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Estimation of the number of FADs active and FAD deployments per vessel in the WCPO

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Executive Summary

Purse seine fishing on drifting Fish Aggregating Devices (FADs) accounts for about 40% of the purse seine tuna catch in the WCPO. Fishing on FADs can have negative impacts on tuna stocks and the marine ecosystem. However, the number of FADs deployed annually and their prevalence remains unknown in the WCPO. This paper attempts to estimate the number of deployments and active FADs per vessel over the last 7 years.

Estimates were derived using two different approaches. Firstly, based on fishery data for 2011–2017, the number of deployments recorded in the observer data, the observer coverage by vessel, and a clustering of vessels based on their FAD fishing strategy were used to estimate the total number of buoy (and FAD) deployments per vessel and total in the WCPO. The number of deployments varied from 0 to 500 per vessel but few vessels (depending on the estimation method and year, Table I) deployed/redeployed more than 350 buoys per year. This corresponds to a total estimated number of deployments between 21,000 and 51,000 per year in the WCPO for the 2011–2014, but the numbers drop thereafter, likely due to delays in receiving observer data for recent years.

The second approach combined fishery data and the PNA FAD tracking data and therefore only covered 2016 and 2017 with precise estimates only possible for some vessels. The estimated number of deployments per vessel varied between 1 and 550 (mean = 129) in 2016 and 1 and 999 (mean = 226) in 2017 and the estimated number of active FADs per vessel varied between 1 and 454 (mean = 102) in 2016 and 1 and 955 (mean = 163) in 2017. At the scale of the WCPO, this corresponds to 30,700–56,900 deployments in 2016 and 44,700–64,900 in 2017; and 26,200–37,300 active FADs in 2016 and 38,000–48,200 in 2017. The ratio between number of deployments/redeployments per year and number of active FADs per vessel and per year average at 1.48. Less than 16% of the vessels were estimated to have more than 350 active FADs per year (Table I).

Table I. Percentage of vessels with more than 350 FAD deployments, more than 350 active FADs monitored per year or more 150 active FADs monitored per day estimated using two methods and data sets (when using FAD tracking data only a portion of vessels are included).

	Vessels with ≥350 deployments per year by estimation method				Vessels with	
	Vessel	Mean	Quantile 95%	FAD tracking	≥350 active FADs per year FAD tracking	≥150 active FADs per day FAD tracking
2011	1.9 %	0 %	18.4 %	-	-	-
2012	0.4 %	0 %	2.7 %	-	-	-
2013	0.4 %	0 %	2.7 %	-	-	-
2014	2.5 %	0 %	2.5 %	-	-	-
2015	0 %	0 %	0 %	-	-	-
2016	0 %	0 %	0 %	10.4 %	1.1 %	0 %
2017	0 %	0 %	0 %	25.5 %	15.7 %	3.9 %

Results from both methods correspond to estimates per vessel per year, and given this deployment/active ratio and an average active time of a FAD of 6 months found in the FAD tracking data, it is clear that at any given time, few/no vessels would have more than 350 active FADs in the water. We note that FADs regularly change ownership, and buoys are on average active for 6 months and may subsequently be deactivated. The estimates of FADs per vessel, and FAD densities, may be underestimated as a result.

We also investigated the influence of FAD density on the number of associated and unassociated sets, as well as catch and CPUE per species. The number of associated sets, and catch increased with FAD density. However, skipjack, bigeye, yellowfin and total CPUE from associated sets showed a slight decrease with increasing FAD density, with the analysis suggesting that CPUE decreases with FAD densities above 250 per 1° cell per month. No clear trend could be detected for unassociated sets.

We invite WCPFC-SC14 to:

- Note the progress being made by PNA in FAD tracking for the purpose of improving FAD management in PNA waters.
- Note the analysis of the number of FAD deployments and active FADs per vessel and the challenges encountered in this analysis.
- Note the conclusion that FAD density appears to influence CPUE, with a slight decrease of skipjack, bigeye, yellowfin and total CPUE with increasing FAD density, although this still needs further investigation.

1. Introduction

Purse seine fishing on drifting Fish Aggregating Devices (FADs) has increased since the 1990s and has become a major fishing method for catching tropical tuna worldwide (Fonteneau et al., 2013). In the Western and Central Pacific Ocean (WCPO), the number of sets on artificial FADs has exceeded the number of sets on natural logs for the last 10 years and represented more than 40% of the total purse seine tuna catch in recent years (Williams et al., 2017). This sharp increase in the use of FADs over the last decade is linked to the arrival of new technological developments. These include satellite buoys to track the FAD and more recently echo-sounder buoys to estimate the quantity of tuna aggregated below it (Fonteneau et al., 2013; Lopez et al., 2014).

The number of FADs deployed in the WCPO in 2013 was estimated at between 30,000 and 50,000 (Gershman et al., 2015). Beyond this uncertainty in the number of active FADs present, and noting the technological developments described above, several issues remain unknown: i) the number of instrumented FAD deployments; ii) the number of satellite buoy deployments (could be higher as vessels may deploy buoys on FADs or logs found at sea); and iii) the number of 'active' buoys on FADs at any time.

The increased use of FADs has wider implications. Sets on FADs have relatively high bycatch rates, including vulnerable species such as sharks and sea turtles (Dagorn et al., 2013), which may also become entangled in the nets of the FADs underwater appendages (Filmalter et al., 2013). FADs could potentially change some natural behaviors of tuna (Hallier and Gaertner, 2008) or, when deployed extensively, may lead to tuna school fragmentation (Sempo et al., 2013). In addition FADs drifting out of productive areas are generally abandoned by fishers and may strand in coastal areas, potentially damaging coral reefs, or disintegrate at sea leading to pollution (Davies et al., 2017; Maufroy et al., 2015). Finally, the increased use of FADs and the potential impacts on stocks led the Parties to the Nauru Agreement (PNA) and WCPFC to implement a three to four month FAD closure where all FAD-related activities (e.g. fishing, deployment) are prohibited (WCPFC, 2017).

Given the uncertainty in the number of FADs deployed within the WCPO, there is a need to better understand the pattern of FAD deployment at the vessel level. The PNA has been undertaking a FAD tracking programme since 2016 to provide information for improving the management of FADs in PNA waters, which is beginning to provide data on FAD use. In addition, FAD deployments recorded by observers since 2011 (the first year of 100% observer coverage requirement) could provide further information on vessel-level patterns in the WCPO.

Using these data sources, the aims of this paper are to 1) estimate the number of FADs currently deployed per vessel; 2) estimate the number of active FADs per vessel; 3) estimate the number of FAD deployments in the whole WCPO; and 4) evaluate the potential impact of high FAD density on catch and CPUE.

2. Methods

2.1 Data

We used complementary datasets combining fishery data over the 2011–2017 period (observer, operational and aggregated logsheet data) and the 2016–2017 PNA FAD tracking data. Firstly, observer data include information on FAD deployments and associated sets[1] per vessel, as well as the origin of any FAD encountered by a vessel at sea. Since 2011, there has been a 100% observer coverage requirement, however, data coverage is at 70–81% of the fishing trips, with some data not yet received for recent years (see Table 1 in Williams et al. (2018)). Secondly, operational logsheet data that are recorded by vessel captains, and include catch per species at the set level. These were complemented by the corrected and aggregated logsheet data (S-BEST), with complete number of sets and catch per species per 1° grid cell and month. Finally, the corrected PNA FAD tracking data (see Escalle et al. (2018) for details of the correction procedure), covering 2016 and 2017, contained a subset of buoy deployments and active buoys for some vessels fishing in PNA waters.

2.2 Identification of groups of vessels with similar FAD fishing strategy

A hierarchical clustering analysis, based on Ward minimum variance, was used to group vessels by year based on their FAD fishing strategy. The clustering was at the vessel and year level and based on vessel length, the number of associated sets recorded in operational logsheet data, the number of associated sets recorded in observer data, the percentage of associated sets over total number of sets performed (unassociated, anchored FADs and live whales and whale sharks) and the origin of all FADs investigated at sea (set, serviced and only investigated[2]). The output of the clustering consists of a dendrogram and number of statistics (e.g. cubic clustering criteria, pseudo t_2 and Hubert index) that were used to select the appropriate number of clusters.

As limited data are currently available in the observer data for 2016 and 2017, a general clustering over the whole period was also performed, and used in the estimation of FAD number using FAD tracking data. This general clustering was also at the vessel level (only vessels present in 2016 and 2017) and based on vessel length, the percentage of associated sets over total number of sets performed in the 2011–2017 period by vessel, the origin of all FADs investigated at sea in the 2011–2017 period and the number of associated sets in the operational logsheet data in 2016 and in 2017, separately.

Vessels with less than five associated sets recorded in operational logsheet data and in observer data for a given year were removed prior to the clustering analysis.

2.3 Estimated number of FAD deployments per vessel using fishery observer data

Here, a FAD deployment is defined as all FAD and buoy (i.e. deployed on an already drifting FAD or log) deployments recorded by observers. Events where a buoy was deployed at the same time as a FAD were removed to avoid double counting. The number of FAD deployments per vessel and per year was then calculated based on observer coverage and the number of deployments recorded by observers. Vessels with no observer coverage in a given year, were therefore removed from the analysis. First, per vessel and year, the number of deployments recorded (D) was raised using the vessel observer coverage (OC) as follow: Total deployments = D + (D * (1 - OC)).

[1] In this document associated sets only include drifting FAD which includes logs and excludes anchored FADs and sets on live whales and whale sharks.
[2] It was tested with FAD set and FAD investigated separately, with similar results.

In order to standardise the estimation, we also calculated the total number of deployments per vessel and per year using the observer coverage of the vessel and the minimum, quantile 5%, mean, quantile 95% and maximum number of deployments (D) recorded by a cluster of vessels with similar strategy.

Finally, to also get estimations of the total number of FAD deployments made in the whole WCPO per year, we added to all the vessel estimates, an estimation of the deployments from vessels with no observer coverage. This was done using the mean number of deployments per cluster and estimation method (i.e. vessel, minimum, quantile 5%, mean, quantile 95% and maximum).

2.4 Estimated number of FAD deployments and active FADs per vessel using FAD tracking and fishery data

Estimates combining both FAD tracking and fishery data could only be made for 2016 and 2017 and were developed considering the following features of the data: i) submitting PNA FAD tracking data is mandatory for vessels fishing in the PNA waters, not the whole WCPO; ii) most FAD trajectories in the PNA FAD tracking data have been modified by fishing companies prior to submission, with FAD positions outside PNA waters removed; iii) the data only corresponds to a fraction of the total number of FADs in the WCPO (30-40%), with some vessels not submitting any FAD trajectories; iv) the vessel owner of a FAD was sometimes limited to the fishing company; and v) a set performed on a given FAD can be performed by a vessel that is not the owner of the FAD (Escalle et al., 2018). Therefore, the FAD tracking data could not be used alone, and it was necessary to match fishery data of a given associated set or deployment to a FAD trajectory.

At sea positions from the FAD tracking data were matched with i) buoy and FAD deployments positions from observer data; and ii) associated sets positions from operational logsheet data using position (<2 km) and date/time (Escalle et al., 2017b).

Two main hypotheses have being formulated for these analyses: i) the percentage of matching between FAD trajectories and fishing sets per vessel or company and the total number of associated sets performed reflects the total number of FADs used (owned or found at sea) by a vessel; and ii) the number of deployments/redeployments recorded for a buoy owned by a certain vessel also reflect the number of FAD deployments made by that vessel. The latter is by nature incorrect as buoys may be deployed on FADs already drifting or could potentially be leased from other vessels.

First assessing the estimation of number of buoy deployments per vessel (when available, i.e. 77 vessels in 2016 and 102 in 2017) and per year, the number of deployments matched with a FAD trajectory was divided by the total number of deployments (D) from the FAD tracking data (deployments from observer data was also tested giving similar results, considering that both are currently incomplete for 2016 and 2017) to get a matching percentage (M) and used to estimate the total number of deployments: Total deployments = D + (D * (1 - M)).

Secondly, estimating the number of FADs used per vessel and per year, as the vessel owner was not always available, the list of vessels per company in the FAD tracking data was compiled. For each vessel and company, the percentage of matching (M) between associated sets from operational logsheet data and FAD trajectories was used to raise the number of FADs active (A) in the FAD tracking data: Total number of FADs used = A + (A * (1 - M)). In the case of company name only, this was then divided by the number of vessels per company.

To get an overall number of deployments and FADs used per vessel, an estimate was also made for the vessels (or companies) not in the FAD tracking data, using the quantile 5%, mean or quantile 95% value per cluster (general clustering over 2011–2017).

2.5 Influence of at sea FAD density on CPUE, catches and occurrences of FAD and free school sets

To investigate the influence of FAD density on the occurrence of FAD and free school sets, as well as on CPUE and catch, we used aggregated FAD densities per 1° grid cell at various temporal resolutions (day, week, month and year). These were obtained by i) selecting at sea sections of FAD trajectories from the PNA FAD tracking data; and ii) compiling the number of individual FADs transmitting per 1° cell per day, week, month or year.

These aggregated FAD densities were then compared to catch and number of sets derived from operational logsheet data (Tufman 2), and aggregated and corrected logsheet data (S-BEST). The latter corresponds to the most complete dataset corrected for species composition, but is aggregated by 1° cell and month. Therefore, in order to access the catch per set and account for a potential vessel effect, we also use operational logsheet data recorded by captains. Given that most FAD trajectories outside PNA waters have been removed by fishing companies (i.e. geo-fencing), leading to biased FAD densities outside PNA waters, these were removed from the comparison (17.0% of associated sets and 12.8% of unassociated sets in the S-BEST data set and 9.8% and 7.2% in uncorrected logsheet data).

Relationships between FAD density and catch, CPUE or number of sets were developed. Generalised additive models were used to assess the influence of FAD density on catch per species, CPUE and number of associated and unassociated sets. Model selection was performed using a backward stepwise selection procedure based on AIC and BIC, residuals analysis, examination of predicted versus observed values, and deviance explained.

3. Estimates using fishing data only

3.1 Clustering by vessel and year

Each year vessels were divided into 7 groups of similar FAD fishing strategy (Figure 1 and Appendix 1). These were classified as clusters A to G following a decreasing number of associated sets recorded in logsheets. Similarly, the number of associated sets in clusters based on observer data generally decreased, although it is not necessarily true for the first clusters as a result of differences in observer coverage between datasets. The percentage of associated sets and vessel length also generally decreased, at least between the first and last clusters. One cluster, generally A or B, also corresponded to vessels mostly setting and investigating their own FADs, or another vessels' with its consent, therefore corresponding to vessels with a large array of FADs. One cluster, generally F or G, represented small vessels with many FADs deployed by supply vessels or sets by other vessels without consent. Finally, the rest of the clusters operate on their own FADs in 35–50% of the time, and up to 60% if we included activity on other vessels' FADs with consent.

Generally, vessels in cluster A and B are the largest vessels and have a fishing strategy orientated toward FADs, with more than 50 (or 75%) of their sets being associated, and they use a large array of their own FADs. Vessels in cluster C to E, are intermediate, can also present high rates of associated sets, they rely on their own FADs and on FADs found drifting at sea. Finally, clusters F and G are relatively opportunistic, having less than 20% of their sets on FADs and include the smallest vessels (domestic fleets of two Pacific Island nations) of the WCPO.

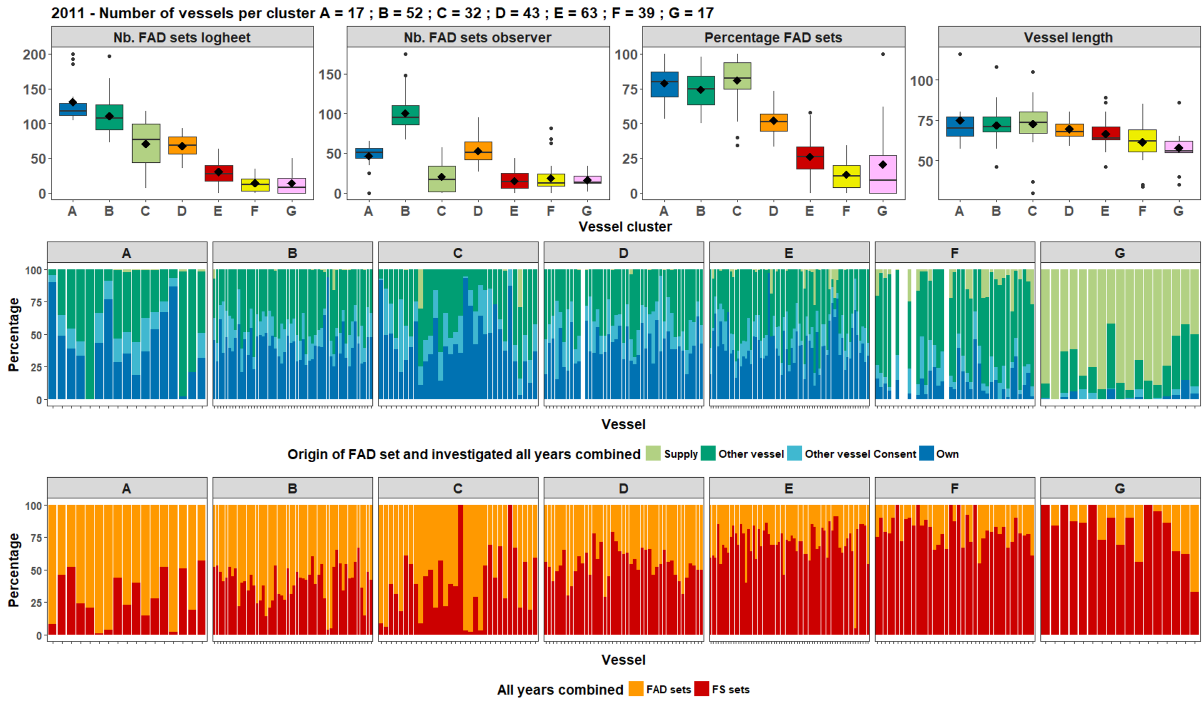


Figure 1. Fishing strategy clusters for 2011 (see supplementary materials for the other years). Top = number of FAD sets in logsheet and observer data, percentage of associated sets (FAD and log) per vessel in the considered year and vessel length per cluster. Middle = origin of all FAD encountered by a vessel over 2011–2017. Bottom = percentage of associated sets (FAD and log) per vessel over 2011–2017.

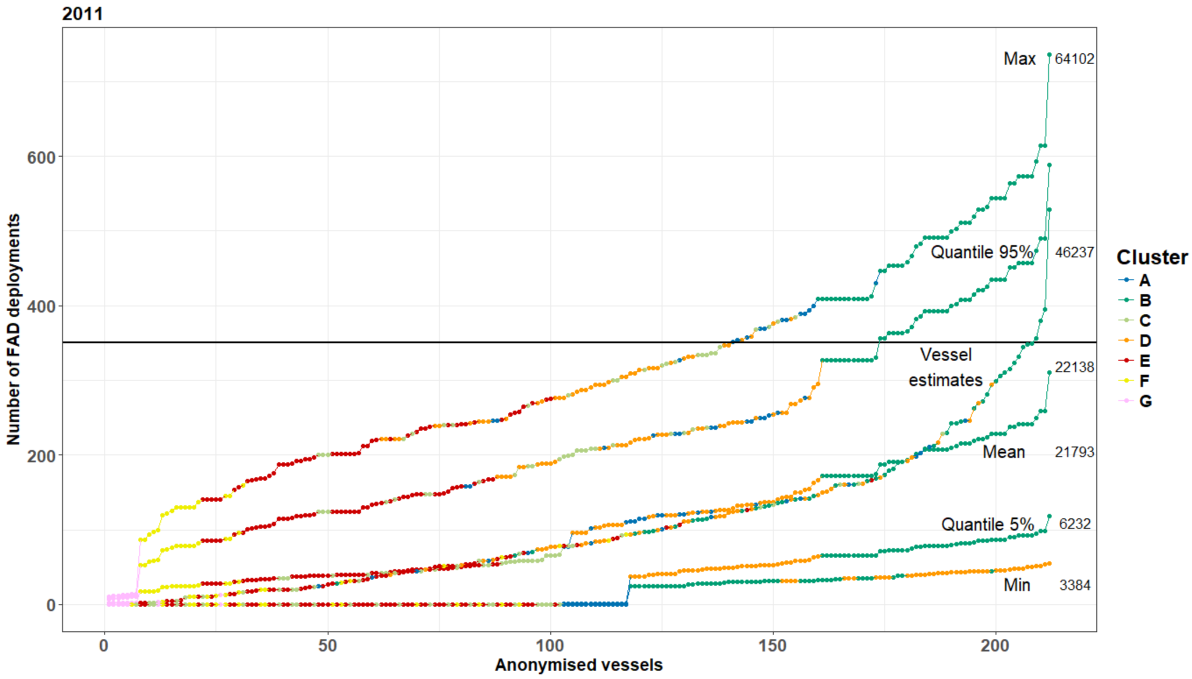
3.2 Estimates of number of deployments per vessel

In this section, a deployment is defined as the record by an observer of an initial or repeat deployment at sea of a FAD (buoy deployment not recorded or FAD only deployed), a buoy (on a log, or a FAD already drifting) or both a FAD with a buoy[3].

The total number of deployments per vessel and year, estimated using alternative methods, is shown for vessels with observer coverage in Figure 2. Vessels in cluster A, B and C deployed the most FADs each year, as expected given that they are the vessels relying the most on FADs in their fishing strategy. Estimates corresponding to each vessel (unique number of deployments recorded by vessels and raised by the observer coverage) varied between 0 and 500 deployments per vessel per year (Figure 2). However, very few vessels undertook more than 350 deployments per year: 1 in 2012 and 2013, 4 in 2011 and 6 in 2014 (Table 1). These estimates were generally similar to those derived using mean deployment per cluster. However, for vessel deploying the most FADs (right–hand side of Figure 2), the estimates were somewhat intermediate between standardized estimates using mean and quantile 95% deployments per cluster. If we hypothesise that the number actual total number of deployments per vessel per year is between the mean and quantile 95% estimates, 6 vessels were found to have

[3] Note that FADs are never deployed without a buoy, but sometimes the observer only record the deployment of the FAD.

more than 350 deployments per year in 2012, 2013 and 2014, and a maximum of 39 vessels in 2011 (Table 1).



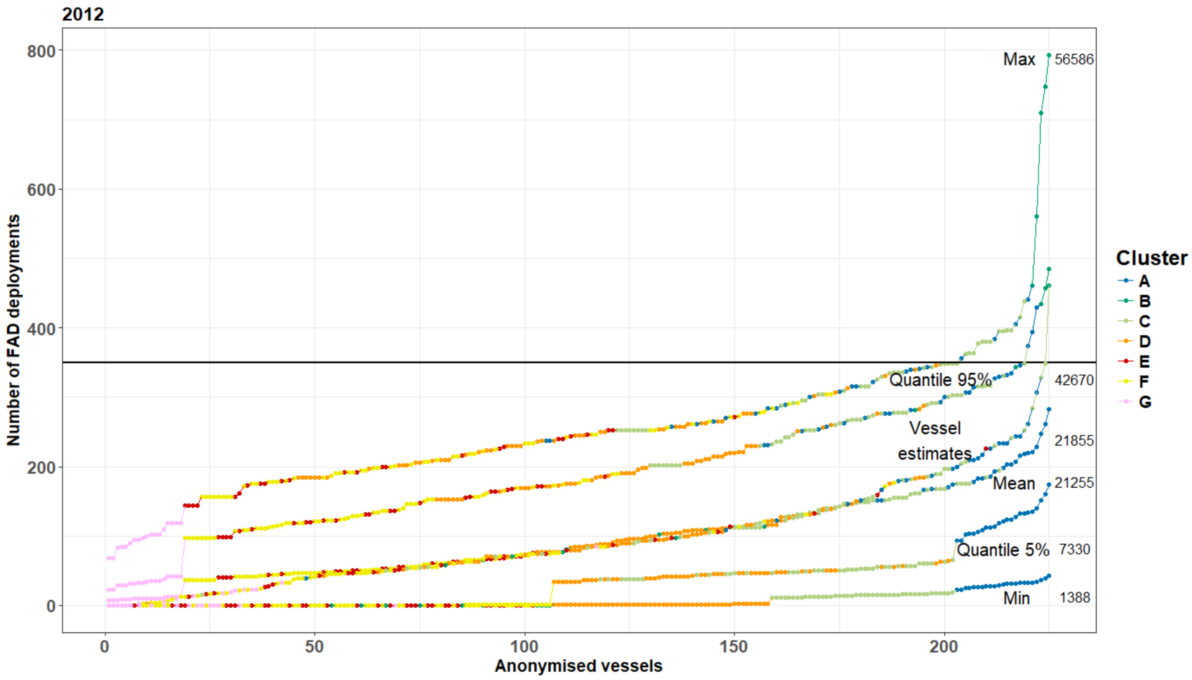
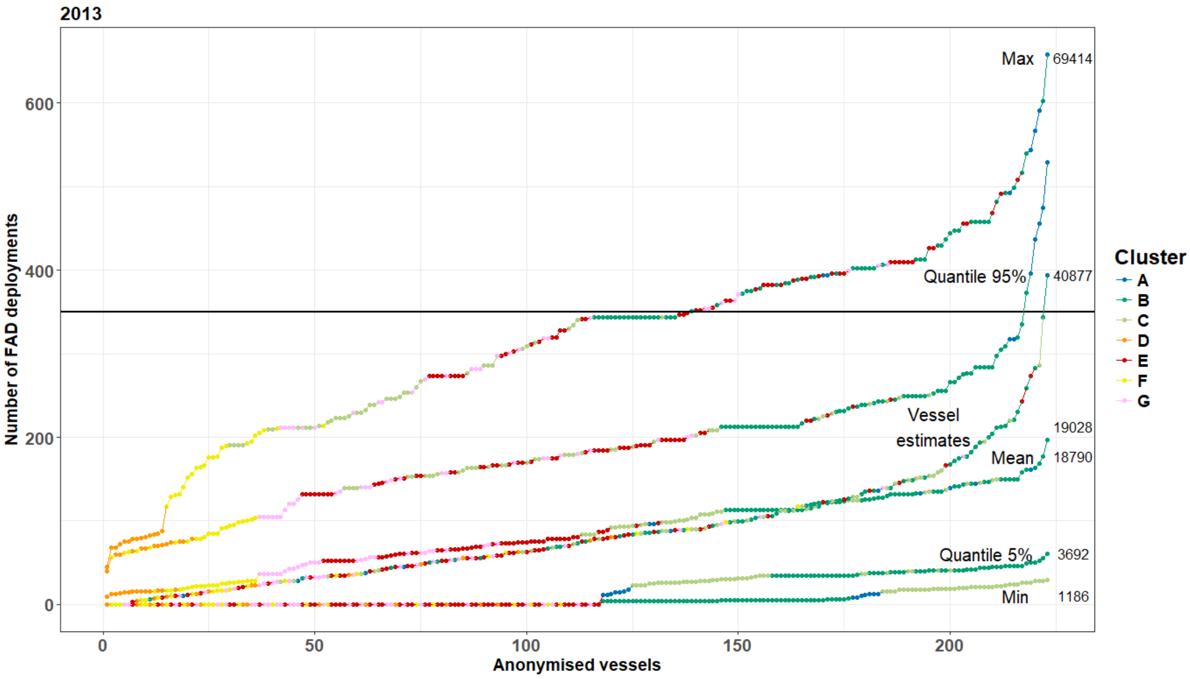


Figure 2(1). Estimated number of deployments per vessel per year (2011–2017) based on different standardisation methods: observer coverage of the vessel x number of deployments of the vessel (vessel estimates), or minimum, quantile 5%, mean, quantile 95% or maximum number of deployments per cluster. Estimated total number in the WCPO indicated on the right-hand side of each curve.



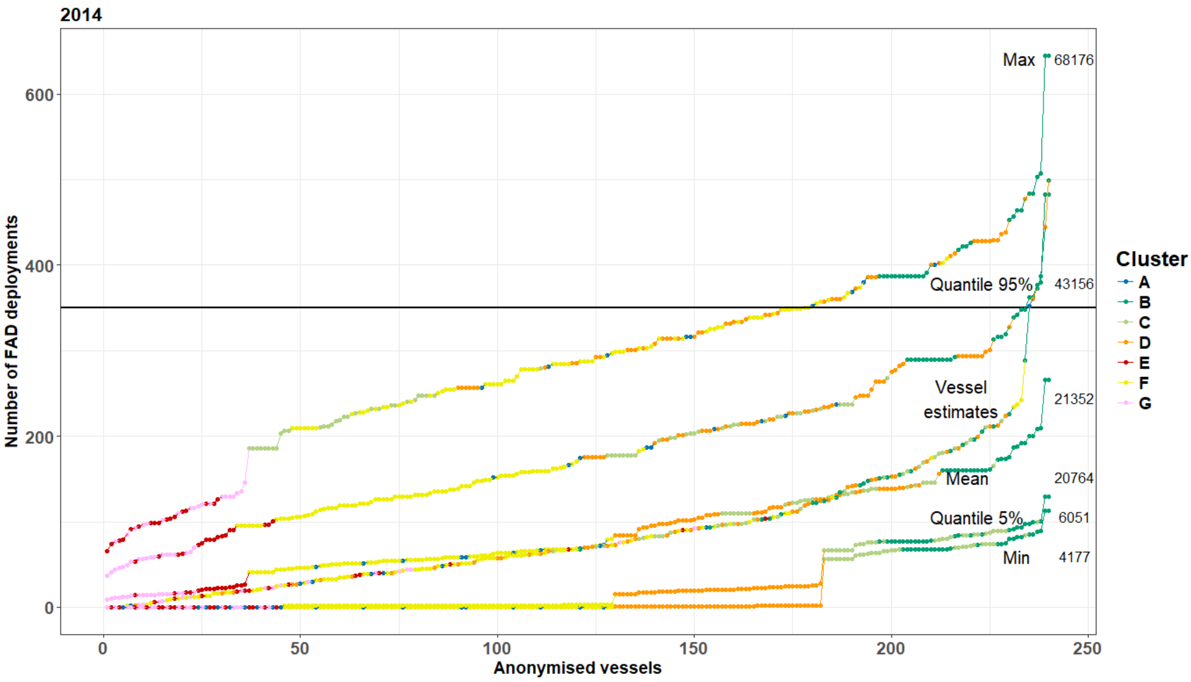


Figure 2(2). Estimated number of deployments per vessel per year (2011–2017) based on different standardisation methods: observer coverage of the vessel x number of deployments of the vessel (vessel estimates), or minimum, quantile 5%, mean, quantile 95% or maximum number of deployments per cluster. Estimated total number in the WCPO indicated on the right-hand side of each curve.

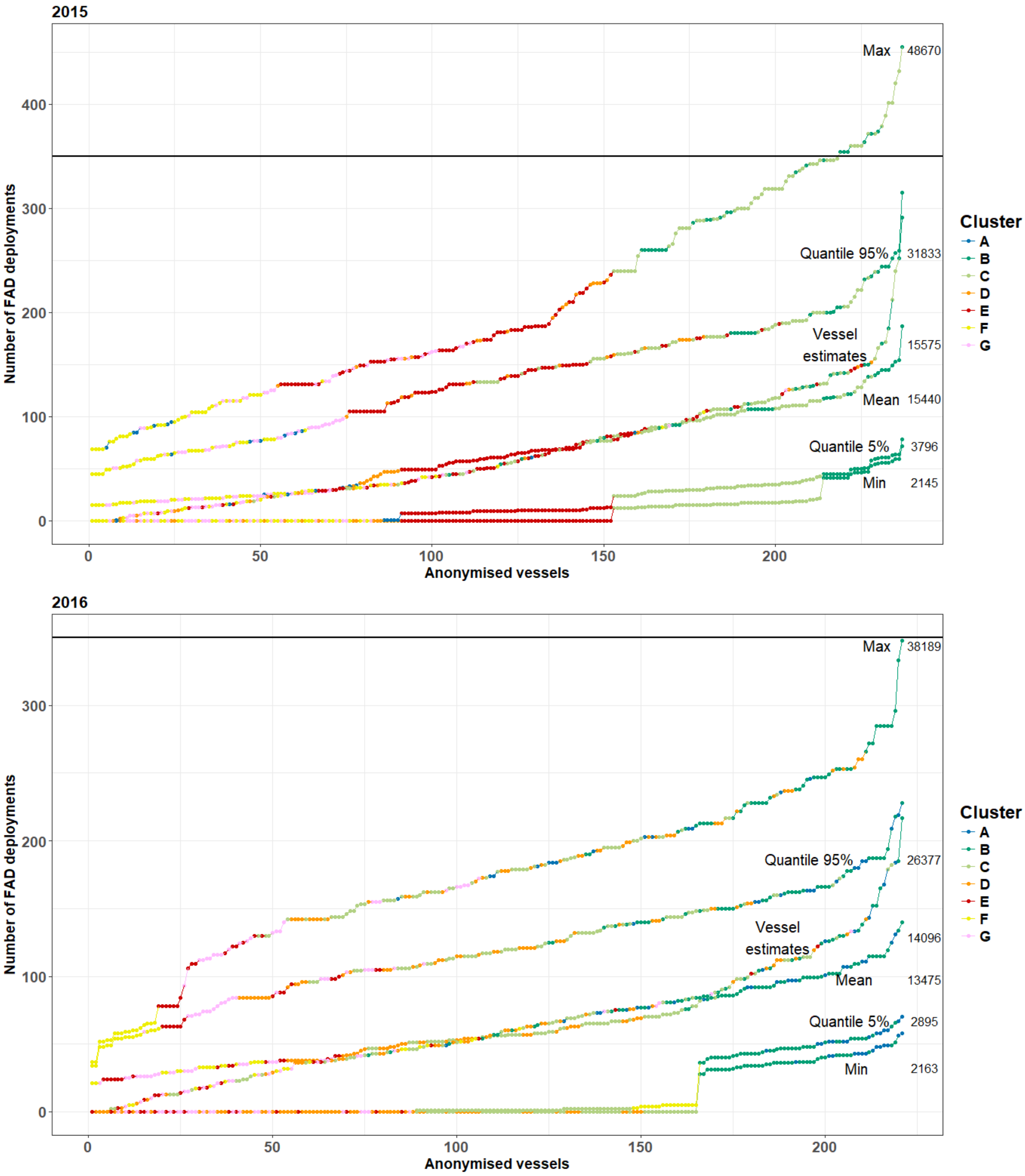


Figure 2(3). Estimated number of deployments per vessel per year (2011–2017) based on different standardisation methods: observer coverage of the vessel x number of deployments of the vessel (vessel estimates), or minimum, quantile 5%, mean, quantile 95% or maximum number of deployments per cluster. Estimated total number in the WCPO indicated on the right-hand side of each curve.

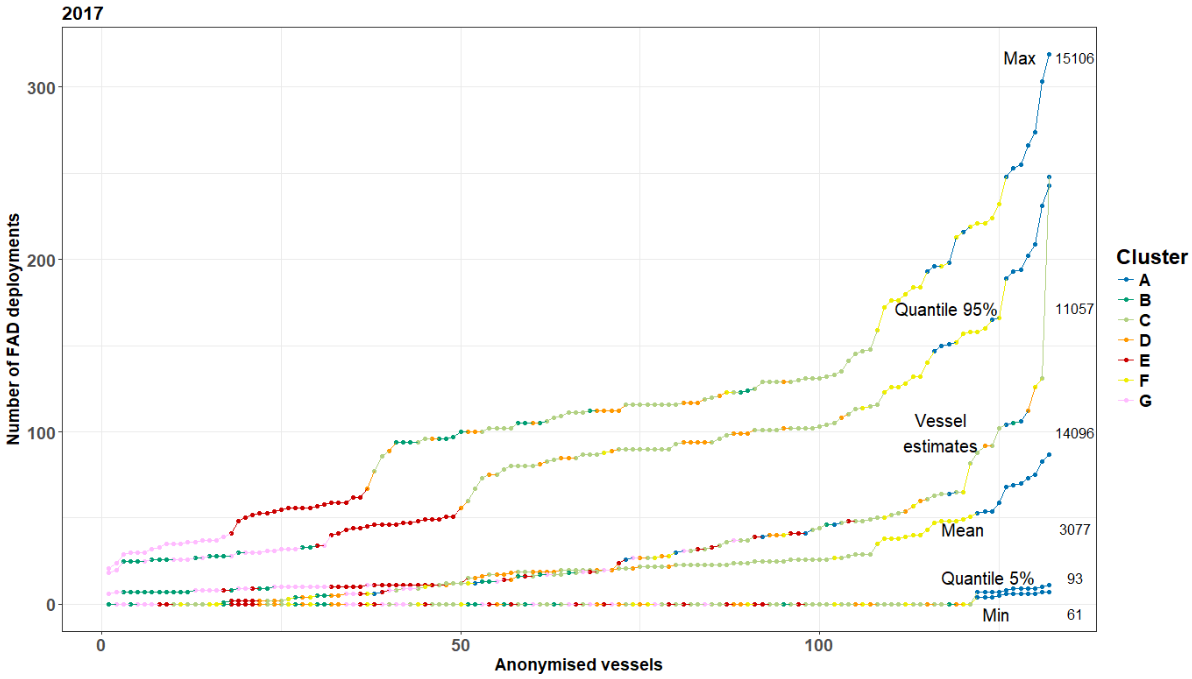


Figure 2(4). Estimated number of deployments per vessel per year (2011–2017) based on different standardisation methods: observer coverage of the vessel x number of deployments of the vessel (vessel estimates), or minimum, quantile 5%, mean, quantile 95% or maximum number of deployments per cluster. Estimated total number in the WCPO indicated on the right-hand side of each curve.

Table 1. Estimates of the number of deployments per year and of the number of vessel with more than 350 FAD deployments per year depending on the estimation method used*.

			Total nb. in WCPO				Mean nb. per vessel				Nb. of vessels ≥ 350 FADs			
		Nb. of vessels	Vessel	Mean	Q95	Max	Vessel	Mean	Q95	Max	Vessel	Mean	Q95	Max
2011	Vessels with obs. coverage	212	22,138	21,793	46,237	64,102	104	103	218	302	4	0	39	72
	All vessels estimates	263	23,949	23,324	50,972	71,787	91	89	194	273				
2012	Vessels with obs. coverage	225	21,855	21,255	42,670	56,586	97	94	190	251	1	0	6	22
	All vessels estimates	288	24,462	23,256	48,740	67,781	85	81	169	235				
2013	Vessel with obs. coverage	223	19,028	18,790	40,877	69,414	85	84	183	311	1	0	6	85
	All vessels estimates	294	21,944	21,096	48,043	82,936	75	72	163	282				
2014	Vessels with obs. coverage	240	21,352	20,764	43,156	68,176	89	87	180	284	6	0	6	63
	All vessels estimates	292	23,147	22,001	47,215	75,873	79	75	162	260				
2015	Vessels with obs. coverage	237	15,575	15,440	31,833	48,670	66	65	134	205	0	0	0	19
	All vessels estimates	282	17,008	16,697	35,565	54,072	60	59	126	192				
2016	Vessels with obs. coverage	221	14,096	13,475	26,377	38,189	64	61	119	173	0	0	0	0
	All vessels estimates	257	15,674	14,849	29,732	43,370	61	58	116	169				
2017	Vessels with obs. coverage	130	2,233	1,710	5,909	8,624	17	13	45	66	0	0	0	0
	All vessels estimates	227	3,593	2,543	9,414	14,448	16	11	41	64				

*Vessel = observer coverage vessel x number of deployments vessel; Mean = observer coverage vessel x mean number of deployments per cluster ; Q95 = observer coverage vessel x Quantile 95% of number of deployments per cluster ; Max = observer coverage vessel x Maximum number of deployments per cluster.

The number of deployments per vessel and the total number of deployments in the WCPO showed a sharp decrease from 2015 (Figure 2 and 3 and table 1), this is probably due to delays in observer data submission (Williams et al., 2018). However, the total number of deployments per year is relatively stable for the 2011–2014 period. Using the vessel estimates method the total number of deployments varied between 19,000–22,100 per year; using the mean per cluster estimates ranged between 18,800–21,900; and for the estimates with quantile 95% per cluster estimates ranged between 40,900–46,200 (Table 1). When adding vessels with no observer coverage, the values increased to 21,000– 23,900 for vessel estimates and mean per cluster methods and 47,200–50,900 for estimates with quantile 95% per cluster (Figure 3 and Table 1). These numbers are very similar to the number of deployments in the WCPO estimated at 30,000–50,000 in 2013 (Gershman et al., 2015).

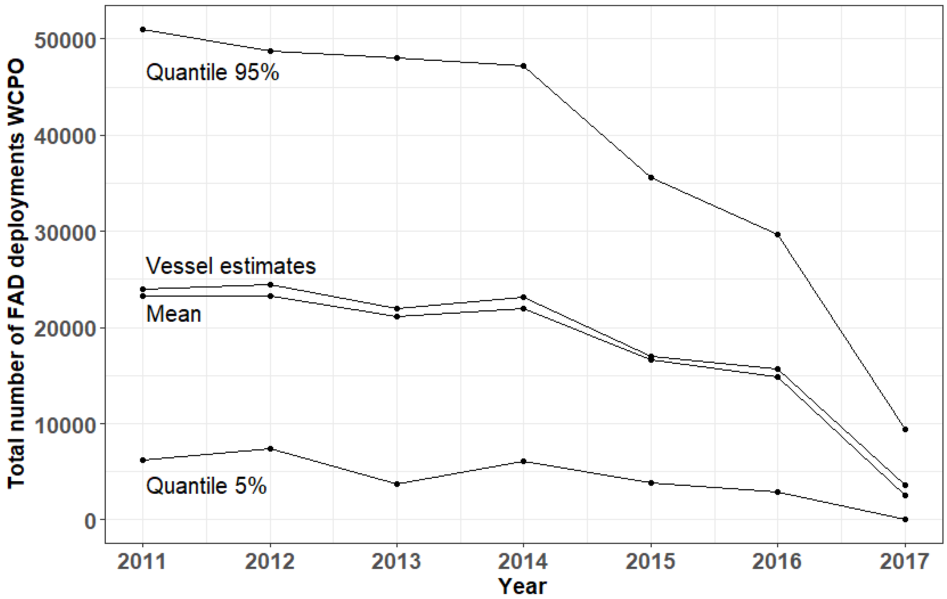


Figure 3. Estimates of the total number of deployments per year in the WCPO with different estimating methods.

The estimated number of deployments per vessel per year were compared to the number of associated sets performed (Figure 4), which shows a correlated increase between sets and deployments but with higher deployments than sets, as shown by the position of the 1:1 line over the scatter plot. A slight plateau appears when deployments are estimated using the mean, quantile 95% and maximum value per cluster, but this is less evident than in a recent paper in the EPO (Lennert-Cody et al., 2018). This is probably due to the number of deployments remaining likely underestimated for some vessels while the number of sets is certain.

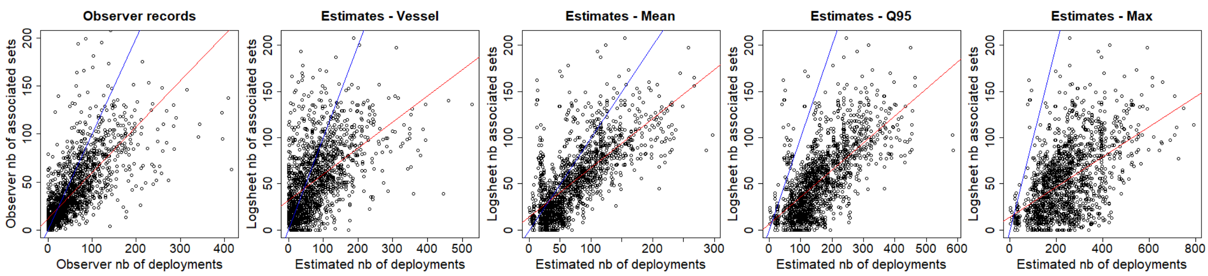


Figure 4. Number of associated sets in observer or logsheet data in function of the number of deployments recorded by observers or estimated using standardisation methods. Red lines are the linear regression and blue lines the 1:1 line.

The tuna total catch increased with the number of deployments (Figure 5), as expected considering an increase in the number of sets with deployments. However, the catch per set was stable or slightly decreasing for vessels fishing mostly on FADs (Clusters A to C), and increasing for the others (Clusters D to G) (Figure 5). For vessels in cluster A, the largest vessels fishing dominantly on FADs, this could be due to some fleets fishing also in the EPO, for which we only have a small number of deployments but the highest catch per set (all dots in the top-left corner). This raises the question of how many FADs used in the WCPFC have been deployed in the EPO and are unseen in any estimates, either through vessels fishing in both areas or through potential leasing processes.

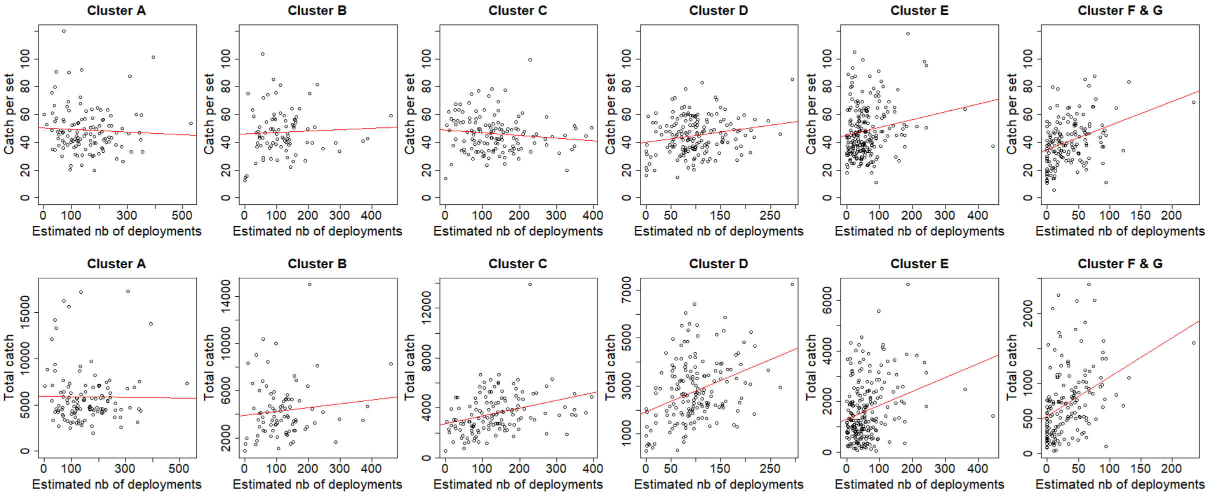


Figure 5. Estimated number of associated sets per vessel per year, using the vessel estimates method, compared to the catch per associated sets (top) and total catch (bottom) and per vessel cluster of similar FAD fishing strategy.

To conclude, the estimated number of deployments made per vessel and per year represents the total number of FAD and buoy deployments per year, while CMM-17-01 limits the number of FADs active per vessel at any given time. Given that the average active duration of a FAD is 6 months[4] in the FAD tracking data (Escalle et al., 2018), the number of FAD active at any time is potentially 2 times less than the number of deployments. Getting some estimations of this ratio between deployments and active FADs per vessel is therefore important. This requires the use of a combination of both fishery and FAD tracking data.

4. Estimates combining FAD tracking data and fishing data

4.1 Number of deployments per vessel

To complement the estimation of the number of deployments per vessel based on observer records only, we also used information from the PNA FAD tracking data and matched both datasets. While estimates will only be available for 77 and 102 vessels in 2016 and 2017 (some FADs in the PNA tracking data have no known vessel owner with only information on the fishing company available), these will likely be more accurate for these vessels than when using observer data only. In addition, some simple extrapolation using the average/quantile estimated number of deployments per vessel within clusters of a similar fishing strategy will allow the estimation of total number deployments

[4] ISSF skipper workshops highlighted that skippers consider that FAD should last 6 to 9 months (Murua et al., 2018).

made in the WCPO per year. The resulting estimated number of deployments per vessel varied between 1 and 550 (mean = 129) in 2016 and 1 and 999 (mean = 226) in 2017, corresponding to a total of 9,966 deployments for 77 vessels in 2016 (average of 129 per vessel) and 23,107 for 102 vessels in 2017 (average of 226 per vessel) (Figure 6).

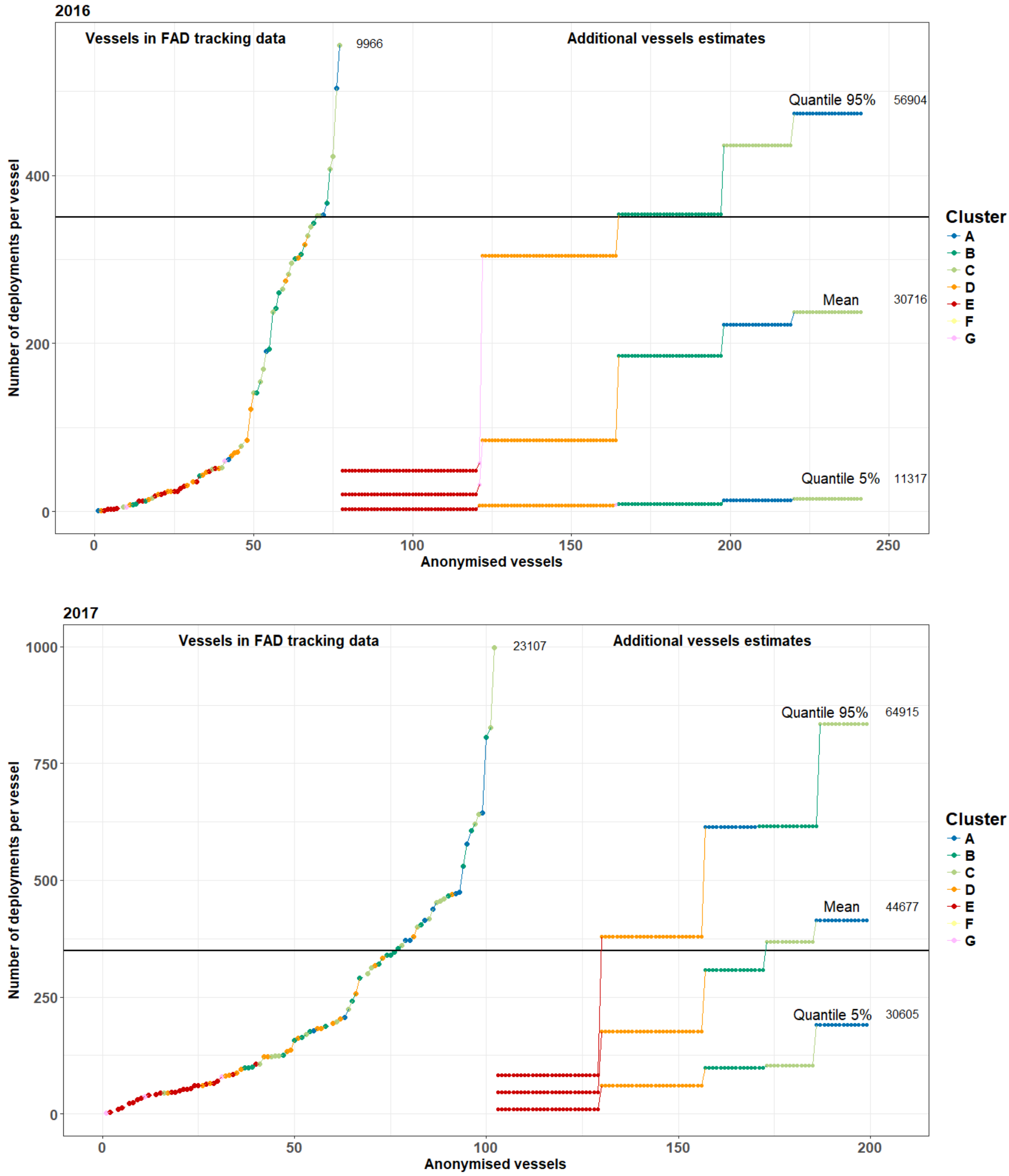


Figure 6. Estimated number of deployments in 2016 and 2017 based on number of deployments recorded in the FAD tracking data per vessel and raised by matching with observer data deployment position and date (left side). Additional vessels (i.e. where fishing company or vessel information are not present in FAD tracking data), were added based on quantile 5%, mean and quantile 95% value per cluster (general clustering with all 2011–2017 years combined) (right side). The estimated total number of deployments in the WCPO is indicated on the right-hand side of each curve.

The total number of deployments varied between 30,700 and 56,900 in 2016 (based on average and quantile 95%) and 44,700 and 64,900 in 2017 (Figure 6 and 7, Table 2). When comparing these results with the estimates based on observer data only (Figure 7), this either indicates i) an increase in the number of deployments since 2014 (considering the lack of observer data from 2015 to 2017); or ii) an underestimation of the deployments from observer data only (unnoticed deployments and/or FADs from the EPO being used). The difference between 2016 and 2017 is also striking, but is likely due the increased reporting of FAD tracking data by fishing companies in 2017 (see Escalle et al. (2018) for temporal trend in reporting).

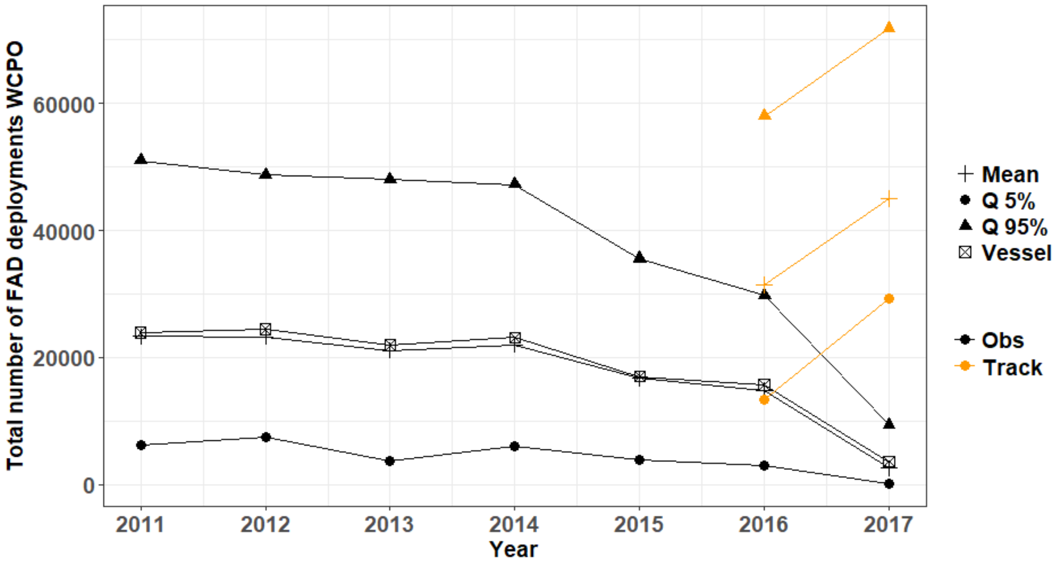


Figure 7. Estimates of the total number of deployments per year in the WCPO with different estimating methods based on observer data only (black line) and using a combination of PNA FAD tracking and observer data (orange line).

Table 2. Estimates of the total number of deployments per year in the WCPO using a combination of PNA FAD tracking and observer data.

		Total nb. in WCPO			Average nb. per vessel		
	Nb. of vessels	Q5	Mean	Q95	Q5	Mean	Q95
2016	241	11,317	30,716	56,904	47	127	236
2017	199	30,605	44,677	64,915	154	225	326

4.2 Number of FADs active per vessel

The number of FADs active is considered in this section, by matching FAD tracking data and associated sets recorded in operational logsheet data. Comparable to the previous estimates, the number of active FADs is estimated only for vessels present in the FAD tracking data (77 and 102 in 2016 and 2017), as well as for fishing companies by dividing by the number of vessels per company (additional 110 and 104 vessels). Estimates for the whole WCPO are then extrapolated.

The number of active FADs per vessels varied between 1 and 454 (mean = 102) in 2016 and 1 and 955 (mean = 163) in 2017. (Figure 8). Those numbers are, however, potentially overestimated as some FADs may be shared by several vessels and some sets may be performed on FADs from other vessels.

Regarding the total number of active FADs being used in the WCPO per year, estimates varies between 26,200 and 37,300 in 2016 and between 38,000 and 48,200 in 2017 (Figure 8 and Table 3).

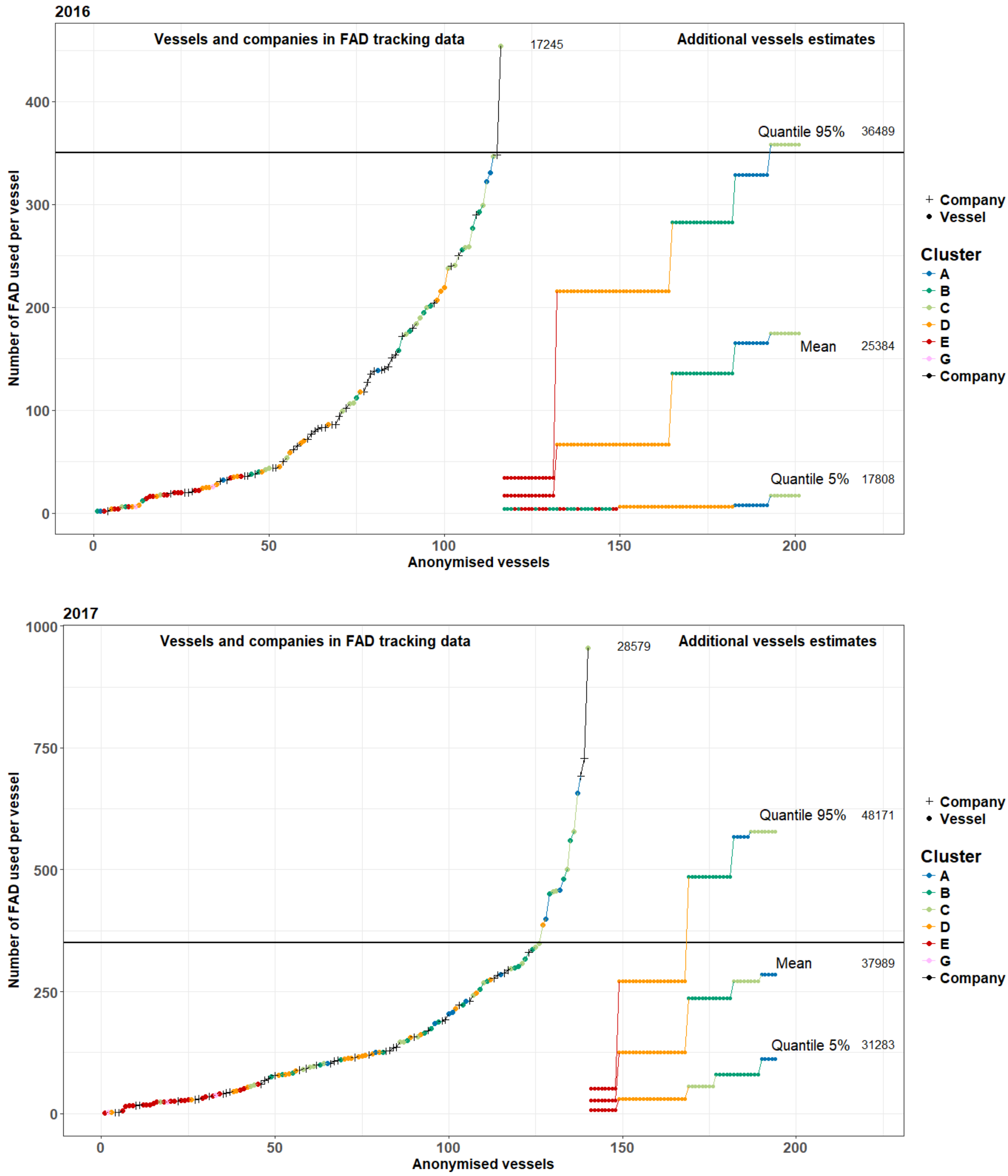


Figure 8. Estimated number of FAD active per vessel in 2016 and 2017 based on number recorded in the FAD tracking data per vessel or fishing company (when owner vessel not known) and raised by matching sets in logsheet based on position and date (left side). Additional vessels (i.e. fishing company nor vessel present in FAD tracking data), where added based on quantile 5%, mean and quantile 95% value per cluster (general clustering with all 2011–2017 years combined) (right side). Estimated total number of FAD active in the WCPO indicated in the right–hand side of each curve.

Table 3. Estimates of the total number of FADs active year in the WCPO using a combination of PNA FAD tracking and operational logsheet data.

	Nb. of vessels	Total nb. in WCPO			Average nb. per vessel		
		Q5	Mean	Q95	Q5	Mean	Q95
2016	275	18,318	26,224	37,344	67	95	136
2017	258	31,283	37,989	48,171	121	147	186

From vessels in the FAD tracking data, it was found that 10–26% deployed more than 350 FADs annually and 29–40% more than 200 FADs (Table 4). Similarly, only 1–17% had more than 350 active FADs per year and 12–43% more than 200 FADs. For those vessels, a comparison with the number of associated sets performed in PNA waters was also made (Figure 9), indicating that vessels deploying very high number of FADs and having high number of active FADs do not make the highest number of associated sets. Finally, the relationship between number of active FADs per year and number of deployments was performed (Figure 9 right), with a ratio deployments/active FADs varying between 1 and 4 and an average value of 1.48. In addition, it can be noted that the number of active FADs per vessel per day ranged between 1 and 318 (Figure 10), with an average per vessel ranging from 4 to 100. These features are derived from the FAD tracking data, with no extrapolation applied and therefore likely underestimated. Additional analyses on more complete data would be required to access precise number of FAD active per vessel per day.

Table 4. Number of vessel exceeding a certain limit of FAD deployments or FADs active per year.

		2016	2017	% 2016	% 2017
Deployments	Vessels with ≥350 deployments	8	26	10.4	25.5
	Vessels with ≥300 deployments	15	34	19.5	33.3
	Vessels with ≥250 deployments	20	37	26.0	36.3
	Vessels with ≥200 deployments	22	41	28.6	40.2
	Nb. of vessels	77	102		
Active FADs	Vessels with ≥350 active FADs	2	16	1.1	15.7
	Vessels with ≥300 active FADs	4	25	2.1	24.5
	Vessels with ≥250 active FADs	15	35	8.0	34.3
	Vessels with ≥200 active FADs	22	43	11.8	42.5
	Nb. of vessels	187	206		

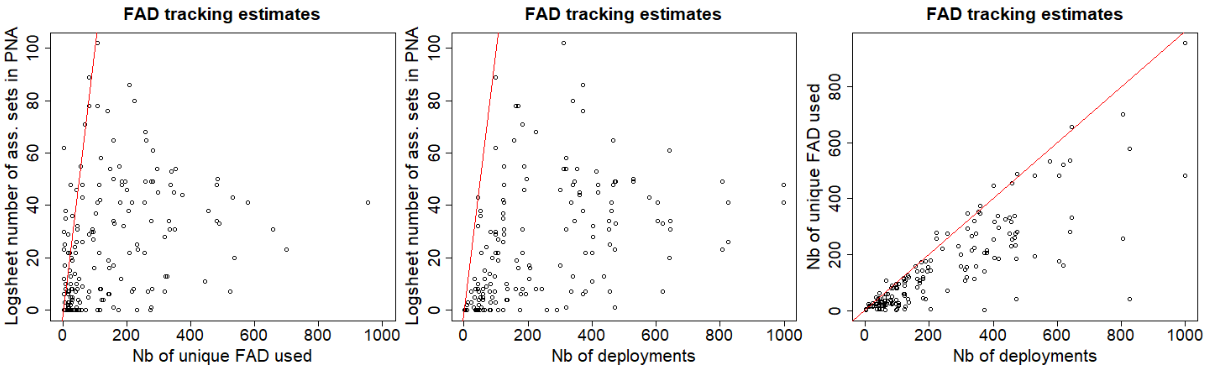


Figure 9. Number of associated sets in PNA waters as a function of the number of active FADs per vessel or of FAD deployments per vessels. Red lines are the 1:1 lines.

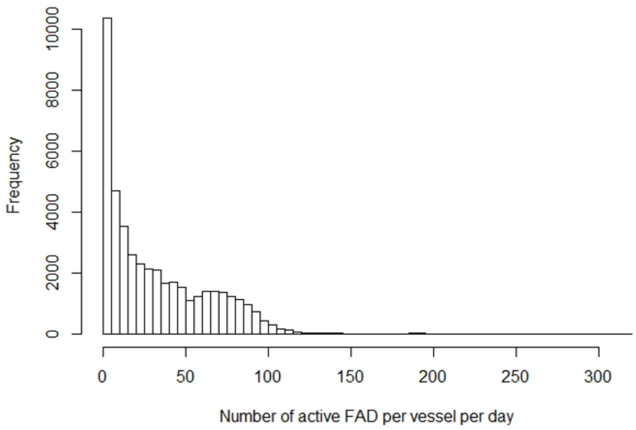


Figure 10. Number of active FAD per vessel per day as recorded in the FAD tracking data.

5. FAD densities and CPUE

The influence of FAD density on CPUE, total catch and the occurrence of FAD and free school sets was investigated using the PNA FAD tracking data and operational or aggregated S-BEST at the set level or aggregated at different temporal resolutions (see Figure 11 for maps of FAD density for the selected cells, i.e. within PNA waters in which associated sets performed). In general, an increase in the number of associated sets and related tuna catch is detected for every data aggregation performed (year, month, week, day; Figure 12), which was expected given that highest FAD density occur in the main FAD fishing areas (Figure 11). However, a slight decrease was detected for skipjack, bigeye, yellowfin and total CPUE with increasing FAD density (Figure 12).

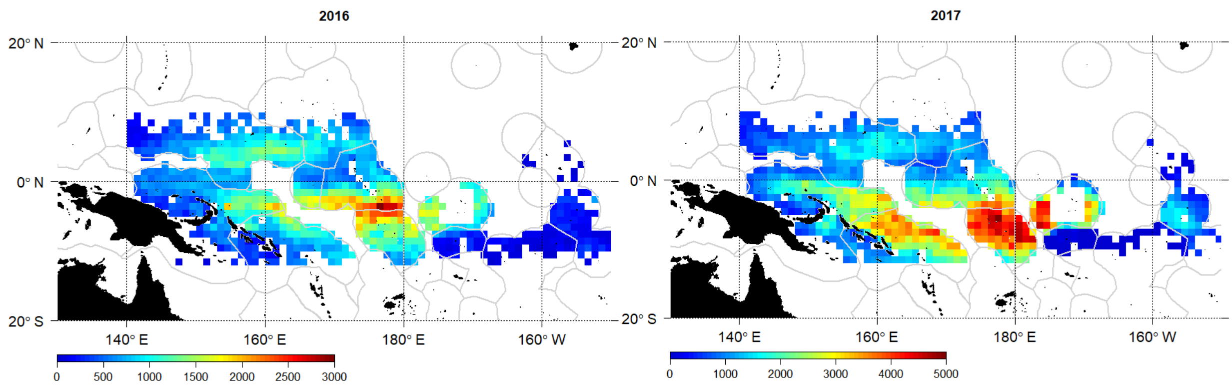


Figure 11. Map of FAD density per year used in this analysis, with cells area outside PNA waters removed as the density would be biased due to lower number of FAD transmitting (geo-fencing), as well as cells with no fishing cells (see Escalle et al. (2018) for complete density maps).

GAM models were used to investigate the influence of FAD density on number of associated sets and bigeye, skipjack, yellowfin and total CPUE (lognormal), and bigeye presence (binomial) with aggregated data per 1° cell and month, as well as bigeye, skipjack, yellowfin and total catch (lognormal), and bigeye presence (binomial) at the set level. The first set of models using aggregated (S-BEST) data and FAD density, latitude, longitude and the interaction between FAD density and longitude as explanatory variables. These models explained from 6 to 17% of the deviance. FAD density was always significant but explained less deviance than the coordinate variables, and showed a general decrease in CPUE with FAD density, with highest skipjack and total CPUE in cells with monthly FAD density of 250 FADs (see observed and simulated relations in Figure 12).

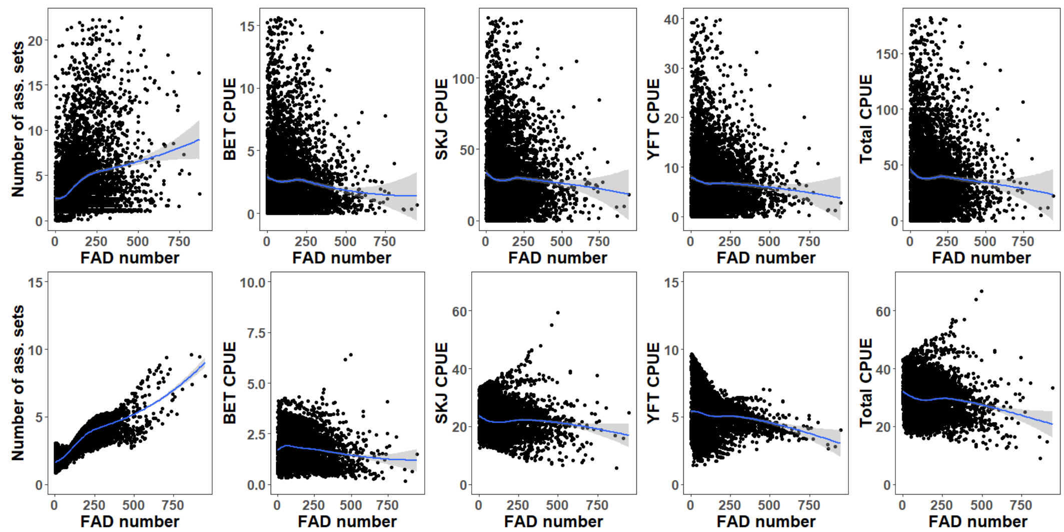


Figure 12. Observed (top) and simulated from GAM models (bottom) number of associated sets, and CPUE per species in function of the number of FADs per 1° cell and month. The blue line is the smoothing regression (loess) with 95% confidence interval.

Regarding unassociated sets, no clear trend could be detected in terms of number of sets, catch per species and CPUE (Figure 13) and FAD density was not significant in GAM models of unassociated sets number, catch and CPUE.

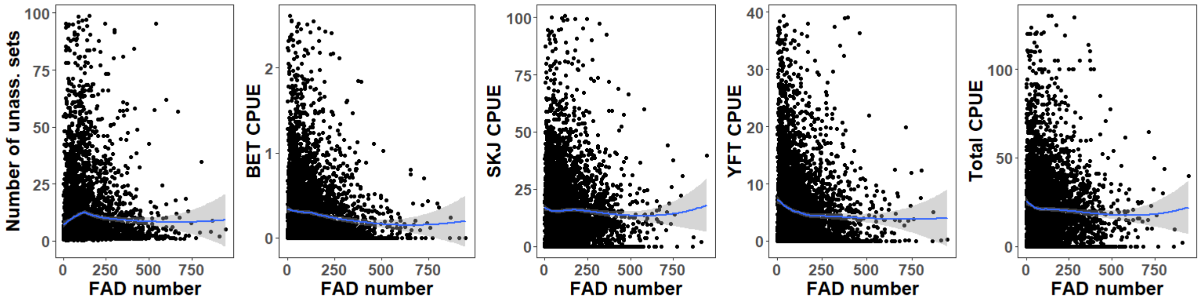


Figure 13. Observed number of unassociated sets, and CPUE per species in function of the number of FADs per 1° cell and month. The blue line is the smoothing regression (loess) with 95% confidence interval.

Analyses of the influence of daily FAD density and tuna catch per set allowed the inclusion of additional variables in the model, such as vessel length or vessel cluster (FAD fishing strategy), thermocline depth (isocline 15°), moon phase and longitude (latitude was excluded as it was correlated with thermocline depth). Skipjack catch, total catch and bigeye presence explained less than 4% of deviance, with FAD density the explanatory variable explaining the least (Longitude, vessel length or vessel cluster, moon phase, then FAD density and thermocline depth). As for the aggregated models, a slight decrease in the skipjack and total catch, and bigeye presence per set was detected with increasing FAD density (Figure 14). In contrast, FAD density did not appear to influence bigeye and yellowfin catch per set, nor catch per species in unassociated sets.

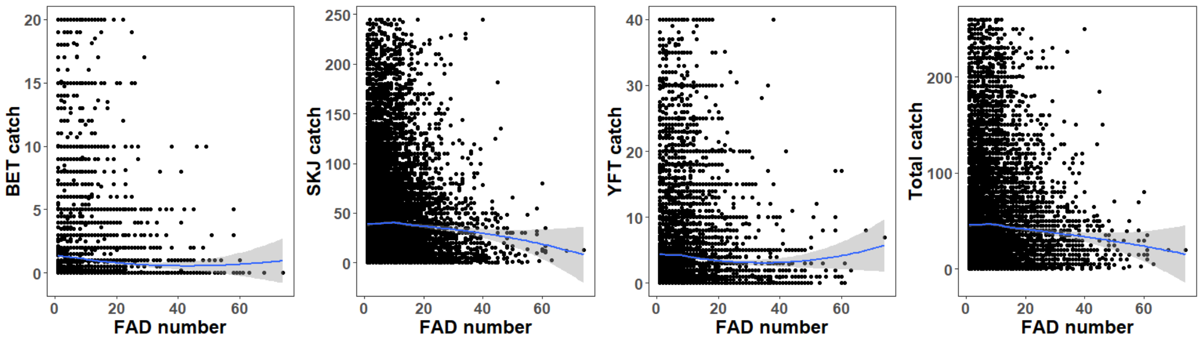


Figure 14. Observed bigeye, skipjack, yellowfin and total catch per set in function of the daily number of FADs per 1° cell. The blue line is the smoothing regression (loess) with 95% confidence interval.

While these results indicate an influence of FAD density on the number of associated sets (increase), total catch (increase) and CPUE (decrease), the high variability of the data and the fact that FAD density remains likely underestimated and spatially heterogeneous due to FAD trajectory data modifications, they should be interpreted with caution. In particular, given the fact that the FAD tracking dataset remains incomplete, general trends rather than particular numbers should be looked at. Finally, additional analyses at the set level could include additional explanatory variables, such as FAD characteristics (depth, length and width (Escalle et al., 2017a)), FAD soaking time, drifting distance, drift speed and other vessel characteristics, and could better evaluate the influence of FAD density.

In addition, the number of deployments per vessel also appears to influence the number of associated sets performed and the catch per set, as indicated by models run only on vessels present in the FAD tracking data (77 and 102 in 2016 and 2017) for which the number of deployments was estimated (see section 4.1). These showed an increase in both number of sets and catch per set with the number of FADs deployed, which is expected given that vessels with large FAD arrays will be able to select FADs with higher aggregated tuna biomass before setting (Lennert-Cody et al., 2018).

6. Discussion

This paper highlights the challenges in estimating the number of FAD deployments and active FADs per vessel in the WCPO. While the FAD tracking data presents the best insight into the FADs used by purse seiners in PNA waters, this dataset is still incomplete and the data are modified by fishing companies prior to submission. Therefore, some uncertainties remain even for the vessels identified in the FAD tracking data. Nevertheless, for these vessels, we estimated the number of FADs deployed and the number of active FADs per vessel per year, which allowed the estimation of the ratio between these two values. Regarding the observer data, the high delay before accessing near-full observer data precludes estimations for recent years and therefore a comparison with the FAD tracking data estimates. In addition, deployments unnoticed by observers, performed by supply vessels or made in the EPO would not be accounted for.

Both methods used showed that very few vessels deploy more than 350 FADs per year, and this includes both new FADs and buoys deployed on logs or FADs found at sea. In addition, the average value of the ratio between deployments and active FADs is 1.5. This would mean that a vessel in general would have no more than 233 active FADs per year (Table 5). Finally, given the FAD tracking data showing that average life of an active FAD is 6 months, we can assume that a vessel would have a maximum of 117 active FADs at any given time (Table 5).

Table 5. Simulated relationship between number of deployments per vessel per year and number of active FADs a vessel is monitoring at any given time.

Nb. of deployments per year[1]	Nb. of active FADs monitored per year[2]	Nb. of active FADs monitored per day[3]	Nb. of deployments per year[1]	Nb. of active FADs monitored per year[2]	Nb. of active FADs monitored per day[3]
D	**D / 1.5**	**D / 1.5 / 2**	**D**	**D / 1.2**	**D / 1.2 /2**
150	100	50	150	125	63
200	133	67	200	167	84
250	167	84	250	208	104
300	200	100	300	250	125
350	233	117	350	292	146
400	267	133	400	333	167
450	300	150	450	375	188
500	333	167	500	417	208
550	367	183	550	458	229
600	400	200	600	500	250

[1] This include deployment and redeployments of FADs. [2] The ratio between deployments and active FADs found in this paper is of 1.5, a lower ratio number (1.2) was also tested as a comparison. [3] Considering an average FAD active duration of 6 months.

While areas with higher FAD density mostly correspond to the main FAD fishing grounds, FAD density also appears to influence CPUE, with a slight decrease of skipjack, bigeye, yellowfin and total CPUE with increasing FAD density. There is an observable trend of lower CPUE in 1°cells that have very low FAD densities and higher CPUE in those that have very high densities. Noting the limitations in the data set (including that it is based on only 2 years), this analysis suggests that the highest CPUE are achieved with FAD densities approximating 250 per 1° cell per month. It should be noted that there are few natural floating objects (logs) in the centre and east of the WCPO, and therefore fishing patterns identified in those regions are primarily due to artificial FADs. This reinforces this hypothesis that FAD density could impact tuna school size (i.e. through school fragmentation) and therefore CPUE (Sempo et al., 2013). However, this still needs further investigation and additional data to validate it. It should also be noted that these figures do not include deactivated and non-transmitting FADs that will still aggregate tuna, but which will not be captured within these density estimates.

To improve the ability of Scientific Committee to estimate potential FAD levels, the collection of additional information is suggested. For example, to better understand the total number of FADs in the water, this could include the submission of i) the number of new FADs deployed per year per vessel; ii) the average daily or total number of active FADs per vessel per month; and iii) the number of deactivated FADs per month. The first could be derived from fishery data, if observers can record all FAD deployments or if captains start recording these data in a FAD logsheet. In order to obtain an estimate of the average daily or total number of active FADs per vessel these data could be derived from FAD tracking data. In parallel, to better study FAD density, aggregated summaries per 1° cell and month including number of buoys activated, number of buoys deactivated and number of FAD deployments could be considered (Restrepo and Justel-Rubio, 2018).

We invite WCPFC-SC14 to:

- Note the progress being made by PNA in FAD tracking for the purpose of improving FAD management in PNA waters.
- Note the analysis of the number of FAD deployments and active FADs per vessel and the challenges encountered in this analysis.
- Note the conclusion that FAD density appears to influence CPUE, with a slight decrease of skipjack, bigeye, yellowfin and total CPUE with increasing FAD density although this still needs further investigation.

Acknowledgments

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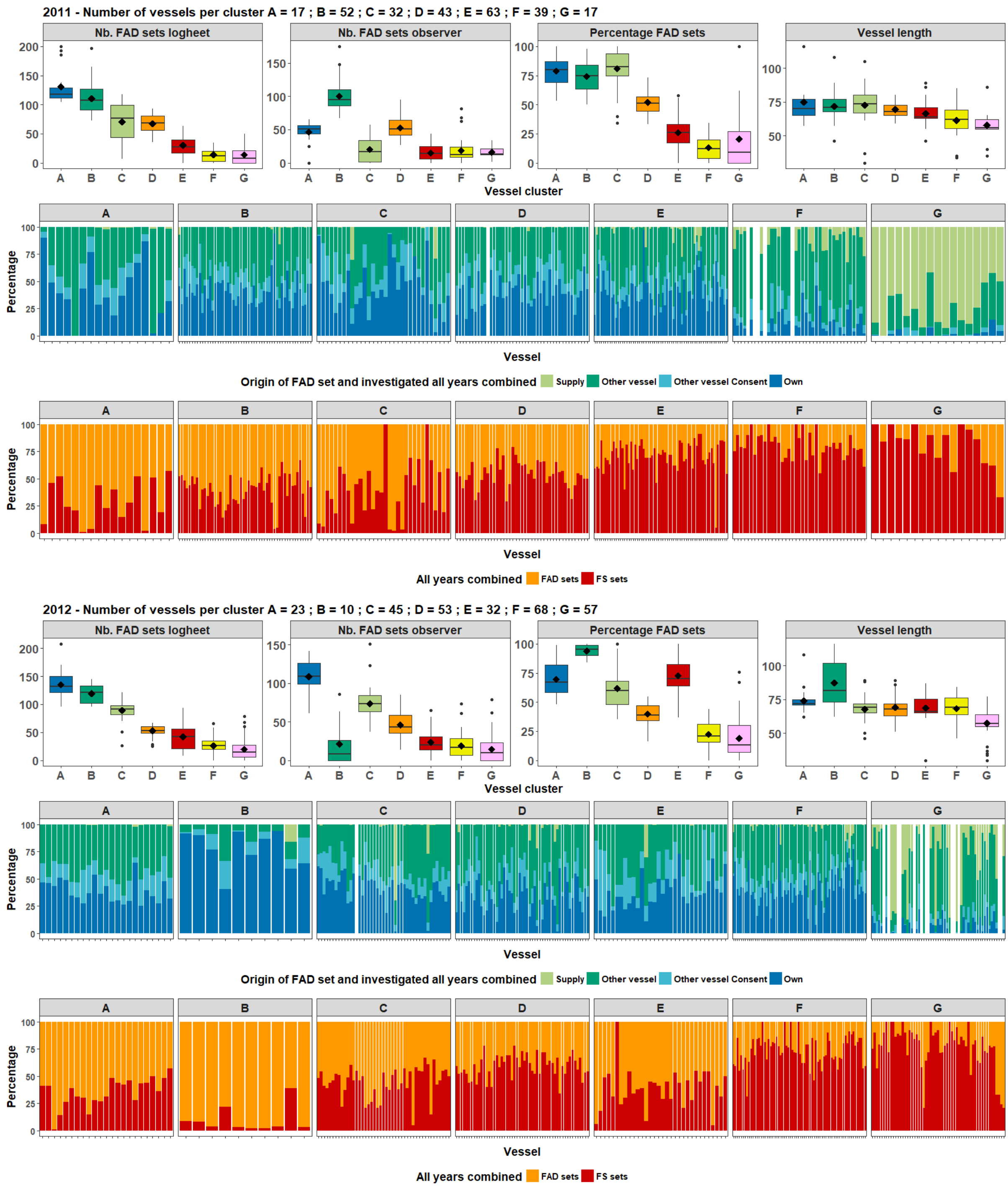
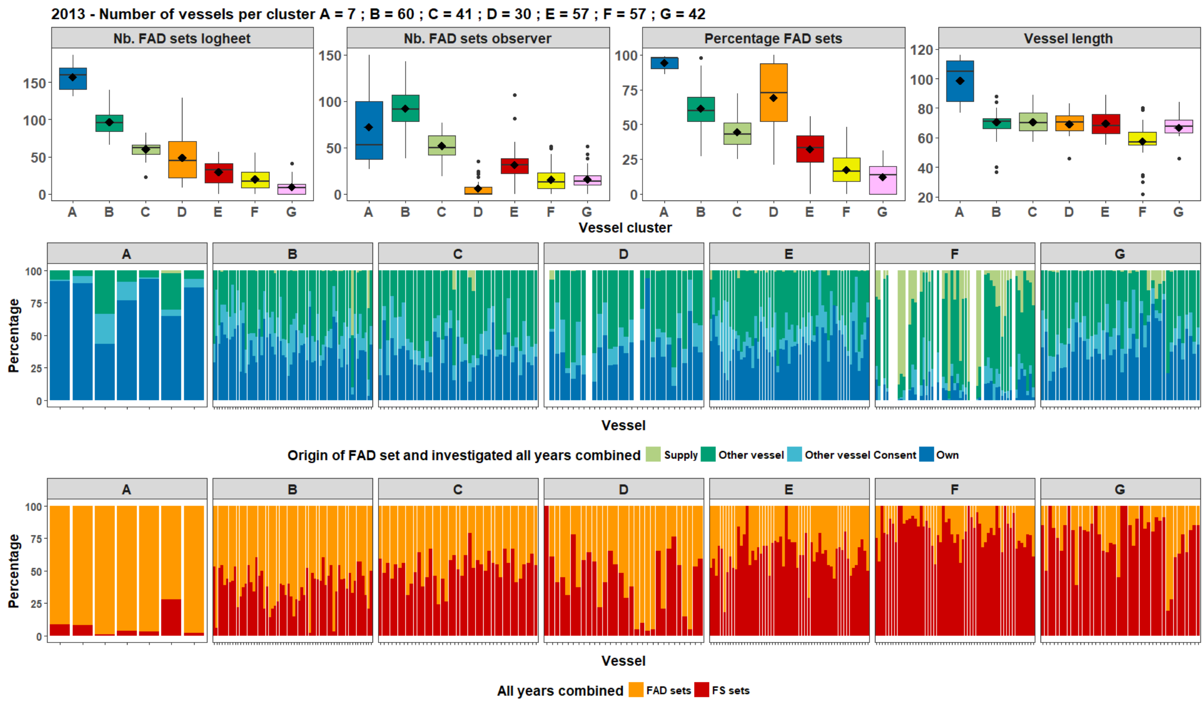
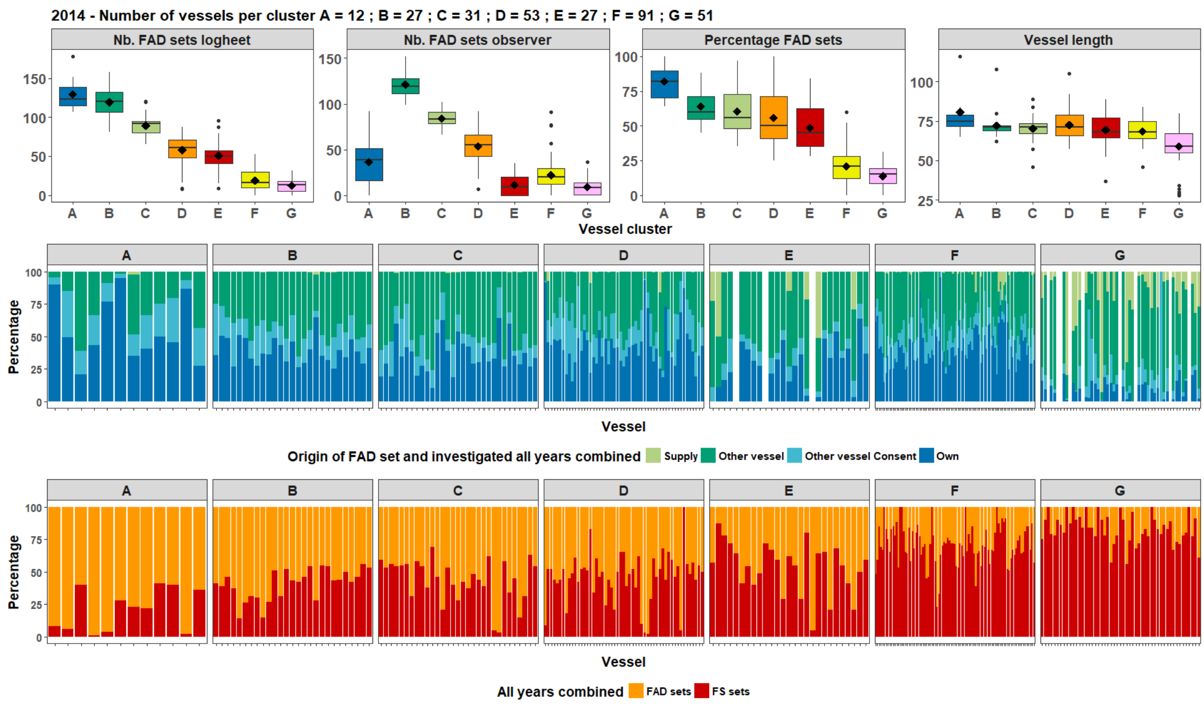
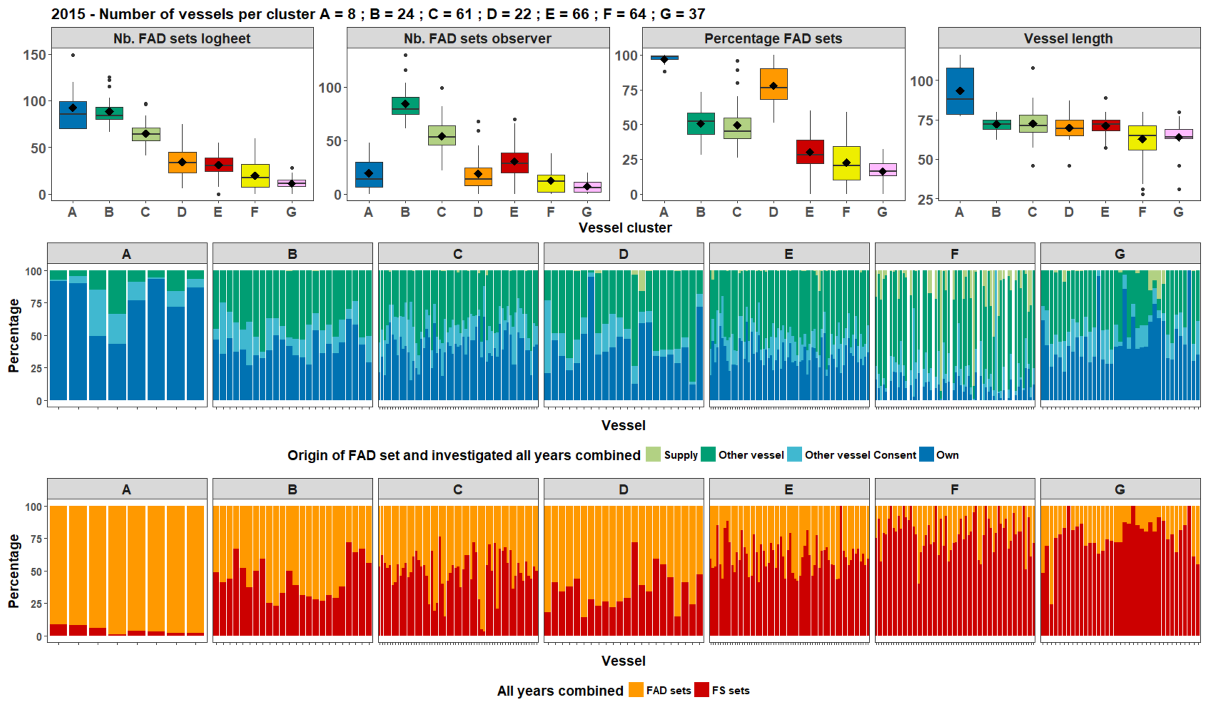
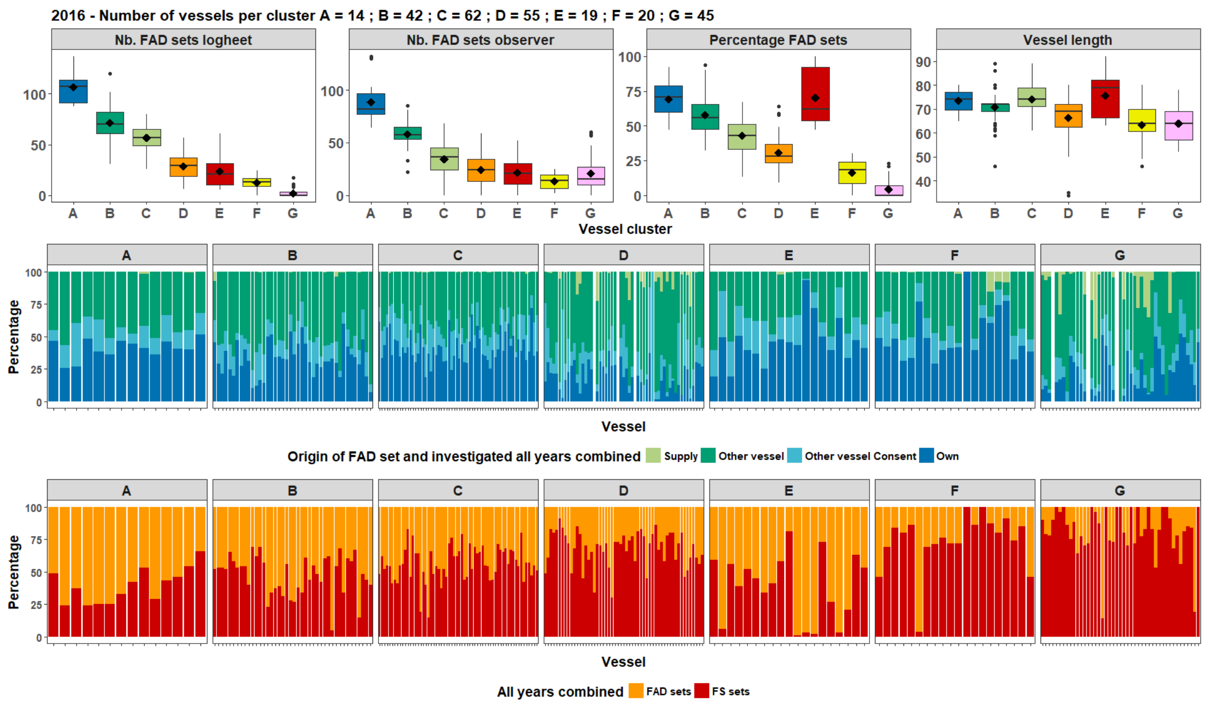
Appendix 1. Fishing strategy clusters. Top = number of FAD sets in logsheet and observer data, percentage of associated sets (FAD and log) per vessel in the considered year and vessel length per cluster. Middle = origin of all FAD encountered by a vessel over 2011–2017. Bottom = percentage of associated sets (FAD and log) per vessel over 2011–2017.

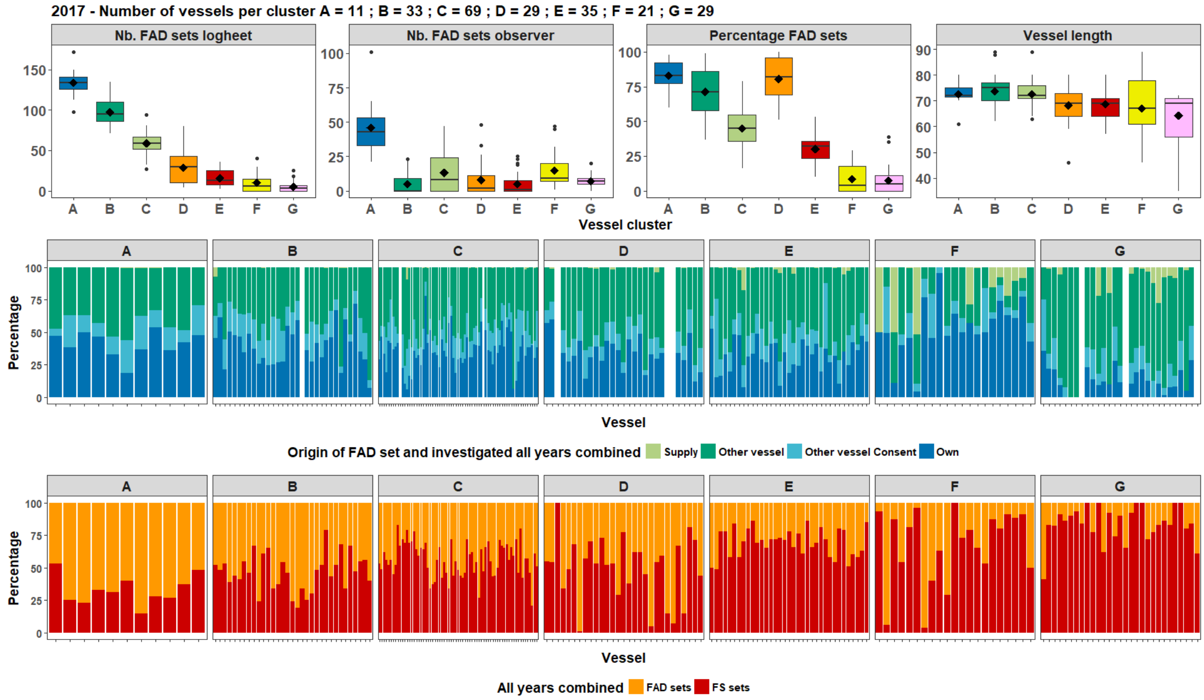



2013 - Number of vessels per cluster A = 7 ; B = 60 ; C = 41 ; D = 30 ; E = 57 ; F = 57 ; G = 42
Nb. FAD sets logheet
Nb. FAD sets observer
Percentage FAD sets
Vessel length
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
Percentage
Vessel
All years combined
FAD sets
FS sets


2014 - Number of vessels per cluster A = 12 ; B = 27 ; C = 31 ; D = 53 ; E = 27 ; F = 91 ; G = 51
Nb. FAD sets logheet
Nb. FAD sets observer
Percentage FAD sets
Vessel length
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
Percentage
Vessel
All years combined
FAD sets
FS sets


2015 - Number of vessels per cluster A = 8 ; B = 24 ; C = 61 ; D = 22 ; E = 66 ; F = 64 ; G = 37
Nb. FAD sets logheet
Nb. FAD sets observer
Percentage FAD sets
Vessel length
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
FAD sets
FS sets


2016 - Number of vessels per cluster A = 14 ; B = 42 ; C = 62 ; D = 55 ; E = 19 ; F = 20 ; G = 45
Nb. FAD sets logheet
Nb. FAD sets observer
Percentage FAD sets
Vessel length
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
FAD sets
FS sets


2017 - Number of vessels per cluster A = 11 ; B = 33 ; C = 69 ; D = 29 ; E = 35 ; F = 21 ; G = 29
Nb. FAD sets logheet
Nb. FAD sets observer
Percentage FAD sets
Vessel length
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
A
B
C
D
E
F
G
Percentage
Vessel
All years combined
FAD sets
FS sets