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Report on analyses of the 2016/2020 PNA FAD tracking programme

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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; 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 individual FADs, therefore for the purposes of this analysis we followed the satellite buoys, 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 are modified by fishing companies prior to submission, for example information outside PNA Exclusive Economic Zones (EEZs) may be removed (i.e., "geo-fenced"), which could introduce a bias to the analyses. After undertaking the correction procedure, the filtered dataset consisted of 29.3 million transmissions from 58,441 unique buoys and covered the period from 1st January 2016 to 21th April 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. Most of the buoys are Satlink (66%), followed by Zunibal (17%), Kato (12%) and Marine Instruments (5%). In addition, most buoys also have an echo-sounder, with an increase in echo-sounder buoy use through time, from 75% in 2016 to 99% in 2020 (with 8% being double-frequency echo-sounder). A similar increase in echo-sounder buoy use through time was also detected in the data recorded by observers. Finally, a variability in brand and echo-sounder buoy use was detected between fleets.

The number of deployments varied over time, with a total of 84,429 deployments from 2016–2020 (from 254 vessels including 227 buoy owner vessels and an additional 27 vessels where the fishing company was known, but the buoy ownership was not). The spatial distribution of deployments showed the main deployment areas to be in Kiribati south of the Gilberts Islands and Kiribati east of the Phoenix Islands, Nauru, and north of Tuvalu.

The number of transmissions from buoys almost doubled in 2017 (9.2 million compared to 4.9 in 2016), likely reflecting an increase in data provision rather than an increase in FADs. 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 beginning of 2020, the number of transmissions per day was however lower (10,000–15,000). The number of individual FAD buoys active increased almost constantly since 2016, with 14,815 buoys in 2016; 21,681 in 2017; 23,328 in 2018; and 21,080 in 2019.

The average drift time and straight-line drift distance per FAD were 4 months and 1,231 km, whereas the average active time (including on-board sections) was 7 months, and the average distance between first and last position was 1,813 km.

The raw spatial distribution of buoy densities was investigated, with higher densities observed in Kiribati south of the Gilbert Islands and around the Phoenix Islands; Tuvalu (particularly in 2017 and

2018); 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 issues related to geo-fencing. While the location and extent of FAD density hotspots remained relatively consistent over the four years studied, the number of buoys transmitting at least once per 1° cell and per year highly increased through time, with a maximum around 4,000 per year in 2016 to around 10,000 per year in 2019.

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).

Buoy positions at the end of their trajectories were investigated to study the fate of FADs, using a refined approach that considered that a FAD was abandoned when drifting outside the fishing ground of the company owning it (where the majority of that company's vessels were fishing). The distance between the last position of abandoned FADs and core fishing ground of the company owning the FAD was 895–2,512 km, with an average of 1,824 km. Abandoned FADs were also found at a distance of 502–952 km from port, with an average of 780 km. Using this classification, 42.1% of FADs were classified as lost, 9.4% were retrieved; 7.4% were beached; 20.0% were sunk, stolen or had a malfunctioning buoy; and 21.1% were deactivated by the fishing company and left drifting, unmonitored at sea. In addition, the number of FADs with a final position classified as “drifting” increased over the four years studied (from 35% in 2016 to 46% in 2019), the ones beached fluctuated between 6–9% per year and the number of recovered or lost FADs decreased. This may be due to the more rapid deactivation of buoys by fishing companies, potentially linked to the implementation of a limit in the number of active buoys per vessel at any given time of 350 in 2018.

We invite WCPFC-SC16 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 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 42.1% of buoys were estimated to be abandoned and 7.4% beached; as well as the increase in number of buoys with uncertain fate.

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 arrival of new technological developments to track FAD locations such as satellite and echo-sounder buoys (Escalle et al., 2019b; 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 study this year that estimated that 30,000–40,000 FADs are deployed/redeployed annually in the WCPO between 2011 and 2019 (Escalle et al., 2020). 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 month 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) .

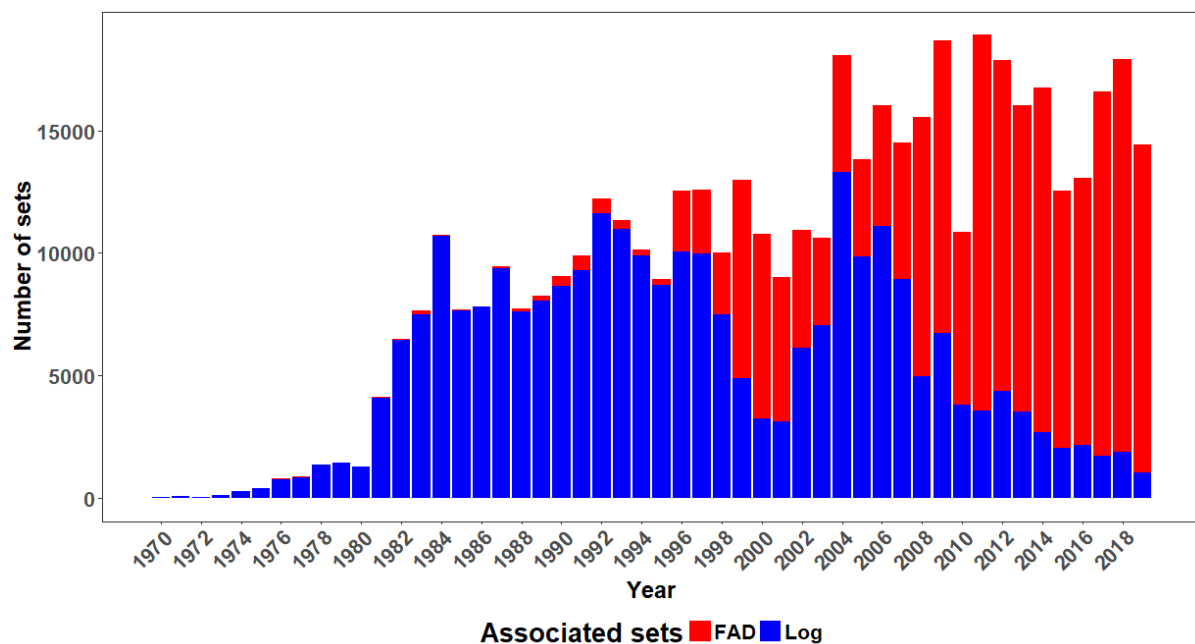


Figure 1. Number of associated sets performed specifically on deployed FADs and natural logs, as recorded in the aggregated logsheet data (“S-BEST” database: most complete dataset corrected for species composition, aggregated by 1° cell and month) in the Western and Central Pacific Ocean between 1979 and 2019. Similar trends were detected in the observer data but due to low coverage prior to 2010, these data are not shown.

This paper presents 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, 2019a). 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 analyses of i) spatio-temporal distributions of FAD buoy deployments; ii) the temporal distribution of drifting FADs in the WCPO; iii) FAD densities; and iv) the fate of FADs at their last buoy's transmission, including a focus on FAD beaching. In general it should be noted that for the five years considered here (2016–2020), we had access to a larger and more complete dataset than in previous SC reports (Escalle et al., 2017, 2018b, 2019a; see Section 2.1 for details), although the inherent bias of having lower transmission rates outside PNA members EEZ ('geo-fencing') still remains.

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.

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 moved between multiple FADs.

2. General description of the data

2.1 Data processing

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 21st April 2020 (data uploaded on 24th of April 2020). The raw dataset included more than 32.3 million transmissions from 61,676 satellite buoys. Each transmission included location, time, the 'owner' of each FAD buoy (a fishing company or directly a vessel name, or 'none' for 94 buoys), water temperature, course direction, and drifting speed. In total, 260 vessels were found to be linked to FAD information in the FAD tracking data, which comprised 227 identified FAD owner vessels and 27 additional vessels belonging to an identified fishing company. Data originated from four different satellite buoy companies: Satlink; Zunibal, Marine Instrument and Kato. The amount and quality of the FAD tracking data has increased for this study, including both an additional year and enhancement of data received previously and used in earlier reports (Escalle et al., 2017, 2018b, 2019a). Between 2016 and 2018, there was an increase in data transmission of 6 to 13% per year. Additional data regarding use of Marine Instrument satellite buoys since 2018 has recently been received as well, but not included in this report.

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, 2019a for details). The filtered dataset included 29,303,748 transmissions from 58,441 satellite buoys for analysis (Table 1), comprising annual estimates of active buoys of 14,815 in 2016; 21,681 in 2017; 23,328 in 2018; 21,080 in 2019; and 9,603 in the four months of 2020 (Table 2). 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 93% of the buoys (54,080) had records of the owner's vessel name. This corresponds to a total of 227 vessels in the dataset, including 213 purse seiners and 14 support vessels. For the rest of the buoys, only the fishing company was known (4267 buoys, i.e. 7%) or neither were known (94 buoys, i.e. 0.1%).

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

Year	Number of transmissions	Number of FADs	Number of (re)deployments
2016	4,934,359	14,815	18,229
2017	9,200,069	21,681	21,566
2018	7,878,562	23,328	21,904
2019	5,906,829	21,080	18,838
2020 (4 months)	1,383,929	9,603	3,892
Total	29,303,748	58,441	84,419

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 Data summary 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 comprise 46 to 74% of the buoys in the dataset (Figure 2). The other buoy brands are Zunibal (around 17% of all buoys), Kato (12%) and Marine Instruments (5%), the latter being only found in the dataset prior to 2019 (Figure 2). While the number of Zunibal and Kato buoys remain relatively constant through time, the number of Satlink buoys has increased from 6,800 in 2016 to ~15,500 in 2018 and 2019 (Figure 2).

Variability in the satellite buoy brand used was also detected by fleet (Figure 2). While some fleets preferred to use only the Satlink brand (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).

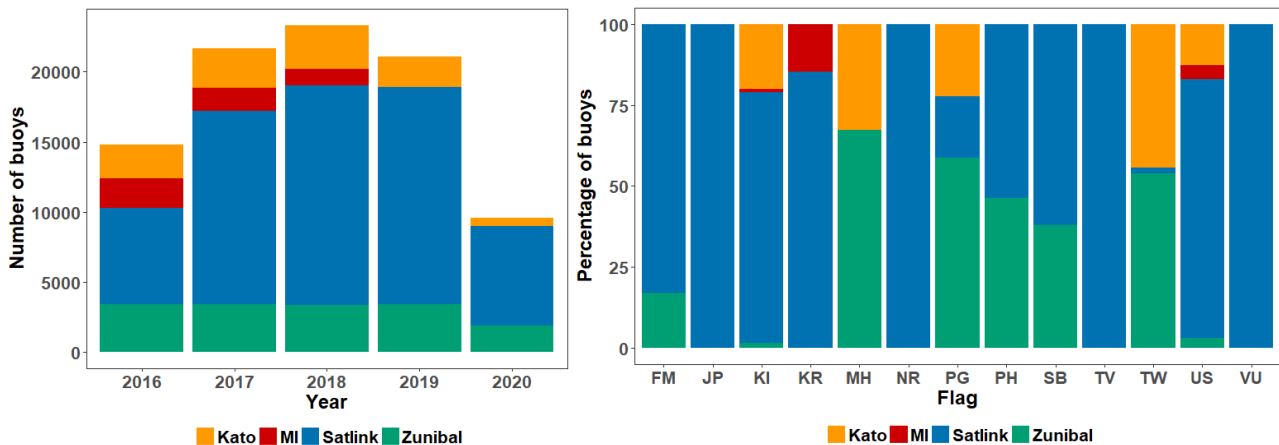


Figure 2. Number or percentage of satellite buoys (Kato, Marine Instrument MI, Satlink and Zunibal) used in the WCPO, per brand company and year (left) or flag (right). Note that for the graph per flag, the number of buoys per flag in our dataset highly varies, with some flags having no buoys in the 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, the 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) have started to be used, with up to 8% 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).

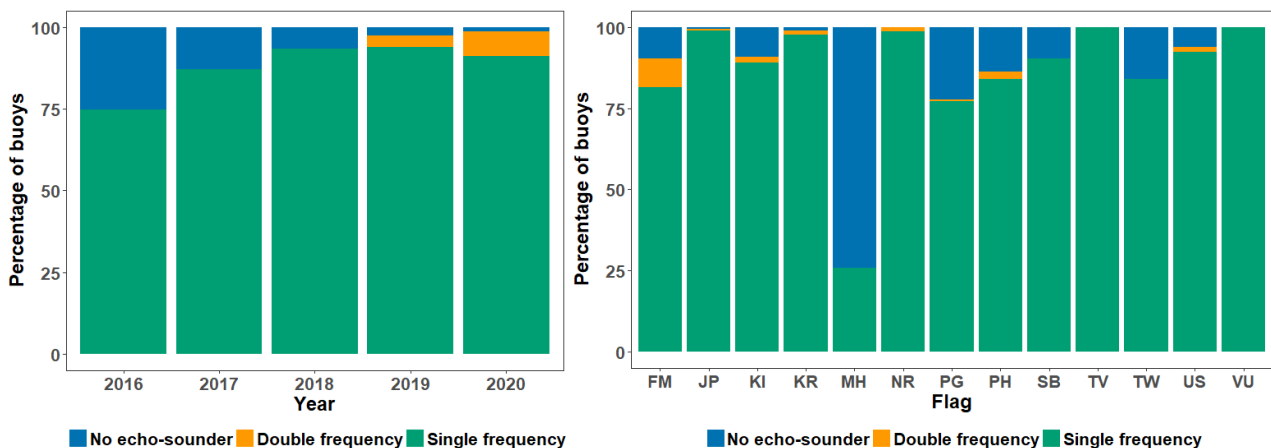


Figure 3. Percentage of satellite buoys used in the WCPO without an echo-sounder, with a single frequency echo-sounder or with a double frequency echo-sounder (when known) per year (left) or flag (right). Note that for the graph per flag, the number of buoys per flag in our dataset highly varies depending 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 or precisely recorded by observers. When the buoy ID number is accurately recorded (13% of records of any FAD related activity), it was deduced that over 75% of the satellite buoys used in the WCPO had an echo-sounder in 2016 and 2017 and over 90% in 2018 and 2019 (Figures 4 and 5). While improving, a more systematic and precise record of the buoy ID number should be recorded, when possible, by observers. This is especially important in view of effort creep¹ (Vidal et al., 2020) and the importance 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.

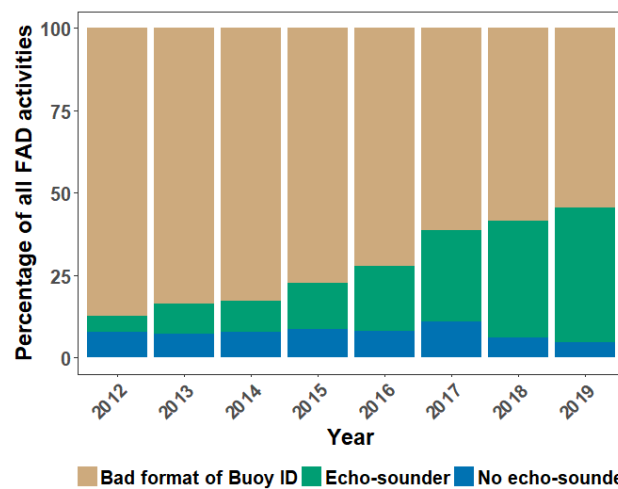


Figure 4. Percentage of satellite buoys with or without an echo-sounder (derived from the format of the buoy ID number, when available) per year, as recorded by observers for any activity performed on FADs (deployment, visit, set, retrieval).

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.

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.

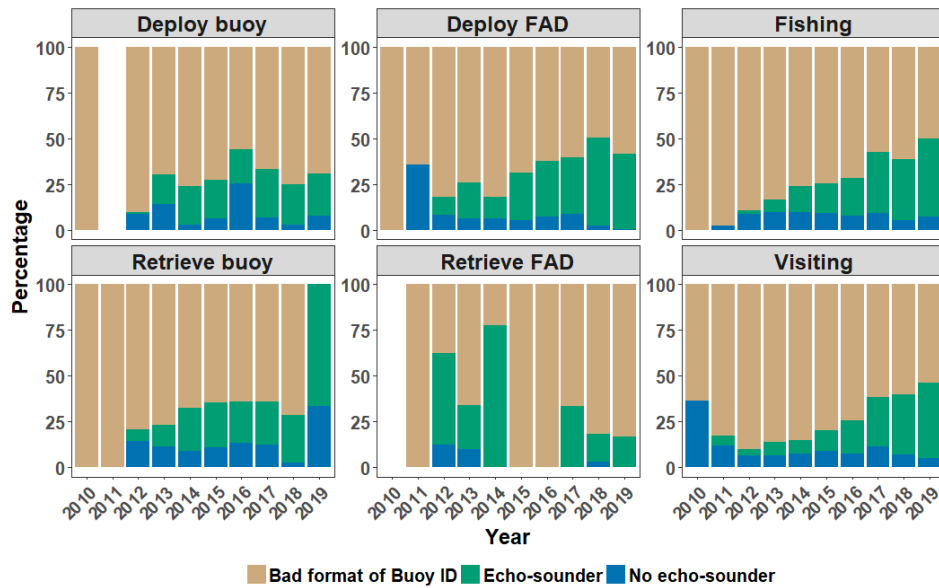


Figure 5. Percentage of satellite buoys with or without an echo-sounder (derived from the format of the buoy ID number, when available) per year and per FAD activity, as recorded by observers.

3. Deployments

The number of estimated buoy deployments varied over time (59 to 1,886 per week; Figure 6), with a total of 84,419 estimated over the study period. This corresponds to 18,229; 21,566; 21,904; 18,838 and 3,892 deployments estimated for 2016, 2017, 2018, 2019 and 2020 respectively (Table 2).

Different patterns of deployments through time are detected in the new more complete database compared to those described in previous papers (Escalle et al. (2019)). Generally, besides several short-term peaks in 2016 and the general 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).

It should also be noted that a bias in the deployment position 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 seas zone).

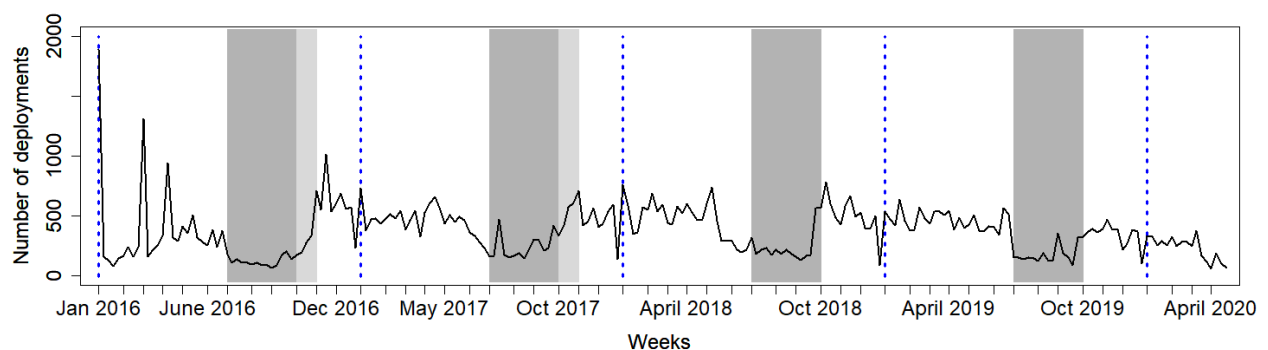


Figure 6. Estimated number of deployments by week. Grey areas correspond to the FAD-closure periods (1st of July through 30th of October or November).

For the buoys with identified-owner vessel (227), the number of deployments per vessel was investigated (Figure 7). The total number of buoy deployments with identifiable vessels in 2016–2019, was 74,934 deployments (i.e. 89% of deployments). Annual deployments increased over the first three years of the programme with 15,448 in 2016; 19,807 in 2017; 21,039 in 2018 and then decreased slightly to 18,640 in 2019 (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 and 0 to 347 in 2019. 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).

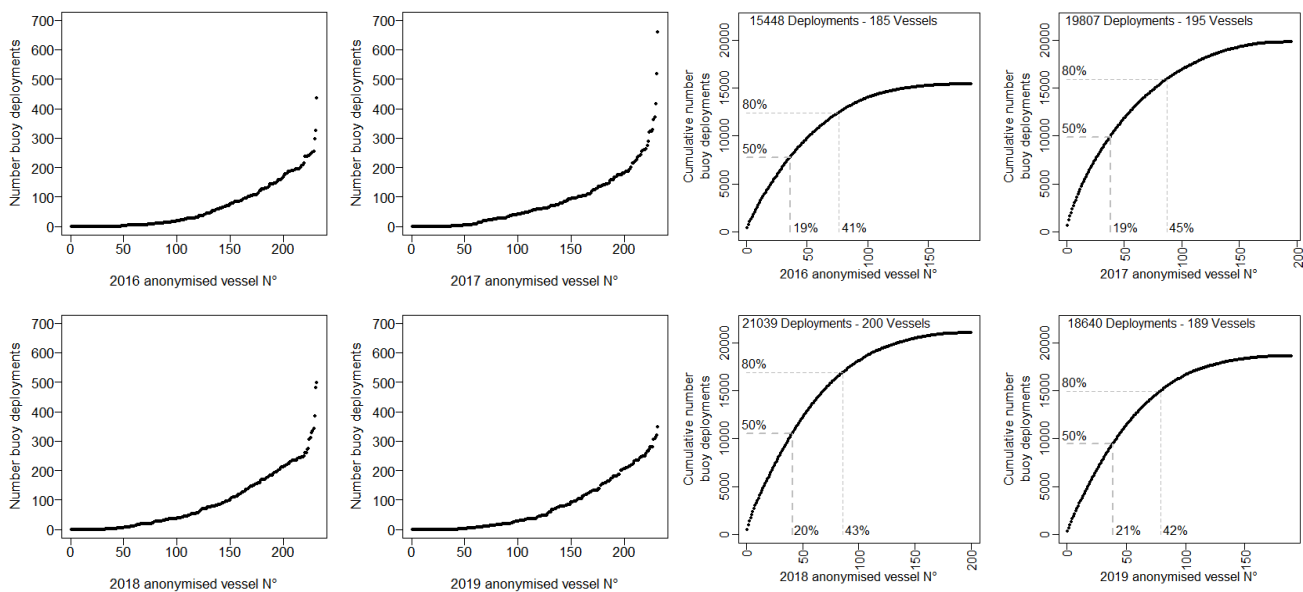


Figure 7. Estimated number (left panel) and cumulative number (right panel) of FAD buoy deployments for known vessels in the tracking data per year, 2016–2019. Given that the data for 2020 are incomplete, this year was not shown here.

Over the four complete years of data (2016–2019), a large proportion of the deployments occurred in Kiribati south of the Gilbert Islands, north of Tuvalu and in the Nauru EEZs (Figure 8 and Figure S5). Starting in 2017, two additional deployment hotspots were identified in Kiribati, one east of the Phoenix Islands and another 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 (smoothed kernel density using ade4 library in R, Venables and Ripley, 2002) used tends to extend the hotspots artificially, linking the PIPA with areas of high deployment. Note that perceived deployments in the eastern high seas are also in part an artefact of the kriging method extending the hotspots artificially, 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 EEZs or at the eastern boundary of the Marshall and Gilbert Islands EEZs.

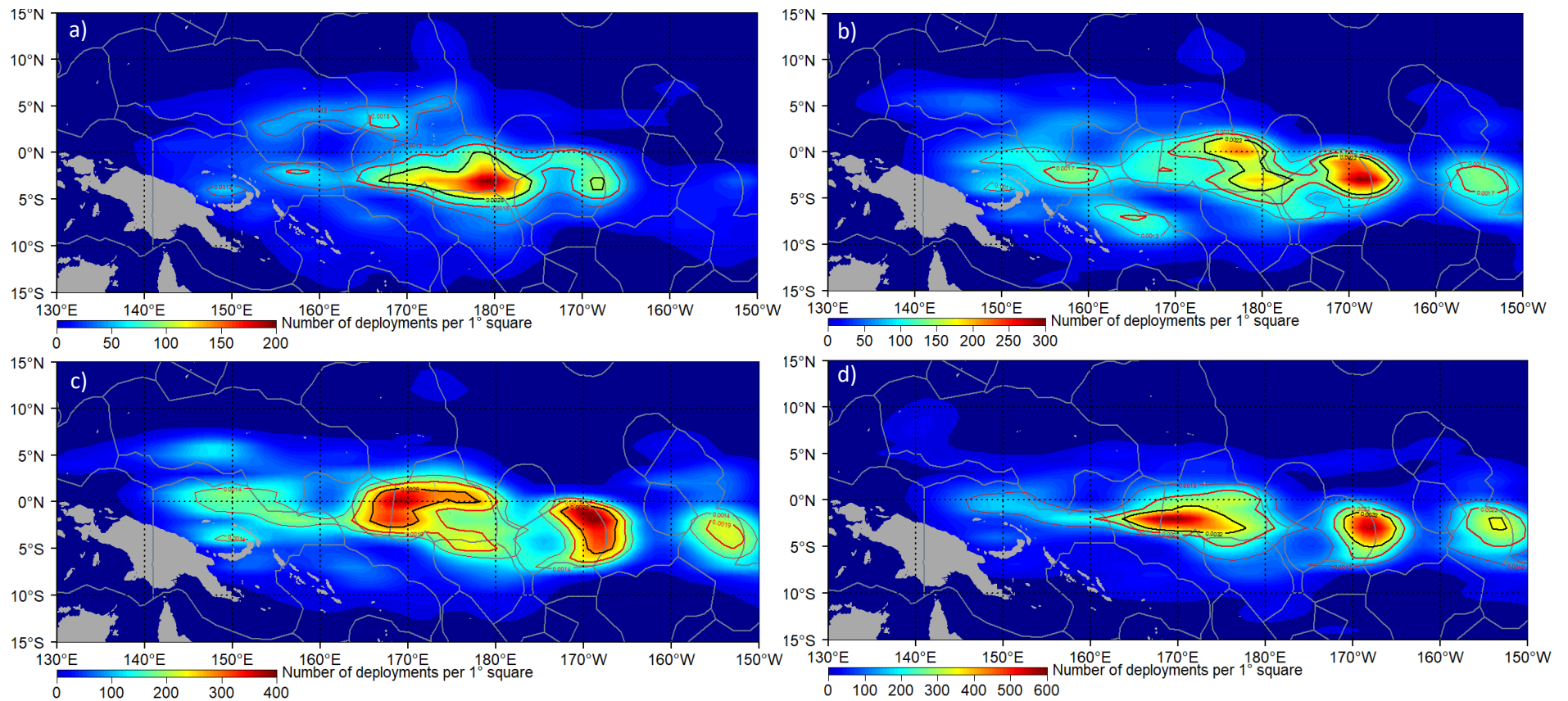


Figure 8. Smoothed kernel density of buoy deployments per 1° grid cell during a) 2016, b) 2017, c) 2018, and d) 2019. Red and black lines correspond to the 95th and 98th quantiles. Colour scale corresponds to the proportion of buoy deployment per 1° cell. Note that the scales are different on each plot.

4. Temporal distribution of drifting FADs

4.1 Temporal variability in transmissions

There was a general increase in data quantity and quality received recently due to a change in data transfer method. It should nevertheless 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 for unknown reasons (Figure 9). The filtered dataset of 29,315,492 transmissions was comprised of 20% on-board positions and 80% 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 the beginning of 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, with 14,815 buoys in 2016; 21,681 in 2017; 23,328 in 2018; and 21,080 in 2019 (Table 2). The decrease in transmissions despite the increased deployments implies that the patterns of transmission rate have changed since 2019 (Figure 9).

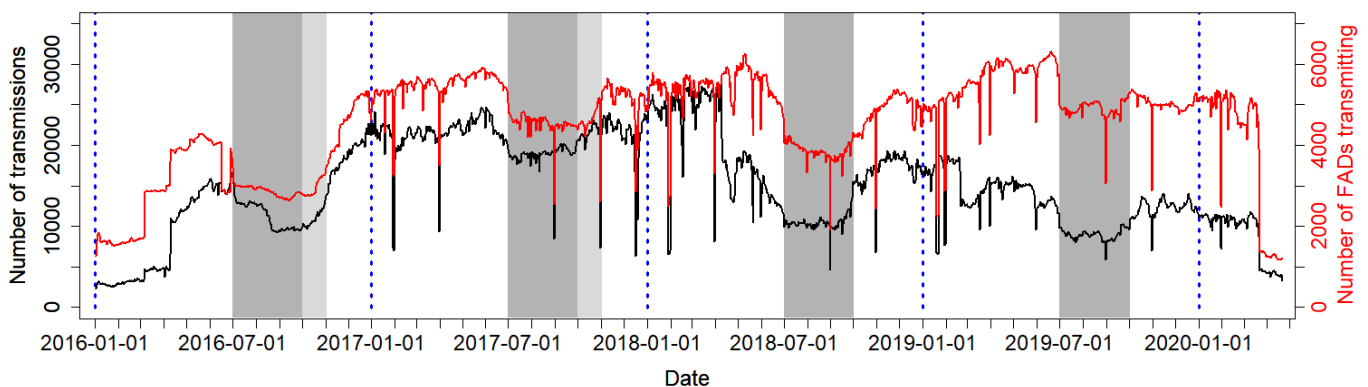


Figure 9. Number of transmissions (black line) and unique buoys transmitting (red line) daily from at-sea buoy positions only. Grey areas correspond to the FAD-closure periods (1st of July through 30th of September or October), and the blue lines denote January 1st. Note that the decrease after March 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 over time 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 (Figure 10). The average drift time is around four months (116 days) with an average linear drift distance of 1,231 km, whereas the average active time (including on-board sections) was seven months (205 days) with an average straight-line distance between first and last position of 1,813 km (Figure 10).

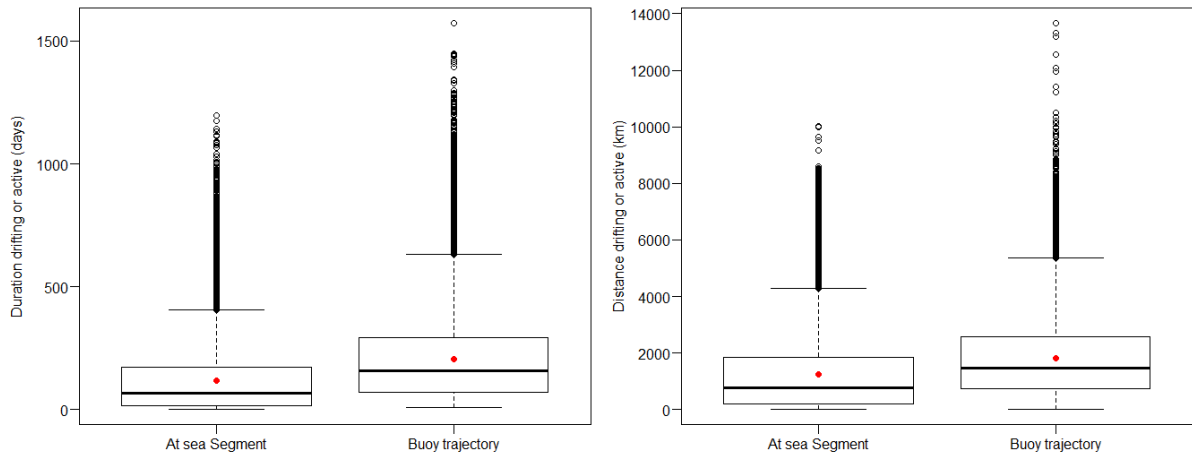


Figure 10. Duration (left) and distance (right) of drifting per FAD buoy trajectory (whole buoy trajectory, including on-board segments) or at-sea segments (on-board segments removed).

Regarding the number of buoys monitored per vessel, for buoys with identified vessel owner (93%), one to 350 active buoys were monitored per month and one to 200 active buoys per day (Figure 11). However, the majority of vessels had less than 100 active buoys per month and less than 50 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 (see Escalle et al., 2020b) for raised number of active buoys monitored per vessel). In addition, these patterns represent the activity of a total of 213 purse seine vessels (174 vessels in 2016, 185 in 2017, 186 in 2018 and 178 in 2019), whereas an average of 280 active purse seiners per year were in the WCPO logsheet data for 2016–2019.

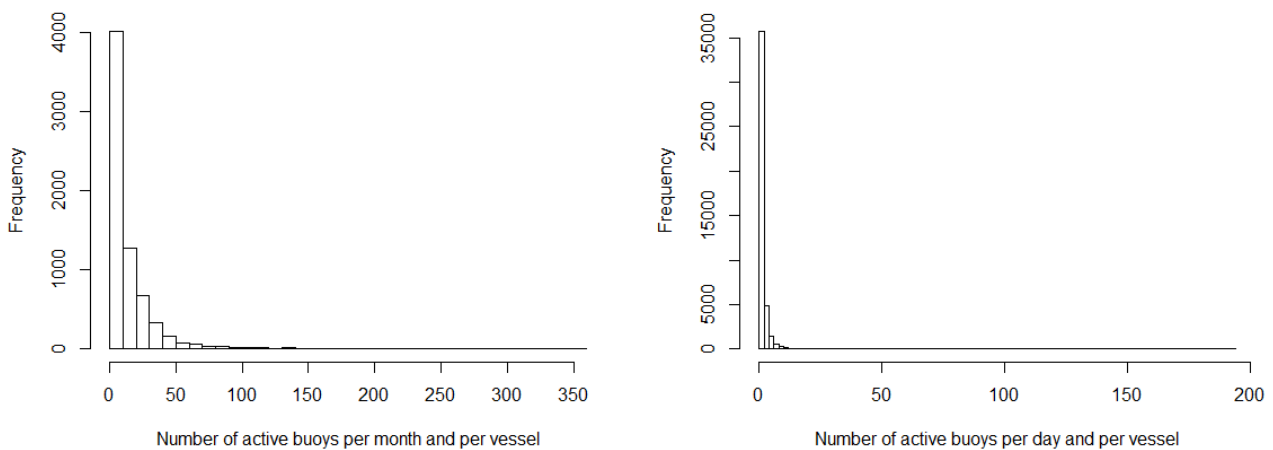


Figure 11. Histograms of the number of active buoys per month (left) or per day (right), per vessel (when vessel name was available) from 2016–2019, as recorded in the PNA FAD tracking data (see Section 4.1 for estimated data submission rates).

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 in Kiribati south of the Gilbert Islands and around the Phoenix Islands; Tuvalu (particularly in 2017 and 2018); eastern area of Papua New Guinea and off the Solomon Islands (Figure 13 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 13).

While the location and extent of FAD density hotspots remained relatively consistent over the four years, the number of buoys transmitting at least once per 1° cell per year increased through time, from a maximum of around 4,000 per year (average of 350 per month) in 2016 to around 10,000 per year (average of 900 per month) in 2019 (Figure 12 and 13). 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, with the main distribution ranging from 2,500 to 6,000 FADs per year per cell (Figure 12).

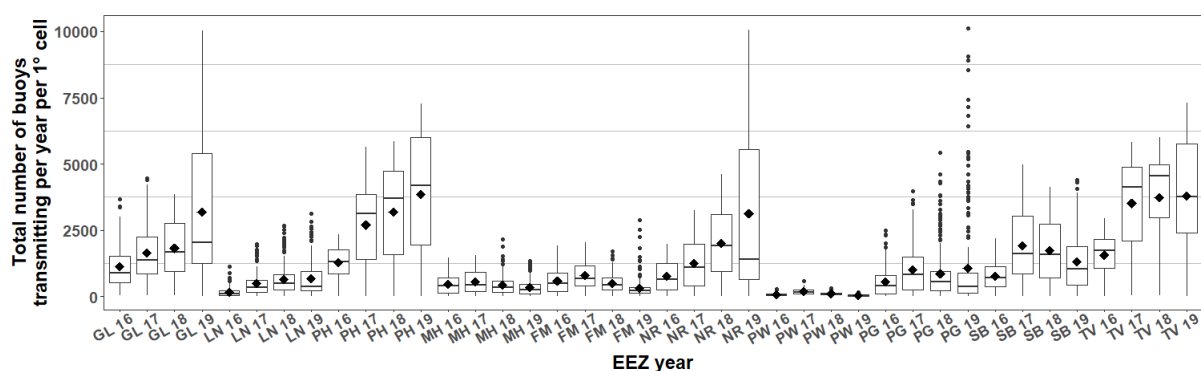


Figure 12. Number of buoys transmitting at least once per 1° cell per year, classified by PNA EEZ and year (most transmissions occur within PNA EEZs due to issues related to geo-fencing). GL = Gilbert Islands (Kiribati); LN = Line Islands (Kiribati); PH = Phoenix Islands (Kiribati); MH = Marshall Islands; FM = Federated States of Micronesia; NR = Nauru; PW = Palau; PG = Papua New Guinea; SB = Solomon Islands; TV = Tuvalu.

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 transmissions per day per cell in 2019 ranging from 3–14; 4–18; 2–14; and 5–16, respectively (Figure 14).

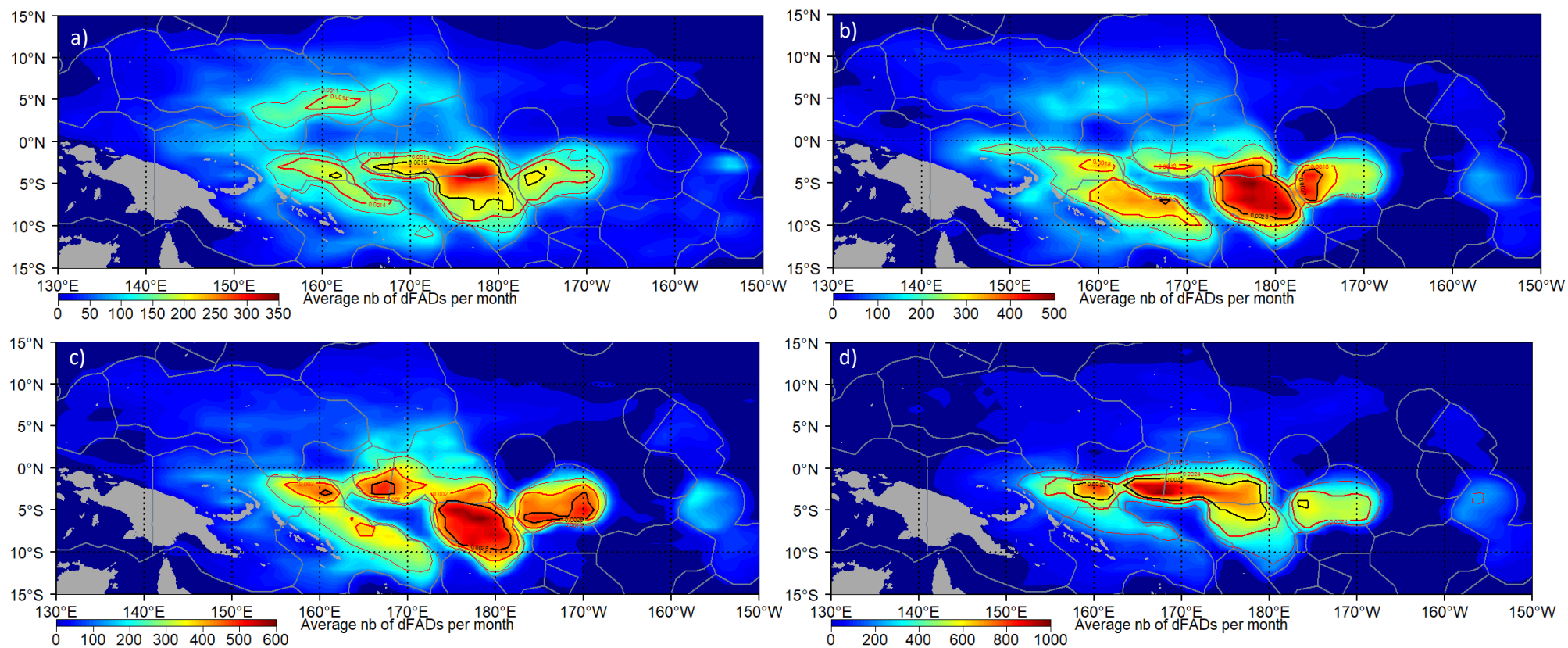


Figure 13. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, and d) 2019. Red lines correspond to the 95th quantile. Colour scale corresponds to the average number of buoys transmitting per 1° cell per month. Note that the scales are different on each plot.

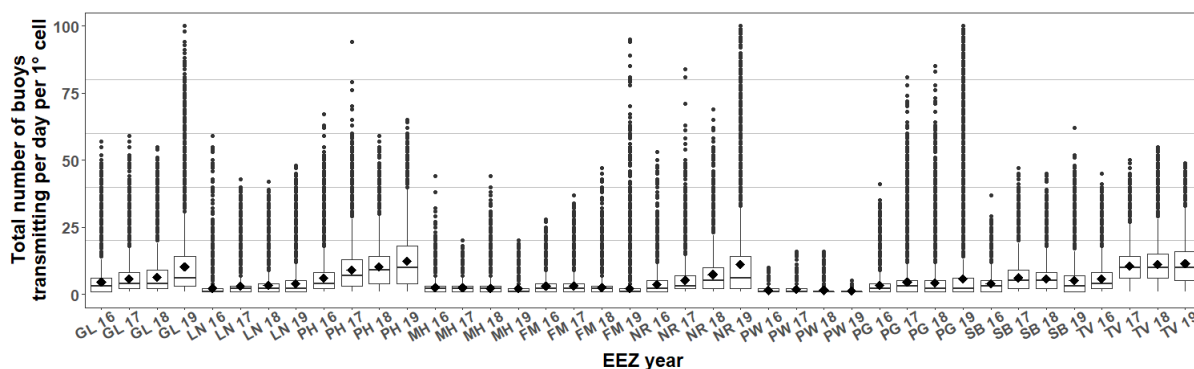


Figure 14. Number of buoys transmitting at least once per 1° cell per day, classified by PNA EEZ and year (as most transmissions occur within PNA EEZ due to issues related to geo-fencing). PNA EEZs: GL = Gilbert Islands (Kiribati); LN = Line Islands (Kiribati); PH = Phoenix Islands (Kiribati); MH = Marshall 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.

5.4. 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 EEZ and year (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, PNG and Kiribati Gilbert Island, (Figure 15), where the median inter-FAD distances were 8.4, 9.6, and 10.7 km, respectively in 2019. 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.

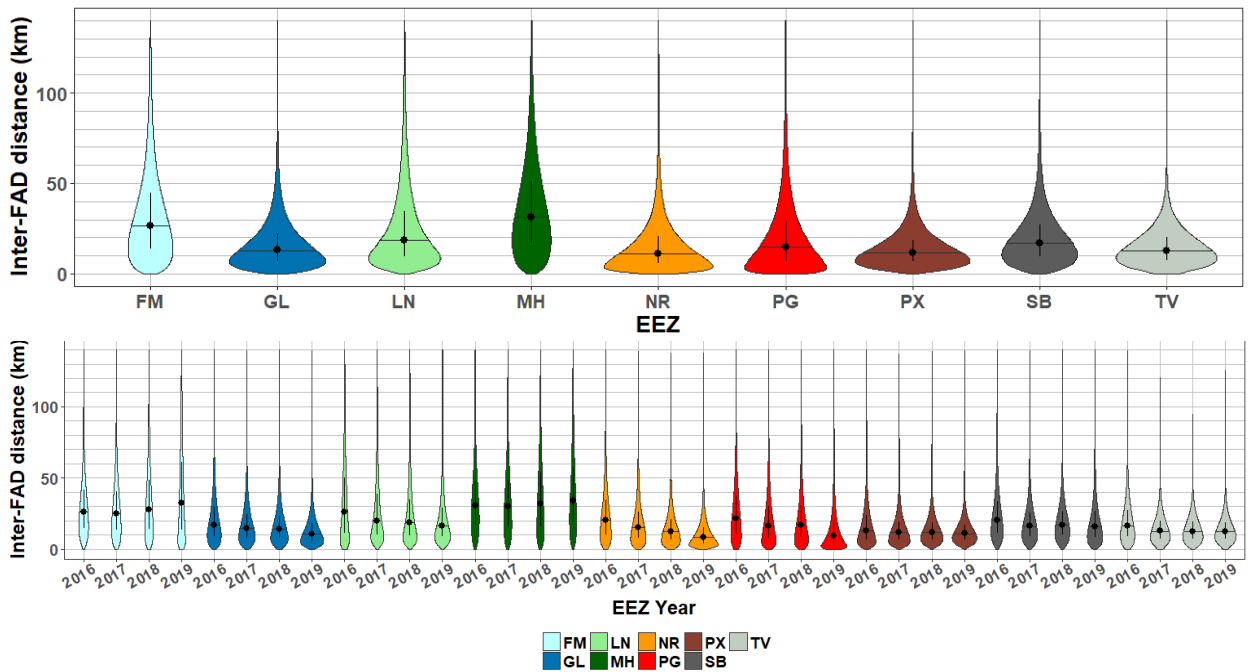


Figure 15. Violin plot of the distances between each individual FAD and its nearest neighbour drifting in the WCPO per day, by EEZ for the 2016-2019 period (top) and per EEZ and year (bottom) (black dot = median; vertical black line = 0.25 to 0.75 quantiles). Only EEZs with total number of FAD transmitting/day 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).

The variability in inter-FAD distance among EEZs is displayed yearly through maps (Figure 20). 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 20).

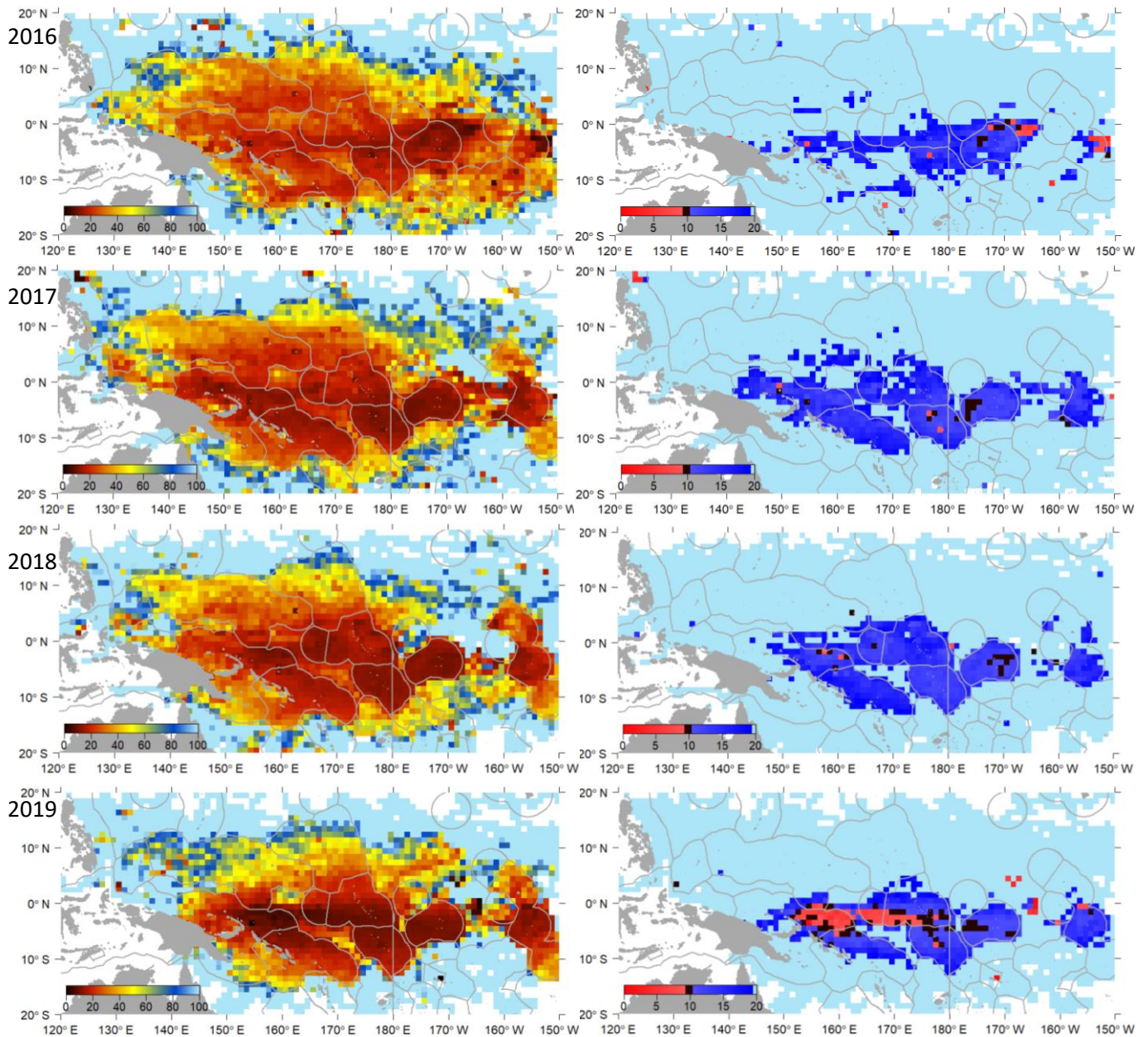


Figure 20. Spatial distribution of inter-FAD distances. The scales correspond to the median distance (km) between each individual FADs and the nearest neighbour FAD per day and 1° cell. The right-hand maps highlight the cells with a median inter-FAD distance below 20 km.

6. Fate of FADs

Buoy positions at the end of their trajectories were investigated to study the fate of FADs (Figure 21). 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.

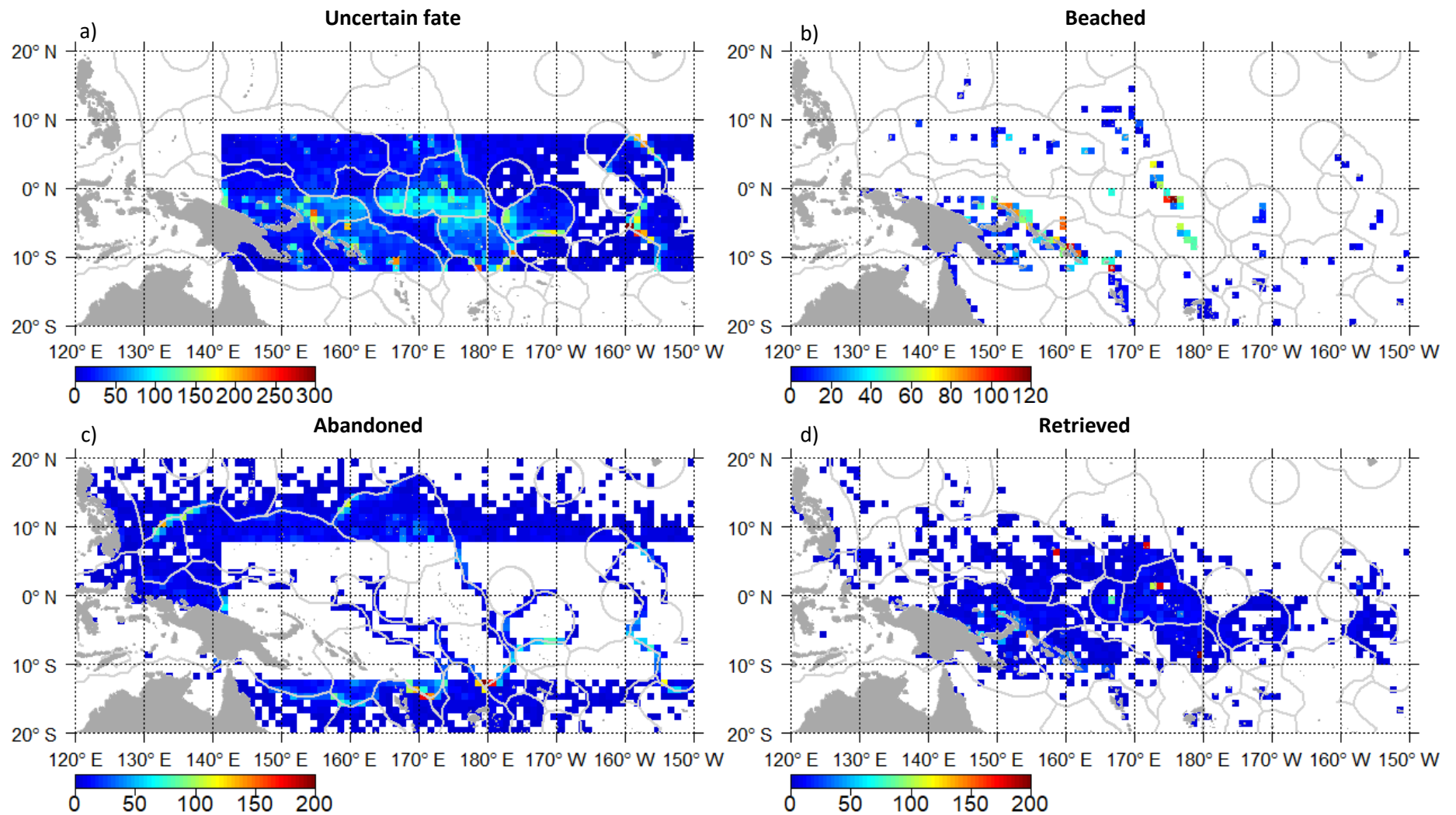


Figure 21. Density maps of last recorded position of each buoy in the FAD tracking data: a) uncertain; b) beached; c) abandoned; and d) retrieved in 2016–2020 period. Note the different scales.

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 (January–April 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 22). 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 currently be complicated and expensive. 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).

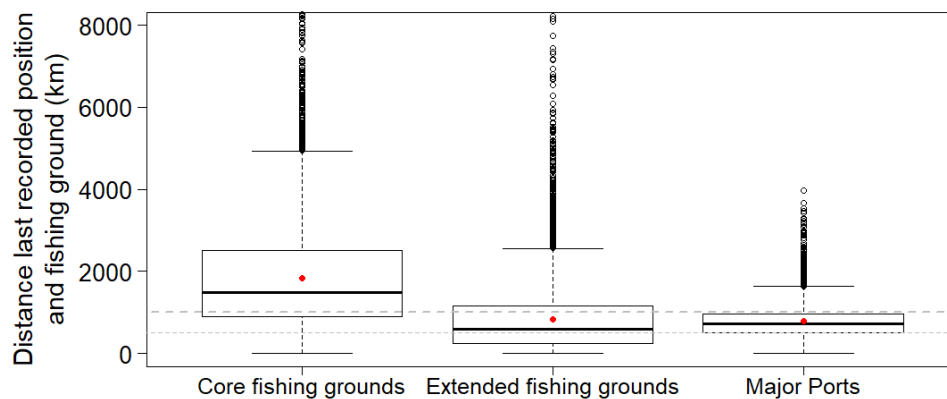


Figure 22. Distance between the last recorded position of abandoned FADs and the core or extended fishing grounds of the company owning the buoys and the closest major port. Dotted grey lines indicate 500 and 1000 km.

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 23). Under this classification approach, the majority of buoys were classified as abandoned (42.1%), with 22.4% being abandoned within the fishing grounds of all purse seiners, and the remaining 19.7% outside the main fishing grounds. The number of buoys classified as uncertain at the end of their trajectory decreased to 41.1%, half being buoys deactivated at a specific time (end of the year or during the closure, two periods when buoys are deactivated in high numbers) 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 21c), 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% 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 21 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, 7.4% of the buoys were beached, with most (5.4%) not moving at all at the end of their trajectories (Figure 21 and 23).

In general, 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 23) 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 should be taken into account when assessing FAD densities, and when reviewing the impact of FAD density on CPUE.

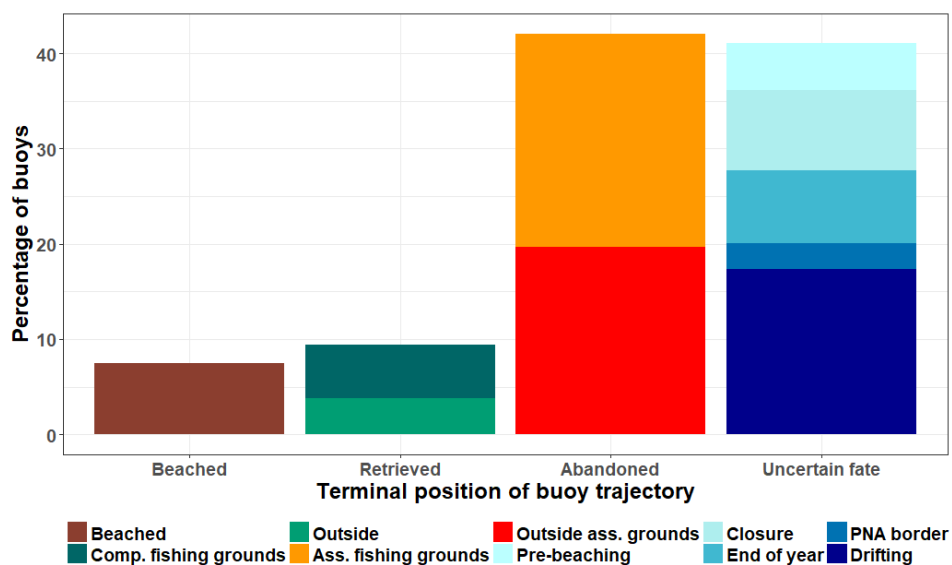


Figure 23. Percentage of buoys’ terminal position classified as beached; retrieved (within or outside the fishing grounds of the company owning the FAD) by any vessel; abandoned (within or outside the general purse seine associated fishing grounds, i.e. see Figure 22): or uncertain from 2016–2020. These results are based on buoys from companies with at least three purse seiners and with the last transmission in the dataset before 2020 (37,210 buoys).

Using this refined approach to classify the fate of a buoy, we estimated that 42.1% of buoys were abandoned; 9.4% were retrieved; 7.4% were beached; 21.1% were deactivated by the fishing company and left drifting unmonitored at sea (uncertain fate classified as “Closure”, “End of Year” and “Pre beaching”); and 20.0% 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 16,147 buoys (43.4%) are unmonitored within PNA waters. In addition, distances between FADs and the ‘owning’ fleet are generally large, and may limit direct recovery.

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 over the four years studied (from 35% in 2016 to 46% in 2019). In contrast, the number of buoys recovered or abandoned decreased. 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 24).

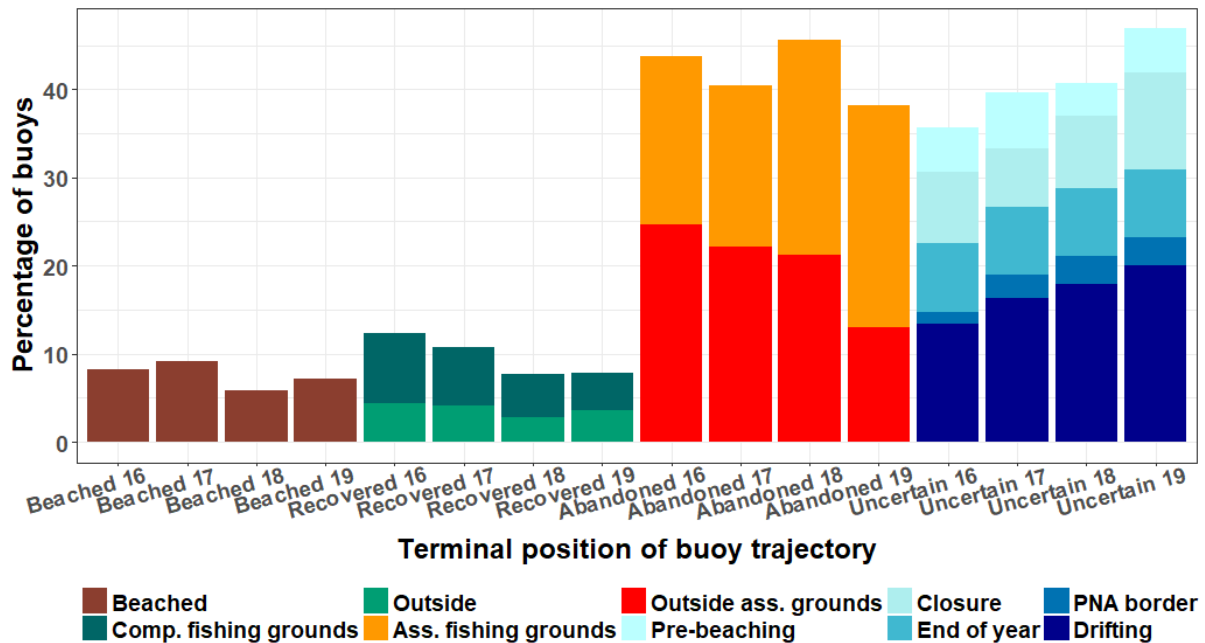


Figure 24. Percentage of buoys’ terminal position classified as beached; retrieved (within or outside the fishing grounds of the company owning the FAD) by any vessel; abandoned (within or outside the general purse seine associated fishing grounds, i.e. see Figure 21): or uncertain per year between 2016 and 2020. These results are based on buoys from companies with at least three purse seiners and with the last transmission in the dataset before 2020 (37,210 buoys).

7. Discussion and Conclusion

The data volume submitted to PNA has clearly increased overtime, and quality of the data for analysis has also recently improved for the whole study period. Data quality has also been further enhanced through the implementation of the filtering and processing methods undertaken here. However, the lack of full submission of the data by fishing companies and the editing of the data before submission to PNA, 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 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 (13% of all records of FAD related activities), and only covers 2011–2019. 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).

A new method of analysis based on the distance between last transmitted position of a FAD and the main fishing ground of the company owning, enabled better estimates of FAD fates. In particular, it highlighted the high potential rate of FAD loss (>50%) 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).
- Investigation of FAD tracking and VMS data matching. A data matching approach could be used to detect FAD fishing activities during the FAD closure, to link associated fishing set and deployment with the corresponding FAD, and to follow the life history of a specific FAD through appropriation and leasing processes.
- 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.
- Perform a matching between FAD sets from logsheet data and the PNA FAD tracking data to estimate coverage rates of the PNA FAD tracking data over time.
- 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-SC16 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 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 42.1% of buoys were estimated to be abandoned and 7.4% beached; as well as the increase in number of buoys with uncertain fate.

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References

- Escalle, L., Brouwer, S., Scutt Phillips, J., Pilling, G., PNAO, 2017. Preliminary analyses of PNA FAD tracking data from 2016 and 2017. WCPFC Sci. Comm. WCPFC-SC13-2017/MI-WP-05.
- Escalle, L., Brouwer, S., Pilling, G., PNAO, 2018a. Estimates of the number of FADs active and FAD deployments per vessel in the WCPO. WCPFC Sci. Comm. WCPFC-SC14-2018/MI-WP-10.
- Escalle, L., Muller, B., Brouwer, S., Pilling, G., 2018b. Report on analyses of the 2016/2018 PNA FAD tracking programme. WCPFC Sci. Comm. WCPFC-SC14-2018/MI-WP-09.
- Escalle, L., Muller, B., Scutt Phillips, J., Brouwer, S., Pilling, G., PNAO, 2019a. Report on analyses of the 2016/2019 PNA FAD tracking programme. WCPFC Sci. Comm. WCPFC-SC15-2019/MI-WP-12.
- Escalle, L., Vanden Heuvel, B., Clarke, R., Brouwer, S., Pilling, G., 2019b. Report on preliminary analyses of FAD acoustic data. WCPFC Sci. Comm. WCPFC-SC15-2019/MI-WP-13.
- Escalle, L., Muller, B., Hare, S., Hamer, P., Pilling, G., PNAO, 2020a. Report on analyses of the 2016/2020 PNA FAD tracking programme. WCPFC Sci. Comm. WCPFC-SC16-2020/MI-IP-14.
- Escalle, L., Vidal Cunningham, T., Hare, S., Hamer, P., Pilling, G., 2020b. Estimates of the number of FAD deployments and active FADs per vessel in the WCPO. WCPFC Sci. Comm. WCPFC-SC16-2020/MI-IP-13.
- Fonteneau, A., Chassot, E., 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. *Aquat. Living Resour.* 26, 37–48. <https://doi.org/10.1051/alr/2013046>
- Gershman, D., Nickson, A., 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 Environ. Gr.* 1–24.
- Girard, C., Benhamou, S., Dagorn, L., 2004. FAD: Fish Aggregating Device or Fish Attracting Device? A new analysis of yellowfin tuna movements around floating objects. *Anim. Behav.* 67, 319–326. <https://doi.org/10.1016/j.anbehav.2003.07.007>
- Harley, S., Tremblay-Boyer, L., Williams, P., Pilling, G., Hampton, J., 2015. Examination of purse seine catches of bigeye tuna. WCPFC Sci. Comm. WCPFC-SC11-2015/MI-WP-07 29pp.
- Lopez, J., Moreno, G., Sancristobal, I., 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. *Fish. Res.* 155, 127–137. <https://doi.org/10.1016/j.fishres.2014.02.033>
- Maufroy, A., Chassot, E., Joo, R., 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. <https://doi.org/10.1371/journal.pone.0128023>
- Moreno, G., Dagorn, L., Sancho, G., Itano, D., 2007. Fish behaviour from fishers' knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). *Can. J. Fish. Aquat. Sci.* 64, 1517–1528. <https://doi.org/10.1139/f07-113>
- Scutt Phillips, J., Leroy, B., Peatman, T., Escalle, L., Smith, N., 2019. Electronic tagging for the mitigation of bigeye and yellowfin tuna juveniles by purse seine fisheries. *WCPFC Sci. Comm.* WCPFC-SC15-2019/EB-WP-08.
- Venables, B., Ripley, B., 2002. *Modern Applied Statistics with S*, 4th ed. Springer-Verlag New York.
- Vidal, T., Hamer, P., Wichman, M.-O.-T.-A., PNAO, 2020. Examining indicators of technological and effort creep in the WCPO purse seine fishery. *WCPFC Sci. Comm.* WCPFC-SC16-2020/MI-IP-15.
- WCPFC, 2017. CMM-2017-01 Conservation and management measure for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean.
- WCPFC, 2018. CMM-2018-01 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	32,294,237	61,676		
Positions outside the Pacific Ocean	128 051	1432	0.40	2.32
Buoy with ≤ 3 transmissions	125 825	1372	0.39	2.22
Double transmissions (same time and position)	69 073	0	0.21	0.00
One position per day (Kato and Marine Instrument)	2 608 158	0	8.07	0.00
Buoy with only one position	46 770	360	0.14	0.58
Buoy with only port position	8 974	41	0.03	0.07
Consecutive transmissions with high speed (>200 knots)	1 567	5	0.00	0.01
Large gap at the beginning or end of trajectory	2 071	24	0.01	0.04
Total removed	2,990,489	3,235	9.3	5.2
Filter dataset	29,303,748	58,441		

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. It was found that more than 90% (52,701) of the buoys had more than 50% of their transmissions at sea. Additionally, around 78% (45,808) of the buoys transmitted from sea 81–100% of the time.

Appendix 2. Characteristics of the PNA FAD tracking database.

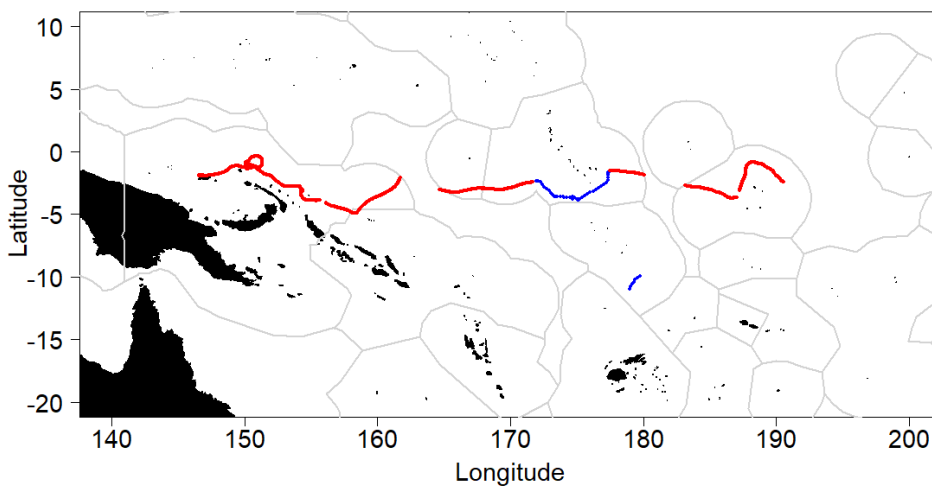


Figure S1. Example of a trajectory of a geo-fenced buoy, blue line represents on-board positions and red at-sea positions.

Patterns of buoys being geo-fenced (Figure S1) by fishing companies prior to transmission to PNA appear variable between companies. Approximately 9% 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., 2018b), limiting the analyses performed on the data. Overall, a total of 38,495 (66%) FADs have been geo-fenced in the data from 2016–2020.

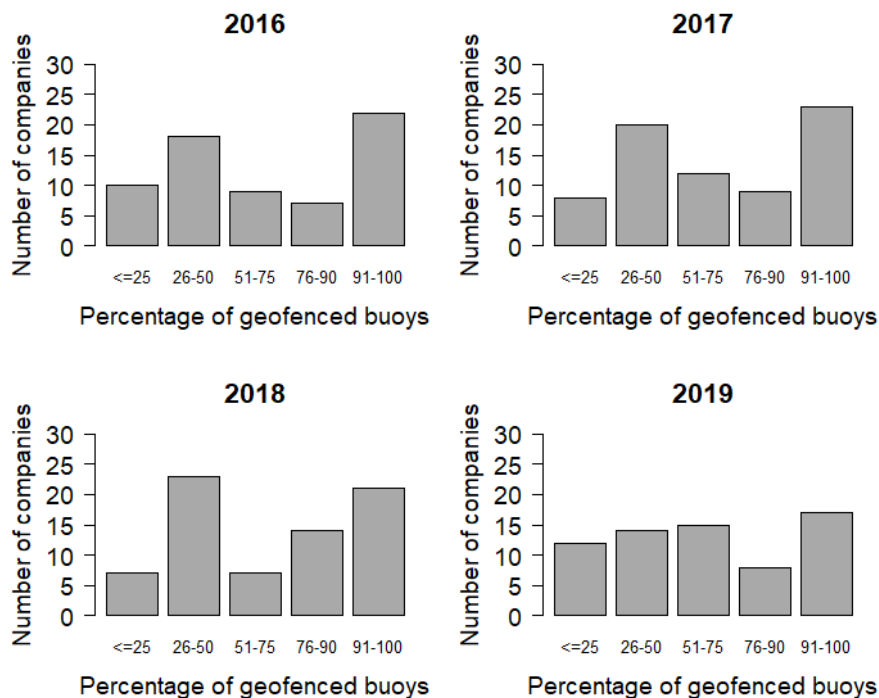


Figure S2. Percentage geo-fenced FAD buoys by fishing company prior to transmission to PNA during 2016-2019. Given that the data for 2020 are incomplete, this year was not shown here.

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 50 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).

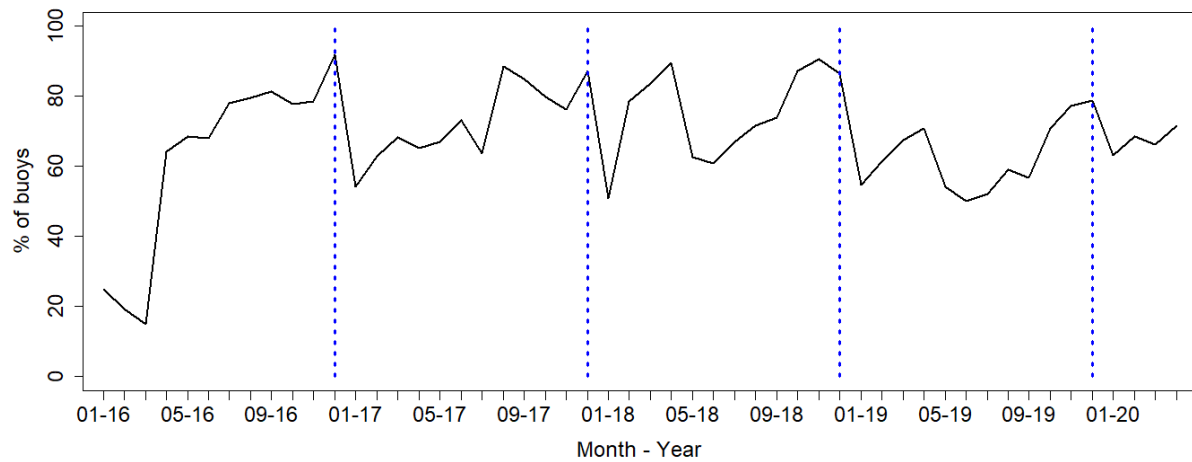


Figure S3. Percentage of geo-fenced buoys by month in 2016–2020.

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.

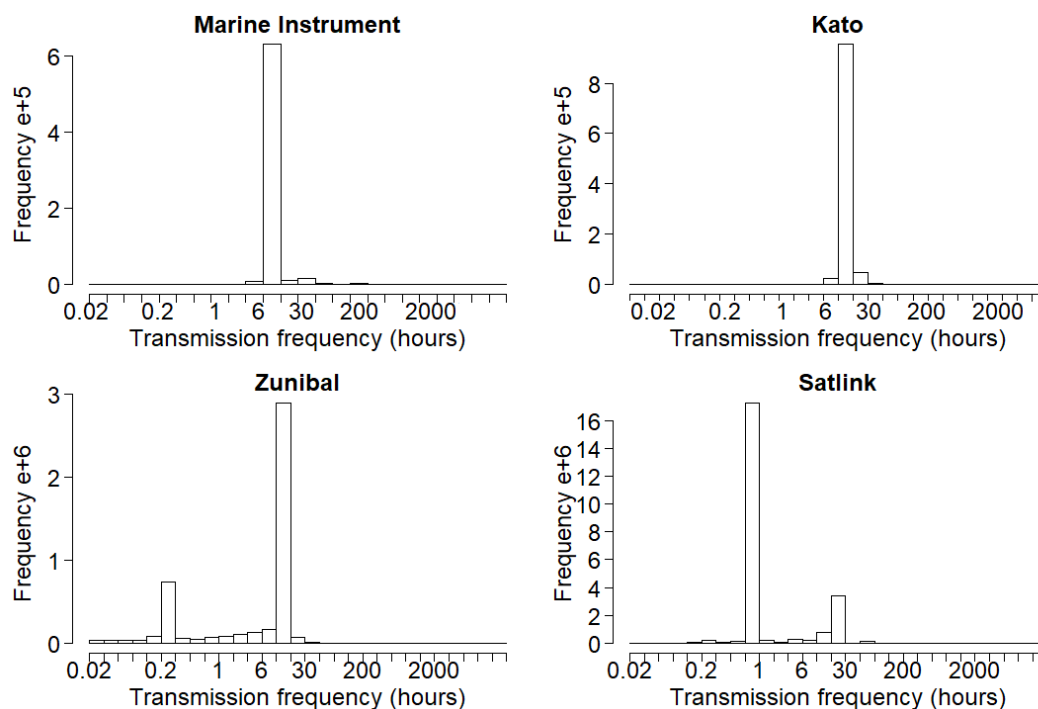


Figure S4. Frequency of transmission (in hours) for all buoys assessed from 2016–2020.

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

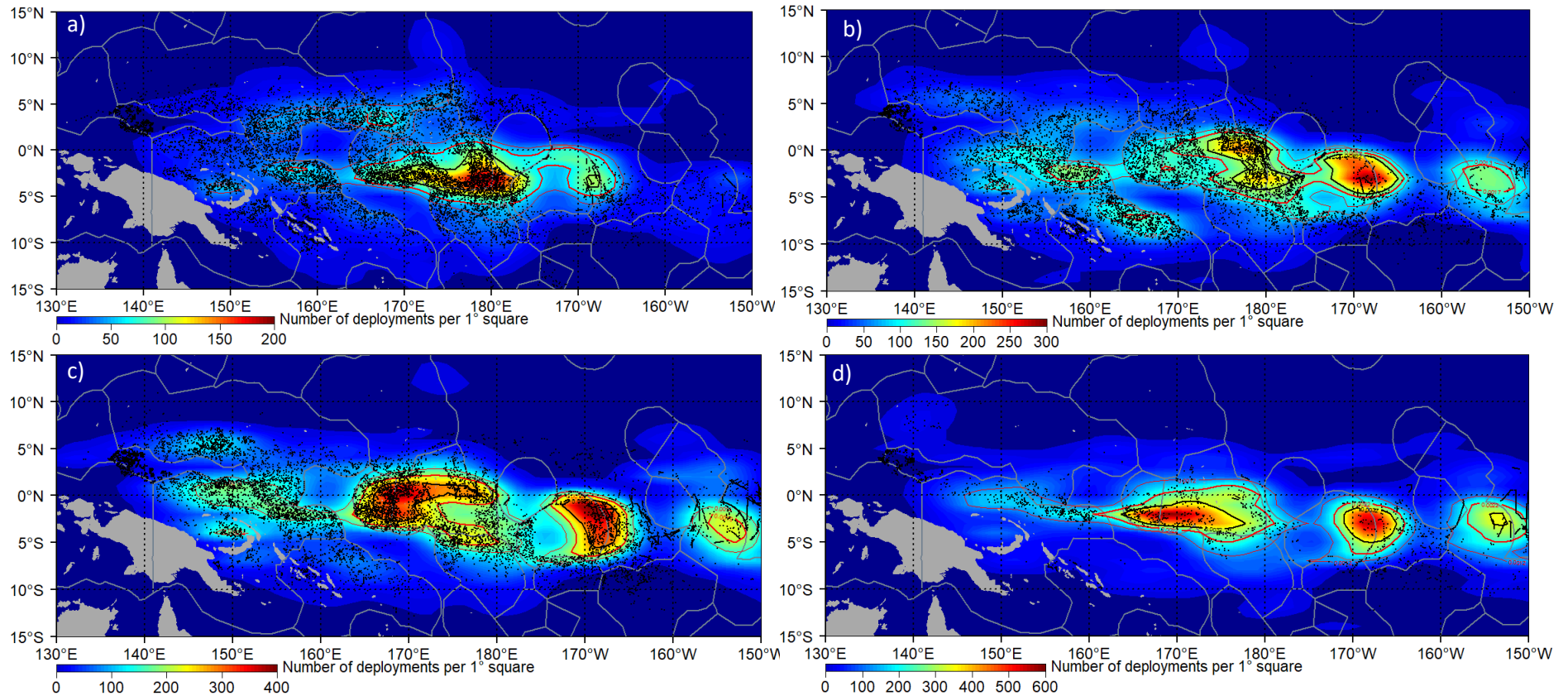


Figure S5. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, and d) 2019; with position of deployments recorded in observer data shown as black dots. Red lines correspond to the 95th quantile.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

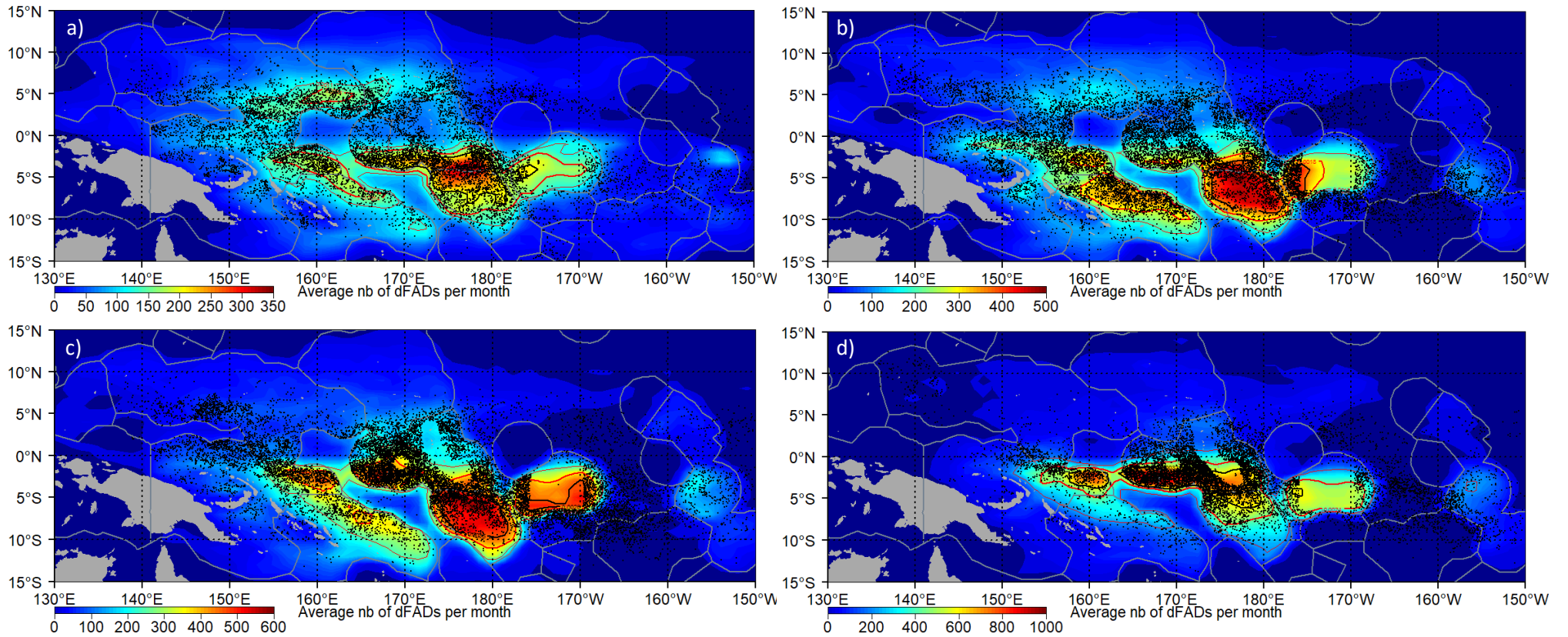


Figure S6. Smoothed kernel density of the average number (nb) of FAD satellite buoys transmitting at least once per month and per 1° grid cell during a) 2016, b) 2017, c) 2018, and d) 2019 with position of associated sets recorded in logsheet data shown as black dots. Red lines correspond to the 95th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

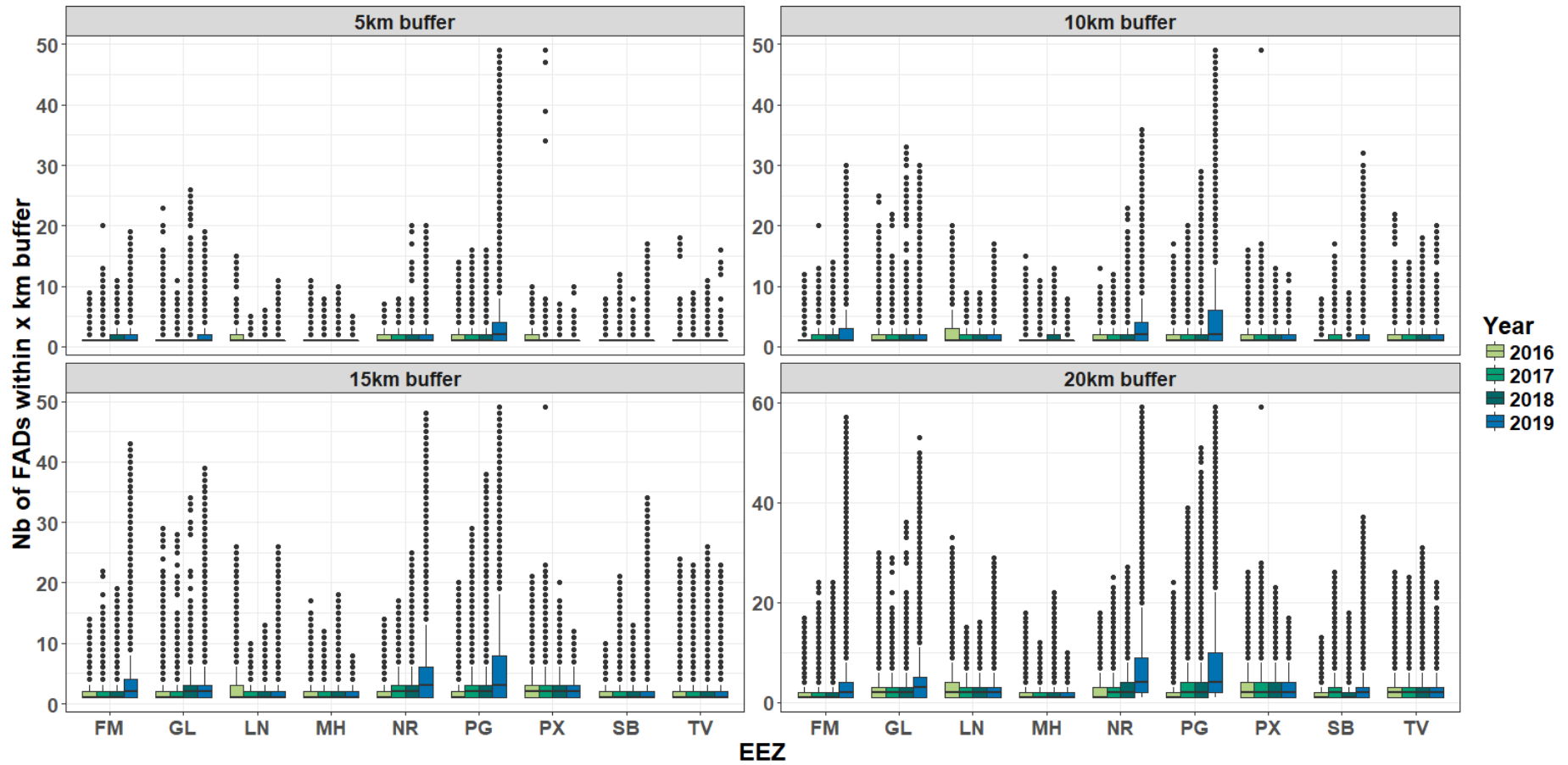


Figure S7. Number of FADs within a 5, 10, 15 and 20 km buffer around each specific FAD per day (if more than one is present), per EEZ and year.

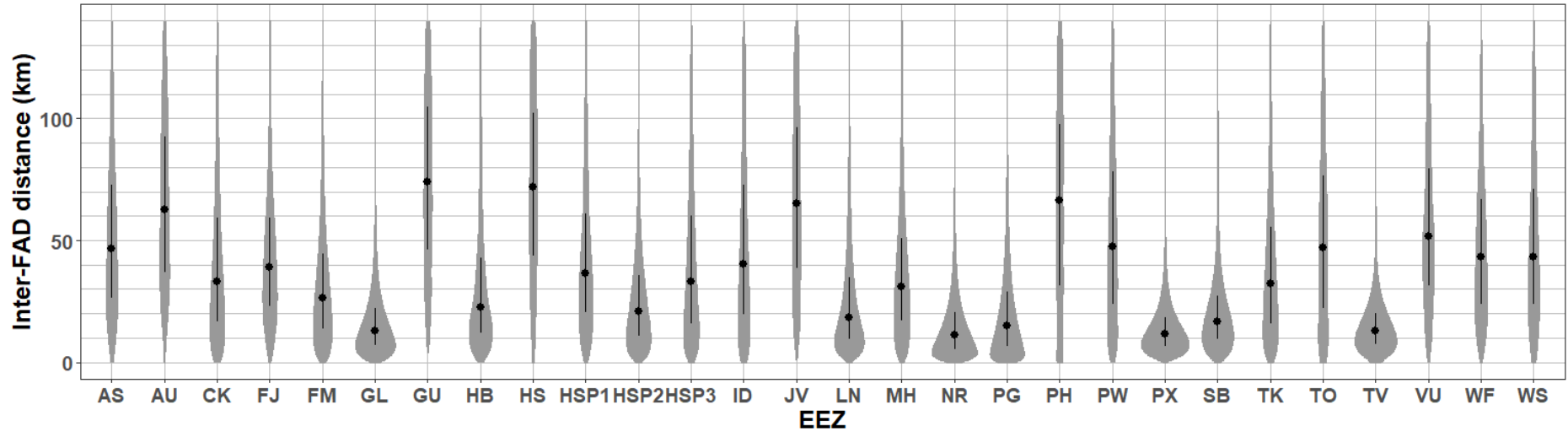


Figure S8. Violin plot of the minimum distance between each individual FADs drifting in the WCPO per day, by EEZ for the 2016-2019 period (horizontal black line = average; black dot = median; vertical black line = 0.25 to 0.75 quantiles). Wake, Palmyra and Johnston Islands, Hawaii, Niue, French Polynesia, 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 37,210 buoys (63.7 % of the 58,441 buoys available in the dataset).

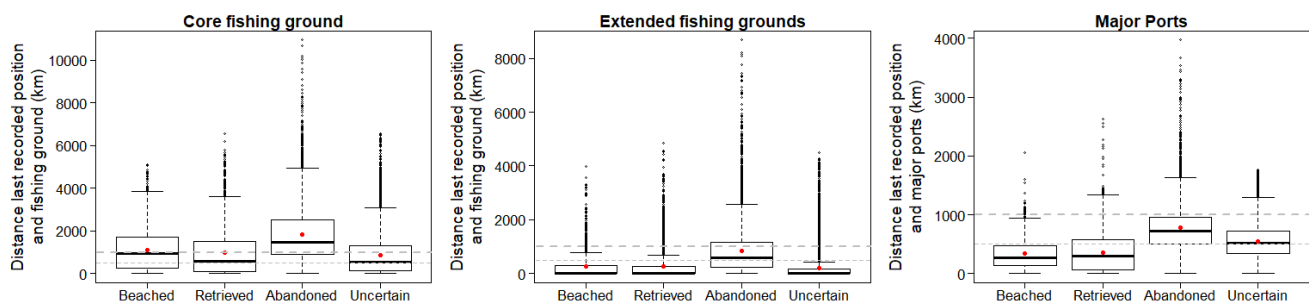


Figure S9. Distance between the last recorded position and; a) the core fishing ground of the company owning the buoys; b) the extended fishing grounds; and c) the closest major port, depending on the classification of buoy fates described above as: beached, recovered, abandoned or uncertain. Dotted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

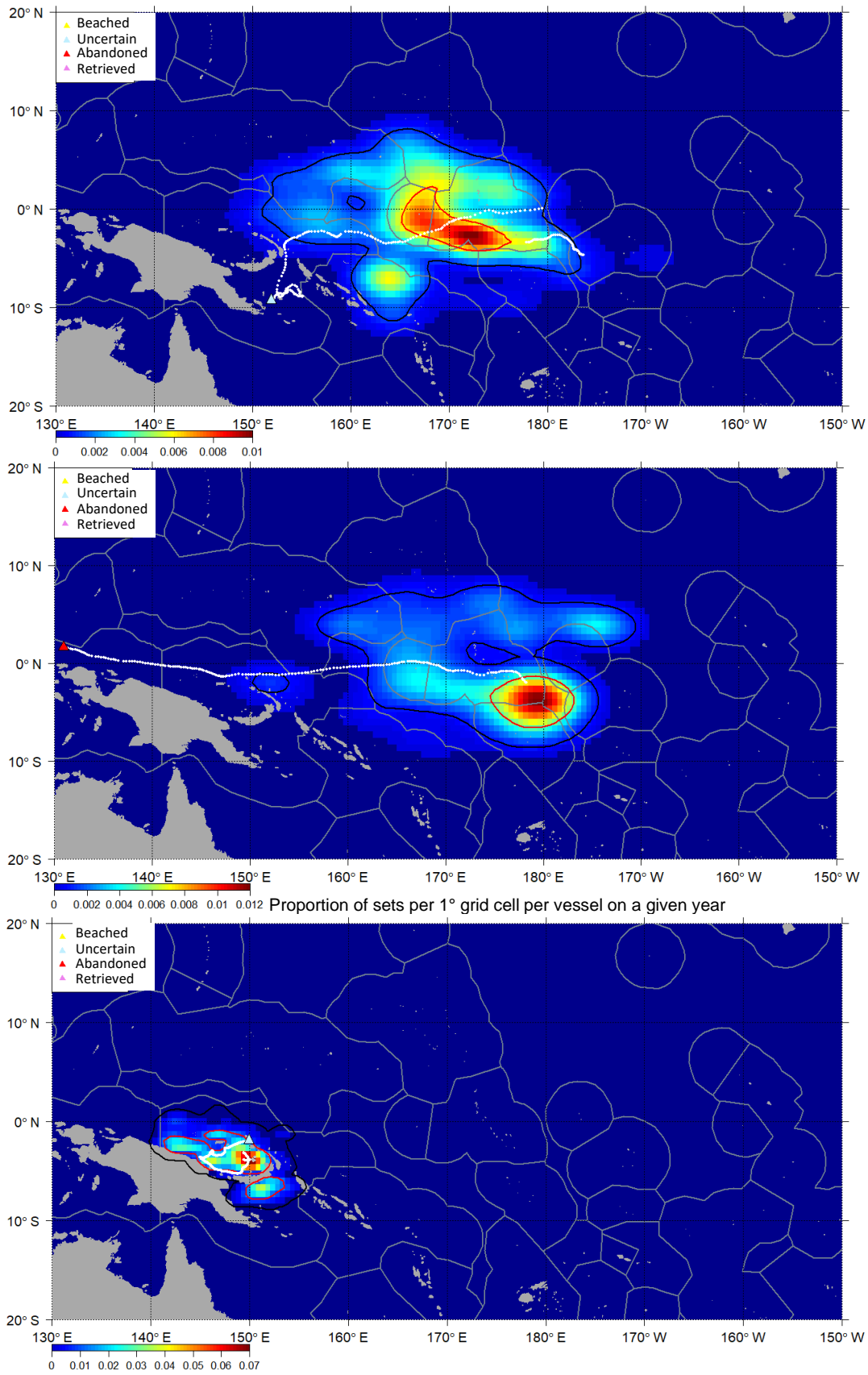


Figure S10. Examples of density map of purse seine fishing sets for three different fishing companies in a given year, with the track of a FAD from that company depicted in white. Black and red lines correspond to the extended (0.99 quantile) and core (0.90 quantile) fishing grounds.