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Towards non-entangling and biodegradable drifting fish aggregating devices – Baselines and transition in the world's largest tuna purse seine fishery

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ABSTRACT

Drifting Fish Aggregating Devices (dFAD) are widely used in purse seine tuna fisheries globally. DFADs are often lost or abandoned by the fishing industry which can lead to marine pollution, entanglement of sensitive species and habitat damage. They are considered as a high-risk lost or abandoned fishing gear due to their common construction with long-lasting synthetic materials, including netting. This study used data collected by fishery observers to investigate materials and designs used in dFAD construction over the last 10 years in the Western and Central Pacific Ocean (WCPO). Results indicated that apart from bamboo, which is commonly used in dFAD rafts with other synthetic materials for buoyancy, very few natural materials are used. The depth of dFAD appendages varied, with a median of 50 m. Most dFADs used netting of various mesh sizes in some aspect of their construction. There is limited information to assess the uptake of lower entanglement risk dFAD designs. Transition towards more environmentally friendly dFAD designs is being promoted by management measures imposed by the Western and Central Pacific Fisheries Commission that include banning of netting by 2024 and encouraging the use of natural materials. Scientific trials are underway to support industry adoption of biodegradable dFAD materials. This paper provides important baseline data to detect and monitor future changes in dFAD construction and materials in response to management measures, and also highlights limitations to data collected by observers that will need to be improved to better monitor these changes.

1. Introduction

Abandoned, lost, or discarded fishing gear (ALDFG) presents an issue for fisheries worldwide and is a major source of anthropogenic marine pollution [1,2]. For example, it is estimated that 5.7 % of nets and 29 % of fishing lines are abandoned, lost or discarded at sea [1] and that material from fishing nets accounts for 46 % of the mass of the 'Great Pacific Garbage Patch' [3]. ALDFG can have direct impacts on marine life through entanglements, including 'ghost fishing', and can potentially damage habitats with implications for other fisheries. ALDFG can also impact on aesthetic, cultural and tourism values, and it presents risks to other uses of the marine and coastal environments, such as aquaculture, shipping and boating [4]. Recently, studies have also indicated that degraded synthetic materials from fishing gears are likely an important contributor to microplastic pollution [5].

The impacts and persistence of ALDFG have no doubt increased over the last 50 years as fishing industries transitioned from natural fibres (e.g., cotton, flax and hemp) to the use of synthetic materials. Nowadays, fishing gear mostly consists of various synthetic polymers, including nylon, polyethylene and polypropylene that can have long life-spans in the marine environment [6]. While reducing the amount of ALDFG should clearly be a focus of responsible fisheries operations, so long as fishing gears are deployed in the ocean, ALDFG will continue to occur. Measures additional to reduction will therefore be required to mitigate its impact while ensuring that fisheries can continue to operate and provide food security, income and employment for many dependent communities. One such measure involves returning to the use of natural biodegradable materials as much as possible.

Due to the commonly observed aggregation of pelagic fish around floating objects [7–9], artisanal and industrial fishers have long used

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either natural or purpose-built floating objects to aggregate pelagic fish and increase fishing efficiency. However, the distribution of natural floating objects, such as logs, varies across the ocean, influenced by the location of land masses, rivers, ocean currents and wind [10]. To achieve greater control and reduce the uncertainty in finding floating objects, modern fisheries have increasingly deployed purpose-built Fish Aggregating Devices (FADs) [11]. In the Pacific region, FADs were first used in the early 1900s by Indonesian and Philippine fishers [12], and their use has become more wide-spread since the late 1970s by both artisanal and industrial fishing sectors [13]. Since the 1990s, the use of drifting FADs (dFADs) by the industrial purse seine fishery has increased considerably, and in recent years [14,15], has almost totally replaced fishing on natural floating objects such as logs [16]. This has been facilitated by the use of attached satellite tracking buoys that allow dFADs to be easily relocated by fishing vessels [17].

Purpose-built dFADs consist of two parts: i) the raft itself, including components to ensure buoyancy (e.g., bamboo, buoys, floats, drums, pipes), which are often covered by old netting or sacking to limit detection by other vessels or to increase shadow to attract fish; and ii) submerged appendages (tails) to increase drag to reduce drifting speed, and increase fish attraction [18,19]. The submerged appendages are of different sizes, shapes and length, but typically extend to 50–70 m depth [10]. Although satellite tracking buoys are attached to dFADs, relatively few dFADs are actively recovered by industry and many are lost, sink or are abandoned with the tracking buoy switched off remotely when they drift away from a company's preferred fishing grounds [20–22]. DFADs have recently been classified as a high risk derelict fishing gear, along with gillnets [23], and studies have begun to explore the impacts of lost dFAD materials on marine habitats [24]. Mitigation measures are therefore required to reduce the problem of ALDFG created by lost or abandoned dFADs and to reduce their ecological impacts.

The Western and Central Pacific Ocean (WCPO, Fig. 1) is home to the world's largest tuna fishery, with recent annual catches accounting for over 50 % of the world's total tuna catch (at approximately 2.7 million metric tonnes) [16]. Over 70 % of the WCPO catch comes from the purse seine fishery, with about 40 % of the purse seine catch being taken in association with dFADs. Recent estimates of dFAD use in the WCPO suggest that the number per vessel is relatively low at 45–75 active dFADs per vessel per day when compared to estimates for other oceans [18,24–26]. However, while the dependence on dFAD fishing is lower in the WCPO, the large size of the WCPO purse seine fishery means the overall number of dFAD deployments (buoys and/or rafts) may be twice that of any other ocean region, with estimates ranging between 30,000 and 40,000 annually [15].

Historically, dFAD designs used in the WCPO have varied depending on the fleet [18,27], but the use of bamboo within the raft construction is common, supplemented by synthetic buoys or, in some cases, sealed PVC-tubes, for flotation (Fig. 2). A summary of recent research also found that synthetic floats and bamboo canes were the most frequently used materials to construct rafts, and netting was the most common material for submerged appendages; however variation in construction among fleets was not documented [28]. Due to the large amount of netting used, the submerged appendages are considered the highest risk component of dFADs, both in relation to entanglement of species and habitat damage, and have been of most interest for mitigation work [29]. In the WCPO, the average dFAD tail depth has previously been estimated at 40 m, with some geographic variation detected [28,30], although this needs to be updated for recent fishing practices.

Recent Conservation and Management Measures (CMMs) of the Western and Central Pacific Fisheries Commission (WCPFC), the tuna

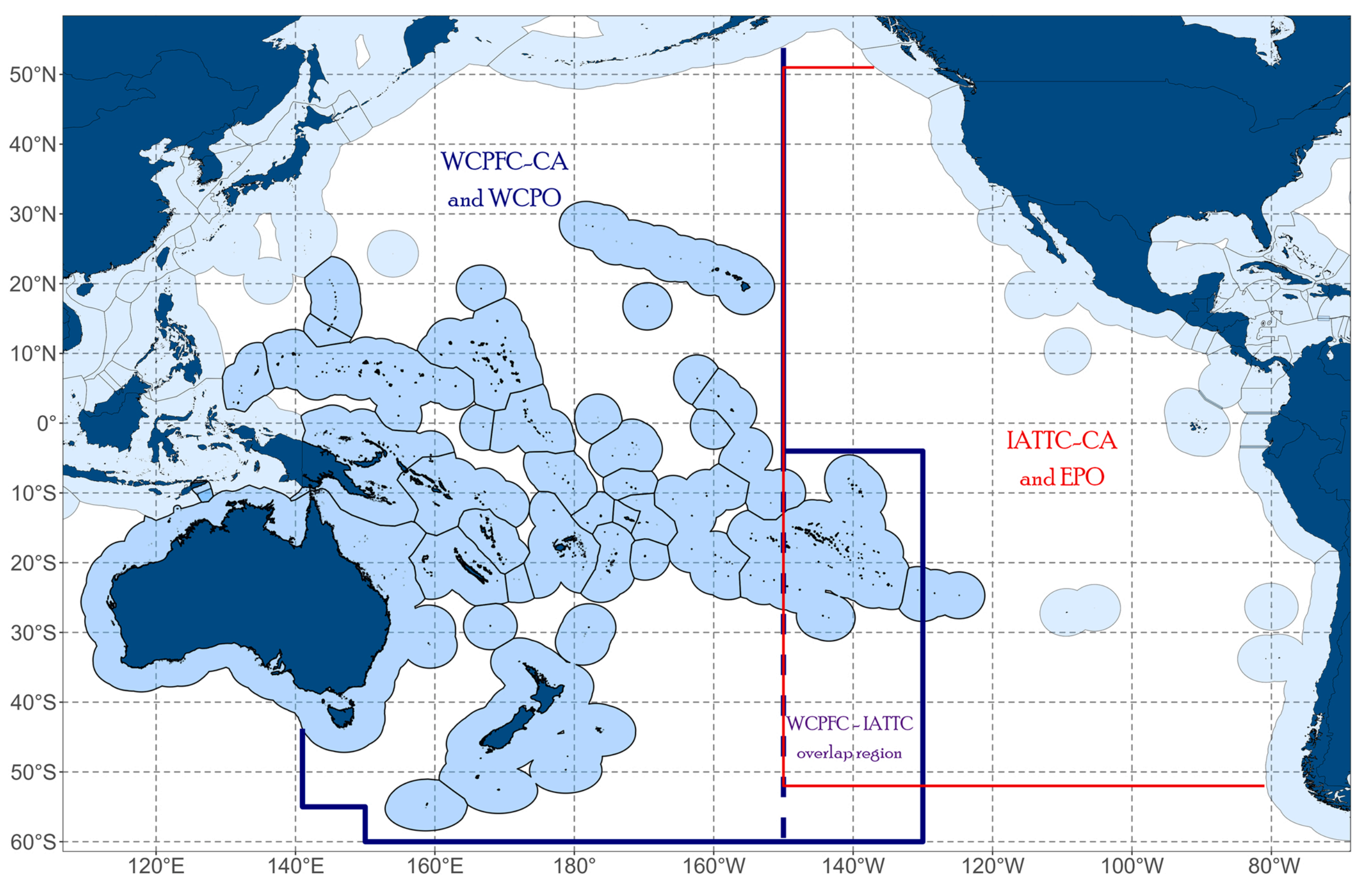

Fig. 1. Map of the Western and Central Pacific Ocean (WCPO, delimited by the blue dotted line) and the Western and Central Pacific Fisheries Commission Convention Area (WCPFC-CA) (delimited by the solid blue line, which includes the region of overlap with the Inter-American Tropical Tuna Commission convention area (IATTC-CA)). The Eastern Pacific Ocean (EPO) and the IATTC CA are indicated in red.

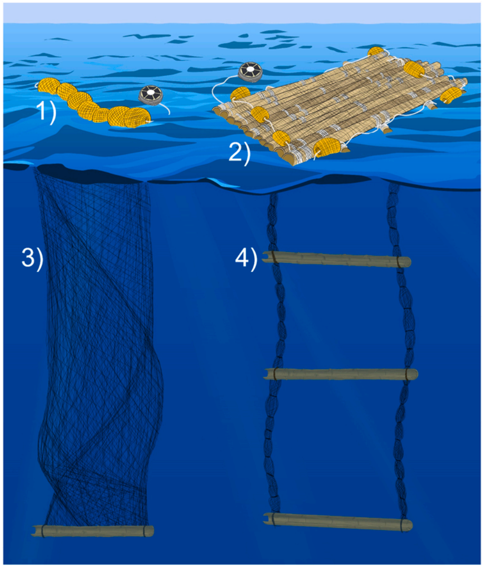

Fig. 2. Diagram representing the most common dFAD designs in the WCPO. DFAD rafts are often made of: 1) several purse seine corks tightly wrapped in purse seine nets; or 2) a bamboo raft, with or without purse seine corks and covered by purse seine nets. The submerged appendages are typically: 3) open panels of purse seine nets; or 4) purse seine nets rolled up in a sausage and separated by bamboos.

Regional Fisheries Management Organisation (tRFMO) for the WCPO, have been implemented to reduce the environmental and ecological impacts of dFAD use. These include: i) a transition towards Non-Entangling dFAD designs (Fig. 3), where the use of netting material will be completely prohibited by 2024 [31], and ii) a transition to the use of biodegradable materials in the construction of dFADs. The move towards Non-Entangling dFADs has the clear objective of reducing the entanglement of sensitive species. The use of biodegradable materials is now an objective globally to mitigate the adverse impacts of dFAD use on the environment, such as marine pollution, sea floor damage, stranding events and damage to coastal habitats. Trials to inform adequate designs and materials are ongoing [32–35]. While management initiatives are focused on modification of dFAD materials and designs, there is a lack of studies that document the current materials and designs, and no monitoring of the trends in materials and designs used in the WCPO exists. This information is particularly important in order to define baseline conditions, against which further monitoring can assess the progress and success of any management measures that are implemented. Furthermore, the extent to which some fleets may have already begun to adapt dFAD designs and materials is unclear but is important in terms of gauging the level of change required for industry-wide transition.

The aim of this paper is therefore to evaluate recent materials and designs that have been used in dFAD construction in the WCPO focussing on the last 10 years, including: i) materials, with a focus on natural vs synthetic materials; ii) the presence of netting used in any part of the dFAD; and iii) the current size of dFADs, in particular, the submerged appendages.

2. Methods

The Pacific Islands Regional Fisheries Observer (PIRFO) programme standardizes the data collection protocols and training framework adopted by observer programmes of the Pacific Islands Countries and Territories [37]. The regional minimum data standards and collection formats are used for independent fisheries monitoring data collection, including a set of forms aimed at gathering information for the management of the stocks, for monitoring ecosystem impacts, and the implementation of WCPFC CMMs. One form, GEN-5 (Appendix 1) has been specifically designed to collect information related to FAD configuration (dFADs, aFADs and natural floating objects). Information recorded on GEN-5 includes the nature of the FAD (artificial or natural, anchored or drifting), the dimensions (length, width and depth) and the materials used (for both the raft and for submerged appendages), as well as the unique ID number from the satellite buoy attached to a dFAD. Since 2011, and the implementation of this form, observers have recorded this information, when possible, for any dFADs encountered at sea, including during deployment, fishing, servicing or visiting a dFAD. It should be noted, however, that this information is often irregularly recorded, as observers may have difficulties accessing the materials of the submerged part of the dFAD when it is in the water, for instance during fishing, servicing or visiting activities.

Analyses were conducted separately for purpose-built dFADs and debris found at-sea, hereafter referred to as “floating objects”, which could include natural objects, potentially modified by fishers (e.g., addition of synthetic floats, bamboo and/or netting) or anthropogenic debris. The way dFADs or floating objects are classified here is based on the observer record. Floating objects that have been transformed by fishers using synthetic materials may therefore sometimes be classified as floating objects and sometimes as dFAD, depending on the observer. Floating objects may also be equipped with a satellite buoy to follow their position remotely.

The type of materials used for each part of dFADs and floating objects, the raft and the submerged appendages, are investigated here separately. The initial list of materials reported by observers in GEN-5 (Appendix 1) was simplified into broader categories for analyses (Table 1). Materials were then classified as ‘natural’ or ‘synthetic’. Materials considered as ‘natural’ in this paper include bamboo, logs, trees or parts of trees referred to as branches, natural debris, coconut fronds, planks, pallets and timbers (Table 1). Any other material was considered to be synthetic, commonly plastics or metals. We note that cords, ropes, sacks and bags could potentially be of natural origin (e.g., cotton, hemp, jute), but the use of these natural materials is considered to be uncommon and so were assumed within this analysis to be synthetic unless otherwise specified by the observer.

Firstly, patterns of natural and synthetic material use in dFAD construction are examined over time and across fleets. This was investigated considering the approach proposed by the WCPFC and IATTC FAD working groups[1] to categorise dFADs and transition to Biodegredable dFADs:

- Category I. The dFAD is made of 100 % biodegradable materials.
- Category II. The dFAD is made of 100 % biodegradable materials except for plastic-based flotation components (e.g., plastic buoys, foam, purse-seine corks).
- Category III. The subsurface part of the dFAD is made of 100 % biodegradable materials, whereas the surface part and any flotation components contain non-biodegradable materials (e.g., synthetic raffia, metallic frame, plastic floats, nylon ropes).
- Category IV. The subsurface part of the dFAD contains non-biodegradable materials, whereas the surface part is made of 100 % biodegradable materials, except for, possibly, flotation components.
- Category V. The surface and subsurface parts of the dFAD contain non-biodegradable materials.”

Two additional categories (Category IIb and IVb) were added here to detect dFADs with a natural raft except for plastic-based flotation components, and the presence of netting and ropes, that can be easily

[1] WCPFC FAD Management Options - Intersessional Working Group www.wcpfc.int/FADMgmtOptions-IWG.IATTC Ad Hoc Working Group on FADs www.iattc.org/en-US/Event/DetailMeeting/FAD-05a

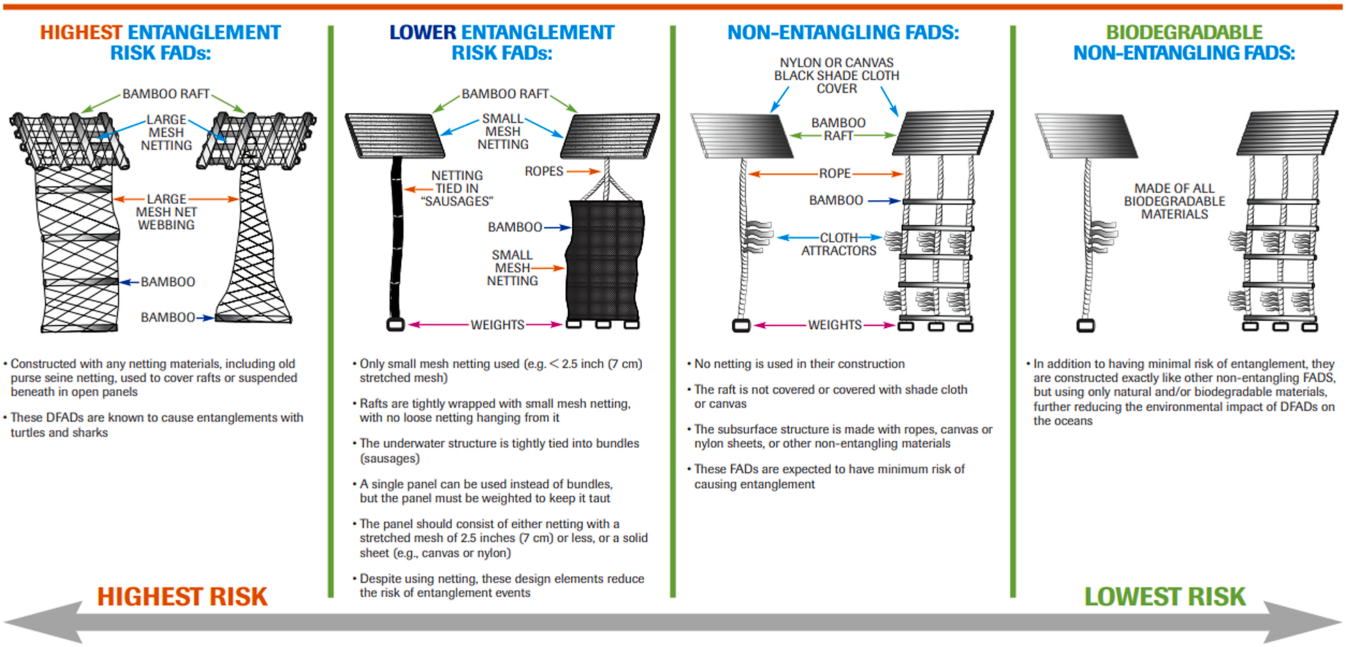

Fig. 3. Type of dFAD designs from highest Entanglement-risk dFADs to Non-Entangling and Biodegradable dFADs [36].

Table 1
List of materials used in the GEN-5 form completed by observers when describing dFADs (see Appendix 1), as well as the simplified list of materials used for analyses. Materials were classified as natural or synthetic and can be used in the raft and/or the submerged appendages.

List of dFAD "materials" found in observer form GEN-5 (Appendix 1)	Simplified list of dFAD "materials"	Type	Raft	Appendages
Bait containers	Drum	Synthetic	X	
Bamboo/cane	Bamboo	Natural	X	X
Chain, cable rings, weights	Weights	Synthetic		X
Coconut fronds/tree branches	Branches	Natural	X	X
Cord/rope	Cord	Synthetic	X	X
Floats/corks	Floats	Synthetic	X	
Logs, trees or debris tied together	Logs	Natural	X	
Metal drums (i.e., 44 gallon)	Drum	Synthetic	X	
Netting hanging underneath FAD	Netting	Synthetic		X
Philippines design drum FAD	Drum	Synthetic	X	
Plastic drums	Drum	Synthetic	X	
Plastic sheeting	Sheeting	Synthetic	X	X
PVC or plastic tubing	Pipes	Synthetic	X	
Sacking/bagging	Sacking	Synthetic	X	X
Timber/planks/pallets/spools	Planks	Natural	X	
Other (describe)	Unknown	Synthetic	X	X

removed or replaced by natural alternatives (e.g., cotton ropes).

Secondly, a more detailed examination of the different materials used for the raft and submerged appendages is presented. Thirdly, the use of netting is examined over time and across fleets. Finally, the depth and dimensions of dFADs, as recorded by observers, are described. Unrealistic values of depth and mesh size of dFADs were removed by excluding negative values and values above the 0.95 quantile (i.e., 200 m and 20 cm, respectively).

3. Results

3.1. Number of records of dFAD materials

The number of records related to dFAD activities ranged between 50,000 and 65,000 per year between 2011 and 2019 (Fig. 4), with most records corresponding to dFAD visits and sets. Note that the decline in observations in 2020 and 2021 reflects both the impact of COVID-19 restrictions on observer deployments and data entry patterns.

Information related to the materials of dFADs was recorded in less than 42.7 % of all records. Nonetheless, a general increase through time was detected in terms of information related to dFAD materials (Fig. 4), with records in less than 5.8 % of the instances in 2011 to 55.1 % in 2019 and 58.7 % in 2020. It should be noted however, that the dFAD-related form was rarely filled in by the observers during certain activities, such as deployments, retrievals and servicing, potentially due to the observers not typically observing these activities, not considering it being a priority or their occurrence when observers are busy with other duties or resting.

3.2. General pattern in dFAD material use

Over the study period, we found that dFADs were composed of: solely synthetic materials (32.9 %), or a mix of synthetic and natural materials (612.4+9.6+11.4.8 %) (Table 2). Only 2.3 % of dFADs were recorded as being composed of all natural materials. Floating objects were mostly reported as all natural materials (71.7 %), but 27.5 % had been modified, with some synthetic materials added, mostly as submerged appendages (12.7 %) (Table 3).

The use of natural materials in dFAD construction has been consistently low over the last 10 years (Fig. 5). The composition of many observed dFADs has been completely artificial (Cat. V; 29.3–57.9 %) and this percentage has been stable over the time series (Fig. 5). Similar proportions of dFADs have been reported as natural raft with buoys (category IV) and/or ropes and nets (category IVb) with appendages that are completely artificial or a mix of artificial and natural materials (between 12.8 % and 52.2 %). There has been an increase in the proportion of dFADs that have a natural raft with buoys and natural appendages over time (Cat. II; 2.8 % in 2011 and 16.3 % in 2018). Finally,

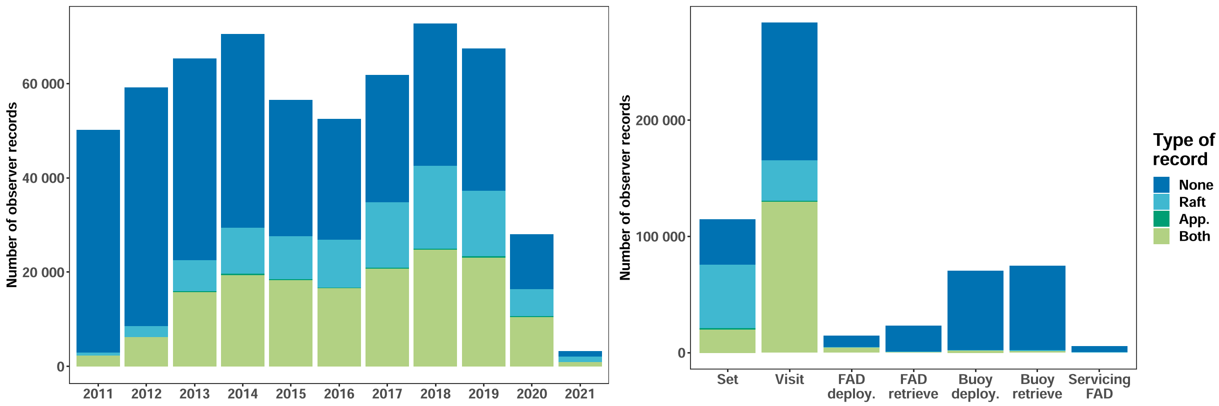

Fig. 4. Number of observer records related to dFADs and floating objects by year (left); and by type of activity reported for all years (right). The number of records are partitioned among those that provide information on the raft, the submerged appendages (App.) or both, or where neither dFAD component is specified (None).

Table 2
Percentage of dFADs with synthetic and/or natural materials recorded by observers in the 2011–2021 period. N corresponds to the total number of dFADs with information related to materials.

dFADs (N = 145,074)		Raft			
		Synthetic	Synthetic & Natural	Natural	Total
Appendages	Synthetic	32.9	40.6	2.4	75.9
	Synthetic & Natural	11.4	9.8	0.3	21.6
	Natural	0.1	0.2	2.3	2.6
	Total	44.4	50.6	5.0	100

Table 3
Percentage of floating objects with synthetic and/or natural materials recorded by the observers in the 2011–2021 period. N corresponds to the total number of floating objects with information related to materials.

Floating objects (N = 44,302)		Raft			
		Synthetic	Synthetic & Natural	Natural	Total
Appendages	Synthetic	2.4	9.6	11.4	23.4
	Synthetic & Natural	0.9	3.1	0.8	4.8
	Natural	0.03	0.04	71.7	71.8
	Total	3.3	12.7	84.0	100

less than 10.7 % of dFADs observed across years were composed of completely natural materials (Cat. I; Fig. 5), and these observations were mostly due to those dFADs having no submerged appendages.

Observers recorded that annually, 55.3–88.4 % of the floating objects were natural (Cat. I), and about 6.2–33.3 % of floating objects had an additional mix of both synthetic and natural materials, or only synthetic materials (Cat. IV; 3.4–10.5 %) as appendages (Fig. 5).

To evaluate fleet-specific patterns of construction, observer information recorded during any dFAD-related activity, e.g., dFAD deployment, setting, visiting and servicing, were used. This may have added some uncertainty in the analyses, as setting, visiting and servicing may occur on dFADs that have been deployed by a fleet other than the one from which the observation was made. The bulk of dFADs deployed were made of either: i) completely synthetic materials (Cat. V; see for instance Figure 2.1), or, ii) a natural raft with purse seine floats (see for instance Figure 2.2) and a mixed synthetic/natural, or 100 % synthetic appendages (Cat. IV) (Fig. 6). These dFADs are typically made of, respectively, a series of purse seine corks wrapped up in nets and panels of nets as appendages; and a bamboo raft with floats and panels of nets as appendages (Fig. 2). Differences were detected for some fleets. For instance, more than 56.9 % of dFADs deployed by the Spanish and Philippines fleets are almost exclusively synthetic structures (Cat. V) and between 20.6 % and 22.0 % are natural raft with synthetic buoys with at-least some synthetic appendages (Cat. IV; Fig. 6 and S1). Excluding Indonesia, due to the very small sample size, fleets using the highest relative proportion of 100 % natural dFADs (Cat. I) are the Cook Islands (24.7 %), Ecuador (22.0 %) and El Salvador (15.5 %), with up to 34.4 %, 24.2 % and 17.5 % of their dFADs, respectively, being constructed of natural materials except for the synthetic purse seine floats on the raft (Cat. II) (Fig. 6). Regarding floating objects, patterns did not vary among fleets and, hence, reflected the general pattern described previously (Figs. 5 and 6). However, some fleets, for example Cook Islands and El Salvador, had no information on floating object materials recorded by observers, presumably as they performed very few floating object sets. This is not surprising given that these fleets operate in areas far from large land masses.

3.3. Details of the type of synthetic and natural materials

Where natural materials were used in the construction of dFAD rafts (see Fig. 7), they included bamboo, logs (which includes trunks, branches or other natural debris) and planks (including pallets, timbers or spools). Logs were the most commonly used natural material, followed by bamboo (Fig. 7). Some fleets used specific designs (Fig. 7) with a dominance of: i) bamboo (Spain, Tuvalu, El Salvador); or ii) bamboo and planks for the raft, but no natural materials used in the submerged appendages (Ecuador) (Fig. 7). For the remaining fleets, natural appendages were rarely used, but when present, they typically included branches, including coconut fronds. Note that when dFADs were recorded to be constructed from a completely natural material it was mostly due to the raft being natural with no submerged appendages (i.e., floating objects transformed into dFADs, or dFADs having lost their appendages).

Synthetic materials used in the dFAD rafts were mostly purse seine floats, which dominate dFAD flotation for most fleets (Fig. 8). However, some fleet-specific designs can be identified. The Philippines fleet, for instance, used drums (plastic or metal drums). El Salvador and Ecuador use plastic pipes in more than 48 % of their rafts which contain synthetic materials; and for Spain this was 72 %. In general, netting, cords or sacking are used in less than 19 % of rafts with synthetic materials (Fig. 8).

Finally, the types of synthetic materials used in dFAD appendages were mostly cords and nets, or only net, with or without attractors, and represented up to 88.7 % of dFADs with synthetic appendages. In the case of synthetic material, the terms “attractors” refers to plastic sack or plastic sheeting which is present in 53 % of appendages. It should also be noted that weights are often used on the appendages in combination

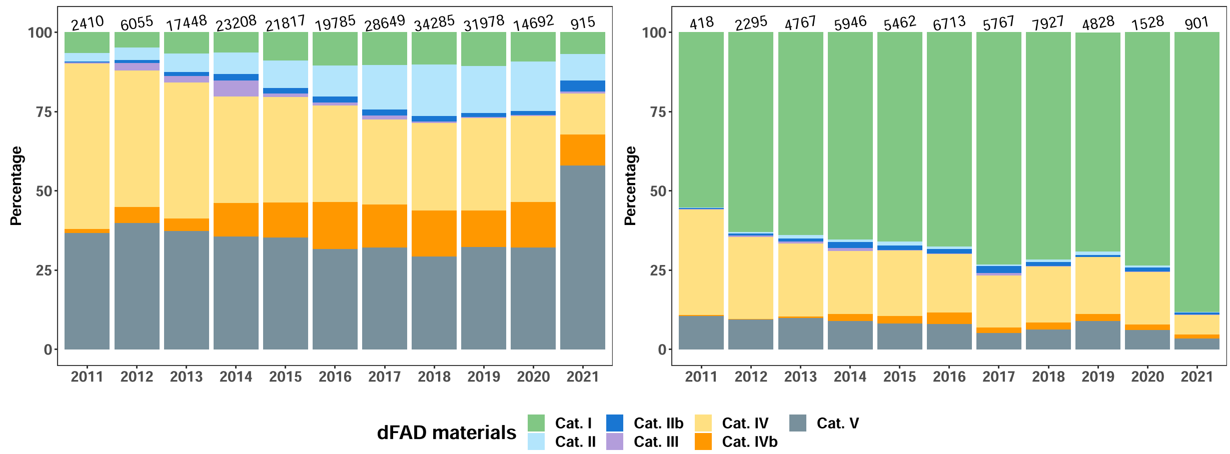

Fig. 5. Percentage of dFADs (left) and floating objects (right) per year employed with natural and synthetic materials in the design of the raft or the appendages, as recorded by observers (2011–2021). Categories (Cat.) are Cat. I: 100 % natural; Cat. II: natural except synthetic floats in the raft; Cat IIb: natural except synthetic floats in the raft and ropes or nets in the raft; Cat. III: synthetic raft and 100 % natural appendages; Cat. IV: natural raft except for, possibly, synthetic floats, and at-least some synthetic appendages; Cat. IVb: natural raft except for, possibly, synthetic floats, and ropes or nets in the raft, and at-least some synthetic appendages; and Cat. V: 100 % synthetic. Numbers on the top of the figure correspond to the number of dFADs or floating objects with information on materials per year.

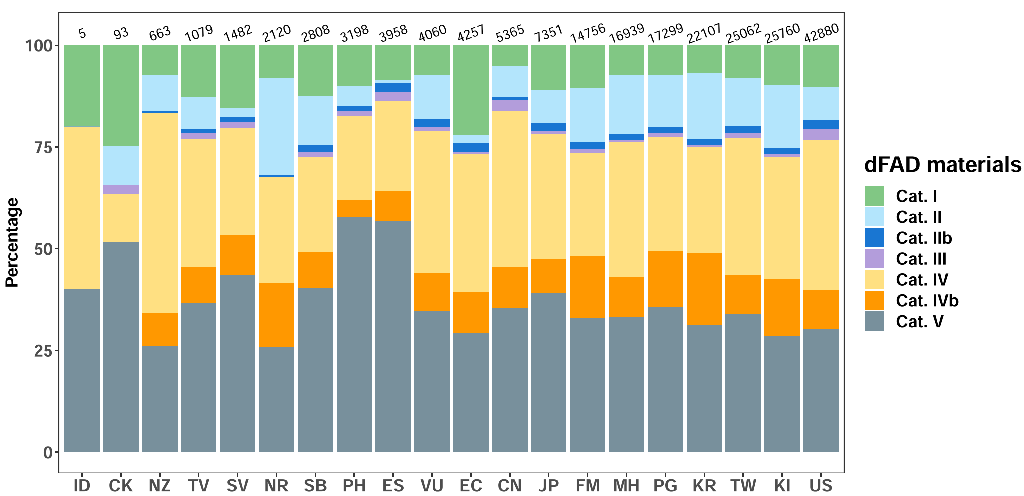

Fig. 6. Percentage of dFADs per year employed with natural and synthetic materials in the design of the raft or the appendages, as recorded by observers (2011–2021). Categories (Cat.) are Cat. I: 100 % natural; Cat. II: natural except synthetic floats in the raft; Cat IIb: natural except synthetic floats in the raft and ropes or nets in the raft; Cat. III: synthetic raft and 100 % natural appendages; Cat. IV: natural raft except for, possibly, synthetic floats, and at-least some synthetic appendages; Cat. IVb: natural raft except for, possibly, synthetic floats, and ropes or nets in the raft, and at-least some synthetic appendages; and Cat. V: 100 % synthetic. Numbers on the top of the figure correspond to the number of dFADs with information on materials per fleet. Cook Islands (CK); China (CN); Spain (ES); Federated States of Micronesia (FM); Indonesia (ID); Japan (JP); Marshall Islands (MH); Nauru (NR); New Zealand (NZ); Papua New Guinea (PG); Philippines (PH); Solomon Islands (SB); El Salvador (SV); Tokelau (TK); Tonga (TO); Tuvalu (TV); Chinese Taipei (TW); United States of America (US); Vanuatu (VU); Samoa (WS).

with cord, netting and attractors (Fig. S3). Appendages also vary among fleets. Fig. 6 indicates that Philippines, Spain and El Salvador had the highest percentages of artificial dFADs, but Fig. 8 shows that Philippines most commonly used attachments composed of cord without attractors (34.9 %), whereas Ecuador, El Salvador and Spain most frequently used cords and nets without attractors (respectively 76 %; 74.3 %; 58.8 %). However, the design of appendages are not comprehensively recorded by observers, and even if a fleet shows a high percentage of appendages with netting, the netting may be loosely hanging or could be bundled to limit entanglement risks.

3.4. Use of netting and mesh size

Mesh size of the netting used on rafts ranged from 0.1 to 20 cm, with an average of 6.9 cm and median of 8.0 cm (Fig. 9). Mesh sizes of the netting used in submerged appendages ranged from 0.1 to 24 cm, with an average and median of 8.0 cm. Note that very small mesh categories likely represent other material than netting misreported by observers. A slight decrease in mesh size was detected in 2020, with an average of 6.2 cm for rafts and 7.0 cm for appendages (Fig. 9). Differences between fleets were also detected, with some fleets, such as Ecuador, Spain and El Salvador, using smaller mesh netting (i.e., <5 cm) only.

The proportion of dFADs with some netting used in the raft or appendages was investigated as an indication of uptake of Low Entanglement risk/Non-Entangling dFADs (Fig. 3). Less than 11 % of observed dFADs did not use netting in their construction. No clear longer term trend in use of netting was detected. However, while data are still incomplete, 2021 showed the highest percentage of dFADs with no netting used (Fig. 10). Moreover, even if there was no clear trend in the use of netting across time, there was an increase in the number of observations of rafts without netting, but unknown presence of netting in the appendages (i.e., no materials reported), 11 % in 2011 compared to 27 % in 2020. Importantly (excluding 2021) most dFADs had at least some netting as appendages (65–90 %), with a slight decrease in the use of netting in appendages over time across the study period (Fig. 10). Philippines, Vanuatu and Japan used the least netting, with 35 %, 15 %

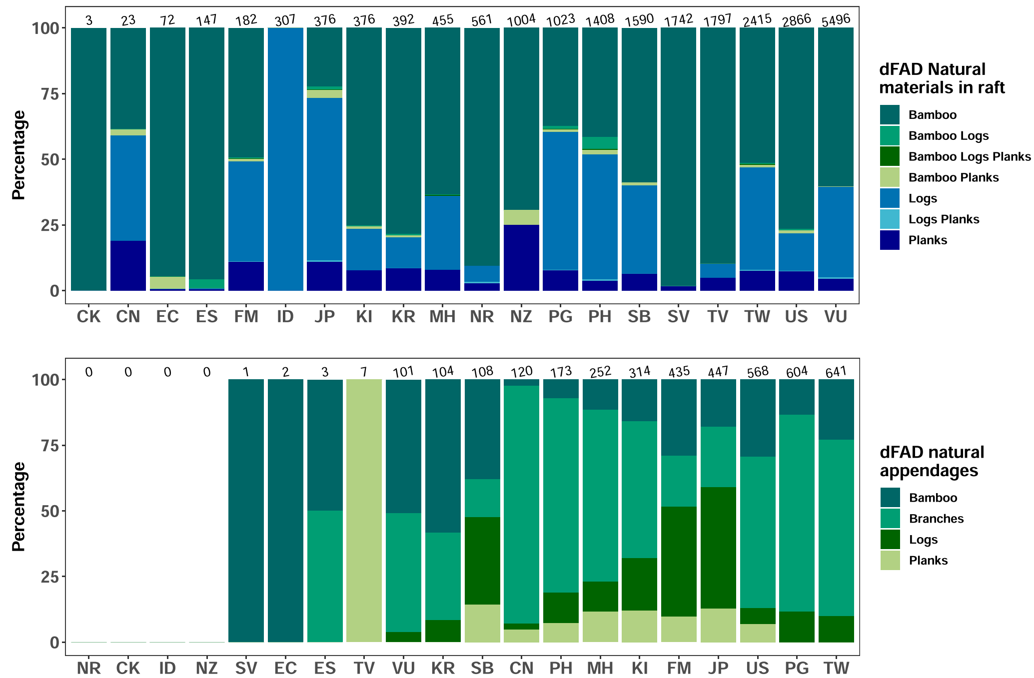

Fig. 7. Natural materials used in the dFAD rafts (top) and appendages (bottom), as recorded by observers (2011–2021). Branches include coconut fronds; planks include pallets and timbers. Numbers on the top of the figure correspond to the number of dFADs with natural appendages, those with no coloured bars correspond to dFADs with no natural appendages recorded, i.e., the submerged part of the dFAD is synthetic. Country abbreviations same as Fig. 6.

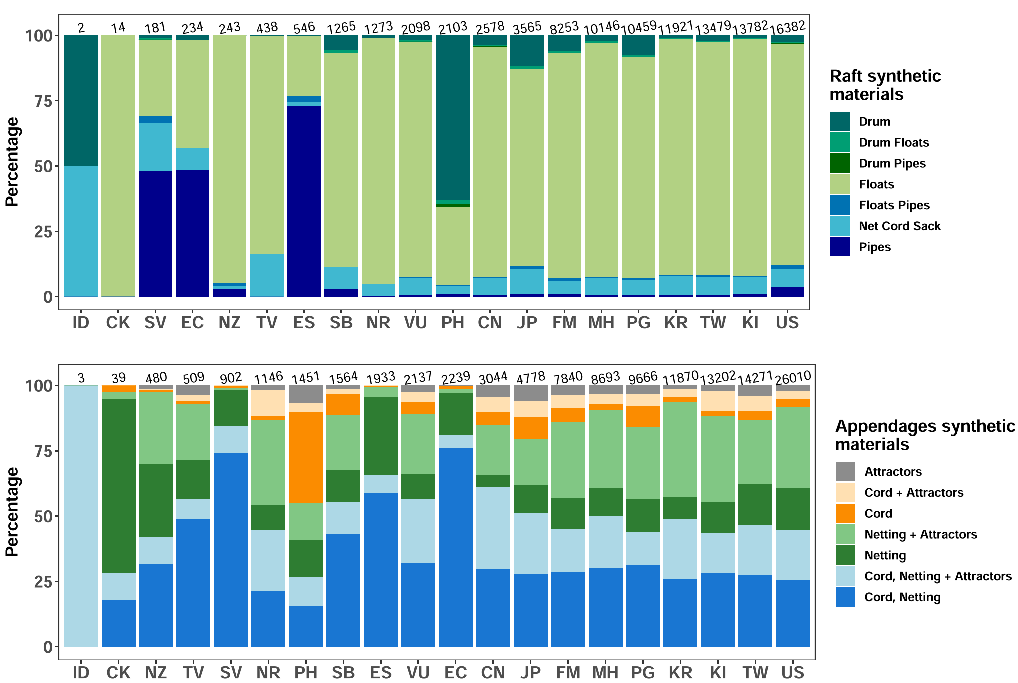

Fig. 8. Synthetic materials used as dFAD rafts (top) and appendages (bottom), as recorded by observers (2011–2021). Synthetic materials present as appendages were separated into the structure of the appendages (Cord, Netting, Cord and Netting, or none of these), and the presences of attractors (sack or plastic sheeting). Any other materials, such as weights was ignored here, but see Fig. S3 for details of the proportion of each individual synthetic material in appendages. Numbers on the top of the figure correspond to the number of dFADs observed with synthetic appendages. Country abbreviations same as Fig. 6.

and 13 % of their dFADs, respectively, observed to have no netting (Fig. 10). El Salvador and New Zealand tended to use netting as appendages but their use of netting on the raft was rare.

3.5. dFAD depth

The depth of the underwater appendages, estimated when possible by observers, varied from very shallow for some dFADs, similar to natural floating objects, to more than 100 m (Fig. 11). In the WCPO, the most common dFAD depth was 50–59 m (23.1 % of all dFADs). Six percent of dFADs had appendages that were less than 10 m length, potentially linked to dFADs having lost their tail or to floating objects classified as dFADs. Some fleets however, such as Japan (16.2 %), PNG (11.3 %), Solomon Islands, China and Vanuatu (all 9 %) had higher percentages of dFADs with appendages less than 10 m depth. The median depth of submerged appendages was 50 m. Only 2 % of all dFADs were found to have underwater appendages greater than 150 m, which would likely represent erroneous records.

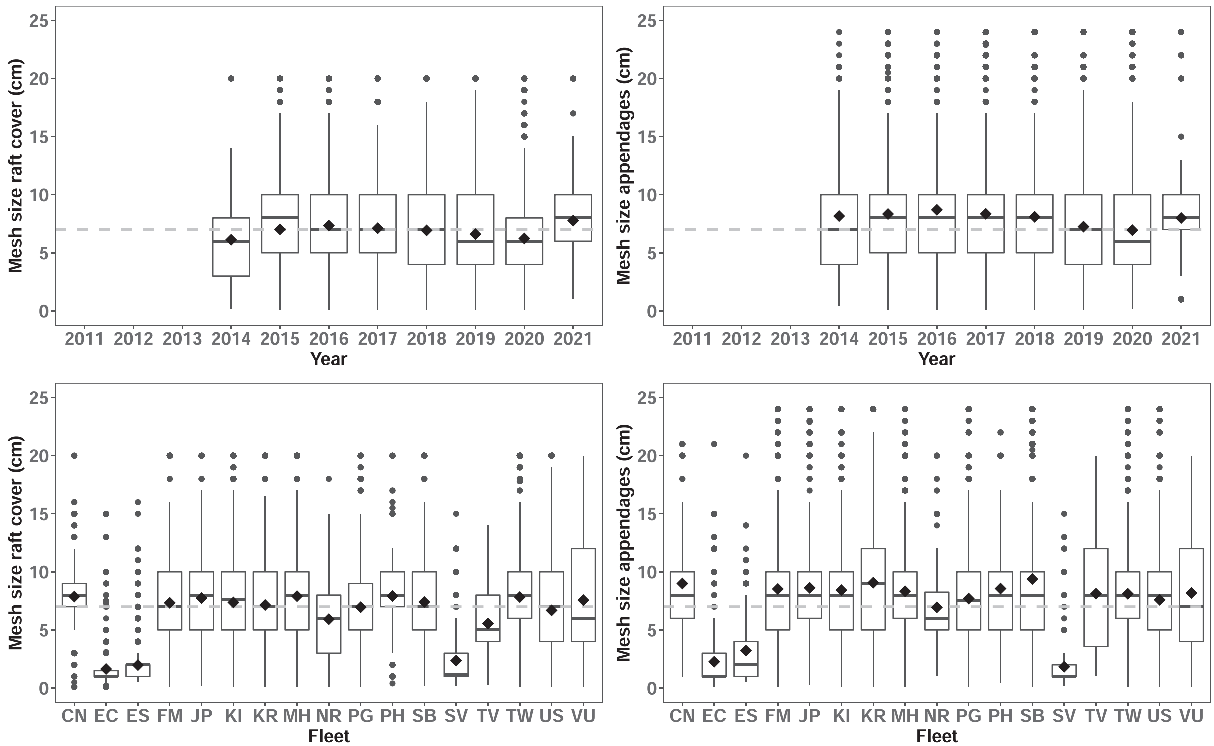

Fig. 9. Mesh size of netting used to cover rafts (left) and as appendages (right) of dFADs, as recorded by observers per year (top) and fleet (bottom) (2011–2021). The grey dotted line indicates the 7 cm mesh size, used to classify dFADs as high or low entanglement risk by WCPFC (see Fig. 2). Country abbreviations same as Fig. 6.

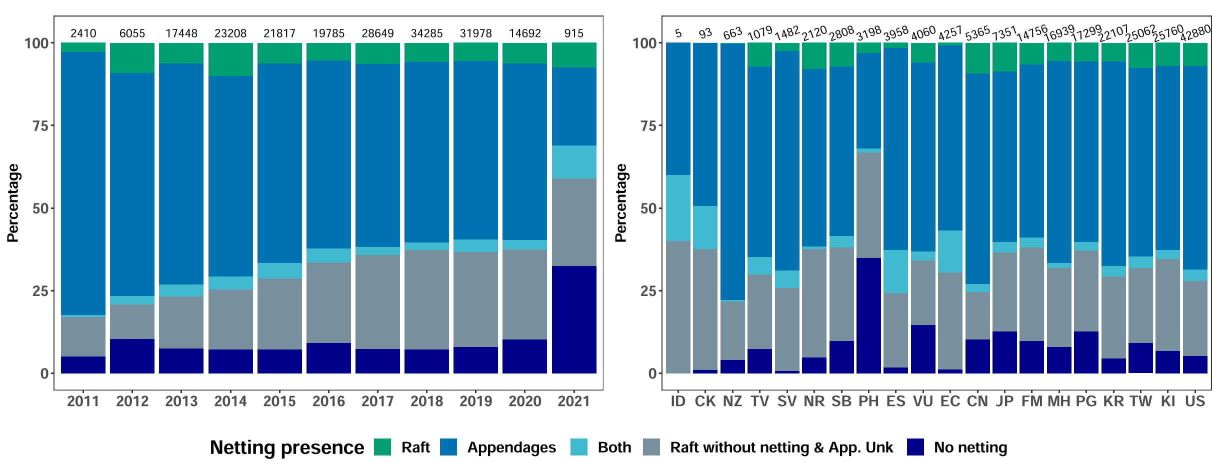

Fig. 10. The use of netting in rafts and appendages of dFADs, as recorded by observers per year (left) and fleet (right) (2011–2021). Raft without netting & app. Unk = raft without netting and unknown netting presence in appendages. Numbers on the top of the figure correspond to the number of dFADs observed per year or fleet. Country abbreviations same as Fig. 6.

4. Discussion

This paper reviewed available data from onboard fishery observers on the materials used to construct dFADs in the WCPO tuna fishery, the largest tuna fishery in the world. The aim was to identify a 'baseline' of dFAD construction and design that can be used to assess the impact of national and regional management measures being implemented within the fishery. We focussed the analyses on the use of synthetic materials and netting, including mesh size, and the length of dFAD underwater appendages.

4.1. dFAD designs and materials in the WCPO

Over the last decade we did not detect any clear temporal trends in dFAD construction and materials. This indicates that fleets have tended to use similar materials and construction approaches over recent years. It was notable that natural materials have been used to a very limited extent in dFAD rafts and submerged appendages in the WCPO. Synthetic floats, sometimes combined with bamboo or logs, are used by most fleets to provide buoyancy for dFAD rafts; and the submerged appendages tend to be constructed mostly from synthetic materials, with limited use of natural materials such as branches and coconut fronds. Finally, most dFADs use netting in some aspect of their construction. In 2021, a legally binding conservation and management measure to reduce the use of

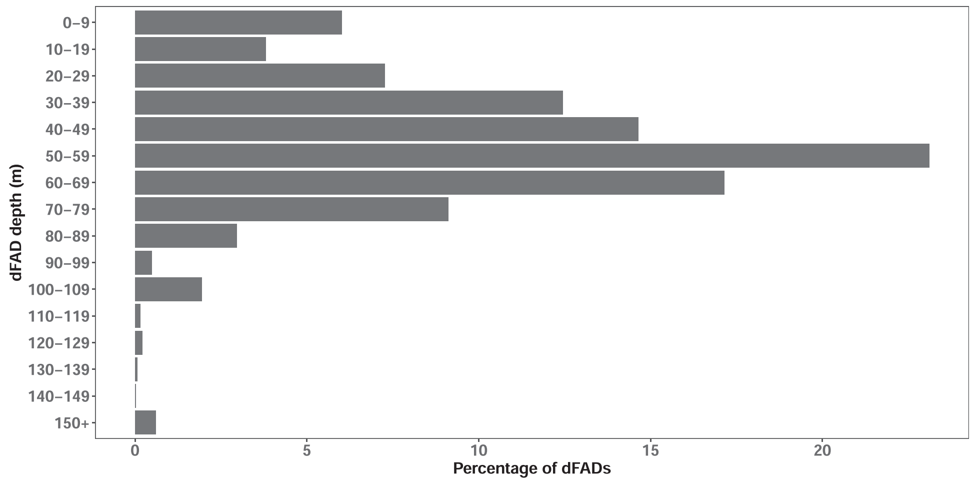

Fig. 11. Percentage of dFADs with submerged appendages of different depths (m), as recorded by observers between 2011 and 2021.

materials that present high entanglement risk was introduced by the WCPFC [38], which would be expected to lead to a reduction in the use of netting in dFADs. While a reduction in the presence of netting was observed in 2021, the data are limited due to COVID related low observer coverage and additional data are needed in coming years to confirm a reduction in the use of netting.

Analyses presented in this paper were guided by an approach proposed recently in the WCPFC and IATTC FAD working groups to transition to Biodegradable dFADs. Most dFADs currently used corresponded to dFADs of Category V, with synthetic materials only, and Category IV, synthetic appendages but natural raft, with the exception of synthetic buoys. Ropes and netting were also commonly used in rafts (Categories Vb and IIb) and could be easily removed or replaced by natural alternatives. This classification provides a baseline against which future data can be compared, in particular in relation to current and future management measures and the environmental impacts of dFADs. In addition to these categories, it would however also be useful to collect information on the proportion of natural and synthetic materials in dFADs, as another approach to track the transition to biodegradable dFADs could be to monitor the percentage of natural materials in the total volume or weight of dFADs.

4.2. Limitations with the available data

Our analyses highlight the need for more systematic records related to dFADs (i.e., records were available for less than 50 % of the activities on dFADs; Fig. 4). The primary reason for this is that observers have numerous tasks to perform (e.g. monitoring of targeted species catch and species composition; monitoring of bycatch and fates, including sensitive species; monitoring of marine pollution; monitoring of illegal fishing; biological sampling), and they cannot always monitor all these at once. During fishing operations, the observers may be too busy to record all the dFAD details. In addition, dFAD deployments sometimes occur at night, or while the observer is busy or resting; and dFAD visits without sets often occur early in the morning, before sunrise, limiting the observer's ability to record dFAD design and materials. Collaboration with skippers and crew may also be challenging, with sometimes no information given to observers or being limited by language barriers.

Further, important information for scientists and managers may often be missing or not directly recorded in the current GEN-5 form filled out by observers (Appendix 1), making assessment of dFAD use, materials, potential ecosystem impacts, and the uptake of management measures difficult. Firstly, regarding materials used in construction of dFADs, additional information on their biodegradable nature is needed. Currently, several materials recorded by observers could either be synthetic or natural (e.g., cords, ropes, canvas, netting, sacks and bags), but have been assumed here to be synthetic. In addition, proportions of each material in volume or weight, in the overall dFAD is lacking, but the practicality of observers making such assessments seems low. Secondly, while the presence of netting, and sometimes the mesh sizes are recorded, it is generally difficult to observe and record the design of submerged appendages. For instance, if the netting is tied in bundles, as is required for Low-Entanglement risk designs (Fig. 3), this cannot be assessed easily. A dFAD's design, for both raft and appendages, is an indication of both the entanglement risk of dFADs as well as other ecosystem impacts. This key information is currently not readily collected by observers, and likely requires alternative approaches to data collection before the dFADs are deployed.

While the data collection process and form are standardised across the PIRFO programs, variation in the amount and type of data collection between observers cannot be prevented, in particular for new observers. For instance, some observers might not record all dFAD materials, but focus only on the materials that make up most of the dFAD, such as the raft and appendages, without recording components such as ropes or attractors. Analyses accounting for the experience level of the observer could be considered, while training of fisheries observers related to dFAD data collection should continue, given the increase in dFAD-related management measures. Further, the priority of dFAD data collection by observers needs to be considered in relation to other tasks, and if dFAD data collection is considered a low priority, alternative data collection approaches will need to be considered.

The estimates of dFAD depth presented here may be biased, as they are based only on the observer's estimate, either when dFADs are lifted from the water or dragged by the speedboat close to the vessel's side. The observers do not have opportunity to actually measure the submerged appendages, and more accurate data on this dFAD component would require measurements made prior to deployment.

4.3. Additional data needed

Our paper has highlighted the need for better data collection on dFADs in the WCPO. While the study provides a useful baseline of the current materials and designs used in this region, the data collected by observers is limited in the level of detail and precision needed to fully document all the features of dFAD materials and designs. Greater efforts to obtain data on mesh size, dFAD design, biodegradability of materials, and their proportion in the overall materials, including on all new dFADs deployed, any retrieved dFADs or those that are found beached, should also be undertaken. Protocols to estimate dFAD submerged appendage depth could also be considered. However, it seems unlikely that all this information can be obtained by observers and alternative sources of information will be required to improve monitoring of dFAD materials and designs.

Data quantity and information content could be improved by updating the form currently used by fisheries observers to record dFAD related information, and/or in a specific dFAD logsheet filled out by vessel captains [39]. This would include more precise quantitative and measurable information, including proportion of each dFAD material and whether they are synthetic or biodegradable. This information may best be provided by dFAD manufacturers, as a set of standard dFAD specifications provided to skippers for each dFAD. Drawings/specifications from which dFAD designs can be chosen or categorised on logsheets would also simplify data collection. A dFAD logsheet, which includes most of these components mentioned above, has recently been developed in the WCPO and is being tested in 2022 [40]. Skippers have access to all the dFAD information, including materials, design, dimensions, mesh size and buoy ID number, which should, if filled in correctly, greatly improve the data collected. A comparison of data collected in both logsheet and observer data should however be implemented to verify this.

A further method to gather dFAD-related information could include the development of e-monitoring, with specific settings for dFAD deployments and visits. Photos could also be taken by observers to better characterise dFAD designs and materials. Port visits to dFAD construction yards or recording of information from dFADs while still stored on the vessel, could also be considered. Ultimately it may be possible that details of dFAD designs and materials could be maintained by dFAD manufacturers that supply the vessels, along with information on the numbers supplied to vessels.

In addition, more information on the satellite buoy attached to the dFAD is needed to better track dFADs throughout their lifetime, as this has been adopted as the dFAD marking mechanism by many tRFMOs [41]. The unique buoy identification number therefore should be systematically recorded [21] to allow individual dFAD trajectories to be accurately matched to fisheries data. Information regarding the date of activation/deactivation is also important. DFAD marking schemes [41] should also be considered, as buoys attached to dFADs are often exchanged, making it harder to follow the life history of an individual dFAD. DFAD buoys could then be matched with dFADs that they are initially deployed on.

Additional information on the fate of dFADs, particularly quantifying the number that are lost or abandoned and their ecosystem impact is important to sustainably manage dFAD use. Full trajectories from satellite buoys attached to dFADs, ideally both while monitored by vessels but also when drifting outside fishing areas [21] would be invaluable in quantifying dFAD fates. Collecting data in-county on impacts of dFADs would also complement fishery and trajectory data [42,43].

Finally, dedicated trials under real fishing conditions should be implemented to test novel dFAD designs and materials that are adapted to the WCPO conditions. While several trials have occurred worldwide for more than 15 years [44-46], trials have been limited in the WCPO [34,47]. Oceanography, fishing strategies, fisher design preferences and material availability should all be considered to determine acceptable and effective ecologically friendly dFAD designs. Several trials involving collaboration between governments, industry and international non-profit organisations, or led by fishing companies themselves, have recently started and results should help guide the transition towards novel Biodegradable and Non-entangling dFAD designs and materials in the WCPO [19].

4.4. Environmental impacts of dFAD structures

Pacific Island Countries and Territories (PICTs) have raised concerns about their islands receiving lost or abandoned dFADs, with stranding of dFAD rafts and their submerged appendages snagging and potentially damaging habitats, such as coral reefs and mangroves. The stranding of dFADs is also viewed as contributing to coastal pollution by ALDFG brought in by ocean currents [48,49]. Recent studies using dFAD positional data have estimated that around 7 % of dFADs become stranded in the WCPO [20,41]. In addition, it has been estimated that this level of stranding could affect 4–6 km^2 of coral reef habitat per year in the eight PICTs that are part of the Parties to the Nauru Agreement (PNA) [50]. This stranding rate is however likely to be a significant underestimate given that most dFADs stop being monitored before reaching coastal areas. In the Atlantic and Indian oceans, higher rates of stranding events have been detected, at 15–22 % of dFADs deployed over the last decade [51]. The likely underestimation in the Pacific Ocean triggered the need for data collection on lost and stranded dFADs directly in PICTs, to assess the real stranding rate, and to explore the impacts of dFADs on coastal ecosystems and communities [42]. Finally, a significant fraction of the lost and abandoned dFADs are likely to sink, with unknown and unmonitored consequences to the sea bed [52], including sensitive ecosystems like seamounts [24].

The dominance of dFADs incorporating netting in their construction used in the WCPO, as described in this study, could have negative ecological effects. Entanglement of sensitive species, such as turtles and sharks, can occur at different stages of a dFAD's life, from the time drifting at-sea, through to longer-term ghost fishing when the dFAD is lost or abandoned, to the final life stages if the dFAD strands and becomes snagged on coral reefs or other structured habitats [43,53-55]. When netting is used in dFADs, an important parameter to estimate for entanglement potential is the mesh size (particularly if it is above or below 7 cm). While a decrease in mesh size has been detected in recent years, more monitoring of this trend is required. Some fleets also only used very small mesh netting corresponding to vessels fishing in the Eastern Pacific Ocean (EPO) for a large part of the year (Ecuador, Spain and El Salvador). The investigation of netting use and mesh size did not account for how the netting was incorporated into the dFAD design (e.g., netting rolled up as sausages, freely hanging etc.), which can reduce entanglement risk (Low-Entanglement design, Fig. 3). This aspect of dFAD construction is currently not recorded by observers on the FAD-related data form and should be collected by observers where possible, as is already the case in the EPO [44].

4.5. Management measures

In relation to driving industry improvement in reducing, or preventing, marine pollution from dFADs, the WCPFC implemented two key CMMs: CMM 2017–04 (Conservation and Management Measure on Marine Pollution) [56] and CMM 2021–01 (Conservation and Management Measure for Bigeye, Yellowfin, and Skipjack tuna in the Western and Central Pacific Ocean) [31].

The first CMM prohibits the discharge of any plastics. Although it excludes fishing gear, WCPFC members are encouraged to prohibit their vessels from discarding fishing gear [56]. Additionally, WCPFC members are encouraged to retrieve, or report the location, size and age of abandoned, lost or discarded fishing gear. The second CMM contains provisions regarding both Non-Entangling and Biodegradable dFADs [31]. Specifically, to reduce the entanglement of sharks and sea turtles, under CMM 2021–01 WCPFC members are encouraged to limit the use of entangling materials, such as mesh netting. The provision to not use mesh netting will become mandatory as of January 1st 2024. Since January 2020, and until this measure becomes mandatory, dFADs are expected to comply with the Low-Entanglement risk designs. This means the use of mesh netting only if; i) the mesh size is $<$ 7 cm, or; ii) if netting is used in the appendages of a dFAD, the netting is rolled-up and secured as a bundle or "sausage" [38]. Additionally, WCPFC members are encouraged to transition their vessels towards using natural and biodegradable materials [31].

The design of most dFADs deployed over the last decade corresponds to high entanglement risk dFADs, as defined in Fig. 3, with limited use of natural materials. The high reliance on synthetic materials and netting presents a challenge to transitioning to Non-Entangling and Biodegradable dFADs. This likely relates to the types of materials that are readily available depending on the fleet and the different ports they use, as well as the current practice to recycle materials from purse seine activities (e.g., recycled purse seine nets, floats, ropes, salt bags etc.). Slight reductions in use of netting and the reduction in mesh size detected most recently might be an early indication of transition towards Low-Entanglement risk dFADs, influenced by the recent CMM. However, the use of fully Non-Entangling and Biodegradable dFADs appears to be very limited so far. This may indicate that voluntary adoption of such dFADs is unlikely and/or that there are other barriers to uptake (i.e., logistics, costs, material availability, perceptions of effectiveness, etc.).

A key factor influencing slow adoption of non-entangling and biodegradable designs is the need to move away from re-using readily available and low or no-cost materials (e.g., purse seine nets, corks, bamboos, salt bags) to new materials, often not available locally (biodegradable ropes or canvas, made of cotton, hemp or sisal). This transition will also imply a period where new designs need to be tested and may not initially work as effectively or for as long as conventional dFADs, leading to potential financial loss through lower catches or the need to re-deploy dFADs more often. Skipper awareness activities should therefore be promoted, through skipper workshops or training on biodegradable dFAD designs [45,57], using examples of designs and materials used by other fleets and oceans [19].

The importance of research and development in this area being in collaboration with industry cannot be understated and will be critical to driving the transition to new dFAD materials and designs. This collaborative work is currently ongoing in the WCPO [58], and large-scale industry-science collaborations have already been performed, including testing of a new biodegradable and non-entangling dFAD design, the Jelly-FAD, that was developed with advice from oceanographers [19,35]. The CMMs related to Non-Entangling and Biodegradable dFADs are very recent and are worded to encourage but do not yet mandate changes. Therefore, any noticeable effect may take at least one to two years, or likely longer to be detected. The implementation of these and future CMMs will ultimately force the industry-wide adoption of Non-Entangling and Biodegradable dFADs but will need to be cognizant of the time requirements for industry to identify materials and designs that are feasible, effective and economic, and supported by initial research and development, as well as the development of effective supply chains.

While the evolving CMM regulations mentioned above are encouraging, there remain a number of issues to address in order to reduce or mitigate the effects of dFADs on the marine ecosystem of the WCPO [59,60]. First, while more environmentally friendly, Non-Entangling and Biodegradable dFAD designs may still strand or sink and, when lost, the satellite and echosounder buoy attached to the dFAD can create marine pollution. Additional measures, such as buoy re-use/recycling programmes, may therefore complement the transition to environmentally friendly dFAD designs and materials. Second, dFAD recovery programs [22,61] could be implemented. A range of options for facilitating such programmes are possible, including requiring continued satellite broadcasting of dFAD location once outside the active fishing area or when entering a buffer zone around a sensitive area or high vessel use areas (FAD watch, [62,63]), to a rewards system for recovered dFADs or buoys. DFAD recovery by purse seiners could also be encouraged more widely [64], through mandated retrieval of dFADs encountered or set upon within a time period just prior to the dFAD closure period. Larger scale and more systematic recoveries are however challenging given the large spatial scale over which dFADs are distributed in the Pacific, the numerous island states, and the number of purse seine vessels in some regions (up to 300 in the WCPO, [16]). Finally, changes to the deployment strategies or locations could be implemented to avoid high numbers of dFAD losses or beaching events [51,61].

4.6. Comparison to other oceans

Management measures to mitigate the impacts of dFAD use on the marine ecosystem have been implemented by other tRFMOs (Table 4). In particular, the Indian (IOTC) and Atlantic (ICCAT) oceans tRFMOs are the most advanced in terms of Non-Entangling and Biodegradable dFADs use [65]. Trials to find appropriate Non-Entangling dFAD designs have been ongoing for more than 15 years in these oceans [66,67,46] and led to the mandatory use of Non-entanglement dFADs (as defined by ISSF, see Fig. 3) as of 2020 in the Indian Ocean and 2021 in the Atlantic Ocean [26,68] (Table 4). The Pacific (WCPFC and Inter-American Tropical Tuna Commission) has only recently, i.e., 2019 and 2020, started promoting the adoption of Low-Entangling designs (Table 4), and will transition to mandatory Non-Entangling dFAD designs in 2024. Regarding the use of Biodegradable dFADs, the Atlantic and Indian oceans implemented the mandatory use of Biodegradable dFAD materials from 2021 and 2022, respectively (Table 4). However, even if mandatory, the actual ocean-wide adoption of Biodegradable dFADs might not be occurring rapidly as they are still being tested and refined by the fishing fleets. Several trials of Biodegradable dFADs have already been implemented with a range of designs tested [32,33]. Despite management measures in place, studies on the level of actual adoption of Non-Entangling and Biodegradable dFADs by fishing fleets have occurred in some oceans [47], but are limited in the Pacific Ocean.

While all tRFMOs have also adopted a limit on the number of active buoys attached to dFADs that can be monitored by vessels at any given time, the Indian Ocean also limits the overall number of satellite buoys that can be purchased by a vessel each year to 500 buoys [26]. This annual limit would further limit the total number of dFAD deployments. DFAD recovery has also been discussed as an option to reduce the level of dFAD loss, however while some tRFMOs encourage the recovery of dFADs [68,69] it is not specifically required in dFAD-related management measures.

5. Conclusion

ALDFG is a significant concern for fisheries globally. In the purse seine fishery, high rates of dFAD loss and abandonment, and the high dependency on long lasting synthetic materials in the construction of dFADs, have raised concerns regarding the persistent ecosystem impacts of the dFAD fishery. While fleets in some oceans are achieving good progress towards fully Non-Entangling and Biodegradable dFADs, changes are occurring more slowly in the WCPO. Designs and materials currently used are dominated by synthetic materials, though sometimes mixed with bamboo or other natural or plant-based materials, but these

Table 4
Status of Non-Entangling and Biodegradable dFAD management measures in each tuna Regional Fisheries Management Organisations (tRFMO): Western and Central Pacific Fisheries Commission (WCPFC); Inter-American Tropical Tuna Commission (IATTC); Indian Ocean Tuna Commission (IOTC); and International Commission for the Conservation of Atlantic Tunas (ICCAT).

tRFMO	Low or Non-Entangling dFADs		Biodegradable dFADs	
	Status	Start date	Status	Start date
WCPFC	Low-Entangling (CMM-2019) Non-Entangling (CMM 2021–01)	2020 2024	Encouraged (CMM 2021–01)	2019
IATTC	Low-Entangling (C19–01)	2019	Encouraged (C19–01)	2019
IOTC	Non-Entangling (CMM-19–02)	2020	Encouraged (CMM-19–02) Mandatory (CMM-19–02)	2020 2022
ICCAT	Non-Entangling (REC 19–02)	2021	Encouraged (REC 19–02)	2021

generally remain a minor component of the whole structure. Encouragingly, trials of Biodegradable dFAD designs are now happening and should assist the fishing industry to transition towards more environmentally friendly dFADs. DFADs in the WCPO also typically include netting. Following the recent implementation of CMM 2021–01 by the WCPFC, which includes banning the use of netting by 2024, we expect to see reduction in the use of netting on dFADs in the WCPO, although the transition should start before that time, so that fishers can identify providers and test alternative designs and materials. It is important to collect relevant data to monitor the ongoing adoption of improved dFAD designs and materials by the industry; and to support implementation and enforcement of mandates. Increased awareness of the impact that lost or abandoned dFADs can have on the environment can also serve to accelerate adoption of best practice. A transition strategy with clear regional objectives, which couples the research and development needs with an industry uptake timeline, is now important in the WCPO. This paper can provide a baseline to further detect and monitor the changes in dFAD construction and materials, as the management evolves and industry responds.

CRediT authorship contribution statement

LE, NBP, PH, SH, JM and GP designed the analyses and interpreted the results, LE and NBP and JM performed the analyses. All authors contributed to the writing of the manuscript; and reviewed and revised the manuscript.

Data availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105500.

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