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A PRELIMINARY ANALYSIS OF THE RELATIONSHIP BETWEEN THE NUMBER OF FAD DEPLOYMENTS AND THE NUMBER OF FAD SETS FOR THE EPO PURSE-SEINE FISHERY

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SUMMARY

Limits on the numbers of fish-aggregating devices (FADs) and/or on the number of FAD sets, by vessel, are management options that have been proposed for, and in some cases implemented in, purse-seine fisheries that target tropical tunas associated with FADs. However, quantitative analyses supporting such management options are lacking. Therefore, two analyses of AIDCP[1] observer data for Class-6[2] purse-seine vessels operating in the eastern Pacific Ocean (EPO) during 2012-2015 were conducted to provide information on fishing strategies of vessels making floating-object sets, and on the relationship between FAD deployments and floating-object sets. Different purse-seine vessel fishing strategies were identified using agglomerative hierarchical cluster analysis methods. The relationship between the number of FAD deployments and the number of floating-object sets were investigated with mixed-effects models. The cluster analysis results indicate vessel groups with the following fishing strategies: a tendency to make dolphin sets *versus* floating-object and unassociated sets; and, among vessels making floating-object sets, a tendency to make floating-objects sets on the vessel's own FADs *versus* on objects found drifting and/or on FADs of unknown origin. Vessels fishing primarily on their own FADs tended to fish further offshore within the EPO than other vessels making floating-object sets and made a greater number of FAD deployments. The overall relationship between number of FAD deployments and number of floating-object sets is characterized by an increasing, nonlinear relationship that begins to asymptote at several

[1] Agreement of the International Dolphin Conservation Program
[2] Carrying capacity > 363 t

hundred deployments. However, this nonlinear relationship differs between those vessels fishing primarily on their own FADs and those vessels making a greater proportion of their sets on other types of floating objects. These preliminary results highlight the complexity of FAD fishing in the EPO, which has implications regarding development of any management strategies that limit FAD usage, both in terms of the conservation of tunas and in terms of the economic performance of the different purse-seine fleet components operating in the EPO.

1. BACKGROUND

Several of the potential management options that have been proposed for the EPO[3] tuna purse-seine fishery on floating objects are limits on the numbers of FADs and/or on the number of FAD sets (IATTC-90 PROP A-3 COL; IATTC-90-INF-B ADDENDUM 1). Although per-vessel FAD limits have been adopted by two other tuna RFMOs, 425 in IOTC (IOTC Resolution 16-01) and 500 in ICCAT[4] (ICCAT Recommendation 16-01), there are no scientific 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 current numbers of FADs deployed, as well as on the dynamics of the population of FADs at sea. This lack of information is problematic because FAD limits may influence vessel fishing strategies, both as regards floating-object sets and as regards other purse-seine set types, and may affect the associative behavior of tunas (Marsac *et al*. 2000).

To better inform management options regarding limits on FAD usage, several key questions related to purse-seine fleet behavior need to be examined quantitatively. These questions include: how diverse are different components of the fleet with regard to floating-object set and FAD set activity; how many FADs do the different components of the purse-seine fleet deploy; what percentage of FADs are monitored at sea; and, what is the relationship between the number of FAD sets and the number of FADs deployed. Because of the nearly 100% observer coverage of trips by Class-6 purse-seiners operating in EPO and the detailed data collected by AIDCP observers on fishing activities, analyses that will help to address some of these questions can be undertaken for the EPO purse-seine fishery. This work provides quantitative analyses that extend information currently available on EPO FAD fishing (*e.g*., SAC-08-08a; SAC-08-03e; Hall and Román 2013).

This document presents preliminary results of several analyses conducted using AIDCP observer data for the 2012-2015 fishery. First, cluster analysis methods were used to identify different components of the purse-seine fleet with regard to their floating-object and FAD set activity and fishing strategies. Second, the relationship between the number of FAD deployments and the number of floating-object sets, and the number of FAD sets, for each of the purse-seine fleet components identified by the cluster analysis, are described. For those fleet components focusing on fishing on tunas not associated with dolphins, the relationships between deployments and sets are estimated, using mixed-effects models.

2. DATA AND METHODS

The data used in the analyses were collected by AIDCP observers aboard Class-6 purse-seine vessels during 2012-2015. Depending on the type of analysis (see below), either calendar year data (year of the specific fishing activity) or departure year data (trip departure year; to include complete trips in the analysis) were used. The data were limited to those vessels making at least five floating-object sets during 2012-2015.

Two types of analyses were conducted. First, a cluster analysis was conducted to identify purse-seine fishing strategies. Second, an analysis of the relationship between the number of FAD deployments and

[3] Pacific coast to 150°W and 50°S-50°N

[4] These FAD limits were set by vessel and represent the numbers of active buoys at sea belonging to a purse seine vessel.

numbers of floating-object sets and FAD sets was conducted and used to evaluate whether the relationship differed by vessel fishing strategy. Each of these analyses is described in detail below.

2.1. Fishing strategies

Agglomerative hierarchical clustering methods were used to evaluate the extent to which homogeneous groups of vessels could be defined based on the proportion of sets they made by set type (floating-object, unassociated, dolphin), the proportion of floating-object sets they made by origin of the object, and the proportion of floating-object sets they made in the western region of the EPO. The data for the cluster analyses were limited to the EPO. For the origin of floating objects set upon, only first sets were considered (*i.e.*, data on repeat sets were not used; repeat sets comprised approximately 10% of floating-object sets). The object origin categories used in this analysis were: FADs deployed by the vessel on the current trip, FADs deployed by the vessel on a previous trip, other FADs of known origin, FADs of unknown origin, and drifting objects (*e.g.*, a natural floating object). Objects that were of “unknown” and “other” origin were not included in the analyses (proportionally, there were very few sets on these types of objects). The spatial location of fishing on floating objects was summarized as 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 approximately 95°W. Cluster analyses were conducted on the pooled data (*i.e.*, year was not considered in the analysis).

The cluster analyses were based on using a dissimilarity matrix computed from Euclidean distance and several different options for the type of clustering method, including Ward’s method and the Group Average Method (Kaufman and Rousseeuw, 1990). The Group Average Method yielded a lower agglomerative coefficient (a measure of clustering strength that ranges from 0 to 1; Kaufman and Rousseeuw 1990), and so Ward’s method was used in the final analyses. All cluster analyses were conducted in R (R Core Team 2016) with the *hclust* function, and the *agnes* function of the package cluster (Maechler *et al*. 2016).

2.2. Relationship between FAD deployments and sets

Entire trips with departure years in 2012 to 2015 were used to study the relationship between the number of FAD deployments and number of floating-object and FAD sets. For each vessel, annual tallies (based on departure year) were computed: number of FAD deployments by the vessel, number of floating-object sets made by the vessel, and number of FAD sets made by the vessel on its own FADs or on other FADs of known origin (hereafter for this particular analysis referred to collectively as “FADs of known origin”). All sets, including repeat sets on the same object and sets made outside the EPO (to 180°W), were included in this analysis. Note is that it is not possible to know from the observer data base the number of FADs *deployed* for all but a small percentage of the data because it is not possible to track FADs deployed on one trip to subsequent trips, and therefore it is not possible to know whether FADs are re-used from one trip to the next, and if so, how many times.

To describe the relationship between deployments and sets, mixed-effects models (*e.g.*, Pinheiro and Bates, 2004) were fitted to the data of several of the groups identified by the cluster analysis (see below). The general model form was selected based on the assumption that the relationship between deployments and sets could have an asymptote (see below). The base model had the following form:

$$number\ of\ sets_{ij} = \alpha * \gamma_j * \left(number\ of\ deployments_{ij}\right)^{\beta} \quad (1)$$

which was fitted to the data using the following linearized equation:

$$\log\left(number\ of\ sets_{ij}\right) = \tilde{\alpha} + \tilde{\gamma}_j + \beta * log\left(number\ of\ deployments_{ij} + 1\right) \quad (2)$$

where $\tilde{\alpha} = \log(\alpha)$, $\tilde{\gamma}_j = \log(\gamma_j)$, γ_j is the vessel effect for the *j*th vessel (random effect), *i* indexes departure year (*i* = 2012, …, 2015), the number of sets was either the number of floating-object sets or the number of sets on FADs of known origin, and a value of 1 was added to the number of deployments because a few vessels had no FAD deployments in a given year[5]. In addition, models that include departure year as a main effect (fixed effect) and an interaction between number of deployments and departure year were also fitted to the data. Based on preliminary analyses, a Gaussian error distribution was assumed for the log-transformed data. The benefit of including year as a predictor was evaluated using the Akaike Information Criterion and the Bayesian Information Criterion ("AIC" and "BIC", respectively; Pinheiro and Bates, 2004). All models were fitted to the annual vessel-specific tallies of sets and deployments using the *lme* function of the *nlme* package (Pinheiro *et al*., 2016). Predicted curves were obtained by assuming a value of 0 (on the log scale) for the random effect (vessels are exclusive to a particular cluster group) and applying a bias correction factor (= ½ the estimated residual squared error) to the estimated intercept.

3. RESULTS

3.1. Fishing strategies

The cluster analysis of the 2012-2015 data showed clear differences among vessels based on a tendency to make dolphin sets *versus* floating-object and unassociated sets, and a tendency to make sets on tunas associated with their own FADs *versus* sets on tunas associated with objects found drifting and/or with FADs of unknown origin (Figure 1).

The dendrogram from the cluster analysis was used to identify five large groups of vessels. The number of vessels per group ranged from 25 to 37 (Figure 1). The first broad category of vessels corresponds to those vessels making a large proportion of their sets on tunas associated with dolphins, with very few sets on tunas associated with floating-objects (Groups 1-2). Groups 1 and 2 differ from each other by the proportion of objects that vessels set upon that were found drifting *versus* that were FADs of unknown origin. The second broad category (Groups 3-5) consists of vessels that made proportionally few, if any, dolphins sets, and for which a relatively larger fraction of their floating-object sets were made on FADs the vessels themselves deployed on a previous trip. Groups 3-5 differ in terms of the proportion of floating-objects *versus* unassociated sets made by the vessels, the proportion of sets on tunas associated with the FADs of unknown origin *versus* associated with other FADs of known origin (Figure 2), and the proportion of floating-object sets made west of 100°W. Vessels in Group 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 Group 4 fished almost exclusively on FADs they deployed themselves or on other FADs of known origin, and they fished on objects furthest to the west. The behavior of vessels in Group 5 fell between the behavior of vessels in Groups 3 and 4. The agglomerative coefficient for this analysis was 0.98, which indicates strong clustering (the agglomerative coefficient based on the Group Average method was 0.85).

The FAD deployment activity of vessels in these five cluster groups also was found to differ, even though deployment information was not explicitly included in the cluster analysis. The spatial distributions of FAD deployments, as well as floating-object sets, differed by cluster group (Figure 3). Among those groups of vessels with proportionally few dolphin sets, the vessels in Groups 3 and 5 tended to deploy FADs in more nearshore waters, compared to the vessels in Group 4. In addition, the number of FAD deployments made annually by each vessel differed among these three groups, but was fairly similar across years within the same group (Figure 4). Vessels in Group 3 had the fewest FAD deployments, whereas vessels in Group 4

[5] Only 1.8% of the year-vessels "observations" for Groups 3-5 had a value of 0 for deployments, most of these occurring in Group 5.

had the most FAD deployments.

3.2. Relationship between FAD deployments and sets

The overall relationship between the number of FAD deployments and the number of sets, without regard for cluster group, shows an increasing, nonlinear relationship that begins to asymptote at about 200 to 300 deployments (Figure 5). Among cluster groups, the relationship of deployments to sets was found to differ (Figures 6-7). For groups setting primarily on tunas associated with dolphins (Groups 1-2) there are few deployments and few floating-object sets, and so the data of these two groups were not analyzed further.

The predicted curves obtained from fitting the base model (eq. (2)) to the data for floating-object sets groups (Groups 3-5) (Figure 8; Table 1) show differences among groups that may be due to differences in fishing strategies related to overall fishing location (Figures 1 and 3). Predicted curves were generated by predicting the number of sets over the same range of numbers of FAD deployments for each vessel group (1 to 700 deployments), regardless of the actual range of observed number of deployments (Figure 4), which represents an extrapolation at higher numbers of deployments for Group 3. Despite this, if it were assumed that the underlying relationship between number of FAD deployments and number of sets is adequately described by the data, some insights may be gained. Overall, the predicted curves suggest that the rate of return on FAD deployments, in terms of numbers of sets, decreases beyond several hundred deployments (Figure 8). The predicted curves for sets on FADs of known origin suggest that the rate of return on FAD deployments could be less when fishing closer to the coast than when fishing further offshore (Figure 8; compare Group 3 to Group 5 and Group 5 to Group 4). Also, including sets on tunas associated with FADs of unknown origin and with drifting objects appears to have the greatest effect on the relationship between deployments and sets for Groups 3 and 5 (Figure 8), which are the two floating-object sets groups fishing closer to the coast and making proportionally more unassociated sets (Figures 1, 3).

The high level of variability in deployments *versus* sets within and among vessel groups (Figures 6-7) resulted in the base model being the most parsimonious (as measured by AIC and BIC) (Table 2) (but see Discussion section). Given the assumed nonlinear relationship, vessels of Group 4 appear to be the most homogeneous and vessels of Group 5 the most heterogeneous (per the estimated vessel effects, Table 1).

4. DISCUSSION AND FUTURE WORK

This quantitative analysis of the behavior of purse-seine vessels in the EPO with respect to floating-object set activity has shown the heterogeneity of strategies using FADs. The complexity of FAD fishing strategies is due in part to the fact that the ownership of a FAD can change during its lifetime, so that the number of deployments for a given purse-seine vessel may not correspond with the monitored, active FADs at sea for that vessel, and somehow with the chances of making a set.

The groupings of purse-seine vessels by their different fishing strategies were clearly defined in our data, illustrating that for the recent period there were two groups of purse-seine vessels (Groups 1 and 2) that focused mainly on fishing on tunas associated with dolphins, two groups (Groups 4 and 5) that focused mainly on fishing on tunas associated with FADs, and another group (Group 3) that was the most heterogeneous in terms of the proportion of sets on unassociated tunas and on FADs (Figure 1). FAD deployments were low for the fleet components fishing on tunas associated with dolphins, and their FAD sets were made on FADs of unknown origin more often than those of the groups that are focused on FAD fishing. Those groups that focused on FAD fishing had a higher number of FAD deployments (Figure 4) and fished mainly on their own FADs (Figures 1-2). Thus, the non-linear relationships for FAD deployments to FAD sets shown in Figures 6-8 for the different groups mirror the complexity of FAD fishing in recent years and the different strategies adopted by purse-seiners fishing on FADs in different regions in the EPO. This complicates the understanding of the real effects of any limitation on FAD deployments (or numbers of FADs), both in terms of tuna conservation and in terms of the economic performance of the different purse-seine fleet components operating in the EPO.

Although it may be difficult to understand the potential effects of different limits set on FAD usage (e.g., FAD deployment limits or FAD set limits), as stated above, the benefit to a vessel of increasing the number of deployments to obtain a greater number of sets may decrease beyond several hundred deployments (Figure 8). However, in addition to using the number of FAD sets as a measure of the effectiveness of FAD deployments, it may be more meaningful to look at catch per set as an output of number of FAD deployments. This research is ongoing by the authors.

Finally, research should also be devoted to understanding the effects of different numbers of FADs at sea (for all purse-seine vessel groups combined) on the associative behavior of tunas at FADs (schooling behavior, residence time at FADs, *etc*.), so that, combined with an understanding of fleet behaviors on FAD fishing, more effective management decisions regarding numbers of FADs deployed or/and set upon and/or monitored at sea could be reached. This would require data that are not currently available from the AIDCP observer program, such as satellite position data for FADs.

As part of ongoing research, future work on modelling numbers of deployments *versus* numbers of sets will focus on different modelling options including the assumed error structure of the data, which may allow for effects of departure year to be detected. Prediction intervals for fitted curves also will be computed. Cluster analyses of data for earlier years are currently being conducted to describe the evolution of fishing strategies since 2006 (the first full year for which AIDCP data on FAD details are available).

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TABLE 1. Estimates of model parameters and approximate 95% confidence intervals for the base model (eq. (2)). Based on AIC and BIC, adding a year effect did not substantially improve model fit (see Table 2). "OBJ": floating-object sets.

	Estimate of $\tilde{\alpha}$	Estimate of β	Vessel effect distribution s.e.	Residual error
OBJ				
Group 3	3.02 (2.559, 3.487)	0.273 (0.166, 0.380)	0.24 (0.14, 0.42)	0.45 (0.39, 0.53)
Group 4	2.97 (2.514, 3.423)	0.309 (0.226, 0.392)	0.14 (0.07, 0.28)	0.31 (0.26, 0.37)
Group 5	1.98 (1.543, 2.409)	0.496 (0.408, 0.585)	0.34 (0.21, 0.54)	0.46 (0.39, 0.54)
Groups 3-5	2.50 (2.246, 2.752)	0.393 (0.341, 0.445)	0.26 (0.19, 0.35)	0.43 (0.39, 0.47)
FADs of known origin				
Group 3	1.83 (1.254, 2.407)	0.427 (0.294, 0.560)	0.26 (0.14, 0.49)	0.59 (0.51, 0.68)
Group 4	2.82 (2.359, 3.278)	0.318 (0.234, 0.401)	0.16 (0.09, 0.29)	0.31 (0.26, 0.37)
Group 5	1.94 (1.393, 2.495)	0.445 (0.332, 0.558)	0.32 (0.19, 0.53)	0.51 (0.43, 0.60)
Groups 3-5	1.88 (1.571, 2.195)	0.454 (0.389, 0.518)	0.29 (0.22, 0.40)	0.50 (0.46, 0.55)

TABLE 2. AIC for different models fitted to the data for Groups 3-5, separately and combined. Similar results were obtained for BIC (not shown). Models fitted were as follows: "deploy" is the base model with only number of deployments (eq. (2)); "deploy + year" is the base model plus a departure year effect (main effect, treated as a fixed effect); "deploy * year" is the base model that includes both a main effect for departure year (fixed effect) and an interaction between departure year and number of FAD deployments. "OBJ": floating-object sets.

	deploy * year	deploy + year	deploy		deploy * year	deploy + year	deploy
OBJ				FADs of known origin			
Group 3	223	215	203	Group 3	286	276	263
Group 4	91	87	77	Group 4	94	88	76
Group 5	203	205	194	Group 5	233	222	209
Groups 3-5	503	496	483	Groups 3-5	609	594	579

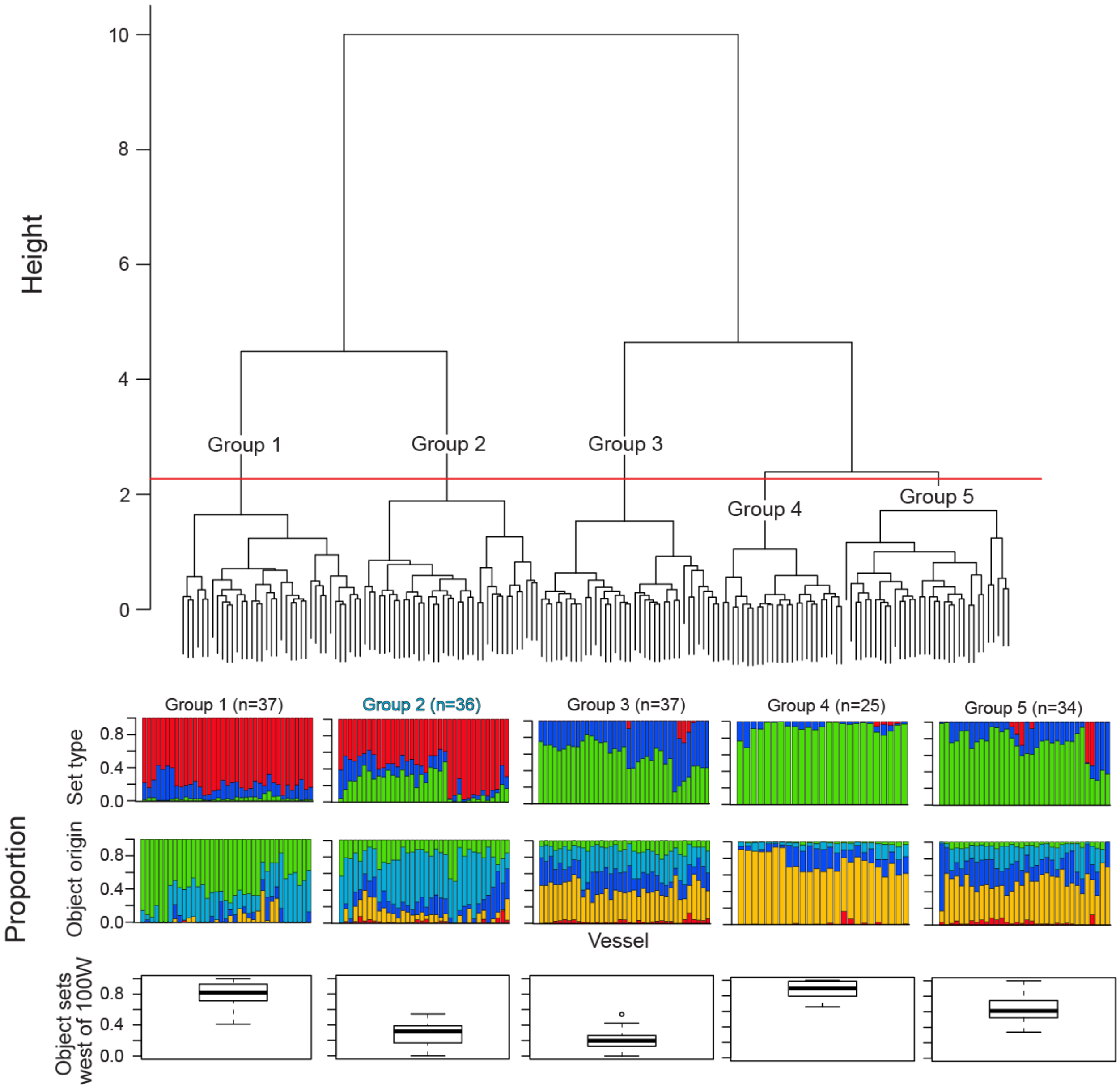

FIGURE 1. Dendrogram resulting from the cluster analysis of 2012-2015 data. The red horizontal line indicates the height at which the dendrogram was sliced to create the five groups of vessels, labeled Group 1 through Group 5. The number of vessels per group is shown in parentheses above the bar graphs. Each bar in the bar graphs represents an individual vessel. The colors 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 colors 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 – drifting object found.

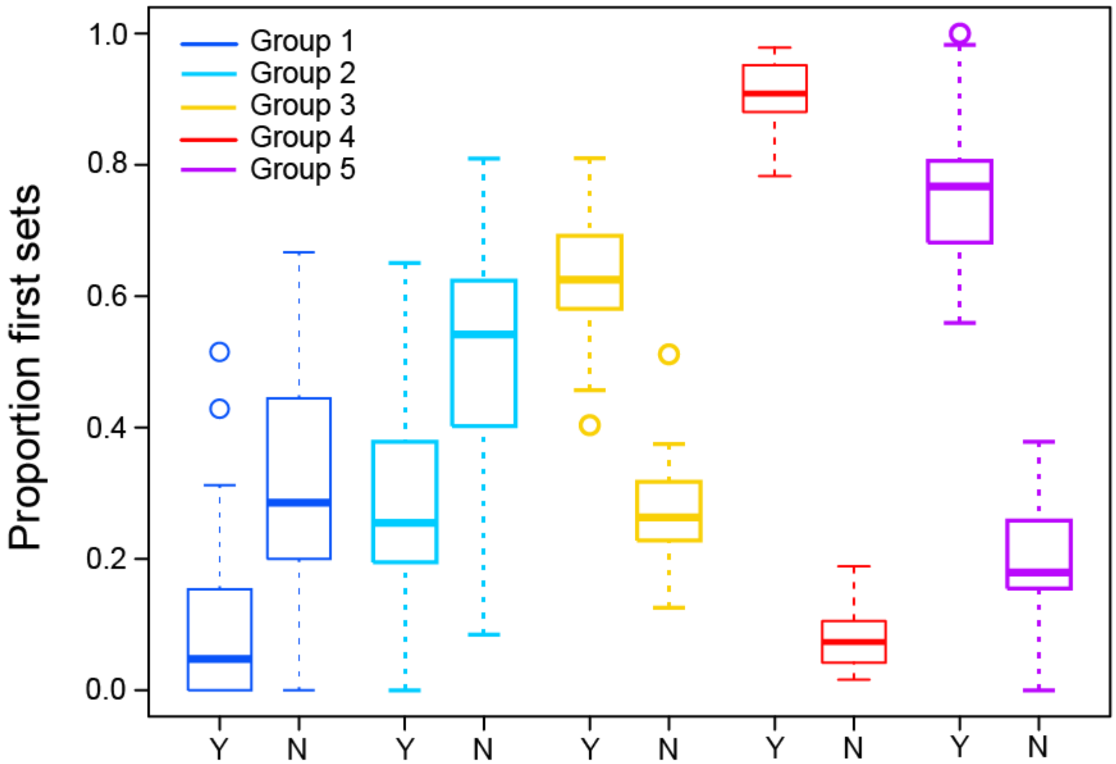

FIGURE 2. Box-and-whisker plots of the proportion of sets that were on the vessel's own FADs or on other FADs of known origin ("Y"), and FADs of unknown origin ("N"), by vessel within each cluster group (Figure 1). The horizontal bar within each box indicates the median value of the proportion of sets 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.

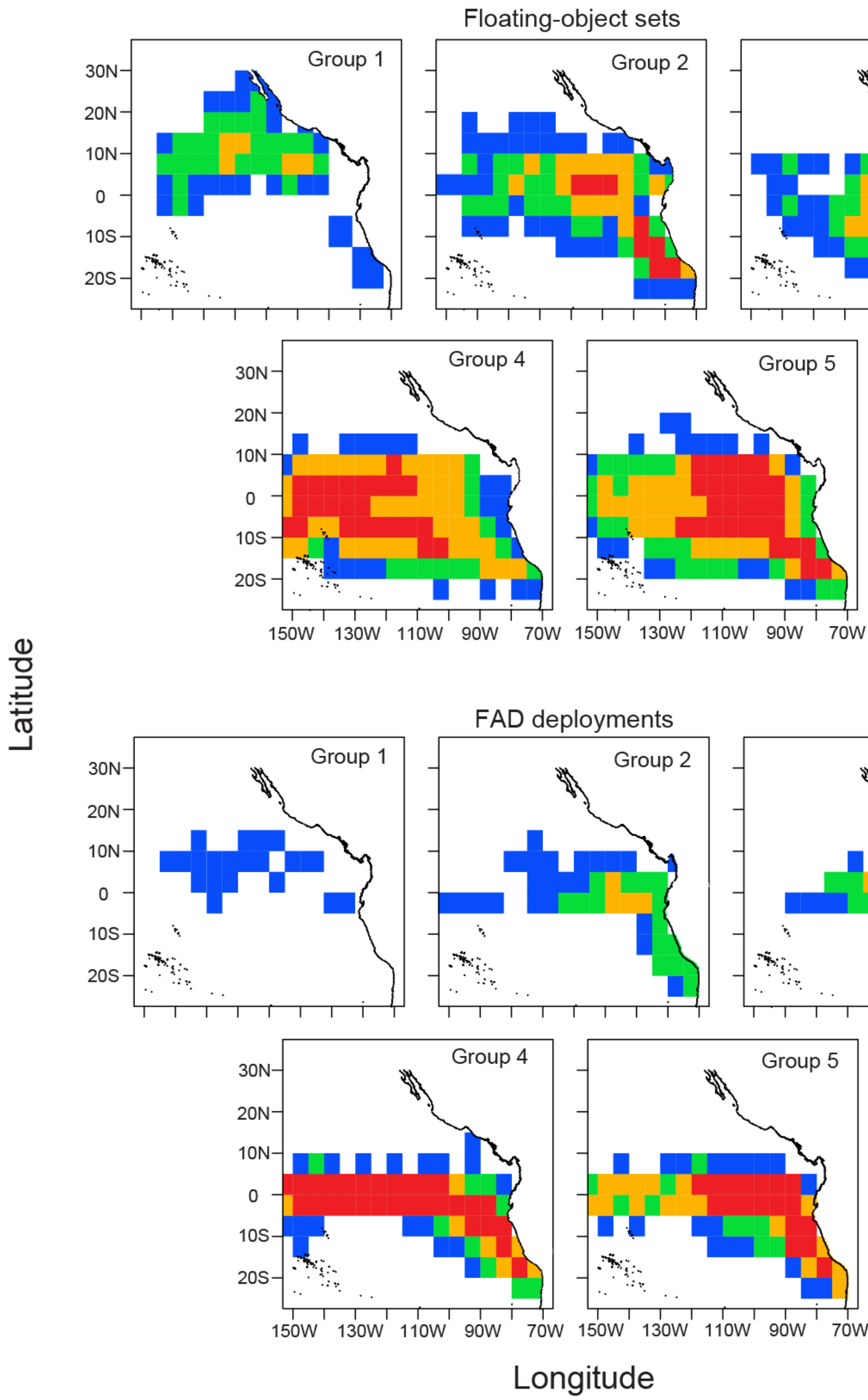

FIGURE 3. Number of floating-object sets and FAD deployments, by 1° area, for each cluster group. Colors for number of floating-object sets are: blue – 1 to 20 sets; green – 21 to 90 sets; gold – 91 to 320 sets; red – greater than 320 sets. Colors for number of FAD deployments are: blue – 1 to 10 deployments; green – 11 to 40 deployments; gold – 41 to 140 deployments; red – greater than 140 deployments.

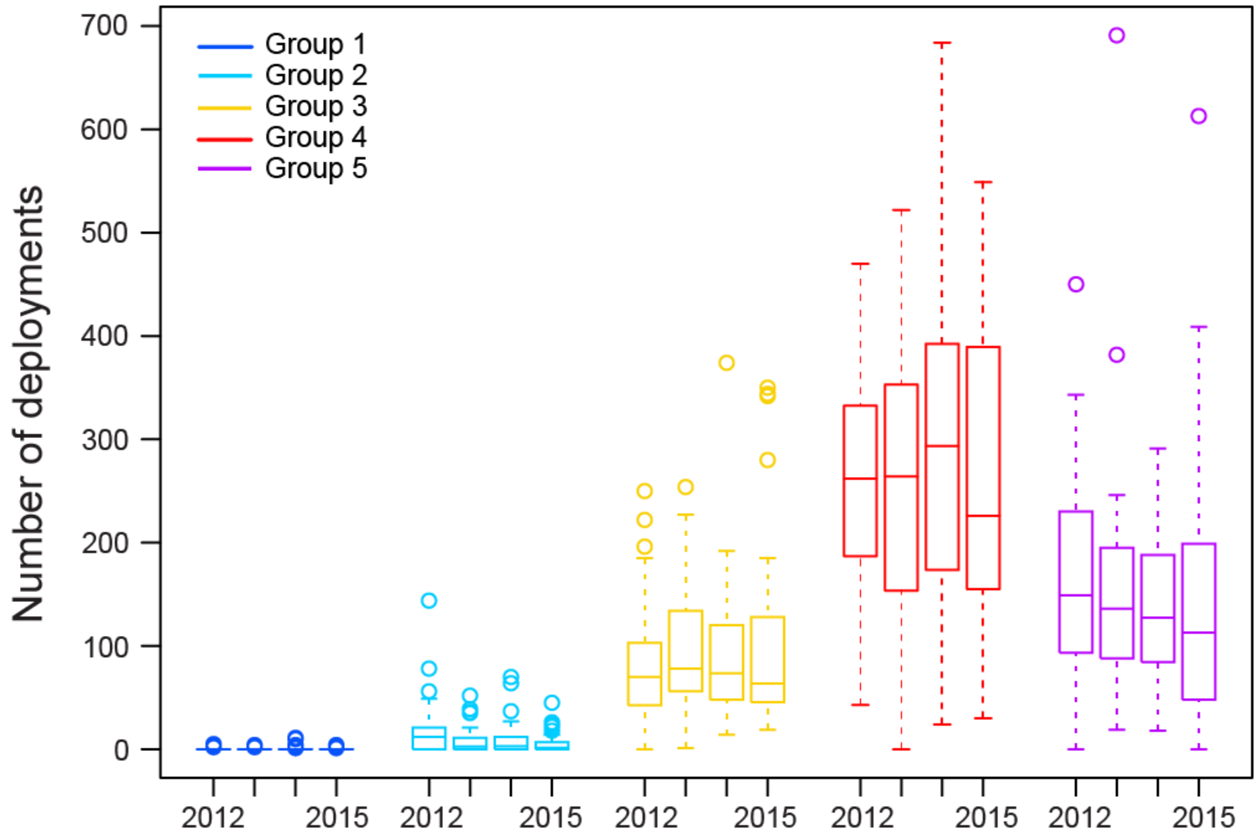

FIGURE 4. Box-and-whisker plots of the number of FAD deployments per vessel, by year within cluster group.

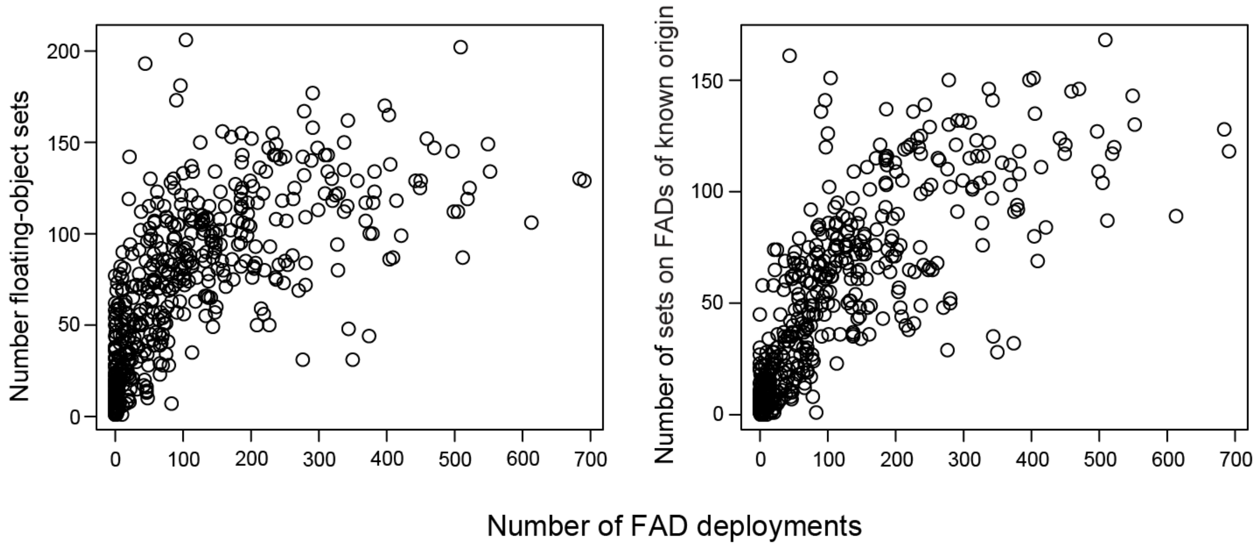

FIGURE 5. Number of FAD deployments *versus* number of floating-object sets per vessel, and number of sets on FADs of known origin, per vessel, for data pooled over 2012-2015, and regardless of cluster group.

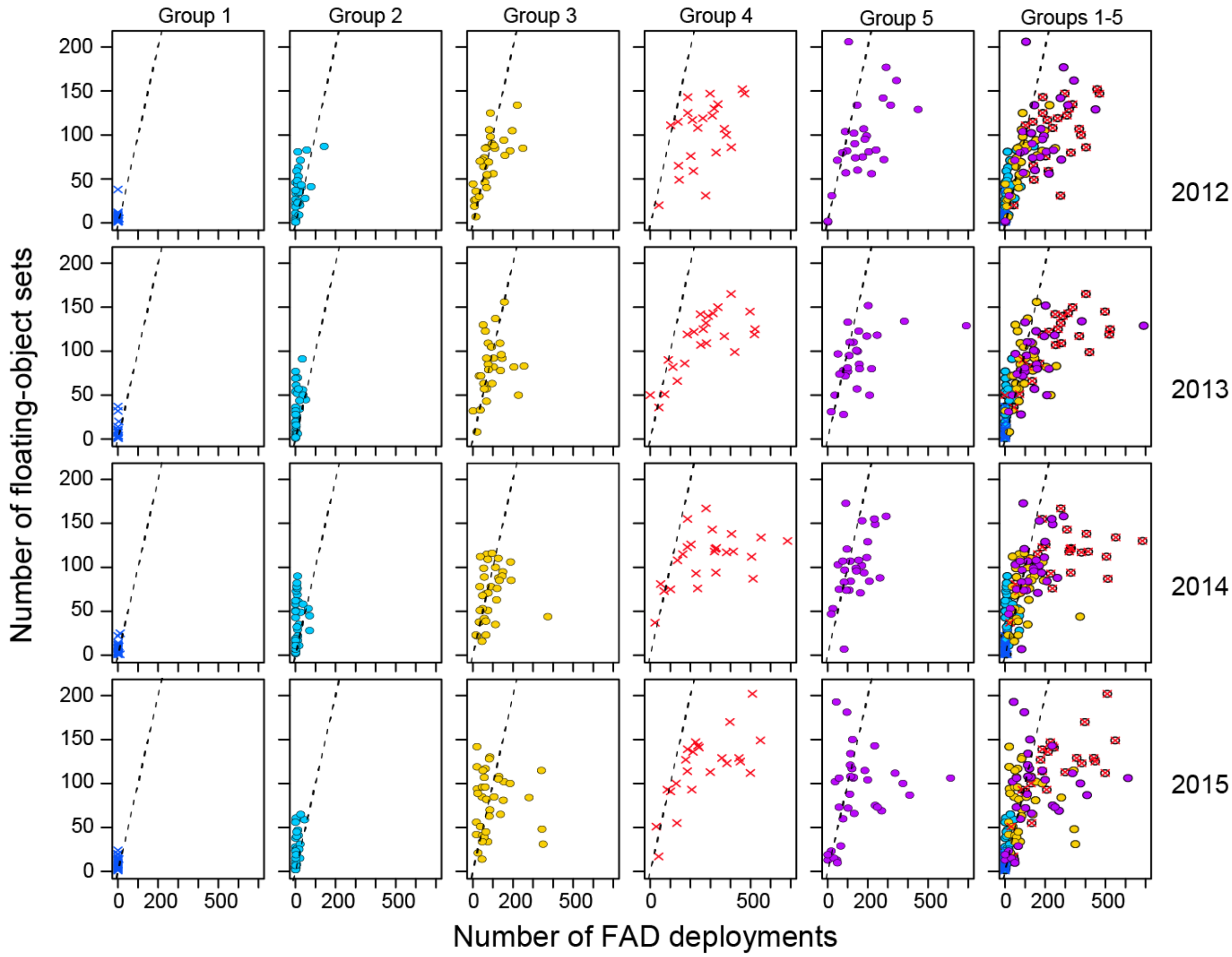

FIGURE 6. Annual plots of the number of FAD deployments *versus* the number of floating-object sets, per vessel, by cluster group and year.

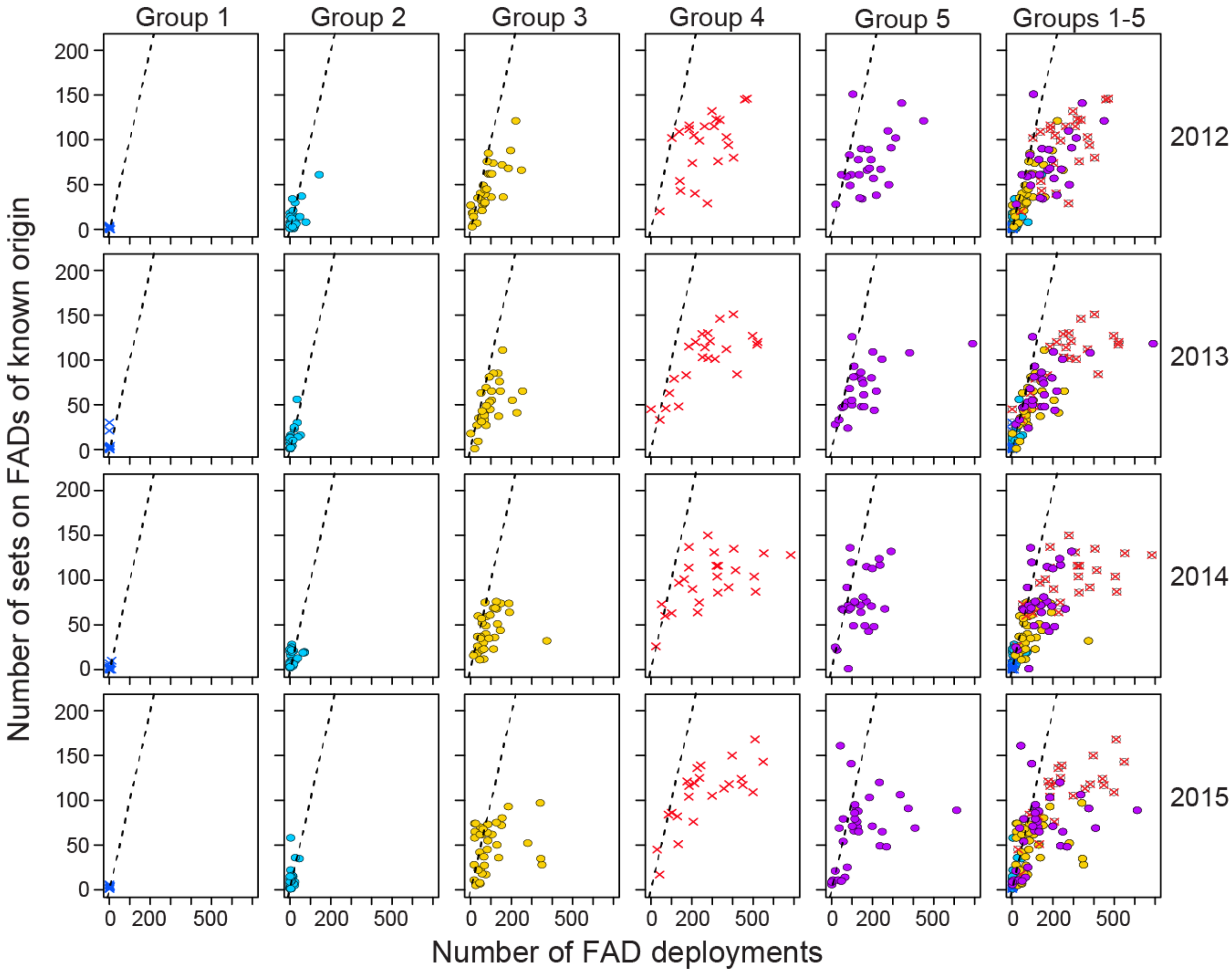

FIGURE 7. Annual plots of the number of FAD deployments *versus* the number of sets on FADs of known origin, per vessel, by cluster group and year.

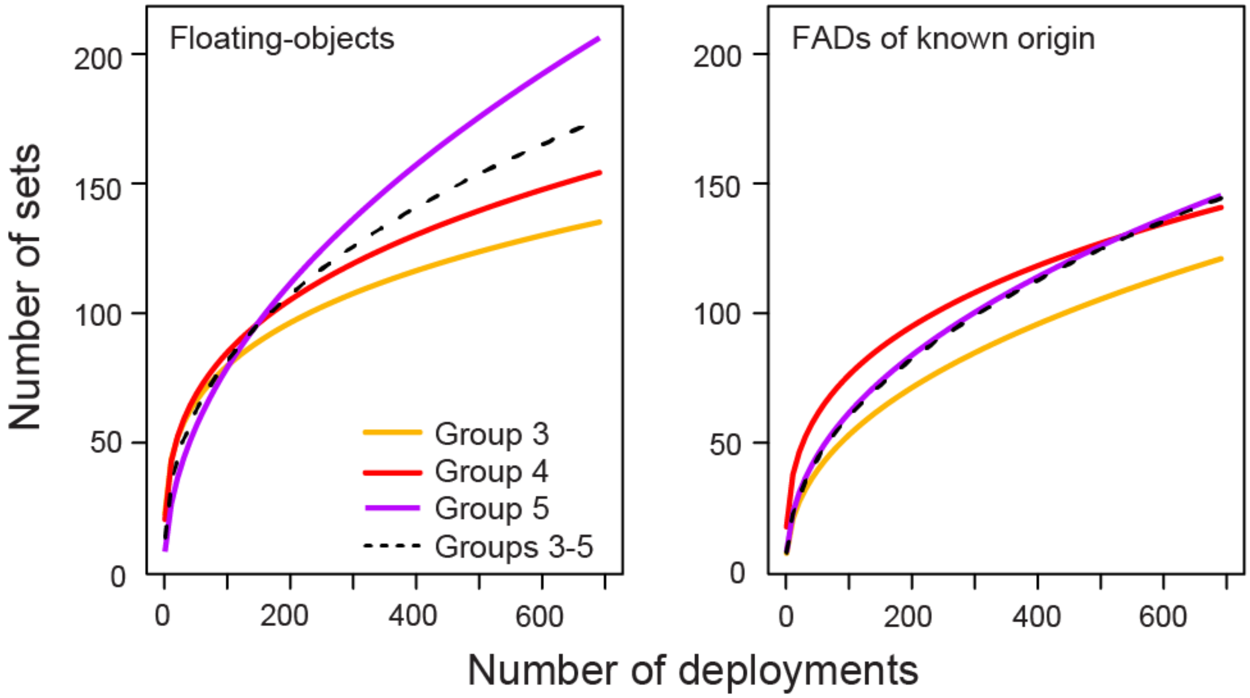

FIGURE 8. Predicted curves of number of FAD deployments *versus* number of sets, for floating-object sets and on FADs of known origin, for cluster Groups 3-5, separately and combined.