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Report on analyses of the 2016/2021 PNA FAD tracking programme

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Revision 1:

Revision one of this paper includes a modification of Figures 1, which now excludes the fisheries in Indonesia and Philippines archipelagic water and Vietnam.

Executive Summary

This paper presents analyses of the PNA's Fish Aggregating Device (FAD) tracking trial programme including: a description of the data processing techniques used; a description of the spatio-temporal distribution of buoy deployments and number of FADs at sea; FAD densities; matching between VMS and deployment positions and an analysis of the fate of FADs. As FADs drift in the ocean, the associated electronics can be replaced making it difficult to follow each individual FAD. Therefore, for the purposes of this analysis we followed the satellite buoys attached to FAD, unless otherwise stated.

To better distinguish drifting buoys from those onboard vessels, data were analysed using a Random Forest model to identify the drifting at-sea section of each buoy trajectory, and at the same time identify deployment positions. In addition, as for previous years, the data received by PNA have been modified by fishing companies prior to the submission, for example information outside PNA Exclusive Economic Zones (EEZs) may be removed (i.e., "geo-fenced"), which could introduce bias to the analyses. After undertaking the correction procedure, the filtered dataset consisted of 32.1 million transmissions from 67,074 unique buoys and covered the period from the 1st of January 2016 to the 31st of December 2020.

The brand and model (i.e., echo-sounder or not) of satellite buoys in the dataset were deduced from the buoy manufacturer identification number. Depending on the year, most of the buoys used were Satlink (46–74%), followed by Zunibal (14–23%), Kato (7–16%) and Marine Instruments (0–14%). In addition, most buoys also had an echo-sounder, with an increase in the usage of the echo-sounder buoy through time, from 75% in 2016 to 99% in 2020 (less than 1% being double-frequency echo-sounders in 2020).

The number of deployments per year varied over time, with a total of 96,599 deployments across the 2016–2020 period. The spatial distribution of deployments showed the main deployment areas to be in Kiribati south of the Gilbert Islands, east of the Phoenix Islands, and the central part of the Line Islands; Nauru, and north of Tuvalu. The type of vessel (purse seiner, supply vessels or other non-purse seine vessels) has been investigated using FAD tracking data matching to all vessels in the VMS database. The majority of FADs were deployed by purse seiners (57%), while 4.6% were identified to be deployed by non-purse seine vessels (mostly cargo vessels). Twenty-five percent of FADs appeared directly at-sea in the dataset, which could indicate remote activation or re-activation due to buoy transfer between vessels. Finally, 9% of deployments were not matched with any vessels, indicating that deployments may be by vessels not present in the VMS database or some bias in the method to identify deployments (small errors in positions recorded by the buoy creating high speed between two consecutive transmissions identified as on-board segment by the algorithm).

The number of transmissions from buoys almost doubled from 2016 to 2017, likely reflecting an increase in data provision. In 2017 and 2018, the number of transmissions per day was around 20,000–25,000, except during the closure period where a decrease was detected. In 2019 and 2020, the number of transmissions per day decreased to 10,000–15,000, likely due to a decrease in transmission frequency, as the overall number of FADs transmitting did not decrease sharply. The number of individual active FAD buoys reported per year increased between 2016 and 2018, with 14,817 buoys in 2016; 21,683 in 2017 and 23,337 in 2018; but then decreased in 2019 (21,145) and 2020 (19,346, noting that the 2020 data are still incomplete due to delays in data transmission by some companies).

The average drift time and straight-line drift distance per FAD were 4 months and 1,296 km, whereas the average active time (including on-board sections) was 7 months with an average distance between first and last transmitted position of 1,891 km.

The highest buoy densities were in Kiribati south of the Gilbert Islands and around the Phoenix Islands; Tuvalu (particularly in 2017 and 2018); the eastern area of Papua New Guinea (PNG) and off the Solomon Islands. However, this distribution clearly highlights the lack of FAD tracking data in some high seas' areas due to geo-fencing. While the location and extent of FAD density hotspots remained relatively consistent over the five years, the number of buoys transmitting at least once per 1° cell and per year was investigated for the 2016–2019 period. This showed an increase through time from 2016 to 2019, then a decrease in 2020. In Tuvalu, the area with the highest FAD density, the number of FAD per cell was the highest from 2017 to 2019, with the main distribution ranging from 2,500 to 6,000 FADs per year per cell.

As another proxy of FAD density, inter-FAD distances, i.e., the distance from each drifting FAD to the next closest neighbour drifting FAD on a day, was investigated. Besides FSM and the Marshall Islands, the majority of inter-FAD distances for other PNA member EEZs were generally below 30 km. In Kiribati Gilbert and Phoenix Islands, Nauru and Tuvalu EEZs, most inter-FAD distances were 6–22 km, with a median of 12 km; and showed a general decrease in the inter-FAD distances through time (i.e., increased density).

Investigation of buoy fates showed that 44.1% of buoys were abandoned, 9.6% were retrieved; 6.6% were beached; 18.4% were sunk, appropriated or had a malfunctioning buoy; and 21.3% were deactivated by the fishing company and left drifting, unmonitored at sea. The number of buoys with an unknown fate (sunk, appropriated, malfunctioning or left drifting unmonitored) increased from 35% in 2016 to 46% in 2019, then decreased in 2020 (34%). The percentage of beached buoys fluctuated from 6–9% per year and the number of buoys classified here as recovered or abandoned decreased. Accessing better information on the fate of FADs, including the reason why a buoy is deactivated, would be crucial to better understand the impact that the high number of abandoned and lost FADs may have on the environment.

FAD efficiency preliminary analyses showed that setting on own FADs with an echosounder leads to only a marginal improvement in catch rates over sets made on foreign FADs or without echosounder.

We invite WCPFC-SC17 to:

- Note this analysis on the PNA FAD tracking data and the progress being made by PNA in FAD tracking for the purpose of improving FAD management in PNA waters.
- Note the importance of complete FAD tracking data to support scientific analyses and encourage their provision by fishing companies.
- Note that 57% of FADs were deployed by purse seiners, 4.6 by other vessels, and that 25% of FADs could have been activated at-sea remotely.
- Note these analyses and the patterns identified. In particular, note the increase through time in the number of FAD per 1° cell in areas of high FAD densities. This corresponds to FADs being less than 12 km from each other.
- Note that findings of this paper highlighted that more than 44.1% of buoys were estimated to be abandoned and 6.6% beached; as well as the increase in number of buoys with uncertain fate (21.3 % in 2020).

1. Introduction

The use of drifting Fish Aggregating Devices (FADs) by tropical tuna purse seiners has increased globally in the last few decades, particularly with the new technological developments to track FAD locations such as satellite and echo-sounder buoys (Escalle et al., 2019c; Fonteneau et al., 2013; Lopez et al., 2014). In the Western and Central Pacific Ocean (WCPO), the number of sets on artificial FADs has increased almost continuously since the 1990s and is currently more prevalent than sets on natural logs (Figure 1). In 2013, the number of FADs deployed in the WCPO was estimated at more than 30,000 per year (Gershman et al., 2015). This is confirmed by a recent study that estimated that 20,000–40,000 FADs are deployed/redeployed annually in the WCPO between 2011 and 2019 (Escalle et al., 2020b, 2021). To reduce the impact of FAD fishing on tuna stocks, specifically to manage the high capture rates of small bigeye tuna on FAD associated sets (Harley et al., 2015), the Parties to the Nauru Agreement (PNA) and the Western and Central Pacific Fisheries Commission (WCPFC; hereafter ‘the Commission’) implemented an annual three to four months FAD closure, during which all FAD-related activities (e.g., fishing, deployment, servicing) are prohibited (CMM-2018-01; WCPFC, 2018). In addition, in 2018, the Commission implemented a limit of 350 FADs with activated instrumented buoys (activation on-board only) per vessel, at any given time (CMM-2017-01; WCPFC, 2017). Finally, to limit the impact of FADs on the marine ecosystem, the Commission also adopted measures to use low-entanglement risk FADs (CMM-2018-01; WCPFC, 2018) and to promote the use of biodegradable material on FADs (CMM-2017-01; WCPFC, 2017) .

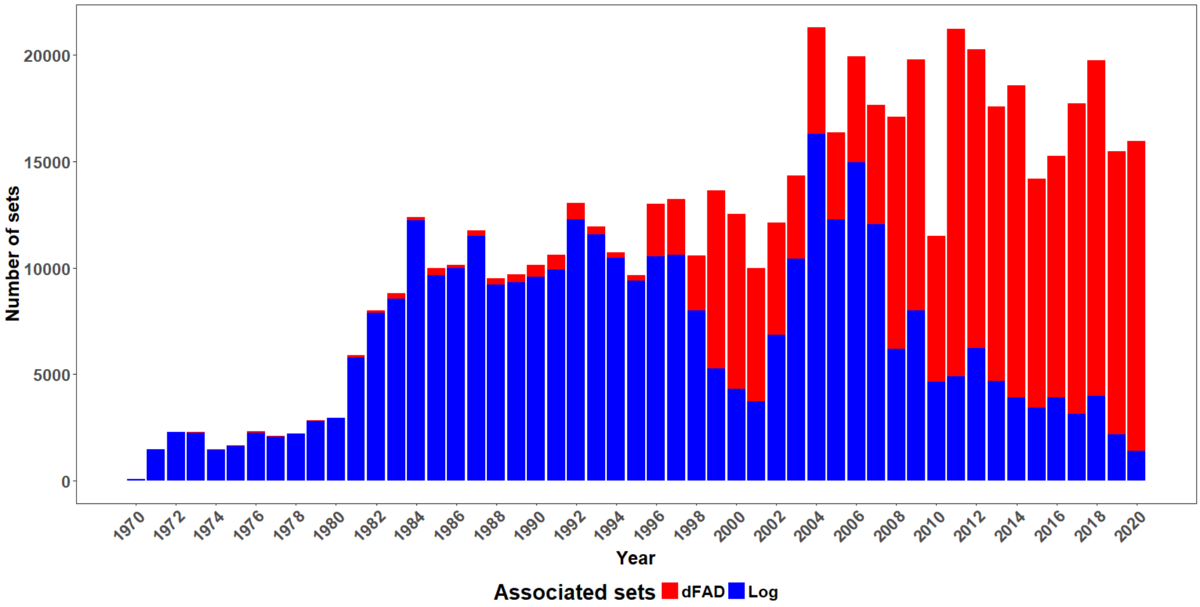

Figure 1. Number of associated sets performed specifically on deployed FADs and natural logs, as recorded in the aggregated logsheet data (“S-BEST” database: most complete dataset corrected for species composition, aggregated by 1° cell and month; without fisheries in Indonesia and Philippines archipelagic water and Vietnam) in the Western and Central Pacific Ocean between 1979 and 2020.

This paper presents updated analyses of the PNA’s FAD tracking trial programme, which tracked satellite buoys attached to drifting FADs used by purse seine vessels (Escalle et al., 2017, 2018b, 2019b, 2020a). The aim was to improve the understanding of the use of FADs and their impacts. The scientific objectives of the programme are to:

a) improve our understanding of the use of FADs,

b) provide better scientific information on the impacts of FADs and fishing on them,
c) better understand the economics of FAD use, and
d) inform FAD management.

In this paper, we present the dataset, the processing method performed on the raw data and the amount and type (brand and model) of data available. We also present results from updated analyses of i) spatio-temporal distributions of FAD buoy deployments; ii) the temporal distribution of drifting FADs in the WCPO; iii) FAD densities; iv) matching between VMS and deployment positions; v) the fate of FADs at their last buoy's transmission, including a focus on FAD beaching; and vi) the efficiency of FAD sets, in relation to echosounder presence and FAD origin.

On the basis of the value of the results from the FAD tracking FAD trial period, PNA Members have agreed to require all FAD buoys to be registered and transmit regular position data to the PNA while a vessel is licensed to a PNA Member, including transmitting data from high seas areas between 20° North and 20° South of the WCPFC convention area. This should be fully implemented by 1th January 2023.

As FADs drift in the ocean, the associated electronics (i.e., GPS buoys or GPS and echo-sounder buoys) can be replaced making it difficult to follow individual FADs. Therefore, for the purposes of this analysis we followed FAD buoys with GPS satellite-positioning systems (referred hereafter as buoys), unless otherwise stated. Note that a buoy trajectory may not constitute a single FAD track, but rather can be a single buoy track that could have been deployed consecutively on multiple FADs.

2. General description of the data

2.1 Data summary

The FAD tracking data set used in this analysis comprised transmitted locations and time stamps from buoys attached to drifting FADs, between 1st January 2016 and 31st December 2020 (data uploaded on 22nd of February 2021). The raw dataset included more than 35.7 million transmissions from 71,247 satellite buoys. Each transmission included location, time, the 'owner' of each FAD buoy (a fishing company or directly a vessel name, or 'none' for 144 buoys), water temperature, course direction, and drifting speed. In total, 298 vessels were found to be linked to FAD information in the FAD tracking data, which comprised 274 identified buoy owner vessels and 24 additional vessels belonging to an identified fishing company. Data originated from four different satellite buoy companies: Satlink; Zunibal, Marine Instrument and Kato.

The raw buoy tracking dataset received by the Parties to the Nauru Agreement Office (PNAO) contained duplications and errors, as well as transmissions from active buoys that were still on-board a vessel; therefore, the dataset needed to be filtered and processed before any analysis could be undertaken (see Appendix 1 and Escalle et al., 2017, 2018b, 2019b, 2020a for details).

The filtered dataset included 32,068,675 transmissions from 67,074 satellite buoys for analysis (Table 1), corresponding to annual estimates of active buoys of 14,817 buoys in 2016; 21,683 in 2017 and 23,337 in 2018; 21,145 in 2019; and 19,346 in 2020 (Table 1, note that buoys may be active for several years, leading to the overall number of buoys in the dataset being lower than the sum of the annual numbers). Then a processing method (Random Forest and additional correction procedure) was implemented (Appendix 1) to identify at-sea and on-board positions of a buoy to avoid bias in analyses focusing on effective at-sea time of FADs, as well as deployment positions.

Finally, the fishing company that owned each buoy with an associated vessel name recorded was added so that each buoy in the filtered dataset presented an actual fishing company and a vessel name when available. A total of 92% of the buoys (61,708) had records of the owner's vessel name. This corresponds to a total of 274 unique vessels in the dataset (187 in 2016; 201 in 2017; 205 in 2018; 196 in 2019 and 235 in 2020), including 260 purse seiners and 14 support vessels. For the rest of the buoys, only the fishing company was known (5,515 buoys, i.e., 8%) or neither were known (149 buoys).

Table 1. Summary statistics from the FAD tracking dataset, by year.

Year	Number of transmissions	Number of buoys	Number of (re)deployments
2016	4,939,936	14,817	18,230
2017	9,207,941	21,683	21,568
2018	7,880,847	23,337	21,909
2019	5,914,208	21,145	18,873
2020	4,125,743	19,346	16,019
Total	32,068,675	67,074[1]	96,599

[1] Note that buoys may be active for several years.

The previously-identified systematic modification of buoy transmissions with information outside PNA EEZs being removed prior to data transmissions (i.e., "geo-fenced" FAD; see Figure S1 as an example) occurred throughout the whole 2016–2020 period (Appendix 2). Geo-fenced buoys were identified as having no transmitted positions outside PNA waters.

2.2 Trend per brand and echo-sounder buoy use

The brand, model and type of buoy (e.g., echosounder or not) is not available in the dataset, but from the format of the buoy manufacturer's identification number (ID), they can be deduced. The main satellite buoy brand used in the WCPO is Satlink which comprises 46 to 74% of the buoys in the dataset (Figure 2). The other buoy brands are Zunibal (around 14–23% of buoys, depending on the year), Kato (7–16%) and Marine Instruments (0–14%) (Figure 2).

Variability in the satellite buoy brand used was also detected by flag (Figure 2). While some flags preferred to use only the Satlink brand (China, Japan, Nauru, Tuvalu and Vanuatu), others used mainly Satlink but have a small proportion of all the other brands, likely to keep abreast of the performance of other technology available (US, Kiribati, Korea, FSM). Finally, some fleets have very few Satlink buoys, with more than half being Zunibal (RMI, PNG, Philippines, Solomon Islands, Taiwan).

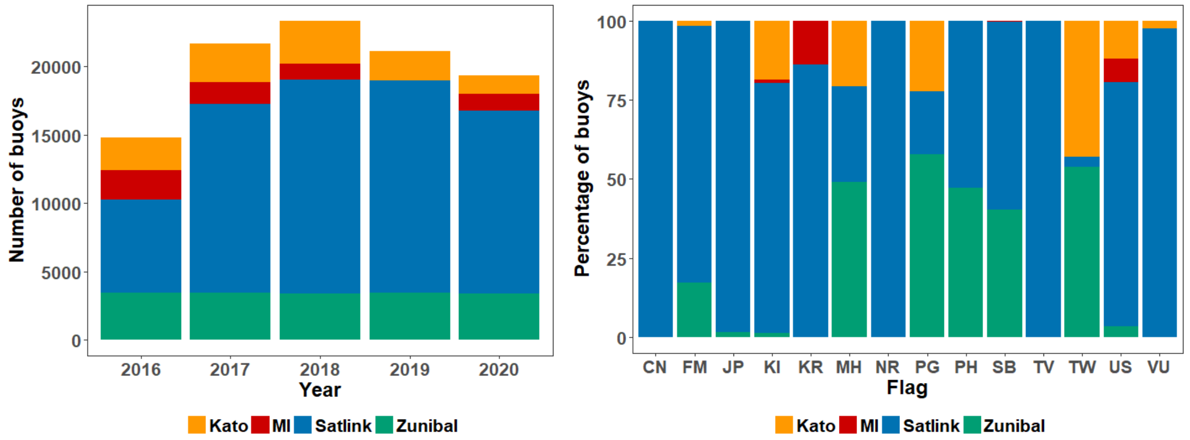

Figure 2. Number or percentage of satellite buoys (Kato, Marine Instrument MI, Satlink and Zunibal) used in the WCPO, per brand company and year (left) or flag (right). Note that for the graph per flag, the number of buoys per flag in our dataset highly varies, with some flags having no buoys in the database at all (FM = Federated States of Micronesia; JP = Japan; KI = Kiribati; KR = Korea; MH = Marshall Islands; NR = Nauru; PG = Papua New Guinea; PH = Philippines; SB = Solomon Islands; TV = Tuvalu; TW = Chinese Taipei; US = United States; VU = Vanuatu).

An increase in the use of satellite buoys with echo-sounder can be detected through time (Figure 3). In 2016, 75% of the buoys had an echosounder; 87% in 2017; 93% in 2018; 97% in 2019 and 99% in 2020. It is also notable that since 2019, double-frequency echo-sounder buoys which can be identified for Satlink and Marine Instrument buoys, (for the other brands, it was not possible to determine, at this stage, if they are single or double frequency) started being used, with less than 1% of the buoys known to have a double-frequency echo-sounder in 2020 (Figure 3). Some fleets also presented a higher proportion of echo-sounder buoys (Japan, Korea, Nauru, Tuvalu, US, Vanuatu; >94% of echo-sounder buoys).

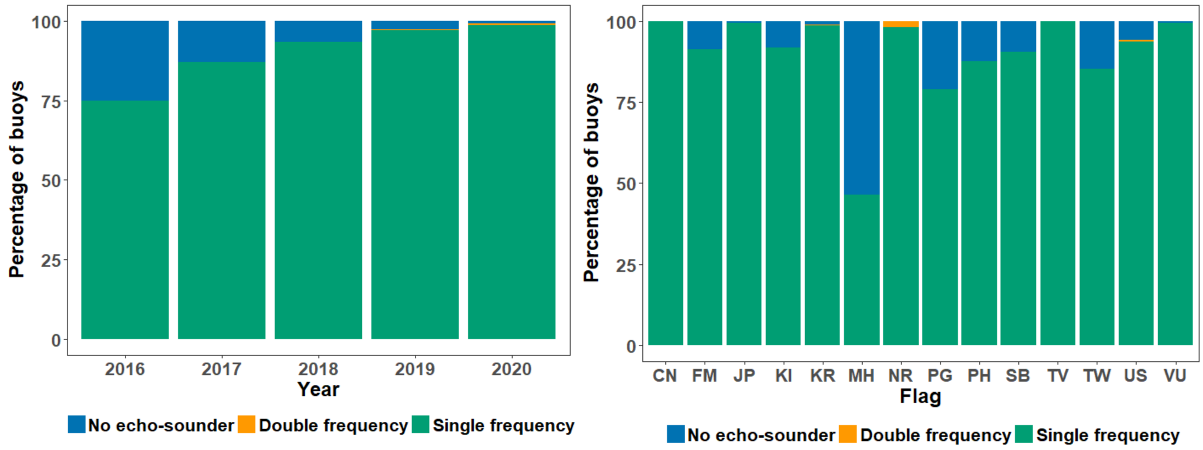

Figure 3. Percentage of satellite buoys used in the WCPO without an echo-sounder, with a single frequency echo-sounder or with a double frequency echo-sounder (when known) per year (left) or flag (right). Note that for the graph per flag, the number of buoys per flag in our dataset highly varies depending on the flag considered (FM = Federated States of Micronesia; JP = Japan; KI = Kiribati; KR = Korea; MH = Marshall Islands; NR = Nauru; PG = Papua New Guinea; PH = Philippines; SB = Solomon Islands; TV = Tuvalu; TW = Chinese Taipei; US = United States; VU = Vanuatu).

A similar increase in the use of echo-sounder buoy was also detected when considering data recorded by observers (Figure 4 and 5), although this was based on the format of the buoy ID number, which is still not systematically (absence of records in 82%) or precisely recorded by observers (bad format in 12% of the records). When the buoy ID number is accurately recorded (6% of records of any FAD related activity), it was deduced that over 71% of the satellite buoys used in the WCPO had an echo-sounder in 2016 and 2017, over 85% in 2018 and over 94% and 97% in 2019 and 2020 (Figures 4 and 5). A more systematic and precise record of the buoy ID number should be recorded, when possible, by observers. This is especially important in the view of effort creep[1] (Vidal et al., 2021) and the impact that FAD electronics, especially echo-sounder (single or double frequency) buoys, may be having on fishing efficiency. However, we acknowledge the difficulties encountered by observers in accessing and recording buoy ID numbers for some activities (i.e., visits or sets on FADs that do not belong to the vessel, or other situations where the buoy is not brought onboard the vessel). For some other activities, such as deployments and setting on FADs belonging to the vessel, this number should be accurately recorded, where possible, and the importance of this data should be emphasized.

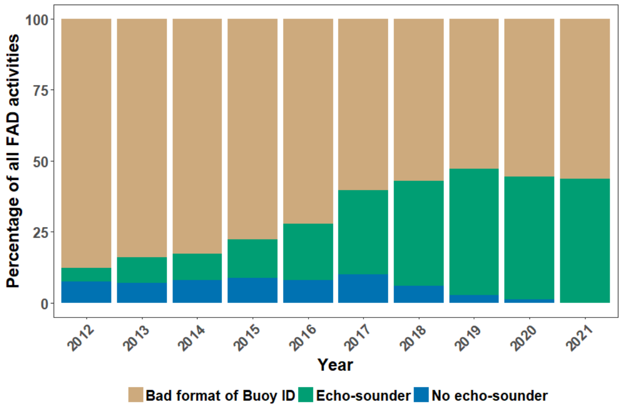

Figure 4. Percentage of satellite buoys with or without an echo-sounder (derived from the format of the buoys ID number, when available) per year, as recorded by observers for any activity performed on FADs (deployment, visit, set, retrieval).

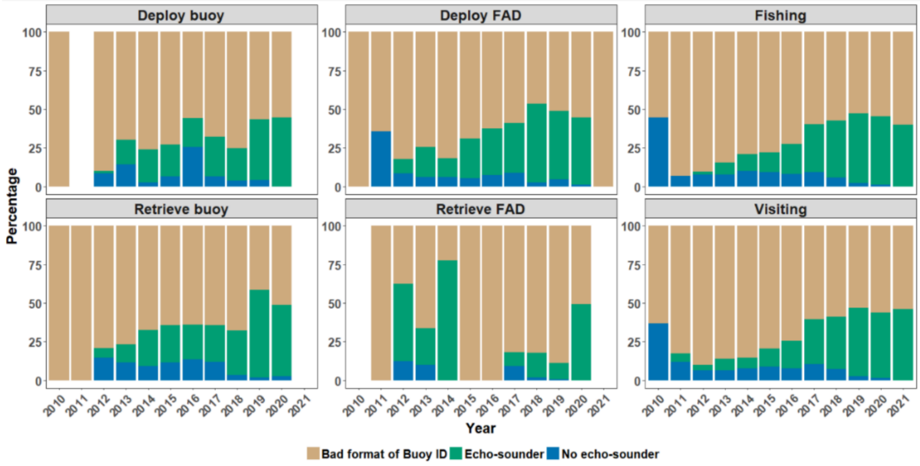

Figure 5. Percentage of satellite buoys with or without an echo-sounder (derived from the format of the buoy ID number, when available) per year and per FAD activity, as recorded by observers.

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[1] Effort creep is an increase in effective fishing effort due to advances in technological or other factors, a phenomenon that can mask trends in stock indicators such as CPUE.

3. Deployments

3.1 Temporal and spatial variability

The number of estimated buoy deployments varied over time (23 to 1,924 per week; Figure 8), with a total of 96,599 estimated over the study period. This corresponds to 18,230; 21,568; 21,909; 18,873 and 16,019 deployments estimated for 2016, 2017, 2018, 2019 and 2020 respectively (noting data is incomplete for 2020, with some companies having >2 months delay in data submission) (Table 1).

Generally, besides several short-term peaks in 2016 and one in 2020; as well as the decrease in deployments during the FAD closure periods, the number of buoy deployments per week remained relatively constant at around 400–600 (Figure 6). During the FAD closure each year, although the number of buoy deployments decreased, a substantial number of deployments still occurred during that period (Figure 6). A large peak in the number of deployments is detected for one day during the 2020 closure period, for unknown reasons. It should also be noted that bias in the deployment positions arises from geo-fencing of the data, with 3.5% of the estimated deployments corresponding to the first position of a geo-fenced buoy appearing at the border of the PNA EEZs (i.e., the buoy was likely deployed in a high sea zone).

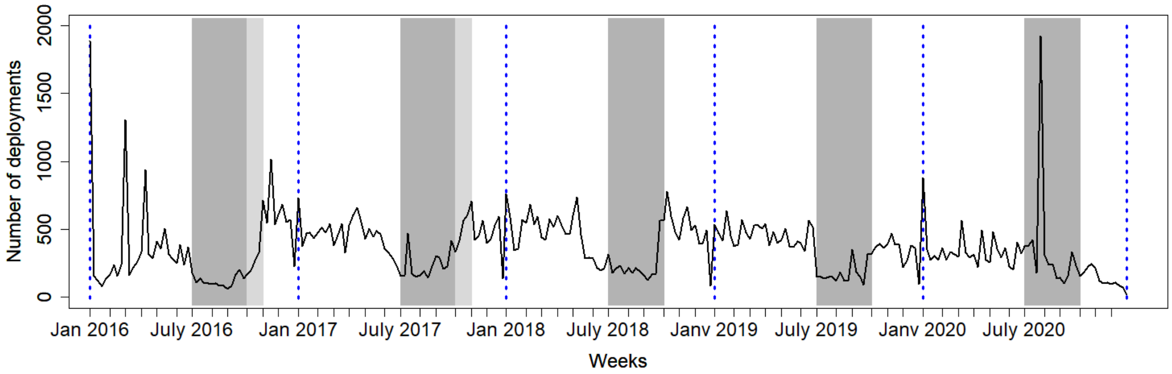

Figure 6. Estimated number of deployments by week. Grey areas correspond to the FAD-closure periods (1st of July through the 30th of October or November).

For the buoys with identified-owner vessel (274), the number of deployments per vessel was investigated (Figure 7). The total number of buoy deployments with identifiable vessels in 2016–2020, was 89,602 (i.e., 93% of total deployments). Annual deployments increased over the first three years of the programme with 15,449-8 in 2016; 19,807 in 2017; 21,043 in 2018 and then decreased slightly to 18,640 in 2019 and to 14,628 in 2020 (Figure 7). Further, the number of deployments per identifiable vessel ranged from 0 to 436 in 2016; 0 to 660 in 2017; 0 to 497 in 2018;0 to 348 in 2019 and 0 to 257 in 2020. Curves of cumulative number of deployments per vessels show that around 20% of vessels are responsible for 50% of deployments each year; and 41–45% of vessels responsible for 80% of deployments. While numbers presented here are likely underestimated, a recent paper uses both the PNA FAD tracking data and fishery data to raise the number of deployments and number of active FADs per vessel and in the WCPO (see Escalle et al., 2020b).

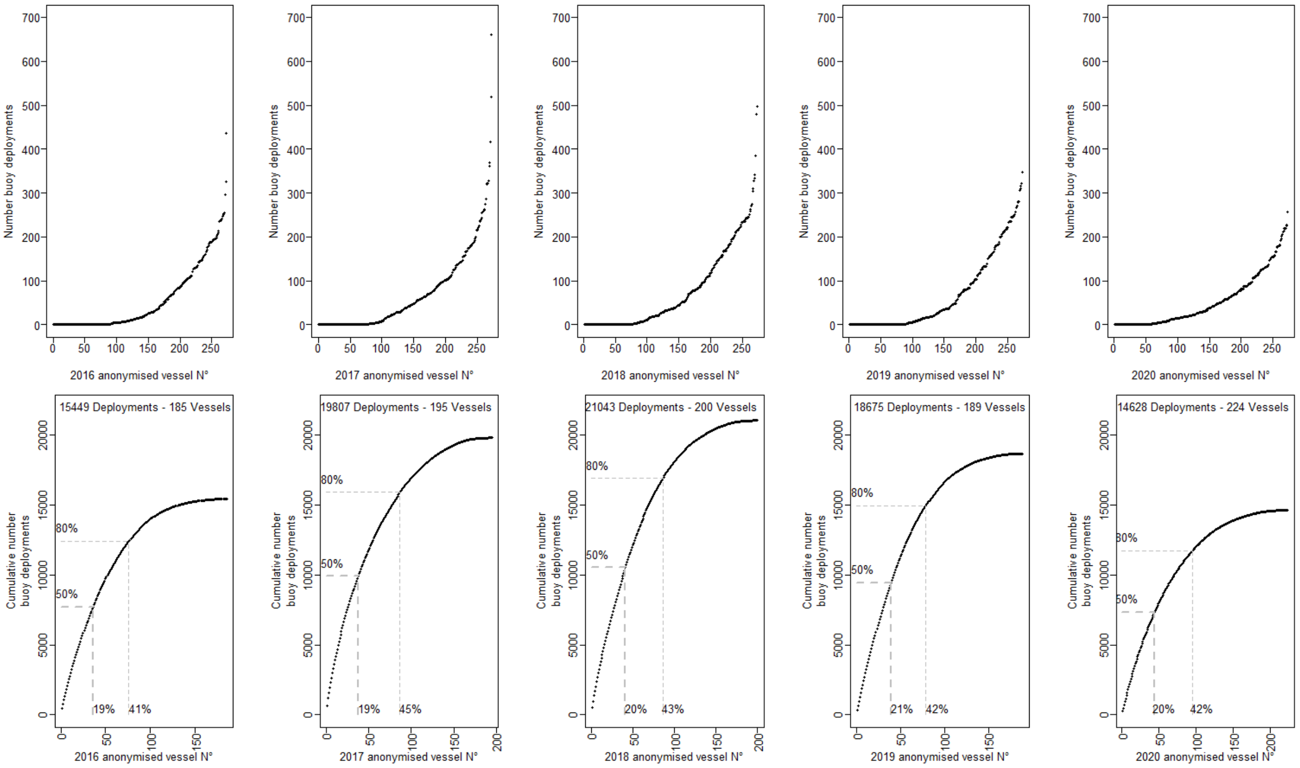

Figure 7. Estimated number (top) and cumulative number (bottom) of FAD buoy deployments for known vessels in the tracking data per year, 2016–2020.

Among the five years of data, a large proportion of the deployments occurred in Kiribati south of the Gilbert Islands and east of the Phoenix Islands, north of Tuvalu and in the Nauru EEZs (Figure 8 and Figure S5). In addition, in 2017, 2018 and 2019, an additional deployment hotspot was identified in Kiribati in the central part of the Line Islands (Figure 8). Few deployments were detected within the Phoenix Islands Protected Area (PIPA), however the kriging method used (kde2d function of the R package MASS (Venables and Ripley, 2002)) tends to spatially extend the hotspots artificially, linking the PIPA with surrounding areas of high deployment. Note that deployments in the eastern high seas are also in part this artefact of the method, given that the majority of data are geo-fenced. In the current dataset, deployments in the eastern high seas or FADs drifting from the Eastern Pacific Ocean (EPO) would appear as a deployment at the border of the Line and Phoenix Islands or at the eastern boundary of the Marshall and Gilbert Islands.

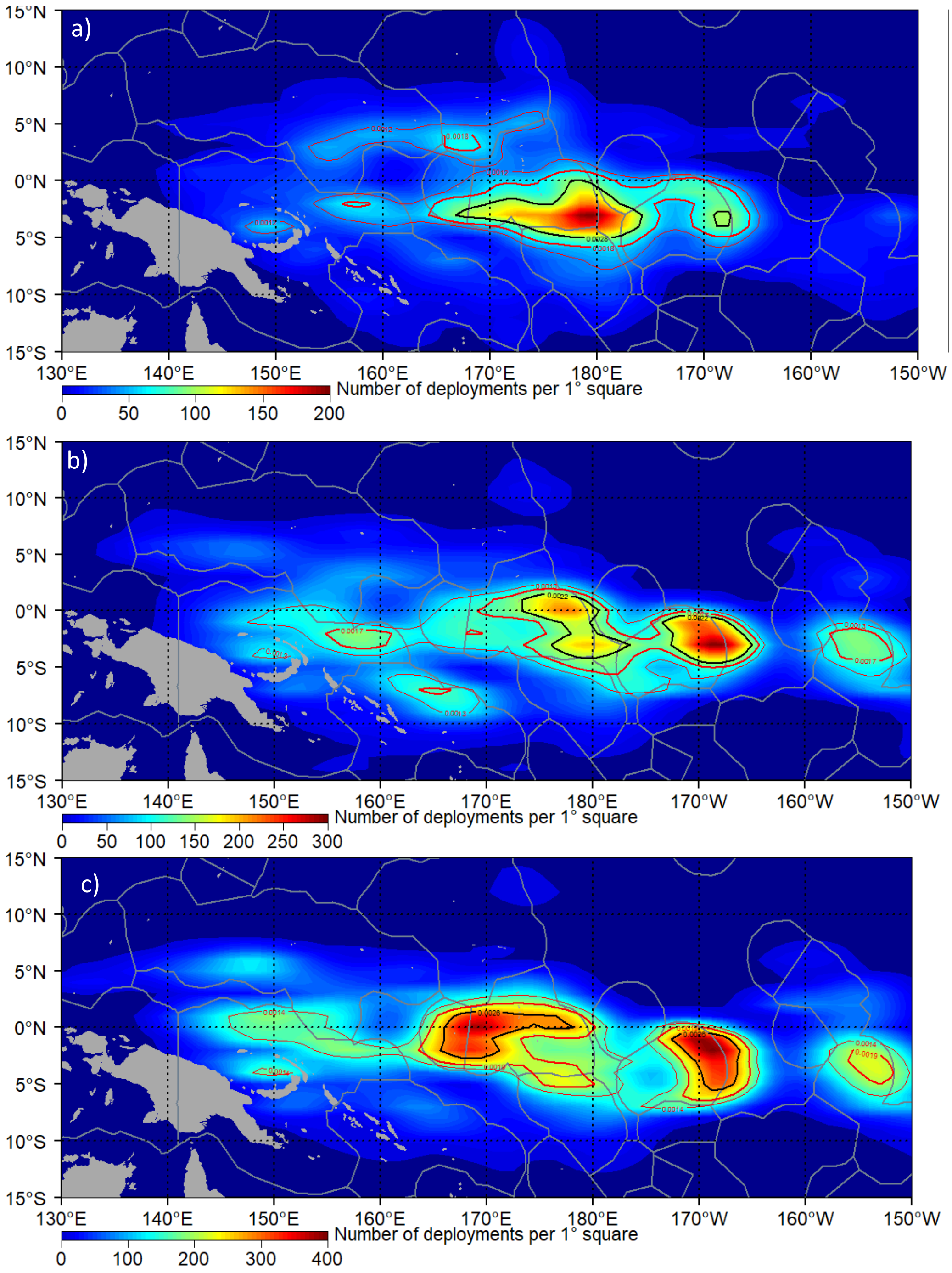

Figure 8. Smoothed kernel density of buoy deployments per 1° grid cell during a) 2016; b) 2017; c) 2018; d) 2019 and e) 2020. Red and black lines correspond to the 95th and 98th quantiles. Colour scale corresponds to the proportion of buoy deployment per 1° cell.

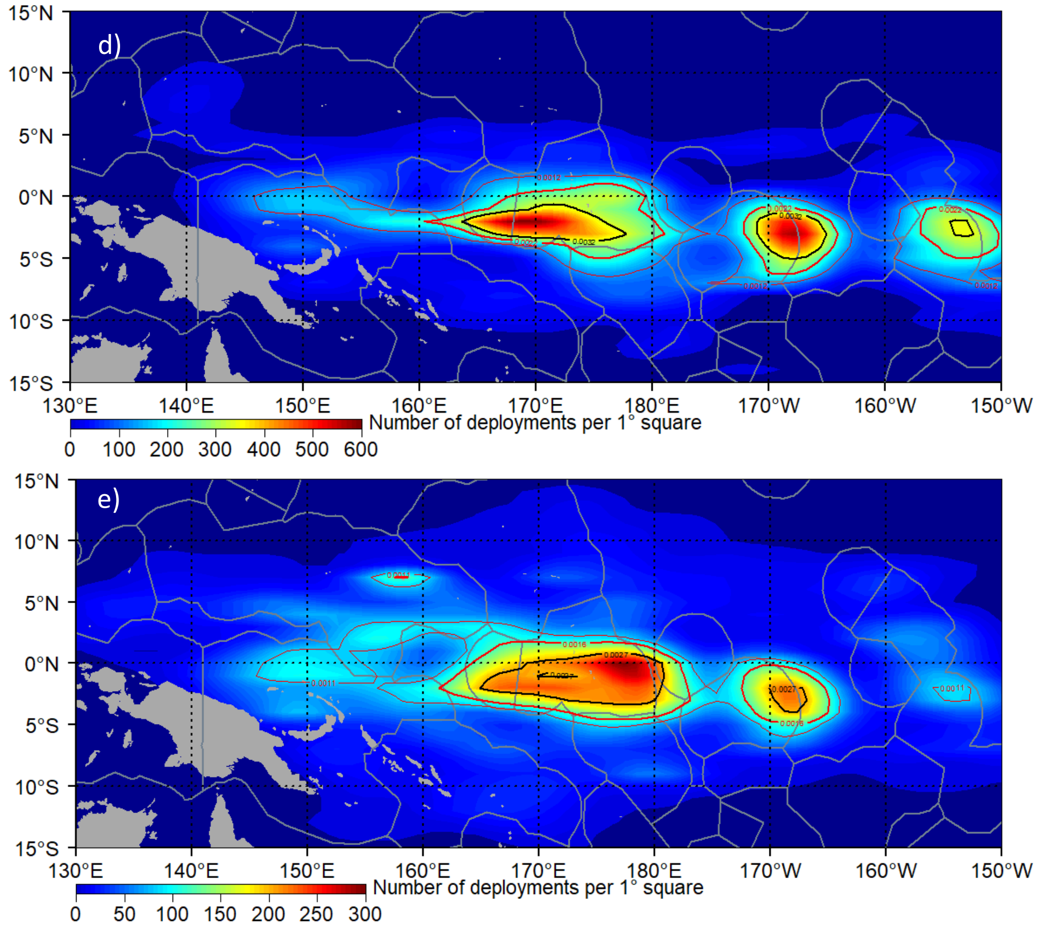

Figure 8 bis. Smoothed kernel density of buoy deployments per 1° grid cell during a) 2016; b) 2017; c) 2018; d) 2019 and e) 2020. Red and black lines correspond to the 95th and 98th quantiles. Colour scale corresponds to the proportion of buoy deployment per 1° cell.

3.2 Deployment and VMS

FAD trajectories and VMS data were matched to investigate the strategies of deployments and the type of vessels deploying FADs (i.e., the purse seiner owner of the FAD, another purse seiner from the same company, or another vessel) for the 2016–2019 period (2020 could not be included, due to the late availability of the data). All VMS available data were used, which includes all purse seine vessels (transmission every hour), all longline and pole and line vessels (transmitting every 4 hours); as well as other vessels, such as carrier, bunker, etc. (transmitting every 4 hours). In the period 2016–2019, on some days a very low and unrealistic amount of VMS data were indicated, hence the matching was not performed on these days to avoid any bias, leading to a few deployments being removed for this matching analysis (0.9% of all deployments; see Table 2).

Matching was investigated on the day of deployment (identified using the Random Forest algorithm mentioned in section 2.1) and 5 transmissions before and after the estimated deployment position to account for some uncertainty that can exist on the precise date/time and position of deployments. For each FAD position (11 positions maximum per FAD around the deployment), the closest vessel in the VMS dataset within a 1-hour time window before and after the deployment time was identified.

Several types of matching were then investigated depending on the type of vessel in the VMS data and the distance between VMS position and deployment position (Table 2).

A total of 57.2% of the deployments could be matched with a purse seine vessel, with the majority (56.6% of all deployments) being the same purse seiner as the vessel owner declared in the FAD tracking database (Table 2). More than half were matched exactly on the deployment position, while some matches occur for the 5 positions before or after deployment, highlighting some potential timing differences between FAD buoys and VMS transmissions. Some deployment positions could not be matched with any VMS position (29.3%) but could either correspond to “fake deployments” (i.e., 3.0% at the border of a PNA EEZ country and 1.6% at the beginning of the programme), or to remote activations (24.8%). Indeed, for these buoys, the first position in the dataset would directly be at-sea and not close to any vessel, which could indicate a prior deployment with an activation (or re-activation if the buoy is transferred to another vessel) directly at-sea. A small fraction of the deployments (4.5%) was matched with non-purse seine vessels (usually a cargo vessel). Various distances were investigated, given that non purse seine vessels typically transmit every 4 hours. It was noted that a small list of non-purse seine vessels was responsible for a large portion of the deployments matched. Finally, 9.0% of deployments were not matched with any vessels, but presented at least a few transmissions on-board a vessel before the deployment (i.e., identified by the Random Forest algorithm, largely due to high drifting speed). This could be explained by the deployments of FADs from vessels not in the VMS database, or by some mistakes in the identification of deployments. The latter could be due to errors in buoy positions, leading to the higher speed recorded, for buoys that are still drifting at-sea and that have not been picked up and redeployed. Given the size of the database and the generalisation of the correction procedure, these would be difficult to identify and correct with certainty.

Table 2. Summary of matching between FAD trajectories around deployments and VMS positions in the 2016–2019 period.

Type of deployments		Nb.	%	
Subset of deployments for VMS matching analysis		79,898		
Matching trajectory with purse seiner (PS)	Matching position day of deployment (<5km) same PS	26,220	32.8	57.2
	Matching position day of deployment (<5km) other PS	44	0.1	
	Matching position before or after deployment (<5km) same PS	19,026	23.8	
	Matching position before or after deployment (<5km) other PS	393	0.5	
No matching – bias in deployments	Deployment at PNA border	2,363	3.0	29.3
	1st deployment on 1st January 2016	1,241	1.6	
	1st segment of FAD at-sea (remote activation?)	19,793	24.8	
Matching trajectory with non-purse seiner (non-PS)	Matching position before or after deployment (<10km) non-PS	1,570	2.0	4.6
	Matching position before or after deployment (10–50km) non-PS	933	1.2	
	Matching position before or after deployment (50–90km) non-PS	1,149	1.4	
No Matching	No Matching	7,166	9.0	9.0

4. Temporal distribution of drifting FADs

4.1 Temporal variability in transmissions

The filtered dataset of 32,068,675 transmissions was comprised of 21% on-board positions and 79% at-sea positions. An increase in the number of transmissions and number of buoys transmitting within the data set was detected after the first year of the program, linked to better data provision (Figure 9). In particular, the number of transmissions from drifting buoys (at-sea) doubled in 2017 (9.2 million compared to 5.0 million in 2016). In 2017 and 2018, the number of transmissions per day was around 20,000–25,000, except during the closure where a decrease in number of transmissions is detected each year. In 2019 and 2020, the number of transmissions per day was lower, at around 10,000–15,000. Nevertheless, the number of individual active buoys increased almost constantly from 2016 to 2018, then decrease in 2018 to 2020; with 14,817 buoys in 2016; 21,683 in 2017; 23,337 in 2018; 21,145 in 2019; and 19,346 in 2020 (Table 1). The decrease in transmissions despite the increased deployments implies that the patterns of transmission rate have changed since 2019 (Figure 9). It should also be noted that some large short-term drops in both transmission and number of FADs active per day still occur, mostly at the end of some months (Figure 9).

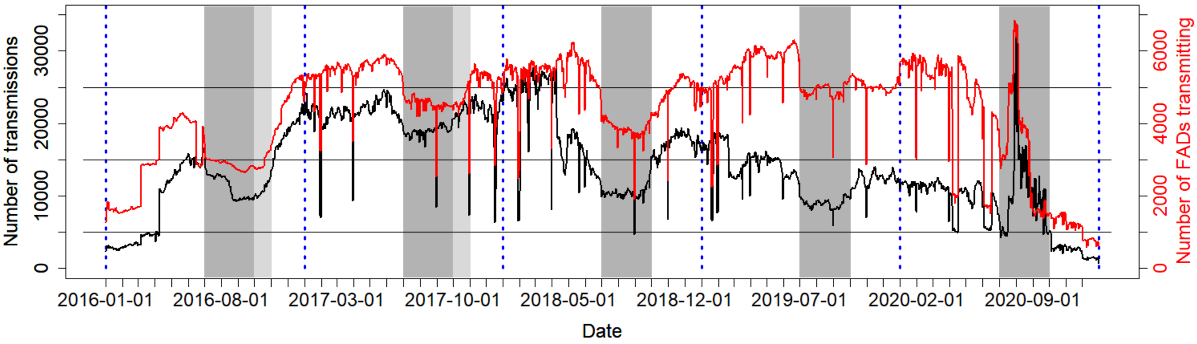

Figure 9. Number of transmissions (black line) and unique buoys transmitting (red line) daily from at-sea buoy positions only. Grey areas correspond to the FAD-closure periods (1st of July through 30th of September or October), and the blue lines denote January 1st. **Note that the decrease after September 2020 is simply due to the lack of full data being received yet.**

4.2 Time and distance at sea

The longevity of FAD drift and the linear drift distance were examined. At-sea drift periods per FAD varied from less than 10 days to two years, with shorter times for buoys that were redeployed several times. The average drift time is around four months (118 days) with an average linear drift distance of 1,296 km, whereas the average active time (including on-board sections) was seven months (207 days) with an average straight-line distance between first and last position of 1,891 km (Figure 10).

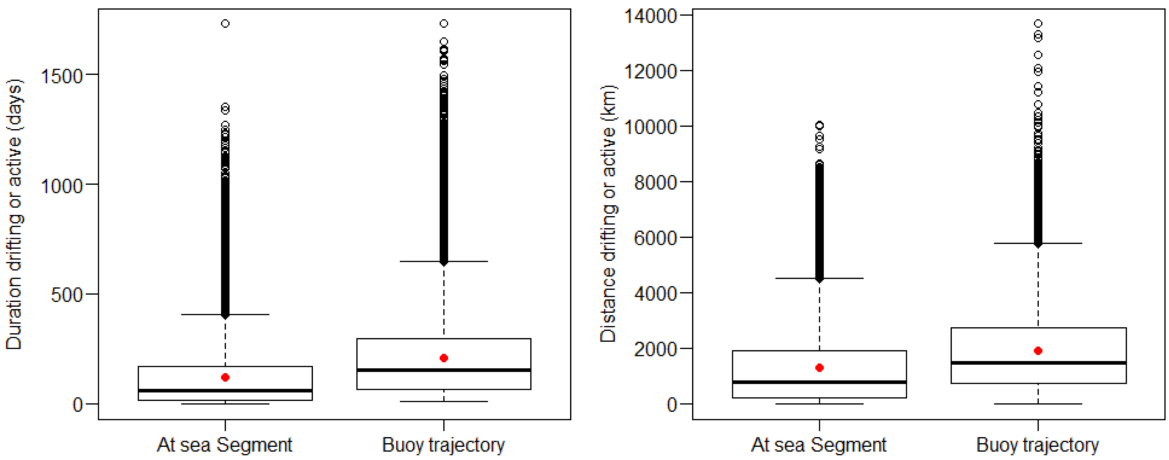

Figure 10. Duration (left) and distance (right) of drifting per FAD buoy trajectory (whole buoy trajectory, including on-board segments) or at-sea segments (on-board segments removed). Red dots are the mean value and vertical bars the median and the boxes correspond to the lower and upper quartiles.

Regarding the number of buoys monitored per vessel, for buoys with identified vessel owner (92%), one to 400 active buoys were monitored per month and one to 350 active buoys per day (Figure 11). However, the majority of vessels had less than 120 active buoys per month and less than 100 per day. It should be noted that these statistics correspond to the data submitted by fishing companies to PNA, so they are likely underestimates of the true number of active buoys (Escalle et al., 2020b + scientific paper).

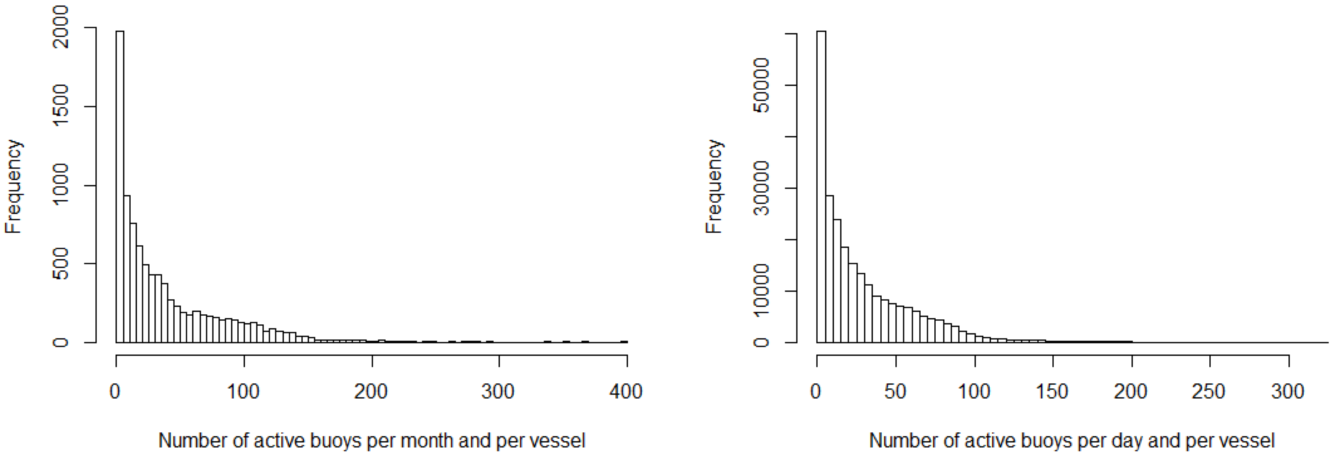

Figure 11. Histograms of the number of active buoys per month (left) or per day (right), per vessel (when vessel name was available) from 2016–2019, as recorded in the PNA FAD tracking data (see Section 4.1 for estimated data submission rates).

5. FAD densities

5.1 Distribution of FAD densities

In addition to the overall numbers of and trends in FADs used in PNA waters and given that FAD density could affect CPUE (Escalle et al., 2020a), the variability of FAD density through space and time has been investigated. The distributions of drifting buoys indicated areas with highest FAD density were in Kiribati south of the Gilbert Islands and around the Phoenix Islands; Tuvalu (particularly in 2017 and 2018); the eastern area of Papua New Guinea and off the Solomon Islands (Figure 12 and Figure S6).

These areas of high FAD densities also correspond to areas where a high number of associated sets occur (see Figure S6). However, it should be noted that a non-trivial number of associated sets occur outside of these high FAD densities areas, for instance in the southeast of the WCPO, particularly in 2017, 2018 and 2019 (Figure S6).

Temporal variability in FAD density distribution was detected through the course of the year, which may be linked to the influence of the ENSO (El Niño–Southern Oscillation) cycle, as these patterns were different between years. Lower transmission rates in 2016 may also have biased the observed FAD density.

Similar to the deployment maps, it is clear that we are missing some information due to geo-fencing and periods of non-transmission, with very low FAD densities in some areas outside PNA waters where some FAD sets are made. Such areas include, for instance, the southeast and northeast regions of the WCPO and the high seas between Tuvalu and Phoenix Islands EEZs. When complete and unmodified FAD tracking data become available it will be possible to achieve a broader and more comprehensive appreciation of the spatial extent and variation of FAD densities. Finally, we can clearly see the border of the PIPA, with no fishing sets within the reserve but a high density of FADs drifting through (especially in 2018, see Figure 12).

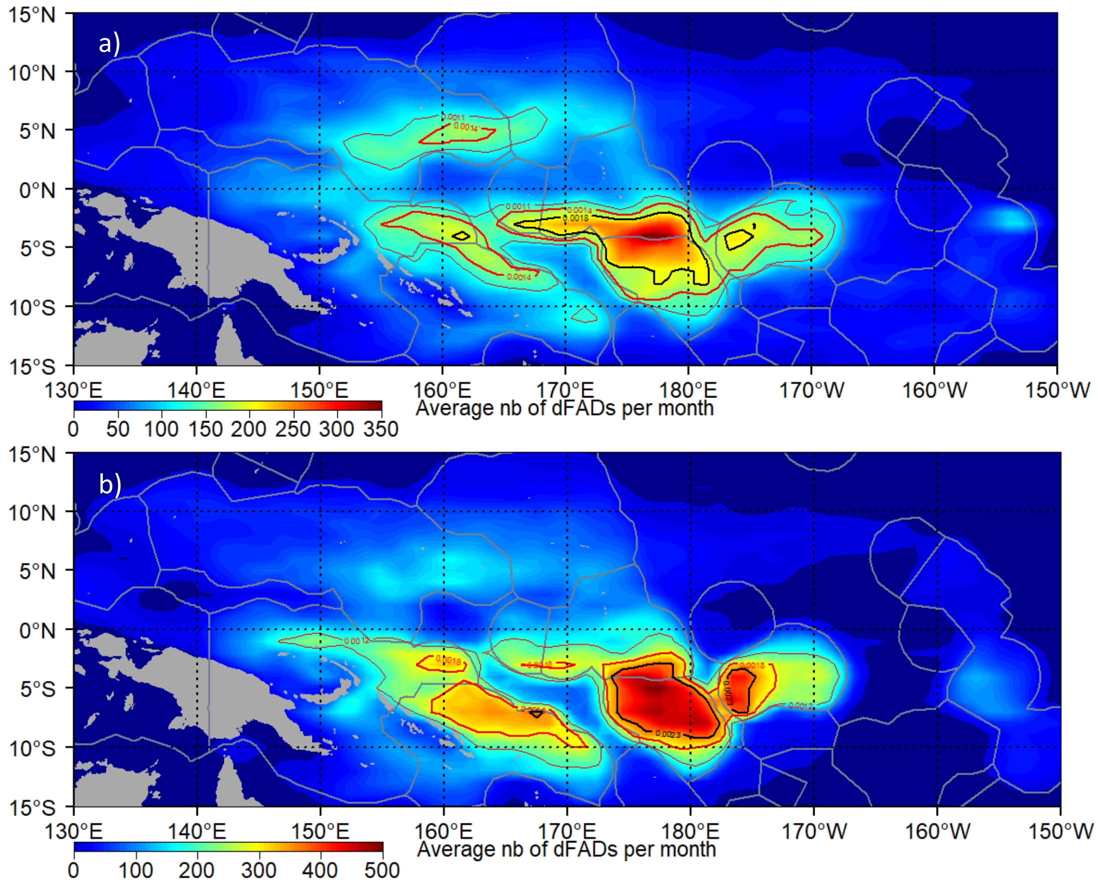

Figure 12. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, d) 2019 and e) 2020. Red lines correspond to the 95th quantile. Colour scale corresponds to the average number of buoys transmitting per 1° cell per month.

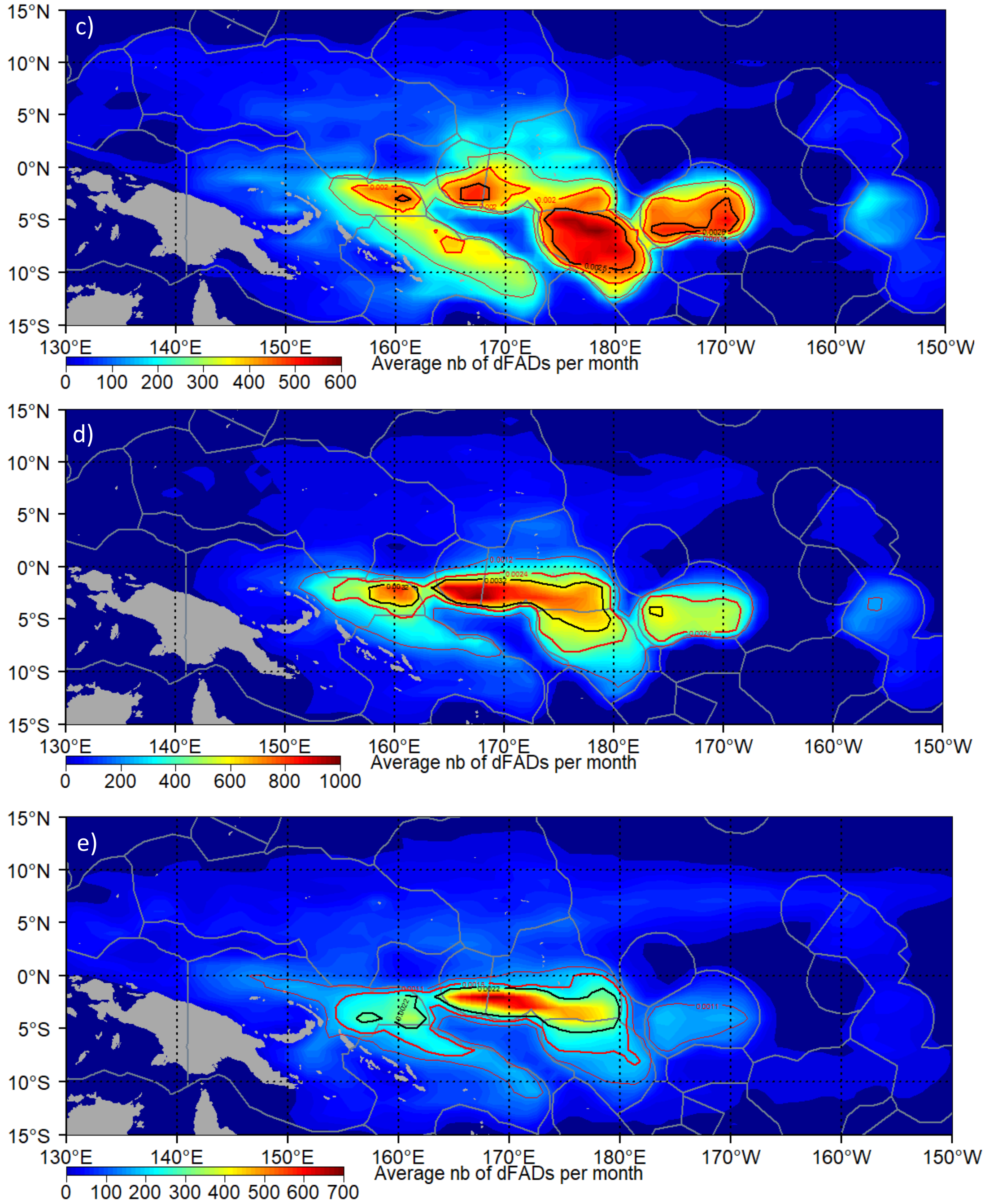

Figure 12 bis. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, d) 2019 and e) 2020. Red lines correspond to the 95th quantile. Colour scale corresponds to the average number of buoys transmitting per 1° cell per month.

While the location and extent of FAD density hotspots remained relatively consistent over the five years, the number of buoys transmitting at least once per 1° cell per year increased through time from 2016 to 2020, then it decreased in 2020 (Figures 13 and 14). While the EEZs of Kiribati Gilbert and Phoenix Islands, and Nauru showed the greatest increase through time, there was also high variability among cells. The number of FADs per cell in Tuvalu remained high from 2017 to 2019, with the main distribution ranging from 2,500 to 6,000 FADs per year per cell (Figure 13).

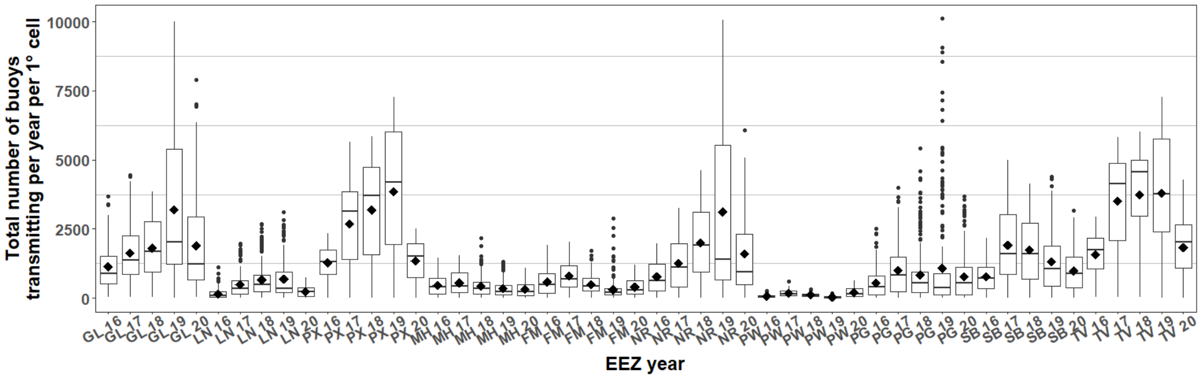

Figure 13. Number of buoys transmitting at least once per 1° cell per year, classified by PNA EEZ and year (most transmissions occur within PNA EEZs due to issues related to geo-fencing). GL = Gilbert Islands (Kiribati); LN = Line Islands (Kiribati); PH = Phoenix Islands (Kiribati); MH = Marshall Islands; FM = Federated States of Micronesia; NR = Nauru; PW = Palau; PG = Papua New Guinea; SB = Solomon Islands; TV = Tuvalu. Dots correspond to the mean value and vertical bars to the median.

Considering the number of FADs transmitting per day and 1° cell, the areas with highest FAD density of Kiribati Gilbert, Kiribati Phoenix, Nauru and Tuvalu had distributions of FAD transmitions per day per cell in 2019 ranging from 3–14; 4–18; 2–14; and 5–16, respectively (Figure 14). Then it decreased to less than 10 per day in 2020.

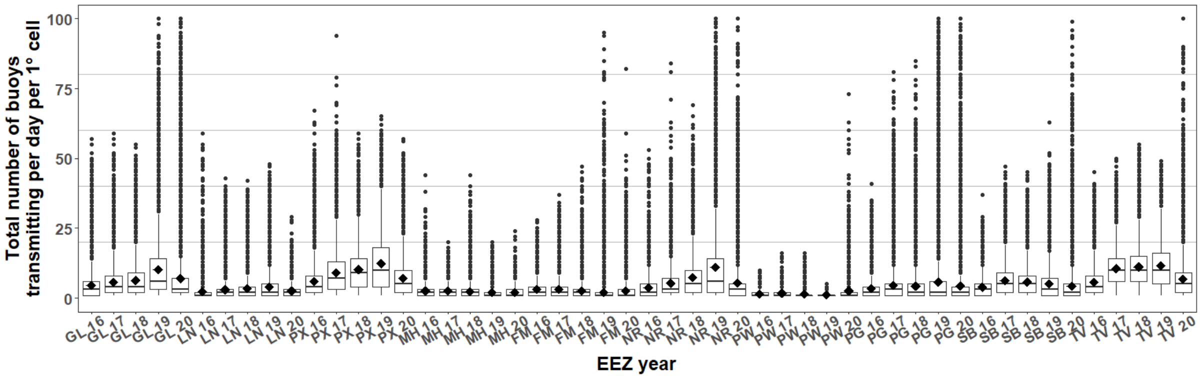

Figure 14. Number of buoys transmitting at least once per 1° cell per day, classified by PNA EEZ and year (as most transmissions occur within PNA EEZ due to issues related to geo-fencing). PNA EEZs: GL = Gilbert Islands (Kiribati); LN = Line Islands (Kiribati); PH = Phoenix Islands (Kiribati); MH = Marshall Islands; FM = Federated States of Micronesia; NR = Nauru; PW = Palau; PG = Papua New Guinea; SB = Solomon Islands; TV = Tuvalu. For the graph, the maximum number of buoys per day and 1° cell was limited to 100, but the maximum numbers are 293 for PNG in 2019; 135 for Nauru in 2019 and 104 for Kiribati Gilbert Islands in 2019. Dots correspond to the mean value and vertical bars to the median.

5.2. FAD network

Relative FAD density indices were also compiled by considering the total number of FADs drifting at sea as a network, and measuring their inter-FAD distances, i.e., the distance from each drifting FAD to the next closest neighbour drifting FAD on a particular day. Comparisons of the daily inter-FAD distances were made across EEZs and years (Figure 15), and the spatial distribution of inter-FAD distances was computed using the median inter-FAD distances per 1° cell and year (across all FADs and days).

The inter-FAD distances varied depending on the EEZ (Figure 15) and were consistent with the patterns found in the FAD density distribution (Figure 12). In the Federated States of Micronesia (FSM) and the Marshall Islands' EEZ, the inter-FAD distances were generally higher than in the other main EEZs considered here and varied from less than 10 km to 652 km (Figure 15). While very large inter-FAD distances were also found in the other EEZs, the core of the distribution of distances was generally below 30 km. Specifically in Kiribati Gilbert and Phoenix Islands, Nauru and Tuvalu EEZs, which had the highest FAD densities, 75% of the FADs and days showed inter-FAD distances of 6–22 km, with a median of 12 km (Figure 15). For these EEZs, a general decrease in the distribution of the inter-FAD distances over time was also detected, implying increased FAD density. This was particularly the case for Nauru and Kiribati Gilbert Island (Figure 15). In general, only 1 to 2 FADs were found within a 10km buffer of the considered FAD (Figure S7), this density however increased in 2019 as well, with up to 10 FADs within a 10km buffer in some EEZs.

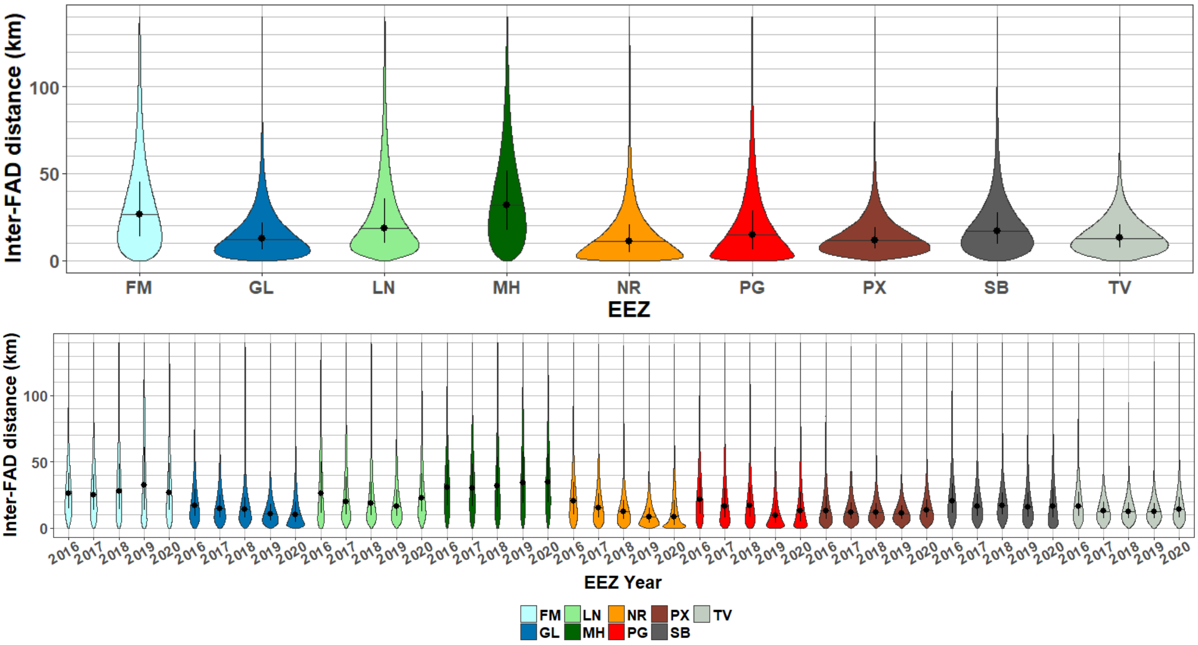

Figure 15. Violin plot of the distances between each individual FAD and its nearest neighbour drifting in the WCPO per day, by EEZ for the 2016-2020 period (top) and per EEZ and year (bottom) (black dot = median; vertical black line = 0.25 to 0.75 quantiles). Only EEZs with total number of FAD transmitting/day above the 0.75 quantile of all EEZs (see Figure S8 for all EEZs) were used, and the y-axis was restricted to the 0.99 quantile of the data (maximum inter-FAD distances of 600 km). Dots correspond to the mean value and vertical bars to the median.

The variability in inter-FAD distance among EEZs is displayed yearly through maps (Figure 16). This highlights that in the areas with high FAD density, i.e., Kiribati south of the Gilbert Islands and around the Phoenix Islands; Tuvalu; Nauru; and eastern area of Papua New Guinea and off the Solomon Islands, the median of the distance between FADs is less than 20 km. In 2019, the median of the inter-FAD distance decreased to less than 10km in the high FAD densities areas of Nauru, southwest Gilbert Island and eastern PNG EEZs (Figure 16).

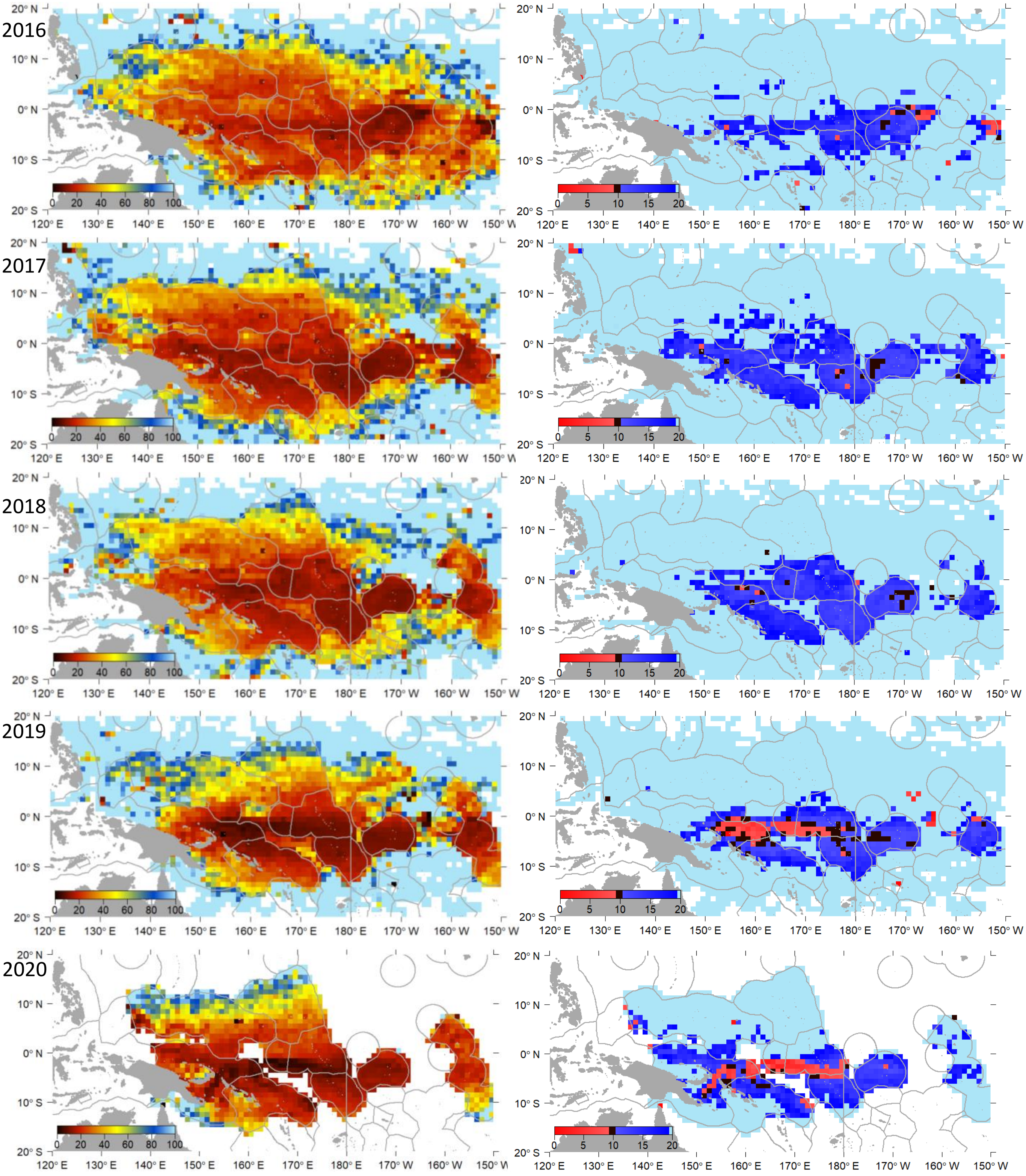

Figure 16. Spatial distribution of inter-FAD distances. The scales correspond to the median distance (km) between each individual FADs and the nearest neighbour FAD per day and 1° cell. The right-hand maps highlight the cells with a median inter-FAD distance below 20 km.

6. Fate of FADs

Buoy positions at the end of their trajectories were investigated to study the fate of FADs (Figure 17). The end of a trajectory was classified as: i) beached if the last position was "at-sea" and within 10 km of shore (excluding positions located at less than 10km from major ports) and at least the last three positions at 0m, <10m, or <100m from each other; ii) recovered if the last position was "on-board"; iii) abandoned if the last position was "at-sea" but outside the main purse seine fishing grounds or at a PNA member EEZ border; and iv) uncertain fate if the last position was "at-sea" and within the main purse seine fishing grounds (141°W, 210°E, 8°N, 12°S), but the signal was lost for unknown reason.

To remove potential bias in the analysis due to buoys that might transmit again when data are loaded again in the near future, buoys with transmissions over the last 4 months of the dataset (September–December 2020) were removed.

In addition, to better identify abandoned buoys and potential for retrieval, the distance between the last position of a buoy and the fishing ground of the company owning it in the year considered was assessed (Appendix 4). Distances between the last position of abandoned buoys and the core fishing grounds of the companies owning the buoys were mostly between 895–2,512 km, with an average of 1,824 km (Figure 17). When considering the extended fishing grounds, the distances decreased to between 235–1,166 km, with an average of 830 km. Finally, abandoned buoys were typically found at distances 502–952 km from port, with an average of 780 km (Figure 22). This suggests the potential recovery of abandoned buoys would be complicated and expensive currently. For buoys found beached, recovered, or with uncertain fate, the distances from the core and extended fishing grounds were generally shorter, with averages around 550–950 km and 200–280 km, respectively (Figure S9).

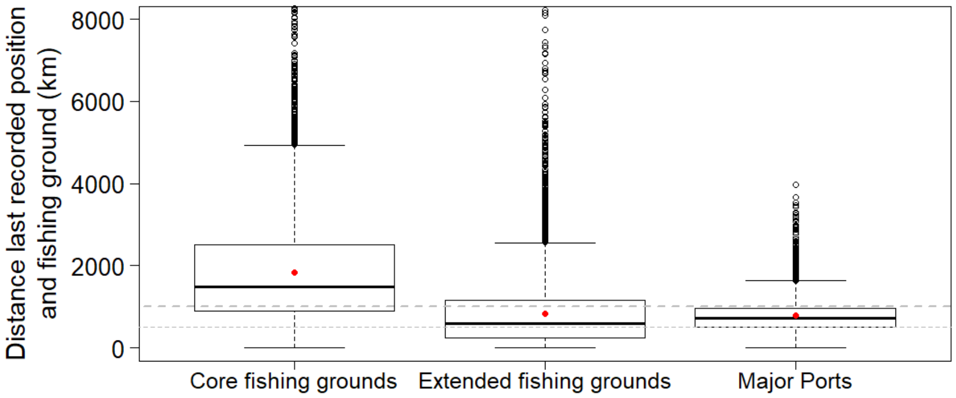

Figure 17. Distance between the last recorded position of abandoned FADs and the core or extended fishing grounds of the company owning the buoys and the closest major port. Dotted grey lines indicate 500 and 1000 km. Red dots are the mean value and vertical bars the median and the boxes correspond to the lower and upper quartiles.

The classification of an abandoned buoy was re-assessed, taking into account the fact that the last position was outside the extended fishing ground of the company owning the buoy, rather than the general purse seine associated fishing ground (Figure 18).

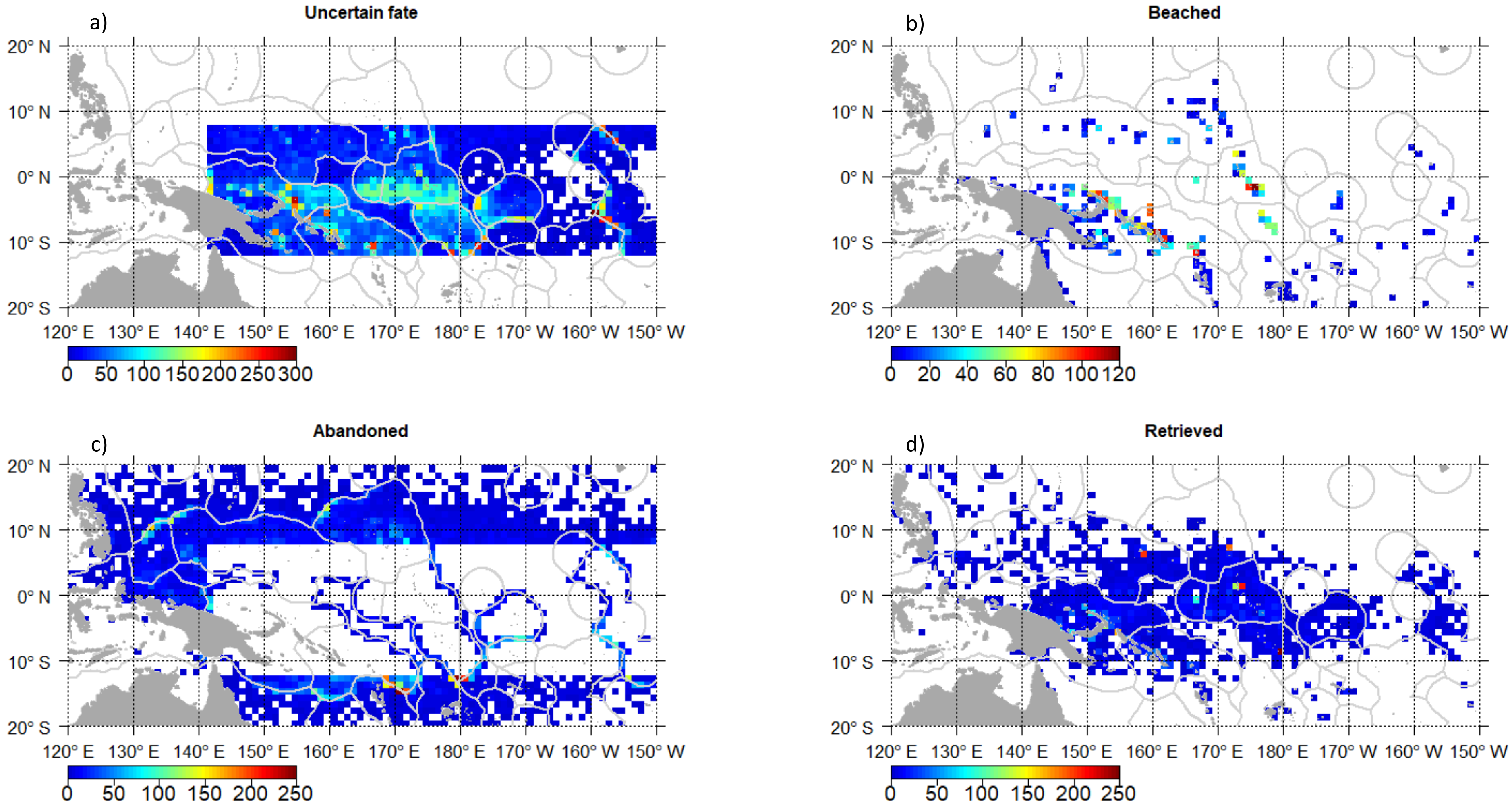

Figure 18. Density maps of last recorded position of each buoy in the FAD tracking data: a) uncertain; b) beached; c) abandoned; and d) retrieved in 2016–2020 period.

Under this classification approach, the majority of buoys were classified as abandoned (44.1%), with 24.2% being abandoned within the fishing grounds of all purse seiners, and 19.9% outside the main fishing grounds (Figure 19). The number of buoys classified as uncertain at the end of their trajectory decreased to 39.7%, half being buoys deactivated at a specific time (end of the year or during the closure) or with transmissions not transferred to the PNA (i.e., the last position at the border of a PNA member EEZ). Some buoys with uncertain fates were also at the edge of the main fishing grounds (i.e., within an area comprising the two exterior 1° squares surrounding the main fishing grounds at the time of signal loss; Figure 18c), and 10.3% were 50 km from shore, indicating potential abandonment or beaching in the near future. However, this should be interpreted with caution given that local currents can bring FADs back to the fishing grounds or away from shore. A total of 9.6% of buoys were retrieved, however there is no indication whether the vessel retrieving the buoy was the owner of the buoy, another purse seine vessel, or another vessel (for example when the recovery is close to shore). In addition, the map of recovered buoys in Figure 18 corresponds to the last position of the recovered buoys, which could be in a port. It would be more relevant to map the first position post-recovery of these buoys, which implies further data manipulation. Finally, 6.6% of the buoys were beached, with most (5.4%) not moving at all at the end of their trajectories (Figure 18 and 19).

We hypothesise that the buoys with uncertain fate (i.e., FADs found drifting within the main purse seine fishing grounds) with unexplained deactivation (classified as “unknown” and “pre-beaching” in Figure 19) correspond to buoys that have sunk, buoys being disabled during FAD appropriation by another vessel, or buoy malfunction. Except for the latter case, the remaining categories would not lead to FADs floating unmonitored. Abandoned buoys, however, would remain in the water for an unknown period of time, and this number of unmonitored abandoned or lost FADs cannot currently be taken into account when assessing FAD densities, and when reviewing the impact of FAD density on CPUE.

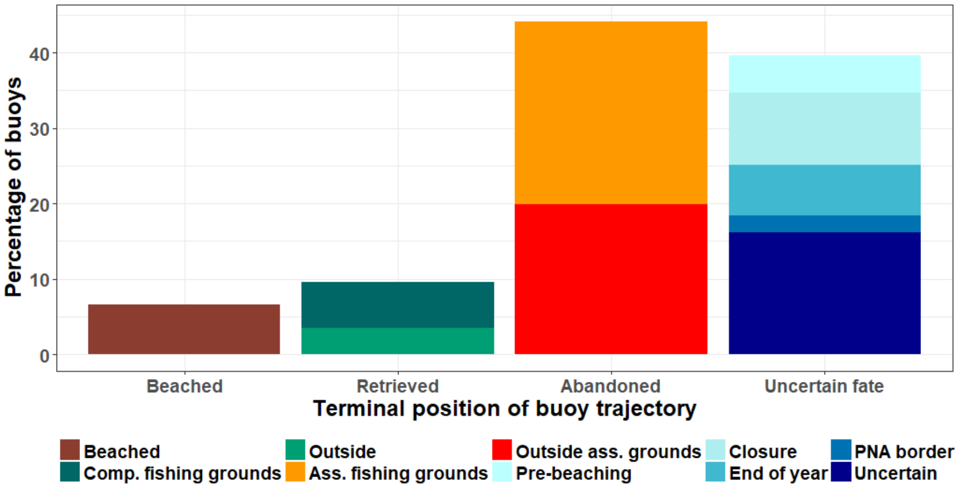

Figure 19. Percentage of buoys’ terminal position classified as beached; retrieved (within or outside the fishing grounds of the company owning the FAD) by any vessel; abandoned (within or outside the general purse seine associated fishing grounds, i.e., see Figure 18): or uncertain from 2016–2020. These results are based on buoys from companies with at least three purse seiners (47,418 buoys).

Using this refined approach to classify the fate of a buoy, we estimated that 44.1% of buoys were abandoned; 9.6% were retrieved; 6.6% were beached; 21.3% were deactivated by the fishing company and left drifting unmonitored at sea (uncertain fate classified as “Closure” “End of Year” and “Pre beaching"); and 18.4% were sunk, appropriated, or with a malfunctioning buoy (uncertain fate classified as "Unknown" and "PNA border"). Overall, if we included those deactivated buoys and the ones abandoned but still within the purse seine fishing grounds, we estimated that 22,743 buoys (45.5%) are unmonitored within PNA waters. This could therefore lead to an additional 1,501 buoys beaching (based on a 6.6% beaching rate found above). In addition, distances between FADs and the 'owning' fleet are generally large, and therefore may limit direct recovery potential.

The evolution of a buoy's fate through time was also investigated (Figure 24). The number of buoys with an uncertain fate (i.e., final position at-sea and within the main purse seine fishing grounds) increased between 2016 and 2019 (from 35% in 2016 to 46% in 2019). In contrast, the number of buoys recovered or abandoned decreased, except for in 2020.

This may be due to earlier deactivation of buoys by fishing companies when buoys are no longer considered usable by their vessels (i.e., having drifted far from their fishing grounds). This could also be linked to the implementation of a WCPFC limit in the number of active buoys per vessel at any given time of 350 in 2018 (CMM-2018-01; WCPFC, 2018). To avoid exceeding this limit, vessels or fishing companies may therefore tend to deactivate buoys sooner than they did previously and then deploy new FADs back in their main fishing grounds.

Finally, we also note that the number of beached buoys fluctuated between 6–9% per year but did not show a clear pattern through time (Figure 20).

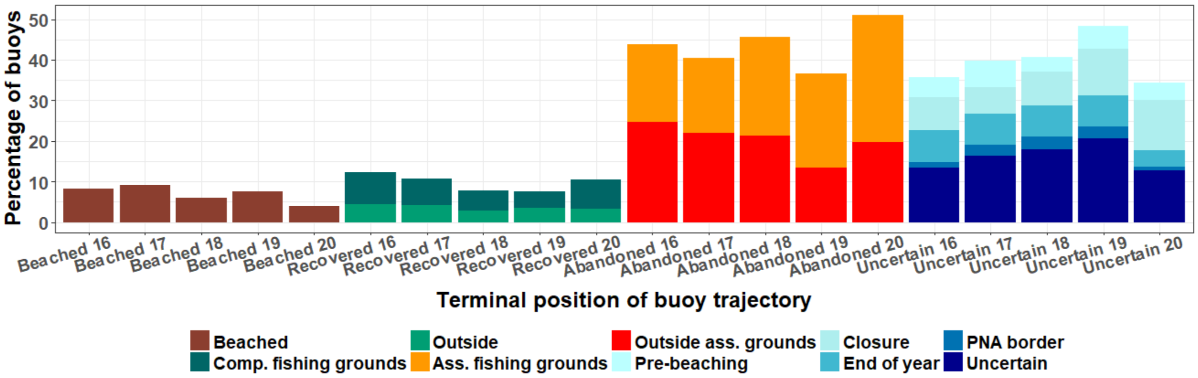

Figure 20. Percentage of buoys' terminal position classified as beached; retrieved (within or outside the fishing grounds of the company owning the FAD) by any vessel; abandoned (within or outside the general purse seine associated fishing grounds, i.e., see Figure 18): or uncertain per year between 2016 and 2020. These results are based on buoys from companies with at least three purse seiners (47,418 buoys).

7. FAD efficiency

Understanding effort creep and efficiency of fishing efforts is important for the monitoring, assessment, and management of tuna stocks, especially within an effort-based management framework. It is often assumed that increased sophistication of FAD technologies will enhance the ability of fishers to more reliably locate and harvest tuna schools, potentially increasing catch rates due to the improved information networks that FADs contribute to.

In a recent paper Wain et al. (2021) evaluated the efficiency of FAD sets in the Indian Ocean tropical purse seine fishery. They compared sets made on a vessel's own FAD with an echosounder buoy (O+E), sets made on a vessel's own FAD without an echosounder buoy (O-E), and sets made on what they referred to as 'foreign' FADs (F). Foreign simply means that the buoy was not registered to the vessel making the sets, and therefore, was likely to be an opportunistic set as opposed to one informed by buoy instrumentation. In their study, there were only very modest improvements in catch size (~2.6t) due to the presence of an echosounder (O+E sets) as compared with foreign FAD sets.

Here, we set out to conduct a similar analysis, to evaluate whether the same patterns were observed in the WCPO, or if there was evidence of more productive sets resulting from FAD buoy technology. We adopted the same set category terminology as used in their study.

7.1 Data preparation

Observer-reported catch and effort data and FAD tracking data were used for purse seine fleets operating in the WCPO from 2016–2019. There is a mandate for 100% observer coverage for purse seine vessels operating in the WCPO, and although observer reports are not received for all trips coverage of fishing activity throughout the region is generally between 84–98% (Panizza et al., 2021). With each data set, the time and location of activity is reported, for fishing sets and FAD positions, respectively. Observers provide detailed information on the catch composition as well as FAD characteristics, including buoy ID, when possible. The FAD tracking database was used to identify FAD positions, but also buoy type and ownership.

The two data sets were matched based on the time and locations reported. A match was determined if the set took place within 3 km and 3 hours of the nearest FAD position. We further evaluated the matches by comparing the observer records on the buoy ID and buoy ownership. The match was confirmed if the data sets were in agreement, but if the observer was unable to record the FAD buoy ID, it was not possible to confirm the match. The FAD tracking data do not include tracking information for all FADs in the WCPO; therefore, they represent only a subset of the drifting FAD network. We did however, proceed with the matched records, even if unconfirmed because the matching criteria was relatively conservative. Enhancements to the data sharing for all complete FAD trajectories, and to the buoy ID records by observers would improve these analyses and remove some of the uncertainty associated at this point in time.

In the analysis by Wain et al. (2021) additional criteria were required to define buoy ownership because they used logbook data for which the time of day was not reported. Therefore, they needed to estimate which buoy a vessel was making a set based on a broader time and distance window. Here, we have more detailed information on fishing sets and the FAD buoys themselves. Therefore, our classification may be more precise given to the additional data elements provided by observers; however, the FAD tracking data may be more limited. Wain et al. (2021) had more complete access to the drifting FAD network in the Indian Ocean for the single fleet considered in their analysis, whereas for our analysis, while a large portion of the purse seine fleets are included, the incomplete nature of the data set and the relatively short time-series are limiting factors.

We filtered the data set to retain a subset of vessels that were relatively active over the time period of interest, 2016–2019. Vessels that fished in every year with at least 5 sets per year were included in the analysis. We constrained the spatial extent to the main purse seine fishing grounds (i.e., regions 6-8 of the most recent stock assessment; Vincent et al. (2019)), and removed observations that were missing key data elements or had unreasonable catch values, prior to the statistical modelling.

7.2 Statistical modelling

To evaluate whether FAD catch rates were influenced by ownership and information received from an echosounder buoy, and to compare these results to those from the Indian Ocean where FAD reliance is much higher, we used the approach adapted from Wain et al. (2021). We used a series generalized additive and linear mixed models (GAMMs; GLMMs, respectively) to evaluate the relative efficiency of different FAD set categories while controlling for spatial and temporal variability, and individual vessel variability. We modelled total tuna catch as the response variable, as to date, fishers have limited ability to discern species composition from the FAD acoustic data nor from visual cues prior to making a set. Therefore, we were most interested in understanding whether total tuna catch increased when a vessel had access to additional information from their own FADs, mounted with echosounders.

Similar to Wain et al. (2021) we modelled spatial variability as either a smooth effect or as a fixed factor at a 5°x5° resolution (Table 3). When spatial variability was modelled as a smooth term, it was grouped by quarter to account for seasonal variability, using 3 knots. Year was modelled as a fixed categorical effect or a smooth term and set category was modelled as a categorical variable. We included a random vessel effect in all models, to account for individual vessel variability in size, skill, and fishing strategy and to account for the potential autocorrelation in sets made by the same vessel. The vessel effect was modelled as a Gaussian distribution with a mean of zero and an estimated variance parameter. All models were fit assuming a gamma error distribution with a log link function.

Table 3. Description of generalized additive and linear mixed models explored to evaluate the impact of FAD ownership and buoy sophistication on catch rates. The model variables are denoted as follows: TUN = total tuna catch (mt), SKJ.prop = the transformed proportion of skipjack catch, SC = set category, Lon and Lat represent the geographic locations of the observations, qtr is the 3-month quarter effect, YR is year which was modelled as a factor, and V is the vessel effect which was modelled as a random effect RE(), C5 id the 5∘x5∘ geographic cell, and CC is the catch category. The spatial location was typically modelled as a smooth term te() with a seasonal effect, but was modelled as a factor in Model L1. All models were generalized mixed models, with all but one containing smooth terms.

Model	Response	Error dist.	Type	Equation
A1	TUN	Gamma (log-link)	GAMM	TUN ~ te(Lon, Lat, by=qtr) + YR + SC + RE(V)
A2	TUN	Gamma (log-link)	GAMM	TUN ~ te(Lon, Lat) + YR + SC + RE(V)
L1	TUN	Gamma (log-link)	GLMM	TUN ~ C5 + qtr + YR + SC +RE(V)
B1	SKJ.prop	Beta	GAMM	SKJ.prop ~ te(Lon, Lat, by=qtr) + YR + SC + RE(V)
N1	SC	Binomial	GAMM	SC ~ te(Lon, Lat, by=qtr) + YR + s(CC) + RE(V)

In addition to modelling tuna catch rates, we investigated whether the proportion of skipjack in the catch was related to buoy ownership and sophistication. Skipjack is by far the dominant harvested species from the purse seine sector, and we wanted to better understand whether FAD-derived information was influencing the proportion in the catches. Specifically, bigeye and yellowfin tuna both have a swim bladder, whereas skipjack do not, a difference that is likely to influence the acoustic signal. Advancements in technology to analyse acoustic signals is making it possible to better discern species composition (Moreno et al., 2019) but the technology has not been fully developed for the WCPO. Therefore, this variability in acoustic signal may have an influence on the resulting catch composition. Lastly, we modelled the set category as a function of location, year, and catch magnitude (10 t bins). Here, we assessed the difference between foreign FADs (F) and a vessel's own FAD with an echosounder (O+E) with a binomial error structure. All model formulations are described in Table 3.

7.3 Preliminary results

In total, we matched 4,934 sets to buoys in the FAD tracking data set from 2016–2019, for use in the modelling exercise. The vast majority of the buoys that were matched to the observer data, were categorized a O+E, with the O-E category declining rapidly even across this short time series (Figure 21). The F sets represented about 20% of the matched sets in any given year. The catch rates (Figure 22) showed a slight increase for O+E sets but the proportion of large sets (>15t) tended to be greater for sets made on a vessel's own FAD (Figure 23). The species composition was relatively consistent across the set categories. It should be noted, when interpreting these trends, that the sample size in the O-E category is quite small in the most recent years, leading to high variability in the trends.

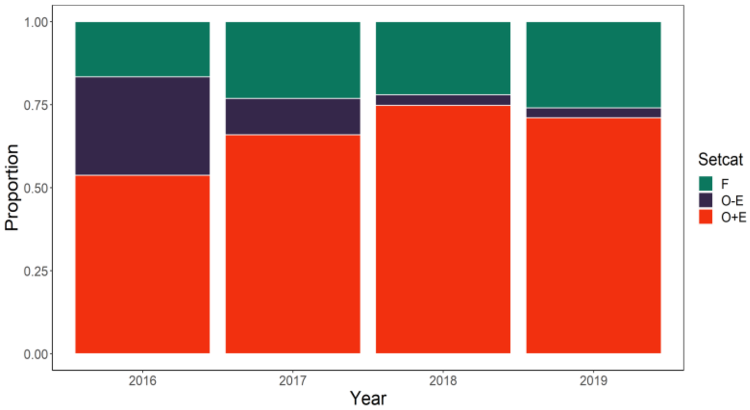

Figure 21. The proportion of matched observer sets to the FAD-tracking data in each of the 3 set categories: O+E, O-E, and F.

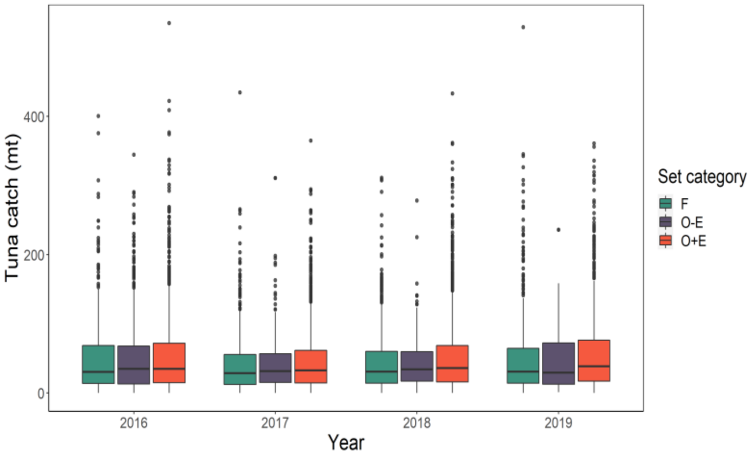

Figure 22. Distribution of catch sizes across the three set categories (F, O-E, O+E). There is a slight increase in the catch size for O+E sets, but with notable variability across all categories. Vertical bars correspond to the median and the boxes correspond to the lower and upper quartiles.

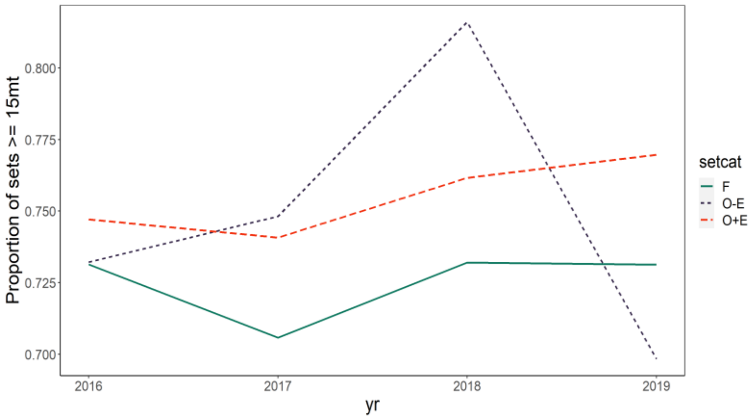

Figure 23. The proportion of matched observer sets, within each set category, that produced at least 15mt of tuna catch. Again, note that there are relatively few observations in the O-E category in recent years, resulting in highly variable trends.

The set category coefficient estimates from all models evaluated, excepting model N1, are detailed in Table 4. The effect of the O-E category was only marginally significant the 0.05 level, but for all models the O+E category had a positive significant effect on the response variables. The foreign FAD set category (F) was the reference level in all models.

Model diagnostics suggested an improved fit to the data when position was fitted as a seasonal smooth term (i.e., comparing A1, A2, and L1). Our overall results were comparable to those from Wain et al. (2021) in that for most models, the sets made on a vessel's own buoy were generally more productive than sets made on a foreign FAD, but only by about 3 t, on average.

Table 4. Set category coefficients, on the scale of the linear predictor, indicating the effect of FAD ownership and sophistication on the associated response variable.

Model	O-E coefficient (p-value)	O+E coefficient (p-value)
A1	0.10 (0.08)	0.07 (0.05)
A2	0.09 (0.06)	0.07 (0.04)
L1	0.12 (0.06)	0.07 (0.04)
B1	0.22 (0.07)	0.11 (0.05)

The proportion of skipjack tended to increase when fishing a vessel's own FAD, which is not surprising, as the vast majority of the catch is skipjack for this region. When we evaluated the probability of F versus O+E set categories relative to catch magnitude (model N1), we observed a general increase in the probability of an O+E set at higher catch sizes. But again, the increase in probability between F and O+E sets based on catch size is quite small (Figure 24).

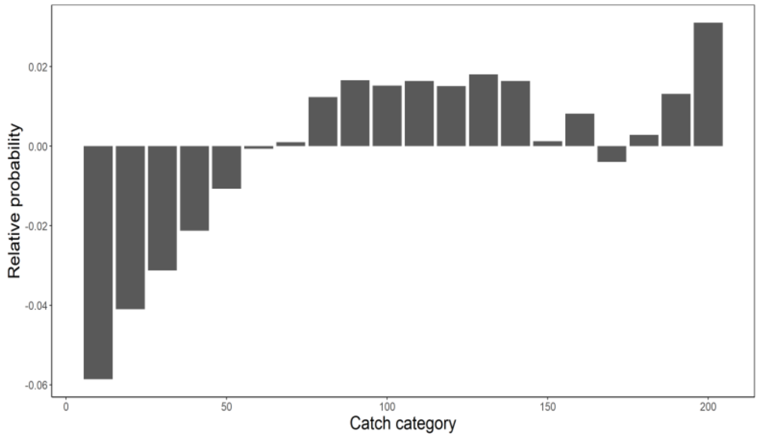

Figure 24. The relative probability that an O+E set (compared to F sets) would produce a catch in the 10t catch bin labelled on the x-axis. This plot indicates a slightly higher probability of producing largest catch sizes from O+E sets, as compared to sets made on foreign FADs (F).

These preliminary analyses show only a marginal improvement in catch rates over sets made on foreign FADs. These analyses could be enhanced with improved access to FAD tracking data, and may prove valuable for quantifying changes in catchability and addressing effort creep from the modern fishery.

8. Discussion and Conclusion

The data volume submitted to PNA has clearly increased overtime. However, the lack of full submission of the data by fishing companies and the editing of the data before submission to PNA still limits and complicates the analyses and outputs of potential interest to managers. This is of particular importance in the compilation of FAD densities, and a correction procedure should be developed to obtain more homogenised spatial distribution of FAD densities at the scale of the WCPO (Escalle et al., 2019a). Nevertheless, complete and unmodified FAD tracking data will always remain the most precise source of information regarding FAD densities and number of FADs or buoys at-sea. This is of particular importance in the compilation of FAD densities, and a correction procedure should be developed further to obtain more homogenised spatial distribution of FAD densities at the scale of the WCPO (Escalle et al., 2019a). Nevertheless, complete and unmodified FAD tracking data will always remain the most precise source of information regarding FAD densities and number of FADs or buoys at-sea. Further investigation on the effect of FAD density and inter-FAD distances on CPUE could hence be performed. It should be noted that PNA Members have agreed to adopt a requirement for FAD buoys to be registered and provide position information to PNA including while in the high seas (i.e., between 20°N and 20°S of the WCPFC convention area), for the purpose of improving FAD management in PNA waters. This can be expected to improve the coverage of FAD buoy position data.

Where these tracking data are currently most complete, within PNA EEZs, this paper has revealed the degree to which density and inter-FAD distances vary. In PNA countries such as Tuvalu, where almost half of all FADs are less than 12km from each other, this may have significant effects on the behaviour and vulnerability of tropical tunas. The direct effect of FADs on these species is believed to occur at around this distance (Moreno et al., 2007), with directed movements towards FAD-aggregated schools identified from 10km away in electronic tagging studies (Girard et al., 2004). Similarly, extensive but continuous associations between two close FADs by bigeye and yellowfin tuna have been observed in recent sonic tagging studies in the WCPO (Scutt Phillips et al., 2019). Given the very close distance between the majority of FADs in EEZs such as Tuvalu, the possibility that any school does not 'associate' with a FAD during any given 24-hour period must be considered. Catch and tagging data that exist within these networks of short inter-FAD distances could be examined to further quantify the likely effect on free schooling and associated behaviours within these FAD dense, but data-rich, areas.

The importance of *in-situ* data related to FAD characteristics (observer data as recorded until now or captain's records) has also been highlighted. In particular, FAD depth and FAD drift duration have been shown to influence catch per set. Hence, we emphasize again the need for precise records of i) every FAD related activity (e.g., set, deployment, service, beaching), which would allow the matching with trajectories in the FAD tracking data; ii) FAD and buoy deployment date (given that FADs themselves are marked); and iii) information on the FAD (depth, width/length). Priority should therefore still be given to obtaining high quality FAD related information from observer or logsheet data. The FAD data collection app currently under development by the PNA will assist in filling these gaps. Acknowledging the current limitation in the fishery data (limited records of FAD characteristics or buoy ID number), future investigation using the buoy tracking data and already available fishery datasets (observer, logsheet, VMS) could enhance our understanding in the operational use of drifting FADs, ecosystem interactions they influence, as well as effort creep and purse seine fisher behaviour.

In this paper, an increase in echo-sounder buoy use through time was detected (almost all the buoys in the WCPO having an echo-sounder in 2019), included double-frequency echo-sounder buoys. While similar results were found in the observer database, the record of such information through the buoy ID number remains limited (6% of all records of FAD related activities), and only covers 2011–2021. It should also be noted that the limited observer placement due to the COVID-19 pandemic will limit the analyses that can be performed using observer data. Long-term investigation of FAD-related technologies from this dataset would therefore be limited. Such parameters have however been identified as important in effort creep investigations, as increasing or stable catch rates linked to the introduction of these technologies may offset and mask a potential decrease in biomass (Vidal et al., 2020).

The method to identify FAD fates based on the distance between last transmitted position of a FAD and the main fishing ground of the company owning, enabled better estimates. In particular, it highlighted the high potential rate of FAD loss (>40%) and FAD beaching (7%). However, it is clear that the lack of complete FAD trajectories underestimates the number of beaching events, specifically in non-PNA countries. In addition, even with a complete FAD tracking dataset, buoys may be deactivated before reaching coastlines, leading to unnoticed beaching events. This therefore highlights the importance of considering the use of bio-degradable FADs in the WCPO, and/or potentially considering buoy recovery programs or more collaboration between fishing companies when buoys drift out of one company's fishing grounds, in order to mitigate impacts. An increase through time in number of buoys with uncertain fate was detected. This could be linked to the implementation of a WCPFC limit in the number of active buoys per vessel at any given time of 350 in 2018, leading to buoys being deactivated sooner since the measure entered into force (CMM-2018-01; WCPFC, 2018). Indeed, to avoid exceeding the 350 active buoy limit, vessels or fishing company may tend to deactivate buoys as soon as they drift out of their fishing grounds or of productive areas, in order to be able to deploy new FADs back in their main fishing grounds. However, recent investigations revealed that few vessels would monitor more than 350 buoys per day (Escalle et al., 2020b). Accessing better information on the fate of FADs, including the reason why a buoy is deactivated, would be crucial to better understand the impact that the high number of abandoned and lost FADs may have on the environment.

Potential additional research topics include:

- Additional work and parameterisation of a simulation method to re-construct FAD tracks with missing sections. For instance, different current models could be tested, but validation of the different ocean forcing models using known trajectories is also needed.
- Further investigate the link between FAD densities and occurrence of FAD and free school sets, CPUE, and catch per set. Additional variables could be included, such as FAD drift speed, distance to closest FAD, vessel characteristics, and environmental variables (e.g., SST, thermocline depth).
- FAD network analyses could further integrate catch and even other data such as tagging, to examine apparent effects on distribution at meso-scales and inform stock assessments through catchability or other parameters.
- Investigate the frequency of setting on individual FADs per vessel or fleet, in relation to the overall array of FADs available and environmental variables.
- Investigate the effectiveness of the FAD closure to manage FADs and catch of small tuna on FADs, as well as potential alternative arrangements.

We invite WCPFC-SC17 to:

- Note this analysis on the PNA FAD tracking data and the progress being made by PNA in FAD tracking for the purpose of improving FAD management in PNA waters.
- Note the importance of complete FAD tracking data to support scientific analyses and encourage their provision by fishing companies.
- Note that 57% of FADs were deployed by purse seiners, 4.6 by other vessels, and that 25% of FADs could have been activated at-sea remotely.
- Note these analyses and the patterns identified. In particular, note the increase through time in the number of FAD per 1° cell in areas of high FAD densities. This corresponds to FADs being less than 12 km from each other.
- Note that findings of this paper highlighted that more than 44.1% of buoys were estimated to be abandoned and 6.6% beached; as well as the increase in number of buoys with uncertain fate (21.3 % in 2020).

Acknowledgments

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WCPFC, 2017. CMM-2017-01 Conservation and management measure for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean.

Appendix 1. Description of the FAD tracking filtering and processing method.

The first filtering process was to remove buoys activated for short periods. This served to verify functioning and avoid bias in the analyses due to very short overall active time. This process included the removal of buoys with less than 10 transmissions, those active for less than seven days, and those with transmissions exclusively from a single position (Table S1). In addition, double transmissions, consecutive transmissions corresponding to unrealistic speeds, as well as consecutive transmissions separated by more than three months at the end or beginning of a buoy track were removed. Finally, date/time recorded by Kato and Marine Instruments buoys presented some high acceleration in the buoy drift speed (i.e., significant distances travelled over short times) due to data recorded within a few minutes but at different positions leading to misclassification in the processing method (see below). To avoid this, only one position per day was kept for the data from these two buoy brands (8% of total number of transmissions for all buoys, see Table S1).

Table S1. Summary information of the buoy tracking dataset showing the number (and %) of records removed during filtering processes.

	Number of transmissions	Number of buoys	% of transmissions	% of buoys
Raw dataset	**35,700,915**	**71,247**		
Positions outside the Pacific Ocean	127,925	1643	0.36%	2.31%
Buoy with ≤ 3 transmissions	4,186	1861	0.01%	2.61%
Double transmissions (same time and position)	198,650	0	0.56%	0.00%
One position per day (Kato and Marine Instrument)	2,974,685	0	8.33%	0.00%
Buoy with only one position	60,272	554	0.17%	0.78%
Buoy with only port position	9,724	41	0.03%	0.06%
Consecutive transmissions with high speed (>200 knots)	3,264	4	0.01%	0.01%
Large gap at the beginning or end of trajectory	253,534	70	0.71%	0.10%
Total removed	3,632,240	4,173	10.2%	5.9%
Filter dataset	32,068,675	67,074		

Second-stage processing of the data consisted of identifying at-sea and on-board positions of each buoy to avoid bias in analyses focusing on effective at-sea time of FADs (Escalle et al., 2017; Maufroy et al., 2015). Transmissions start when a buoy is activated. Activation may occur following a deployment, or it may occur a few hours to several days before deployment, and continued until deactivation (e.g., when a FAD is considered “lost” by the company, or is recovered). Each transmission was classified into an “at-sea” or “on-board” position following the method developed by Maufroy et al. (2015). First, a subset of the data was used to compile a learning dataset (1,060 buoys and 939,200 transmissions, i.e., 3.5% of the buoys when the method was first developed, see Escalle et al., 2017b), for which at-sea and on-board positions were visually classified. This learning dataset was used to configure a Random Forest model and a cross validation procedure was implemented to check the performance of the model. The learning dataset was randomly split 100 times into a training dataset and a validation dataset, with 50% of the learning buoys in each dataset. Random Forest models were calibrated using the training datasets, then the position classification (at-sea or on-board) in the validation datasets was predicted. Performance statistics (accuracy rate, Kappa statistic, specificity, sensitivity; see Maufroy et al. (2015) for details) were then generated.

In addition, as Random Forest models consider each position independently, with no consideration of the prior or following positions, an additional correction procedure was needed to eliminate isolated or short at-sea or on-board sections surrounded by long on-board or at-sea positions. An additional statistic called segmentation rate was therefore added to account for this feature of the data. The correction procedure to reduce the segmentation rate consisted of; i) changing to on-board positions, those sequences of one to three isolated at-sea positions, ii) changing to at-sea positions, those sequences of one to three isolated on-board positions with a speed <5 km/h, and iii) changing to on-board positions, those additional isolated sequences of at-sea positions lasting less than 24 hours. This additional correction procedure was selected as the preferred method after testing different correction procedures, and based on the statistics mentioned above, combined with visual investigation of some buoys. Once the Random Forest model and the correction procedure were calibrated, they were run over the entire filtered dataset. Each buoy track (i.e., trajectory) then consisted of one (73% of the FADs) or several drifting ("at-sea") segments (2–58 segments per FAD), separated by "on-board" positions.

Appendix 2. Characteristics of the PNA FAD tracking database.

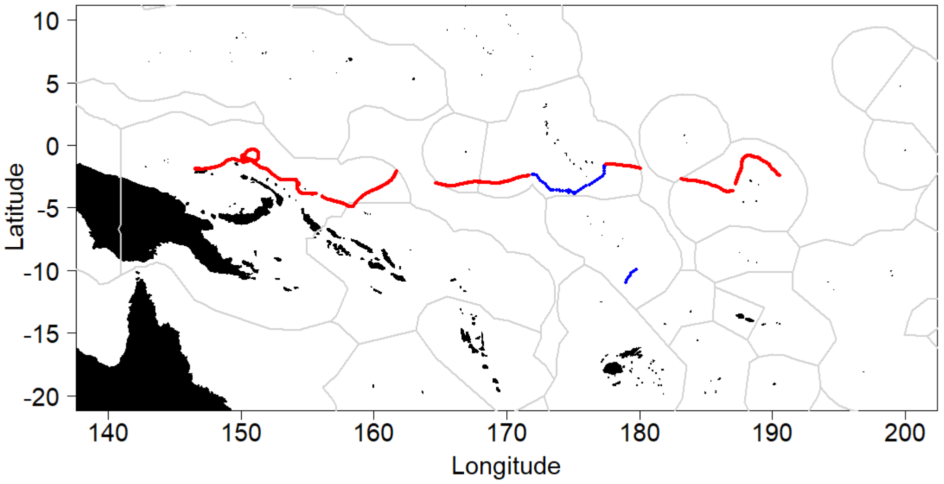

Figure S1. Example of a trajectory of a geo-fenced buoy, blue line represents on-board positions and red at-sea positions.

Patterns of buoys being geo-fenced (Figure S1) by fishing companies prior to transmission to PNA appear variable between companies. Between 6 and 30% f of the fishing companies geo-fenced less than 25% of their FAD trajectories, while half were found to have geo-fenced their FAD data more than 75% percent of the time (Figure S2). Additionally, when FADs are geo-fenced it leads to gaps in the FAD trajectories of approximately a few days to one month (Escalle et al., 2018), limiting the analyses performed on the data. Overall, a total of 44,174 (66%) FADs have been geo-fenced in the data from 2016–2020.

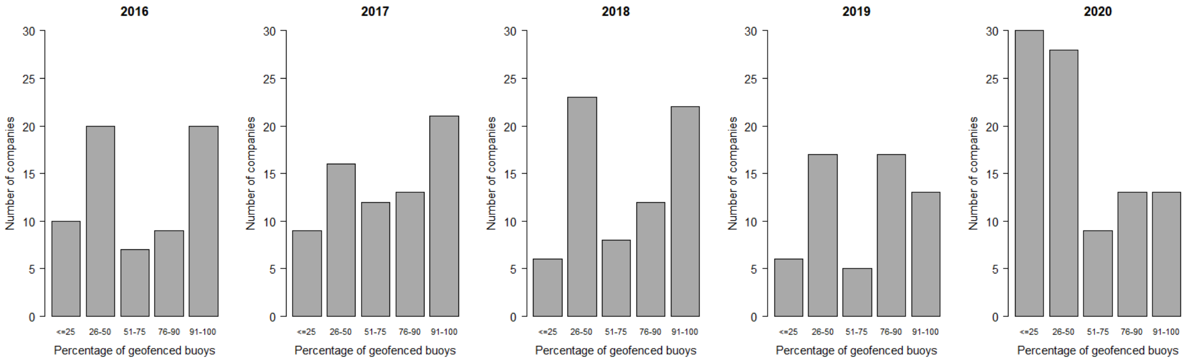

Figure S2. Percentage geo-fenced FAD buoys by fishing company prior to transmission to PNA during 2016-2019.

Regarding temporal variability, besides the fact that few buoys were geo-fenced during the first three months of the programme, no temporal trends in the number of geo-fenced buoys by company could be determined (Figure S3). Since April 2016, between 24 and 92% of the FADs had been geo-fenced monthly. However, we can note an increasing trend each year, with lower geofencing rate at the start of the year (Figure S3).

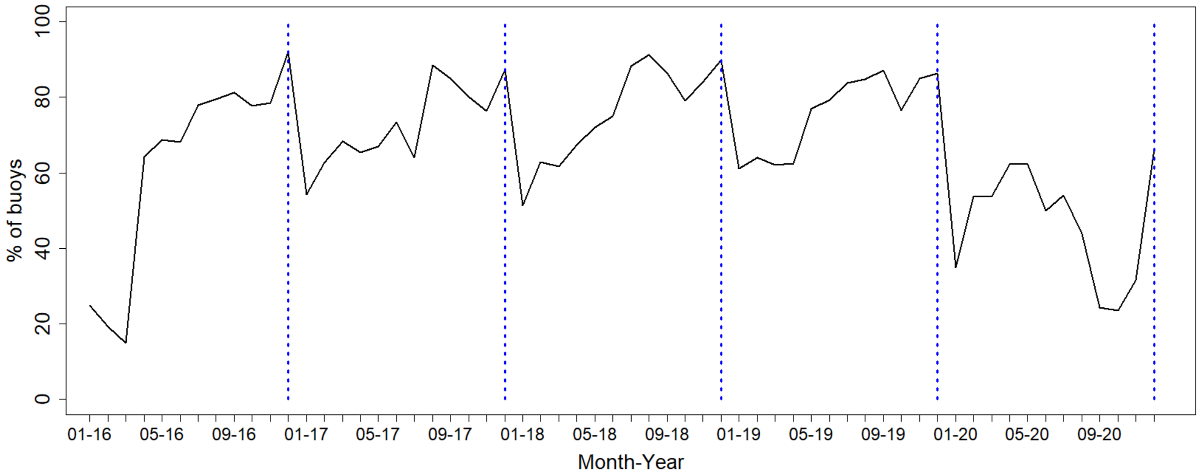

Figure S3. Percentage of geo-fenced buoys by month in 2016–2020.

We note that the geo-fencing of data supplied to the PNA affects many of the analyses described in this paper, including the identification of deployment events and locations (which may be outside PNA EEZs), estimation of FAD density (constrained to occur inside PNA EEZs only), soak time, the fate of FADs, etc., and hence it also affects also the scientific advice that can be provided to inform management options.

The transmission rate (i.e., frequency of transmission through time) varied by buoy brand (Figure S4 in Appendix 2), with Satlink buoys mostly transmitting every hour, or every day. For Kato and Marine Instruments, the raw data that we received indicated that although these brands transmit several times per day, either only one position per day (Marine Instruments) is recorded or only one position per day is retained for the processing method to avoid high rates of mis-classification. Hence these two brands showed a transmission pattern in the filtered dataset used for analyses of one position per day. Finally, Zunibal buoys mostly transmitted once per day, or every 30 min (Figure S4), likely when fishers need a more precise position of the buoy, for instance before a fishing set.

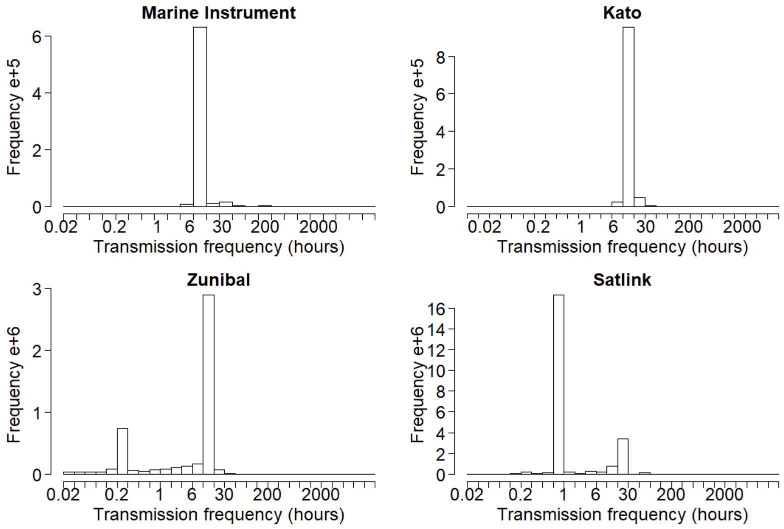

Figure S4. Frequency of transmission (in hours) for all buoys assessed from 2016–2021.

Appendix 3. Additional figures related to FAD deployments and FAD densities.

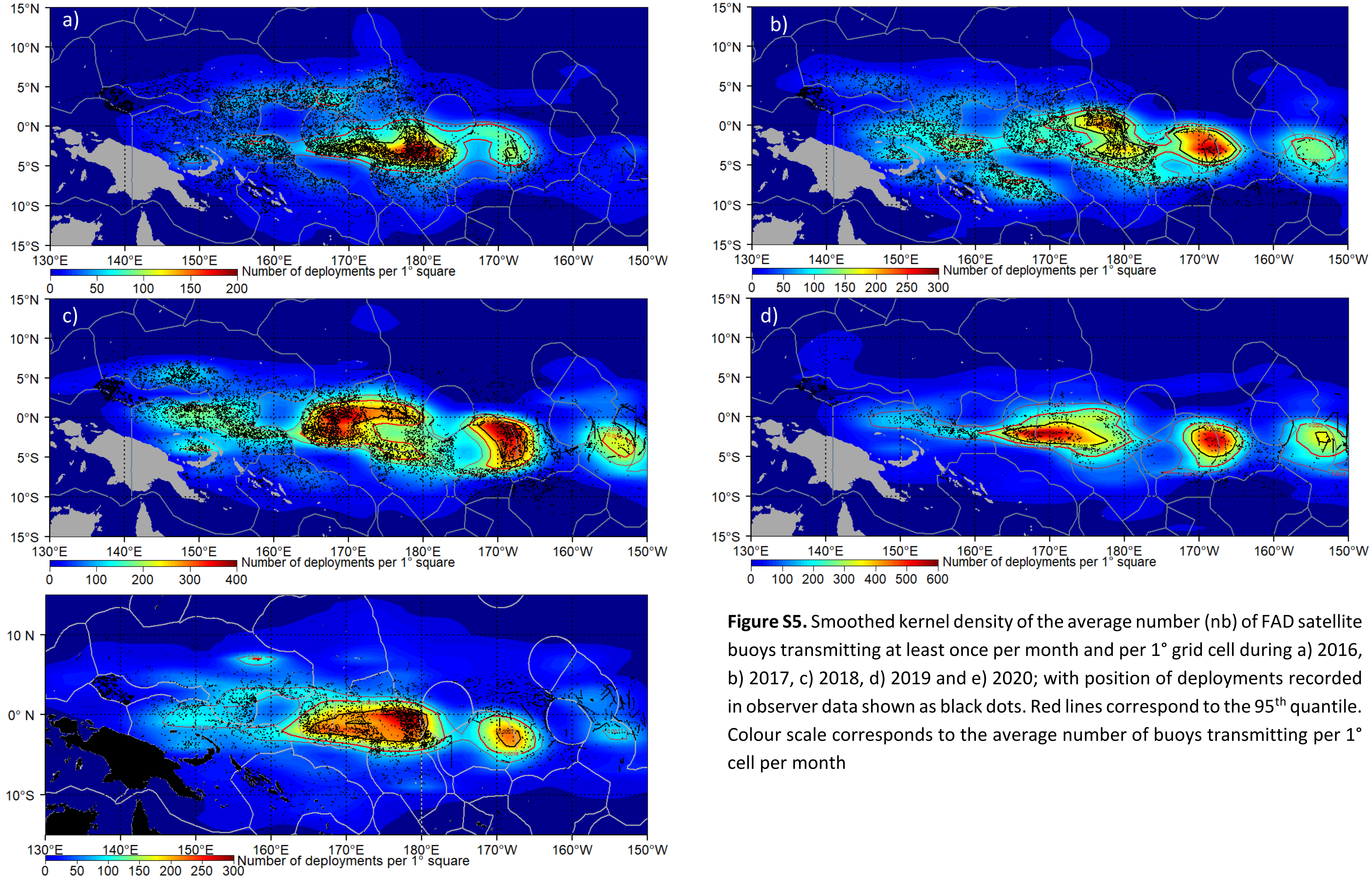

Figure S5. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, d) 2019 and e) 2020; with position of deployments recorded in observer data shown as black dots. Red lines correspond to the 95th quantile. Colour scale corresponds to the average number of buoys transmitting per 1° cell per month

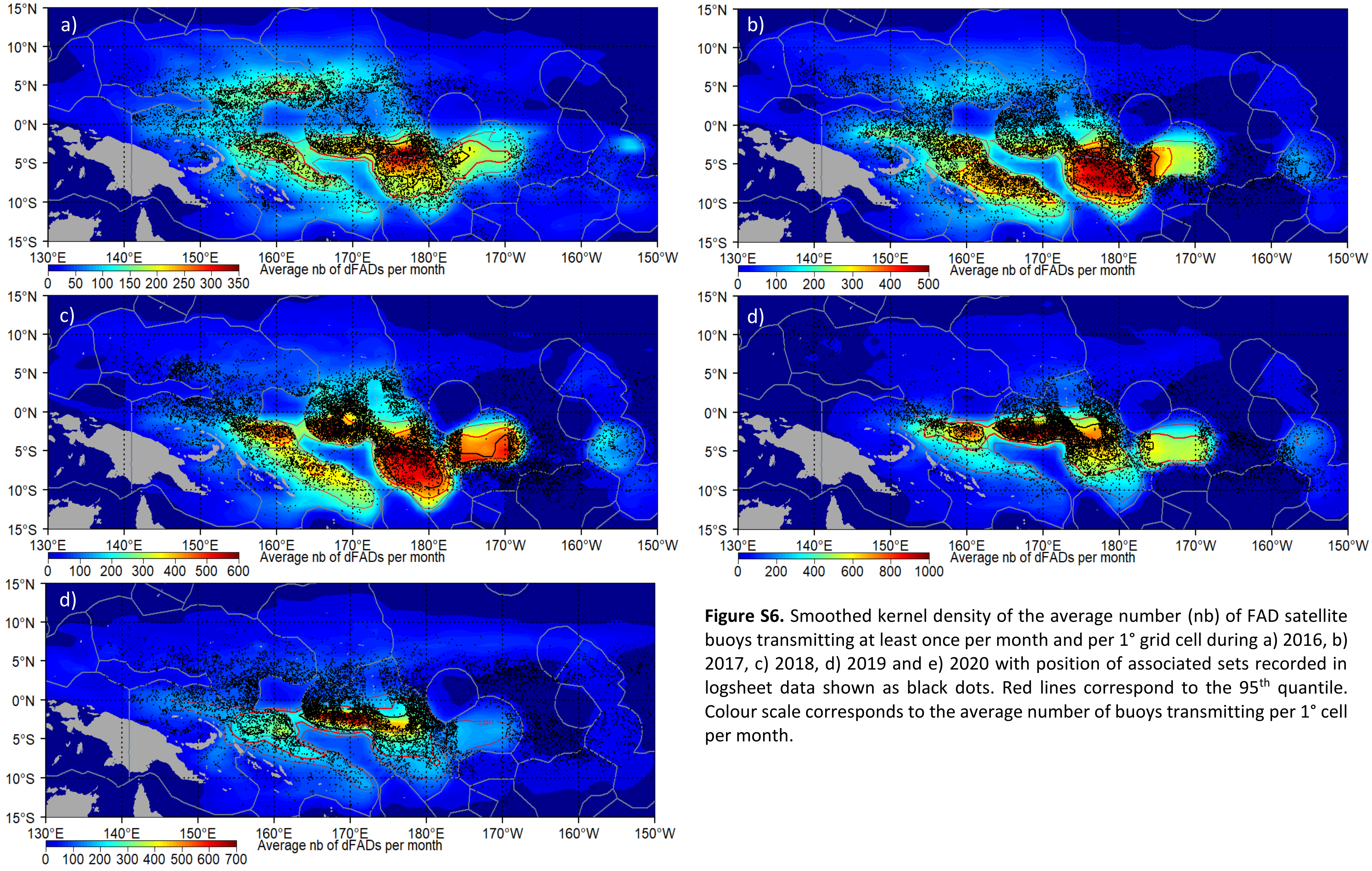

Figure S6. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, d) 2019 and e) 2020 with position of associated sets recorded in logsheet data shown as black dots. Red lines correspond to the 95th quantile. Colour scale corresponds to the average number of buoys transmitting per 1° cell per month.

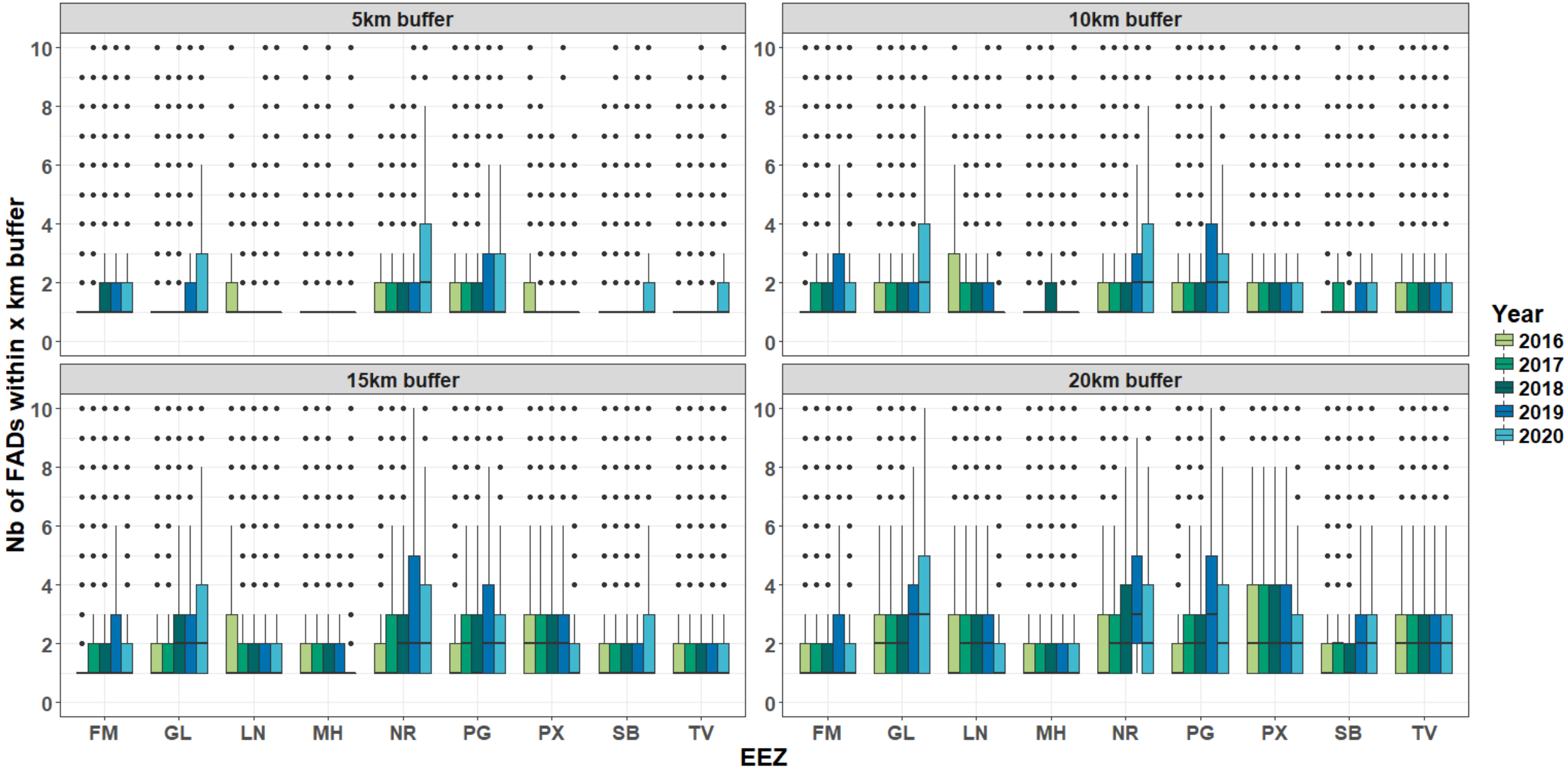

Figure S7. Number of FADs within a 5, 10, 15 and 20 km buffer around each specific FAD per day (if more than one is present), per EEZ and year.

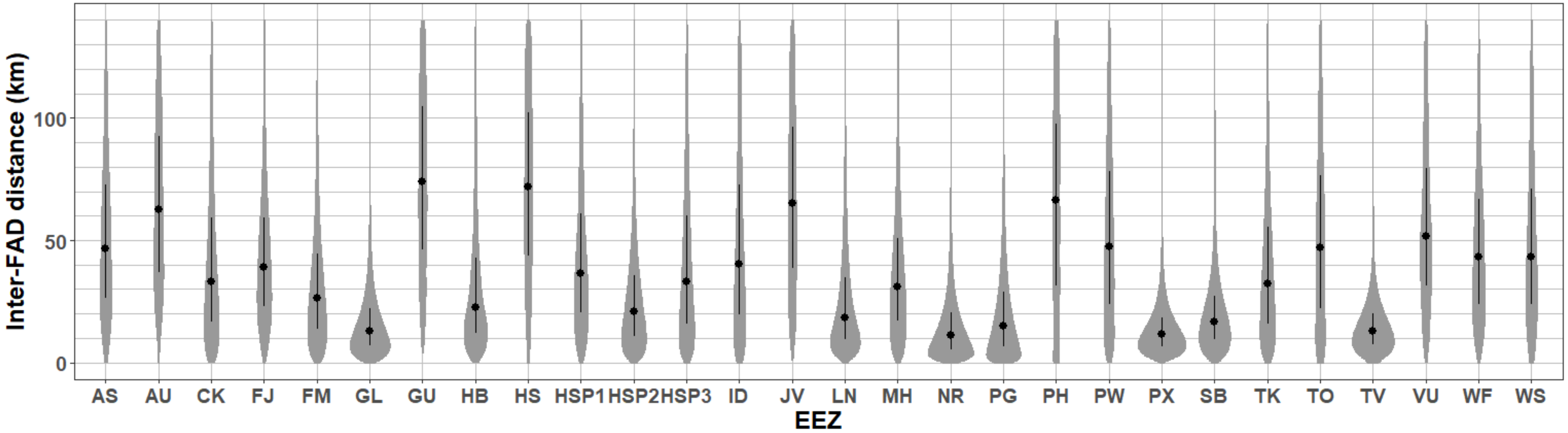

Figure S8. Violin plot of the minimum distance between each individual FADs drifting in the WCPO per day, by EEZ for the 2016-2019 period (horizontal black line = average; black dot = median; vertical black line = 0.25 to 0.75 quantiles). Wake, Palmyra and Johnston Islands, Hawaii, Niue, French Polynesia, and the high sea pocket between the Cook Island and French Polynesia are not displayed, as they have less than 5000 unique FAD transmitting per day over the four years considered.

Appendix 4. Fate of FADs at their last recorded position in relation to owning fishing company's fishing grounds.

The distance between the last position of a buoy and either the edge of the core (0.99 quantile of number of purse seine sets per 1° cells) and extended (0.90 quantile) fishing grounds (all purse seine sets) of the company per year were calculated (Figure S9). Only companies with at least three purse seiners were considered. The distance of the buoy from the nearest port was also examined, to identify whether recovery from that location was feasible. Figure S9 shows the fishing grounds of some fishing companies during a given year, with an example buoy track from the related company. For this analysis we only considered fishing companies with at least 3 vessels and more extensive fishing grounds (fishing in more than 15 x 1° squares in a given year), and only included buoys with a terminal position before 2020. This resulted in a subset of 47,418 buoys (66.7% of the 71,054 buoys available in the dataset).

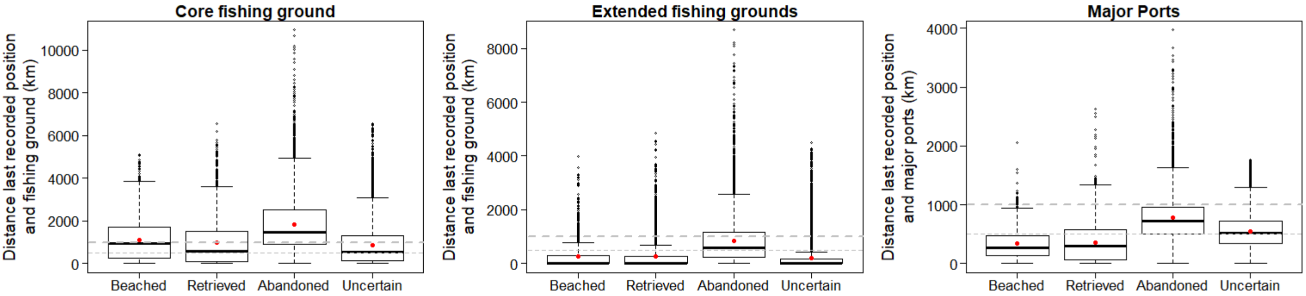

Figure S9. Distance between the last recorded position and; a) the core fishing ground of the company owning the buoys; b) the extended fishing grounds; and c) the closest major port, depending on the classification of buoy fates described above as: beached, recovered, abandoned or uncertain. Dotted grey lines indicate 500 and 1000 km.

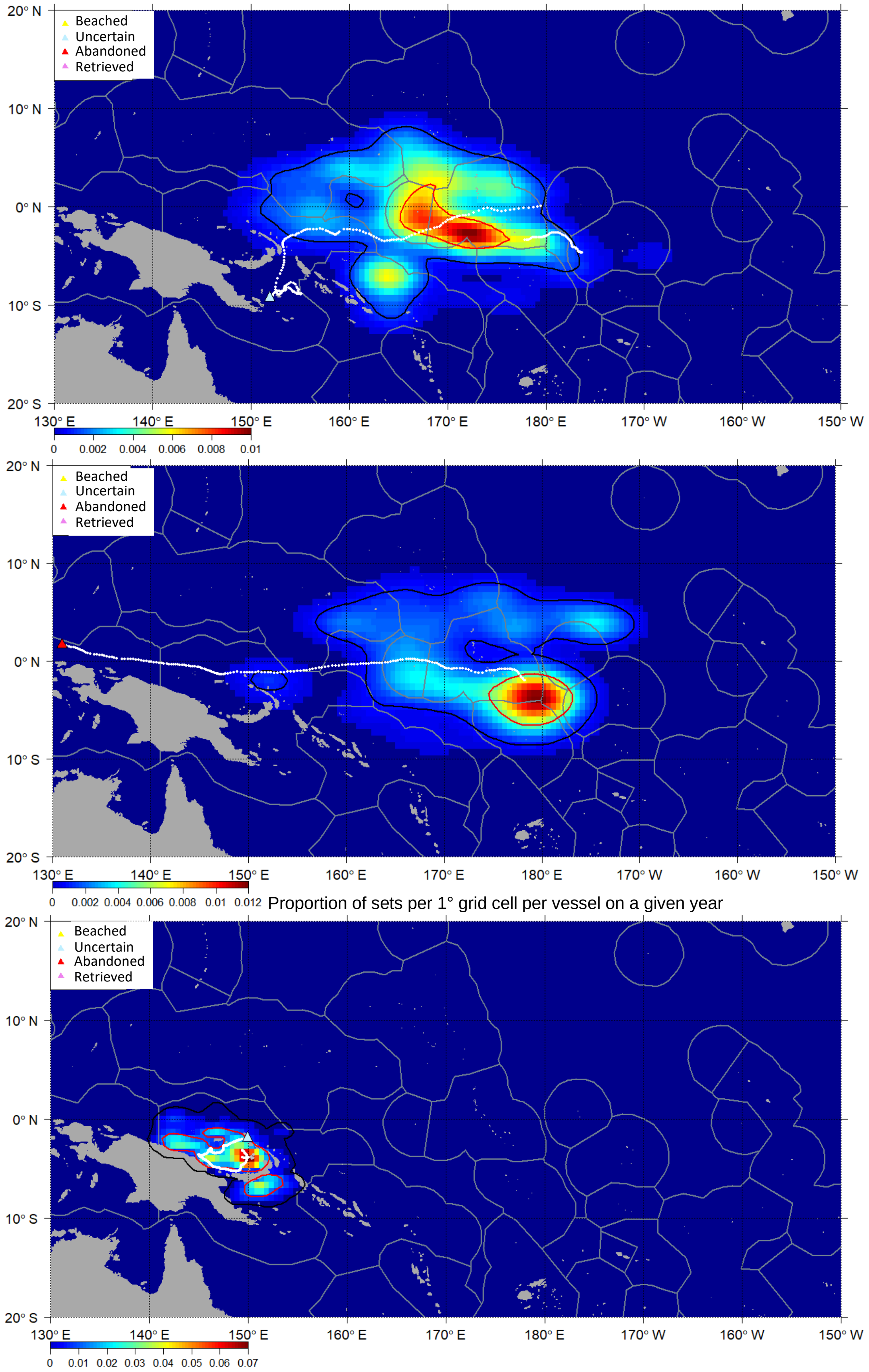

Figure S10. Examples of density map of purse seine fishing sets for three different fishing companies in a given year, with the track of a FAD from that company depicted in white. Black and red lines correspond to the extended (0.99 quantile) and core (0.90 quantile) fishing grounds.