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Recent purse-seine FAD fishing strategies in the eastern Pacific Ocean: what is the appropriate number of FADs at sea?

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Concerns about the ecological impact of recent increases in the use of drifting fish-aggregating devices (FADs) have led to implementation of FAD limits worldwide in purse-seine fisheries targeting tropical tunas. However, quantitative analyses supporting such management measures are needed. Analyses of observer data for purse-seine vessels operating in the eastern Pacific Ocean (EPO) during 2012–2015 were conducted. FAD fishing strategies identified in this analysis were found to vary with distance to the coast. Vessels that operated furthest offshore made a large number of FAD deployments and fished primarily on FADs they deployed themselves. Vessels that operated closest to the coast made the fewest FAD deployments and fished about equally on FADs they deployed themselves and on FADs deployed by other vessels. Independent of the FAD fishing strategy, the estimated relationship between deployments and sets was increasing but nonlinear, with a reduced rate of return beyond about 200 deployments. An analysis of the relationship between deployments and standardized catch per successful set, however, provided some support for the hypothesis that more deployments may allow vessels to optimize fishing efficiency. These results highlight the complexity of EPO FAD fishing strategies and have management implications for limits on FAD usage globally.

Keywords: drifting FAD, eastern Pacific Ocean, purse seine, tuna.

Introduction

Development of effective management measures for tuna purse-seine fisheries that use drifting fish-aggregating devices (FADs) has become a priority worldwide because of the widespread increase in FAD use in tropical waters (Dagorn *et al.*, 2012; Fonteneau *et al.*, 2013; Davies *et al.*, 2014; Maufroy *et al.*, 2017). This increase also occurred within the eastern Pacific Ocean (EPO; Pacific coast west to 150°W and 50°S–50°N) (e.g. IATTC, 2017a). There, purse-seine vessels have made sets on natural floating objects, such as tree trunks and dead whales, and on anthropogenic debris (e.g. metal drums, ropes), since at least the mid-1960s (Watters, 1999). From the mid-1990s to 2000, the percentage of sets of large purse-seine vessels (carrying capacity > 363 t) on floating objects that were FADs increased from 40 to 86%, and the fishery expanded westward (Lennert-Cody and Hall, 1999; IATTC, 2010; Hall and Román, 2013). Since 2012, over 96% of floating objects set upon by large vessels were estimated to have been FADs (IATTC, 2016, 2017a). The fishery on floating objects (i.e. FADs and non-FADs combined) catches predominantly skipjack tuna, but also bigeye tuna, and to a lesser extent yellowfin tuna (IATTC, 2016). Between 2012 and 2015, sets on floating objects produced on average 194 269 t of skipjack tuna and 58 614 t of bigeye tuna, annually, the latter equivalent to ~97% of the annual EPO purse-seine catch of bigeye.

In the EPO purse-seine fishery, a FAD is defined as any type of floating object that was expressly modified by fishers. However, as in other oceans, FADs typically have been made of bamboo rafts with netting or ropes hanging underneath (Hall and Román, 2013). FADs are typically monitored through buoys that track their trajectory via satellite communication systems. These buoys can be equipped with sea surface temperature sensors and/or echo-sounders that estimate associated fish biomass (Hall and Román, 2013; Lopez *et al.*, 2014; Moreno *et al.*, 2016). Given the large-scale upper-ocean currents within the EPO (e.g. Kessler 2006), FADs typically drift westward, although eastward drift can occur (Hall and Román, 2013). Unlike in other oceans (Fonteneau *et al.*, 2015), the use of tender vessels to deploy FADs has not been permitted in the EPO since 1999 (IATTC, 1999).

Per-vessel FAD limits were recently adopted for the Indian and Atlantic Oceans (IOTC, 2016; ICCAT, 2016), the Western and Central Pacific Ocean (WCPFC, 2017), and the EPO (IATTC, 2017b). However, there are few quantitative studies addressing the appropriateness of these limits or the ideal sustainable number of FADs and FAD sets. This is mainly due to a lack of information on the numbers of FADs deployed and on the details of FAD usage following deployment. Factors affecting FAD usage include heterogeneity in fishing strategies among fleet segments and FAD appropriation by other vessels (Fonteneau *et al.*, 2015; Lopez *et al.*, 2015), and loss due to sinking or drifting out of the fishing grounds (Maufroy *et al.*, 2015). Thus, it is difficult to estimate the total number of FADs in use at any given time, although attempts have been made for the Indian and Atlantic Oceans (Fonteneau *et al.*, 2015; Maufroy *et al.*, 2017). The lack of information is problematic because FAD numbers at sea may influence vessel behaviour (Fonteneau *et al.*, 2015), as well as the associative behaviour of tunas (Marsac *et al.*, 2000).

Because of the nearly 100% onboard observer coverage of trips by large purse-seiners operating in EPO and the detailed data collected by AIDCP (Inter-American Tropical Tuna Commission [IATTC] Agreement of the International Dolphin Conservation Programme onboard observer programme) observers on fishing activities, quantitative analyses that will help to inform management decisions on FAD fishing can be undertaken. There were three objectives of the work presented in this paper: (i) identify different segments of the purse-seine fleet based on their general fishing behaviour and on their FAD-related activity; and, for fleet segments identified in (i), explore the relationship between (ii) the number of FAD deployments and the number of sets; and, (iii) the number of FAD deployments and catch per successful set (CPSS).

Material and methods

The data used in all analyses were collected by AIDCP observers aboard large purse-seine vessels that fished during 2012–2015. The data were limited to those vessels making at least five floating-object sets during 2012–2015. Hereafter the term "floating object" is used to refer to FADs and non-FADs, combined.

Three types of analyses were conducted. First, clustering methods were used to identify homogeneous groups of purse-seine vessels, hereafter referred to as fleet segments. Second, the relationship between the number of FAD deployments and numbers of floating-object and FAD sets per vessel was evaluated for each fleet segment identified with the cluster analysis. For fleet segments that focussed on fishing on FADs, this relationship was modelled with linear mixed-effect models. Finally, for the fleet segment with the most sets on its own FADs, catch per successful FAD set was standardized using generalized additive models (GAMs) and its relationship to the number of deployments per vessel evaluated using weighted least squares. Each of these analyses is described in detail below.

Identification of fleet segments

The following by-vessel variables were used to define fleet segments: the proportion of floating-object sets by object "origin" category, the proportion of sets made by set type, and the proportion of floating-object sets made in the western region of the EPO.

Information on FAD origin, in terms of ownership, was included in this analysis because FAD sharing and appropriation have been identified as important components of FAD-related activity (Fonteneau *et al.*, 2015; Lopez *et al.*, 2015) and important to consider when evaluating the impact of FAD limits (Fonteneau *et al.*, 2015). AIDCP observers recorded detailed data on the characteristics of each FAD visited by a vessel, regardless of whether a set was made. The FAD origin was determined by the observer at sea, based on information from the vessel captain and crew, and any identifier on the FAD itself or on the attached buoy (e.g. vessel name). The origin of the FAD could have been from the vessel itself, or from another vessel whose identity may or may not have been known. Within a trip, observers kept track of visits to each FAD they could repeatedly identify, as long as the FAD remained in the water. In such cases, multiple sets on the same FAD ("consecutive" or "repeat" sets) were identifiable. (Often these repeat sets happened within a few days of the original set and may have occurred because part of the tuna school initially evaded capture. Repeat sets on non-FAD objects can also occur.) If a FAD was removed from the water, either to be retained onboard or moved and redeployed, the link to the FAD's history was lost; it became a "new" FAD because it was disassociated from its biomass community. Because there were no IATTC requirements in place at the time that FADs be uniquely identified, it also was not possible for observers to track individual FADs from one trip to the next.

To determine the proportion of sets by floating-object origin, only the first set on each object was considered (i.e. data on repeat sets on the same floating object, 10% of all floating-object sets, were excluded).There were five categories used: FADs deployed by the vessel itself on the current trip; FADs deployed by the vessel itself on a previous trip; other FADs of known origin; FADs of unknown origin; and, non-FAD floating objects (i.e. natural drifting objects and anthropogenic debris). Other FADs of known origin were FADs deployed by a different vessel, but apparently that vessel was contacted at some point by the vessel that made the set (*e.g.*, as might be the case for FADs shared among vessels of the same company). FADs of unknown origin were FADs deployed by a different vessel and encountered by chance by the vessel that made the set. Floating objects that did not fall into one of these five categories were excluded from the analyses (~0.06% of first sets were exclude for this reason).

Purse-seine vessels operating in the EPO can make three types of sets (e.g. Hall *et al.*, 1999; Hall and Román, 2013; IATTC, 2016), and it is important to include information on all set types in any analysis of fishing strategies. In addition to floating-object sets, vessels may make sets on tunas associated with dolphins ("dolphin" sets) or sets on unassociated tuna schools ("unassociated" sets). These three set types differ somewhat in their spatial distribution and in their tuna catch composition. The majority of dolphin sets are made north of 5°N, whereas floating-object sets primarily occur south of 8°N. Unassociated sets tend to be more coastal than either dolphin sets or floating-object sets. Dolphin sets catch primarily yellowfin tuna, but also some skipjack tuna. Unassociated sets catch primary skipjack tuna, with lesser amounts of yellowfin tuna and only a small amount of bigeye tuna. The average size of yellowfin tuna caught in dolphin sets is larger than that caught in unassociated sets, while the yellowfin tuna caught in floating-object sets are primarily juveniles.

The spatial location of fishing on floating objects was summarized by the proportion of floating-object sets west of 100°W. The value of 100°W was selected based on the distribution of floating-object set longitudes within the EPO. The mean and median longitude values were 108°W and 102°W, respectively, and the mode of the distribution was ~95°W.

Agglomerative hierarchical clustering methods were used to identify fleet segments using calendar-year data on the proportion of floating-object sets by object "origin" category, the proportion of sets made by set type, and the proportion of floating-object sets made in the western region of the EPO. These data were pooled over years and limited to the EPO. The cluster analysis was based on a dissimilarity matrix computed from Euclidean distance and Ward's method for merging clusters (Kaufman and Rousseeuw, 1990). The cluster analysis was conducted in R Core Team (2016) with the package *cluster* (Maechler *et al.*, 2016).

Deployments vs. sets

To study the relationship between the number of FAD deployments and number of floating-object and FAD sets, data from entire trips, including repeat sets, and deployments and sets made outside the EPO to 180°W, were used. Deployments outside the EPO can lead to sets within the EPO, and similarly, deployments inside the EPO can lead to sets west of 150°W. For each vessel, the following annual tallies (based on departure year) were computed: number of FAD deployments, number of floating-object sets, and number of FAD sets on the vessel's own FADs or on other FADs of known origin (hereafter collectively referred to as "FADs of known origin").

To quantitatively describe the relationship between FAD deployments and sets, mixed-effects models (e.g. Pinheiro and Bates, 2004) were fitted to the data of the fleet segments that focussed on fishing on FADs. The number of deployments each vessel makes depends on vessel-specific factors such as space for storing FAD components, operational costs associated with monitoring FADs at sea, and the extent to which echo-sounder data are used to plan FAD visits (Moreno *et al.*, 2016). However, only a few sets are made per day for most vessels because there is a strong preference to make FAD sets early in the morning (Hall and Román, 2013; IATTC, 2017a). As a result, the relationship between FAD deployments and sets across a group of vessels may not be linear. To this point, recent data on the annual catch per vessel for the Indian Ocean show little increase at large numbers of deployments (Gaertner *et al.*, 2016), which may have occurred because the number of sets did not increase linearly with the number of deployments. Thus, in this analysis the general model form selected was based on the assumption that the numbers of sets (s) could reach an asymptote as the number of deployments (d) increased (i.e. $s = \alpha \cdot d^{\beta}$, for shape parameters α and β). To account for the longitudinal structure of the data, the following linearized mixed-effects model was fitted to the annual by-vessel data:

$$\log\left(s_{ij}\right) = \tilde{\alpha} + \tilde{\gamma}_j + \beta * \log\left(d_{ij}\right) + \varepsilon_{ij} \qquad (1)$$

where s_{ij} is the number of sets on FADs of known origin for vessel j and year i ($i = 2012, \ldots, 2015$), $\tilde{\alpha}$ is an overall constant, $\tilde{\gamma}_j$ is a vessel effect (Gaussian random effect), d_{ij} is the number of FAD deployments for vessel j and year i, and ε_{ij} is a Gaussian error term. There were four out of 336 vessel-year data points that had a value of zero for the number of deployments and were excluded from the analyses. All models were fitted using the *lme* function of the *nlme* package (Pinheiro *et al.*, 2016) in R.

In preliminary analyses, models that included departure year and models that also included an interaction between number of deployments and departure year (as fixed effects) were fitted to the data. However, this resulted in an increase in the Akaike Information Criterion (AIC) (and in the Bayesian Information Criterion) values, and thus departure year was not included in the final models. A Gaussian error distribution was used for the log-transformed data because, based on preliminary analyses and model diagnostics, this provided a reasonable fit to the data.

From the fitted models a predicted curve for each fleet segment was obtained for a "typical" vessel (i.e. assuming a value of 0 for $\tilde{\gamma}$, which gives the population-averaged predictions; Liu *et al.*, 2015), with a bias correction (=0.5 times the residual variance). Approximate 95% point-wise prediction intervals were computed for these curves assuming asymptotic normality of the estimated fixed-effects and using the variance–covariance matrix of the estimated fixed effects, plus the residual variance, but without considering the uncertainty of the random effects (Bolker, 2008; Liu *et al.*, 2015). (See computational steps for prediction intervals in http://bbolker.github.io/mixedmodels-misc/glmmFAQ.html and https://github.com/bbolker/mixedmodels-misc/blob/master/glmmFAQ.rmd.)

Deployments vs. standardized CPSS

To evaluate whether there was any relationship between CPSS and the number of FAD deployments per vessel, standardized CPSS by vessel was computed and then modelled as a linear function of the number of deployments. This was a two-step analysis because factors potentially affecting catch rates were not all available at the same resolution. In most cases it was not possible to relate a set to a specific FAD, or even a group of FAD deployments. Thus, the number of FAD deployments used in this analysis was an aggregate variable with one value per vessel per year. However, in order to evaluate any effect of the number of deployments on a vessel's CPSS, it was necessary to control for "nuisance" factors that might affect catch rates on a set-by-set basis (e.g. fishing location).

To compute standardized CPSS, a GAM (Wood, 2006) was fitted to by-set data on summed catch of the three target tuna species (yellowfin, bigeye, and skipjack). Catch of all three species was used, although bigeye tuna has primarily been the management concern (Maunder and Harley, 2006), because the purpose was to identify an overall relationship. Following the results of the cluster analysis and that of deployments vs. sets, only vessels of the fleet segment that made most of their sets on their own FADs were used here. Vessels that defined this fleet segment fished primarily on FADs of known origin, which could have given them access to additional information that might allow them to optimize their fishing behaviour (Moreno *et al.*, 2016; Tidd *et al.*, 2017). As in the analysis of deployments vs. sets, the data were limited to FAD sets on objects of known origin.

The following log-linear model was fitted separately to the by-set data of each year:

$$\log\left(c_{jk}\right) = \theta + \mu_j + f_1\left(lat_{jk}, lon_{jk}\right) + f_2\left(m_{jk}\right) + f_3\left(t_{jk}\right). \qquad (2)$$

where c_{jk} is the mean CPSS for set k and vessel j, θ is an overall constant, μ_j is a vessel effect (fixed effect), f_1 is a smooth surface of latitude (*lat*) and longitude (*lon*) (tensor product smooth using cubic regression splines), f_2 is a smooth term for month (m) to capture seasonal effects (cubic cyclic regression splines), and f_3 is a smooth term for decimal hour (t) to capture time of day effects (Lennert-Cody and Hall, 1999; IATTC, 2017a) (thin plate regression splines). A gamma error structure, instead of a Gaussian error structure, was selected for this analysis based on model diagnostics (residual plots and AIC). The numbers of sets per year that were used in the analyses ranged from 2172 to 2384. All models were fitted using the *gam* function of the *mgcv* package (Wood, 2011) in R.

Standardized CPSS for each vessel for a given year was defined as the predicted CPSS for that vessel at fixed values of the other covariates. Those fixed values were: 5°S and 130°W (an arbitrary location within the area of highest floating-object set density for the fleet segment), June (the median month), and 6.23 h (the median time of a set).

To test for a relationship between number of FAD deployments and vessel-specific standardized CPSS, by year, a simple linear model was fitted with weighted least squares (weights equal to the inverse of the variance of the predicted CPSS values). This analysis was limited to vessels making at least three trips per year to try to control for the effect of fishing effort (i.e. the more time spent fishing, the more likely large catches and hence greater CPSS). A t-test of the slope for each year was used to evaluate the hypothesis of no relationship.

Results

Fleet segments

The cluster analysis results showed clear differences in fishing behaviour among vessels, achieving an agglomerative coefficient of 0.98, which indicates strong clustering. The resulting dendrogram was used to define five fleet segments, with 25–37 vessels per segment (Figure 1). These five fleet segments fell into two broad groups. The first (fleet segments 1–2) corresponds to vessels that made a large proportion of their sets on dolphin-associated tunas, with proportionally few sets on FADs they deployed themselves.

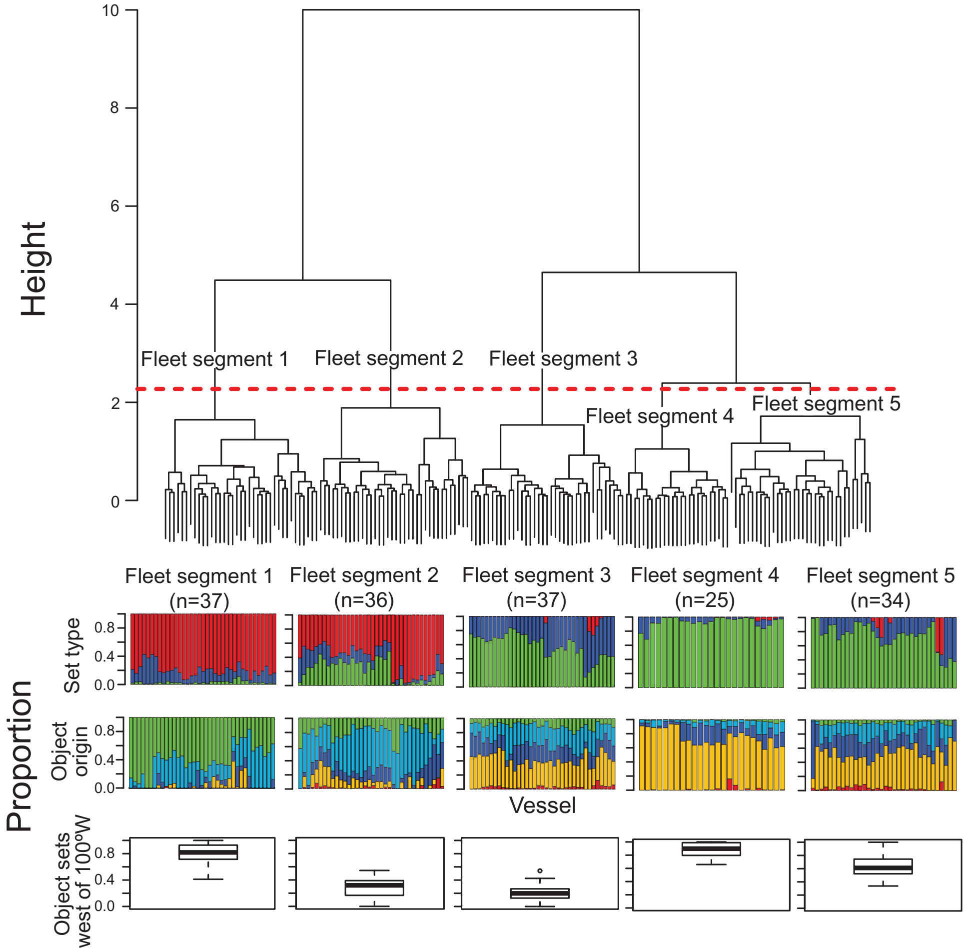

Figure 1. Dendrogram resulting from the cluster analysis of 2012–2015 data. The red horizontal line indicates the height at which the dendrogram was sliced to create the five groups of vessels, labelled Fleet segments 1 through 5. The number of vessels per group is shown in parentheses above the bar graphs. Each bar in the bar graphs represents an individual vessel. The colours for the bar graphs of the proportion of sets by set type are: red, dolphin sets; blue, unassociated sets; and green, floating-object sets. The colours for the bar graphs of the proportion of first sets by object origin are: red, own vessel, this trip; gold, own vessel, previous trip; dark blue, other FADs of known origin; light blue, FADs of unknown origin; and, green, non-FAD object.

Fleet segments 1 and 2 differ from each other in the proportion of objects set upon that were non-FADs vs. FADs of unknown origin, and in the proportion of floating-object sets made west of 100°W.

The second group (fleet segments 3–5) consists of vessels that made proportionally few, if any, dolphins sets, and for which a large fraction of their floating-object sets were made on FADs they deployed themselves. Fleet segments 3–5 differ in terms of the proportion of floating-objects vs. unassociated sets made, the proportion of sets on tunas associated with FADs of unknown vs. known origin (Figure 2), and the proportion of floating-object sets made west of 100°W. Vessels in fleet segment 3 made proportionally more unassociated sets, fished on floating objects more coastally, and had the greatest proportion of sets on tunas associated with FADs of unknown origin. In contrast, vessels in fleet segment 4 made few unassociated sets, fished on objects furthest to the west, and fished almost exclusively on FADs they deployed themselves or on other FADs of known origin. The behaviour of vessels in fleet segment 5 fell between the behaviour of vessels in fleet segments 3 and 4.

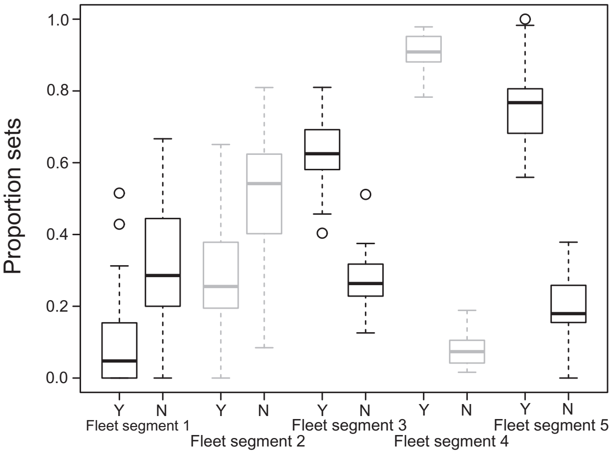

Figure 2. Box-and-whisker plots of the proportion (by vessel) of first sets that were on the vessel's own FADs or on other FADs of known origin ("Y"), and on FADs of unknown origin ("N"), for each fleet segment identified in the cluster analysis. The horizontal bar within each box indicates the median value of the proportion of sets by vessel, the box indicates the middle 50% of observations (i.e. from the 0.25 to 0.75 percentiles), the whiskers extend to 1.5 times the interquartile range, and the open circles show extreme values beyond the whiskers.

The FAD deployment activity of vessels differed among fleet segments, even though deployment information was not explicitly included in the cluster analysis. Vessels in fleet segments 3 and 5 tended to deploy FADs in more nearshore waters, compared with the vessels in fleet segment 4 (Figure 3). In addition, the annual number of FAD deployments, by vessel, differed among these three fleet segments, but was relatively similar across years within the same fleet segment (Figure 4). Vessels in fleet segment 3 had the fewest FAD deployments, whereas vessels in fleet segment 4 had the most FAD deployments. The spatial distribution of the FAD activity of vessels in fleet segment 3 coincides with the area of higher overall purse-seine fishing effort (as measured by days fishing for all sizes of purse-seine vessels) (Figures 3 and 5).

Deployments vs. sets

The relationship between the number of FAD deployments and the number of sets was found to be increasing but nonlinear, with a reduced slope beginning at around 200 deployments (Figure 6). Fleet segments 1–2 were not analysed further because of the limited number of FAD deployments (Figures 4 and 7). The estimated relationships for vessels of fleet segments 3–5 show differences among fleet segments; however, the prediction intervals are broad and overlap (Figure 8). The estimates of $\tilde{\alpha}$ differed among these three vessel groups, reflecting differences in the overall level of FAD deployments per fleet segment (Figure 4), while the estimates of β were very similar (Table 1). Thus, for the same number of deployments by a "typical" vessel of each fleet segment, the predicted number of sets is least for fleet segment 3 and greatest for fleet segment 4, with fleet segment 5 falling in between. Comparison of the confidence intervals for the standard deviations of the $\tilde{\gamma}$ distributions shows that the vessels of fleet

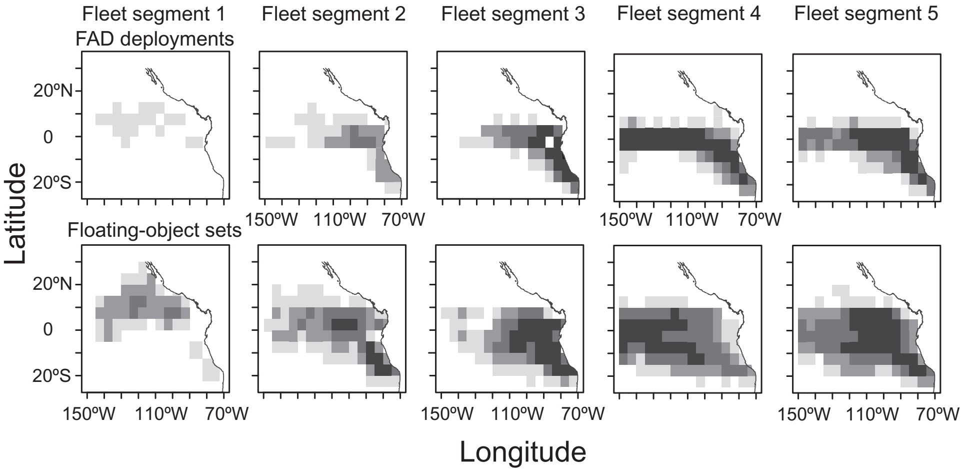

Figure 3. Number of FAD deployments (top row) and number of floating-object sets (bottom row), by 5° area, for each fleet segment identified in the cluster analysis. Colours for number of FAD deployments, from the lightest grey to black, are: 1–10 deployments; 11–40 deployments; 41–140 deployments; and >140 deployments. Colours for number of floating-object sets, from the lightest grey to black, are: 1–20 sets; 21–90 sets; 91–320 sets; and >320 sets.

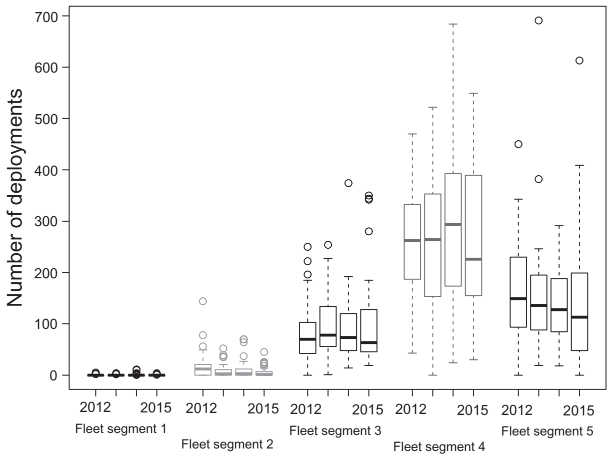

Figure 4. Box-and-whisker plots of the number of FAD deployments per vessel, by year, for each fleet segment identified in the cluster analysis.

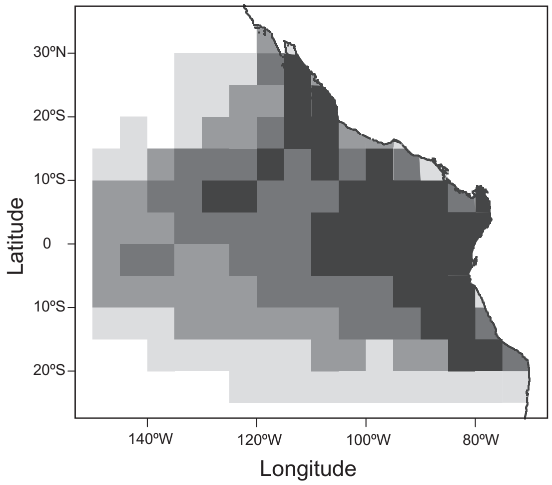

Figure 5. Total estimated days fishing by 5° area for 2012–2015 for all size classes of purse-seine vessels (based on the IATTC catch-and-effort data base). Colours are as follows, from lightest grey to black: 0 –122 days; 123–610 days; 610–1257 days; >1257 days.

segment 4 were considerably more homogeneous than vessels of fleet segments 3 and 5 (Table 1).

Deployments vs. standardized CPSS

In all 4 years, there was an increasing relationship between number of FAD deployments and standardized CPSS for the vessels of fleet segment 4 (Figure 9), however, the rate of increase differed by year. The explained deviance by the fitted GAMs was 24–29%, depending on the year. The estimated slopes, assuming a linear relationship between deployments and standardized CPSS, were significantly greater than zero in 2 of the 4 years (2012 and 2015, Figure 9). Including the few data points that corresponded to vessels making less than three trips per year did not affect these results in that the estimated slopes remained significantly different from zero in 2012 and 2015, and not so in 2013–2014.

Discussion

Our analyses have identified clear inshore vs. offshore differences in fishing strategies among FAD-fishing vessels (Figures 1 and 4). Offshore, vessels made larger numbers of FAD deployments, fished primarily on their own FADs and made proportionally fewer unassociated sets. Inshore, vessels made fewer FAD deployments, fished about equally on FADs they deployed themselves and FADs deployed by other vessels, and made proportionally more unassociated sets. Because the ownership of a FAD can change during its lifetime, the level of fishing activity in an area may play a role in structuring FAD-fishing strategies. To this point, the spatial distribution of overall purse-seine fishing effort was greater inshore (Figure 5), in the main area of operation of the fleet segment that made proportionally more sets on FADs deployed by other vessels. Even as the FAD fishery in the EPO has evolved, a greater number of unassociated sets have always been made coastally, compared with offshore (e.g. Watters, 1999; IATTC, 2016). Although not investigated in this study, the density of FADs also would be expected to affect FAD fishing strategies.

As with any analysis, there are several caveats that must be kept in mind. First, because it was not possible for observers to uniquely identify FADs from one trip to the next, the observers' determinations of FAD origins may not always be accurate. However, the object origin classifications show spatial structure (Figures 1 and 3). This would not be expected to occur by chance, and therefore we believe that the overall tendencies identified in

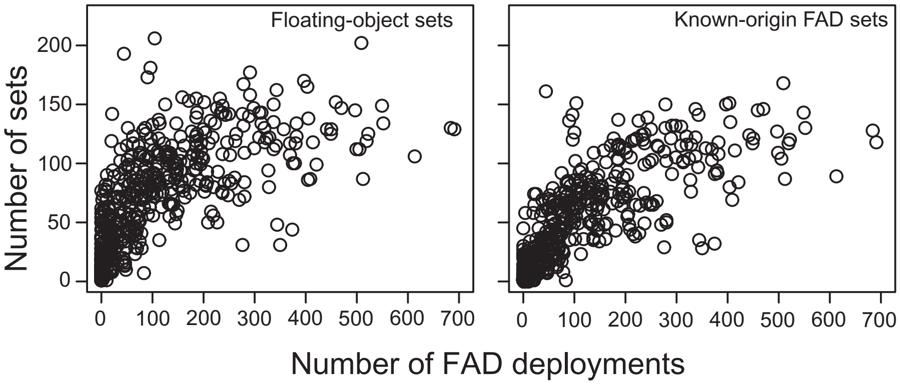

Figure 6. Number of FAD deployments per vessel vs. number of floating-object sets per vessel, and vs. number of sets on FADs of known origin per vessel, for all years and fleet segments (each data point is a vessel-year).

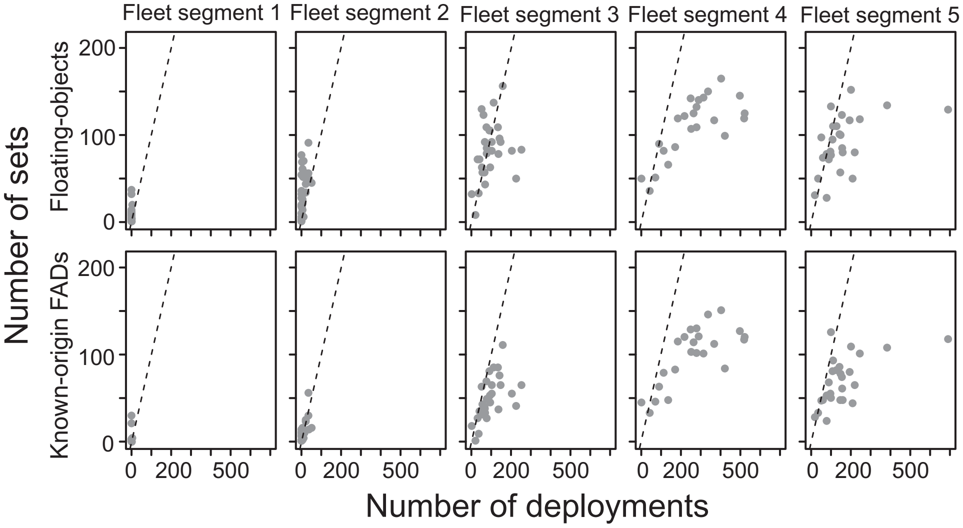

Figure 7. Number of FAD deployments per vessel vs. number of floating-object sets per vessel, and vs. number of sets on FADs of known origin per vessel, by fleet segment for 2013. Dashed lines are the 1-to-1 line.

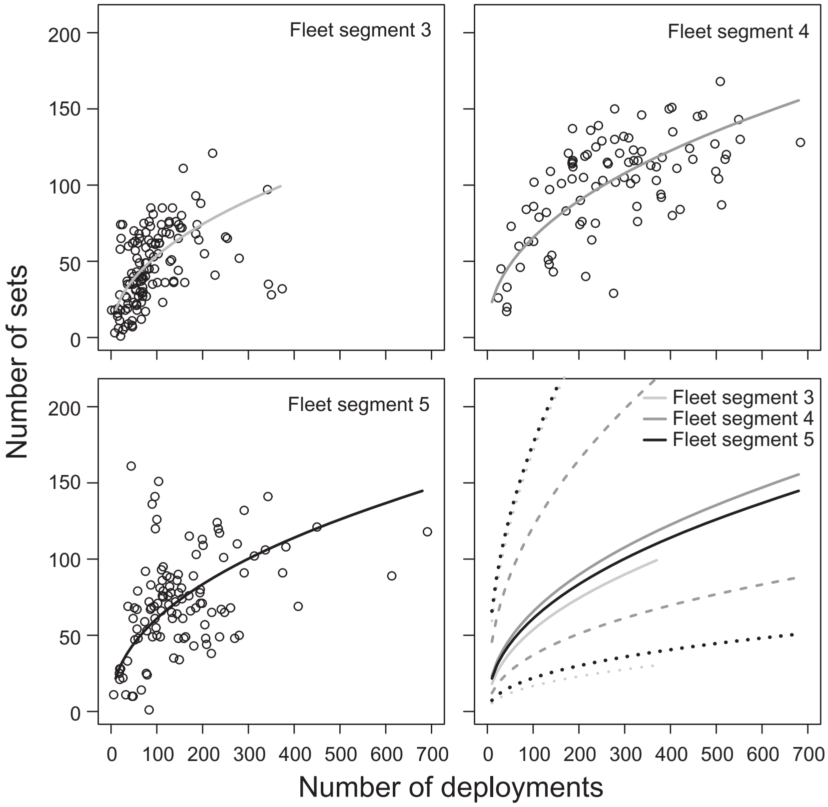

Figure 8. Predicted curves (solid lines) for number of FAD deployments vs. number of sets on FADs of known origin, by fleet segment for fleet segments 3–5 (the open circles show the data points used to fit the curves). Shown in the lower left panel are the three predicted curves and point-wise prediction intervals (dashed lines) for each curve. Predicted curves were generated by predicting the number of sets over the range of the number of FAD deployments of each vessel group (Figure 4).

these analyses are robust. Second, observers may not have been able to determine if FADs were deployed at night, an activity that would mean the numbers of deployments recorded by observers is negatively biased. However, such a bias would not be anticipated to change our overall results about the nonlinear relationship of deployments to sets because numbers of deployments would be minimum numbers and setting is almost exclusively a daytime activity (Hall and Román, 2013; IATTC, 2017a).

Table 1. Estimates of model parameters and approximate 95% CIs for the linear mixed-effect models fitted for FAD deployments vs. FAD sets.

	Estimate of $\tilde{\alpha}$	Estimate of β	Vessel effect distribution *SD*	Residual error *SD*
Fleet segment 3	1.65 (1.06, 2.23)	0.47 (0.34, 0.61)	0.26 (0.14, 0.48)	0.58 (0.50, 0.67)
Fleet segment 4	2.07 (1.52, 2.62)	0.45 (0.35, 0.55)	0.13 (0.06, 0.26)	0.29 (0.25, 0.34)
Fleet segment 5	1.91 (1.20, 2.62)	0.45 (0.31, 0.60)	0.32 (0.19, 0.53)	0.51 (0.44, 0.60)

"*SD*", standard deviation.

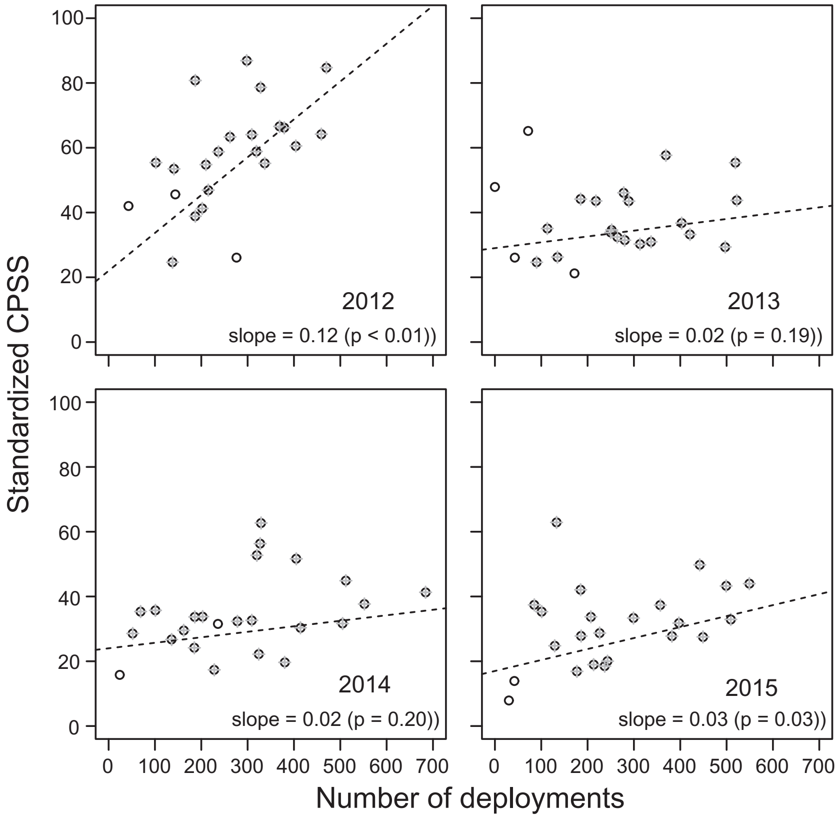

Figure 9. Standardized CPSS (sets on FADs of known origin) vs. number of FAD deployments for fleet segment 4, by trip departure year. Each point represents a particular vessel in that year; open circles without grey crosses indicate points based on only one to two trips for that departure year. The black dashed lines show the fitted linear relationship. Estimated slopes ("slope") for an assumed linear relationship are based on those vessels making three or more trips in that departure year (*p*-values for the estimated slopes are shown in parentheses).

Third, observers may not be able to determine if FADs are deployed by other vessels belonging to the same company as the purse seiner. Although the use of supply or tender vessels has been prohibited in the EPO since 1999 (IATTC, 1999), it is possible that small purse seiners, which are not regularly monitored by the AIDCP observer programme, deployed FADs that might have been shared with some of the larger vessels included in these analyses.

Absent a specific metric from which to establish FAD deployment thresholds, three different views of the estimated relationship between deployments and sets from the fleet segment fishing primarily on its own FADs (fleet segment 4) might be informative. Specifically, those views are: the estimated curve, its first derivative ("velocity" of change in FAD sets per deployment) and its second derivative ("acceleration" of the change in FAD sets per deployment) (Figure 10). The greatest rate of return per deployment for this fleet segment occurred below 200 deployments. In contrast, current per-vessel limits on FADs monitored at sea are $\geq$300 for the EPO (for large vessels, IATTC, 2017b), 350 for the Indian Ocean and the Western and Central Pacific Ocean (IOTC, 2016; WCPFC, 2017) and 500 for the Atlantic Ocean (ICCAT, 2016). These limits fall where the acceleration is almost zero and the velocity is nearly constant (Figure 10). In this region the estimated curve is approximately linear with a slope <5:1 (Figure 8). Of course, the conversion from FAD deployments to FADs monitored at sea is not known. FADs may be lost due to sinking, beaching events and drifting out of the fishery area (Maufroy *et al.*, 2015), or appropriated by other vessels (Fonteneau *et al.*, 2015; Lopez *et al.*, 2015). This means that to maintain a constant number of FADs monitored at sea, the number of FADs deployed would need to be greater. In addition, any potential FAD limit based on this analysis would be negatively biased if the number of deployments is underestimated.

For vessels setting primarily on FADs they deployed themselves, larger numbers of deployments may have resulted in

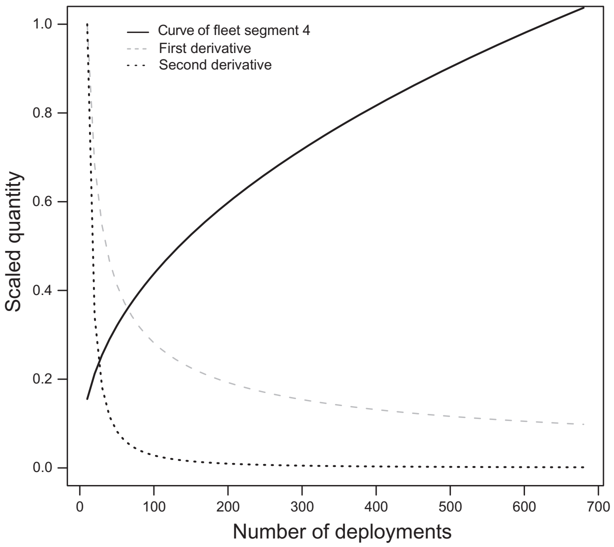

Figure 10. Fitted curve of fleet segment 4 (dark gray curve of Figure 8), and first and second derivatives (using estimated parameters from Table 1), each scaled by their respective maximums.

improved fishing success (Figure 9), even if they did not equate to greater numbers of FAD sets (fleet segment 4 in Figure 8). World-wide, it is increasingly common that FADs are tracked with buoys equipped with echo-sounders (Hall and Román, 2013; Lopez *et al.*, 2015; Moreno *et al.*, 2016). Purse seiners that use echo-sounders to remotely evaluate FAD-associated biomass have the option to approach a given FAD once the estimated biomass makes it worthwhile (Tidd *et al.*, 2017). Thus, although making fewer sets per deployment, following biomass evolution could allow for selection of those FADs with higher biomass, and ultimately result in better catch performance. Nonetheless, as with many analyses of catch rate data, the GAMs used to standardize CPSS explained only part of the variability in the data, and catch standardization is notoriously problematic (Maunder *et al.*, 2006). In addition, we do not know how well these results would generalize to different/more diverse groups of vessels. Therefore, our results on the number of FAD deployments vs. CPSS should be interpreted cautiously.

The complexity of FAD fishing strategies observed for EPO purse seiners could be occurring in purse-seine fisheries elsewhere. Our results are consistent with the hypothesis that spatial gradients in fishing effort contribute to diversity of FAD fishing strategies. Fishing grounds in the Indian and Atlantic oceans (e.g. Maufroy *et al.* 2017) are smaller compared with those of the EPO, concentrating fishing effort spatially, and potentially producing spatial gradients in fishing effort.

This study has identified two aspects of FAD fishing strategies relevant to understanding the impact of FAD limits. First, the practice of setting on a vessel's own FADs vs. on FADs deployed by other vessels can be spatially heterogeneous, potentially contributing to spatially heterogeneity in the impact of FAD limits on the ecosystem. Second, the relationship between deployments and sets is nonlinear and therefore larger numbers of deployments may not lead to larger numbers of sets, but could lead to increased fishing efficiency. More in-depth studies would greatly benefit from collection of data that uniquely identify individual FADs over their lifetime. Such data also would allow for quantitative studies of the effects of FAD density on tuna associative behaviour at FADs.

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