



## Original Article

# Quantifying drifting Fish Aggregating Device use by the world's largest tuna fishery

Lauriane Escalle<sup>1,\*</sup>, Steven R. Hare<sup>1</sup>, Tiffany Vidal<sup>1</sup>, Maurice Brownjohn<sup>2</sup>, Paul Hamer<sup>1</sup>, and Graham Pilling<sup>1</sup>

<sup>1</sup>Oceanic Fisheries Programme, The Pacific Community (SPC), B.P. D5, 98848 Nouméa, New Caledonia

<sup>2</sup>The Parties to the Nauru Agreement (PNA), P.O. Box 3992, Majuro, Republic of the Marshall Islands

\*Corresponding author: tel: +687 26 20 00; e-mail: [lauriane@spc.int](mailto:lauriane@spc.int)

Escalle, L., Hare, S. R., Vidal, T., Brownjohn, M., Hamer, P., and Pilling, G. Quantifying drifting Fish Aggregating Device use by the world's largest tuna fishery. – ICES Journal of Marine Science, 0: 1–16.

Received 15 January 2021; revised 14 April 2021; accepted 20 May 2021.

Drifting Fish Aggregating Devices (dFADs) are a major fishing mode for tropical tuna purse seine fisheries worldwide. However, the extent of dFAD use remains poorly understood. We present novel approaches for estimating annual dFAD deployments and number of dFADs monitored by individual vessels, using empirical data and robust estimation procedures. We leveraged observer and logbook data, combined with new dFAD tracking data from the Western and Central Pacific Ocean (WCPO) purse seine fishery, the largest tuna fishery in the world, to evaluate trends in dFAD use across the entire WCPO between 2011 and 2019. Average estimates ranged between 20 000 and 40 000 deployments per year, depending on the methodology, with the total number of deployments appearing relatively stable over the last decade. The median number of active buoys monitored per vessel per day ranged from 45 to 75 depending on the year, well below the current management limit of 350. Our results contrast with other oceans, having fewer buoys monitored per vessel, a unique stable trend, but overall number of deployments two times higher than any other ocean. This study provides a basis for improved monitoring and management of dFAD use in the WCPO, with applicability for other regions.

**Keywords:** Fish Aggregating Device, monitoring, purse seine fishery, tuna, Western Central Pacific Ocean

## Introduction

Fishers have always exploited the natural aggregating behaviour of marine species around floating objects to locate and catch fish in the open ocean (Castro *et al.*, 2001). In the tropical tuna purse seine fishery, natural floating objects, especially logs, have been used by fishers globally since the development of the fishery in the 1980s (Fonteneau *et al.*, 2000). Since the 1990s, fishers have constructed and deployed their own drifting Fish Aggregating Devices (dFADs). Constructed dFADs are typically made of a bamboo raft with a 50–70 m tail of old netting and other miscellaneous materials (Dagorn *et al.*, 2013b). Fishing on dFADs, both natural (i.e. logs) and constructed, has increased considerably since the 2000s, and with the introduction of satellite tracking and sonar technology

to the dFAD buoys, has become a major fishing mode for catching tropical tuna worldwide (Fonteneau *et al.*, 2013; Maufroy *et al.*, 2017).

Globally, many issues linked to the extensive use of dFADs have been raised. Sets on dFADs often have higher bycatch rates relative to “free school” sets (i.e. sets on tuna schools not associated with a floating object), including catch of vulnerable species such as sharks and sea turtles (Dagorn *et al.*, 2013b). These species may also become entangled in the netting of a dFAD's underwater appendages (Filmlater *et al.*, 2013). In addition, dFADs abandoned or lost by fishers, may continue to pose a risk of entanglement; strand in coastal areas and potentially damage coral reefs; or disintegrate at sea leading to pollution (Maufroy *et al.*, 2015; Davies *et al.*, 2017; Escalle *et al.*, 2019). DFADs may also have detrimen-

tal interactions with tuna stocks. For example, dFADs may disrupt natural behaviours and distribution patterns of tuna (Hallier and Gaertner, 2008; Dagorn *et al.*, 2013a; Fonteneau *et al.*, 2015) or cause tuna school fragmentation when deployed extensively (Sempo *et al.*, 2013). Of particular concern is the higher catch of small bigeye (*Thunnus obesus*) and yellowfin (*Thunnus albacares*) tuna on dFAD sets, which has implications for the sustainability of the stocks of these species in some areas (Dagorn *et al.*, 2013b; Matsumoto *et al.*, 2016; Tolotti *et al.*, 2020).

In the Western and Central Pacific Ocean (WCPO), the purse seine fishery, with a recent annual tuna catch of approximately 2 million tons (dominated by skipjack tuna, *Katsuwonus pelamis*), is presently the largest tuna fishery in the world, accounting for 70% of the tuna catch in the WCPO (Williams *et al.*, 2020b). In this region, dFAD fishing increased, along with overall purse seine fishing effort and harvest, until approximately 2009 (see Figure S1), at which point catch and effort stabilized and has remained relatively consistent over the last decade (Williams *et al.*, 2020a). The number of sets on constructed dFADs has exceeded the number of sets on natural logs for the last 10 years and dFAD sets have accounted for more than 35% of total purse seine sets and more than 40% of total purse seine catch in recent years (Williams *et al.*, 2020a). The sharp increase in the use of dFADs in the 1990s and 2000s was influenced by the arrival of new technological developments (Lopez *et al.*, 2014; Tidd *et al.*, 2017), such as satellite buoys to track and locate dFADs, and more recently the use of echo-sounder satellite buoys to estimate and remotely transmit information on the quantity of tuna aggregated below them (Fonteneau *et al.*, 2013; Lopez *et al.*, 2014; Escalle *et al.*, 2020a). In 2009, the increased use of dFADs, and the potential impacts on the bigeye stock, in particular, led the Parties to the Nauru Agreement (PNA, comprising Federated States of Micronesia, Kiribati, Republic of the Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu, Figure S2) and the Western and Central Pacific Fisheries Commission (WCPFC) to implement an annual three to 5 month dFAD closure during which all dFAD-related activities (e.g. fishing, deploying, servicing) are prohibited (subject to some exemptions, see WCPFC, 2018). This coincided with the 2009 implementation of the Vessel Day Scheme (VDS) by the PNA (<https://www.pnatuna.com/vessel-day-scheme-texts/purse-seine-vds-text>), which sets a total allowable effort in fishing days per year across the main purse seine fishing grounds in the WCPO.

The PNA VDS and the dFAD closure measure were implemented, in part, to manage the number of dFAD sets made by limiting total effort and reducing purse seine dFAD fishing during some months of the year. In the period following the implementation of these measures, the number of dFAD sets and associated catch has remained relatively stable (Leroy *et al.*, 2013; Williams *et al.*, 2020a). However, while the number of sets on dFADs has stabilised, as typically sets on dFADs are only productive around dawn in the WCPO, the number of dFADs deployed annually in the WCPO remains unknown. While it is likely that the number of dFADs deployed would have increased concomitantly to the number of dFAD sets until 2009, when the daily effort limits came into effect, the trend since then is less clear. We hypothesise that there are advantages and incentives to deploy more dFADs because greater availability of dFADs equipped with echo-sounder capability per vessel affords a skipper more opportunities to locate a productive dFAD to set on.

Recently, WCPFC members adopted a Conservation and Management Measure (CMM) to limit the number of active dFAD

buoys, at any given time, to 350 per vessel (WCPFC, 2018). However, data and analyses to evaluate this management limit and its effectiveness are lacking. While the need to quantify and monitor the number of dFADs used per vessel, and at the scale of the WCPO, has been highlighted, access to adequate data for analysis has been a limiting factor. This is largely due to the confidential nature of the information (Fonteneau *et al.*, 2015; Lennert-Cody *et al.*, 2018). However, the PNA recently obtained access to a large number of trajectories from satellite buoys deployed on dFADs in the WCPO and provided these to the Pacific Community (SPC) through their dFAD tracking programme. This programme was implemented in 2016 to provide information to improve management of dFADs in PNA waters, and the wider WCPO, and is beginning to provide valuable data on dFAD use (Escalle *et al.*, 2020b). While very detailed, the dataset is incomplete, in particular due to dFAD trajectories outside PNA waters being removed (hereafter referred to as “geofencing”) prior to submission to PNA; or some trajectories not being reported at all (Escalle *et al.*, 2020b). These data are complemented by those from the Pacific Islands Regional Fisheries Observer Programme (PIRFO) for the tuna purse seine fleets operating within the WCPO, which includes records made by observers on-board purse-seiners for all dFAD-related activities. Since 2011, the quantity of dFAD-related data recorded by observers has greatly increased, due to the 100% observer coverage requirement in the WCPO (implemented in 2010 between 20°N and 20°S; WCPFC, 2008; Williams *et al.*, 2020a). However, one crucial data element, i.e. the unique buoy identification number, remains difficult to record by observers in the field or is not provided by the skipper, and is often missing. This number is required to assess the number of dFADs used and to readily match observer data with dFAD trajectories in the PNA dFAD tracking database. Therefore, while available data related to dFADs to guide management in the WCPO are unique in terms of quantity, quality and type of information compared to most ocean basins, and allow new estimation techniques to be developed, they remain incomplete.

Other difficulties with quantifying dFAD use relate to the complexity of dFAD fishing strategies (Lennert-Cody *et al.*, 2018). A diverse array of vessels and fleets operate in the WCPO; some vessels rely heavily on a large array of their own dFADs, while others fish more often on free schools or rely on logs and dFADs found and appropriated at-sea. Several types of measurements are therefore needed to quantify the number of dFADs used per vessel at the scale of the WCPO (Fonteneau *et al.*, 2015). For example, to quantify the total number of dFADs drifting at sea, and characterize their impact on catch rates, both monitored (i.e. with an active buoy) and unmonitored dFADs need to be estimated. However, no data are currently available for unmonitored dFADs; alternative methods, such as simulations, or ongoing monitoring and management, should therefore be investigated (Escalle *et al.*, 2019). Similarly, to investigate impacts of dFADs on the ecosystem, the number of dFADs deployed annually, the number recovered, and the overall changes to the quantity and local densities of floating objects (including logs) (Dagorn *et al.*, 2013a) are important. Finally, the number of buoys monitored by a vessel is crucial information to quantify effort.

Generally, a high degree of uncertainty exists around the total number of dFADs deployed in the WCPO. The only previously available estimates were based upon publicly available data, industry consultations and strong assumptions on dFAD use per vessel size and flag (Gershman *et al.*, 2015). That study estimated the number of deployments in the WCPO to be between 30 000–50 000 in 2013. There is, therefore, a need for more comprehensive and robust

analyses, based on fishery data, to estimate the number of dFADs deployed and used in the WCPO, and to provide a basis for ongoing monitoring and management. This lack of information on dFAD use, as well as implications for tuna stocks, tuna behaviour and the marine environment, are key uncertainties for the sustainable management of dFAD use and tuna fisheries (Dagorn *et al.*, 2013b; Davies *et al.*, 2014; Evans *et al.*, 2015). Indeed, better knowledge on dFAD use is important for various research activities to guide management, including better estimates of fishing effort (Vidal *et al.*, 2020) and capacity of the dFAD fishery (Fonteneau *et al.*, 2015); purse seine catch-per-unit-effort (CPUE) standardization (Vidal *et al.*, 2020); and tuna school behaviour (Leroy *et al.*, 2013; Scutt Phillips *et al.*, 2019b).

While taking into account the incomplete nature of available dFAD activity data and the different measurements linked to the number of dFADs that could be compiled, the aim of this paper is to provide the best available estimates of recent dFAD use in the WCPO. Notwithstanding the data deficiencies noted above, this paper aims to estimate (i) the total number of buoys or dFADs currently deployed per vessel, as well as across the entire WCPO per year, and, (ii) the number of active buoys (on constructed dFADs or logs) monitored by individual vessels over certain periods of time. Analyses are performed over the 9 years from 2011–2019. This period allows an investigation of recent trends and provides a baseline against which to measure future changes in dFAD usage.

## Methods

### Data

We used complementary datasets combining three fishery data over the 2011–2019 period: observer data, operational logsheet data, and Vessel Monitoring System (VMS) data; and the 2016–2019 PNA dFAD tracking data (Escale *et al.*, 2020b) (See Table 1 for the description of the four available data types). Observer data include information on dFAD deployments, visits to dFADs, dFAD sets per vessel and associated catch, as well as the origin of dFADs encountered by a vessel at sea. The origin of dFADs and logs was recorded by observers in 23% of the records and corresponded to (i) deployment from the same vessel (53.8%); (ii) a vessel of the same company or another vessel with consent (14.9%); (iii) another vessel without consent or unknown origin (27.8%); or (iv) a support vessel (3.5%) (Table S1). Since 2010, there has been a goal for 100% observer coverage; however, annual data availability (considered in this document as observer data coverage) is at 65–78% of the fishing trips (see Table 1 for annual observer data coverage), because some data have not yet been received for recent years or some observer reports are excluded/never received for some trips (see Williams *et al.* 2020a). Operational logsheet data are required for all fishing trips (available logsheet data coverage was 91% of trips), are recorded by vessel captains and include estimates of catch per species at the set level. VMS data (100% coverage) were used to obtain the number of days at-sea per vessel and, by comparing with the number of observer days at-sea, to estimate annual observer data coverage (i.e. considered here as the amount of observer data received and processed by the SPC) per vessel. Finally, the PNA dFAD tracking data comprised transmitted locations and time stamps from buoys attached to dFADs between 1 January 2016 and 31 December 2019 (see Escalle *et al.* 2020a for details of the data compilation procedure and database characteristics). Each transmission included the unique buoy identification number, location, time and the owner of

**Table 1.** Main statistics of logsheet, observer, VMS, and FAD tracking data from the WCPO for the 2011–2019 period.

	2011	2012	2013	2014	2015	2016	2017	2018	2019
No. of vessels in observer and logsheet data	No. of vessels in observer and logsheet data	268	293	314	322	307	281	282	282
	No. of vessels used in clustering analysis (vessels with missing length and weight removed)	257	286	306	318	306	280	282	282
	% of vessels with observer data coverage < 10%	5.4%	7.0%	14.4%	13.2%	9.8%	4.3%	5.3%	3.9%
	No. of vessels used in matching analysis (vessels with observer data coverage < 10% removed)	243	266	262	276	276	268	267	271
Observer data coverage	Estimated no. of trips from VMS data	1827	2061	2131	2320	2215	2135	2304	2427
	Overall trip data coverage	66.9	73.3	85.5	83.1	87	64.7	86.5	72.9
Observer and logsheet data	Raw no. of deployments in observer data	20 143	19 008	20 147	20 170	15 497	13 216	18 381	16 490
	Raw no. of deployments in observer data (vessels with observer data coverage < 10% removed)	19 646	18 353	19 110	19 005	14 993	12 969	18 259	16 341
	No. of fishing sets in logsheet data	14 573	14 131	13 100	13 430	10 771	14 587	16 010	12 508
FAD tracking data	No. of vessels in FAD tracking data					186	197	202	194
	% of vessels in FAD tracking data					65.0%	70.1%	71.6%	68.8%
	No. of active buoys					13 916	20 779	22 710	20 531
	% active buoys without known vessel owner					17.6%	10.5%	6.1%	0.7%
	No. of buoy (re)deployments					18 229	21 566	21 904	18 838

each dFAD buoy. The dFAD tracking data used for the analyses presented in this paper corresponds to a subset of buoy deployments (13 916–22 710 per year) and active buoys (18 229–21 904 per year) for most vessels fishing in PNA waters (from 65 to 72% of vessels) covering the 2016–2019 period (Table 1).

### Identification of vessels groups with similar dFAD fishing strategy

A clustering analysis was performed to identify groups of vessels, ranging from 268 to 322 vessels depending on the year (Table 1) with similar dFAD fishing strategies, which was then used to develop a range of metrics of annual deployments (in this manuscript, dFAD refers to both constructed and natural (i.e., logs) dFADs). This was important given that most vessels did not have 100% observer data coverage for all the years considered. The vessel clusters were then used to raise the observed number of deployments to account for unobserved trips.

A hierarchical clustering analysis (*hclust* function in R; R Development Core Team, 2017), based on Ward's minimum variance (Murtagh and Legendre, 2014), was used to group vessels by year based on their dFAD fishing strategy. Vessels vary in terms of dFAD reliance, with some vessels focused almost entirely on fishing free schools, while others are dependent on a large array of dFADs. Clustering was at the vessel and year level and based on: vessel length; number of associated sets (dFAD and logs) recorded in operational logsheet data; number of days at-sea derived from VMS data; percentage of associated sets (dFAD and logs) over the total number of all sets from operational logsheet data; and origin of all dFADs set on, serviced or investigated at sea from observer data. Vessels with missing information regarding length were removed, resulting in 257–308 vessels being available for the clustering analysis (Table 1). The output of the clustering consists of a dendrogram and several diagnostic statistics (e.g. cubic clustering criteria, C-index, DB index, Hubert index, and Dunn Index) that were used to select the appropriate number of clusters.

### Estimated number of dFAD or buoy deployments using fishery data

In this analysis, a deployment is defined as an initial or repeat deployment at sea of a dFAD with a buoy (55.8% of all deployments recorded by observers); a buoy only either on a log or dFAD already drifting (10.5%); or a dFAD only due to the buoy deployment not being recorded by the observer (33.7%). Estimates are calculated on an annual basis, as this corresponds to the main temporal variability in the WCPO due to the El Niño–Southern Oscillation (ENSO) cycle, with seasonal variability being relatively low (Lehodey *et al.*, 2020; Williams *et al.*, 2020a).

First, the raw estimates of deployments per vessel  $v$  and year  $y$  ( $D_{v,y}$ ), as recorded by observers, were compiled alongside the observer data coverage per vessel ( $OC_{v,y}$ ; i.e. proportion of total VMS fishing days with observers) (Table 2). Overall trip data coverage varied between 64.7 and 78.0% (Table 1). Events where a buoy was deployed at the same time as a dFAD were only counted once. Data from vessels with observer data coverage of < 10% of their fishing days each year were deemed too imprecise and removed from the analysis, resulting in removal of 4–13% of vessels per year, and 243–276 vessels remaining available (Table 1).

Second, the total number of dFAD deployments per vessel  $v$  and per year  $y$  ( $Dtot_{1,v,y}$ ) was estimated using a “scaled-vessel metric” calculated as follows:

$$\text{Scaled-vessel metric : } Dtot_{1,v,y} = D_{v,y}/OC_{v,y}, \quad (1)$$

and an estimate of the total number of dFAD deployments across all  $N_y$  vessels included in the analysis in year  $y$  is given by

$$Dtot_{1,y} = \sum_{v=1}^{N_y} Dtot_{1,v,y}. \quad (2)$$

In order to provide alternative metrics of annual deployments for robust comparison, to account for the unknown number of deployments during the unobserved trips (i.e. 13–35% of trips, Table 1) and the different vessel clusters, and to obtain a plausible estimate of the range of the total number of deployments per year, three additional estimates of the total number of deployments per vessel  $v$  and per year  $y$  ( $Dtot_{2,v,c,y}$ ;  $Dtot_{3,v,c,y}$ ;  $Dtot_{4,v,c,y}$ ) were calculated (see below and Table 2). These drew on the results of the clustering analysis, where estimates of the number of deployments for the unobserved trips were derived from the 0.1 quantile ( $Dtot_{q10,c,y}$ ), mean ( $Dtot_{mean,c,y}$ ), and 0.9 quantile ( $Dtot_{q90,c,y}$ ) values of total number of deployments ( $Dtot_1$ ), calculated previously using the scaled-vessel metric, and recorded per vessel cluster  $c$ . This corresponds to

$$\begin{aligned} \text{Q10 cluster – based metric : } Dtot_{2,v,c,y} &= D_{v,y} + Dtot_{q10,c,y} * (1 - OC_{v,y}) \\ \text{Mean cluster – based metric : } Dtot_{3,v,c,y} &= D_{v,y} + Dtot_{mean,c,y} * (1 - OC_{v,y}) \\ \text{Q90 Cluster – based metric : } Dtot_{4,v,c,y} &= D_{v,y} + Dtot_{q90,c,y} * (1 - OC_{v,y}) \end{aligned} \quad (3)$$

and the corresponding estimate of the total number of dFAD deployments across all vessels in year  $y$  is given by

$$\begin{aligned} Dtot_{2,y} &= \sum_{c=1}^8 \sum_{v=1}^{N_{c,y}} Dtot_{2,v,c,y}, \\ Dtot_{3,y} &= \sum_{c=1}^8 \sum_{v=1}^{N_{c,y}} Dtot_{3,v,c,y}, \\ Dtot_{4,y} &= \sum_{c=1}^8 \sum_{v=1}^{N_{c,y}} Dtot_{4,v,c,y}, \end{aligned} \quad (4)$$

where  $N_{c,y}$  is the number of vessels in cluster  $c$  in year  $y$ . The quantile range of 0.1 to 0.9 provides an 80<sup>th</sup>-percentile range of uncertainty for the mean estimate.

Finally, to estimate the total number of dFAD deployments made in the whole WCPO per year, we included estimates of the deployments from vessels with no observer data coverage (assigned to a vessel cluster based on logsheet data), using the average total number of deployments per cluster and estimation metric (i.e. mean of  $Dtot_{1,v,y}$ ,  $Dtot_{2,v,c,y}$ ,  $Dtot_{3,v,c,y}$ , and  $Dtot_{4,v,c,y}$ ).



**Table 2.** Methods used to estimate the number of deployments made per vessel and per year in the WCPO.

Method	Metric	Abbreviation	Data used	Time period
Fishery data only	<i>Scaled vessel</i>	$Dtot_1$	– Raw observer record of number of deployments per vessel and year – Annual observer data coverage	2011–2019
	<i>Cluster-based</i>			
	– q10	$Dtot_2$	– Total number of deployments per vessel and year from <i>scaled vessel</i> metric	
	– mean	$Dtot_3$	– 0.1 quantile, mean and 0.9 quantile of the number of deployments per cluster of vessel and year from <i>scaled vessel</i> metric	
Combined dFAD tracking and observer data	– q90	$Dtot_4$	– Annual observer data coverage	2016–2019
	<i>Tracking-observer</i>	$Dtot_{trk-obs}$	– Raw observer record of deployments per year (buoy ID number, position and date/time) – Deployments from the dFAD tracking database (buoy ID number, position and date/time)	

This leads to the overall estimates per year calculated as follow:

$$\begin{aligned}
 Dtot_{1,y} &= \sum_{v=1}^{N_y} Dtot_{1,v,y} + \sum_{v=1}^{O_y} \overline{Dtot_{1,y}}, \\
 Dtot_{2,y} &= \sum_{c=1}^8 \left[ \sum_{v=1}^{N_{c,y}} Dtot_{2,v,c,y} + \sum_{v=1}^{O_{c,y}} \overline{Dtot_{2,c,y}} \right], \\
 Dtot_{3,y} &= \sum_{c=1}^8 \left[ \sum_{v=1}^{N_{c,y}} Dtot_{3,v,c,y} + \sum_{v=1}^{O_{c,y}} \overline{Dtot_{3,c,y}} \right], \\
 Dtot_{4,y} &= \sum_{c=1}^8 \left[ \sum_{v=1}^{N_{c,y}} Dtot_{4,v,c,y} + \sum_{v=1}^{O_{c,y}} \overline{Dtot_{4,c,y}} \right], \quad (5)
 \end{aligned}$$

where  $O_{c,y}$  is the number of vessels in cluster  $c$  in year  $y$  for which  $OC < 10\%$ .

### Estimated number of buoy deployments using combined dFAD tracking and observer data

Estimates combining both dFAD tracking and observer data could only be made for the 2016–2019 period and were developed considering the following features of the data: (i) submission of dFAD tracking data to the PNA is mandatory for vessels when fishing in PNA waters, but not the whole WCPO (see Figure S2 for the map of the PNA and the WCPO); (ii) most dFAD trajectories in the PNA dFAD tracking data have been geofenced by fishing companies prior to submission, with dFAD positions outside PNA waters removed; (iii) the data correspond to an unknown fraction of the total number of dFADs in the WCPO, with some vessels not submitting any dFAD trajectories (65–72% of vessels of all vessels found as FAD owners in the dFAD tracking database, Table 1); iv) the vessel owner of a dFAD (buoy owner) was sometimes not provided (17.6; 10.5; 6.1 and 0.7% of active buoys in the database in 2016–2018 and 2019, respectively, Table 1); (v) a set made on a given dFAD can be performed by a vessel that is not the owner of the dFAD, or a

dFAD can be deployed by another vessel of the same company as the owner; and (vi) deployments in the PNA dFAD tracking data correspond to buoys, which may be deployed, picked-up, then re-deployed several times (Table 1, Escalle et al., 2018b, 2020b).

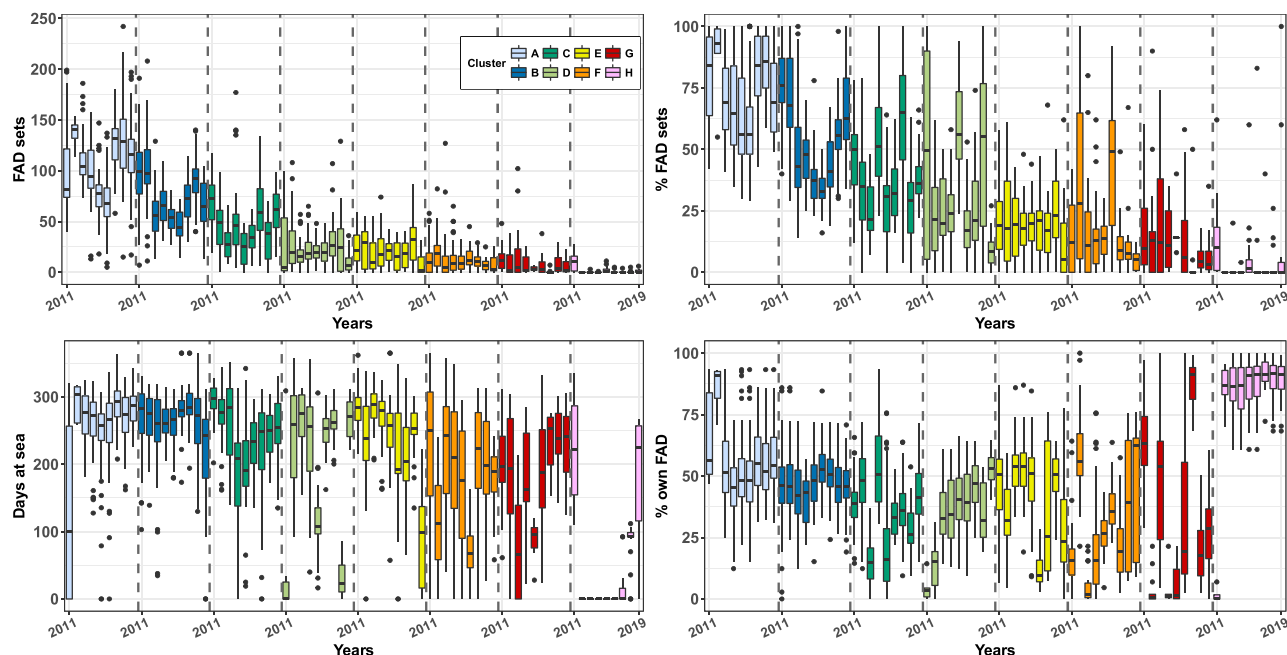
Given the complexity and incompleteness of the dFAD tracking data, it was necessary to match observer data on a given dFAD deployment to a dFAD trajectory (Table 2). At-sea positions from the dFAD tracking data were matched with buoy and dFAD deployment positions from observer data (see Table 1 for available data in both databases) using; (i) buoy identification number; or (ii) matching fishing company and date, and plausible speed between position/time of deployments in dFAD tracking and the observer data (i.e., vessel cruising speed  $\leq 15$  knots). Deployment positions on the border of a PNA country and not preceded by several on-board positions, were removed, as these likely resulted from the geo-fencing of the data and therefore were not actual deployments.

The total number of deployments per year ( $Dtot_{trk-obs}$ ) was estimated by adding the number of matched deployments ( $D_{matched}$ ) with the number of non-matched deployments in the dFAD tracking database ( $D_{track \text{ non-matched}}$ ) and the number of non-matched deployments in the observer database ( $D_{obs \text{ non-matched}}$ ) (see Table S2 for the annual contribution of each part to  $Dtot_{trk-obs}$ ). Note that  $D$  used in the estimates using fishery data only (section 2.3) corresponds here to  $D_{matched} + D_{obs \text{ non-matched}}$ .

#### Tracking–observer metric : $Dtot_{trk-obs,y}$

$$\begin{aligned}
 &= D_{matched_{v,y}} + D_{track \text{ non-matched}_{v,y}} \\
 &\quad + D_{obs \text{ non-matched}_{v,y}}. \quad (6)
 \end{aligned}$$

Note that not all vessels were listed as buoy owners in the PNA dFAD tracking data; 186 vessels were listed as buoy owners in 2016, 197 in 2017, 202 in 2018 and 194 in 2019, out of a total of 286, 281, 282, 282, respectively, in the WCPO. Estimates for the unlisted vessels were either (i) based on observer records only or (ii) raised from the estimates based on observer records using the ratio of the mean total number of deployments per year and cluster ( $T_{c,y}$ ) for vessels with tracking data to the mean total number of deployments per year for vessels with no tracking data ( $U_{c,y}$ ). The raised estimates



**Figure 1.** Boxplots by cluster and year (2011–2019) of the number of dFAD sets in logsheet data (top left-hand panel), the percentage of dFAD sets from logsheet data (top right-hand panel); the number of days at-sea per vessel derived from VMS data (bottom left-hand panel); the percentage of owner dFADs (i.e. belonging to the vessel) visited or set on by a vessel from observer data (bottom right-hand panel). The median (horizontal black lines), and lower (q1) and upper (q3) quartiles (box limits) are shown for each vessel cluster and year. Upper whiskers represent the smaller of the maximum value and  $q3 + 1.5 \times$  interquartile range, and lower whiskers are the larger of the minimum value and  $q1 - 1.5 \times$  interquartile range. Circles are data points outside these ranges.

( $Dtot_{trk-obs}$ ), for vessels with no tracking data  $v_{NT}$ , are as follows:

$$Dtot_{trk-obs, v_{NT}, y} = Dobs \text{ non matched}_{v,y} \times \frac{T_{c,y}}{U_{c,y}}, \quad (7)$$

In addition, total estimates of deployments also included those from the PNA FAD tracking data with no vessel owner declared (Table S3).

### Estimated number of buoys monitored per vessel

The number of buoys, inclusive of instrumented logs and dFADs, monitored per vessel over different time periods was investigated for the top 50 vessels with the highest number of estimated deployments per year for the methods with fishery data only and with combined dFAD tracking and observer data.

For the *scaled-vessel* metric, the top 50 vessels were used to investigate the number of buoys monitored. The sum of the number of buoy-only deployments from observer data (raw numbers) over a certain period is considered a proxy for the number of active buoys at any given time. The assumption was made that each buoy deployed at a given time would remain active for a certain period, called the “survival period” (see Figure S3). Three survival periods were chosen, 4 months, corresponding to the mean at-sea time of buoys before re-deployments; 6 months, the average active time of buoys; and one year as an extreme (Figure S3, Escalle et al., 2018).

For the *tracking-observer* metric, the top 50 vessels per year were defined as those with the highest number of deployments estimated by this metric and that were present in the PNA dFAD

tracking data. The maximum number of active buoys monitored ( $Bmax$ ) at any given time  $t$  per vessel  $v$  was investigated by raising the raw number of active buoys ( $B$ ) from the PNA dFAD tracking data, then using a raising factor derived from the relationship between raw number of deployments from the PNA dFAD tracking data and the total number of deployments estimated per vessel and per year. The raising factor (RF) used, and the maximum number of active buoys ( $Bmax$ ) are calculated according to the following:

$$RF = \frac{Dmatched_{v,y} + Dtrack \text{ non matched}_{v,y} + Dobs \text{ non matched}_{v,y}}{Dmatched_{v,y} + Dtrack \text{ non matched}_{v,y}}, \quad (8)$$

$$Bmax_{v,t} = B_{v,t} \times RF.$$

The raw and raised number of active buoys per vessel was investigated per day and per month and at monthly and annual time-steps. Differences between years and months were assessed using Kruskal Wallis tests and *ad hoc* Wilcoxon pairwise comparisons. All statistical analyses were performed using R 3.4.0 (R Development Core Team, 2017).

## Results

### Clustering by vessel and year

For each year, vessels were divided into eight groups (see Table S4 for statistics used to determine the optimum number of clusters and Figure S4 for the dendrograms each year) of similar dFAD fishing strategy, discriminated on the basis of both fishing and ves-

sel characteristics (Figures 1 and S4). These were classified as clusters A–H in decreasing order of the number of dFAD sets recorded in logsheets (Figure 1 and Figure S5). Similarly, the percentage of dFAD sets also generally decreased from cluster A–H (Figure 1). Vessel length and vessel speed were relatively consistent among clusters B–D, but significantly smaller/slower for cluster H and larger/faster for cluster A in 2011 and 2012, indicating the presence of large vessels that subsequently left the fishery (Figure S5). The number of days at-sea was highly variable depending on the cluster considered, but was generally high for clusters A to C–E. These clusters were associated with vessels that made higher numbers of dFAD sets annually (A to C or D), typically set on and investigated dFADs they deployed and owned, or another vessel's dFAD with its consent based on knowledge of the observer, for example a dFAD from a vessel of the same fishing company that shares information with other company vessels. These clusters therefore correspond to vessels with a large array of available dFADs. These findings were similar for cluster H, mostly because these vessels made very few associated sets, but mostly on their own dFADs (Figure 1). Vessels in the rest of the clusters operated on their own dFADs for less than 50% of the time.

Generally, vessels in clusters A and B were the largest vessels; fished most of the year; had a fishing strategy oriented toward dFADs, with more than 50–75% of their sets being on dFADs and with a large array of their own dFADs (Figures 1 and S5). Vessels in clusters C and D were intermediate, in that they also showed high rates of dFAD sets and days at sea, but they relied on both their own dFADs and other dFADs found and appropriated at sea. Clusters E–G represented relatively opportunistic vessels, having less than 20–50% of their sets on dFADs and included smaller vessels (e.g. domestic fleets of Pacific Island nations). Finally, cluster H included very small vessels, conducting very few dFAD sets that were mostly on their own dFADs. Most vessels were classified in the same cluster for more than one year over the whole study period (84.6% of vessels), with 36.6% of vessels classified in the same cluster for at least 4 years.

The raw number of deployments per vessel recorded by observers shows a general decrease from vessel cluster A–H. This is broadly in line with our observations based on logsheet data, even if a higher number of deployments was detected in some years for clusters F and H (Figure 2); high variability between vessels within a cluster was also detected.

### Estimated number of dFAD or buoy deployments using fishery data

The cumulative total number of deployments per vessel and year, estimated using the *scaled-vessel* and *cluster-based* metrics, is shown for vessels with observer data coverage in Figures 3 and S6. This was compiled to assess the proportion of deployments accounted for by a specific fraction of the fleet. Based on the *scaled-vessel* estimates, for all years, 14–25% of vessels were responsible for 50% of the deployments, with a decrease in the number of vessels responsible in recent years (Figures 3 and S6). This suggests that, recently, fewer vessels are responsible for more deployments (e.g. 14–17% of vessels responsible for 50% of deployments since 2017; Figures 3 and S6). For the *cluster-based* metrics, 17–27% of vessels were responsible for 50% of deployments in the *q10* metric; compared to 20–30% of vessels in the mean metric; and 20–32% of vessels in the *q90* metric (Figure S6).

Very few vessels in the WCPO undertook more than 350 deployments per year, based either on the *scaled-vessel* metric: 4% in 2011, 2018, and 2019, and 1–2% for the other years, or the *cluster-based* metrics: 0–4% of vessels (Table 3 and Figure S7). For all the estimation metrics, most vessels deployed less than 250 dFADs per year, with 0–11% of vessels deploying more than 250 (except for 2011 when this percentage was 19% for the *q90 cluster-based* metric and 15% for the *scaled-vessel* metric; Table 3 and Figure S7). In general, more than half of the vessels deployed less than 150 dFADs per year.

The number of estimated deployments in the WCPO was compiled for vessels with observer data coverage > 10% (numbers indicated on Figure 3 and Figure S7) and for all vessels by adding average number of deployments per cluster for vessels with observer data coverage < 10% (Figure 4). Estimates using the *scaled-vessel* (i.e.  $Dtot_1$ ) and the *mean cluster-based* metric (i.e.  $Dtot_3$ ) showed very similar results, with the total number of buoy or dFAD deployments varying between 21 000–31 000 per year (Figure 4). Using all the estimation metrics, including the *q10* and *q90 cluster-based* metrics, the range of total number of deployments estimated per year varied between 23 000–39 500 in 2011 and 17 400–23 800 in 2016, including 11–42 vessels per year with no observer data coverage.

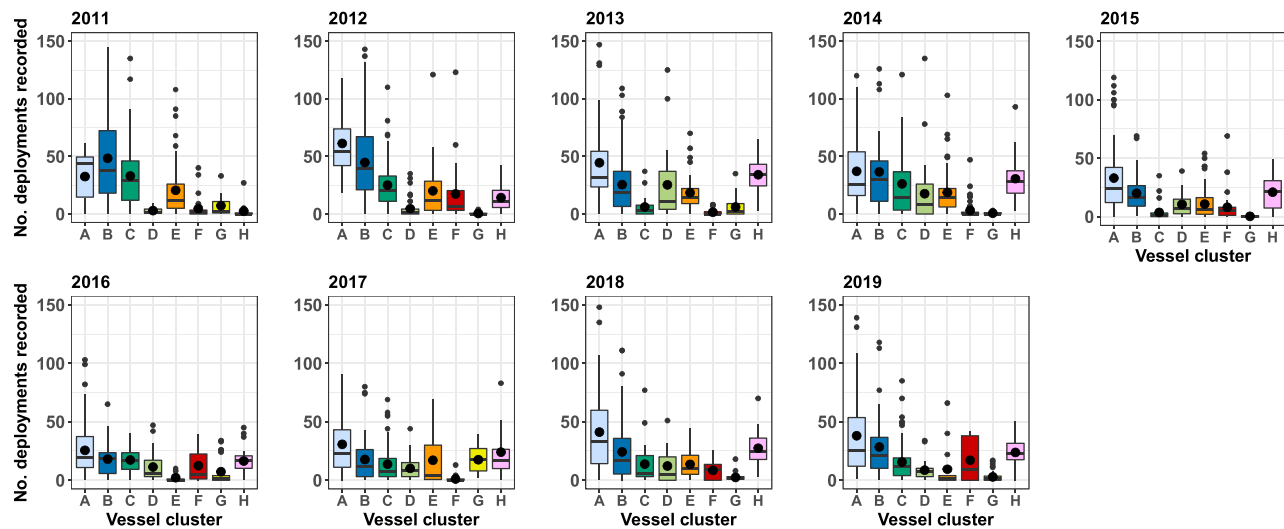
### Estimated number of buoy deployments using combined dFAD tracking data and observer data

The *tracking-observer* metric estimated that the number of buoy deployments per vessel varied between 1 and 598 (mean = 98) in 2016; 1 and 845 (mean = 114) in 2017; 1 and 699 (mean = 135) in 2018; and 1 and 700 (mean = 120) in 2019 (Figure 5). Similar to estimates from the previous method, very few vessels deployed/redeployed more than 350 buoys per year (1–4% of vessels, Figure 5 and Table 3) and more than half of the vessels typically deployed less than 150 dFADs, with only 13–17% of vessels deploying more than 150 buoys per year (Table 3). Cumulative numbers of deployments per vessel per year showed that 18–19% of vessels (i.e. around 50 vessels) were responsible for 50% of the deployments (Figure 5).

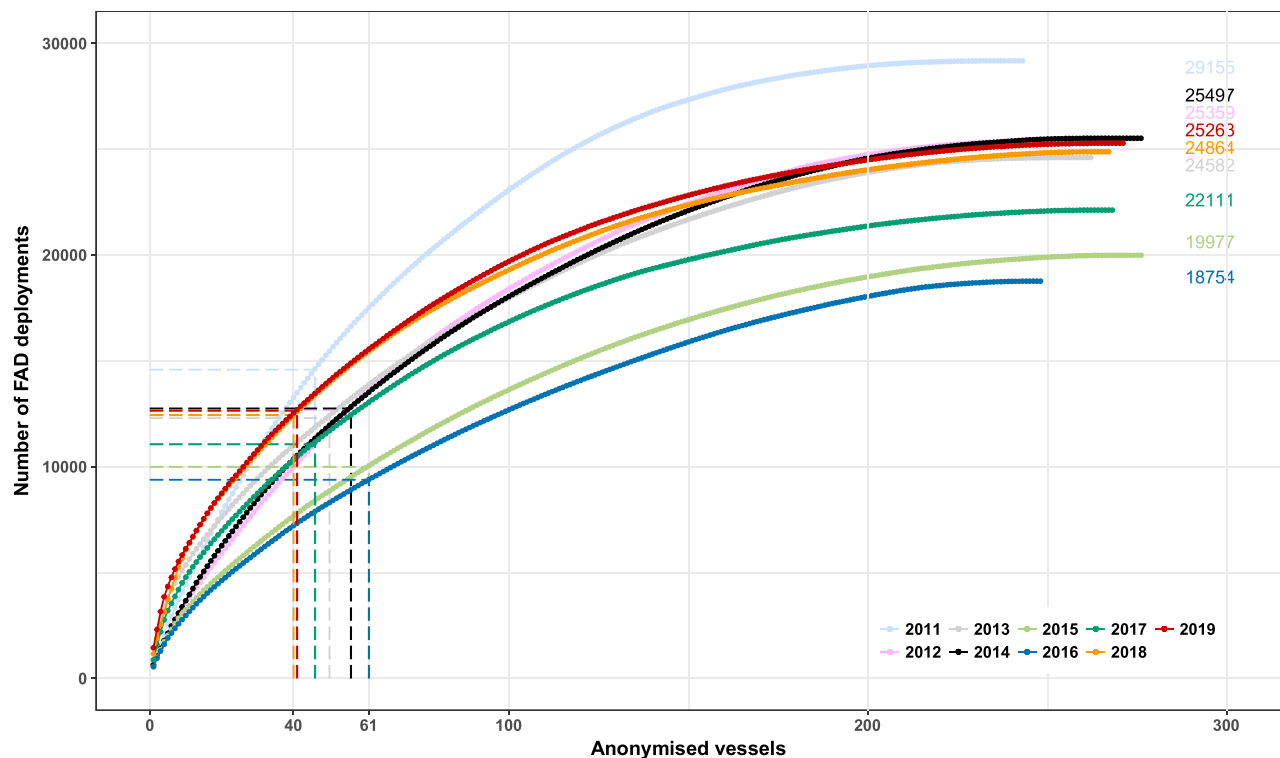
Using the *tracking-observer* metric, the total number of estimated buoy deployments was 31 093 in 2016, 34 140 in 2017, 39 521 in 2018, and 35 207 in 2019, including deployments not linked to any vessel owner declared in the PNA FAD tracking data (Figure 4 and Table S3). This represents a level of deployment that is similar to the *q90 cluster-based* metric for 2011–2015. The raised number of estimated buoy deployments accounting for vessels with no available FAD tracking data was 36 951 in 2016, 39 582 in 2017, 46 937 in 2018 and 42 623 in 2019 (Figure 4 and Table S4).

### Investigating the number of active buoys per vessel

The number of deployments per vessel per year estimated in previous sections is different from the actual number of buoys monitored at any given time by a vessel, which has been limited to 350 since 2018 (WCPFC, 2018). Most of the top vessels (57%) were only classified accordingly for 1 or 2 years, while a core group of vessels (17%, i.e. 30 vessels) appears to be regularly deploying more dFADs than others (in 5 to 7 years out of 9). Under the assumption that all buoys remained active for a 4-month survival period, the median number of buoys monitored for the top vessels was 50, the maximum number was 250 and 50% of the vessels monitored 25–75 dFADs at any particular time (Figure 6). This increases



**Figure 2.** Raw number of dFAD and/or buoy deployments, recorded by observers, per vessel cluster and year. All other information as for Figure 1.



**Figure 3.** Cumulative estimated number of deployments per vessel per year (2011–2019) using the *scaled-vessel* metric. Estimates of the total number of dFADs in the WCPO (for vessels with observer data coverage < 10%), by year, are indicated on the right-hand side of each curve. Horizontal dotted lines correspond to 50% of the number of deployments per year and vertical dotted lines to the corresponding number of vessels (range added on the x-axis) having deployed 50% of the dFADs.

to a median of 50–75 buoys for survival periods of 6 months and 100–150 for survival periods of one year (Figure 6). Longer survival periods result in a higher number of monitored dFADs because it was assumed that all buoys remained active for the whole period.

An alternative method investigated the number of active buoys per vessel at any given time using data from the PNA dFAD tracking programme only. To do so, the top 50 vessels with the highest number of estimated buoy deployments present in the dFAD tracking database were selected (*tracking-observer* metric). The raised num-



**Table 3.** Estimates of the percentage of vessels with more than 150, 250, and 350 dFAD deployments per year depending on the estimation metric used\*.

Year	% vessels with > 150 deployments					% vessels with > 250 deployments					% vessels with > 350 deployments				
	Scaled vessel	Cluster-based		Tracking observer	Scaled vessel	Cluster-based	Mean	q10	q90	Tracking observer	Scaled vessel	Cluster-based	Mean	q10	q90
		Mean	q90												
2011	30	29	49	-	15	7	9	7	19	-	4	2	2	1	3
2012	21	18	26	-	4	2	3	2	4	-	1	1	1	1	1
2013	14	13	18	-	5	3	4	3	5	-	2	2	2	2	2
2014	17	16	24	-	6	3	4	3	5	-	1	1	1	1	1
2015	7	8	10	-	3	2	2	2	4	-	1	0	0	0	2
2016	6	5	6	15	2	0	0	0	0	2	1	1	0	0	0
2017	13	11	24	13	4	1	1	1	5	4	2	1	1	1	1
2018	18	17	26	17	6	5	5	5	9	6	4	2	2	2	4
2019	16	18	33	15	6	3	4	3	11	5	4	2	2	1	3

\*Scaled-vessel estimates; cluster-based estimates (mean; 0.1 quantile "q10"; and 0.9 quantile "q90") and tracking-observer estimates.

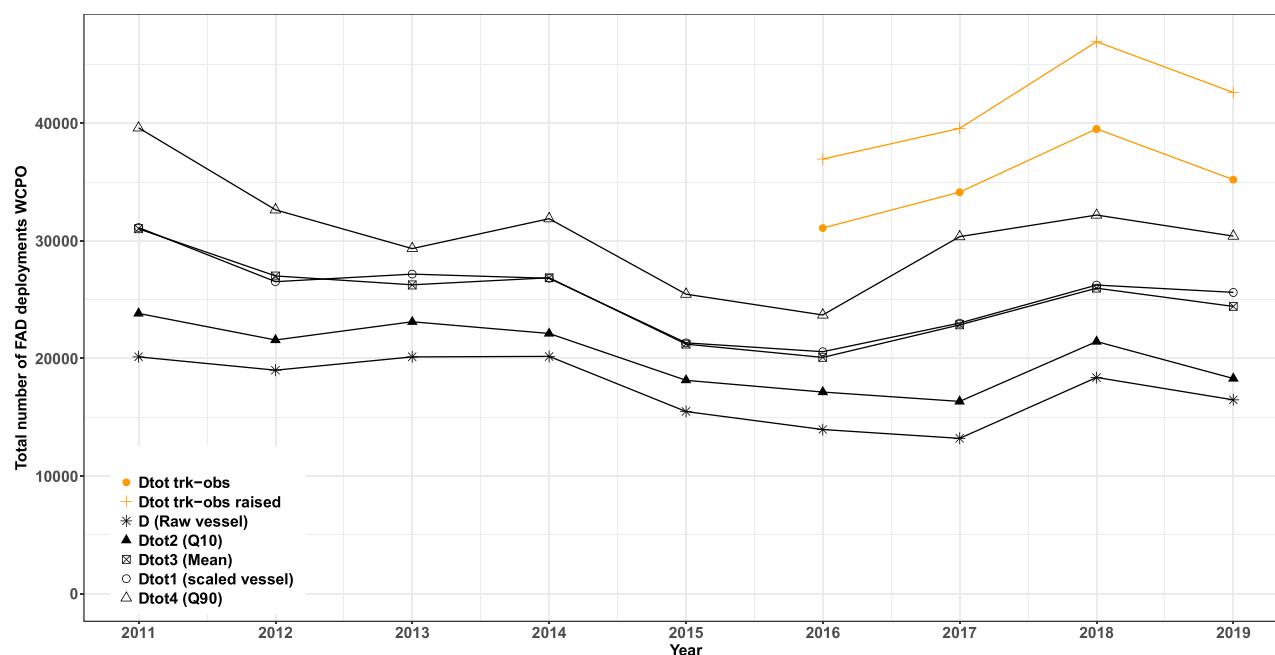
ber of active buoys ranged between 0 and 330 per vessel per day (Figure 7) and between 0 and 400 per vessel per month (Figure S8). A general increasing trend was detected through time, with a median raised number of active buoys of 45 per vessel per day in 2016 compared to 75 in 2019 (Figure 7). Significant differences between years were found using a Kruskal–Wallis test ( $\chi^2 = 6299.7$ ; and 256.4 for the raised number per day and per month respectively,  $df = 3$ ;  $p < 0.001$ ) and all years presented a significantly different number of buoys with the exception of 2017 and 2018 (multiple comparison tests with significance criterion of  $p \leq 0.05$ ). No monthly trend was detected, with a median of 50–60 active buoys per vessel per day and 75–80 per vessel per month (Figure 7; Kruskal–Wallis test  $p > 0.05$ ).

## Discussion

### Novel advances and continued challenges for dFAD deployment estimates

This paper presents the first estimates of dFAD deployments in the largest tuna purse seine fishery in the world and offers novel approaches for robust empirical estimation of dFAD use. It also highlights the current challenges in estimating and monitoring the total number of dFAD deployments and the numbers of active buoys on dFADs being monitored by individual vessels at any particular time. The methods developed in this study, using various data sources and considering vessel-level fishing strategies, provide a way to monitor the use of dFADs at the ocean basin scale of the WCPO, where the size and complexity of the fishery, as well as data availability, have previously limited our ability to compile robust estimates. It should be noted that the contributions of sub-regional management groups, in particular, the PNA, to both improving data collections and making data available has been critical, and will continue to be essential to improve the monitoring of dFAD use. The improved data on dFAD use will in turn contribute to other research on dFAD influences on tuna catch rates and ecosystem interactions more generally in the WCPO. The estimation approaches we have developed using different combinations of available data, should be applicable in other oceans and fisheries to improve assessments of dFAD use globally.

The purse seine fishery in the WCPO covers approximately 20 million km<sup>2</sup> (10°S–10°N and 130°E–150°W) primarily spanning the Exclusive Economic Zones (EEZs) of 15 different countries and territories. The number of purse seine vessels has remained stable at around 250–300 since 2010 (excluding small domestic vessels in Indonesia, Philippines and Vietnam; Williams *et al.*, 2020b), covering more than 15 fleets. While such complexity presents challenges for scientific analyses and management, the fishery data available are of a high standard. For data related to dFADs, this includes the requirement for 100% observer coverage since 2010, with records of deployments, sets and any other dFAD related activities (WCPFC, 2008; Williams *et al.*, 2020b). This coverage level exceeds that used in other studies to estimate dFAD use (e.g. 5–10% coverage; Maufroy *et al.*, 2017). Additional detailed data have also been made available through the PNA's dFAD tracking programme initiated in 2016 (Escalle *et al.*, 2020b). While these data present the best insight into dFAD usage by purse seiners in PNA waters, this dataset is still incomplete. Thus, many uncertainties around dFAD use remain. Regarding observer data, the time lag before near-complete observer data are available precludes precise estimation for recent years and therefore the comparison with the dFAD tracking data



**Figure 4.** Estimates of the total number of deployments per year in the WCPO for all vessels. Different estimating metrics were used based on fishery data only (black line) and a combination of PNA dFAD tracking and observer data (orange line). Estimates using fishery data only consisted of five metrics ( $D$  = raw vessel;  $D_{tot1}$  = scaled vessel metric;  $D_{tot2}$  = using 0.1 quantile by vessel cluster;  $D_{tot3}$  = using mean by vessel cluster;  $D_{tot4}$  = using 0.9 quantile by vessel cluster). For all metrics, the raw data only was used for vessels with observer data coverage < 10%. Estimates using a combination of PNA dFAD tracking and observer data (*tracking-observer* metric  $D_{tot_{trk-obs}}$ ) included deployments with no vessel owner declared in the PNA FAD tracking database. For vessels missing in the PNA FAD tracking data, estimates from raw ( $D_{tot_{trk-obs}}$ ) or raised ( $D_{tot_{trk-obs}}$  raised) observer data only were used.

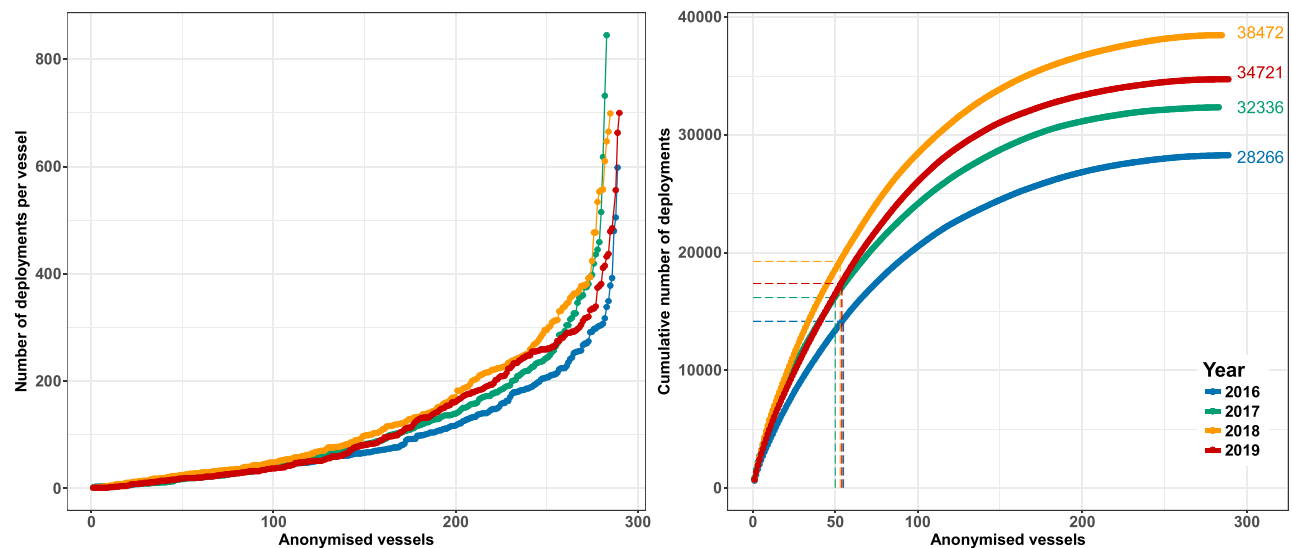
estimates should be treated with some caution. In addition, deployments not documented by observers, performed by supply vessels, or made in the EPO and then transported to the WCPO by the general westward current circulation in the tropical Pacific (Scutt Phillips *et al.*, 2019a) would not be accounted for. To overcome these challenges and increase confidence in estimates, two complementary approaches were used in this paper.

### Perspectives on deployment estimates, estimation methods, and global comparisons

The results from the *scaled-vessel*, *cluster-based* and *tracking-observer* metrics suggest that the total number of dFADs deployed/redeployed each year in the WCPO has an 80<sup>th</sup> percentile range of 16 000–47 000 for the 2011–2019 period (mean of 20 000–30 000 using fishery data only and 30 000–40 000 using FAD tracking and observer data). These numbers are similar to the 30 000–50 000 deployments estimated based on industry declaration in 2013 by Gershman *et al.* (2015). In addition, the annual number of total deployments estimated in the WCPO is the highest of all the oceans, with estimated maxima of 15 000 in the Indian Ocean; 18 000 in the Atlantic Ocean; and 19 000 in the EPO in 2013 (Fonteneau *et al.*, 2015; Gershman *et al.*, 2015; Maufroy *et al.*, 2017); compared to our estimates of 20 000–30 000 for the WCPO in 2013. This is not surprising given the scale of the WCPO fishery, and within region differences are not surprising as the data used for this study exceed those used in the past (i.e. Gershman *et al.*, 2015), combined with the more robust estimation procedures used here.

With the exception of a decrease in the 2015–2017 period, a stable trend through time in the total number of deployments in the WCPO was detected using the *scaled-vessel* and *cluster-based* metrics. This is likely due to delays in observer data availability in recent years, rather than any “real” decline in dFAD deployment rates. When results from all methods are compiled together, higher number of deployments are detected in 2018 and 2019. Hence, results from this paper and comparison with previous estimates (Gershman *et al.*, 2015) tend to indicate that the number of dFAD deployments has remained stable over the last decade, or has recently increased. This is consistent with trends in the number of dFAD sets and associated catch that, after a continuous increase from the mid-1990s, has remained relatively consistent over the last decade (Leroy *et al.*, 2013; Williams *et al.*, 2020a).

The stability, or recent increase, in the WCPO differs from the sharp increases detected in other oceans at least up until 2013. Studies of dFAD trends in the Atlantic and Indian oceans were, however, based on fishery data from specific fleets only and with limited observer coverage (Fonteneau *et al.*, 2015; Maufroy *et al.*, 2017); or based on assumptions and generalisations in the other oceans (Baske *et al.*, 2012; Gershman *et al.*, 2015). Since then, to our knowledge, there is no scientific paper or report indicating trends in the overall number of dFAD deployments per year, although fleet-specific trends in buoy use have been reported. The French fleet has seen a continued increase in number of active buoys per day, reaching 4000 and 1500 in 2019 in the Indian and Atlantic oceans, respectively (Floch *et al.*, 2019a, 2019b). If we consider an active buoy survival period of 6 months, this could correspond to more than 8000 and 3000 buoy deployments/redeployments per year, respec-



**Figure 5.** Estimated number of deployments per year in 2016 to 2019 (left-hand panel) and estimated cumulative number of deployments per year between 2016 and 2019 (right-hand panel) based on the tracking-observer metric. Individual data points represent individual vessels. Horizontal dotted lines, on the right plot, correspond to 50% of the number of deployments per year and vertical dotted lines to the corresponding number of vessels having deployed 50% of the dFADs. Estimates of the total number of dFADs deployments in the WCPO, excluding deployments with no vessel owner declared in the PNA FAD tracking database, by metric, are indicated on the right-hand side of each curve, on the right-hand plot.

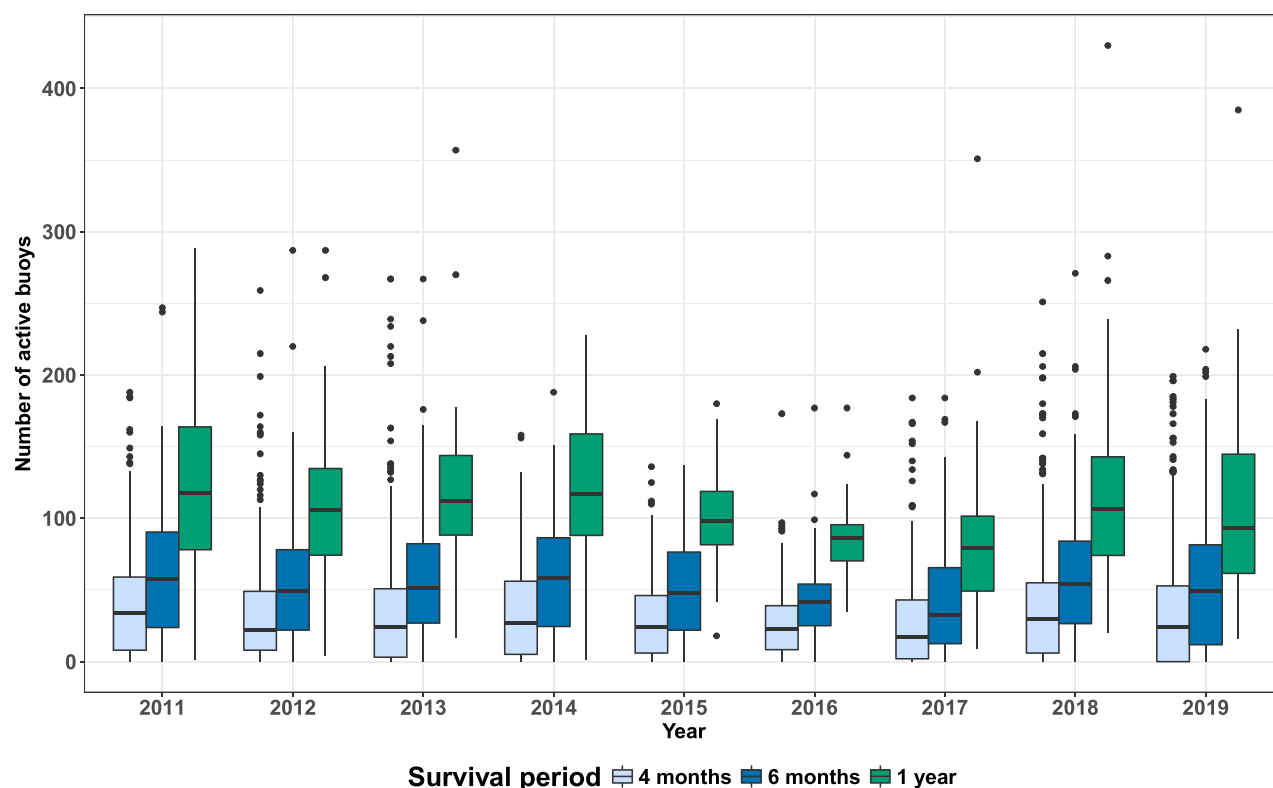
tively. However, with numerous dFAD exchanges and buoy swaps during a dFAD's at-sea life, it is difficult to assess trends in annual dFAD deployments from the number of active buoys monitored. Similarly, for a buoy survival period of 6 months in the Indian Ocean, it is estimated that 12 500–14 800 buoys are monitored per month by the entire purse seine fleet (IOTC, 2020a), potentially indicating an increase from the 15 000 annual dFAD deployments estimated by earlier studies (Gershman *et al.*, 2015; Maufroy *et al.*, 2017).

The relatively stable trend over the study period detected with the available data in the WCPO might be explained by the substantial changes in dFAD use that had already occurred in the decade preceding the initiation of the data collection that supported this study (2000–2010) (Tidd *et al.*, 2017). These aforementioned changes in the fishery include the introduction of the PNA's VDS, FAD closure periods, and the uptake of dFAD buoy technologies by fishers (Lopez *et al.*, 2014). The more recent period considered in this study is concomitant with the arrival and increased use of dFAD buoys with tracking and acoustic capabilities (Lopez *et al.*, 2014). These technologies have likely increased operational efficiency through easier location of dFADs and monitoring of associated biomass both in historically productive fishing grounds, as well as marginal areas. It is thought that this has allowed the geographic extension of the fishery (T. Vidal, pers. comm.). In general, a larger array of echosounder-equipped dFADs gives fishers greater choice and flexibility to choose the best aggregations, at convenient distances from their positions at sea or base ports (Lennert-Cody *et al.*, 2018).

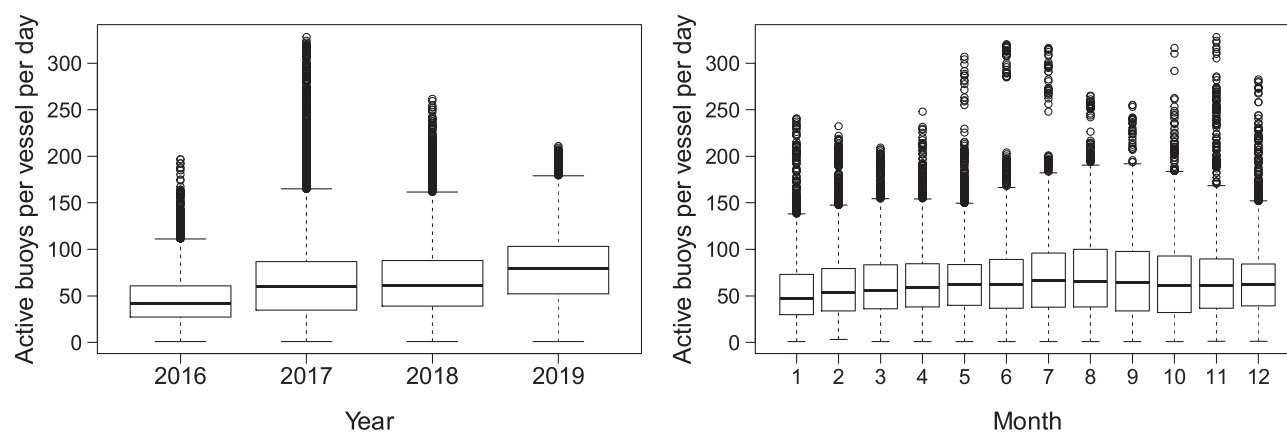
The stable trend since 2011 may suggest that an optimal number of dFADs has been reached under the current operational constraints, at least by some companies. Another explanation might be that the limitations of the available data over the 2011–2019 period biased our assessment to some extent. Indeed, as mentioned earlier, the data recorded by observers used in the analyses included

any deployments of dFADs with buoys or the addition of buoys to a dFAD or log found at-sea, but will not include those unnoticed by observers for reasons explained above. It is possible that increased deployments by non-purse seiners (cargo, longliner or support vessels) might explain the recent decrease in the number of vessels responsible for more than 50% of the deployments. These deployments would not be recorded by observers but would still appear in the PNA dFAD tracking data which, while incomplete, remains the most useful dataset to estimate the number of deployments in the WCPO. When raising the estimates for vessels absent from the FAD tracking data, an increasing trend is detected in the number of deployments since 2017, which highlights an apparent underestimation when directly using the currently available data. Generally, it can be considered that all the limitations mentioned (i.e. geo-fencing and incomplete nature of the dFAD tracking data, lack of full observer data coverage at this time, deployments unnoticed by observers) will likely lead to an underestimation of the active buoy numbers and deployments described in this paper. Accessing a longer time series of buoy trajectory data would therefore be important to more precisely assess the number of dFADs in use and the trends over time. This will be particularly important for a number of research questions, such as the impact of dFAD density on catch rates; better understanding of effort dynamics, including effort creep; standardization of purse seine CPUE; and tuna behavioural responses (Leroy *et al.*, 2013; Vidal *et al.*, 2020). In general, a comprehensive understanding of the number of dFADs being deployed and strategies of dFAD fishing will be a critical element for compiling reliable estimates of purse seine fishing effort for use in stock assessments (Fonteneau *et al.*, 2015).

Based on the overall number of deployments in the WCPO estimated here, and considering an average number of 280 purse seine vessels operating per year (Williams *et al.*, 2020a), each vessel would deploy an average of 107–142 dFADs per year. This estimate is lower than reported in other studies (Scott and Lopez, 2014; Fonteneau



**Figure 6.** Number of active buoys per vessel, derived from observer data using three buoy survival periods: 4 month, 6 month and 1 year, for the top 50 vessels deploying the highest number of dFADs. All other information as for Figure 1.



**Figure 7.** Annual (left-hand panel) and monthly (right-hand panel) variability in the raised number of active buoys per vessel and per day in the PNA dFAD tracking vessel for the top 50 vessels deploying the highest number of dFADs. All other information as for Figure 1.

*et al.*, 2015; Lennert-Cody *et al.*, 2018; Floch *et al.*, 2019a, 2019b). However, this may in part relate to the limitations of the data available to the other studies. Estimates per vessel per year derived here using two alternative methods showed that in most years only a small proportion of vessels deployed more than 150 dFADs. If we consider an average buoy survival period of 6 months Escalle *et al.*, 2018), less than 150 buoys would be actively monitored by a vessel. This was confirmed by estimation of the number of active buoys per vessel at any given time. Vessels deploying the highest number of buoys in the WCPO per year had a median number of active buoys

per day ranging from 45 in 2016 to 75 in 2019. Generally, an increasing trend was detected from 2016 to 2019 in terms of the number of active buoys, which suggests an increase in the number of dFADs monitored per vessel at a particular point in time by some fleets. This trend is supported by echosounder buoy adoption, which allows remote monitoring of fish aggregations below dFADs. This is different from the stable trend detected in the overall number of deployments in the WCPO. This difference could be explained in part by increased dFAD sharing within a company, despite a regulatory change that now requires dFADs to be registered to a given vessel



rather than a fishing company (B. Vanden Heuvel, pers. comm.). There may be benefits associated with strategic deployments if multiple vessels can monitor the same buoys, thereby increasing relative fishing capacity without scaling up total deployments. Interestingly, no monthly trend was detected, and fishers did not appear to monitor fewer dFADs during the FAD closure period. This could be due to the monitoring by fishers of the aggregation behaviour of tuna around their array of dFADs, as an additional guide for free school fishing during the closure, or to plan fishing after the closure period.

### Global dFAD fishing strategies

While the overall number of deployments per year estimated in the WCPO is the highest of all the oceans, the number of buoys deployed per vessel estimated in this paper is the lowest of all ocean basins, indicating less dependence on dFADs in the WCPO compared to other oceans. For example, 40% of the WCPO purse seine catch in 2019 was on floating objects, compared to approximately 60, 70 and 80% in the EPO, Atlantic Ocean and Indian Ocean, respectively (Pascual-Alayón *et al.*, 2019; IOTC, 2020b; Lopez *et al.*, 2020; Williams *et al.*, 2020a). In the EPO, it was also found that a certain portion of the fleet relied more heavily on dFADs and deployed higher numbers, ranging between 150–400 dFADs per year for those vessels deploying the highest numbers (Lennert-Cody *et al.*, 2018). In the Atlantic Ocean, the number of dFADs deployed per vessel has been estimated to have reached more than 500 for the Spanish fleet (Fonteneau *et al.*, 2015; Maufroy *et al.*, 2017) and 250 for the French fleet (Floch *et al.*, 2019b). In the Indian Ocean, 90% of the French purse seine sets are made on floating objects, with an estimated 315 dFADs deployed per vessel each year (Floch *et al.*, 2019a). This peak was reached after a very sharp increase in dFAD deployments between 2007 and 2013 (Fonteneau *et al.*, 2015; Maufroy *et al.*, 2017).

Differing rates of dFAD loss, e.g. drifting out of the fishing area, might also explain why some oceans show higher dFAD deployment rates per vessel, with higher loss rates being compensated for by greater levels of deployment per vessel. Alternatively, some fishing companies may decide to manage fewer dFADs, but keep them within the spatial range of their purse seiners, to avoid large dFAD loss. This would be influenced by local oceanographic currents and the expanse of the fishing area. While information on rates of dFAD loss is not available for other oceans, loss rates of 42.1% have been estimated for the WCPO based upon dFAD tracking data in 2016–2020 (Escalle *et al.*, 2020b). For other oceans, this could be investigated in further detail using appropriate data (detailed observer data and dFAD tracking data) and/or simulation based on oceanographic data (Imzilen *et al.*, 2016; Scutt Phillips *et al.*, 2019a).

### dFAD management strategies

In the other oceans, management measures are in place to limit the number of active buoys at 70–450 (depending on vessel size) in the EPO (IATTC, 2020), 300 in the Indian Ocean (IOTC, 2019) and 300 for the Atlantic Ocean (ICCAT, 2020). However, except for the Indian Ocean, there are no limits on total annual deployments. In the Indian Ocean, where the number of sets on dFADs has reached more than 80% of all sets performed (Floch *et al.*, 2019a; Báez *et al.*, 2020), the number of buoys monitored at any given time for Spanish and Seychelles vessels decreased from almost 600 to less than 300 following the initial implementation and subsequent decrease in the limit on active buoys (Santiago *et al.*, 2017; Chassot *et al.*, 2019). The

opposite has been observed for the French fleet in the same ocean, where the IOTC limit replaced a self-imposed buoy limit by the fishing companies, and the number of buoys monitored per vessel increased from approximately 200 per month in 2012 to more than 300 by 2016 (Maufroy and Goujon, 2019). This highlights the need for reliable monitoring of the number of dFADs used per vessel at the scale of each ocean basin.

For more than a decade, the management of the dFAD purse seine fishery in the WCPO has mostly relied on an annual dFAD closure period (prohibition of dFAD-related activities for three to five months depending on the EEZ or high seas area; WCPFC, 2018). The dFAD closure was primarily initiated to reduce the impact of dFAD fishing on bigeye tuna stocks, due to high catch rates of small bigeye in dFAD sets. However, it is also likely contributing to the stabilisation of the number of dFAD sets since 2010 (Leroy *et al.*, 2013; Williams *et al.*, 2020a). The number of sets that can be performed in a year by a vessel is limited by the characteristics of the aggregation and vertical distribution of tuna at dFADs. Notably, tunas aggregate more tightly to the dFAD and closer to the surface just before sunrise (Scutt Phillips *et al.*, 2019b). This means that only one dFAD set per day is commonly performed in the WCPO. Further, while the PNA's VDS management system would constrain the number of dFADs sets that can be conducted through a limit on the number of fishing days, the number of dFADs deployed by a vessel may have increased. Thus, resulting in an expansion of the array of dFADs with echo-sounder satellite buoys available to fishers, and hence allowing greater opportunity to maintain or increase daily catch rates. Therefore, more recently, WCPFC also adopted another CMM to limit the number of active dFADs (i.e. a dFAD with an activated satellite buoy), at any given time to 350 per vessel (WCPFC, 2018). However, this was not based on scientific data and if all vessels (~250–280) were to reach this level, the number of annual deployments could be above 85 000. As such, this limit would not be considered a conservation measure. This paper shows that currently this maximum level is rarely, if ever, reached in the WCPO. However, the increasing trend in the number of active buoys detected from 2016 to 2019 is noteworthy.

In addition, a measure restricting the number of active buoys per vessel, at any given time, cannot take into account the fact that buoys are commonly deactivated (i.e. satellite transmissions are terminated) when dFADs are considered lost by fishers or after an optimum period at sea. This approach is therefore likely insufficient for limiting the overall number of dFADs and floating objects at sea and mitigating their impact on tuna behaviour and distribution or on the marine ecosystem more broadly (e.g. entanglement of sensitive species, pollution, beaching). However, we note the implementation of non-entangling designs and encouragement of the use of biodegradable dFADs is a proactive area of current research and development by industry. While the ratio between dFAD deployments and active dFADs remains generally unknown, deployments are higher than the number of active dFADs used by a vessel every year, as dFADs are often redeployed several times by the owner or other vessels (Fonteneau *et al.*, 2015; Lennert-Cody *et al.*, 2018). Therefore, incorporating a limit on the number of deployments per year may be a more effective approach than relying solely on limits on the number of active dFADs.

### Recommendations for improved dFAD monitoring

While current levels of dFAD use remain challenging to determine with high certainty worldwide, the long-term management of

dFADs could benefit from a better understanding of the optimum number of dFADs to maximize profitability while limiting impacts on tuna stocks and ecosystems. Results from this study could provide baseline data to monitor dFAD use and impact in the WCPO, with application of these methods in other oceans. However, to improve the ability to estimate potential dFAD levels (e.g. deployments, dFAD density, active buoys), the collection of additional information is suggested. For example, to better understand the total number of dFADs in the water and the number of dFADs used per vessel, the provision of: (i) the number of new dFADs deployed per year per vessel or fleet; (ii) the average daily or total number of active dFADs per vessel per month; and (iii) the number of deactivated dFADs per month, would enhance these efforts. Some of these data are already being collected by some Regional Fisheries Management Organisations (Báez *et al.*, 2020). This could also be achieved through complete submission of dFAD trajectories, which in turn will be a key addition to scientific studies on dFAD density (Restrepo and Justel-Rubio, 2018); impacts on catch rates, and tuna behaviour (Scutt Phillips *et al.*, 2019b). The PNA FAD tracking database, through the compilation of local dFAD density will allow for such additional studies on the impacts of dFADs on tuna ecology to be performed. New FAD logsheets have been launched in 2020 in the WCPO by the PNA and will require captains to fill in any dFAD related information, including the unique buoy identification number, which will improve some of the issues with the data currently collected. In addition, given the connectivity between the WCPO and the EPO and the general westward trend in currents, collaboration between scientists working in both these Pacific regions should be encouraged. Additional data sources could also be considered (e.g. dFAD marking with fishery-independent autonomous satellite devices; data collection of dFADs reaching coastal areas). This could help to better assess other environmental impacts, such as dFAD loss, marine pollution, and beaching, or to follow individual dFADs instead of the satellite buoy attached to it which may be swapped several times. Overall, the compilation of these data would allow better scientific analyses and advice on the optimum management strategies for sustainable use of dFADs by the purse seine fleets in the WCPO and other ocean basins.

## Supplementary Data

Supplementary material is available at the ICESJMS online version of the manuscript.

## Data Availability Statements

The data underlying this paper cannot be shared publicly due to their sensitivity nature, as they are linked with high resolution fishery data. The aggregated data can be shared, under certain conditions, on reasonable request to the Pacific Community or the PNA.

## Acknowledgments

The authors are grateful to the members of the PNA for access to their dFAD tracking data and their proactive approach towards improving data collection on dFAD use. The authors also thank the Pacific Islands Regional Fisheries Observer Programme, as well as observers and skippers involved in the collection of observer and logsheet data. We thank Jed I. Macdonald for ideas and comments that helped improve this paper and the Editors David Kaplan and

Howard I. Browman, as well as three anonymous reviewers for constructive comments on a previous version of the paper.

## References

- Báez, J. C., Ramos, M. L., Herrera, M., Murua, H., Cort, J. L., Déniz, S., Rojo, V. *et al.* 2020. Monitoring of Spanish flagged purse seine fishery targeting tropical tuna in the Indian ocean: Timeline and history. *Marine Policy*, 119: 104094. Pergamon. <https://www.sciencedirect.com/science/article/abs/pii/S0308597X19307559>. (last accessed 13 January 2021).
- Baske, A., Gibbon, J., Benn, J., and Nickson, A. 2012. Estimating the use of drifting fish aggregation devices around the globe—Pew Environment Group. <https://www.pewtrusts.org/~media/legacy/uploads/fadreport1212pdf.pdf> (last accessed 9 June 2021).
- Castro, J. J., Santiago, J. A., and Santana-Ortega, A. T. 2001. A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. *Reviews in Fish Biology and Fisheries*, 11: 255–277. <http://link.springer.com/10.1023/A:1020302414472>. (last accessed 9 October 2020).
- Chassot, E., Santiago, J., and Lucas, V. 2019. Major reduction in the number of FADs used in the Seychelles purse seine fishery following IOTC limitations. Working Party on Data Collection and Statistics. 15: 1–7. (WPDCS) IOTC-2019-WPDCS15-21\_Rev1.
- Dagorn, L., Bez, N., Fauvel, T., and Walker, E. 2013a. How much do fish aggregating devices (FADs) modify the floating object environment in the ocean? *Fisheries Oceanography*, 22: 147–153. <http://doi.wiley.com/10.1111/fog.12014> (last accessed 21 August 2020).
- Dagorn, L., Holland, K. N., Restrepo, V., and Moreno, G. 2013. Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? *Fish and Fisheries*, 14: 391–415.
- Davies, T., Curnick, D., Barde, J., and Chassot, E. 2017. Potential environmental impacts caused by beaching of drifting Fish Aggregating devices and identification of management solutions and uncertainties. IOTC Technical Report IOTC-2017-WGFAD01-08, 14pp.
- Davies, T. K., Mees, C. C., and Milner-Gulland, E. J. 2014. The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean. *Marine Policy*, 45: 163–170. <http://www.sciencedirect.com/science/article/pii/S0308597X13002972> (last accessed 22 June 2016).
- Escalle, L., Muller, B., Brouwer, S., and Pilling, G. 2018. Report on analyses of the 2016/2018 PNA FAD tracking programme. WCPFC Scientific Committee WCPFC-SC14-2018/MI-WP-09.
- Escalle, L., Scutt Phillips, J., Brownjohn, M., Brouwer, S., Sen Gupta, A., Van Sebille, E., Hampton, J. *et al.* 2019. Environmental versus operational drivers of drifting FAD beaching in the Western and Central Pacific Ocean. *Scientific Reports*, 9: 14005. <http://www.nature.com/articles/s41598-019-50364-0> (last accessed 1 October 2019).
- Escalle, L., Vanden Heuvel, B., Clarke, R., Dunham, R., and Pilling, G. 2020a. Updates on Project 88: FAD acoustics analyses. WCPFC Scientific Committee WCPFC-SC16-2020/MI-IP-20.
- Escalle, L., Muller, B., Hare, S., Hamer, P., and Pilling, G., and PNAO. 2020b. Report on analyses of the 2016/2020 PNA FAD tracking programme. WCPFC Scientific Committee WCPFC-SC16-2020/MI-IP-14.
- Evans, K., Young, J. W., Nicol, S., Kolody, D., Allain, V., Bell, J., Brown, J. N. *et al.* 2015. Optimising fisheries management in relation to tuna catches in the western central Pacific Ocean: a review of research priorities and opportunities. *Marine Policy*, 59: 94–104. Pergamon. <https://www.sciencedirect.com/science/article/abs/pii/S0308597X15001335?via%3Dihub> (last accessed 21 August 2020).
- Filmler, J., Capello, M., Deneubourg, J. L., Cowley, P. D., and Dagorn, L. 2013. Looking behind the curtain : quantifying massive shark mortality in fish aggregating devices. *Frontiers in Ecology and the Environment*, 11: 291–296. <http://www.documentation.ird.fr/hor/fdi:010060610>. (last accessed 17 August 2015).

- Floch, L., Depetris, M., Dewals, P., Duparc, A., Kaplan, D., Lebranchu, J., Marsac, F. *et al.* 2019a. Statistics of the French purse seine fishing fleet targeting tropical tunas in the Indian Ocean (1981–2018). IOTC-2019-WPTT21-11\_Rev1. Indian Ocean Tuna Commission Working Party on Tropical Tunas (WPTT), Donostia.
- Floch, L., Depetris, M., Duparc, A., Guillou, A., Hervé, A., Kaplan, D., Lebranchu, J. *et al.* 2019b. Statistics of the French purse seine fishing fleet targeting tropical tunas in the Atlantic Ocean (1991–2018). Collective Volume of Scientific Papers ICCAT, 76: 793–820 (2020).
- Fonteneau, A., Pallares, P., and Pianet, R. 2000. Worldwide review of purse-seine fisheries on FADs. J.-Y. Le Gall, P. Cayré, and M. Taquet (eds). Actes de colloques IFREMER, 28: 15–35. Ifremer, Actes Colloq.
- Fonteneau, A., Chassot, E., and Bodin, N. 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): taking a historical perspective to inform current challenges. Aquatic Living Resources, 26: 37–48. [http://www.alr-journal.org/action/article\\_S0990744013000466](http://www.alr-journal.org/action/article_S0990744013000466). (last accessed 3 June 2016).
- Fonteneau, A., Chassot, E., and Gaertner, D. 2015. Managing tropical tuna purse seine fisheries through limiting the number of drifting fish aggregating devices in the Atlantic: food for thought. Collective Volume of Scientific Papers ICCAT, 71: 460–475.
- Gershman, D., Nickson, A., and O'Toole, M. 2015. Estimating the use of FAD around the world, an updated analysis of the number of fish aggregating devices deployed in the ocean. Pew Environment Group 1–24.
- Hallier, J., and Gaertner, D. 2008. Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. Marine Ecology Progress Series, 353: 255–264. <http://www.int-res.com/abstracts/meps/v353/p255-264/>. (last accessed 3 June 2016).
- IATTC. 2020. Resolution C-20-06. Conservation measures for tropical tunas in the Eastern Pacific Ocean during 2021 pursuant to resolution C-20-05. [https://www.iattc.org/PDFFiles/Resolutions/IATTC\\_English/C-20-06-Active\\_Conservation%20Tropical%20Tunas%20in%20the%20EPO%20during%202021%20Pursuant%20to%20RES%20C-20-05.pdf](https://www.iattc.org/PDFFiles/Resolutions/IATTC_English/C-20-06-Active_Conservation%20Tropical%20Tunas%20in%20the%20EPO%20during%202021%20Pursuant%20to%20RES%20C-20-05.pdf) (last accessed 09 June 2021).
- ICCAT. 2020. Recommendation 20-01. Supplemental recommendation by ICCAT to amend the recommendation 19-02 by ICCAT to replace recommendation 16-02 by ICCAT on a multi-annual conservation and management programme for tropical tunas. <https://www.iccat.int/Documents/Recs/compendioidf-e/2020-01-e.pdf> (last accessed 09 June 2021).
- Imzilen, T., Lett, C., Chassot, E., and Barde, J. 2016. Modeling trajectories of Fish Aggregating Devices with satellite images: use cases related to fisheries. IOTC Technical Report IOTC-2016-WPDCS12-29-Rev1 11pp.
- IOTC. 2019. Resolution 19/02. Procedures on a Fish Aggregating Devices (FADs) management plan. <https://www.iotc.org/cmm/r-resolution-1902-procedures-fish-aggregating-devices-fads-management-plan> (last accessed 09 June 2021).
- IOTC. 2020a. Summary overview of buoy data submitted to the IOTC secretariat for the period January–July 2020. IOTC-2020-WPDCS16-17.
- IOTC. 2020b. Review of the statistical data and fishery trends for tropical tunas. IOTC-2020-WPTT22(AS)–03\_Rev4.
- Lehodey, P., Bertrand, A., Hobday, A., Kiyofuji, H., McClatchie, S., Menkès, C. E., Pilling, G. *et al.* 2020. Chapter 19. ENSO impact on fisheries and ecosystems. In M.J. McPhaden, A. Santoso, and W. Cai (Eds) El Niño Southern Oscillation in a Changing Climate. Geophysical Monograph 253. pp. 429–451.
- Lennert-Cody, C. E., Moreno, G., Restrepo, V., Román, M. H., and Maunder, M. N. 2018. Recent purse-seine FAD fishing strategies in the eastern Pacific Ocean: what is the appropriate number of FADs at sea? ICES Journal of Marine Science, 75: 1748–1757. <https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsy046/4976455> (last accessed 21 June 2018).
- Leroy, B., Phillips, J. S., Nicol, S., Pilling, G. M., Harley, S., Bromhead, D., Hoyle, S. *et al.* 2013. A critique of the ecosystem impacts of drifting and anchored FADs use by purse-seine tuna fisheries in the Western and Central Pacific Ocean. Aquatic Living Resources, 26: 49–61. EDP Sciences. <http://www.alr-journal.org/10.1051/alr/2012033> (last accessed 5 December 2017).
- Lopez, J., Moreno, G., Sancristobal, I., and Murua, J. 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fisheries Research, 155: 127–137. <http://www.sciencedirect.com/science/article/pii/S0165783614000794>. (last accessed 8 April 2016).
- Lopez, J., Román, M. H., Lennert-Cody, C. E., Maunder, M. N., and Vogel, N. 2020. Floating-object fishery indicators. Inter-American Tropical Tuna Commission, Ad-hoc permanent working group on FADs.
- Matsumoto, T., Satoh, K., Semba, Y., and Toyonaga, M. 2016. Comparison of the behavior of skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) tuna associated with drifting FADs in the equatorial central Pacific Ocean. Fisheries Oceanography, 25: 565–581. John Wiley & Sons, Ltd. <http://doi.wiley.com/10.1111/fog.12173> (last accessed 23 March 2021).
- Maufroy, A., Chassot, E., Joo, R., and Kaplan, D. M. 2015. Large-scale examination of spatio-temporal patterns of drifting fish aggregating devices (dFADs) from tropical tuna fisheries of the Indian and Atlantic Oceans. Plos One, 10: 1–21. <http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0128023> (last accessed 19 July 2016).
- Maufroy, A., Kaplan, D. M., Bez, N., De Molina, A. D., Murua, H., Floch, L., and Chassot, E. 2017. Massive increase in the use of drifting Fish Aggregating Devices (dFADs) by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. ICES Journal of Marine Science, 74: 215–225. Oxford Academic. <https://academic.oup.com/icesjms/article/74/1/215/2418180> (last accessed 21 August 2020).
- Maufroy, A., and Goujon, M. 2019. Methodology for the monitoring of FOB and buoy use by French and Italian tropical tuna purse seiners in the Indian Ocean. IOTC Working Party on Tropical Tunas IOTC-2019-WPTT21-53.
- Murtagh, F., and Legendre, P. 2014. Ward's hierarchical agglomerative clustering method: which algorithms implement Ward's criterion? Journal of Classification, 31: 274–295.
- Pascual-Alayón, P. J., Floch, L., N'Gom, F., Dewals, P., Irié, D., Amatcha, A. H., and Amandé, M. J. 2019. Statistics of the European and associated purse seine and baitboat fleets, in the Atlantic Ocean (1991–2017). Collective Volume of Scientific Papers ICCAT, 75: 1992–2006.
- R Development Core Team. 2017. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Version 3.4.0.
- Restrepo, V., and Justel-Rubio, A. 2018. Recommended best practices for tropical tuna purse seine fisheries in transition to MSC certification, with emphasis on FADs. ISSF Technical Report 2018-05. International Seafood Sustainability Foundation, Washington, DC, USA.
- Santiago, J., Murua, H., Lopez, J., and Krug, I. 2017. Monitoring the number of active FADs used by Spanish and associated purse seine fleet in the IOTC and ICCAT convention areas. IOTC 1ST AD HOC WORKING GROUP ON FADs.
- Scott, G. P., and Lopez, J. 2014. The use of FADs in tuna fisheries; European Parliament's Committee on Fisheries. European Parliament's Committee on Fisheries IP/B/PECH/IC/2013-123 PE 514.002.
- Scutt Phillips, J., Leroy, B., Peatman, T., Escalle, L., and Smith, N. 2019a. Electronic tagging for the mitigation of bigeye and yellowfin tuna juveniles by purse seine fisheries. WCPFC Scientific Committee WCPFC-SC15-2019/EB-WP-08.
- Scutt Phillips, J., Escalle, L., Pilling, G., Sen Gupta, A., and van Sebille, E. 2019b. Regional connectivity and spatial densities of drifting fish aggregating devices, simulated from fishing events in the Western and Central Pacific Ocean. Environmental Research Communications, 1: 055001. IOP Publishing. <https://iopscience>



- [.iop.org/article/10.1088/2515-7620/ab21e9](https://doi.org/10.1088/2515-7620/ab21e9). (last accessed 5 July 2019).
- Sempo, G., Dagorn, L., Robert, M., and Deneubourg, J.-L. 2013. Impact of increasing deployment of artificial floating objects on the spatial distribution of social fish species. *Journal of Applied Ecology*, 50: 1081–1092. Wiley/Blackwell (10.1111). <http://doi.wiley.com/10.1111/1365-2664.12140> (last accessed 28 June 2018).
- Tidd, A., Brouwer, S., and Pilling, G. 2017. Shooting fish in a barrel? Assessing fisher-driven changes in catchability within tropical tuna purse seine fleets. *Fish and Fisheries*, 18: 808–820. <http://doi.wiley.com/10.1111/faf.12207> (last accessed 21 August 2020).
- Tolotti, M. T., Forget, F., Capello, M., Filmlalter, J. D., Hutchinson, M., Itano, D., Holland, K. *et al.* 2020. Association dynamics of tuna and purse seine bycatch species with drifting fish aggregating devices (FADs) in the tropical eastern Atlantic Ocean. *Fisheries Research*, 226: 105521. <https://www.sciencedirect.com/science/article/abs/pii/S0165783620300382>. (last accessed 23 March 2021).
- Vidal, T., Hamer, P., and Wichman, M.-O.-T.-A., and PNAO. 2020. Examining indicators of technological and effort creep in the WCPO purse seine fishery. WCPFC Scientific Committee WCPFC-SC16-2020/MI-IP-15.
- WCPFC. 2008. CMM-2008-01 Conservation and management measure for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean. <https://www.wcpfc.int/system/files/CMM%202008-01%20%5BBigeye%20and%20yellowfin%5D.pdf> (last accessed 09 June 2021).
- WCPFC. 2018. CMM-2018-01 Conservation and management measure for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean. <https://www.wcpfc.int/doc/cmm-2018-01/conservation-and-management-measure-bigeye-yellowfin-and-skipjack-tuna-western-and> (last accessed 09 June 2021).
- Williams, P., Reid, C., and Ruaia, T. 2020a. Overview of tuna fisheries in the WCPO, including economic conditions –2019. WCPFC Scientific Committee WCPFC-SC16-2020/GN-IP-01.
- Williams, P., Panizza, A., Falasi, C., and Loganimoce, E. 2020b. Status of observer data management. WCPFC Scientific Committee WCPFC-SC16-2020/ST-IP-02.

*Handling editor: Howard Browman*