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Benefits, concerns, and solutions of fishing for tunas with drifting fish aggregation devices

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Abstract
Drifting fish aggregating devices (dFADs) are human-made floating objects widely used by tropical tuna purse seine (PS) fisheries to increase catch of target species. However, dFAD use has several negative impacts, including increased potential for overfishing, higher juvenile tuna catch, higher bycatch compared to other PS fishing modes, ghost-fishing, and generation of marine litter. Based on these impacts, some stakeholders, especially environmental non-governmental organizations and other competing fishing industries, suggest that dFADs should be completely banned. We list the pros and cons of dFAD fishing; address how to improve current management; and suggest solutions for the sustainability of dFAD fishing in the long term. A dFAD ban would lead to major changes in the availability and sourcing of tuna for human consumption and decrease the licensing revenue received by many developing states. Most importantly, we argue that tools exist today to manage for, reduce or eliminate most of the negative impacts of dFADs (e.g., bans on discards, limits on active dFADs, biodegradable non-entangling constructions, time-area deployment closures, recovery programs, and full data transparency, among others). Management decisions based on sound scientific reasoning are needed to address the legitimate concerns surrounding dFAD use and ensure the sustainability of both pelagic and coastal ecosystems and tropical tuna PS fisheries.

KEYWORDS
ecosystem impact, FAD, fisheries management, marine conservation, purse seine, tropical tunas

1 | INTRODUCTION

Fish aggregating devices (FADs) are human-made drifting or anchored structures that aggregate pelagic fish, making them easier to find and catch. Fishers have known for centuries that fish aggregate around naturally occurring floating objects such as logs or large animals and have taken advantage of this effect to harvest fish aggregations more easily (Castro et al., 2002; Freon & Dagorn, 2000). This has led fishers to purposely construct and deploy artificial objects in the ocean to facilitate fishing. Though this fishing strategy has been commonplace in many fisheries since the 1980s (Freon & Dagorn, 2000), there has been an explosion in the use of human-made drifting fish aggregating devices (dFADs, Figure 1) in tropical tuna purse seine (PS) fisheries (Fonteneau et al., 2013; Maufroy et al., 2017) since the advent of low-cost satellite-transmitting tracking buoys in the late 1990s/early 2000s. When attached to dFADs, these devices allow fishers to remotely follow dFADs in real time and identify the presence and approximate biomass of fish associated with each dFAD (Lopez et al., 2014). Today, for example, an average of 20,000–40,000 dFADs are deployed each year in the Western and Central Pacific Ocean (WCPO), the largest tuna fishery in the world (Escalle, Hare, Vidal, et al., 2021), and around 16,000 to 25,000 in the Eastern Pacific Ocean (EPO) (Lopez et al., 2021). The technological devices mentioned above reduce searching time compared to free-swimming schools (FSC) (i.e., not associated with floating objects) (Lopez et al., 2014). In addition, dFAD sets have a much higher fishing success rate compared to other PS sets. For example, in the 2003–2015 period, the European PS fleet reported that 96% and 94% of the dFAD sets, in the Atlantic Ocean (AO) and Indian Ocean (IO), respectively, resulted in at least one ton of tuna catch (called positive sets). On the other hand, only 80% and 58% of the sets on FSC, respectively, resulted in positive sets of tuna catch (Escalle, Gaertner, et al., 2019). Due to these advantages, over the past 2–3 decades, dFAD fishing has dominated other major PS fishing modes, such as fishing on FSC and dolphin-associated tuna schools (or dolphin-sets, DS; in the EPO only). Today, 66% of the global total tuna catch comes from purse seining and 37% of the tropical tuna PS sets are associated with floating objects (dFADs and to a lesser extent natural floating objects or anchored FADs—aFADs), 27% on FSC and 3% are DS (ISSF, 2022). The main species caught in dFADs sets (around 71% by weight, Table S1) is the skipjack tuna (*Katsuwonus pelamis*, Scombridae). The PS industry is increasingly dependent on dFADs, challenging fisheries management by region and at a global scale.

Tuna fisheries, including the use of dFADs, are regulated and managed by tuna regional fisheries management organizations (tRFMOs). Four of five tRMFOs manage tropical tuna fisheries worldwide, one for each large ocean basin: the Western and Central Pacific Fisheries Commission (WCPFC) in the WCPO, the Inter American Tropical Tuna Commission (IATTC) in the EPO, the Indian Ocean Tuna Commission (IOTC) in the IO, and the International Commission for the Conservation of Atlantic Tunas (ICCAT) in the AO. Management measures implemented by tRFMOs related to dFADs have long focused on concerns related to growth overfishing of target species due to the higher catch of juvenile yellowfin (*Thunnus albacares*, Scombridae) and bigeye (*Thunnus obsesus*, Scombridae) tunas and higher incidental catch of other species on dFAD sets compared to FSC sets (Dagorn et al., 2013).

Most tropical tunas are managed at sustainable levels in all regions. According to the last stock assessments, skipjack tuna is in a healthy state (not experiencing overfishing and not overfished) in all tRFMOs management areas, while yellowfin and bigeye tunas are overfished and experiencing overfishing in the IO. In the AO and EPO, bigeye tuna are very close to the fishing mortality target reference

FIGURE 1 (a) Underwater view of an old traditional highly entangling dFAD (mesh size above 2.5 cm) currently prohibited by all tRFMOs (© FADIO/IRD/Ifremer/Marc Taquet and zoom in image on the top right from Murua et al., 2017). (b) example of a more recent low entangling dFAD design (mesh size below 2.5 cm) that PS vessels are mandated to use in AO, WCPFC and EPO, in IOTC the use of netting is forbidden and in WCPO will be from 2024 on (© ISSF). (c) example of a fully non-entangling dFAD (no netting of mesh material in any of the components) required in the IO and in the WCPO from 2024 on (© Ugavi).

points and yellowfin stocks are in a healthy state (ISSF, 2023). All tuna stocks are managed under some type of effort controls (i.e., spatio-temporal closures, limits in the number of fishing days, limits on the number of active dFADs, among others) but only bigeye and yellowfin in the AO and skipjack and yellowfin in the IO have annual catch limits (ISSF, 2023).

Publicly available data on catch by set type is aggregated differently among tRFMOs, but it can be roughly grouped into associated (i.e., sets on dFADs, aFADs, whale sharks, and other floating objects), unassociated (FSC), and, in the case of the EPO, DS. Before the 1970s, catch on floating objects was minor, generally less than 2% of the total catch, predominantly from the EPO (Figure 2). Some catches also came from the AO, but catch by set type are not available for this region prior to 1991. In the last ten years (2010–2020), associated catches (including mostly dFAD and aFAD) accounted for 52% and 45% of the PS total catch in the EPO and WCPO respectively, compared to 75% and 84% in the AO and IO (Figure 2).

While floating objects can be of natural origin (e.g., driftwood) all recent data indicates that the vast majority (>85%) of floating objects that are fished in the world's oceans are human-made dFADs (Dupaix et al., 2021; FAO, 2021; Maufroy et al., 2017). These objects therefore represent a new, artificial, additional element to the pelagic ecosystem that must be managed with care to limit or eliminate a number of potential negative environmental impacts. These, in conjunction with higher catch of juvenile tunas and incidental catch of other species compared to other fishing methods, have motivated several calls from non-governmental organizations (NGOs), some stakeholders and fishing industries that do not use dFADs to eliminate or severely limit their use. However, an evaluation of such a ban, considering pros and cons of using dFADs, is lacking.

The objectives of this article are therefore to present in detail both the benefits (Section 2) and concerns of dFAD use (Section 3), investigate the impact of a dFAD ban on worldwide tuna supply and present several other solutions to the known negative impacts dFAD use has on ecosystems. We compare PS fishing with dFADs to other PS fishing modes, as well as compare dFAD fishing to other fishing gear, such as longline, trolling, and pole-and-line (also referred to as "bait boat" fishing or abbreviated "BB" due to the use of live bait by pole-and-line fisheries). In particular, we demonstrate that though dFADs have a number of detrimental effects, banning dFADs would result in considerable perturbations to PS fisheries and likely reduce overall tuna catch. An expansion of other non-dFAD fishing methods (e.g., FSC or BB replacing dFADs) seems unlikely (see Section 4 on consequences of banning dFADs), and alternatives to a full dFAD ban already exist for addressing the negative impacts of dFADs (see Section 5 on management solutions).

2 | BENEFITS OF FISHING WITH dFADS

2.1 | Efficient fishing method to catch tunas

dFAD usage in tropical tuna PS fisheries dates to at least the 1990s and has increased over time (Dagorn et al., 2013; Maufroy et al., 2017). This increased use is highly suggestive of increased fishing efficiency with dFADs, and it has recently been shown that just the introduction of echosounder buoys after ~2011 has increased catch per dFAD set by 10% (Maufroy et al., 2017; Wain et al., 2021). The benefits of dFAD fishing have been ascribed to a number of factors: (i) reduction of searching times; (ii) remote identification of promising fishing areas; (iii) a reduction in the number of null sets (i.e., sets where the vessel is not successful in encircling the fish school); (iv) improved job security via more stable catches; and (v) an increase in overall landings (e.g., Wain et al., 2021). Floating object PS fishing is about 1.35–3 times more productive (in metric tons (mt) per set, including null sets) than FSC fishing in terms of total catch

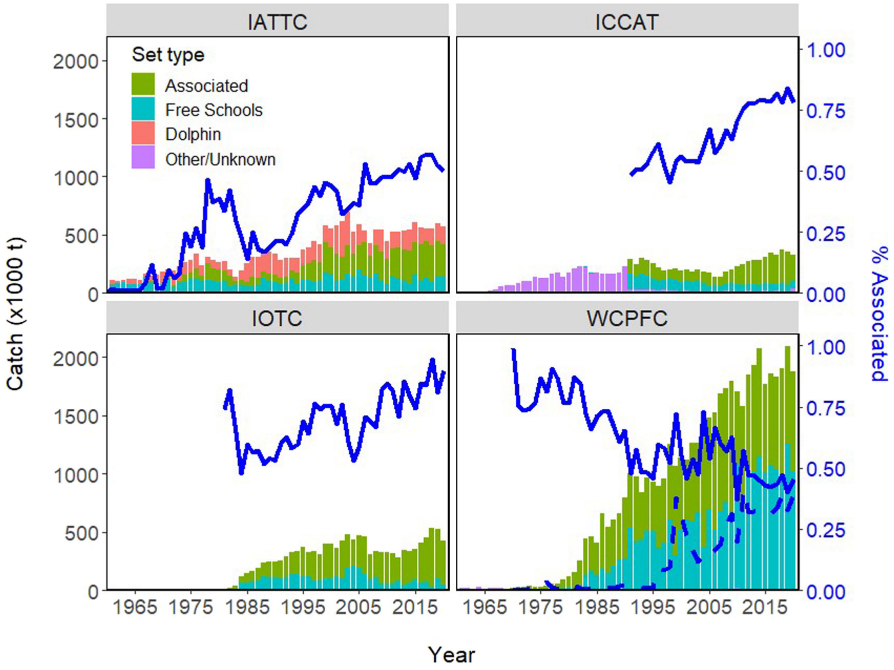

FIGURE 2 Global PS catches of skipjack, yellowfin and bigeye tunas (thousands of mt) by fishing mode, year and tRFMO. Solid blue line represents the percentage of associated catches over the total. In particular, for the WCPFC, the percentage of dFAD catches is represented by the dashed blue line. *Source*: tRFMO public domain data. Data by set type have been raised to total catches. Associated = dFAD + aFAD + logs + others (debris, dead animals, etc), as reported by tRFMOs.

of tropical tunas (i.e., yellowfin, bigeye, and skipjack combined) and about two to seven times more productive for skipjack tuna, the principal target species of dFAD fishing (Scott & Lopez, 2014).

2.2 | Contribution to food security and employment

Increased fish production via the high fishing efficiency of dFADs described above increases access to protein in many parts of the world and plays an important role in food security and subsistence (Galland et al., 2016). The PS fishery also contributes revenue to developing states via fishing license fees (Robinson et al., 2010). This is particularly the case in the WCPO, where PS fishing zones are mostly located in the Exclusive Economic Zones (EEZs) of small Pacific Island countries and territories where fishing license fees provide up to 98% of government revenues (Conservation International, 2022). Additional employment opportunities and other economic returns from the tuna industry come from the processing sector, port facilities, landing sites and canneries (Barclay & Cartwright, 2007). For example, in the WCPO, total employment related to tuna fisheries for the Pacific Islands Forum Fisheries Agency members for 2021 was estimated at 27,442 people, 42% more than in 2015 (FFA, 2022). The onshore processing sector accounts for 60%–70% of all employment, and observers and the public sector contributes to around 3% and 5%, respectively.

In some oceans, dFADs make available to PS a large amount of skipjack tuna, a food resource that would largely be inaccessible in the absence of floating objects (Marsac et al., 2000). Approximately 71% by weight of dFAD catch is composed of skipjack tuna (Table S1). In the IO and AO, catching skipjack in FSC is rare and the vast majority of PS skipjack catch comes from schools targeted around floating objects (see Section 4 for more details). The limited FSC catch of skipjack in the AO and IO may be due to the high density of dFADs in these oceans (Dupaix et al., 2022), though the decline in AO FSC skipjack catch appears to have begun a decade before the explosion in dFAD use starting in the mid-2000s (Figure 2). The IO skipjack catch has been dominated by floating objects since the beginning of the European fishery in the early 1980s and the number of dFADs in the WCPO is by no means small (Escalle, Hare, Vidal, et al., 2021), making a simple, direct link between dFAD use and declines in FSC skipjack catch improbable.

Bell et al. (2019) estimated the recent contribution of canned products to fish supply in the Pacific Islands, with an average of 53% of the canned fish consumption in Fiji and 92% in Solomon Islands corresponding to canned tuna. They suggested that increasing the market share of locally canned tuna by helping national canneries to obtain more tuna supplies to compete effectively in both domestic and international canned fish trade could increase employment and contribute directly and indirectly to local food security.

2.3 | Less bycatch than other non-PS fishing modes

Bycatch to catch ratios in PS fisheries are low (<10% overall by weight) (Amandè et al., 2010; Kaplan et al., 2014) compared with other fishing methods such as trawl fisheries (e.g., trawl fisheries for shrimp and demersal finfish account for over 50% of total estimated discards, Kelleher, 2005). For sea turtles, Wallace et al. (2013) found that gillnet and trawl fisheries are the fisheries that have the highest impacts on sea turtle populations worldwide. Even though, bycatch from PS sets using dFADs include some sensitive and charismatic species, such as sea turtles and sharks (Fonteneau et al., 2015), incidental mortality of sea turtles is low, with more than 90% of them being released alive (Bourjea et al., 2014; Restrepo et al., 2017). Mortality rates are higher for sharks in dFAD PS sets (e.g., Hutchinson et al., 2015 reported that it is more than 84% and Eddy et al., 2016 up to 91.5% for silky sharks, *Carcharhinus falciformis*, Carcharhinidae) compared to 3% in longline fisheries (Hutchinson et al., 2022). However, PS fishing is not, in general, the principal source of mortality for these sensitive species (Poisson, Filmalter, et al., 2014).

For manta rays (*Manta* spp., Myliobatidae, and *Mobula* spp., Mobulidae), Escalle, Gaertner, et al. (2019) reported that in the IO, manta ray bycatch was more frequent in FSC sets (8.6%) and whale and whale shark (*Rhiniodon typus*, Rhincodontidae) associated sets (6.7%), than in dFAD sets (1.8%). Nevertheless, mitigation measures to reduce incidental catch of threatened and endangered species still need to be considered in any PS fishery (see Section 5.7).

2.4 | Lower carbon footprint than other non-PS methods

A number of recent studies using different data sources and numerical methods concur that PS fishing for tropical tunas (including dFAD sets) has a lower fuel use intensity (i.e., the ratio of biomass caught to fuel consumed) and overall carbon footprint compared to other non-PS fishing methods and most terrestrial forms of meat production (Basurko et al., 2022; Chassot et al., 2021; Mckuin et al., 2021; Parker et al., 2015; Parker & Tyedmers, 2015). Parker and Tyedmers (2015) found that "surrounding nets" fishing methods (including fishing for both small and large pelagics) had the lowest fuel use intensity of all industrial fishing methods included in their analysis. However, these analyses also concur that PS fishing on dFADs has a higher fuel use intensity than PS fishing on FSC (Basurko et al., 2022; Chassot et al., 2021; Parker et al., 2015). The higher fuel consumption when using dFADs compared to FSC is likely explained by (i) the use of supply vessels (in some oceans); (ii) the larger vessel size (>80 m) of highly dFAD-dependent purse seiners; and (iii) the larger spatial extent of the dFAD fishery (Chassot et al., 2021). Overall, fishing for large pelagics (including a variety of non-PS gear types), had a carbon footprint per kilogram (kg) of catch comparable to that of pork, chicken and some forms of aquaculture; all of which are considerably lower than those of wild-caught crustaceans and beef production (Mckuin et al., 2021). In particular, Mckuin et al. (2021) found that, for skipjack catch, the climate forcing (which combines fuel use consumption and fuel-specific global warming potentials) with highly selective gears like trolling is as much as 12 times higher than the skipjack caught with the less selective gear such as PS, and PS skipjack climate forcing is lower than all terrestrial and other fishery food sources. Moreover, carbon emissions could be further reduced by the development of more efficient motors (e.g., electrical engines) and route-planning tools (Granado et al., 2021).

2.5 | Other potential benefits

Harvesting on dFADs diversifies the species composition of PS catch via catch of different tunas and tuna-like species, and the size composition of PS catch via catch of small to large skipjack tuna and juvenile yellowfin and bigeye tuna. It is therefore consistent with the balanced harvest hypothesis (Garcia et al., 2012, 2016). If this hypothesis is valid for tropical pelagic ecosystems, this could mitigate adverse effects better than increasing selectivity, as fishing on dFADs results in the capture of a wide range of species and sizes. However, something else to consider for this hypothesis to be valid is the balance on the removal of juveniles in PS fisheries compared to the removal of adults of yellowfin and bigeye tuna in other fisheries (i.e., longline, pole-and-line, etc.). However, new studies to test and valid this hypothesis are needed.

Another potential benefit of dFADs is their use as observatory platforms for scientific purposes. A single dFAD can remain at sea for months, sometimes even years, and can cover thousands of kilometres collecting acoustic data on fish and plankton biomass and oceanographic data. The spatial and temporal data that could be collected by dFADs therefore represent a fisheries-independent dataset in a pelagic ecosystem that no scientific program alone could achieve and with no extra cost. This new data source could complement traditional fisheries-dependent data in order to improve stock assessments for tunas, sharks, and billfishes.

3 | CONCERNS OF FISHING WITH dFADS

3.1 | High catch of juvenile yellowfin and bigeye tunas

dFADs in industrial PS fisheries are primarily aimed at increasing the catch of adult skipjack tuna. Although most of the skipjack caught on dFADs are mature (Table S3), the remaining dFAD catch is comprised primarily of yellowfin and bigeye tunas less than 10 kg in weight (Figure 3, Dagorn et al., 2013). Though all fishing gears have the potential to negatively impact non-target fish stocks, one of the main arguments for restricting dFAD usage is linked to the fact that the majority of yellowfin and bigeye tuna catch are immature individuals (Dagorn et al., 2013; Leroy et al., 2013).

dFAD juvenile catch is actually the source of two different but complementary concerns: one related to the biological sustainability of fisheries targeting juveniles and the other with respect to different fisheries competing for the same species (see next paragraph), potentially at different ages. With respect to biological sustainability, catch of individuals before they can reproduce is logically a considerable threat to population persistence and must be carefully assessed. The length-frequency distribution of dFAD catch can shift the overall fishery selectivity towards smaller sizes and may reduce yield per recruit and the maximum sustainable yield (MSY) (Leroy et al., 2013).

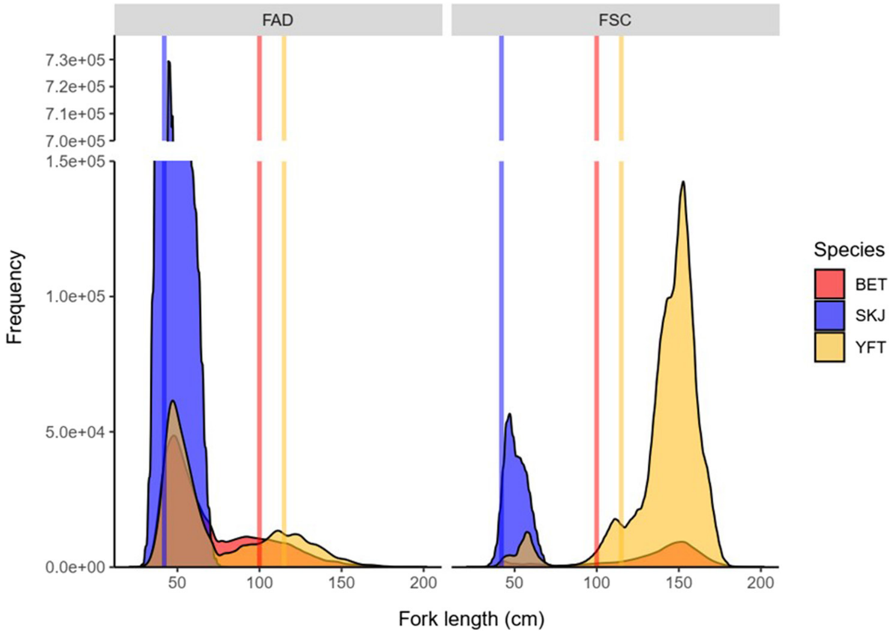

FIGURE 3 Frequency in weight of the catch at size by tropical tuna species (from ICCAT T2CS database) in the PS fishery in the Atlantic Ocean for the period 2010–2020. The vertical lines represent length at 50% maturity for each species. YFT: yellowfin tuna, length at maturity at 115 cm (ICCAT, 2019). BET: bigeye tuna, length at maturity at 100 cm (ICCAT, 2021c). SKJ: skipjack tuna, length at maturity at 42 cm (ICCAT, 2015).

Within tRFMOs, the debate surrounding dFAD juvenile catch is most often linked to the multi-species and multi-gear type nature of tropical tuna fisheries as biological sustainability is considered assured by standard stock assessment strategies that account for dFAD juvenile catch; particularly the trade-off between the benefits of dFADs for PS fishers and the impact of this activity on catch for other gear types. For example, longline fisheries targeting adult bigeye and yellowfin tuna often express concern that excessive catch of juveniles in dFAD sets could be limiting the recruitment of individuals to the longline fishery, and therefore often support restrictions on dFAD fishing. Similarly, pole-and-line fisheries often see the dFAD fishery as their natural competitor for skipjack catch and therefore generally oppose the use of dFADs (Purves et al., 2021). In this management context, finding an optimum balance in terms of yields or economic benefits across gear types and species can be extremely challenging, particularly when there is usually a conflict of interest among stakeholders and, more broadly, fishing fleets.

3.2 | Lack of reliable estimates of fishing effort

A persistent difficulty associated with assessing stocks fished using dFADs is the lack of reliable estimates of fishing effort and thus relative abundance indices. This increases the uncertainties in the assessment, particularly for skipjack stocks which are primarily caught by this fishing method (ISSF, 2012). Estimating effort from searching or fishing times or the numbers of dFAD sets is challenging since the number of dFADs and fishing efficiency have been increasing continuously over time due to the adoption of new technologies. For example, the very notion of "searching time" breaks down when dFAD tracking buoys incorporate echosounders allowing remote detection of fish schools. Failure to account for efficiency changes and therefore increases in catchability, resulting from powerful new searching tools, could strongly bias estimates of fleet fishing effort and the resulting estimates of stock status and productivity (ISSF, 2012; Wain et al., 2021). These difficulties increase when considering the lack of detailed historical data on the time of introduction and intensity of these innovations in the tuna PS fleets (Fonteneau et al., 2015; Gaertner, 2010).

3.3 | Higher bycatch rates of non-target species compared to FSC

Bycatch of non-target species is one of the main concerns of dFAD fishing due to the higher catch rate in comparison to other PS fishing methods, such as fishing on FSC (Gilman, 2011). For example, Amandè et al. (2010) found that bycatch to catch rates on dFAD sets (8.1 mt bycatch for every 100 mt of catch) is considerably greater than the bycatch rates fishing on FSC (2.8 mt bycatch for every 100 mt of catch) in the AO. Vulnerable species such as sea turtles, sharks (mainly the silky shark and oceanic whitetip (*Carcharhinus longimanus*, Carcharhinidae)) and billfishes (Amandè et al., 2010; Gaertner et al., 2002) are caught in higher proportion in dFAD sets compared to FSC sets. Amandè et al. (2010) reported that shark bycatch is 3 times higher than FSC per mt of target tunas in the AO. Hall and Roman (2013) reported that for the period 1995–2007 in the WCPO, turtle catch rates were two times higher for dFAD sets than for FSC sets although 75%–90% are released alive (Bourjea et al., 2014; Restrepo et al., 2017). Other bony fishes such as mahi-mahi (*Coryphaena hippurus*, Coryphaenidae), oceanic triggerfish (*Canthidermis maculate*, Balistidae), rainbow runner (*Elagatis bipinnulata*, Carangidae) (Forget et al., 2020), and wahoo (*Achanthocybium solandri*, Scombridae) (Torres-Irineo, Amandè, et al., 2014) have also been reported as common bycatch in dFAD sets although not all of these bony fishes are discarded. Amandè, Dewals, et al. (2017)

documented an important trade and utilization of these species that are retained and landed in Cote d'Ivoire by PS vessels (see Section 5.8.).

3.4 | Ghost fishing

Design, size, and materials used in dFAD construction vary between oceans and fleets, but often share common features. The majority of dFADs are composed of a surface raft and a submerged appendage (Figure 1). The raft, which is usually made of bamboo canes, plastic materials (i.e., bottle and containers), and/or corks, is covered by netting to increase structural integrity and to reduce visibility by other vessels (Lauriane Escalle et al., 2023). The submerged appendage has commonly been made of netting panels that reduce the drifting speed of the dFAD and produce shelter and shade for associated non-tuna finfish. dFAD structures are on average 25–50 m deep, but can reach up to 80–120 m depending on the ocean and fleet (Escalle, Brouwer, et al., 2017; Lopez et al., 2019). Early dFAD design included surplus netting from PS gear of large mesh size of 10–20 cm (4–8 inches) (Itano, 2007).

These large mesh netting panels used in traditional dFAD designs are known to cause incidental entanglements of marine megafauna, such as sharks and turtles, that exhibit an associative behaviour towards dFADs (Bourjea et al., 2014; Filmalter et al., 2013; Hall & Roman, 2013). Shark and turtle entanglements are considered to be hard to detect. Unless the dFAD is lifted out of the water or the entanglement occurs close enough to the surface to be seen, the incident may go undetected. Most captains do not lift dFADs out of the water when checking for fish or making a set (Murua et al., 2017). Observer's data show that the number of turtles entangled in traditional dFADs has been consistently low across oceans, but quantification of entanglements is difficult as these processes are only periodically observed over short time scales (fishers and thus observers, visit dFADs only a few times, whereas the dFAD itself may remain drifting in the open ocean from weeks to years). The only study to-date examining shark entanglement levels in dFADs through diving censuses combined with electronic tagging data, estimated that in 2010–2011, shark entanglement in traditional dFADs caused five to 10 times higher shark mortality than active PS fishing in the IO (Filmalter et al., 2013). Since then, all tRFMOs have required the use of low entanglement risk dFADs (see Section 5.9 for more details).

3.5 | Habitat perturbation/ecological trap

It has long been hypothesized that increased deployment of dFADs perturbs pelagic ecosystems in ways that could negatively impact tunas and other pelagic species (Marsac et al., 2000). Presumably, fish are programmed to gather around floating objects because they have historically derived some evolutionary benefit from this behaviour, and anthropogenic modifications to this can disrupt the link between environmental cues (e.g., presence of a floating object) and benefits so that the cues are no longer an indicator of favourable habitat. Natural floating objects, like logs, branches and algae, typically originate in river estuaries and coastal areas and thereafter follow ocean currents. These same ocean currents also bring nutrient-rich waters into the oligotrophic pelagic environment. Tuna species may therefore use the presence of a natural floating object as a cue of a nutrient-rich area ("indicator-log hypothesis"; Hall, 1992).

When misinterpretation of those cues is sustained over time and yet animals continue to follow the cues due to evolutionary programming, this represents an "ecological trap" that may have (negative) consequences for animals' growth, migration, reproduction, and survival (Battin, 2004; Schlaepfer et al., 2002; Swearer et al., 2021). Fishers do not deploy dFADs randomly, instead these are strategically seeded to match spatio-temporal patterns of tuna migrations and aggregations to maximize the opportunity of catching tunas. If dFADs drift into "poor habitat areas", the floating object "cue" is no longer associated with nutrient-rich areas, potentially creating an ecological trap. Support for this possibility comes from studies showing emptier stomachs and lower lipid concentrations (both consistent with poor feeding) in tunas found around floating objects than in FSC (Hallier & Gaertner, 2008; Jaquemet et al., 2011), though not all studies concur that this is evidence of an ecological trap (Robert et al., 2014).

For dFADs to act as ecological traps, various conditions need to be met and tested, first of which is the modification of the habitat by fishers. A number of studies have now shown that dFADs far outnumber natural floating objects over large areas and are regularly found outside of normal fishing areas (e.g., Dupaix et al., 2021; Imzilen et al., 2022; Maufroy et al., 2017), and therefore have clearly modified the network of natural floating objects.

The next condition to be tested is if the increased number of dFADs modifies the behaviour of tuna species at different spatial and temporal scales. At a fine-scale, working on aFAD arrays, Pérez et al. (2020) showed that when aFAD density increases, tuna visit more aFADs and exhibit longer residence times, increasing the total time spent in the aFAD array. However, there are no studies on the effect of dFADs on tuna behaviour in oceanic waters, and available scientific information are contradictory. Conventional tagging data in the AO revealed different migratory directional patterns between tuna recaptured near dFADs and those in FSC (Hallier & Gaertner, 2008), whereas electronic tagging in the EPO suggests that migrations of bigeye tuna are not influenced by dFADs (Schaefer et al., 2009; Schaefer & Fuller, 2010). A study of tuna behaviour at dFADs using local ecological knowledge found that a whole tuna aggregation abandons a dFAD when the dFAD's direction changes dramatically, suggesting that tunas can adapt to unfavourable conditions (Moreno et al., 2007). Overall, the lack of knowledge on what directly influences tunas to remain or leave a dFAD, combined with the challenges of disentangling the effect of the dFAD from that of the environment itself, makes it difficult to truly test the ecological trap hypothesis.

3.6 | Impact on the habitat of lost and abandoned dFADs/marine pollution/stranding

Studies show that a majority of dFADs eventually exit fishing grounds (Imzilen et al., 2022), and 7%–22% of deployed dFADs end up stranded in coastal areas, potentially harming coastal ecosystems (Escalle, Scutt Phillips, et al., 2019; Imzilen et al., 2021; Moreno et al., 2018). These impacts result from both unintentional dFAD loss and intentional dFAD abandonment. Unintentional dFAD loss may be due to the malfunction of the tracking buoy so that the fishers cannot know its position and thus cannot visit, fish, or retrieve it. Loss may also occur when dFADs sink due to insufficient flotation (e.g., as a result of fouling). Intentional dFAD abandonment can be caused by dFADs drifting off fishing grounds or fishers moving to other fishing areas (Imzilen et al., 2022). In these cases, fishers deliberately abandon the dFAD because the travelling cost of retrieving it is too high.

While dFADs are increasingly moving towards non-entangling and biodegradable designs, they can still cause ecosystem impacts. Currently, lost and abandoned dFADs are most often made of plastic (nylon nets, buoys and polypropylene ropes; Figure 1). In addition, dFADs are equipped with satellite-transmitting echosounder buoys, whose components include batteries, solar panels and other electronics. In the WCPO, it has been estimated that we do not know the final fate of ~80% of dFADs (Escalle, Scutt Phillips, et al., 2019), and there is no reason to believe the WCPO is an outlier. One of the difficulties encountered by scientists and managers trying to quantify dFAD stranding and sinking events is that once a dFAD has drifted away from the fishing zone, fishers deactivate the attached positioning buoy before it reaches coastal areas. This situation limits our ability to quantify dFAD stranding events and the impact of the thousands of dFADs that are lost and abandoned every year. Impacts caused by lost and abandoned dFADs include ghost fishing (see Section 3.4, Filmalter et al., 2013; Balderson & Martin, 2015), accumulation of plastic at sea, potential damage to coral reefs (Escalle et al., 2022; Macmillan et al., 2022) and interference with other economic activities such as tourism and aquaculture (Burt et al., 2020). The legal status of such loss or abandonment is still debated and the owner of a dFAD drifting at-sea or reaching coastal waters is difficult to determine; however, a recent paper considered that abandonment would constitute "dumping", a breach of Annex V of MARPOL (Churchill, 2021).

3.7 | Problems of ownership and tracking

Another concern associated with dFAD fishing is the question of their legality, given the lack of clarity around their ownership, behaviour, and use. Gomez et al. (2020) suggested that dFAD use could be considered Illegal, Unreported, and/or Unregulated (IUU) fishing in some areas or EEZs. As deployed dFADs are legally considered to be fishing until recovery (Hanich et al., 2019), Gomez et al. (2020) argue that when they drift into closed areas or contravene national or international agreements or regulations, they are essentially illegally fishing, as is the vessel that deployed them. This argument is the subject of debate, however, the assignment of ownership to deployed dFADs is non-trivial.

As mentioned before, fishers deploy dFADs with a satellite-transmitting GPS and echosounder-equipped buoy attached. dFADs remain drifting freely at sea until the owner, driven by the biomass estimates sent by the echosounder, decides to visit and/or fish on them. These buoys, owned and managed by fishers, are often used by scientists and tRFMOs as a dFAD identification system, but the use of the buoy identification code as a dFAD identification system does not allow the full monitoring of the trajectory of the dFAD structure itself. The main issues related to this identification system are:

- The swapping of buoys by fishers: while drifting at sea, dFADs may be encountered by other vessels. If sufficient biomass has accumulated at the dFAD, then any PS vessel that encounters it will set on it, whether or not it is the "owner" of the dFAD. Fishers encountering productive dFADs generally replace the original GPS buoy with their own, and the original vessel that constructed and deployed that dFAD loses communications with the buoy or follows the track of the buoy alone, without the dFAD. Moreover, many vessels use tools such as high-tech binoculars, bird radars, helicopters or supply vessels, to actively search and find other vessels' dFADs (Murua et al., 2020) This practice is commonplace worldwide (e.g., between 25% and 50% of the floating object sets by the French fleet in the IO are on objects deployed by other fishing vessel; Wain et al., 2021), with some tuna PS ports having specific zones where appropriated buoys are dropped off and can be recovered by the original owner.
- Fishers deactivate geolocating buoys once the dFAD drifts out of the fishing zone: this makes it almost impossible to know the fate of and track the dFAD until the end of its lifetime (see Section 3.6).
- The buoys identification code (visual mark) may be hard to record by observers if the buoy is not brought onboard the vessel and/or when the crew is not collaborative, preventing a complete accounting of fisher interactions with specific dFADs.

The prevalent practice of exchanging satellite buoys hinders the ability of scientists to follow the history of the dFAD from the deployment until the end of their lifetime and, thus, the dynamics of fish and fishers around them. As a result, adopted and potential management measures, such as limits on dFADs numbers at sea or limits on dFADs sets, lack the necessary background knowledge, such as the effect of dFAD densities on tuna behaviour or the effect of soak time on species composition caught at dFADs.

4 | CONSEQUENCES OF PROHIBITING dFAD USE

As demonstrated above, dFAD fishing for tropical tunas has several important advantages and disadvantages. Though most concerned

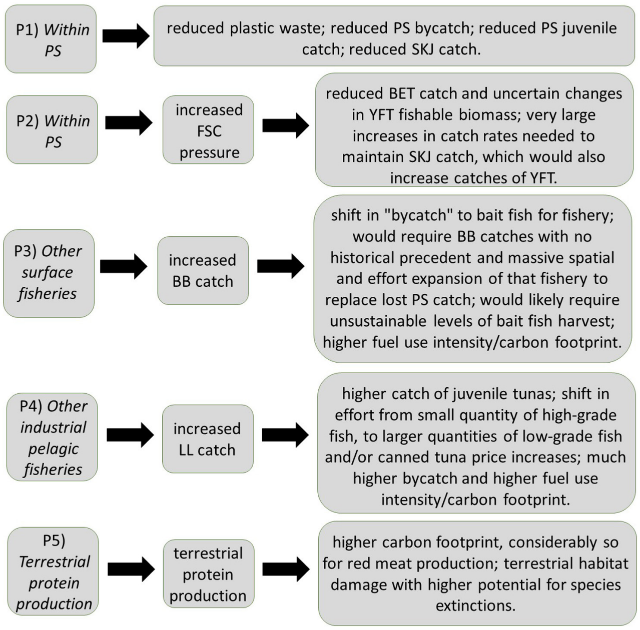

FIGURE 4 Flowchart of possible consequences of prohibiting dFAD use (see Section 4). YFT: yellowfin tuna; BET: bigeye tuna; SKJ: skipjack tuna; LL: longline; BB: pole-and-line.

stakeholders would likely agree that both the advantages and disadvantages exist, there are significant differences of opinion regarding the importance of each, with some, notably among environmental NGOs, competing fisheries and conservation-focused academics, arguing that the disadvantages are so severe that only a total or near-total ban will address them. The principal intended benefits of a ban would be reduced juvenile tuna catch and bycatch of certain sensitive species, such as sharks, reduced marine waste and impacts on coastal ecosystems via dFAD strandings, and less conflict among different gears.

Before considering some alternative solutions to mitigate the disadvantages of using dFADs, it is important to summarize briefly the likely consequences of banning dFAD use by tropical tuna PS fisheries (see flowchart in Figure 4). The main and first clear positive consequence of banning dFAD fishing is the reduction in plastic waste, reduction in PS bycatch and PS juvenile yellowfin and bigeye catch (P1 in Figure 4). Other consequences are explained in more detail in the next sections.

The PS dFAD fishery harvested an average of 1,501,952 mt of tropical tunas per year worldwide over the period 2010–2020 (Table S1), the majority of which is destined for the canned tuna market, compared to 1,331,273 mt in non-dFAD PS sets (Table S2). The impacts of a ban on dFAD fishing would likely occur at multiple levels, both within and outside the PS fishery itself (Figure 4), and vary by fishing area, species and fishing gear. Within the PS fishery, such a ban would probably lead to a large increase in fishing pressure on FSC (P2 in Figure 4). In all areas except the WCPO, non-dFAD PS catch is predominantly composed of large, mature yellowfin (Figure 3, Table S3), so an increase in fishing on FSC would probably lead to a net shift in species composition away from skipjack and bigeye tunas and towards yellowfin tunas (P2 in Figure 4). This would be the case even if the catch of skipjack in FSC in the AO and IO, where it has been suggested that intensive dFAD use may be limiting recruitment of skipjack to FSC (Dupaix et al., 2021), rebounds after a dFAD fishing ban to 1990s species compositions (Table 1), before the large increase in dFAD use starting in the early- to mid-2000s (Maufroy et al., 2017). In the WCPO, due to a combination of non-negligible aFAD catches and high catches of skipjack in FSC, the species composition (by weight) of non-dFAD PS sets is closer to that of dFAD sets (Table S3), although bigeye tunas are notably absent as adult bigeye are generally inaccessible to purse seine as they feed below the mixed layer during daylight hours in tropical waters (Reygondeau et al., 2012). This would suggest that there is more capacity in the WCPO for maintaining overall species composition and notably catch of skipjack tuna in the event of a prohibition on dFAD use. A 76% increase in non-dFAD PS harvests would still be required to maintain total catch (Table 2) and size composition of the catch would undoubtedly shift towards larger individuals (Figure 3, Table S3).

A reduction in the PS catch of juvenile yellowfin and bigeye tunas due to a shift towards fishing on FSC would likely be welcomed by those concerned about levels of juvenile catch (ISSF, 2022). However, given the lack of evidence for recruitment limitation or a stock-recruitment relationship in tunas (Anonymous, 2011; Fonteneau et al., 2000), it is consistent with the precautionary approach to assume that, while such a change might address growth overfishing, it is unlikely to lead to increased recruitment. If this is the case, then there would be a net loss of PS bigeye catch (P2 in Figure 4) given the minor catches of bigeye in non-dFAD sets (Table A2). Assuming species composition does not change, the net losses of bigeye PS catch would be 153,105 mt per year if there is no change in FSC catches and reduced to 129,615 mt per year if FSC catches are doubled. For yellowfin tuna, changes in biomass caught will depend on the relative importance of the weight increase from the typical age of dFAD-associated individuals to the typical age of FSC-associated individuals and the loss of individuals over time due to natural mortality. Relatively simple estimates suggest that both increases and decreases in yellowfin tuna biomass accessible to PS fisheries are possible as a function of the poorly known age/size-specific mortality rates (Supporting Information) though a full accounting of the size-/age-frequency of catch would be necessary to provide a more precise assessment.

Undoubtedly, the most important impact of a ban on dFADs would be on skipjack catches. With the exception of the WCPO, maintaining skipjack catch via non-dFAD PS fishing would require at least tripling current catch rates (Table 2; assuming species composition of non-dFAD catch does not change as an indirect result of a dFAD ban) and would lead to much higher catches of yellowfin tuna. Even if the fraction of skipjack in FSC catch in the AO and IO increases to 1990s levels, before intensive dFADs use (Maufroy et al., 2017), maintaining skipjack catch with PS sets would require a 7–9 fold increase in FSC catch (Table 2). Just maintaining overall catch while ignoring species composition would require at least

TABLE 1 Fraction of catch for each tropical tuna species by gear, school type and ocean.

Ocean	Gear	School type	Catch tropical tunas (1000 t)	Total (%)	Bigeye (%)	Skipjack (%)	Yellowfin (%)
AO	BB		767	18.76	25.21	21.35	10.09
AO	PS	dFAD	2492	60.95	61.11	70.07	38.41
AO	PS	Other	830	20.29	13.67	8.58	51.51
AO[a]	PS	Other			3.9	33.8	62.3
IO	BB		983	21.25	0.90	29.59	10.13
IO	PS	dFAD	2953	63.82	76.27	64.74	59.99
IO	PS	Other	691	14.93	22.83	5.68	29.89
IO[a]	PS	Other			4.3	30.0	65.7
EPO	BB		3	0.04	0.00	0.02	0.08
EPO	PS	dFAD	3373	53.24	98.38	68.73	21.26
EPO	PS	Other	2960	46.71	1.62	31.25	78.66
WCPO	BB		1845	8.50	0.00	9.50	6.13
WCPO	PS	dFAD	7703	35.48	76.48	35.74	27.36
WCPO	PS	Other	12,164	56.02	23.52	54.76	66.51

Note: Total catches are in thousands of mt and correspond to the total catch declared to tRFMOs for the period 2010–2020. Percentages sum to 100% for each column of the table by ocean (e.g. the three values for the AO in the column '% bigeye' sum to 100% except for the rows noted with a). Note that reporting by the EPO pole-and-line (BB) fishery was very limited over the period 2010–2020 and, therefore, the reported catches may not reflect the true catch.

[a]Represents catch species composition for non-dFAD purse seine sets in the AO and IO for the period 1991–1999, the earliest possible period for which catch species composition is reasonably reliable and before the major increase in dFAD use that started in the early- to mid-2000s (Maufroy et al., 2017).

doubling non-dFAD PS catches in all areas except in the WCPO, for which a 76% increase would be necessary. The need for such large increases in non-dFAD PS catches suggests that a dFAD ban could lead to a large decrease in skipjack tuna catch by PS fisheries (currently representing 1,058,356 mt per year, Table A2). Skipjack tuna is considered to be the most robust tropical tuna to exploitation due to its smaller age and size at maturity, and yellowfin tuna and bigeye tuna are each considered to be overfished in one or more of the four main tropical tuna fishing areas, so replacing skipjack catch with catch of yellowfin and bigeye is undesirable.

These losses in skipjack and bigeye tuna catches are unlikely to be recovered via increased fishing effort in other surface fisheries. For example, pole-and-line fishing are regularly evoked as a desirable alternative to PS fishing given its relatively similar species composition to PS dFAD fishing (Table 1, P3 in Figure 4) and very low bycatch rates (Miller et al., 2017), though these estimated rates do not include the catch of live bait for pole-and-line fishing, which, if included, would roughly represent a similar bycatch rate to PS fishing (Gillett, 2011; Kaplan et al., 2014). Nevertheless, in all tropical tuna fishing zones, current pole-and-line catches are a relatively small proportion of overall industrial tropical tuna catch, representing roughly 20% of the total catch in the AO and IO, 9% in the WCPO and a negligible fraction of declared catch in the EPO (Table 1). There is also no historical precedent for pole-and-line fishing at the scale of the current PS fishery. For example, while PS catches in the WCPO have been above 1.5 million mt in the latest decade, pole-and-line catches were highest in the 1970s and 1980s, at approximately 350,000 mt per year, and have been below 250,000 mt in the last decade (Williams & Ruaia, 2021). This at best corresponds to roughly half the 684,818 mt per year caught by the PS dFAD fishery in the WCPO over the last decade. Furthermore, expansion of pole-and-line fishing will require increasing catches of bait fish to levels that are potentially impossible or unsustainable (Gillett, 2011) and a non-negligible percentage of current pole-and-line catch occurs around dFADs (presumably deployed by PS vessels as pole-and-line fishery is not known to extensively deploy dFADs). In the AO, the only region for which pole-and-line school type is sometimes reported, 20.8% of overall pole-and-line catch and 46.1% of pole-and-line catch with a reported school type, was on floating objects.

Replacing lost tropical tuna catch due to a dFAD ban via other surface fisheries will also require large changes in spatial distributions of fishing (P3 in Figure 4). The distribution of pole-and-line fishing is limited by the need for live bait, in most cases restricting them to relatively coastal areas (e.g., the Maldives; Figure 5c). Non-dFAD PS skipjack tuna catch (Figure 5b) also has a somewhat different and more patchy spatial distribution than dFAD PS skipjack tuna catch (Figure 5a) although the WCPO is an important exception to this general pattern. As PS dFAD fishing is the dominant method for catching skipjack tuna (and tropical tunas more generally) over much of the world's tropical oceans (Figure 5d), replacing lost catch due to a ban on dFADs would require not only large increases in catch and effort of other surface fisheries (Table 2) but also major changes in spatial distributions, fishing strategies and deployed fleets; which could cause other unforeseen consequences.

TABLE 2 Percent increase in catch (by ocean and gear-school type) that would be necessary to recover lost catch from a ban on dFADs assuming that catch species composition of other gears and fishing modes does not change in response to a dFAD ban and based on catch rates reported for the period 2010–2020.

Ocean	Gear	School type	Total (%)	Bigeye (%)	Skipjack (%)	Yellowfin (%)
AO	BB		325	242	328	381
AO	PS	Other	300	447	817	75
AO	PS + BB		156	157	234	62
AO[a]	PS	Other		711	660	80
IO	BB		300	8508	219	592
IO	PS	Other	428	334	1140	201
IO	PS + BB		176	321	184	150
IO[a]	PS	Other		713	868	208
EPO	BB		129,348		359,312	26,466
EPO	PS	Other	114	6062	220	27
EPO	PS + BB		114	6062	220	27
WCPO	BB		417		376	446
WCPO	PS	Other	63	325	65	41
WCPO	PS + BB		55	325	56	38

Note: Each line of the table indicates the necessary percent change in catch for the ocean in the first column and gear and school type in the second and third columns that would be required to maintain overall total catch (fourth column) or catch of a specific species (columns 5–7) in that ocean assuming that catches of other gears do not change. BB: pole-and-line; PS-Other: non-dFAD purse seine. Percentages represent increases so 100% corresponds to a doubling of catch rates (catch/year). 'PS-Other' catch would predominantly consist of catch on FSC, though it would also include relatively small amounts of catch from unclassified sets and, particularly for the WCPO, non-negligible catch on aFADs. Note that reporting by the EPO pole-and-line fishery was very limited over the period 2010–2020 and, therefore, the estimated percentage increases may not be reliable. Empty cells for bigeye (column 5) indicate no reported catch of that species by BB.

[a]Percent augmentation in non-dFAD purse seine catch in the AO and IO needed to maintain total catch of each of the three major tropical tunas if dFAD fishing is banned assuming that non-dFAD catch species composition returns to what it was in the 1990s (specifically, 1991–1999) after the ban. The period 1991–1999 is the earliest possible period for which catch species composition is reasonably reliable and before the major increase in dFAD use that started in the early- to mid-2000s (Maufroy et al., 2017).

Beyond industrial surface fisheries, there are a number of other ways that one can imagine potentially replacing some of the global protein production that would be lost due to a dFAD ban, including increased longline fishing (P4 in Figure 4), artisanal and semi-industrial fishing, and terrestrial meat production (P5 in Figure 4). All of these approaches suffer from drawbacks and limitations that make them undesirable. Longline fishing in tropical waters currently primarily targets relatively small quantities per vessel of large, high-grade yellowfin tuna, bigeye tuna and billfishes, the majority of which are destined for raw fish sashimi and fish steak markets. As longline fisheries catch little to no skipjack, replacing lost skipjack biomass would require redirecting part of the yellowfin and bigeye tuna catch to the currently far less lucrative canned market. This would either raise the price of canned tuna or require important changes to the spatial distribution, fishing fleet, processing and transformation of longline catch. Furthermore, longline fishing has higher bycatch rates than PS fishing, estimated to represent as much as 40% of the overall biomass caught and impacting a number of sensitive pelagic species, such as seabirds, turtles and sharks (P4 in Figure 4; Lewison et al., 2014; Savoca et al., 2020). Artisanal and semi-industrial fisheries have the advantages of high employment rates, resource utilization rates and value for coastal communities (Johnson, 2018), but they are largely restricted to coastal areas and have a history of poor data reporting, creating problems for management (Herrera & Pierre, 2010). Increased terrestrial meat production is equally problematic given the existing extinction debt and challenges for conservation faced by terrestrial ecosystems (P5 in Figure 4; Johnson et al., 2017). Finally, all of these alternative methods of production are likely to have considerably higher fuel use intensity and carbon footprints than PS fishing (Mckuin et al., 2021; Parker & Tyedmers, 2015).

In summary, banning dFADs would reduce catch of juvenile yellowfin and bigeye tune, bycatch on sensitive and non-target species and limits marine, but would also likely lead to a large decrease in the catch of tropical tunas, and in particular skipjack tuna. Available options to replace this global loss of protein, either by expanding other fishing methods or terrestrial modes of food production, are either impractical, unlikely to be feasible or potentially present equally or more important challenges for resource management, conservation and climate change mitigation. Though a ban may reduce catch of juvenile yellowfin and bigeye tunas, PS bycatch and plastic waste from PS fisheries, the net benefit of such a change depends on the evolution of other production methods and consequences that are hard to predict.

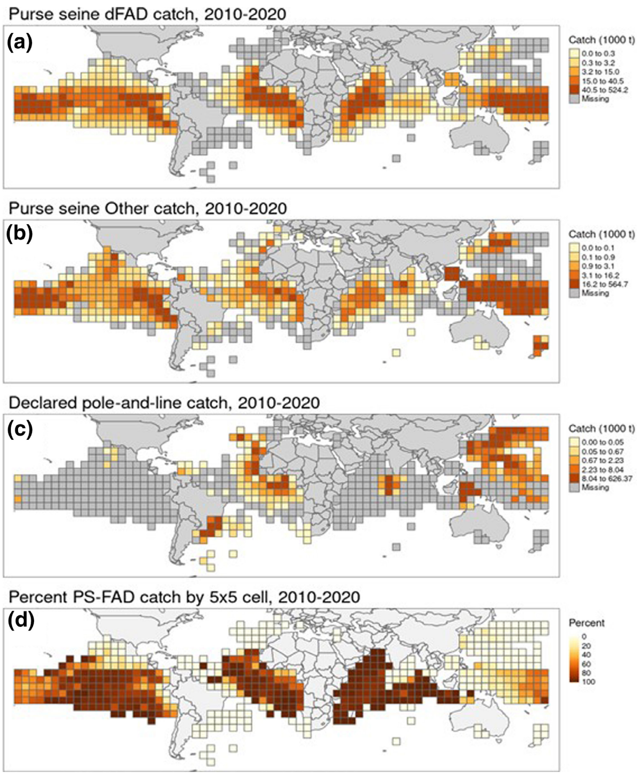

FIGURE 5 Worldwide spatial distribution of skipjack tuna catch in PS and pole-and-line fisheries. Panels from the top indicate PS dFAD catch (a), PS catch from non-dFAD sets (b), pole-and-line catch (c) and the percentage of total catch that is PS dFAD catch (d). To better highlight spatial variability, colouring of the top three panels (a–c) is by quantile of the data and is, therefore, non-linear.

5 | MANAGEMENT SOLUTIONS

Given the difficulties and unintended consequences that would potentially result from a dFAD ban, we highlight below alternative management solutions to some of the problems associated with dFAD fishing. Some of these alternatives are already in place, others remain to be partially or fully implemented, whereas others are still being developed or tested. Table 3 shows a list of potential negative impacts of dFAD use, as explained in Section 3, as well as one or more proposed solutions to each problem (detailed in this section and ordered to correspond to each con) and their implementation status in each tRFMO. Whereas some of these measures are specifically pertinent to dFAD fishing, others are generally valuable for PS fishing management, though they become particularly valuable or urgent given the negative impacts of dFAD fishing.

5.1 | Improving stock assessments

Tuna catches associated with dFAD fishing have two main impacts on tuna populations: i) reducing yield per recruit (by shifting selectivity to small sizes) and ii) reducing spawning stock biomass. Dagorn et al. (2013) found that there is no obvious pattern between the relative magnitude of the catch on dFADs and whether a stock is overfished or experiencing overfishing, suggesting that fishing on dFADs alone does not result in overfishing of tuna stocks. However, it is important to integrate and account for the effects of juvenile catches of yellowfin and bigeye in dFAD sets in current stock assessments to account for all sources of fishing mortality. Today, all stock assessment models used by tRFMOs include at least some sort of data coming from dFADs fishing, such as standardized catch per unit effort (CPUE) indices and/or length composition data used to determine PS fishery selectivity, allowing for the effects of dFAD fishing to be accounted for (Table 3; ISSF, 2022).

As mentioned before, the major concern in interpreting CPUE data from dFAD PS fisheries is the large increase in fishing power observed in the last decades. Significant efforts have been devoted to standardizing the effects of technological improvements on target species' catchability (Torres-Irineo, Gaertner, et al., 2014; Wain et al., 2021). The inclusion of these changes in catchability in formal dFAD CPUE standardizations for stock assessment purposes is currently a work in progress and should be considered in all dFADs CPUE standardization processes. Currently, the primary population abundance indices used for yellowfin and bigeye tuna stock assessments are the standardized CPUEs from longline fisheries, but tRFMOs have also begun to use biomass estimates from echosounder buoys as fishery independent indices for recent recruitment of tropical tunas in stock assessments (e.g., ICCAT, 2021b, 2019).

5.2 | Allocation between fishing gears/set types

Even when the catch or effort distribution among fleets can be scientifically determined, quota allocation is one of the most contentious issues in tRFMOs. Disputes between countries that have industries that use primarily one type of gear (e.g., longline vs. PS) are very common with countries seeking advantage for their preferred gear by criticizing other gears for their unsustainable or poorly monitored fishing practices. This also happens within tropical tuna PS fisheries as some countries favour FSC fishing over dFAD use, and vice-versa. As tRFMO decision-making is mostly a consensus-building process, such disputes tend to weaken management measures by reducing them to the minimal set of restrictions acceptable to all, thereby preventing optimal allocation of quotas and/or fishing effort among gears to maximize economic and conservation objectives.

Báez et al. (2020) noted that, in the IO, the implementation of a quota for yellowfin tuna created a shift in PS effort from FSC (for large yellowfin tuna) to dFADs (for relatively smaller quantities of juvenile yellowfin tuna) to avoid reaching the yellowfin quota. This had the unintended effect of increasing juvenile yellowfin and silky shark catches (Tolotti et al., 2022). The possibility of these shifts happening needs to be taken into account when implementing and allocating catch quotas. Sharma and Herrera (2019) suggest using effort controls instead for the PS fishery as catch controls are difficult to implement and enforce for multi-species fisheries such as dFAD fishing. Some effort limits for PS fisheries exist in each tRFMO

TABLE 3 A list of potential negative impacts of dFAD use, proposed solutions and their implementation status in each tRFMO.

Negative impacts	Proposed solution	Implementation status in tRFMOs
3.1. High catch of juvenile yellowfin and bigeye tunas	5.1. Improving stock assessment	Catch from dFADs fisheries are included in all tRFMOs and CPUE standardization is a work in progress
	5.2. Allocation between fishing gears/set types	No catch allocations among fishing gears. Only effort limits in PS fisheries (fishing days in WCPFC, total closures in IATTC, FAD closures in ICCAT)
	5.3. Discard bans and valorization of non-target species	Discard bans are applied in all tRFMOs but vary by region. The valorization of non-target species is well developed in the AO and developing elsewhere
	5.4. Availability of echosounder buoy biomass and position data to science	All data required by IATTC and PNA in WPO. In IO position data available only for compliance and no data availability in AO
3. 2. Lack of reliable estimates of fishing effort	5.1. Improving stock assessment	Relative indices of abundance are included in different ways in some tRFMOs
	5.4. Availability of echosounder buoy biomass and position data to science	All data required by IATTC and PNA in WPO. In IO position data available only for compliance and no data availability in AO
3. 3. Higher bycatch rates of non-target species compared to FSC	5.5. Increase observer coverage	100% in all tRFMOs except IOTC
	5.6. Limits on the number of deployments and active dFADs	Different limits in each tRFMO. A limit on FAD purchases per year in IOTC
	5.7. Bycatch mitigation measures and best release practices	Required by all tRFMOs, implemented in different ways
3. 4. Ghost fishing	5.8. Require low entanglement risk dFADs	Required by all tRFMOs. Only in IOTC and in WCPFC (from 2024 on) the use of netting is forbidden
3. 5. Habitat perturbation / ecological trap	5.6. Limits on the number of deployments and active dFADs	Different limits in each tRFMO. A limit on FAD purchases per year in IOTC
3. 6. Impact on the habitat of lost and abandoned dFADs/Marine pollution/Stranding	5.6. Limits on the number of deployments and active dFADs	Different limits in each tRFMO. A limit on FAD purchases per year in IOTC
	5.9. Biodegradable dFADs	Encouraged in all tRFMOs
	5.10. Establish ownership rules	None
	5.11. dFAD recovery programs	Only in IATTC (15 days prior to the closure, recovering same number of FADs as sets are done)
	5.12. Spatial management of dFADs deployments	None
3. 7. Problems of ownership and tracking	5.10. Establish ownership rules	None

(fishing days in WCPFC, spatio-temporal closures in IATTC and ICCAT). Some efforts have been done to evaluate the effect of catch and effort controls in tuna fisheries (see Pons et al., 2017; Sharma & Herrera, 2019), but a complete evaluation of the effect in each sector is needed to fully understand how management regulations should be implemented before considering allocation among fleets and fishing gears.

5.3 | Discard bans and valorization of non-target species

Even though no evaluations of the success of discard bans exist today, it is understood that discard bans of non-vulnerable finfish species are more effective in conjunction with an observer program (already in place in all PS fisheries in all oceans) to assess fishers' compliance. Partial discard bans (e.g., not including non-target bycatch species) are currently in place in the convention areas of IOTC (Res. 19/05, IOTC 2019b); WCPFC (CMM 2021-01, WCPFC, 2021), ICCAT (Rec. 17-01, ICCAT, 2017) and IATTC (C-21-04, IATTC, 2021); where PS vessels must retain onboard and land or transship to port all yellowfin, bigeye and skipjack tuna caught except fish considered unfit for human consumption (i.e., damaged by predation, meshed or crushed, spoiled in the net, among others). In addition, the IOTC requires all PS vessels to retain onboard non-targeted species such as other tunas, rainbow runner, mahi-mahi, triggerfish, billfish, wahoo, and barracuda (*Sphyraena* spp., Sphyraenidae), except when considered unfit for human consumption (Res. 19/05, IOTC, 2019b).

The requirement to retain discards onboard reduces vessels' hold capacity for commercial fish, so this management strategy should be applied in combination with the development and implementation of fishing strategies and technology to avoid and/or commercialize tuna and non-tuna discards (MRAG, 2017). Consumption or utilization of highly productive non-target species associated with dFADs such as mahi-mahi, rainbow runner, wahoo or triggerfish, should also be encouraged, as long as these stocks are not vulnerable to overfishing. These species in many dFAD fisheries are considered bycatch, but if bycatch is utilized, it can decrease the bycatch to discard ratios. Some of these species are usually consumed onboard (i.e., mahi-mahi and wahoo) and others are sold in local markets and ports. For example, "faux poisson" markets for non-tuna species have existed for years in Western Africa (Amandè, Amalatchy, et al., 2017; Romagny et al., 2000).

5.4 | Availability of echosounder buoy biomass and position data to science

Data from satellite buoys attached to dFADs, such as echosounder and position data, are stored and archived by each buoy manufacturing company. Scientists, NGOs and other stakeholders have requested access to high resolution dFAD tracking data to better follow the history of a given dFAD, assign catches to specific dFADs, support science and better understand the use of dFADs. Though such data have in some regions been voluntarily made available by fishing companies to national scientists for part or all of the vessels of their respective fleets (e.g., Baidai et al., 2020; Maufroy et al., 2015; Santiago et al., 2019; Uranga et al., 2022), industrial confidentiality issues have been the main reason cited for not making this data more widely available.

Currently, availability, resolution and specifications of dFAD data received by each tRFMOs are variable. Most tRFMOs gather information on active buoys at sea, including daily positions and acquisition invoices, to monitor compliance with limits on number of active buoys (Rec. 21-01, ICCAT, 2021b; Res. 21-04, IATTC, 2021; Res. 19-02, IOTC, 2019b). Generally, the temporal resolution is low (i.e., one dFAD position per day), limiting the scope of analyses that can be carried out. Since 2022, IATTC (C-21-04) now requires the transmission of both daily position data and echosounder biomass measurements. Data are provided with a maximum time lag of 90 days, and in the same format as the raw data provided by the buoy manufacturers to fishers (i.e., the whole trajectory, echosounder data and readings from other sensors on the buoy, such as sea temperature). In the WCPO, the Parties to the Nauru Agreement (PNA), through their licensing requirements (Escalle, Vidal, Heuvel, et al., 2021), have required buoy trajectory data of vessels fishing in their EEZ (corresponding to most of the PS fishing grounds in the WCPO). Previously, this had been limited to trajectories within their EEZ, but in 2022, the agreement was extended to trajectories within 20° S–20° N. In the AO and IO, only daily position information and vessel dFAD ownership information are available to tRFMOs.

Despite these advances, dFAD data collected by tRFMOs are generally not available to scientists or other stakeholders outside of those institutions. For example, whereas in the WCPO, dFAD data have been widely used by tRFMO scientists for scientific purposes (e.g., Escalle, Hare, Moreno, et al., 2021), in the AO and IO, dFAD daily position data are currently used purely for control purposes (though fine-scale Spanish and French data are available to some national scientists), despite multiple demands to make this data widely available for scientific purposes. Given the value of this information for science and management, these data should be made available for scientific purposes both within and exterior to tRFMOs in all regions.

5.5 | Increase observer coverage

Observer programs, either by onboard scientific observers or Electronic Monitoring, are crucial to acquire information related to tuna discard, bycatch, pollution and monitoring of dFAD-related activities. Amandè et al. (2017) analyzed the observed and estimated bycatch of the PS fishery in the Eastern AO (2.9% of observer coverage) and they found that bycatch was highly underestimated by onboard observers at sea compared to data collected at port. Tunas kept onboard (small tuna-like-species and small skipjack, yellowfin, and bigeye) were more than 10 times underestimated. On the other hand, the number of billfishes observed onboard was higher than estimated, likely because they are discarded at sea. This demonstrates the need for high onboard observer coverage to compile good quality data related to the catch of tunas, tuna-like species and bycatch. Today, the coverage of the observer programs is approximately 100% on large industrial PS vessels in the EPO since 1993, 100% in the WCPO since 2010 for vessels fishing on the high seas and in most EEZs, 100% in the AO (either human or electronic) since 2022 (Rec. 21-01, ICCAT, 2021b); and a minimum of 5% in the IO for vessels over 24 m since 2010 (Res. 10/04 IOTC, 2010), though a voluntary, industry-financed observer program for European PS vessels has increased the total European coverage by physical observers in recent years to 20% to 40% (IOTC, 2022b) and electronic monitoring systems increase total coverage to as much as 90% (Maufroy et al., 2020). Though some issues, such as the threat of piracy in Somalia's EEZ in the IO, complicate achieving 100% human observer coverage everywhere, this should be the goal and coverage levels should be maintained or increased to achieve this goal.

Onboard observers not only monitor fishing operations and collect data on the catch, but their presence is often vital to ensure that management and mitigation measures are implemented and effective (MRAG, 2017). However, we recognize that there are several difficulties associated with having observers onboard fishing vessels. Some of these are elevated costs involved in placing an observer, the limited availability of space onboard, piracy (i.e., in the IO), or observer safety, among others. Electronic Monitoring offers potential solutions to alleviate some of these problems; providing at sea coverage where none previously existed, increasing, and complementing existing onboard observer programs. Today, all tropical tRFMOs have dedicated Working Groups that are developing standards and procedures for the use of Electronic Monitoring, though issues with automatic species identification and coverage of all essential vessel remain areas of active research and discussion (Briand et al., 2018).

5.6 | Limits on the number of deployments and active dFADs

All tRFMOs have adopted a limit on the number of active buoys (used by fishers to track dFAD structures) at sea. The limits vary from 300 active buoys at sea in the IO and AO (Res. 19-02, IOTC, 2019a; Rec. 21-01, ICCAT, 2021a) to 350 in the WCPO (WCPFC, 2021, CMM-21-01) and in the EPO limits are set by vessel capacity with a maximum limit of 400 in 2022 and 350 in 2023 for vessels of 1200 mt or more (C-21-04, IATTC, 2021; Table 3).

The limits adopted by tRFMOs have raised diverse concerns that we summarize here:

- Recent research in the WCPO and EPO regions shows that few vessels reach current limits, so that those limits may not be equally effective for all fleet segments differing in their dFAD use strategies (Escalle et al., 2020; Lennert-Cody et al., 2018).
- Despite the limits, the total numbers of dFADs at sea are probably increasing. This is because dFAD fishing is so efficient that fleets are relying more on dFADs as (i) vessels that previously fished primarily on FSC or DS have shifted to fish on dFADs and (ii) vessels that were already working with dFADs are deploying more dFADs, while still complying with existing limits.
- The number of active buoys at sea, which is monitored by tRFMOs, is not the same as the number of dFADs at sea. Fishers deactivate buoys when dFADs are lost or drift out of fishing zones. While not tracked and not accounted for in tRFMO limits, these dFADs may continue to impact ecosystems via stranding, ghost fishing or ecological trap effects. In the IOTC only, apart from the limit of active buoys at sea, there is a limit on buoy purchases to 500 per year for each PS vessel (Res. 19/02, IOTC, 2019a). This additional measure likely reduces the actual number of dFADs at sea and incentivizes fishers to avoid loss or abandonment of dFADs.
- There are few quantitative studies addressing the appropriateness of these limits or the ideal sustainable number of dFADs at sea. This is mainly due to a lack of information on the numbers of dFADs deployed and on the details of dFAD usage following deployment.
- The establishment of limits has incentivized collaboration between vessels by sharing dFADs data, thereby potentially increasing the amount of dFAD data available to fishers even if the overall number of dFADs decreases.

Despite the limitations of current measures on active buoys, these limits have forced those vessels deploying large numbers of dFADs to reduce dFAD usage and encourage dFAD and tracking buoy reuse, while raising awareness of the need to limit dFAD numbers within the fishing industry. For example, the current IOTC limit represents a ~50% reduction from the limit set when they were first introduced in 2015 and further reductions are currently under discussion.

There are other options that can be utilized to reduce the number of dFADs at sea, such as (i) limiting deployments and (ii) limiting the use of supply vessels (in the oceans where they are allowed). Supply vessels are vessels exclusively dedicated to deploying and maintaining networks of dFADs for PS vessels, so limiting them would likely limit the size and spatial extent of dFAD networks available to PS vessels. However, to set effective limits of dFAD numbers and deployments at sea, it is necessary to understand the effect of different dFAD densities both on fishing fleets that display different dFAD fishing strategies and on tuna and non-tuna species.

5.7 | Bycatch mitigation measures and best release practices

There are several stages at which bycatch mitigation can take place when species interact with the tuna PS fishing gear. In general, the sooner the release practice is undertaken, the higher the probability of survival. Thus, the order of mitigation preference would be (1) preventing bycatch from interacting with the gear before the set, (2) releasing bycatch from the net, once it has been encircled by the fishing net, and finally (3) releasing the animals from the deck. In terms of reducing interactions with the fishing gear before the set, dFADs management developed by tRFMOs in the past decades has been mainly based on spatial and/or temporal closures (Davies et al., 2012; Rec. 21-01, (ICCAT, 2021a), IOTC Res. 10-01, IOTC, 2010, Res. 21-04, IATTC, 2021; CMM 2021-01, WCPFC, 2021). However, these closures are mainly designed to reduce the catch of juvenile yellowfin and bigeye tuna, not other bycatch species. One of the main problems of the efficiency of time and area closures has often been the redistribution of fishing effort to sensitive areas outside the closure or non-compliance (Escalle, Gaertner, et al., 2017). Fonteneau et al. (2015) explained that, in the AO, because nominal fishing effort has been changing from year to year, the effects of time-area closures have been difficult to evaluate quantitatively but, in most cases, their effects have been quite limited for dFADs. This overall conclusion is consistent with observed correlation of target and bycatch species in PS catch, limiting the effectiveness of spatial closures (Kaplan et al., 2014; Pons et al., 2022) and the highly stochastic nature of pelagic bycatch leading to poor predictability.

According to Hall and Roman (2013), gear modifications continue to be one of the best ways to reduce bycatch without reducing economic performance and loss of employment. Different technical solutions and gear modifications have been suggested (Restrepo et al., 2018) and should be considered on a case-by-case basis. However, gear modification measures have only been given relatively minor attention in the context of tropical tuna PS fisheries as the nature of the fishery, catching entire fish schools at once, complicates separating target from non-target species after encirclement. Today, most of the conservation measures in tRFMOs focus on best release practices from the deck, such as the prohibition of the use of gaffs and lifting with hooks among others (IOTC 2021 Res 12/04; ICCAT, 2011 Rec. 13/11; IATTC, 2004 C-04-07; and WCPFC, 2021 CMM 2018-04). This is mainly due to the economic effort needed to test innovative ideas and technologies under real commercial operations, such as setting-up an escape window in the net or using sophisticated equipment to handle bycatch (Itano et al., 2012; Restrepo et al., 2018).

Despite the important advances in bycatch reduction in the tuna PS fishery, there are still challenges to be met. Sharks deserve special consideration given the status of some of these vulnerable species (Dulvy et al., 2021). Fundamental research investigating the physiology and behaviour of threatened species is necessary to explore bycatch mitigating tactics and technology that would keep them away from dFADs when the PS is setting or to help release them from the net. In the future, newly built PS vessels should include bycatch release devices integrated directly into ship decks (e.g., shoots for live release of sharks) just as they do for other equipment like winches, power blocks, or cranes (Murua et al., 2021).

5.8 | Require low entanglement risk dFADs

Since the mid-2000s, scientists and fishers have been collaborating to develop and test prototypes of dFADs constructed specifically to minimize entanglement of sensitive species, while retaining desired traits of traditional dFADs, such as the ability to aggregate tunas, low cost of materials and durability in the water (Franco et al., 2012; Murua et al., 2016; Restrepo et al., 2018). The International Seafood Sustainability Foundation (ISSF) published in 2012 (with a 2019 updated version) recommendations for the development of non-entangling dFADs. Three types of dFAD structures were described according to their entanglement risk of marine fauna: (i) Highest Entanglement Risk FADs (HERFADs), including netting with large mesh sizes (>2.5 inches; Figure 1a) capable of entangling sharks (Filmalter et al., 2013) and other marine species; (ii) Lower Entanglement Risk FADs (LERFADs), constructed with netting that is tightly tied into sausage-like bundles, or if in open net panels, a small mesh-size (<2.5 inch) is used; and iii) Non-Entangling FADs (NEFADs), using no netting, only ropes and/or canvas panels (ISSF, 2019, Figure 1). With LERFADs, fishers can use either (i) large mesh size wrapped into bundles or (ii) small mesh size netting. These designs still present a potential risk of entanglement with (i) the bundles unwrapping with time leading to open large mesh nets or (ii) small mesh size degrading over time leading to larger holes with higher likelihood of entanglement.

In the last decade, most fleets have moved from highest entanglement to lower entanglement dFADs. All tRFMOs have adopted measures requiring the use of LERFADs and/or NEFADs by PS fleets (Table 3). IOTC does not allow the use of netting, i.e., mandatory use of NEFADs (IOTC, 2019a). WCPFC requires the use of LERFADs since 2020 and of NEFADs from 2024 (WCPFC, 2021, CMM 2021-01). IATTC also requires the use of LERFADs (IATTC, 2021, C21-04) and ICCAT (ICCAT, 2021b, Rec. 21-01) recommends the use of NEFADs.

For many reasons, quantification of entanglement events by thousands of dFAD structures that drift in the open ocean for years is very hard. However, the solution is clear, as in the IO and WCPO, management measures in all oceans should prohibit the use of any netting to construct dFADs. The requirement of fully non-entangling dFADs would minimize, and perhaps eliminate, ghost-fishing by dFADs.

5.9 | Biodegradable dFADs

Research on the use of organic materials in dFAD construction have been ongoing for more than a decade (De Molina et al., 2006; Moreno et al., 2023). Along with mandating designs reducing entanglement, all tRFMOs have implemented management measures that encourage, but do not yet mandate, the use of biodegradable dFAD designs (Res. 19/02, IOTC, 2019a; CMM 2020-01, WCPFC, 2021; and IATTC, 2019, C19-01, Table 3). Nevertheless, there are proposals to most tRFMOs to mandate some measure of biodegradability for dFADs (IOTC, 2022a).

dFADs have been classified into various levels of biodegradability, from little to no biodegradable elements, as in most current dFADs, to dFADs with a biodegradable subsurface structure and all the way to fully biodegradable for which all subsurface, surface, shading and flotation elements, are biodegradable except the tracking buoy (IOTC, 2022a). Bamboo rafts for surface flotation have been used by fishers for decades, however additional materials, such as synthetic floats, are normally added as bamboo loses buoyancy with time (Franco et al., 2009; Moreno et al., 2016). Potential alternative materials that are being tested to maintain buoyancy include balsa wood, although its availability varies by region (Moreno et al., 2016). Various organic submerged appendages have been tested with different plant-based materials, including ropes made of cotton, jute, sisal, coconut husk fibre, among others (e.g., Lopez et al., 2019; Moreno et al., 2019; Wang et al., 2021). In most of the experiences testing biodegradable dFADs, the same design as in conventional dFADs (Figure 1) was used but replacing plastic by biodegradable materials. One of the challenges for this type of biodegradable dFAD is to increase their lifetime (between 5 and 12 months depending on the region and fishers' strategy Moreno et al., 2016), as the structural stress of the conventional dFAD design makes them break before their required lifetime for fishing (Moreno et al., 2023). However, in the IO, dFAD structures are simpler and smaller (because simpler dFADs suffer less structural stress) compared to other oceans, so the transition to biodegradable dFADs would likely be easier. In this ocean, diverse biodegradable dFAD designs were tested during a pilot project, and the lifetime of some elements, such as biodegradable ropes, was proven to meet fishers' requirements in this ocean of up to 6 months (Moreno et al., 2023). A novel concept of dFADs, called the Jelly-FAD, in which structural stress is reduced mirroring neutral buoyancy aspects of jellyfish, was designed in collaboration with physical oceanographers and tested in real fishing conditions in the AO, WCPO, and EPO, showing similar tuna aggregation patterns than the conventional dFADs and with a lifetime of at least 7 months at sea (Moreno et al., 2023).

Large-scale trials of biodegradable dFADs have now been implemented in all oceans (Moreno et al., 2023). In the IO, 771 biodegradable dFADs of different prototypes have been tested since 2017 as part of the BIOFAD project (Murua et al., 2023a; Zudaire et al., 2020). Biodegradable dFAD designs tested were found to last less than the target lifetime set for this project of one year, but overall tuna biomass aggregation and tuna catch was similar to that of conventional dFADs. Reduced lifetime was found for canvas covering the raft, while the lifetime for the main biodegradable rope used for the dFAD construction was considered long enough for fishers and in fact, fishers have incorporated the use of that biodegradable rope in the IO for the construction of dFADs. In the AO, trials in partnership with the Ghanaian fleet started to test fully biodegradable dFADs, except for the floats used to maintain raft buoyancy and the tracking buoy, in order to monitor the time evolution of biodegradable materials (Moreno et al., 2018). Unfortunately, the limited visits of fishers to biodegradable dFADs during the trial did not allow to conduct in-depth study of the efficiency of dFADs. However, fishers were able to work with biodegradable materials and were trained in the construction of new biodegradable dFAD designs. Similar initiatives have started in the WCPO and preliminary results show the effectiveness of biodegradable dFADs in terms of tuna aggregation and lifetime (Escalle, Moreno, et al., 2021; Moreno et al., 2023). However, dFADs structures of different designs should be tested in each ocean region due to the specific oceanographic conditions and the various fleets that may have a favourite type of dFADs. In addition, there are still some work to be done to ensure fully biodegradable dFADs that last over a year in working conditions.

5.10 | Establish ownership rules

Clear ownership rules for dFADs would assist in assigning responsibilities for impacts and answering numerous scientific and management questions related to dFAD use, distributions and regulation compliance. Gilman et al. (2018) found that almost all stakeholders think that the owner of a dFAD, and responsibility for any damage caused by a dFAD, should be the fishing company that owns the satellite buoy that is currently attached to the dFAD. If no satellite buoy is attached, then the company that last had their satellite buoy attached, if this can be determined by a unique identifier, should be considered the dFAD's owner. Though most dFADs do not currently carry a unique identifier other than the tracking buoy, the technology for such identifiers largely exists and a number of proposals have been made to mandate their addition to dFADs, both for control purposes and for answering questions related to dFAD lifetimes (IOTC, 2022a). Identifying dFAD ownership is complex because the fishing company tracking the position of a given dFAD may change multiple times over a dFAD's lifetime and unique identifiers on dFADs themselves need to survive long periods in the water, however, almost all stakeholders agreed on the basic principles of ownership described above (Gilman et al., 2018).

Ongoing research (i) by IATTC on an electronic dFAD marking system that can be interrogated remotely by onboard observers and (ii) by ISSF and Collecte Localisation Satellites (CLS) to develop a dFAD tracker independent from the fleet that sends dFAD positions via satellite represent interesting potential innovations that would facilitate tracking of dFADs and dFAD ownership.

5.11 | dFAD recovery programs

Some of the issues with dFAD use mentioned above – marine pollution, ghost fishing and habitat damage – are linked to the extensive use of dFADs and the general tendency to lose and abandon dFADs, which may have increased since the introduction of active buoy limits but needs to be further studied when appropriate data are available to scientists. Imzilen et al. (2022) found that approximately 40% of French dFAD trajectories in the IO and AO exited PS fishing grounds never to return, highlighting the scale of dFAD loss and the need for dFAD recovery options. A certain level of dFAD recovery should be required by tRFMOs in order to limit the ecosystem impacts that can be caused by lost and abandoned dFADs (see Section 3.6). Some tRFMOs encourage the recovery of dFADs (WCPFC, 2021, CMM-2017-04), although it is not explicitly specified in dFAD-related management measures. Many fishing countries (e.g., Seychelles) have plans for monitoring and retrieval of lost dFADs where skippers are encouraged to prevent, as much as possible, the loss of dFADs at sea by using tracking systems, but the practical impacts of these plans have not been quantified. In the event of a loss or of the impossibility of retrieving a dFAD, operators must record its last known date and position in their logbooks (IOTC-2021-CoC18-10). Only in the EPO, an obligation of dFAD recovery exists 15 days prior to the closure, in which fishers need to retrieve during those 15 days the same amount of dFADs as number of sets made (IATTC, 2021 C-21-04, Table 3).

Potential recovery options have been investigated and could include recovery close to shore before dFADs could impact sensitive areas such as coral reefs, as well as high seas recovery in space–time areas of high dFAD loss (Escalle et al., 2021c; Imzilen et al., 2022; Zudaire et al., 2018). Imzilen et al. (2022) found that approximately 20% of French dFAD trajectories lost from fishing grounds in the AO and IO pass within 50 km of a port, suggesting that dedicated recovery programs could be created in these areas. In terms of implementation, “FAD watch” programs first emerged in the IO in 2015 as a collaboration between the Seychelles' Fishing Authority, a local NGO and fishing companies. As part of this program, positions of dFADs entering five and three nautical mile buffers around six islands of the Seychelles archipelago are transmitted to partners in order to intercept the dFAD at sea (Zudaire et al., 2018). A similar initiative is currently under development in the WCPO for dFADs approaching Palmyra Atoll (Escalle, Hare, Moreno, et al., 2021). Other recovery options could be considered in oceanic areas where high rates of dFAD abandonment have been identified; however, the large spatial scale covered by dFADs and the high number of PS vessels in some regions (Imzilen et al., 2022; Williams & Ruaia, 2021) make such programs complex and expensive to implement. These could involve the PS vessels themselves, PS supply vessels, or other vessels present in the areas (e.g., longliners) (Escalle, Hare, Hamer, et al., 2021).

Assuming ownership can be assigned, most of the time the high at-sea operating cost for PS vessels makes it cost-prohibitive for the owner to retrieve distant dFADs. Moreover, the cost to the PS sector of abandoning dFADs and replacing them with new ones is much lower than the cost of retrieving dFADs that drift out of range (Gilman et al., 2018). One solution would be to require dFAD recovery plans with compensation programs for third-party dFAD retrievers paid by contracting parties and organized by tRFMOs. Another would be for contracting parties to tRFMOs to offset pollution caused by dFAD by paying for coastal cleanup of marine debris (Imzilen et al., 2022); potentially in part offset by recovery of used dFAD tracking buoys, though the value of this will be highly dependent on the complexity and cost of shipping buoys from retrieval locations to PS fishing ports. In the EPO some artisanal fisher's communities sell buoys they found back to their owners. These solutions could be implemented quickly trough pro-active fleets or if appropriate pressure was applied via different organizations, such as the Marine Stewardship Council (MSC) or other environmental organizations.

5.12 | Spatial management of dFADs deployments

Recent research have indicated that spatial management of dFAD deployments could reduce stranding up to 40% in the AO and IO (Imzilen et al., 2021) and/or dFAD abandonment in the WCPO (Escalle et al., 2021c). Optimal areas to be closed to deployments to avoid dFAD strandings in the AO and IO were found generally to be away from main dFAD deployment areas, suggesting that this solution could be effective with relatively little impact on fishing activities (Imzilen et al., 2021). Nevertheless, predicted reductions in dFAD strandings were found to be heterogeneous over space, with some areas receiving a near-total elimination of strandings and others receiving little benefit. The areas receiving least benefit often coincided with areas of high recovery of dFAD tracking buoys by coastal fishers, suggesting that dFAD recovery programs in these areas may be a useful complement to spatial management of dFAD deployments (see Section 5.11).

6 | CONCLUSIONS

dFAD fishing has several negative impacts on the environment, including the potential for overfishing, increased bycatch, environmental pollution, and ghost fishing, among others. However, there are a wealth of potential management solutions for reducing or eliminating these negative impacts (Table 3). These solutions roughly fall into three categories. The first category includes solutions that have already been extensively implemented for PS fisheries, such as detailed stock assessments for target species, high observer coverage, use of dFAD entanglement minimizing designs, and best practices for bycatch live release. Extensive advancement in these issues has occurred in all tropical tuna PS fishing areas, especially in the last decade. This does not preclude, however, the need for further improvements or scientific studies, and could improve even more if the current measures in place were strengthened and effectively enforced.

The second category includes management options that have not to date been implemented, but could be rapidly implemented, because extensive background analyses and feasibility studies have already been carried out, management experience with similar tools already exists and/or societal pressures are likely to mandate their rapid implementation. This category includes non-entangling and largely biodegradable dFADs, wider availability of dFAD data, discard bans, valorization of non-target species, spatio-temporal management, dFAD unique identifiers and ownership rules, and recovery programs. In all these cases, extensive background work for their implementation has already been carried out. For example, in order to assess the impact and the effectiveness of the diverse solutions, it is necessary to obtain data on dFAD deployments, trajectories, and fates. These data already exist, but scientists and other stakeholders currently have very limited access to them (Escalle, Muller, Hare, et al., 2021). This issue could be almost immediately addressed if appropriate societal and/or political pressures were put in place.

The third category of solutions consists of very promising future innovations in PS and dFAD management that require additional research and advancement before their large-scale applicability and effectiveness can be assessed. This category includes gear modifications and PS strategies to reduce bycatch, using an enhanced understanding of target and non-target aggregative behaviour to reduce dFAD environmental impacts, fully biodegradable dFADs (i.e., including all flotation and potentially even the tracking buoy itself), echo-sounder buoys with reliable biomass estimates per species and self-navigating dFADs. These are all extremely interesting ideas for which promising proposals and/or initial trials exist, but further work is needed to realize the full promise of these solutions.

If most of these solutions were applied and enforced, fishing activities that use dFADs could be sustainable. Developing incentives with eco-labelling, co-management and MSC programs could also help to improve and motivate best practices for dFADs fishing. There are some dFADs fisheries already certified by MSC such as the Echebastar PS skipjack tuna fishery in the IO, among others (see https://www.iss-foundation.org/fishery-goals-and-resources/the-marine-stewardship-council-standard/msc-certified-tuna-fisheries/). Others are in the process of MSC certification such as the PNA Western and Central Pacific skipjack, yellowfin, and bigeye tuna PS fishery on dFADs (skipjack and yellowfin unassociated is already certified). If this fishery is certified it will cover around 1.5

million mt of catch. PNA has its own control mechanism in place in the EEZs of PNA members, through the highly successful Vessel Day Scheme and annual reviews of all requirements set by WCPFC to limit the total tuna fishing effort to 2010 levels.

A ban on dFAD fishing could either reduce global food supplies or transfer food production to other methods that are less efficient and or have larger environmental impacts (e.g., higher bycatch rate), possibly risking overfishing of species that are currently fished at sustainable levels or increasing overall impacts on marine ecosystems. For these reasons, it is essential to consider the full scope of positive and negative impacts of any dFAD management initiative, including a dFAD ban, particularly in light of the many viable management solutions for reducing the negative impacts of dFADs discussed here.

Finally, it is noteworthy that some of the solutions to bycatch, ghost-fishing and marine pollution identified in this study have been developed together with or by fishers (Jefferson Murua, Moreno, et al., 2023; Poisson, Séret, et al., 2014; Restrepo et al., 2018, 2019). Some key fleets have voluntarily shared with scientists, data on dFAD tracking and biomass estimates, participated in research and agreed to a self-limitation on the number of dFADs to be used per vessel, even before a limit on active dFADs per vessel were mandated by different tRFMOs. The support of fishers, both to fish more sustainably and to provide data to scientists, is the product of a decade of collaborative research to mitigate dFAD-related impacts between scientists of different institutions and fishers from tropical tuna PS fleets around the world (Murua et al., 2023b). Although social pressure, through environmental NGOs, led to faster progress of the fishing industry towards more sustainable fishing, numerous research projects (e.g., ISSF skippers' workshops) focused on participatory approach and co-management, have generated strong connections between the fishing industry and scientists. This unprecedented scale of cooperation with hundreds of vessels taking part in research and fishers educated in best practices, will probably lead to a faster implementation of mitigation measures and solutions for the long-term sustainable fishing with dFADs.

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DATA AVAILABILITY STATEMENT

The data used in this study is publicly available in each tRFMO webpage.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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