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THE JELLY-FAD: A PARADIGM SHIFT IN BIO-FAD DESIGN

Gala Moreno[1], Joaquín Salvador[2], Hilario Murua[1], Jon Uranga[3], Iker Zudaire[3], Jefferson Murua[3], Maitane Grande[3], Ohiane Cabezas[3], Victor Restrepo[1]

SUMMARY

Fishers and scientists in the three tropical oceans are investigating different designs of biodegradable FAD (bio-FAD) efficient for fishing. The tactic followed by most fishers is to maintain the same traditional drifting FAD (dFAD) design (submerged netting panels hanging from the raft) but made of organic ropes and canvas. Results of those experiences show that the lifetime of bio-FADs that maintain the traditional FAD design with organic materials, is shorter than that required by fishers. The short lifespan of those bio-FADs is due to the structural stress suffered by dFAD designs traditionally used. Thus, in order to use organic materials instead of the strong plastic and increase the lifespan of those bio-FADs, a paradigm shift is needed. Bio-FAD structures should be re-designed to suffer the least structural stress in the water. The present document aims at (i) summarizing what we learned across the different experiences testing bio-FADs in the three oceans, (ii) proposing a new concept in dFAD design, the Jelly-FAD design, and (iii) showing preliminary results of the tests of the Jelly- FAD.

KEYWORDS

Fish Aggregating Devices, Ecosystem impact, ghost fishing, FAD, biodegradable

[1] International Seafood Sustainability Foundation (ISSF). 1440 G Street NW Washington DC 20005. U.S. gmoreno@iss-foundation.org
[2] Instituto de Ciencias del Mar (ICM). Passeig Marítim de la Barceloneta, 37, 08003 Barcelona.Spain
[3] AZTI. Herrera kaia, Portualdeal z/g 20110 Pasaia-Gipuzkoa. Spain

1. Introduction

Drifting Fish Aggregating Devices (dFADs), which are comprised by a surface raft and a submerged appendage, are most often made of plastic (nylon nets, buoys and polypropylene ropes). The submerged appendages are mostly made of netting material and can reach up to 80-100 m depth for some fleets in the Atlantic Ocean. It is estimated that ~100,000 dFADs are deployed every year by fleets operating in the Indian, Atlantic and Pacific oceans (Gershman *et al*. 2015). Due to the complexity of dFAD fishing strategy, in which dFADs are left drifting with a geo-locating buoy, it is estimated that around 7% - 22% of these dFADs end up stranded (Maufroy et al., 2017; Moreno et al., 2018; Escalle et al., 2020; Imzilen et al. 2021). Impacts caused by lost and abandoned dFADs are ghost fishing (Filmater *et al*. 2013), accumulation of plastic at sea, damage on coral reefs and interference with other economic activities, such as tourism.

1.1 Entanglement issues

Both entanglement in dFAD netting and ghost-fishing are known to cause incidental mortalities for marine megafauna (FAO 2020). Current conservation measures in the tuna Regional Fisheries Management Organizations (tRFMO) in the Pacific and Atlantic Oceans, i.e., the Inter-American Tropical Tuna commission (IATTC) Resolution C-20-06 (Annex II of Res C-19-01), the Western and Central Pacific Fisheries Commission (WCPFC) Conservation Management Measure (CMM) 2020-01, and Recommendation 19-02 of the International Commission for the Conservation of Atlantic Tunas (ICCAT) allow the use of netting to construct dFADs.

The recommendation in ICCAT suggested that the (i) surface structure of the FAD is not covered or only covered with material implying minimum entangling risk and (ii) sub-surface is composed of non-entangling material (e.g. ropes or canvas). However, the recommendation does not define any technical criteria of what minimum entangling risk implies and what a non-entangling material is. According to the ISSF guide of Non-Entangling FADs (**Figure 1**; https://iss-foundation.org/knowledge-tools/guides-best-practices/non-entangling-fads/download-info/non-entangling-and-biodegradable-fads-guide-english/), these types of dFADs may correspond to Low Entanglement Risk (LER) FADs.

Although the use of Low Entanglement Risk FADs, (i.e. dFADs with netting but of small mesh size or tied in bundles), reduces the entanglement of marine fauna at dFADs while those structures remain intact and unbroken, it is highly likely that with time dFADs´ netting end up untied and broken. Due to the persistence of plastic netting, those dFADs may eventually become High Entanglement Risk FADs (ISSF, 2019). Only in the Indian Ocean Tuna Commission (IOTC) (Res 19-02), netting material is not allowed in dFAD construction (IOTC, 2019). The total removal of the netting in dFADs is the only way to avoid entanglement both when the dFAD is being monitored by the fleet and when it ends up lost or abandoned.

1.2 FAD Stranding issues

One of the difficulties encountered by scientists and managers to quantify dFAD stranding events, is that once a dFAD has drifted away from the fishing zone, fishers deactivate the dFAD positioning system. The communication is stopped before the dFAD beaches and, as result, those dFADs remain at sea without any owner tracking their trajectories. This situation limits our ability to quantify dFAD stranding events and their impact on the ecosystem. Escalle et al. (2020) estimated for the western Pacific that ~80% of the dFADs deployed by purse seine fleets they have an unknown fate (i.e. there is no information on the end of their lifespan).

Recent scientific literature and ISSF´s workshops with fishers identified potential dFAD accumulation areas in the Atlantic Ocean. They occur mainly along the West African coast and the Gulf of Guinea between 20ºN and 20ºS (Imzilen et al. 2021) and Nigeria, Equatorial Guinea and Mauritania were identified by fishers as main dFAD stranding areas during an ISSF workshop on FAD structure impact reduction (Moreno et al.,2018a). However, oceanic currents can take dFADs far from the fishing grounds as the recently reported dFAD beaching events in the Caribbean Sea (Tom Pitchford, pers comm) and Brazil in the Atlantic Ocean (Maufroy et al. 2017; Imzilen et al. 2021).

Because dFAD fishing strategy implies a risk for dFADs to be abandoned or loss, the reduction of the impact of dFAD structure on the ecosystem, would need various mitigation practices along the chronology of the fishing activity, i.e., reducing the number of dFADs deployed, eliminate the use of netting in their construction, using organic materials, instead of plastic, to construct dFADs that degrade after a given time, applying good practices to avoid dFAD loss and abandonment, and collecting non-utilized dFADs, as much as possible. Each fishery should search for solutions best suited to their fishing operations. In the case of dFADs used by tuna fleets in the tropical zones of the Indian, Atlantic and Pacific Oceans, the impact caused by their structure has triggered a response by coastal countries, by scientists and research institutes working on dFAD fishing, and by the fishing industry, conscious of potential impacts of lost or abandoned dFAD structures. A direct outcome are initiatives, both by the fishing sector and research institutes, to develop biodegradable dFAD (Bio-FAD) structures efficient for fishing for around one year. Currently, projects exist in the three oceans to test dFAD prototypes constructed mostly with biodegradable materials (Moreno et al., 2017; Zudaire et al., 2017; Moreno et al., 2018; Roman et al. 2020; Zudaire et al. 2020). In the Atlantic Ocean specifically, the Ghanaian fleet, in a project funded by FAO-GEF common oceans, have deployed 100 bioFADs. But there are also numerous individual initiatives by fishing companies and captains that are trying to find alternatives to the plastic and netting used at dFADs. The present document aims at (i) summarizing what we have learned across the different bio-dFADs experiences in the three oceans, (ii) proposing a new concept in dFAD design, the Jelly FAD design and (iii) showing preliminary results of the tests of the Jelly FAD.

2. What we learned

2.1 Structural features needed for a drifting FAD to be productive

One of the research questions that drives our work in the search for a bio-FAD, is what structural components are needed for a dFAD to be efficient for aggregating tuna. There is no scientific 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). 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. 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.

a) **Slow drift**: It is not clear if a dFAD that drifts slowly is 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 netting panels, for which their submerged components can reach up to 100 meters depth in the Atlantic Ocean (**Figure 2**). The primary purpose of this large, submerged appendage is to help slow down dFAD´s drifting speed.

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.

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, 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 (*Lobotes surinamensis*, *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 dFAD), such as tunas (Paryn and Fedoryako, 1999). For instance, fishers report that rough triggerfish 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).

2.2 Main difficulties encountered to find an efficient biodegradable FADs and the potential solutions

During our research in the three tropical oceans to find a bio-FAD structure that fulfilled the two main characteristics above (slow drift and shade effect) with diverse fleets (Moreno et al., 2020), we identified three common, main difficulties towards the implementation of bio-FADs. Here we summarize these difficulties and their potential solutions:

- The tactic followed by most fishers to develop a bio-FAD is to maintain the same traditional dFAD design (submerged netting panels hanging from the raft; **Figure 1**) but made of biodegradable ropes and canvas. Results show that lifetime of those biodegradable dFADs, that maintain the same design but just replace the materials (organic materials for plastic), is shorter than that required by fishers (around one year). This is due to the structural stress that bioFADs with traditional design dFADs suffer in the water. Plastic materials allow traditional dFADs persist without breaking despite the tension and structural stress suffered. However, once plastic is replaced by organic materials, the tension and structural stress make the bio-FAD break.
  Proposed solution: in order to use organic materials instead of the strong and durable plastic and allow an efficient lifespan of bio-FADs, a paradigm shift is needed. Bio-FAD structures should be re-designed to suffer the least structural stress.

- There is no clear alternative for the plastic buoys used for bio-FAD´s flotation. Balsa wood is one of the promising organic alternatives that is under test in the IATTC region but this type of wood is also available in the western Pacific and Africa. Bio-based plastic buoys are also under test in Sarebio project, however the biodegradability benefits of using bio-based plastics instead of plastic buoys are not clear enough yet (Zimmermann et al., 2020).
  Proposed solution: under the lack of a clear alternative for plastic buoys used for flotation, the need for plastic buoys or corks to ensure bio-FADs flotation should be reduced as much as possible, re-designing the structure.

- As a result of the clear trend to increase the size of the dFAD structure (see section above on slow drift), fishers employ higher amounts of netting and other plastics to build large and deep structures (some fleets recycle the purse seine gear netting to build dFADs, but some others buy plastic nets and ropes to build their dFADs, as recycled nets are not enough for the amounts of dFADs used). In addition to the increased impact due to bulky structures, because organic materials are more expensive than same components made of plastic, the increase of dFAD structure makes a bio-FAD much more expensive than the traditional one. The raise in costs to move from traditional dFADs to bio-FADs increases with the size of the structure.
  Proposed solution: reduce the size of the structure, both, to reduce the impact and reduce the costs to build bio-FADs.

From our research through 2019, we identified the most promising biodegradable materials for dFADs construction, 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, re-designing a dFAD made of organic materials and without netting, reducing its structural stress, reducing its size and the need for flotation, while allowing a slow drift and shade effect, were the challenges to be faced.

3. The Jelly-FAD: a paradigm shift in bio-FAD design

In the past 15 years, we have witnessed the introduction and refinement of advanced technology in large purse seine vessels targeting tropical tunas, allowing remote detection of tuna, the remote tracking of dFADs and its aggregated biomass, the high-resolution satellite derived environmental variables used onboard, etc. The high technology developed in purse seines clashes with the rudimentary and undeveloped structure of the traditional dFAD in use, whose design has evolved very little for decades compared to the technology used on board. Just as we rely on different experts to develop and refine new technology, we identified the need to work with experts on drift behavior to design a new bio-FAD structure, which until now had been left mainly in the hands of fishers. Thus, in order to address the challenges faced to build an efficient bio-FAD, ISSF began a collaboration with physical oceanographers from the Insitute de Ciències del Mar (CSIC, Spain) experts in oceanic current dynamics and drifters´ behaviour. Specifically, we collaborated to better understand the physical behavior of dFADs in the water column in order to find a bio-FAD structure that aggregates tuna but also:

- Reduces dFAD´s structural stress to be used successfully with organic materials
- Reduces presently used large dFAD sizes
- Reduces the need for flotation (plastic buoys)
- Eliminates netting
- Drifts slowly
- Provides shade

The result of this collaboration was an innovative dFAD design that we called the Jelly-FAD (**Figure 3**). The Jelly-FAD is a dFAD that drifts with the least structural stress, like jellyfish. The assessment of the density of the organic materials used in its construction allowed making the Jelly-FAD drift with quasi-neutral buoyancy, like Jellyfish. For that, we worked in a sea-water tank in ICM´s facilities to measure the evolution of the density of the organic materials used in the Jelly FAD (**Figure 4**). The objective of those measurements was to design a dFAD for which density was similar to that of seawater. 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.

3.1 Main features of the Jelly-FAD

3.1.1 An effective drag for the slow drift of dFADs

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 drogue is 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. 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) (**Figure 5**), 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 a good performance (resistance to motion) which would allow in turn for a decrease in the total area of the structure. 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 2**) currently in use in the tuna fishery worldwide have a very inefficient and low drag coefficient, that is why large structures/areas are needed to create an effective drag. 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.

The selected drogue to make the dFAD drift slowly is a symmetric three-dimensional cube structure of 1 m^3 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 dFADs with flat net panels.

- *The placement of the cubic drogue*:

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). In the case of dFADs the idea is to "anchor" the drogue 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 7**). 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 drogue should be placed on the deepest part of the dFAD structure.

3.1.2 Drag on the surface components of dFADs

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. These forces on the surface components of the dFADs (flotation buoys, raft and geolocating tracker) 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. This drag on the surface, if opposed to the underwater drag´s direction could heavily affect the integrity of the dFAD structure. 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. 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 6**, from Niiler et al. 1987). Drifting FAD´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 6**). 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.

Minimizing the emerged component of dFAD structures at the surface would allow increasing its lifetime through reduced structural stress. Thus, we recommend placing the raft or shade providing components submerged somewhere from 5 to 15 meters depth and just the buoys or components for flotation emerged in the surface.

3.1.3 Materials used in Jelly-FAD construction

For our experiments on the behaviour of the Jelly-FAD in controlled conditions, the materials selected to construct it were organic, plant-based materials (**Figure 3**). The cubic structure was made of bamboo canes, cotton canvas and cotton rope and the same cotton rope connected both the drogue with the surface component. For the experiments at sea, different organic materials were used (see section 5 below). Biodegradable materials used in the jelly-FAD construction (and other bio-FADs) should be made of 100% organic 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 jelly-FAD structure and link the surface component of the dFAD with the deeper components (drogue).

3.1.4 Weight and flotation required for the Jelly-FAD

Results from the tests of density evolution of bamboo and cotton ropes monitored in the seawater tank helped assessing precisely the weigh and flotation needed for the Jelly-FAD to drift with quasi-neutral flotation. The correct assessment of weight and flotations reduces structural stress and allows increasing the lifespan of bio-FADs. The results tank showed that:

- In 20 days the bamboo is saturated in seawater and its density is very similar of that of seawater. Thus, the cubic structure made of bamboo will neutrally drift in the water column and won´t need any extra weight added.
- In 25 days the cotton rope will saturate in seawater and its weight after 25 days will be100 gr / 1m of rope.

Thus, the Jelly FAD won´t need any extra weight to be added and the flotation needed would be that to neutralize the weight of the cotton rope, which would be proportional to the number of meters used (for example, in our case, the 70 m of cotton rope used, will weight after one month 7 kg so that adding a flotation component at around 10 m depth of 6-6,5 kg will be enough to achieve the desired neutral drift minimizing structural stress). We will also need to add a buoy on sea surface of another 6 Kg maximum to sustain the sub-surface structure and attach the dFAD geo-locating buoy.

Finally, during the deployment of the Jelly FAD extra weight would need to be attached for the cubic structure made of bamboo to sink. The weight (in our case, 4 kg of small stones) was hanged in four paper bags of one Kg each from the cubic structure. The paper degrades in 20 days and release the stones, so that the structure remains at sea without any extra weight added. It is important to note that the numbers for weights and flotation provided in this paragraph, are specific for the cubic structure made of bamboo and cotton rope 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 the weight 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.

4. Ongoing research at sea with the Jelly-FAD

Currently these structures are under test in controlled conditions monitored by ICM and ISSF in the Mediterranean sea. In the Atlantic Ocean, Ghanaian fleets have deployed Jelly-FADs and traditional dFAD structures made of organic materials, 108 bio-FADs in total, the data from those bio-FADs will be soon shared with ISSF scientists but the results are not available yet. In the western Pacific, the fleet from Caroline Fisheries Corporation (CFC) from Federated States of Micronesia (FSM) deployed 70 bio-FADs with a plan to deploy 30 more, in this section we summarize preliminary results.

4.1 Tests in controlled conditions in the Mediterranean sea

For two months (December 2020-January 2021) tests were carried out to determine the evolution of the density of bamboo, rope and cotton canvas when submerged in seawater till saturation. These tests were carried out at the ICM facilities in Barcelona, in a seawater tank (**Figure 4**). The purpose of these tests was to know in detail the variation of the density of organic materials during the process of saturation in seawater. These data would later allow to obtain the necessary buoyancy and weight for a dFAD built with these materials, so that it drifts with the most neutral buoyancy possible, without suffering structural stress and thus increasing its useful life span. Results from these measurements are summarized in section 3.1.4 above.

The Mediterranean Sea was selected for our controlled experiments, due to the lack of fleets fishing with dFADs so that we could monitor the Jelly-FADs without interference from the tuna fleets. Ten Jelly-FADs were deployed in the Gulf of Lion in early February 2021 (**Figure 8**). Prior to deployment, a study of the currents and winds in the area was carried out to ensure a southward trajectory for the deployed Jelly-FADs. This trajectory would allow later visiting them without having to travel long distances at sea. Figure 8 shows the deployment of the structures in the Gulf of Lion and Figure 9 the trajectories followed by the Jelly-FADs.

The Jelly-FADs will be visited three times along their trajectory, the first visit took place in March 2021 and the entire structure was found to be in perfect condition, without any degradation or deviation from the drift and resistance expectations. The second visit is planned for the end of May /beginning of June 2021, depending on the sea conditions and the position of the different dFADs. Finally, the third visit will take place in September 2021, 8 months after deployment. During the visits, the condition of each dFAD component (surface component, submerged, flotation, etc.) will be observed by filling out a form designed for this purpose and replacing those components that require replacement or maintenance.

Once the monitoring period is over, about one year (depending on whether the Jelly-FAD resist in the water without stranding), a detail analysis of the trajectories of the Jelly- FADs will be carried out to determine whether the drift is correct and sufficiently slow in relation to the sea conditions. An analysis of the durability of the different components (bio-based buoys, cotton and bamboo ropes and fabrics) will also be carried out. Final results will be available by the end of the year 2021.

4.2 Jelly-FAD deployments in the western Pacific

The fleet from Caroline Fisheries Corporation (CFC) from Federated States of Micronesia (FSM) deployed 70 bio-FADs in 2020 with a plan to deploy 30 more in 2021. Each experimental bio-FAD was deployed close to a traditional dFAD, so that the 2 types of dFADs could be compared in terms of tuna aggregation and life span.

- *Raft :* This fleet decided that the raft and floatation should remain the same as used in traditional dFADs so that experimental dFADs would just change the submerged component of the bio-FAD. 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 inches mesh size) was used.

- *Tail:*
  -Experimental dFAD´s tail eliminated any plastic and netting component.
  -The materials used for the tail were: bamboo, manila rope, jute canvas, palm leaves and stones or sand and recycle chain for the weight.
  -2 types of bio-FADs were constructed: 50% of the experimental dFADs to be tested was a design that copies the traditional dFAD but that uses the biodegradable materials listed above. The other 50% deployed were the jelly-dFAD, a cubic drogue submerged at 60 m depth but with a surface raft instead of the sub-surface structure proposed by oceanographers.
  -The depth of the dFADs´tail was of 60 m (35 FTH)
  -The approximate cost of the tail 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).

4.2.1 Preliminary results

Figure 10 shows the trajectories followed both by bio-FADs and conventional dFADs in the western Pacific. Most of the dFADs drifted westward as it´s expected in equatorial waters where experimental dFADs were deployed. The trajectories shown are provided by the satellite buoys attached to the experimental dFADs. Among observed trajectories there are pairs of bio-FAD and conventional dFADs that show diverging trajectories, others show partly similar trajectory and others drift closely with a similar trajectory. From our preliminary results there is not a clear evidence of a dFAD type-based drift pattern. Similar results were also observed in the Indian Ocean BIOFAD trials (Zudaire et al., 2020).

General information in **Table 1** shows the maximum, mean and minimum days of monitorization of the 2 type of dFADs. The reasons for the end of the data provided by the buoys are not well known, the different causes for a buoy to stop sending information could be the malfunction of the buoy, a dFAD sinking event, a replacement of the buoy, or deactivation. In any case, the data could be used as a proxy of the life span for the different dFAD types, which is a maximum of 331 days for the Jelly-FAD and a maximum of 373 days for the conventional dFAD (**Figure 11**).

Biomass estimates are directly gathered from the echo-sounder buoys attached to experimental dFADs. The 90th percentile of the biomass estimated by the echo-sounder buoys was used for our analysis. Preliminary results show that there is no significant difference in the biomass aggregated by the 2 type of structures during the first 3-4 months. Afterwards, biomass estimations between both dFAD types show greater variability (**Figure 12**, **Table 1**). Similar results were observed in the Indian Ocean BIOFAD trials, where biomass estimation resulted in slightly constant values during the first months after deployment for both dFAD types, with greater variability estimates between pairs after month five-six (Zudaire et al., 2020). Further analyses will be conducted to improve the biomass estimates provided by the buoy.

Finally, for the drift speed, a priori, no significant difference was found for pairs (traditional dFADs and bio-FADs) that drifted close, following the same trajectory, neither for those pairs showing partly similar or divergent trajectories (**Figure 13**).The slow drift speed achieved by bio-FADs are similar to those of traditional dFADs.

Further and more detailed analyses will be conducted and another 30 Jelly-FAD deployed in the summer of 2021. Final results will be available by the end of 2021.

5. Recommendations for the construction and use of biodegradable dFADs to reduce ecosystem impacts by dFAD structures, based on this research and previous experiences described in Moreno et al. (2020):

1. 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.
2. To reduce the dFAD structural stress so as to enlarge the lifetime of biodegradable materials for the construction of dFADs, an innovative bio-FAD design named Jelly-FAD is recommended.
3. Biodegradable dFADs should be made of 100% organic 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).
4. 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.
5. 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.
6. 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.
7. 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.
8. 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.

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Tables

Table 1. General information on the days monitored, biomass aggregated and drift speed by FAD-type

FAD type	Number of records	Max_days monitored	mean_days monitored	min_days monitored	Biomass_max	Biomass_mean	Biomass_min	Drift speed_max	Drift speed_mean
BIO	449	331	226	3	259	8.2	1	2.3	0.7
CON	265	373	246	25	514	9.5	1	3.7	0.7

Figures

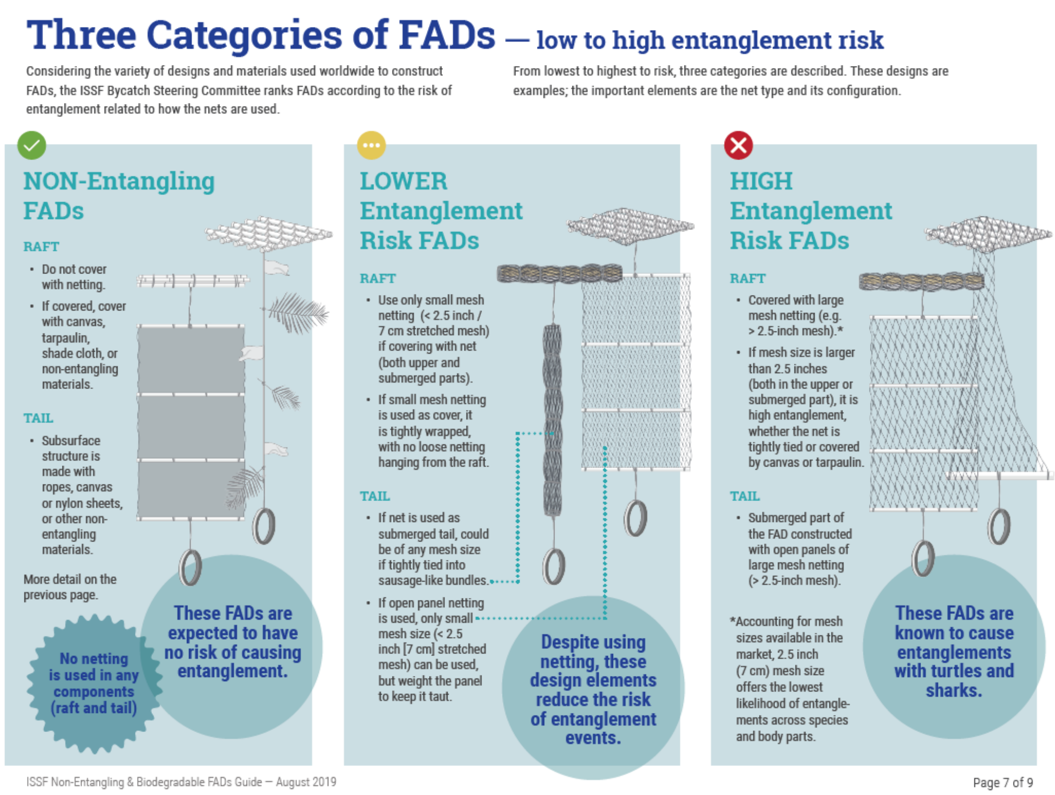

Figure 1. ISSF´s non-entangling FAD´s guide: Three categories of FADs related to their entanglement risk

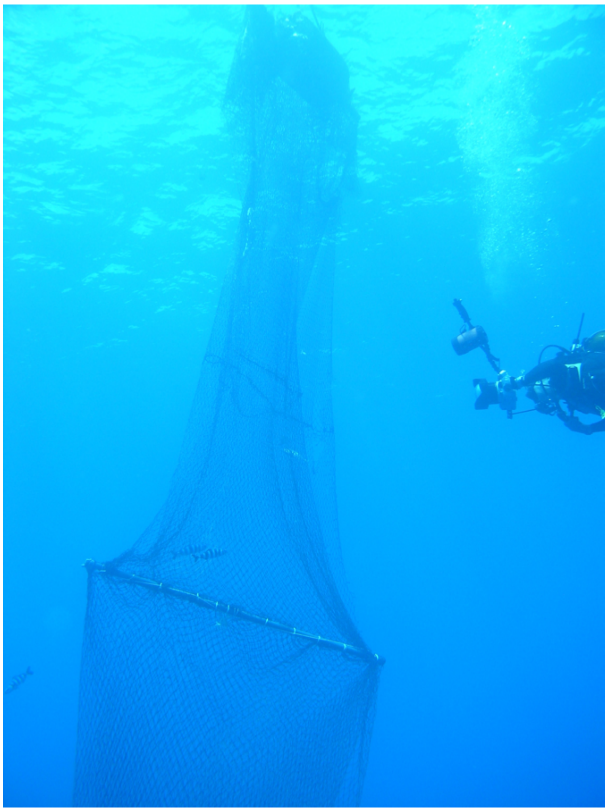

Figure 2. Underwater view of a conventional dFAD (© FADIO/IRD/ Ifremer/ Marc Taquet)

Figure 3. The Jelly-FAD mounted at ICM facilities

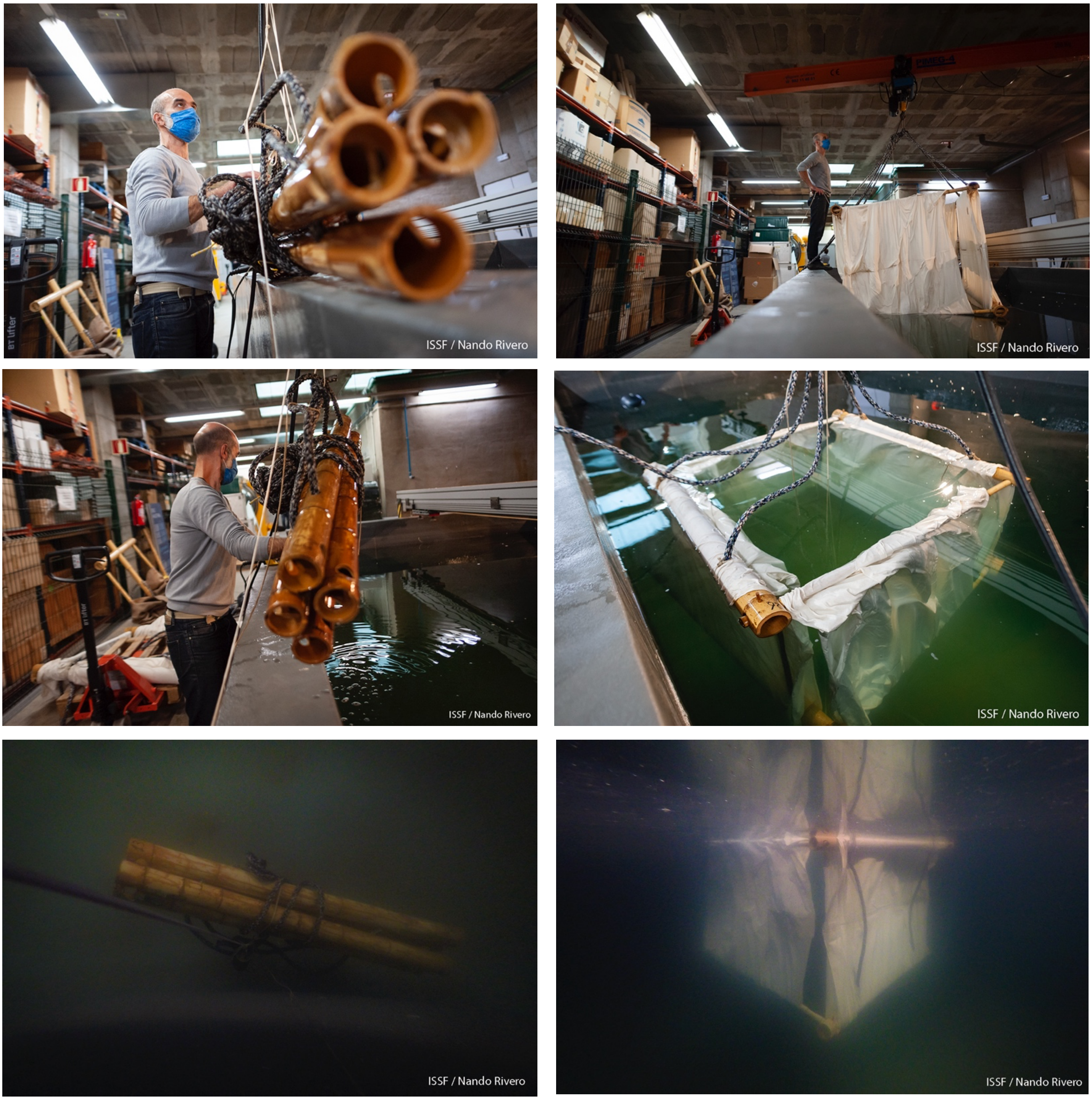

Figure 4. Assesment of the evolution of the density of the organic materials (bamboo canes, rope and cotton fabric and cubic structure) during two months in a seawater tank.

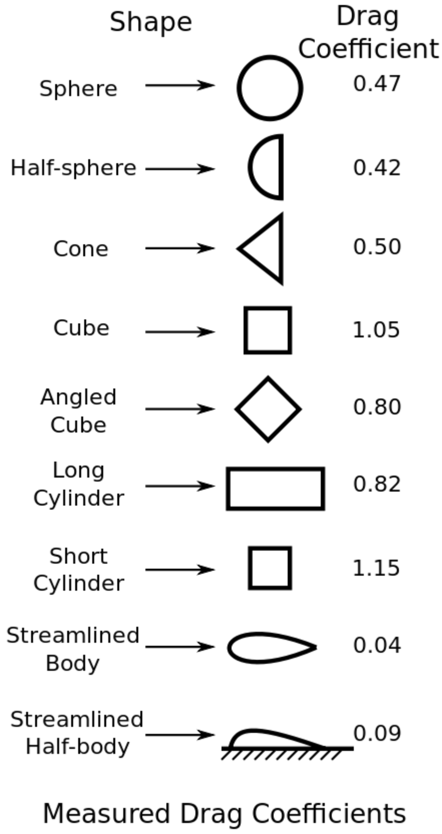

Figure 5. Measured drag coefficients for different shapes

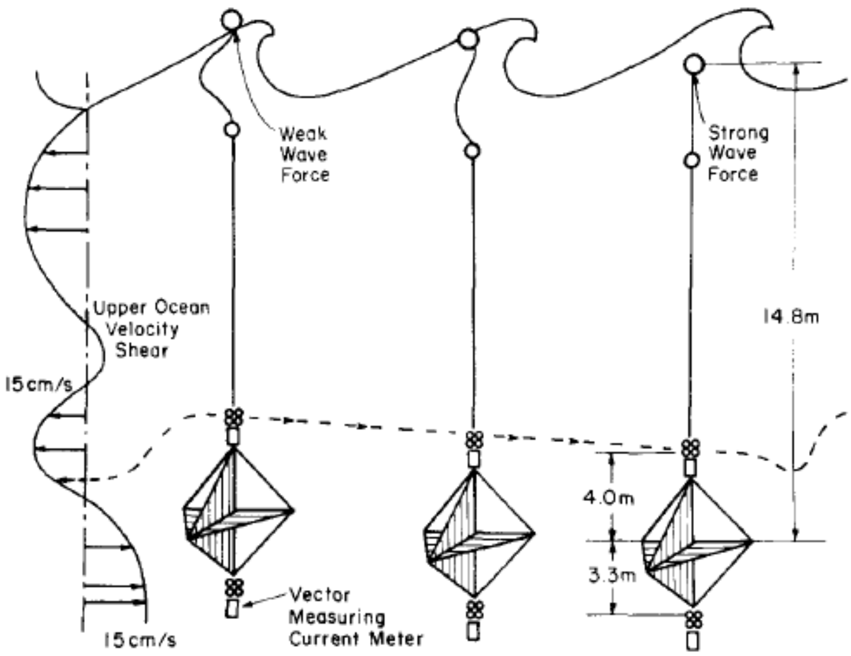

Figure 6. Diagram of the observed motion of a drifter in surface waves (from Niiler et al. 1987)

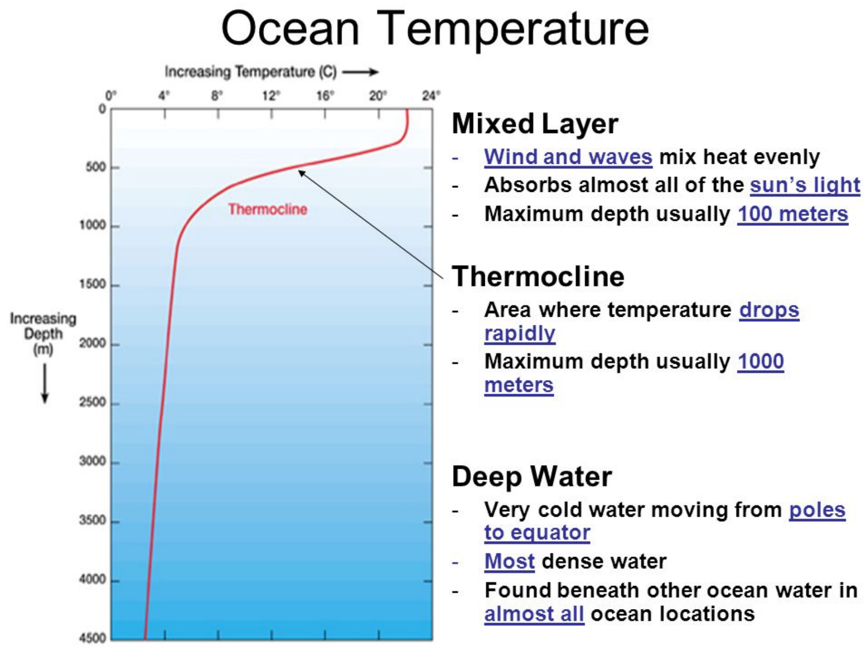

Figure 7. Illustration of the different layers in the water column.

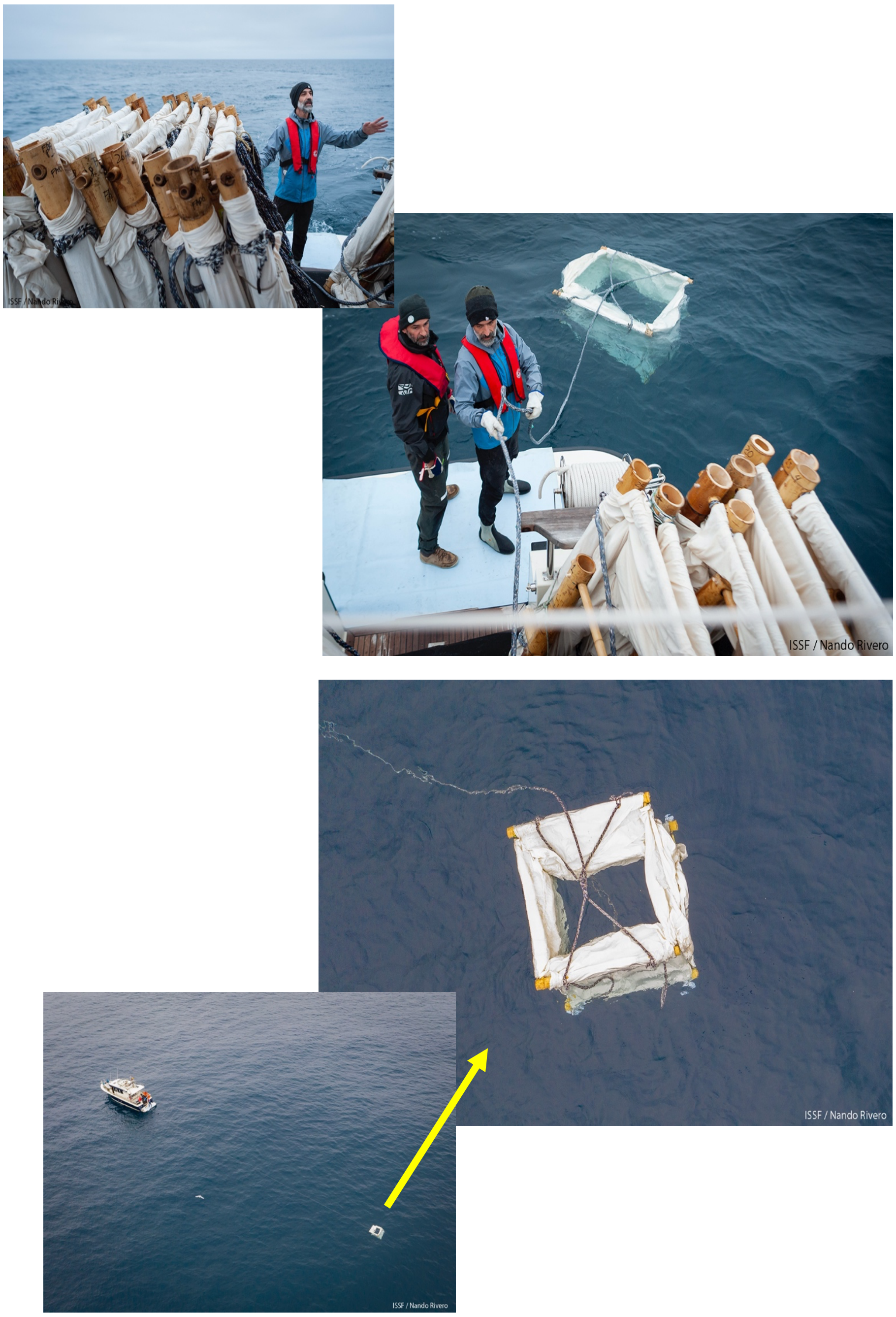

Figure 8. Deployment of the Jelly-FADs in the Gulf of Lion, Mediterranean sea

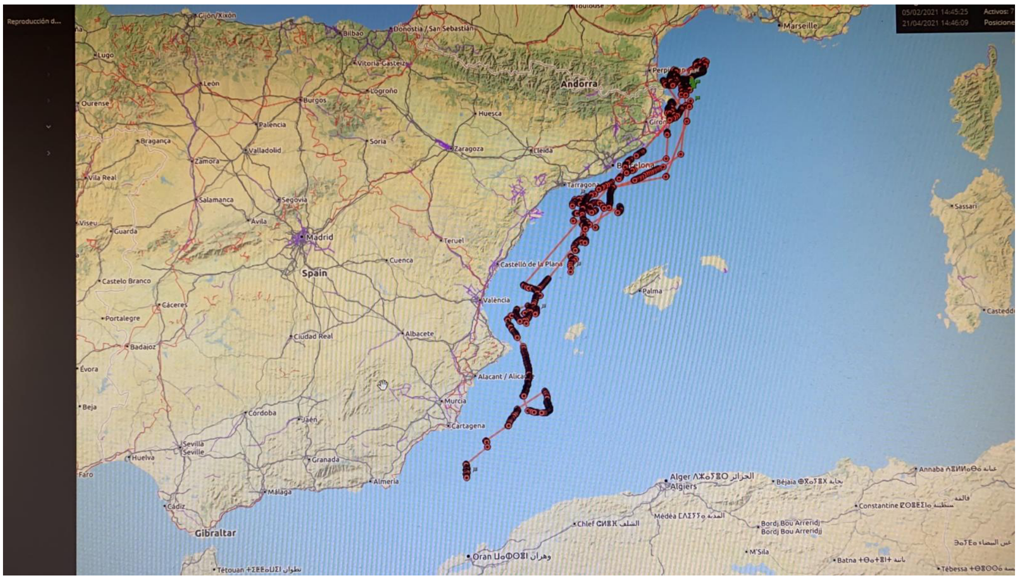

Figure 9. Trajectories of the Jelly-FAD in the Mediterranean Sea by April 202, after 3 months at sea

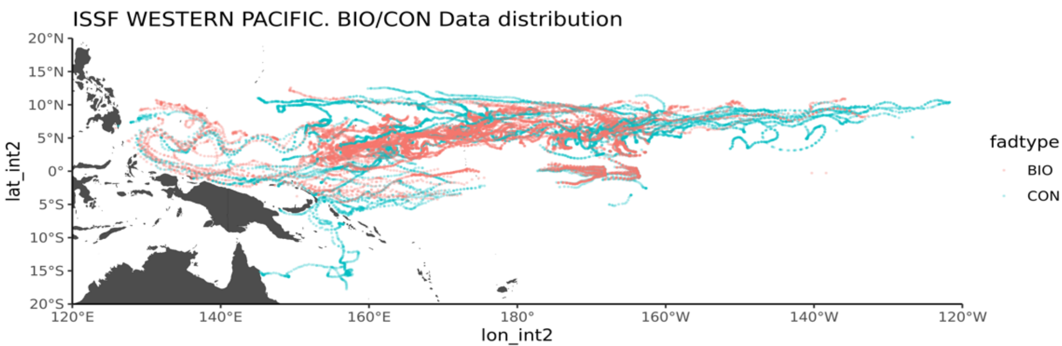

Figure 10. Map of the trajectories followed by both, bio-FADs and traditional FADs.

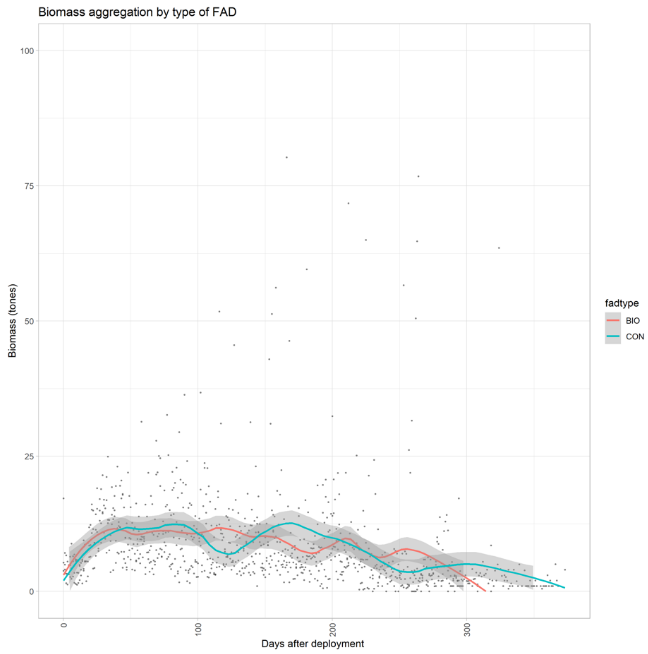

Figure 11. Monitoring days by type of dFAD

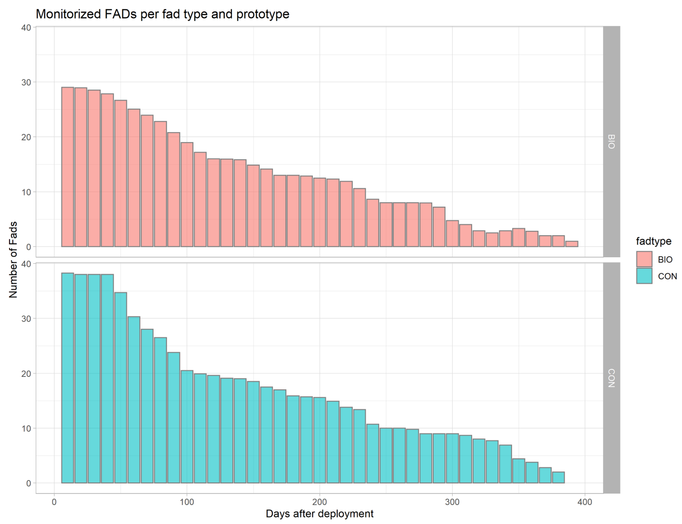

Figure 12. Biomass aggregated by type of dFAD

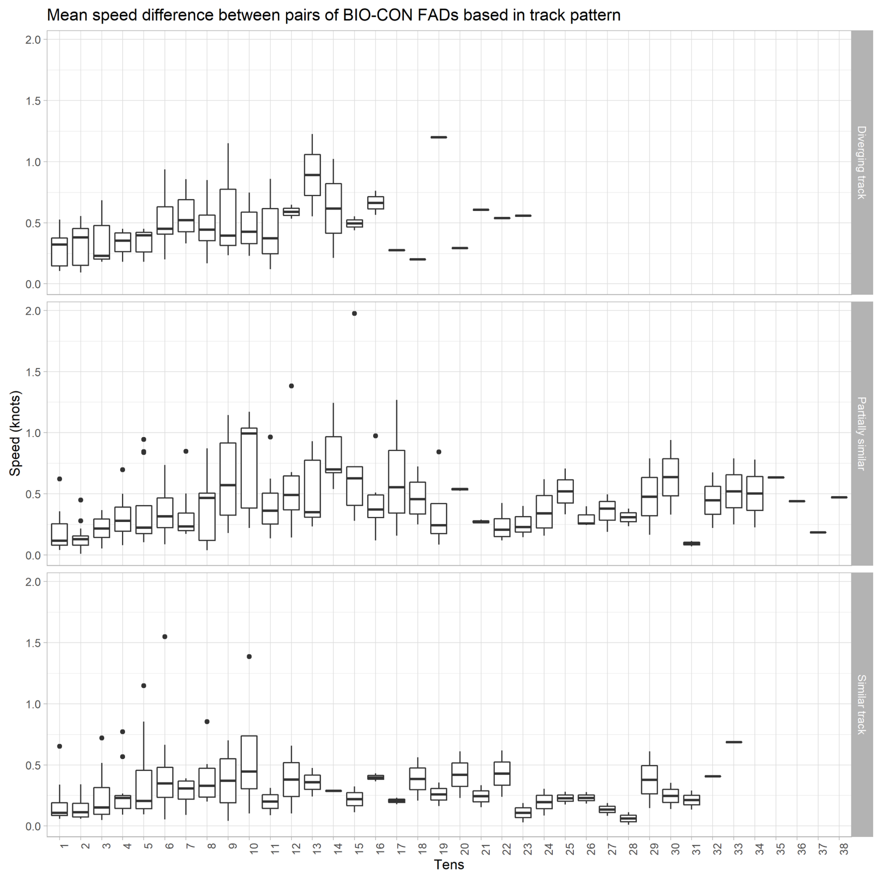

Figure 13. Mean drift speed difference between pairs that drifted separately (top), drifted together and then split and for pairs that drifter together (botton).