SCIENTIFIC COMMITTEE
SIXTEENTH REGULAR SESSION

ELECTRONIC MEETING
11-20 August 2020

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

WCPFC-SC16-2020/MI-IP-13

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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 Western and Central Pacific Ocean (WCPO). Fishing on FADs has become important for the efficiency of the purse seine fleet targeting skipjack tuna. However, it can have undesirable impacts, such as increased bycatch, including catch of small bigeye and yellowfin tuna, and environmental pollution, ghost fishing and habitat damage from lost or abandoned FADs. Monitoring the number of FADs deployed annually, and their spatio-temporal prevalence is important for assessing their influence on the tuna fisheries and other environmental and ecological risks. This paper attempts to estimate the number of deployments and active FADs per vessel over the last nine years. Estimates were derived using two different approaches.

First, we estimated the total number of FAD or buoy deployments per vessel and the total in the WCPO based on fishery data for 2011–2019. The data used included 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. Given the use of observer data, a deployment was defined in this method as all FAD and/or buoy (i.e., deployed on an already drifting FAD or log) deployments recorded by observers. The number of deployments/redeployments per year varied from 0 to 700 per vessel but few vessels deployed/redeployed more than 350 FADs and/or buoys per year. This corresponds to a total estimated number of deployments/redeployments of between 23,000 and 30,000 per year in the WCPO for the 2011–2019 period, with a slight decrease after 2015, likely due to delays in receiving observer data for recent years. Investigation of the number of active buoys monitored by the most FAD-reliant vessels in each year suggested that if all buoys deployed (as recorded by observers) over a four-month period remained active over this period, the median number of buoys monitored per vessel would be approximately 50.

The second approach combined fishery data and the Parties to the Nauru Agreement (PNA) FAD tracking data and therefore only covered 2016 to 2019 and estimated the number of buoy deployments. The estimated number of buoy deployments per vessel varied between 1 and 598 (mean = 97) in 2016; 1 and 845 (mean = 112) in 2017; 1 and 699 (mean = 134) in 2018; and 1 and 663 (mean = 180) in 2019, indicating again that very few vessels deployed/redeployed more than 350 buoys per year (<4% of vessels). At the scale of the WCPO, this corresponds to 31,000 buoy deployments in 2016; 34,500 in 2017; 39,500 in 2018; and 33,400 in 2019. The number of active buoys per vessel per day was investigated for the top 50 vessels deploying the most FADs. Across these vessels the median number of active buoys per day ranged from 45–75 buoys and the maximum was 330 buoys. A general increasing trend in the number of active buoys monitored per vessel per day was detected through time.

We invite WCPFC-SC16 to:

- Note the progress being made in monitoring FAD numbers for the purpose of informing FAD management.
- Note the analysis of the number of FAD deployments and active FADs per vessel and the challenges encountered in this analysis.
- Note that this study indicated that most vessels deployed less than 150 FADs per year and very few vessels deployed/redeployed more than 350 FADs per year. The current limit for the number active buoys an individual vessel can have at any one time is 350 under CMM-2018-

01 (paragraph 23). These results indicate that this measure is not constraining FAD deployments or buoy monitoring.

- Note the estimates of 30,000–50,000 FADs deployed/redeployed per year in the WCPO.

Table I. Percentage of vessels with more than 150 or 350 FAD/buoy deployments/redeployments per year estimated using three methods* and data sets.

	% vessels with ≥150 deployments per year by estimation method			% vessels with ≥350 deployments per year by estimation method		
Year	**Observer Scaled vessel**	**Observer mean cluster based**	**Combined observer/ FAD tracking**	**Observer Scaled vessel**	**Observer mean cluster based**	**Combined observer/ FAD tracking**
2011	30	29	–	4	2	–
2012	21	18	–	1	1	–
2013	14	13	–	2	2	–
2014	17	16	–	1	1	–
2015	7	8	–	1	0	–
2016	6	5	15	1	0	1
2017	13	11	13	2	1	1
2018	18	17	17	4	2	4
2019	16	18	15	4	2	3

*Additional two methods (observer data only quantile 10% and quantile 90% cluster-based methods), corresponding to a confidence interval around the scaled-vessel and mean cluster-based methods.

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., 2020b). This corresponds to an estimated number of FADs deployed in the WCPO of between 30,000 and 50,000 in 2013 (Gershman et al., 2015). There has been a sharp increase in the use of FADs over the last decade, which is linked to the arrival of new technological developments. These include use of satellite buoys to track FADs, and more recently, the use of echo-sounder satellite buoys to estimate the quantity of tuna aggregated below them (Escalle et al., 2019c; Fonteneau et al., 2013; Lopez et al., 2014).

The increased use of FADs has wider implications. Sets on FADs have relatively high bycatch rates, including catch of vulnerable species such as sharks and sea turtles (Dagorn et al., 2013). These species may also become entangled in the nets of a FAD's underwater appendages (Filmalter 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; Escalle et al., 2019b; Maufroy et al., 2015). FADs can also have detrimental interactions with tuna stocks themselves. 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). More importantly, the high catches of juvenile bigeye and yellowfin tuna on FAD sets has raise concerns regarding the sustainability of the stocks. In 2009, the increased use of FADs and the potential impacts on stocks led the Parties to the Nauru Agreement (PNA) and the Western and Central Pacific Fisheries Commission (WCPFC) to implement an annual three or four months FAD closure during which all FAD-related activities (e.g., fishing, deploying, servicing) are prohibited (WCPFC, 2018). More recently, WCPFC also adopted a Conservation and Management Measure to limit the number of active FADs, at any given time, to 350 per vessel (CMM-2018-01, paragraph 23[1]). The Measure also requires the use of low entanglement risk FADs and encourages the use of biodegradable FADs (CMM-2018-01, paragraph 19–22). However, in the absence of a documented objective for the per-vessel buoy limit, scientifically evaluating its impact is difficult. We therefore evaluate the patterns of FAD numbers by vessels to inform discussions.

Generally, a high degree of uncertainty exists around the total number of FADs used in the WCPO. The main challenges in compiling robust scientific information to quantify FAD use in the WCPO are i) the incomplete nature of FAD activity data; and ii) the different measurements linked to the number of FADs that could be compiled. Firstly, while data related to FADs available to guide management in the WCPO are unique in terms of quantity, quality and type of data, and exceed those available in other areas, they are incomplete. The first source of data related to FADs are the records made by observers on-board purse-seiners for any FAD related activities (deploying, setting, servicing, retrieving). Since

[1] A flag CCM shall ensure that each of its purse seine vessels shall have deployed at sea, at any one time, no more than 350 drifting Fish Aggregating Devices (FADs) with activated instrumented buoys. An instrumented buoy is defined as a buoy with a clearly marked reference number allowing its identification and equipped with a satellite tracking system to monitor its position. The buoy shall be activated exclusively on board the vessel. A flag CCM shall ensure that its vessels operating in the waters of a coastal State comply with the laws of that coastal State relating to FAD management, including FAD tracking.

2011, the quantity of FAD related data recorded by observers has greatly increased, due to the 100% observer coverage requirement in the WCPO (implemented in 2010 between 20°N to 20°S) and to the development of a new form related to FAD activities (GEN-5). However, one of the crucial pieces of data required to assess the number of FADs, i.e., the unique buoy identification number, remains hard to record by observers and is often missing.

The second source of data comes from the PNA FAD tracking programme, which was implemented in 2016 to provide information for improving the management of FADs in PNA waters, and which is beginning to provide valuable data on FAD use. The programme uses satellite buoys attached to drifting FADs that provide position and date/time data. This is a very detailed dataset but it is still incomplete, with portions of trajectories outside PNA waters removed by buoy companies ("geofencing") prior to submission to PNA (Escalle et al., 2020).

Secondly, beyond these uncertainties related to available data, the type of measurements to quantify the number of active FADs are numerous and different. Ideally, the number of active buoys per vessel per day should be compiled. Currently, this is complicated by the absence of some portion of trajectories due to geofencing. To estimate the number of FADs drifting at-sea and its effect on catch rates, the overall number of FADs, both monitored (with active buoys) and unmonitored (without buoy or with deactivated buoy), should be compiled. Finally, with the current available data, two additional measurements relevant for management and monitoring the ecosystem impacts of FADs and the overall number of FAD deployments in the WCPO are easier to compile: i) the number of instrumented FAD deployments; and ii) the number of satellite buoy deployments (could be higher than the number of FAD deployments as vessels may deploy buoys on FADs or logs found at sea). While all these measurements are different, they could still be used as alternative metrics to help inform management.

Using the data mentioned above, the aims of this paper are to:
1) estimate the number of buoys or FADs currently deployed per vessel,
2) estimate the number of active buoys monitored by individual vessels; and,
3) estimate the total number of buoys or FAD deployments in the whole WCPO.

2. Methods

2.1 Data

We used four complementary datasets combining fishery data over the 2011–2019 period (observer, operational logsheet, and VMS data) and the 2016–2019 PNA FAD tracking data. Observer data include information on FAD deployments (Figure 1) and associated sets[2] per vessel, as well as the origin of any FAD encountered by a vessel at sea. Since 2010, there has been a 100% observer coverage requirement, however, annual data availability (considered in this document as observer data coverage) is at 63–93% of the fishing trips, because some data have not yet been received for recent years or some observers sheets are excluded/never received for some trips (see Table 1 in Williams et al. (2020a)). Operational logsheet data are recorded by vessel captains, and include catch per species at the set level (Figure 1). VMS data were used to get the number of days at-sea per vessel, and by a

[2] In this document associated sets only include drifting FAD and logs and excludes anchored FADs and sets on live whales and whale sharks.

comparison with the number of observed days at-sea reported from observer records. These data were used to compile the observer coverage (i.e., considered here as the amount of observer data received and processed at SPC) per vessel and per year. Corrected PNA FAD tracking data, covering the 2016–2019 period, contained a subset of buoy deployments and active buoys for most vessels fishing in PNA waters (see Escalle et al. (2020) for details of the correction procedure and of the database characteristics).

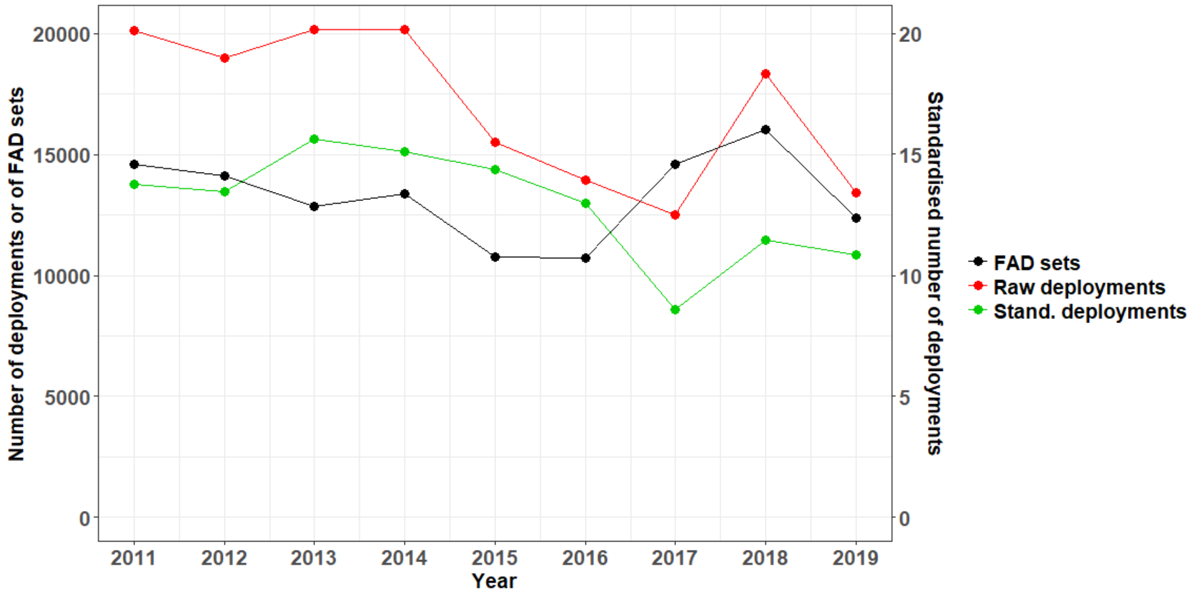

Figure 1. Number of FAD sets (i.e., drifting FAD and log sets) recorded in operational logsheet data (black); raw number of FAD and buoy deployments recorded by observers (red); and standardised raw number of FAD and buoy deployments (raw number of deployments / number of FAD sets).

2.2 Identification of groups of vessels with similar FAD fishing strategy

A hierarchical clustering analysis, based on Ward minimum variance (Murtagh and Legendre, 2014), 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 days at-sea derived from VMS data, the percentage of associated sets over total number of sets (unassociated, anchored FADs and live whales and whale sharks) from operational logsheet data and the origin of all FADs investigated at sea (set, serviced and only investigated[3]). The output of the clustering consists of a dendrogram and a number of statistics (e.g., cubic clustering criteria, pseudo t_2 and Hubert index) that were used to select the appropriate number of clusters (from the hclust function in R).

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 only counted once. First, the raw number of deployments per vessel and per year (D), as recorded by observer data, were compiled (Figure 1) alongside the observer coverage (OC) (see Section 2.1). Vessels with no observer coverage or observer coverage <10% each year were removed

[3] Sensitivity analysis with FAD set and FAD investigated treated separately had similar results.

from the analysis to avoid overestimates. Then the total number of FAD deployments per vessel and per year (D tot) was calculated as follow:

Scaled vessel method: *Total deployments* $D\ tot = D / OC$

In order to standardise the estimates, to account for the unknown number of deployments during the unobserved trips, and to obtain a plausible range estimate of the total number of deployments per year, some additional estimates were compiled. The total number of deployments per vessel and per year was also calculated where estimates of the number of deployments for the unobserved trips were derived from the quantile 10%, mean and quantile 90% values of total number of deployments (D tot) recorded per cluster of vessels with similar FAD fishing strategy (see previous paragraph). This corresponds to:

Cluster-based method - Quantile 10%: $D\ tot = D + tot_{q10} * (1 - OC)$
Cluster-based method – Mean: $D\ tot = D + tot_{mean} * (1 - OC)$
Cluster-based method - Quantile 90%: $D\ tot = D + tot_{q90} * (1 - OC)$

Finally, to also get estimates of the total number of FAD deployments made in the whole WCPO per year, we included estimate of the deployments from vessels with no observer coverage, using the average total number of deployments per cluster and estimation method (i.e., vessel, quantile 10%, mean and quantile 90%).

The top 50 vessels with the highest number of estimated deployments per year and observer coverage above 80% (i.e., ~20 vessels per year) were used to investigate the actual number of buoys monitored at any given time. In the observer data, the sum of the number of buoy-only deployments from observer data (raw numbers) over a certain period could be considered as a proxy for the number of active buoys at any given time. The assumption was made that each buoy deployed at a given time would remain active for a certain period called 'survival period'. Three survival periods were chosen, 4-months, corresponding to the mean at-sea time of buoys before re-deployments; 6-months, average active time of buoys; and one year (Escalle et al., 2019a).

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

Estimates combining both FAD tracking and fishery data could only be made for the 2016–2019 period 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, but not the whole WCPO; ii) most FAD trajectories in the PNA FAD tracking data have been geofenced by fishing companies prior to submission, with FAD positions outside PNA waters removed; iii) the data only correspond to a fraction of the total number of FADs in the WCPO, with some vessels not submitting any FAD trajectories (Escalle et al., 2017); iv) the vessel owner of a FAD was sometimes not provided; v) a set performed on a given FAD can be performed by a vessel that is not the owner of the FAD, or a FAD can be deployed by another vessel of the same company as the owner (Escalle et al., 2018b); and vi) deployments in the PNA FAD tracking data correspond to buoys, which may be deployed, picked-up, then re-deployed several times.

Given these complexities, the FAD tracking data could not be used alone, and it was necessary to match fishery data of a given deployment to a FAD trajectory. At sea positions from the FAD tracking data were matched with buoy and FAD deployment positions from observer data using i) same buoy identification number recorded; or ii) same fishing company, same date and plausible speed between position/time deployments in FAD tracking and the observer data (i.e., vessel cruising speed ≤15 knots).

The total number of deployments per year was estimated by adding the number of matched deployments (D matched) and the number of non-matched deployments in the FAD tracking database (D track non-matched) and the number of non-matched deployments in the observer database (D obs non-matched).

Combined observer and FAD tracking method: *Total deployments*

D tot = D matched + D track non-matched + D obs non-matched

Note that not all vessels were present as buoy owners in the PNA FAD tracking data (174 in 2016, 185 in 2017, 186 in 2018 and 178 in 2019), so estimates for these vessels use only observer records.

The top 50 vessels per year, defined as those with the highest number of deployments estimated by the combined observer and FAD tracking method and that were present in the PNA FAD tracking data, were used to investigate the maximum number of active buoys monitored at any given time per vessel. This was done by i) using the raw number of active buoys from the PNA FAD tracking data, and ii) raising this raw number using a raising factor derived from the link between raw number of deployments from PNA FAD tracking data and the total number of deployments estimated per vessel and per year. The raw and raised number of active buoys per vessel was investigated per month and per day and by looking at monthly and annual variability.

3. Estimates using fishing data only

3.1 Clustering by vessel and year

Each year, vessels were divided into 8 groups of similar FAD fishing strategy, discriminated on the basis of both fishing and vessel characteristics (Figure 2 and Appendix 1). The optimum number of clusters was assessed through a combination of statistics (see section 2.2) and considering the objective of grouping vessels based on similar FAD fishing strategy. These were classified as clusters A to H following a decreasing number of FAD associated sets recorded in logsheets. Similarly, the percentage of associated sets also generally decreased from cluster A to H, at least between the first and last clusters. Vessel length and vessel speed were relatively consistent among groups, but lower for Group H in some years (Appendix 1). The number of days at-sea was highly variable depending on the cluster considered, but was generally high for clusters A to C–E. These clusters, with vessels setting higher numbers of FAD sets (A to C or D) also mostly set and investigated their own FADs, or another vessels' with its consent, therefore corresponding to vessels with a large array of available FADs. Similar findings were found for the last cluster (H), but this was mostly because these vessels performed very few associated sets (Figure 2 and Appendix 1). The rest of the clusters operate on their own FADs for less than 50% of the time. One or two clusters, generally representing smaller vessels, had some FADs deployed by supply vessels.

Generally, vessels in clusters A and B are the largest vessels, fishing most of the year, and having a fishing strategy orientated toward FADs, with more than 50–75% of their sets being associated, and using a large array of their own FADs. Vessels in clusters C and D are intermediate, in that they can also present high rates of associated sets and days at sea, but they rely on both their own FADs and on other FADs found drifting at sea. Clusters E to G are relatively opportunistic, having less than 20–50% of their sets on FADs and include smaller vessels (domestic fleets of two Pacific Island nations). Finally, cluster H includes very small vessels, conducting very few FAD sets but that are mostly on their own FADs.

The raw number of deployments per vessel recorded by observers shows a general decrease with vessel cluster (vessels highly relying on FADs deploying more). This is broadly in line with our observations based on logsheet data, even if a higher number of deployments could also be detected some years for clusters G and H (Figure 3). High variability between vessels within a cluster was however also detected.

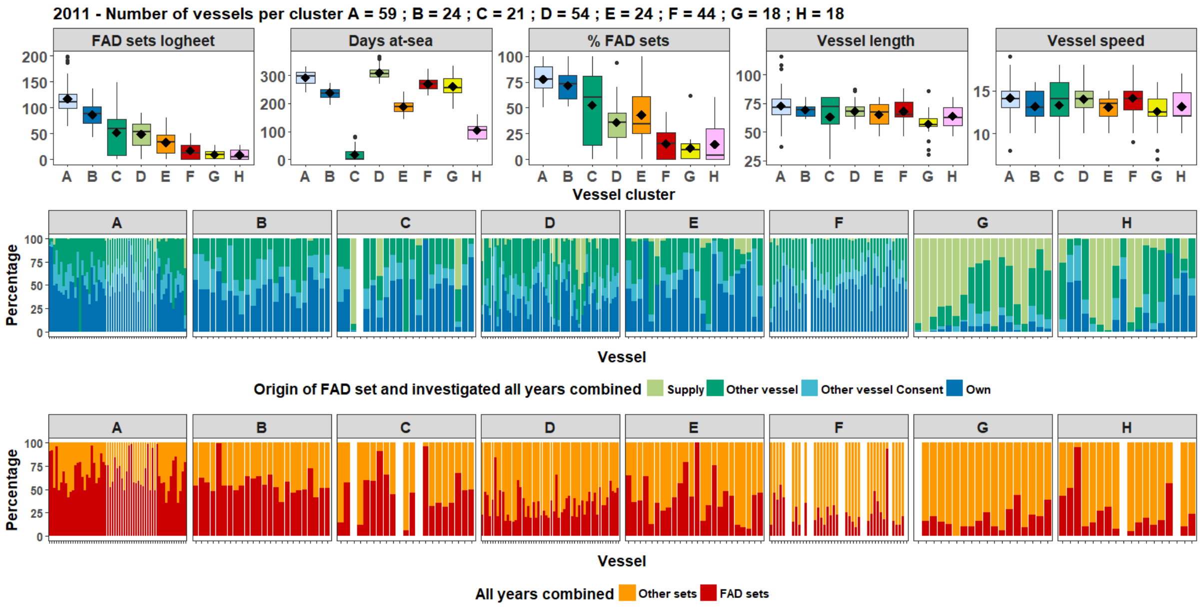

Figure 2. Fishing strategy clusters for 2011 (see Appendix 1 for the other years). Top = number of FAD sets per vessel in logsheet data; number of days at-sea per vessel derived from VMS data; percentage of associated sets (FAD and log) per vessel in the considered year; vessel length; and vessel speed per vessel cluster. Middle = origin of all FADs encountered by a vessel over 2011–2019. Bottom = percentage of associated sets (FAD and log) per vessel over 2011–2019.

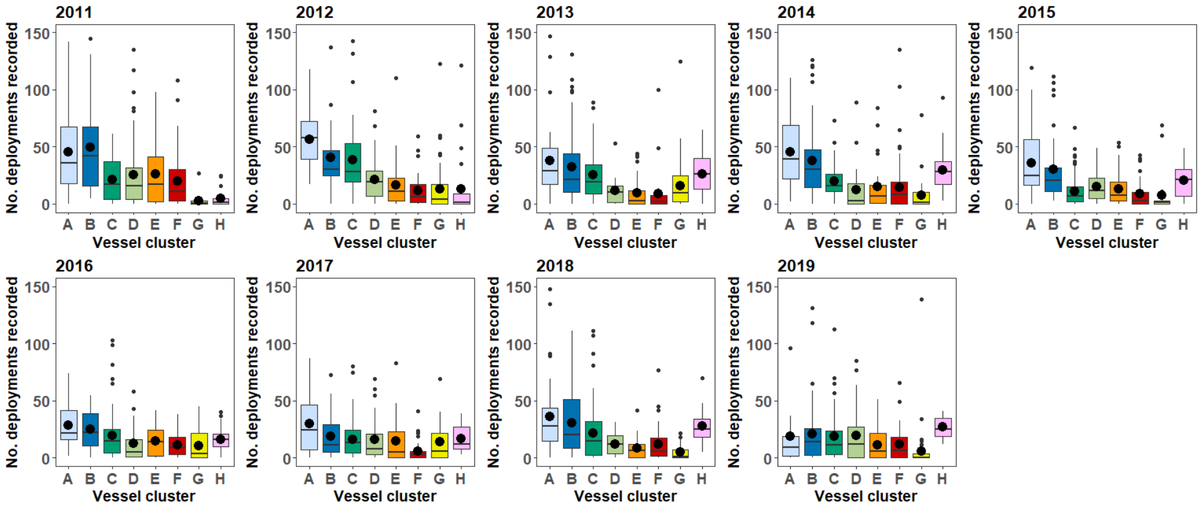

Figure 3. Raw number of FAD and/or buoy deployments, recorded by observers, per cluster and year.

3.2 Estimates of number of FAD or buoy deployments per vessel and total deployments per year

In this section, a deployment is defined as an initial or repeat deployment at sea of both a FAD with a buoy; a buoy only (on a log or on a FAD already drifting); or a FAD only (likely because the buoy deployment was not recorded by the observer)[4], as reported by observers.

The total number of deployments per vessel and year, estimated using alternative methods (scaled-vessel method versus cluster-based method), is shown for vessels with observer coverage in Figure 4 for 2011 as an example, and Appendix 2 for all years. Using the scaled vessel method, estimates corresponding to each vessel (unique number of deployments recorded by vessels and raised by the observer coverage) varied between 0 and 700[5] deployments per vessel per year (Figure 4).

For the cluster-based methods, the total number of deployments per vessel generally varied between 0 and 500, with the curves based on the mean and the 90% quantile of deployments showing higher total number of deployments for vessels that deploy FADs relatively infrequently (left-side of the graphs) compared to the estimates from the scaled vessel method. Very few vessels undertook more than 350 deployments per year, based either on the scaled vessel method: 4% in 2011, 2018 and 2019, and 1 or 2% the other years (Table 1), or the cluster-based methods: 0–4% of vessels (see Table 1). For all the estimating methods, most vessels deployed less than 250 FADs per year, with 0 to 11% of vessels deploying more than 250 (except for 2011 using the quantile 90% cluster-based method; Table 1). In general, 4–49% of vessels would deploy more than 150 FADs per year.

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

[5] Note that in four years, one vessel had more than 700 buoy or FAD deployments per year (875–1500, Appendix 1), likely due to overestimation linked to low observer coverage.

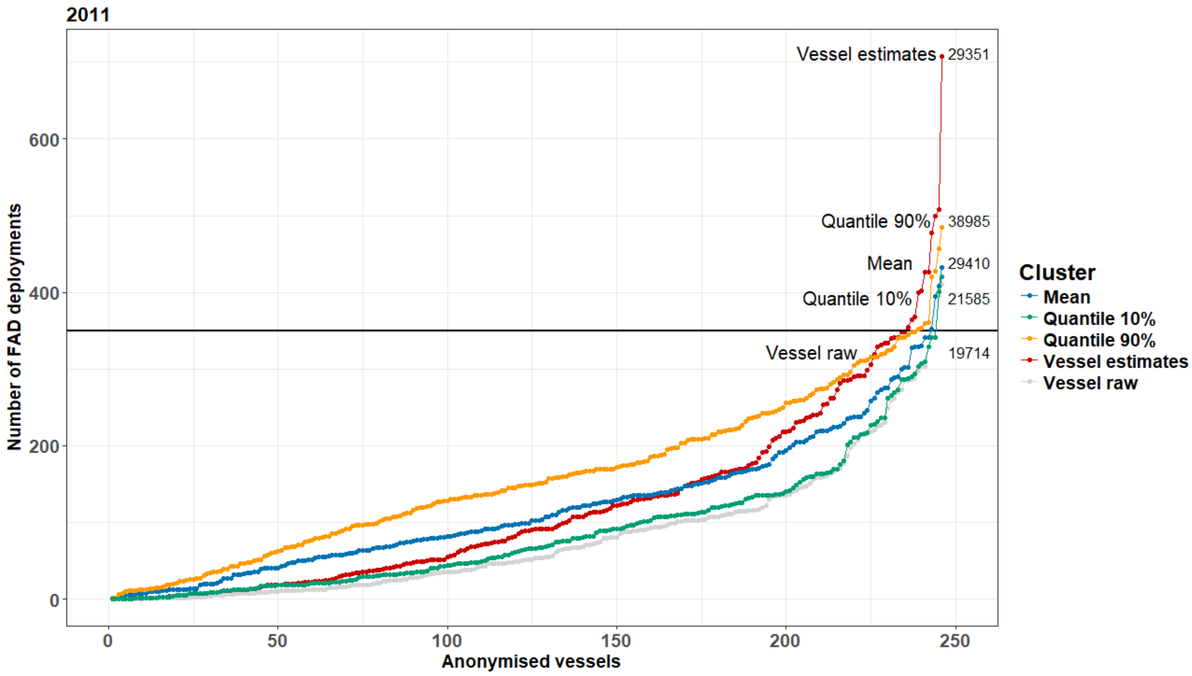

Figure 4. Raw and estimated number of deployments per vessel per year for 2011 (see Appendix 2 for the other years). Estimates are based on different standardisation methods: observer coverage of the vessel x number of deployments of the vessel (Vessel estimates = 'scaled vessel estimates'), or quantile 10%, mean, quantile 90% number of deployments per cluster ('cluster-based methods'). Estimates of total number of deployments in the WCPO, by method, are indicated on the right-hand side of each curve. Individual data points represent individual vessels.

Table 1. Estimates of the number of deployments per year and of the number of vessels with more than 150, 250 and 350 FAD deployments per year depending on the estimation method used*.

Year	**% vessels with > 150 deployments**				**% vessels with > 250 deployments**				**% vessels with > 350 deployments**			
	Scaled Vessel	*Cluster-based method*			*Scaled Vessel*	*Cluster-based method*			*Scaled Vessel*	*Cluster-based method*		
	Est.	*Qu. 0.10*	*Mean*	*Qu. 0.90*	*Est.*	*Qu. 0.10*	*Mean*	*Qu. 0.90*	*Vessel*	*Qu. 0.10*	*Mean*	*Qu. 0.90*
2011	30	17	29	49	15	7	9	19	4	1	2	3
2012	21	14	18	26	4	2	3	4	1	1	1	1
2013	14	11	13	18	5	3	4	5	2	2	2	2
2014	17	14	16	24	6	3	4	5	1	1	1	1
2015	7	6	8	10	3	2	2	4	1	0	0	2
2016	6	4	5	6	2	0	0	0	1	0	0	0
2017	13	6	11	24	4	1	1	5	2	1	1	1
2018	18	12	17	26	6	5	5	9	4	2	2	4
2019	16	8	18	33	6	3	4	11	4	1	2	3

*Scaled-vessel estimates = observer coverage vessel & number of deployments vessel; Mean cluster-based estimates = observer coverage vessel & mean total number of deployments per cluster; Qu. 10 cluster-based estimates = observer coverage vessel x Quantile 10% of number of deployments per cluster; Qu. 90 cluster-based estimates = observer coverage vessel x Quantile 90% of number of deployments per cluster.

The total number of deployments in the WCPO showed a slight decrease through time (Figure 5), this is probably due to delays in observer data (i.e., not all data having be processed and available to analyses yet) in recent years (Williams et al., 2020a). Estimates using the scaled vessel method and the cluster-based methods showed very similar results, with the total number of buoy or FAD deployments varying between 20,000–31,000 per year (Figure 5). Using all the estimation methods, including the quantile 10% and 90% cluster-based methods, the range of total number of deployments estimated per year varied between 23,000–40,700 in 2011 and 16,900–23,000 in 2016; but generally oscillating around 23,000 to 30,000 (including ~20 vessels per year with no observer coverage, for which values were derived for the mean value per cluster and year).

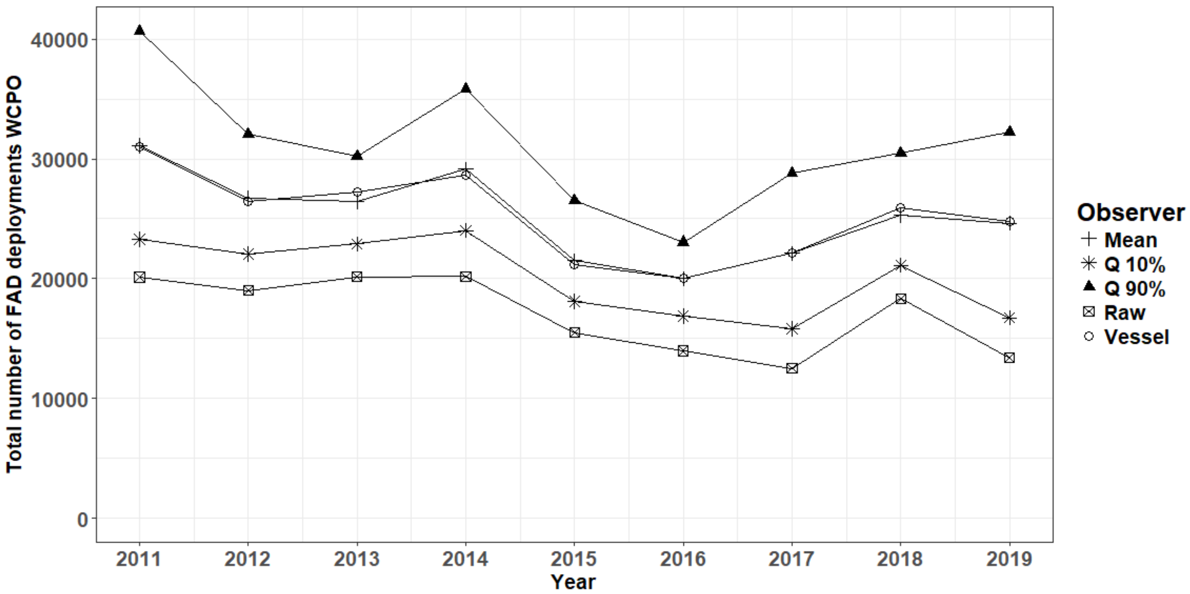

Figure 5. Estimates of the total number of deployments per year in the WCPO with different estimation methods (Vessel = scaled vessel estimates; Mean = mean cluster-based estimates; Q 10% = Quantile 10% cluster-based estimates; Q 90% = Quantile 90% cluster-based estimates). Total estimates include vessels with no observer coverage, and therefore, no estimates of number of deployments per vessel per year, so values for those vessels were obtain by taking the mean number of deployments per cluster per year.

The cumulative number of deployments per vessel were compiled to assess the proportion of deployments accounted for by a specific fraction of the fleet (Figure 6 and Appendix 3). For all years, 14–25% of vessels were responsible for 50% of the deployments, based on the scaled-vessel estimates method, with a decrease in recent years (Appendix 3). This means that recently, fewer vessels are responsible for more deployments (i.e., 14–17% since 2017). For the cluster-based methods, it varies from 17–27% of vessels responsible for 50% of deployments in the quantile 10% method; 20–30% of vessels in the mean method; and 20–32% of vessels in the quantile 90% method.

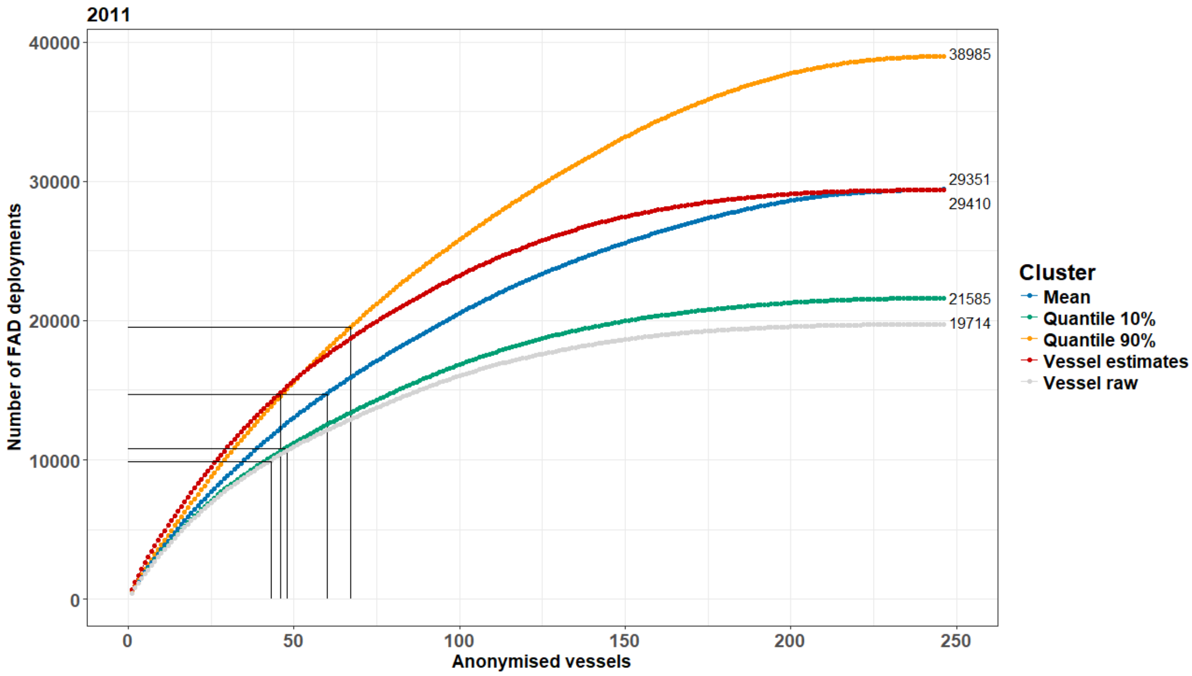

Figure 6. Cumulative raw and estimated number of deployments per vessel per year (2011; see Appendix 3 for other years) based on different standardisation methods: scaled-vessel estimates or cluster-based method (quantile 10%, mean, quantile 90% number of deployments per cluster). Estimates of the total number of FADs in the WCPO, by method, are indicated on the right-hand side of each curve. Black lines correspond to 50% of the number of deployments per year and the corresponding number of vessels having deployed 50% of the FADs.

3.3 Investigating the number of active FADs per vessel at any given time

As mentioned in the introduction, the estimates compiled above, corresponding to the number of deployments (FADs and buoys) performed per vessel per year, are different than the actual number of buoys monitored at any given time ("active buoys" as stated in the Conservation and Management Measure; WCPFC, 2018). The only available data that could be a proxy for the number of active buoys at any given time is the sum of the number of buoy-only deployments from observer data (raw numbers) over a certain period, combined with an assumption about the length of time that each buoy remains active ('survival period'; i.e., 4-month, 6-month, and one year). This was done for ~20 vessels per year corresponding to the top 50 vessels with the highest number of estimated deployments per year and observer coverage above 80%.

Under the assumption that all buoys remained active for the 4-month survival period, the median number of buoys monitored was 50, the maximum number was 250 and 50% of the vessels monitored 25–75 FADs at any particular time (Figure 7). This increases to a median of 50–75 buoys for survival periods of 6 months and 100–150 for survival periods of a year (Figure 7). Longer survival periods result in a higher number of monitored FADs because it was assumed that all buoys remained active for the whole period.

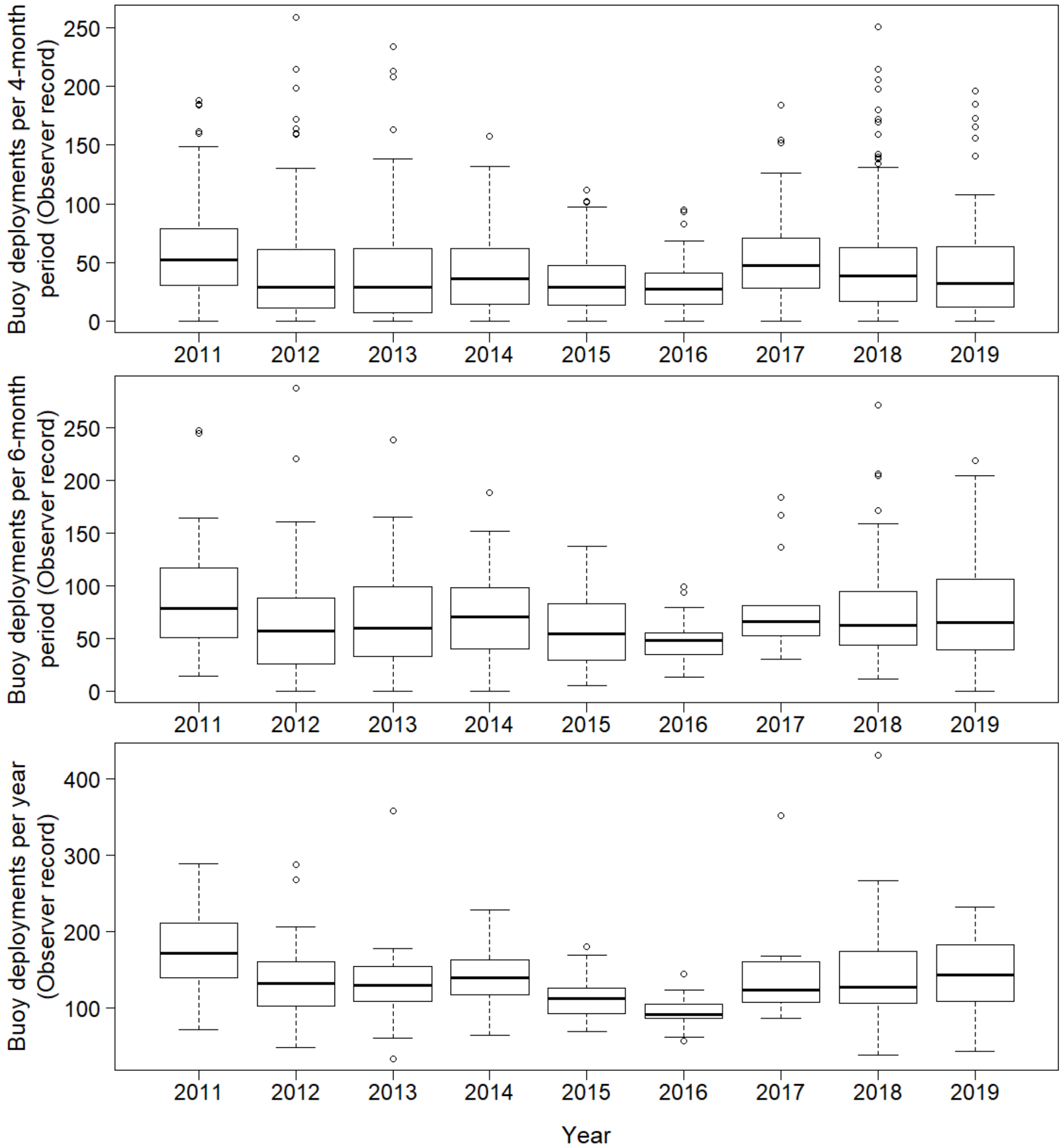

Figure 7. Number of buoy deployments, as recorded by observers, per vessel and per 4-month (top), 6-month (middle) and 1-year periods for the top 50 vessels deploying the highest number of FADs and with an observer coverage >80% (i.e., ~20 vessels per year). If all buoys deployed remain active for the whole period considered, this could reflect the number of buoys monitored per vessel as any given time.

4. Estimates combining FAD tracking data and fishing data

4.1 Number of buoy deployments per vessel and total deployments

To complement the estimates 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. Only 174 vessels in 2016, 185 in 2017, 186 in 2018 and 178 in 2019 were present as buoy owners in the PNA FAD tracking data (out of a total of 289, 284, 285, 284, respectively, Table 2), estimates for the remaining vessels were therefore derived from observer data.

Table 2. Estimates of the percentages of vessels with a total number of deployments per year above 150, 250 and 350 in the WCPO using a combination of PNA FAD tracking and observer data.

Year	No. of vessels*	% vessels with more than 150 deployments	% vessels with more than 250 deployments	% vessels with more than 350 deployments
2016	289	15	2	1
2017	284	13	4	1
2018	285	17	6	4
2019	284	15	5	3

* Note that the vessel list was compiled using observer and PNA FAD tracking data, and therefore the annual numbers might slightly vary from the list in Table 3 of Williams et al. (2020b). Vessels may have changed name in one database but not the other yet or some FADs may still have a declared "owner" in the FAD tracking data corresponding to a vessel that has not fished in the WCPO on the considered year.

The resulting estimated number of buoy deployments per vessel varied between 1 and 598 (mean = 97) in 2016; 1 and 845 (mean = 112) in 2017; 1 and 699 (mean = 134) in 2018; and 1 and 663 (mean = 180) in 2019 (Figure 6). Similar to previous estimates using fishery data only, very few vessels deployed/redeployed more than 350 buoys per year (1–4% of vessels, Figure 8 and Table 2). This increased to 13-17% of vessels deploying more than 150 buoys per year (Table 2).

Cumulative number of deployments per vessel per year was also compiled (Figure 9). It showed than 18–19% of vessels (i.e., around 50 vessels) are responsible for 50% of the deployments.

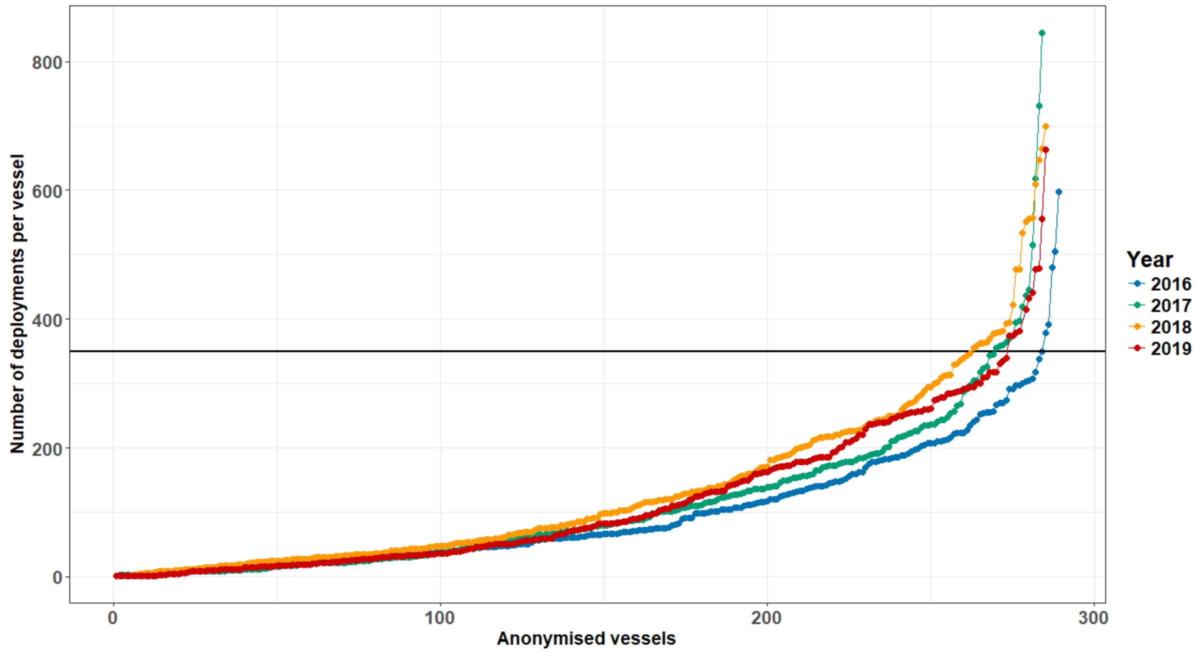

Figure 8. Estimated number of deployments per year in 2016 to 2019 based on the combined observer and FAD tracking method. Individual data points represent individual vessels.

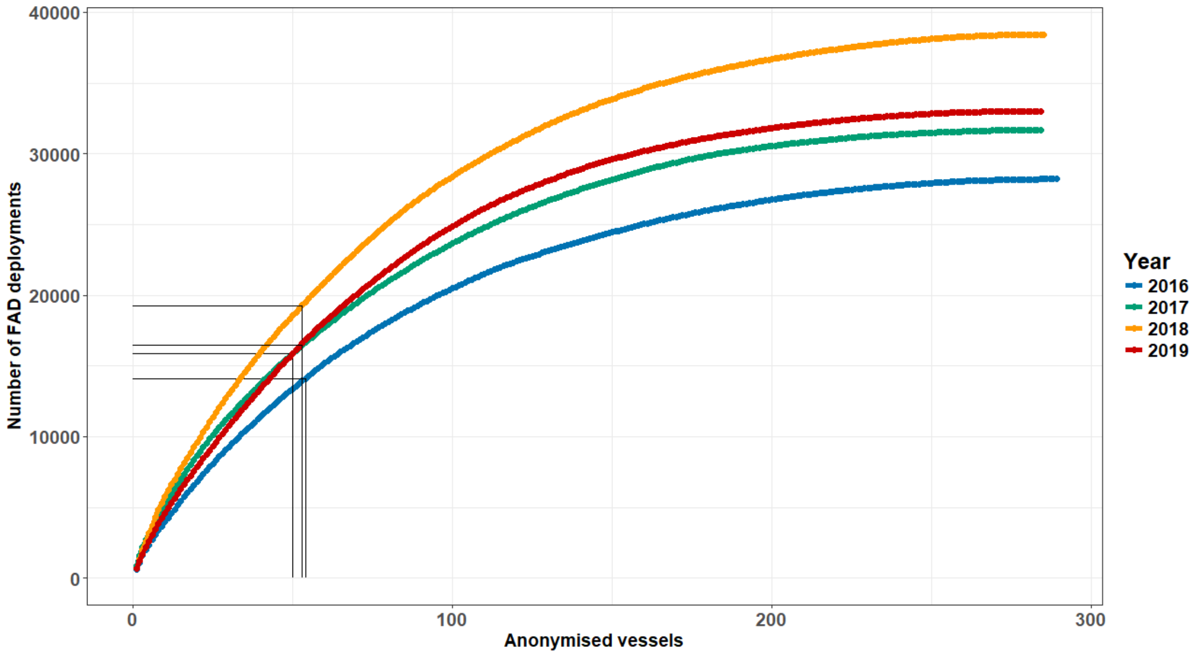

Figure 9. Estimated cumulative number of deployments per year between 2016 and 2019 based on the combined observer and FAD tracking method. Black lines correspond to 50% of the number of deployments per year and the corresponding number of vessels having deployed 50% of the FADs.

Using the combined observer and FAD tracking method, the total number of buoy deployments varied between 31,000 in 2016; 34,500 in 2017; 39,500 in 2018; and 33,400 in 2019 (Figure 10). When compared to estimates based on observer data only (Figures 5 and 10), this represents a level of deployment that is similar to the 90% quantile from the cluster-based method for 2011–2015, with lower estimates from the observer-based methods (both scaled-vessel and cluster-based methods). Refined estimates, when more observer data have been processed, would allow the validation of the number of deployments estimated here for the more recent period. However, given results from all the methods (scaled-vessel and cluster-based observer methods and combined observer/ FAD tracking method), we could reasonably suggest that total number of FADs deployed per year is likely in the 30,000 to 40,000 range for the 2011–2019 period, similar to findings from Gershman et al. (2015).

The total number of FADs or buoys deployments estimated per year was standardised by the number of FAD sets recorded in logsheet data (Figure 11). This allowed evaluation of actual trends in buoy deployments in relation to annual changes in the fishery. This standardised deployment index is decreasing from 2014 to 2018 when considering observer data only (scaled-vessel and cluster-based methods) (Figure 11). However, it is stable when considering a mix of the 90% quantile cluster-based estimates in 2011–2015 followed by the combined observer/ PNA FAD tracking estimates in 2016-2019

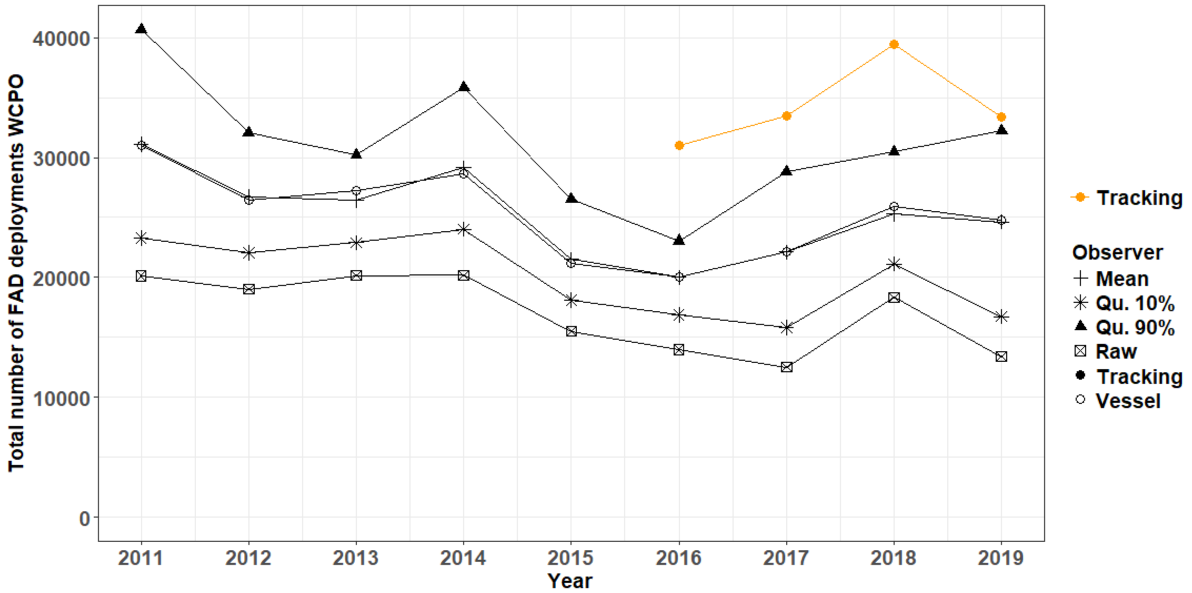

Figure 10. Estimates of the total number of deployments per year in the WCPO with different estimating methods based on observer data only (black line) and using a combination of PNA FAD tracking and observer data (orange line).

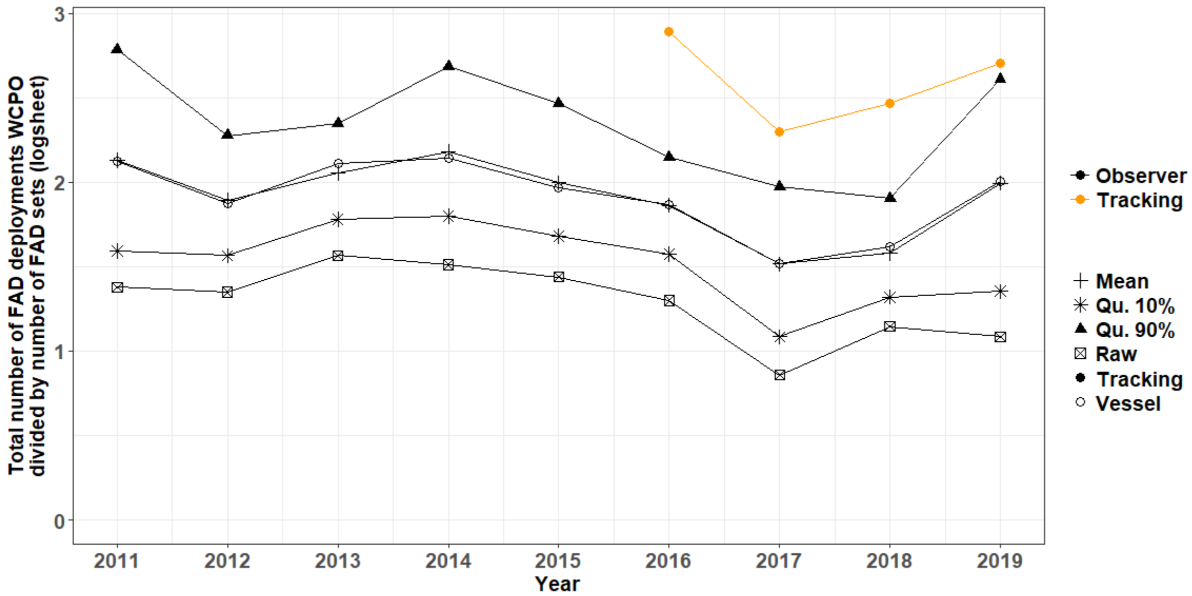

Figure 11. Standardised estimates of the total number of deployments per year (number of deployments / number of FAD sets in logsheet data) in the WCPO with different estimating methods based on observer data only (black line) and using a combination of PNA FAD tracking and observer data (orange line).

4.2 Investigating the number of active buoys per vessel

Based on results from the previous section, the number of active buoys per vessel at any given time was investigated using data from the FAD tracking programme. To do so, the top 50 vessels present in the FAD tracking database that had the highest number of buoy deployments estimated were selected. For each vessel, the number of active buoys per month or per day were then compiled. These numbers were raised using the same raising factor per vessel previously estimated between the raw number of buoy deployments in the PNA FAD tracking data matched with total number of buoy deployments, in the previous section.

Both the raw and raised number of active buoys per vessel and per month ranged between 0 and 400, and the raw and raised number of active buoys per vessel and day ranged between 0 and 330 (Figure 12). A general increasing trend is detected through time, with a median raised number of active buoys per vessel per month of 60 in 2016 and 100 in 2019 and a median raised number of active buoys per vessel and per day of 45 in 2016 and 75 in 2019 (Figure 12). However, there was no monthly trend detected, with a median of around 75–80 active buoys per vessel per month and around 50–60 active buoys per vessel and per day (Figure 13).

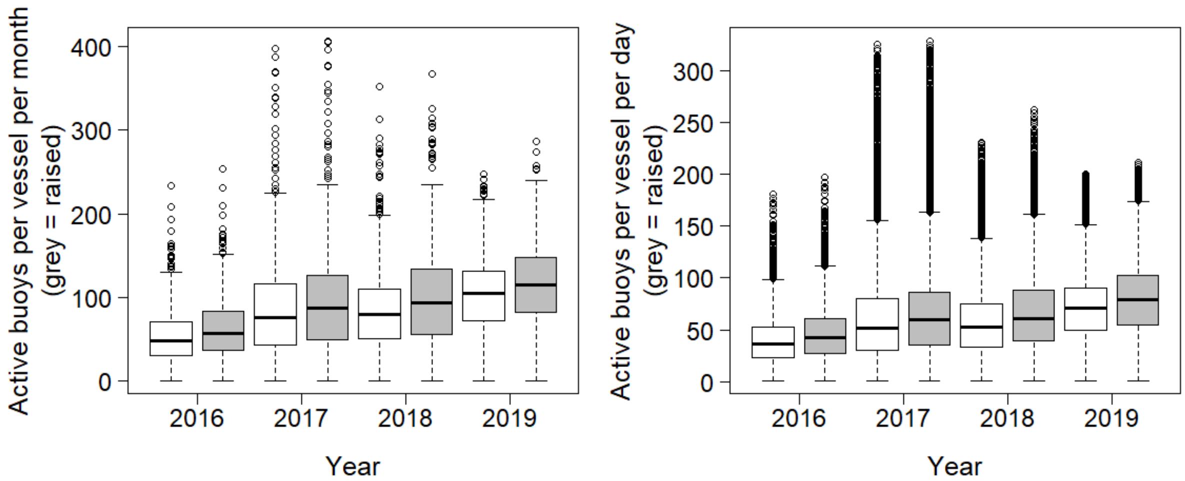

Figure 12. Annual variability in the raw (white) or raised (grey) number of active buoys per vessel and per month (left) or per day (right) in the PNA FAD tracking vessel for the top 50 vessels deploying the highest number of FADs.

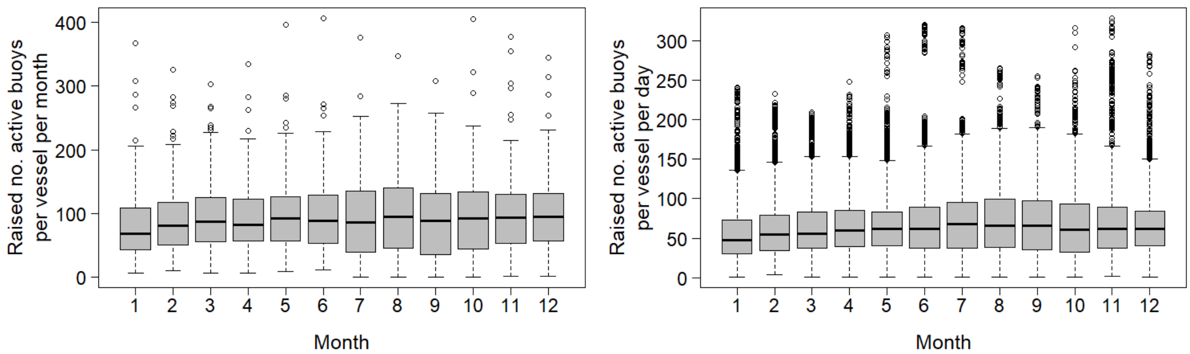

Figure 13. Monthly variability in the raised number of active buoys per vessel and per month (left) or per day (right) in the PNA FAD tracking vessel for the top 50 vessels deploying the highest number of FADs.

5. Discussion

This paper highlights the challenges in estimating the number of FAD deployments and active buoys on FADs per vessel in the WCPO. While the FAD tracking data presents the best insight into the FAD usage by purse seiners in PNA waters, this dataset is still incomplete, both because not all FADs are present and because many of the FAD trajectories are geofenced by fishing companies prior to submission. Therefore, some uncertainties remain, even for the vessels identified in the FAD tracking data. Regarding the observer data, the delay before accessing near-complete 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. To overcome these challenges, two complimentary methods were used in this paper, one based on fishery data and vessels clustered into groups of similar FAD fishing strategy (separated into a scaled-vessel method and a cluster-based method), and a second, combining both the observer data and the PNA FAD tracking data (combined observer and FAD tracking method) so both databases may complement each other.

Both methods showed that very few vessels deploy more than 350 FADs per year, and this includes both new FADs and buoys re-deployed on logs or FADs found at sea. Most years, only a small proportion of vessels deployed more than 150 FADs (i.e., 6–21% of vessels based on the combined observer and FAD tracking method and the scaled-vessel method; except for 2011 with 30% of vessels, see Tables 1 and 2). The 90% quantile cluster-based method showed a maximum of 50% of vessels with more than 150 deployments per year. Even this upper bound corresponds to 150 deployments per year, and therefore suggests only half this number in terms of number of active FADs at any given time, if we consider an average buoy active life of 6 months (Escalle et al., 2019a). This was confirmed by estimation of the number of active buoys per vessel at any given time using available information. Even vessels deploying the highest number of buoys in the WCPO per year never had more than 350 active buoys per day, the median being from 45 in 2016 to 75 in 2019 (Figure 13). This suggests that the 350 'active FAD per vessel' limit introduced by the WCPFC in 2009 is not limiting FAD use at this point in time. To the contrary, the increasing trend detected from 2016 to 2019, in terms of number of active buoys, tends to indicate an increase in number of FADs monitored per vessel by some fleets.

If all vessels in the WCPO were to monitor 350 active buoys, this could represent 70,000 to 100,000 FADs drifting in the WCPO at any given time (based on the recent average number of purse seiners of 280 (Williams et al., 2020b), or based on a lower number if we assume 200 purse seiners, considering that not all vessels will have a FAD-orientated fishing strategy). Even if we consider that these 70,000 to 100,000 corresponds to the total number of FADs deployed per year in the WCPO, these numbers are striking. In this paper, we have estimated that 30,000 to 40,000 FADs are deployed/redeployed each year. These numbers are very similar, although lower, to the number of deployments in the WCPO estimated at 30,000–50,000 in 2013 by Gershman et al. (2015), but they are different from results found in a previous paper in 2018 (Escalle et al., 2018a). This difference is likely due to higher data quantity and quality this year allowing better estimates to be compiled, but also the more refined raising method used (Escalle et al., 2020; Williams et al., 2020a). Here, a slight decrease through time in the total number of deployments in the WCPO was detected using fishery data only (scaled vessel and cluster-based methods), but this is probably due to delays in observer data availability, rather than to any real decline in FAD deployment rates. When results from all methods are compiled together, no clear temporal trend could be detected.

While current levels of FAD use remain challenging to determine with high certainty, the longer term management of FADs could benefit from a better understanding of the optimum number of FADs to maximise profitability while limiting impacts on tuna stocks and ecosystems. In parallel to improve the ability to estimate potential FAD levels (e.g., deployments, FAD density, active buoys), 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).

This paper shows that the maximum level specified in the current WCPFC tropical tuna Conservation and Management Measure (WCPFC, 2018; 350 active FADs per vessel per day) is rarely, if ever, reached in the WCPO. The increasing trend detected from 2016 to 2019, in terms of number of active buoys, is also noteworthy. In addition, a measure restricting the number of active buoys per vessel, at any given time, cannot take into account the fact that buoys are commonly deactivated when FADs are considered lost by fishers or after an optimum period at sea. This approach may not therefore be sufficient to limit the overall number of FADs at sea (FAD density, and the impact on tuna school size and therefore tuna catch) and mitigate their impact on the marine ecosystem (e.g., entanglement of sensitive species, pollution, beaching - although the implementation of non-entangling designs and encouragement for the use of biodegradable FADs is noted). While the ratio between FAD deployments and active FADs (i.e., active buoy on a FAD) remains generally unknown, deployments are higher than the number of active FADs used by a vessel every year, as FADs are often redeployed several times by the owner or other vessels (Fonteneau et al., 2015; Lennert-Cody et al., 2018). Limiting the number of deployments may therefore be more relevant.

We invite WCPFC-SC16 to:

- Note the progress being made in monitoring FAD numbers for the purpose of informing FAD management.
- Note the analysis of the number of FAD deployments and active FADs per vessel and the challenges encountered in this analysis.
- Note that this study indicated that most vessels deployed less than 150 FADs per year and very few vessels deployed/redeployed more than 350 FADs per year. The current limit for the number active buoys an individual vessel can have at any one time is 350 under CMM-2018-01 (paragraph 23). These results indicate that this measure is not constraining FAD deployments or buoy monitoring.
- Note the estimates of 30,000–50,000 FADs deployed/redeployed per year in the WCPO.

Acknowledgments

The authors would like to thank the members of the Parties to the Nauru Agreement for giving us access to their data for this analysis. We thank Elizabeth Heagney for valuable comments on an earlier version of the paper.

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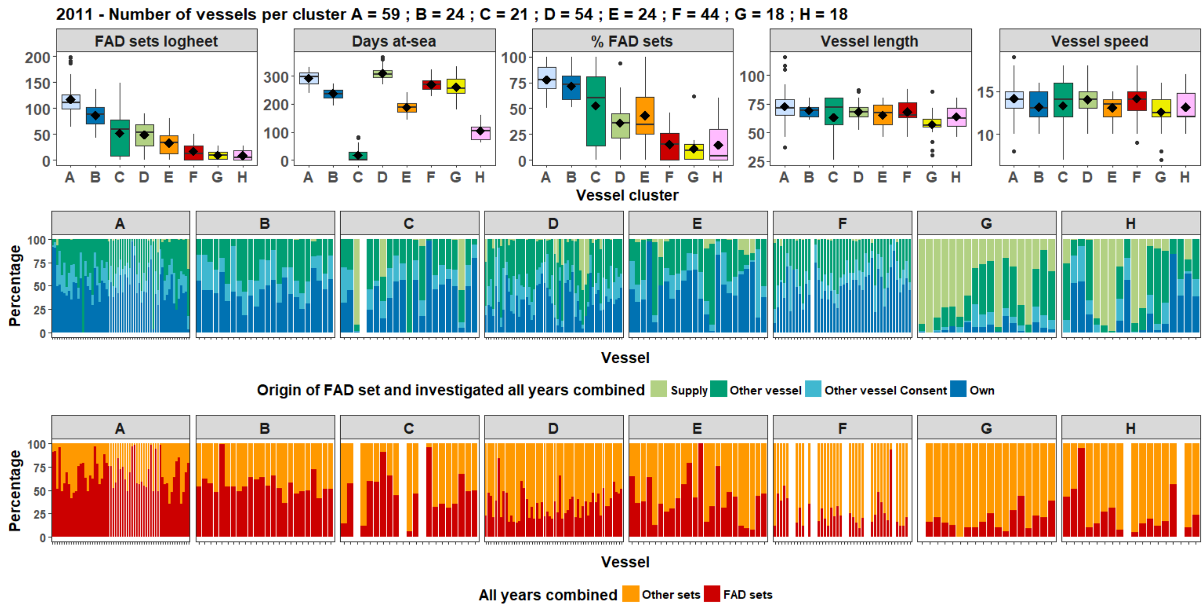
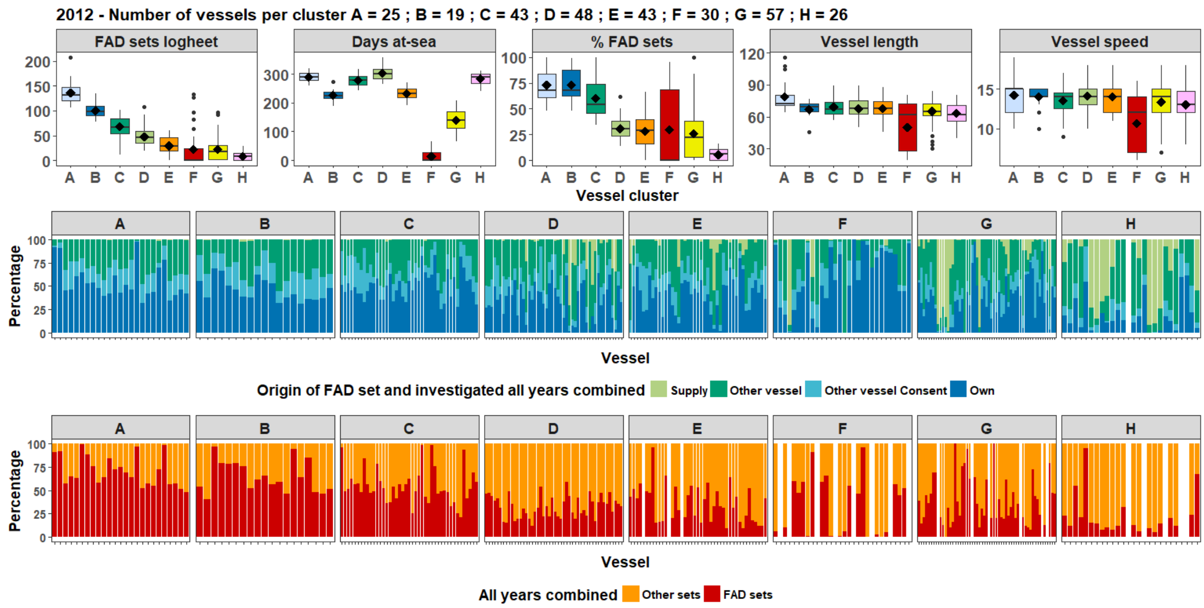
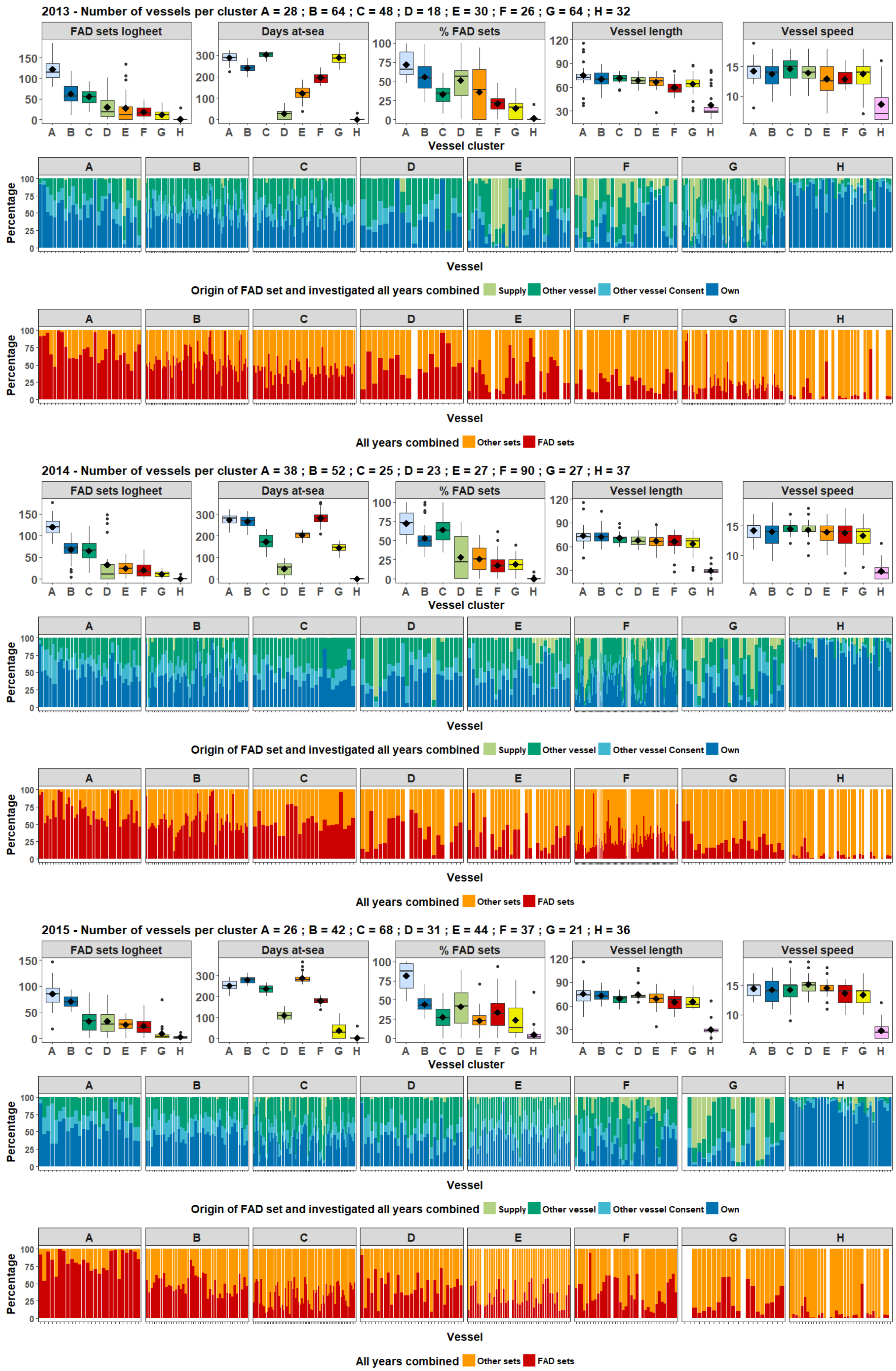
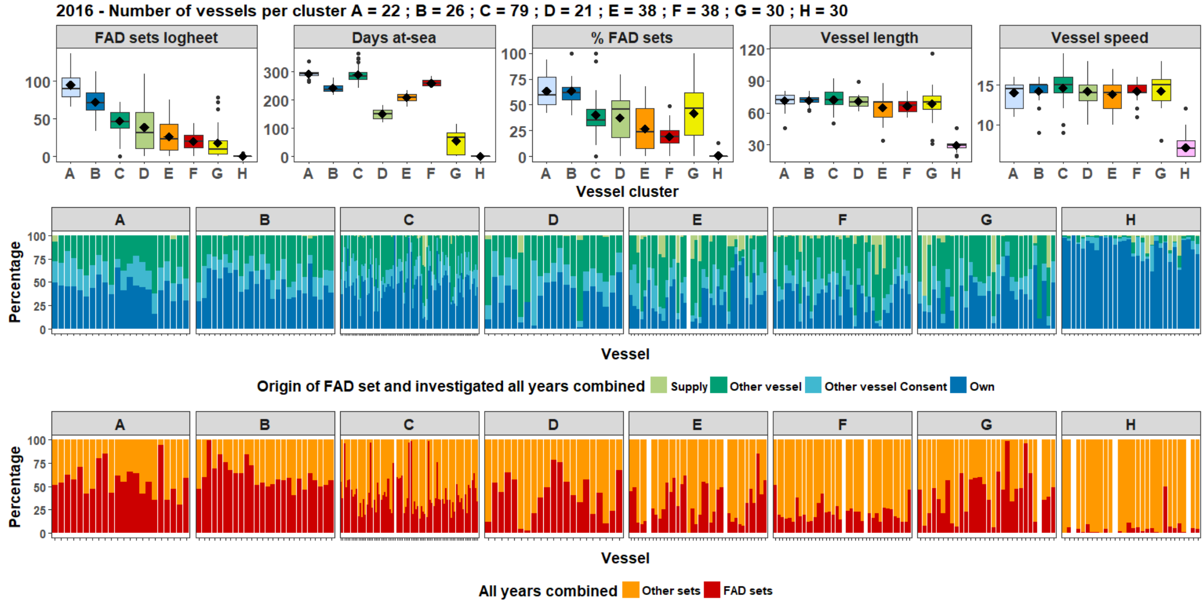
Appendix 1. Fishing strategy clusters per year (2011–2019). Top = number of FAD sets per vessel in logsheet data; number of days at-sea per vessel derived from VMS data; percentage of associated sets (FAD and log) per vessel in the considered year; vessel length; and vessel speed per vessel cluster. Middle = origin of all FADs encountered by a vessel over 2011–2019. Bottom = percentage of associated sets (FAD and log) per vessel over 2011–2019.



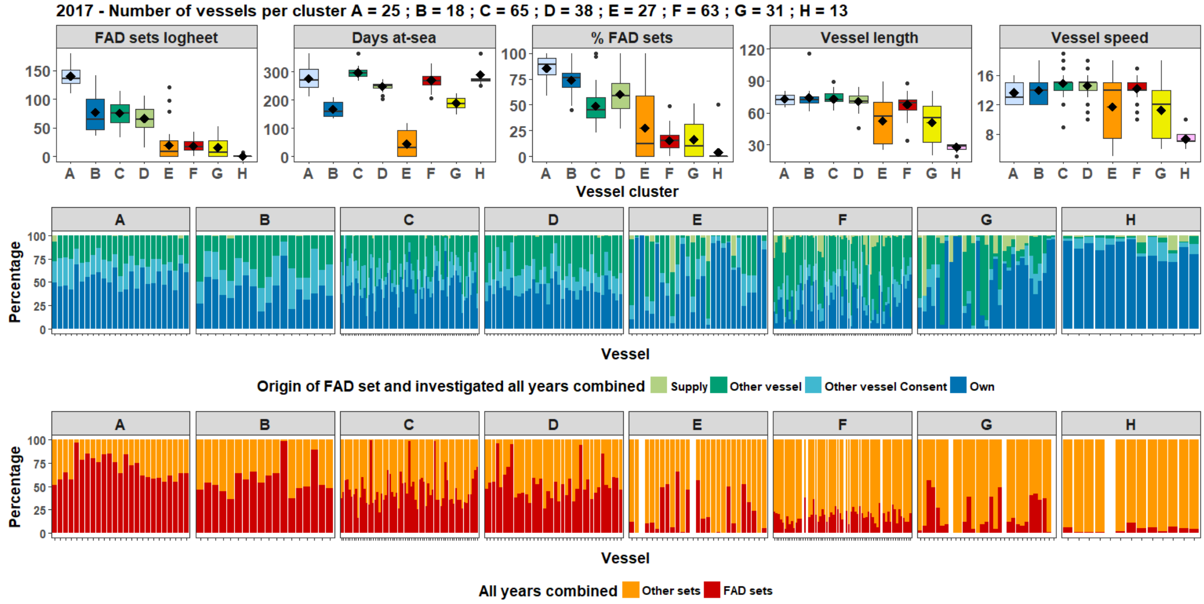




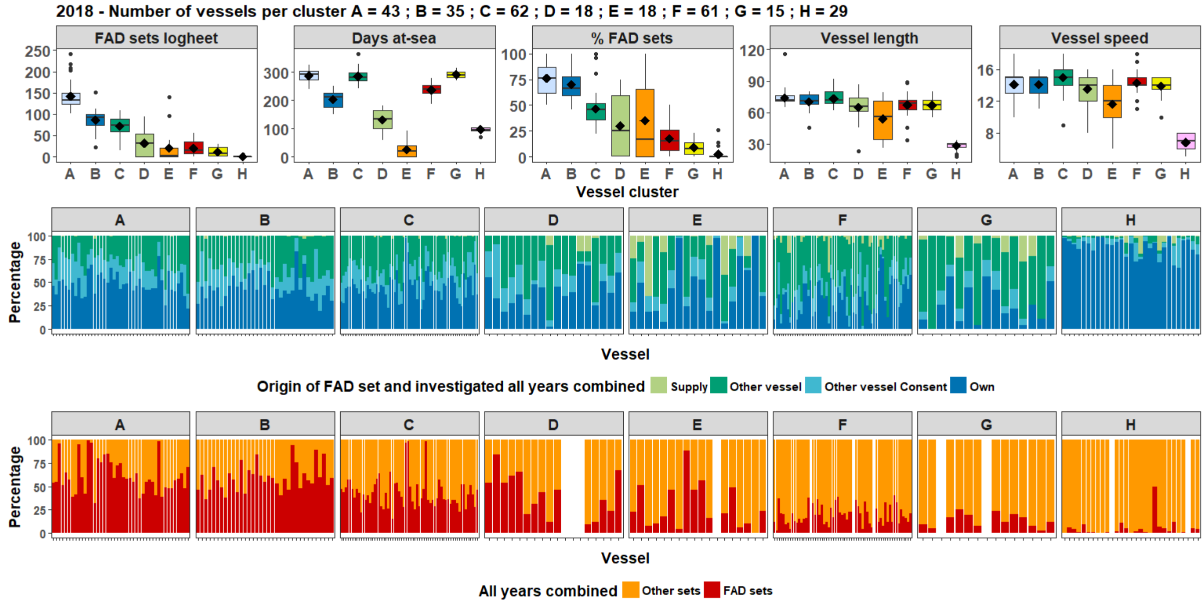
2013 - Number of vessels per cluster A = 28 ; B = 64 ; C = 48 ; D = 18 ; E = 30 ; F = 26 ; G = 64 ; H = 32
FAD sets logheet
Days at-sea
% FAD sets
Vessel length
Vessel speed
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
Other sets
FAD sets
2014 - Number of vessels per cluster A = 38 ; B = 52 ; C = 25 ; D = 23 ; E = 27 ; F = 90 ; G = 27 ; H = 37
2015 - Number of vessels per cluster A = 26 ; B = 42 ; C = 68 ; D = 31 ; E = 44 ; F = 37 ; G = 21 ; H = 36



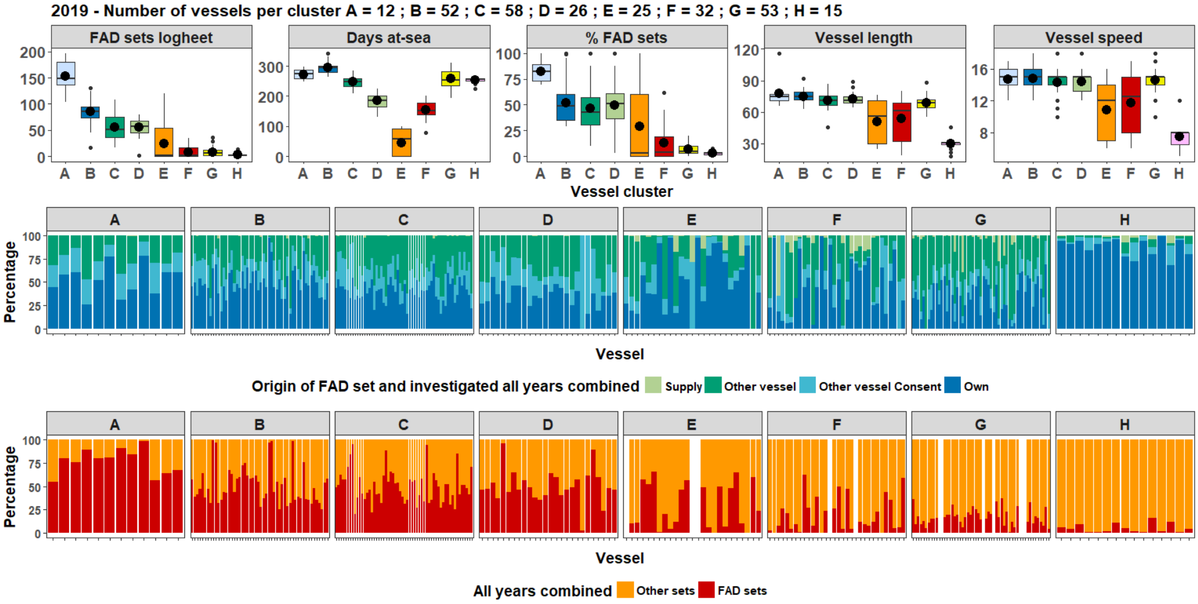
2016 - Number of vessels per cluster A = 22 ; B = 26 ; C = 79 ; D = 21 ; E = 38 ; F = 38 ; G = 30 ; H = 30
FAD sets logheet
Days at-sea
% FAD sets
Vessel length
Vessel speed
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
Other sets
FAD sets



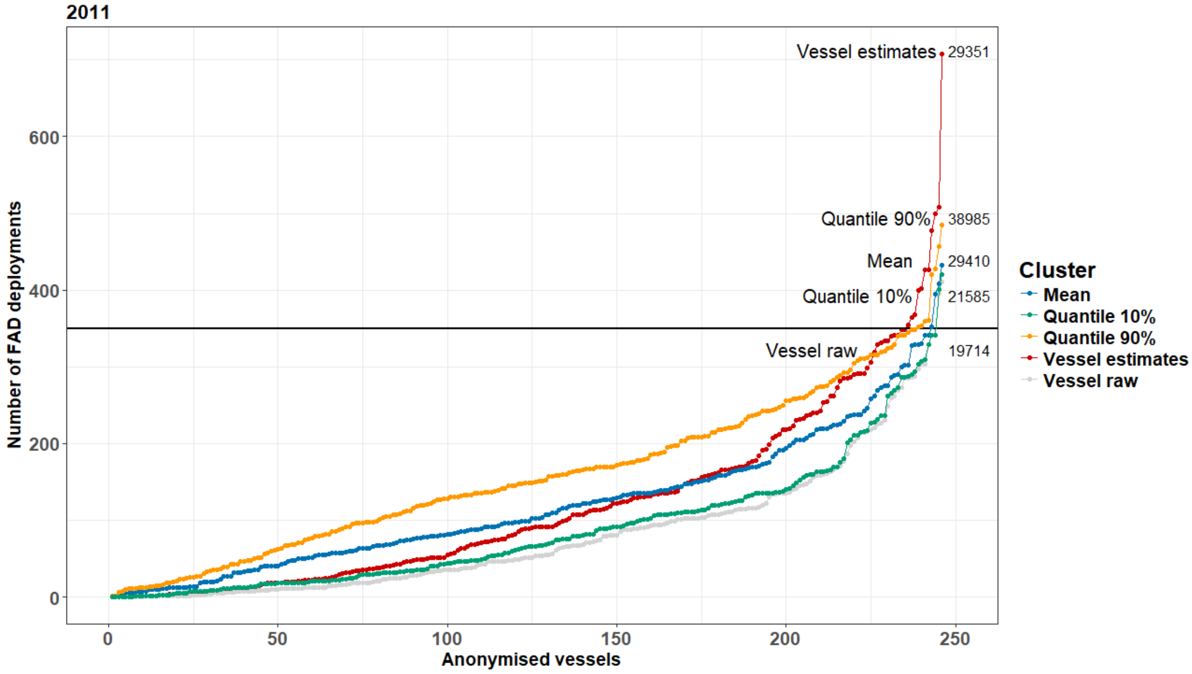
2017 - Number of vessels per cluster A = 25 ; B = 18 ; C = 65 ; D = 38 ; E = 27 ; F = 63 ; G = 31 ; H = 13
FAD sets logheet
Days at-sea
% FAD sets
Vessel length
Vessel speed
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
Other sets
FAD sets

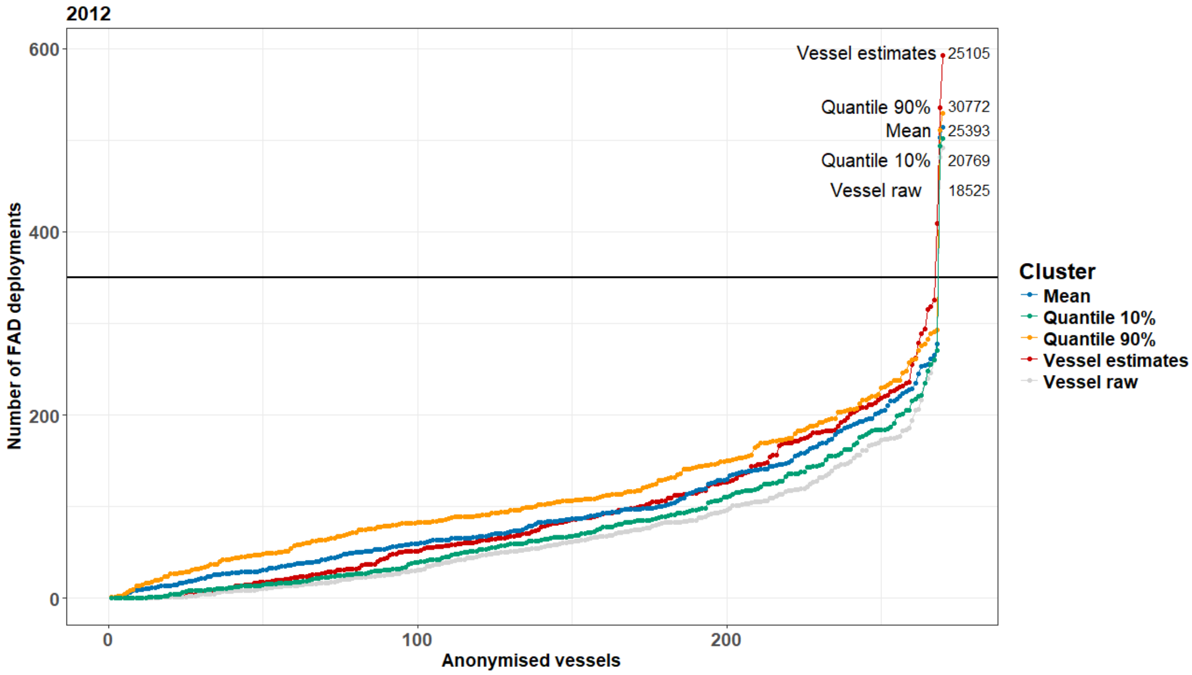


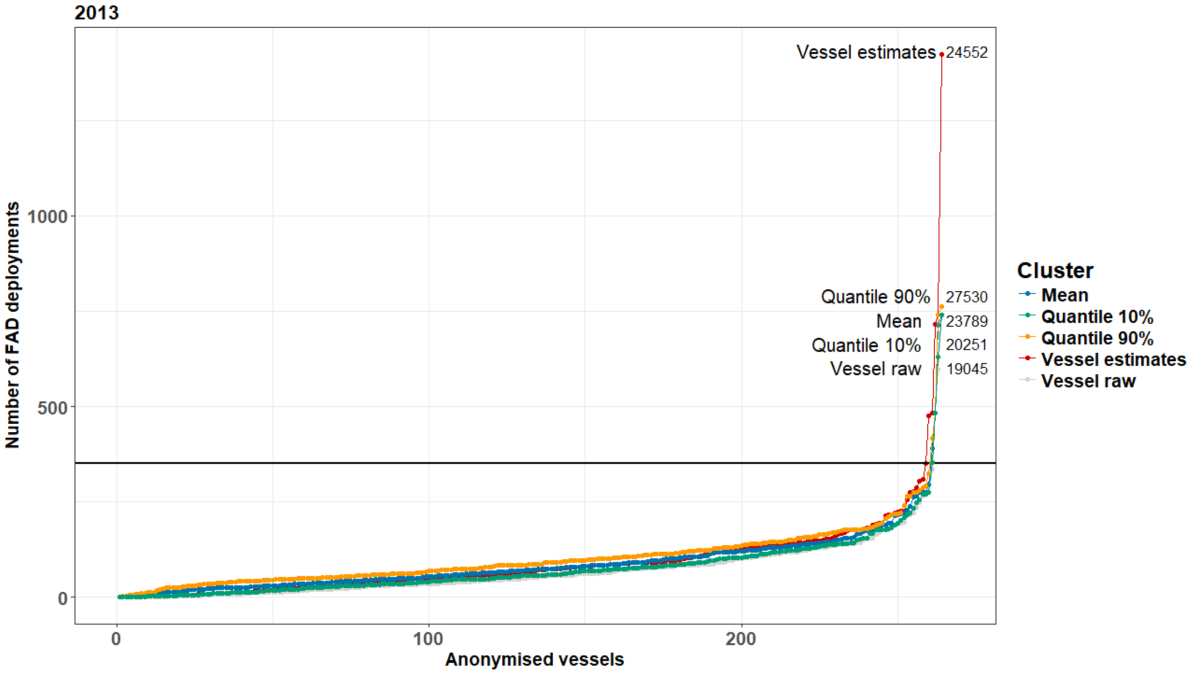
2018 - Number of vessels per cluster A = 43 ; B = 35 ; C = 62 ; D = 18 ; E = 18 ; F = 61 ; G = 15 ; H = 29
FAD sets logheet
Days at-sea
% FAD sets
Vessel length
Vessel speed
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
Other sets
FAD sets

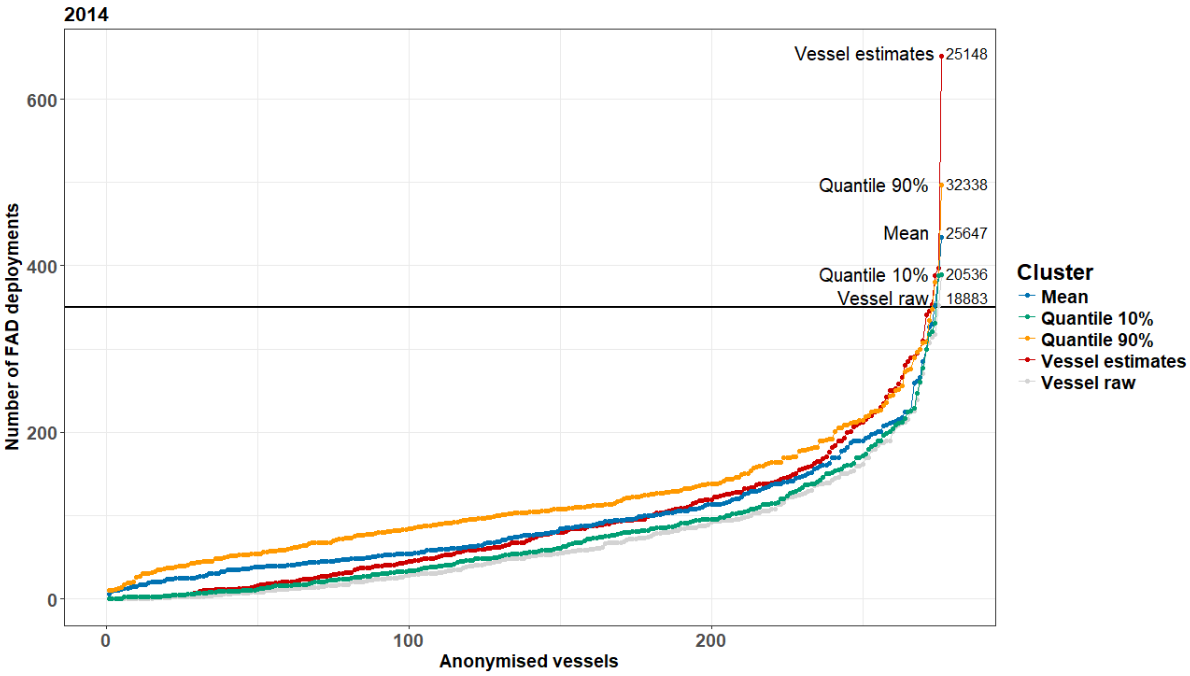

2019 - Number of vessels per cluster A = 12 ; B = 52 ; C = 58 ; D = 26 ; E = 25 ; F = 32 ; G = 53 ; H = 15
FAD sets logheet
Days at-sea
% FAD sets
Vessel length
Vessel speed
Vessel cluster
Percentage
Vessel
Origin of FAD set and investigated all years combined
Supply
Other vessel
Other vessel Consent
Own
All years combined
Other sets
FAD sets

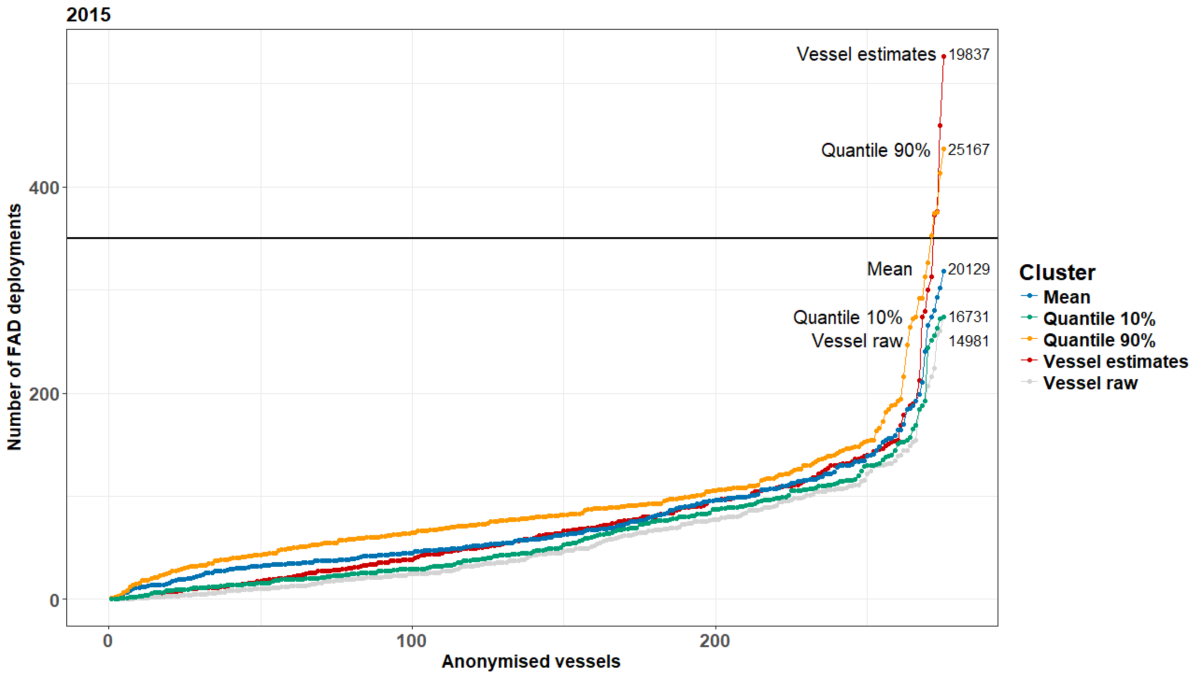
Appendix 2. Raw and estimated number of deployments per vessel per year (2011–2019). Estimates are based on different standardisation methods: observer coverage of the vessel x number of deployments of the vessel ('scaled vessel estimates'), or quantile 10%, mean, quantile 90% number of deployments per cluster ('cluster-based methods'). Estimates of total number of deployments in the WCPO, by method, are indicated on the right-hand side of each curve. curve.

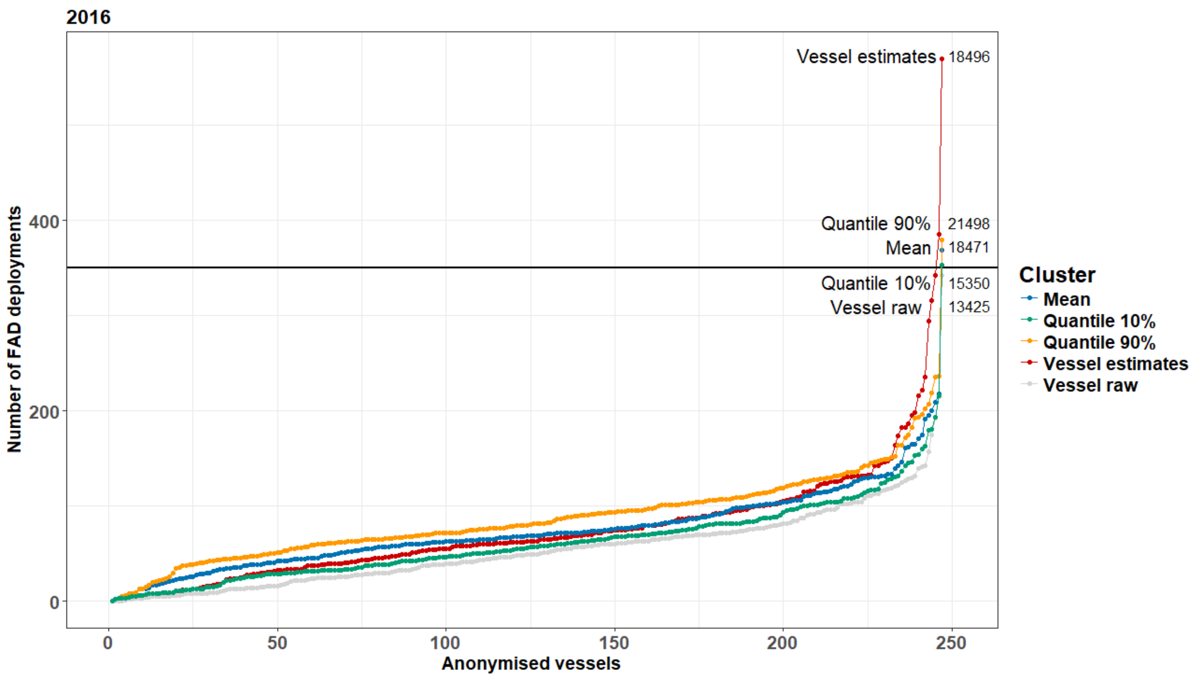


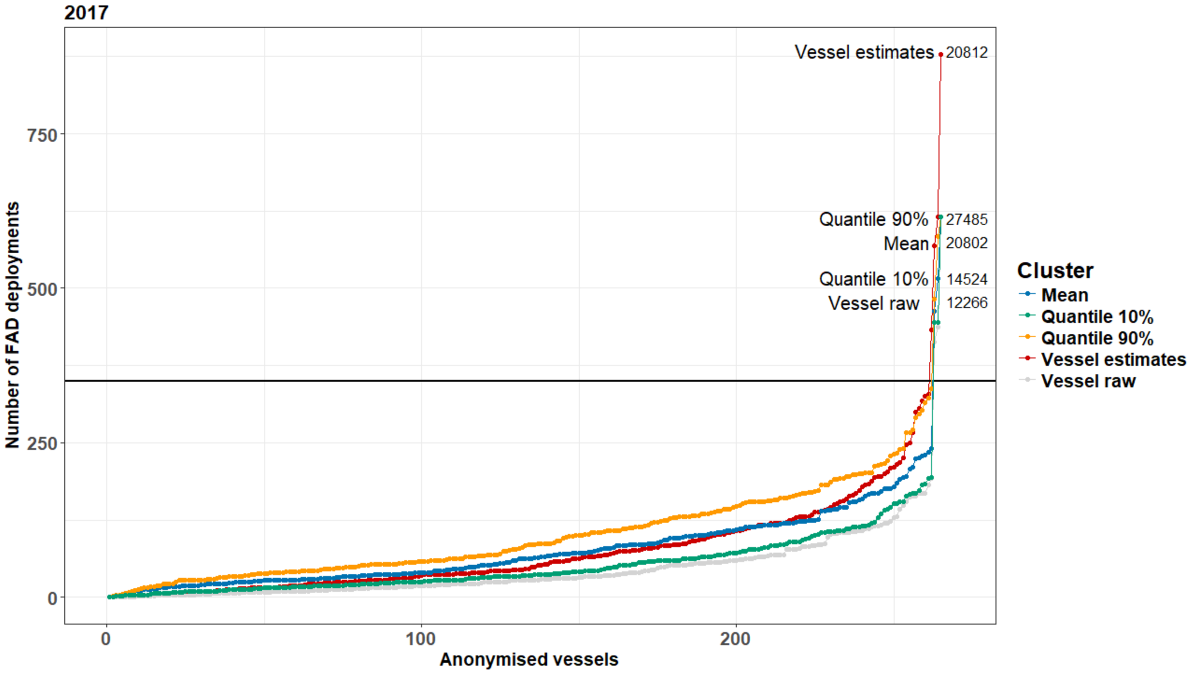


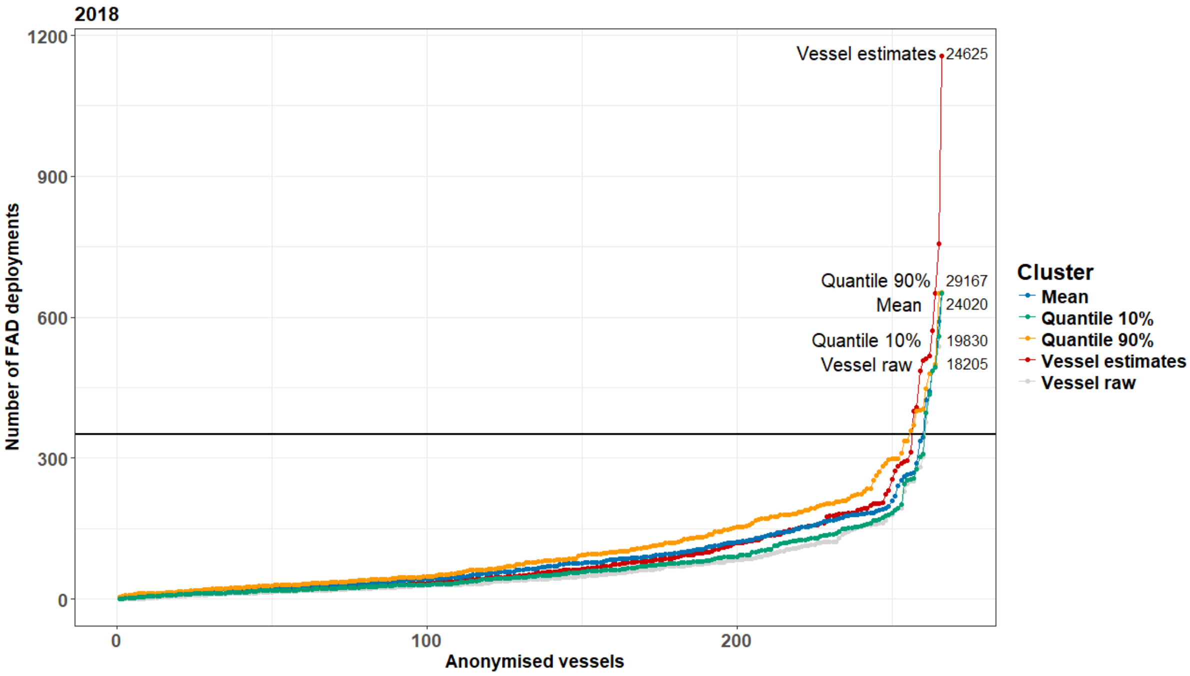

2013
Vessel estimates
24552
Quantile 90%
27530
Mean
23789
Quantile 10%
20251
Vessel raw
19045
Number of FAD deployments
1000
500
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw

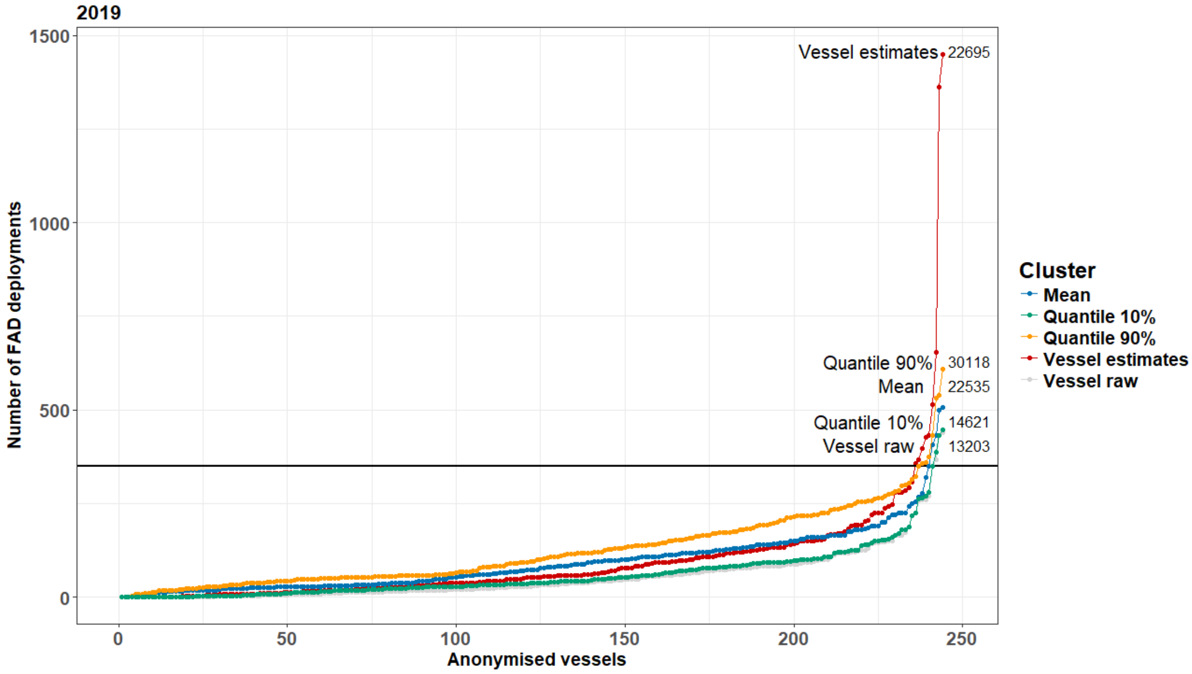

2014
Vessel estimates
25148
Quantile 90%
32338
Mean
25647
Quantile 10%
20536
Vessel raw
18883
Number of FAD deployments
600
400
200
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw


2015
Vessel estimates
19837
Quantile 90%
25167
Mean
20129
Quantile 10%
16731
Vessel raw
14981
400
200
0
Number of FAD deployments
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw


2016
Vessel estimates
18496
Quantile 90%
21498
Mean
18471
Quantile 10%
15350
Vessel raw
13425
400
200
0
Number of FAD deployments
0
50
100
150
200
250
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw

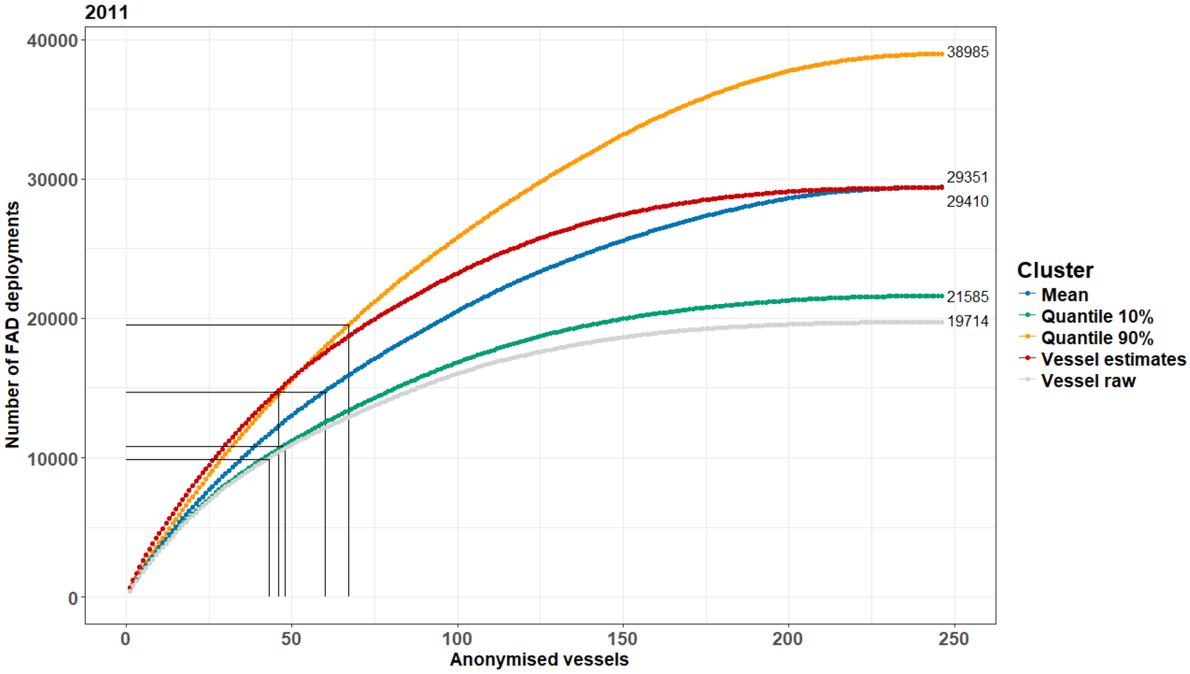

2017
Vessel estimates 20812
Quantile 90% 27485
Mean 20802
Quantile 10% 14524
Vessel raw 12266
Number of FAD deployments
0
250
500
750
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw

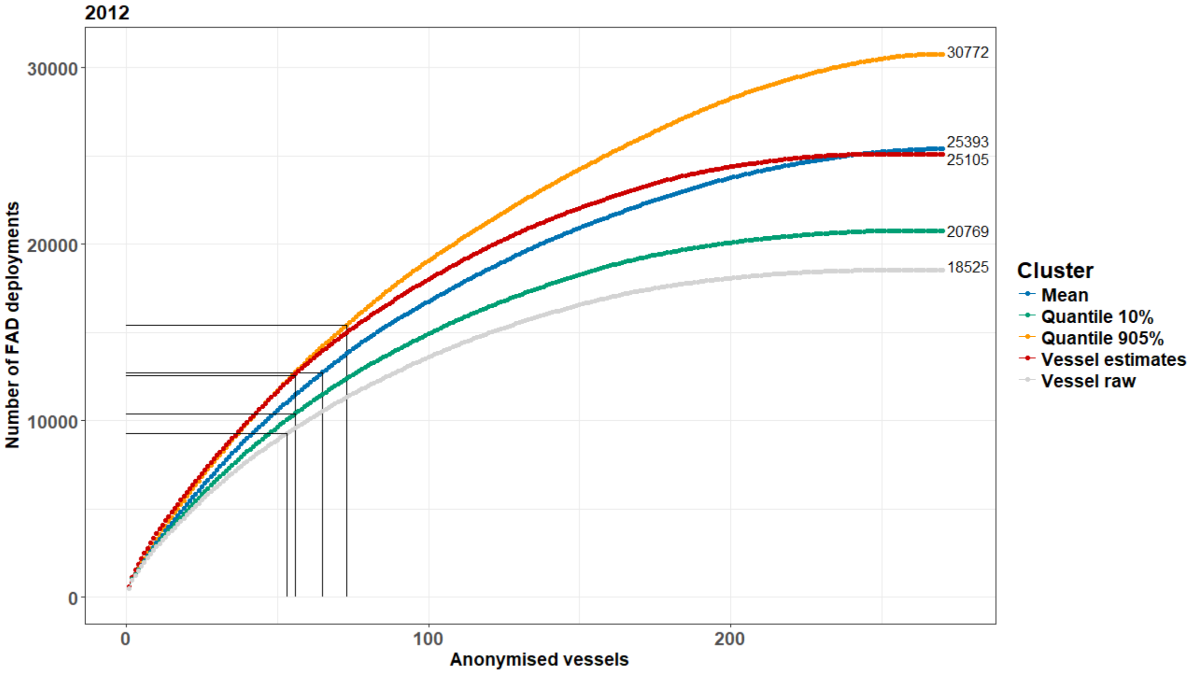

2018
Vessel estimates 24625
Quantile 90% 29167
Mean 24020
Quantile 10% 19830
Vessel raw 18205
Number of FAD deployments
0
300
600
900
1200
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw

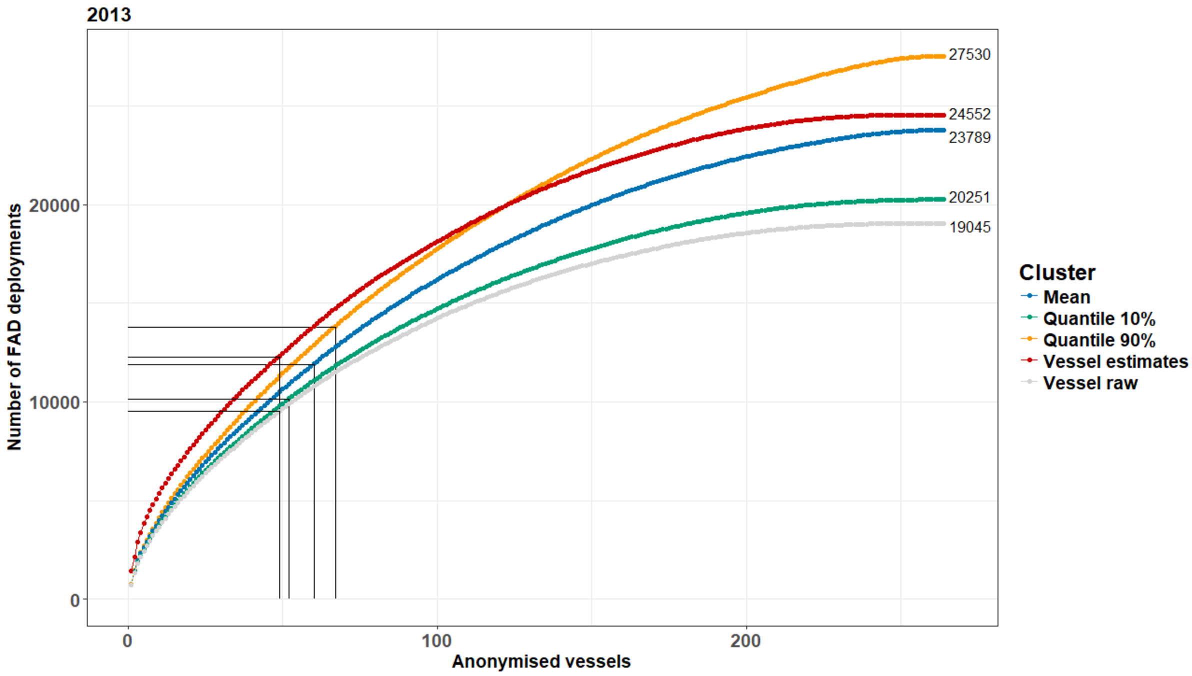


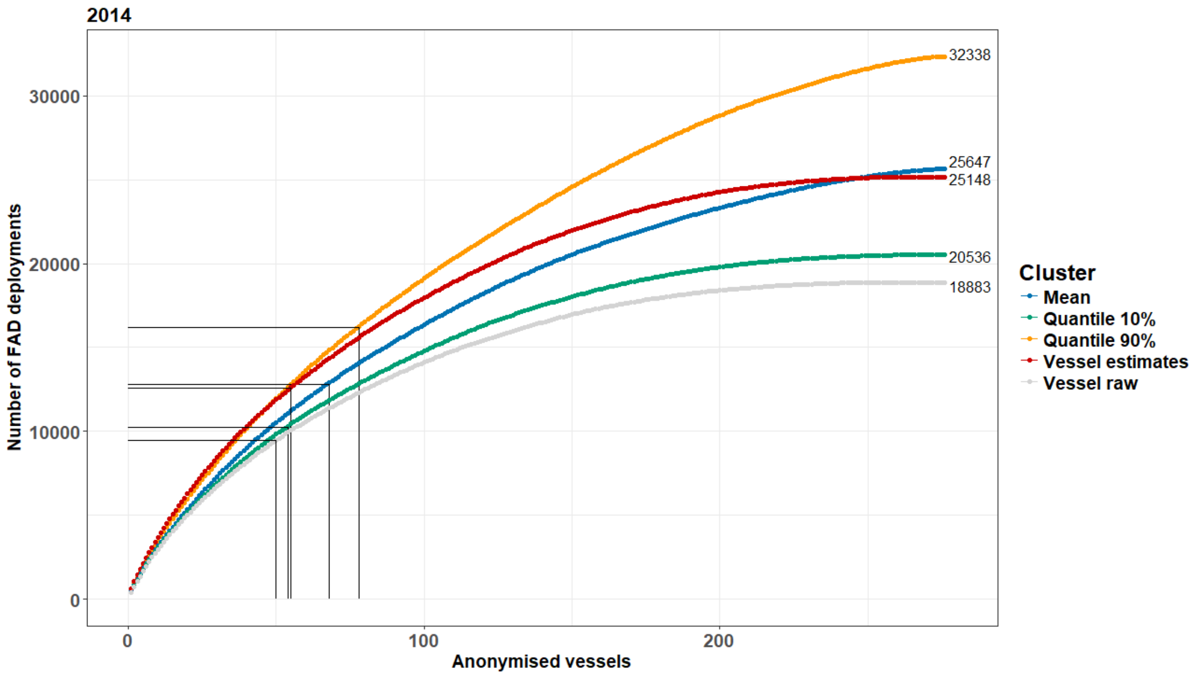
2019
1500
1000
500
0
Number of FAD deployments
0
50
100
150
200
250
Anonymised vessels
Vessel estimates
22695
Quantile 90%
30118
Mean
22535
Quantile 10%
14621
Vessel raw
13203
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw

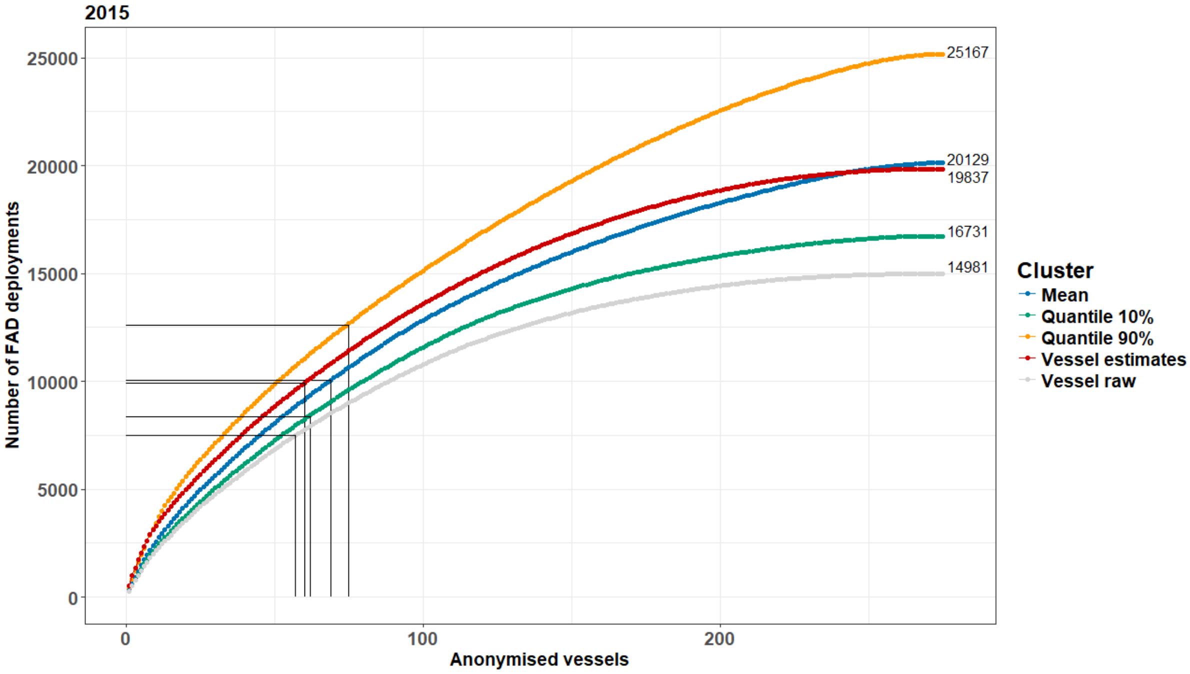
Appendix 3. Cumulative raw and estimated number of deployments per vessel per year (2011–2019) based on different standardisation methods: scaled-vessel estimates or cluster-based method (quantile 10%, mean, quantile 90% number of deployments per cluster). Estimates of the total number of FADs in the WCPO, by method, are indicated on the right-hand side of each curve.

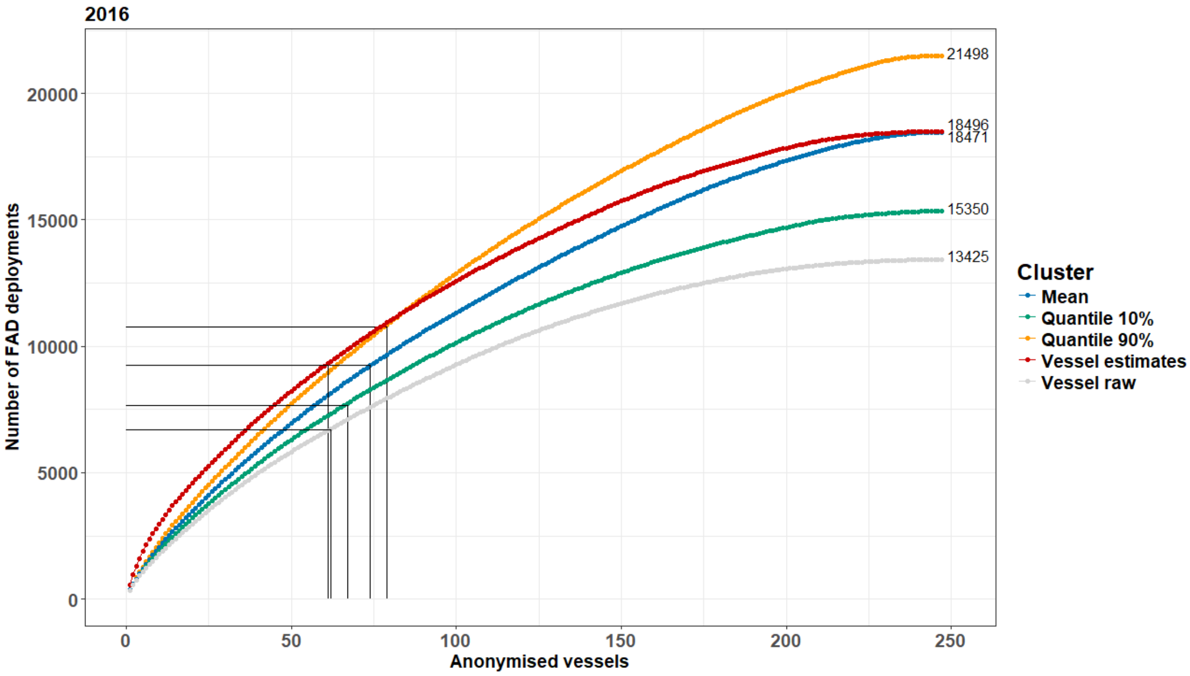


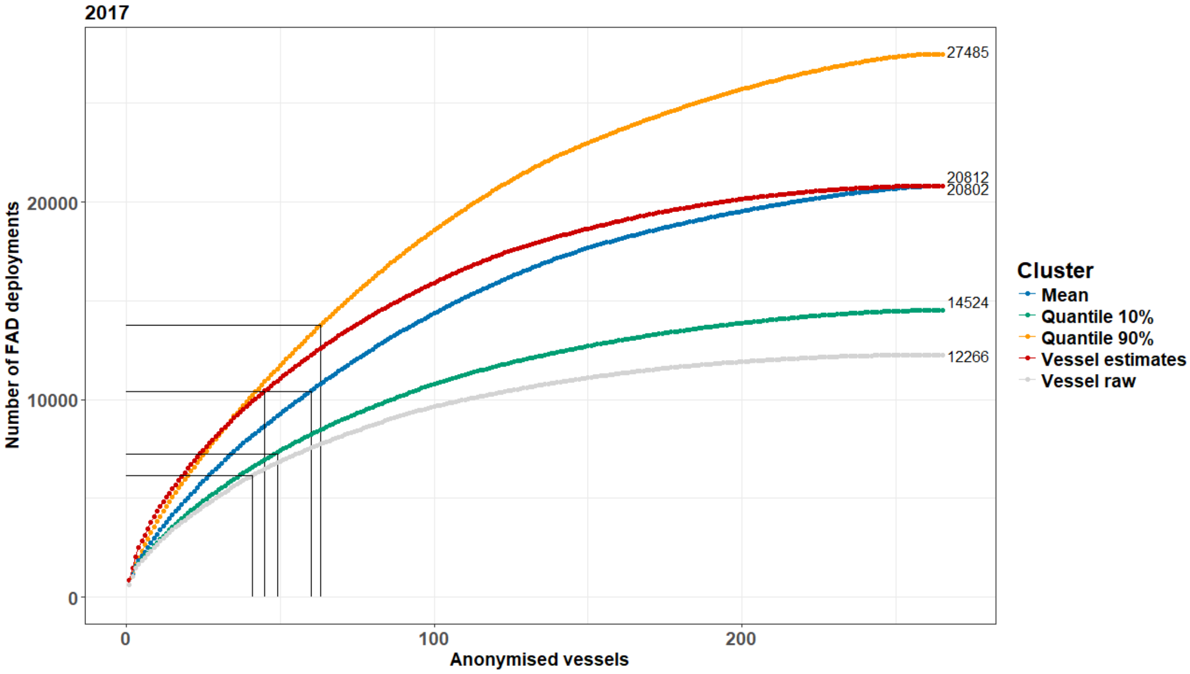


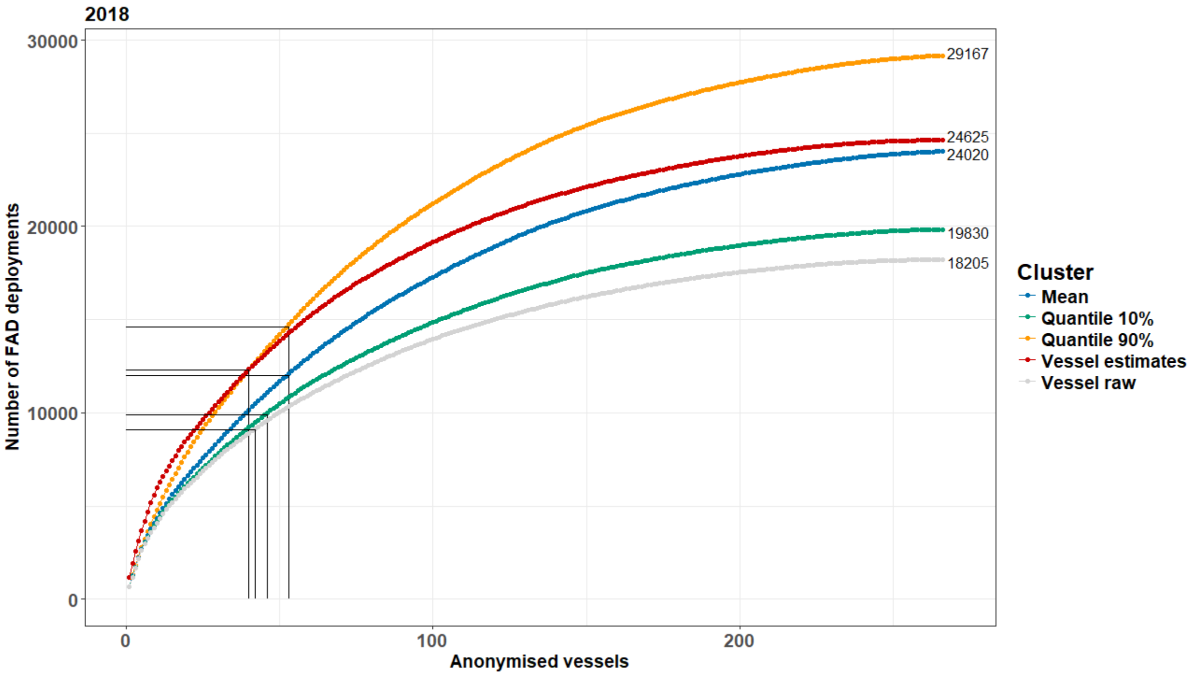

2013
27530
24552
23789
20251
19045
Number of FAD deployments
20000
10000
0
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw

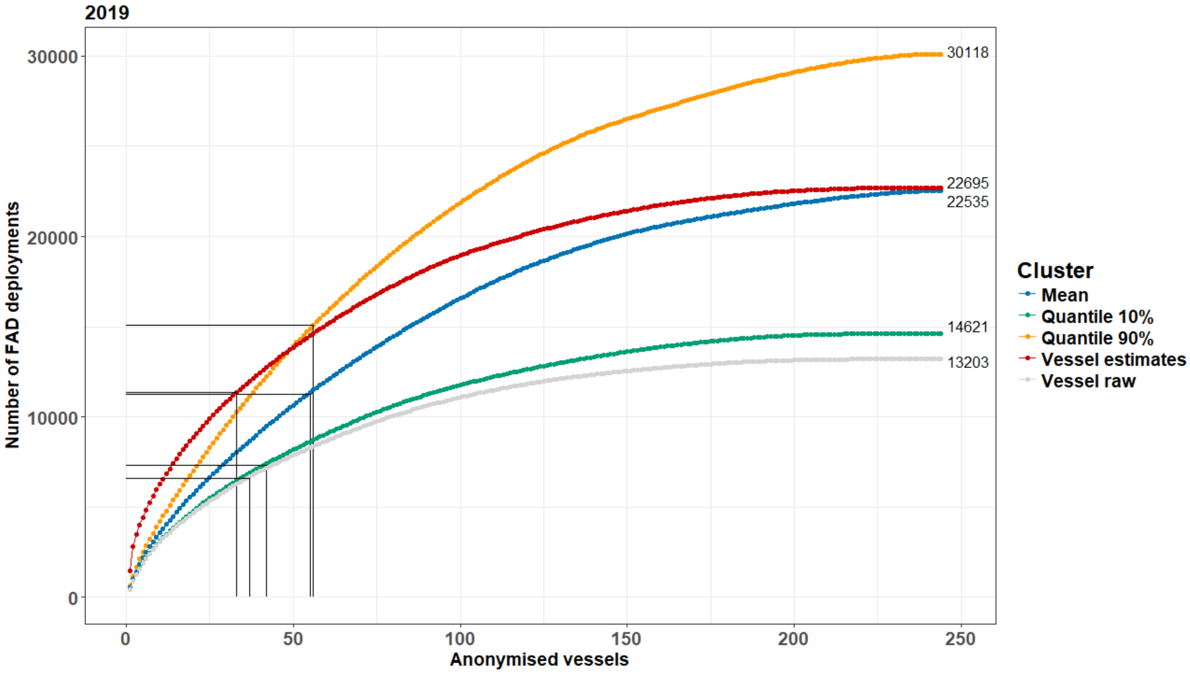

2014
32338
25647
25148
20536
18883
Number of FAD deployments
30000
20000
10000
0
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw


2015
Number of FAD deployments
Anonymised vessels
25167
20129
19837
16731
14981
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw


2016
Number of FAD deployments
Anonymised vessels
21498
18496
18471
15350
13425
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw


2017
27485
20812
20802
14524
12266
Number of FAD deployments
0
10000
20000
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw


2018
29167
24625
24020
19830
18205
Number of FAD deployments
0
10000
20000
30000
0
100
200
Anonymised vessels
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw



2019
Number of FAD deployments
30000
20000
10000
0
0
50
100
150
200
250
Anonymised vessels
30118
22695
22535
14621
13203
Cluster
Mean
Quantile 10%
Quantile 90%
Vessel estimates
Vessel raw