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Report on analyses of the 2016/2018 PNA FAD tracking programme

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Executive Summary

This paper presents analyses of the PNA's fish aggregating device (FAD) tracking programme including: a description of the data processing required; estimated data submission rates to the PNA; a description of the spatio-temporal distribution of buoy deployments; FAD densities; FAD connectivity; and an analysis of the fate of FADs including a focus on FAD beaching. As FADs drift in the ocean, the associated electronics can be changed 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 on board vessels, data were analysed using a Random Forest model to identify, and select, the drifting at-sea section of each buoy trajectory, and at the same time identify deployment positions. In addition, using two methods matching buoy tracks and observer or logsheet data, we estimated that ~60–70% of buoy transmissions collected by fishing companies are not forwarded to the PNA. We noted that some of 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 added a bias to the analyses. After undertaking the correction procedure, the cleaned dataset consisted of 14.8 million transmissions from 26,466 buoys and covered the period from 1st January 2016 to 18th March 2018.

The number of deployments varied over time, with a total of 36,831 deployments in 2016–2018 (from 193 vessels including 102 buoy owner vessels and an additional 91 vessels where the fishing company was known, but the buoy ownership was not). The spatial distribution of deployments was very similar between observer data and FAD tracking data, both showed the main deployments areas to be in Kiribati South of the Gilberts Islands and East of the Phoenix Islands, Nauru, East of PNG.

The number of transmissions from buoys almost doubled in 2017 (8.6 million compared to 4.5 in 2016) and the number of individual buoys active in the available data was 10,915 in 2016 and 18,405 in 2017. A decrease in both numbers was detected during the FAD closure in 2016 and 2017, although in 2017, both remained relatively high and constant during the first 3 months of the closure. Although influenced by the issues arising due to geo-fencing, the spatial distribution of buoy densities were investigated, with higher densities in Kiribati South of the Gilbert Islands and around the Phoenix Islands, Tuvalu, PNG and the Solomon Islands. Buoys movement between large grouped areas of the WCPO was also investigated. Patterns varied between areas; for instance, the Southwestern area mostly received buoys from the East and had a high proportion remaining or being deactivated there, compared to the Southeastern area which showed high deployment and emigration rates.

Finally, at least 5% of the buoys ended up beached (probably underestimated as buoys may be deactivated before reaching coastlines), with the connected FAD potentially damaging sensitive ecosystems such as coral reefs. At least 26% of the buoys in our dataset could be considered lost, likely leading to marine pollution.

We invite WCPFC-SC14 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.
- Noting on-going WCPFC considerations, and findings that an estimated 25% of the FADs drifted out of main fishing areas and a minimum of 5% are beached, SC14 is invited to discuss i) the importance of FAD marking and monitoring programmes to better identify and follow individual FADs and ii) the potential benefit of using biodegradable material on FADs.

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 (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 widely performed 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) and considered likely to have increased every year since. To reduce the impact of FAD fishing on tuna stocks, specifically due to the high capture of juvenile bigeye tuna on FAD associated sets (Harley et al., 2015), the Parties to the Nauru Agreement (PNA) and WCPFC implemented a three to four months FAD closure where all FAD-related activities (e.g. fishing, deployment, servicing) are prohibited (e.g. CMM-2017-01). While the number of active buoys at any time and the precise number of FAD deployments per year is currently unknown, last year 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). In addition, to limit the impact of FADs on the marine ecosystem, the Commission will also discuss this year the adoption of measures on the implementation of non-entangling and/or biodegradable material on FADs (CMM 2017-01).

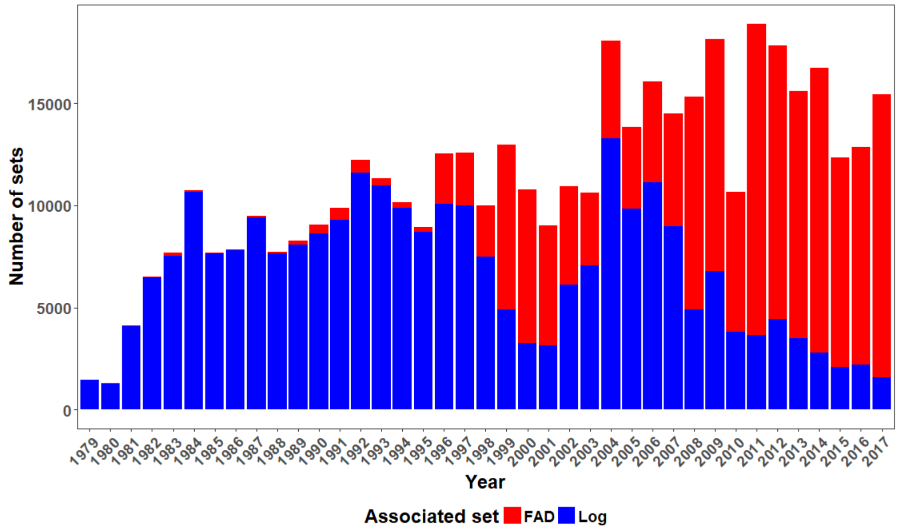

Figure 1. Number of associated sets performed specifically on deployed FADs and natural logs, as recorded in the logsheet data in the Western and Central Pacific Ocean between 1979 and 2017. Note similar trends were detected in the observer data but as there was low coverage prior to 2010 these data are not shown.

This paper presents analyses of the PNA's FAD tracking programme, which tracked satellite buoys attached to drifting FADs used by purse seine vessels. 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 data processing performed on the raw data and discuss the issues limiting analyses including the estimated data submission rates to PNA. We also present results from analyses of spatio-temporal distributions of buoy deployments and FAD density, FAD connectivity between large areas of the WCPO and fate of FADs at their last buoys transmission, including a focus on FAD beaching.

As FADs drift in the ocean, the associated electronics can be changed making it difficult to follow individual FADs, therefore for the purposes of this analysis we followed the buoys with GPS satellite positioning systems referred to here 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. Methods

2.1 Data cleaning processes

The raw buoy tracking dataset received by the PNAO contained duplications and errors, as well as transmissions from active buoys that were still on-board a vessel, therefore the dataset needs to be cleaned before any analysis can be undertaken (Escalle et al., 2017). The first cleaning process was to remove buoys activated for short periods to verify functioning and avoid bias in analyses due to very short overall active time. This included the removal of buoys with less than 10 transmissions; those active for less than 7 days; and those with transmissions from only the same position (Table 1). In addition, double transmissions; consecutive transmissions corresponding to unrealistic speeds; as well as consecutive transmissions separated by more than 3 months at the direct end or beginning of a buoy track were removed.

Secondly, additional processing of the data consisted of identifying at-sea and on-board positions of a 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, which may be following deployment or a few hours to several days before deployment, and continued until deactivation (e.g. when a FAD is considered “lost” by the company). Each transmission was classified into “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), 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 class (at-sea or on-board) positions in the validation datasets were 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 in i) changing to on-board positions, sequences of 1 to 3 isolated at-sea positions, ii) changing to at-sea positions, sequences of 1 to 3 isolated on-board positions with a speed <5 km/h and iii) changing to on-board positions, additional isolated sequences of at-sea positions lasting less than 24 hours. This additional correction procedure was selected as the best when testing different procedures and based on the statistics mentioned above and visual investigation of some buoys. Once the Random Forest model and the correction procedure were calibrated, it was then run over the whole cleaned dataset.

2.2 Deployments and end of track positions

For each of the drifting segments (i.e. at-sea sections), deployment positions were defined as the first "at-sea" position. End of tracks were classified as i) still drifting if the last position was "at-sea" and within main fishing grounds (142°W, 210°E, 9°N, 11°S), ii) lost if the last position was "at-sea" but outside main fishing areas or at the PNA border, iii) recovered if the last position was "on-board" or iv) beached. Beaching events were identified as a FAD having i) the last position "at-sea" and within 10 km of shore (excluding positions located at less than 10km from major ports) and ii) at-least the 3 last positions immobile.

3. Results

3.1. General description of the data

The FAD tracking data comprise transmitted locations and time stamps from buoys attached to drifting FAD, between 1st January 2016 and 18th March 2018 (data uploaded on the 17th of April 2018). The raw dataset included 15.1 million transmissions from 30,000 buoys. Each transmission included location, time, "fishing company" each buoy belongs to (actual fishing company or a vessel's name), water temperature, course direction and drifting speed. The fishing company owner of each buoy with a vessel name recorded was added, so that each buoy in the cleaned dataset presented an actual fishing company and a vessel name when available (61% of the buoys with recorded vessel name). The type of buoy (e.g. echosounder or not) is not recorded, but from the format of the buoy manufacturer identification number (ID), it was deduced that at least 72% of the buoys are echo-sounder buoys (11% without and 17% unknown), and mostly manufactured by Satlink (60%) or Zunibal (23%).

Table 1. Summary information of the buoy tracking dataset showing the number (and %) of records removed during cleaning processes.

	Number of transmissions	Number of buoys	% of transmissions	% of buoys
Raw dataset	**15,148,063**	**30,069**		
Buoy with ≤ 3 transmissions	74,713	1,666	0.49	5.54
Double transmissions (same time and position)	164,874	0	1.09	0.00
Buoy with only one position	10,165	96	0.07	0.32
Buoy with only port position	3,047	6	0.02	0.02
Consecutive transmission with high speed (>200 knots)	1,634	1	0.01	0.00
Large gap at the beginning or end of track	896	5	0.01	0.02
Buoy active ≤ 7 days or < 10 transmissions	34,923	1,614	0.23	5.37
Buoy with total distance <10km	75,012	86	0.50	0.29
Total removed	365,264	3,474	**2.41**	**12.00**
Clean dataset	**14,780,799**	**26,595**		

The data correction procedures resulted in the removal of 12% of the buoys, leading to 14,780,799 transmissions from 26,595 buoys being available for analysis (Table 1). Each buoy track (trajectory) consisted of a single (72% of the buoys) or several repeated drifting ("at-sea") segments (2–14 at-sea segments per buoy), separated by "on-board" positions. It was also found that 74% (19,727) of the buoys have more than 80% of their transmissions at sea. Transmission frequency varied between and within buoys, as it can be adjusted by fishers depending on the intended use of a FAD, but most buoys present transmission time steps of either 1 hour or 1 day (Figure 2).

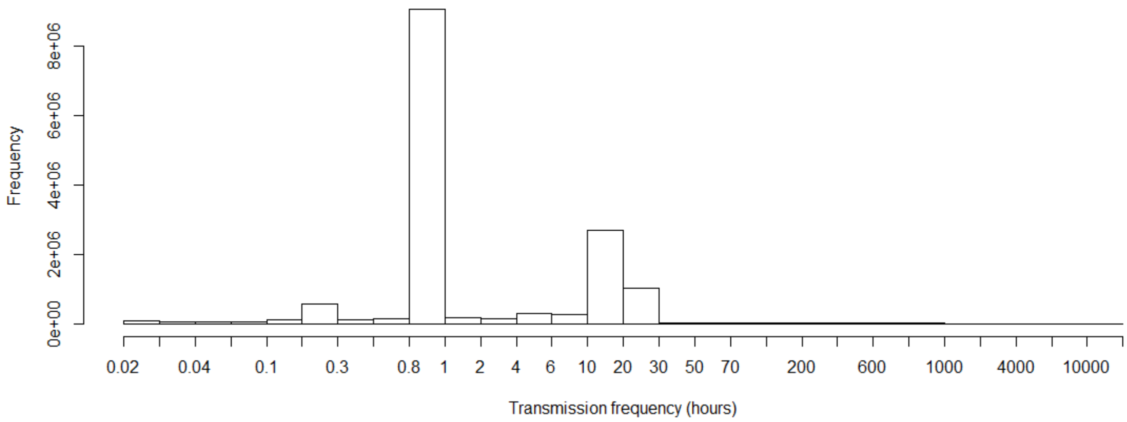

Figure 2. Frequency of transmition (in hours) for all buoys assessed from 2016– 2018.

The modification of buoy transmissions with information outside PNA Exclusive Economic Zones (EEZs) removed prior to data submissions i.e., "geo-fenced" (see Figure 3 as an example) was investigated to identify potential temporal patterns or patterns among companies. Geo-fenced buoys were identified as having no transmissions outside PNA waters. A total of 18,491 buoys were geo-fenced (i.e. 70%).

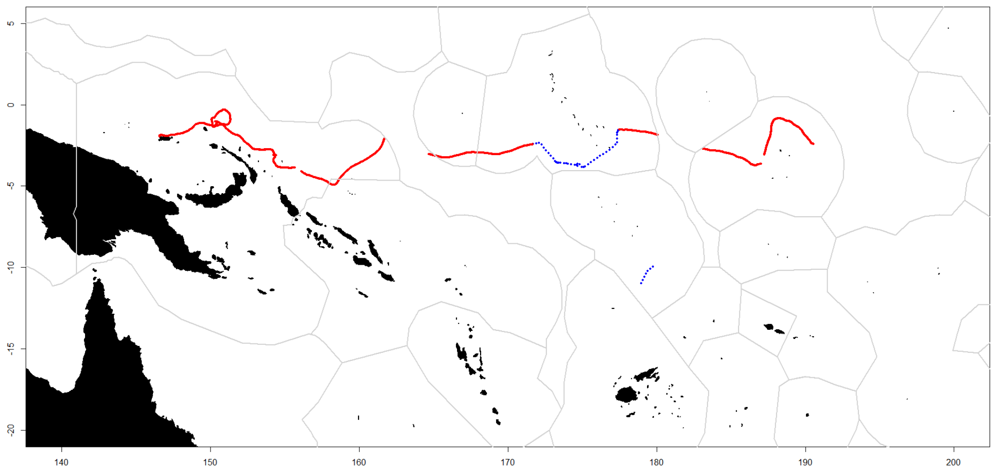

Figure 3. Example of a trajectory of a geo-fenced buoy, blue line represents on-board positions and red at-sea positions.

Patterns of buoys being geo-fenced by fishing companies prior to submission to PNA varies between companies. Approximately 20% of the companies geo-fenced less than 25% of their buoy trajectories whereas 35% of the fishing companies were found to have geo-fenced more than 90% of their buoys (Figure 4). When buoys are geo-fenced it leads to gaps in the trajectories of a few days to 1 month, limiting the analyses performed on the data.

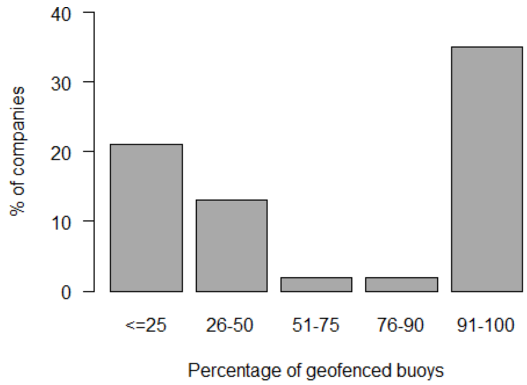

Figure 4. Percentage of geo-fenced buoys by company between 2016–2018.

Regarding temporal variability, besides the fact that few buoys were geo-fenced during the three first months of the programme, no temporal trends in the number of geo-fenced buoys by company could be determined (Figure 5). Since April 2016, between 66 and 94% of the buoys had been geo-fenced per month (apart for December 2016 and 2017 were few data were submitted).

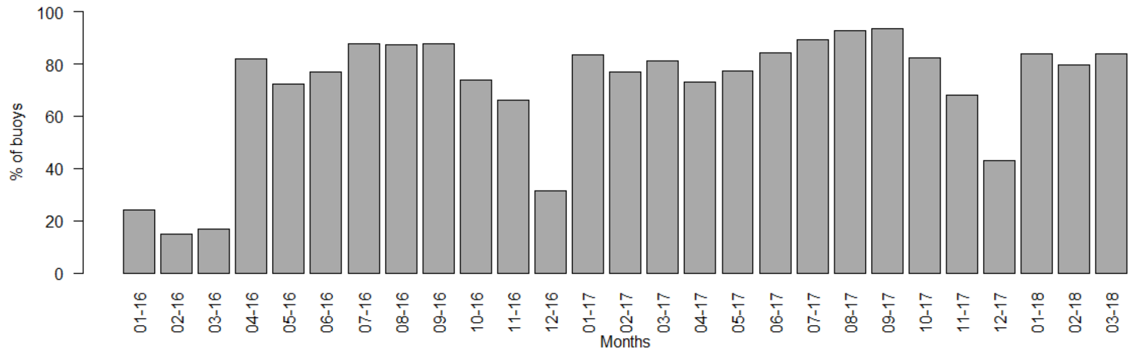

Figure 5. Percentage of geo-fenced buoys by month in 2016–2018.

Finally, gaps in the FAD trajectories, in particular recurrent gaps, and their potential causes were investigated. The highest number of buoys (>1,000) presenting gaps of more than 30 days in their trajectories occur mid-year during the FAD closure when companies either change the transmission frequency during the closure to stop following their buoys during that period; or data are not provided to PNA (Figure 6). An additional peak is detected during November and December, but the cause remains unclear.

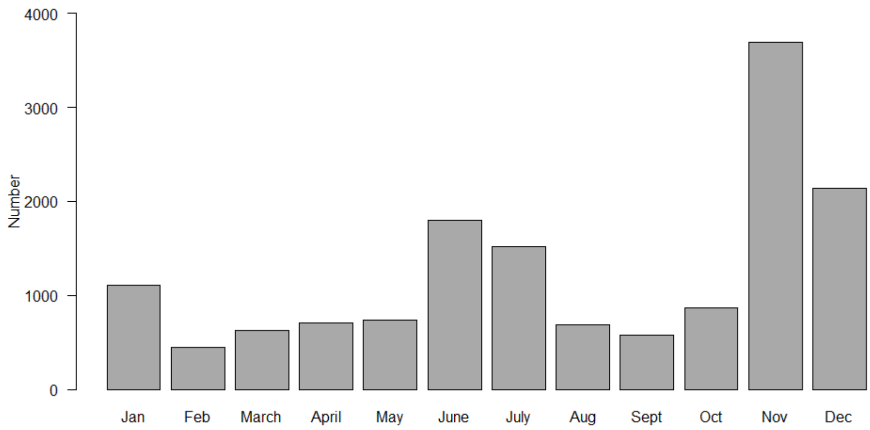

Figure 6. The monthly distribution of the number of buoys with gaps >30 days that are not due to geo-fencing (the date corresponds the last recorded transmission, i.e. gap in June could correspond to a last transmission 30^{th} and therefore a gap in July).

3.2. Estimated data transmission rates to PNA

Two different approaches were used to estimate the volume of data that were submitted by fishing companies to the PNA.

Firstly, the list of buoy ID numbers recorded by observers during an associated fishing set or a FAD deployment was compiled and compared to the buoy ID numbers in the FAD tracking data. Buoy ID numbers are not often recorded by observers (20% of the sets and 50% of the deployments), and when they are, information rarely corresponded to correct formats of a buoy ID (25% of the recorded numbers during sets and deployments) (Table 2). This was either because this ID is incomplete and makes the identification of the actual ID very complicated or because the ID appears to be completely random (e.g. corresponds to the vessel buoy number (1 to 'x' for instance) and not the actual buoy manufacturer ID). The percentage of buoys that could be matched in both datasets range from 27 to 32% of the fishing sets and 22 to 31% of the deployments (see Table 2 for details).

Table 2. Number of associated fishing sets and deployments (FAD or buoy) recorded in the observer database in 2016 and 2017 and effective matching with the FAD satellite buoys tracking data using the buoy identification number.

	All			**PNA waters**			**Companies found in FAD tracking data**		
	Number	Match with buoy track	%	Number	Match with buoy track	%	Number	Match with buoy track	%
DEPLOYMENTS									
All	18,744			15,069			10,504		
Buoy ID recorded	2,958			2,157			1,538		
Buoy ID with good format*	831	185	**22.3**	553	**160**	**28.9**	423	**131**	**31.0**
SETS									
All	11,599			9,763			7,107		
Buoy ID recorded	2,454			2,013			1,451		
Buoy ID with good format*	684	187	**27.3**	509	**164**	**32.2**	461	**148**	**32.1**

*Good formats after applying a simple procedure to correct and homogenise the recorded IDs.

Secondly, all sets and deployments were matched with buoy drift tracks based on position (≤2km) and date/time (≤3 hours) (Table 3). This resulted in 29–41% of the associated fishing sets and 25–35% of the deployments in the observer dataset matched with a buoy track and 34–44% of the associated fishing sets in the logsheet dataset matched with a buoy track (Table 3).

Table 3. Number of associated fishing sets and deployments (FAD or buoy) recorded in the observer or logsheet databases in 2016 and 2017 and matching with the buoys tracking data using position (≤2km) and time (≤3 hours).

	Number	Match with buoy track	%
DEPLOYMENTS Observer			
All	18,744	4,680	**25.0**
In the PNA waters	15,069	4,335	**28.8**
From companies found in FAD tracking data	10,504	3,712	**35.3**
SETS Observer			
All	11,599	3,415	**29.4**
In the PNA waters	9,763	3,184	**32.6**
From companies found in FAD tracking data	7,107	2,876	**40.5**
SETS Logsheet			
All	21,454	7,302	**34.0**
In the PNA waters	18,412	7,077	**38.4**
From companies found in FAD tracking data	14,889	6,499	**43.6**

Both methods showed similar results, with 30–40% of the buoy data being matched with a fishing set or a deployment in the observer and logsheet datasets (Table 3 and 4). This either showed i) poor results in the matching methods potentially due to position and dates uncertainties or ii) that a relatively limited portion of the buoy data are transferred to PNA. The latter could be potentially caused by two processes: i) some companies only transferring data for part of their buoys; and ii) some companies while performing associated fishing sets in PNA waters, do not transfer any buoy tracking data to PNA (>35 companies corresponding to >60 purse seiners. This scenario is potentially overestimated because some companies in the dataset could not be matched with any purse seine vessels).

3.3. Deployments

The number of estimated buoy deployments varied over time (40 to 1,245 per week; Figure 7), with a total of 36,831 deployments over the study period (13,701 in 2016, 19,039 in 2017 and 4,091 in 2018). This correspond to an average of 71 and 98 deployments per vessel in 2016 and 2017, respectively (based on 193 vessels linked to the FAD data; i.e. 102 identified FAD owner vessels and 91 additional vessels belonging to the identified fishing companies). Three peaks of deployment corresponding to the 1st week of January 2016, 2017 and 2018 can be identified, the first corresponded to the beginning of the tracking programme and the location of each buoy when the companies started transmitting data (i.e. these are potentially not real deployments). Peaks in the beginning of 2017 and 2018 are plausible given the increase in buoy transmissions detected in Figure 10, but whether it corresponds to real deployments or to buoys already in the water being activated/ reactivated at that time or for which data only started to be transmitted to PNA remains unclear (only 12% of the buoys deployed the 1st week of 2017 were already active in 2016). In addition to this bias in the deployments due to data starting to be submitted to PNA, another bias in the deployment positions arises from the geo-fencing of the data, with 5.6% of the estimated deployments corresponding to the first position of a geo-fenced buoy at the border of a PNA EEZ.

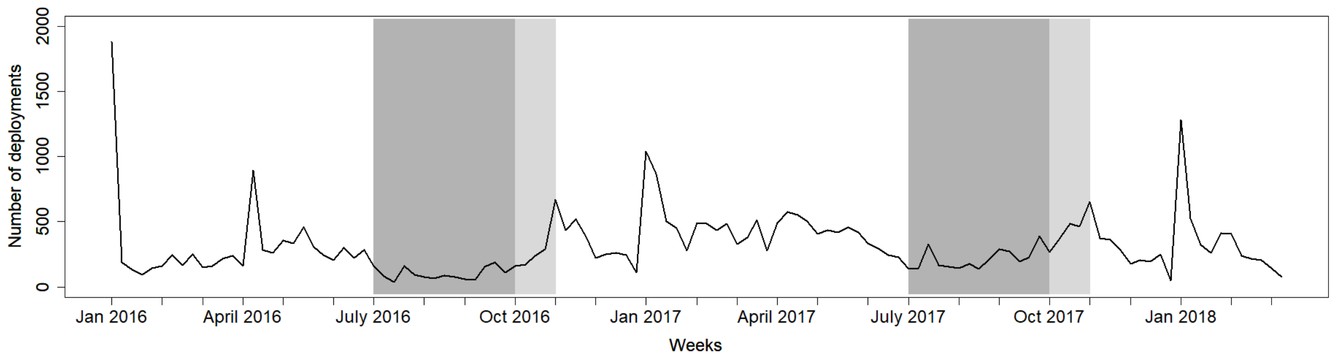

Figure 7. Estimated number of deployments by week. Grey areas correspond to the FAD-closure periods (1st of July through 30th of September or October).

The number of deployments per vessel was investigated for buoys with identified owner vessel (Figure 8). The total number of deployments by vessels (19,615 i.e. 53% of deployments) doubled from 5,375 in 2016 to 11,746 in 2017 (Figure 8). The number of deployments per vessel range from 0 to 283 (mean = 68) in 2016, to 0 to 499 (mean = 108) in 2017. This corresponds to a mean deployment of 2 buoys per vessel and per day (range 1–74) or of 11 buoys per vessel and per month (range 1–268). At the buoy level, a buoy is on average deployed/redeployed 1.4 times in its life (range 1–14), with 73% of the buoys deployed only once, 17% twice, 6% 3 times and 5% four times or more.

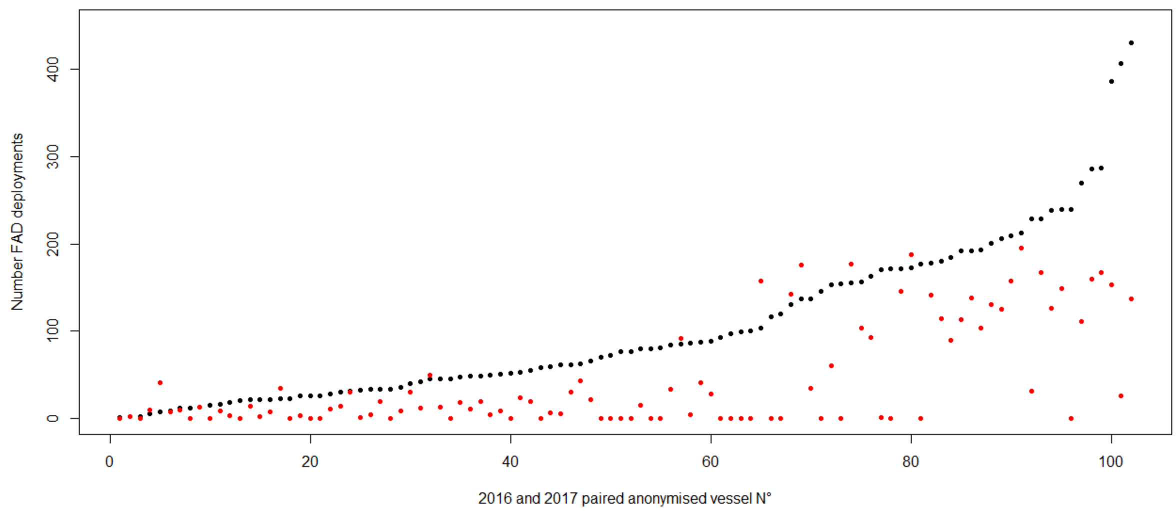

Figure 8. Estimated number of FAD deployments for known vessels in the tracking data per year, 2016 (red) and 2017 (black), vessels numbers are common between both years but ordered based on the 2017 numbers to allow a comparison between years.

Most deployments occurred in Kiribati South of the Gilbert Islands, Nauru and East of the PNG EEZ in 2016 and 2017, as well as East of the Phoenix Islands in 2017 (Figure 9 and A1). When combining both years of data, three deployment hotspots could be distinguished, based on 95th quantile of the data: i) East of the PNG EEZ and extending to the High Sea pocket 2 (called Hotspot 1); ii) a large hotspot in the centre of the WCPO mostly covering Kiribati, Nauru, North of Tuvalu and high Seas (Hotspot 2); and iii) West of Kiribati Phoenix Island EEZ (Hotspot 3). When comparing with the FAD and buoy deployment positions recorded in the observer data (specifically in 2016, as complete observer dataset is still lacking for 2017), the main deployment positions are almost identical (Figure 9, A1 and A2). We also note the non-negligible number of deployments outside PNA waters, specifically in the eastern High Seas, as recorded by observers, which do not appear in the FAD tracking data due to the geo-fencing of the data (Figure 9).

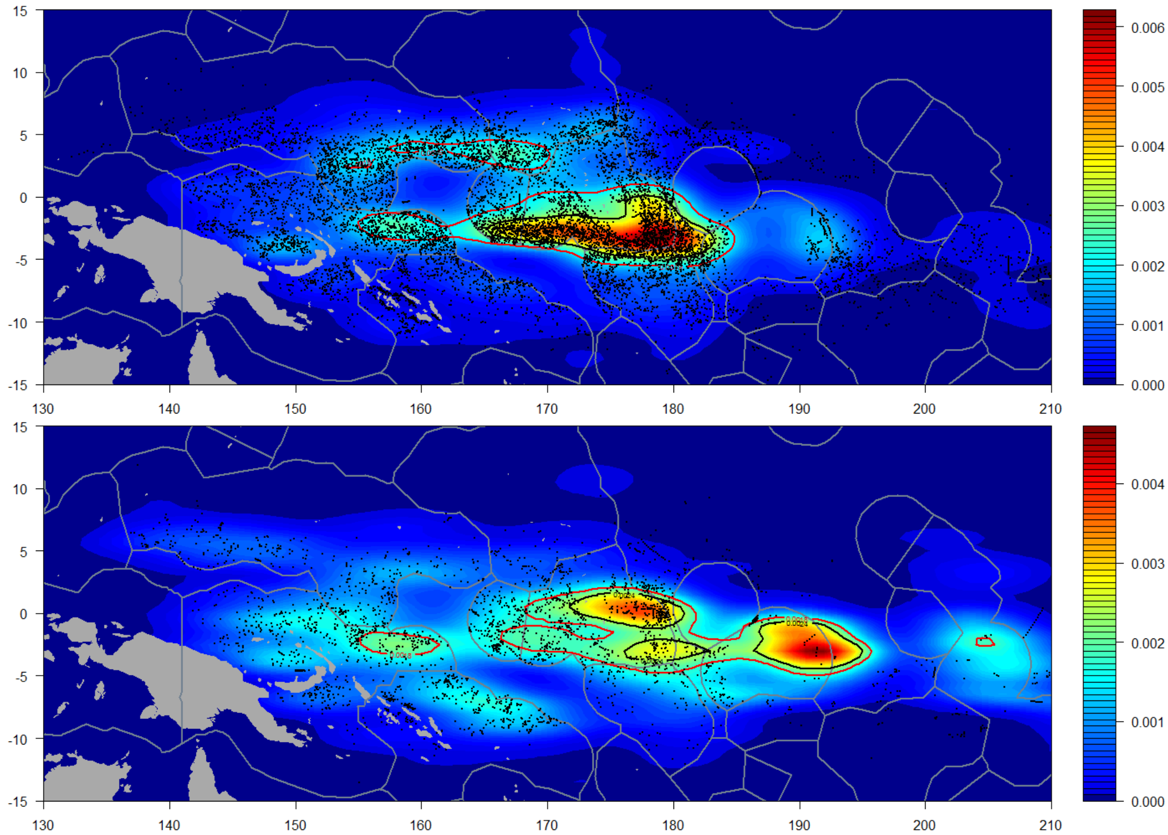

Figure 9. Smoothed kernel density of deployments of buoys per 1° grid cell during 2016 (top) and 2017 (bottom) (maximum number of deployments per cell of 140 in 2016 and 300 in 2017). Position of FAD and buoy positions recorded in observer data (14,576 in 2016 and 4100, i.e. incomplete, in 2017) are indicated as black dots (see Figure A1 for density maps only). Red and black lines correspond to the 95th and 98th quantiles. Colour scale corresponds to the proportion of buoy deployment per 1° cell.

3.4. Spatio-temporal distribution of FAD densities

The corrected dataset of 14,780,799 transmissions comprised 20% of on-board positions and 80% of at-sea positions. An increase in the number of transmissions and number of buoys transmitting was detected over time (Figure 7). In particular, the number of transmissions from drifting buoys (at-sea) almost doubled in 2017 (8.6 million compared to 4.5 in 2016), and the number of individual buoys active was 10,915 in 2016 and 18,405 in 2017. In addition, the transmission patterns during 2016 (e.g. general increase over time) were not seen for 2017, reflecting changes in reporting rates. Additional data will be necessary to identify general within-year patterns. A decrease in the number of transmissions and number of buoys transmitting is detected during the FAD closure in 2016 and 2017 (Figure 7). However, note that in 2017, both remain relatively high and constant during the first three months of the closure, apart from a dip on the 31st of August 2017. In both years, a large decrease in the number of transmissions and number of buoys transmitting was detected in December, recovering to the previous level, or higher, in the first week of January. This is also detected in the number of deployments with a large peak in the first week of January during the three years assessed (Figure 7).

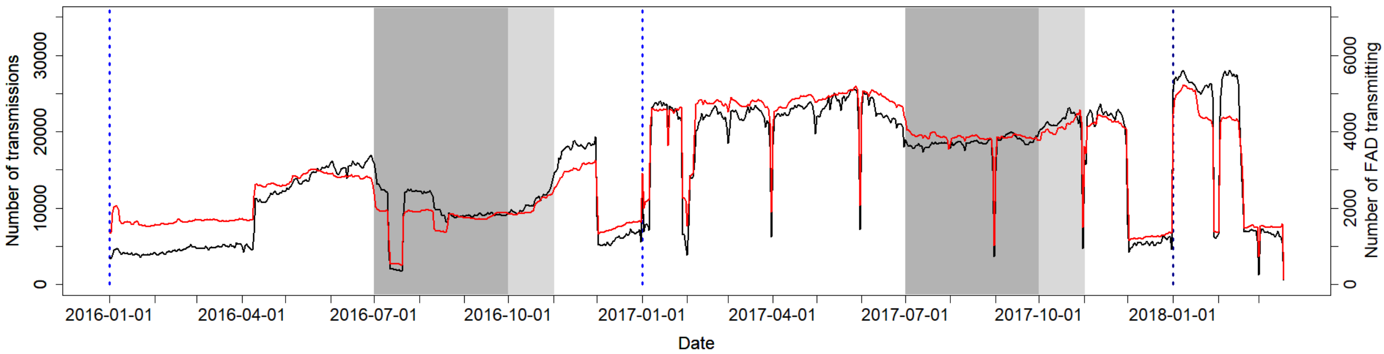

Figure 10. Number of transmission (black line) and unique buoys transmitting (red line) daily from buoys at-sea positions only. Grey areas correspond to the FAD-closure periods (1st of July through 30th of September or October) and blue line January 1st.

Regarding the number of buoys per vessel, for buoys with identified owners (61%), vessels monitored 1 to 350 active buoys per day or per month (Figure 11). However, the majority of vessels had less than 150 active buoys per month and less than 100 per day. It should be noted that this corresponds to the data effectively submitted by fishing companies to PNA, so is likely to be underestimated (see section 3.2). In addition, this reflect the pattern of only 102 purse seine vessels.

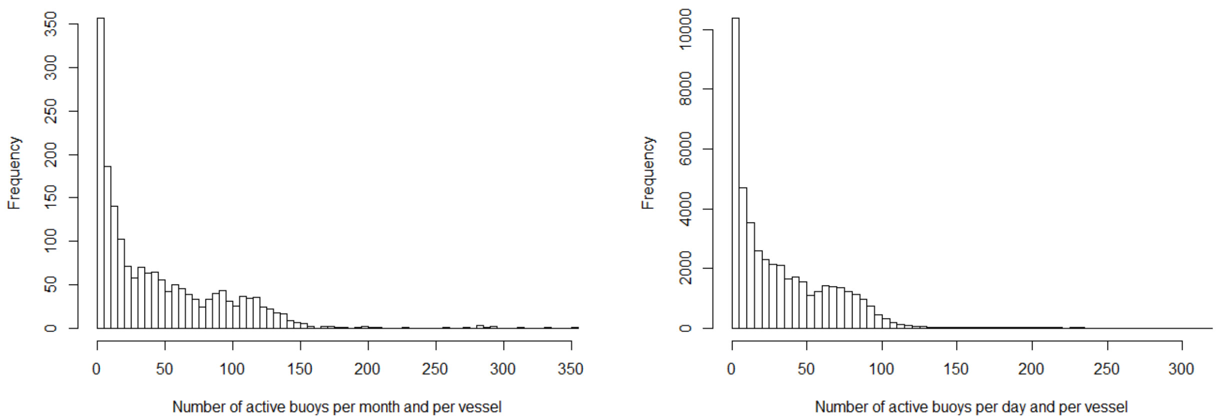

Figure 11. Histograms of the number of active buoys per month (left) or per day (right) per vessel (when vessel name was available), as recorded in the PNA FAD tracking data (see section 3.2. for estimated data submission rates).

Standardised drifting buoy density indicated areas with higher FAD density in Kiribati South of the Gilbert Islands and around the Phoenix Islands; Tuvalu (particularly in 2017); Papua New Guinea; and the Solomon Islands (Figure 12 and A3). Note that a temporal variability in FAD density distribution was detected through the course of the year, which may also be linked to the influence of the ENSO cycle, as these patterns were different between 2016 and 2017. Lower submission rates in 2016 may also have biased the FAD density observed.

Similar to the deployment maps, it is clear that we are missing some information due to geo-fencing with very low FAD densities in some areas outside PNA waters where some FAD sets are performed. For instance, the Southeast or Northeast areas or the High Seas between Tuvalu and Phoenix Islands EEZ. FAD density maps will likely present more extended areas or higher FAD densities, once complete and unmodified FAD tracking data are obtained. Finally, we can clearly see the border of the Phoenix Islands Protected Area (PIPA), with no fishing sets within the reserve but a high density of FADs drifting through.

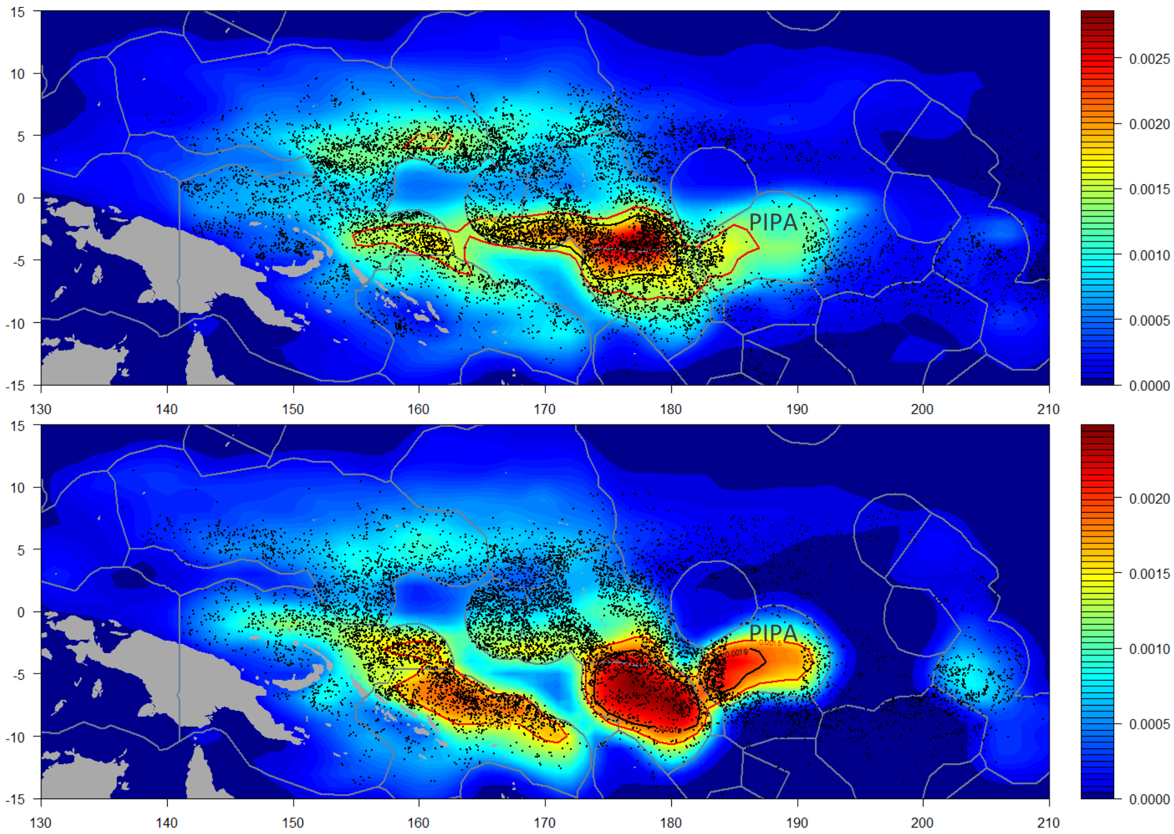

Figure 12. Smoothed standardised kernel density of FAD satellite buoys transmitting at least once per day and per 1° grid cell during 2016 (top) and 2017 (bottom) (maximum number per cell of 3000 in 2016 and 5000 in 2017), with position of associated sets recorded in logsheet data shown as black dots (see Figure A3 for densities maps only). Red lines correspond to the 95th quantile. Colour scale corresponds to the proportion of transmitting per 1° cell.

Drifting at-sea times, varied from less than 10 days to 2 years, with shorter times for buoys redeployed several times (Figure 13). The average drifting time is around 3 months (92 days) with an average drifting distance of 1092 km, whereas the average active time (including on-board sections) is 6 months (173 days) with an average distance between first and last position of 1625 km (Figure 14).

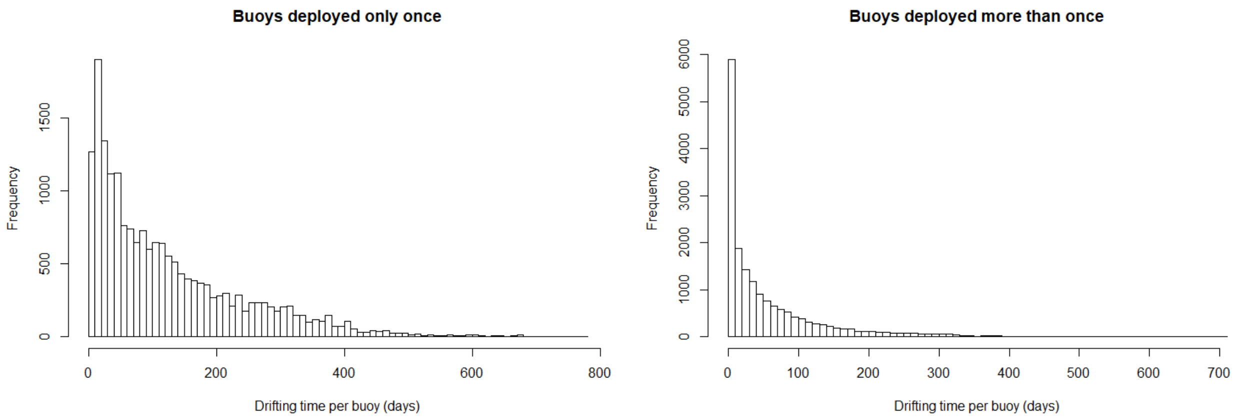

Figure 13. Drifting duration of FAD buoy tracks, for buoys only deployed once and buoys redeployed at least one time.

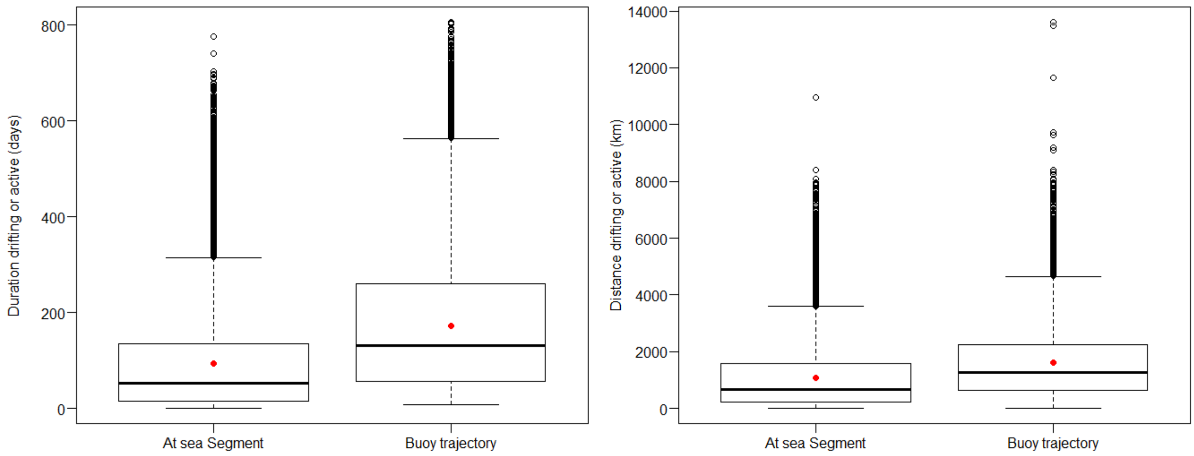

Figure 14. Duration (left) and distance (right) drifting per at sea segment or whole buoy trajectory (whole track including on board segments).

3.5. FAD connectivity

To study FAD connectivity, the WCPO was divided into 4 main areas: i) North (areas above the equator, including FSM and Marshall Islands EEZs), ii) Southwest (including PNG and Solomon Island EEZs), iii) South center (including high seas pocket 2, Nauru, Gilbert Island and Tuvalu EEZs), and iv) Southeast (including the Eastern High Seas, Phoenix and Line Island EEZs, and other areas East of 180°E). For each buoy position in the FAD tracking data at a time *t*, the position of this buoy one month later or one month earlier was studied (Table 4).

In the North and Southwest areas, most buoys were found in the same region (63 and 57%) one month later or have been deactivated (28 and 34%). In the two other areas, the South center and Southeast, around 45% of the buoys were still within the same region one month later, or found to have drifted to the West: in the Southwest (13%) or the Southeast (21%). Finally, 29% and 26% of the buoys were deactivated in these areas, a number relatively constant among areas.

Regarding the source of buoys one month before a certain position, some differences between areas were also detected. Most buoys in the Southeast were deployed there (47%), compared to 35% in the South center, 21% in the North and 18% in the Southwest. Other patterns were similar to those observed for presence one month after a certain position, and as described in the previous paragraph.

Table 4. Buoy connectivity (in %) by large areas of the WCPO.

	Position month t + 1					
Position month t	N	SW	SC	SE	Deactived[1]	Unknown[2]
North (N)	63.2	2.4	1.2	1.1	27.9	4.3
Southwest (SW)	3.1	57.0	2.5	0.2	33.9	3.4
South center (SC)	4.6	13.0	46.0	1.9	28.7	5.9
Southeast (SE)	2.3	0.2	20.6	43.6	26.0	7.2
	Position month t - 1					
Position month t	N	SW	SC	SE	Deployed[3]	Unknown[2]
North (N)	57.6	4.0	9.1	3.6	21.0	4.8
Southwest (SW)	2.4	49.5	23.3	0.8	18.0	5.9
South center (SC)	0.8	2.4	37.6	20.4	35.3	3.5
Southeast (SE)	1.7	0.4	4.4	41.7	46.9	4.9

[1] If the buoy have been deactivated (lost, beached, etc.) in the month following the position t.

[2] If no position is available between the 30th and 60th day after the position t (gap in the data).

[3] If the just have been deployed or redeployed in the month preceding the position t.

3.6. Fate of FADs

More than half of the buoys were found to be drifting within the main purse seine fishing area at the end of each trajectory and about a quarter could be considered 'lost' i.e. still drifting but outside the main fishing areas of the PNA waters (Figure 15 and 16). Around 10% of the FADs were recovered by a vessel (owner or another vessel), either at sea, or close to shore (<10km from shore) (Figure 15 and 16). Finally 5% of the buoys ended up beached (i.e. stranded on shore, see next section for details).

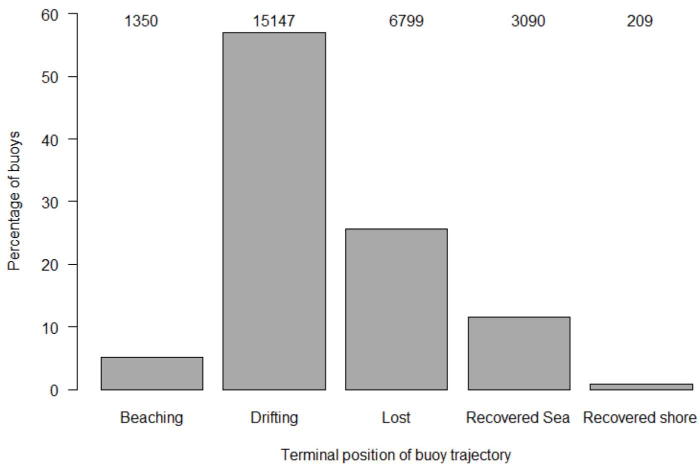

Figure 15. Percentage of buoys terminal position. See section 2.2 Deployments and end of track positions, for definition of each end of track category.

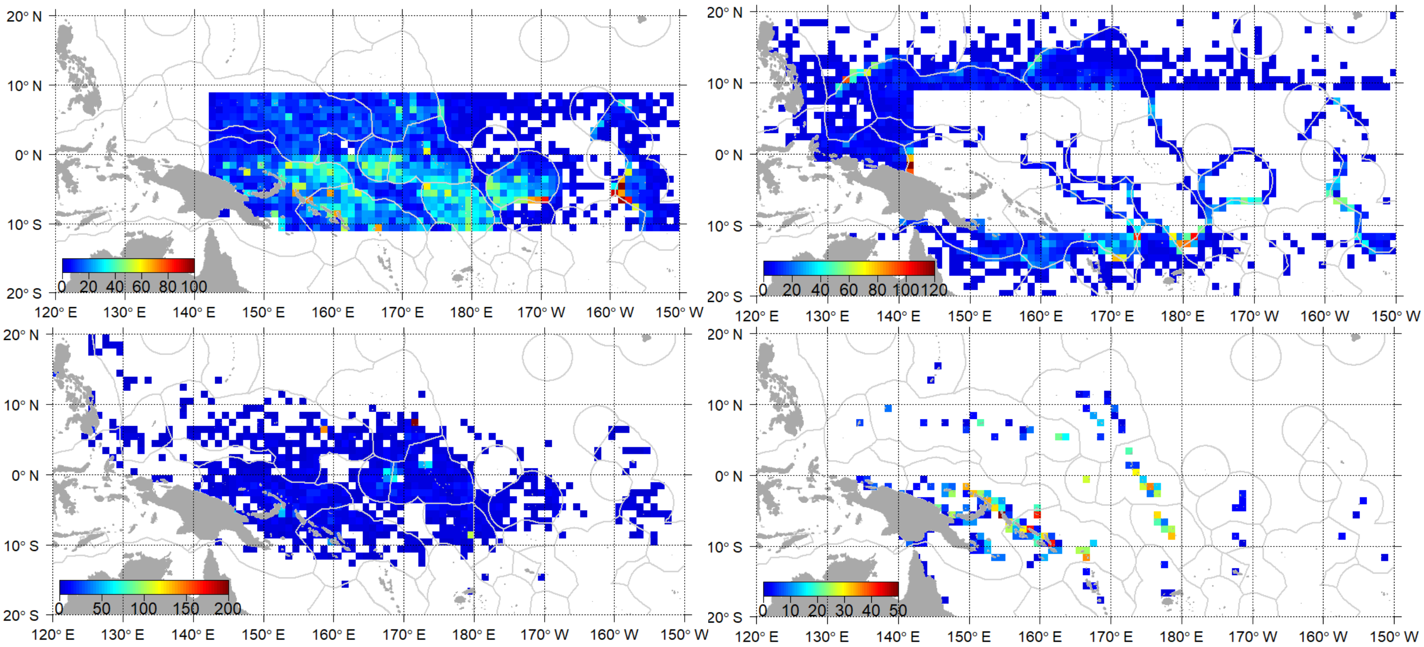

Figure 16. Density maps of last position for each buoy in the FAD tracking data i) still drifting (top left), ii) lost (top right), iii) recovered (bottom left) or beached (bottom right).

3.7. Beaching

Beaching events (FADS washing up on shore or entangling on a reef), were identified where the buoy location does not change for 3 consecutive transmissions when within 10km of land. Most beaching events occurred in the EEZs of Papua New Guinea and Solomon Islands, as well as Kiribati's Gilbert Islands and Tuvalu (Figure 17 and Table 5). Generally, three main areas of beaching could be identified: the Southwest area, with the most beaching events; the South centre area, with relatively high beaching rates; and the Northern area, with lower beaching rates (Figure 17).

Table 5. Number of beaching events in the 2016–2018 period by EEZ.

EEZ	Number of FAD beaching events
Kiribati Gilbert	155
Nauru	23
Tuvalu	117
PNG	483
Solomon islands	379
Marshall Islands	45
FSM	85
Other	79

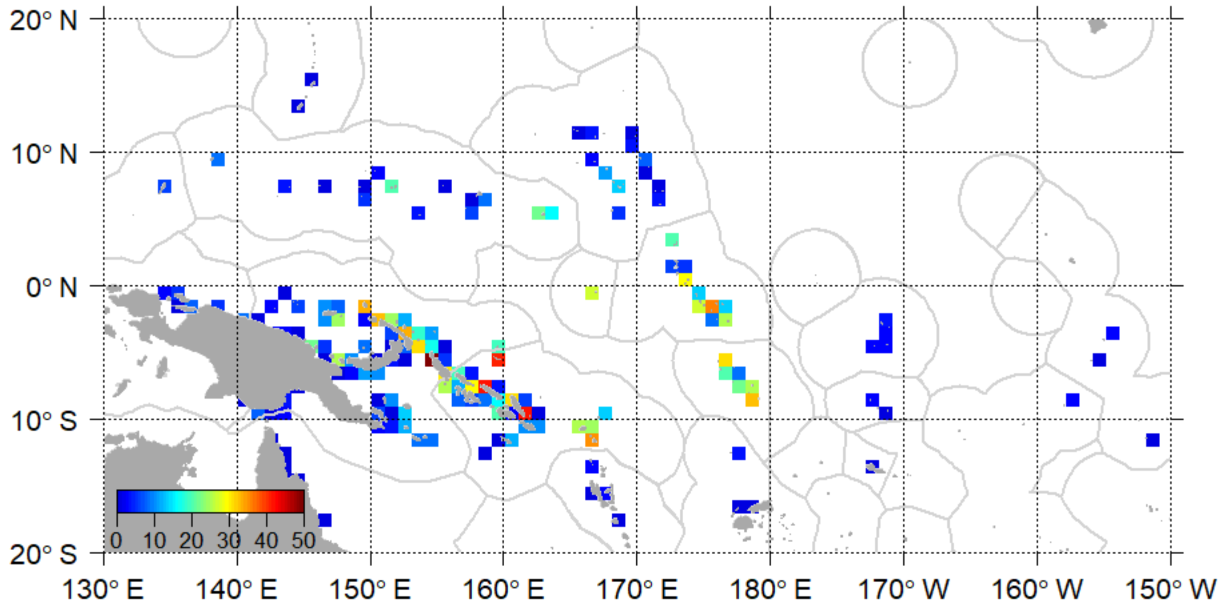

Figure 17. Density of FAD beaching events by 1° grid cell over the 2016–2018 period.

To investigate drifting and deployment patterns of beached FADs, we first defined deployment areas based on the general deployment patterns for the whole study period (see Figure 9 for patterns per year). Three main hotspots of deployments were considered: i) East of the PNG EEZ and extending to the High sea pocket 2 (called Hotspot 1) ; ii) a large hotspot in the centre of the WCPO mostly covering Kiribati, Nauru, North of Tuvalu and high seas (Hotspot 2); and iii) West of Kiribati Phoenix Island EEZ (Hotspot 3). Deployments outside these three main areas were classified by general area (North, i.e. >0°, Southwest of 165° and Southeast of 165°).

Deployment areas were investigated for FADs classified as beached using the buoy trajectories, with varying patterns depending on beaching and deployments areas and drifting duration (Figure 18 and 19). For instance most FADs beaching in the Southwest area were deployed either i) in the same region outside the deployment hotspots and had a drift duration of <3 months; or ii) in the deployment Hotspot 2 and drifting for longer time. In the South centre area, most beached FADs were deployed in the deployment Hotspot 2 and drifted for less than 3 months. Finally, most FADs beaching in the North were deployed in the same area and had been drifting for various durations (Figure 18 and 19).

	OUT North					OUT Southwest					Hotspot 1					Hotspot 2					OUT Southcenter					Hotspot 3				
Beaching cells	<1	1-3	3-6	6-9	9+	<1	1-3	3-6	6-9	9+	<1	1-3	3-6	6-9	9+	<1	1-3	3-6	6-9	9+	<1	1-3	3-6	6-9	9+	<1	1-3	3-6	6-9	9+
North	5	20	22	15	12	0	1	1	1	1	0	0	0	0	1	0	1	1	4	6	0	0	0	1	2	0	0	0	1	2
Southwest	0	0	1	1	1	8	15	13	5	4	0	2	2	0	0	0	3	9	7	6	0	0	2	5	8	0	0	1	3	4
Southcenter	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	15	17	8	4	3	3	6	11	5	8	0	6	8	2	3

Figure 18. Percentages of beaching events by beaching area (left) depending on area of deployments (top) and drifting duration in months.

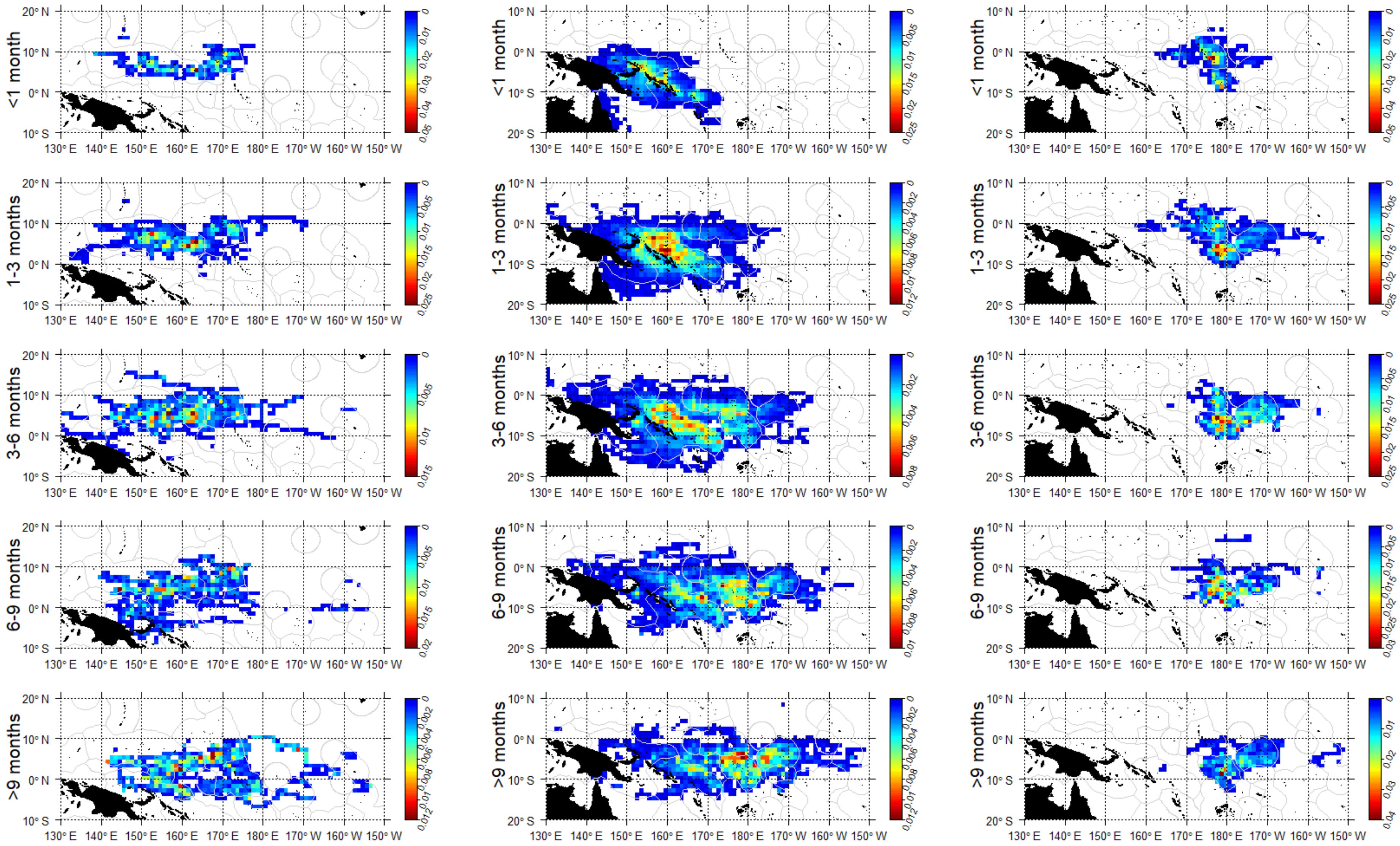

Figure 19. Spatial probability density of buoys trajectories entering beaching cells in the North (left), Southwest (center) and South center (left) (no beaching events identified in the Southeast area). Standardised densities during five drifting-time bins prior to beaching are shown (rows).

4. Discussion and Conclusion

The data volume submitted to PNA has clearly increased overtime, and quality of the data for analysis can be improved through the implementation of the cleaning 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 for management purposes that could be formulated. Similarly, *in-situ* data related to FAD characteristics (observer data as recorded until now or captain's records) are still too rare and imprecise. FAD tracking analyses could be greatly improved with complete and precise records of i) manufacturer buoy ID number; ii) FAD and buoy deployment date (given that FADs themselves are marked); and iii) information on the FAD (depth, width/length) and by the complete unmodified submissions of data from satellite buoys deployed on FADs by companies fishing in PNA waters.

Nevertheless, the analyses presented in this report increase our understanding of the spatial and temporal use of FADs in the WCPO, as well as the potential utility of a larger and complete FAD tracking dataset. We estimated that the number of buoys with data submitted to PNA represent ~30–40% of the buoys used by the purse seine fleet in the PNA waters. Therefore, with the dataset comprising 10,915 and 18,405 active buoys in 2016 and 2017, respectively, the total number of FADs used per year, in PNA waters only, could be 18,556–31,289, in agreement with previous estimations for the whole WCPO (Gershman et al., 2015). Estimates of FAD deployments or FADs active per vessel and overall in the WCPO are studied in more detail in WCPFC-SC14-MI-WP-10 (Escalle et al., 2018).

This year, as mentioned in CMM-2017-01, the Commission will consider the adoption of measures on the implementation of non-entangling and/or biodegradable material on FADs. This report estimated that at least 5% of the buoys end up beached, however we note that this is probably an underestimate as buoys may be deactivated before reaching coastlines. Beaching can damage sensitive ecosystems such as coral reefs (Balderson and Martin, 2015). Furthermore at least 26% of the buoys on drifting FADs in our dataset could be considered 'lost', likely leading to marine pollution or unnoticed beaching. This therefore highlights the importance of considering the use of bio-degradable FADs in the WCPO.

Potential additional research topics include:

- Re-construct the whole track of geo-fenced FADs using a drift model in order to get a more spatially representative estimates of FAD density.
- Investigate the operational use of FADs and fishing strategies, for instance through i) the change in ownership/ leasing of buoys and/or FADs; ii) the change in transmission frequency, which may be linked to fishing events or to FADs leaving main fishing areas; iii) accessing information not recorded by observers (e.g. deployments by night or by non-purse seine vessels); and iv) analysing patterns of deployments and drifting behaviour between areas/EEZs or seasonally, using multiple FAD deployments at the same position and time.
- Analyse the link between tuna catch and specific factors such as soak time, drift speed, FAD characteristics, FAD vs Log or echo sounder buoy, and ocean environment experienced throughout a trajectory.
- 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 FAD density related to CPUE and catch data. In particular, compare the size of the tuna school captured in areas of high and low FAD density to investigate tuna school fragmentation.
- Potentially, incorporate biomass data from sonar buoys within the analysis, where operational and FAD tracking data can be related. This could provide significant insights into purse seine vessel behaviour and potential implications for effort creep, as well as offering new sources of information on stock biomass and factors affecting abundance.

We invite WCPFC-SC14 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.
- Noting on-going WCPFC considerations, and findings that an estimated 25% of the FADs drifted out of main fishing areas and a minimum of 5% are beached, SC14 is invited to discuss i) the importance of FAD marking and monitoring programmes to better identify and follow individual FADs and ii) the potential benefit of using biodegradable material on FADs.

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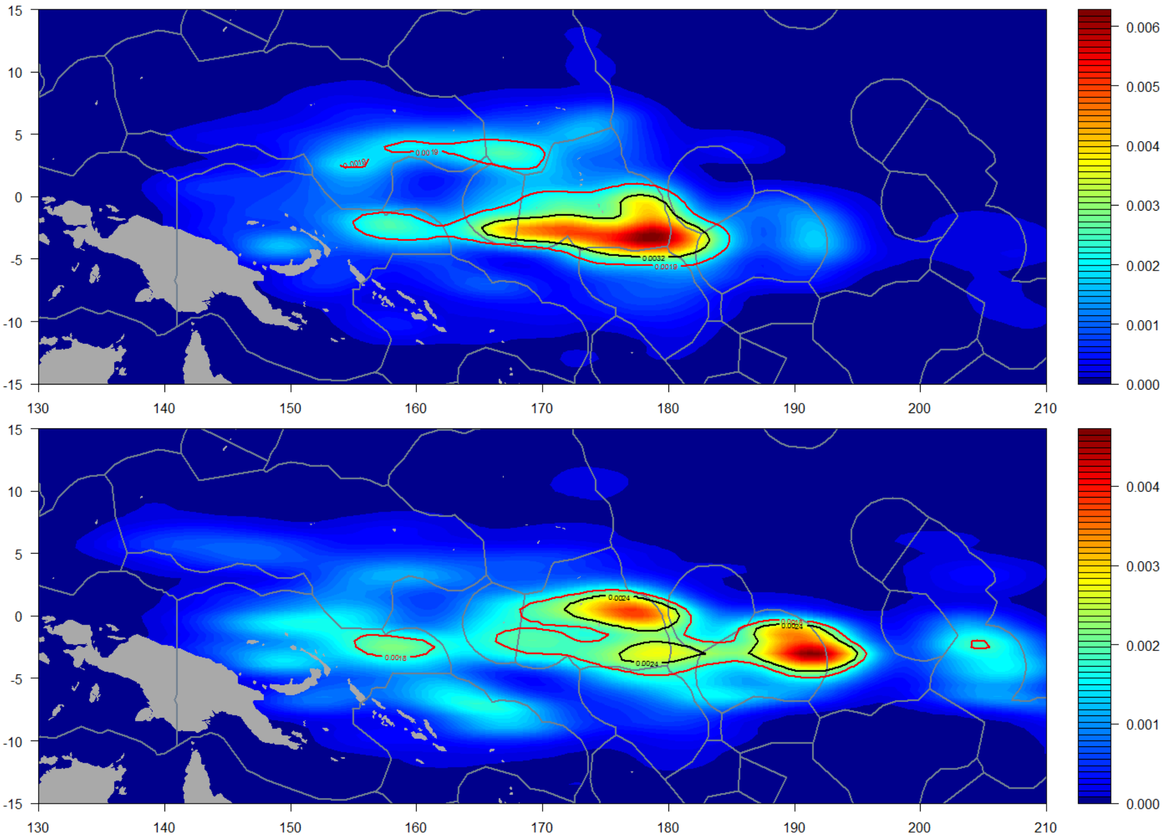

Figure A1. Smoothed kernel density of deployments of buoy per 1° grid cell during 2016 (top) and 2017 (bottom) (maximum number of deployments per cell of 140 in 2016 and 300 in 2017). The red line corresponds to the 95th quantiles. Colour scale corresponds to the proportion of buoy deployment per 1° cell.

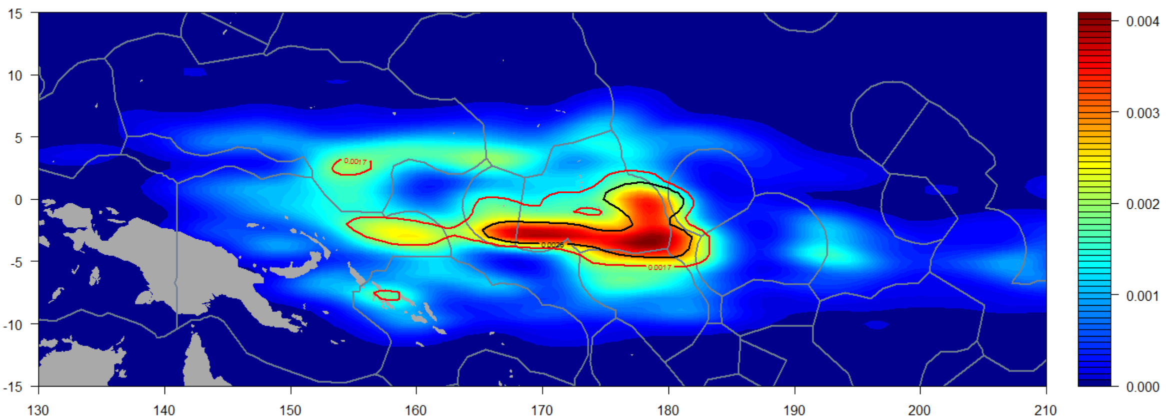

Figure A2. Smoothed kernel density of FAD and buoy deployments recorded in observer data in 2016 (maximum number of deployments per cell of 190 in 2016). Red and black lines correspond to the 95th and 98th quantiles. Colour scale corresponds to the proportion of buoy deployment per 1° cell.

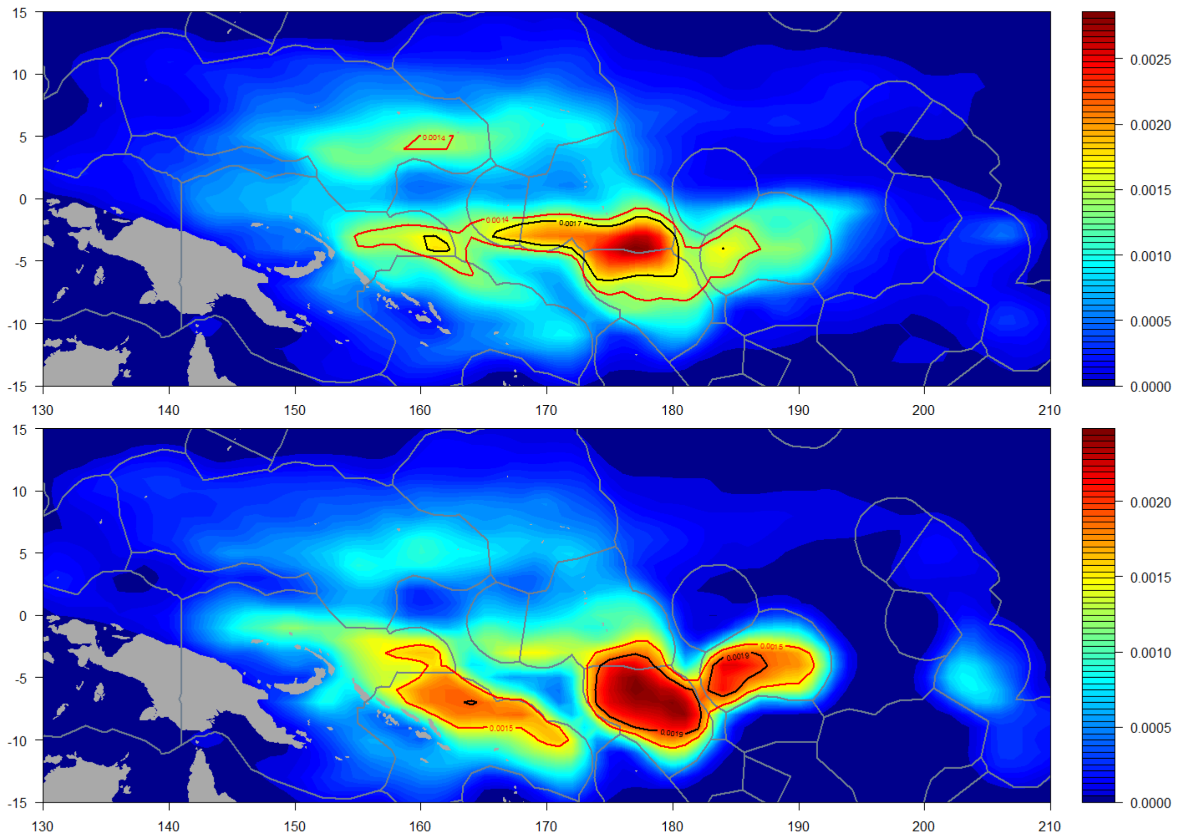

Figure A3. Smoothed standardised kernel density of FAD satellite buoys transmitting at least once per day and per 1° grid cell during 2016 (top) and 2017 (bottom) (maximum number per cell of 3000 in 2016 and 5000 in 2017). Red lines correspond to the 95th quantile. Colour scale corresponds to the proportion of transmitting per 1° cell.