the distance between pairs.

Binary choice analysis was conducted to illustrate the competition between the two types of FADs by calculating the percentage of time only one type of FAD had tuna presence, the percentage of time both types had tuna presence and the proportion of time none of the types had presence of tuna. For this comparison only those FADs with at least 30 days at sea after deployment and a maximum distance of 500 km between pairs were considered. In 53 % of the cases, both pairs had tuna presence; in 13 % of pairs both, bioFADs and NEFADs, showed no tuna presence; in 21 % of the cases NEFADs had tuna presence while its bioFAD pair did not; and in 13 % the opposite pattern was observed.

3.2.4. *Biomass aggregation estimation*

Echo-sounder buoy acoustic data was analyzed by pairs, when acoustic data for both FADs of a pair existed, grouped by month since deployment day and distance between pairs. For this analysis the information derived from different buoy models was analyzed separately, i.e., data from M3i, M3i+ and ISL+ models. Biomass was estimated as the 99th percentile of daily echosounder biomass signal or estimation.

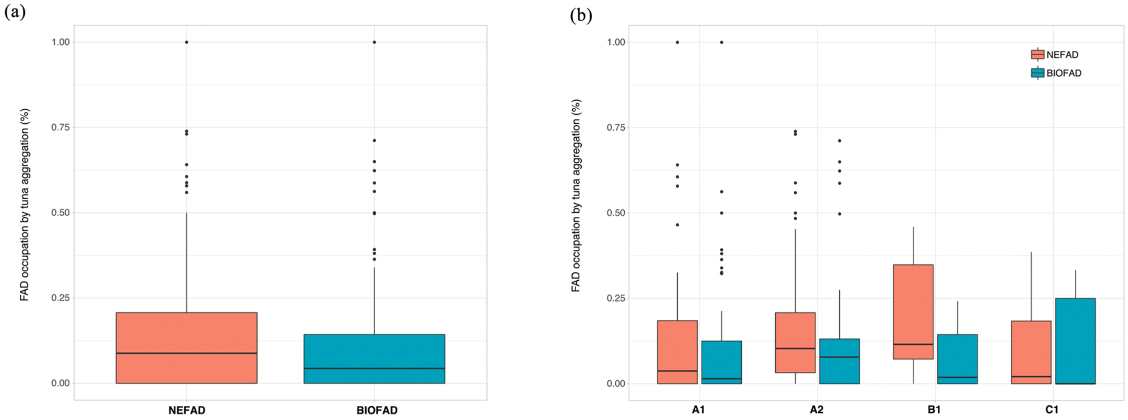


Fig. 10. Proportion of FAD occupied by tuna aggregation: (a) by FAD type (left panel) and (b) by FAD type and prototype (right panel).

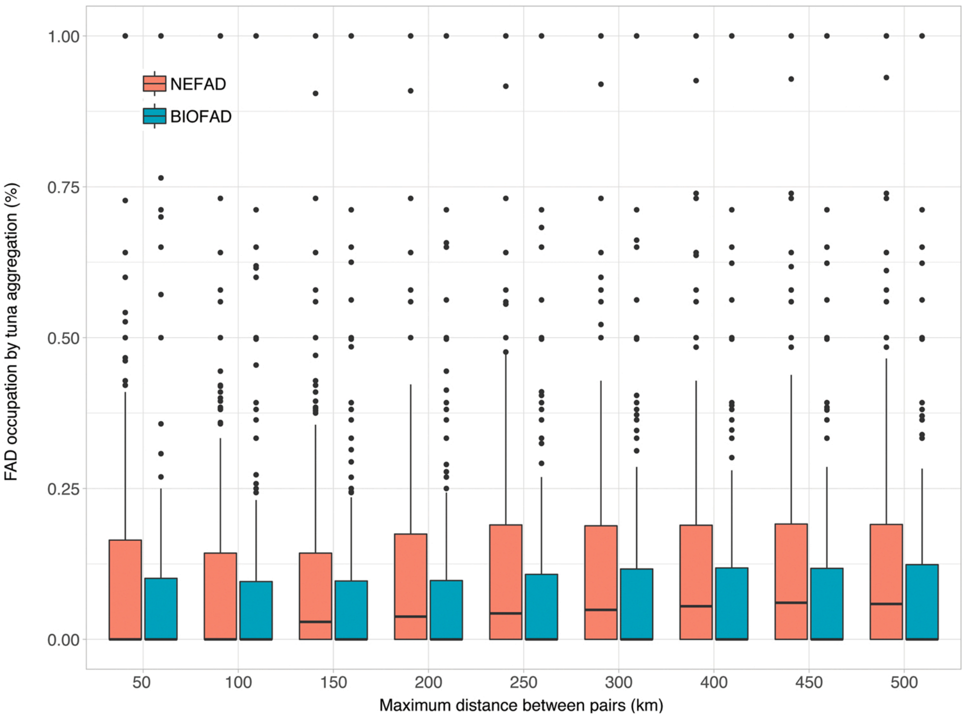
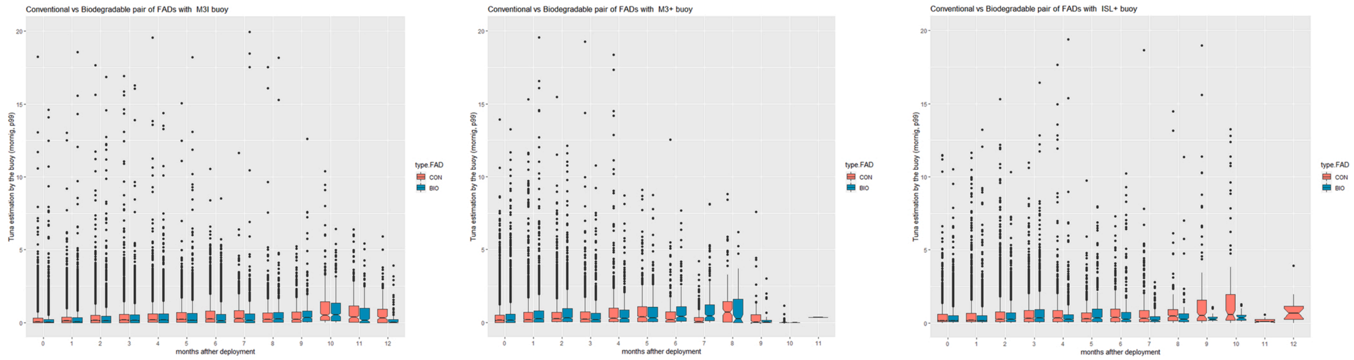
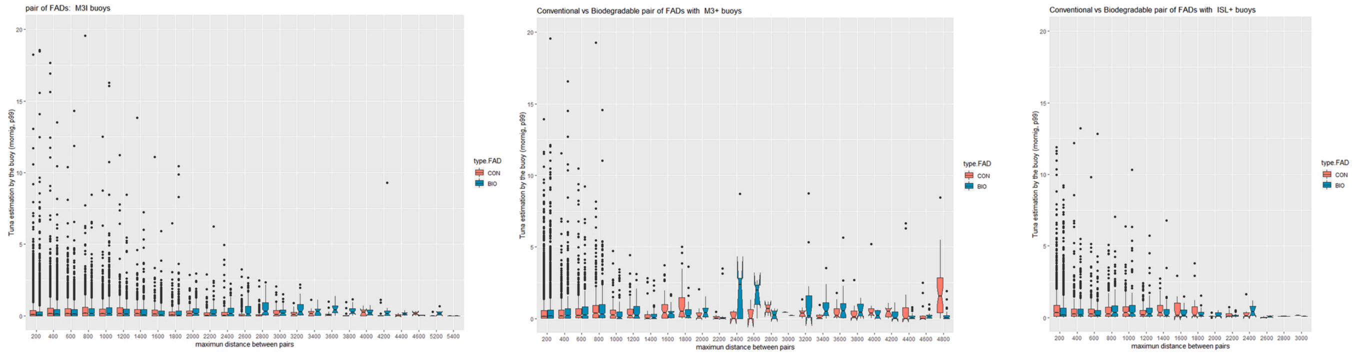


Fig. 11. Proportion of FAD occupation by tunas by FAD type and by distance range (km) between FAD pairs.



(a) (b) (c)

Fig. 12. Tuna biomass estimation (in tons) using echo-sounder data by FAD type and by month since first deployment for buoy models: (a) M3i (left panel), (b) M3i+ (middle panel), and (c) ISL+ (right panel).



(a) (b) (c)

Fig. 13. Tuna estimation (in tons) by FAD type and by the distance between pairs. Biomass estimation was done using acoustic energy from buoy model: (a) M3i (left panel), (b) M3i+ (central panel), and (c) ISL+ (right panel).

Only those samples obtained around sunrise, between 4 a.m. and 8 a.m., were considered. These time segment samples are supposed to capture echo-sounder biomass signals that better represent fish abundance under the FADs, as it is the time of the day when tunas are observed to be more closely aggregated under FADs [32–34].

Overall, very low tuna biomass estimations for both FAD types were observed for the three buoy models (Fig. 12). In the three buoy models (M3i, M3i+, ISL+), biomass estimation for both FAD types resulted in similar values during the first months after deployment. Afterwards, in months five and six, biomass values showed more variability between pairs and different patterns were observed depending on the buoy model and brand. For example, M3i (Fig. 12a) and ISL+ (Fig. 12c) showed higher values in NEFADs, while with M3i+ (Fig. 12b) the pattern was not clear, showing higher values in bioFADs and NEFADs depending on the month. These results are in line with the outcome of previous analysis on tuna presence/absence.

Tuna biomass estimation was also analyzed by FAD type and distance between pairs. For the three buoy models (M3i, M3i+, ISL+), tuna biomass estimations were low and differences between pairs were mostly constant when distance between them was lower than ∼2000 km (Fig. 13). Over this distance, biomass values showed more variability between pairs, and different patterns were observed depending on the buoy model and brand. For example, M3i and M3i+ models showed higher values in bioFADs than in NEFADs, while with model ISL+ the pattern was not clear when the distance between pairs increased. The number of observations for pairs having large distances between them decreased as the distance increased, which may limit the interpretation of the results. However, according to Fig. 13, as pair distances increased the tuna aggregation values obtained for bioFADs were higher. While this can be a bias caused by the low number of observations, it could also be explained by those bioFADs being located in a more productive area than their NEFAD pairs.

3.2.5. Catch data

The efficiency of bioFADs in comparison with NEFADs was further compared through the analysis of tuna catch data. In total, from April 2018 to August 2019, 68 fishing sets were associated to these experimental FADs, 36 to bioFADs and 32 NEFADs pairs. This is a positive result itself as the rate of fishing set events on bioFADs and homologous NEFADs was similar. There were no significant differences (at 5 % level) among medians of catches (i.e., tons of tuna by set) among FAD types when all species were considered jointly (P value = 0.808). The spatio-temporal effect was not considered on this analysis. Most of the sets were conducted in A1 prototypes in both FAD types which could be due to its higher number of deployments relative to others. Indeed, when the number of sets by each prototype was analyzed relative to the number of deployments of each prototype, no differences among them were observed (Table 4). The low number of sets performed on some of the other prototypes prevents such comparative analysis.

Table 4
Catch data (maximum and mean in tons), number of sets, number of deployments and % of use by FAD type and prototype.

	BioFAD	NEFAD			
Max (tons)	150	225			
Mean (tons)	27.96	44.20			
± SD	33.61	48.66			
Sets	36	32			
Deployments	771	736			
% use	5%	4 %			
BioFAD	A1	A2	B1	B2	C1
Max (tons)	150	75	0	0	0
Mean (tons)	32.21	40.00	0	0	0
± SD	34.36	49.49	–	–	–
Sets	26	5	2	0	2
Deployments	545	142	29	18	37
% use	5 %	4 %	7 %	0 %	5 %
NEFAD	A1	A2	B1	B2	C1
Max (tons)	98	225	0	0	70
Mean (tons)	29.38	75.71	0	0	67.50
± SD	23.83	81.56	–	–	3.53
Sets	21	8	0	0	3
Deployments	497	128	43	20	42
% use	4 %	6 %	0 %	0 %	7 %

4. Discussion

Due to the extensive use of dFADs by the tropical tuna purse seine fisheries and their potential high rate of lost and abandoned [6,7,35], tuna RFMOs strive to minimize their impacts on the ecosystem, such as entanglement and ghost fishing [8], accumulation of plastic and marine litter at sea, damage on sensitive areas (e.g., coral reefs) [7] and disturbance of other economic activities (e.g., tourism).

It is estimated that between 4.8 and 12.7 million metric tons of plastic enters the coastal waters and oceans annually [36], from which at least 22% is originated from ocean activities [37]. Moreover, Morales-Caselles et al. (2021) estimated that 61 % of the marine litter items found in the open oceanic waters was originated from Abandoned, Lost, or otherwise Discarded Fishing Gear (ALDFG) (e.g., synthetic ropes, strings, threads, buoys and nets). Furthermore, dFADs were estimated to have the third highest gear-specific ALDFG relative risks which would contribute to the impacts mentioned above [38]. Therefore, dFAD global conservation efforts and improvements could be achieved through application of ALDFG sequential mitigation hierarchy (i.e., avoidance, minimization and remediation) and implementing effective monitoring, surveillance and enforcement systems [38]. In the case of dFADs, this includes the use of non-entangling FADs without netting material and biodegradable FADs to minimize adverse effects from derelict FADs.

This study presents the first large-scale research trial at sea conditions to implement biodegradable FADs that will reduce dFAD fishery and dFAD related ALDFG impacts on (i) entanglement risk of sensitive fauna and (ii) plastic related marine pollution and debris. The tested bioFAD prototypes were fully non-entangling without netting and, therefore, potentially with zero risk of fauna entanglement. Moreover, all the bioFAD prototypes significantly contribute to the reduction of the synthetic plastic-based materials in FAD construction and considerably reduced the use of plastic material in the FAD construction. For example, bioFAD Prototype A1, which is the FAD design most use and preferred by the fleet, reduces 81 % the synthetic material on the bioFAD construction and the use of plastic fraction is around 14 % of its total weight (only the floats to ensure buoyancy and the twine to tie the raft). Moreover, in addition to significantly increasing the use of biodegradable materials, bioFADs reduce the total material weight used in FAD construction, which is also important as the impact of FADs are considered to be proportional to its size [39]. For example, bioFAD prototypes A1, A2 and B2, in comparison to their equivalent NEFADs, required less material (in kg) for their construction, with a reduction of 44 %, 50 % and 11 % of material used, respectively. This represents a reduction of 54 kg, 61 kg and 6 Kg of material in each of them, respectively. And the use of biodegradable material increased significantly, with prototype A1 using around 47 kg (70 % of total weight) of biodegradable material, prototype A2 around 40kg (66 %) and B2 16 kg (33 %) of biodegradable materials.

In general, results showed that the fishing performance regarding presence/absence of tuna around FADs, first day of tuna aggregation detection, proportion of FADs occupied by tuna, the biomass aggregation underneath the FADs from the echosounder buoys and catch per set between bioFADs and conventional NEFADs were similar. This provides support of the efficacy of bioFADs regardless the degradation experienced by the bioFAD prototypes with the materials tested in this first large-scale experiment. This result was also expected as the fishers and scientists have reported since the beginning of the fishery that large tuna aggregations could be found in small natural logs and other objects, provided that those floating objects were drifting in productive areas. This is an important result itself, indicating that tunas do not differentiate between natural and synthetic materials and/or floating objects structure and design, however, this does not overcome the logistical necessity for the bioFADs to last for a long enough time (e.g., one year) and drift slowly, as required by fishers, to increase the chances of an object to aggregate fish in productive areas without drifting outside the fishing grounds [39].

The FAD drifting analysis showed the large variability between bioFADs and NEFADs drift patterns ranging from FAD pairs showing totally different patterns to pairs following the same trajectory, which could be due to slight differences in the structure and construction of the bioFADs and NEFADs, different currents suffered during deployment or other factors. Although this pattern cannot inform the efficacy of bioFADs drift in relation to conventional NEFADs, the observed divergence was somewhat expected as this is commonly observed by fishers when deploying their conventional NEFADs; which support the use and validity of the bioFADs tested [40].

Although the lifespan of the different bioFAD types showed a maximum lifespan longer than 1 year, which is the FAD time required by fishers for commercial fishing, this analysis did not consider the degradation process of the FAD's components. The observed degradation of, particularly, the cotton canvas (i.e., used in the raft) and, to a lesser extent, cotton ropes (i.e., for the construction of the tail) suggest that biodegradable materials using conventional FAD designs were not strong enough to withstand the tension suffered by oceanographic currents to remain at sea the required time for fishing [39]. This is an important lesson learned and future trials should consider the effect of construction designs (i.e., distribution of elements in the surface and submerged FAD parts) on the durability of the biodegradable material tested.

From the beginning of the bioFAD deployments and posterior fishing-related activities, provision of biodegradable degradation status of the different bioFAD components was generally limited. This information was considered crucial to assess the degradation stage of materials over a FAD's lifetime and to quantify the replacement rate needed for each of the components. The low reporting rate of this information, in terms of quantity and quality, hindered a comprehensive analysis of the degradation status of the bioFADs. This was partly because only a few vessels lifted the FADs out of the water during their daily operational activities, making it difficult to gather data regarding the degradation stage of the submerged components (e.g., FAD's tail). Most of the vessels do not generally lift FADs during fishing operations for various reasons, including avoidance of possible structural stress to the FAD when pulling it out which could affect its longevity, to prevent disturbance to the fish community aggregated around the FAD that helps attract more tuna, or simply not wanting to spend the extra time it takes to lift a FAD. Nevertheless, a partial assessment of the degradation of the three biodegradable materials (i.e., cotton canvas and two type of cotton ropes) was conducted based on the assessment reports that were obtained. For example, the cotton canvas on the raft degraded faster than expected and did not meet fisher's expectations and needs, as the bioFAD should last in working conditions maintaining its structure for at least around one year according to fishers [2].

Contrary to the perception of the cotton canvas, and according to the feedback received from fishers during the workshops, the absence of the bioFAD's tail cotton ropes was related to failures in the attachment between the tail and the raft (e.g., type of knot joining them) rather than to a high degradation of the cotton materials. If not correctly attached, these components could be lost resulting in the reported absences. However, in general the industry positively valued the performance of these two biodegradable rope components. Although some companies were expecting a longer lifetime for those materials, others have already incorporated them in their current commercial FADs constructions after this experiment. According to these results and fleet feedback, tested cotton ropes could be considered as a feasible solution for FAD tail in the Indian Ocean, and thus, as replacement of netting materials used in the tail, which is usually tied into sausage-like bundles. If the cotton ropes are used in the tail of the FADs, it will contribute to eliminate large amounts of netting in FAD construction and provides viable options for the industry to partly comply with fully non-entangling FAD requirements of Annex V in IOTC resolution 19/02 and employ biodegradable materials.

The construction of a bioFAD maintaining the same conventional FAD design (i.e., submerged open panels hanging from the raft) but made of biodegradable ropes and canvas tested in this project (Fig. 1), shows that bioFADs works well and reduce the amount of material in its construction, however, it seems that the lifetime of those bioFADs is shorter than that required by fishers. This is mainly due to the structural stress suffered by conventional FAD structure designs, which are subject to different directional forces between superficial and subsurface currents [39]. Strong synthetic plastic materials allow conventional FADs to persist without breaking despite the tension and structural stress suffered in the different layers of the water column. However, once plastic is replaced by weaker organic materials, the tension and structural stress suffered by conventional design make the bioFADs deteriorate before the time required by fishers to operate with them. Despite this limitation and lessons learned, which will inform future developments and trials on biodegradable FADs such as the ones currently being conducted in other oceans [39], this project showed that bioFAD prototypes tested significantly contribute to the reduction of the synthetic material in FAD constructions. Moreover, the willingness of the fleet to use the cotton ropes in the tail of commercial FADs and the incorporation of this material by some companies demonstrates the utility of this large-scale trial to mitigate the potential contribution of lost and abandoned FADs to marine litter, reducing consequently impacts on the ecosystem, which is the objective promoted by IOTC Res. 18/04 and 19/02.

In summary, this first large-scale bioFAD experiment corroborates the results and conclusions from other smaller trials, pointing out the need to find alternative FAD designs that will suffer less structural stress than conventional FAD designs made of biodegradable materials. Our results suggest that conventional FAD designs using biodegradable materials are not strong enough to withstand oceanographic stress forces and tension suffered by tested biodegradable FAD prototypes to remain at sea the required time for fishing. This is particularly relevant for the biodegradable materials used in rafts, such as cotton canvas, which are exposed to multiple deteriorating forces (e.g., sun, wind and surface currents) making them prone to quickly break down and, therefore, unsuitable for the construction of the types of FADs currently used in the Indian Ocean. The cotton ropes used in the subsurface tail of the bioFADs appeared to work much better and seems to resist and, hence, be valid for FADs used in the Indian Ocean. However, the submerged tail structure used in the Atlantic and Pacific Ocean is more complex and bigger than in the Indian Ocean, usually made of open panels of old netting acting as submerged sails or anchors. As such, the cotton ropes used in the Indian Ocean experiment alone might be of less use in other oceans with stronger subsurface currents, as they will not offer enough resistance to slow down their drift. Altogether, the lessons learned in this first biodegradable FAD large-scale trial will contribute to refine future materials and designs for biodegradable FADs with the objective of lasting in working conditions for one year and favoring slow drift for tuna aggregation as required by the fishers. Achieving fully functional bioFADs will help mitigate the ecosystem impacts and marine plastic pollution currently produced by conventional plastic-built FADs.

5. Conclusions and recommendations

5.1. Conclusions

(i) The distribution of the deployed experimental FADs covered the principal western Indian Ocean tuna fishing areas and the deployment effort was seasonally balanced.
(ii) BioFAD prototypes significantly reduced the amount of synthetic material used for FAD construction and the risk of fauna entanglement.
(iii) BioFAD prototypes significantly increase the use of biodegradable materials and reduce the total material weight used in FAD construction reducing the overall impact of FADs in the ecosystem.
(iv) High variability in the drifting patterns of bioFADs and conventional FADs were observed: (i) pairs following totally different trajectories, (ii) pairs following partly similar trajectories and (iii) pairs following same drifting trajectories.
(v) With the exception of prototype B2, which was deployed in low numbers for analysis, all other prototypes showed a lifespan longer than a year in both FAD types, however, the degradation status was not assessed in those FADs that lasted more than 6 months. Thus, the degradation status should be considered in future trials as the bioFAD needs to continue aggregating fish for the time required by fishers.
(vi) The raft cotton canvas showed high degradation during the first months at sea, while cotton ropes employed in the tail were less degraded until the fifth month. The implementation of the cotton canvas in the raft using current FAD designs does not seem feasible. However, the cotton ropes used in the tail could be a good solution as a biodegradable replacement for the FAD's tails in the Indian Ocean.
(vii) Although tuna presence/absence data showed faster colonization in NEFADs than in bioFADs, the differences were not statistically significant and, thus, can be considered similar.
(viii) Tuna presence/absence data showed higher FAD occupation by tuna aggregation in NEFAD than in bioFAD when all prototypes were analized together, however, the differences were not significant for the most common prototype (A1) tested and, thus, the tuna FAD occupation between bioFAD and NEFAD can be considered similar.
(ix) Variability in biomass estimation by FAD type was observed in the analysis of different buoy models. Overall, NEFADs had higher values of biomass during the first month, while bioFADs showed higher biomass values after the ninth month at sea.
(x) Few sets were observed in both FAD types, with the number of sets being slightly higher in bioFADs. No significant differences were observed in tuna catch data by FAD type.

5.2. Recommendations

(i) It is recommended to agree on a biodegradable and bioFAD harmonized definition by tuna RFMOs. This will provide clear guidance and clarity for stakeholders when using the term biodegradable to define the materials used for FAD construction.
(ii) An effective replacement of non-biodegradable FADs by those fully biodegradable still requires investigation to solve important practical and technical aspects for the operationalization of this type of FADs, including improving the operational condition of bioFADs to reach one year before they fully degrade. Thus, further research with already tested and new materials that meet the agreed biodegradability definition to construct bioFADs is required. However, the cotton ropes used in the tail is a good solution as a biodegradable replacement for the FAD's tails in the Indian Ocean.
(iii) Acknowledging that biodegradable materials employed in conventional FAD designs are not strong enough to support the tension suffered by these structures for maintaining the original structure (e.g., to be in good conditions at sea) for longer than one year (i.e., the required time for fishing), it is recommended either to follow a stepwise process, including a timeline, towards the implementation of fully biodegradable FADs (e.g., starting with the submerged part of the FAD made by 100 % biodegradable material and progressively increasing the % of biodegradability in the surface part, targeting full FAD biodegradability) [41] or to design a completely different biodegradable FAD concept which will suffer less structural stress and, hence, can provide a longer lifetime in the water (i.e., at least one year) without losing its original structure as required by fishers to drift slowly and aggregate tuna [39].
(iv) As smaller FADs equate to lower quantities of material, a gradual modification of current large FAD designs towards a reduction in the amount of materials employed (e.g., shallower depth of tails) and in the synthetic fraction used in their construction, should be promoted. The bioFAD tested in this project achieved that goal as bioFAD prototypes tested significantly reduced the amount of synthetic material and the total material used for FAD construction.
(v) The development and implementation of biodegradable FADs requires the collaboration of all stakeholders, fishing industry and research centers including experts in material development to achieve desired objectives in a faster and more efficient way.

Data availability

Data will be made available on request.

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Appendices

Annex I

Characterization of BIOFADs and conventional NEFADs. Missing = information being collected. The % of biodegradability was estimated as the ratio between the sum of total biodegradable material weight and total material weight for each of the prototypes.

	Comp. 1		Comp. 2		Comp. 3		Comp. 4		Comp. 5		Comp. 6	Comp. 7	GENERAL INFO			
Model	floating structure	Weight [kg]	Canvas for cover	Weight [kg]	Main ropes [m]	Weight [kg]	Rope - atractor [m]	Weight [Kg]	Floats		Ballast weight [kg]	Twine to tie [kg]	TOTAL weight [kg]	BIO Material Weight	Synthetic Material Weight	% Biodegradability
									Un.	Weight [kg]						
BIOFAD_A1	10 bamboo canes	30	Black cotton cover	2.2	Cotton 60 m	18	1 m looped cotton rope set each 2 m (30 m)	4.8	4 + 3 = 7	8.9	5	0.5	69.4	55	14.4	79.3
BIOFAD_A1.1	4 bamboo canes	12	Black cotton cover	2.2	Cotton 60 m	18	1 m looped cotton rope set each 2 m (30 m)	4.8	4 + 3 = 7	8.9	5	0.5	63.6	37	26.6	58.2
	Metallic frame	12.2														
BIOFAD_A1.2	4 bamboo canes	12	Doble Black cotton cover	4.4	Cotton 60 m	18	1 m looped cotton rope set each 2 m (30 m)	4.8	4 + 3 = 7	8.9	5	0.5	65.8	39.2	26.6	59.6
	Metallic frame	12.2														
BIOFAD_A2	10 bamboo canes	30	Black cotton cover	2.2	Cotton 40 m	12	1 m looped cotton rope set each 2 m (20 m)	3.3	4 + 3 = 7	8.9	5	0.5	61.9	47.5	14.4	76.7
BIOFAD_A2.1	4 bamboo canes	12	Black cotton cover	2.2	Cotton 40 m	12	1 m looped cotton rope set each 2 m (20 m)	3.3	4 + 3 = 7	8.9	5	0.5	56.1	29.5	26.6	52.6
	Metallic frame	12.2														
BIOFAD_A2.2	4 bamboo canes	12	Doble Black cotton cover	4.4	Cotton 40 m	12	1 m looped cotton rope set each 2 m (20 m)	3.3	4 + 3 = 7	8.9	5	0.5	58.3	31.7	26.6	54.4
	Metallic frame	12.2														
BIOFAD_B1	10 bamboo canes	30	Black cotton cover	2.2	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	87.2	62.8	24.4	72.0
BIOFAD_B1.1	10 bamboo canes	30	Doble Black cotton cover	4.4	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	89.4	65	24.4	72.7
BIOFAD_B1.2	4 bamboo canes	12	Black cotton cover	2.2	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	81.4	44.8	36.6	55.0
	Metallic frame	12.2														
BIOFAD_B1.3	4 bamboo canes	12	Doble Black cotton cover	4.4	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	83.6	47	36.6	56.2
	Metallic frame	12.2														

(*continued on next page*)

Annex I (*continued*)

	Comp. 1		Comp. 2		Comp. 3		Comp. 4		Comp. 5		Comp. 6	Comp. 7	GENERAL INFO			
Model	floating structure	Weight [kg]	Canvas for cover	Weight [kg]	Main ropes [m]	Weight [kg]	Rope - atractor [m]	Weight [Kg]	Floats		Ballast weight [kg]	Twine to tie [kg]	TOTAL weight [kg]	BIO Material Weight	Synthetic Material Weight	% Biodegradability
									Un.	Weight [kg]						
BIOFAD_B1.4	Metallic frame	12.2	Black cotton cover	2.2	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	69.4	32.8	36.6	47.3
BIOFAD_B1.5	Metallic frame	12.2	Doble Black cotton cover	4.4	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	71.6	35	36.6	48.9
BIOFAD_B2	6 bamboo canes (18 kg)	18	Black cotton cover	2.2	Cotton 80 m	24	1 m looped cotton rope set each 2 m (40 m)	6.6	4 + 3 = 7	8.9	15	0.5	106.2	81.8	24.4	77.0
	Pallet (31 kg)	31														
BIOFAD_B2.1 "Cube"	Doble Metallic frame	24.4	Black cotton cover	2.2	–	0	cotton rope 4 × 3 m (12 m)	3.6	3 + 3 = 6	7.6	0	0.5	46.2	13.7	32.5	29.7
							Looped cotton rope 16 × 3 m (48 m)	7.9								
BIOFAD_B2.2 "Cube"	Doble Metallic frame	24.4	Doble Black cotton cover	4.4	–	0	cotton rope 4 × 3 m (12 m)	3.6	3 + 3 = 6	7.6	0	0.5	48.4	15.9	32.5	32.9
							Looped cotton rope 16 × 3 m (48 m)	7.9								
BIOFAD_C	10 bamboo canes	30	Black cotton cover	2.2	–	0	Looped cotton rope 8 × 5 m (40 m)	6.6	4 + 3 = 7	8.9	0	0.5	48.2	38.8	9.4	80.5
BIOFAD_C.1	10 bamboo canes	30	Doble Black cotton cover	4.4	–	0	Looped cotton rope 8 × 5 m (40 m)	6.6	4 + 3 = 7	8.9	0	0.5	50.4	41	9.4	81.3
BIOFAD_C.2	4 bamboo canes	12	Black cotton cover	2.2	–	0	Looped cotton rope 8 × 5 m (40 m)	6.6	4 + 3 = 7	8.9	0	0.5	42.4	20.8	21.6	49.1
	Metallic frame	12.2														
BIOFAD_C.3	4 bamboo canes	12	Doble Black cotton cover	4.4	–	0	Looped cotton rope 8 × 5 m (40 m)	6.6	4 + 3 = 7	8.9	0	0.5	44.6	23	21.6	51.6
	Metallic frame	12.2														
NEFAD A1-A2 "conventional"	Metallic frame	12.2	Synthetic black raffia	2.1	80 m* Twisted polyamide net and tied	54	Flags of synthetic raffia 1mx 1.5 m	4.5	4 + 3 = 7	8.9	25	0.5	121.4	12	109.4	9.9
	4 bamboo canes	12	Polyester net mesh size < 3 mm	2.2												
NEFAD B1 "semi-surmerged"	Metallic frame	12.2	Synthetic black raffia	2.1	80 m* Polyethylene rope 20 mm Ø	16	Flags of synthetic raffia 1mx 1.5 m	4.5	6 + 2 = 8	10.1	15	0.5	62.6	0	62.6	0.0

(*continued on next page*)

Annex I (*continued*)

Model	Comp. 1		Comp. 2		Comp. 3		Comp. 4		Comp. 5		Comp. 6	Comp. 7	GENERAL INFO			
	floating structure	Weight [kg]	Canvas for cover	Weight [kg]	Main ropes [m]	Weight [kg]	Rope - atractor [m]	Weight [Kg]	Floats		Ballast weight [kg]	Twine to tie [kg]	TOTAL weight [kg]	BIO Material Weight	Synthetic Material Weight	% Biodegradability
									Un.	Weight [kg]						
NEFAD B2 "cube"	Doble Metallic frame	24.4	Polyester net mesh size < 3 mm Synthetic black raffia	2.2 2.1	No	0	Flags of synthetic raffia	1.2	4 + 6 = 10	12.6	0	0.5	54.4	0	54.4	0.0
NEFAD C "superficial"	Metallic frame 4 bamboo canes	12.2 12	Polyester net esh size < 3 mm Synthetic black raffia Polyester net mesh size < 3 mm	4 2.1 2.2	No	0	Polyethylene rope 16 × 3 m (48 m) 8×5 m (40 m) Polyethylene rope 20 mm Ø	9.6 8	4 + 3 = 7	8.9	0	0.5	45.9	12	33.9	26.1

*Mean value estimated from data collected at FADs Logbook.
The weight of the 80 m twisted polyamide net and tied was estimated using the weight of a 23 m depth tail: total weight 15,5 kg and composed by nylon twine of 1,3 mm and 195 mm mesh size.
These materials identified as biodegradable follow the definition proposed by Zudaire et al. (2018).

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