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Quantification and characterization of the environmental impacts of stranded FAD events on coastal zones in the Pacific Ocean

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Glossary

AFAD...................................... Anchored Fish Aggregating Devices
ALDFG................................. Abandoned, Lost or Otherwise Discarded Fishing Gear
AU.. Australia
BNER FAD.............................. Biodegradable Non-Entangling FADs
CA.. Convention Area
CK.. Cook Islands
DFAD..................................... Drifting Fish Aggregating Devices
EEZ .... Economic Exclusive Zone
FAD...................................... Fish Aggregating Device
FAME .... Fisheries, Aquaculture and Marine Ecosystems
FFA.. Pacific Islands Forum Fisheries Agency
FM .... Federated States of Micronesia
HER FAD .... Highest Entanglement Risk FADs
HW... Hawai'i
IATTC.................................... Inter American Tropical Tuna Commission
IUCN.................................... International Union for Conservation of Nature
LER FAD............................... Lowest Entanglement Risk FADs
MARPOL................................ International Convention for the Prevention of Pollution from Ships
MH... Republic of the Marshall Islands
NER FAD................................ Non-Entangling Risk FADs
NC.. New Caledonia
NGO..................................... Non-Governmental Organisation
PF... French Polynesia
PICT...................................... Pacific Island Country and Territory
PN.. Pitcairn Islands
PNA..................................... Parties to the Nauru Agreement
PNA TIA .... PNA Tracking Implementation Arrangement
PS... Purse Seine
PY.. Palmyra Atoll
SPC...................................... The Pacific Community
SSI .... Species of Special Interest
TNC....................................... The Nature Conservancy
tRFMO.................................. Tuna Regional Fisheries Management Organisation
TV... Tuvalu
USFWS.................................. U.S. Fish and Wildlife Service
VU.. Vanuatu
WCPFC................................. Western and Central Pacific Fisheries Commission
WCPO................................. Western and Central Pacific Ocean
WF... Wallis and Futuna
WS... Samoa Islands

1. Introduction

1.1. Marine pollution from Abandoned, Lost or Discarded Fishing Gear (ALDFG)

Abandoned, Lost or Otherwise Discarded Fishing Gear (ALDFG) are a growing concern for sustainable fisheries in terms of environmental, social and economic impacts (Richardson *et al.*, 2019; Burt *et al.*, 2020; Gilman *et al.*, 2021; Giskes *et al.*, 2022). ALDFG represents a substantial part of the global marine debris (10%, following Macfadyen *et al.*, 2009), especially marine plastic pollution (Wilcox *et al.*, 2014; Lebreton *et al.*, 2018; Richardson *et al.*, 2019). As an example, up to 46% of the “Great Pacific Garbage Patch” is composed of ALDFG (Lebreton *et al.*, 2018). Fishing gear is often made of synthetic fibber which can degrade into small particles and then integrate the microplastic compartment. For instance, Xue *et al.*, (2020) found that fishing gear represented up to 61.6% of the microplastics at the surface of the ocean’s floor of a small traditional fishing ground bay and were found as deep as 60 cm into the sediment. In addition to the plastic pollution issue, ALDFG also represents a navigation hazard for vessels and therefore represents a safety issue for users (Macfadyen *et al.*, 2009; Hong *et al.*, 2017; Gilman *et al.*, 2021); but also an entanglement risk for marine life and particularly for species of special interest (SSI) (Wilcox *et al.*, 2014; Escalle *et al.*, 2019b; Forget *et al.*, 2021). Fishing gear is designed to catch marine species, when abandoned or lost, it can therefore continue to catch target and non-target species, indiscriminately. This phenomenon is known as “ghost fishing” and is one of the main impacts from ALDFG (NOAA, 2015; Link *et al.*, 2019; Gilman *et al.*, 2021). It also damages sensitive ecosystems such as coral reefs (Donohue *et al.*, 2001; Gershman *et al.*, 2015; Maufroy *et al.*, 2015; Escalle *et al.*, 2019b), benthic habitats (Consoli *et al.*, 2020) or mangroves, which are considered as nursery grounds for many marine species (Arifanti, 2020; Giskes *et al.*, 2022). To reduce plastic pollution in the environment, one of the solutions would be to remove it. However, the price for removing plastic waste can be high, particularly for small insular countries and territories, with often limited collection plans or specific recycling infrastructures. As an example, Burt *et al.*, (2020) removed 25 tonnes of plastic wastes out of the 513 tonnes estimated locally from an atoll of about 155 km² located in Indian ocean; and 83% of the litter removed came from the fishing industry. The cost to remove these 25 tonnes was of $224,537, while removing the total amount from the island was estimated at $1.95–$7.28 million. It illustrates that plastic pollution is not only an environmental issue, but also an economic one faced by small countries and territories, with the fishing industry responsible for a significant part. This is the case for Pacific Islands Countries and Territories (PICTs), which voiced their concerns about the increasing number of marine debris stranding on their shores, and particularly fishing gear and devices. For instance, Hawai’i Island receives on its coast around 52 tons of derelict fishing gear each year (Gilardi *et al.*, 2010). These PICTs might not always have facilities or plans to collect, manage or recycle what washes up on shores (Escalle *et al.*, 2020). Moreover, main government incomes, as well as community livelihood, often come from tourism and/or fishing activities and ALDFG are putting at risk these activities (Escalle *et al.*, 2020). Generally, Richardson *et al.*, (2019) found that 5.7% of nets; 8.6% of traps; and 29% of lines were lost each year worldwide. However, the type of fishing gear that are lost, abandoned or found stranded may vary from one location to the next, depending on the fishing type used locally; national and international regulations; and marine currents (Richardson *et al.*, 2019). While the loss of some fishing gear (i.e. nets, traps, and lines) is well studied (Macfadyen *et al.*, 2009; NOAA, 2015; Richardson *et al.*, 2019), others fishing gear and devices receive less attention, likely due to the difficulties in estimating loss and abandonment (Richardson *et al.*, 2021). This is the case for Fish Aggregating Devices (FADs), which lack dedicated assessments related to loss, abandonment and their consequences (Macfadyen *et al.*, 2009; Richardson *et al.*, 2019) but can have negative environmental impacts on marine and coastal ecosystems and species (Bromhead *et al.*, 2003; Dagorn *et al.*, 2013; Consoli *et al.*, 2020).

1.2. What are Fish Aggregating Devices (FADs) ?

The use of FADs originates from Mediterranean, Southeast Asian and Western and Central Pacific fishermen more than one hundred years ago who noted that their catches were better under natural floating objects such as logs, seaweed mats, branches and palm leaves, than in the open ocean (Bromhead *et al.*, 2003). Consequently, fishermen started to deploy their own artificial FADs. Several theories exist to explain the aggregative behaviour of tunas ; it could be a an indicator of food rich environment (Freon and Dagorn, 2000; Bromhead *et al.*, 2003), a meeting point (Freon and Dagorn, 2000; Bromhead *et al.*, 2003), or because it is aggregating large schools, it could act as a shelter from predators (Freon and Dagorn, 2000).

There are two types of artificial FADs[1] : anchored (aFADs) and drifting (dFADs). The first one, widely used by artisanal fishers, is composed of a floating structure, typically made of bamboo or floats, but also could be a large metal drum attached to an anchor at the bottom of the ocean, often nearshore (Appendix l). Fishermen use aFADs to facilitate the location of fish, and insure continuous fishing effort, but it also transfers fishing effort from lagoon to oceanic area and play a key role in food security in many small PICTs (Desurmont and Chapman, 2000; Bromhead *et al.*, 2003; Bell *et al.*, 2015). Regarding the second type of FADs, used in the open ocean by industrial purse seine vessels, historically fishers used natural logs, randomly encountered at-sea (Leroy et al., 2013) but gradually, fishers started deploying their own dFADs to which they attached a

[1] In this report, « FADs » includes all types of floating object, natural or artificial, whereas words « aFADs » and « dFADs » refer to an artificial raft made by fishermen.

beacon(Lopez *et al.*, 2014). DFADs are often composed of a surface structure made of bamboo and/or PVC tubes, selected for their lightweight and waterlogging resistance nature (Bromhead *et al.*, 2003; Franco *et al.*, 2009). To increase the buoyancy properties of the raft, some floats from purse seine nets are also often added (Franco *et al.*, 2009). This upper structure is also often wrapped in black nets to avoid detection from other vessels. There is also a sub-surface structure which is generally composed of nets and/or ropes (Bromhead *et al.*, 2003; Dagorn *et al.*, 2013; Abascal *et al.*, 2014). The size of this sub-surface structure varies among fleets and oceans, and fishers believe that it is a major component to attract fish (Dagorn *et al.*, 2013) (Appendix I). For instance, European skippers use between 10 and 15 meters of nets in Indian Ocean, whereas Korean skippers use up to 100m in Atlantic Ocean (Dagorn *et al.*, 2013). In the WCPO, the depth approaches 41m (Abascal *et al.*, 2014). A satellite buoy is also attached to the dFAD, allowing fishermen to keep track and position of the dFAD at any given time (Lopez *et al.*, 2014) (Appendix I). The most recent buoys are equipped with an echosounder which estimates the biomass underneath in real time, as well as, for some buoys, inform on the species composition of the school associated with the dFAD (Dagorn *et al.*, 2013; Davies *et al.*, 2017).

Globally, dFADs are widely used in tropical and subtropical tuna fisheries (Fonteneau et al. 2000). From the past two decades, dFADs improvement has made dFAD associated sets one of the most common tuna purse seine fishing mode and sets associated to dFAD represents half of the catches of tunas worldwide (Balderson and Martin, 2015). Even if it is commonly and widely use, it is still difficult to access the number on dFAD used globally. Gershman *et al.* (2015), estimated that between 47,000 and 105,000 dFADs are deployed annually.

1.3. Impacts of FADs globally

From an environmental point of view, dFADs can lead to numerous issues. The first one is related to long-term sustainability issues of tuna stocks. The purse seine fishery, catches the three species of tropical tuna : the skipjack tuna (*Katsuwonus pelamis*), the yellowfin tuna (*Thunnus albacares*), the bigeye tuna (*Thunnus obesus*), with most of catches are of skipjack (65–77%), followed by yellowfin (20–30%) and bigeye (2–5%) (Williams and Ruaia, 2021). These species, as many pelagic fish, have a tendencies to aggregate under floating objects such as FADs (Ménard *et al.*, 2000; Bromhead *et al.*, 2003). In this fishery, tunas can be caught either on free schools (mostly monospecific school), or on FADs which can aggregate several tunas species, mostly dominated by skipjack, but also juveniles yellowfin and bigeye tuna, as well as other pelagic species, such as wahoo (*Acanthocybium solandri*), billfish (*Xiphiidae* and *Istiophoridae*), barracudas (*Sphyranea barracuda*), or sharks (Ménard *et al.*, 2000; Escalle *et al.*, 2019a). At the set level, juveniles bigeye and yellowfin catch remains low, however given the extent of the purse seine fishery, quantities are large and this raised concerned about the sustainability of the stocks (Marsac *et al.*, 2000; Hallier and Gaertner, 2008; Dagorn *et al.*, 2013). Catching small individuals cause two main problems for tunas stocks ; the first one is the decrease of yield per recruit, whereas they could be caught later and bigger (Fonteneau *et al.*, 2000; Hallier and Gaertner, 2008; Dagorn *et al.*, 2013; Leroy *et al.*, 2013), and the second one is the reduction of the spawning biomass because of overfishing (Fonteneau *et al.*, 2000). Overfishing a stock is not threatening only stock's health and ecosystems functioning, but also the economic prosperity of fisheries (Giskes *et al.*, 2022).

In addition to the overfishing issue, dFADs could represent an "ecological trap" for tunas (Fonteneau *et al.*, 2000; Marsac *et al.*, 2000; Hallier and Gaertner, 2008; Dagorn *et al.*, 2013). Natural floating objects such as logs often come from rivers and lands, which release large amount of nutrients. In the open ocean, dFADs act like natural floating objects (Marsac *et al.*, 2000) and therefore potentially leading tuna to stay in unproductive areas altering movement patterns (Fonteneau *et al.*, 2000; Marsac *et al.*, 2000), and potentially have negative effects on life history traits (Fonteneau *et al.*, 2000).

The purse seine fishery associated to dFADs have bycatch rates 3–4 times higher than fishing on free schools (up to 6 times higher in the Pacific Ocean) (Dagorn *et al.*, 2013), but this remains low compared to other fisheries like longline or trawling (Abascal *et al.*, 2014). SSI have life history traits which are sensitive to non-natural mortality. They often present a long lifespan with low reproductive rates and incidental mortality leads to conservation issues (Hall *et al.*, 2000, 2017). Bycatch in purse seine fishery accounts for less than 1% in weight, but because of the impressive volume of catches, the total bycatch is significant (Dagorn *et al.*, 2013; Forget *et al.*, 2021). For instance, silky shark is often associated with tuna schools and thus caught as a bycatch by purse seine fisheries (Compagno, 1984). In the world, it has been estimated that between 400,000 and 2 million silky sharks (*Carcharhinus falciformis*) are fished as bycatch in the tuna purse seine fishery (Filmalter *et al.*, 2013). As a consequence, since 2017, it has been classified as vulnerable by the International Union for Conservation of Nature (IUCN) red list but population is still decreasing (Rigby *et al.*, 2017). Although, it is difficult to monitor and estimate bycatch because of low percentage coverage of observers, and changes in fishermen behaviour in observer's presence (Bourjea *et al.*, 2014; Hall *et al.*, 2017).

DFADs also present an important entanglement risks and ghost fishing to SSI (Franco *et al.*, 2009; Dagorn *et al.*, 2013; Filmalter *et al.*, 2013; Balderson and Martin, 2015; Escalle *et al.*, 2019b). Nets or ropes from the surface and the sub-surface structure used to aggregate fish, can cause entanglement of sensitive species such as sharks (Filmalter *et al.*, 2013; Rigby *et al.*, 2017), turtles (Franco *et al.*, 2009; Bourjea *et al.*, 2014) or seabirds (Hall *et al.*, 2017). For instance, turtles could use a dFAD as a resting spot or spent a part of their life aggregating to floating objects and be entangled in the nets (Franco *et al.*, 2009; Balderson and Martin, 2015).

Once dFADs are abandoned or lost, they drift with marine currents and can potentially strand on near-shore environments (Balderson and Martin, 2015; Maufroy *et al.*, 2015; Escalle *et al.*, 2019b). “Stranding” events are defined as any floating objects arriving near shores and ends up grounded or beached and may cause environmental damages (Davies *et al.*, 2017).When stranding occurs, dFADs can still impact sensitive species but marine habitats too such as coral reefs. Coral reefs are characterized by a high primary productivity and a high biodiversity (Hoegh-Guldberg, 2004). They are also important ecosystems in terms of economic and social development of small insular territories : subsistence fishing as well as artisanal fishing, tourism and recreation and coastal protection (Hoegh-Guldberg, 2004; Banks and Zaharia, 2020). In fact, nets and ropes used in the dFAD construction can be entangled in coral reefs or snatch them (Balderson and Martin, 2015; Consoli *et al.*, 2020). Entanglements and ghost fishing, mentioned previously can also happened when dFAD are stranded.

In addition to entanglements and ghost fishing, stranded dFADs may represent a significant part of the coastal marine pollution (Balderson and Martin, 2015; Escalle *et al.*, 2019b). Many dFAD components are synthetic and could break apart into smaller pieces and contributes to plastic pollution. Satellite buoys could also add pollution, in particular in regards to their many electronic components. However the recovery and the cleaning are expensive and a tough job to resolve (Burt *et al.*, 2020).

1.4. The purse seine fishery and FADs in the WCPO

The WCPO presents the higher total tuna catch and accounted for 2,493,571 t (tons) in 2021. It represents 56% of the global tuna catch (with global estimate around 4,436,543 t for 2021). The WCPO purse seine fishery is the largest in the world, with 262 vessels registered in 2021 catching 69% of tuna catch in the WCPO (Williams and Ruaia, 2021). From an economic point of view, the total WCPO tuna catch in 2020 was valued at around $4.9 billion, in which the purse seine fishery yielded at $2.8 billion, representing 56% of the total value (Williams and Ruaia, 2021). Almost half of the catch by the purse seine fishery is made using dFADs (48% in 2021). This source of incomes is extremely important for PICTs, as it represents up to 98% of the national revenue (FFA, 2017) and is a major source of employment. As an example, employments in governments and fishing industries within members of the Pacific Islands Forum Fisheries Agency (FFA) combined (i.e. 15), concerned around 23,000 people in 2015 (FFA, 2017). Onshore, the processing sector gathers about 11,000 workers in which 70–90% are women (FFA, 2017). In the Western and Central Pacific Ocean (WCPO), estimates of dFADs have been compiled and oscillate between 30,000 and 40,000 per year.

The fates of these dFADs and their ecological impacts when leaving fishing grounds are however not well known. A recent report by Escalle *et al.*, (2021) highlighted the miscellaneous fates of buoys, and likely of dFADs attached to it as well. Over the 67,074 buoys studied between 2016 and 2020 ; 44.1% of buoys were abandoned, 9.6% were retrieved; 6.6% stranded; 18.4% sunk, appropriated or had a malfunctioning buoy; and 21.3% were deliberately deactivated by the fishing company and left at sea. This highlights the uncertainty with the fate of many dFADs in the WCPO, and also the likely high rates of abandonment and loss. It should also be mentioned that the rate of stranding events estimated are likely under-estimated because of the general deactivation of buoys because of geo-fencing issue. Thus, there is no current data available to follow buoys and/or dFADs after deactivation and a lot of uncertainty exists related to the actual environmental impact assessment. Once a dFAD is abandoned, there is no way to monitor damages it could cause in terms of entanglement onshore or offshore. Then, there is a lack of studies to assess precisely the mortality of sensitive species associated with entanglements, or the damaged coral surface (Dagorn *et al.*, 2013; Escalle *et al.*, 2019b).

1.5. FAD Management and monitoring in the WCPO

In order to reduce the impacts of dFADs on tuna stocks and on the environment, management measures have been implemented in the WCPO. The Western Central Pacific Fisheries Commission (WCPFC) is the tuna Regional Fisheries Management Organisation (tRFMO) regulating tuna stocks in the WCPO. It implemented 3 to 4 months period where all activities linked to dFAD are prohibited (WCPFC, 2021). In addition, vessels can only monitor 350 buoys at any given time. Additional conservation and management measures have recently been implemented to reduce the impact of dFAD use on the environment. For instance, measures linked to dFAD design and construction have been implemented. Mandatory use of Low Entanglement Risk FADs (LER FAD) has been put in place from 1st January 2020 and stipulates that if nets are present in the sub-surface appendage, it should be either with a mesh nets size inferior to 7 cm, or should be tied as a sausage bundle to avoid any potential entanglement of SSI (Franco *et al.*, 2009; WCPFC, 2018; Murua *et al.*, 2021). In addition, as from January the 1st 2024, construction of non-entangling dFADs (NER FAD) will be required (WCPFC, 2021). It means that use of nets will then be totally prohibited in any part of the FAD. As well, WCPFC encourages the use of biodegradable and plastic free material dFADs construction to avoid plastic pollution, and scientific research concerns related to the development of biodegradable FADs (BNER FAD) is currently ongoing (WCPFC, 2021). However, even though efforts are made to transition to more eco-friendly dFAD designs, there is no regulation or sanction existing for fishing companies when a dFAD is lost or deliberately abandoned/deactivated because it is judged to be not productive or outside authorized fishing areas (Hanich *et al.*, 2019; Churchill, 2021).

In addition to WCPFC, another international management body is very important for the purse seine fishery in the region: the Parties of the Nauru Agreement (PNA). It is composed of 9 Pacific countries (Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, Tuvalu and Tokelau), which have launched, through their licencing agreements, a FAD tracking program in order to access trajectories of dFADs, from vessels fishing in their waters (Escalle *et al.*, 2021c). It is a unique system in the world for monitoring dFADs at a large scale (Baske *et al.*, 2015; Banks and Zaharia, 2020). Despite this innovative system, because of fishermen's concerns over the confidentiality of the data, they are not obliged to transmit entire trajectories of buoys. As a consequence, some trajectories present gaps, especially outside the authorized fishing grounds (i.e. geo-fencing), leading to bias in any scientific analyse, in particular under-estimation of stranding events outside PNA EEZs (Escalle *et al.*, 2019b).

1.6. Current lacks, needs, and objective of study

While concerns about the environmental impacts of dFADs through marine pollution and stranding events have been raised, few studies exist to quantify and assess more precisely the number of dFADs reaching coastal areas and the environmental damages they could cause (Dagorn *et al.*, 2013). There is a substantial lack of assessment of the environmental impacts of lost and abandoned dFADs. These are key components to design effective conservation and management measures to mitigate against potential impacts and to design adequate dFAD management measures. Several stakeholders, NGOs and PICTs have raised concerns about these issues, including PICTs without purse seine activities (e.g., French Polynesia, Hawai'i or Palmyra).

In view of the context mentioned above, this study aims at assessing the environmental impact of dFADs in the WCPO, particularly on coastal environment and in view of the current designs and materials used. Three objectives have therefore been defined : (i) characterize stranding events using data collected directly *in-situ*, and evaluate the environmental impact; (ii) assess the design and materials currently used in the dFAD construction and compare it to the designs and materials of dFAD found stranded in the WCPO; (iii) highlight any origin areas of dFAD found stranded and owner fleets.

2. Materials and methods

2.1. Study site and regional organisations involved

This study focuses on the WCPO, which includes several PICTs. The fisheries in the region are managed by several organisations. First, the tuna Regional Fisheries Management Organisations (tRFMO), such as the WCPFC and the Inter American Tropical Tuna Commission (IATTC), which are responsible for the conservation and management of tuna and tuna-like species, associated species and their ecosystems, through the management of high sea fisheries. There are also organisations between countries such as the Parties of the Nauru Agreement (PNA) and the Pacific Islands Forum Fisheries Agency (FFA) which work together to have more weight in discussions related to management and conservation of oceanic resources (Figure 1).

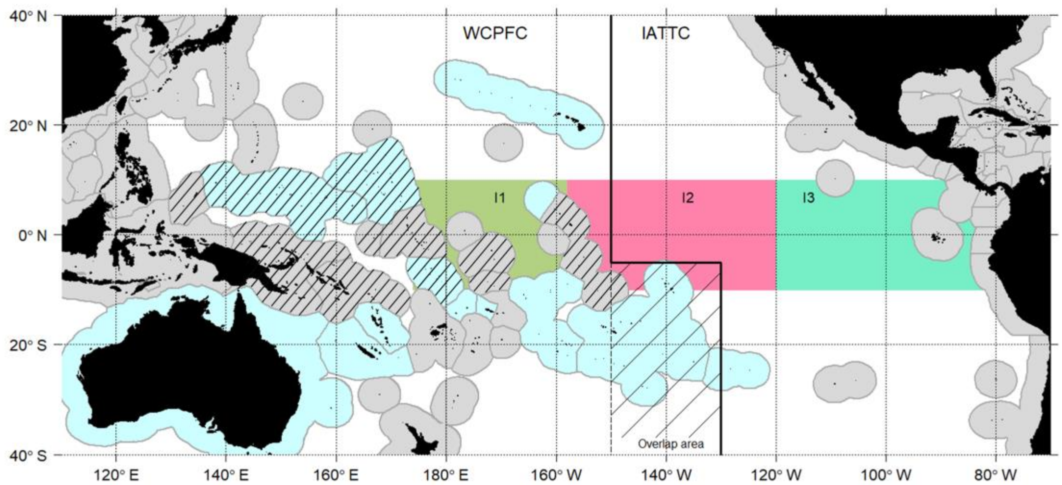

Figure 1. Map of the Pacific Ocean with the convention area of the WCPFC and the IATTC. In cross-hatched, country members of PNA waters, and in blue countries involved in the stranded data collection program.

2.2. Stranded database collection

2.2.1. Data collection

In the context outlined above and the need to assess more accurately the number of dFAD fates and assess their environmental impacts, in particular those reaching coastal areas, programs to collect data *in-situ* have started in some of the PICTs (Table 1). These programs have started in the Cook Islands (CK), Wallis and Futuna (WF), the Federated States of Micronesia (FM) and the Republic of the Marshall Islands (MI), Hawai'i (HW), Palmyra (PY) and French Polynesia (PF) for couple of years, and in New Caledonia (NC) and Tuvalu (TV) this year. Samoa (WS) and the Solomon Islands (SB) have also shown interest in joining the data collection effort.

First, some data collection programs have involved collaboration between fisheries departments, Non-Governmental Organisations (NGOs) and SPC (CK, WF, FM, MI, NC, TV). It involves local communities reporting lost or stranded FADs and satellite buoys to fisheries officers who enter data into a local database. This data collection being highly reliant on reports from local communities, either through an existing program or opportunistic reports, communication and awareness activities were essential. Posters, newspaper articles, radio announcements or TV broadcasts were used as communication tools to raise awareness around this project (Appendix ll) (Escalle *et al.*, 2022).

Second, in addition to, or prior to existing programs, opportunistic data collection has also been reported to SPC since 2018, including through SPC's existing data collection networks. This includes additional records from Australia (AU), Pitcairn Islands (PN), Samoa (WS), Tuvalu (TV) and Vanuatu (VU).

Third, other programs have been developed in PY, HW and PF prior to the regional data collection from SPC. In PY, The Nature Conservancy (TNC) and the U.S. Fish and Wildlife Service (USFWS) have started visual surveys across reefs, lagoons and beaches since 2009. Specific areas with more stranding events have been identified in the first years of the program and led to more precise and regular surveys in the following years. In HW, the Center for Marine Debris Research have collected data since 2014. The program is based on reports from several collaborators and when the location allowed it, satellite buoys are retrieved and stored on O'ahu in order to be reused as tracking devices for marine debris like fishing nets (Escalle *et al.*, 2022). In PF, a program started in 2019 by the Marine Resources Authority and involved several types of data. Reports from local communities were made via a form that can be directly downloaded or filled up on the marine resources authority's website (Escalle *et al.*, 2022). Scientific surveys in 9 islands of the Tuamotu archipelago were also implemented, which included visits to communities, a drone to survey the shoreline and initiatives to recycle satellite buoys or dFADs (Escalle *et al.*, 2022).

Generally, all these data collection programs aimed at:

- quantifying the number of dFAD stranding events or dFADs drifting nearshore;
- assessing the impacts of stranding events on ecosystems, particularly on coral reefs, and SSIs through recording of the FAD design and materials;
- appraising recycling and re-using of satellite buoys and dFADs materials by local communities; and

- considering ways to mitigate these impacts and providing scientific-based advice to guide the management of dFADs in the Pacific Ocean.

Similar data were collected in all the programs, and a unique form a database is now used in all the programs (apart from PF). When a FAD and/or a satellite buoy was found, a FAD sighting form has to be filled up to facilitate the data collection and in order to have a standardized format to allow comparison between PICTs (Appendix lll). Some information was requested in priority such as the type of object, the date and the location it was found. In addition, if a buoy was present, the buoy ID number and any marks on it, was required, as this is a valuable information to allow potential link with other fishery databases (see next section). Other information was also required, such as the type of environment where the FAD or buoy was found; as well as any observations of entangled coral or animals. In terms of FAD-related information, the size, shape, condition, but also the materials of the raft and the attachments were recorded, when possible. The fate of the FAD and buoy was also required when available (i.e. removed, left, fished). When possible, photos were also taken in order to allow fisheries officers and/or SPC to check or complete the recorded information.

Once information was collected, data was entered by local partners into Google spreadsheets, specific to each PICT, that can been available and updated at any time by the partners and SPC (Appendix IV). Finally, each individual databases were merged together by SPC into a unique regional database. So far, over 1,159 stranding events were recorded from all programs around the Pacific region (Table 1).

Table 1. Summary of the data collected through stranded dFAD data collection programs in the WCPO

PICT	Start of the program	Events recorded
French Polynesia	2019	536
Wallis and Futuna	2020	160
Federated States of Micronesia	2021	139
Cook Islands	2020	96
Hawai'i	2014	83
Palmyra	2009	64
New Caledonia	2022	32
Republic of Marshall Islands	2021	24
Tuvalu	2022	10
Samoa	Under discussion	1
Pitcairn	Opportunistically	7
Australia	Opportunistically	4
Vanuatu	Opportunistically	3
Total		1,159

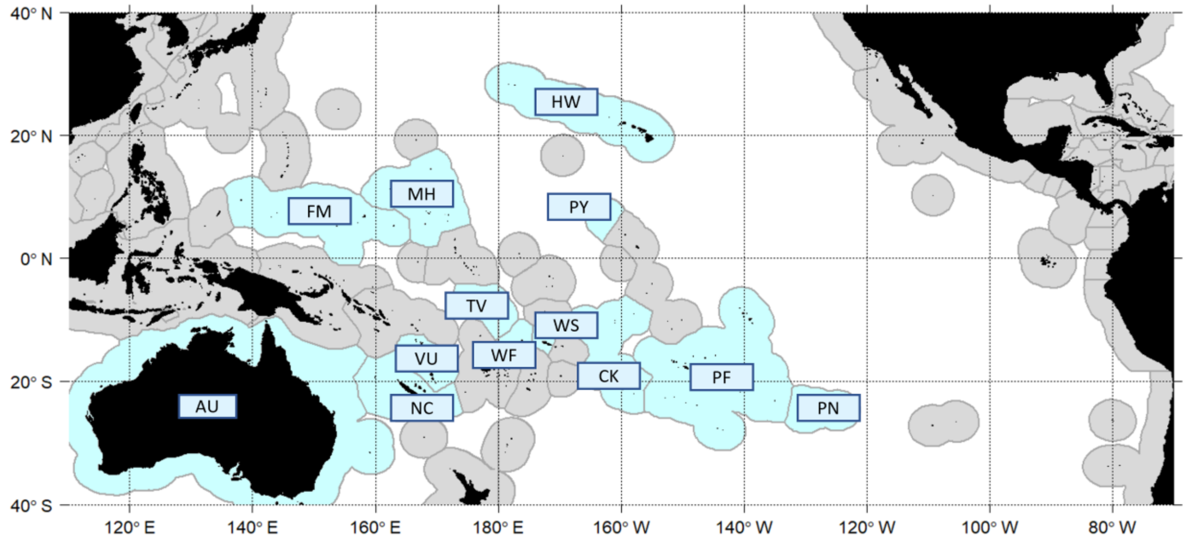

Figure 2. Pacific countries involved in the data collection. See glossary for country codes.

2.2.2. Database homogenization

This regional database from the 9 PICTs (+ opportunistic records) was then processed using several data cleaning, processing and homogenising steps. This was particularly needed because the data collection involved citizen-science and opportunistic records, leading to missing or imprecise information. When some fields were not recorded or were imprecise, several steps were taken. First, we contacted the fisheries officer or the scientist involved in the data collection. Second, photos were used to double check or complete missing information. Third, if information were still missing, the field was marked as "unknown".

The exact GPS coordinates were often not recorded, with often only the name of the island and location where the FAD or buoy was found. The Google Earth software was therefore used to access the coordinates of each stranding event. When we only had the name of the island, without precise information about the location, we associated the GPS coordinates to the center of the island and did not consider the environment where it has been found, as coordinates were only used for mapping. We did this approximation because the scale of the map used for this study is high, islands are often small and can be approximative for some points.

For the environmental damages and entangled animals, we considered a damage either when it was already recorded or when it was visible in the pictures. While photos were not always provided and this information was sometimes lacking there might be a significant underestimation of environmental impact from dFADs stranding events.

2.3. Other types of data

Several databases were used to maximize information about stranding events such as the PNA FAD tracking dataset, but also observer data from the WCPFC and IATTC. For the three fishery databases, the buoy ID number was the key to link with the stranded database.

As said previously, the PNA FAD tracking data is a system which monitors buoys attached to dFADs. Every buoy registered presents a unique ID number. For each buoy, the GPS position is recorded with a regular frequency (often hourly, otherwise daily) and transmitted to PNA and SPC. Other information is also available, such as the vessel and the company owner of the buoy, and the fate of the buoy (assessed using a random forest classification, (see Escalle *et al.*, 2021c)).

The WCPFC observer program (the Pacific Islands Regional Fisheries Observer) has a specific form dedicated to recording FAD related information (aFADs, dFADs and logs). This form named GEN-5 reunites practical information such as date and location of the FAD related activity but also on the materials (Appendix V). It describes the raft size (length and width) as well as the depth of submerged appendages, details materials used for the cover and the tail, and has the ID number of the attached satellite buoy, as well as GPS coordinates and date at the time of each observation. However, the preciseness of the information depends on the observer access to the FAD (often in the water), therefore some information are often lacking or are imprecise (materials or buoy ID number).

For the IATTC database, similar information is available. For this particular study we requested specific information linked to each activities from buoys found in the FAD stranded database. This included the buoy ID number ; the date and location (GPS coordinates) of each activity from buoys and/or FADs found in the FAD stranded database. Due to confidentiality issues, vessel or company name were not available for this study, even if they exist in the database.

2.4. Analyses

2.4.1. Characterization of stranding events

First, descriptive statistics were performed to characterize FADs stranding events. First of all, characterization of the type of floating object that has been found (e.g. type of FAD and/or buoy). Spatial mapping was then performed, to investigate potential patterns of stranding events by PICTs and the type of habitat impacted. The fates of satellite buoys and FADs were also investigated to see if some countries found ways to transform and/or recycle these items locally. Coral entanglement as well as any entangled animals or traces (e.g. bones, scales, body parts) of it, were quantified.

2.4.2. Analysis of the material used to build FADs

Once the stranding events were characterized, one of the objectives was to analyse the materials used in dFADs construction. Flotation materials and covering of rafts and sub-surface appendages materials, were separated for analyses in order to investigate the i) ratios of natural vs synthetic materials; ii) presence of netting (entangling potential). Then, wider categories of materials were created. Moreover, when it was recorded, netting mesh size was also investigated and classified into “small” or “large” categories.

A complementary study, based on WCPFC observer records, was also performed to characterize the materials used in dFADs constructions (Escalle *et al.*, under review) and compare to the ones found stranded. dFADs could either be man-made, or potentially a log modified by fishers and with a satellite buoy attached or not. Both categories were included in this analysis. All materials were, again, classified as natural, synthetic or a mix of both, for the surface and the sub-surface structure, over time and across fleets (if present) (Escalle *et al.*, under review). The depth of submerged attachments was also investigated. Note that due to the difficulty for observers to see FADs in the water, entanglements are also never recorded and therefore could not be investigated here.

2.4.3. Trajectories and origin

One of the main objectives of this study was to identify the origin of floating objects stranded in different PICTs. We used the three fishery databases mentioned above (PNA FAD tracking data; IATTC and WCPFC observers programs) to track the origin of buoys on dFADs as well as nationality of the last fishing vessel that monitored or used the buoy and the Convention Area (CA) it fishes in. Two options were therefore investigated. Firstly, buoys and sometimes FADs, presented markings, which was often the name of the vessel. The WCPFC and IATTC online vessel registry were used to identify, when possible, the owner vessel, as well as the flag and the CA.The second option was to use the unique ID number of the buoy found in the *in-situ* stranded database and cross referenced it with the WCPFC and IATTC observer data and the PNA FAD tracking database. When the ID number was identified, the last known position and the data associated with, was selected, also identify the flag of the owner vessel. The PNA FAD tracking data was launched in 2016, therefore all buoys collected *in-situ* prior to 2016 would not appear in the matchings with this database. In each database, the last known date and position was isolated and identified as the last “known position”. Note that this would corresponds to a different data type depending on the database considered. For the WCPFC and IATTC observer data, the last observation of the satellite buoy corresponds to the last activity recorded by the observers on the dFAD (deployment, set, visit). In the PNA FAD tracking database, we had access to the whole (or part) of the buoy trajectory, with positions recorded, in general, at regular intervals, so the last known position corresponds to the last transmission of the buoy (attached or not to ad FAD). Trajectories in this database have however been modified or “geo-fenced”, with the removal of transmissions outside of PNA EEZs by the buoy companies upon request from the fishing companies. This added a bias to any analyses linked to the PNA FAD tracking database.

Time difference between the stranded date and the date of the last known position in the WCPFC, IATTC, and FAD tracking data was investigated. These were then categorized in five classes : less than six months; between six months and one year; between one and 1.5 years; between 1.5 and two years; and more than two years. Finally, in the PNA FAD tracking database records of the buoy fate was also available, based on the last position on the buoy in the trajectory (before deactivation, (Escalle *et al.*, 2021c)). Then a comparison has been made with the FAD stranded database to explore and eventually correct numbers of stranding events in the WCPO (Escalle *et al.*, 2021c).

3. Results

3.1. Characterization of stranding events

Out of the 1,159 stranding events recorded, 45.4% were a buoy alone, 30.0% were a FAD alone, and 19.0% were a buoy attached to a FAD. The remaining 5.6% corresponded to an unknown presence of a FADs and/or a buoy (Table 2). More precise investigations related to the FADs found stranded (583) indicated that dFADs were dominant (79.9%), followed by aFAD (9.1%) and dFAD parts (4.5%) (Figure 3). For 6.5% of remaining events, the type of object was unknown. In terms of buoys found (780), it was mostly satellite buoys (97.5%), with the remaining 2.5% been radio and CO_2 monitoring buoys (Figure 3). The type of object found was however slightly different between PICTs. As an example, FM and MH recorded 21.6% and 66.7% of aFADs, respectively. In addition, many dFADs parts were found in Wallis and Futuna (14.4%), suggesting they have been previously collected, brought back to privates homes in order to be transformed in objects.

Table 2. Numbers (in brackets) and percentages of type of objects found stranded. FADs included dFADs, aFADs and dFAD parts; buoys include FAD satellite buoys, radio buoys and weather buoys.

		FADs (583)		
		Presence	Absence	Unknown
Buoy (780)	Presence	19.0% *(220)*	45.4% *(526)*	2.9% *(34)*
	Absence	30.0% *(348)*	0% *(0)*	0% *(0)*
	Unknown	1.3% *(15)*	0.3% *(3)*	1.1% *(13)*

With the increasing number of stranding events recorded in each PICT and the number of local programs increasing, the regional database has extended as well. The first FAD stranding events recorded were in Palmyra in 2009 and the only country with more than 14 years of data (Figure 3). The number of reports has increased in the recent years, with more than 150 stranding events per year in 2019 and 2020, and more than 300 in 2021 and 2022 (Figure 3). At the beginning of each program, the data collection involves an inventory of what has already been collected by local communities, often stored in gardens or private homes. As a result, dates of finding are often uncertain or unknown (7.6% of all stranding events).

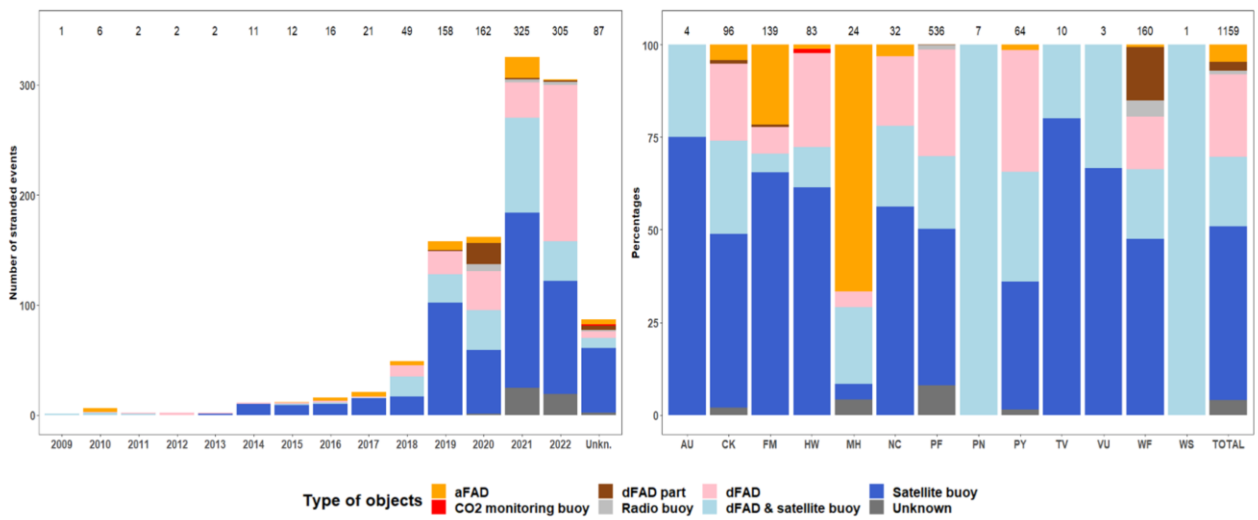

Figure 3. Numbers and percentages of FAD stranding events found by year (LEFT) and country (RIGHT), coloured by type of findings. Numbers on the top of the figure correspond to the number of stranding events per year.

The type satellite buoys brands found stranded was investigated, as this could be an indication of the origin of the fleet that deployed it, as some are more inclined to use one brand than another. Satlink (34.9%), Marine Instruments (22.4%) and Zunibal (15.4%) were the main brands found. The three brands are Spanish and the leaders worldwide in terms of dFAD satellite buoys. Few Ryokusei and Kato, which are Japanese and Taiwanese brands respectively and less common and mostly used by Asian fleets (Table 3). Finally, the brand was unknown for 23.2% of the buoys. Based on buoys model, 51.9% have an echosounder, and 41.5% was unknown. French Polynesia presented a higher proportion of Zunibal buoys, and in FM a higher proportion of Kato buoys.

Table 3. Model and type of buoys found stranded.

	Type of buoy		Echo-sounder (number)		
	Number	%	No	Yes	Unknown
Satlink	272	34.9	1	258	13

Marine Instruments	175	22.4	18	81	77
Zunibal	120	15.4	23	66	31
Ryokusei	17	2.2	0	0	16
Kato	15	1.9	0	0	15
Unknown	181	23.2	6	0	174
Total	780				
% Echosounder			6.2	51.9	41.5

3.2. Spatial distribution

The FAD stranding events, collected through the data collection programs in PICTs, showed a large distribution in the WCPO (Figure 4). Some countries presented higher numbers of stranding events per 1° cell, such as WF, CK and FP (up to 80—120 stranding events). Locally, the stranding events also showed different spatial patterns. For instance, in some PICTs more stranding events were detected on one coast compared to another. This is the case for Hawaiian Islands or Rangiroa Atoll (PF). Others countries are more sensitive to vulnerable habitats, especially PY and WF which present high density of coral reefs (Appendixes VI).

It can be noted that the type of floating object found differed between countries. In FP, stranded FAD or stranded FADs attached to a buoy were found more often than a buoy alone (Appendix VI).

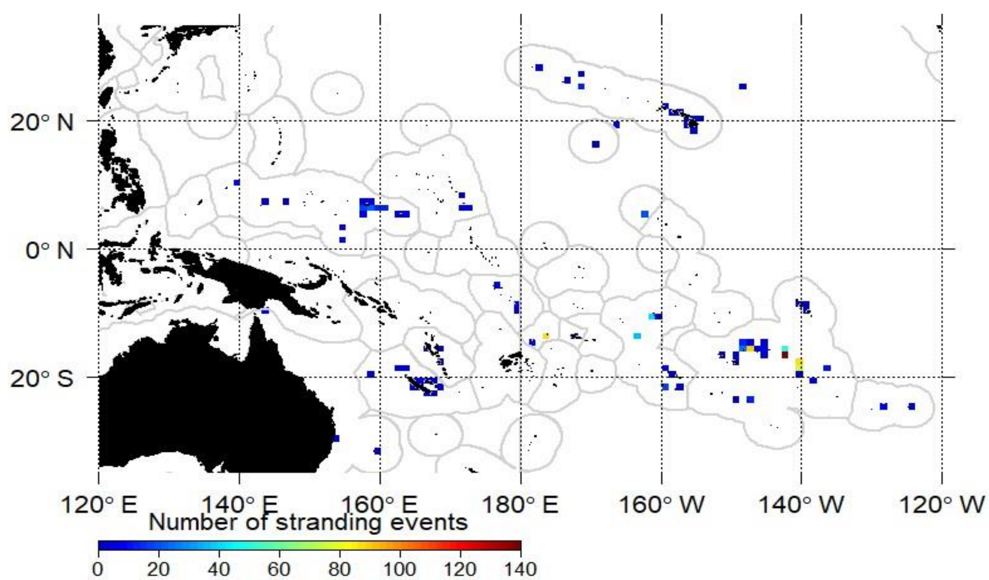

Figure 4. Aggregated map of stranded FADs found in Pacific Island Countries and Territories between 2009–2022.

3.3. Habitats impacted

After characterizing the type of stranding events in PICTs and their spatial distribution, the habitat type where the object was found was investigated. 39.0% of the FADs or buoys were found on a beach, 7.6% were drifting in the ocean and 6.8% were entangled on coral reefs. A substantial part (27.5%) was previously collected by local communities, and recorded here as found in gardens or private homes. When looking at results for buoys or FADs separately, patterns were slightly different. First, buoys were mostly found in gardens (36.0%), or beached (26.7%), and followed by other habitats (37.3%). Second, FADs were mostly found beached (55.2%), in gardens (14.2%) and on coral reefs (8.9%). AFADs were mostly beached (52.0%) whereas a high majority of dFADs were found on beaches (70.3%). The presence of sub-surface appendages also appears to influence the type of habitat impacted, dFADs with appendages were more found on coral reefs (23.1%) than those without any appendages (4.3%), while the latter was highly found on beach (77.8%) (Table 4).

Table 4. Percentages and numbers (in brackets) of stranding events per habitat type and FAD type/component.

Environment	Total	FADs	Buoys	dFAD with tail	dFAD without tail	aFAD
Beach	39.0% (*452*)	55.2% (*322*)	26.7% (*208*)	50.0% (*26*)	77.8% (*126*)	52.0% (*26*)
Coral reef	6.8% (*79*)	8.9% (*52*)	6.2% (*48*)	23.1 (*12*)	4.3% (*7*)	8.0% (*4*)
Drifting in the lagoon	2.6% (*30*)	3.8% (*22*)	3.1% (*24*)	0.0% (*0*)	1.9% (*3*)	2.0% (*1*)
Drifting in the ocean	7.6% (*88*)	7.9% (*46*)	8.8% (*69*)	21.2% (*11*)	1.9% (*3*)	2.0% (*1*)
Mangrove	0.3% (*4*)	0.7% (*4*)	0.1% (*1*)	0.0% (*0*)	0.6% (*1*)	4.0% (*2*)
Previously collected*	27.5% (*319*)	14.2% (*83*)	36.0% (*281*)	5.8 (*3*)	9.9% (*16*)	16.0% (*8*)
Shore	3.8% (*44*)	3.8% (*22*)	3.5% (*27*)	0.0% (*0*)	3.1% (*5*)	14.0% (*7*)
Unknown	12.3% (*143*)	5.5% (*32*)	15.6% (*122*)	0.0% (*0*)	0.6% (*1*)	2.0% (*1*)

*Found in garden, wharf or landfill.

Differences between PICTs were, again, detected in terms of habitat impacted. Objects previously collected were dominant in the findings of both buoys and FADs, in the CK (37.7%) and NC (16.0%) for buoys, and FM (35.3 %; 14.6%), FP (57.3%; 18.0%) and WF (17.4%; 26.3%), (Figure 5). Higher percentages of standing events on coral reefs were detected in NC (28.6%), PY (22%), FM (18.8%), WF (17.1%), PN (14.3%), and HW (12.9%).

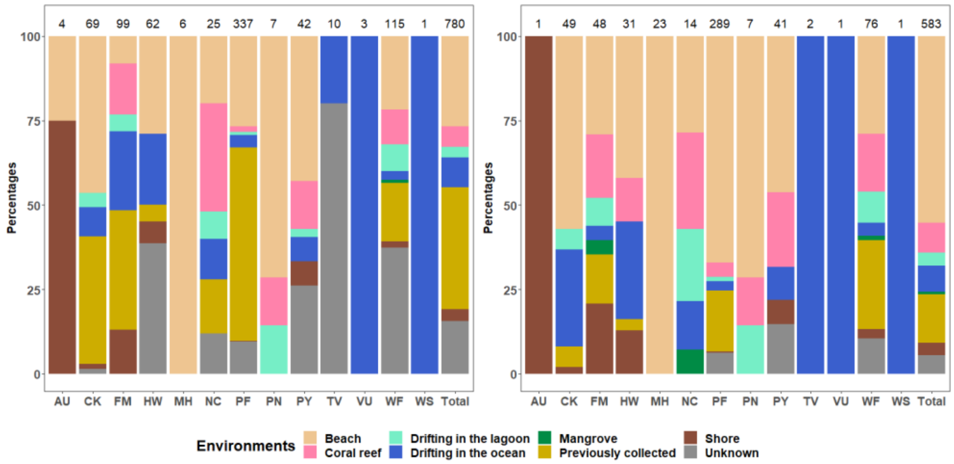

Figure 5. Percentages of stranded buoys (LEFT) and stranded FADs (RIGHT) per habitat type and country. Numbers on the top of the figure correspond to the number of stranding events per country. See glossary for country codes.

3.4. Materials investigation and environmental damages

The presence of appendices was studied for all FADs combined (aFADs and dFADs). FADs without any appendages represented 60.9% of all FADs; 20.8% had appendages; 18.4% was unknown (Table 5). Few records concerned the condition of the FAD (43.4%); 23.3% were intact, 12.0% were mostly fallen apart and 8.1% were beginning to break (Table 5).

Table 5. Number and percentages of stranded FADs with submerged appendages and FADs condition.

Submerged appendages			Condition (%)			
	N	%	Intact	Beginning to break up	Mostly fallen apart	Unknown
Present	121	20.8	8.2	1.0	2.6	8.9
Absent	355	60.9	12.7	5.5	6.0	36.7
Unknown	107	18.4	2.4	1.5	3.4	11.0
Total	583		23.3	8.1	12.0	56.6

Out of all the FADs found, 301 have materials recorded (53.5%). Bamboo, bamboo and floats, and floats were the main flotation materials used (more than 50% of all FADs) (Figure 6). Different patterns were highlighted depending on the country. For example, MH and FM presented a substantial part of aFADs mainly made of metal or fiberglass drums. The other FADs found were a mix of bamboo, floats and/or PVC tubes, metal drums and plastic foam (polystyrene). 20.3% of the FADs with materials recorded, were without any nets, as most of them corresponded to aFADs (Figure 6).

In all PICTs, nets and ropes were the main components of attachments (53.3%), but a mix of nets, ropes and plastic sheeting and canvas were also found. For both the raft and the attachments, 31.6 % of FADs did not present any nets. Mesh size was sometimes recorded, with 13.3% of FADs presenting small mesh netting; 10.6% large mesh netting and 8.3% both small and large mesh netting (Figure 7).

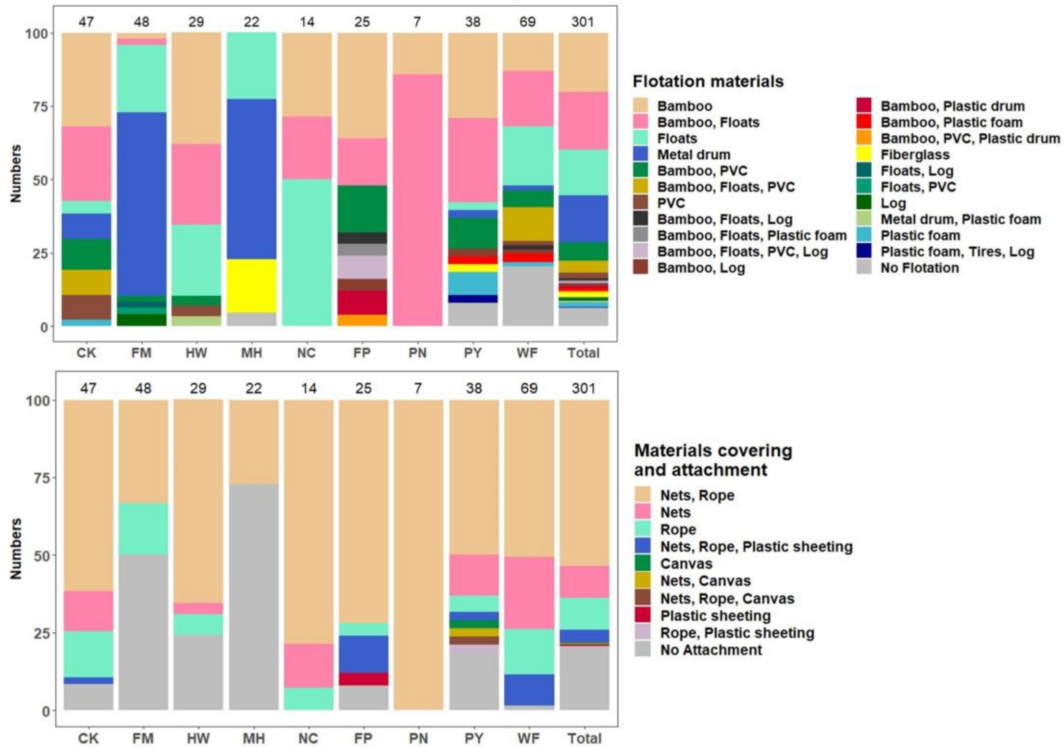

Figure 6. Flotation (TOP) and covering and attachment (BOTTOM) materials of FADs found stranded with materials recorded per country. Numbers on the top of the figure correspond to the number of stranding events with materials recorded per country. See glossary for country codes.

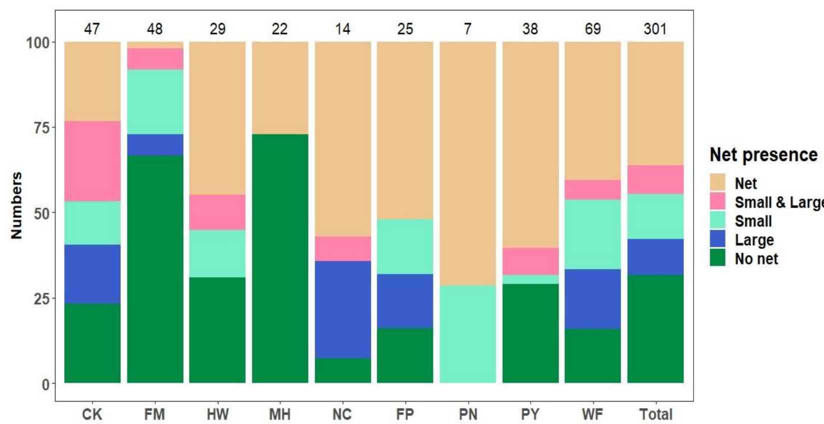

Figure 7. Presence and mesh size (small or large mesh size; visually estimated) of net for FADs found stranded with materials recorded, per country. Numbers on the top of the figure correspond to the number of stranding events with materials recorded per country. See glossary for country codes.

Limited number of environmental damages related to the stranding events were recorded (8.8% of all stranding events). However, a high uncertainty should be noted as 56.6% of the stranding events presented unknown damage (Table 6). Most of the environmental damages recorded were coral damages (4.8%), pollution (3.3%) or animals entangled like turtles body parts (0.5%) and dead birds (0.2%). Damages were recorded especially with FADs presented attachments (10.1%).

Table 6. Environmental damage caused by stranded FADs recorded in the database.

	FADs - total	dFAD	dFAD with tail	dFAD without tail	aFAD
No damage recorded	202 *(34.6%)*	148 *(35.5%)*	35 *(32.1%)*	0 *(0.0%)*	32 *(60.4%)*
Coral damage	28 *(4.8%)*	26 *(5.9%)*	22 *(20.2%)*	1 *(1.6%)*	2 *(3.8%)*
Dead birds	1 *(0.2%)*	1 *(0.2%)*	1 *(0.9%)*	0 *(0.0%)*	0 *(0.0%)*
Turtles body parts	3 *(0.5%)*	3 *(0.7%)*	0 *(0.0%)*	0 *(0.0%)*	0 *(0.0%)*
Sperm whale	19 *(3.3%)*	2 *(0.5%)*	1 *(0.9%)*	1 *(1.6%)*	16 *(30.2%)*
Unknown	330 *(56.6%)*	262 *(59.3%)*	50 *(45.9%)*	62 *(96.9%)*	3 *(5.7%)*
TOTAL	583	442	109	64	53

When FADs were found still drifting in the water, animals interactions were investigated such as aggregating fish, but record of such information was, again, rare with 94.2% without any interaction recorded. Artisanal fishing activity was recorded for 5 dFADs, and aggregated fish for 9 dFADs and 3 aFADs (Table 7).

Table 7. Aggregated, interacting, or caught animal detected in the vicinity of the FADs.

	FADs - total	dFAD	dFAD with tail	dFAD without tail	aFAD
Aggregated fish	11 *(1.9%)*	9 *(2.0%)*	6 *(5.2%)*	2 *(0.8%)*	3 *(5.7%)*
Caught fish	5 *(0.9%)*	5 *(1.1%)*	4 *(3.4%)*	0 *(0.0%)*	0 *(0.0%)*
Barnacles	15 *(2.6%)*	13 *(2.9%)*	11 *(9.5%)*	1 *(0.4%)*	1 *(1.9%)*
Seabirds	2 *(0.3%)*	2 *(0.4%)*	2 *(1.7%)*	0 *(0.0%)*	0 *(0.0%)*
Monk seal	1 *(0.2%)*	1 *(0.2%)*	1 *(0.9%)*	0 *(0.0%)*	0 *(0.0%)*
Unknown	553 *(94.2%)*	417 *(93.3%)*	92 *(79.3%)*	237 *(98.8%)*	49 *(92.5%)*
TOTAL	587	447	116	240	53

3.5. Fate and recycling potentials of dFADs and satellite buoys

The fate of floating objects found stranded was studied and 74.1% of buoys and 23.8% of FADs were removed from the habitat. However, a substantial part of the data presented an unknown fate (18.1% of buoys and 64.3% of FADs) (Table 8).

Table 8. Fate of buoys and FADs found stranded

	Buoy		FAD	
	Number	%	Number	%
Left	60	7.7	69	11.8

Removed	578	74.1	150	25.7
Removed partly	0	0	4	0.7
Fished and removed	1	0.1	0	0
Fished and left	0	0	2	0.3
Unknown	141	18.1	358	61.4

When the buoy was removed from the environment (21.4%), 38.2% of them were used for research and 37.4% were stored (Figure 8). Others were recycled or transforms by local communities to use batteries, solar panels and electronic components (1.6%), or reused as a house furniture (8.9%). Some countries, such as HW and PY showed high percentages of buoys used for research (69.4% and 100.0%, respectively), whereas WF, FM and MH presented high rates of buoys transformed (4.8%, 40.0% and 100.0% respectively). Despite high numbers of stranding events in French Polynesia, fates were rarely recorded due to the incomplete data at the time of analyses. When the FAD was removed from the environment (63.5%), it was often transformed in other object in WF (64.7%) and in FM (46.7%), whereas it was removed for environmental issues in MH (77.8%), but with unknown fate (Figure 8). FADs could also be reused as aFADs especially in FM (33.3%). As for the buoys, HW and PY removed FADs for research purposes (52.2% and 83.3% respectively), and FP FAD fates were rarely recorded.

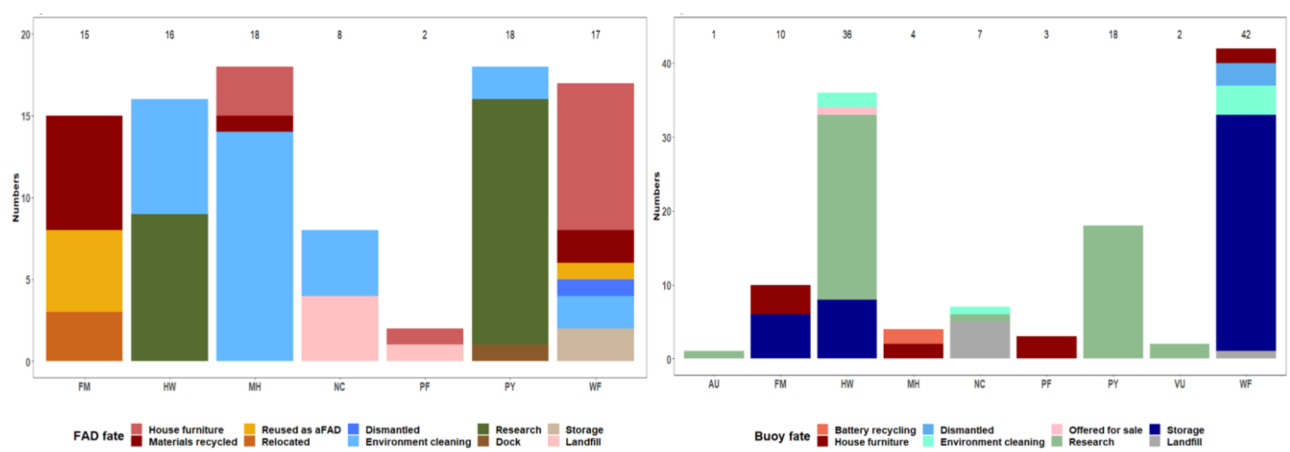

Figure 8. Purpose of FADs (n=94) (left) and buoys (n=123) (right) removed for the stranded location.

3.6. Trajectories and origins

One of the main objectives of this study was to identify the origin of floating objects stranded in different PICTs. High variability of origins was detected regarding the flag and the CA of the fishing vessel associated with the buoy (attached or not to a FAD) (Figure 9). From the buoy markings, 16 flags were identified with

26.6% of buoys were from Ecuadorian, 20.8% from US and 12.1% from Korean vessels (Figure 9). With the second method, similar patterns were identified, although, in the IATTC there is no flag information. Vessel registered in the WCPFC contributed the most to stranding events (52.6%), followed by the vessel in the IATTC (38.7%) or both (8.7%) (Figure 10). From the second method, 65.8% of matching buoys were coming the WCPFC, and 34.3% from the IATTC. Most of the buoys found in PF, were coming the IATTC-CA, in particularly Ecuador, US and Panama (Figure 9). Most of the buoys found in FM were from WCFPC-CA vessels. In WF, vessels from Korea, US, Kiribati and Ecuador represented more than 65% of the findings, mostly from the WCPFC-CA. In CK, 75% of the last known position were in the WCPFC-CA, from 3.3% of vessels fishing in the WCPFC-CA, 22.2% from the IATTC and 33.3 from both CA. As well, most buoys were flagged as US, Korean, Ecuador and El Savador (Figure 9).

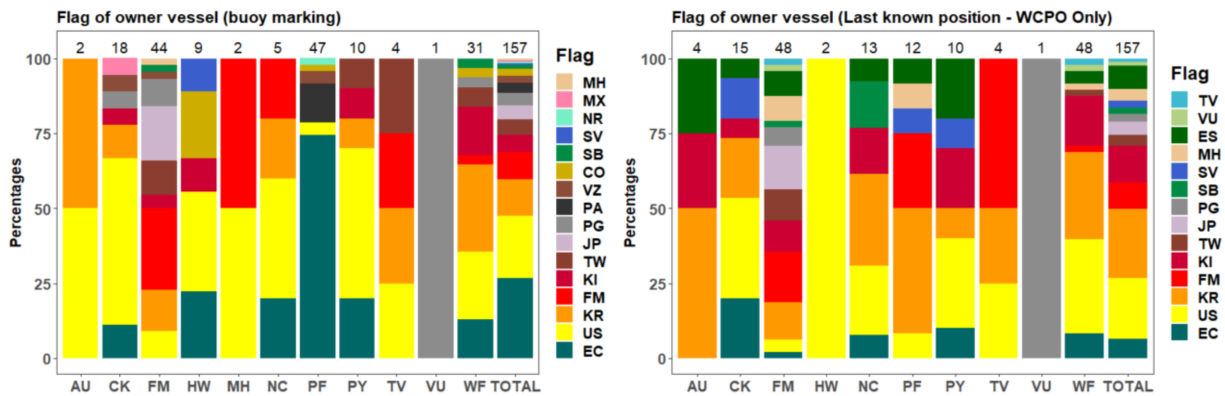

Figure 9. Flag of owner vessel identified using marks painted on the satellite buoys (LEFT) and from the last known position in the PNA FAD tracking data and the WCPFC observer data (RIGHT), by stranded location. Note that vessel and flag from the last activity recorded with each buoy ID was not available from the IATTC database. CO = Columbia; EC = Ecuador; ES = Spain; JP = Japan; KR = Korea; MX = Mexico; NR = Nauru; PA = Panama; PG = PNG; KI = Kiribati; SV= El Salvador; SB = Solomon Islands; TW = Chinese Taipei; US = USA; VZ = Venezuela.

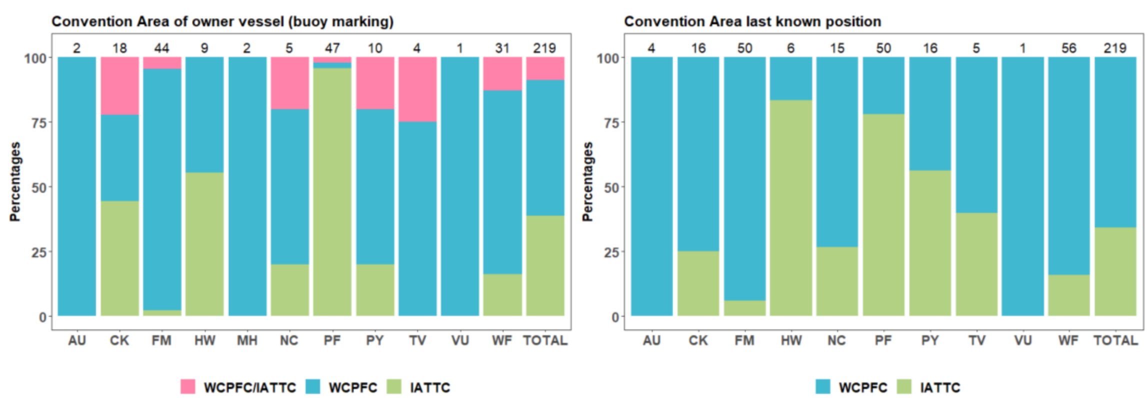

Figure 10. Convention area of owner vessel identified using marks painted on the satellite buoys (LEFT) and from the last known position in the PNA FAD tracking data, the WCPFC and IATTC observer data (RIGHT) by stranded location. Positions found in the IATTC/WCPFC overlap area were considered in the IATTC convention area. See glossary for country codes.

The time difference between the last position and stranded position was studied by PICTs and CA, (Figure 11). High variability was detected, likely because a FAD stranded years ago and was not been found until the program began, or because in some PICTs, programs started a long time ago like in PY with a 2009—2022 range. The time difference was up to 3,000 days (about 8.2 years) for some buoys in FP. Time differences were also different depending on the dataset used. Matching from the WCPFC data indicated higher differences compared to the the PNA FAD tracking data. For CK, NC, PF, WF and FM, more than 75% of the matches from the WCPFC presented a time difference between both locations under 5 years, and under 7 for PF.

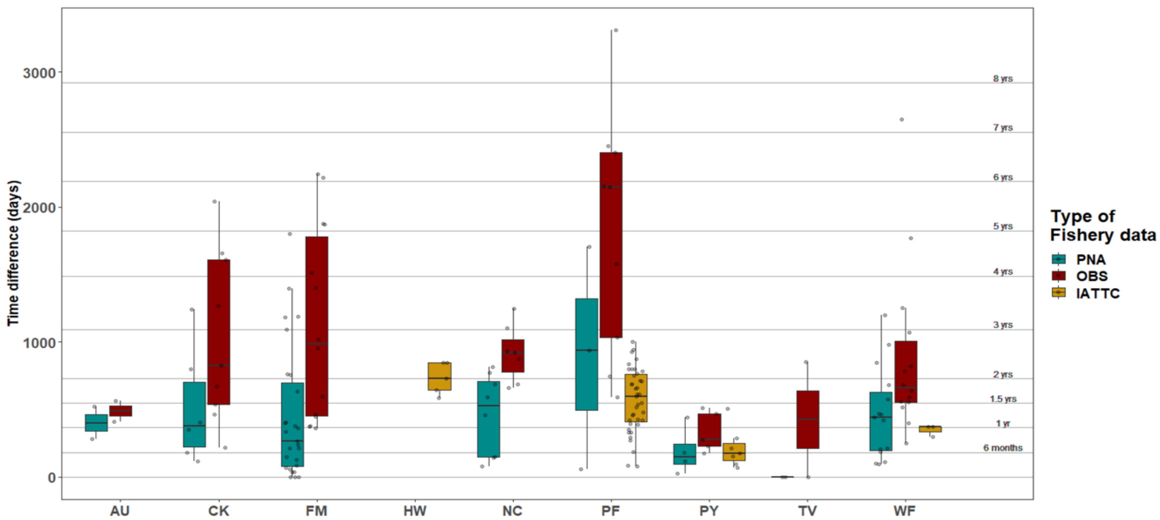

Figure 11. Time difference between the date found stranded and the last known position in the fishery databases: the PNA FAD tracking data, the WCPFC observer data and the IATTC observer data; by PICT of stranding event. See glossary for country codes.

Figure 12 shows that certain PICTs such as HW and PY received buoys from vessels which almost only fish in the IATTC-CA and drifting for one and up to more than two years before stranding (Appendix VII). In FM, WF and NC, most of the buoys were coming from buoys registered in the PNA FAD Tracking program with respectively mostly coming from the Southwest to Southeast and from the Northeast (Figure 12). Noted that similar patterns of origin were detected for buoys from the WCPFC and the PNA FAD tracking data (Figure 12).

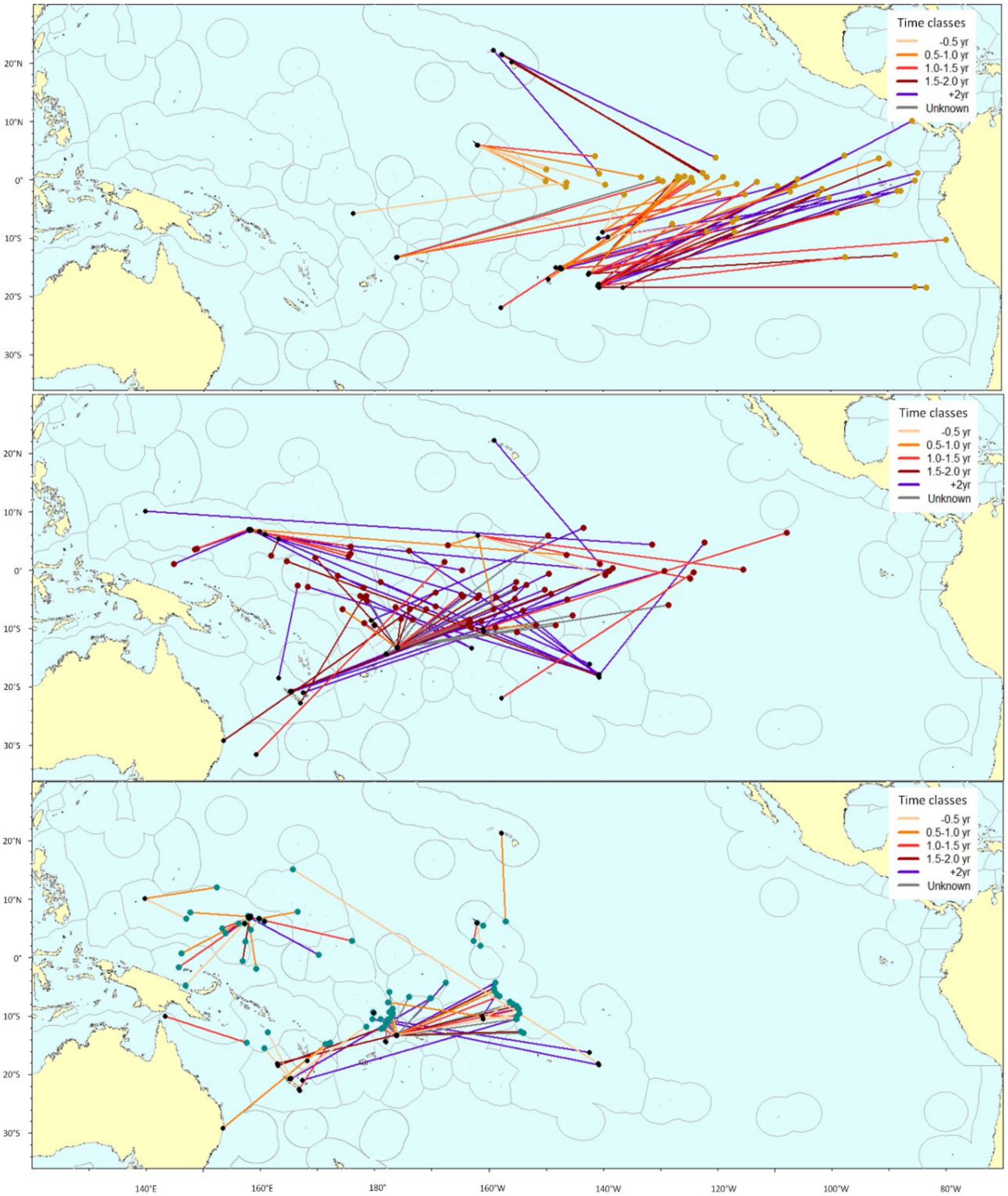

Figure 12. Maps with the stranded position (black dots) and the last known position of buoys from the IATTC observer data only (TOP; orange dots); the WCPFC observer data (MIDDLE; red dots); and the PNA FAD tracking (BOTTOM; blue dots). The color of the lines indicates the time between last known position and the date found stranded.

Comparison of buoy fates has been made between ones recorded by the PNA FAD database and the FAD stranded database (Figure 13). Most of the buoys classified as "stranded" by PNA had already reach coastal areas were 20% beached, 26.6% found on shores and 13.3% were previously collected in the stranded database, which makes a total of 59.9%. However, 42.8% buoys were found on coasts (i.e. *beach, shore and* *previously collected*) whereas it was registered as “drifting” and 14.2% were indeed drifting. Only 12.2% were declared as lost by PNA FAD database.

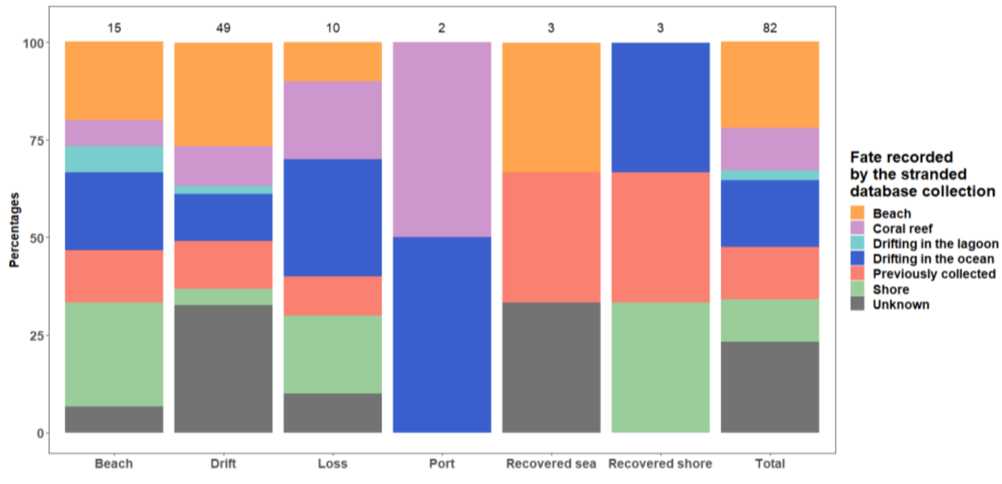

Figure 13. Fate of buoys estimated in the PNA FAD tracking data using updated high-resolution map for the 82 buoys found stranded that could be matched with this database compared to the fate of buoys and dFADs recorded in the stranded database.

4. Discussion

4.1. Results and limits associated with the study

This study is the first in the WCPO, but also globally, to investigate the impacts of dFADs on coastal ecosystems using data collected *in-situ* and at a regional scale. It complements previous studies looking at the fate of dFADs using trajectory data, or the numerous studies that looked at the impacts of dFADs on target stocks, bycatch species and SSI. This is particularly timely, given that PICTs have raised concerns about the increasing number of dFAD stranding events and potential impacts they would cause to marine life and habitats (Dagorn *et al.*, 2013). FADs may damage vulnerable habitats in addition to the accumulation of marine debris on coastal areas and lead to environmental and economic issues (Zudaire *et al.*, 2018). The economy of PICTs and quality’s life of habitants, depends on the health of marine ecosystems and the quality of resources they can provide. Human activities continue to put pressure on marine ecosystems and thus putting the prosperity and the food security at risk, especially in a context of human population increase (Gilman *et al.*, 2021; Giskes *et al.*, 2022).

This study relies on citizen participation to reports any FADs or satellite buoys they could encounter. This sampling method allows investigations at broad spatial and temporal scales, as well its cost effectiveness in order to develop or guide policy implementations. In this study, it allowed 1,159 reports of stranding events between 2009 and 2022 across several Pacific countries. However, even with the use of a standardized FAD sighting form, one of the main issue with citizen science data is the accuracy of the information collected (Earp and Liconti, 2020). One way to assess the quality of the data would be to compare data collected through citizen-science programs with data collected via scientific protocols. In our study, data collected through in a more "scientific" ways, with surveys performed in the whole coast line of some islands were done in PF and FM only. Implementing scientific surveys in all countries like in PF or FM could be interesting in order to compare both citizen data and scientific surveys as a means of data validation (Earp and Liconti, 2020). Studies involving citizen data have tendencies to produce more descriptive studies (Sandahl and Tøttrup, 2020).

First of all, stranded FAD data collection programs have started recently, and the number of reports increased each year. The first step in each program, was to do an inventory of objects that have been previously collected by local communities. Then additional years would allow for a better characterization and quantification of stranding events in a given period. However, it is difficult to conclude on the informative power of the data given the difficulties to differentiate whether it is an actual increasing number of stranding events or it is linked to the data collection effort. In order to assess the extent of the problem and provide advice for potential management measures, it will be necessary in the future to identify the reason of this increasing number of reports/stranding events recorded.

Using results from this and previous studies, an estimation of the percentages of dFAD that strand each year was performed. A study from Escalle *et al.*(2021c), shows that on the 47,418 buoys investigated between 2016—2020, 6.6% would be estimated beached, which gives a number around 625 buoys only per year stranded. In this study, about 300 stranding events were recorded in 2021 and 2022 in 9 PICTs out of the 15 in the Pacific region. Only 16 were also classified as stranded (or "beached") in the classification used by Escalle *et al.*(2021c). Using both numbers, we get around 925 stranding events per year, corresponding to 2.3–3.1% of the dFADs deployed in the WCPO. However, it is not that simple because the number of reports could be i) highly underestimated and ii) concerning only some countries and for some, reports are just opportunistic and not really representative of the actual number of stranding events. A proper estimation of stranding events, using a longer period and larger spatial scale would be required in order to guide management measures. As well, because of the heterogeneously distributed presence only data, it is therefore difficult to correct biases and conclusions on long-term trends and spatial pattern of distribution. Complete and pool opportunistic reports with scientific surveys would help to fill gaps and increase the coverage density (Carcia-Soto and van der Meeren, 2017).

A majority of findings were either a buoy alone or a FAD alone, meaning that either the ropes linked to the dFAD broke or had deliberately been cut off, as this is common practice when dFAD are appropriated by other purse seiners. However, given that a high proportion of buoys was found in gardens, it is possible that dFADs were left in the environment. In addition, the type of findings was pretty similar in all the PICTs with some small differences underlined. As an example, FM received more drifting aFADs, as well as Kato and Ryokusei buoys, than other PICTs. It would suggest that this country would be more subject to lost fishing gear from south-eastern Asia like Papua New Guinea, Indonesia and Philippines, where this industrial aFAD fishing occurs.

For some countries, data collection was only starting, with opportunistic reports, which can be useful at a large scale to describe and characterize stranding events in general, but is limited in terms of the accuracy of the information recorded. Here, we investigated 1,159 stranding events that occurred between 2009 and 2022, which is a small window among the 514,000—711,000 dFADs loss estimated in the next decade (Banks and Zaharia, 2020).

Few studies tried to assess and record stranding events. The only other study, using data collected on-shore is from Balderson and Martin (2015), who did a first assessment of stranding events in Seychelles Island, but it is limited to one country only. Here, because of the scale of the study, it could provide some indicators or some patterns on the type of objects stranded, their environmental impacts, origins and trajectories. Some PICTs presented high densities of stranding events like WF, FM, PF, HW. However, additional years are needed to further assess the spatial differences and draw any conclusion to explain those differences. For instance it could be due to higher data collection effort or to area actually being more subject to stranding events.

An important part of the stranding events was found on a beach. A higher number of dFADs with attachments were found entangled on coral reefs compared to dFAD without any attachments. Not every PICTs have the same sensibility to stranding events on coral as they present different surface areas of coral reefs around their coasts. For instance, it could be expected that NC, PY, FM, WF, PN and HW would be more sensitive to stranding events. Between 30°N and 30°S, there are 88 million of squared km of coral reefs. Coral reefs are already facing bleaching events caused by numerous environmental changes such as global warming and ocean acidity, and FADs impact are added to the list of challenges. FADs presenting attachments would impact much more coral reefs because of the entanglement and the wave force would increasing the surface impacted. However, there is no precise assessment of this impact, but in the review from Banks and Zaharia (2020), it was estimated that 4 to 6 km^2 of coral reefs could be impacted each year by FAD stranding events. Further and more precise assessment of coral reef impact from FADs are still required.

A large part of the stranding events were also found in a garden or a house with the objects previously collected by communities, particularly for communities. This could be explained by their recycling potential, particularly for electronic components, but also because it is easier to transport a buoy than a 2 meters raft.

Most of dFADs were found almost intact, which could indicate a small amount of time spent drifting. This means that they could have the potential to be reused by purse seiners through a FAD recovery program. However, difficulties remain to assess how much time a dFADs spent in the water because the presence of a buoy is necessary to have trajectories.

In this study, bamboo canes and synthetic floats were the most used materials to ensure flotation of the raft, and similar construction patterns were found in Abascal *et al.* (2014) and Escalle *et al.* (Under review). Most of FADs materials were synthetic, except for bamboo and log, which accounted for less than 25% of all FADs. In the study focused on FAD materials, based on WCPFC observers data, completely natural FADs represented less than 4.1%, often due to the lack of submerged appendages, and percentages of FADs with synthetic materials remained stable over years (Appendix VIII.1) (Escalle *et al.*, Under review). This result poses serious concerns for marine pollution, and the need to shift to an eco-friendly design. In terms of fleets, even if the amount of natural dFADs is small, Japan, Philippines, El Salvador, Federated States of Micronesia and Papua New Guinea were most inclined to use natural materials only, on FADs (Appendix VIII.1).

Nets were also an important part of materials used. Small amounts of FADs presented attachments, and among attachments, most of them were composed of ropes and/or nets. For FADs with nets, a large proportion of them presented a small mesh net, but shows that large mesh nets appeared as important in dFADs design too. From Escalle *et al.* (Under review), average mesh size was around 6.9cm for nets on the raft, and around 8.0 cm for nets in attachments. Large mesh nets (>7cm), especially in appendages, presents a high risk of marine life entanglement (marine megafauna and corals). However, when looking at the evolution over years, there is slight decrease in mesh size, potentially linked to the low entanglement risks FADs measure implemented by the WCPFC since 2020. Also, some countries presented high rates of stranding events with dFADs composed with nets, and in particular large mesh nets. NC, as an example, presented high rates of events recorded on coral reefs but also high rates of dFADs with large mesh nets, in particular in the attachments part. Some designs were also more associated with a fishing fleet in particular. For example, Korea often used colourful plastic sheeting as attachments to attract fish. Looking at designs found in PY, a lot of FADs have been found with this type of construction. Korea was also found as one of the fleet that owned the FADs found stranded, and identified using buoy trajectories. Additional investigation are needed to further assess the link between construction patterns and origins.

Programs have started recently for some PICTs and would be interesting to investigate the evolution of dFAD design, numbers and impacts throughout the years. In particular, investigating the use of nets and the type of appendages that are while management measures are slowly being put in place. Unfortunately, currently the data collection effort did not allow such comparison because of the heterogeneity of the events recorded among years. Additional years of data would be needed to check this hypothesis.

In this study, the number of recorded entanglements was quite limited. Photo taken during the discovery of a dFAD accounted as a "proof" of environmental damages. Although, photos were not always provided and this information was sometimes lacking, there might therefore be a significant underestimation of environmental impact from dFADs stranding events. In addition, arriving onshore, even if a dFAD is entangled on corals, because they are fragile, they can just be snatch on the reef, then detach and not be visible and recorded here. Similarly, for entangled animals, once dead, they can be eaten by scavengers and then disappear quickly before a dFAD is found and damage noticed. However, as underlined by (Davies *et al.*, 2017), entanglement assessments is difficult to monitor in real time what is happening to a dFAD, and the present study is no exception. Damages are therefore likely under-estimated.

Limits related to the analyses of the origin of FADs can be underlined. First, only buoys can be tracked, or a buoy attached to a FAD, but not a FAD alone. So, when we have referred to dFADs tracking, it is actually satellite buoys tracking and currently we cannot access the monitoring of dFADs. Also, there is no any information of what happened to the buoy if it was a sabotage by other vessels or just the end of the dFAD lifespan (Balderson and Martin, 2015; Escalle *et al.*, 2021c).

Another point to be underlined, is the calculation of the time difference between the last known position of the buoy and the date it was found stranded. Three databases were used, however, in the WCPFC and IATTC observer programs, the last known position is in reality the last observation, and could still have been used after. Indeed, the time difference could be over-estimated. It is therefore useful to complete trajectories in missing areas especially outside fishing grounds, and international waters from the PNA FAD tracking database due to geo-fencing issue. In the PNA FAD tracking database, the last position is closer to the real date of last transmission, because frequencies of the transmissions are regular (daily or every few hours), and so if the buoy is not transmitting its position for more than a certain time, it would mean that fishermen deactivated remotely, or had a malfunction issue. In addition, the PNA FAD tracking database was launched in 2016 so there is no access to trajectories for buoys found before 2016. The time difference could also have been over-estimated due to the fact an object could have been stranded and found months or years later. Currently, there is no way to investigate the exact date of stranding events. However, with the start of collection programs in many countries, if surveys are more and more frequent, the uncertainty in the time difference between the real date of stranding event and the date it has been found, would be reduced. Finally, the distance between stranding position and last known position was calculated using a straight line, because the main goal was to highlight origins of drifting FADs, but it could override some areas that could be impacted due to the influence of currents.

Finally, to help guide the implementation of management measures, it would be interesting to link the number of stranding events recorded for each country identified to the fishing effort. It would help to identify if the number of stranding events is linked to the fishing effort, or could be due to less efficient management measures.

4.2. Perspectives of research

Several pathways of study would be interesting to investigate in order to better assess the environmental impact of dFADs, and better characterize areas of origin.

The improvement of the FAD sighting form would help to characterize more precisely the type of events that occurs, the materials used, and environmental damages they would cause. In fact, the form is currently being revised, to be distributed to local partners involved, in order to facilitate the data collection.

Lagrangian particle analysis simulations would be an efficient tool to complete data on observed trajectories to fill gaps and better identify some patterns. High number of virtual particles drifting in the ocean would quantify possible trajectories but also allow to identify eventual source and arrival locations (Escalle *et al.*, 2019b).

One of the most awaited measures is the launch of the PNA FAD Buoy Tracking Implementing Arrangement (4IA) from January 2023. After this date, all FADs from vessel fishing with licences in the PNA waters will need to be active between 20°S and 20°N in the WCPO, and trajectories transmitted to PNA and SPC (PNA, 2020). Therefore complete trajectories of buoys would allow to better investigate trajectories in international waters and better assess origins for stranding events. As a result, a possible pathway of study to improve assessment on coral reefs would be look deeper in trajectories of buoys. Some of them could drift near shores without been completely beached. For these buoys attached to a dFAD, it would be interesting to evaluate and assess more precisely spatial and temporal impacts, particularly to coral reefs .

An estimated 4 to 6 km² of coral reef are destroyed as a result of dFAD use each year (Banks and Zaharia, 2020).

An interesting pathway would be to characterize the lifespan of dFAD and to eventually identify more precisely the time that a dFAD could reach a non-return point. Observations of a same dFAD through observer databases could be a useful tool to assess the evolution of a dFAD condition, as well as the study of materials for a given time. If there is access to trajectories of a buoy attached to it, it could also highlight some areas that might cause more damages to dFADs, decreasing its lifespan and increasing the risk to sink and add pollution to benthic habitats.

In addition, quantifying coral entanglements depending on the type of attachments would allow to assess the efficiency of management measures concerning dFAD design. Ropes and nets tied in bundles would potentially pass more easily between coral structures than nets (Balderson and Martin, 2015). Though, it would need more accurate descriptions from the stranded data collection, and the improvement of the FAD Sighting Form discussed above.

4.3. Management advice

There is a reel need to adopt effective monitoring, surveillance and enforcement systems to limit the number of abandoned or lost fishing gear and devices (Gilman *et al.*, 2021; Murua *et al.*, 2021). Below we disccused the potential management measures that could be adopted.

4.3.1. FAD conception and construction (natural materials, no net, etc.)

Slow steps have been taken in the WCPO to modify dFAD design in order to reduce entanglements of marine species and plastic pollution. In the WCPO, Highest Entanglement Risk FADs (HER FAD) with nets used in every part of the dFAD, are prohibited since January 2020, with the requirement to use LER FADs. NE FADs will be mandatory as from 1st January 2024 (WCPFC, 2021). Natural materials are however only recommended in the construction of FADs. All types of FADs are subject to buoyancy loss and water logging of bamboo cane. FADs have lifespan varying between 10—12 months to 2 years (Banks and Zaharia, 2020). While the transition from HER FAD to NER FAD is ongoing and allows to decrease the entanglement risks, the use of synthetic materials is still the norm and contributes to marine plastic pollution. Active current research concerns biodegradable FADs (Franco *et al.*, 2009; Banks and Zaharia, 2020; Consoli *et al.*, 2020; Moreno *et al.*, 2020; Escalle *et al.*, 2021a; Murua *et al.*, 2021), and the introduction of a “Jelly FAD-design” (Murua *et al.*, 2021). It could be a way to mitigate both entanglements and plastic pollution issues. Lifespan of BNER FAD appeared to be reduced and could sunk before reaching coastal areas and then having lower beaching events occurring (Banks and Zaharia, 2020). Although using BNER FAD could appearing as the most promising option, it might lead to an increase of deployments. In addition, a lesser number of stranding events implies a higher number of sunk events, and the impact on deep habitats such as seamounts is unknown (Banks and Zaharia, 2020). A survey organised by Gilman *et al.* (2018), shown that some fishers were interested to investigate a self-navigable dFAD that would reduce the number of abandonment and the grounding risk, but also a remotely sink biodegradable dFADs if it is too close of sensitive habitats (Banks and Zaharia, 2020).

4.3.2. Deployment

Some management measures have been adopted to reduce the impact of dFADs on ecosystems in the WCPO. The limit of the 350 buoys actively used per vessel however needs to be reviewed as it has been estimated that only 45—75 are commonly used at any given time (Escalle *et al.*, 2021d), so it currently does not limit FAD use. Furthermore, because buoys are sometimes deactivated deliberately by fishermen, limiting the number of deployments and not the number of active dFADs could be a more efficient management measure to limit environmental impacts (entanglement, tunas behaviour and ecology, plastic pollution, beaching) (Escalle *et al.*, 2021d). Limiting deployments in specific areas to reduce beaching events could also be an interesting management measure (Escalle *et al.*, 2021b; Imzilen *et al.*, 2021).

4.3.3. In fishing grounds

The WCPFC imposed a FAD closure time period were any activity related to FADs is prohibited. The FAD closure is of 3—4months from July to September. In high seas, 2 additional months before or after the FAD closure time period are established where activities on FADs are forbidden (WCPFC, 2021). The main objectives of the FAD closure are to limits the impacts on the tunas stocks and the impacts on bycatch. Drifting FADs has a satellite buoy with a unique identification number but even with this, adding a identification number and/or mark to the dFAD, could be easier to identify a dFAD, in the perspectives of a FAD retrieval program or eventual sanctions (Macfadyen *et al.*, 2009).

4.3.4. Outside fishing grounds

Many reasons exist to explain why ALDFG are lost, abandoned or discarded (Macfadyen *et al.*, 2009). Firstly, gear loss may occurs as a result of poor weather condition and quality of the gear (Macfadyen *et al.*, 2009). WCPO is subject to extreme climatic events such as hurricanes leading to stranded marine debris including from the fishing sector (Macfadyen *et al.*, 2009). Noted that with the increasing extreme climatic events with the global warming it may be possible that the number of marine debris, including FADs, arriving nearshore could increase in the future (Macfadyen *et al.*, 2009). Secondly, there is high competitivity among fishermen, thus some fishermen can steal a productive dFAD, cut out the satellite buoy without the original owner knowing it (Macfadyen *et al.*, 2009). Thirdly, FADs could be abandoned for economic reasons. FADs often present low construction cost and it is not economically viable to retrieve it when it is outside fishing grounds, it would cost more than it is worth to recover (Macfadyen *et al.*, 2009).

WCPFC only encourage vessels to "*make reasonable efforts to retrieve lost drifting FADs*" and *"report the loss of drifting FADs, and if the loss occurred in the EEZ of a coastal State, report the loss to the coastal State concerned.*". Several international laws exist on marine pollution (Churchill, 2021), but because of the complexity to assess the intentional abandonment of dFADs, sanctions may be difficult to apply. If a dFAD is deliberately abandoned, it breaks the MARPOL Annex V, and the London Convention (Davies *et al.*, 2017).

4.3.5. Close to shore

A study conducted by Escalle *et al.* (2021b), tried to look at the feasibility of retrieval program involving fishing companies as well as satellite buoys industries which could provide information anonymously. Also a survey addressed to fishing companies about this topics highlighted that i) the responsibility for FAD lies with the owner identified using the buoy ID number; and ii) because of the high cost (ecologic and financial) to retrieve FADs that are far away, cooperation between fishing companies should be implemented (Gilman *et al.*, 2018). It would be feasible according to some respondent for the purse seine fisheries to retrieve dFAD and stop abandonment, however it would necessarily implies a re-adjustment of budget which would lead to less dFADs in activity, and then an economic loss (Gilman *et al.*, 2018). An option more economically viable would be acting at the local scale with local partners such as fisheries departments and NGOs, for instance using a FAD watch (Zudaire *et al.*, 2018). It implies to transmit complete trajectories of buoys and when it comes close to shore, a boat could carry it on land. The cost would have been estimated at $4,166 per DFAD intercepted (Banks and Zaharia, 2020). A FAD Watch program would be an interesting option to prevent and thus mitigate, damage to coastal habitats. At PY, a FAD watch program based on collaboration between fishing companies and local partners to warn if a dFAD come close to shores and retrieved it before causing any environmental damage (Escalle *et al.*, 2022). As highlighted previously, NC, PY, FM, WF, PN and HW, which present higher surface areas of coral, would be more sensitive to stranded objects, therefore efforts for an eventual FAD watch should focused on these PICTs.

4.3.6. On land

Stranded objects can be beneficial to local communities as they can re-use materials, with materials often not available locally to make other objects. Satellite buoys have a great potential to be recycled as they are composed with electronics that are often not available or expensive on PICTs. Once extracted, solar panels can be used to build a solar charger, or lamps (Escalle, 2021). For the moment, these activities to re-use buoys are still limited because of the lack of knowledges to transform these items, and could be interesting to explore this idea further. It is easier though for dFADs materials, which are often transformed into house furniture, especially nets and bamboo. Another interesting idea coming from HW, is to turn materials of fishing gear and devices into energy from incineration. One ton incinerated provides the equivalent of 5 months electricity for one home (Yates, 2009 in: Macfadyen *et al.*, 2009).

For the dFADs already stranded, implementing a management plan to collect and recycle stranded objects could be a way to reduce waste presence on coastal areas and benefit to local communities for the recycling part. However, as highlighted by Burt *et al.* (2020), removing plastic from coastal areas have a high cost, especially for small PICTs, and raises the question of "who have to pay for it ?" (Banks and Zaharia, 2020)

Table 9. Overview of mitigation and management measures of FAD in the WCPO, and measures that could be implemented

	Already in place	Could be put in place
FAD conception and construction	• Low entanglement risk FADs • Non entangling FADs (Prohibition in the use of nets appendages)	• Biodegradable FADs
Deployment	• Limit of 350 active buoys per vessel	• Reducing the number of deployments, or limit deployments in some areas • Set a limit according to the real use of the number of FADs
In fishing grounds	• FAD closure period (3—4months) • Unique buoy ID number • Use of echosounder buoys to assess biomass in real time	• Marking fishing devices
Outside fishing grounds	• The MARPOL Annex V ; The London Convention	• PNA FAD tracking implementing arrangement (4IA)
Close to shore	• No measure; opportunistic reports only	• FAD Retrieval • FAD watch
On land	• Recycling infrastructures	• Improvement of recycling infrastructures and management plans to retrieve FADs stranded

Conclusion

This study constitutes a preliminary analysis of stranding events and their impacts on Pacific coastal areas. It is one of the first study based on an *in-situ* data at a regional scale in the Pacific Ocean and worldwide. Thus, it is essential to continue to quantify the number of stranding events and assess more accurately environmental damages. Some study perspectives have been highlighted and would be interesting for management and conservation measures.

From this study, several points could be retained. Firstly, most of stranded objects were satellite buoys, or FADs alone, which raised questions linked to the reason of the few stranding events that included both items. Also, the spatial distribution of stranded FADs showed that some PICTs were more subject to certain types than another, as FM and MH which present higher rates of aFADs, or WF were high quantities objects have been recycled/transformed locally. In terms of habitats, some PICTs presented different stranding rates depending on habitats ; NC, PY, FM, WF, PN and HW would be more sensitive to stranded objects on coral reefs for instance. Materials investigated in this study and the comparison with the study from Escalle *et al.* (Under review), showed that FADs are rarely completely naturals, which poses serious issues of plastic pollution. Moreover, nets were almost omnipresent in design, and an important part with large mesh nets which causes entanglement risks for marine life. Few environmental damages were recorded in the stranded database, but the development of numerous programs in PICTs, in addition to the improvement of the FAD Sighting Form should help to complete data, and precise it in future assessments. Finally, trajectories and origins of buoys revealed that again, stranding events in PICTs had clear patterns. For example, PF received almost all buoys from the IATTC-CA with mostly vessels coming from North, Central or South America, whereas in FM it is mostly South-eastern Asia vessels registered in the WCPFC-CA.

In general, the regional database is mostly composed from opportunistic report and citizen participation, which allows an investigation at broad spatial and temporal scale, maybe at the expense of the quality's data that might be less accurate than a scientific surveys, and then an assessment and comparison of both methods should be explored as data validation. As well, additional years of data are needed to assess more precisely and identify patterns of stranding events as well as patterns of origins. Some management measures are in place to mitigate the loss and abandonment of dFADs and the environmental damages linked to it, but it mostly focuses on modifying dFAD design. Some measures will be implemented soon, such as the PNA 4IA, would allow scientists to investigate further and more accurately the trajectories and origins of dFAD found stranded. Although even if recycling dFADs could be interesting to improve, actuals management measures need to be taken in priority, in order to reduce the number of stranding events and thus marine pollution and all environmental issues linked to it.

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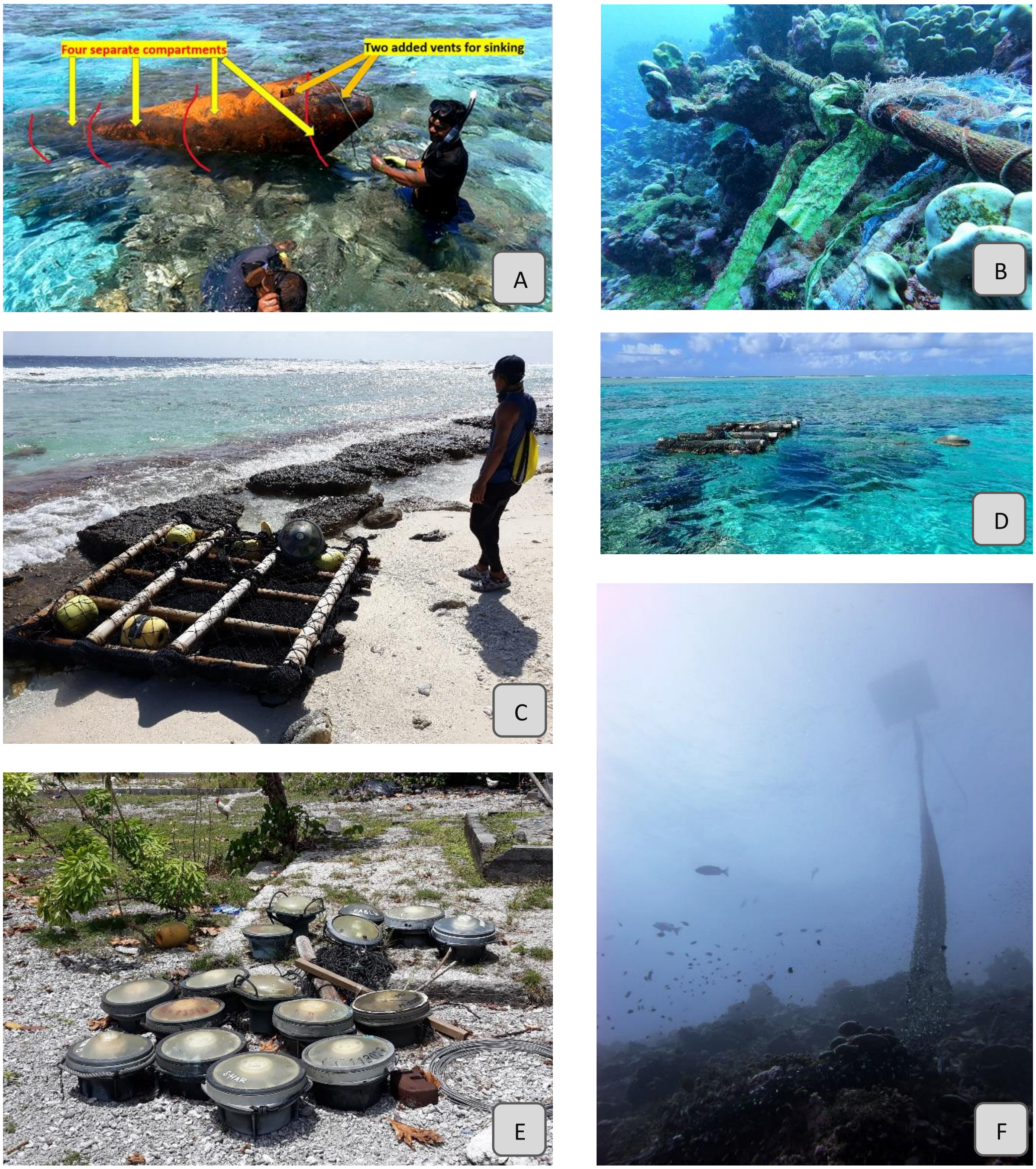
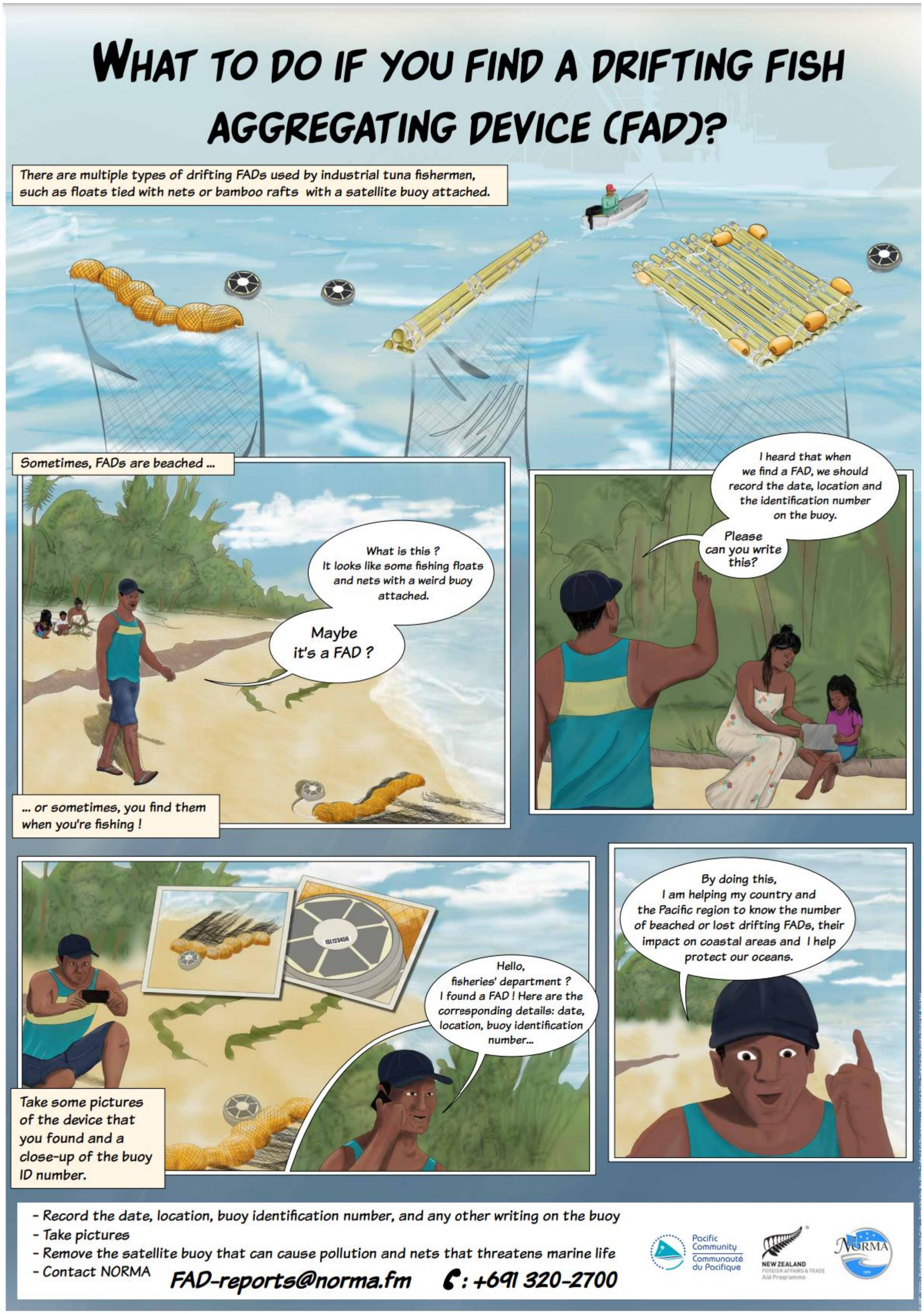
Appendixes

Appendix I : Photos of some dFADs and satellite buoys found stranded and recorded in the data collection programs.



A : AFAD on a reef in FM (© SPC James Wichman); B. dFAD entangled on corals in FM (© SPC James Wichman); C-D. dFAD and the satellite buoy in the CK; E. satellite buoys in the CK ; F. dFAD with attachment entangled on corals in PY.

Appendix II: Example of posters for local communities in the Federated States of Micronesia.


WHAT TO DO IF YOU FIND A DRIFTING FISH AGGREGATING DEVICE (FAD)?
There are multiple types of drifting FADs used by industrial tuna fishermen, such as floats tied with nets or bamboo rafts with a satellite buoy attached.
Sometimes, FADs are beached ...
What is this ? It looks like some fishing floats and nets with a weird buoy attached.
Maybe it's a FAD ?
... or sometimes, you find them when you're fishing !
I heard that when we find a FAD, we should record the date, location and the identification number on the buoy.
Please can you write this?
Take some pictures of the device that you found and a close-up of the buoy ID number.
Hello, fisheries' department ? I found a FAD ! Here are the corresponding details: date, location, buoy identification number...
By doing this, I am helping my country and the Pacific region to know the number of beached or lost drifting FADs, their impact on coastal areas and I help protect our oceans.
- Record the date, location, buoy identification number, and any other writing on the buoy
- Take pictures
- Remove the satellite buoy that can cause pollution and nets that threatens marine life
- Contact NORMA
FAD-reports@norma.fm
: +691 320-2700
Pacific Community
Communauté du Pacifique
NEW ZEALAND
NORMA

Appendix lll: FAD sighting form to report FAD stranded to SPC.

FAD Sighting form

Entered in the database ☐

Data collected by a FSM fishery officer regarding FADs, FAD debris and/or satellite buoys found beached or at-sea. Contact James Wichman at MRO at 320 7523 or send an email to FAD-reports@norma.fm

Form

Completed on: Click here to enter a date **Form number (if more than one on the same day, 1 to x):** Click here to enter text

Completed by: Name: Click here to enter text

Observer/ person who found the FAD

Name: Click here to enter text **Phone number:** Click here to enter text **Email:** Click here to enter text

Sighting information

(Tick one or several) ☐ **A FAD** ☐ **A buoy** - **ID Number:** Click here to enter text

Date: Click here to enter text **Island:** Click here to enter text

Location (*If no GPS, write name and/or describe it*): Click here to enter text

Environment: ☐Beach ☐Coral reef ☐Drifting in the lagoon ☐Drifting in the ocean ☐Rocky shore ☐Mangrove ☐Garden (found previously) ☐Wharf (found previously) ☐Other: Click here to enter text

Latitude: Click here to enter text **Longitude:** Click here to enter text

Comments Click here to enter text

Number of pictures - taken locally: Click here to enter text **- taken by the fishery officer:** Click here to enter text

FAD Information

Painted marks on the buoy: Click here to enter text **Mark on the FAD:** Click here to enter text

FAD condition: ☐Intact with submerged tail ☐Intact without submerged tail ☐Beginning to break ☐Mostly fallen apart

The following details should be completed by the fishery observer if the FAD was seen, or if transmitted by the observer:

Raft materials: ☐Bamboo ☐Wood ☐Plastic or metal drums ☐Floats ☐PVC tubes ☐Cords ☐Nets ☐Steel ☐Cotton canvas ☐Plastic sheet ☐Palm leaves ☐Other: Click here to enter text

Submerged tail materials: ☐Net ☐Net tied as a "sausage" ☐Cord ☐Plastic sheet ☐Palm leaves ☐Other: Click here to enter text

Estimated size of the raft *(Length x Width)*: Click here to enter text

Estimated depth of submerged tail (m): Click here to enter text

Any additional information to complete the FAD description: Click here to enter text

Fate of the FAD/ the buoy

FAD removed? ☐Yes ☐No **If so, why?** ☐Avoid pollution ☐Landfill ☐Burned ☐Recycled: Click here to enter text

Other fates: ☐Unknown ☐Left ☐Fished, species and catch (kg): Click here to enter text ☐Sunk ☐Other: Click here to enter text

Buoy removed? ☐Yes ☐No **If so, why?** Click here to enter text

Impact on marine life

Entangled animals? ☐None ☐Turtle ☐Shark ☐Coral ☐Fish ☐Marine mammal ☐Other: Click here to enter text

Status: ☐Dead ☐Alive ☐ Unknown **Species** (if known): Click here to enter text **Number of individuals:** Click here to enter text

Fish aggregated under the FAD ☐Yes ☐No **Species** (if known): Click here to enter text

If FAD is entangled on coral reef please state the approximate size of the area impacted: Click here to enter text

Appendix IV : Variables of the regional stranded FAD database

Description of data collection for FADs found stranded or at sea

For any information contact laurianee@spc.int

Why are we collecting these data?

We are collecting these data in order to quantify the number of lost and beached FADs, and to note their impact on coastal areas, which will help improve the management of FAD fishing. FADs are always deployed with a satellite buoy, so that fishers know the position of their FAD. FADs are usually also equipped with an echosounder to estimate the amount of tuna aggregated underneath. Fishing companies have started sharing data both of the FAD's position, as well as the echosounder data from the satellite buoys deployed on FADs. These data are used in scientific studies that guide management of FAD fishing. When FADs are found at sea or beached, it is therefore very important to record the unique buoy ID number, to potentially match found FADs with these existing datasets.
In addition, fishers commonly remotely deactivate satellite buoys when FADs drift outside fishing areas. The dataset transmitted by fishing companies hence only gives a partial image of the FAD trajectories and the number of beaching events is underestimated in this dataset. Therefore, having access to additional information on beaching events, but also on FADs drifting in coastal areas (with the buoy ID number, if still attached to the FAD) will help complement the existing dataset and better estimate the impact that FAD may have on coastal areas.

Description of the fields in the spreadsheet

- **Entry number**
  (Internal use only. Number of FAD and/or satellite buoy found (1 to n). Used to rename the pictures.)

- **Entered by**
  Name of the person entering the data.

- **Date entered**
  Date of data entry.

- **Found by**
  Name of the person who found the FAD and/or satellite buoy.

- **Contact**
  Enter contact detail (email address, number) of the person who found the FAD and/or the satellite buoy.

- **FAD present**
  Was a FAD present (i.e., FAD by itself or FAD with a buoy)? Yes/No.

- **Buoy present**
  Was a satellite buoy present (i.e., buoy attached to a FAD or buoy by itself)? Yes/No.

- **Buoy ID number (very important if a buoy is present)**

Enter the satellite buoy ID number, see poster for how to find it (depends on the buoy brand and model). Examples of satellite buoy ID number:
DL+123456 ; **ISL+**123456 ; **DSL+**123456 ; **SLX+**123456
M3I123456; **M3+**123456; **M4+**123456
T07123456789 ; **Te7**123456789 ; **T7+**123456789 ; **T8X**123456 ; **F8E**123456789 ; **Z07**123456789
P1234**NF** ; **P1**234**N** ; **WF**1234**N** ; **CN**123**N**
123456

- **Date found**
  Date that the FAD and/or satellite buoy was found. Could be an approximate date if not known, e.g., August 2019.

- **Location**
  In particular if the lat/lon were not recorded, note where the FAD and/or satellite buoy was found, e.g., name of beach, town, island, etc.

- **Environment (if provided or visible on the pictures)**
  Where the FAD has been found: drifting at-sea in the lagoon or the ocean, on a beach, a coral reef, a beach, a rocky shore, a mangrove; or previously found and reported from a garden, a wharf, etc.

- **Latitude and longitude (If provided)** Record latitude and longitude in decimal.

- **Painted marks (if provided or visible on the pictures)**
  Record any marks painted on the satellite buoy. Could be a vessel name, or the abbreviation of a vessel names, just a letter, a number, a number and a letter, and sometimes the buoy ID number.

- **Mark on the FAD (if provided or visible on the pictures)** Record any mark attached to the FAD or painted on it.

- **FAD condition (if provided or visible on the pictures)**
  What is the condition of the FAD when found? Intact with the submerged tail, intact without the submerged tail, beginning to break, mostly fallen apart.

- **Raft materials (if provided or visible on the pictures, can be multiple entries)**
  List all the materials making the raft of the FAD: bamboo, wood, floats, drum, net, cord, canvas, etc.

- **Tails materials (if provided or visible on the pictures, can be multiple entries)**
  List all the materials making the tail of the FAD (underwater appendages): bamboo, wood, net, cord, canvas, etc.

- **Size of the raft (if estimated)**
  Estimates of the size of the FAD raft, Length (m) x Width (m).

- **Tail length (if estimated)**
  Estimates of the length of the FAD tail, i.e., the materials (rope, net, etc.) hanging under the FAD raft (could be absent, then put 0) in meters.

- **Fate of the FAD (if provided)**

What has been done with the FAD: removed from the water, removed from land, left drifting, left on shore, sunk, fished, etc.

- **Purpose if FAD removed**
  If the FAD has been removed from the location it was found, mention why it has been removed: avoid pollution, landfill, burned, recycled (to do what?), etc.

- **Fate of the buoy (if provided)**
  What has been done with the satellite buoy: removed from the water, removed from land, left drifting, left on shore, sunk, etc.

- **Purpose if buoy removed**
  If the buoy has been removed from the location it was found, mention why it has been removed: avoid pollution, recycling (use battery, solar panels…), etc.

- **Environmental damage (if provided or visible on the pictures)**
  Any environment damage recorded: e.g., tail of the FAD caught up on corals.

- **Entangled animals (if provided or visible on the pictures)**
  Record if any animals were found entangled on the net hanging beneath the FAD and/or the net used to cover the raft. If possible, record the species and the number of individuals.

- **Aggregated fish and/or fished (if provided)**
  Record if any fish (or other animals) were seen aggregated under the FAD and/or if any fishing was performed. If it was the case, mention the species (if know), the number and/or the catch in kg.

- **Other comments**
  Any other comments: e.g., some tuna were aggregated under the FAD, the FAD could not be removed because too heavy, materials reused as fishing gear, etc.

- **Number of pictures received**
  Record how many pictures have been received.

- **Pictures name**
  Rename the pictures using a unique identifier containing, country, date and the entry number (first field).
  <CountryCode>_<Seq. No.>_<Date:YYYYMMDD>   Ex: CK_1_20190923
  Add another number if more than one picture: e.g., CK_1_20190923_P1; CK_1_20190923_P2; CK_1_20190923_P3. Then copy the pictures in the folder in google drive.

- **Buoy ID number verified**
  Has the satellite buoy ID number been verified by the fishery officer on a picture or directly: Yes/No.

Appendix V: GEN-5 form (Fad related information) from the by the WCPFC observer program

FAD/PAYAO and FLOATING OBJECTS INFORMATION RECORD — **Form GEN-5**

REVISED 2018

OBSERVER NAME:	VESSEL NAME:	OBSERVER TRIP ID NUMBER:	PAGE OF

Date	Time (from PS-2)	Set No.	Object number	Origin of FAD	Deployment date	latitude dd°mm.mmm'	N S	and longitude ddd°mm.mmm'	E W	FAD as found	Beacon/ FAD lifted	FAD as left	Comments / Change details
											Beac/FAD/ NO		

FAD materials Main materials			net/mesh size	Attachments		net/mesh size	Max est. depth	FAD length	FAD width	Buoy serial number	Beacon/FAD ID markings	SSI seen	SSI trapped
			cm			cm	M	M	M			Y / N / U	Y / N / U

Date	Time (from PS-2)	Set No.	Object number	Origin of FAD	Deployment date	latitude dd°mm.mmm'	N S	and longitude ddd°mm.mmm'	E W	FAD as found	Beacon/ FAD lifted	FAD as left	Comments / Change details
											YES / NO		

FAD materials Main materials			net/mesh size	Attachments		net/mesh size	Max est. depth	FAD length	FAD width	Buoy serial number	FAD / Payao No. and or markings	SSI seen	SSI trapped
			cm			cm	M	M	M			Y / N / U	Y / N / U

Date	Time (from PS-2)	Set No.	Object number	Origin of FAD	Deployment date	latitude dd°mm.mmm'	N S	and longitude ddd°mm.mmm	E W	FAD as found	Beacon/ FAD lifted	FAD as left	Comments / Change details
											YES / NO		

FAD materials Main materials			net/mesh size	Attachments		net/mesh size	Max est. depth	FAD length	FAD width	Buoy serial number	FAD / Payao No. and or markings	SSI seen	SSI trapped
			cm			cm	M	M	M			Y / N / U	Y / N / U

Date	Time (from PS-2)	Set No.	Object number	Origin of FAD	Deployment date	latitude dd°mm.mmm'	N S	and longitude ddd°mm.mmm'	E W	FAD as found	Beacon/ FAD lifted	FAD as left	Comments / Change details
											YES / NO		

FAD materials Main materials			net/mesh size	Attachments		net/mesh size	Max est. depth	FAD length	FAD width	Buoy serial number	FAD / Payao No. and or markings	SSI seen	SSI trapped
			cm			cm	M	M	M			Y / N / U	Y / N / U

Diagrams- *label with 'Object number'*

Appendix VI: Maps of stranding events in PICTs involved in the data collection

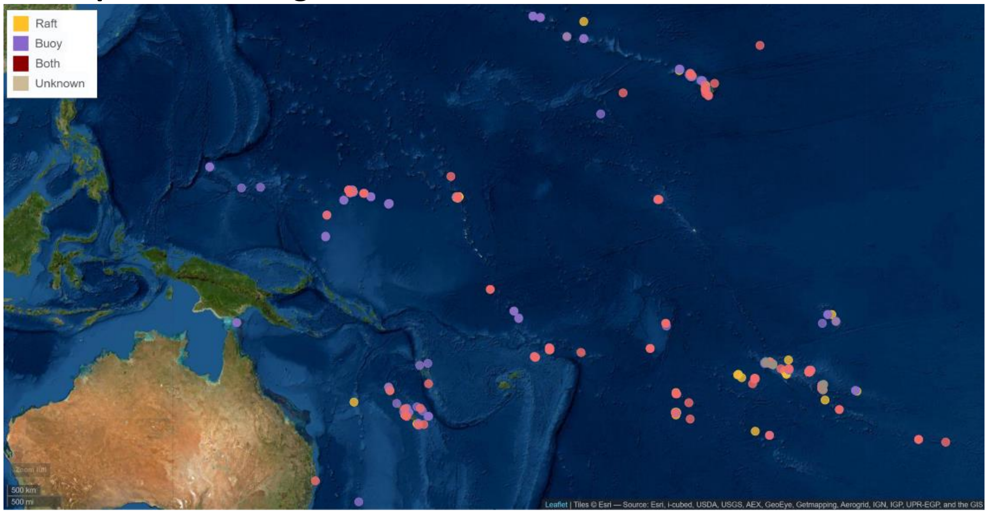


Figure VI.1. Map of stranding events in Mokil Atoll (Federated States of Micronesia).

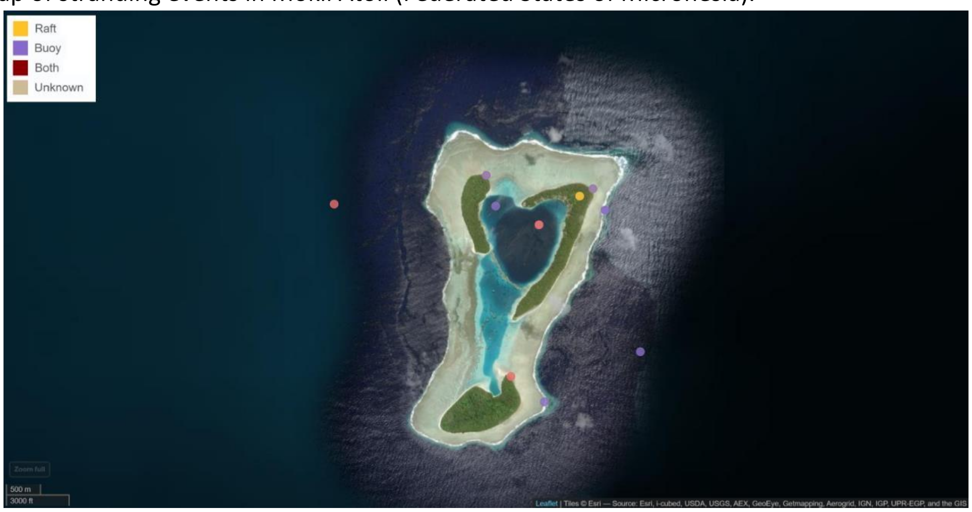


Figure VI.2. Map of stranding events in Mokil Atoll (Federated States of Micronesia).

Figure VI.3. Map of stranding events in Pohnpei, Ant Atoll and Pakin Atoll (Federated States of Micronesia).

Figure VI.4. Map of stranding events in the Main Hawaiian Islands (Hawai'i).

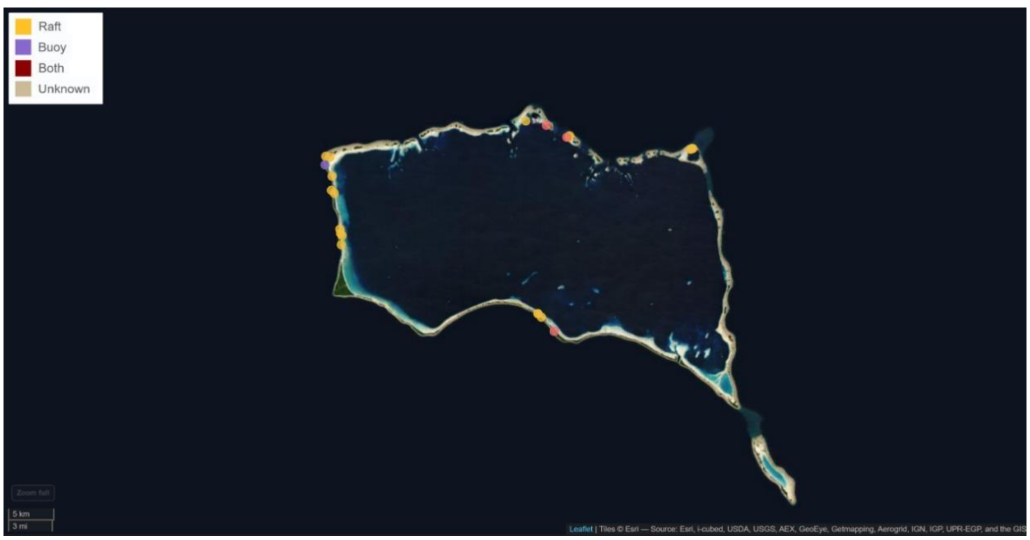


Figure VI.5. Map of stranding events in Mili Atoll (Republic of the Marshall Islands).

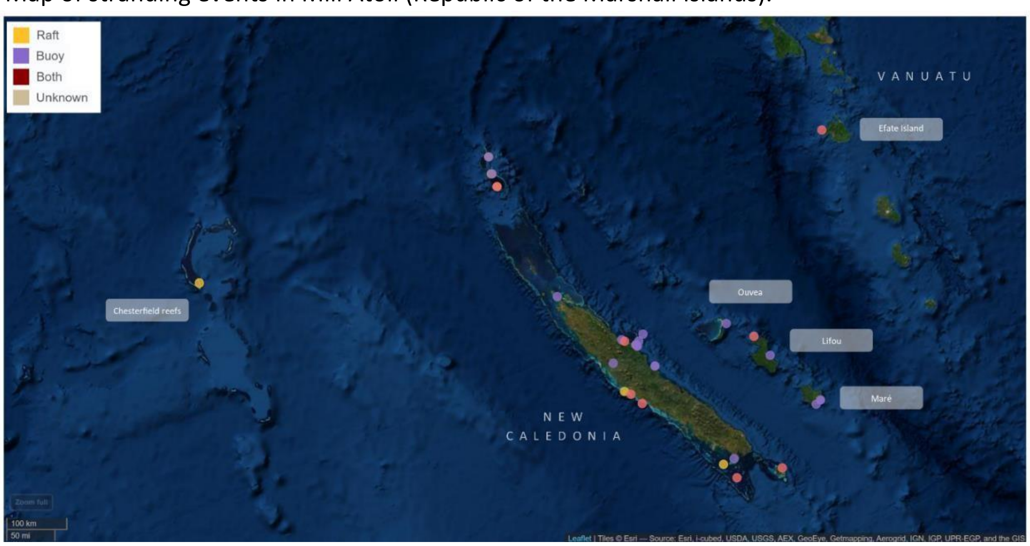


Figure VI.6. Map of stranding events in New Caledonia and Vanuatu (Southwest Pacific example).

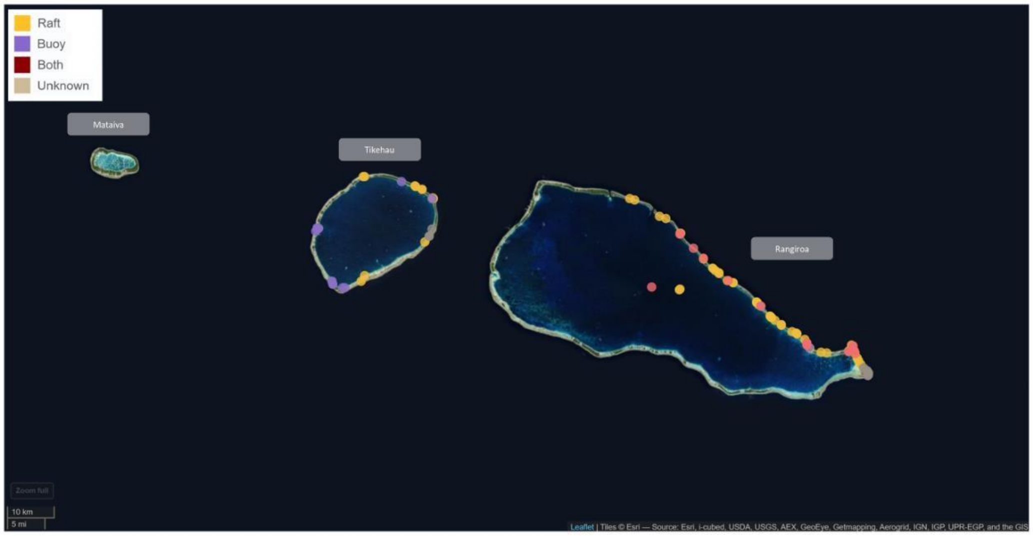


Figure VI.7. Map of stranding events in Mataiva, Tikehau and Rangiroa Atoll (French Polynesia).

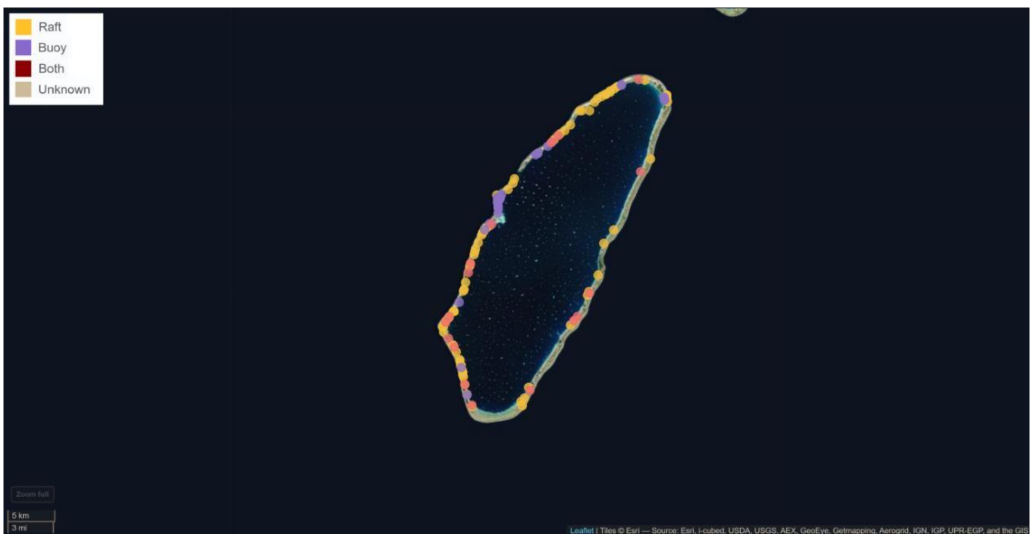


Figure VI.8. Map of stranding events in Raroia Atoll (French Polynesia).

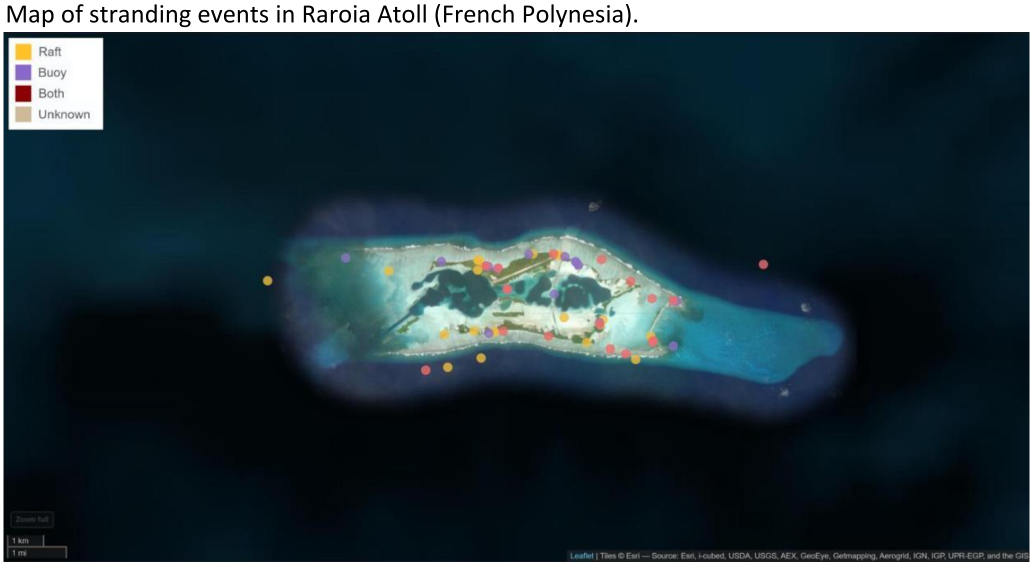
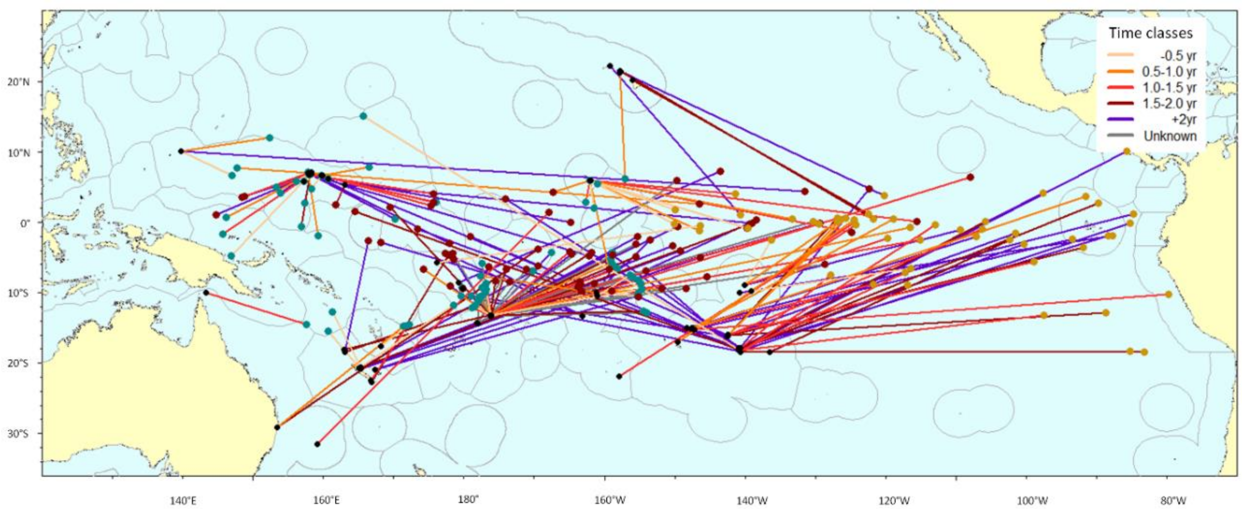


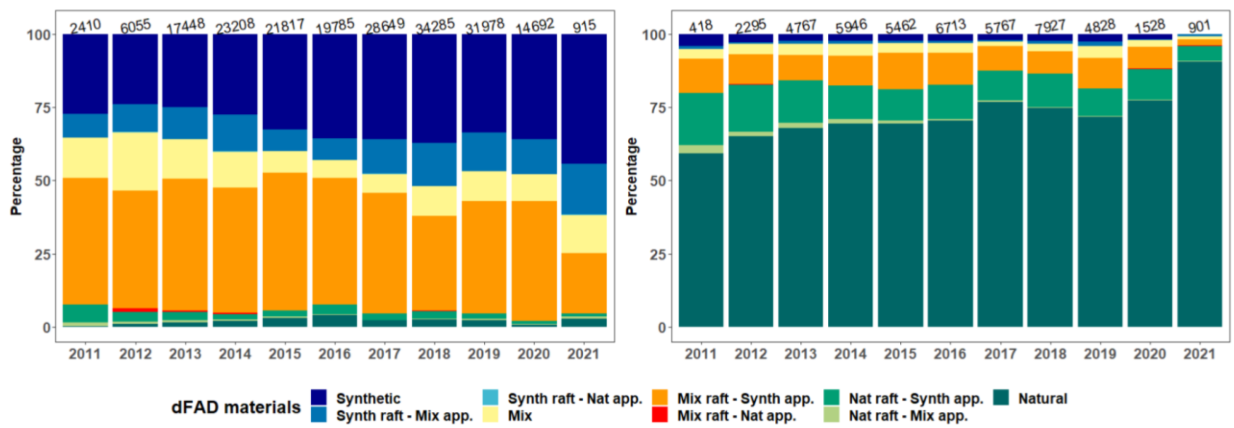
Figure VI.9. Map of stranding events in Palmyra Atoll.

Figure VI.10. Map of stranding events in Wallis (left) and Futuna (right).

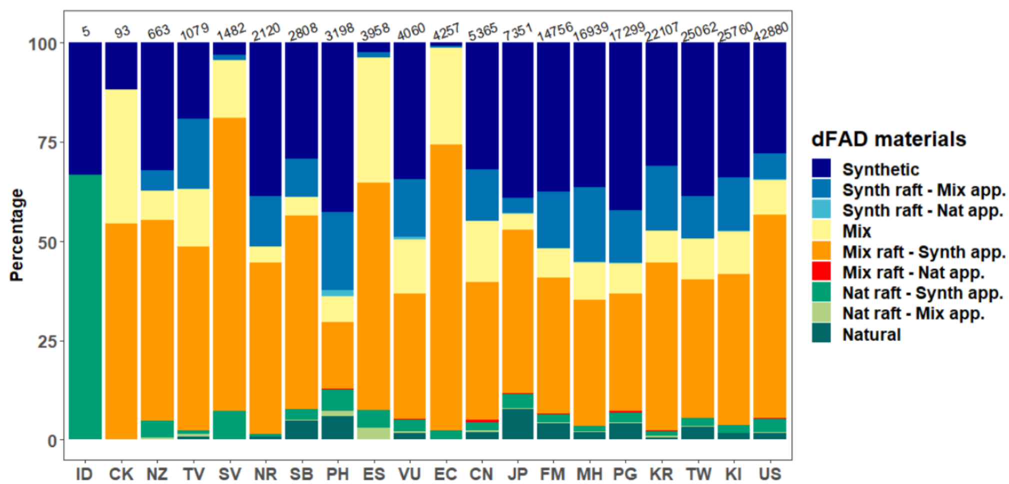
Appendix VII: Map with the stranding position (black dots) and the last known position of buoys from the three fishery databases: the PNA FAD tracking data (blue dots); the WCPFC observer data (red dots) and the IATTC observer data (orange dots). The color of the lines indicates the time between last known position and date found stranded.



Appendix VIII: Selected results from the paper "Towards Non-Entangling and Biodegradable drifting Fish Aggregating Devices baselines and transition in the world's largest tuna purse seine fishery" (Escalle *et al.* under review).



Appendix VIII.1. Percentages of dFADs (LEFT) and logs (RIGHT) per year constructed with natural (Nat), synthetic (Synth) or a mix of both materials in the design of the raft or the appendages (app.), as recorded by observers (2011–2021). Numbers on the top of the figure correspond to the number of dFADs with information on materials per year (Escalle *et al.* under review).



Appendix VIII.2. Percentage of natural (Nat), synthetic (Synth) or a mix of both materials in the design of the raft or the appendages (app.) of dFADs per fleet, as recorded by observers (2011–2021). 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).

Appendix IX: Others objectives related closely or not to the internship.

I could participate to numerous meetings with fisheries departments members, the PNA office, the WCPFC, and the annual Stock Assessment and Modelling team.

Several workshops occurred during this 6 months internship where I could learnt and develop my skills :

- The Github workshop administered by Arni Magnusson (Senior Fisheries Scientist),
- The Stock Assessment Workshop (SAW), animated by Sam McKechnie and Marino Wichman (Fisheries Scientists),
- The 18th regular session of the Scientific Committee of the WCPFC,
- Coming soon, a workshop on dFADs with all PICTs involved in the regional data collection program, aimed at presenting results, and discussing the improvement of the database and concerns raised by each member,
- Coming soon too, results of this study will be presented online to the 7th Debris Marine Conference in Busan (South Korea).

Related to dFADs, I could participate to the elaboration of scientific papers on "*Towards Non-Entangling and Biodegradable drifting Fish Aggregating Devices - baselines and transition in the world's largest tuna purse seine fishery*" for the Marine Policy Journal. My role was to analyse materials used in dFADs construction from observer programs. I also could participated to the analyses and writing of a report for the 18th Scientific Committee on "*Preliminarily analyses of the regional database of stranded drifting FADs in the Pacific Ocean (WCPFC-SC18-2022/EB-IP-03)*".

Also, I have been able to meet, present some results and discuss with the Ho-üt Association in Touho, which have provided us some of the data in New Caledonia (photos below).

L'INSTITUT agro Rennes Angers	Diplôme : Master 2 Spécialité : SML Biologie Parcours / option : Sciences Halieutiques et Aquacoles, (Ressources et Ecosystèmes Aquatiques) Enseignant référent : Etienne Rivot

Auteur(s) : Jennyfer MOUROT Date de naissance : 13.07.1998	Organisme d'accueil : The Pacific Community Adresse : 95 Promenade Roger Laroque, BP D5, 98848 Nouméa, Nouvelle-Calédonie Maître de stage : Lauriane Escalle
Nb pages : 63 dont Annexe(s) : 14	
Année de soutenance : 2022	

Titre français : Quantification et caractérisation de l'impact environnemental de l'échouage de DCP en zones côtières dans l'Océan Pacifique

Titre anglais : Quantification and characterization of the environmental impacts of stranded FAD events on coastal zones in the Pacific Ocean

Résumé :

Les zones côtières reçoivent des dispositifs concentrateurs de poissons (DCP) dérivants utilisés dans la pêche à la senne, entrainant des échouages, de la pollution et/ou causant des dommages environnementaux, en particulier sur les récifs coralliens. Pour quantifier ces événements et évaluer leurs impacts, plusieurs pays et territoires du Pacifique, en collaboration avec la Communauté du Pacifique (CPS), ont lancé des programmes de collecte de données *in-situ*. Au total, 1 159 échouages ont été recensés entre 2009 et 2022 avec 45.4% de bouées seules, 30.0% de DCP seuls et 19.0% de DCP attachés avec une bouée. Des analyses préliminaires ont été effectuées pour caractériser les échouages, notamment le type d'objets trouvés selon l'année ou le pays, les matériaux des DCPs, le type d'environnement dans lequel ils ont été trouvés et les dommages éventuels enregistrés. En outre, grâce aux données collectés par les observateurs à bords des thoniers senneurs et des données de trajectoires de DCPs des pays de l'Accord des Parties de Nauru (PNA), la nationalité des navires de pêche et les lieux d'origine des DCPs trouvés échoués ont été identifiés afin de guider au mieux l'adoption de mesures de gestion.

Abstract :

Drifting Fish Aggregating Devices (dFADs) used in purse seine fishery are reaching coastal areas where they can become stranded, adding to pollution and/or causing environmental damage especially to sensitive habitats such as coral reefs. To quantify these events and assess their impacts, several Pacific Countries and territories, in collaboration with the Pacific Community (SPC), have started programs to collect *in-situ* data. A total of 1,159 stranding events were identified in the 2009–2022 period, in which 45.4% were a buoy alone, 30.0% were a FAD alone, and 19.0% were a buoy attached to a FAD. Preliminary analyses were done to characterize stranding events such as the type of objects found among years or countries, dFADs materials, type of environment were dFADs were found and eventual damages recorded. Moreover, data from purse seine observers programs in the Pacific Ocean and FAD tracking data from the Parties of Nauru Agreement (PNA), nationality of fishing vessels and origins of dFAD found stranded have been identified in order to guide adoption of management measures.

Mots-clés : DCPs dérivants, design, impact environnemental, évènements d'échouage, Pacifique, WCPFC, PNA, IATTC

Key Words: Drifting FADs, design, environmental impact, stranding events, Pacific, WCPFC, PNA, IATTC