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Report of Project 110: Non-entangling and biodegradable FAD trial in the Western and Central Pacific Ocean

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Executive Summary

WCPFC Project 110 (the project) will conduct trials of non-entangling and biodegradable drifting Fish Aggregation Devices (dFADs) in the Western and Central Pacific Ocean (WCPO). It will provide essential information to the tuna fishing industry on the designs, types of materials, performance and cost-effectiveness of non-entangling and biodegradable dFADs in the WCPO context, with the goal of supporting industry's uptake of more ecologically sustainable dFAD designs. The aims of the project are the following:

1. Design/refine cost-feasibility of non-entangling and biodegradable dFADs. Informed by previous trials in the WCPO and other oceans, project 110 will build on fostering industry and national fishery agency input and utilize readily available (locally or shipped) suitable construction materials.
2. Undertake at-sea experiments to compare the performance of non-entangling and biodegradable dFADs to conventional dFADs.
3. Provide robust scientific advice to industry and national fisheries managers on the performance of non-entangling and biodegradable dFAD designs.
4. Increase regional support, capacity building and partnerships on dFAD research with various stakeholders in the WCPO.

Project 110 will include four stages:

1. Information gathering and planning workshops, identifying dFAD construction locations, detailing design of at-sea trials, and initiating capacity building on design and construction;
2. Constructing the experimental dFADs;
3. Conducting at-sea trials and broader industry outreach program;
4. Data analysis, reporting, final workshop and development of an industry plan of action.

Project 110 was initially planned to start in March 2021, however, the design phase of the non-entangling and biodegradable dFADs and the trials at-sea could not start in 2021 due to the COVID-19 pandemic and the associated restrictions put in place by various coastal states with access to ports and materials. As a result, fishing companies contacted could not commit to starting such activities in 2021.

Several partner fishing companies have now been identified, with an agreement in principle to construct and deploy biodegradable dFAD in late 2022. The agreement in principle has been achieved between three fishing companies, and will be finalised with Letter Of Agreements (LOAs) in the coming weeks. In addition, a workshop with skippers of one fishing company occurred in June 2022 to discuss the intent of project 110 and better understand skippers perspectives and the logistics for achieving the projects objectives. Other activities within stage 1 have also commenced, with the literature review and online consultations with other researchers on dFAD designs was done to develop potential designs and identify materials needed. The summary of previous work is presented in Appendix 2 of this paper. Regular meetings with the International Seafood Sustainability Foundation (ISSF) collaborators and potential partner fishing companies have been occurring since the beginning of 2022. An agreement has been made, between SPC, ISSF and the partner fishing companies, to test the Jelly-FAD design developed by ISSF. Discussions are continuing in terms of base ports, FAD construction locations and materials to be purchased. A purchase order for the satellite echo-sounder buoys to be deployed on the biodegradable FADs has been issued by SPC, for delivery later in 2022. Discussion with companies on the procurement of materials and construction of the bio-FADs are ongoing.

As the project was not able to start as planned in 2021, due to the impacts of the COVID19 pandemic, this has had a ripple effect with further delays in the project's implementation. It is anticipated that the outcomes of project 110 will be delayed and will likely need at least a 1-year project extension request.

We invite WCPFC-SC18 to:

- Note the delays in the activities planned due to the COVID-19 pandemic.
- Note a no-cost project extension of at least one year can be expected to be requested from the donors and the WCPFC.
- Note the updated timing of activities, including those planned over the first year of the project.
- Note that first results from this project are expected to be available by SC19.
- Note the review of worldwide trials of Non-entangling and Biodegradable dFADs presented in Appendix 2.

1. Introduction

Recent estimates indicate that the number of drifting Fish Aggregation Device (dFAD) buoy deployments in the Western and Central Pacific Ocean (WCPO) have varied between 23,000 and 40,000 per year over the last decade (Escalle et al. , 2020, 2021a). Traditional dFAD designs can lead to entanglement and unnecessary mortality of Species of Special Interest (SSIs; i.e. sharks, turtles). Of increasing concern is the rate of subsequent abandonment and stranding of deployed dFADs, recently estimated at 41% and 7%, of tracked dFADs, respectively (Escalle et al., 2019, 2021b). The resulting marine pollution, ghost fishing and ecosystem impacts on coastal environments are of concern to the coastal states of the region, fishery stakeholders and impact the social perspective of the purse seine tuna industry in the WCPO. To mitigate these undesirable impacts of dFAD use, there is a growing need to transitions to dFADs that are constructed from materials that are both biodegradable and mitigate the entanglement of SSIs. For the fishing industry to accept and make this transition, collaboration with fishing industry on research and development is required to design and test dFADs made of biodegradable and non-entangling materials and to demonstrate their performance relative to traditional designs.

2. Project description

In recognition of the need to reduce the environmental and ecological impacts of dFADs in the WCPO, CMM 2021-01 (Conservation and Management Measure for bigeye, yellowfin and skipjack tuna in the western and central Pacific Ocean), requires that the design and construction of any dFAD to be deployed in, or drifts into, the WCPFC Convention Area, by 1 January 2024, shall comply with the following specifications:

- all dFADs in the WCPFC Convention Area should comply with low-entanglement design specifications (as described in CMM 2018-01) from January 2020, and;
- all dFADs in the WCPFC Convention Area should comply with non-entangling materials and design specifications (the use of mesh net shall be prohibited for any part of a dFAD) from January 2024 and;
- the use of biodegradable materials to construct dFADs is encouraged.

A recent review of observer data (2010–2020) shows limited use of non-entangling and/or biodegradable dFAD designs in the WCPO (Phillip and Escalle, 2020) thus far. However, there are data limitations with the 2020 and 2021 data, and it is therefore not yet possible to identify the recent response to the requirements of CMM 2018-01 and CMM 2021-01. Importantly, greater support to national fisheries agencies and information is needed to guide construction and encourage the use of ‘effective’ non-entangling and biodegradable dFADs, which will be essential to drive wider industry uptake. This will require that industry are consulted at every stage of this process.

While trials of non-entangling and biodegradable dFADs have been adapted to the WCPO (Moreno et al., 2020), the methodologies have been initiated by the International Seafood Sustainability Foundation (ISSF), in collaboration with industry, government and The Pacific Community (SPC). Additional work and collaborative action are required if non-entangling and biodegradable dFADs are to become the ‘norm’ in the WCPO. The current project will build on the recent trials in the WCPO and elsewhere (e.g., Moreno et al., 2020b; Appendix 2), it will also provide and investigate additional data required to deliver robust information to industry on the designs, types of materials, performance and cost-effectiveness of non-entangling and biodegradable dFADs in the WCPO. The project has the following objectives:

1. Design/refine cost-feasibility of non-entangling and biodegradable dFADs. Informed by previous trials in the WCPO and other oceans, project 110 will build on fostering industry and national fishery agency input and utilize readily available (locally or shipped) suitable construction materials.
2. Undertake at-sea experiments to compare the performance of non-entangling and biodegradable dFADs to conventional dFADs.
3. Provide robust scientific advice to industry and national fisheries managers on the performance of non-entangling and biodegradable dFAD designs.
4. Increase regional support, capacity building and partnerships on dFAD research with various stakeholders in the WCPO.

3. Methodology

Stage 1: Information and planning workshop: identify dFAD construction locations and initiate capacity building in design and construction.

Initially, project 110 will compile relevant information from previous ISSF and other studies on non-entangling and biodegradable dFADs worldwide (Moreno et al., 2020b) and identify potential industry partners. Following this, in collaboration with ISSF, industry partners, national fisheries agencies, Regional Observer Programme (ROP) representatives and local dFAD construction experts, a planning and information sharing workshop will be held. The workshop will identify plausible dFAD materials and designs to trial and inform the design, data collection protocols and logistics of the at-sea trials. The workshop will also aim to identify locations for land-based construction of non-entangling and biodegradable dFADs for the project, and ongoing support to industry will also be an important part of this initial workshop. Based on the outcomes from the planning workshop a detailed design for the at-sea trials will be developed by the lead SPC scientist in collaboration with ISSF project collaborator and presented back to the initial planning workshop attendees, industry partners, ROP representative for comment and endorsement. Project 110 detailed design will include all aspects of the at-sea trials and clearly outline the data collection protocols and other support required from the relevant stakeholders, in particular industry, national fisheries agencies, and observers. dFAD construction will be ongoing from stage 1 once the prototype dFADs designs are endorsed by industry partners.

Stage 2: Construction of non-entangling and biodegradable dFADs

Based on the outcomes and recommendations of the locations for dFAD construction activities, capacity building activities, in-design and construction of biodegradable and non-entangling dFADs, it is anticipated that these phases of the project will be integrated as part of the construction of the prototype dFAD design, and eventually rolled out to all dFADs for the project.

Stage 3: Conduct at sea trials and broader industry communications program

The project will aim to deploy a minimum of 200 ‘experimental’ non-entangling and biodegradable dFADs that will be compared with 200 ‘conventional’ (currently used) dFADs. It will also aim to increase this number subject to support from industry partners and availability of other funds. We envisage that the performance of the experimental and conventional dFADs will be monitored over eight to ten months. The timing of trials is dependent on COVID-19 restrictions in port(s) where participating fleets dock and ports which will be the primary access way for the construction and distribution of the experimental dFADs. Trials are hoped to begin in the second half of 2022. If logistically feasible, at-sea experimental dFAD trials will follow normal deployment practices, with trials to be coordinated by the lead scientist from the SPC with support from ISSF. Observer involvement and coverage will be important and will be supported by SPC and ISSF in monitoring and data collection. The monitoring program will be developed in collaboration with the observers and industry partners, skippers to ensure it is feasible given their other work commitments. Monitoring of the dFADs will include information on dFAD condition, catch history, acoustic data and drift trajectories (following approaches previously employed in ISSF projects). Comparative analyses of the performance of the two dFAD types will include; aggregative power and drift behaviour; catch rates per species; costs and handling requirements; effective lifespan and condition at different times-at-sea. Analyses of data from echo-sounder buoys deployed on the dFADs will build on knowledge gained through EU funded Project 88 (FAD acoustics). Acoustic buoys will be provided by manufactures used by the participating fleets to ensure data is comparable with their standard dFADs deployed in the region.

The trials will be performed in close partnership with industry (skippers) and the observer programme to ensure marking, deployment, identification and monitoring/data recording of dFADs occurs in a consistent and coordinated way. Two levels of industry participation are anticipated:

- the partner fleets that deploy the dFADs and are actively engaged in the research depending on their fishing activities, and;
- all other fleets that find and/or fish the experimental dFADs. Information from (2) will be important to the success of the research.

Stage 4: <u>Data analysis, reporting, final workshop and industry adoption of plan of action</u>
Data from the at-sea trials will be summarised (and analysed to the extent possible) as it becomes available and reported back to industry partners at six monthly intervals, including a mid-project review workshop, the WCPFC's dFAD Management Options Intersessional Working Group (FAD-IWG) and papers to the WCPFC Scientific Committee (SC). The final analyses and reporting of results will be delivered to SC20 and a final workshop with industry partners, national fisheries agencies, NGOs and ROP representatives. Assuming positive results of the trial, the final workshop would include a session on 'industry adoption' with an objective of developing an adoption plan of action. SPC is also developing a dFADs communication strategy and will build this project into that broader strategy.

Table 1. Updated timing of activities. D = delayed; C = completed; P= planned.

	2021									2022												2023												2024							
Activity	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
Stage 1	D	D	D	D	D	D	D	D	D	C	C	C	C	C	C	C	P	P	P																						
Stage 2																	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P								
Stage 3																				P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Stage 4					C											C				P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

4. Updates on activities of the project

WCPFC project 110 was initially planned to start in 2021, with the non-entangling and biodegradable dFAD trials starting in October 2021, following the FAD closure period. Several fishing companies were contacted in 2021 and 2022 with all indicating interest in joining the project. However, none of the companies were in a position to start the project in 2021, including the workshops with fishers to design the non-entangling and biodegradable dFAD and the at-sea trials phase, due to the COVID-19 restrictions. In early 2022, discussions have continued with three fishing companies, with an agreement in principle to construct and deploy biodegradable dFAD(s) in late 2022. Letter Of Agreement (LOAs) have now been developed and are currently being reviewed to finalise the agreement with fishing companies and to start project 110 activities. A recent workshop with skippers of one of the companies has been organized to discuss the project and better understand their perspectives and understand the logistical requirements and needs of industry.

In terms of activities already performed, a literature review has been undertaken (Appendix 2), listing the designs and materials that have already been used globally as well as summarising previous initiatives in terms of their efficiencies, effectiveness, cost and the lessons learnt (Lopez et al., 2016; Moreno et al., 2020a, 2020b; Zudaire, 2017). Regular meetings with ISSF collaborators and potential fishing company partners have been occurring since the beginning of 2022. An agreement has been made to test the Jelly-FAD developed by ISSF (Moreno et al., 2022, 2020). Discussions are continuing in terms of base ports, dFAD construction locations and materials to be purchased. A purchase order for the satellite echo-sounder buoys to be deployed on the experimental biodegradable dFADs has been issued. Finally, a dedicated form to collect data on the effectiveness and conditions of the experimental biodegradable dFADs has been drafted (Appendix 1) and will be reviewed and endorsed by the project's stakeholders.

Work on the communication and engagement strategy, including with the purse seine sector, coastal communities, managers and fisheries departments, NGOs will also anticipated to begin. Defining ways to communicate and inform the ROP and all fishing companies will be an important step to gather independent data sources to compliment the operational data from the partner fishing companies.

As the project has not been able to start as planned in 2021, both in terms of work conducted and expenditure, the project is expected to require an extension at some point, likely at no additional cost to complete the required activities under the original funded workplan.

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Appendix 1. Potential form to be filled up by vessel captains.

BIO-FAD DATA FORM

WCPFC Project 110 Non-entangling and Biodegradable FAD trial

Created April 2022

General Information								
Vessel name		Company name			Skipper Name			
Date and time *(GMT)*					Latitude		Longitude	
YY	*MM*	*DD*	*hh*	*mm*	*(dd°mm.mmm')*	*N/S*	*(dd°mm.mmm')*	*E/W*

FAD activity and identification					
FAD Activity *(tick)*				FAD ownership *(tick)*	
Deployment		Buoy deactivation		This vessel	
Visit		Buoy loss		Other vessel from company *(specify)*	
Retrieval		Buoy replacement		Other vessel *(specify)*	
Set		Other *(specify)*		Unknown	
Comment on FAD activity and ownership					

Type of FAD (tick biodegradable (Bio) or Conventional (Conv) FAD and enter number)							
Bio-FAD *(tick)*		Bio-FAD Number		Conv-FAD *(tick)*		Conv-FAD Number	

(1) Bio-FAD information					(2) Conventional FAD information			
Fill up part (1) and (2) in case of joint-deployment								
Buoy ID number					Buoy ID number			
New buoy ID number *(if replaced)*					New buoy ID number *(if replaced)*			
Design type *(tick)*		Flotation *(tick)*			Raft type *(tick)*		Submerged structure *(tick)*	
Jelly-FAD		Surface			Bamboo raft		Ropes	
Other *(add in comments)*		Submerged			Bamboo bundle		Canvas	
FAD depth *(m)*		Weight type			Metal		Bamboo	
		Weight *(kg)*			Plastic		Palm leaves	
State of FAD *(tick)*	Raft	Submerged struct.		Other	Corks		Open net	
Good					Other *(specify)*		Net rolled up	
Needs repair					Raft cover *(tick)*		Other *(specify)*	
Destroyed					Not covered		Flotation *(tick)*	
Not visible					Canvas		Surface	
Abstent					Netting		Submerged	
Raft repaired component					Other *(specify)*		Weight type	
Raft replaced component					FAD depth *(m)*		Weight *(kg)*	
Submerged repaired component								
Submerged replaced component								
Comments/drawings on FAD information and design								

Catch data					
Catch	YFT	BET	SKJ	Bycatch	Total
Tonnage					
Comment on catch and set					

Appendix 2. Review of previous Non-Entangling and Biodegradable dFAD trials and potential biodegradable materials.

1 <u>Historical review of models tested, from conventional dFADs to Non-Entangling and Biodegradable dFADs</u>

1.1 Conventional dFADs

1.1.1 Common designs in the Western and Central Pacific Ocean (WCPO) and worldwide in the 2000s

In 2009, dFADs mainly consisted of bamboo rafts of 4–6 m^2 covered with old purse seine black netting and submerged appendages of old purse seine nets as well (from a few meters up to tens of meters) (Franco et al., 2009). The mesh size of the netting is usually between 200–900mm. Smaller mesh sizes were considered to attract sessile organisms, and quickly become fouled and unmanageable due to heavy weight, while larger mesh netting led to turtle and shark entanglements. A segment of chain or cables was sometimes used as weight to maintain the net in a vertical position. Other designs included bundles of bamboo, with the advantage that turtles cannot climb on top of it, however it was often not preferred by fishers as it was more detectable by other fishers and considered to not provide enough shade. Black purse seine netting was sometimes replaced by black plastics to cover the rafts. Plastic floats, for instance recycled from the purse seine float line Ethylene Vinyl Acetate copolymer (EVA) were also used to insure buoyancy. PVC pipes were also used in the Pacific Ocean (Franco et al., 2009).

The criteria used by fishers for designing dFADs as described by Franco *et al.* (2009) are the following:

1. Efficiency to aggregate tunas, with the three following factors considered important by fishers: i) fouling organisms on the netting; ii) shade produced by the structure of the FAD; and iii) length of the hanging panel of netting.
2. Not detectable by other vessels.
3. Availability and low cost of materials.
4. Ease to construct onboard.

Figure 1. Classical dFAD in the 2000s, from Franco *et al.* (2009), © Fadio/IRD/AZTI/gmoreno (left) and © Fadio/IRD/ Ifremer/mtaquet (middle left and right, and right).

In the WCPO, dFAD designs varied depending on the fleet (Itano, 2007; Itano et al., 2004a). EU and Japanese fleets used the common bamboo raft, with additional buoys to insure buoyancy (Figure 2). While the Taiwanese fleet generally tied bamboos in a bundle, and an array of colorful attractors attached to the purse seine netting were used in the submerged part of the structure. US vessels were using a combination of bamboo rafts as well as PVC tubes (Figure 2), although it was considered more expensive than buoys from purse seine float lines, the later was preferred. Several designs with bamboo rafts and purse seine netting were tested by the US fleets in the Eastern Pacific Ocean (EPO) in the 1990s and are described in Armstrong and Oliver (1996).

Figure 2. dFAD design used in the WCPO in the 2000s, from Itano *et al.* (2004), typical European (top-left); US (top right); Japanese (bottom left); and Taiwanese (bottom middle and right).

1.1.2 Current designs in the WCPO

The current designs of dFADs in the WCPO are still very similar to the ones described above in the 2000s (Abascal et al., 2014; Escalle et al., 2018; Phillip and Escalle, 2020). Purse seine floats and bamboo canes are the most frequent materials for dFAD rafts. In terms of submerged appendages, netting panels are still the most common, usually in combination with chains, cable rings and weights and/or ropes. Spanish companies have however declared to mostly use non-entangling dFADs (98.5% of rafts and 100% of submerged appendages) including in the WCPO since 2014 (Goñi et al., 2016). Average dFAD raft dimensions are 2.37m ± 1.11 in length and 1.15m ± 1.04 width; and a depth of hanging appendages of 41.17m ± 24.20 (Abascal *et al.*, 2014). Note that deeper dFADs were found east of 180°E and shallower dFADs in archipelagic waters.

1.2 Non-Entangling (NE) FADs

1.2.1 Alternative designs tested in the 2000s – fishers own initiative

In the 2000s, alternative dFAD designs were also tested by fishers. These included some subsurface dFADs (Figure 3) with a polyethylene pipe cylinder in the upper part and agricultural netting material (Franco et al., 2009). Subsurface drums filled with bait was also tested (Figure 3).

Figure 3. Alternative dFAD designs tested in the 2000s, from Franco *et al.* (2009), © Inpesca (left and middle) and © Fadio/IRD/ Ifremer/mtaquet (right).

1.2.2 First trials of NE dFADs

First trials of NE (and biodegradable where possible) dFADs were implemented in the Indian Ocean (IO) in 2005, by several Spanish fishing companies (Delgado de Molina et al., 2006, 2005). A total of 22 different designs were tested. Three main shapes of raft were tested: cylinder, grid, and raft. Cylinder models were commonly made with rubber tubing (empty or filled with sand), sailcloth, semi-natural fabric or jute and ropes (sisal or plastic-based). Buoys from purse seine float line or cork were also used to ensure buoyancy. Depths varied generally between 3 to 6m and sometimes a tail of purse seine netting (additional 15m).

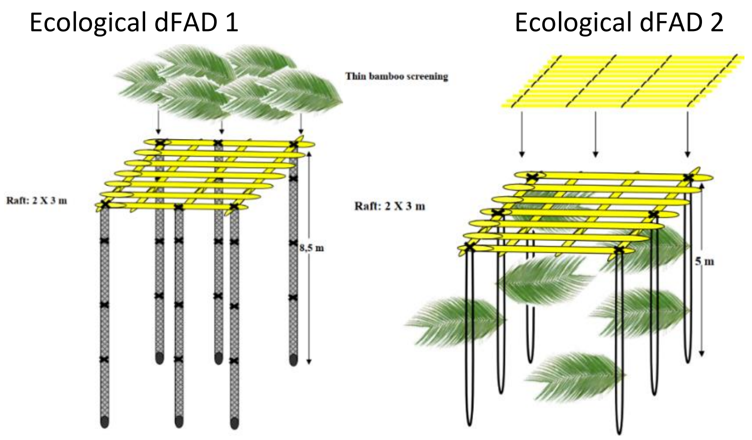
Only eight sets were performed on the NE dFAD prototypes, with limited assessment of prototypes performances in terms of tuna aggregation and related catches. The duration at-sea of each prototype is also not discussed. However, authors noted, the absence of entangled animals.

Figure 4. Examples of dFAD designs tested in the scientific trial to reduce entanglement of sharks and turtles from Delgado de Molina *et al.* (2006).

1.2.3 Ecological dFADs proposed and tested by Franco et al. (2009, 2012)

1.2.3.1 dFAD designs proposed by Franco *et al.* (2009)

The first NE and Biodegradable dFAD designs proposed, were called “ecological dFADs” and were proposed by Franco et al. (2009) to be tested by fishers, but performances and longevity were not discussed in the paper as no trials were implemented yet. One design consisted of a bamboo raft covered with palm leaves, and a submerged structure of sisal nets tied up in sausages. The second design proposed was also a bamboo raft covered with thin bamboo screening, and a submerged structure made of half biodegradable mussel ropes hanging in a U shape. Palms leaves were also used as attractors.



Item	Quantity	Cost (in euros)
Bamboo canes	10	7.5
Bamboo screening	1 (2 X 5 m)	19
Sisal net	6	60
Instrumented Buoy	1	1000
Total cost of FAD gear	1	**1086.5**

Item	Quantity	Cost (in euros)
Bamboo canes	10	7.5
Bamboo screening	1 (2 X 5 m)	19
Mussel ropes	60 meters	60
Instrumented Buoy	1	1000
Total cost of FAD gear	1	**1086.5**

Figure 5. “Ecological” dFADs designs proposed in Franco *et al.* (2009) to be tested by fishers.

1.2.3.2 dFAD designs tested by Franco *et al.* (2012)

Two NE and biodegradable dFAD prototypes were tested in the Atlantic Ocean (AO) between 2010 and 2011 (Franco et al., 2012) by the Spanish fleet. The raft itself was the same, a bamboo raft of 2*2.5m (17–23 bamboos), but the submerged appendages differed in both prototypes. The first one had submerged appendages made of six sisal ropes ending together at 25m and extended by a single sisal rope hanging at 60 meters depth with a 25kg weight (EXP 1, Figure 6). Palm leaves were attached to the sisal ropes to provide shade and volume. The second prototype had submerged appendages made of a 9m long thick sisal rope (50mm of diameter), followed by a sisal netting with three sisal ropes with palm leaves hanging until 60m depth (EXP 2, Figure 6).

No results regarding tuna catch or longevity at-sea were discussed in these trials. However, the authors noted that biomass detected by the echosounder attached to these prototypes was low (maximum of 17t). A large deployment of these ecological dFADs was planned for the following years.

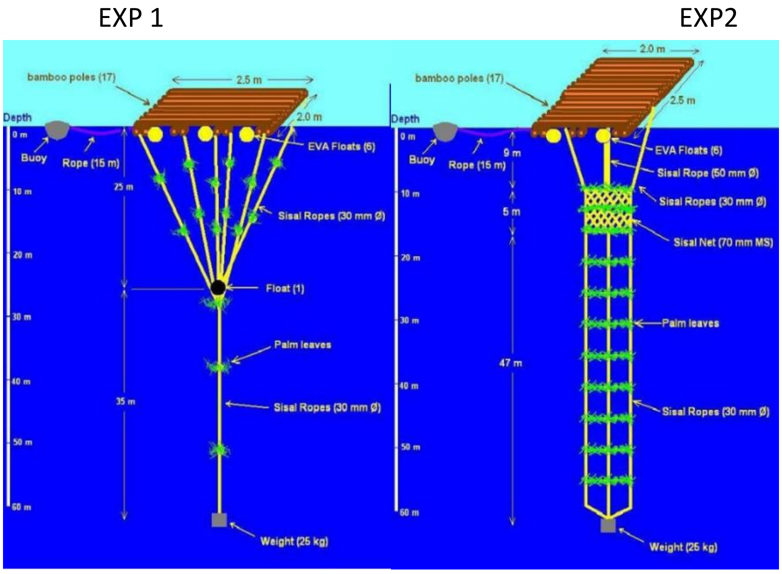


Figure 6. Biodegradable and non-entangling dFAD designs tested in 2010–2011 in the AO by Franco *et al.* (2012).

Figure 7. Picture of biodegradable and non-entangling dFAD tested in 2010–2011 in the AO by Franco *et al.* (2012).

1.2.4 NE dFAD designs tested by Goujon et al. (2012)

Designs of dFADs considered as "eco-FAD" meaning "turtle & shark friendly" or "non-entangling FAD" were developed and tested by the French fleet in the AO and IO in 2010–2012 (Goujon et al., 2012). The maximum lifetime of conventional dFADs (time between deployment and loss or replacement) was considered to be at eight months, similar lifetime was sought for the "eco-FAD" prototypes.

Three designs were developed and tested (Figure 8). The raft was identical for the three designs, with 8 to 12, 2m bamboo canes and cork floats, covered by 2 to 4 layers of thick black small-mesh netting (50mm) sewn together. Black cotton cloth to cover the rafts was also tested but was considered not durable enough.

The first NE design had submerged appendages made of 1 to 4 recycled ropes weighted by a piece of chain or cable at the bottom and with salt bags or small unbraided sections of recycled ropes attached as attractors (Figure 8). The second NE design had submerged appendages made of one or two nets twisted into a "sausage", hanging from the middle of the raft, weighted by a piece of chain or cable at the bottom, and with salt bags or small unbraided sections of recycled ropes attached as attractors (Figure 8). The third NE design had submerged appendages made of 2–4 strips of nets twisted into a "sausage", weighted by a piece of chain or cable at the bottom, attached to the corner of the raft, and with salt bags or small unbraided sections of recycled ropes attached as attractors. The last two dFAD designs were preferred by the fishers (corresponding to 98% of the dFADs tested).

A total of 1,103 NE dFADs (+67 additional dFADs released but without information collected) were deployed. Two cases of entanglement of sharks were reported, when the net was insufficiently braided and sewn. Similar level of tuna catch was detected on the new NE dFADs (average of 26.5t/set from 67 sets) compared to conventional dFADs (average of 25.2t/set).

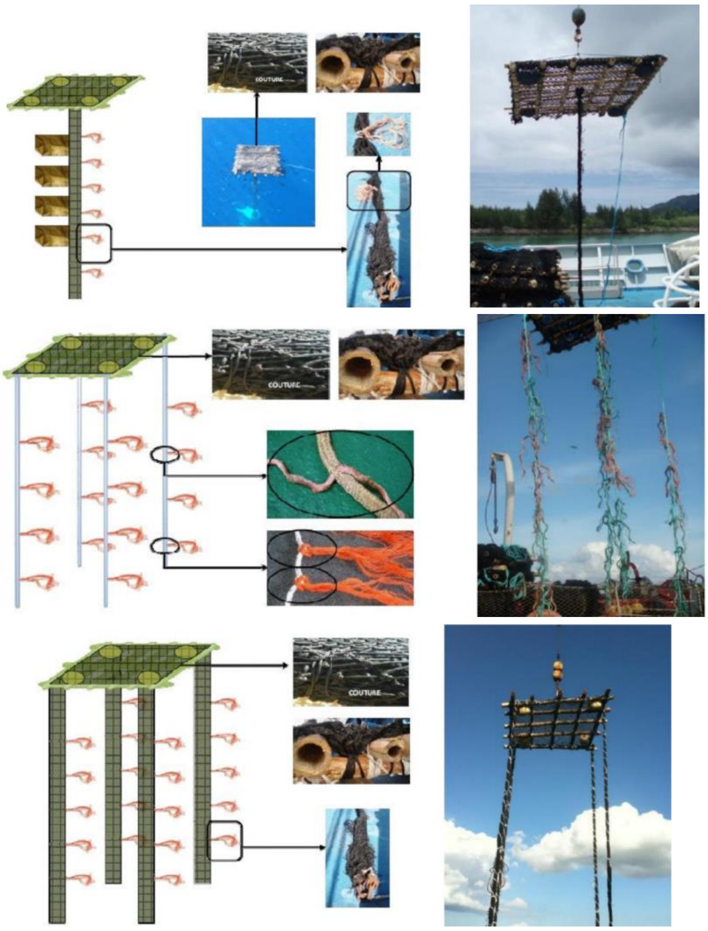


Figure 8. NE dFAD designs tested in 2010–2012 in the AO and IO by Goujon *et al.* (2012), design B (top), design C (middle) and design D (bottom).

1.2.5 Towards adoption of LER or NE dFADs in most ocean basins

Bycatch reduction workshops with fishers lead by ISSF provided some insight into fishers behavior, and in particular here, the adoption of new dFAD designs, such as LER and NE dFADs (Figure 9) (Murua et al., 2017b, 2017a).

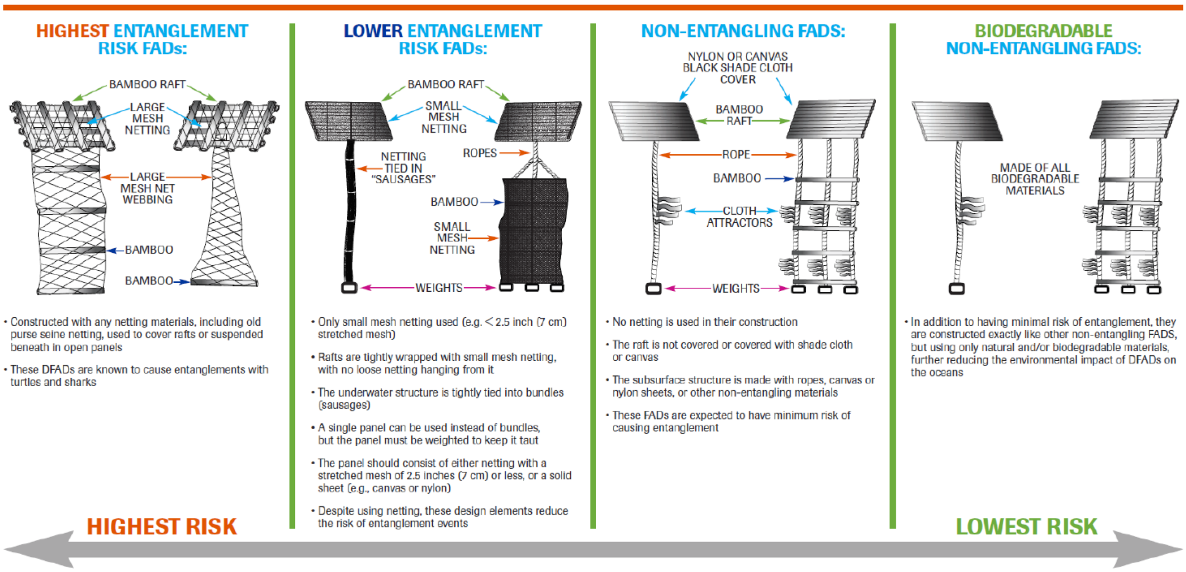


Figure 9. Type of dFAD designs from highest Entanglement-risk dFADs to NE and Biodegradable dFADs (ISSF, 2015)

1.2.6 Performance of shallow vs standard depth dFADs (Schaefer et al., 2021)

Trials of two types of NE dFADs were implemented in the EPO to assess the effectiveness of shallow depth (5m) dFADs compared to standard depth (40m) dFADs. 150 dFADs from each prototype were deployed in 2015. Both prototypes were NE dFADs, with small mesh netting and purse seine netting twisted and tied as submerged appendages for the standard depth dFAD (Figure 10).

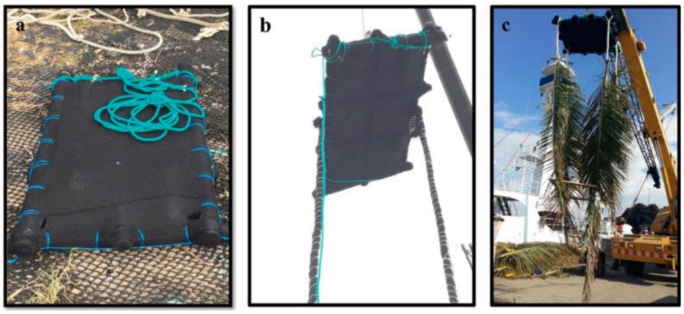


Figure 10. Prototypes of standard (~40m) and shallow NE FADs tested in the EPO (Schaefer et al., 2021)**.**

Drift patterns were similar between both prototypes, but the speed was slightly faster for shallow depth dFADs. DFADs were equipped with Marine Instruments M3i buoys and evaluations of the timeseries of acoustic data indicated differences in aggregation patterns of tuna and non-tuna species for both prototypes. The average time before aggregation by i) non-tuna species was 15.3 days for shallow dFADs and 18.2 days for standard dFADs; and ii) tuna was 62.2 days for shallow dFADs and 70.2 days for standard dFADs (Table 1).

Generalized additive mixed models with Bayesian inference were used to study the catch per set and showed no significant differences in catch rates from sets on shallow and standard depth dFADs. The authors also found a similar proportion in terms of bigeye tuna in the catch on the shallow and standard depth dFADs (Figure 11).

Table 1. Summary of aggregation times (days) by non-tunas and tunas for the two NE FAD prototypes tested estimated, using acoustic data from the Marine Instruments M3i echosounder buoys attached to the dFADs (Schaefer et al., 2021).

	Standard			Shallow		
	n	$\bar{x}$	Range	*n*	$\bar{x}$	Range
Non-Tuna	143	18.2	1.1 – 101.2	146	15.3	3.2 – 65.5
Tuna	128	70.2	1.5 – 270.5	130	62.2	3.3 – 248.3

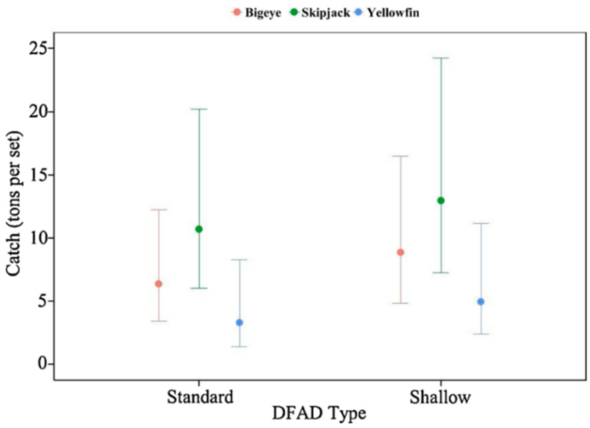


Figure 11. Expected catch rate per set (t) by the two NE FAD prototypes tested from a Bayesian geoadditive GAMM with hurdle log-normal likelihood (Schaefer et al., 2021).

1.3 Biodegradable (BIO) dFADs

1.3.1 *Fishers/scientists collaborative development of BIO dFAD designs* (Moreno et al., 2016a)

In 2016, a workshop between fishers from all oceans and scientists facilitated i) design of new BIO dFADs; and ii) review of the different alternative materials that could be used (Moreno et al., 2016a). Variability in the expected lifetime of a dFAD for fishers was discussed, with views that depending on the region and ocean, dFADs could last between 5–12 months in the AO; 6–12 months in the EPO; and 12 months in the IO and WCPO.

Seven BIO dFADs were designed during the workshop, from 2m depth (IO) to 60–80m (AO), including five designs with buoys included in the raft to insure buoyancy and two fully biodegradable (Figure 12). The following materials were selected for the different BIO dFAD designs:

- Balsa wood (buoyancy)
- Bamboo canes (buoyancy and submerged structure)
- Pinewood (surface structure)
- Cotton canvas (cover of the raft, submerged flags and drift anchor)
- Cotton rope with loops (submerged structure)
- Cotton rope without loops (submerged structure and to assemble canes and balsa wood for the raft)
- Tencel ropes (eucalyptus)
- Stone (weight)
- Sand (weight)
- Hydrostatic release (to release the buoy when the FAD sinks)
- Buoys or purse seine corks

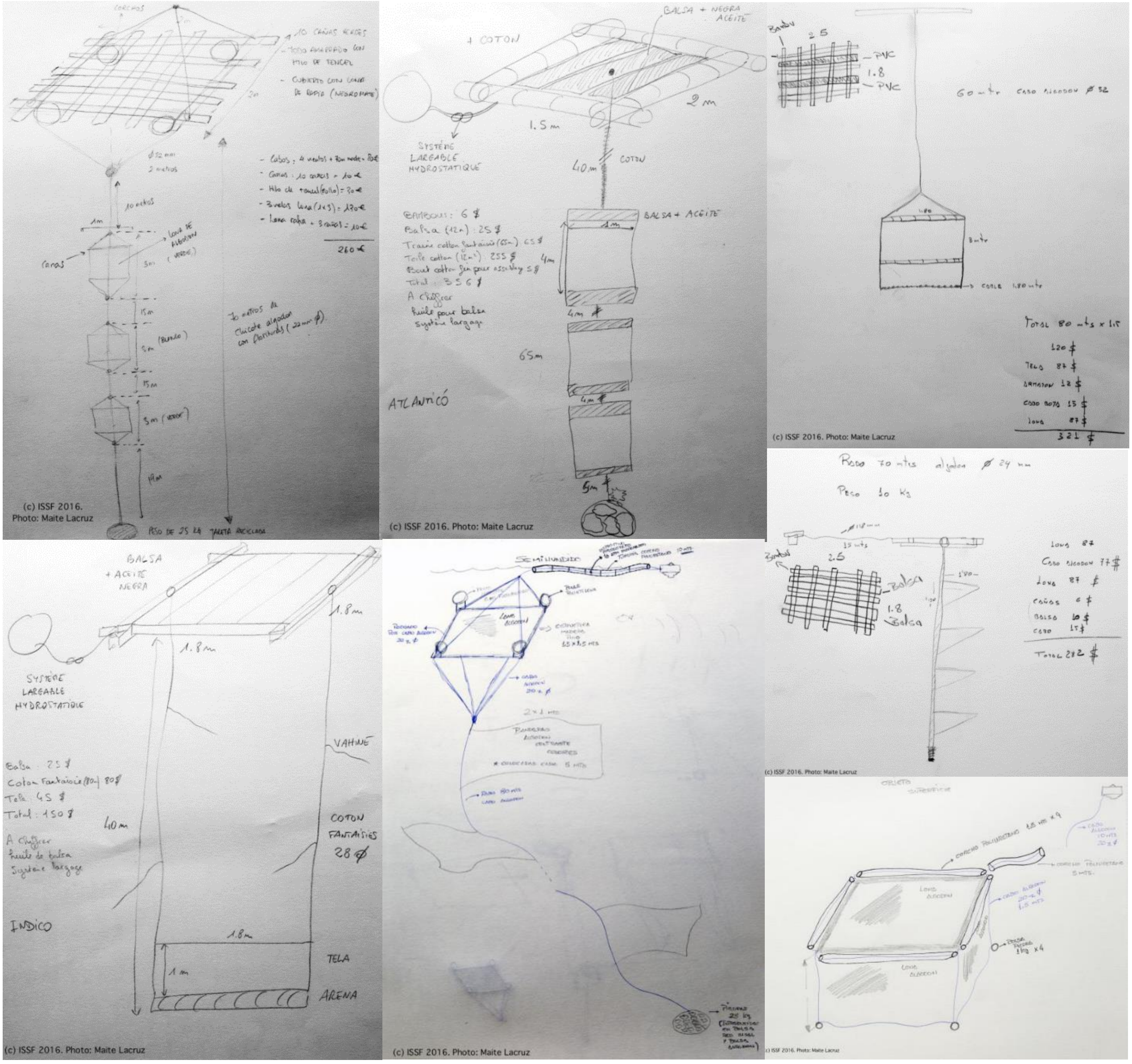


Figure 12. BIO dFAD designed during the workshop described in Moreno *et al.* (2016). Prototypes 1 to 7.

1.3.2 Scientists trials of BIO dFADs in the IO in 2017 (Moreno et al., 2017c)

85 BIO dFADs were tested by ISSF, in collaboration with a Spanish fishing company (six purse seiners) in the IO in 2017 (Moreno et al., 2017c). In parallel, 89 conventional dFADs were deployed and monitored during the same period.

Two different BIO dFAD designs were tested (Figure 1). It was decided to allow the use of synthetic floats in the raft construction, to ensure buoyancy, and be able to test the biodegradable ropes for longer time periods in real fishing conditions. Two designs were therefore tested, using ropes made of 100% cotton, with or without loops made by *Itsaskorda* rope manufacturer (Figure 13). 100% cotton was previously identified as resistant enough for the required lifetime of a dFAD, i.e. 1 year, followed by rapid degradation (Moreno et al., 2017b). The first design was a shallow dFAD, with a depth of 10 or 30m (Figure 13) and the second was a deeper dFAD at depths of 30, 50 and 70m (Figure 13d). To allow comparison, both conventional and BIO dFADs were constructed using the same design, but with traditional ropes or net tied in sausages for the first category and biodegradable ropes for the latter.

Figure 13. Biodegradable ropes made of 100 % cotton without loop (left) and 100 % cotton with loops (center left), used to construct biodegradable dFAD tested in real fishing conditions in the IO by Moreno et al. (2017c). Two designs were tested, a shallower dFAD at 10 m and 30 m depth (Center right); and d) a deeper dFAD at depths of 30 m, 50 m and 70 m.

Preliminary results only covered four months at-sea and showed no significant differences in terms of tuna and non-tuna species aggregation patterns (using analyses of echosounder buoy data) between conventional and BIO dFADs and the two designs.

Authors mentioned some limitations in terms of BIO dFADs that could not be tested in a certain period due to the limit in the number of active dFADs that can be monitored by a vessel (IOTC, 2019).

1.3.3 *Scientists trials of biodegradable dFADs in the AO in 2018* (Moreno et al., 2018)

A workshop was organised with the Ghanaian purse seine and pole and line fleets to design BIO FADs appropriate to the fishing needs of the Ghanaian fleet. Five BIO FAD designs were developed by the workshop participants, and they all presented a similar general design (Figure 14). While finding a successful biodegradable raft is still challenging, purse seine corks were still used to maintain floatation of the raft. All the submerged appendages were however made of biodegradable materials, such as cotton. This BIO dFAD design was then tested during real fishing condition in large quantities (around 600 BIO dFADs), but no information was available on the dFADs effectiveness, aggregation patterns and longevity.

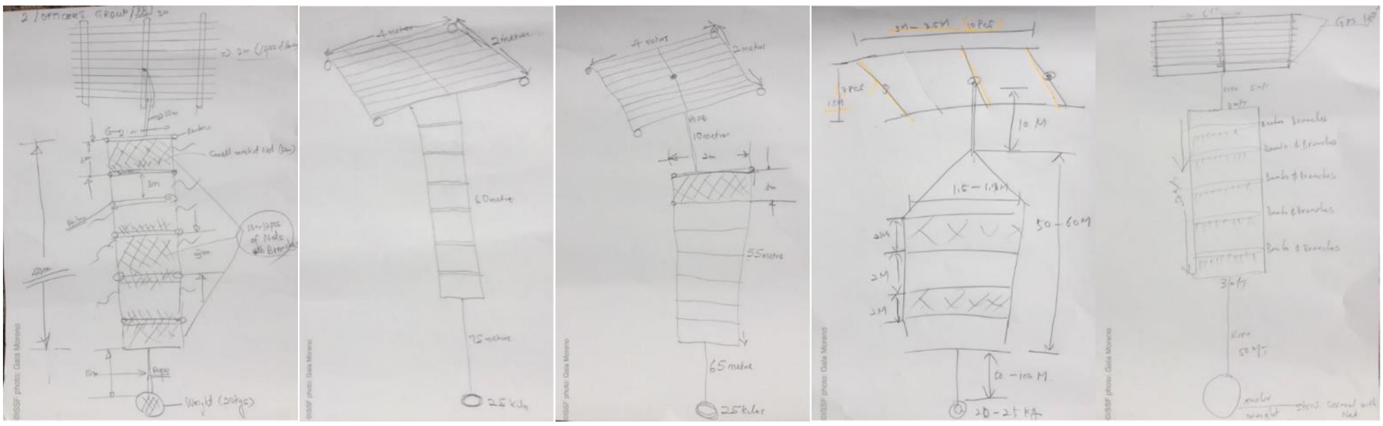


Figure 14. Prototypes of BIO dFAD designed by the Ghanaian fleet and tested in the AO (Moreno et al., 2018)

1.3.4 Large scale trial of BIO dFADs in the IO (Zudaire, 2017; Zudaire et al., 2020, 2019)

A large scale trial of 1,000 BIO dFADs was implemented in 2017–2019 in the IO, in collaboration between European research centres (AZTI, Institut de recherche pour le développement (IRD) and Instituto Español de Oceanografía (IEO) , ISSF and the EU tropical tuna purse seine fleet (Zudaire, 2017). Five prototypes of three main types, were designed and tested during the project duration. These included fishermen's requirements, preferences and needs, in particular the different drifting performance sought by each fisher were considered. Prototypes included surface dFADs (BIO FAD prototype C); medium/deep dFADs (BIO FAD prototypes A1 and A2); and high-deep dFADs (BIO FAD prototypes B1 and B2) (Figure 15) (Zudaire, 2017). Deployment of each BIO dFAD was accompanied by a conventional dFAD, for comparison. Condition of the BIO dFAD was assessed at each visit, and replacement of any part of the BIO dFAD was monitored.

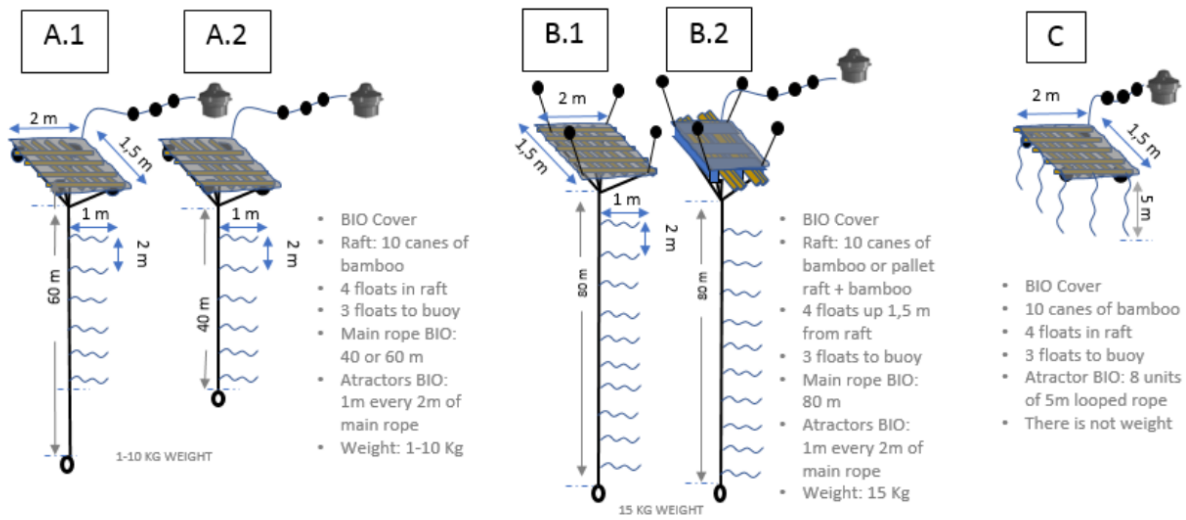


Figure 15. Prototypes of BIO dFAD designed and tested by the EU fleet in the IO in 2017–2019 (Zudaire, 2017; Zudaire et al., 2020).

Figure 16. Prototypes of BIO dFAD A1 designed and tested by the EU fleet in the IO in 2017–2019 (Zudaire, 2017; Zudaire et al., 2020).

Table 2. Weight comparison between BIO and NE materials for each prototype (Zudaire et al., 2020).

	TOTAL weight (kg)	Biodegradable Material (Kg)	Synthetic Material (Kg)	Total Weight in BIOFAD (Kg)	Total Synthetic weight in BIOFAD (kg)
A1- BIOFAD	67.6	47.1	20.5	↓ 44%	↓ 81%
NEFAD_1	121.4	12	109.4		
A2-BIOFAD	60.1	39.6	20.5	↓ 50%	↓ 81%
NEFAD_1	121.4	12	109.4		
B1-BIOFAD	79.4	48.9	30.5	↑ 27%	↓ 51%
NEFAD_2	62.6	0	62.6		
B2-BIOFAD	48.4	15.9	32.5	↓ 11%	↓ 40%
NEFAD_3	54.4	0	54.4		
C1-BIOFAD	46.4	30.9	15.5	↑ 1%	↓ 54%
NEFAD_4	45.9	12	33.9		

Materials used included bamboo or wood, cotton canvas and two types of cotton ropes (Zudaire et al., 2020). The first rope was a wax covered twisted cotton rope and was used for the large submerged appendaged part (i.e., main rope). The wax used was a non-hazardous palm oil derived wax (EC 1999/45/EEC), with a melting point interval between 48–59 ºC and it is non-soluble in water below 70ºC. The second rope was twisted looped cotton rope; and was used as short-length attractors attached at intervals to the main rope.

A total of 771 BIO dFADs were tested between 2018 and 2020 in the IO, with a majority of prototype A1 (71%; compared to 18% of A2; 4% of B1; 2% to B2; and 5% to C1) (Zudaire et al., 2020, 2019). Condition of the BIO dFADs was assessed and indicated different degradation rates depending on the materials and part of the raft considered (Figure 17).

Cotton canvas used to cover the raft and replace synthetic netting was starting to degrade during the first month at-sea and were considered in bad, very bad or absent conditions after 3 to 4 months in 50% of the BIO dFADs (Figure 17). Degradation was slower for the main cotton rope used as submerged appendages and the looped cotton rope used as attractors. Both ropes were considered in very good, or good conditions until the fourth month at-sea, however some were missing after the first month already (Figure 17). In the fifth month, the ropes were absent in 70% of the visits. Fishers mentioned that the absence of the ropes was likely due to deficient attachment between raft and tail, rather than due to a high degradation of the material. Note that after six months, the number of visits were too small to assess the conditions of the different materials.

Lifespan of NE and BIO dFADs, defined as the period between deployment and the day the dFAD was considered no longer active, was investigated with a maximum lifespan of over 12 months for all prototypes except B2 (limited number of deployments). Highest lifespan values were detected for BIO dFADs B1 (average of 242 days) and A1 (191 days); and NE dFADs A1 (209 days) and (182 days).

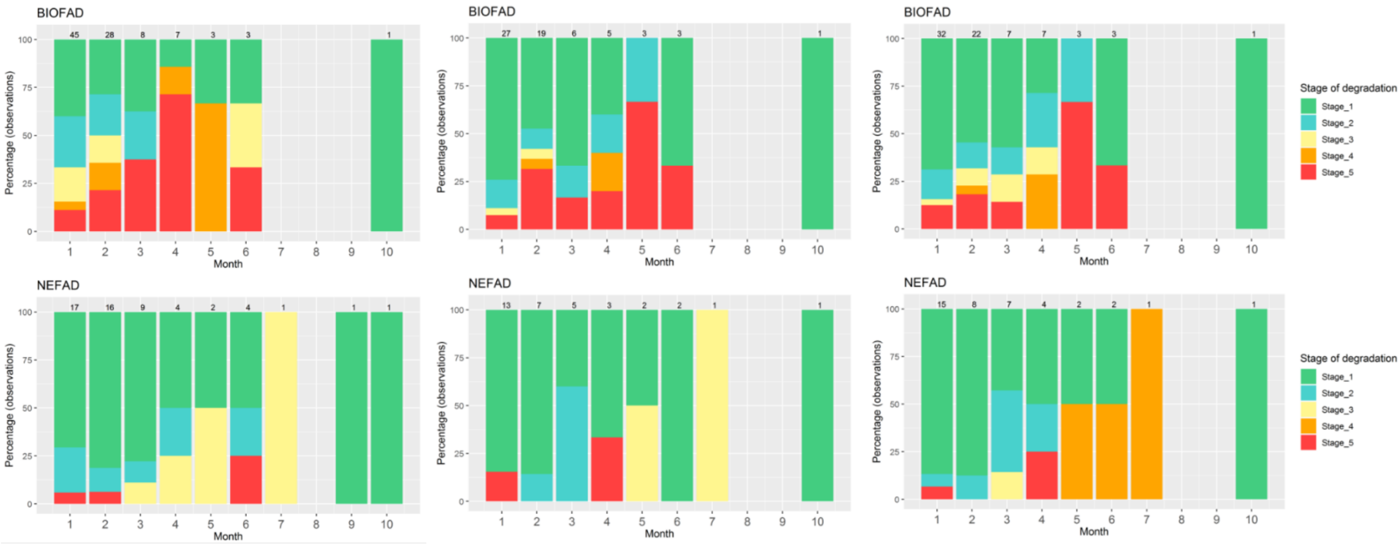


Figure 17. Status control assessment for the cotton canvas (left), main cotton rope (middle) and the cotton rope used as attractors (right) for BIO dFAD (upper figures) and synthetic material used as cover (left), tail (middle) and attractors (right) for NE dFAD (down figures). Stage 1 =Very good; Stage 2 = Good; Stage 3 = Bad; Stage 4 = Very bad; and Stage 5 = Absent (Zudaire et al., 2020, 2019).

A total of 68 fishing sets were made on the dFADs from the project, including 36 on BIO dFADs and 32 on conventional NE dFADs. No significant differences in the catches (total catch or by species) between BIO dFADs and conventional NE dFADs was detected (Table 3, (Zudaire et al., 2019). It can be noted that for both NE and BIO dFADs, most sets were performed on A1 prototypes.

Table 3. Catch data (maximum and mean in tons), number of sets, number of deployments and % of use by dFAD type and prototype (Zudaire et al., 2019).

	BIOFAD	CONFAD			
Max (tons)	150	225			
Mean (tons)	27.96	44.2			
±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	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%
CONFAD	A1	A2	B1	B2	C1
Max (tons)	98	225	0	0	70
Mean (tons)	29.38	75.71	0	0	67.5
±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%

Similar pattern of tuna aggregation was detected between BIO and NE dFADs (Figure 18), with no statistical difference in first day of detection found between dFAD types and prototypes. However, when distance between dFADs was considered, faster tuna presence was detected in NE dFADs compared to BIO dFADs. Higher occupation ratios were also detected in NE dFADs compared to BIO dFADs (Figure 18), particularly for prototypes A2 and B (not for prototypes A1 and C1).

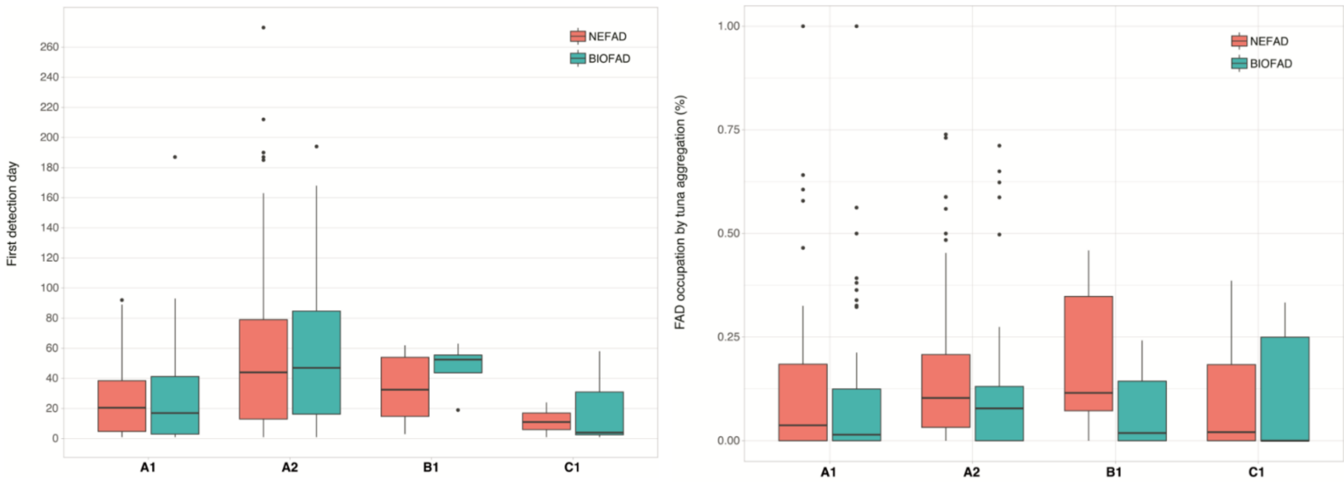


Figure 18. First day of tuna detection and dFAD occupation, by dFAD type and prototype (Zudaire et al., 2020).

Impact assessment was also performed for all prototypes of BIO and NE dFADs. In terms of carbon footprint and marine ecotoxicity, the BIO dFAD prototypes C performed the best. As expected, the prototypes with the most materials used had a higher environmental impact score, such as BIO dFAD A and B1. In case of NE dFAD prototypes, the fact that netting and weight are reused from purse seine nets highly decrease their carbon footprint score. It should however be mentioned that the impact generated by lost dFADs is not considered in this assessment. It has also been estimated that the replacement to BIO dFADs will drive an increase in costs of 1.05% (Table 3).

Generally, prototype A1 was considered as the favourite prototype by fishers, and A1 presented the highest number of sets and A2 the highest catch. Both lead to a high decrease in synthetic material used and an increase in natural materials used. The two cotton ropes were considered as good candidates to replace synthetic materials and showed similar degradation rates.

1.3.5 Large scale trial of BIO dFADs in the EPO (Román et al., 2022, 2020)

Three prototypes on NE and BIO dFADs were developed in collaboration with industry partners in the EPO (Figures 19). The prototypes included a bamboo and balsa wood raft, with some covering with canvas (Abaca or cotton) and submerged appendages composed of a main rope (abaca or cotton), bamboos, a tightening rope (abaca) and some canvas (cotton; prototype 2 and 3). A total of 796 NE and BIO dFADs were targeted to be deployed during the project duration in the EPO. Each deployment was accompanied by the deployment of a conventional dFADs within 10–15 miles, and each was marked with a metallic tag. A total of 715 NE and BIO dFADs, and paired conventional dFADs, were deployed between 2019 and 2022. Most deployments were of prototype 2 (392), followed by prototype 3 (209) and 114 prototype 1 (114) (Figure 19, Table 4). A total of 86 visits and 56 sets were conducted on the NE BIO dFADs (Table 4).

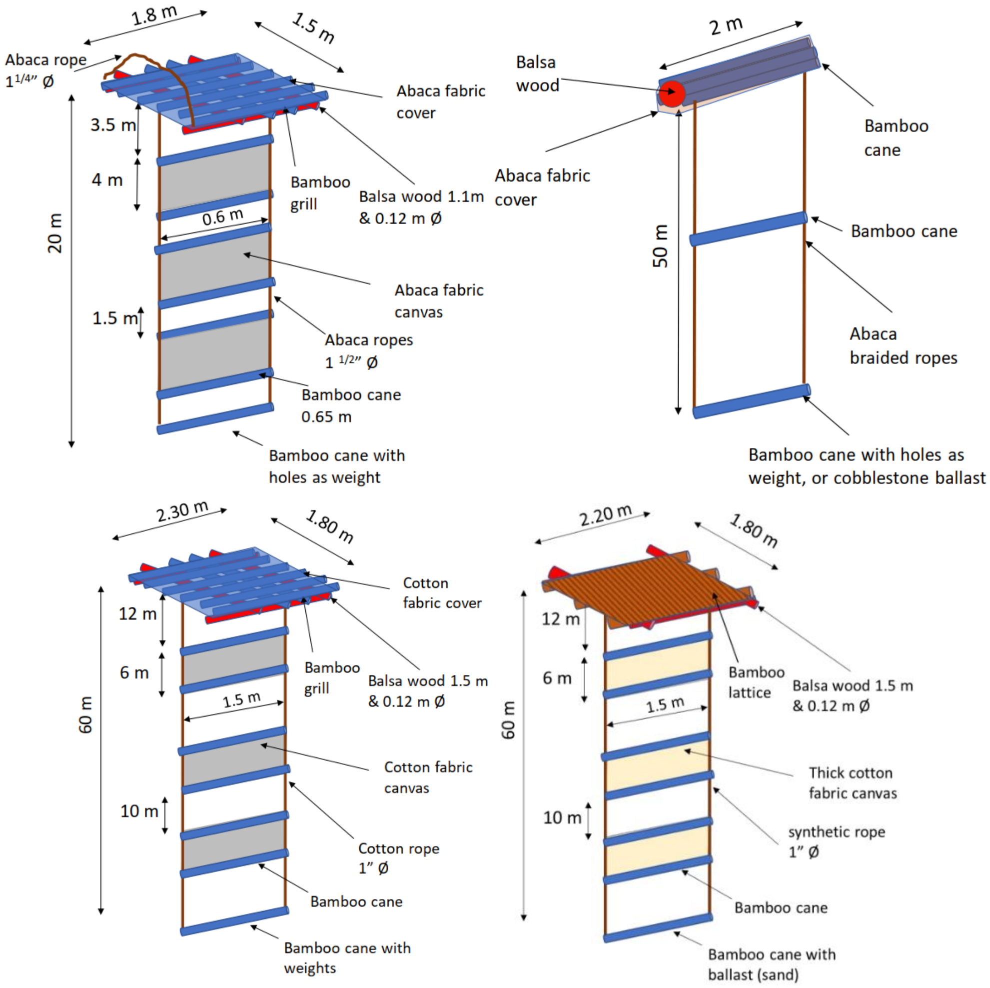


Figure 19. Prototypes of BIO dFADs tested in the EPO: prototypes 1 to 3 and 3 bis (Román et al., 2022, 2020).

Figure 20. Prototypes of NE BIO dFADs and conventional dFAD tested in the EPO, with corresponding marking (Román et al., 2022, 2020).

Condition of the NE BIO dFADs was investigated through time. Prototype 1 was observed 12 times, and the materials of both the floating (bamboo, balsa wood, abaca canvas and rope) and submerged components (abaca ropes, bamboo) were considered to be in good to very good condition after at least three months. Prototype 2 was observed 111 times, and the materials of both the floating (bamboo, balsa wood, abaca canvas) and submerged components (abaca ropes, bamboo), were in general, considered to be in a very good condition for two months; a good to fair condition until three months, but after that the materials were in poor conditions, particularly for the submerged appendages. Prototype 3 was observed nine times and presented the lowest durability. Some of the materials were deemed to be in poor condition or disappeared after two months of deployment, particularly in the submerged appendages part. The distribution of days between deployment and retrieval or last visit was also considered, with an average of 62, 43.6 and 66.9 days for prototypes 1, 2 and 3, respectively (Figure 19). The conventional dFADs presented an average time at sea of 87.4 days.

Note that prototype 3 was then modified (Figure 21), using cotton canvas and ropes from another supplier (better quality and thickness), and were tested with synthetic ropes to insure cohesion and integrity of the NE BIO dFADs. Small nylon ropes were added to reinforce connection between the raft and the submerged appendages.

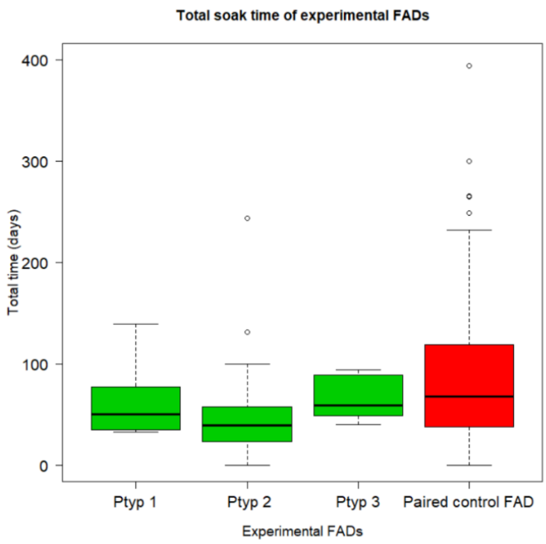


Figure 21. Prototypes of BIO FADs tested in the EPO (Román et al., 2022, 2020).

Soak time (days)			Floating component				Submerged component			
	Prototype	N	Bamboo	Canvas	Balsa	Tightening rope	Canvas	Main rope	Tightening rope	Bamboo	Bamboo (ballast)
1-30	1	4	1.8	1.8	1.2	1.2	NA	1.8	1.7	1.3	1.8
31-60	1	4	1.5	1.8	1.2	1.8	NA	2.5	1.5	1.3	1.5
61-90	1	3	2.9	3.8	2.1	2.2	NA	3.5	2.5	1	2.9
>90	1	1	3	3	2	1	NA	3	3	NA	3
1-30	2	63	1.6	1.9	1.6	1.8	1.8	1.9	1.9	1.6	1.6
31-60	2	34	1.9	2.1	2	2.1	2.2	2.3	2.1	2.1	2.1
61-90	2	12	2.2	3.4	2.4	2.6	3.4	3.6	3.3	3.2	3.4
>90	2	2	4.5	6	4.5	5	6	6	6	6	6
1-30	3	2	4	4.5	1.5	4.2	3	2.8	3	3	3
31-60	3	4	2.2	5.6	2.8	2.9	5.2	4.4	5.2	5.2	5.2
61-90	3	1	5	NA	1	5	3	3	3	3	3
>90	3	2	NA	NA	NA	NA	NA	NA	NA	NA	NA

Figure 22. Average of the NE BIO dFAD condition based on soak time. N: number of prototypes in each category of soak time. 0: Not observed; 1: Excellent; 2: Very good; 3: Good; 4: Regular; 5: Poor, and 6: Very Poor. NA: A NED that is not composed of a specific material (e.g., the submerged canvas of prototype 1), or the NED or some of the components were lost and only the satellite buoy was found (e.g., '>90' soak time of prototype 3) (Román et al., 2022, 2020).

Similar catch levels were detected on both NE BIO dFADs and conventional dFADs, with an average of 34mt/set on the NE BIO dFADs and 31.2 mt/set on the conventional dFADs.

Table 4. Number of deployment, visits, sets and catch for each NE and Bio dFAD and conventional dFADs deployed in the EPO (Román et al., 2022, 2020).

	Deployments	Visits	Sets	Catch (mt)	Catch per set (mt)
NED – Prototype 1	114	5	8	488	61
NED – Prototype 2	392	73	46	1342	29.2
NED – Prototype 3	209	8	2	76	38
Total NEDs	715	86	56	1906	34
Paired control FAD	705	106	134	4177	31.2

1.3.6 BIO dFAD trials by the Tunacons fleet in the EPO (Garcia et al., 2022)

During a pilot project phase in 2017, the Tunacons fleet tested different BIO dFADs in the EPO under standard fishing conditions, by anchoring the test BIO dFADs 9 miles off shores in Ecuador (Garcia et al., 2022). Three main types of biodegradable materials were used: jute, cabuya (agave sisal plant) and acaba, that are from a sustainable market, available in Ecuador and biodegradable. It was assessed that the BIO dFADs became non-functional after 25, 35, and 67 days for the BIO dFADs constructed with jute, cabuya and acaba, respectively (figure 23). For the later, the acaba BIO dFADs, additional lab tests were performed and indicated that after the 67 days, the loss resistance was 94% (with a Strength reduction from 251.6 kgF to 13.8 kgF).

Figure 23. Biodegradable level of BIO dFADs constructed with jute (a), cabuya (b), and abaca (c) (Garcia et al., 2022).

Following the pilot phase, the abaca-based BIO dFADs were selected for at-sea trials. Improvements to the canvas were carried out to increase impermability and resistance. This included testing different treatments, such as using animal fat, organic palm oil, fish oil, *sangre de drago* and natural rubber or latex (Garcia et al., 2022). The treatment that showed the best results were natural rubber, followed by animal fat (cow) and palm oil.

In 2021, the tunacons fleet deployed 20% of their total number of dFADs deployed as BIO dFADs, with a prototype constructed using abaca fibers (canvas and ropes) treated with natural rubber (Figure 22, right panel). This corresponds to a total of 1,401 BIO dFADs. The prototypes tested were similar to the BIO dFADs tested under the IATTC trials (Román et al., 2020, 2022)., with some adjustments that included added two sections of balsa stick of 1.10 m (Ø 10 or 12 cm) for greater flotation; and 3 sections of guadúa cane of 0.65 m injected with animal fat as attractant Figure 24). A total of 222 visits and were made on the BIO dFADs (Table 5). The soaking time, defined as period between deployment and fishing set ranged between 1 and 100 days. The average catch per set was of 26.7 tons.

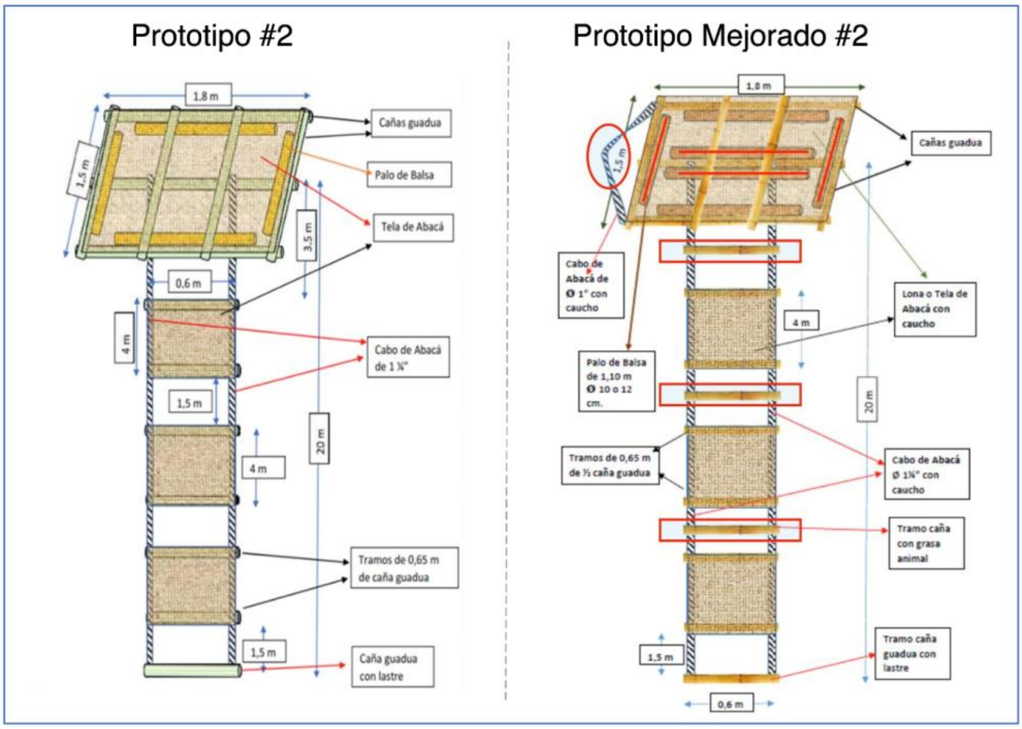


Figure 24. Designs of the BIO dFADs tested by the Tunacons fleet in the EPO, protype tested with IATTC (left) and prototype tested by the fleet in their experimental trial (right, Garcia *et al.*, 2022).

Table 5. Number of visits, sets, catch, and soaking time for each BIO FAD deployed in the EPO by the Tunacons fleet (Garcia et al., 2022).

	fishing cruises	visits Eco-FADs	Sets on Eco-FADs	catches in Eco-FADs	Catch per set	soaking period	biodegradation floating part	biodegradation submerged
TUNACONS Fleet	188	222	148	3964	26,8	1 – 100	46% MB 25% B 20%R 7%M	43%MB 14%B 28%R 8%M

The condition of the BIO dFADs was assessed during each set (Table 6) and indicated that both the raft and submerged appendages were in good condition for 60 days, degradation started after 61 days, particularly for the submerged appendages, considered as in bad condition during the 3rd month.

Table 6. Conditions of the BIO FAD deployed in the EPO by the Tunacons fleet after different soaking periods (Garcia et al., 2022).

soaking period	Sets	floating structure	Submerged structure
< 30	29	1,9	2,1
31 - 60	44	2,8	3,2
61 - 90	19	3,7	4,7
> 91	2	4,0	4,0

N obs	0
Excelente	1
Muy Bueno	2
Bueno	3
Regular	4
Malo	5
Muy Malo	6
Sin Rabo	7

1.3.7 The Jelly-FAD – a paradigm shift (Moreno et al., 2022, 2020)

A new type of BIO dFADs was developed by ISSF, in collaboration with the Insitute de Ciències del Mar (CSIC, Spain) and experts in physical oceanography. Previous BIO dFAD trials have indicated that when using a design that is similar to the conventional dFADs, typically submerged panels hanging from the raft), the lifetime of the dFADs is shorter than what is expected by fishers (from four to nine months, depending on the area) due to the structural stress that these designs support and the lower robustness of biodegradable materials to these stress (Moreno et al., 2022). Currently there is no clear alternative for the plastic buoys that are used in the dFAD raft to ensure buoyancy. The new proposed design also reduces the number of buoys needed by reducing the weight. Finally, the size of the dFAD structure need to be reduced to decrease the impact on the environment, allowing easier retrieval and reducing the cost of the BIO dFADs.

The purpose of the new BIO dFAD prototype, called the "Jelly-FAD" is to make the dFAD drift slowly by anchoring it in the mixed layer depth and having a structure that is almost neutrally buoyant. Hence, reducing the structural stress that the submerged structure suffers. Controlled experiments were undertaken to evaluate the density of the materials used in the Jelly-FAD through time (Figure 25). Materials need to have a similar density to the sea-water to allow minimum torsion and stress and therefore decrease the need for buoyancy assistance. The emergent part of the Jelly-FAD should also be minimized to avoid surface drag created by wind and waves (Moreno et al., 2022, 2020).

A symmetric three-dimensional cube structure of 1 m^3 was selected as a drogue, hanging from the surface using a rope to a depth below the mixed layer depth. Weight (8kg of stone) was used so that the cubic structure would sink, but once the materials absorbed saltwater to saturation, weight is no longer needed. It was found that after 20 days for bamboo and 25 days for a cotton rope of 22mm of diameter, the materials became fully saturated in sea water, making the bamboo cubic structure neutrally drifting in the water column. Weight only needed to be added so the structure initially sunk and to submerge the dFAD materials. The surface component of the dFADs needs to be reduced to limit stress from wind, waves and surface vs deeper currents. A raft was then submerged at 5–10m depth and can act as aggregator and create shade.

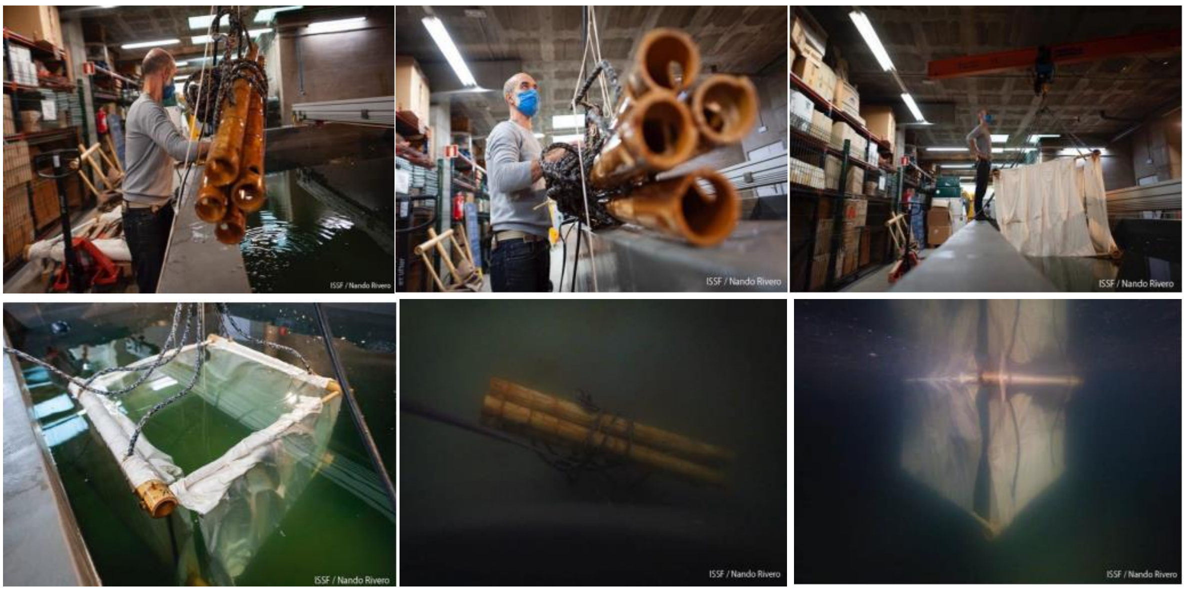


Figure 25. Longevity of the Jelly-FADs tested under controlled conditions (Moreno et al., 2022).

1.3.7.1 Controlled trials in the Mediterranean Sea (Moreno et al., 2022)

Ten Jelly-FADs were deployed in the Mediterranean Sea in 2021 to monitor their integrity over time. After 7 months at-sea, 4 Jelly-FADs were still intact, 3 had sunk and 3 were stolen or stranded. Additional trials are ongoing currently in 2022.

1.3.7.2 First trials in the WCPO (Moreno et al., 2020)

In order to test appropriate biodegradable dFAD tails, considered as the most impactful component, a conventional raft with a line of purse seine corks covered with non-entangling net (mesh size <2.5'') were used. Two BIO dFADs prototypes were then designed using fully biodegradable submerged appendages of 60m (Figures 26 and 27). Materials used for the submerged appendages included bamboo, manila rope, jute canvas, palm leaves, and sand or stone. Alternatively cotton canvas and cotton ropes (100% cotton 20 mm diameter, 4 strands in torsion Z) were tested to increase durability. Details about the construction of the Jelly-FADs are available in Moreno *et al.* (2020, 2022).

The project had an objective of deploying 100 BIO dFADs (50 for each prototype), and a matching 100 conventional dFADs. 49 dFADs (39 of prototype A and 10 of prototypes B) were deployed in 2020 (Table 7) (Moreno et al., 2020). Two fishing sets were performed, one on each prototype, with 35 and 95t of tuna caught.

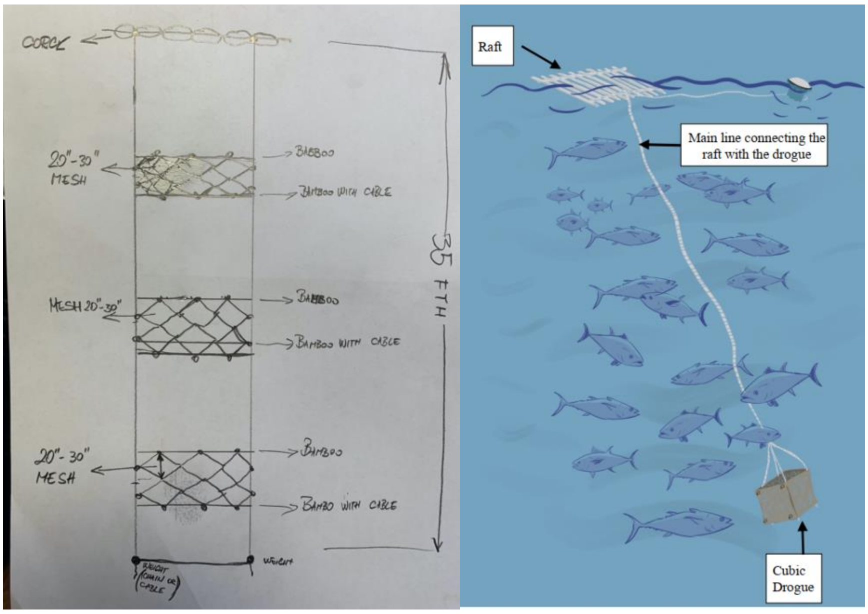


Figure 26. Designs of the BIO dFADs tested in the WCPO: prototype A (left), and B (right, the Jelly-FAD) (Moreno et al., 2020)

Figure 27. Jelly-FADs tested in the WCPO (Moreno et al., 2020)

Table 7. Number of BIO dFAD deployed, retrieved and set on in the WCPO and associated tuna catch (Moreno et al., 2020).

BIOFAD prototype	Deployment	Retrieval	Removal, end use of FAD	Set
Type-A	39	1	1	1
Type-B	10		1	1
Total	**49**	**1**	**2**	**2**

BioFAD Prototype	BET	SKJ	YFT	Total Catch
Type-A		35		35
Type-B	65	5	25	95
Total	65	40	25	130

A second trial of Jelly-FADs is currently ongoing using cotton ropes and juste canvas.

1.3.7.3 Large scale trials in the EPO (Moreno et al., 2022)

In the EPO, the Ugavi fleet deployed 500 Jelly-FADs in 2021 (Figure 28). Preliminary results indicated that 14 Jelly-FADs were set on, with catch rates ranging from 10 to 125 tons (average of 47.9 t). Days at-sea until set varied from 1.6 months to 6 months (Table 8 and Figure 29).

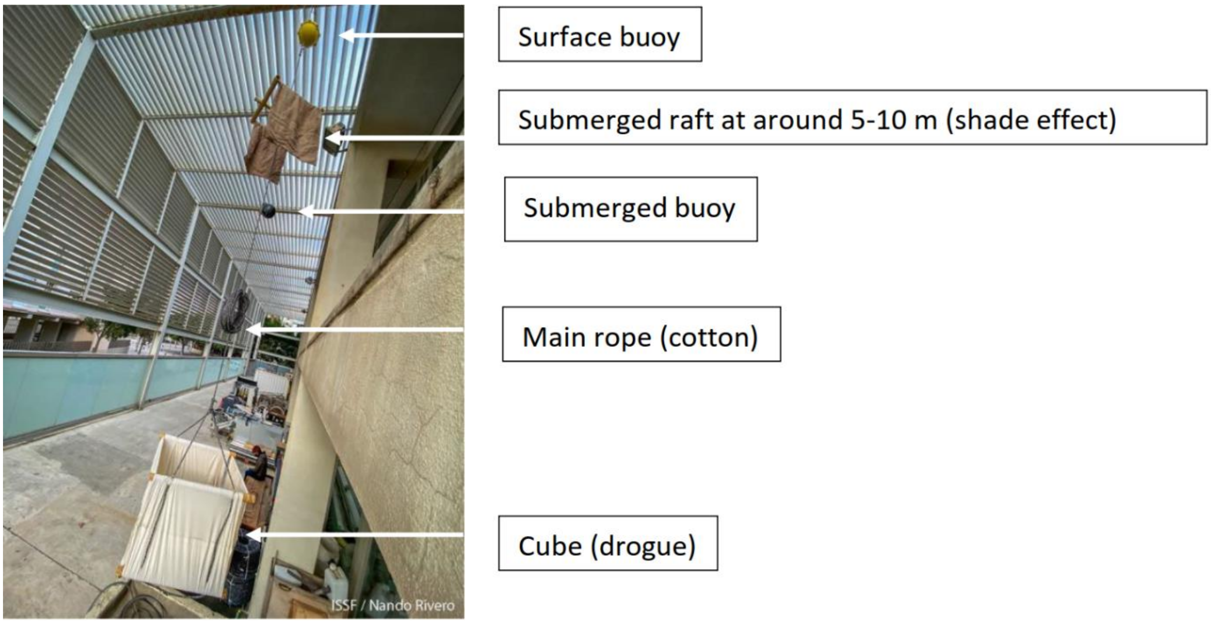


Figure 28. Jelly-FADs tested in the EPO (Moreno et al., 2022)

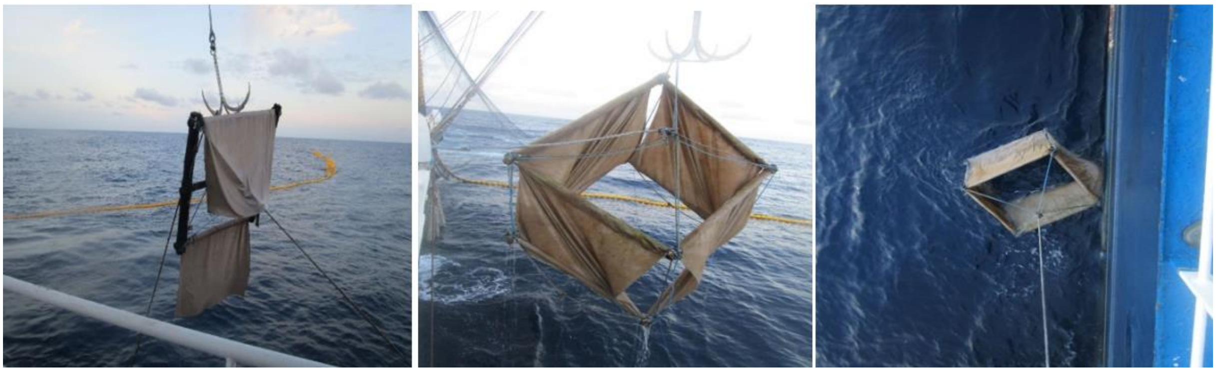


Figure 29. A Jelly-FADs after 5 months at-sea, it was fished, with 45 tons of tuna captured and redeployed in the EPO (Moreno et al., 2022).

Table 8. Sets and associated catch on the Jelly-FADs deployed in the EPO in 2021 (Moreno et al., 2022).

FAD	Deployment date	Set date	Days at sea	Months at sea - until set	Catch (tons)
1	29/10/21	15/1/22	129	2,6	40
2	29/10/21	19/1/22	129	2,7	45
3	9/8/21	23/1/22	93	5,6	55
4	29/10/21	1/3/22	179	4,1	120
5	25/1/22	14/3/22	182	1,6	125
6	27/12/21	19/3/22	179	2,7	15
7	18/10/21	24/2/22	62	4,3	45
8	18/7/21	24/11/21	65	4,3	30
9	18/7/21	12/9/21	93	3,1	20
10	11/6/21	4/2/22	179	6,0	10
11	9/8/21	5/2/22	182	6,1	10
12	7/8/21	30/1/22	179	6,0	60
13	4/8/21	27/3/22	62	2,1	85
14	22/1/22	28/3/22	65	2,2	10

1.3.7.4 *Additional trials currently ongoing* (Moreno et al., 2022)

In the AO, three fleets have been or will trial the Jelly-FAD in 2022. The Ghanaian fleet trialed a total of 35 Jelly-FADs, but few visits were made due to the loss of the Jelly-FADs. Echosounder buoy trajectories and biomass are currently being analyzed. The Opagac fleet (Spain) aimed at testing 350 Jelly-FADs. 84 have already been deployed, with 7 visits made. The Pevasa fleet (Spain) will trial around 200 Jelly-FADs in 2022. In the EPO, 100 Jelly-FADs will be tested by the NIRSA fleet in 2022.

1.3.8 *Summary of Bio dFAD trials worldwide (ISSF)*

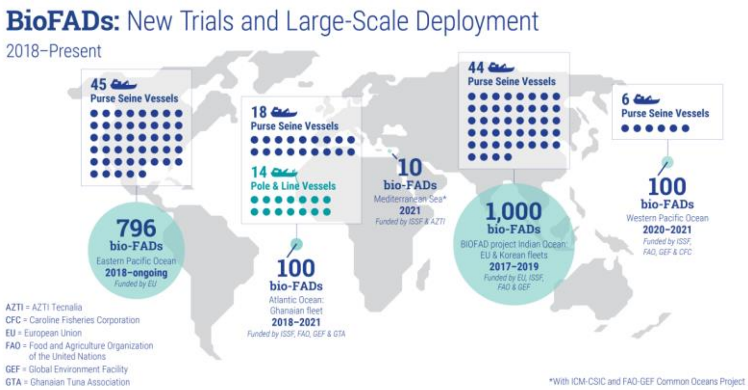


Table 9. Summary table of BIO dFAD trials.

Reference	Ocean	Year	Type of FADs	Synthetic materials?	Objective deployed	Prototypes	Details	Material	Nb deployed	Nb visits	Nb sets	Mean catch per set	Nb sets on conv FADs	Conv FADs mean catch	Condition	Max days at-sea	Echo-sounder	Type of buoy
(Moreno et al., 2017a)	IO	2017	Ropes only	Floats in raft	Unkn.	1a	Shallow (10 and 30m)	100% cotton ropes twisted without loop	85	Unkn.	0	NA	5 sets	5-80t	Up 6 months at sea		No significant difference in aggregation patterns	3 types
						1b	Shallow (10 and 30m)	100% cotton ropes with loop										
						2a	Deep (30m, 50m and 70m)	100% cotton ropes twisted without loop										
						2b	Deep (30m, 50m and 70m)	100% cotton ropes with loop										
(Moreno et al., 2018)	AO	2018?	Open pannels	Floats in raft	600	1		Bamboo, cotton tope without loops, cotton canvas, palm leaves	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.		Unkn.	Unkn.
						2												
						3												
						4												
						5												
(Zudaire, 2017; Zudaire et al., 2019, 2020)	IO	2018-2020	Ropes and attractors	Floats in raft	1000	A1	Medium	Bamboo, cotton canvas, waxed twistted cotton rope or looped twisted cotton rope	545		26	32.2	21	29.4		191	Similar pattern of tuna aggregation	
						A2	Medium		128		5	40	8	75.7				
						B1	Deep		43		2	0	0	0		242		
						B2	Deep		20		0	0	0	0				
			Attractors			C	Shallow		42		2	0	3	67.5				
(Román *et al.,*	EPO	2019-2022	Open pannels	No	796	1		bamboo and balsa wood, abaca	114	5	8	61	56	34		140		

2020, 2022)								canvas and rope										
			Ropes only			2		bamboo and balsa wood, abaca canvas and rope	392	73	46	29.2				100		
			Open pannels			3		bamboo and balsa wood, cotton rope and canvas	209	8	2	38				90		
Garcia 2022	EPO	2021	Open pannels	no	20% = 1381	100%	check	check	1401	222	148	26.8		26.9 t/ set (EPO average)	Good = 60 days. Bad 61-100		Not mentionned	?
Moreno 2020	WCPO	2020	Open pannels	buoys (raft)	100	A		bamboo, manila rope, jute canvas, palm leaves, and sand or stone	39	Unkn.	1	35	Unkn.	Unkn.				Satlink
			Jelly-FAD			B	Jelly-FAD		10		1	95						
	EPO	2021	Jelly-FAD	Buoys	500	1	Jelly-FAD	bamboo, cotton rope and canvas	500		14	47.9	Unkn.	Unkn.		6 months	Unkn.	
	AO	2021	Jelly-FAD	Buoys	Unkn.	1	Jelly-FAD	Unkn.	35	low	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.
	AO	2022	Jelly-FAD	Buoys	350	1	Jelly-FAD	Unkn.	84	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.
	AO	2022	Jelly-FAD	Buoys	200	1	Jelly-FAD	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.

2 Prices associated to the different models

Table 10. Summary table of prices of NE, BIO and conventional dFADs.

Reference	Type	Nb	Year	Ocean	Materials breakdown	Total (€)	Buoy (€)	Human effort
Delgado de Molina *et al.* (2006)	NE	126 of 22 types	2005	IO	No price mentioned			
Franco *et al.* (2009)	Conv		2009	IO	Bamboos: 6–8€ Recycled PS net : free	6–8	600–1300	6–8 pers. 40min
Franco *et al.* (2009)	Conv		2009	PO	Bamboos: 6–8€ PVC pipes: Recycled PS net : free + bought (more FADs used)	> 6–8		

Franco *et al.* (2009)	NE BIO	0	2009	IO	Bamboos: 7.5€ Bamboo screening: 19€ Sisal net or mussel ropes: 60€	86.5	1000	
Franco *et al. (*2012)	NE BIO	44 of 2 types	2010-11	AO				
Goujon et al. (2012)	NE	1170 of 3 types	2010-12	IO	Price x10 or x20 if biodegradable materials used (Design B)			Can transformed the currently used dFADs. Which takes <1h (design C) or longer (design D).
Goñi *et al.* (2016)	Conv		2014	AO/IO/PO		27.5		
Goñi *et al.* (2016)	NE		2014	AO/IO PO		122–191 160–170		
Moreno *et al.* (2016)	BIO	0 type 1 0 type 2 0 type 3 0 type 4 0 type 5 0 type 6 0 type 7	2016	AO AO PO PO IO IO IO	- 10 bamboos= 10€; Cotton rope >70m= 80€; Tencel stitch= 30€; Rafia canvas (sail)=130€; Rafia canvas=10€ - Bamboo= 6$; balsa=25$; cotton rope= 65$; cotton canvas= 255$; small cotton ropes= 5$. - Rope =120$; Bamboo = 12$; small cotton ropes = 15$; canvas 87$+87$ - Canvas= 87$+87$; cotton ropes = 77$; Bamboo = 6$; balsa=10$; ropes = 15$ -Balsa=25$; cotton ropes = 80$; canvas= 45$	260 310 280 245 ? 130 ?		
Moreno *et al.* (2017)	Conv	89	2017	IO				
Moreno *et al.* (2017)	BIO	85 of 2 types	2017	IO		?		
(Moreno et al., 2019)	NE		2019			260–440		
(Moreno et al., 2018)		0 of 5 types (plan for 600)	2018	AO				
(Murua et al., 2017a)	LER NE				Construction cost of LERFADs were slightly higher than purse seine net HERFADs, they were still comparable according to fleet managers. NEFADs, many designs also require low costs in materials and are easier to assemble and store onboard, as they have a simpler construction with ropes and no raft cover is required		1000-1800$	

(Zudaire, 2017; Zudaire et al., 2020)	NE and Bio	771 (goal of 1000) of 5 types	2017-2019	IO	Floating structure 30 euros Canvas: 24 Main ropes: 67 Rope attractor: 27 Floats: 33	116 206 (+212 euros as replacement cost/yr)	1000 euros	25 euros
(Román et al., 2020, 2022)								
Garcia 2022								
(Moreno et al., 2020)	NE BIO			WCPO	Type A Type B (raft = conventional: recycled PS corks and nets)	 120$ (tail)		
(Moreno et al., 2022)	NE BIO			EPO		180-280$		

3 Potential biodegradable materials considered in dFAD construction

3.1. Review of potential biodegradable materials

Table 11. Biodegradable materials explored or tested to be used in the different parts of dFAD construction.

Part of dFADs	Materials currently used	Alternatives	Available information and limits	References
Raft (buoyancy)	Floats, drums, pipes Bamboo Planks, timbers, pallets	**- Bamboo**	- Cheap but loses buoyancy with time due to water seeping inside canes' air chamber. Good when combined with other materials to ensure buoyancy. Green canes or recently cut canes have higher lifetime. Natural oils or waxes could be explored to extend lifetime.	(Franco et al., 2009; Moreno et al., 2016a) (Delgado de Molina et al., 2006)
		- Balsa wood (*Ochroma pyramidale*)	- Great buoyancy. Ongoing test of raft combining balsa wood and bamboo canes. Availability could not be easy in some regions.	(Moreno et al., 2018, 2016a)(Moreno et al., 2018, 2016b; Román et al., 2022)(Murua et al., 2017b)
		- Coconuts	- Potential alternatives suggested.	
		- Containers made of polymers from natural origin	Never been tested ?	(Moreno et al., 2016a)

		- Pine wood	Lose buoyancy with time and suffer bites from large marine animals.	(Moreno et al., 2016a)
		- Radiata pine	Tested in controlled conditions, maintained buoyancy for least 130 days when coated.	(Delgado de Molina et al., 2006; Franco et al., 2009)
		- Cork	Tested in controlled conditions, maintained buoyancy for least 130 days when coated or not.	(Zudaire et al., 2020)
		- Recycled Polyamide from fishing nets	Recycled plastic from circular economy. Tested in controlled conditions, maintained buoyancy for 45days.	(Zudaire et al., 2020)
		- Blend of Polylactic acid (PLA)/ Polyhydroxyalkanoates (PHA)	Biodegradable thermoplastic materials (synthetic materials with biodegradable material certification for packaging applications). Recycled plastic from circular economy. Tested in controlled conditions, maintained buoyancy for 45days.	(Zudaire et al., 2020) (Zudaire et al., 2020)
Raft cover	Nets Sacks, bags	- **Palm leaves**	- Cheap.	(Franco et al., 2009; Moreno et al., 2018)
		- **Cotton** (*Gossypium spp*.) **canvas**	- Good alternative; exist in dark colours.	(Moreno et al., 2016a)
		- Bamboo slats or thin bamboo tied with galvanised wire	- Expansive (estimated at 19euros/5m in 2009).	(Franco et al., 2009)
		- Black cotton cloth	- Increase furtiveness (water over it) but is not strong enough.	(Goujon et al., 2012)

		- Abaca (*Musa textilis*) canvas, also known as Manila hemp	- Tested on Bio-FADs in real fishing conditions, lasted for at least 3 months. Animal lard was applied as antifouling, however, longevity could be increased by coating in with natural products such as rubber (lab experiments). - Tested anchored at-sea and lasted for 67 days, with a Strength reduction from 251.6 kgF to 13.8 kgF. Treatment were also used to enhance impermability and resistance in sea water, and the best results were natural rubber, followed by animal fat (cow) and palm oil.	(Román et al., 2022) (Garcia et al., 2022)
		- Jute (*Corchorus capsularis*)	- Tested anchored at-sea and lasted 25 days only. Tested in BIO FAD trials in the WCPO.	(Garcia et al., 2022; Moreno et al., 2020)
		- Cabuya (Agave sisal plant)	- Tested anchored at-sea and lasted 35 days only.	(Garcia et al., 2022).
Submerged appendages	Nets Cords, ropes	- **Cotton ropes not allowing bio-fouling**	- Without loops. More stable over time compared to ropes allowing biofouling. Similar aggregative patterns were observed for non-biodegradable and biodegradable dFADs (trial of 6 months at sea). On-going tests (EPO, AO, IO). - 3 designs were tested offshore Maldives for 1 year: i) twisted cotton; ii) twisted cotton and sisal ropes; and iii) cotton, sisal and linen ropes with loops. Twisted cotton ropes considered more appropriate (can still resist 1 year and ductile), while twisted cotton and sisal ropes were the most resistant. Need to be tested in real dFADs. Variations in manufacturing processes will affect degradation rates.	(Moreno et al., 2016, 2017c, 2018)(Moreno et al., 2016a) (Moreno et al., 2017b)
		- Cotton ropes with loops allowing bio-fouling (used to grow	- Decreased floatability over time, but biofouling could be helpful in the first stages of colonisation. Less resistant over time than ropes not allowing bio-fouling.	(Moreno et al., 2016, 2017c, 2018) (Moreno et al., 2017b)

		mussels) - Other vegetal fibre ropes - Coir (coconut husk fibre) - Tencel ropes from Eucalyptus - Sisal, raffia ropes - Vegetal fibre nets (sisal *Agave sisalana*) <7cm mesh rolled - Abaca (*Musa textilis*) ropes - Manila ropes	- Designs mixing cotton, sisal, linen, and hem. Degradation rate varies with the fibre and design used, additional at sea trials are necessary. Twisted cotton presented slow colonisation rate and one of the highest initial strength and longevities. - Tested at anchored FADs in Hawaii. Decompose quickly and low biofouling. Could be appropriate for the appendages but not to bind the raft. - Potential alternatives suggested. - Potential alternatives suggested. - Potential alternative suggested. nets of 4,5 mm wire width and less than 80mm mesh size. Estimated at 7.6 euros for 12m^2 in 2009. - Tested on Bio-FADs in real fishing conditions, lasted for at least 3 months. Animal lard was applied as antifouling, however, longevity could be increased by coating in with natural products such as rubber (lab experiments). Tested in BIO FAD trials in the WCPO.	Lopez et al. (2016, 2019) (Moreno et al., 2017a) (Moreno et al., 2016a) (Franco et al., 2009) (Delgado de Molina et al., 2006; Franco et al., 2009) (Román et al., 2022) (Moreno et al., 2020)
Submerged appendages	Sacks, bags	- **Cotton canvas** - **Palm leaves** - Jute (genus	- Used as “flags” to create more volume and as drift anchors. Fishers preferred thicker cotton canvas. Different numbering depending on thickness, thickest (number 12) preferred by the fleet testing it. - Can last several months - Too fragile. Becomes covered by sessile organisms and bites from	(Moreno et al., 2016, 2018) (Franco et al., 2009) (Delgado de Molina et

		Corchorus) fabric - Coco fibre fabric - Abaca (*Musa textilis*) fabric	predators. Fish eating the fabric. - Too fragile. Fish eating the fabric. - Tested on Bio-FADs in real fishing conditions, lasted for at least 3 months. Animal lard was applied as antifouling, however, longevity could be increased by coating in with natural products such as rubber (lab experiments).	al., 2006; Franco et al., 2009; Moreno et al., 2016a) (Moreno et al., 2016b) (Moreno et al., 2016b) (Román et al., 2022)
Weight	Weight	- Stones - Sand - No weight - Bamboos with holes - bamboo soaked in sea water	- ex: cobblestone - Not used by some fishers, who consider that the weight of encrusted animals is enough Bamboo are saturated in sea water after 20 days making them neutrally buoyant in the water column; and there removing the need for weight. Used for instance in the case of the jeely-FAD.	(Moreno et al., 2016a)(Román et al., 2022) (Moreno et al., 2016a)(Delgado de Molina et al., 2006) (Franco et al., 2009) (Román et al., 2022) (Moreno et al., 2022, 2020).
Satellite buoy		- Hydrostatic release	- Hydrostatic release before the dFAD sink. The issue of retrieving buoys to limit pollution remains.	(Moreno et al., 2016)

3.2. Different materials considered as biodegradable alternatives discussed with fishers during workshops

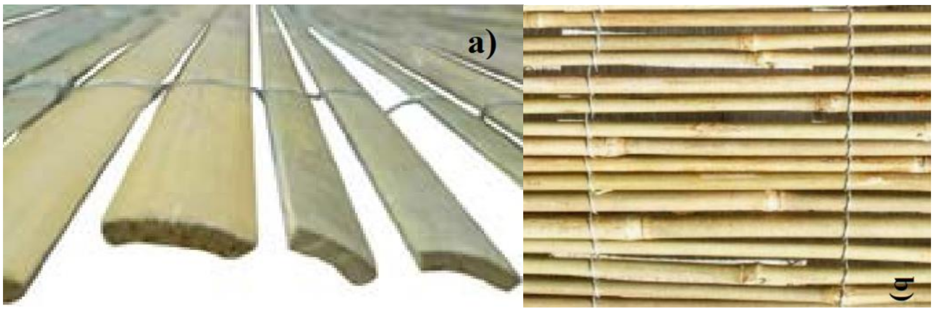


Figure 30. a) Bamboo slats (average width = 15mm, varying from approx 5mm to 20mm, and b) thin bamboo; tied together with horizontal galvanised wires.

Figure 31. Biodegradable dFAD build with balsa wood (a and b); detail of basla wood (c); biodegradable cotton cava of various thickness (d); and different rope types from natural origin (e) (Moreno et al., 2016).

3.3. Trials to test resistance of ropes and canvas for dFAD construction

3.3.1.Test of biodegradable twines (Lopez et al., 2019, 2016)

Five natural twines were tested in the AO (Lopez et al., 2019, 2016): i) twisted cotton; ii) twisted regenerated cotton and sisal; iii) plaited and bulked regenerated cotton and linen; iv) plaited and bulked cotton, regenerated cotton and linen; and v) plaited and bulked regenerated cotton, sisal and hemp twines (designed, manufactured and distributed by Itsaskorda Cordage Building Supplies). Twines were first assessed for their diameter; weight; breaking strength, defined as the point at which the twines breaks when placed under stress (in kgf); and Rtex, defined as the linear density or mass per unit length (1 tex = 1 g/1 m) (Table 2). Five samples of 4m of each twine were then tested on inshore aquaculture grounds in Spain for 161 days to measure degradation in breaking strength.

Under the condition tested, the twines made of twisted cotton (twine 1) and plaited and bulked cotton, regenerated cotton and linen (twine 4) showed a time a failure (breaking strength reaching 0 kg) abobe the expected lifetime of dFADs (10–12 months), with 417d and 557d, respectively (Figure 33, derived from Lopez et al. (2016, 2019)). Both twines showed very different initial breaking strength (Table 12). Authors therefore concluded that material type, construction design, and Rtex are not sufficient predictors of degradation rate observed at sea when such twines are constructed with both different designs and materials. It was also found that plaited and bulked twines experienced a faster and more complex colonization than twisted twines.

Table 12. Initial characteristics of five twine types evaluated by Lopez et al. (2016, 2019).

Twine	Twine type	Construction	Breaking strength (kgf)	Diameter (mm)	Rtex (gr/m)
1	Cotton	Twisted	1645	20	202.7
2	Regenerated cotton + sisal	Twisted	1144	20.62	210.93
3	Regenerated cotton + Linen	Plaited + bulked	194	16.7	221.16
4	Cotton + Regenerated cotton + Linen	Plaited + bulked	189	16.4	234
5	Regenerated cotton + Sisal + Hemp	Plaited + bulked	288	12.2	212.87

Figure 32. Pictures of the 5 different biodegradable twines tested by Lopez et al. (2016, 2019)

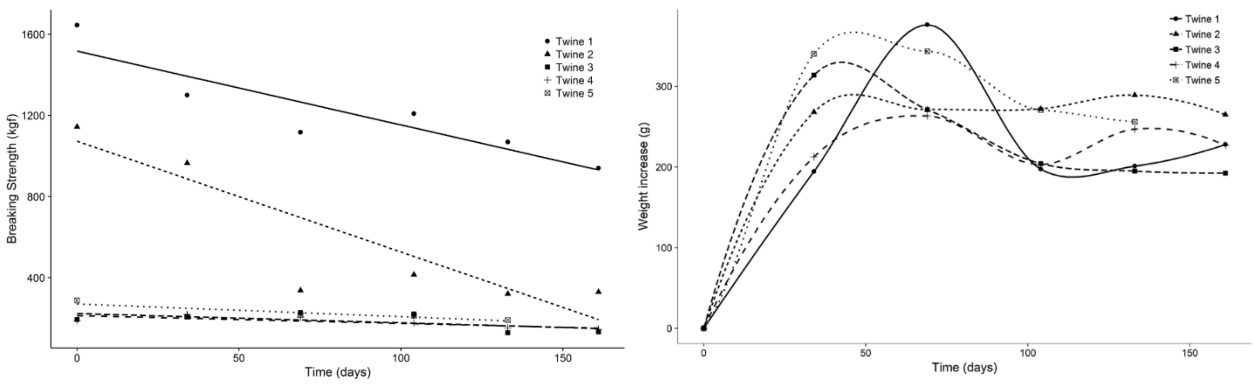


Figure 33. Relationships between breaking strength (kgf) and soak time (days) (a); and weight (g) and soak time (days); for the 5 different biodegradable twines tested by Lopez et al. (2016, 2019).

3.3.2. Test of biodegradable ropes (Moreno et al., 2019, 2017b)

Three types of rope were monitored in controlled conditions during 1 year in the Maldives in 2016 (Moreno et al., 2019, 2017b):

- Twisted 100 % cotton rope: 20 mm diameter, 4 strands in torsion Z (1645 Kg breaking strength).
- Twisted 50% cotton and 50% sisal rope: 20 mm diameter 4 strands in torsion Z (1144 Kg breaking strength).
- Cotton, Sisal and linen rope with loops (similar to those used in mussel farming but made of natural origin): 16 mm diameter core with loop (194 Kg breaking strength).

The three ropes were selected based on the following criteria: accessibility and availability in high quantities; cost; 100% natural origin; diameter easy to handle onboard; availability as close as possible to fishing grounds.

The most resistant rope was the cotton and sisal twisted rope, followed by the 100% cotton rope (Figure 35). Authors however mentioned that the 100% cotton twisted rope was matching the characteristics needed for use in biodegradable dFAD construction. The breaking strength showed that the rope could be resistant for the expected lifetime of a dFAD at-sea, i.e. 1 year, then degrade quickly, compared to the cotton and sisal twisted rope that would remain strong after 1 year. It is also ductile and easy to use for fishers. The rope with loops will allow biofouling, but is not strong enough as a main rope. However, authors suggested that this rope with loops could be used as attractors, hanging from the raft.

Manufacturing process and quality of cotton could affect rope degradability and strength, so a different cotton rope from the one used by Moreno et al. (2017b) might be less resistant. It is be noted that degradation was found similar in a lagoon and offshore, under similar temperature, light exposure and oxygen levels.

Figure 34. Biodegradable ropes made of (a) 100 % cotton; b) 50% cotton and 50% sisal; and c) cotton, sisal and linen rope with loops, tested by Moreno et al. (2017b).

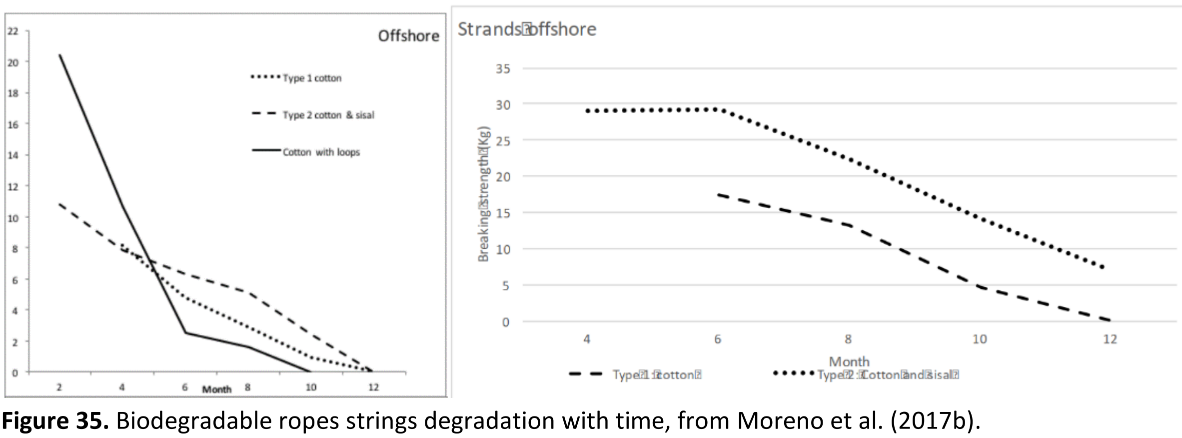


Figure 35. Biodegradable ropes strings degradation with time, from Moreno et al. (2017b).

Figure 36. Settings of the experiment to study degradation with time of biodegradable ropes in Maldives, tested by Moreno et al. (2019, 2017b).

Figure 37. Biodegradable ropes tested by Moreno et al. (2019, 2017b) after 2 (top) and 12 (bottom) months at-sea.

3.3.3. Test of biodegradable ropes in real fishing conditions

100% cotton ropes with and without loops were tested in real fishing condition and were working for at least 4 months (Moreno et al., 2017c).

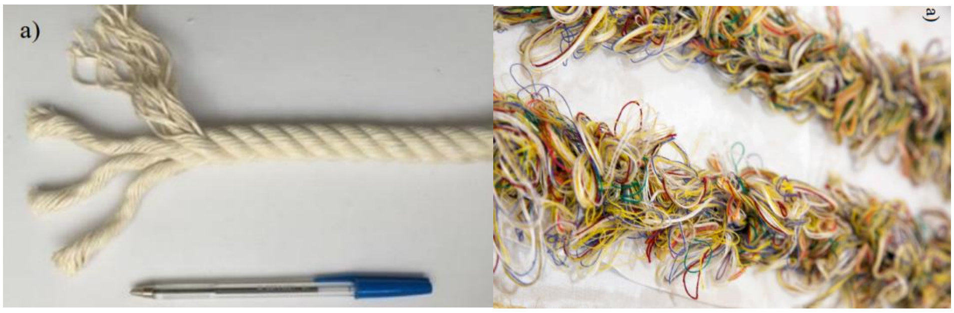


Figure 38. Biodegradable ropes made of (a) 100 % cotton without loop and b) 100 % cotton with loops, tested in real fishing conditions by Moreno et al. (2017c).

3.3.4.Evaluation of natural fibre ropes degradability (Wang et al., 2021)

The degradability of three types of natural ropes, i) a cotton rope (3-strand, 96-thread, twisted, Slay); a jute rope (3-strand, 13-thread, twisted, Z-lay); and iii) a sisal rope (3-strand, 8-thread, twisted, Z-lay) was performed by evaluating breaking strength and retention ratio of rupture elongation *(Wang et al., 2021).* The cotton rope was the one maintaining its integrity for the longest, with breaking strength at half initial value after 10 months of soaking time at-sea and stable retention ratio of rupture elongation. To the contrary, a sharp decrease in breaking strength was found for the jute and sisal ropes, after the first month at-sea only.

Table 13. Structural parameters for three types of ropes tested (Wang et al., 2021).

Rope type	Diameter (mm)	Lay length (mm)	Construction	Linear density (ktex)	Cost (dollar per meter)
Cotton 3-strand twisted rope	14.5	37.7	96-thread, S-lay[a]	35.253	0.30
Jute	10.5	36.5	3-ply, 13-thread, twisted, Z-lay[b]	46.898	0.16
Sisal	11.0	39.5	3-ply, 8-thread, twisted, Z-lay[b]	50.922	0.35

[a] Twisting the strands in clockwise direction.
[b] Twisting the strands in counterclockwise direction.

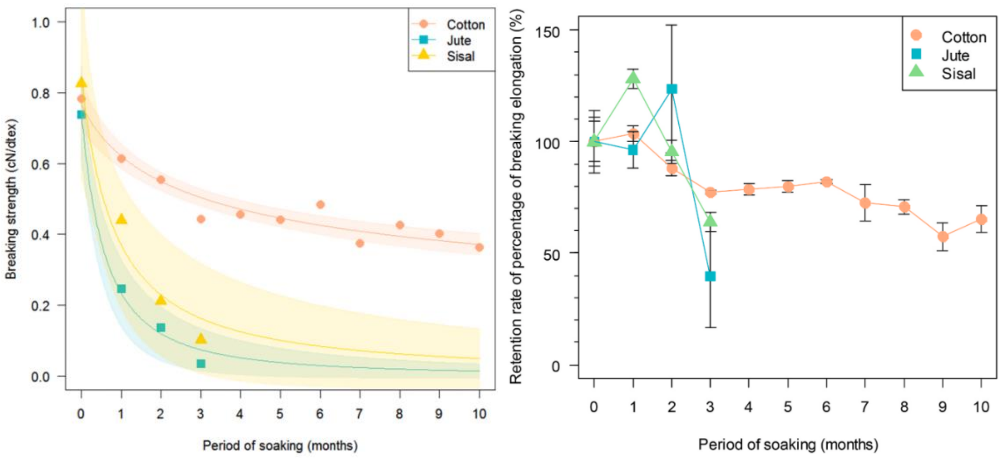


Figure 39. Variation of breaking strength (left) and retention ratio of rupture elongation (%) (right) with soak time (months) for three types of ropes over a total periods of 10 months (Wang et al., 2021)

3.3.5.Test of natural canvas resistance (Garcia et al., 2022)

Three main types of biodegradable materials were tested on FAD anchored nine miles off shores in Ecuador by the Tunacons fleet in the EPO (Garcia et al., 2022). These included jute, cabuya (agave sisal plant) and acaba, that are from a sustainable market, available in Ecuador and biodegradable. It was assessed that the BIO FADs became non-functional after 25, 35, and 67 days for the BIO FADs constructed with jute, cabuya and acaba, respectively. For the later the acaba BIO FADs, additional lab tests were performed and indicated that after the 67 days, the loss resistance was 94% (with a Strength reduction from 251.6 kgF to 13.8 kgF).

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