SCIENTIFIC COMMITTEE
SIXTEENTH REGULAR SESSION

ELECTRONIC MEETING
11-20 August 2020

A multidisciplinary approach to build new designs of biodegradable Fish Aggregating Devices (FADs)

WCPFC-SC16-2020/EB-IP-08

Gala Moreno[1], Joaquín Salvador[2], Jefferson Murua[3], Naiten Bradley Phillip Jr.[4], Hilario Murua[1], Lauriane Escalle[5], Ben Ashigbui[1], Iker Zudaire[3], Graham Pilling[5], Victor Restrepo[1]

[1] International Seafood Sustainability Foundation (ISSF), Washington, USA, gmoreno@iss-foundation.org
[2] Institut de Ciències del Mar, Consejo Superior de Investigaciones Científicas (CSIC, Barcelona, Spain)
[3] AZTI Tecnalia, Sukarrieta, Spain
[4] National Oceanic Resource Management Authority (NORMA), Federated States of Micronesia
[5] Oceanic Fisheries Programme, The Pacific Community (SPC), Noumea, New Caledonia

A multidisciplinary approach to build new designs of biodegradable Fish Aggregating Devices (FADs)

Gala Moreno[1], Joaquín Salvador[2], Jefferson Murua[3], Naiten Bradley Phillip Jr.[4], Hilario Murua[1], Lauriane Escalle[5], Ben Ashigbui[1], Iker Zudaire[3], Graham Pilling[5], Victor Restrepo[1]

Summary
The present document aims at summarizing ongoing research by ISSF on the reduction of the impacts of Drifting Fish Aggregating Devices´ (DFADs) structure on the ecosystem, particularly on the use of biodegradable DFADs. ISSF is collaborating with physical oceanographers from the Insitute de Ciències del Mar (CSIC, Spain) experts in oceanic currents´ dynamics and drifters to better understand the physical behavior of DFADs in the water column. The aim is to find a DFAD design that aggregates tuna but also (i) reduces presently observed large DFAD sizes and (ii) reduces the need for plastic buoys used for flotation. In this document, we share information on the physical behavior of drifters, gathered from our collaboration with oceanographers, that could be helpful to build new biodegradable DFAD designs by purse seine fleets; we also propose a new biodegradable DFAD design and finally we present an ongoing experiment to test the proposed design in the Western Pacific Ocean with the collaboration of Caroline Fisheries Corporation fleet and National Oceanic Resource Management Authority (NORMA, FSM) and SPC scientists.

1. Introduction

One of the impacts of Drifting Fish Aggregating Devices (DFADs) on the marine ecosystem is related to the DFAD structure itself, which is mainly made of plastic derived components (netting and ropes). Impacts occur when lost or abandoned DFADs damage coral reefs or other benthic ecosystems, cause ghost fishing, create marine litter, or interfere with other economic activities, such as tourism (Maufroy et al. 2015; Escalle et al. 2019). It has recently been estimated that the currently assessed number of beached DFADs (i.e. 7%) affected 4 to 6 km^2 of coral reef habitat per year (Banks and Zaharia, 2020).

1.International Seafood Sustainability Foundation (ISSF), Washington, USA, gmoreno@iss-foundation.org
2. Institut de Ciències del Mar, Consejo Superior de Investigaciones Científicas (CSIC, Barcelona, Spain)
3.AZTI Tecnalia, Sukarrieta, Spain
4. National Oceanic Resource Management Authority (NORMA), Federated States of Micronesia.
5. Oceanic Fisheries Programme, The Pacific Community (SPC), Noumea, New Caledonia

To reduce those impacts, ISSF — with support from the FAO-GEF Common Oceans Tuna Project — launched a series of workshops and projects, including the promotion of biodegradable FADs.

There are a range of solutions that could be used to minimize the impact of DFADs´structure on the ecosystem (e.g., biodegradable and non-entangling DFADs; DFADs recovery program, beach cleaning). These solutions need to be customized for each ocean, because oceanographic conditions and fleet strategies are region-specific Escalle et al., 2019; Moreno et al. 2020). Given the fishing strategy associated with DFADs, they are left drifting in the ocean, so even with best practices to avoid their loss and abandonment, a percentage will inevitably end up lost. Thus, the need for DFADs to be constructed with biodegradable materials instead of plastic derived components, so they do not remain at sea for hundreds of years, is clear. Scientists and fishers are collaborating in three oceans to build DFADs that are efficient for fishing purposes but degrade as soon as possible after their useful working lifetime ends. Research projects to test biodegradable materials' durability in controlled conditions (Lopez et al. 2016; Moreno et al. 2019), pilot tests at sea (Franco et al. 2012; Goujon et al. 2012; Moreno et al. 2012) and large-scale deployments of biodegradable DFADs undertest have been conducted in recent years (Moreno et al. 2020; Zudaire et al. 2020). In the Western and Central Pacific Ocean (WCPO), besides isolated trials lead by some fishing companies, very few trials and research projects have been implemented to test the efficiency of biodegradable DFADs specifically designed for this ocean with specific oceanographic conditions and fishery characteristics.

Since January 1st 2020 the Western and Central Pacific Fisheries Commission (WCPFC) requires DFADs deployed or drifting into the WCPO be low entanglement risk DFAD (paragraphs 19, 20 WCPFC, 2018), and since 2017 encourages the use of biodegradable materials in the construction of DFADs (paragraph 20 WCPFC, 2017). A recent study however highlights that very few non-entangling or lower risk entanglement DFADs are used in the WCPO. Similarly, very few natural materials are used in DFAD rafts and submerged appendages. Less than 8% of DFADs had a natural raft with some plastic or metal derived appendages (floats, metal or plastic drums, pipes, cords, ropes, sacks and bags) and less than 3% of the DFADs were completely plant-based mostly due to the raft being natural (bamboos, trees, branches, natural debris, coconut fronds, planks, pallets and timber) with no submerged appendages (Phillip Jr. and Escalle 2020). Regarding the design of DFADs, few information is currently available. Observers record a visual estimate of the size of the raft, the depth of submerged appendages and the mesh size, with high uncertainty due to the distance to the DFADs. Based on these observations, we can however derive a general picture of the size and volume of DFADs used in the WCPO. The average depth of submerged appendages is 45m (Escalle et al., 2017); and the average raft dimension of 2.8 * 0.9 m (average surface of 2.8 m^2) (Observer data covering the 2011–2019 period). Common DFAD designs are bamboo raft with PVC tubes or cork-line buoys, or a line of cork-line buoys and bamboos tied in a 'sausage' (Phillip Jr. and Escalle 2020).

One of the trends detected by ISSF´s scientists is that the tactic followed by most of fishers on the way to find a biodegradable DFAD, is to maintain the same traditional DFAD design (submerged netting panels hanging from the raft; Fig 1) but made of biodegradable ropes and canvas. However, it seems the lifetime of those biodegradable DFADs that maintain the same design but just change the materials, so far, has not proven to be as long as required by fishers (around one year). In the WCPO, the only recommendation from the commission on DFAD designs relates to the entanglement risk of DFAD (i.e. any DFADs deployed or drifting in the WCPO with submerged appendages will have no net or net with a mesh < 7cm or tied tightly in bundles; WCPFC, 2018). There is still room for research to find efficient biodegradable materials and treatments for those materials to increase their lifetime, however another line of research that has not been investigated in depth is the modification of its design to increase biodegradable DFADs´ lifetime. The lifetime of the DFAD would depend on the amount of structural stress suffered due to the shearing and torsion forces created by currents in the water column and wind and waves affecting the DFAD structure in the surface. Physical oceanographers experts on drifters and oceanic currents have a lot to say on how a given design could minimize the structural stress. Hence, this collaboration emerges from the need to (i) find a design that reduces structural stress of DFADs at sea, but also (ii) reduces DFAD structure size, to minimize their impact on the ecosystem when DFADs are lost abandoned or discarded.

The present document shares (i) the results of a recent collaboration by ISSF with oceanographers from the Institut de Ciències del Mar (CSIC, Spain), to build with the help of their expertise on oceanic currents' dynamics and drifters, a new biodegradable FAD structure and (ii) an ongoing experiment to test the new biodegradable DFAD design in collaboration with scientist from National Oceanic Resource Management Authority (NORMA, FSM) and The Pacific Community (SPC).

2. What structural features does a DFAD need to be productive?

One of the research questions that drives our work in the search for a biodegradable DFAD, is what structural components are needed for a DFAD to be efficient in terms of aggregating tuna. From the scientific point of view, there is no evidence of the effect by different DFAD´s structure components or different designs on the attraction or aggregation process of tunas. Diverse research showed that no major characteristics of DFADs could explain the attraction of tuna species (Rountree 1989, Hall et al. 1992, Nelson 2003, Shaefer et al. 2018). It has been proposed that anchored FADs can more easily attract tuna because of the sounds produced by their anchoring chains or the influence of current on the mooring ropes (Freon and Dagorn, 2000), but scientific literature has also shown that DFADs can attract tuna from considerable distances without these submerged structures (Girard et al 2004).

This implies that the structure or design of DFADs might not play a key role in determining attraction processes, and therefore it has been hypothesized that other factors as (i) the DFAD history or trajectory (Moreno et al. 2007) and (ii) the non-tuna fish aggregations around DFADs (Itano et al. 2004), may play an important role in attracting tuna schools. From the fishers´ point of view, results from the ISSF Skippers´ Workshops consistently showed over a decade that there are two main DFAD features that fishers consider crucial for it to be productive: (i) the slow drift and (ii) the shade (Murua et al. 2014). Interestingly, these two features are related to the two scientific hypotheses mentioned above, on the role of the trajectory and the non-tuna species on DFAD efficiency to aggregate tuna.

From fisher's perspective the main features needed for a DFAD to aggregate tuna are:

a) **The slow drift**:

It is not clear if a DFAD that drifts slowly makes it more attractive for tuna or if fishers need the slow drift to keep it within their fishing area, avoiding DFADs drifting out from their fishing grounds or if the slow drift serves the two purposes. What is clear is that in order to make the DFADs drift slowly, the tendency worldwide has been to build larger DFAD structures, constructed with net panels, for which their submerged components can reach up to 100 meters depth (Figure 1). The primary purpose of this large submerged appendage is to help slow down DFAD´s drifting speed. One of the principal concerns deriving from the need for slower drift is the fact that fishers employ higher amounts of netting and other plastics to build large and deep structures. Fishers believe these deep DFADs move slower than DFADs with shallow appendages. Importantly, the pollution impact of DFAD structures on the ecosystem is related to their size (i.e. the impact of 5 DFADs of 20 meters depth is proportionately 4 times less than 5 DFADs of 80 meters depth). Thus, in order to decrease the impact of DFAD structures on the ecosystem, reducing their size (i.e. amount of polluting material and netting) would be a significant step.

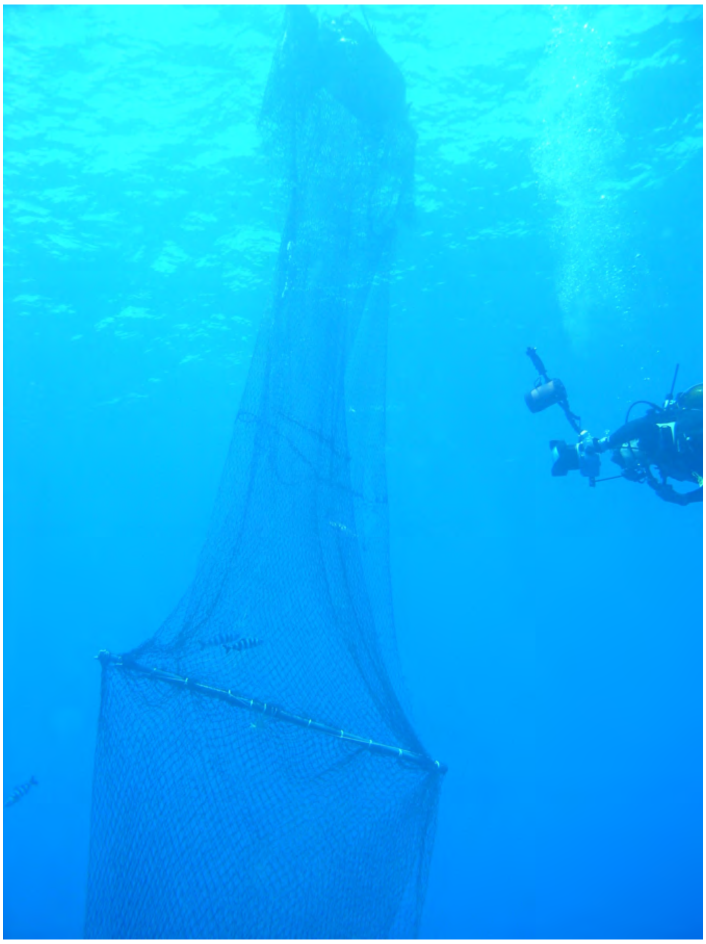


Figure 1. Underwater view of a DFAD (© FADIO/IRD/ Ifremer/ Marc Taquet)

b) **Shade effect:**

Fishers believe the DFAD should provide shade. This shade is provided both, by the floating surface of the DFAD, also known as raft[1], and also by the submerged net panels, strips, flags and palm leaves that fishers add to the submerged part of the DFAD. Some fleets have totally submerged their rafts and instead of providing shade at the sea surface, they deploy the raft submerged a couple of meters below the surface (Murua et al. 2019, Zudaire et al. 2020). The latter are as efficient at aggregating tuna as traditional DFADs but the probability of being detected by other purse seine vessels, and thus being stolen, is lower. In any case, for fishers, the purpose of these attracting structures is to provide shelter and shade to marine fauna, which for fishers is like "creating an artificial reef in oceanic waters", a heterogeneity attracting fish in the vast and homogeneous oceanic waters.
Non-tuna species, which likely influence the attraction and retention behaviors of tuna at DFADs, could first be attracted and retained because of the specific design of the DFAD, in this case the shade or shelter provided.

The shade produced by the floating structure of the DFAD as well as the attractor strips and flags that are usually added to the shallow part of the submerged structure, are considered by fishers crucial to attract those species that occupy the space closest to the DFAD structure (i.e. within 2 m), named *intranatans* (Tripletail (*Lobotes surinamensis)*, Sergeant-major (*Abudefduf saxatilis)*, etc.). *Intranatant* species in turn, may play the role of attractors of other species that occupy the space at greater distances from the DFAD (i.e from 50 m to several nautical miles from the FAD), such as tunas (*Thunnus obesus, Thunnus albacares, Katsuwonus pelamis, etc*) (Paryn and Fedoryako, 1999). For instance, fishers report that rough triggerfish *Canthidermis maculata* plays a key role in the attraction of tunas, as this species emits loud grunt-like sounds. It may be that once the DFAD is colonized by *intranatant* species, the structure of the FAD (colour, shade, etc.) loses importance on the ability to attract tunas. *Intranatant* species once present at DFADs, may serve as a more powerful attractor than the FAD structure itself (Moreno et al. 2016).

3. What modifications could be done to DFAD structures to reduce their impact while still being productive for fishing?

Basically, to decrease the impact of DFAD structures on the ecosystem there are three main modifications to address (i) eliminate the netting materials to avoid ghost-fishing when DFADs are lost, abandoned or discarded. The small-mesh net used in low entanglement risk DFADs, as currently required in the WCPO (WCPFC, 2018), will reduce the chances of shark and turtles entanglement, but after long periods of time at sea the net will start to break down and larger holes will appear, thus increasing the potential to entangle marine fauna (ISSF, 2019) (ii) replace plastic derived components by biodegradable materials to build FADs and (iii) reduce the size of the structure so that the impact when a DFAD is lost is minimized and also to facilitate the logistics to retrieve them.

[1] In this report we adopt the term raft to refer to any type of surface structure used in DFADs, such as bamboo rafts, metal frames, "burrito" shape surface structures, etc.

From our research through 2019, we have identified the most promising biodegradable materials to be used to construct DFADs, and various biodegradable DFAD designs that could be used successfully in some regions, such as the Indian Ocean (Moreno et al. 2020; Zudaire et al. 2020). Yet, reducing the size of the DFAD while allowing a slow drift and reducing the plastic needed for the flotation[2] are challenges to be faced.

In order to address these challenges ISSF is collaborating with physical oceanographers from the Insitute de Ciències del Mar (CSIC, Spain) experts in oceanic current dynamics and drifters. Specifically, we collaborated to better understand the physical behavior of DFADs in the water column in order to find a biodegradable DFAD structure that aggregates tuna but also:

1-Reduces presently observed large DFAD sizes
2-Reduces the need for extra flotation (plastic buoys)
3-Drifts slowly
4-Provides shade
5-Its working lifetime reaches one year

Apart from the features listed above, new DFAD designs should be cost-effective or at least costs be similar to traditional DFADs. Also, they should allow easy transportation recovery and storage onboard.

4. Physical behavior of DFADs in the water column

In this section we share information on the physical behavior of drifters, gathered from our collaboration with oceanographers, that could be helpful in the application of biodegradable DFAD structure´s construction:

a) An effective drag for the slow drift

The physical concept of drag is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid. In the case of DFADs, the drag is created by the submerged structure, which we will call “drogue”, the component of the DFAD structure that makes them drift slowly.

The shape of the drogue:

The drag coefficient denotes how much an object resists movement through a fluid such as water and is determined by the shape of the drogue. The higher the drag coefficient the higher the resistance to move (Figure 2). These drag coefficients are independent from the area or size of the drogue (Niiler et al. 1987).

The resistance to movement of an object, is calculated as the drag coefficient (determined by its shape) multiplied by its area (determined by the size of the structure). Thus, in the case of DFADs, selecting a shape with a high drag coefficient would allow

[2] there is no clear biodegradable alternative for the plastic buoys used for DFAD´s flotation, balsa wood is one of the promising alternatives that is undertest in the IATTC region.

a good performance (resistance to motion) which would allow for a decrease in the total area of the structure.

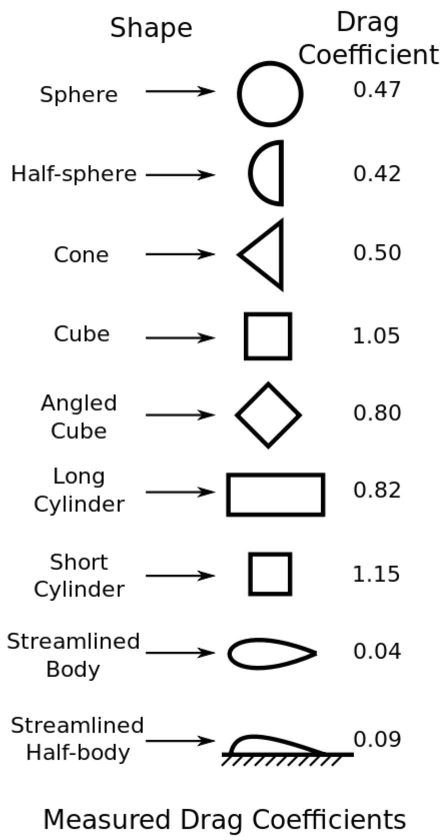


Figure 2. Measured drag coefficients for different shapes

The DFAD´s shape should have as much drag coefficient as possible to reduce motion. Thus, an effective drogue for DFADs should be **three-dimensional**. Also, the drogue should be **symmetric** so that the drag created is independent from the orientation of the drogue.

From this physics information we conclude that the traditional two-dimensional DFADs (Figure 1) currently in use in the tuna fishery worldwide have a very inefficient and low drag coefficient. Changing its shape to a three-dimensional and symmetric structure of a smaller size, would allow the desired slow drift avoiding the need for massive and bulky structures.

b) Forces affecting DFAD structures

The emerged and submerged components of DFADs are subject to various forces: wind, waves, surface currents and deeper currents in the water column. These forces can act independently having different or similar intensities and directions depending on oceanographic conditions. Thus, adding or subtracting forces when acting on DFADs´ motion.

Drag in the surface components of the DFAD

Forces on the surface components of the DFADs (flotation buoys, raft and geolocating tracker) are mainly due to waves, surface currents and wind. These forces will affect the DFAD depending on the DFADs´ raft shape and area (as seen before) (Kiman et al. 1975). The wind affects intermittently the raft of the DFAD, but its intensity is much higher compared to that of surface currents. In the case of DFADs, the ideal situation would be to keep to the minimum the effect of the wind and waves on the surface structure. Thus, it would be beneficial to have a raft shape that has a low drag coefficient and the least emerged area out of the sea surface to reduce tension on the structure created by wind forces affecting the surface component and the currents affecting the underwater drogue.

Waves can affect and drag intermittently the DFAD´s surface structure. This drag, if opposed to the underwater drag´s direction could heavily affect the integrity of the DFAD structure. In order to reduce wave generated drag, the raft and floats in the surface should freely ride on the waterline, with little tension from the tether connecting the raft with the submerged appendage. If there is tension in the line that connects the raft on the surface and the underwater drogue, the raft and floats would sink and be much more affected by the wave´s drag (case of the drifter on the right in Figure 3, from Niiler et al. 1987). DFAD´s rafts should oscillate in the waterline without tension from the underwater appendage connecting line, the smaller the tension the smaller the drag (case of the drifter on the left in Figure 3). Therefore, the correct assessment of the weight and flotation needed by a given structure to reduce tension in the main line is critical to ensure the lowest stress on materials and a greater DFAD lifetime.

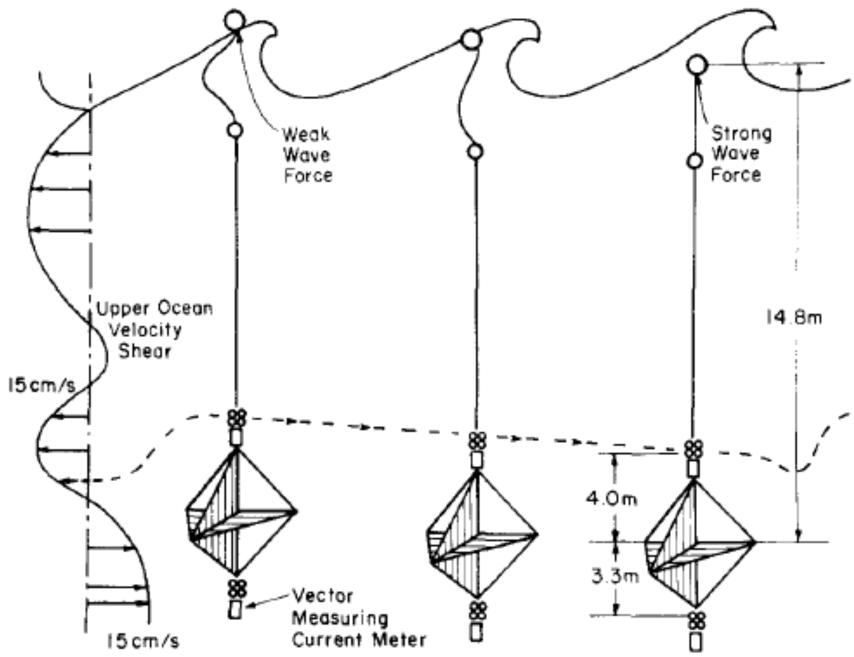


Figure 3. Diagram of the observed motion of a drifter in surface waves (from Niiler et al. 1987)

Drag in the water column:

The submerged appendages of DFAD´s structure may be subject to different current intensities and directions. The deeper the drogue is in the water column the slower the drift, as in general, current speed decreases with depth (Webster el al. 1967; Gasser et al 2000). The depth at which the drogue should be located in the water column is a matter of finding a compromise between DFAD´s life span and the desired slow drift.

In the case of DFADs the idea is to “anchor” it to depths below the mixed layer or at a depth where ocean – atmosphere interactions, such as waves and winds, do not affect the drogue (Figure 4). This depth will be different depending on the oceanographic conditions of each oceanic region, such as depth of the mixed layer, thermocline etc. In order for the DFAD to match the slow currents below the mixed layer, the highest drag coefficient of the drogue should be placed on the deepest part of the DFAD structure.

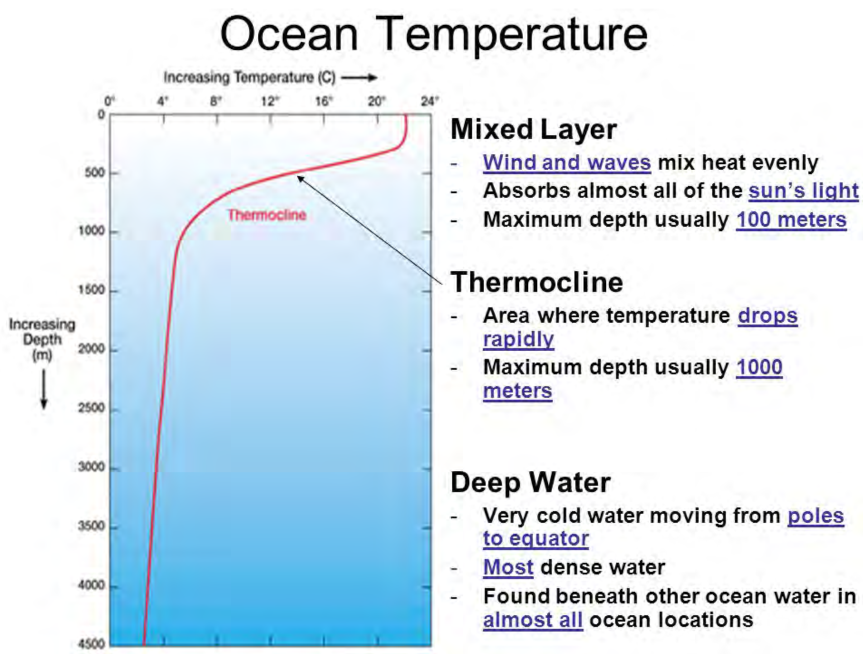


Figure 4. Illustration of the different layers in the water column.

The purpose is to make the DFAD drift slow anchoring it below the mixed layer. However, it is important to note that placing drogues along the different depths of the DFAD´s structure would weaken it. These drogues at different depths would be subject to different current directions and intensities producing torsion and shearing forces that would make the DFAD suffer structural stress and thus decrease its lifetime.

c) The assessment of weight and flotation for the DFAD

The objective here is that the DFAD´s underwater structures have a similar density to that of water. This would allow the minimum torsion and shears forces and thus increase the lifetime of the DFAD. A correct assessment of the weight and flotation is key for the DFAD to suffer the least structural stress and allow the tension of the line to be minimum, which would also avoid the drag created by waves. The flotation should be the minimum necessary as to avoid surface drags created by wind and waves.

5. New biodegradable FAD structure proposed

From this collaboration a biodegradable DFAD was designed, that should fulfill all the conditions listed before: slow drift, creating drag but with reduced size, reduces the need for plastic flotation and provides shade working during one year at sea. The conceptual drawing is shown in Figure 5 and the guide to build this biodegradable DFAD is provided in Annex 1.

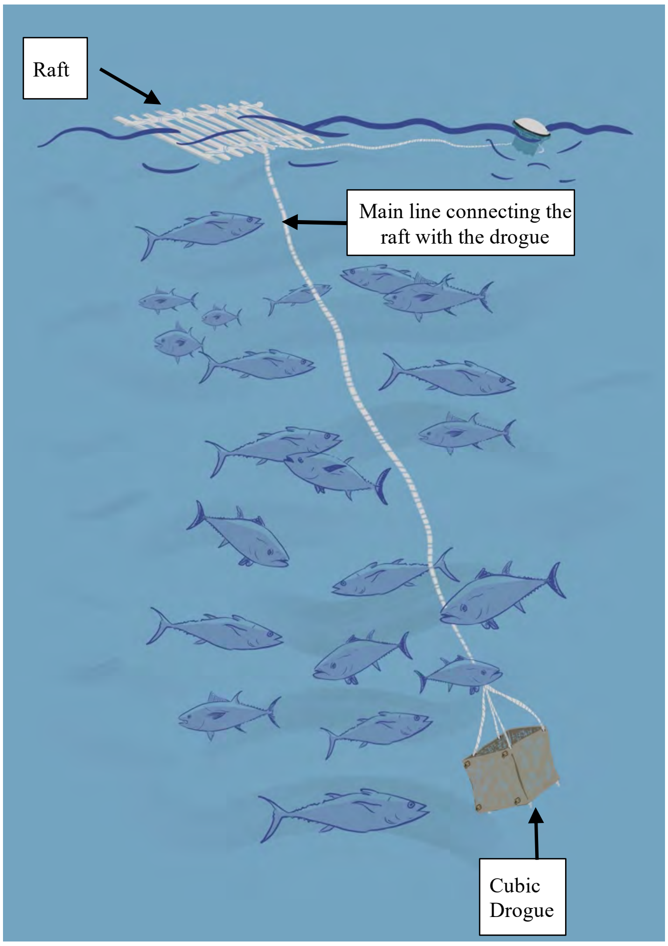


Figure 5. Conceptual drawing of the new DFAD design

The drogue

The selected drogue to make the DFAD drift slowly is a symmetric three-dimensional cube structure that is hanging from the surface structure with a rope to a depth below the mixed layer (this depth varies depending on the oceanic area, could be from 60 m to 100 m). The drag coefficient of this structure is higher compared to that of traditional flat net panels DFADs (see guide in Annex 1 for more details).

The weight and flotation required

The cubic structure of 1 m^3 (1m x1m x1m) was weighed down with 8 kg of stones in order to make it sink. The weight of the drogue (cubic structure) in the water, was monitored until the materials absorbed saltwater to saturation. At this point the structure did not gain more weight. The maximum weight of the drogue in the water was 4.6 kg (including the 8 kg added for the structure to sink) and the flotation needed was estimated as that weight (4.6 kg) multiplied by three. So that the flotation needed would be to sustain a weight of 14 kg, which is a similar flotation to that provided by just the echo-sounder buoy used to track DFADs. It is important to note that the numbers for weights and flotation provided in this paragraph, are specific for the cubic structure of $1m^3$ trialed in our study, those numbers should be recalculated for other shapes and materials used.

Fishers, when constructing traditional DFADs add extra weight, as it is believed that the weight creates the drag and maintains the DFAD in vertical position. However, with this new structure the drag is created by the three-dimensional structure and there is no need to add extra weight, just that to make the DFAD sink. Therefore, the need for floatation is also significantly reduced, resulting in less plastic buoys used for flotation and thus, reducing the plastic components of the DFAD.

Fishers could use more than one cubic structure to create more drag (this would increase the area of the drag), in this case, flotation should be multiplied by the number of cubic structures used. In case of using 2 cubic structures, we recommend placing the 2 drags at the end of the line, the deepest part of the DFAD, as placing different drogues along the line at different depths, would result in stronger shear forces due to the different current directions and intensities that may be affecting the DFAD at different depths, and thus making it weaker.

The surface components and attractors

Minimizing the emerged component of DFAD structures at the surface would allow increasing its lifetime through reduced structural stress. Thus, we recommend placing the minimum emerged components or those with the lowest drag coefficient (just the components that provide buoyancy). In the shallow part of the line, different attractors including biodegradable ropes, canvas and palm leaves could be attached to the line to create shade. Another possibility could be placing a smaller cubic structure as attractor at a depth of 15- 20 m, where the influence of waves is less than that on the surface.

6. Ongoing research with the new design of biodegradable DFAD

Currently these structures are under test in the Western Pacific Ocean, where 100 biodegradable DFADs will be deployed by a purse seine fleet, specifically Caroline Fisheries Corporation (CFC) from Federated States of Micronesia (FSM).

In order to design the experiment, a workshop was held in Zadar (Croatia), home of the fishing masters from CFC fishing company based in Pohnpei (FSM). Previous to the workshop held in Zadar, three workshops were organized in Philippines (General Santos), Papua New Guinea (Port Moresby) and Marshall Islands (Majuro). The general objective of the workshops was to promote the use of non-entangling and biodegradable FADs in the fleets operating in the WCPO as well as to understand DFAD structure types and the strategy to fish with them in the WCPO. In the case of the workshop in Zadar, we also set the protocol to test 100 biodegradable FADs with the CFC fleet.

The workshops allowed ISSF scientists to present the latest results on biodegradable DFAD initiatives in the Indian, Atlantic and eastern Pacific Oceans and gather feedback from fleets in the WCPO on the type of FADs used, the difficulties that could be encountered when changing the structure of their DFADs and how to best proceed with experimental work to test and find non-entangling and biodegradable DFADs that are productive for fishing in the WCPO. An oceanographer expert on oceanographic instrumentation and drifting buoys from the Institute de Ciències del Mar (CSIC) in Spain, was also invited to provide his expertise on the drift behavior of the DFADs related to the shape of the structure.

Pilot project to test 100 biodegradable DFADs

Most of the fleets in the WCPO and also the fleet from CFC are using for the DFAD raft a line of purse seine corks, draped with a net. The submerged part of the DFAD is made of recycled purse seine net, palm leaves, nylon ropes and bamboo canes.

During the workshop, discussions were mainly focused on the technical features of DFAD structures related to their drift behavior. From these discussions the protocol to test biodegradable DFAD prototypes in the western Pacific Ocean in 2020, was developed. As a result, the following guidelines and protocol was set:

Biodegradable DFAD structure design and materials

The most impacting part of the DFAD structure is the submerged tail, which can get entangled in coral reefs and remain at sea for hundreds of years, if made with plastic components (nylon nets and ropes). Fleets have generally increased the depth of the submerged part of the DFAD and nowadays these structures are very large (60 - 80 m). Thus, priority should be given to the replacement of the tail with biodegradable materials so that they degrade fast when DFADs are lost or abandoned. Such a change in the design of the tail would allow decreasing the impact of DFADs while alternatives for the floatation are under research. To date, no biodegradable alternative to plastic buoys or purse seine corks suitable for the floatation has yet been found, but some, such as balsa wood, are under test.

a) Raft

Previous experiments have shown that the flotation of the DFAD is a key factor for the effectiveness of a DFAD and that if floatability is not well calculated the DFAD could easily sink, shortening the duration of the on-going trial. Because the most impacting part of the DFAD is the tail, priority was given to find an alternative for the tail and in order to maximize results from the experiment, it was decided that the raft and floatation should remain the same as used in traditional DFADs so that experimental DFADs remain operational without sinking. Thus, for this project, the traditional raft made of a line of purse seine corks draped with a non-entangling net (less than 2.5´´ mesh size) will be used.

b) Tail

- Experimental DFAD´s tail should eliminate any plastic component.
- The materials used for the tail will therefore be: bamboo, manila rope, jute canvas, palm leaves and stones or sand and recycle chain for the weight.
- 2 types of biodegradable DFADs will be constructed. 50% of the experimental DFADs to be tested will be a design that copies the traditional DFAD (Figure 6, prototype A) but that uses the biodegradable materials listed above. The other 50% will be a biodegradable DFAD designed during the workshop with fishers, oceanographer and ISSF scientists (the proposed structure in point 5 of this document, Annex I).
- The depth of the DFADs´tail was of 60 m (35 FTH)
- The approximate cost of the tail of prototype B is estimated at around $120, including the cubic structure (4 bamboo canes and 10 m of biodegradable canvas and around 100 m of biodegradable rope) (raft and buoy costs remain the same as for traditional DFADs).

The construction of the DFADs would be done in port to ensure that all the designs are constructed in the same way.

Biodegradable DFADs deployment

- A total of 100 biodegradable DFADs will be deployed, (50 of prototype A and 50 of prototype B). Each experimental DFAD will be deployed close to a traditional DFAD, so that the 2 types of DFADs can be compared in terms of tuna aggregation and life span.
- The number of DFADs per vessel was set as follows: 20 biodegradable DFADs (10 of each prototype) deployed by each of the 4 large purse seiners of CFC fishing company and 10 biodegradable FADs (5 of each prototype) deployed by each of the 2 small purse seiners from CFC fishing company. Flexibility is allowed to improve this strategy if necessary, for instance if some vessels are in a better area and season to test biodegradable DFADs, those vessels could deploy more biodegradable DFADs and some others less. It was considered that a minimum of 100 biodegradable DFADs have to be deployed to get significant results.
- The area and season of deployment will be decided once DFADs are constructed and onboard purse seiners. The best area and season for the success of the experiment has to be determined related to the density of vessels in the area of deployment and the

best conditions for fishing and this could not be advanced during the workshop but closer to the deployment date/season.

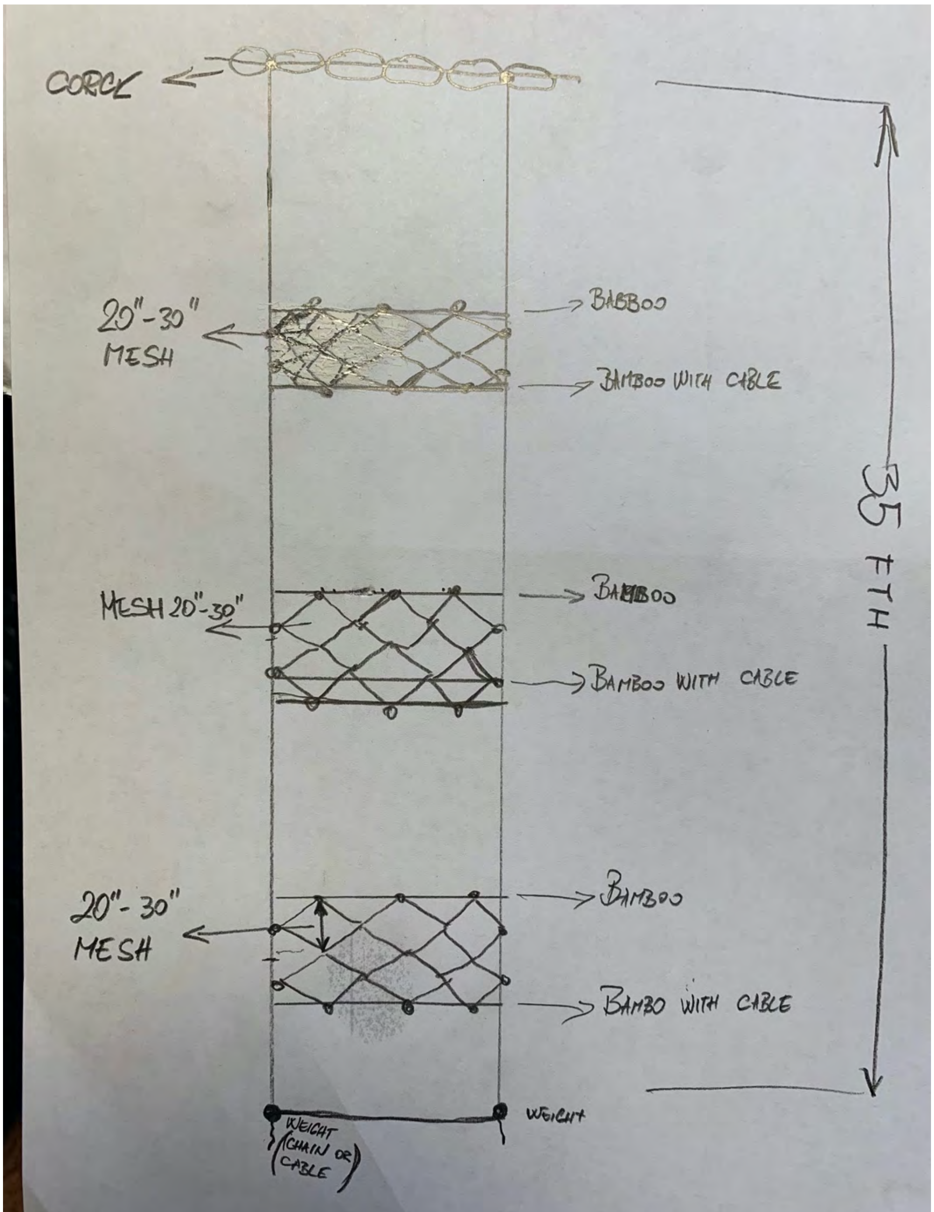


Figure 6. Prototype A: Simplified view of the biodegradable DFAD (prototype A), designed by fishers before the workshop. This prototype has the same design as the traditional ones used by the fleet but without plastic. This figure shows main components of the tail (submerged part) of the DFAD. Two main ropes supporting a structure with “sails” made of jute canvas, i.e. the “mesh” designated on the drawing has been changed to canvas on the real prototypes that will be tested. Metal (chain or cable) is providing the weight.

Data collection of the FADs under test

- An excel data collection form was designed and agreed during the workshop. This data form will be filled by fishers and observers both when deploying the biodegradable DFADs as well as when visiting, encountering or fishing on a biodegradable DFAD.
- Data from the echo-sounder buoys used to track biodegradable DFADs and their traditional pairs will be shared with scientists. This data will be delivered by Satlink buoy manufacturers directly to ISSF scientists, with the agreement of the fishers and ship-owner, with a 2 months delay after the deployment of the DFADs.
- National Oceanic Resource Management Authority, (NORMA) in Pohnpei, will help with the data collection through the observers onboard purse seiners, especially when a vessel that is not from CFC company encounters a biodegradable FAD.

Preliminary results

There are presently 49 DFADs deployed at sea and monitored by CFC fleet (Table 1). Figure 7 shows deployment sites and Figure 8 shows the construction of prototype B in Pohnpei port. Data from echo-sounder buoys will be collected to analyze DFAD trajectories and biomass aggregated related to the time spent at sea. Also, the condition of the DFAD with time spent at sea will be analyzed by prototype.

Table 1. Biodegradable DFAD´s deployments, retrievals, removal and sets for each prototype by June 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**

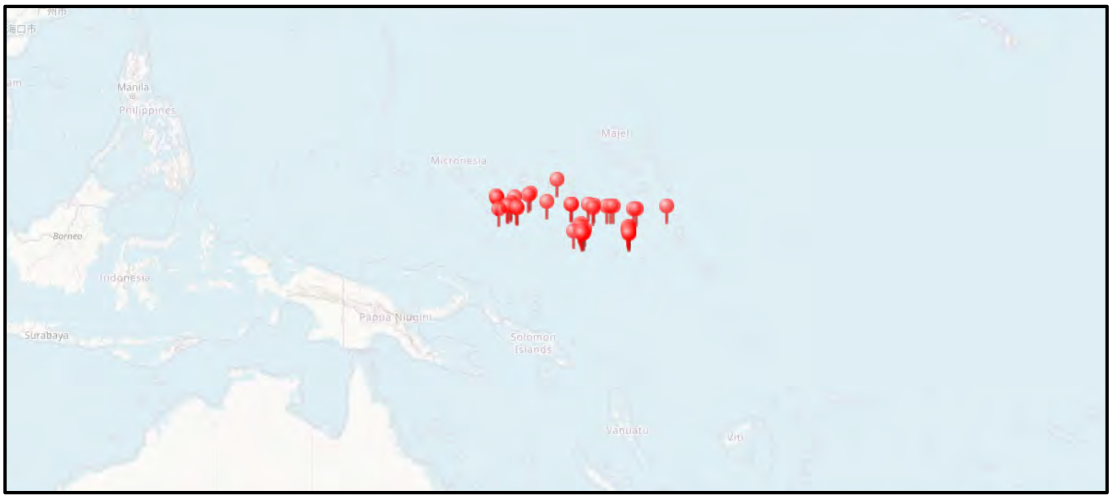


Figure 7. Biodegradable DFAD´s deployment sites

There have been two fishing sets performed on the biodegradable DFADs deployed by the project. The first one, of 95 tons, on a DFAD of prototype B that has been at sea for 20 days; and the second one, of 35 tons, on a DFAD of prototype A that has been at sea for 44 days. Prototype B was in good condition on the date of the set but prototype A needed repair after the set. These fishing activities show the potential of the two types of biodegradable structures to aggregate fish. However, more data is needed to analyze the aggregative behavior of tuna around the two type of biodegradable DFADs. Results will be available by the end of 2020-early 2021.

Table 2. Catch (t), by prototype, made on the two fishing sets performed so far.

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

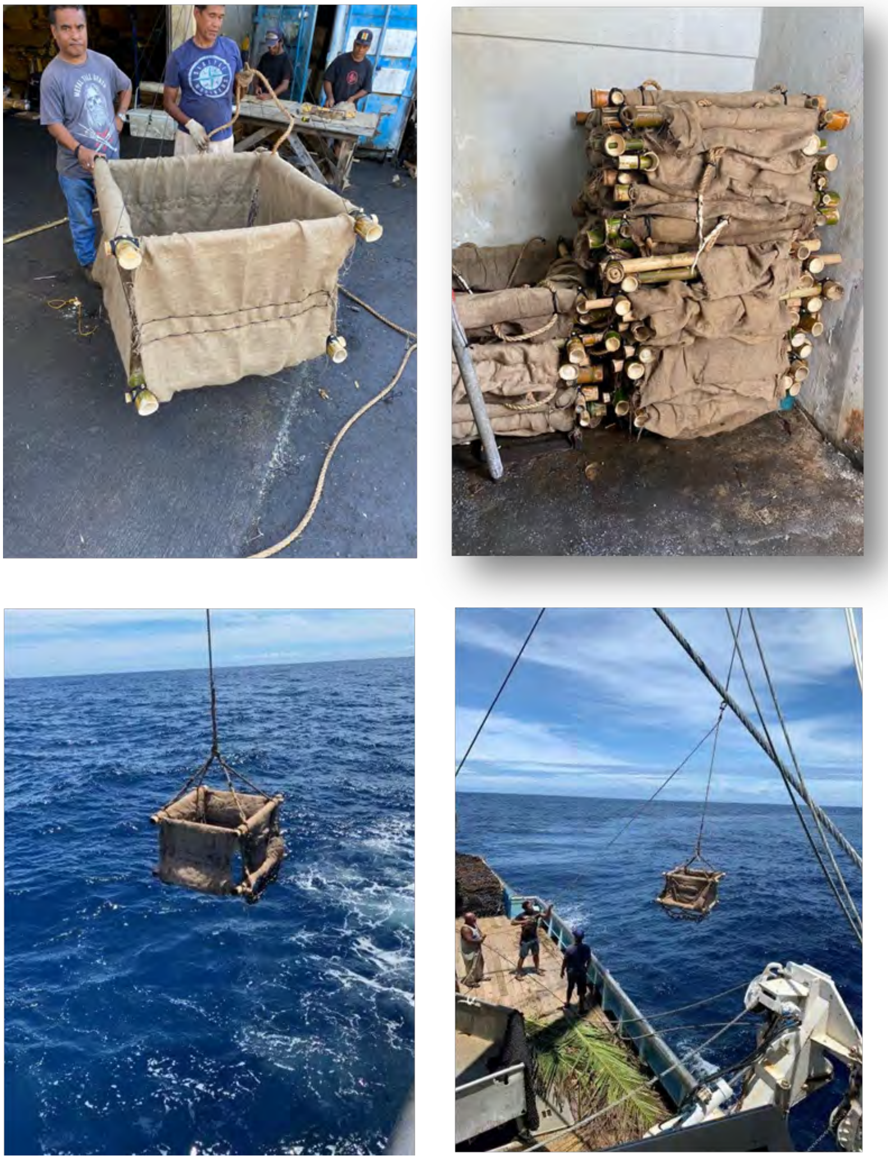


Figure 8. Trials in the western Pacific Ocean with the new biodegradable DFAD design (prototype B).

Conclusion

The present pilot project aims at trialing a limited number of biodegradable DFADs (100 DFADs), using for the first time a new DFAD structure designed with the collaboration of physical oceanographers, fishers and scientific experts on DFADs. These new structures have removed the 60 m length per 2 m wide plastic netting used in traditional DFADs, which is a reduction of around 120 m^2 of plastic components per DFAD. These DFADs still use the traditional raft made with purse seine corks and the metal chain for the weight, while research to find biodegradable alternatives for those components is undergoing, replacing the current plastic tail used at DFADs would be a great step towards the reduction of the impact of DFAD structure on the ecosystem. Although the results remain preliminary, the new DFAD design has shown the capability of aggregating tuna. The design is cheaper compared to DFADs presently used by fleets or alternative biodegradable DFADs trialed in other oceans. It is likely that fishers will improve the new DFAD design structure we propose, following the concept of a three-dimensional drogue. Results obtained in this pilot project would identify potential difficulties during the trials in real fishing conditions, as well as identifying improvements to be made to the current structure, and eventually prepare fishers and scientists for a large-scale trial of biodegradable DFADs in the WCPO.

7. Recommendations for the construction and use of biodegradable DFADs, based on this research and previous experiences described in Moreno et al. (2020):

1. Biodegradable materials for DFADs should be made of 100% plant-based fibers or bio-based materials, for which the product of their degradation is non-toxic for the marine environment, and sustainably harvested and preferably provisioned from local or regional sources. From our research, 100% cotton ropes (20 mm diameter, 4 strands in torsion Z) fulfill the criteria to support the weight of the DFAD structure and link the surface component of the DFAD with the deeper components (drogue).
2. The degradation suffered by biodegradable materials on the sea surface and immediate subsurface (i.e., 0 to 10 m depth) is higher compared to that suffered below, deeper in the water column. Thus, the poor performance of some materials on the sea surface or subsurface layers of the water column should not prevent new experiments from testing the same materials in the tail components of DFADs situated deeper in the water column.
3. For DFADs to drift slowly, the drogue should be three-dimensional and symmetric and should be “anchored” below the mixed layer. The design of the DFAD is crucial to reduce stress on the structure and increase their lifetime.
4. The physical impact of DFAD structures on the ecosystem is proportional to their size. Current DFAD structures are very large and bulky, which makes the logistics for their retrieval and storage difficult. Research to reduce the mass (i.e., size, volume and weight) of traditional and biodegradable DFAD

structures is required. This would also reduce price costs in materials per DFAD.

5. The correct assessment of the flotation and weight distribution in the design of the DFAD is a crucial factor to extend its working lifetime. This is especially important for biodegradable DFADs, as materials might be more susceptible to physical stress. If those parameters are not well calculated, the tension and torsion suffered by the structure will result in substantial damages, and the submerged appendage is more likely to detach from the raft — reducing DFAD's lifetime and aggregation effectiveness.
6. Only DFADs constructed without netting can completely eliminate the entanglement of turtles, sharks and finfish species. New biodegradable materials should not be configured in a net format; instead, they should use other forms such as ropes or canvas.
7. Due to the high incidence of DFAD loss through change of hands, sinking, beaching or out-of-reach deactivations, trials of experimental biodegradable DFADs in real fishing conditions need to test great quantities in order to obtain statistically significant results. Fishers when testing individually biodegradable DFADs, should share with scientists data from echo-sounder buoys attached to biodegradableD FADs (i.e., position and biomass associated), to follow remotely the evolution of the biodegradable FADs that are not visited by fishers, and thus still get results on their performance.

Acknowledgements

We would like to sincerely thank fishers and ship-owner from Caroline Fisheries Corporation (CFC), who generously spent their precious time on land with us, to share their fishing strategy with DFADs, as well as actively participating to find a suitable biodegradable DFAD. We would also like to thank NORMA for the support provided to conduct this project. Finally, this project would have not been possible without the funding of the FAO-GEF Common Oceans Tuna Project.

References

Banks, R., Zaharia, M., (2020) Characterization of the costs and benefits related to lost and/or abandoned Fish Aggregating Devices in the Western and Central Pacific Ocean. Report produced by Poseidon Aquatic Resources Management Ltd for The Pew Charitable Trusts.Escalle, L., Scutt Phillips, J., Brownjohn, M. et al. (2019). Environmental versus operational drivers of drifting FAD beaching in the Western and Central Pacific Ocean. Sci.rep. nature 9 (1):14005. https://doi.org/10.1038/s41598-019-50364-0

Escalle, L., Brouwer, S., Pilling, G., (2017). Report from Project 77: Development of potential measures to reduce interactions with bigeye tuna in the purse seine fishery in the western and central Pacific Ocean ('bigeye hotspots analysis'). WCPFC Sci. Comm. WCPFC-SC13-2017/MI-WP-07.

Escalle, L., Scutt Phillips, J., Brownjohn, M., Brouwer, S., Sen Gupta, A., Van Sebille, E., Hampton, J., Pilling, G., (2019). Environmental versus operational drivers of

drifting FAD beaching in the Western and Central Pacific Ocean. Sci. Rep. 9, 14005. https://doi.org/10.1038/s41598-019-50364-0
Franco, J., Moreno, G., Lopez, J., Sancristobal, I., 2012. Testing new designs of drifting fish aggregating device (DFAD) in the Eastern Atlantic to reduce turtle and shark mortality. Collect. Vol. Sci. Pap. ICCAT 68, 1754-1762. https://www.iccat.int/Documents/CVSP/CV068_2012/n_5/CV068051754.pdf
Gasser, M., Salvador, J., Pelegri, J.L., Sangra, P. (2001). Field validation of a semi-spherical Lagrangian drifter. Scientia Marina 65 (S1):139-143
Goujon, M., Vernet, A-L. and Dagorn, L. 2012. Preliminary results of the Orthongel program "eco-FAD" as June 30th 2012. IOTC-2012-WPEB08-INF21, 1-7 pp.
Hall, M., Roman, M. (2013). Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. FAO Fisheries and Aquaculture Technical Paper No. 568. Rome, FAO. 249 pp. http://www.fao.org/3/i2743e/i2743e00.htm
ISSF (2019). ISSF guide for non-entangling FADs. International Seafood Sustainability Foundation,Washington, D.C., USA
Kiwan. AD., Jr., G. McNally, M.S. Chang and R. Molinari.(1975). The effect of wind and surface currents on Drifters. J.Phys. Oceanogr. 5: 361-368.
Maufroy, A., Chassot, E., Joo, R., Kaplan, D.M., (2015). Large-Scale Examination of Spatio-Temporal Patterns of Drifting Fish Aggregating Devices (dFADs) from Tropical Tuna Fisheries of the Indian and Atlantic Oceans. PLoS ONE 10, e0128023. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0128023
Moreno, G., Dagorn L., Sancho G., Itano D., (2007). Fish behavior from fishers' knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). Can. J. Fish. Aquat. Sci. 64, 1517–1528.
Moreno, G., Restrepo, V., Dagorn, L., Hall, M., Murua, J., Sancristobal, I., Grande, M., Le Couls, S. and Santiago, J. (2016). Workshop on the use of biodegradable fish aggregating devices (FADs). ISSF Technical Report 2016-18A, International Seafood Sustainability Foundation,Washington, D.C., USA. https://iss-foundation.org/knowledge-tools/technical-and-meeting-reports/download-info/issf-2016-18a-workshop-on-the-use-of-biodegradable-fish-aggregating-devices-fad/
Moreno, G., Orue, B., Restrepo, V. (2017) Pilot project to test biodegradable ropes at FADs in real fishing conditions in the Western Indian Ocean. IOTC-2017-WPEB13-INF13
Moreno, G., J. Murua, L. Dagorn, M. Hall, E. Altamirano, N. Cuevas, M. Grande, I. Moniz, I. Sancristobal, J. Santiago, I. Uriarte, I. Zudaire, and V. Restrepo. (2018). Workshop for the reduction of the impact of Fish Aggregating Devices´ structure on the ecosystem. ISSF Technical Report 2018-19A. International Seafood Sustainability Foundation, Washington, D.C., USA. https://iss-foundation.org/knowledge-tools/technical-and-meeting-reports/download-info/issf-2018-19a-workshop-for-the-reduction-of-the-impact-of-fish-aggregating-devices-structure-on-the-ecosystem/
Moreno, G., Jauharee, A.R., Adam, M.S, Restrepo, V. (2019). Towards biodegradable FADs: Evaluating the lifetime of biodegradable ropes in controlled conditions. ISSF Technical Report 2019-13. International Seafood Sustainability Foundation, Washington, D.C., USA.
Moreno, G., Murua, J., Jauharee, A.R., Zudaire, I., Murua, H. and Restrepo, V. (2020). Compendium of ISSF research activities to reduce FAD structure impacts on the ecosystem. ISSF Technical Report 2020-13. International Seafood Sustainability

Foundation, Washington, D.C., USA. https://iss-foundation.org/knowledge-tools/technical-and-meeting-reports/download-info/issf-2020-13-compendium-of-issf-research-activities-to-reduce-fad-structure-impacts-on-the-ecosystem/

Murua, J., Moreno, G., Itano, D., Hall, M., Dagorn, L., and V. Restrepo (2014). ISSF Skippers' Workshops Round 8. ISSF Technical Report 2014-06. International Seafood Sustainability Foundation, Washington, D.C., USA.

Murua, J., Moreno, G., Hall, M., Dagorn, L., Itano, D., Restrepo, V. (2017). Towards global non-entangling fish aggregating device (FAD) use in tropical tuna purse seine fisheries through a participatory approach. ISSF Technical Report 2017–07. International Seafood Sustainability Foundation, Washington, D.C., USA.

Murua, J., Moreno, G., Itano, D., Hall, M., Dagorn, L., and V. Restrepo (2019). ISSF Skippers' Workshops Round 8. ISSF Technical Report 2019-01. International Seafood Sustainability Foundation, Washington, D.C., USA.

Niiler, P. P., R. E. Davis, and H. J. White (1987), Water-following characteristics of a mixed layer drifter, Deep-Sea Research Part a-Oceanographic Research Papers, 34(11), 1867-1881.

Paryn, N.V., Fedoryako, B.I.1999. Pelagic fish communities qround floating objects in the open ocean. Fishing for Tunas associeated with floating Objects, International Workshop. Inter-American Tropical Tuna Commission (11): 447-458.

Phillip Jr. N.B., and Escalle L. (2020) Updated evaluation of drifting FAD construction materials in the WCPO. WCPFC Scientific Committee WCPFC-SC16-2020/EB-IP-03

Schaeffer, K., Fuller, D.W., Chaloupka, M. (2018). Performance evaluation of shallow versus normal depth FADs in the eastern equatorial Pacific tuna purse-seine fishery. [Power point slides]. Retrieved from https://www.iattc.org/Meetings/Meetings2018/SAC-09/FAD-03/PRES/_English/FAD-03a-PRES_Performance-evaluation-of-shallow-versus-normal-depth-FADs.pdf

WCPFC, 2018. CMM-2018-01 Conservation and management measure for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean.

WCPFC, 2017. CMM-2017-01 Conservation and management measure for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean.

Webster F (1967). Vertical profiles of horizontal ocean current, Deep-Sea Research, 1969, Vol 16, pp 85 to 98

Zudaire et al. (2018). Which is the best definition for the biodegradable FADs? Indian Ocean tuna commission, IOTC- 2017-SC20-INF07.

Zudaire, I., Tolotti, M.T., Murua, J., Capello, M., Basurko, O.C., Andrés, M., Krug, I., Grande, M., Arregui, I., Uranga, J., Baidai, Y., Floch, L., Ferarios, J.M., Goñi, N., Sabarros, P.S., Ruiz, J., Ramos, M.L., Báez, J.C., Abascal, F., Moreno, G., Santiago, J., Dagorn, L., Arrizabalaga, H., Murua, H., (2020). Testing designs and identify options to mitigate impacts of drifting fads on the ecosystem. Second Interim Report. European Commission. Specific Contract No. 7 EASME/EMFF/2017/1.3.2.6 under Framework Contract No. EASME/EMFF/2016/008. 193 pp. https://op.europa.eu/en/publication-detail/-/publication/77d2fdc5-7f87-11ea-aea8-01aa75ed71a1/language-en

ANNEX 1

Materials and Method to build the biodegradable DFAD

In this annex we propose the materials and method to build the drogue for the new biodegradable DFAD design. This is an example; fishers could find other methods and materials to successfully construct a biodegradable drogue.

A. Material for the biodegradable FAD construction

- Select 4 bamboo with below specifications:
    - 2 big bamboo canes with diameter of 100 mm
    - 2 small bamboo canes with diameter 40 mm
    - Maintain middle partition of the bamboo cane
    - All bamboo canes should be 1.2m in length
- Cotton canvas
- Cotton ropes
- Wooden pins
- Tools
    - Clamp
    - Drill
    - Mallet
    - Saw

Figure 1. Tools and bamboo canes needed to build the biodegradable FAD.

B. Material preparation

1. Clamp big bamboo canes (100mm diameter) onto work bench

2. Measure 10cm from both ends of the bamboo cane and mark

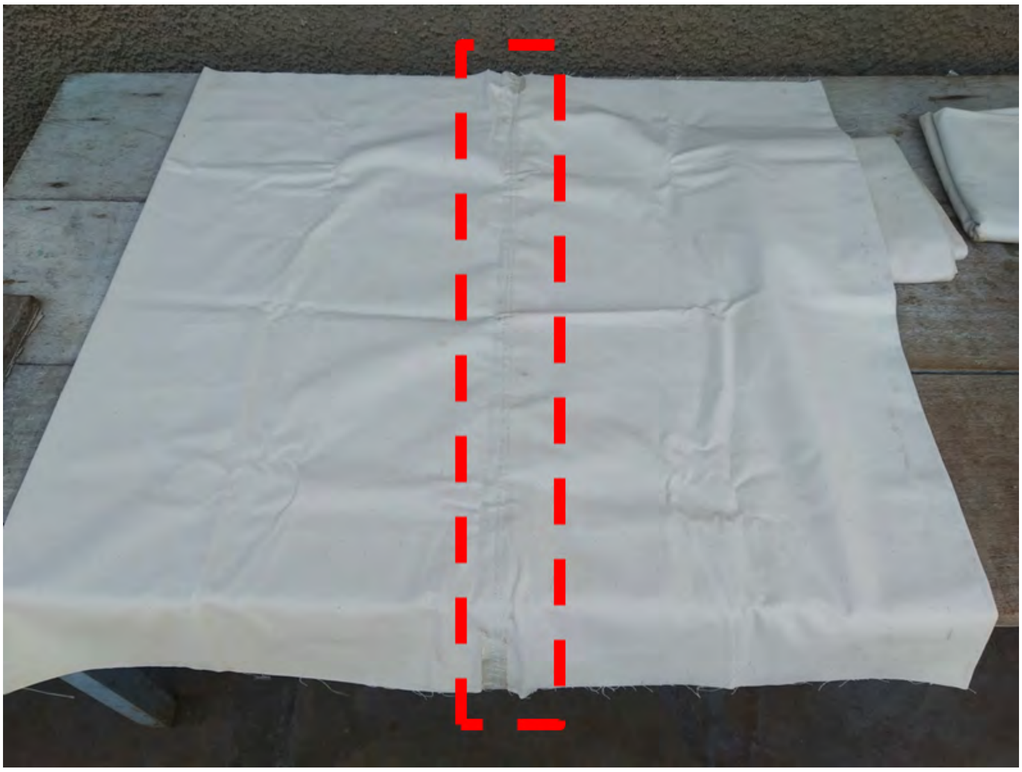
3. Drill a whole of 40mm through the bamboo cane on both sides (to insert the small bamboo canes)

4. Drill a whole of about 20mm diameter through the bamboo cane on both sides (for the rope)

5. Interlock bamboo canes to form a cross joint to ensure holes have been made to specifications

6. Cut cotton canvas to fit bamboo canes: 1m per 2m pieces canvas

7. Fold and sew both ends of the canvas in the middle



8. Pass bamboo canes through the cotton canvas

9. Load 4kg of stones into each thick base bamboo on both sides of the cane, making a total of 8kg of weight added for the structure

10. Drill a hole through the interlock: 8mm hole and Hammer the 9mm diameter wooden pins

11. Pass the cotton rope through the bamboo canes and cotton canvas in a continuous loop and terminate with a blast joint.

12. Blast join

13. The entire structure is supported by the cotton rope, not the cotton canvas