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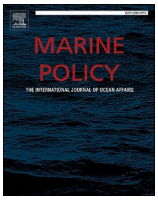

The Jelly-FAD: A paradigm shift in the design of biodegradable Fish Aggregating Devices

Gala Moreno [a,*], Joaquín Salvador [b], Iker Zudaire [c], Jefferson Murua [c], Josep Lluís Pelegrí [b], Jon Uranga [c], Hilario Murua [a], Maitane Grande [c], Josu Santiago [c], Victor Restrepo [a]

[a] International Seafood Sustainability Foundation (ISSF), 3706 Butler Street Suite #316, Pittsburgh, PA 15201-1820, USA
[b] Institut de Ciències del Mar (ICM), Passeig Marítim de la Barceloneta, 37–49, 08003 Barcelona, Spain
[c] AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Pasaia, Gipuzkoa, Spain

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ABSTRACT

Fishers and scientists in the tropical Pacific, Atlantic and Indian Oceans are jointly designing biodegradable fish aggregating devices (bio-FADs) that are efficient for fishing. The tactic followed by most fishers to construct bio-FADs is to maintain the same conventional drifting FAD (dFAD) design (i.e., large, submerged net panels hanging from a floating raft) but replacing plastic ropes and netting with organic ropes and canvases. Results from these experiences show that the lifetime of bio-FADs made with conventional FAD designs is notably shorter than what fishers require, thus precluding their adoption. The short lifespan of these bio-FADs is due to the inefficient design of conventional dFADs, which results in major structural stress. Thus, to successfully replace plastic with organic materials and increase the lifespan of bio-FADs, a paradigm shift is needed. Bio-FAD structures should be re-designed to minimize structural stress in the water. The present study summarizes what we have learned from testing bio-FADs in the three tropical oceans, and it proposes a new concept in dFAD design, the jelly-FAD. Mirroring jellyfish, this new dFAD design will aim for quasi-neutral buoyancy, which should reduce (i) the structural stress of the FAD at sea and (ii) the need for additional plastic flotation. The jelly-FAD is not necessarily a fixed design; it is more of a change in the concept of conventional dFAD construction. Preliminary results show that jelly-FADs aggregate tuna as well as conventional FADs do, with lifespans greater than 6 months at sea. In addition, the jelly-FAD showed average drifting speeds similar to a conventional dFAD. To accelerate the adoption of bio-FADs worldwide, recommendations for jelly-FAD construction and tests are provided.

1. Introduction

Globally 36% of the principal commercial tuna species are caught by fishing with Fish Aggregating Devices (FADs) [1]. Purse seine, pole-and-line industrial fisheries, and artisanal trolling and hand-line fisheries use thousands of anchored and drifting FADs worldwide, exploiting the associative behavior of the three principle tropical tuna species — skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*) tuna — at FADs (Scott & Lopez, 2014). It is estimated that the industrial tuna purse-seine fishery alone deploys globally ~100,000 drifting FADs (dFADs) every year [2].

The dFADs are deployed and left at sea with a geolocating echosounder buoy that provides position and an estimate of the biomass aggregated in real time [3]. After a few weeks or months depending on the fishing region, fishers visit their dFADs based on the biomass information sent by the echosounder buoy. Due to the complexity of dFAD fishing strategy, in which dFADs are left to drift with a geolocating buoy and are unattended for extended periods, it is estimated that around 7%–22% of these dFADs end up stranded [4–7]. One of the impacts of dFAD fishing is marine pollution from lost, abandoned, or discarded dFADs. Other impacts of stranded dFADs include damage to coral reefs and other coastal ecosystems as well as interference with other economic activities, such as tourism [8].

Consisting of a surface raft and a submerged appendage, these dFADs are mostly made of decay-resistant plastics (e.g., nylon nets, plastic buoys, PVC pipes, and polypropylene ropes). The dimensions of submerged appendages can be large, with dFADs extending down an average of 50 m but reaching up to 80–100 m depth in some fleets working in the Atlantic and Pacific Oceans [9,10]. In the Indian Ocean, fishers also use dFADs without deep submerged appendages. In the past,

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* Corresponding author.
E-mail address: gmoreno@iss-foundation.org (G. Moreno).

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fishers reused large-mesh-sized netting panels from the purse-seine net to construct dFADs, but tuna Regional Fisheries Management Organizations (RFMOs) have prohibited them due to the risk of shark and sea-turtle ghost fishing [11,12]. Today, low-risk-entanglement dFADs (i. e., with small-mesh-sized netting below 2.5 in.) are used in the Pacific (WCPFC - CMM 2021–01; IATTC – C19–01 and C-21–04) [13,14], and Atlantic Oceans (ICCAT - Recommendation 21–02) [15]. In the Indian Ocean, netting in dFAD structures has been forbidden since 2020 (IOTC - Resolution-19–02) [16], and in the western Pacific it will be forbidden from 2024 onwards. As a result, to reduce the risk of entanglement, fishers often simply reduce the mesh size of the netting panels but maintain the same FAD design (Fig. 1a). In a few cases, mostly in the Indian Ocean, they use large-mesh-size nets tightly tied into bundles or just a rope hanging from the raft with a weight on the deepest part of the rope [12]. In any case, it is important to note that any mesh size can tear, creating larger mesh size netting portions that will become entangling material. Likewise, bundles may unwind over time and become open netting panels with a high risk of entanglement of marine fauna. Only dFADs constructed without netting can totally eliminate the risk of entanglement for turtles, sharks and finfish species [12].

One of the difficulties encountered by scientists and managers in accurately quantifying dFAD stranding events is that once a dFAD has moved away from a productive fishing zone, fishers often deactivate the dFAD's positioning system to save on telecommunication costs. Since the communication ends before the dFAD beaches, those dFADs then remain at sea without any owner tracking their trajectories. This situation limits our ability to account for dFAD stranding events and their impact on the ecosystem. Escalle et al. (2019) [17] estimated that in the western Pacific ~80% of the dFADs deployed by purse-seine fleets have an unknown fate (i.e., there is no information regarding the end of their lifespan).

Recent scientific literature and International Seafood Sustainability Foundation (ISSF) workshops with fishers identified potential dFAD accumulation areas, both at sea and stranded, in the three oceans. During an ISSF workshop on FAD structure impact reduction, stranding dFAD hotspots were identified by fishers and scientists in the Atlantic Ocean, mainly along the West African coast and the Gulf of Guinea between 20ºN and 20ºS [7] and Nigeria, Equatorial Guinea and Mauritania [5]. Recent scientific literature identified potential dFAD stranding areas in the western Pacific Ocean in Tuvalu, Kiribati Gilbert and Phoenix Islands, Nauru, Papua New Guinea and Solomon Islands [17–19]. However, oceanic currents can also take dFADs to other regions far from the fishing grounds, as in the recently reported dFAD stranding events in the Caribbean Sea (Tom Pitchford, pers comm), Brazil [4–7] and in the Hawaiian Islands [20].

Increased awareness on dFAD stranding events has triggered a response by coastal countries, scientists and research institutes working on dFAD fishing — and also by the fishing industry itself, conscious of potential impacts associated with lost or abandoned dFAD structures. A direct outcome of this awareness are initiatives, both by the fishing sector and research institutes, to develop dFAD structures made of biodegradable materials, commonly referred to as biodegradable dFADs or bio-FADs [21,22]. Since 2010 several research projects in three oceans have focused on designing and testing a dFAD structure constructed mostly with biodegradable materials. The most common biodegradable materials that have been tested so far are cotton, bamboo and manila hemp, although jute, sisal, coconut fiber and others have also been tested. In general, the selection is based on not only the materiaĺs resistance but also its manageability, availability and cost. Initial pilot projects were carried out to test biodegradable materials' durability in controlled conditions [23,24]. Pilot tests were then carried out at sea in real fishing conditions [25–27] and later developed at a larger scale [21,28]. There have been numerous individual initiatives by fishing companies and captains to find alternatives to plastics and net materials in dFADs.

The present research aims to integrate the knowledge acquired in bio-FAD trials and workshops worldwide and to identify key common issues that will help multiple fleets to advance bio-FAD implementation. The specific objectives are (i) summarizing what we have learned across the different bio-FAD research experiments in three oceans, (ii) proposing a new concept in dFAD design, the jelly-FAD, and (iii) offering management recommendations for the transition to biodegradable FADs.

2. Lessons learned in the search for a biodegradable FAD

2.1. Structural features needed for a dFAD to be productive

One of the research questions that drives our bio-FAD work is what structural components are needed for a dFAD to be efficient for aggregating tunas. Unless this condition is fulfilled, fishers will be unwilling to adopt bio-FADs. There is no strong scientific evidence indicating differential effect of dFAD structure components or designs on the attraction or aggregation process of tunas. Diverse research has shown that no major dFAD characteristics (e.g., color, shape) could explain the attraction of tuna species [29–32]. In fact, tunas have been reported to

Fig. 1. a) Traditional dFAD with large-mesh-size netting panels in the submerged appendage (© FADIO/IRD/ Ifremer/ Marc Taquet). b) Construction at port of a dFAD with a small-mesh-size netting appendage. @ISSF/Nando Rivero.

aggregate around floating objects of a different nature, such as those of natural origin (e.g., seaweed, tree logs, whale carcasses) and artificial origin (e.g., FADs, scientific buoys, flotsam) [33]. 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, such as (i) the dFAD trajectory or areas traveled [34,35] and (ii) the non-tuna fish aggregations around dFADs [34,36], may play an important role in attracting tuna schools. ISSF Skippers Workshops consistently showed over a decade that there are two main dFAD structure features considered crucial by fishers for floating objects to be productive: (i) a slow drift and (ii) a shade and/or shelter effect that attracts non-target colonizing fish [37]. Interestingly, these two features identified by fishers correlate with the two scientific hypotheses stated above. Both fishers and scientists identify as important features the dFAD́s trajectory and the presence of a non-tuna fish aggregation for the dFAD to aggregate tuna, which for fishers is the shade/shelter effect.

2.1.1. *Slow drift*

The benefit of slow drift in dFADs is not clear. We need to understand (i) whether a steadily moving dFAD is more attractive for tuna (e.g., lower energy expenditure to follow or remain in the area of interest of tuna); (ii) if fishers prefer the slow drift so that the dFAD remains within their fishing area (e.g., avoiding dFADs drifting out from their fishing grounds, which maintains a greater number of dFADs available for fishing); or (iii) a combination of both. In any case, fishers consistently mention the slow drift as a key factor for a dFAD to be productive. As a result, the tendency worldwide has been to build deeper and heavier submerged dFAD structures in the belief that they will act as larger anchors, resulting in a slower drift. In the 1990 s, fishers were only using simple dFADs with a bamboo or purse-seine float raft, wrapped in spare purse-seine net. The purpose of the netting was to give it more consistency, augment the shade effect, and make it less detectable to competing vessels, due to its dark color. In these earlier dFAD fishery stages, fishers left only a small panel of netting hanging from the raft (e.g., submerged net < 5 m) to provide shade and make it more attractive to fish [34]. Over the years, those underwater appendages began to take on greater importance and evolved into sophisticated structures reaching an average depth of 50–60 m and up to 80–100 m in some fleets. Fishers also added weights of up to 25 kg to those large structures to make them sink below the sea surface level and stay in a vertical position in the water column [38].

Importantly, the pollution impact each dFAD structure has on the ecosystem is closely related to its size and weight (i.e., the pollution from an 80-m depth dFAD is 4 times than that of a 20-m dFAD). Thus, to decrease dFAD structures' impact on the marine environment, reducing their size and weight — especially regarding synthetic polluting materials — would be a significant step. In addition, deeper FADs could be more susceptible to stranding events. FADs often drift in the tropical waters through the continental shelf of archipelagic waters. Shallow FADs can pass through the shelf and drift again into the open ocean, but deep FADs would have more chances to become stranded miles from the coast.

2.1.2. *Shade effect*

Fishers believe a dFAD should provide shade to enhance fish attraction. This shade is provided (i) at the surface by the floating raft and (ii) underwater by the submerged dFAD net panels, often "decorated" with rope or canvas strips and palm leaves, that fishers employ as attractors. For fishers, the purpose of these attractors is to provide shelter and shade for pelagic fauna, or to "create an artificial reef in oceanic waters." The dFAD would be a discontinuity that provides fish with a reference point in an otherwise vast and homogeneous oceanic water mass. Non-tuna species (e.g., triggerfish (*Canthidermis maculatus*, dolphinfish (*Coryphaena hippurus*), and rainbow runner (*Elagatis bipinnulata*)) could initially be attracted and retained at dFADs due to shelter advantages. Fishers consider both the shade produced by the floating structure of the dFAD and the attractor strips and flags usually added to the submerged structure to be important elements to attract those fish species that occupy the space closest to the dFAD structure (i.e., within 2 m), which are called intranatant species (*Lobotes surinamensis, Abudefduf saxatilis*, etc.) [35,37,39].

Intranatant species, in turn, are believed to attract other species that occupy the space at greater distances from the dFAD (i.e., from 50 m to several nautical miles from the dFAD), including tunas. For instance, fishers believe that rough triggerfish at dFADs play a key role in attracting tunas, as this species emits loud grunt-like sounds that could be detected from a range longer than dFAD visual cues. It may be that once the dFAD is colonized by intranatant species, the integrity of the structure of the dFAD (color, shade, etc.) loses importance, with these non-target species serving as a more powerful attractor for tunas [35].

In summary, the slow drift and the shade effect represent two main features that bio-FADs need to have to be effective for fishing.

2.2. *Main challenges when searching for biodegradable dFADs*

During our research in the Indian, Atlantic and Pacific Oceans to design and test bio-FAD structures that fulfilled slow drift and shade effect needs, we have identified three main challenges in implementing bio-FADs, summarized below.

2.2.1. *Reduced lifetime of bio-FADs*

In projects to develop bio-FADs, the tactic followed by most fishers and scientists has been to maintain the same conventional dFAD design (submerged netting panels hanging from the raft; Fig. 1a) but to employ biodegradable ropes and canvases. Different plant-based fibers such as cotton (*Gossypium hirsutum)*, jute (*Corchorus capsularis*), coconut fiber (*Cocos nucifera*) and manila hemp (*Musa textilis*) canvas and ropes have been tested to replace the plastic (i.e. polypropylene and polyamide) netting and ropes used in the conventional dFADs [21,28,40]. However, the lifetime of biodegradable dFADs constructed with the standard dFAD design is shorter than the five months to one year lifetime that is typically required by fishers using dFADs [38]. This shorter lifetime of the weaker biodegradable materials is highly related to the structural stress that conventional dFADs experience in the open ocean.

Most conventional dFAD designs worldwide have 1.5–2 m-wide netting panels hanging from the surface down to depths ranging between 40 and 80 m. Most of the dFAD is fully immersed in the ocean, but a small portion typically stands out from the water. The drift of any such object in the ocean is influenced by the near-surface currents and the direct wind drag on any element of the dFAD that emerges from the water. Any element fully immersed in the water will drift with the surrounding ocean currents. The near-surface currents can be affected by the large-scale circulation (periods of years) driven by the thermohaline structure of the water column and the climatological weather patterns; the mesoscalar ocean structures and synoptic winds (periods from months to several days); and the small-scale motions that include submesoscale structures, inertial oscillations and the Stokes drift associated with waves (periods ranging a few days to hours).

If any part of the drifting element stands out of the water, then the emerged portion will be subject to windage directly-driven motions. These motions will result from direct wind drag (tangential shear stress), from drag (pressure differences across the item), or the 'sail' effect (resulting on a force at an oblique angle to the wind direction). The geometry of the object determines the respective contribution of these factors to the total drift [41].

Finally, surface waves are possibly the most important stressor of the FAD structure because the vertical and horizontal displacements and the speed of water particles that orbit the waves decrease exponentially with depth. For deep-ocean waves, the orbits are circular, and the particle displacements decrease with depth as $a\exp(2\pi z/L)$ while the speed decreases as $2\pi a/L\exp(2\pi z/L)$, where a is the amplitude of the wave, L is the wavelength and z is the water depth. For example, for deep-ocean waves with a moderate surface amplitude of 3 m and wavelength of 100 m, the surface horizontal and vertical displacements of the surface waters is 3 m and the corresponding speeds can reach peak values of 1.88 m s^{-1}; however, at 50 m, the displacement would be only 0.13 m and the associated speed would be only 0.08 m s^{-1}. For these waves the period would be 7.9 s, meaning that the structure of the FAD would be experiencing a repeated fast stretching of nearly 3 m at speeds close to 2 m s^{-1}. During stormy periods the amplitude of the surface waves would increase, leading to a proportional increase in the amplitude and speed of the stretching. This continuous stress on the rigid parts of the FAD is very likely the main factor causing fatigue in the FAD structure.

The floating and submerged components of the dFAD structures are constantly and simultaneously subject to forcing elements: winds, waves and near-surface currents. These forces can act independently, with different or similar intensities and directions depending on the oceanographic conditions. Over their lifetime, traditional dFAD structures' continuous exposure to all of these forces creates high stress on their construction materials.

Synthetic plastic materials produced to be more stress-resistant allow conventional dFADs to withstand these stressors without breaking right away, despite the high structural tensions they suffer. But even these high-strength plastics break eventually, and it is common for fishers to have to repair synthetic traditional dFADs (e.g., replace the netting) after about six months at sea. Since organic materials are less resistant to torsions, shear, and tension forces than synthetic materials, the structural stress shortens bio-FADs' lifetime compared to a conventional FAD.

2.2.2. Lack of alternative to plastic floats

For bio-FAD flotation, currently there is no clear, natural alternative for the plastic buoys in conventional dFADs. Balsa wood (*Ochroma pyramidale*), because of its mechanical properties and density [42], is one of the organic alternatives being tested in the eastern Pacific Ocean region. Balsa wood is available in other tropical regions, including the western Pacific Ocean, but it is not clear yet if once balsa becomes water-saturated it will maintain the necessary flotation for the dFAD to remain effective for the required minimum of 6 months. Ongoing trials at sea will soon provide more information on this issue [28].

In the Sarebio project, bio-based plastic (polymers derived from renewable biological resources) was tested for constructing bio-based flotation buoys [43]. However, the biodegradability benefits of using bio-based plastics are not yet clear yet, as plastics certified as biodegradable under marine conditions are still scarce and have limited functionality [22]. Besides the certification and market limitations of bio-based plastics, the toxicity of chemical additives used in their production, along with the extent of their potential impacts on the environment, remain unclear [44].

Finally, the costs of plant-based flotation materials — i.e. balsa wood, cork etc. and bio-based buoys — are higher compared to plastic buoys. Therefore, reducing the need for flotation would also decrease marine debris (i.e., when FADs are lost or abandoned) and FAD construction costs.

2.2.3. DFAD structures have evolved to be larger and heavier

As a result of the clear trend in increased dFAD structure size and weight (see Section 2.1.1), fishers have employed larger amounts of netting and other plastics to build deeper structures. Larger structures can decrease the drift speed and also are believed to offer greater "shade effect" and be more attractive for tunas — and better able to compete with other vessels' FADs [45]. The western Indian Ocean is the only fishing ground for which dFAD design has evolved towards shallower structures.

Because organic materials are more expensive than plastic ones, the fisher preference for large structures makes it much more expensive to build a bio-FAD with organic materials, than constructed with synthetic ones. The costs of transitioning from conventional dFADs to bio-FADs incrementally rise with the size of the structure, which is an impediment to fisher adoption of bio-FADs. In addition, large bulky dFAD structures are more complicated to retrieve when stranded, since moving and storing 50–80 m-deep structures is not viable for all vessels (i.e., need for powerful cranes, lack of storage space onboard) and even for land-based retrieval programs [5].

From our research up to 2021, we identified the most promising biodegradable materials for dFAD construction. We also reviewed various bio-FAD designs that could be used with a certain degree of success in specific regions, such as the Indian Ocean [21,40]. Yet the challenge has been to find a dFAD made of organic materials that can meet global fisher requirements and address the three main difficulties identified above.

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 fishing technology in large-scale, tropical tuna purse seiners, which enables fishers to track remote dFADs and detect tuna aggregations with sophisticated sonars and high-resolution maps of satellite-derived environmental variables etc. [3,46,47]. This state-of-the-art onboard technology contrasts starkly with the rudimentary and undeveloped structure of dFADs, whose design — apart from the increase in size — has barely evolved since their introduction in the 1980 s [30,34,37]. Just as we rely on different experts to develop and refine new fishing technology, we identified the need to work with experts in the design and operation of oceanographic drifters, a task that until now has been left solely in the hands of fishers. Thus, to build efficient bio-FADs, fishers, scientists expert on FADs and oceanographers have begun to collaborate. Specifically, the collaboration aim to better understand the physical behavior of dFADs in the water column to find a bio-FAD structure made of organic materials that, in addition to eliminating synthetic netting, can drift slowly and provide a shade effect. This includes examining the behavior of bulky dFAD structures that require additional artificial flotation and suffer great structural stress.

The first premise was that if organic, plant-based materials were used instead of the much stronger and durable plastic ones, a paradigm shift was needed to achieve adequate longevity in bio-FADs. Bio-FAD structures had to be re-designed to minimize the structural stress caused by oceanic forces so that organic materials could last longer at sea. This new concept was inspired by jellyfish, which are structurally weak (e.g., no skeletal structure) but still smoothly flow with the ocean currents. Mirroring the jellyfish, this new dFAD design (the "jelly-FAD") would need to have quasi-neutral buoyancy, to reduce (i) the structural stress and (ii) the need for additional plastic flotation.

3.1. Achieving the slow drift while reducing the size of the dFAD

Any object submerged in water experiences a drag force, which depends on the shape and area of the object and is proportional to the relative speed of the water with respect to the object. To clarify the concept, we may consider two extreme situations. The first one corresponds to the object left free inside the water: in this case, there are no counterforces and the object moves with the same speed as the surrounding fluid and experiences no drag. The opposite case is when an object is retained through some rope or cable that is attached to some fixed element: in this case, the object will experience the full drag force (although it will modify its orientation so that the force is minimal) but will remain immobile (if the retaining structure and rope are strong enough to resist the drag force).

The situation of a dFAD is an intermediate one. The surface-most layers of the water column are the ones that move more swiftly; these layers usually coincide with what is called the surface mixed-layer — typically a few tens of meters — which experience the direct effect of the wind (actually the drag force of the wind blowing on top of the water). In contrast, the submerged net panels are found deeper, usually up to 80 m depending on the region, in water layers that do not experience the direct effect of wind and hence move more slowly than the surface layers. The net panels are the components that have the largest area — much more than the summation of the rope that connects this net to the surface, the buoys along the rope that give the entire FAD floatability, and the echosounder buoy that allows dFAD tracking. As a result, the dFAD moves slowly, driven by the weaker currents found at greater depths. In summary, the drag in a conventional dFAD mainly derives from the submerged structure, what we may call "drogue," which is located deep enough to reach waters that move slower than the overlying waters. To slow down the dFADs, fishers rely on a two-dimensional submerged drogue system formed by a flat wall of hanging net panels, with an added 10–25 kg metallic weight at the end that helps maintain the structure vertically in the water column (Fig. 1a).

An object's resistance to movement in a fluid is calculated as the drag coefficient. The drag coefficient denotes how much opposition an object will have to a moving fluid, and it will depend on the shape and materials constituting the object as well as the type of fluid. These drag coefficients are independent from the area or size of the drogue [48]. In the case of a dFAD, it is important that the drag force on the deep elements be substantially greater than the drag force over the elements that connect the drogue to the sea surface (surface and subsurface buoys, raft and echosounder buoy). This is calculated simply as the drag-area (product of drag coefficient and effective area) ratio of the drogue with respect to the overlying elements [48], where C is the drag coefficient and A the projected area:

$$R = \frac{C_d A_d}{\sum C_s A_s}$$

The s and d subscripts are used to indicate the surface-subsurface elements (buoys, rope, and raft) and the drogue, respectively. The higher the *R*, the more the dFAD will drift with the water surrounding the drogue. To get a high *R* value, the drag coefficients and areas of the surface-subsurface elements must be small compared to the drogue.

In the case of dFADs, selecting a drogue with a high drag coefficient (proper shape and material) will cause the dFAD to move with the slower deep waters, thus allowing a decrease in the amount of drogue materials. Specifically, a three-dimensional structure like a cube shape, with a drag coefficient of 1.05, is much more efficient than the two-dimensional one commonly used by fishers, which aligns with the current and hence provides a relatively small effective area. For this reason, a cube was chosen as the most convenient shape for the drogue in the jelly-FADs. Since the drogue has symmetrical sides, the drag created is essentially independent from the orientation of the drogue with respect to the direction of the flow (i.e., even when water mass direction changes, the cube always has one side that resists the prevailing current).

The selected drogue for slow dFAD drift was a symmetrical, three-dimensional cube structure of 1 m^3 (Fig. 2). In addition, the selected cube shape allows for easy assembly and storage, as it can lay folded flat on the vessel's deck and assume an extended 3D shape once immersed in the water.

We can conclude that the traditional, two-dimensional dFADs used worldwide (Fig. 1) have very inefficient and low-drag coefficients, and that large, wide and deep structures/areas are needed to create sufficient drag. Modifying the shape to a three-dimensional, symmetrical structure of a smaller size would allow the same desired slow drift but avoid the need for extensive and voluminous structures.

3.2. Increasing dFADs´ lifetime and reducing its weight and plastic floats need

When constructing traditional dFADs, fishers add extra weights of up to 25 kg (e.g., metal cable or chains) at the bottom of the structure to maintain the net panels in a vertical position so that the drag is maximum, and also because they believe that the weight creates the drag. Often fishers think that the more weight that is added, the slower the drift will be. This additional weight drives the need for more plastic buoys to prevent the dFAD from sinking. The components of such a dFAD model, with a considerable surface structure (i.e., metallic/bamboo frame with numerous buoys wrapped in netting) and a submerged large structure (i.e., wide net panels and extra metallic weights), are inherently subject to greater stress. Wind and waves at the upper part

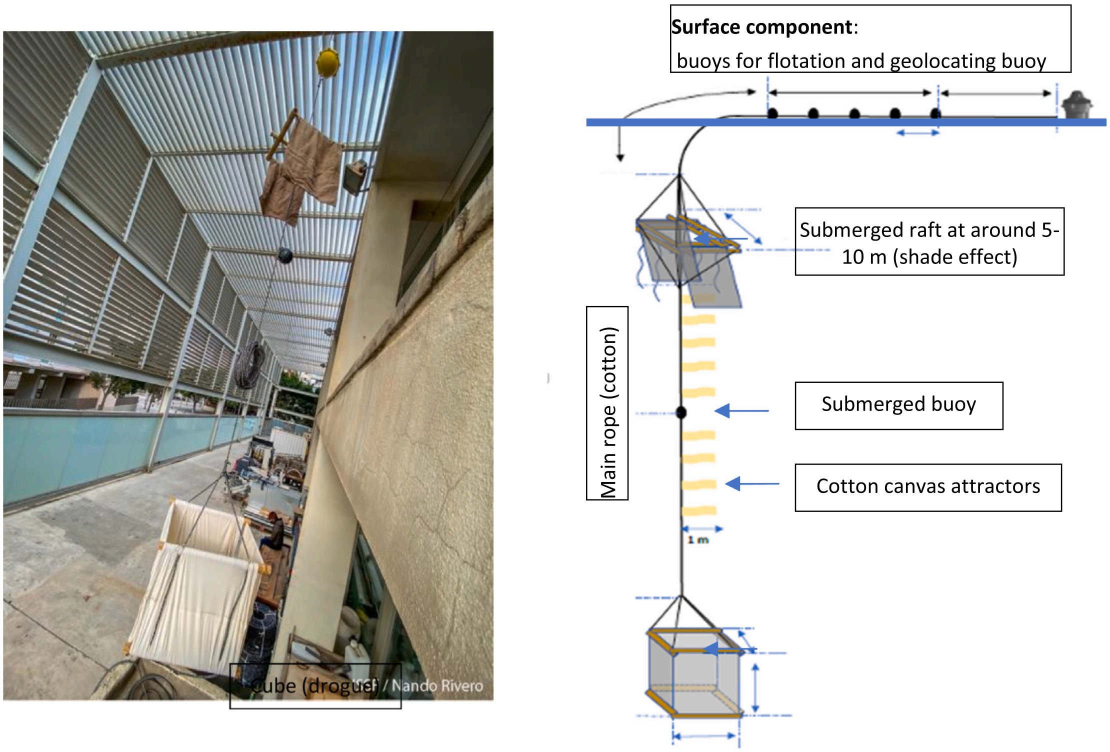

Fig. 2. Picture and schematic drawing of the biodegradable jelly-FAD design.

of the dFAD and the slower deep currents often pull in opposing directions, increasing the tension on the rope and the joining elements. Correctly assessing the weight of the structure required to obtain nearly neutral buoyancy in seawater is key to increasing the lifetime of biodegradable dFADs. Decreasing the size of the surface elements will decrease the drag force on these elements, which will minimize this tension in the surface-to-subsurface tether line. The objective is to design a dFAD that can drift with the near-bottom waters and experience minimum stress, torsion and shear forces, increasing the lifetime of its components.

The biodegradable materials selected to build the jelly-FADs are of plant-based origin and some had been tested in bio-FAD trials. These include the following: (i) 100% recycled cotton ropes of 20 mm diameter, 4 strands in torsion Z with an initial breaking strength of 1400 kg, from Itsaskorda S.L. rope manufacturers; (ii) cotton canvas of 385 g/m^2, with 3×1 twill weaving and an initial tensile strength of 1000 N and 800 N along warp and weft directions respectively from Ternua group; and (iii) bamboo canes of two different diameters, 40–50 mm and 100–120 mm. The ropes were selected following a previous experiment under controlled conditions evaluating the degradation of different types of organic ropes, in which 100% cotton rope of 20 mm was chosen as the most suitable one in terms of strength and durability [23].

To assess the necessary flotation and weight of the jelly-FAD, we measured how the density of the cotton ropes and bamboo canes evolved with time in a seawater tank (Fig. 3). After 20 days of submersion in seawater, the bamboo canes became fully saturated and their weight thereafter remained constant, being very similar to that of seawater. It should be noted that every segment of the bamboo canes was drilled to facilitate their sinking from the beginning of the operation (as should be the case at sea). Thus, the cubic frame structure made of bamboo (the drogue) would neutrally drift in the water column once saturated with seawater. However, the cotton rope tested in seawater reached saturation at around 25 days and weighed 100 gr for every 1 m of rope. The fact that once saturated the cotton rope sinks, permitted using that extra weight to make the cube sink. It is important to note that the plastic ropes fishers use in conventional dFADs float but cotton fiber ropes sink — a significant difference when assessing the necessary weights and floats in biodegradable FADs.

To drift correctly from the beginning of its deployment, the jelly-FAD's structure must be fully stretched in the water column, with the drogue at the bottom end. In our case, due to the biodegradable material saturation process taking 20–25 days, we had to add a temporary weight to the cubic drogue to prevent it from floating at the water surface. This was achieved by filling the hollow bamboo canes with 5–7 kg of sand, gravel or wet mud that gradually filtered out. Another option would be soaking the bamboo in seawater to accelerate the sinking process and reduce the weight needed. Once the biodegradable materials were saturated in seawater, no extra weight was required, as the cube would drift neutrally in the water mass at the depth placed.

The floatability used was the triple of the weight of the whole dFAD structure once saturated in seawater, with the factor of three providing a safe margin in case of accidents (e.g., if one of the buoys loses floatability or if the structure becomes entangled with other drifting elements) or presence of biofouling. In our case, for a 50-m long jelly-FAD with a

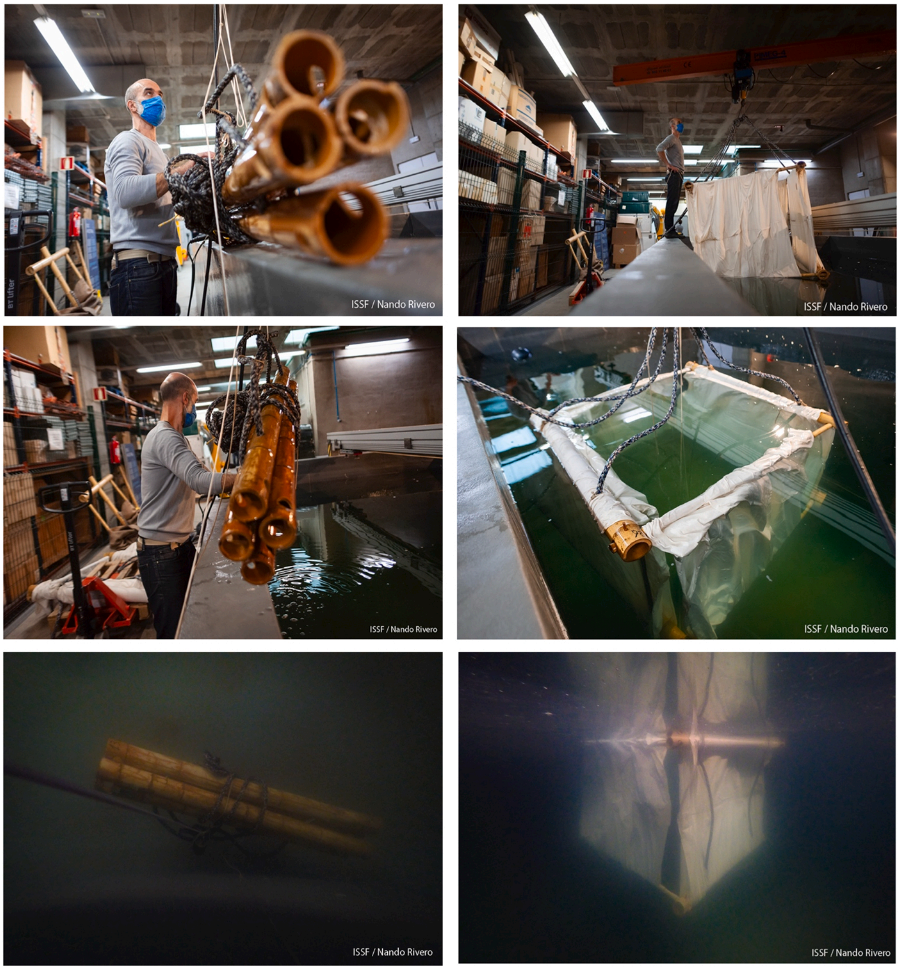
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Fig. 3. Sequence illustrating assessment process of the organic materials' density changes (bamboo canes, rope and cotton fabric and cubic structure) during two months in a lab seawater tank located at the Institut de Ciències del Mar in Barcelona.

20 mm diameter cotton rope, we would add a submerged 5–7 kg plastic buoy to counterbalance the weight of the cotton rope. For the plastic buoys at the surface, it was estimated that a maximum of 25 kg flotation was necessary, depending on the meters and type of rope used. Plastic buoys were the only component of the jelly-FAD that were not made of organic, plant-based origin.

The three-dimensional design of the jelly-FAD optimizes the drag by the slow-deep currents without any extra submerged surfaces and their associated weight (only the temporary weight to make the drogue sink). Specifically, the required flotation is reduced by over 6 times, e.g., from 150 kg flotation (with sometimes up to 25 plastic containers) in a conventional dFAD to a maximum of 25 kg in the jelly-FAD.

The authors now are testing the lifetime of the jelly-FAD in semi-controlled conditions in the Mediterranean Sea. The Mediterranean Sea was selected due to the lack of fleets fishing with dFADs. The idea is to monitor the jelly-FADs' structural integrity over time, without interference from the tuna fleets, for different weight and buoyancy configurations. Ten jelly-FADs were deployed in the Gulf of Lion in early February 2021, and by the end of August 2021 (7 months later) four of them were still working. We visited one of them, which was in a very good condition, and the drogue was working properly. It was not possible to know more about the remaining jelly-FADs at sea, as they were stranded or stolen. New trials started in May 2022 with an improved version of the Jelly-FAD in which the need for flotation was further reduced.

3.3. The shade effect

From fishers' perspective, floating objects must provide shade to attract fish. In this concept of "shade effect," fishers mean not only the shade provided by the structure itself but also the shelter the structure provides to the associated species. This shading component of the conventional dFAD is usually the raft, which is on the sea surface. The drag forces (winds, waves and surface currents) that affect the surface components of the dFADs (e.g., flotation buoys, raft and geolocating tracker) will depend on the dFADs' raft shape and area [49]. The larger the emerged raft and flotation structure, the higher the influence of wind and waves on the dFADs. To avoid the structural stress created by the wind and wave drag forces, the raft should be designed to have the minimum possible drag coefficient and the smallest emerged area out of the sea surface. Thus, we have used a flat 2D-shaped raft to create the shade effect below the surface, at around 5–7 m depth, with only the buoy floating on the surface.

4. Ongoing research at sea with the jelly-FAD

Several field tests of jelly-FADs during regular fishing trips have been performed in the Atlantic and Pacific Oceans. The size and weight of dFAD structures are larger in these two oceans, so the overall impact of transitioning to the jelly-FAD could be very important. On the other hand, a large-scale bio-FAD deployment project took place in the Indian Ocean [21]. Thus, we prioritized the Atlantic and Pacific Oceans for the tests, as shown in Table 1. Additionally, captains and shipowners from other fleets have started testing the jelly-FADs on their own initiative, but these projects are not included in Table 1. In these projects, jelly-FADs and conventional dFADs were deployed together to compare their performance parameters (speed, trajectory and biomass aggregated) under similar environmental conditions (spatial and temporal strata, tuna presence and oceanographic conditions).

Table 1
Current and planned initiatives to test jelly-FADs.

Ocean/ Region	Fleet	# jelly-FAD tested	Materials used	Depth of the cube (drogue)	Preliminary results	Funds
Western Pacific	Caroline Fisheries Corporation (CFC) (6 vessels)	*First trial*: 29 jelly-FADs and 44 conventional design made of organic materials. *Second trial*: 27 jelly-FADs	*First trial*:Rope: Manila hemp Canvas: jute *Second trial*:Rope: cottonCanvas: jute	60 m	SeeSection 4.1	-ISSF-FAO common oceans Tuna project -CFC
Eastern Pacific	Ugavi(5 vessels)	500 Jelly-FADs and a continued effort with a regular 20% of Jelly-FAD deployments of their total dFADs	Rope: cottonCanvas: cotton	50 m	SeeSection 4.1	Ugavi fleet
Eastern Pacific	Nirsa(14 vessels)	100 Jelly-FADs to start and a continued effort with a regular 20% Jelly-FAD deployment of their total dFADs	Rope: cottonCanvas: cotton	50 m	Currently in construction phase; trials to be started in 2022	Nirsa fleet
Eastern and Western Pacific	U.S. fleets from American Tuna Boat Association (12 vessels)	216 jelly-FADs	Rope: cottonCanvas: cotton	50 m	Currently in construction phase; trials to be started in October 2022	-NOAA- Bycatch Reduction Engineering Program -Fleets – ISSF and Satlink
Western Pacific	Diverse fleets to be determined	350 jelly-FADs	Rope: cottonCanvas: cotton	To be determined	Trials will start in 2023	EU-US-ISSF
Atlantic	Ghanaian purse seine & pole and line fleets	130 bio-FADs: 35 jelly-FADs and 95 of conventional design made of organic materials.	Rope: cotton Canvas: cotton	60 m	Few visits due to the loss of bio-FADs mainly because they drifted out of the fishing zone. Paired synthetic dFADs deployed simultaneously also drifted out of the fishing zone. In order to get results on their performance, echosounder buoy trajectories and biomass will be analyzed.	ISSF-FAO common oceans Tuna project
Atlantic	Pevasa (3 vessels)	200 jelly-FADs	Rope: cottonCanvas: cotton	60 m	Currently in deployment phase; data to be collected during 2022-2023	ISSF Pevasa
Atlantic	Opagac (18 vessels)	350 jelly-FADs	Rope: cotton Canvas: cotton	60 m	Up to date 90 Jelly-FADs were deployed with 10 being visited. Jelly-FAD deployments will continue during 2022.	Opagac-Secretaría General de Pesca-Fondos Next Generation

4.1. Preliminary results from ongoing experiences at sea

4.1.1. Trials by the Caroline Fisheries Corporation fleet in the western Pacific Ocean

During the Western Pacific program, 73 bio-FADs were deployed: 44 were the biodegradable version of the conventional dFAD (type A), and 29 were jelly-FADs (type B: same design as in Fig. 2, but with the raft on sea surface as in conventional dFADs). Close to these experimental bio-FADs, 50 conventional dFADs were also deployed (not every bio-FAD had a nearby conventional dFAD) (Fig. 4). Two catches were reported among the 123 dFADs (biodegradable and conventional) deployed during the trials. Both catches were made on biodegradable dFADs, one set of 95 tons on a jelly-FAD (type B) and one set of 35 tons on a bio-FAD with a conventional design (type A), 43 and 20 days after deployment, respectively. No catches were reported on conventional dFADs during the experiments. The low number of visits and catches does not allow for a more comprehensive analysis of the possible differences in catches between biodegradable and conventional dFADs. Most of the experimental dFADs drifted out of the primary fishing ground or were appropriated by other vessels.

To compensate for infrequent visits to the experimental FADs, we used biomass and trajectory data recorded by satellite linked echosounder buoys from Satlink manufacturers, which fishers use to track dFADs. The methodology for working with biomass estimates from the echosounder buoys is described by Orue et al., 2019, Santiago et al., 2020, and Uranga et al., 2021, [50–52].

There was not a clear difference in tuna aggregation patterns between biodegradable and conventional dFADs based on echosounder buoy data. An increasing aggregation pattern was observed for both the biodegradable and conventional dFAD mainly during the first month. The first three months showed similar increasing trends for the two types of dFADs, with a similar pattern, but later the biomass estimations became more variable (Fig. 5). Similar results were observed in the Indian Ocean bio-FAD trials, where biomass estimation resulted in slightly constant values for both dFAD types during the first months after deployment (biodegradable and conventional), with more variable estimates between dFAD pairs after months five or six [21].

Table 2 shows the maximum and mean values of observed speed in the deployed dFADs. The jelly-FAD (type B) showed the smallest maximum velocity, followed by the bio-FAD type A. These data show that both types of bio-FADs have average drift speeds similar to a conventional dFAD. Even more important, the maximum velocities in the bio-FAD are lower than in conventional dFADs, with the jelly-FAD (Type B) displaying the lowest values.

4.2. Trials´ effectiveness during fishing operations

Most tests of bio-FADs so far have deployed a limited number of experimental units per fleet relative to the number of conventional plastic-based dFADs. Due to the very high incidence of dFAD losses and abandonments (i.e., change of hands, sinking, beaching or out-of-fishing area deactivations), bio-FAD trials under real fishing conditions require the deployment of many units continuously over time so that statistically robust and significant results can be obtained.

From the Ugavi fleet´s experience, the fleet that has deployed the most jellyFADs to date, we have learned that the first 150 jelly-FAD deployments did not provide meaningful results due to data scarcity. The initial prototypes were visited less often than conventional units because:

(i) Fishers need time to understand how a substantially different dFAD design like the jelly-FAD operates, both in terms of flotation and weight assessment as well as in their construction and deployment operations. Until fishers learned how to fine-tune jelly-FADs to their working conditions, initial prototypes sank more frequently or worked sub-optimally.
(ii) Fishers rarely visit jelly-FADs during an initial adoption phase due to lack of confidence about their performance, instead prioritizing visits to conventional dFADs.
(iii) Finally, as is common in dFAD fisheries, many jelly-FADs were stolen or drifted out of the fishing zone.

The initial experimental deployments gave fishers a chance to learn from jelly-FAD building and deployments, in particular to gain experience on weight and flotation assessment. If trials had been discontinued after the first phase, fishers would have not been able to test the performance potential of jelly-FADs. This initial phase may be best considered as a preliminary familiarization process, with the second phase as the real test of jelly-FADs' fishing performance, once the structure had been successfully constructed and deployed. In the case of Ugavi, shipowner support to continue deployment trials of jelly-FADs throughout the whole year of 2021 was critical. The results of this continued effort were:

(i) Fishers learned how to properly construct and use jelly-FAD structures, including the deployment operation from the vessel.
(ii) Well-constructed jelly-FADs started working properly and aggregating tuna, hence allowing the vessels to increase visits and catches.
(iii) More visits are related to the presence of aggregated tuna, and the increased visit rate represented an acceleration of the learning process on their performance.
(iv) Fisher confidence in the performance of jelly-FADs grew.

5. Recommendations for jelly-FAD construction and tests

5.1. Bio-FAD construction

- Only dFADs constructed without netting can totally eliminate the risk of entanglement for turtles, sharks and finfish species. New

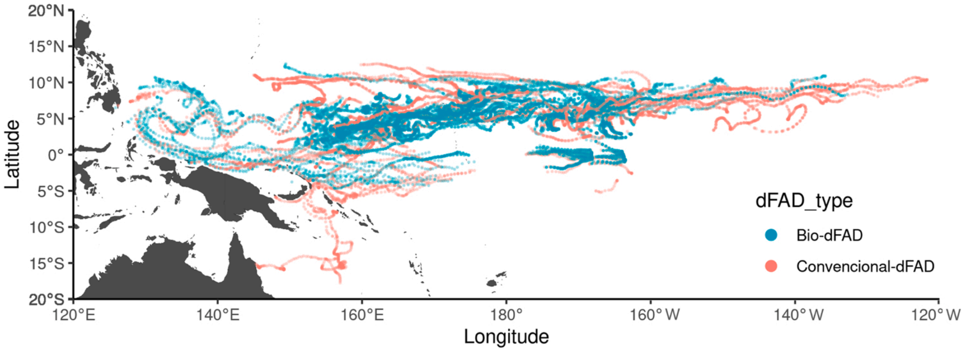

Fig. 4. Trajectories of the 123 experimental dFADs deployed by CFC. Conventional, synthetic FADs are in red and bio-FADs (both type A and B) are in green.

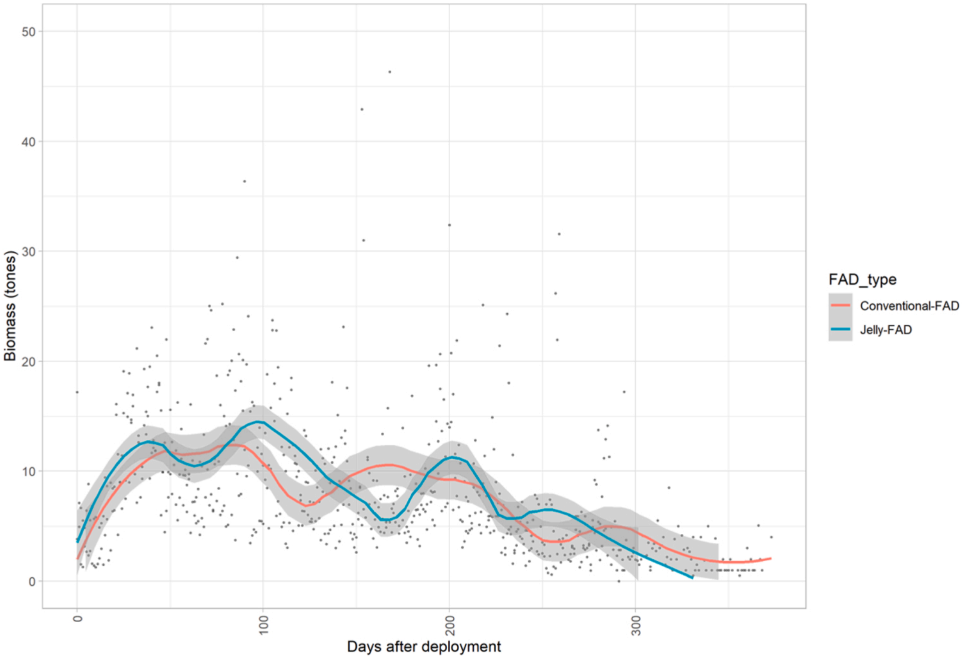

Fig. 5. Biomass in tons (Y axis) for soaking time (days at sea). Conventional, synthetic FADs are in green and bio-FADs (both type A and B) are in red.

Table 2
Observed drift speeds (m s^{-1}), by type of dFAD as measured by the buoy used to track FADs.

FAD type	Design	Number registers	Speed (max)	Speed (mean)
BIO	Type A	149	3	0.7
BIO	Type B	449	2.3	0.7
CON	Type A	265	3.7	0.7

biodegradable materials should not be configured in a net format; instead, they should be used in other formats, such as ropes or canvas.

- To reduce structural stress on a dFAD, which will lengthen the lifetime of biodegradable materials in dFADs, an innovative bio-FAD concept called the "jelly-FAD" is recommended. Interested industry partners should contact the authors for details on designing a suitable jelly-FAD for their region and conditions.
- Bio-dFADs should be made of 100% organic materials except for flotation components; an alternative to plastic buoys needs to be found. The organic materials should be sustainably harvested and preferably sourced locally or regionally, and any byproducts of their degradation must be non-toxic for the marine environment.
- For dFADs to drift slowly, the drogue should be three-dimensional and symmetrical, and "anchored" at a depth below the surface mixed layer (where the direct effect of winds and waves is negligible).
- The physical impact of dFAD structures on the ecosystem is proportional to their size and weight. Current dFAD structures are very large and bulky, which complicates the logistics of their retrieval and deck storage. Research to reduce the mass (i.e., size, volume and weight) of conventional and biodegradable dFAD structures is necessary. The jelly-FAD, though, is smaller in size than conventional dFADs, and offers an additional benefit of lower material cost per dFAD.
- The correct assessment of the flotation and weight distribution in a dFAD design is a crucial factor in extending its working lifetime — especially for bio-FADs, as organic materials are less resistant to physical stress. If those parameters are not well calculated before the FAD is built, the tension and torsion experienced by the structure will result in substantial damage, and the submerged appendage will more likely break away from the raft, reducing the dFAD's aggregation effectiveness and lifetime.

5.2. *Bio-FAD tests*

- Fishers, supported by shipowners, should start trialing jelly-FADs as a continuous sustained effort, deploying systematically a percentage of their dFADs with the jelly-FAD design. A large number of jelly-FADs at sea would increase vessel visits and accelerate the empirical learning process. This in turn would reinforce fishers' confidence in the performance of jelly-FADs.
- Those trials should ideally be performed with the participation of scientists, following sound experimental protocols to adequately analyze the statistical data and in which equal numbers of jelly-FADs and conventional dFADs are tested for comparison. Multiple fleets sharing their experiences with jelly-FADs would accelerate scientific knowledge and design improvements.
- Replacement of jelly-FAD components: The cube, if damaged after a set, could be replaced by a new cube or drogue that fishers can have ready onboard to re-deploy the jelly-FAD, in the same way they replace damaged rafts or submerged components in conventional dFADs to increase their lifetime. To this end, fishers should plan for the construction and provision of additional cubes to replace the old ones.
- In the early jelly-FAD trial phases, the lack of vesseĺs visits and performance data constrained the learning process necessary for prototype improvement. The only way to overcome this situation is:

o *Patience*: Fishers and shipowners need to understand that prototypes rarely work efficiently the first time they are trialed, either because of faulty design elements or limited operational experience.
o *Constructive visits*: Part of the success in developing this new biodegradable dFAD relies on learning from vesseĺs visits, which allow for examining jelly-FADs, identifying weak points, noting where they failed, and informing the fishing company and scientists on how to improve the design.
o *Perseverance*: As pointed out before, a continued effort is needed to overcome the initial difficulties and the reluctance to change that is

common at the beginning of trials, until more positive results are achieved.

- Scientists and shipowners should seek the support of collaborative fishers, who have a good reputation among colleagues and are respected for their fishing skills and knowledge, to start trialing the jelly-FADs. Each fleet has its "influencers," whose innovations, tactics, and procedures are adopted by other fishers (Jenkins 2010). Convincing influencers to transition to bio-FADs should be a priority.

6. Final remarks

The preliminary results show that the jelly-FAD is capable of aggregating commercial quantities of tuna and that its operational lifetime can reach over 6 months. A six-month dFAD lifespan is adequate for fishing purposes, as fishers rarely operate with dFADs older than that because most would likely have been out of the fishing ground, stolen or sunk. The cost of a jelly-FAD depends on the depth of the structure and the quality of its materials. Although biodegradable materials are more expensive than synthetic plastic ones, the cost of jelly-FADs (e.g., between $180-$300 U.S. dollars each depending on type and quantity of biodegradable materials) is very similar to that of conventional plastic dFADs because jelly-FADs require less material. In some cases, jelly-FADs are even cheaper than the conventional dFADs some fleets employ, which can cost $600 without the geolocating buoy. The fact that jelly-FAD costs will be similar or lower than conventional dFAD costs should encourage a smoother industry transition to bio-FADs. After gaining fishers' feedback from various initiatives, researchers in this study will work on improving the jelly-FAD to further reduce its weight and the amount of plastic buoys needed for flotation. An improved jelly-FAD will be tested soon by several fleets working under demanding commercial fishing conditions.

The collaboration with physical oceanographers has further advanced dFAD research, as a worldwide standardized jelly-FAD design could be used to sample the surface currents in the same way standard oceanographic drifters do [53]. Imzilen et al. (2018) [54] carried out an exhaustive study in the South Atlantic and Indian Oceans and found that FADs have similar behavior as standard oceanographic drifters.

Conventional dFADs can remain at sea for long periods of time, mainly due to the long-lasting material used in their construction, and be reused if fishers find them at sea. However, a high percentage of dFADs drift out of the fishing zone, contributing to marine pollution and other potential harmful impacts on the ecosystem. The jelly-FAD design would significantly reduce fishing's impact on vulnerable ecosystems such as coral reefs and other coastal ecosystems compared to a conventional dFAD design that uses a large tail of nylon netting, which will remain in the coral reef indefinitely. In addition, now that tuna RFMOs require each vessel has a limited number of FAD tracking buoys active at sea (to control the number of dFADs), it is more likely that vessels will deactivate the buoy transmissions when the dFAD moves out of their fishing areas, replacing them with new dFADs within the fishing ground and thus increasing the number and impact of abandoned dFADs. One potential operational implication of bio-FADs' limited lifespan is that when they remain within the fishing zone, they may not be as reusable as conventional ones are now. This would imply a change in dFAD fishing strategy, especially in areas where both purse seiner density and the degree of dFAD exchanges among vessels are high, as in the Indian Ocean [55], and for fleets that deploy a low number of dFADs but rely opportunistically on other vessels' dFADs, as is the case in some fleet segments in the Eastern Pacific Ocean (Lennert-Coddy et al., 2019) [56].

In this research we have presented the jelly-FAD concept. The jelly-FAD is less a fixed design than a change in the concept of conventional dFAD construction that has persisted in tropical tuna purse-seine and pole-and-line fisheries over the last 40 years. Until now, more weight and many flotation components meant a better dFAD performance, but in return the device endured a high structural stress. The jelly-FAD concept has shifted the paradigm toward a lighter, neutrally buoyant dFAD: the reduction of weight and flotation guarantees a better performance and longer lifespan than conventional dFAD designs made of biodegradable materials.

We have explained the basic concepts on the organic materials to be used to ensure neutral buoyancy and on the 3D design at the deepest portion of the structure that can create a slow drift. This change of paradigm allows fishers to work with biodegradable materials that otherwise would quickly break in conventional dFAD designs, well before the minimum working lifetime requirements. As experiments progress, the jelly-FAD structure will probably evolve in the hands of fishers — maintaining the key physical oceanography concepts on flotation and drag, but changing the shape of the drogue or raft used for fish attraction. The jelly-FAD concept represents a significant step forward in the use of smaller and more efficient bio-FADs with a much reduced impact on the ecosystem.

CRediT authorship contribution statement

Gala Moreno, Joaquín Salvador, Jefferson Murua, Josep Lluís Pelegrí: Conceptualization. **Iker Zudaire, Jon Uranga, Maitane Grande**: Data curation. **Iker Zudaire, Jon Uranga, Maitane Grande, Joaquín Salvador, Gala Moreno**: Data analysis. **Joaquín Salvador, Gala Moreno**: Field work / data collection. **Gala Moreno, Josu Santiago, Victor Restrepo**: Funding acquisition. **Joaquín Salvador, Gala Moreno**: Methodology. **Gala Moreno**: Writing – original draft. **Gala Moreno, Joaquín Salvador, Iker Zudaire, Hilario Murua, Jon Uranga, Maitane Grande, Jefferson Murua, Josep Lluís Pelegrí, Victor Restrepo, Josu Santiago**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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