Pacific dFAD Retrieval Feasibility Study

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Executive summary

This report presents results from a study, in partnership with fishing companies, to identify and evaluate options for reducing drifting Fish Aggregating Devices (dFADs) loss and abandonment and thus the ecosystem impacts linked to it. The study investigates the spatial and temporal variability of dFAD use and fate, specifically when drifting out of fishing areas, for historical buoy tracking data extending over the last 10 years. These data were made available by Cape Fisheries, the US Tuna group and Marpesca.

Areas with higher dFAD deployments, dFAD density, and four categories of dFAD fate (abandonment, loss, recovery and beaching) were identified. Based on the patterns detected, different options to limit the number of dFADs lost, abandoned, or beached were considered. Firstly, deployments could be limited in areas where deployments lead to higher rates of dFAD beaching and abandonment. This could reduce beaching by 10.4% and dFAD abandonment by 4.4%. Secondly, nine spatial boxes, close to shore, with higher rates of abandonment and beaching were identified. Recovering dFADs transiting in these spatial boxes could lead to a 60.0% reduction in beaching and 34.7% reduction in dFAD abandonment. Thirdly, recovering all dFADs transiting in large dFAD abandonment hotspots, outside main fishing areas, could lead to a 57% reduction in beaching and 57.2% reduction in dFAD abandonment. Finally, recovering dFADs in an area that overlaps the southern dFAD abandonment hotspot and the dFAD density hotspot could lead to a 57% reduction in beaching and 45.4% reduction in dFAD abandonment. It should, however, be noted that the number of dFADs entering the fishing grounds after transiting through the potential recovery areas needs to be considered, as well as the number of dFADs transiting per day or month. Follow-up work based on the results from this study could explore the economic feasibility of the dFAD recovery options identified.

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1. Background and purpose of research

The use of drifting Fish Aggregating Devices (dFADs) by industrial purse seiners has raised several concerns linked to the capture of small bigeye and yellowfin tuna, as well as higher bycatch rates than on free schools (Dagorn *et al.*, 2013). Recently, there has also been an increasing focus on the ecosystem impacts of the expanding use of dFADs including marine pollution, ghost fishing and habitat damage through "beaching" of dFADs on the shores and coral reefs of Pacific Island Countries and Territories (PICTs) (Filmalter *et al.*, 2013; Balderson and Martin, 2015; Escalle *et al.*, 2020a). Recent work has estimated that 20,000 to 40,000 dFADs are deployed annually in the Western and Central Pacific Ocean (WCPO) (Escalle *et al.*, 2021). In addition, some work based upon the position information provided by dFAD satellite buoys (hereafter refers to "dFAD" only in this document) has suggested that only 10% of the dFADs were recovered, while at least 7% were beached (Escalle *et al.*, 2019a, 2020b). The growing focus on the issue of marine pollution, beaching and entanglement of Species of Special Interest (SSI) has led to the implementation of management measures regarding the use of low-entanglement risk dFADs and the encouragement of the use of biodegradable dFADs (CMM-2018-01). In addition, the potential for dFAD retrieval activities to reduce environmental impacts linked to the extensive use of dFADs is also considered. However, the practical and economic feasibility of such a programme needs to be evaluated.

This study, in partnership with fishing companies, has the objective of evaluating the practical and economic feasibility of retrieving dFADs that have drifted outside areas of normal dFAD fishing activity, with a particular focus on those that have the potential to beach on land. This study uses historical buoy tracking data, from three partner fishing companies (Cape Fisheries, the US Tuna group and Marpesca), over the last 10 years to identify and evaluate options to reduce dFAD loss and abandonment and thus the ecosystem impacts linked to it.

2. Methods

2.1. Summary of data

Following analyses of a preliminary dataset encompassing 1-year of anonymised buoy data, i.e., position of buoys deactivated between 26th March 2019 to 25th March 2020 (Table 1), the need for a larger dataset was highlighted. This would allow better characterisation of patterns of dFAD loss, beaching and investigation of the stability in these features through time. Ten years of anonymised historical satellite buoy data were received from two satellite buoy providers, Satlink and Marine Instruments. Zunibal, the third buoy brand used by the partner fishing companies, withdrew from the project due to limitations resulting from the Covid-19 pandemic. Updated data received correspond to all buoys deactivated between 2010 and 2019 and are from buoys transmitting between 3rd March 2010 to 31st December 2019 (Table 1).

The first step, prior to analysis, consisted of processing and cleaning the data to identify and remove transmissions from buoys on board a vessel (before deployments or following recovery). The initial filtering further consisted of:

- removal of buoys activated for short periods to verify functioning and avoid bias in the analyses due to very short overall active time;
- the removal of buoys with less than 10 transmissions;
- removal of buoys active for less than seven days, and;
- removal of buoys with transmissions from a single position.

A Random Forest model was performed to identify on-board and at-sea position and hence identify deployment positions (see method in Escalle *et al.*, 2019).

Table 1. Summary of data received as part of the initial 1-year extract and the updated 10-year extract.

2020 Extract	Satlink	Marine Instruments
Number of dFADs in raw dataset	3,775	277
Number of transmissions in raw dataset	1,599,294	435,441
Number of dFADs in processed dataset	3,769	268
Number of transmissions in processed dataset	1,589,582	50,691
% of positions at-sea	94%	98%
2021 Extract	Satlink	Marine Instruments
Number of dFADs in raw dataset	13,406	524
Number of transmissions in raw dataset	6,676,535	805,872
Number of dFADs in processed dataset	13,178	522
Number of transmissions in processed dataset	6,505,899	804,029
% of positions at-sea	94%	88.4%

For the sake of simplicity, “dFAD” will be used only when referring to buoys deployed on dFADs in this report.

2.2. Spatial and temporal variability in last positions of dFAD trajectories

Locations of the last transmissions of individual FADs, referred to hereafter as “signal loss”, were investigated. These were identified as: i) last position of a trajectory if the signal loss occurred while the dFAD was drifting at-sea (as identified by the Random Forest model mentioned above); or ii) last recorded at-sea position of the trajectory if the signal loss was recorded on-board a vessel (i.e., location of the dFAD immediately before being picked up by a vessel).

A focus was then placed on 1° cells (~12 321 km² or 3600 nm² at the equator) having higher rates of signal loss (i.e., > 0.9 quantile). Spatial boxes presenting higher numbers of signal loss were then defined, with the objective to cover all the high signal loss cells in one specific area, but to maintain the smallest possible area. Temporal variability in signal loss is investigated at different scales: i) 1° cell; ii) spatial box; and iii) Exclusive economic zone (EEZ).

2.3. Fate of dFADs

DFAD positions at the end of their trajectories were investigated to study the fate of DFADs. The end of a trajectory (i.e., last position recorded) was classified as: i) beached if the last position was “at-sea” and within 10 km of shore (excluding positions located at less than 10 km from major ports) and at least the last three positions were at 0m, <10m, or <100m from each other; ii) recovered if the last position was “on-board”; iii) still at-sea.

To further investigate the fate of dFADs identified as still drifting at-sea at the end of their trajectories, additional information was used to differentiate dFADs deliberately abandoned by fishers (i.e., remotely deactivated while still drifting) from dFADs that were simply lost (i.e., unintentional loss of signal). The latter category would include the appropriation of the dFAD by another vessel, the sinking of the dFAD, or buoy malfunction. It could also include the recovery of the dFADs with the buoy rapidly switched off, which would be reclassified as recovered.

For the Satlink buoys, the date of satellite transmission deactivation and the date of manual switch off, if it occurred, were available. For Marine Instruments buoys, only the date of satellite transmission deactivation was available. If a date of manual switch off was available, the dFAD was considered as recovered. If no manual switch off date was available and the date of satellite transmission deactivation was within five days of the last known position, the dFAD was considered as deliberately abandoned by fishers. Finally, if the date of satellite transmission deactivation was more than five days from the last known position, it was considered that fishers had lost communication with the buoy, for an unintentional reason, and therefore classified as lost.

3. Spatial and temporal description of the data

3.1. Deployment areas

The spatial distribution of deployment of all dFADs in the available dataset was compiled (Figure 1). Two main areas of deployments can be identified. The first one in the EPO, along the equator, with a core area from 140°W to 120°W and an extended area toward the East reaching the border of the Galapagos EEZ. The second area is in the WCPO, mostly in the high seas region between the Kiribati Phoenix Islands, the Cook Islands, and the Kiribati Line Islands (Figure 1).

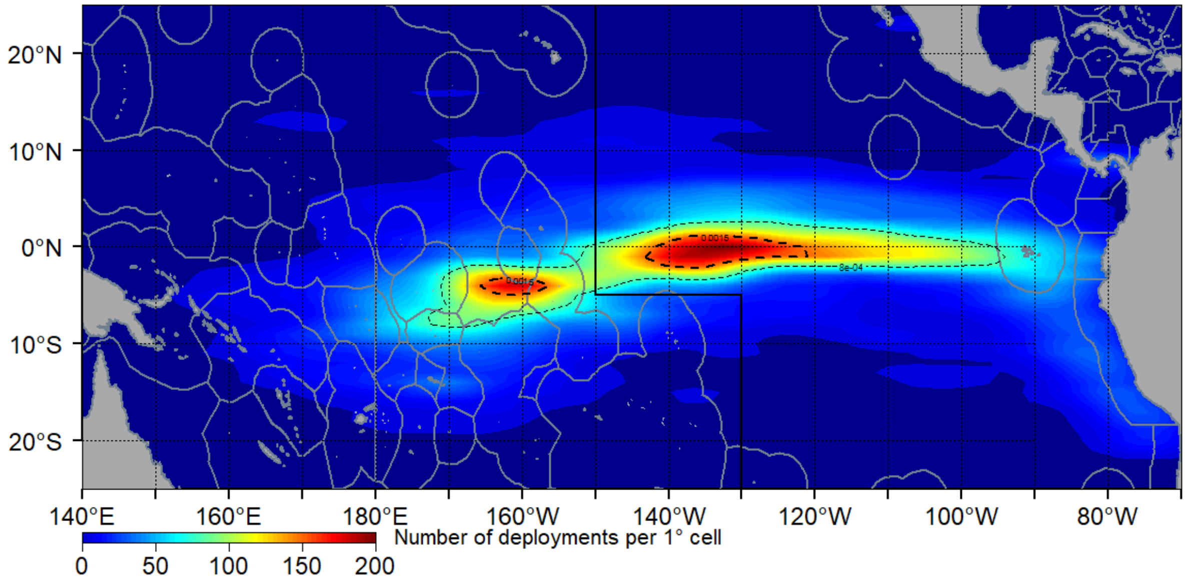

Figure 1. Deployment areas of all dFADs in the available dataset. Dotted black lines indicate the 0.9 and 0.98 quantiles, as main and extended dFAD deployment areas. The black line indicates the limit between the WCPO and the EPO convention areas.

3.2. DFAD density

DFAD density across all years and DFAD (individual DFADs were only counter ones per 1° cells) was also examined and showed two main areas. The main one has been in the WCPO, covering Tuvalu; Kiribati Phoenix Islands, Tokelau, north of the Cook Islands, through the centre of the Kiribati Line Islands and extending to 120°W (Figure 2). In the EPO, the main dFAD density area is north of the equator from 150°W to 130°W and up to 10°N (Figure 2).

Annual variability in dFAD density was examined and did not show major differences, although the core of the distribution shifted from year to year (Figure S1). High monthly variability was detected, with higher dFAD density in the EPO hotspot from July to October, during the WCPO closure period (Figure S2).

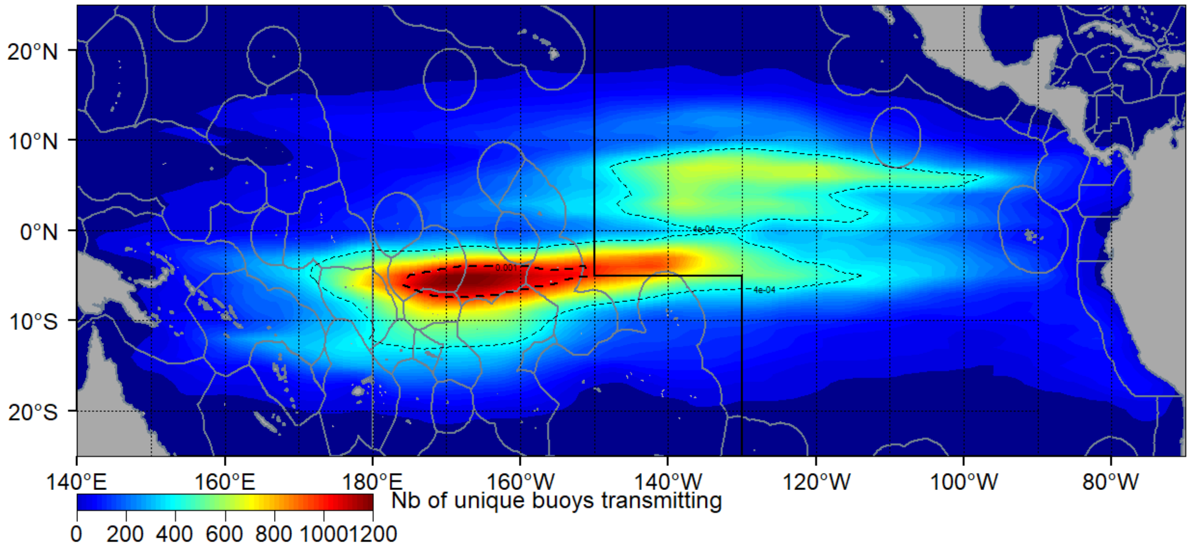

Figure 2. Spatial distribution of dFAD density. Dotted black lines indicate the 0.9 and 0.98 quantiles, as main and extended dFAD density areas. The black line indicates the limit between the WCPO and the EPO convention areas.

3.3. Signal loss

The number of signal loss events fluctuate during the year, with a lower number of signal loss events in August and a higher number in December each year (Figure 3).

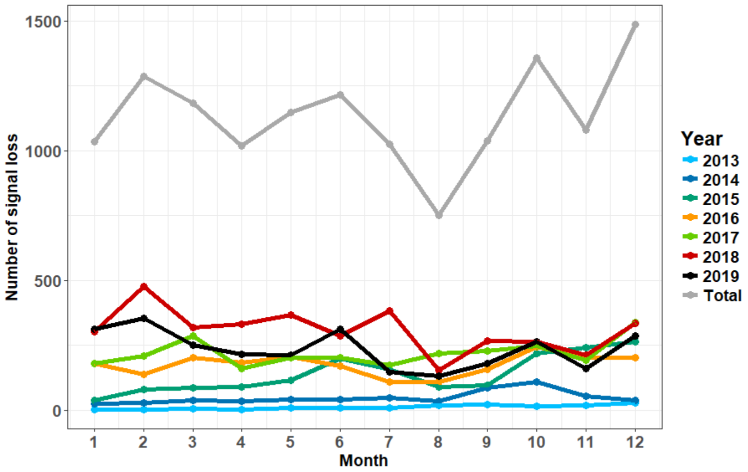

Figure 3. Number of signal loss events per month and year in the whole Pacific Ocean between 2010 and 2019.

A total of 12,870 dFADs lost signal while still drifting (93.9%), and 832 while on-board a vessel (6.1%). Figure 4 shows the location of all signal loss events of dFADs drifting at-sea. Regarding the WCPO specifically, 10,732 signal loss events (78.4%) were found (Figure 1), the rest being in the Eastern Pacific Ocean (EPO). Most signal loss events (38.0%) were in high seas areas (Figure 4 and Table 2). The EEZs with the most signal loss were the Solomon Islands (910, 6.7%), French Polynesia (826, 6.1%), the Cook Islands (796, 5.8%), PNG (595, 4.4%), Tuvalu (591, 4.3%) and Fiji (573, 4.2) (Table 2).

In the above noted EEZs with higher rates of signal loss events, annual and monthly variability was detected (Figure 5). Higher numbers of signal loss events were found in 2017 and 2018 in French Polynesia, 2018 in the Cook Islands, and 2016 in PNG. An increasing trend was detected for Fiji and a stable trend from 2015 for the Solomon Islands. Regarding monthly variability, higher signal loss events occur in the first half of the year in French Polynesia and the Cooks Islands, while for the Solomon Islands and PNG, it occurs in the latter half of the year.

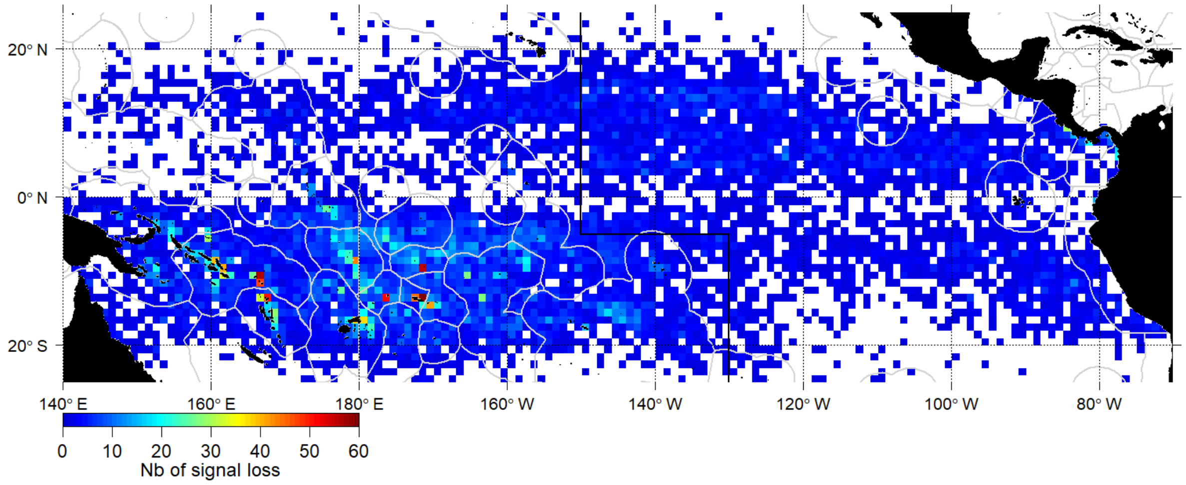

Figure 4. Spatial distribution of signal loss positions in the entire Pacific Ocean. The solid black line indicates the limit between the WCPO and the EPO convention areas.

Table 2. Number and percentages of signal loss events per EEZs. Only EEZ with >1% of all signal loss are shown here. Two letter country codes used in the subsequent figures and Tables are listed for EEZs

EEZ	No. of signal losses	% of total
High seas (HS)	5173	38.0
Solomon Islands (SB)	910	6.7
French Polynesia (PF)	826	6.1
Cook Islands (CK)	796	5.8
Papua New Guinea (PNG)	595	4.4
Tuvalu (TV)	591	4.3
Fiji (FJ)	573	4.2
Kiribati Line Islands (KI LN)	425	3.1
Kiribati Phoenix Islands (KI PX)	376	2.8
Kiribati Gilbert Islands (KI GL)	341	2.5
Vanuatu (VU)	327	2.4
Tokelau (TK)	290	2.1
American Samoa (AS)	257	1.9
Wallis and Futuna (WF)	221	1.6
Tonga (TO)	207	1.5
Marshall Islands (MH)	188	1.4
Samoa (WS)	171	1.3
Australia (AU)	145	1.1
Costa Rica (CR)	141	1.0

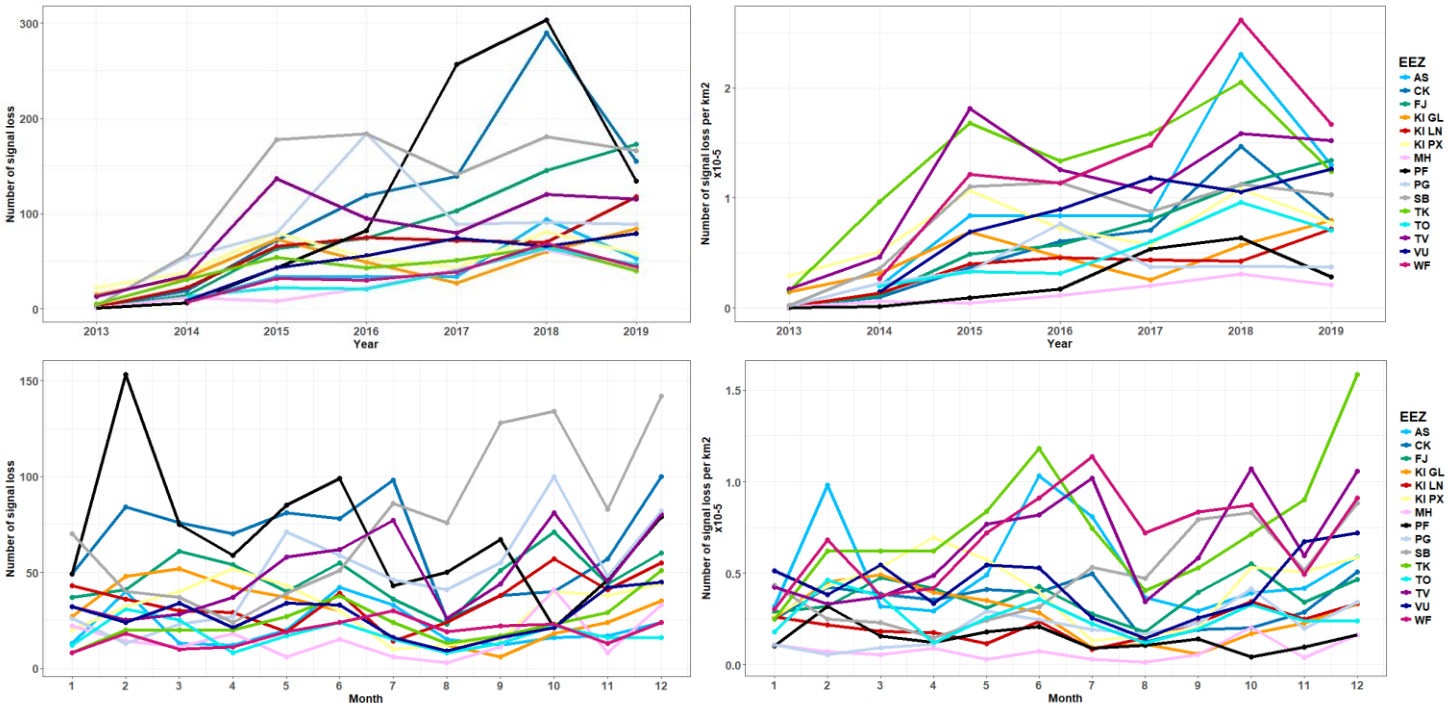

Figure 5. Annual (top) and monthly (bottom) varibility in the number of signal loss events per EEZ (left) and number of signal loss events standaridsed by the EEZ size in km2 (rigth).

To better identify signal loss events outside main fishing areas, the ratio between signal loss events and dFAD density (i.e., number of DFAD transmitting at least once per 1° cell or EEZ) was investigated (Figures 6, 7, S3 and S4). This clearly highlights areas with disproportionate levels of signal loss events relative to dFAD density, especially in the EEZs of French Polynesia, Fiji, Vanuatu, Solomon Island, PNG and around the islands of the Gilbert Islands, Tuvalu, Wallis and Futuna, Samoa and American Samoa (Figure 6). At the scale of each EEZ, a higher ratio was detected in PNG, the Solomon Islands, and the Marshall Islands, with a peak in 2014 and 2019 (Figure 7). These EEZs also have higher ratio at the end of the year (November, December), while Vanuatu showed a higher ratio the first half of the year (Figure 7).

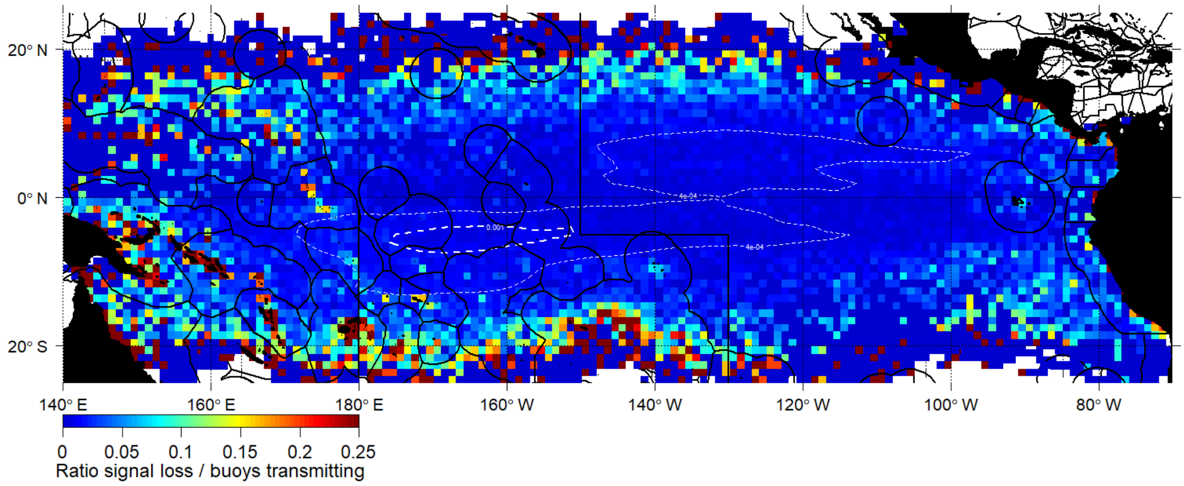

Figure 6. Spatial distribution of the ratio between number of signal loss events and dFAD density per 1°cell. Dotted white lines indicate the 0.9 and 0.98 quantiles of dFAD density, as identified in Figure 2. The solid black line indicates the limit between the WCPO and the EPO convention areas.

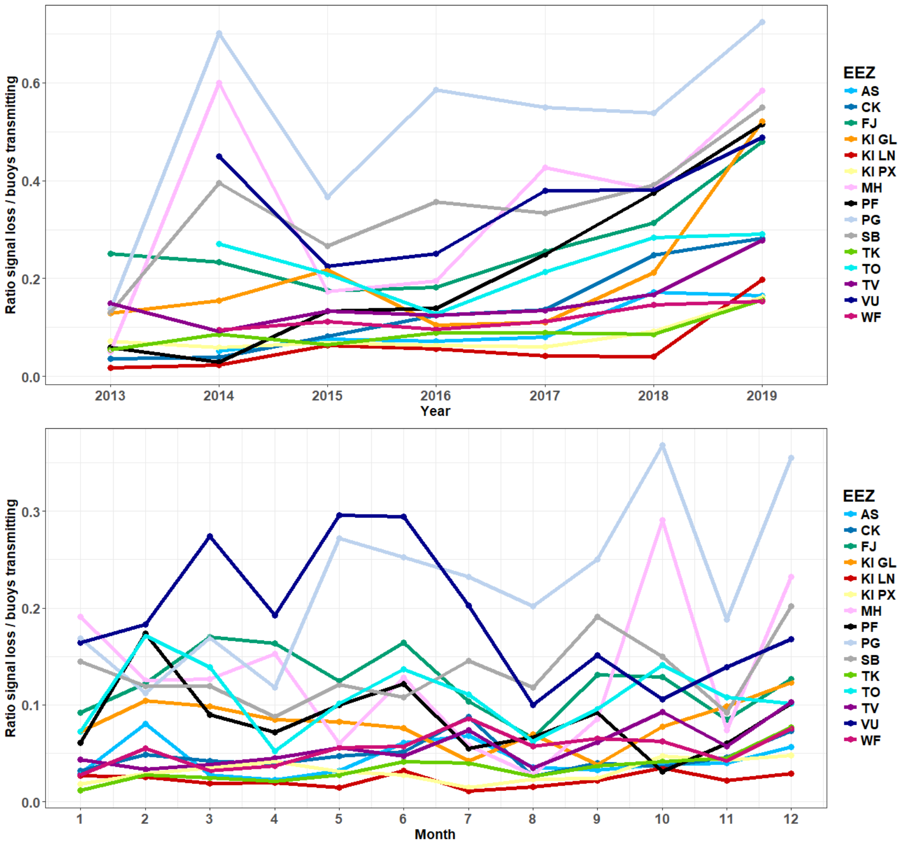

Figure 7. Annual (top) and monthly (bottom) variability in the ratio between signal loss events and DFAD density per EEZ.

3.4. Fate of dFADs

Most dFADs (80.9%) were still drifting at-sea at the end of their trajectories, with 46.5% of dFADs classified as lost and 34.4% abandoned (Table 3). Some difference was detected between the WCPO and the EPO, with 70.6% of dFADs lost in the EPO compared to 39.8% in the WCPO; and 14.4% of dFADs abandoned in the EPO compared to 40.0% in the WCPO (Table 3 and Figure 8). A clear difference in the spatial distribution of lost and abandoned dFADs can be detected, with most lost dFADss having a final position within the main dFAD density areas, while most abandoned dFADs are found outside (Figure 8). The percentage of dFADs recovered is 12.2%, similar in both the EPO and the WCPO (Table 3 and Figure 8). Finally, overall, in the Pacific, 6.9% of dFADs were found beached, with most of them in the WCPO (7.9% of all WCPO fate compared to 3.4% in the EPO, Table 3 and Figure 8)

Table 3. Fate of dFADs in the WCPO and EPO, as indicated by the position of the dFAD last transmitted position.

	WCPO		**EPO**		**Total**	
	Numbers	%	Numbers	%	Numbers	%
Abandoned	4291	40.0	427	14.4	4718	34.4
Lost	4270	39.8	2094	70.6	6364	46.5
Recovered	1326	12.4	343	11.6	1669	12.2
Beached	847	7.9	102	3.4	949	6.9
Total	10734	100.0	2966	100.0	13700	100.0

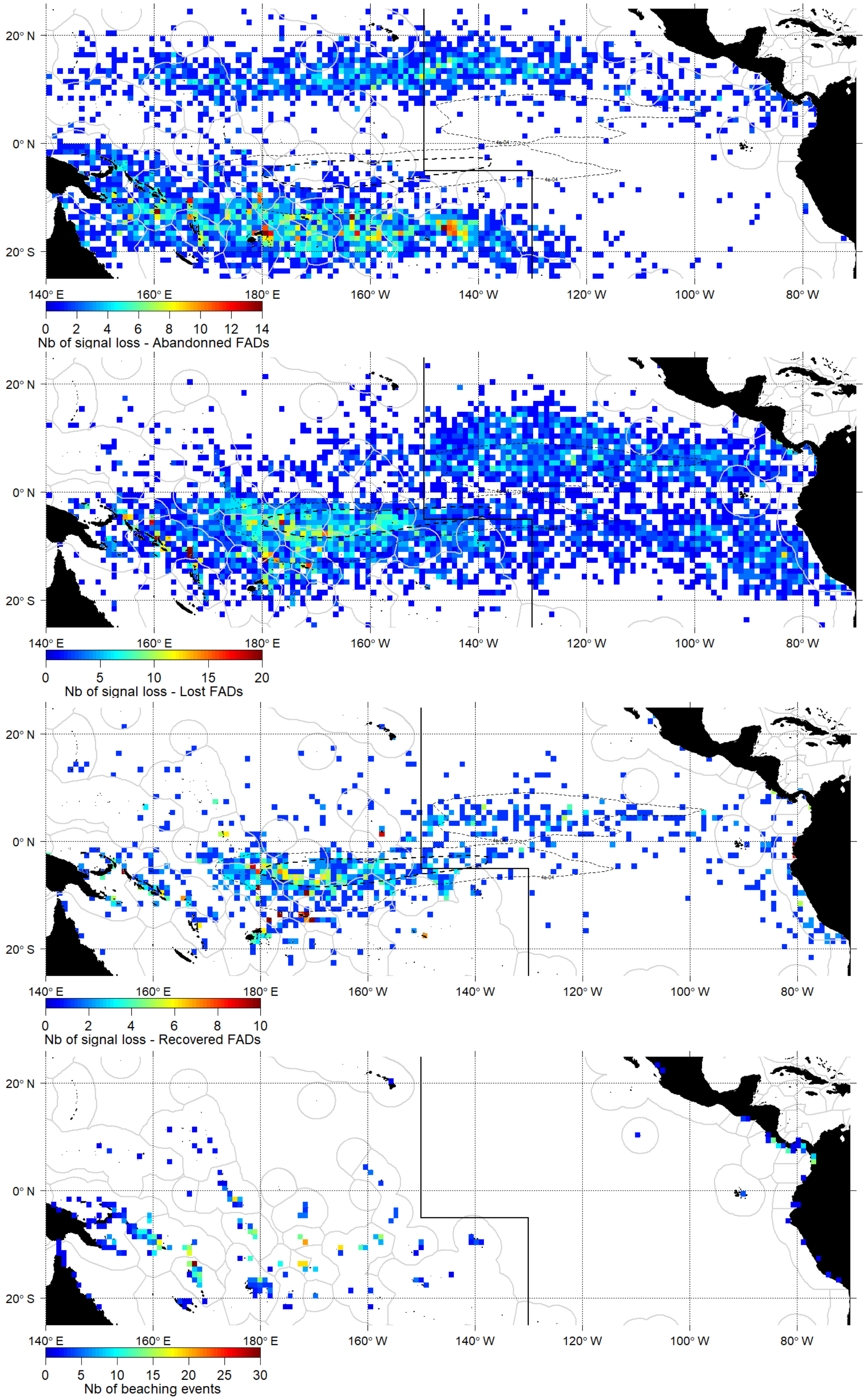

Figure 8. Number of signal loss per 1° grid cell, per fate of dFAD. The black line indicates the limit between the WCPO and the EPO convention areas.

Most beaching events occurred in the WCPO (Table 3 and Figure 8), with the EEZs having the highest number of beaching events being the Solomon Islands (183), Vanuatu (106), PNG (86), the Cook Islands (75), Fiji (71), and Tuvalu (51) (Table 4 and Figure 8). It can also be noted that Samoa, Tokelau and Vanuatu showed very high numbers of beaching events per 1° cell (Table 4). The Solomon Islands showed a very high number of beaching events in 2015, while most other EEZ showed an increasing trend in beaching events through time, in particular Vanuatu, Fiji and PNG (Figure 9). Monthly variability was also detected, with, for instance, higher beaching rates the second half of the year in the Solomon Islands and PNG (Figure 10).

Table 4. Number of beaching events and number of beaching cells per EEZ (only EEZs with >10 beaching events).

EEZ	Beaching events	No. of beaching cells	No. beaching events /cell
SB	183	25	**7.3**
VU	106	11	**9.6**
PNG	86	36	2.4
CK	75	9	**8.3**
FJ	71	16	4.4
TV	51	6	**8.5**
KI GL	49	10	4.9
WS	45	3	**15.0**
TK	34	2	**17.0**
KI LN	30	9	3.3
PF	22	8	2.8
KI PX	17	4	4.3
WF	11	2	5.5
AU	10	8	1.3

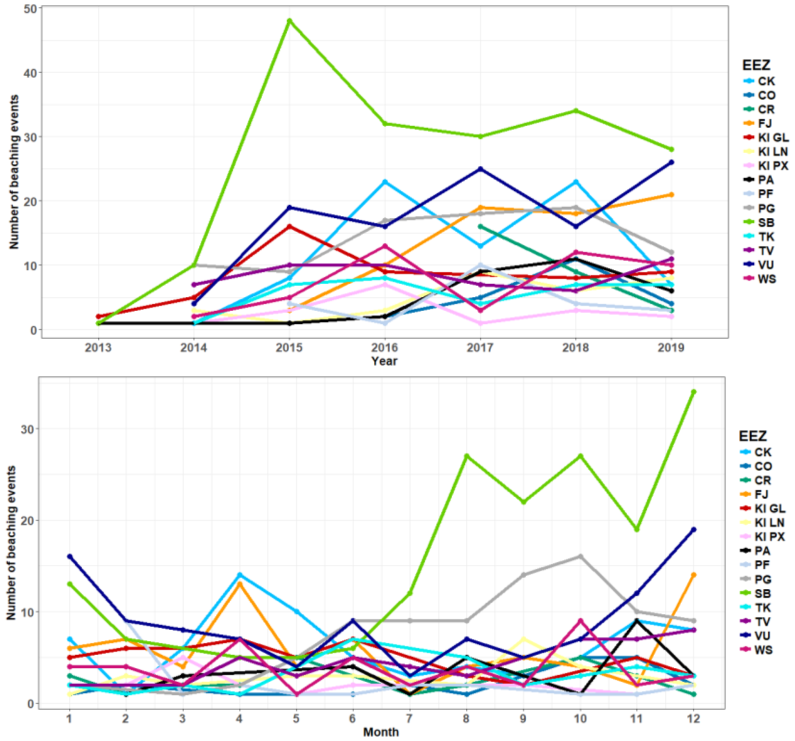

Figure 9. Annual (top) and monthly (bottom) varibility in the number of beaching events per EEZ. CK = Cook Islands; CO = Colombia; CR = Costa Rica; FJ = Fiji; KI GL Kiribati Gilbert Islands; KI LN Kiribati Line Islands (KI LN); KI PX Kiribati Phoenix Islands; PA = Panama; PF= French Polynesia; PG = Papua New Guinea; SB = Solomon Islands; TK = Tokelau; TV = Tuvalu; VU = Vanuatu; and WS = Samoa and American Samoa.

4. Potential recovery areas or options to reduce dFAD abandonment

4.1. High signal loss cells – recovery close to shore

To identify potential dFAD recovery hotspots close to shore, areas with higher rates of signal loss events (above the quantile 0.9) were investigated. A total of 310 cells were identified as having higher rates of signal loss events, ranking between 8 and 58 per cell (Figure 10, Table 5). The Cook Islands, Tuvalu and the Solomon Islands presented the highest number of high signal loss cells, with more than 430 signal loss events per EEZ over more than 30 cells. The other EEZs with a high number of cells with high signal loss rates were Fiji, Tokelau, Kiribati Phoenix Islands, PNG, French Polynesia and American Samoa (Table 5). A high variability between EEZs was detected in the distance between the location of the signal loss events and the shore (Table 5; note that this may include beaching). In the Solomon Islands and PNG, most of these signal loss events were at less than 50 km from shore (78.6% and 79.0%, respectively), with more than 55.2% and 43.5% of signal loss events being at less than 10 km. Conversely, signal loss events in the Cook Islands, Tuvalu, Tokelau, Kiribati Phoenix Islands, French Polynesia and American Samoa were mostly far from shore, with only 10–25% of signal loss events being at less than 50 km from shore. Finally, in Fiji 32.5% of signal loss events were at less than 10 km from shore (Table 5).

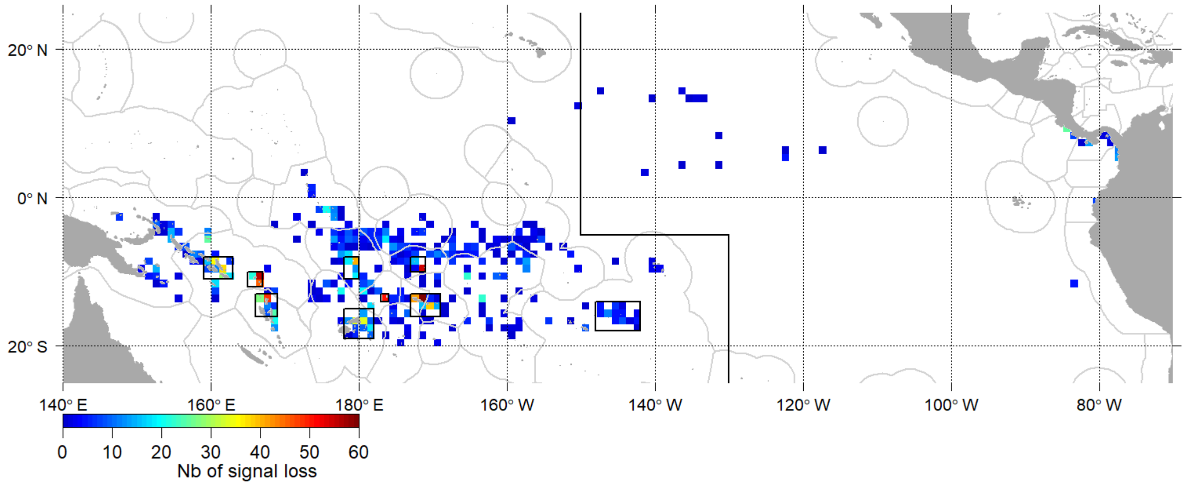

Figure 10. Spatial distribution of cells with numbers of signal loss events above the 0.9 quantile in the entire Pacific Ocean. Black rectangles represent the spatial boxes with high rates of signal loss. The solid black line indicates the limit between the WCPO and the EPO convention areas.

Nine spatial boxes presenting higher numbers of signal loss events or high ratio between signal loss and dFAD density in one specific area were selected (Figure 10 and 11). These corresponded to two cells in the Solomon Islands, one in Vanuatu, a large one in Fiji, one in Tuvalu, one in Wallis and Futuna (covering one cell only), one in Tokelau, one covering Samoa and American Samoa and one in French Polynesia (Figure 2). These spatial boxes had various sizes from 3,600 nm^2 (60 * 60 nm) to 86,400 nm^2 (240 * 360 nm), which corresponds to a possible crossing of a spatial box within a day at a cruising speed of 12 knots.

Overall, it was found that a total of 3,521 dFAD (out of the 13,700 dFADs in the dataset) transited at least once within the high signal loss spatial boxes identified (Table 2). This corresponds to 25% of all dFADs in this study, or 15% if we remove Tuvalu, Tokelau and Samoa/American Samoa that are within the main hotspot.

Table 5. Number of signal loss events in cells within EEZs (only the top 15 EEZs with the highest number of signal loss events are included) with high rates of signal loss events (above the 0.9 quantile, as shown in Figure 10), and % of last positions in these cells that are less than 10 km or 50 km from shore.

EEZ	Total no. of signal loss	No. of signal loss in high signal loss cells	No. of high signal loss cells	% high signal loss 10 km from shore	% high signal loss 50 km from shore
SB	910	571	30	55.2%	78.6%
TV	595	472	33	14.2%	18.0%
CK	796	433	38	17.3%	21.0%
FJ	573	372	26	32.5%	57.0%
TK	290	295	22	21.4%	25.1%
KI PX	376	263	23	8.0%	10.3%
PNG	591	262	21	43.5%	79.0%
PF	826	229	21	15.3%	25.3%
AS	257	217	18	13.4%	30.0%
VU	327	204	9	77.0%	92.6%
KI GL	341	195	16	36.9%	50.8%
WF	221	189	11	32.3%	33.9%
SS	171	162	7	59.3%	72.2%
KI LN	425	158	17	8.2%	12.7%
TO	207	118	12	12.7%	22.0%
TOTAL	6906	4140	304		

The number of dFADs transiting each spatial box was also investigated (Table 6), with higher numbers in Tokelau, Tuvalu and Samoa/American Samoa boxes, which are located within or close to the high dFAD density area (see Figure 2). In French Polynesia, Fiji, and the western Solomon Islands boxes, more than half of the dFADs transiting also lost signal within the spatial box (Table 6). In the eastern Solomon Islands, Vanuatu, Wallis and Futuna and Samoa/American Samoa boxes, 17–32% of the dFADs transiting lost signal within the spatial box, plus an extra 10–16% with lost signal within one month after the transit (Table 6).

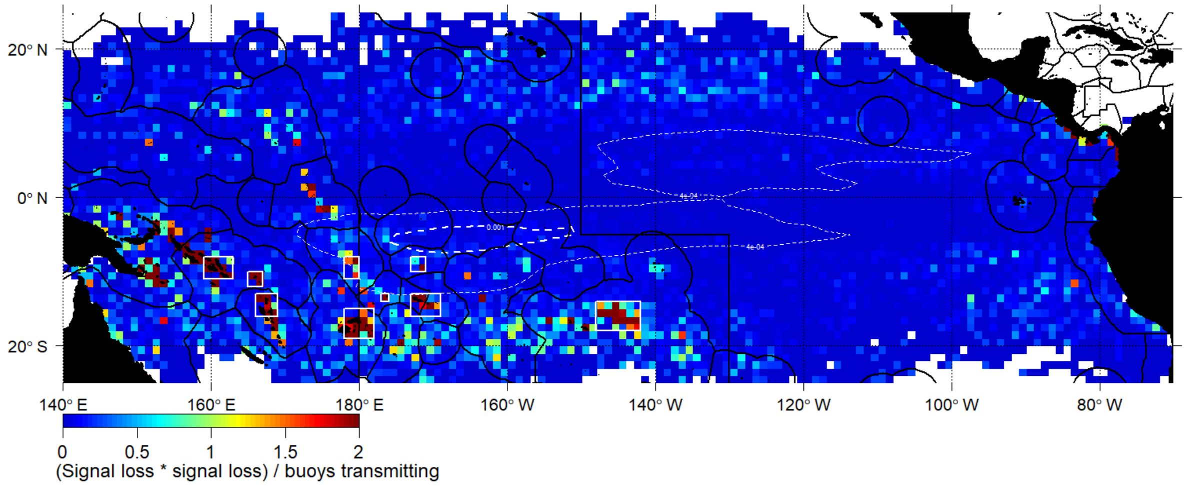

Figure 11. Spatial distribution of the ratio between the squared number of signal loss events and dFAD density per 1°cell. Dotted white lines indicate the 0.9 and 0.98 quantiles of dFAD density, as identified in Figure 2. The solid black line indicates the limit between the WCPO and the EPO convention areas.

Table 6. Number and percentage of dFADs transiting or being deactivated per defined spatial box.

Spatial boxes	No. of transit[1]	No. of dFAD transiting	No. of signal loss inside	No. signal loss outside 1 week after transit	No. signal loss. outside 1 month after transit	% signal loss inside	% signal loss outside 1 week after transit	% signal loss outside 1 month after transit
SB West	617	174	89	8	14	51.15	4.6	8.05
SB East	486	142	45	4	21	31.69	2.82	14.79
FJ	808	149	84	7	15	56.38	4.7	10.07
TK	2,011	620	82	11	32	13.23	1.77	5.16
TV	1,412	625	108	10	42	17.28	1.6	6.72
VU	794	403	129	13	67	32.01	3.23	16.63
WF	388	197	34	4	25	17.26	2.03	12.69
WS	1,542	906	219	21	70	24.17	2.32	7.73
FP	408	305	184	8	19	60.33	2.62	6.23

[1]Individual dFADs may transit several times in each spatial box.

The temporal variability in the number of signal loss events at the scale of the defined spatial boxes was explored (Figure 12). As for trends in the number of signal loss events per EEZ, higher numbers of signal loss events were found in 2017 and 2018 in the French Polynesian box, 2018 in the Cook Islands box, and 2015 in the western Solomon Islands box. An increasing trend was detected for the Fijian box. Regarding monthly variability, peaks in the number of signal loss events were detected in February and June in the French Polynesia and Samoa boxes, October in the western Solomon Island, Fiji and Samoa boxes and April in the Fiji box.

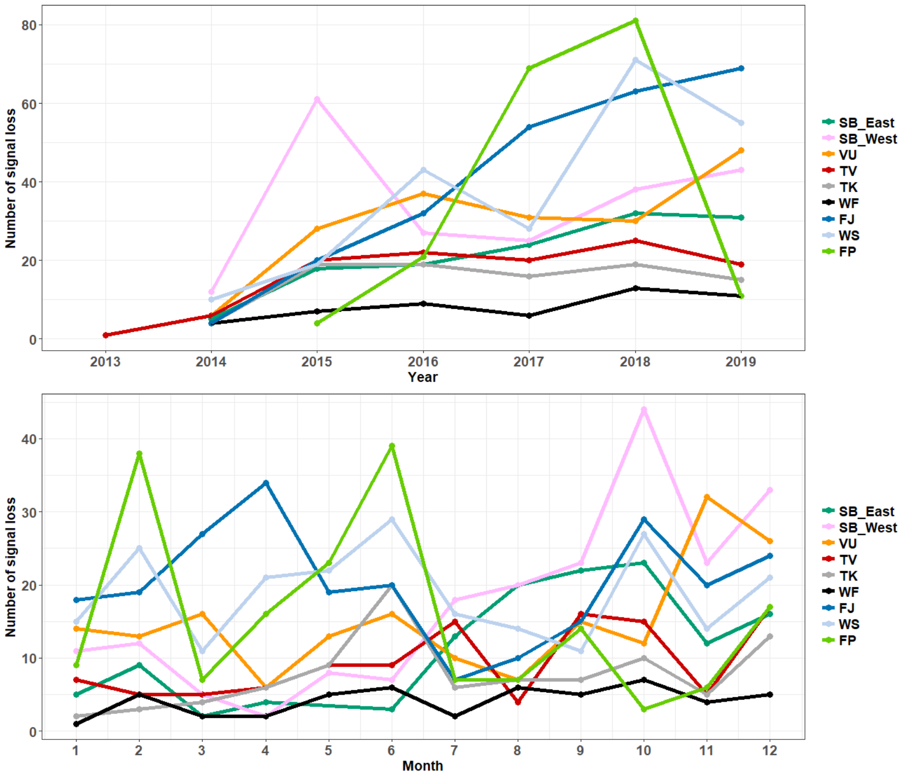

Figure 12. Annual (top) and monthly (bottom) variability in the number of signal loss per spatial box previously defined. SB = Solomon Islands; VU = Vanuatu; TV = Tuvalu; TK = Tokelau; WF = Wallis and Futuna; FJ = Fiji. And WS = Samoa and American Samoa.

To better estimate the number of dFADs that could be retreived at the same time, the number of dFADs present on the same day in each spatial box was investigated (Figure 13). In Wallis and Futuna and the Solomon Islands spatial boxes, most days, less than 5 dFADs were present at the same time in each box, which corresponds to around 1 dFAD per 1° cell. In Vanuatu, Tuvalu, Tokelau and Fiji, the number of dFADs present at the same time in each box was 3 to 12, corresponding to 2 or less per 1° cell. Finally in the Samoa/American Samoa and French Polynesia boxes, 6 to 16 dFADs were present the same day in the spatial box, but this also corresponded to 2 or less per 1° cell (Figure 13).

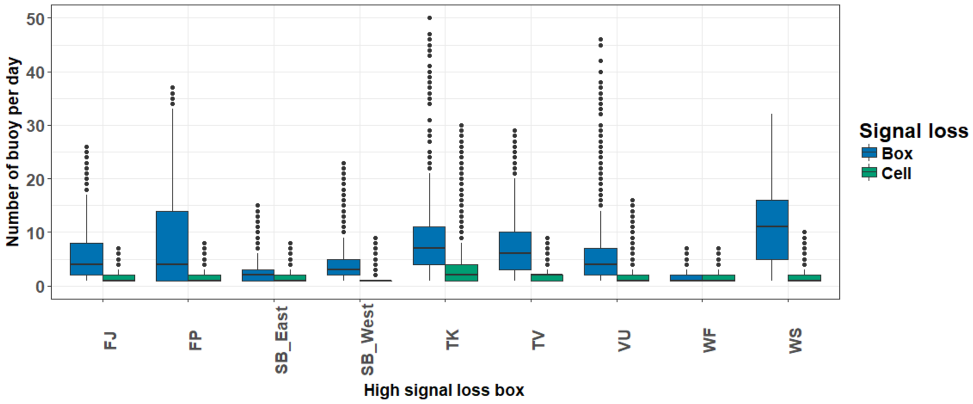

Figure 13. Number of dFADs present on the same day per spatial box or per 1° cell in each of the high signal loss spatial boxes defined.

The time spent by dFADs in each defined spatial box was studied, both for dFAD with a signal loss in the spatial box considered and dFADs just transiting (Figure 14). The time spent in each box for signal loss inside the box was highly correlated to the size of the spatial box and its spatial distribution. In the Wallis and Futuna high signal loss box, which covers only one 1° cell, dFADs generally spent 1 to 6 days (Figure 14). In contrast, in the French Polynesia box, which is the largest box, dFADs spent 12–40 days. In the Solomon Islands boxes, located completely to the west of main dFAD density area, dFADs mostly spent 2 to 17 days. In the Fiji, Tuvalu and Vanuatu large spatial boxes, dFADs mostly spent 1 to 24 days. Finally in the Tokelau and Samoa/American Somoa spatial boxes, which are both large and within the main dFAD density area, dFADs mostly spent 5 to 25 days (Figure 14). DFADs that were only transiting in the high deactivation spatial boxes generally spent less time, with less variation between EEZs, mostly from 2 to 20 days.

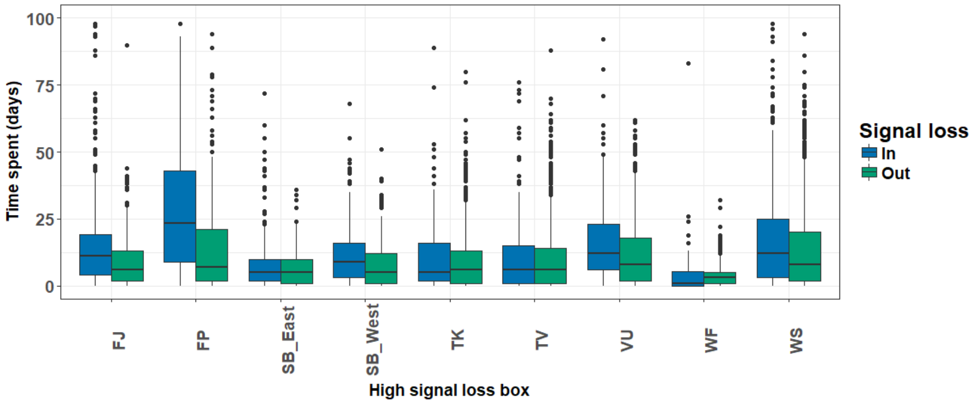

Figure 14. Time spent in each of the high signal loss spatial boxes depending on the area of signal loss: inside the spatial box or outside the spatial box, i.e., transit only.

4.2. DFAD abandonment in oceanic areas

To further identify spatial hotspots of signal loss events, in particular abandonment, we looked at the spatial distribution of the daily position of each dFAD one month before signal loss (Figure 15). This was needed, given the limited number of final dFAD positions in the current dataset and the high spatial extent they cover (see Figure 8 for comparison). These spatial hotspots were compiled for abandoned and lost dFADs (Figure 15) and compared to the density of dFADs used by vessels of the collaborating companies over the study period (Figure 2).

A large hotspot of dFAD abandonment was detected in the south of the WCPO, from the Solomon Islands to the middle of the French Polynesia EEZ (Figure 15). Aside from an area between 10°S and 12°S, the entire hotspot was outside of the extended dFAD density hotspot. By comparison, the hotspost where most lost dFADs were found over the last 30 days before signal loss is completety within the dFAD density hotspot. It covers the central part of the WCPO, including Tuvalu, Kiribati Pheonix Islands, Tokelau, north of French Polynesia and center of the Kiribati Line Islands (Figure 15).

The identification of the dFAD abandonment hotspot could be used, either as a recovery area for purse seiners when dFADs are found at the edge of the fishing area or where a high number of abandoned dFADs could be recovered in a large oceanic zone. The recovery area, indicated by the white rectangle in Figure 15, is approximately 574,763 nm² in size. The southern dFAD abandoment hotspot, indicated by the red linel in Figure 15, is approximately 2,069,148 nm² in size.

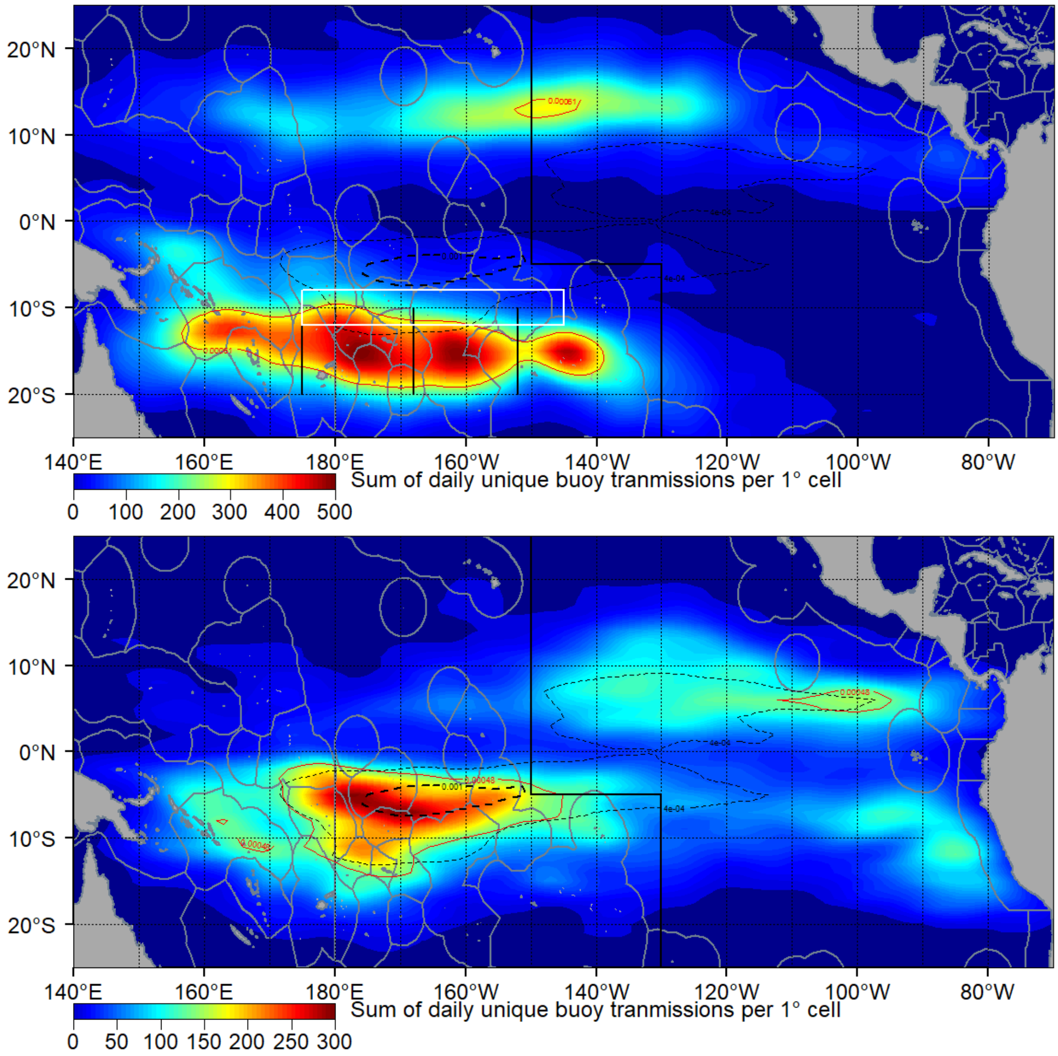

Figure 15. Daily position for the last 30 days before signal loss per dFAD for abandoned (top) and lost (bottom) dFADs. Red lines indicate the core and extended main areas of presence before signal loss (0.95 and 0.99 quantiles); and black dotted lines indicate the main and extended dFAD density areas (0.95 and 0.99 quantiles; see Figure 3). The solid black line indicates the limit between the WCPO and the EPO convention areas. The three vertical lines separate areas within the dFAD abandonment hotspot and the white rectangle indicates a potential purse seiner dFAD recovery area.

4.3. Variability in deployments areas

The spatial distribution of deployments of dFADs transiting in one of the high signal loss spatial boxes (see Figure 10) and the spatial distribution of the dFADs that beached (see Figure 8) were compiled (Figures 16 and 17). The distribution of deployments of dFADs transiting in high signal loss boxes was very similar to the distribution of all deployments, although the former extended more to the west (Figure 17). It mostly covers the central part of the WCPO, including the southern part of the Kiribati Phoenix Islands EEZ, the central part of the Tuvalu EEZ, the central part of the Kiribati Line Islands EEZ and the high seas pocket located in the middle (Figure 17). Similarly, the distribution of deployments of beached dFADs in the WCPO was again very similar to the distribution of all deployments (Figure 16). Finally, the distribution of deployments of beached dFADs in the EPO was very different (Figure 16), corresponding to the eastern part of the distribution of all deployments but extending further east and north.

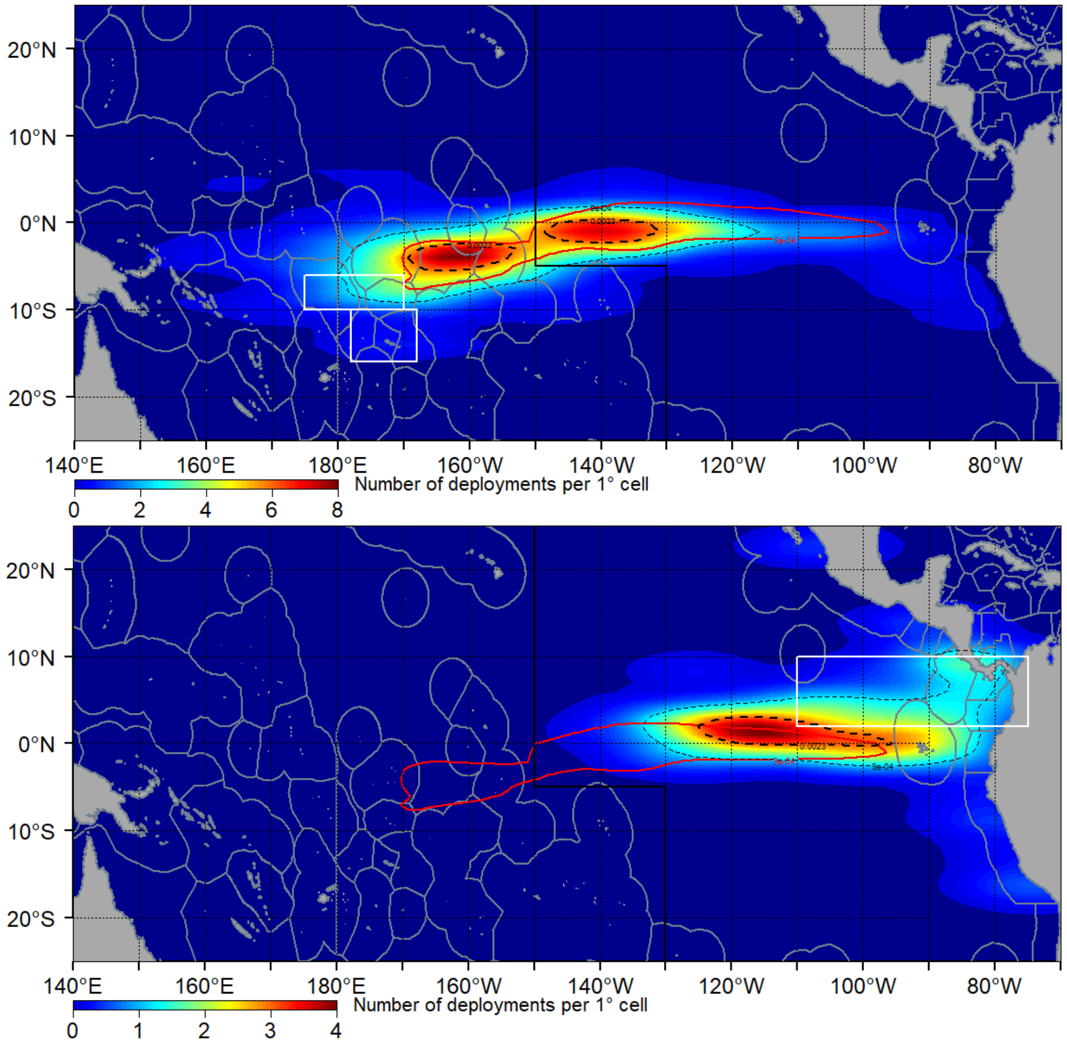

Figure 16. Deployment areas of all dFADs beached in the WCPO (top) and the EPO (bottom). White rectangles indicate potential areas where deployments could be limited to reduce dFAD abandonment and beaching.

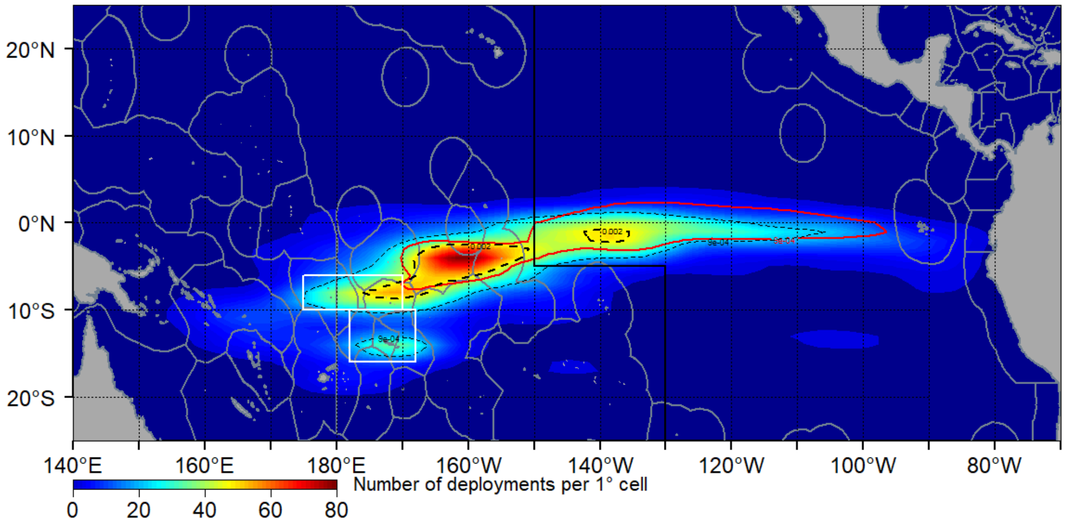

Figure 17. Deployment areas of all dFADs transiting in one of the high deactivation spatial boxes.

5. Scenarios of recovery

Given the results presented in this report from buoy position data over the last 10 years across the whole Pacific Ocean, several options could be considered to reduce dFAD loss, abandonment, and beaching. First, some deployment areas linked to higher rates of abandonment and beaching have been identified. Areas where deployments should be avoided could therefore be considered. Second, recoveries in areas close to shore where high rates of beaching and signal loss are detected could also be considered. Third, a large oceanic area linked to high rates of dFAD abandonment has been identified in the southern WCPO and could be considered if many fleets were included in a regional dFAD recovery programme. Finally, recovery of dFADs at the edge of the main fishing areas and high dFAD hotspot, by purse seiners, could also be considered to reduce dFAD loss, abandonment, and beaching.

5.1. Reduce deployments in some areas

Three areas where dFAD deployments or redeployments lead to higher rates of beaching and abandonment have been identified (see Figure 16). One encompassing Tuvalu and Tokelau, one encompassing Samoa and American Samoa and one in the north-east EPO. Besides the Tuvalu/Tokelau one, the others are located outside the main dFAD density area. A total of 393, 99 and 210 deployments/redeployments were found in the Tuvalu/ Tokelau, Samoa/ American Samoa and north-east EPO spatial boxes, respectively (Table 7). Avoiding deployments in these spatial boxes could lead to a 10.4% reduction in dFAD beaching and 4.4% reduction in dFAD abandonment. In should be noted that most dFADs deployed/ redeployed in the Samoa/ American Samoa and north-east EPO spatial boxes never reached the extented dFAD density hotpsot (only 17% enter the hotspot). To the contrary, most dFADs deployed in the Tuvalu/Tokelau box (71%) are entering the dFAD density hotspot and will likely be used by fishers. Although reducing deployments in this area could lead to the highest reduction in beaching (5.7%) and abandonment (2.8%) of all the areas considered here.

Table 7. Number of dFAD deployments in the identified deployment spatial boxes and potential beaching and abandonment reduction in case of deployment reduction in these zones.

Deployment spatial boxes	Area covered (nm^2)	dFAD deployment/ re-deployment		Potential beaching reduction		Potential abandonment reduction		DFADs entering the dFAD density hotspot	
		No.	%[1]	No.	%[1]	No.	%[1]	No.	%
TV/ TK	215,536	393	3.7%	48	5.7%	119	2.8%	280	71.3%
WS/ AS	215,536	99	0.9%	15	1.8%	28	0.7%	17	17.2%
NE EPO	1,005,836	210	2.0%	25	3.0%	40	0.9%	37	17.6%
Total	1,436,909	702	6.5%	88	10.4%	187	4.4%	331	5.8%

[1]Based on the total number of signal loss (13,700), beaching (949) and dFAD abandonment (4718) in the whole Pacific.

5.2. Recoveries close to shore

A total of 3,166 dFADs (29.5% of all dFADs) transited at least one of the nine high signal loss spatial boxes (Figure 10 and Table 8), with higher numbers in Tokelau (891 dFADs), Samoa/American Samoa (794) and Tuvalu (710). These spatial boxes are located in the main purse seine fishing grounds or areas where high numbers of purse seiners transit. If the recovery of all dFADs transiting through these spatial boxes was possible, it could lead to a reduction of up to 60.0% of beaching events and 34.7% of dFAD abandonment, with some difference between spatial boxes (Table 8). Higher reduction in beaching (17.2% and 15.9%) and abandonment (9.0% and 8.3%) are detected in the Tokelau and Samoa/American Samoa spatial boxes, compared to a reduction of 1.1% to 11.9% per spatial box in beaching and 3.0% to 7.5% in dFAD abandonment for the other boxes (Table 8). In Tokelau and Tuvalu, 35.0% and 15.2% of dFADs transiting through the spatial box drifted into the extended dFAD density hotspot. In the other spatial boxes, this represents less than 1.5% of all dFADs transiting in the boxes (Table 8).

It is noted that in most of the high signal loss spatial boxes, the number of dFADs transiting per day is below five, except for French Polynesia, Tokelau, Tuvalu and Samoa/American Samoa (Figure 13). Most of the dFADs also transited from a couple of days to 3 weeks, with longer retention time in French Polynesia and Samoa/American Samoa, and shorter periods in Wallis and Futuna, and the eastern Solomon Islands boxes (Figure 14).

Table 8. Number of dFADs transiting in the identified high signal loss spatial boxes and potential dFAD beaching and abandonment reduction in case of the recovery of all dFADs transiting in these zones.

High signal loss spatial boxes	Area covered (nm^2)	DFAD transiting		Potential beaching reduction		Potential abandonment reduction		dFADs returning to dFAD density hotspot	
		Nb	%[1]	Nb	%[1]	Nb	%[1]	Nb	%
TK	14,369	891	8.3%	146	17.2%	387	9.0%	312	35.0%
WS/AS	43,107	794	7.4%	135	15.9%	355	8.3%	10	1.3%
TV	43,107	710	6.6%	101	11.9%	320	7.5%	108	15.2%
FJ	28,738	454	4.2%	95	11.2%	211	4.9%	2	0.4%
VU	53,884	441	4.1%	125	14.8%	232	5.4%	3	0.7%
SB West	43,107	391	3.6%	109	12.9%	129	3.0%	13	3.3%
SB East	14,369	368	3.4%	87	10.3%	141	3.3%	8	2.2%
WF	3,592	324	3.0%	54	6.4%	148	3.4%	3	0.9%
PF	86,215	289	2.7%	9	1.1%	227	5.3%	0	0.0%
Total	330,489	3166	29.5%	508	60.0%	1487	34.7%	421	13.3%
Total except TK & TV	273,013	2357	22.0%	427	50.4%	1155	26.9%	36	1.5%

[1]Based on the total number of signal loss (10,734), beaching (847) and dFAD abandonment (4291) in the WCPO only (see Table 3).

5.3. Oceanic recoveries outside fishing areas

The dFAD abandonment hotspot identified in the southern WCPO was divided into four areas and a fifth area was defined in the north, delimited by the 0.9 quantile of dFAD abandonment (Figure 15). A total of 41.3% of dFADs transited in the southern hotspot, with most found in the central part (south hotspot West 2 and south hotspot East 1) (Table 9). 7.1% of these dFADs then re-entered the extended dFAD density hotspot, highlighting the fact that the vast majority of them are already lost to the fishery when transiting in the abandonment hotspot. In the northern abandonment hotspot, only 9.0% of all dFADs transited the hotspot, and only 1.5% of them re-entered the dFAD density hotspot (Table 9). If all dFADs transiting the abandonment hotspots were retrieved, this could reduce the number of beaching events by 57.0% for the southern abandonment hotspot and 0.5% for the northern one, and the number of dFAD abandonments by 57.2% in the southern one and 21.0% in the northern one (Table 9).

The number of dFADs transiting the Southern abandonment hotspot ranged between 160–614 per month in the 2015–2019 period (<100 before 2015), with an average of 303. The number of dFADs transiting in the northern abandonment hotspot ranged between 1–328 per month, with an average of 60.

Table 9. Number of dFADs transiting the identified dFAD abandonment hotspots and potential dFAD beaching and abandonment reduction in case of the recovery of all dFADs transiting in these zones.

DFAD abandonment hotspot	Area covered (nm^2)	DFAD transiting		Potential beaching reduction		Potential abandonment reduction		DFADs returning to dFAD density hotspot	
		Nb	%[1]	Nb	%[1]	Nb	%[1]	Nb	%
South hotspot W1	323,304	1524	14.2%	276	32.6%	793	18.5%	34	2.2%
South hotspot W2	517,287	2931	27.3%	376	44.4%	1433	33.4%	257	8.8%
South hotspot E1	377,188	1838	17.1%	176	20.8%	1110	25.9%	64	3.5%
South hotspot E2	186,798	609	5.7%	23	2.7%	465	10.8%	2	0.3%
Sub-total South hotspot	2,069,148	4432	41.3%	483	57.0%	2454	57.2%	313	7.1%
Sub-total North hotspot	772,338	1237	9.0%	5	0.5%	989	21.0%	18	1.5%
Total	2,841,487	5669	41.4%	488	51.4%	3443	73.0%	331	5.8%

[1] Based on the total number of signal loss (10,734), beaching (847) and dFAD abandonment (4291) in the WCPO only for the South hotspot and the total number of signal loss (13,700), beaching (949) and dFAD abandonment (4718) in the whole Pacific for the North hotspot and the total.

5.4. Oceanic recoveries within fishing area

The potential of purse seiners to recover dFADs at the edge of the fishing grounds is considered by looking at dFADs transiting in an area corresponding to the overlap between the dFAD abandonment hotspot and the dFAD density hotspot (Figure 15). A total of 34.1% of all dFADs transited through this area, or 40.7% of all dFADs deactivated in the WCPO, with 38.0% of them re-entering the dFAD density hotspot (Table 10). If all dFADs transiting in this area were picked up by purse seiners, this could lead to a reduction of 57.0% in beaching and 45.1% in dFAD abandonment (Figure 15).

The number of dFADs transiting in the potential purse seine recovery area ranged between 60–560 per month in the 2015–2019 period (<60 before 2015), with an average of 266.

Table 10. Number of dFADs transiting in the overlap area between the dFAD abandonment hotspot and the dFAD density hotspot (i.e., potential Purse Seine recovery area) and potential beaching and abandonment reduction in case of the recovery of all dFADs transiting in these zones.

Recovery area and total number of DFADs considered	Area covered (nm^2)	DFAD transiting		Potential beaching reduction		Potential abandonment reduction		DFADs returning to dFAD density hotspot	
		Nb	%	Nb	%	Nb	%	Nb	%
PS recovery area - All dFADs[1]	574,763	4368	34.1%	541	57.0%	2126	45.1%	1766	38.0%
PS recovery area - DFADs with last position in the WCPO[2]	574,763	4368	40.7%	541	63.9%	2126	49.5%	1766	38.0%

[1] Using the total number of signal loss (10,734), beaching (847) and dFAD abandonment (4291) in the WCPO only.

[2] Usign the total number of signal loss (13,700), beaching (949) and dFAD abandonment (4718) in the whole Pacific.

6. Conclusion and potential next steps

The availability of a unique and complete 10-year buoy position dataset allowed a detailed spatial and temporal analysis of the data to be performed. In addition, accessing additional information, such as the date of manual switch off and date of satellite transmission deactivation, allowed better determination of dFAD fate, in particular the discrimination between dFAD loss and dFAD abandonment. Areas with higher dFAD deployments, dFAD density, and each category of dFAD fate (abandonment, loss, recovery and beaching) were identified. Based on the patterns detected, different options to limit the number of dFADs lost, abandoned, and beached were considered. It should be noted that the patterns detected correspond to the fishing patterns and distribution of the partner fishing companies. Hence, this analysis would need to be extended if additional companies were to be included in a regional dFAD recovery programme (see Figure S10 and S11 for deployment and dFAD density distribution from all fleets in the PNA FAD tracking data, as a comparison).

A first option considered is to limit deployments in three identified areas that lead to higher rates of dFAD beaching and abandonment (Figure 17). Avoiding dFAD deployments/redeployments in these areas could reduce beaching by 10.4% and dFAD abandonment by 4.4% (Table 11). Although, it should be noted that the majority of the dFADs deployed in one of the three areas (encompassing Tokelau and Tuvalu) are then entering the high dFAD density hotspot, limiting deployments there might therefore slightly impacts the normal use of dFADs.

A second option is to recover dFADs transiting in some areas close to shore where high rates of abandonment and beaching were detected. Nine spatial boxes were identified (Figure 10), and the recovery of all dFADs transiting in these spatial boxes could lead to a 60.0% reduction in beaching and 34.7% reduction in dFAD abandonment (Table 11). However, two spatial boxes could be excluded, as 15–35% of the transiting dFADs are then entering the high dFAD density hotspot. Such an option could be possible, through a type of “dFAD watch” system, where partners in each PICT would be charged to recover dFADs entering the spatial boxes defined.

The third option considered could be the recovery of dFADs that have drifted outside the main fishing areas but are still in oceanic waters. Two large dFAD abandonment hotspots were identified (Figure 15), with the main one in the southern WCPO. Recovering all dFADs in this area could lead to a 57% reduction in beaching and 57.2% reduction in dFAD abandonment. Most dFADs never re-entered the high dFAD density area (Table 11). The reduction in abandonment would be higher than the second option of smaller spatial boxes close to shore, but the reduction in beaching would be similar. It can also be noted that such a recovery programme would no doubt be expensive. With the data from the partner fishing companies only, 160–614 dFADs could be recovered in the southern WCPO per month.

Finally, the last option would be for purse seiners to recover dFADs at the edge of their fishing grounds, for instance one area that overlaps the dFAD abandonment hotspot and the dFAD density hotspot has been identified. Recovering all dFADs in this area could lead to a 57% reduction in beaching and 45.4% in dFAD abandonment (Table 11). However, 38% of the dFADs transiting in the area identified would later enter the dFAD density hotspot.

Table 11. Summary table with area covered and potential beaching and abandonment reduction for the different options considered to reduce dFAD loss, abandonement and beaching.

Option	Area covered (nm^2)	Potential beaching reduction (%)	Potential abandonment reduction (%)
Deployment reduction in 3 areas	1,436,909	10.4	4.4
DFAD recovery in 9 coastal areas	330,489	60.0	34.7
DFAD recovery in South oceanic area	2,069,148	57.0	57.2
DFAD recovery in North oceanic area	772,338	0.5	21.0
PS DFAD recovery area	574,763	57.0	45.1

To conclude, ways to limit dFAD beaching and dFAD abandonment while limiting the impact on the fishing operations and dFAD use may need to be multiple. This would include reducing or avoiding deployments in the areas identified, at least the Samoa/American Samoa and north-east EPO areas, where most dFADs deployments never reach the high-density hotspot. Purse seiners could also recover dFADs at the edge of the fishing grounds, in the area identified or others. To make such recovery more effective, positions of dFADs considered as “lost” by a vessel should be shared amongst different fishing companies, so that the closest vessel could recover it. Other dFAD recovery options, that include non-purse seiners, should also be considered. This could either include some kind of “dFAD watch” system to recover dFADs close to shore, or other vessels recovering dFADs in oceanic areas. DFAD watch in several countries would be expensive and complicated, hence participation and financial contribution from the fishing companies could be considered for such a system to work. It should also be noted, that for some PICTs the recovery might only be possible very close to shore, depending on the type of vessels available. Recovery of dFADs in large oceanic areas would also be expensive, such a recovery programme would therefore need to include the highest number of fishing companies as possible to be cost effective. However, this may require an independent organisation having access to positions of dFADs entering an area or considered as abandoned or lost by vessels. Regional organisations could be considered (e.g., PNA, SPC) to play this role. Other vessels operating in the region, such as longliners, could potentially be involved, with a reward in place. This would be possible if VMS positions were matched in real-time with abandoned dFAD trajectories, and an automated process of alerts to skippers. In both the dFAD watch and oceanic recovery programmes, the recovered buoys could be returned to the owner, which could help pay back some of the cost.

It should be noted that additional investigations are needed to identify the possibilities for dFAD retrieval efforts. This could include the capacity of PICTs, including the potential partners, available vessels, reception facilities, and opportunities for dFAD recycling and disposal in proximity of ports; or the potential for buoys to be sent back to the owner company or resold. In addition, economic analyses are needed to investigate the preliminary cost estimate for a recovery project and explore cost recovery options such as resale of dFAD buoys, sale of recovered dFAD material to recyclers, and surcharges on dFAD buoy sales and services. Finally, accessing near-real-time data of dFADs that would normally be deactivated by fishers because they have drifted out of the fishing grounds would complement the analyses performed in this study. This would allow the geography and feasibility of a recovery process to be better evaluated, and the ground-truthing of the patterns identified using the historical data.

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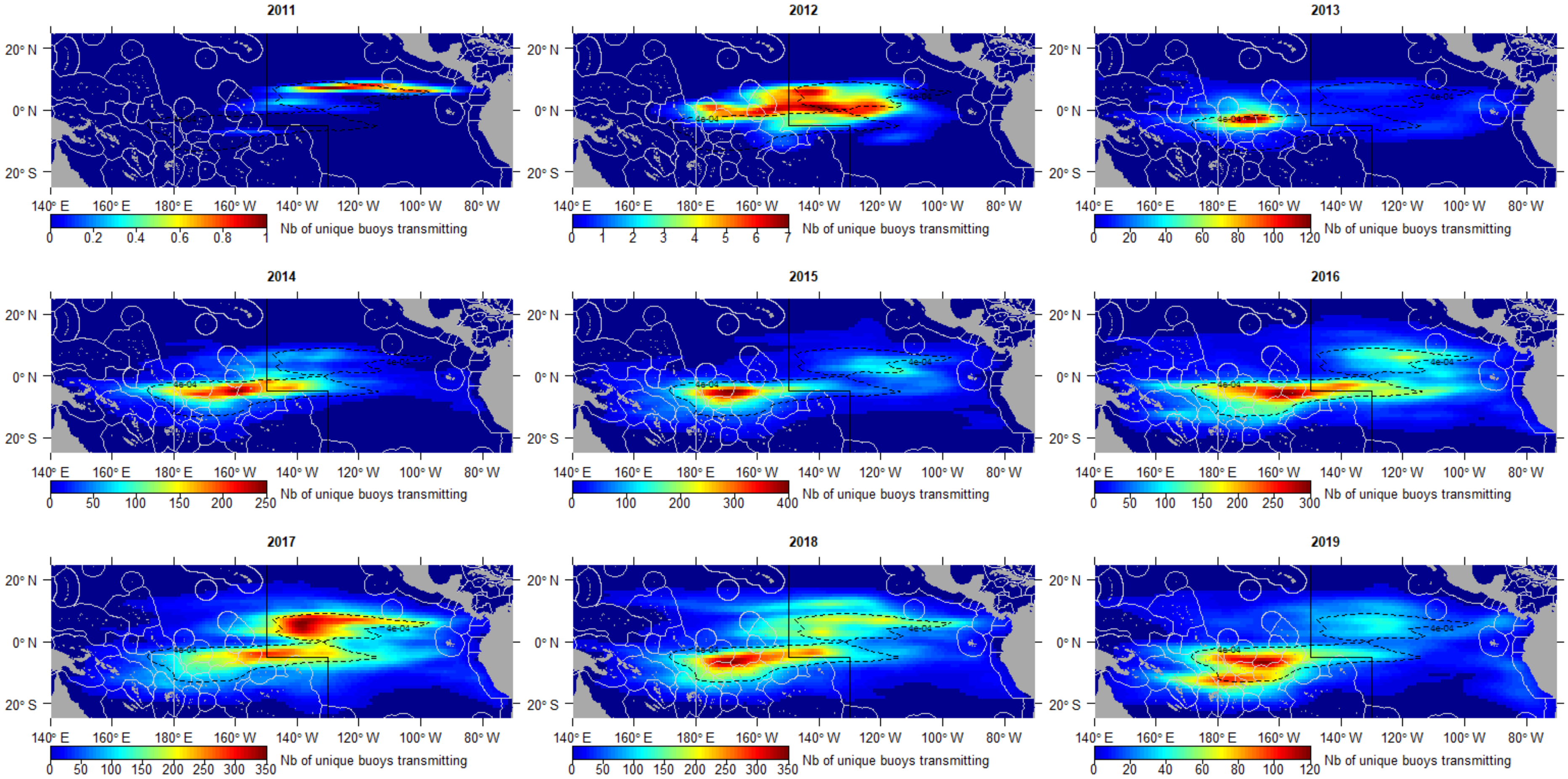

Figure S1. Spatial distribution of dFAD density per 1° cell per year. Dotted black lines indicate the 0.9 and 0.98 quantiles of the overall dFAD density, to examine differences between years. The black line indicates the limit between the WCPO and the EPO convention areas.

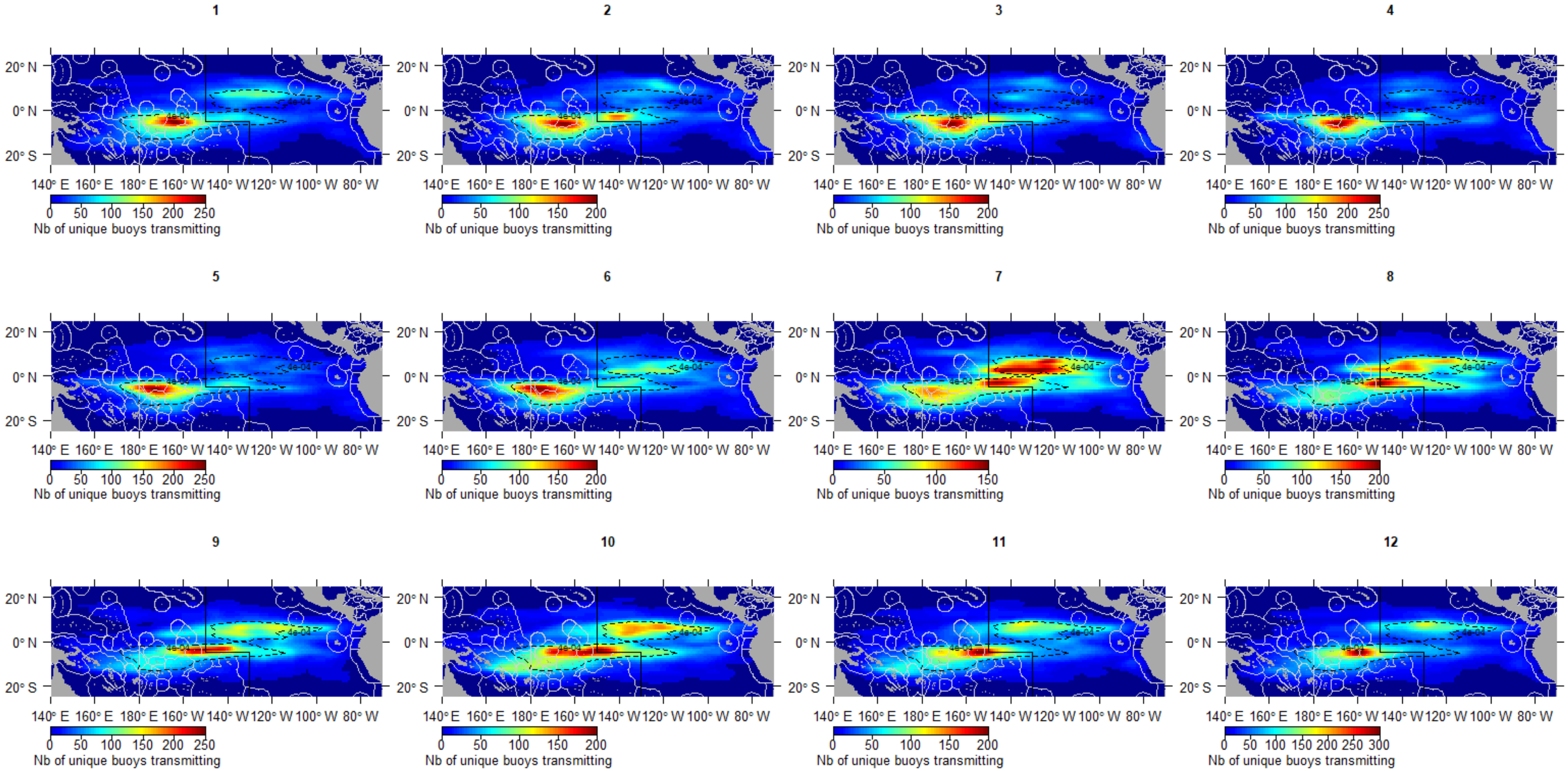

Figure S2. Spatial distribution of dFAD density per 1° cell per month. Dotted black lines indicate the 0.9 and 0.98 quantiles of the overall dFAD density, to examine differences between months. The black line indicates the limit between the WCPO and the EPO convention areas.

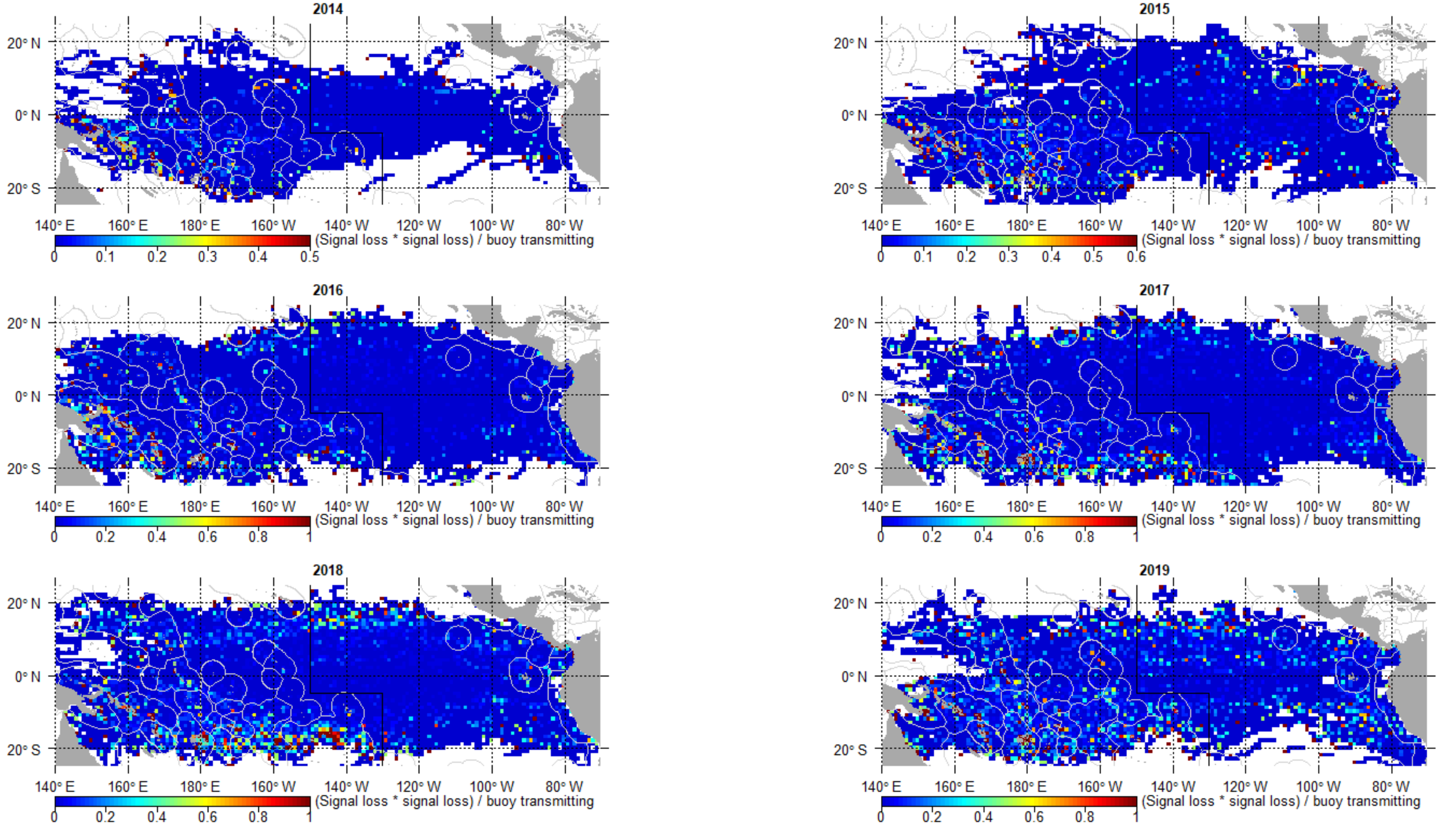

Figure S3. Spatial distribution of the ratio between the squared number of signal loss events and dFAD density per 1°cell per year. Dotted black lines indicate the 0.9 and 0.98 quantiles of the overall dFAD density, to examine differences between years. The black line indicates the limit between the WCPO and the EPO convention areas.

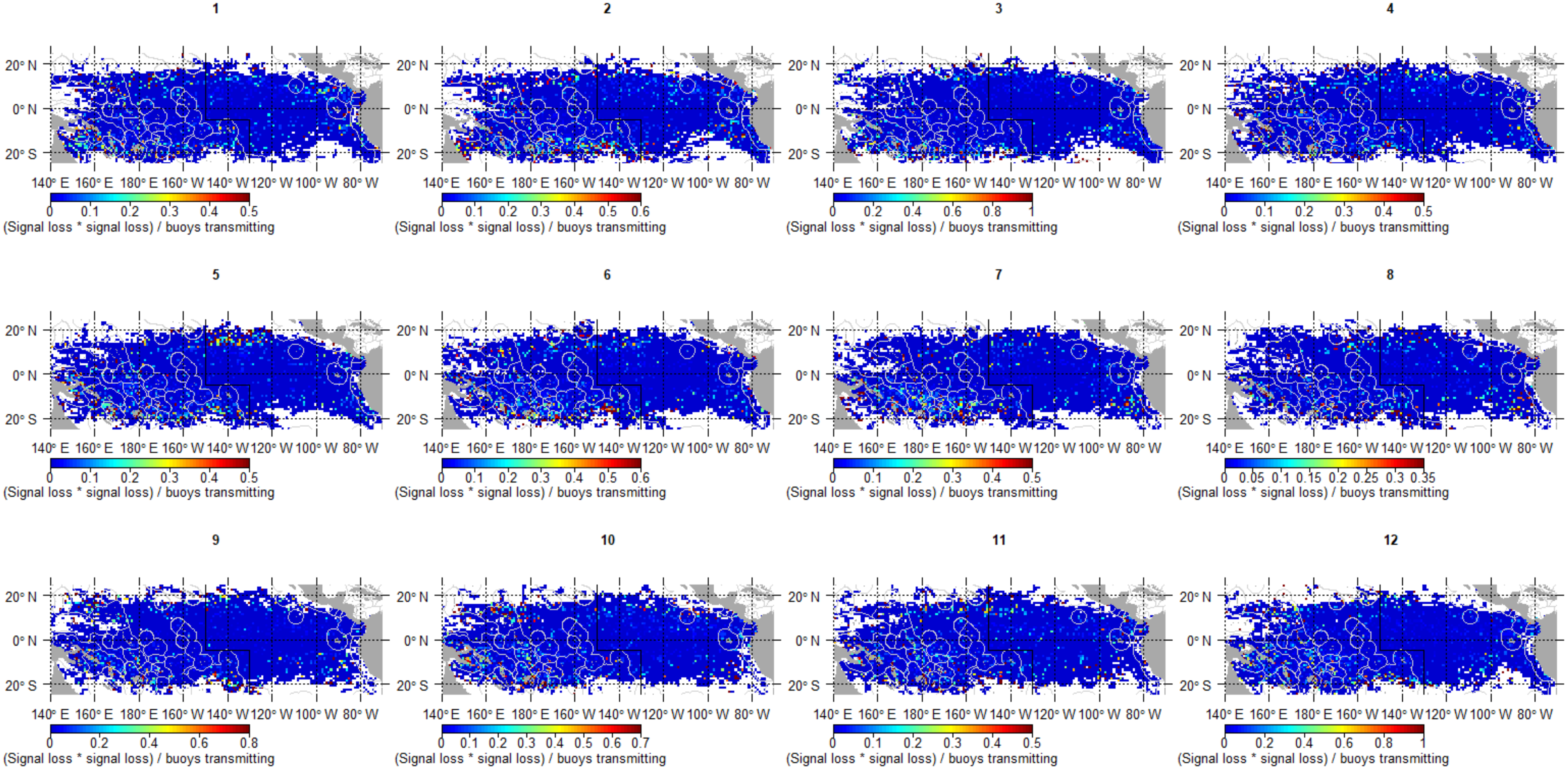

Figure S4. Spatial distribution of the ratio between the squared number of signal loss events and dFAD density per 1°cell per month. Dotted black lines indicate the 0.9 and 0.98 quantiles of the overall dFAD density, to examine differences between months. The black line indicates the limit between the WCPO and the EPO convention areas.

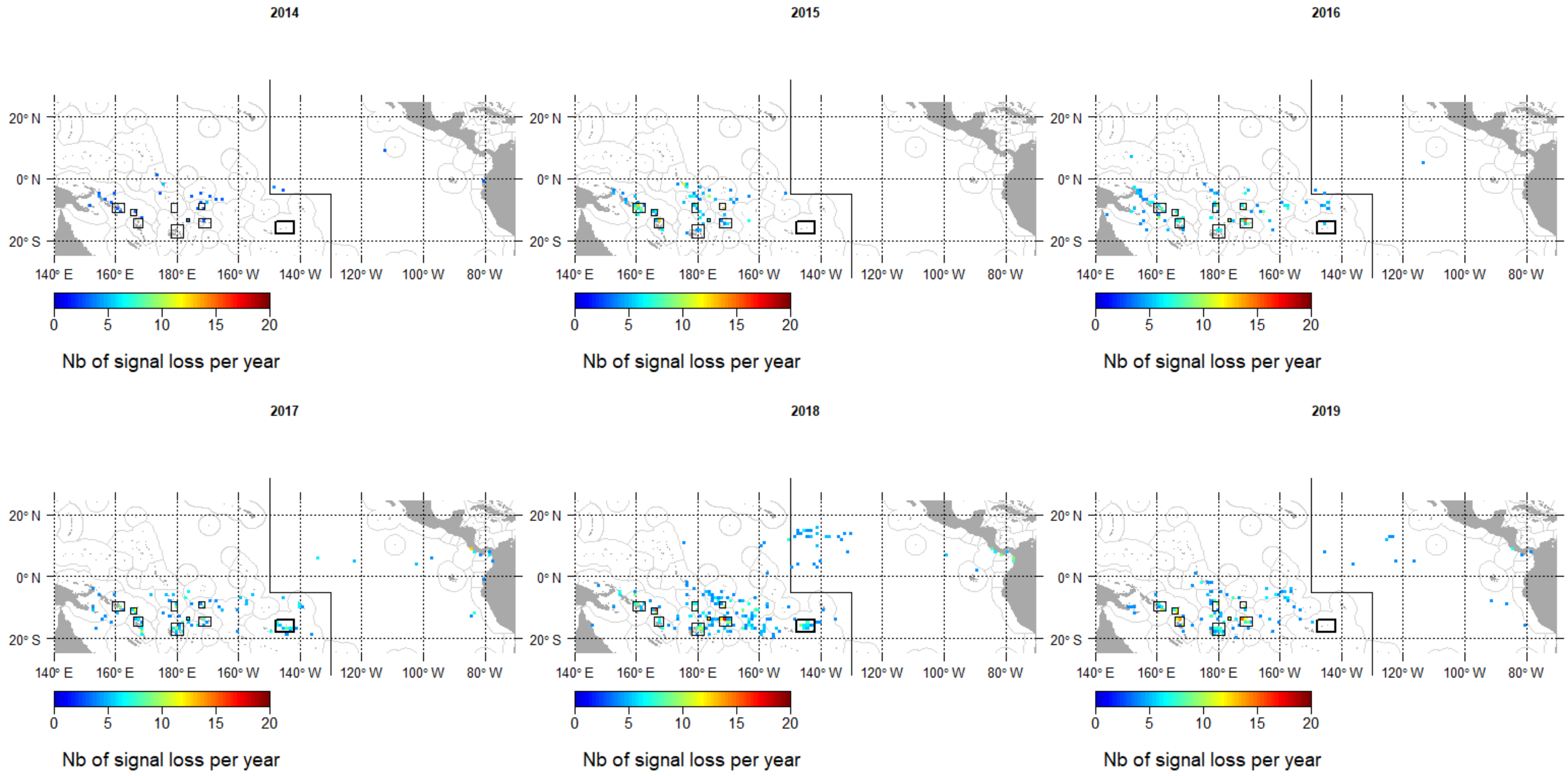

Figure S5. Spatial distribution of cells with signal loss numbers above the 0.9 quantile per year. Black rectangles represent the spatial boxes with high rates of signal loss. The solid black line indicates the limit between the WCPO and the EPO convention areas.

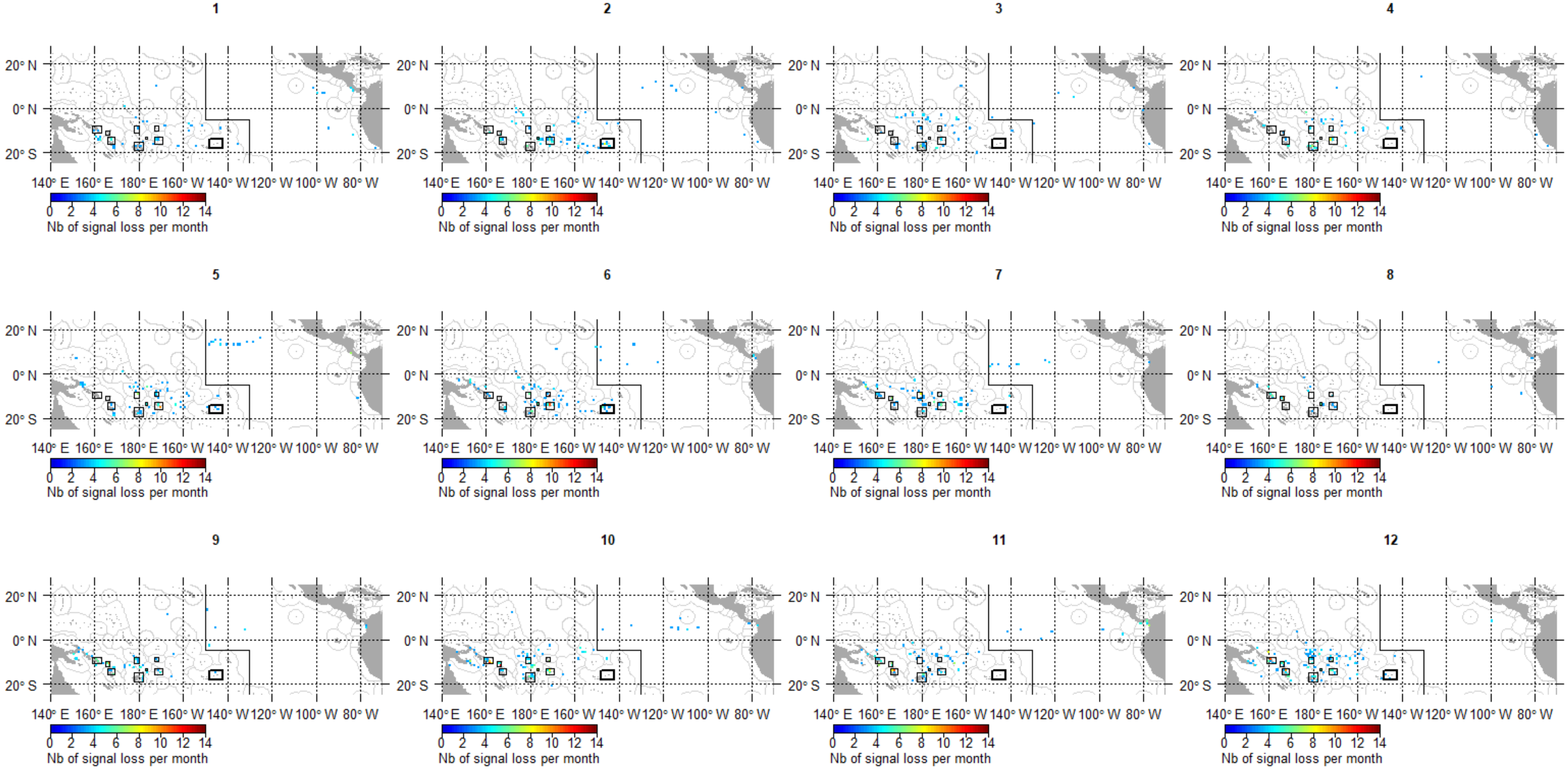

Figure S6. Spatial distribution of cells with a number of signal loss above the 0.9 quantile per month. Black rectangles represent the spatial boxes with high rates of signal loss. The black line indicates the limit between the WCPO and the EPO convention areas.

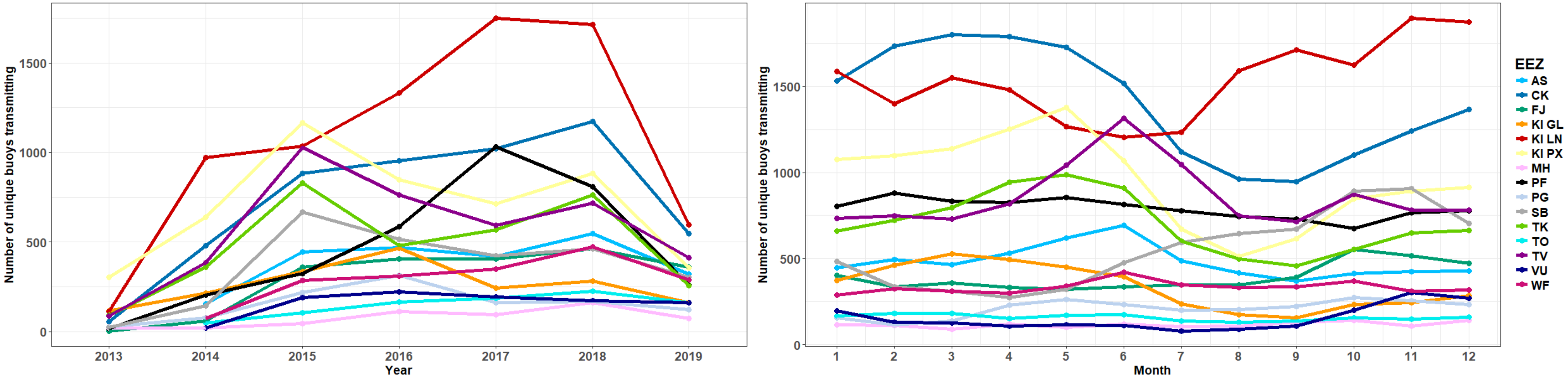

Figure S7. Number of unique dFAD transmitting per EEZ and year (left) or month (right).

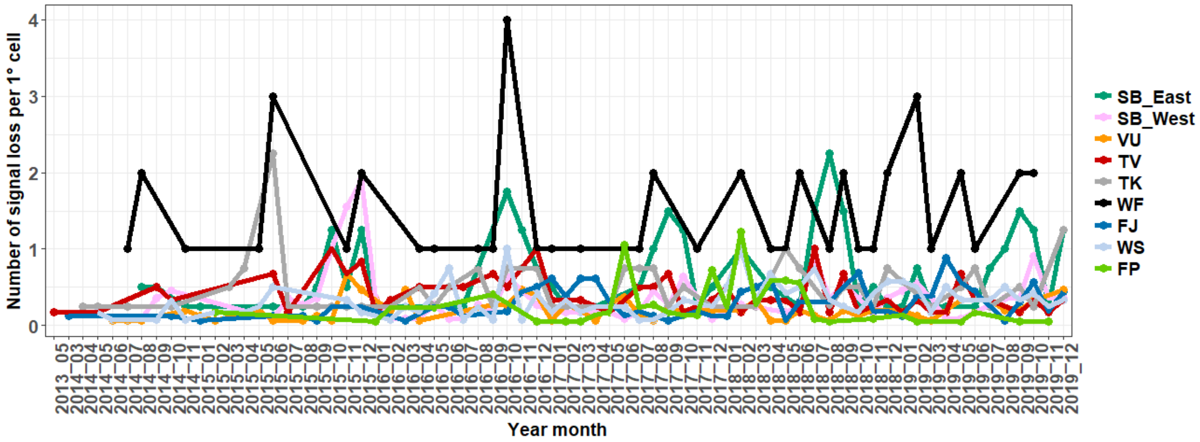

Figure S8. Average number of signal loss per 1° cell in each spatial box per month over the study period.

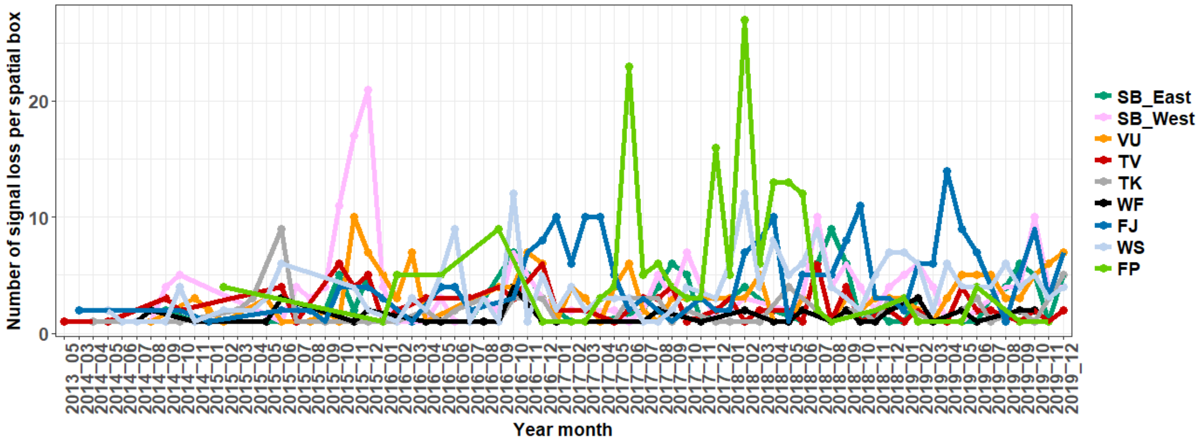

Figure S9. Number of signal loss per spatial box per month over the study period.

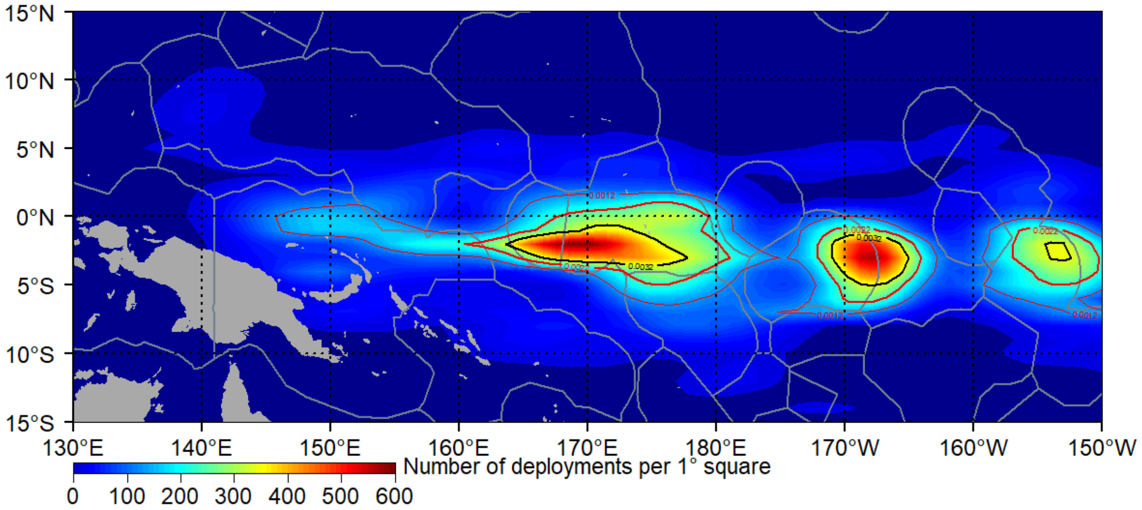

Figure S10. Deployment areas of all dFADs in the PNA dFAD tracking data in 2019. Dotted black lines indicate the 0.9 and 0.98 quantiles, as main and extended dFAD deployment areas. Extracted from Figure 8 in Escalle *et al.*, 2020b.

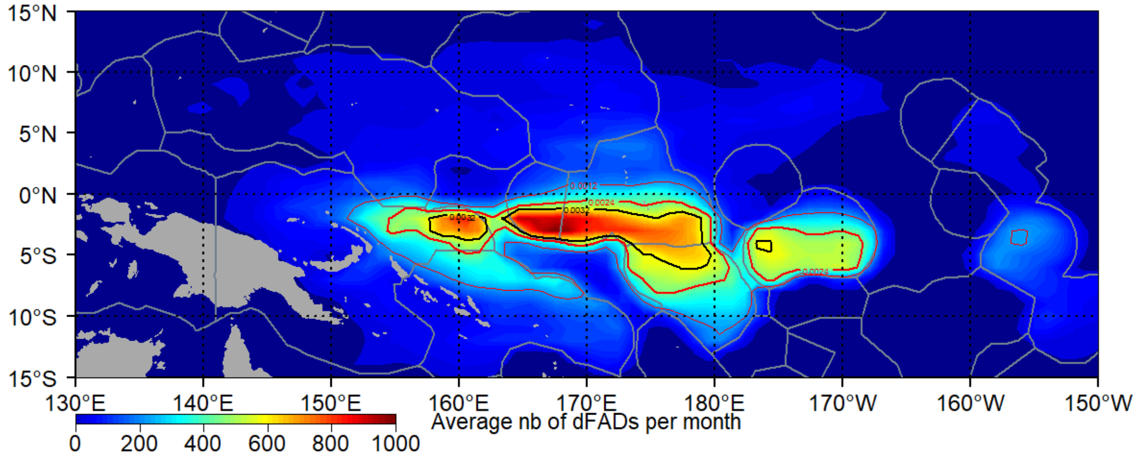

Figure S11. Spatial distribution of dFAD density from the PNA dFAD tracking data in 2019. Dotted black lines indicate the 0.9 and 0.98 quantiles, as main and extended dFAD density areas. Extracted from Figure 13 in Escalle *et al.*, 2020b.