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Report from Project 77: Development of potential measures to reduce interactions with bigeye tuna in the purse seine fishery in the western and central Pacific Ocean ('bigeye hotspots analysis')

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Rev 2 (30 October 2017)

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Revision 2, 30/10/17

Following the discussions and feedback received at SC13, this revision contains:

- Further information on the data sources used within the analysis, in particular the use of observer visual estimates of species composition at the set level.
  See section 2.1 p6 and Attachment 2 p35.

- Information on the geographical (EEZ/high seas) regions contained within each bigeye 'hotspot' identified within the analysis.
  See section 3.3, specifically p26, including Table 8.

- A comparison of the spatial distribution of the bigeye catch and CPUE hotspots between observer data and S-BEST raised logsheet data (stratified by 1x1 degree, month, flag and set type, where catch by species is corrected using observer-based grab sampling corrected for selection bias).
  See section 3.3 p23 and Figures A30, A33 and Table A5.

Executive Summary

This report represents the final report of WCPFC Project 77 ('Development of potential measures to reduce interactions with bigeye tuna in the purse seine fishery in the Western and Central Pacific Ocean'). We investigated the influence of several factors, such as vessel characteristics, FAD design and environmental variables, on bigeye tuna catch by the purse seine fishery in the Western and Central Pacific Ocean (WCPO) between 10°N and 10°S, and examined spatial management considerations.

Analysis of factors related to the occurrence of bigeye tuna in purse seine associated sets

Analyses were based on associated sets from observer data collected between 2011 and 2016 and estimates of catch by species based on observer visual estimations (representing 40–70% of the total tuna catch). For each set, these data also include several vessel and FAD characteristics, when recorded by the observer.

Hierarchical clustering was performed based on bigeye tuna catch per associated set and by area of the WCPO (West, Center and East). Five clusters with increasing bigeye catch and proportion per set were identified. The cluster with 'Very High' bigeye catch represented up to 10% of the associated sets in the Eastern area and landed 32–51% of the bigeye in that region. High set to set variability in bigeye proportion was detected in all clusters and areas.

Investigation of vessel characteristics by cluster showed increasing catch of bigeye with an increase in vessel size, engine power, speed, storage capacity and number of speedboats, but no pattern with net depth or net length. However, this was mostly evident in the Eastern area, where very large vessels operate, and found prior to 2015 as many of these large vessels did not operate in the WCPO in 2015 and 2016. Prior to 2015, large vessels (>90m) caught 11–15% of the total WCPO associated bigeye catch and 4–8% of the total associated tuna catch, and these vessels were highly FAD dependant with >75% of their sets performed on FADs. Some fleets also tended to catch more bigeye tuna (i.e. Chinese Taipei, Marshall Islands, and US in the Central region, and EU in the East).

Most associated sets were made on constructed FADs compared to logs, especially in the Central and Eastern areas. In terms of FAD characteristics, FAD depth i.e. "FAD sub-surface appendage depths" (hereafter referred to as "FAD depth") appeared to influence bigeye tuna catch per set, specifically bigeye catch 'per FAD set' was higher on FADs with sub-surface structures of 30–50m and 0–20m depth in the East and 50–60m in the West, a pattern not detected for total tuna catch. Material used for the main structure or attachment, as well as the FAD surface area also appeared to increase bigeye catch rates, with some specific FAD designs used in the East by some fleets (e.g. EU, Ecuador) corresponding to higher bigeye catch rates by set. However, disentangling a vessel/flag/FAD design effect is difficult.

Strong variability in main fishing areas was detected following ENSO periods, particularly through the presence of a very strong El Niño event in 2015, which led to an eastward displacement of the fleet and which influenced tuna catch distribution. For instance, very high skipjack and yellowfin tuna catch occurred in 2015 in the Eastern area, while bigeye tuna catch dropped drastically at the scale of the WCPO, with similar trends apparent for bigeye in 2016. This may be, in part, linked to the absence of very large vessels during those years. In addition, during El Niño the thermocline is deeper in the East, decreasing bigeye tuna catchability by purse seine nets, even if locally the associated sets performed corresponded to a local relatively shallow thermocline (200–250m). Generally, we detected an influence of the thermocline depth on bigeye tuna catch, mainly in the East.

To identify factors (temporal, vessel and FAD characteristics, thermocline depth) influencing bigeye catch per set at the scale of each area, delta GAMs combining binomial and log-normal models were used. Bigeye were more likely to be found in a set with increasing vessel length, net depth and net length; during La Niña and El Niño; and FAD sub-surface appendage depths of around 50m in the West, and 10m and 40m in the East. If present in a set, bigeye catch i) decreased with increasing thermocline depth and increased with vessel size and net depth in the Center and East; ii) increased during La Niña and with FAD depth (60–70m) in the West; and iii) was influenced by FAD design (main structure or attachment material, dimension).

Characteristics of top bigeye tuna catching purse seine vessels

Top bigeye tuna catching vessels were defined as those vessels that cumulatively caught a specific percentage of the annual bigeye catch. The number of top vessels catching 50% of the bigeye between 2011 and 2016 varied between 23 and 34 vessels, with only seven individual vessels listed as top vessels in at least three of those years. Almost all vessels operating in the East, as well as larger vessels, were classified as top vessels. The 7 to 15 top vessels catching 25% of the total bigeye per year, captured 9–15% of both the skipjack and total tuna catch by year.

In addition, vessels catching more than 500t of bigeye by year were also examined, with these large individual vessel catches occurring mostly in 2011 and 2013. These vessels all fell within the ‘top vessels catching 50% of bigeye’ classification. Where vessels caught > 500t of bigeye per year, the bigeye catch in excess of 500t per vessel represented between 4% (2014) and 15% (2013) of the total bigeye catch in the WCPO (0% in 2015–2016). We simulated the potential implications of imposing an annual 500t bigeye catch limit per vessel, which led to a decrease of 1% to 6% in skipjack and total tuna catch, and bigeye catch was estimated to decrease by up to 15%.

Spatial management considerations

Two bigeye ‘hotspots’ were identified: i) a bigeye catch hotspot (i.e. a high tuna catch hotspot in general) within the EEZs of Nauru and the Western part of Kiribati’s Gilbert Islands; and ii) a bigeye CPUE hotspot in the tropical North-Eastern area (note that both were also identified annually in the S-BEST data, i.e. corrected raised logsheet data stratified by 1x1 degree, month, flag and set type, used for stock assessments). The CPUE hotspot mostly covers International Waters (60%) whereas the catch hotspot covers primarily EEZs of Pacific Island Countries (Kiribati 55%, Nauru 33% and Tuvalu 4%, when considering the contiguous central part of the hotspot). While the bigeye catch hotspot appears highly influenced by ENSO (e.g. shifting toward the East during El Niño), the bigeye CPUE hotspot was relatively stable through time. It should also be noted that similar spatial distribution of both hotspots were found when using S-BEST raised, aggregated and corrected logsheet data over the 2011–2016 period, however prior to 2011 the catch hotspot spread further toward the West. We note that in the East, high bigeye CPUE was detected for all vessels, but extremely high values were only found for large vessels (>90m). In addition, large vessels had higher bigeye CPUE than smaller vessels in all the areas where they operated (although large vessels were absent or performing very few sets in the West). Skipjack CPUE was particularly high for large vessels in the CPUE hotspot during certain years (2011 and 2012), but this was not consistent every year. Hence skipjack CPUE in the bigeye CPUE hotspot was generally comparable to the rest of the WCPO, including for large vessels. Note that these large vessels did not operate in the WCPO in 2015 and 2016, making it difficult to statistically separate the reduction of purse seine bigeye catch in 2015 into either oceanographic or vessel influences.

We simulated the impact of a reallocation of the sets performed in the two hotspot areas to the rest of the WCPO. It was found that the impact of the closure of the catch hotspot was highly variable, and could lead to a decrease of up to 11% of the total tuna catch and 17% of bigeye catch, or an increase up to 10% of the total tuna catch and 3% of bigeye catch, dependent on the year. A closure of the CPUE hotspot had a slightly more consistent effect, and could lead to a decrease of 2–12% in bigeye catch and 0–4% in the total tuna catch.

Challenges

The main challenges in disentangling the effect of each factor separately were i) the lack of observations of large vessels in all three geographic areas, ii) the fact that most vessels of some key fleets fell within a particular size category, iii) the unknown precision of the data on FAD design and some vessel characteristics, iv) observer data representing only a portion of the total bigeye catch and potential low set to set precision of species identification in the observer visual estimates, and v) inter-trip variability in the data regarding technological equipment (including absence of information regarding echo-sounder buoy use), precluding any comparison between vessels or areas.

Recommendations to WCPFC SC13, which remain relevant from this final report were:

- Note this final report of WCPFC project 77.
- In particular, note the uninformative nature of the data to statistically separate the effects of key areas and vessel types.
- Highlight the need for improved information on FAD designs, deployments and type of buoy use within the WCPO to improve future analyses.
- Note the importance of detailed information on the characteristics of vessels fishing in the WCPO, especially on fishing gears and technological equipment increasing fishing efficiency.
- Note the challenges in considering spatial management options for bigeye tuna.

1. Introduction

The 2014 stock assessment of bigeye tuna (*Thunnus obesus*) estimated that the stock was overfished in the Western and Central Pacific Ocean (WCPO) (Harley et al., 2014). In 2017 the WCPO bigeye tuna stock assessment was updated, and the stock was assessed overall as not to be experiencing overfishing or to be in an overfished state (McKechnie et al., 2017). However, given the uncertainty within the assessment there remains an assessed probability that these states are still occurring. The WCPFC Scientific Committee's 2017 advice called for a precautionary approach such that the fishing mortality on the WCPO bigeye tuna stock should not be increased from the current level in order to maintain current or increased spawning biomass, until the Commission can agree on an appropriate target reference point (TRP).

In the WCPO, bigeye tuna are mostly caught as adults by the longline fishery and as juveniles by the purse seine fishery. Despite the improved stock status for WCPO bigeye, further understanding of the impact of the purse seine associated set fishery component, especially on small bigeye tuna, remains highly relevant to enhance stock management.

While the catch of bigeye tuna represents only 3.8% of the overall purse seine tuna catch, approximately 40% of the fishing impact on the WCPO stock can be attributed to purse seine sets on Fish Aggregating Devices (FADs, including here drifting constructed FADs and naturally occurring logs) (Harley et al., 2014). To reduce the impact of the purse seine FAD fishing on bigeye tuna, a three to four month FAD closure, where all FAD-related activities (i.e. fishing, deployment) are prohibited, has been implemented by the Parties to the Nauru Agreement (PNA) and the WCPFC (e.g. CMM-2016-01).

Increasing our understanding of the nature of bigeye tuna interactions in the purse seine fishery is considered to be important for informing management measures. A strong spatial component has already been identified, with high effort and high catch in the Western part of the WCPO (140°W–180°W) and lower effort but high Catch Per Unit of Effort (CPUE) in the Eastern part (180°W–150°E) (Harley et al., 2015). In addition, a relatively limited number of vessels also appeared to be responsible for a large part of the bigeye catch each year (Harley et al., 2015). In this context, WCPFC project 77 ('Development of potential measures to reduce interactions with bigeye tuna in the purse seine fishery in the Western and Central Pacific Ocean'; May 2016 – October 2017; see Attachment 1) aimed to identify the main factors leading to high catches of this species in the purse seine fishery, in order to guide management options. Specifically, it was recognized that several factors may influence purse seine bigeye tuna catch, such as specific vessel characteristics influencing fishing strategies, FAD characteristics, spatial and temporal dimensions and oceanographic variables. Tidd et al. (2016) noted the difficulties in disentangling the influence of these factors, which limits analysis of the available vessel and FAD characteristics at the level of the fishing set. In particular, it has been highlighted that technological advancements in fishing technology (e.g. sonars, satellite maps, acoustically equipped satellite-transmitting FADs) may allow some purse seine skippers to more easily locate aggregations of tuna.

This report represents the final report of WCPFC Project 77 and has been updated in light of feedback received at the 13th WCPFC Scientific Committee. The sections described here cover the key work areas detailed in the Project description (Attachment 1). The work complements previous studies (Harley et al., 2015; Tidd et al., 2016) by investigating the influence of vessel and FAD characteristics, as well as some environmental variables on bigeye tuna catch by the purse seine fishery. The information provided in this report could therefore potentially be the basis for future work towards developing tools beyond temporal FAD closures to support conservation and management measures for bigeye.

2. Methods

2.1. Construction of a set-by-set species-specific dataset of purse seine catch

For the analyses presented herein, data on a set-by-set level is required. Onboard observer data collected between 2011 and 2016 are the most precise and complete unaggregated data currently available at the fishing set level. These include catch, vessel characteristics and FAD characteristics. We selected associated set (drifting FAD and log) data as the majority of bigeye tuna catch from the purse seine fishery in the WCPO is made on FADs (87%). For each set, catch by species was recorded by observers based on visual estimation. The observer-derived species composition based on length frequency analysis was not used as it is an approximate representation of the set catch (sampling of around 0.1–0.2% of the catch). We are aware of the limits of using observer visual estimation, in particular that the precision of bigeye catch estimates on a set-by-set basis is unknown (Lawson, 2013; Lawson and Williams, 2005) and these potential biases should be considered when reviewing the results presented in this paper. A comparison of the observer visual estimation with other available data sources was performed (see Attachment 2) and highlighted that the visual estimates were reasonably consistent with both the sample-based estimates and the logsheet estimates. However the two latter data sources showed relatively frequent occurrences of non-reporting bigeye tuna in a set, while bigeye catch was reported in the corresponding visual estimation. This therefore clearly shows that there is no 'best' dataset for estimating catch by species at the set level, especially for bigeye tuna, but that the visual estimates offer some advantages for the current study. Further work on these issues of the precision of alternative data sources is a research area within the Project 60. In particular a comparison with corrected grab sampling or landing data could also be useful to evaluate the precision of the catch estimates (see Peatman et al. (2017) as an example of the approach).

Despite the 100% observer coverage requirement (see Table 1 in Williams et al., (2017) for observer coverage rates), the available data did not corresponded to 100% of the sets and corresponding catch (40–70% of the total tuna catch). This could be due to missing observer records, or data that may not yet have been processed and loaded into regional databases. Therefore catch presented in this paper represents a minimum estimate for vessel specific bigeye tuna catch. We selected data from the main tropical purse seine FAD fishing grounds (10°N–10°S and 120°E–150°W) excluding Indonesia and Philippines domestic fleets and vessels fishing in archipelagic waters. In addition, vessels performing less than 25 associated sets per year were excluded from the data (15% of bigeye associated catch). For the period 2011–2016 total bigeye tuna annual FAD catch in this selected observer data set were 24–55% of the associated purse seine total bigeye catch estimates from logsheet data aggregated by 1° square, month and year and corrected for species composition using method 3, as described in Hampton and Williams (2016).

From the observer dataset, several corresponding vessel characteristics were available. The main characteristics were vessel flag, vessel length, engine power, gross tonnage, storage capacity, build year and cruising speed. Vessels with these data missing were excluded (3% of the bigeye catch). In addition, for a majority of sets information on net length and depth, number of speed boats and auxillary boats onboard, skipper experience and crew count was available. The presence of a helicopter and the use of other fishing technology (e.g. sonars, satellite maps, etc.) were recorded. However, a high degree of variability was detected in these data between trips by the same vessel, and it was hard to distinguish between the absence of equipment and that information not being recorded by the observer. Information on electronic equipment on board could therefore not be used in this analysis.

From 2011 onward, observers have recorded information on FADs during fishing or servicing activity (e.g. deployment, recovery, visit) on a FAD (see attachment C in WCPFC, 2016). In this paper the term FAD refers to both constructed drifting FADs and logs, unless stated otherwise in the text. Information on FADs include FAD and buoy number, when available, material of the main structure or of attachments, maximum estimated depth of sub-surface structures (hereinafter referred to as "FAD depth"), FAD surface structure length and width, and the mesh size of the net, if used. Records of FAD characteristics increased over the 2011–2016 period (see Table 1 and Table A1 in Appendix for each observer programme), with currently around 25–30% of the associated sets also having detailed FAD information recorded by the observer. The main FAD structure material was the characteristic most often recorded.

Table 1. FAD (drifting FADs excluding logs) characteristics recorded by observers by year. See Table A1 in Appendix for rates of FAD characteristics recorded by each observer programme.

Year	Observed associated sets	% Depth	% Depth & dimensions	% Structure material	% Structure & attachment material	% All FAD characteristics
2011	7916	8.4	7.8	8.9	8.9	7.6
2012	7492	17.4	17	18.4	17.7	16.3
2013	8052	31.6	30.2	34.5	33.1	28.9
2014	8009	31.5	31.2	33.5	29.1	27.1
2015	5774	26.7	26.5	28.5	27.1	25.6
2016	3197	23.4	23.3	26.7	24.6	21.4

We also considered two environmental factors: the thermocline depth (using the 15°C isocline) (Source: ECMWF Ocean reanalysis System 4) and values of the Southern Oscillation Index (SOI) by month to identify ENSO periods (El Niño, La Niña or Neutral) (source: NOAA National Climatic Data Center). Years with a majority of months classified in one of these periods were classified accordingly.

Finally, to investigate the influence of vessel and FAD characteristics and environmental variables independently of spatial influences, the WCPO was divided into three areas (West 130°E–163°E, Central 163°E–175°W, East 175°W–150°W) based on visual examination of bigeye catch and CPUE (see Figure 1).

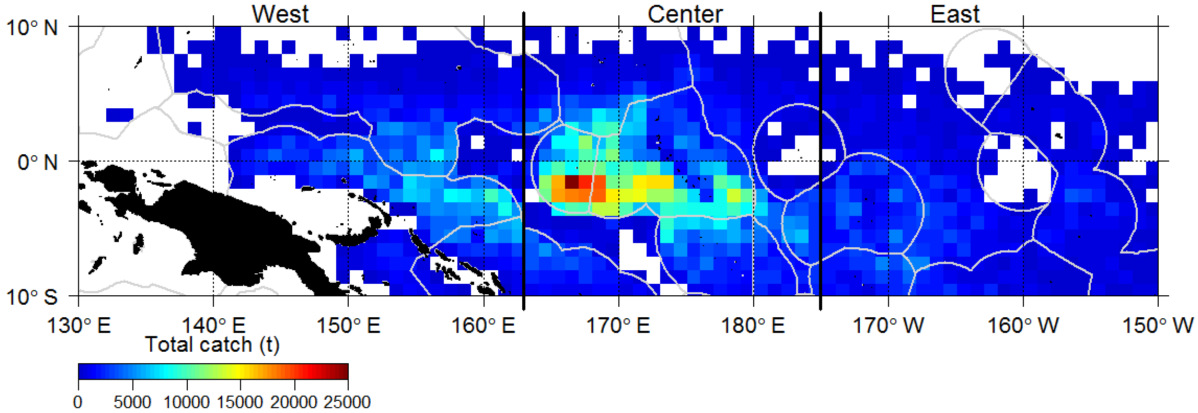

Figure 1. Total catch of skipjack, bigeye and yellowfin tuna in the Western and Central Pacific Ocean between 2011 and 2016 derived from observer data.

2.2. Analysis of factors related to the occurrence of bigeye tuna in purse seine catches

2.2.1 Clustering sets based on BET catches

Fishing sets were classified based on the bigeye tuna catch per set using a hierarchical clustering method based on Ward minimum variance (Tidd et al., 2016). This was done i) on the full dataset; ii) by geographic area (Figure 1); iii) by ENSO period; and iv) by area and ENSO period. Classification based on species composition (proportion of each of the three main tuna species in the global tuna catch) was also tested but resulted in less significant clustering, as some sets having a high proportion of bigeye could correspond to very low catch. Therefore, we decided to only use clustering based on bigeye tuna catch per set as more closely representing stock impact. The output of the clustering consists of a dendrogram and number of statistics (e.g. cubic clustering criteria, pseudo t^2 and Hubert index) that were used to select the clusters.

2.2.2 GLM / GAM

Statistical models were used to identify major factors influencing bigeye catch per set. Explanatory variables included i) area or latitude/ longitude, month, year; ii) vessel characteristics: length, gross tonnage, storage capacity, speed, crew count, age, helicopter presence, net depth and length and number of speedboats; iii) FAD characteristics: depth, surface area (length x width), type of main structure and type of attachment; iv) SOI index and thermocline depth; and v) one first-degree interaction term between variables (considering the number of variables and to keep the model simple). Correlation between variables was examined using Pearson Correlation Index. Generalized linear models and generalised additive models were tested using a two stage 'Delta' model approach. These models combine binomial (on presence/absence of bigeye catch) and log-normal (on sets with bigeye catch >0) models. Model selection was performed using a backward stepwise selection procedure based on AIC and BIC, residuals analysis, examination of predicted versus observed values, and deviance explained.

2.3. Characteristics of top bigeye tuna catching purse seine vessels

Consistent with the approach of Harley et al. (2015), the cumulative catch by each vessel was ranked to identify the top bigeye tuna catching vessels[1] each year, defined as those vessels that combined caught a specific percentage (25%, 50%, 75%) of the total associated purse seine bigeye catch during each year. Top vessels were also identified by areas separately, and an inter-area comparison was performed. The number of years in which specific vessels were found within the top 50% bigeye catching vessels was also assessed. However, as the total bigeye tuna catch varies each year, vessels listed as top vessels do not necessarily catch a specific amount of bigeye tuna. Therefore we also listed vessels catching more than 500t of bigeye tuna by year (i.e. as recorded by the observer), an arbitrary 'high' catch level.

The examination of the characteristics of the top vessels, relative to other vessels, is covered under section 2.2.2.

To investigate the potential reductions in bigeye tuna catch, as well as skipjack and yellowfin tuna catch, we simulated the elimination of the catch of the top vessels and the imposition of an annual 500t bigeye vessel limit. For the first, top vessels were defined as those catching 25% of the total bigeye by year, and the corresponding tuna catch by species from those vessels was calculated. For the second, to simulate the 500t bigeye vessel catch limit, for those vessels catching over this level we calculated the percentage of bigeye tuna catch by year in excess of 500t per vessel (between 30 and 45% of the bigeye catch per year for these vessels). To investigate the corresponding catch for skipjack and yellowfin tunas, we proportionally estimated the corresponding catch based on that proportion of the bigeye catch in excess of 500t per vessel (i.e. 30–45%). The decrease in the number of sets and skipjack and yellowfin catch for these vessels resulting from a 500t bigeye tuna vessel catch limit was then estimated by comparing these ratios to the actual total number of sets and skipjack and yellowfin catch each year.

2.4. Spatial management considerations

The presence of contiguous bigeye catch and CPUE hotspot regions were investigated using kernel density estimation and smoothed kriging maps by 0.5° grid cells ('kde2d' and 'filled.contour' function in R package MASS; Venables and Ripley, (2002)). Hotspots were examined using the full data set across all years and then for each bigeye cluster and year separately. In order to compare the spatial distribution of bigeye catch and CPUE between observer data and S-BEST raised logsheet data (stratified by 1x1 degree, month, flag and set type, where catch by species is corrected using observer-based grab sampling corrected for selection bias and is the data used in stock assessments), hotspots were also examined using the latter dataset over the period 2000–2016. A longer period of time was used as data were available and it allowed the spatial stability of the hotspots over the longer term to be investigated.

To examine the impact of a spatial management approach, we simulated a reallocation of the sets performed in the catch and CPUE hotspot areas to the rest of the WCPO (i.e. to model the impact of

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[1] Vessels in each area that caught the most bigeye are from here on referred to as the 'top vessels'.

a full spatial closure). Therefore, the reallocation of the sets over the remaining 'open' area was made proportionally by 1° grid cell based on the number of sets made in each cell by year. Simulated catch by species was based on the corresponding CPUE by 1° grid cell. These calculations aimed to identify the potential reductions in overall bigeye tuna catch assuming: i) no catch was taken in the hotspot area and the effort was redeployed elsewhere on FAD sets; and ii) the fish within the hotspot were not later caught outside the area.

3. Results

3.1. Factors related to the occurrence of bigeye tuna in purse seine catch

3.1.1 Clustering sets based on BET catch

Each clustering analysis (general, by area, by ENSO period, or by area and ENSO period) based on bigeye tuna catch by set, classified purse seine associated sets into five groups with increasing bigeye catch, as well as bigeye proportion per set (Very low; Low, Medium, High, Very High) (Figure 2 and 3 and Table A2). Vessels were found to perform some sets in each of the five bigeye catch clusters suggesting varying level of bigeye catch depending on the set. We investigate what influences the variation in bigeye catch per set for the same vessel (see sections 3.1.2 to 3.1.5).

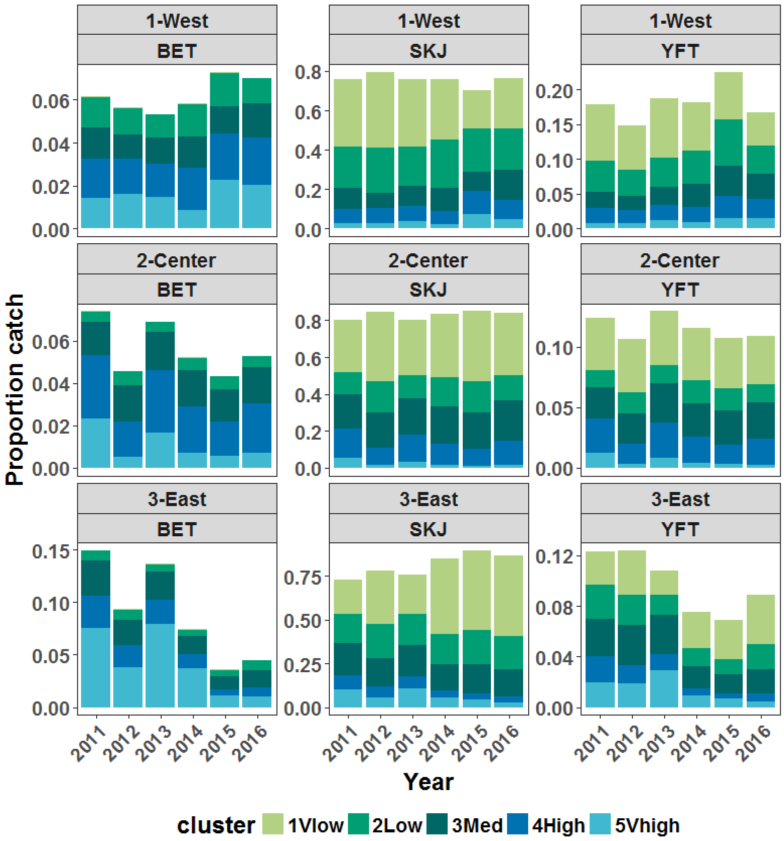

Figure 2. Proportion of each species catch over the total catch by area and year.

The 'Very Low' bigeye catch cluster corresponds to the highest number of sets (31–59% of the sets by year and area) but almost no bigeye (<0.7% of the bigeye catch by year and area) (Figure 2 and Table A2). The 'Very High' cluster corresponds to 1–10% of associated sets, with a higher number in the East where it represents 32–51% of the bigeye catch. In this Eastern area, the bigeye catch makes up to

15% of the total tuna catch (i.e. 2011 and 2013, see Figure 2). However, we note a sharp decrease in the observed bigeye tuna catch over time, particularly in the East, which was not counterbalanced by any increase seen in the West. Also note that while bigeye proportion per set increase with the bigeye catch cluster considered in all three areas, species composition in sets were highly variable (Figure 3).

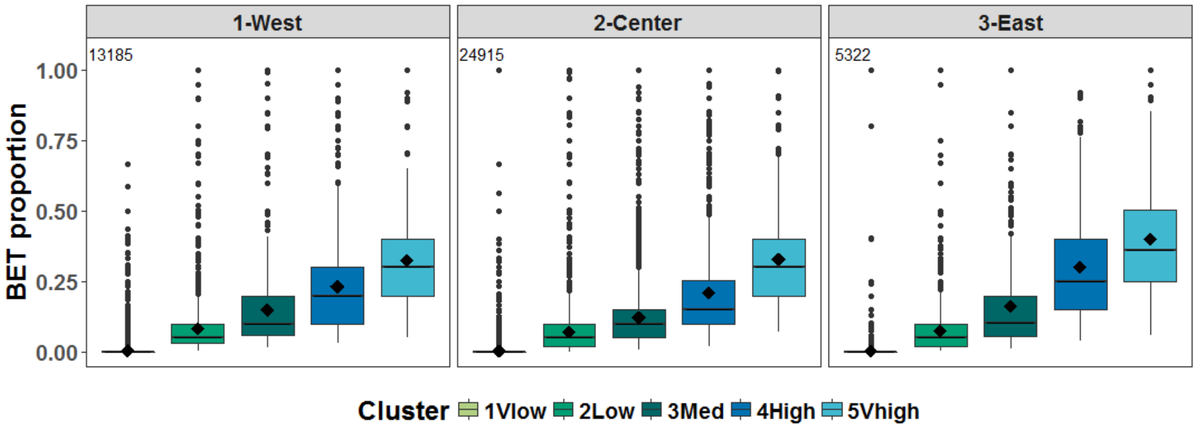

Figure 3. Bigeye tuna proportion over total catch by set for each cluster and by area. Numbers at the top left indicate the number of sets for each area.

3.1.2 Vessel characteristics

In the Eastern area around 50% (7–13% of the bigeye catch of the whole WCPO) of the annual bigeye catch prior to 2015 was made by five very large (>90m) and powerful vessels (Figure 4, A5 and A6). At the scale of the whole WCPO, these very large vessels caught 11–15% of the bigeye catch and 4–8% of total tuna catch prior to 2015. These vessels also mostly made sets classified in the 'Very High' cluster category (bigeye CPUE >40 t per set, Table A2). In 2015 and 2016, most of these large purse seiners did not operate in the WCPO. The bigeye catch in the East in those years was therefore made by medium-sized vessels (Figure 4). In the Western and Central areas, bigeye tuna catch was made by smaller and less powerful vessels. However, among this medium-sized group of vessels, a small shift over time can also be detected, with relatively larger vessels catching a larger proportion of bigeye tuna in recent years (Figure 4, A5 and A6). It should be noted that large vessels (>90m) performed a higher proportion of associated sets (>75% of the total number of sets by vessel and by year) compared to smaller vessels (25–70%). This suggests a greater reliance on associated fishing techniques by these larger vessels.

Some fleets also tended to catch more bigeye tuna, but this varied with area and year (Figure 5 and A7). For instance in the Central region, fleets from Chinese Taipei, Republic of the Marshall Islands and United States, each captured more than 10% of the overall bigeye tuna catch during some years. Similarly, in the East, one of the main fleets catching bigeye was the EU fleet, especially in 2013 and 2014 with more than 10% of the overall bigeye tuna catch in that area.

Investigation of vessel characteristics by cluster showed increasing catch of bigeye (i.e. from Very Low to Very High cluster) with an increase in vessel size, engine power, speed, storage capacity and number of speedboats. Such differences in vessel characteristics were less clear for the general clustering on the full dataset (Figure A8). This pattern was most pronounced in the Eastern area (Figure 6), but no difference was found in vessel characteristics among clusters in the Western and Central areas. Spatial differences in the vessel characteristics among cluster is explained by the presence of large vessels in

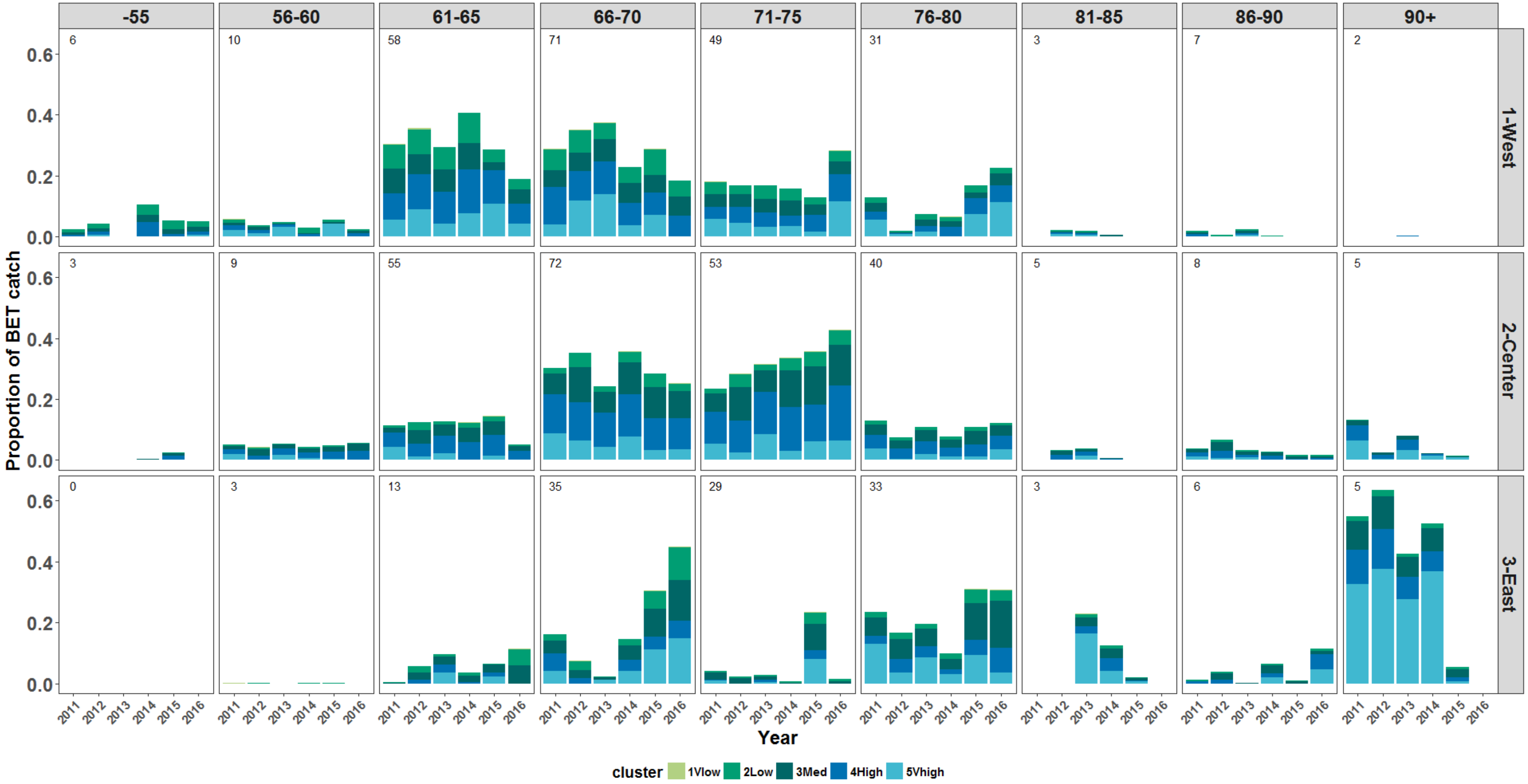

Figure 4. Proportion of bigeye tuna catch by area and year by vessel length (m) category. Numbers in each box represent the total unique number of vessels operating by category and area over the 2011–2016 period.

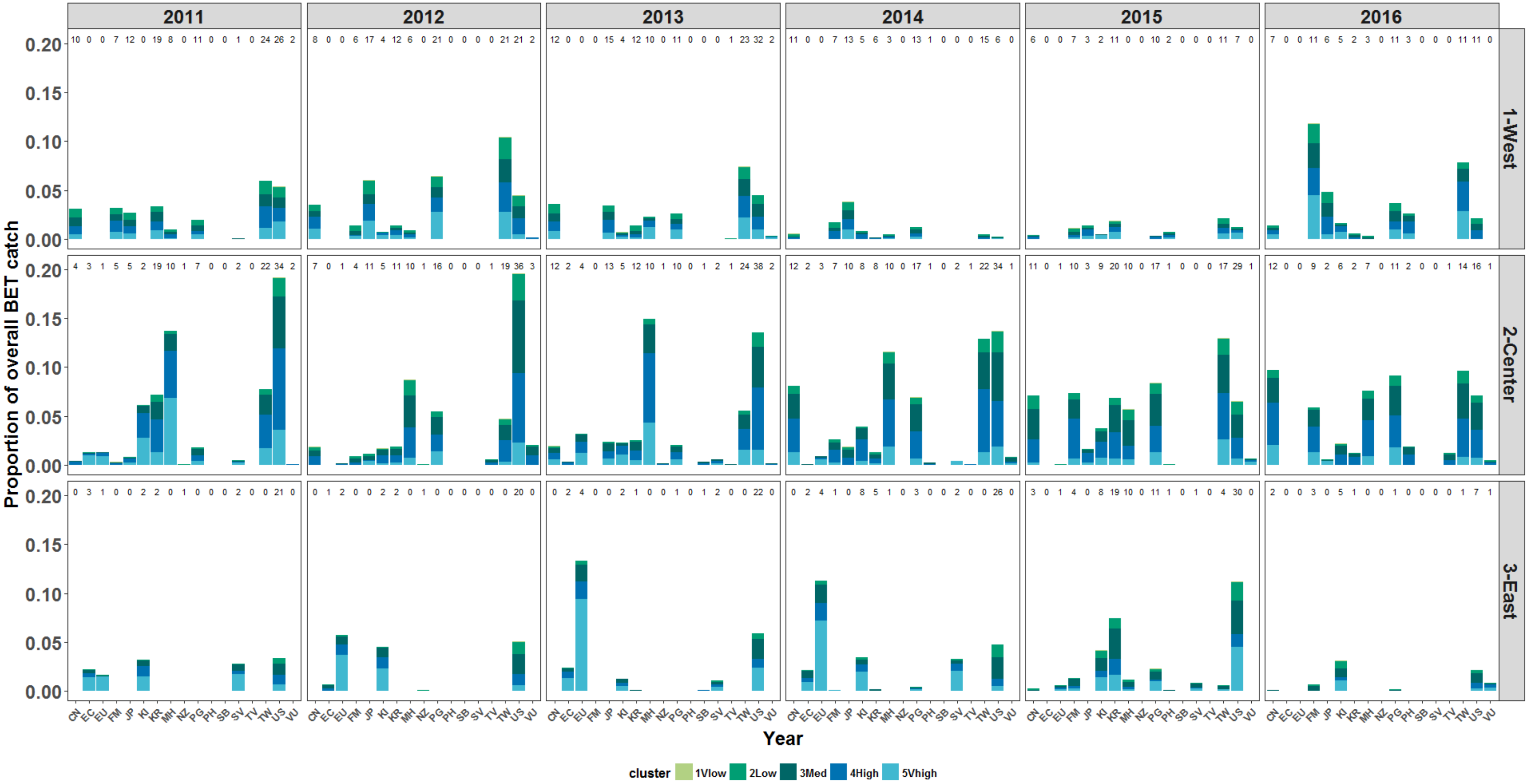

Figure 5. Proportion of overall bigeye tuna catch by area and by year by purse seine fleet. Numbers in each box represent number of vessel operating by fleet and by year in each area.

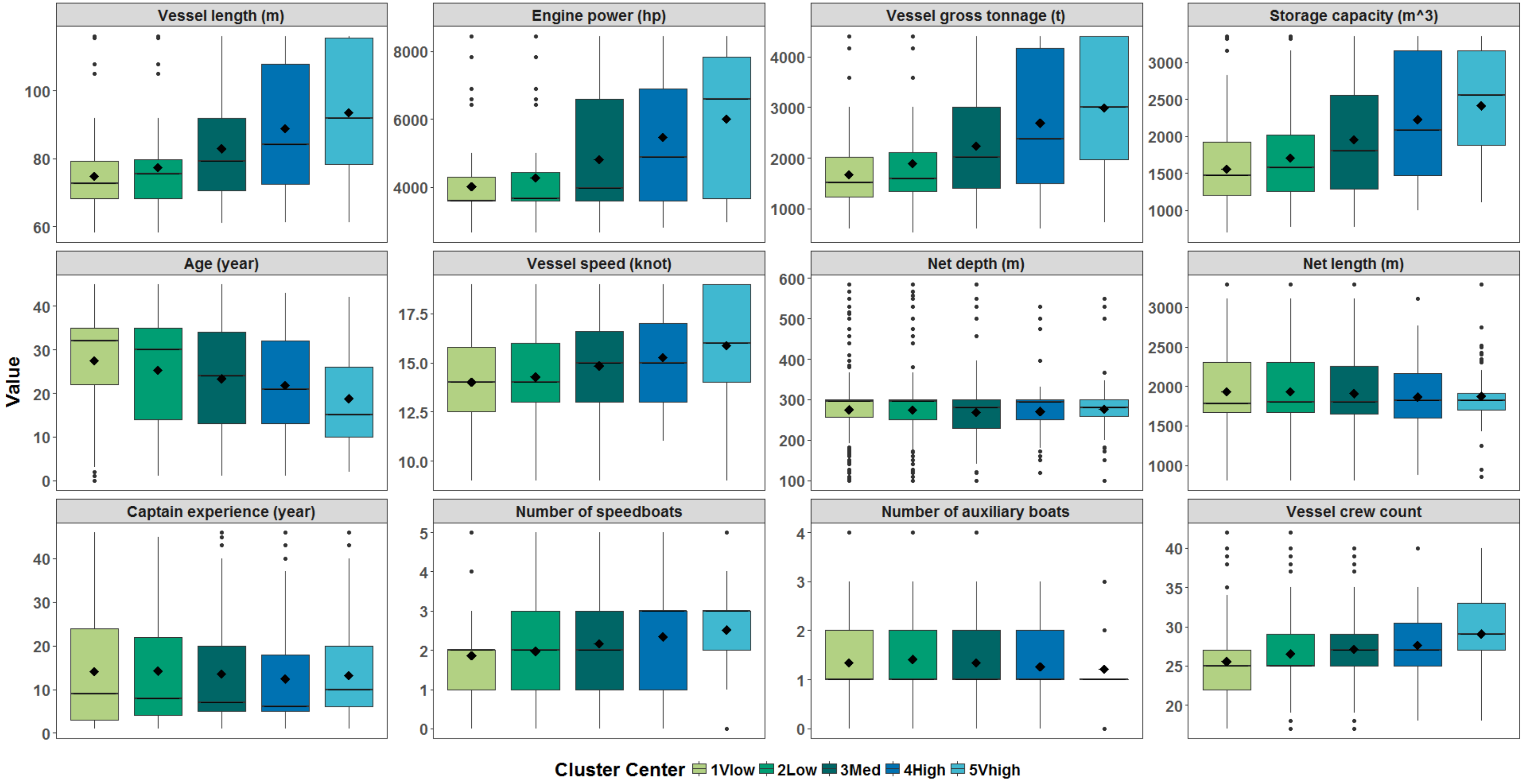

Figure 6. Characteristics of vessels with sets in each individual bigeye catch cluster, from clustering in the Eastern area only (see Supplementary Figure A7 for general clustering).

the East; and is not detected in 2015 and 2016 (Figure A9) when some of these large vessels were no longer fishing in the WCPO. Neither net depth nor net length appeared to influence the bigeye tuna catch.

It should be noted that vessel length, engine power, gross tonnage and storage capacity of vessels are highly correlated (Pearson correlation index >0.8). Length is also correlated with vessel speed, age (negatively) and vessel crew count (Pearson correlation index between 0.2–0.4). In effect, larger vessels are newer, faster, more powerful, and have greater storage capacity. However, some vessels, including these large vessels tend to stay within an area, which makes it difficult to separate the vessel effect from area effect.

3.1.3 FAD characteristics

Associated sets included in this study are mostly made on drifting constructed (man-made) FADs, but log sets account for up to 30% of associated sets in the West (Figure A10 to A13) with no cluster distinctions. In the Central and Eastern areas, fewer log sets are performed and these fall mostly into clusters with lower bigeye catch (except in 2016, where the low overall number of associated sets add a bias in these proportions) (Figure A10). Therefore, in the West, where logs are abundant, no clear pattern in terms of tuna catch can be detected between logs and constructed FADs. In the Central and Eastern areas, logs seem to aggregate fewer bigeye than constructed FADs. This may be due to the size or/and depth of logs compared to constructed FADs. However, it is still hard to draw any conclusion on a constructed FAD/log difference due to the low number of log sets in these areas (particularly in the East). The fact that log sets were mostly classified in clusters with low bigeye catch could simply be due to top vessels deliberately choosing not to perform log sets (i.e. constructed FADs are easier to locate, tuna school sizes potentially estimated with echo-sounder buoys, etc.).

Few differences in the constructed FAD dimensions by cluster are detected in the Western and Central areas (Figure 7). On the other hand, in the East, FADs with higher bigeye catch had shallower sub-surface structures and were slightly larger (in terms of surface area) (Figure 7). This could be linked to some fleets using very specific FAD designs which are noticeable in the East where fewer different fleets are operating. For instance, it appears that European Union and Ecuadorean vessels, fishing mainly in the East, deploy FADs with attachments around 30–40m deep, and have a main structure of 2x2m (see Figure A14) made of bamboo and floats (Figure A15) with a combination of net and another material (rope, sacking, fronds etc.) as attachments (Figure A16). However, these differences are not significant, considering the low number of sets from European Union and Ecuadorean vessels with FAD information compared to the other fleets.

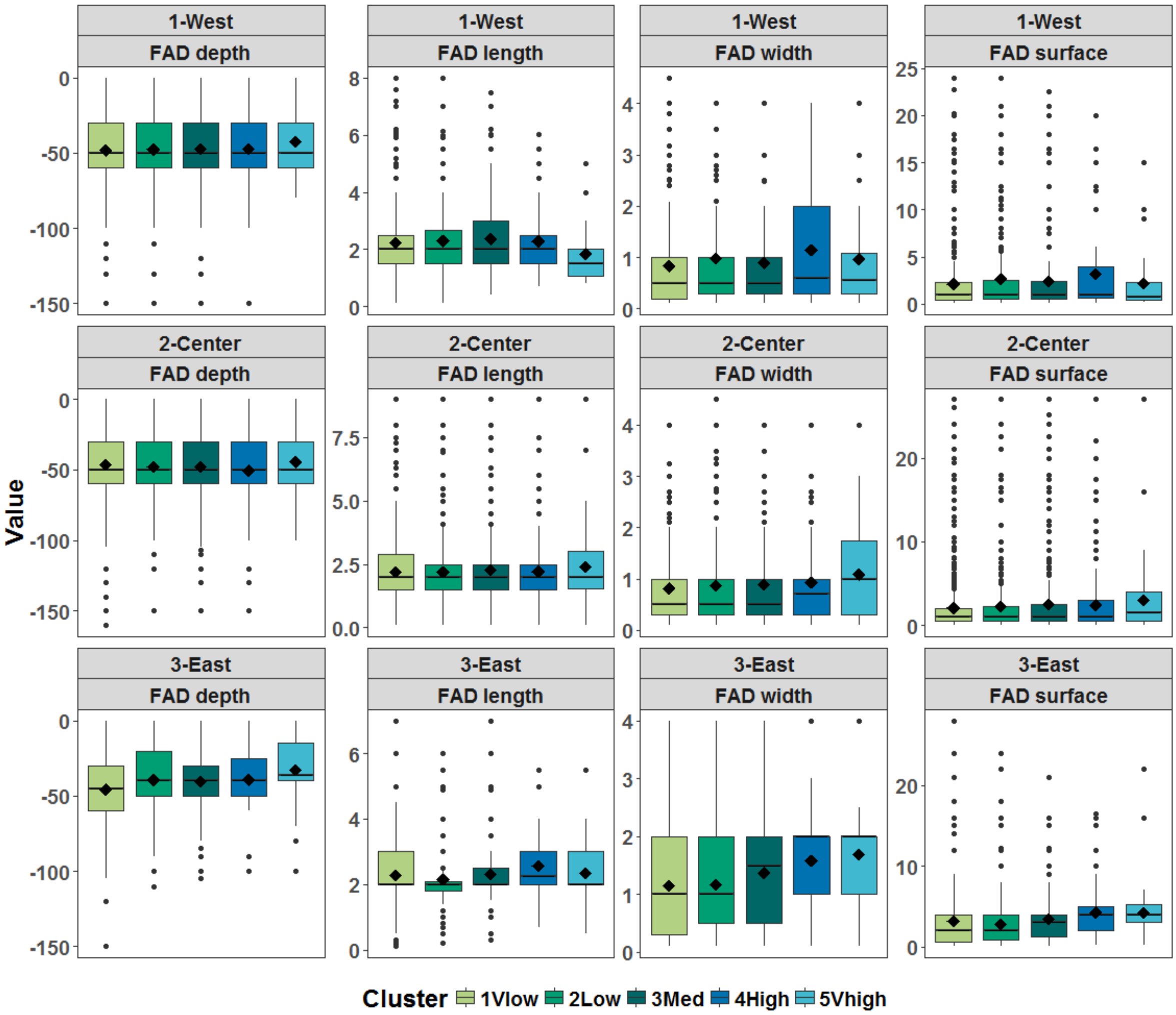

Figure 7. Drifting constructed FAD dimensions by cluster and by area.

Further investigations of FAD maximum attachment depth information showed some differences between areas (Figure 8). In the Western and Central areas, most FADs (more than 35%) had attachments 50–70m deep, which corresponded to the FADs with the highest proportion of bigeye catch in these areas (Figure 8). In the East, most FADs (18%) had a maximum depth of 40–50m, with 25% of bigeye catch taken when fishing on FADs within this depth category, followed by 30–40m category (18% of bigeye catch). Note that in this Eastern area the 50–60 and 60–70m FAD depth categories which were common in the other areas still corresponded to more than 25% of FADs, but less than 16% of the bigeye catch. In addition, a second small peak in bigeye catch is detected for shallow FADs (<20m) in the East even if the proportion of FADs in this depth category was relatively low. Therefore it appears that bigeye catch ‘per FAD set’ is higher on FADs in the 0–20m and 30–50m depth categories in the East and 50–60m in the West, which is not detected for total tuna catch (Figure 8). This suggests a potential interaction between the depth of FAD sub-surface structures and local oceanographic conditions.

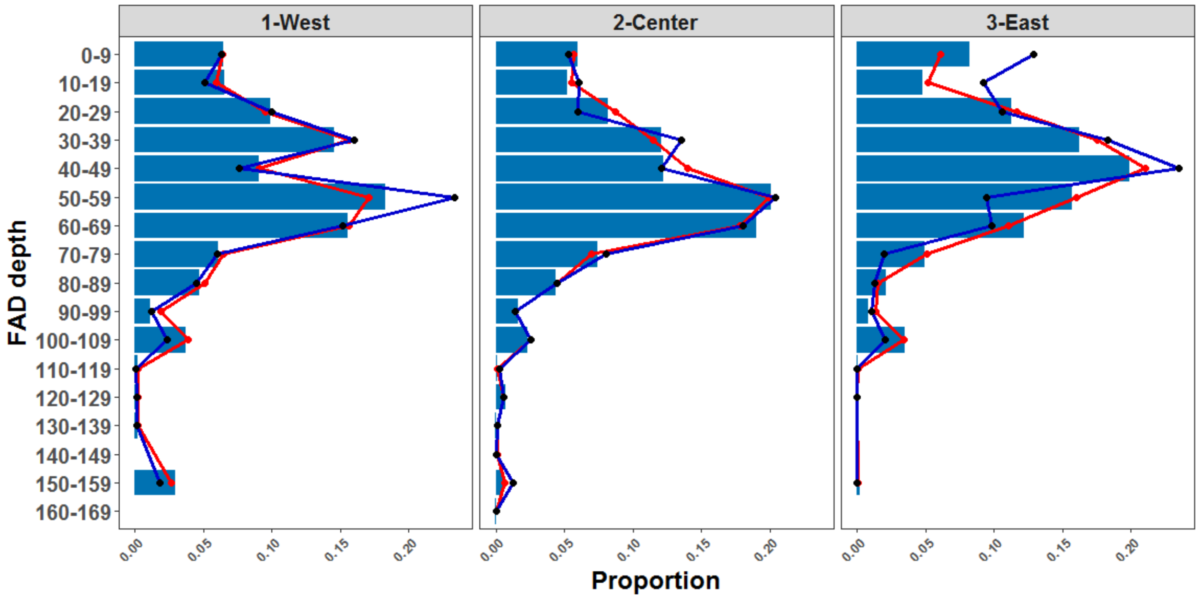

Figure 8. Proportion of drifting constructed FADs by depth, blue lines represent the proportion of bigeye catch by FAD depth category and by area and red lines the proportion of total catch (for FADs with depth recorded by observer, i.e. 2816 (21.4%); 5543 (22.2%) and 1502 (28.2%) observations in the West, Center and East, respectively).

See also Figures A17 to A20 for the proportion of constructed FADs and logs with certain types of attachments and main structure materials.

3.1.4 ENSO periods and thermocline depth

First, it should be noted that over the period considered, only one El Niño year (2015) and one La Niña year (2011) are included, with the remaining four years representing Neutral periods. Higher bigeye CPUE but lower catches were observed in the East during La Niña conditions than the El Niño year, with the opposite pattern in the West (See Figure A21). In the Central area, both catch and CPUE were higher during La Niña conditions compared to El Niño. In addition, in the Eastern area, bigeye catch represented almost 10% of the total catch during La Niña and Neutral conditions, but 3% during the recent El Niño (Figure A22). However, as mentioned previously this may be influenced by the presence/absence of some vessels, for instance during the El Niño year most large vessels did not operate in the WCPO.

Generally, the thermocline is shallower during El Niño and deeper during La Niña (as shown in all areas in Figure 9), particularly in the Western WCPO. In the East, the thermocline is deeper during El Niño than during La Niña and Neutral conditions. No pattern can be identified with bigeye catch clusters in the Western and Central areas (Figure 9), whereas in the East sets with higher bigeye catch occurred where the thermocline was shallower. This was expected, as in these cases, bigeye tuna, restricted to the epipelagic waters, are potentially more available to purse seine nets. Increasing bigeye catch was pronounced with decreasing thermocline depth in the Eastern area during La Niña and Neutral periods. During El Niño, while the thermocline depth was generally deeper in the Eastern area, areas where associated sets were performed corresponded to a local relatively shallow thermocline (200–250m, see Figure 9), hence no clear trend was detectable with bigeye catch cluster.

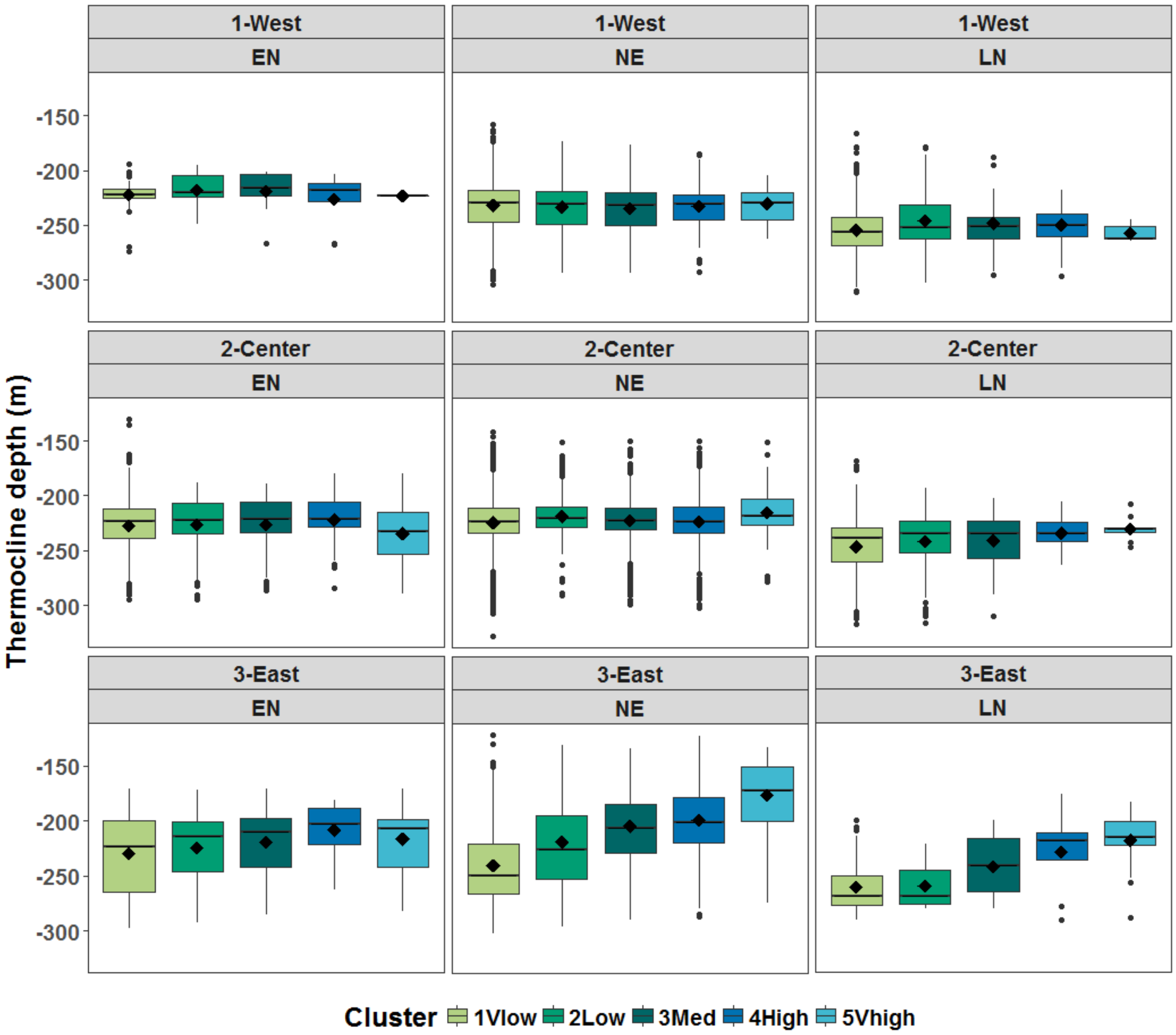

Figure 9. Thermocline depth in the location of each associated set by cluster, area and ENSO period. (EN = El Niño, NE = Neutral, LN = La Niña).

3.1.5 Statistical models

Delta GAMs using binomial and log normal models applied to bigeye catch data by area showed the best performance. Models explained 8.1 to 26.7% of the deviance for the binomial component and 13.4 to 36.9% for the log normal model component (see Table 2). In particular, the model developed for the Eastern region explained more of the variability in bigeye catch per set. The main explanatory variables differed in the binomial and log normal models, and by area. However, in both models engine power, gross tonnage and storage capacity were not included as they are highly correlated with vessel length. Similarly, latitude/longitude and years were not included, as they are highly correlated with SOI and thermocline depth, which were no longer significant if the temporal and spatial variables were added.

First, the presence of bigeye in a set was influenced by: the size of the vessel (length, crew count, speed, age) in the three areas; SOI (especially in the Central and Eastern areas); the length and depth of the net; as well as FAD depth in the Western and Eastern areas (Table 2). Larger vessels, as well as longer/deeper net depth therefore corresponded with higher bigeye presence rates. Bigeye occurrence in a set was also higher for negative and positive values of SOI (i.e. La Niña and El Niño compared to neutral). Concerning FAD depth, higher bigeye occurrences corresponded to sets on FADs with sub-surface depths around 50m in the West, and around 10m and 40m in the East.

Secondly, concerning the log normal models (amount of bigeye caught given presence in a set's catch), thermocline depth explained the most deviance in the Eastern area (Table 2), with thermocline around 175m and shallower corresponding to higher bigeye catch per set. In this area and in the Center, vessel length, age and crew count (larger vessels catching more bigeye), as well as net depth (deeper nets corresponding to higher bigeye catch) also presented relatively high influence on bigeye catch rates. In addition, the type of FAD attachment (the combination of net, weights and another material leading to more bigeye catch) in the Center and the dimension of the FAD (higher surface corresponding to higher catch) in the East also influenced catch rates. In the West, catch rates appear influenced by ENSO periods (La Niña), FAD depth (higher bigeye catch in depth of 60–70m) and the type of FAD structure (logs, bamboo raft and Bamboo with floats corresponding to higher bigeye catch).

Table 2. Binomial (Bin.) and log normal (LogN) models by area and list of significant variables by area with corresponding percentage of deviance explained. % Dev = total percentage of the deviance explained by each model; R^2 = pseudo coefficient of determination.

	West				Center				East		
	Bin.		LogN		Bin.		LogN		Bin.		LogN
% Dev	8.1		13.4	% Dev	14.2		13.1	% Dev	26.7		36.9
R^2	0.09		0.11	R^2	0.15		0.11	R^2	0.27		0.33
Crew Count	24.3	SOI	21.2	Age*Net length	20.5	Age	24.4	Crew Count	19.3	Therm.	27.6
Net depth	15.7	FAD depth	19.6	SOI	18.8	Length	15.3	Length	16.1	Length*Age	20.0
FAD surface	12.3	FAD str.	15.0	Age	12.2	Therm.	14.6	Speed	15.5	Length	17.8
Net length	10.0	SOI*Net Length	14.7	Length	11.3	Age*SOI	13.9	SOI	13.3	Net depth	12.0
FAD depth	9.1	Age	13.4	Net depth	10.4	FAD att.	10.2	FAD depth	10.8	SOI	7.9
SOI	8.5	Net length	10.8	Net length	6.5	Net depth	10.1	Net depth	10.7	Speed	6.8
Length	8.0	Heli.	5.3	Therm.	6.2	SOI	8.6	Net length	8.6	FAD surface	4.1
Speed	6.4			Speed	5.0	Crew Count	2.9	Age	4.5	Age	3.8
Therm.	5.8			Crew Count	4.9			Therm.	1.2		
				FAD att.	4.3						

3.2. Characteristics of top bigeye tuna catching purse seine vessels

The number of top vessels (classified here as those taking 50% of the bigeye catch) in each year varied between 23 and 34 vessels (Figure 10 and Table A3). While the total associated catch of these vessels is also relatively high, bigeye catch is disproportionately high compared to total associated catch (Figure 10). Thirty-three individual vessels were listed as top vessels in at least two years between 2011 and 2016, and seven individual vessels were present in more than three years (see Table 3). Most large vessels (>90m) were classified as top vessels in the years they were operating in the WCPO. In addition, while no difference in the total number of sets between top vessels and the rest of the vessel could be distinguished, prior to 2015 top vessels performed more associated sets than others (>50% of the sets by these top vessels). This may therefore indicate potential different fishing strategies between vessels.

Vessels catching more than 500t of bigeye tuna by year (Table 4 and A4) were also found mostly in the top vessels set in Table 3. For these vessels, the ‘limit’ of 500t of bigeye tuna was exceeded predominantly in 2011 and 2013.

In terms of spatial distribution of top vessel associated sets, most of the sets performed in the Eastern area were made by top vessels, regardless of the bigeye catch cluster those sets were allocated to (see Figures A23 to A25). This indicates that while some top vessels are found in each of the three regions, almost all vessels operating in the East have been classified as top vessels (note that there are fewer vessels operating in the East compared to other areas). In addition, sets in High and Very high bigeye catch clusters performed by top vessels in the Eastern area presented a very high proportion of bigeye tuna over total catch per set (on occasion the bigeye proportion of the total tuna catch exceeded 50%) (Figures A26 and A27).

It should also be noted that when classifying top vessels by area, top vessel lists were very different between areas, probably due to the fact that many fleets mostly operate in a single area in a specific year.

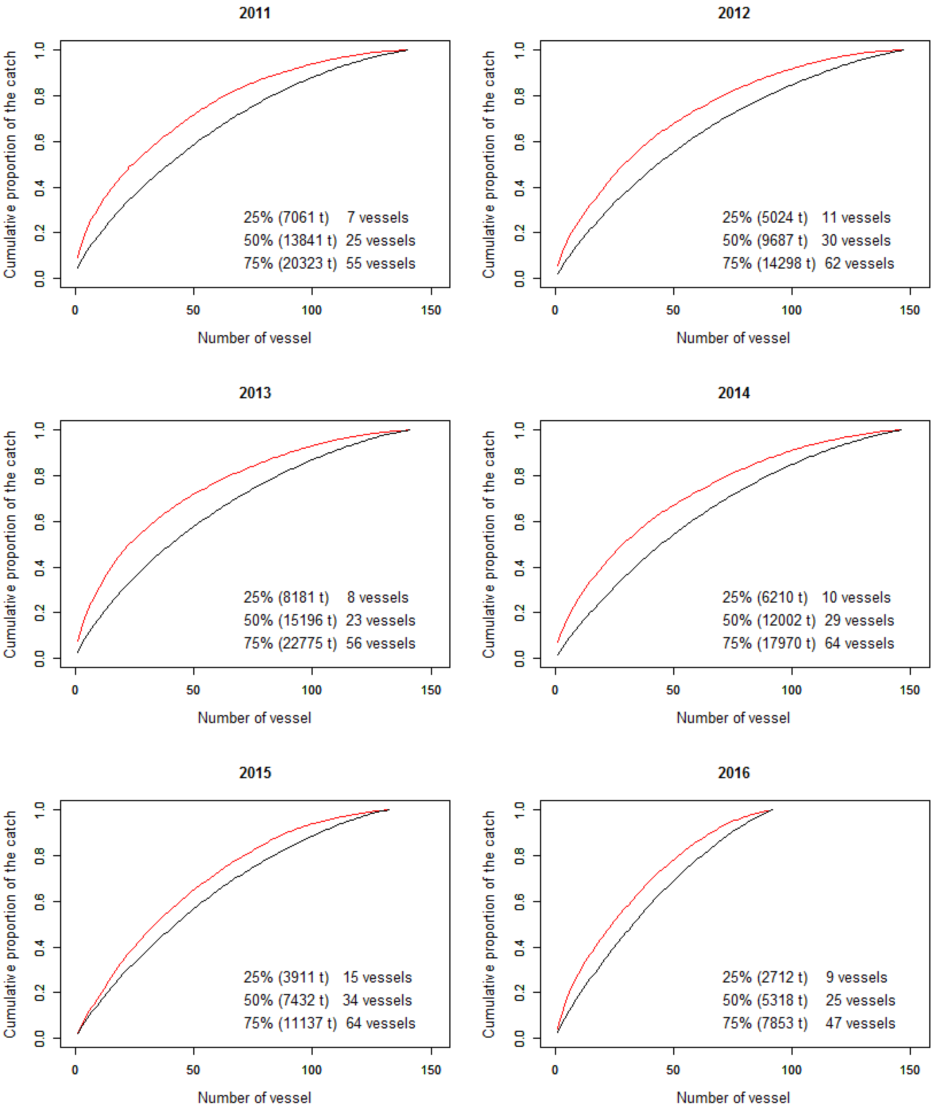

Figure 10. Cumulative proportion of bigeye tuna catch (red) and total tuna catch (black) as a function of number of vessels. Number of vessels catching 25, 50 and 75% of bigeye tuna catch and corresponding tonnage are given each year.

Table 3. Anonymised list of top vessels in at least two years between 2011 and 2016. For each vessel its length and areas (W = West, C = Center, E = East) in which they operated are given. Numbers indicate the rank each year.

Vessel number	Flag	Length (m)$^{\alpha}$	Operating Areas	2011	2012	2013	2014	2015	2016
1	KI	80+	C / E	1	1	6	6	14	
2	US	71-75	W / C / E	4	10	23	5	18	
3	MH	71-75	W / C*	17	18	20	24		6
4	MH	71-75	W / C / E	2	25	21	18		
5	EU	80+	C / E	3	2	10	8		
6	MH	61-65	W / C*	5	12	16	14		
7	MH	71-75	W / C*		30	18	7		24
8	US	71-75	W / C / E	8	29			24	
9	EU	80+	C / E		3	1	1		
10	MH	61-65	W / C*	9		5	10		
11	MH	71-75	W / C*	10	20		4		
12	JP	61-65	W / C		11		28	6	
13	CN	66-70	W / C*		14		22	26	
14	TW	66-70	W / C		16	9	16		
15	TW	71-75	W / C*				13	16	22
16	PG	71-75	W / C*				25	20	9
17	US	66-70	W / C / E		23	11		7	
18	US	71-75	W / C / E	6	13				
19	SV	80+	W / C / E	7			2		
20	US	76-80	W / C / E	11					11
21	KR	76-80	W / C*	18				9	
22	MH	71-75	W / C*	19		4			
23	KR	71-75	W / C*	21				30	
24	US	66-70	W / C / E		5	12			
25	US	76-80	C / E		9	15			
26	US	71-75	W / C*		24			34	
27	EU	80+	C / E			2	3		
28	KI	66-70	W / C / E				11		17
29	CN	71-75	W / C				9		14
30	KI	66-70	W / C / E				26		18
31	FM	80+	W / C / E				29		5
32	TW	71-75	W / C					19	16
33	FM	76-80	W / C / E					28	2

* Vessels operating in the West and Center most years and in the East in 2015 only.

$^{\alpha}$ Length category. Note that the length categories above 80m have been merged to anonymise the vessel list.

When defining a top vessel as those catching 25% of the bigeye catch per year (7–15 vessels, Figure 10), these vessels captured 9–15% of both the skipjack and total tuna catch by year (Table 5 and Table A3). Similarly, the bigeye catch in excess of 500t per vessel represented 4–15% of the total bigeye catch in the WCPO between 2011 and 2014 (Table 5 and see Table 4 for vessel list). No vessel caught more than 500t of bigeye in 2015 and 2016 (Table 5). Therefore in the example that an annual 500t bigeye vessel limit was in place, a 4–15% reduction in bigeye catch could be achieved for a decrease of 1 to 7% of the skipjack and total tuna catch (based on 2012 and 2013, Table 8). However, this simulation only accounted for FAD sets and considered that the vessel stopped fishing once it reached the 500t bigeye catch limit. An alternative approach could consider that when a vessel reached 500t of bigeye tuna it could no longer perform FAD sets, which could reduce the impact on total skipjack catch. Note that in 2011 and 2013, 11% and 15% of the bigeye catch was represented by the catch above 500t per year of some vessels.

Table 4. Anonymised list of vessels catching more than 500t of bigeye tuna in at least one year between 2011 and 2016, showing annual bigeye catch per vessel. For each vessel its length and areas (W = West, C = Center, E = East) in which they operated are given. Shaded cells indicate bigeye catch above 500t, blank cells no bigeye catch (e.g. vessel not operating in the WCPO).

Vessel number	Flag	Length (m)[α]	Operating Areas	2011	2012	2013	2014	2015	2016
1[#]	KI	80+	C / E	2471	1055	728	486	233	
9[#]	EU	80+	C / E		514	2262	1722		
5[#]	EU	80+	C / E	787	599	606	476		
27[#]	EU	80+	C / E			1071	556		
19[#]	SV	80+	W / C / E	564		180	642	114	
10[#]	MH	61-65	W / C*	509	90	779	401	136	92
4[#]	MH	71-75	W / C / E	1105	233	365	310	129	
34	EU	80+	C / E			1044	163	92	
22[#]	MH	71-75	W / C*	329	130	964	81	101	77
2[#]	US	71-75	W / C / E	763	312	347	498	224	
6[#]	MH	61-65	W / C*	758	285	464	355	50	77
35	MH	71-75	W / C*	56	57	680	138	96	88
36	MH	71-75	W / C*	110	187	652	119	133	98
18[#]	US	71-75	W / C / E	614	274	122	106	55	59
14[#]	TW	66-70	W / C	203	265	609	338	25	72
17[#]	US	66-70	W / C / E	218	243	561	202	260	122
24[#]	US	66-70	W / C / E	272	431	553	223	66	35
37	EC	80+	C / E	265		528	199		
38	US	80+	C / E	28	37	518	25	12	
8[#]	US	71-75	W / C / E	511	199	85	136	184	104
11[#]	MH	71-75	W / C*	487	252	269	506	88	

[#] Top vessels listed in Table 3.

* Vessels operating in the West and Center most years and in the East in 2015 only.

[α] Length category. Note that the length categories above 80m have been merged to anonymise the vessel list.

Table 5. Percentage of decrease in the total catch by species in case of i) the absence of the top vessel catching 25% of bigeye catch per year (7–15 vessels, see Table A3); and ii) a 500t of bigeye tuna catch limit by vessel and by year.

	Year	% BET	% SKJ	% YFT	% Total	% Ass. sets
Top vessels 25% bigeye catch	2011	-24.02	-11.53	-12.49	-12.61	-8.31
	2012	-24.85	-9.30	-11.38	-10.39	-8.74
	2013	-24.89	-9.89	-10.18	-11.01	-8.33
	2014	-24.31	-8.62	-9.98	-9.67	-7.92
	2015	-24.96	-14.68	-16.71	-15.31	-12.25
	2016	-24.14	-11.90	-15.18	-13.01	-11.35
Catch >500 t bigeye / vessel / year	2011	-11.08	-5.94	-5.43	-6.25	-4.60
	2012	-3.51	-0.87	-1.42	-1.08	-0.69
	2013	-14.50	-6.45	-6.38	-7.02	-5.69
	2014	-4.62	-1.51	-1.45	-1.68	-1.36
	2015	0.00	0.00	0.00	0.00	0.00
	2016	0.00	0.00	0.00	0.00	0.00

3.3. Spatial management considerations

In terms of spatial management considerations, Harley et al. (2015) highlighted the presence of two types of ‘bigeye hotspot’ areas: i) an area of high overall bigeye tuna catch, with small bigeye catch per set but high effort on associated sets; and ii) an area of high bigeye CPUE. These patterns were also detected in this study (note that both were also identified each year in the aggregated corrected logsheet S-BEST data), and we consider both as theoretical management scenarios.

When considering the area of high bigeye tuna catch across the study period, a hotspot can be identified within Nauru and the Western part of Kiribati’s Gilbert Islands EEZ (Figure 11). This corresponds to the area with the highest effort on associated sets within the WCPO (Figure A28). The temporal stability of this hotspot was examined (Figure 12; as well as among clusters see Figure A29) and, with the exception of 2015, the core area of this hotspot fell within the boundary of the hotspot for all years pooled (defined by the quantile 95% of the data). In 2015, a shift toward the East can be detected at the scale of the whole fishery and is likely linked to the strong El Niño event. As mentioned previously, the thermocline is shallower in the Central area making tuna more available to the purse seine gear. The percentage of bigeye tuna captured within the catch hotspot (quantile 95% across all years) ranged from 30% in 2015 to 48% in 2014 (Table 6). However, a similar proportion of the skipjack and total tuna catch was taken within the hotspot area, indicating that the skipjack and total catch of the three main tuna species is spatially confounded. We note that the catch hotspot is adjacent to the high seas pocket between PNG, Solomon Islands, Nauru and Kiribati, which was generally closed to purse seine fishing over these years. Although there is the potential for the catch hotspot to otherwise extend into this area, this could not be examined using the available historic data.

A comparison of the distribution of the catch hotspot from observer data and from S-BEST data was also performed to validate patterns observed using observer data (Figure A30 and Table A5). For the years considered in this study (2011–2016), similar patterns were found in terms of distribution of the catch hotspot (Figure 12 and A30) and percentage of bigeye and total catch made within this area (Table A5). We can however note that for the 2000–2010 period, the bigeye catch hotspot was less localised and distributed more to the West, over Papua-New Guinea and Federal States of Micronesia EEZs and International Waters (Figure A30), although in some years it still extended to the Nauru and Kiribati EEZs. It was therefore found that, during this period, 15–26% (with the exception of 2002 when it was 38%, corresponding to another El Niño year) of the bigeye catch and 15–22% (35% in 2002) of the total tuna catch was made in the 2011–2016 bigeye catch hotspot, compared to 24-38% and 23-41% for the 2011–2016 period (Table A5).

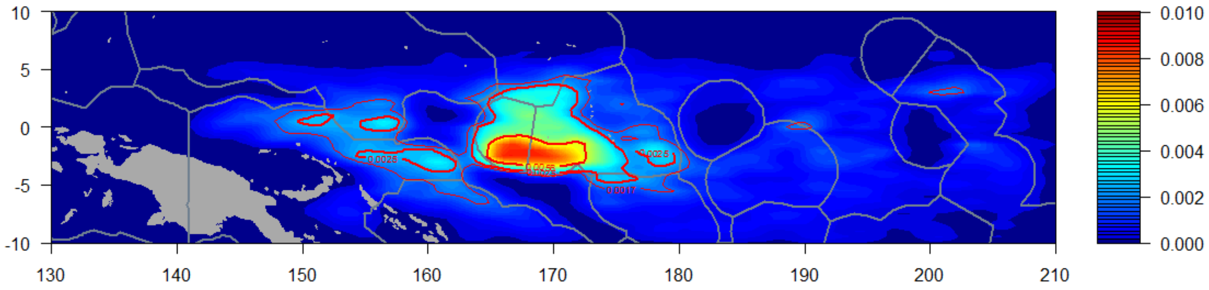

Figure 11. Smoothed kernel distribution of proportion of total bigeye catch over the 2011–2016 period for each 0.5° cell. Lines represent quantile 0.99 of proportion, quantile 0.95 and quantile 0.90.

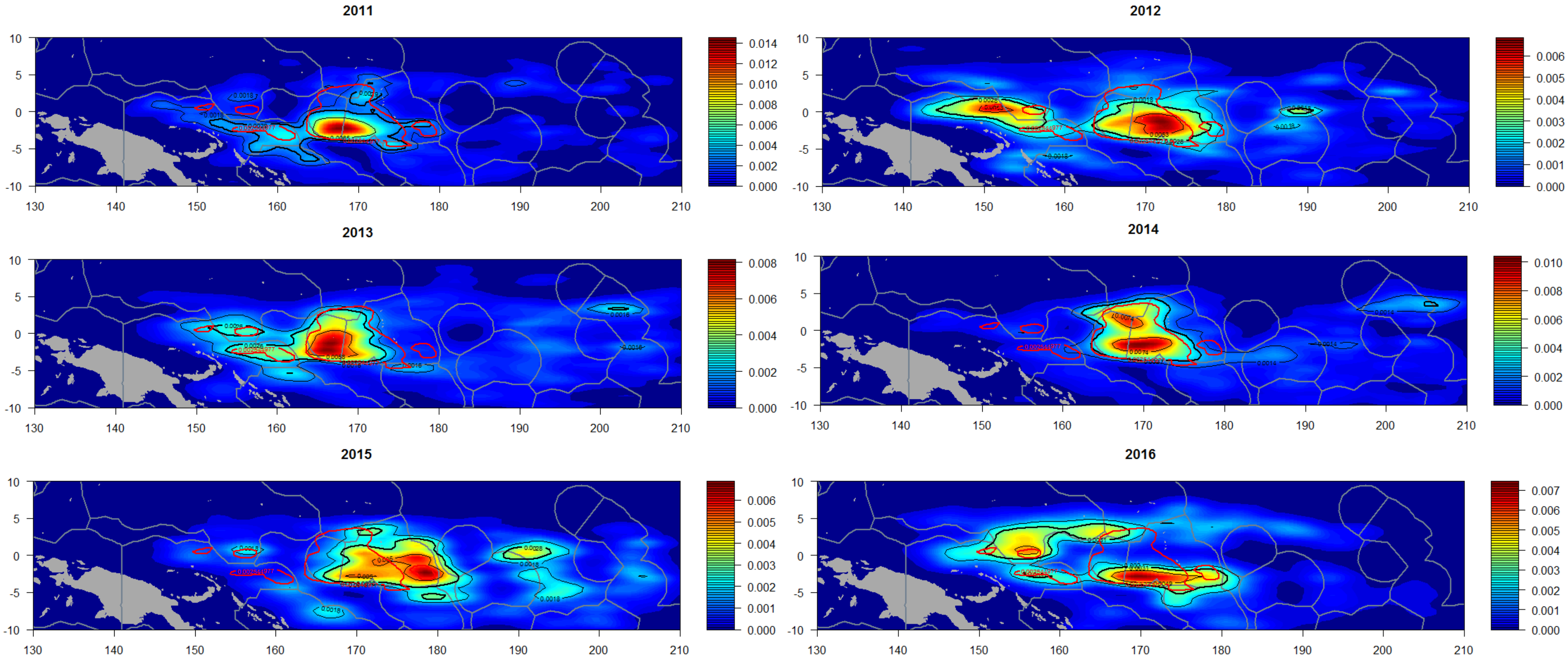

Figure 12. Smoothed kernel distribution of proportion of BET catch for each year for each 0.5° cell. Black lines represent quantile 0.99 of proportion, quantile 0.95 and quantile 0.90 by year, and the red line represents the quantile 0.95 for all years combined (see Figure 11).

In the simulation of a closure of the catch hotspot, with a reallocation of the sets to the rest of the WCPO, the closure could lead to a decrease of up to 11% of the total tuna catch and 17% of bigeye catch (based on 2011 fishing patterns), or an increase up to 10% of the total tuna catch (2015) and 3% of bigeye catch (2014) (see Table 6). Therefore, outcomes may vary based on environmental conditions (i.e. ENSO period influencing the thermocline depth). This suggests that a fixed spatial closure in the Central hotspot area is unlikely to achieve a consistent catch reduction.

Table 6. Percentage of tuna catch performed within the general 'catch hotspot' (quantile 95%) area per year and percentage of increase or decrease in catch following closure and relocation of effort (based on general CPUE covering the whole WCPO except the cluster area).

Year	% BET catch hotspot	% SKJ catch hotspot	% YFT catch hotspot	% total catch hotspot	% ass. set hotspot	% BET catch predicted	% SKJ catch predicted	% YFT catch predicted	% total catch predicted
2011	41.47	36.96	34.84	37.00	29.37	-17.13	-10.75	-7.75	-10.81
2012	32.37	36.21	32.12	35.50	32.16	-0.31	-5.97	0.06	-4.93
2013	37.51	37.74	39.54	37.99	35.78	-2.69	-3.05	-5.85	-3.44
2014	47.65	47.66	54.21	48.40	49.38	3.42	3.41	-9.55	1.94
2015	29.62	23.76	33.27	24.96	30.62	1.44	9.89	-3.81	8.16
2016	31.19	25.47	25.72	25.83	23.11	-10.51	-3.08	-3.40	-3.54

Higher bigeye CPUEs were located in the North-East (172°W–150°W and 2°S–10°N) of the tropical WCPO (Figure 13). This pattern was consistent both during the 6 years studied and among clusters (Figures A31 and A32). This CPUE hotspot represents 3% (2016) to 14% (2013) of the overall bigeye catch by year but only 1 to 3% of the skipjack catch. The exception being 2015 where 10% of the skipjack catch and 13% of the bigeye catch was taken in this area (Table 7).

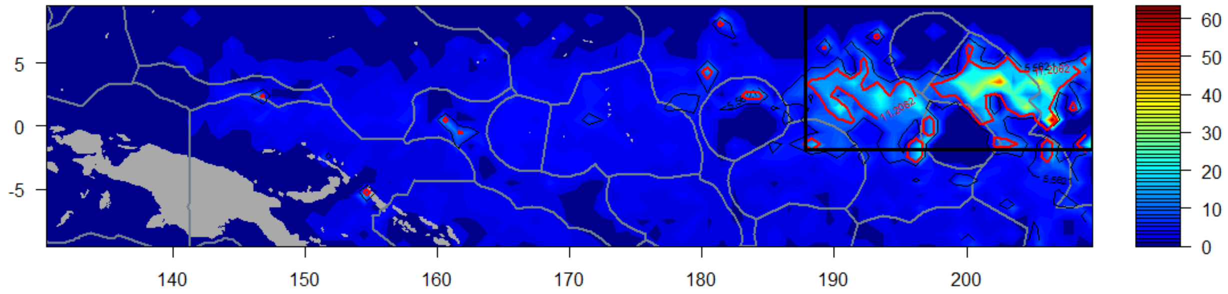

Figure 13. Distribution of bigeye CPUE over the 2011–2016 period for each 1° cell. Red line represents quantile 0.95% of the data, black line quantile 90% and the black rectangle the selected continuous CPUE hotspot.

A comparison of the distribution of the CPUE hotspot from observer data and from S-BEST data was also performed, which confirmed that the main area of high bigeye CPUE was consistently in the North-Eastern area of the WCPO, for the whole 2000–2016 period (Figure A33 and Table A5).

Simulating a reallocation of effort from the CPUE hotspot to the rest of the WCPO revealed that a closure could lead to a decrease of 2–12% of bigeye catch and 0–4% of the total tuna catch (Table 7). Even during the El Niño year, with a higher proportion of the total catch taken in the Eastern area, a closure of the CPUE hotspot led to a decrease of 4% of the overall tuna catch, and a 7% reduction in bigeye catch. Note that the 500t bigeye catch limit would still be exceed for most vessels listed in Table 4 in case of closure of the CPUE hotspot, indicating the potential use of both approaches.

Table 7. Percentage of tuna catch performed within the 'CPUE hotspot' area per year.

Year	% BET catch hotspot	% SKJ catch hotspot	% YFT catch hotspot	% total catch hotspot	% ass. set hotspot	% BET catch predicted	% SKJ catch predicted	% YFT catch predicted	% total catch predicted
2011	5.90	1.72	1.89	2.05	1.07	-4.88	-0.65	-0.83	-0.99
2012	8.11	1.72	2.85	2.20	1.26	-6.93	-0.47	-1.61	-0.95
2013	13.90	2.74	3.91	3.72	2.45	-11.74	-0.30	-1.50	-1.30
2014	12.70	2.15	2.57	2.80	1.96	-10.95	-0.19	-0.63	-0.86
2015	12.77	10.32	7.70	10.16	6.64	-6.57	-3.94	-1.14	-3.77
2016	2.85	1.09	1.58	1.25	1.08	-1.78	-0.01	-0.51	-0.17

The CPUE hotspot mostly covers International Waters (60%), as well as Kiribati's Line (19%) and Phoenix (3%) Islands EEZs and US EEZ (Palmyra 7% and Jarvis 11% Islands) (Table 8 and Figure 13). To the contrary, the catch hotspot covers almost only EEZs (International Waters 2%). If we only consider the contiguous part of the hotspot, it covers Kiribati's Gilbert Islands (55%), Nauru (33%) and Tuvalu (4%) EEZs (Table 8 and Figure 11).

Table 8. Percentage of the catch and CPUE hotspot areas within each EEZ.

	Catch hotspot			CPUE hotspot	
EEZ	Quantile 95	Contiguous central area	EEZ	Quantile 95	North-East area*
Nauru	25.98	32.58	Kiribati	44.29	22.42
Kiribati	48.64	54.55	US	4.29	17.99
Tuvalu	3.63	3.79	IW	51.42	59.59
Marshall Islands	5.74	7.2			
PNG	10.57	0			
Micronesia	3.93	0			
IW	1.51	1.88			

*Black rectangle in Figure 13, defined as the CPUE hotspot in this report.

3.4. *Considerations of spatial and vessel effects*

CPUE by area and vessel size was investigated to disentangle the influence on bigeye catch of i) a purely spatial and temporal/ environmental (through ENSO periods) component; and ii) large vessels operating mostly in the Eastern area (Tables 8, A6 and A7). Bigeye CPUE was generally higher in the East, except in 2015 and 2016 (Table A6). Yellowfin CPUE did not vary with area. Skipjack CPUE was higher in the East compared to the Center in 2015 and 2016, while it was similar between these two areas (and higher than in the West) during the other years (Table A6).

Within the Eastern area, bigeye CPUE was higher in the CPUE hotspot compared to the rest of the area, and this was independent of vessel size (Table 8). However, large vessels (5 vessels with length >90m) showed higher bigeye CPUE compared to smaller vessels, and this was consistent across every area in which they operated (Table 8). It should be noted that while skipjack CPUE was particularly high for these large vessels in the bigeye CPUE hotspot during certain years (2011 and 2012, see Table

A7), in the other areas and years these vessels did not have significantly higher skipjack CPUE than smaller vessels (Table A7).

Table 8. Bigeye CPUE (t/set) of very large (length >90m) vessels in all areas in which they operated, in comparison with smaller vessels. The Central ‘catch hotspot’ was not specifically considered due to the low number of sets performed by vessels >90m in that area.

Area	West	Center		East ‘CPUE hotspot’		East rest of the area	
Vessel size	<=90m	<=90m	>90m	<=90m	>90m	<=90m	>90m
2011	1.99	3.77	10.85	10.01	17.61	4.30	10.15
2012	2.06	2.12	4.82	8.92	17.23	1.47	10.61
2013	2.21	3.80	9.51	16.15	19.60	3.83	11.08
2014	2.03	2.58	9.34	11.36	28.99	1.73	9.78
2015	2.73	2.18	6.10	4.49	6.33	2.00	4.73
2016	3.29	2.83		6.40		0.98	

4. Discussion

This represents the final report of Project 77, the aims of which were i) to identify factors (vessel or FAD specific characteristics, environmental covariates) linked to high purse seine bigeye catch; ii) to identify top bigeye tuna catching purse seiners; and iii) to examine spatial management considerations. It has been expanded following feedback from the 13th WCPFC Scientific Committee meeting. As highlighted in previous studies (Harley et al., 2015; Tidd et al., 2016) it is clear that all the factors mentioned above influence bigeye catch by the purse seine fishery, which therefore makes it challenging to gauge the effect of each factor separately.

Firstly, there is a significant spatial component. An area of high bigeye catch (26–45% of the annual bigeye catch) is detected in the Center of the WCPO primarily within the Nauru and Kiribati’s Gilbert Islands EEZs (Figure 11). However, this corresponds to the main purse seine fishing area on associated sets and the skipjack catch is also high, and as a result, the proportions of the overall catch taken from that area are similar to those of total bigeye (Table 6). On the other hand, the North-Eastern part of the tropical WCPO (Figure 13) is an area with mostly higher CPUE for all three species, and particularly for bigeye, when compared to the rest of the WCPO (Tables 8 and A7). All vessels operating in this area achieved higher bigeye CPUE than the rest of the WCPO. Between 2011 and 2015 6–14% of the total bigeye tuna was caught in the North-Eastern hotspot but only 2–3% of the skipjack catch was taken from there, except in 2015 where it increased to 10% of the skipjack and total catch (Table 7). That year corresponded to a strong El Niño event, which deepened the thermocline in this area, and was associated with an eastward movement of the fishery. This resulted in the East having the highest catch of skipjack and yellowfin of the 6 years during that year. However, this was not the case for bigeye tuna, with very low catch in 2015 and 2016 in the whole tropical WCPO.

Secondly, the physical environment plays a key role in influencing tuna catch of the three species, and catchability is particularly influenced by thermocline depth (Figure 9). It was shown that higher bigeye catches per set were achieved in parts of the areas with a shallow thermocline, which is pronounced in the East during La Niña and Neutral periods. During El Niño, the thermocline depth deepens in the East, decreasing bigeye tuna catchability. In that year (2015) bigeye catch dropped notably in the Eastern Area, which is probably linked to both the effect of oceanographic conditions (deeper thermocline in the East) and the absence of many very large vessels that previously operated in the Eastern area.

Thirdly, vessel size was highly influential on bigeye tuna catch. Very large vessels achieved bigeye CPUEs significantly higher than other sized vessels, a difference that was not as marked for skipjack CPUE. However, besides variables purely linked to vessel size, no specific gear characteristic was found to influence bigeye catch, even if deeper and longer nets were found to lead to higher bigeye occurrence and catch in the GAM models. We may therefore hypothesize – but cannot confirm with the current data set – that these large vessels, in addition to having larger and deeper nets may possess some equipment that increases fishing efficiency such as: helicopter, satellite maps (e.g. for chlorophyll-a, SST), sonar, depth sounder, deployment of an echosounder buoy on FADs or specific FAD designs. Some fleets operating in the East mainly use FADs with a maximum depth of 30–50m (shallower than other vessels), a main structure of 2x2m made of bamboo, floats, net and rope. However, the available FAD characteristics data are not sufficient to identify whether FAD design increases bigeye catch, or if it is a vessel effect (using that particular FAD design) that drives increased bigeye catch. Particularly high bigeye catch and proportion per set may also potentially indicate specific targeting of bigeye. While the proportion of large (>10kg) bigeye tuna in a set recorded by observers is still a relatively uncommon event (25% of the sets since 2013, 10% in 2012 and 1% in 2011), these fish represent 10–20% of the bigeye tuna captured by large vessels, especially in the CPUE hotspot (See Table A8 for details). It should also be mentioned that these vessels appear to have a fishing strategy more orientated toward associated than unassociated sets. Finally, large vessels appear to be equipped with a higher degree of technology associated with fishing, yet the high inter-trip variability precluded any comparison between vessels or area.

Several limitations in the data used in this study should be mentioned: i) catch was visually estimated by observers, which while offering the best set-by-set data source may lead to several potential associated biases (unknown precision of bigeye catch estimates on a set-by-set basis); ii) the precision of the data on FAD characteristics (depth, dimensions), as well as some vessels characteristics (net depth/length) is unknown, while the value of other characteristics are known to vary between data sources; iii) the presence of inter-observer variability (especially regarding the 1st trip by an observer compared to trips observed by experienced observers); and iv) incomplete data for 2016.

Overall, our results indicate the presence of a CPUE bigeye hotspot in the North-Eastern part of the WCPO, with relatively low catch rates of other species, except in 2015, where a strong El Niño event led to an eastward displacement of the fleet. During that year, extremely low catch of bigeye tuna across the WCPO were detected. However, most large vessels, that usually caught up to half the bigeye tuna in this East, did not operate in the WCPO in 2015 and 2016. It is therefore difficult to statically separate the oceanographic influence from vessels' influence in the reduction of purse seine bigeye catch in 2015 and 2016. Net depth and FAD depth also appears to be important, but additional studies would be needed to further elucidate their influence (i.e. are high catch events linked to specific large vessels or does the FAD design have a direct influence?). Further investigation of FAD design by fleet, as well as presence of echo-sounder buoys should be performed. In addition, studies accounting for fishing technology equipment between vessels (at the trip level) should also be undertaken.

In this report, we have presented updated results on factors influencing bigeye tuna purse seine catch to guide management decision making for this species in the WCPO. In the context of the limitations encountered in this study and to reinforce future analyses, we recommend that the WCPFC:

- Collect more detailed and systematic data on the structure and features of FADs (depth, length, width, materials) to improve FAD analyses, including for natural FADs to analyse their influence on school size and species composition.
- Gather comprehensive information on the type of buoys used (echo-sounder buoy or not) and their number.
- Collect more complete information on each vessel's FAD array (e.g. number of FADs deployed, number of active buoys monitored, use of supply vessels, etc.).
- Improve observer collection of detailed information on the purse seine net used (net material and mesh size are almost never recorded, precise depth and length).
- Improve observer recording of vessel electronic equipment as well as helicopter use in the PS-1 form, potentially through the inclusion of a 'not recorded' field.
- Compare results from the North-Eastern area with some IATTC data.

Therefore, we invite WCPFC to:

- Note this final report of WCPFC project 77.
- In particular, note the uninformative nature of the data to statistically separate the effects of key areas and vessel types.
- Highlight the need for improved information on FAD designs, deployments and type of buoy use within the WCPO to improve future analyses.
- Note the importance of detailed information on the characteristics of vessels fishing in the WCPO, especially on fishing gears and technological equipment increasing fishing efficiency.
- Note the challenges in considering spatial management options for bigeye tuna.

Acknowledgments

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Attachment 1. Project ToR

WESTERN AND CENTRAL PACIFIC FISHERIES COMMISSION

TERMS OF REFERENCE

Development of potential measures to reduce interactions with bigeye tuna in the purse seine fishery in the Western and Central Pacific Ocean

BACKGROUND

The conservation status of bigeye tuna in the Western and Central Pacific Ocean (WCPO) is currently estimated to be in an overfished state. The most recent assessment estimates that spawning potential is most likely at (based on 2008-11 average) or below (based on 2012) the limit reference point of 20%$SB_{F=0}$ agreed by the Western and Central Pacific Fisheries Commission, that recent levels of fishing mortality exceed the level that will support the maximum sustainable yield (MSY), and current catch exceeds MSY. Approximately 40% of the fishing impact (i.e. the reduction in spawning potential due to fishing) on bigeye tuna in the WCPO can be attributed to the purse seine fishery targeting skipjack and yellowfin tuna on floating objects. Purse seine fisheries increasingly utilise fishing on floating objects as a method for maximising vessel efficiencies. Currently, around 90% of bigeye tuna taken in the purse seine fishery is caught this way. Although bigeye tuna only make up 3.8% of total tuna catches from the purse seine fleet, there is a need to reduce the impact on bigeye tuna while at the same time being mindful of negative impacts on the overall purse seine fishery.

OBJECTIVE

The objective of this project is to examine the nature of bigeye tuna interactions in the purse seine fishery with a focus on areas that might support the development of mitigation options and management measures. From the findings of this project the design elements for future mitigation / research experiments should be determined, and scientific advice will be provided on possible fishing strategies / management measures that would reduce the catch of bigeye tuna with minimal impact upon the catch of the other species. These would aim to reduce the fishing mortality on bigeye caught in association with floating object fisheries without impacting upon fishery performance for the target species.

SCOPE

The work programme is comprised of a series of desktop activities to be undertaken utilising purse seine logsheet and observer data collected within the WCPFC Convention Area, aimed towards scientific support for the consideration of management measures to reduce the impact of purse seine fishing on bigeye tuna. These activities draw on previous work reviewed by the WCPFC Scientific Committee, including analysis of observer data on FADs (Abascal et al. 2014; WCPFC-SC10-2014/ST-IP-09), approaches to estimate the species composition of purse seine catch (Hampton and Williams 2015; WCPFC-SC11-2015/ST-WP-02) and a preliminary characterisation of bigeye purse seine catch (Harley et al. 2015; WCPFC-SC11-2015/MI-WP-07).

In addition to communication within WCPFC fora, industry dialogue will provide an important source of review and technical guidance to ensure that analyses are undertaken within the correct context (e.g., ensure that we are aware of any interventions that may change interpretation of the data) and that any management recommendations are feasible. Although not budgeted as a specific activity within this project, opportunities to undertake this activity will be used throughout the period of the contract to enhance project outcomes.

The proposed work programme comprises one data compilation activity, and three statistical analysis activities. These are briefly outlined below:

1. Construction of set-by-set and/or trip-by-trip species-specific datasets of purse seine catches

Currently the 'best' estimates of purse seine catch by species are only available at the resolution of 1x1 degree square by month, vessel-flag, and set-type. However, for this work a dataset that provides species-specific catch estimates at the level of the set is desirable, or at the vessel trip level if the set-by-set estimates are considered unreliable. Such data sets need to be developed to provide the basis for the analyses undertaken under activities (2) and (3) below. As logsheet estimates alone have been clearly shown to be unreliable for species breakdown, they must be supplemented by additional data sources. Further details are provided under the Methodology section below.

Under this activity analyses would also be undertaken to validate the set type as recorded by observers and fishing masters on the basis of reported catch and operational factors – and possibly identify potential patterns in reporting that may require further consideration.

2. Analysis of factors related to the occurrence of bigeye tuna in purse seine catches

Once the dataset in (1) is constructed it can be used to better understand how bigeye tuna catches are impacted by various factors, including but not restricted to season, vessel, location, set type, FAD design and purse seine net design (as appropriate). Where size composition data are sufficient, such analyses could consider size-specific differences.

3. Characteristics of top bigeye tuna catching purse seine vessels

Harley et al. (2015) found that some vessels caught bigeye tuna in higher volumes and proportions to others. Using the data set constructed under (1), comparisons between the top, intermediate, and bottom bigeye catching vessels could provide further improved understanding of factors impacting on purse seine bigeye catch.

4. Spatial management considerations

Spatial management is being increasingly used in fisheries management, including for highly migratory stocks. This activity will identify bigeye 'hotspots' based on various criteria and extend the work of Harley et al. (2015) through definition of contiguous (more practical) hotspot regions. The importance of these fishing grounds will be summarised by vessel flag and will also consider EEZ (e.g., does the hotspot cover part of an EEZ, if yes, what percentage).

Methodology

1. Construction of a set-by-set or trip-by-trip species-specific dataset of purse seine catches for analyses under 2) and 3).

The construction of the data set(s) will be an extension of that described in Harley et al. (2015), which covered the period 2010-2013. All available logsheet and observer records will be compiled and linked. These records are primarily reported on the Regional forms (see http://www.spc.int/oceanfish/en/data-collection/241-data-collection-forms for further details). Specifically this will involve linking the fishing vessels logsheet report with relevant observer forms, such as the PS-2 (activity), PS-3 (catch), and PS-4 (length and species composition sampling) observer forms. It is proposed under this activity to link with the GEN-2 (species of species interest) and GEN-5 (FAD data) observer forms to allow inclusion of details on FAD construction (after Abascal et al. 2014). Linking to the GEN-2 form is not necessary for the bigeye analysis, but may facilitate analyses of other species (e.g., whale sharks and manta rays) in the future.

There are two sources of purse seine species composition from observer data of relevance to developing estimates of species catches at the trip or set level – that provided on the PS-3 form (which is essentially a visual estimate by the observer), and that derived from the length frequency samples (PS-4 form). It is proposed that using the length frequency sample derived catch estimates as these will allow bigeye catches to be broken down by size category (<10kg, >10kg). Where possible (e.g. in the case of Japanese purse seiners), these estimates will be cross-validated where accurate unloading data at the trip level exists.

In instances where the observer data are missing for a set, a hierarchical modelling will be used, incorporating factors such as vessel, area, and location to make predictions for the species composition – this is necessary for obtaining catch estimates at the overall vessel or trip level, but imputed data will not be used in the statistical modelling undertaken under activities (2) and (3) below.

It is noted that observer-derived species composition (from PS-4 data) is only a very approximate representation of the set catch, as the observer is only sampling around 0.1-0.2% of the catch. Estimates at the set level may be notably uncertain. If appropriate statistical approaches are unable to deal with that uncertainty, catch estimates will be generated at the trip level and used in subsequent analyses as appropriate. Where feasible, trip-level estimates will be related with available cannery data for that trip as a form of validation and/or for estimate adjustment.

The methods described within Hare et al. (2015; WCPFC-SC10-2014/ST-WP-04) will be applied to the data set and any anomalous reported set type data identified and a new field for 'inferred' set type will be created, but as with imputed species composition, these records will not be included in further statistical modelling.

2. Analysis of factors related to the occurrence of bigeye tuna in purse seine catches

    This activity will involve the application of modern statistical techniques such as generalized linear models, generalised additive models, and regression trees to the data set constructed under (1). Response variables may include bigeye catch, bigeye CPUE, or bigeye catch proportion as deemed appropriate. Environmental covariates will be considered. This activity will identify those factors, such as season, vessel, location, set type and FAD design, associated with higher bigeye tuna (by size category) interactions.

3. Characteristics of top bigeye tuna catching purse seine vessels

    The data set constructed in (1) will be used to generate bigeye purse seine catch estimates at the vessel level. Vessels will be assigned to high, intermediate, and low, in terms of their bigeye catch. The fishing characteristics of these vessels will be compared in the form of simple data summaries (see Table 3; Harley et al. 2015) and using statistical methods applied in (2) above, and where databases allow, may include an examination of vessel characteristics. This more targeted analysis will supplement findings under (2) above and the pattern of catch estimates themselves may be a useful resource for industry. If possible, these results will be discussed with vessel owners and captains to try to cross-check the results of the analyses (see outputs section).

4. Spatial management considerations

    Extending the hotspot analysis of Harley et al. (2015) and the use of the 1°x1° aggregate raised data, hotspots for purse seine bigeye catch, CPUE, and proportion will be identified using hierarchical spatial clustering techniques which will allow the development of contiguous hotspot regions. For these regions the percentage of overall bigeye catch and total purse seine catch taken in these hotspots will be calculated. The calculations will also be undertaken by vessel's flag, and hotspots will also be described in terms of the EEZs that they cover.

    Hotspots will first be identified with an aggregated data set (across recent years) and then for each year in order to determine the temporal stability of any hotspots identified in the aggregated data.

OUTPUTS AND SCHEDULE

The principle outputs of the assignment will be:

- Submission of a progress report, and a final report for SC12 and SC13 respectively with associated presentations. These reports will be provided to the secretariat by the deadline for SC working papers.
- An invoice coincidental with the final report should be submitted to the WCPFC Secretariat by 31 October 2017.

- **Communication**

  The WCPFC Scientific Service Provider will prepare material with collaborators for dissemination of the results to industry operating both within the WCPFC Convention Area and other Tuna RFMOs. The WCPFC Scientific Service Provider will provide communication to WCPFC and its members for the continued development of Conservation and Management Measures aimed at reducing juvenile bigeye catch by purse seine vessels.

  Although outside the remit of this contract, opportunities to discuss the findings of this analysis with vessel owners and captains/fishing masters will be taken where the opportunity allows, in order to determine more precisely what it is that key vessels are doing to avoid, or not, bigeye tuna.

Attachment 2. Examination of bigeye catch estimates from alternative sources.

Observer visual estimates for purse seine tuna catch are used when analyses at the set level are required. All other analyses beyond the set level, which are typically analyses at a higher level of aggregation (for example, at temporal/spatial levels such as flag + 1°x1° lat/lon + year/month) utilize the observer species/size composition sampling data, adjusted for selectivity bias.

For analyses at the purse seine set level, the use of observer visual estimates are the best data available since:

- The observer species/size composition sampling data collected at the set level represents only around 0.2%–0.3% of the sets' catch. There are instances (23% of sets in the observer data since 2012) where the observer reports a visual estimate of bigeye tuna catch when there were no bigeye tuna in the sample taken for that set. The estimate of bigeye catch determined from sampling data at the set level is therefore clearly biased when 23% of sets with bigeye tuna catch identified is estimating a zero bigeye tuna catch.
- The logsheet reporting is the only other source of data that can potentially provide an indication of the bigeye tuna catch at the set level, but there are clearly differences in the reliability of fleets/vessels in reporting bigeye catch levels. While these data are therefore adjusted based upon observer sampling for regional catch estimates (S-BEST), that adjustment is inappropriate at the set level.
- Observers are trained to determine visual estimates of the tuna species catch at the set level. While there may be differences in the capabilities to undertake this task amongst observers, (i) the training, forms, protocols, etc. provided to observers to determine visual estimates is consistent and standard, and (ii) there is a strong motivation for the observer to collect this information. In contrast, there are few vessels that accurately report the bigeye tuna on logsheets, but for the vast majority of vessels, the bigeye tuna catch is rarely reported accurately since there is no commercial incentive and no industry standard to estimate the bigeye tuna catch at the set level in a consistent manner.
- Significantly increasing the number of observer species/size samples at brailing on board the vessel would definitely improve the coverage so that these data could then be used for analyses at the set level, but this would hinder the well loading operation. E-monitoring perhaps offers the best solution to increased sample sizes of the purse seine catch at the set level in the future.

The following graphs show some comparisons of observer visual estimates with other types of data used for WCPFC analyses. Note that data from two example fleets have been selected to show differences among fleets. The following are observations from these graphs:

- Figure A1 shows that the observer visual estimates of the bigeye tuna catch has a relatively high correspondence with the logsheet-reported bigeye tuna catch when considering purse seine vessels from a first example fleet. However, there are some instances (see data in the red ellipse) where the logsheet is not recording bigeye tuna catch in a set that has been reported by the observer in the visual estimates.

- In contrast, Figure A2 shows that the observer visual estimates of the bigeye tuna catch has far less correspondence with the logsheet-reported bigeye tuna catch when considering purse seine vessels from a second example fleet, and that there are a large proportion of set-level reporting on logbooks of zero bigeye tuna catch when the observer has reported some bigeye tuna catch in the visual estimates.
- Figure A3 shows that there is some correspondence between the observer visual estimates (aggregated from data at the set level) and the S-BEST data (i.e. raised logsheet data stratified by 1x1 degree, month, flag and set type, where catch by species is corrected using observer-based grab sampling corrected for selection bias) which is used in the assessments.
- Figure A4 shows some correspondence between the observer visual estimates and the estimates determined from the observer sampling data at the set level at relatively small bigeye catch levels (i.e. <= 2 metric tonnes). The first red ellipse perhaps highlights the selectivity bias for bigeye tuna in the observer sampling data at the set level. The second red ellipse highlights instances where the observer has reported a visual estimate of bigeye tuna catch in the set, but there were no bigeye tuna selected in the random grab sample.

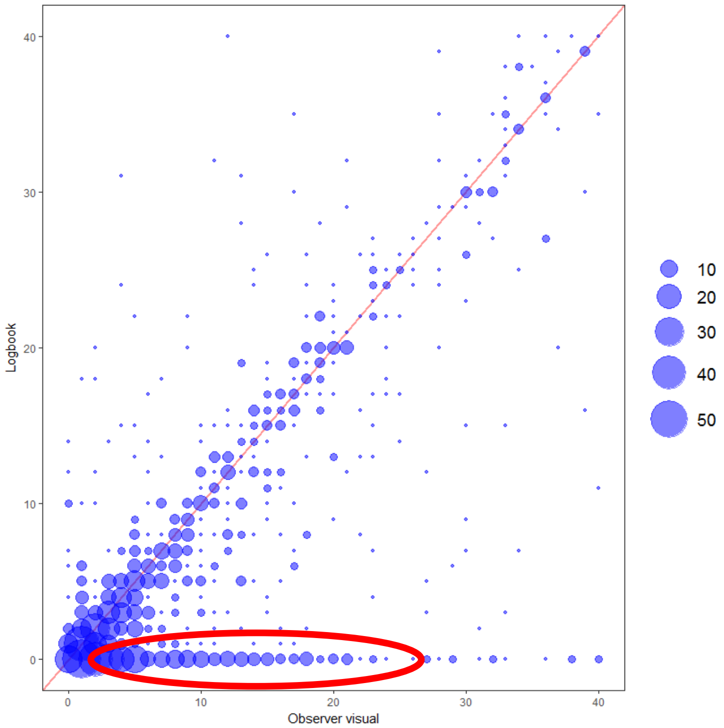


Figure A1. Comparison of set-level bigeye tuna catch of purse seine vessels from a first example fleet. Observer visual estimates (X-axis) versus logbook reporting (y-axis). Red ellipse represents zero catch from logbooks where the observer reported bigeye catch.

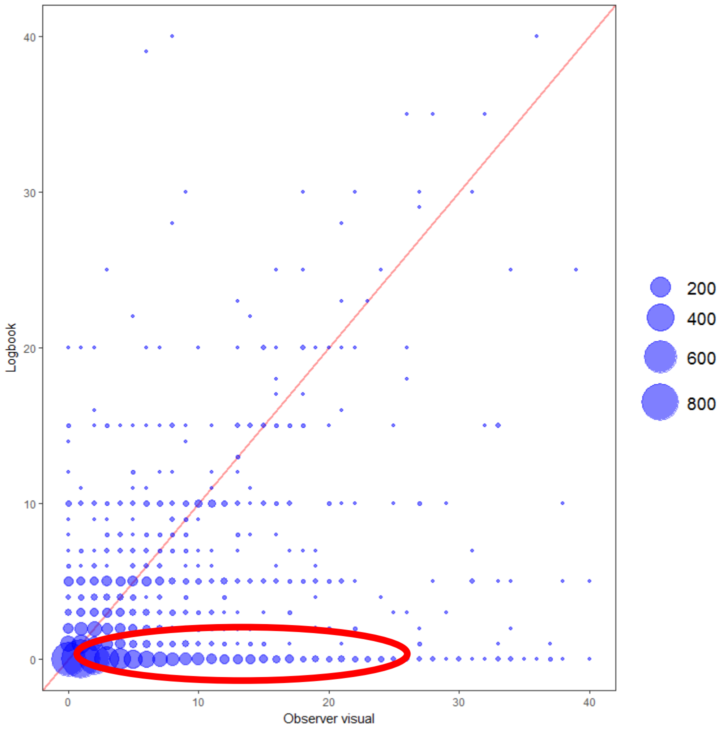


Figure A2. Comparison of set-level bigeye tuna catch of purse seine vessels from a second example fleet. Observer visual estimates (X-axis) versus logbook reporting (Y-axis).Red ellipse represents zero catch from logbooks where the observer reported bigeye catch

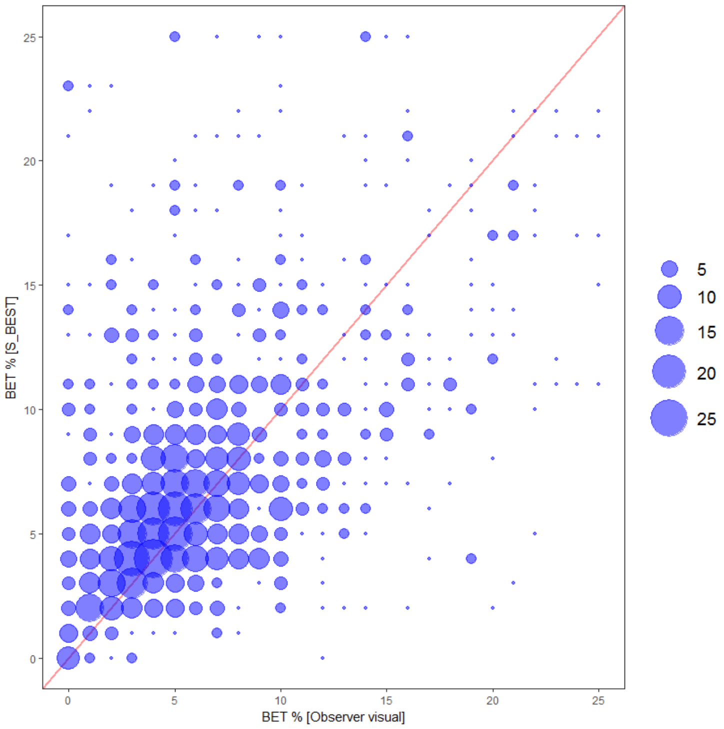


Figure A3. Comparison of bigeye tuna catch composition (%) for all purse seine fleets matched at fleet + year + month + latitude (5°) + longitude (5°). Observer visual estimates (X-axis) versus logbook S-BEST reporting (Y-axis).

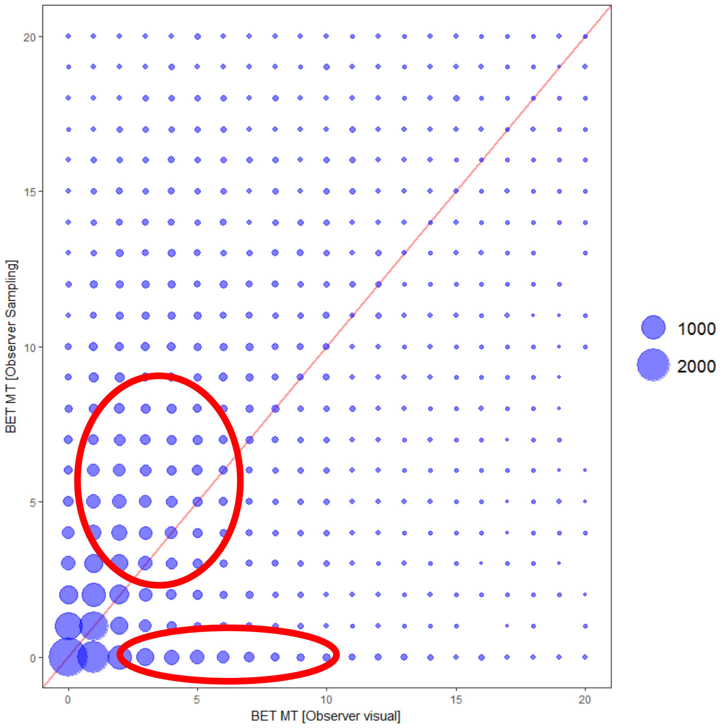


Figure A4. Comparison of bigeye tuna catch for all purse seine fleets at the set level. Observer visual estimates (X-axis) versus observer sampling estimate (Y-axis).

Attachment 3. Appendix

Table A1. Constructed drifting FAD characteristics recorded by observers from each program from 2012–2015.

Program	Observed associated sets	% Depth	% Depth & dimensions	% Structure material	% Structure & attachment material	% All FAD characteristics
TTOB	8922	14.9	14.7	15.6	12.2	11.4
FMOB	5259	24.7	24.4	26.4	25.8	23.8
FAOB	4954	25.1	24.4	27.5	26	23.3
PGOB	4772	39.8	38.4	43.8	42.6	37
KIOB	2458	43.5	42.3	46.6	44.4	40.2
SBOB	1315	37.3	37	38.3	36.3	35.3
TVOB	791	61.8	61.3	64.5	63	61.2
MHOB	759	8.3	8.3	8.4	5.3	5.1
NROB	64	4.7	4.7	4.7	4.7	4.7
WSOB	13	84.6	84.6	69.2	69.2	69.2
SPOB	7	0	0	0	0	0
TOOB	13	100	100	100	100	100

Table A2. Annual bigeye catch and CPUE by cluster and by area.

		West					Center					East				
Year	Groups	BET catch	% BET catch	CPUE BET	Ass. Sets	Vessels	BET catch	% BET catch	CPUE BET	Ass. Sets	Vessels	BET catch	% BET catch	CPUE BET	Ass. Sets	Vessels
2011	1Vlow	43	0.6	0.02	1987	115	32	0.2	0.01	2142	116	6	0.2	0.04	142	26
	2Low	1649	23.0	1.56	1058	106	1081	6.6	1.25	865	103	230	6.5	1.79	128	25
	3Med	1672	23.4	5.29	316	89	3470	21.2	4.53	766	102	782	22.0	7.52	104	17
	4High	2165	30.3	11.64	186	73	6667	40.8	14.46	461	90	738	20.8	18.44	40	14
	5Vhigh	1626	22.7	34.59	47	32	5095	31.2	48.52	105	39	1794	50.6	44.86	40	9
	Total	7156	100.0		3594		16344	100.0		4339		3549	100.0		454	
2012	1Vlow	45	0.7	0.03	1801	113	48	0.5	0.02	2193	120	9	0.3	0.03	325	23
	2Low	1480	22.0	1.52	976	106	1330	14.3	1.2	1110	108	320	10.5	1.6	200	24
	3Med	1306	19.4	5.35	244	72	3413	36.8	4.38	779	104	801	26.3	7.09	113	22
	4High	2001	29.8	11.44	175	63	3451	37.2	13.27	260	70	662	21.8	17.43	38	10
	5Vhigh	1888	28.1	31.46	60	39	1034	11.1	43.06	24	19	1248	41.0	43.03	29	5
	Total	6721	100.0		3256		9275	100.0		4366		3041	100.0		705	
2013	1Vlow	38	0.5	0.02	1986	121	31	0.2	0.02	1731	132	11	0.2	0.04	289	33
	2Low	1610	20.4	1.61	998	112	1049	6.9	1.23	851	119	383	5.3	1.7	226	28
	3Med	1785	22.6	5.38	332	94	3898	25.8	4.53	860	118	1436	19.8	7.56	190	29
	4High	2319	29.4	12.02	193	75	6480	42.9	14.27	454	97	1224	16.9	17.74	69	15
	5Vhigh	2149	27.2	31.61	68	39	3642	24.1	47.3	77	41	4193	57.9	50.51	83	18
	Total	7902	100.0		3577		15100	100.0		3973		7247	100.0		857	
2014	1Vlow	16	0.7	0.03	564	74	59	0.4	0.02	2951	133	14	0.2	0.02	697	43
	2Low	565	25.5	1.63	346	63	1771	11.4	1.23	1439	129	509	8.4	1.65	309	46
	3Med	566	25.5	5.34	106	42	5109	32.8	4.47	1143	124	1448	23.8	7.27	199	38
	4High	751	33.8	11.21	67	30	6538	41.9	13.97	468	108	1076	17.7	18.24	59	21
	5Vhigh	321	14.5	29.22	11	10	2119	13.6	45.08	47	25	3034	49.9	43.98	69	16
	Total	2219	100.0		1094		15597	100.0		6048		6082	100.0		1333	
2015	1Vlow	9	0.6	0.04	231	51	48	0.5	0.02	2075	123	25	0.6	0.03	875	85
	2Low	294	21.2	1.61	183	42	1230	13.7	1.21	1017	122	710	16.2	1.73	410	78
	3Med	240	17.3	5.34	45	26	3195	35.6	4.31	741	119	1595	36.4	6.79	235	72
	4High	414	29.9	11.51	36	17	3353	37.3	13.05	257	81	656	15.0	16.83	39	24
	5Vhigh	428	30.9	35.67	12	8	1159	12.9	44.59	26	22	1392	31.8	35.69	39	23
	Total	1385	100.0		507		8986	100.0		4116		4378	100.0		1598	
2016	1Vlow	12	0.3	0.03	467	62	16	0.3	0.02	964	78	7	0.9	0.03	223	18
	2Low	641	16.8	1.68	381	59	591	10.1	1.23	479	78	150	21.1	1.49	101	16
	3Med	860	22.6	5.18	166	49	1910	32.5	4.47	427	75	259	36.2	6.63	39	12
	4High	1201	31.6	11.23	107	41	2544	43.3	13.61	187	65	134	18.8	19.17	7	6
	5Vhigh	1092	28.7	30.34	36	13	811	13.8	50.69	16	11	164	23.0	32.75	5	4
	Total	3807	100.0		1157		5872	100.0		2073		714	100.0		375	

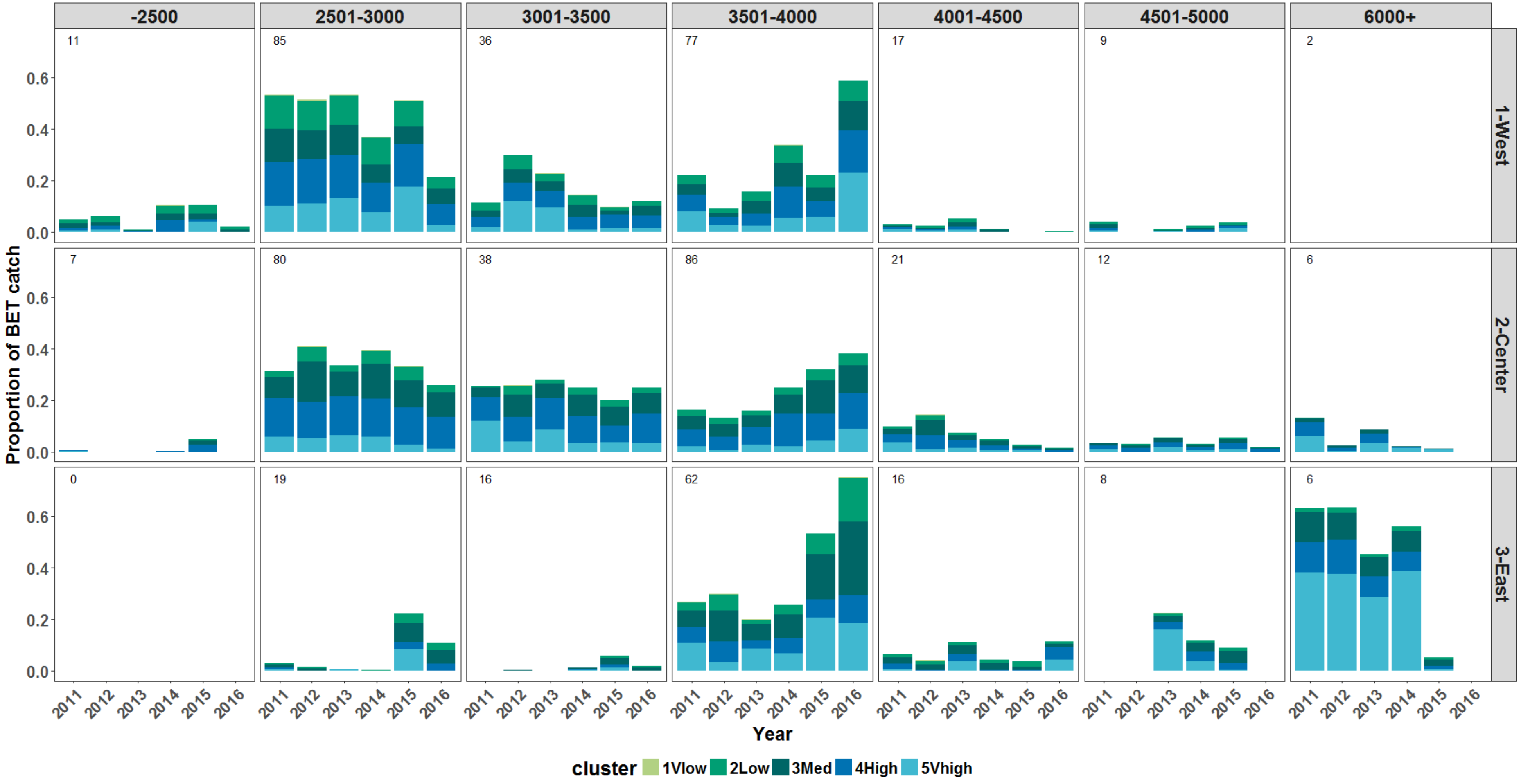


Figure A5. Proportion of BET catch by area and year for each category of vessel engine power (HP). Numbers in each box represent the number of vessels operating by category and year from 2011–2016.

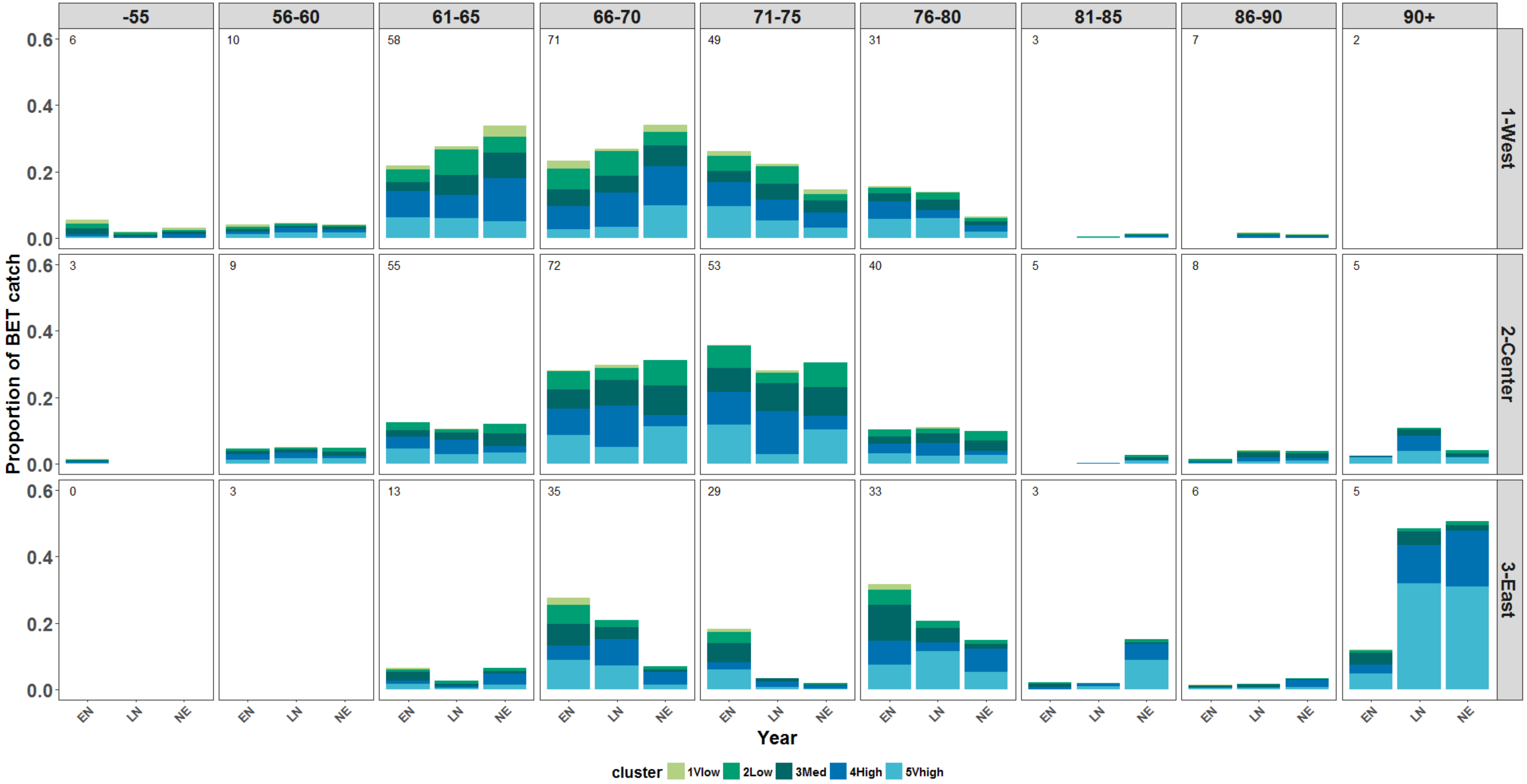


Figure A6. Proportion of bigeye catch by area and ENSO period captured by vessel length category (m). EN = El Niño (2015), LN = La Niña (2011), NE = neutral (2012, 2013, 2014 and 2016).

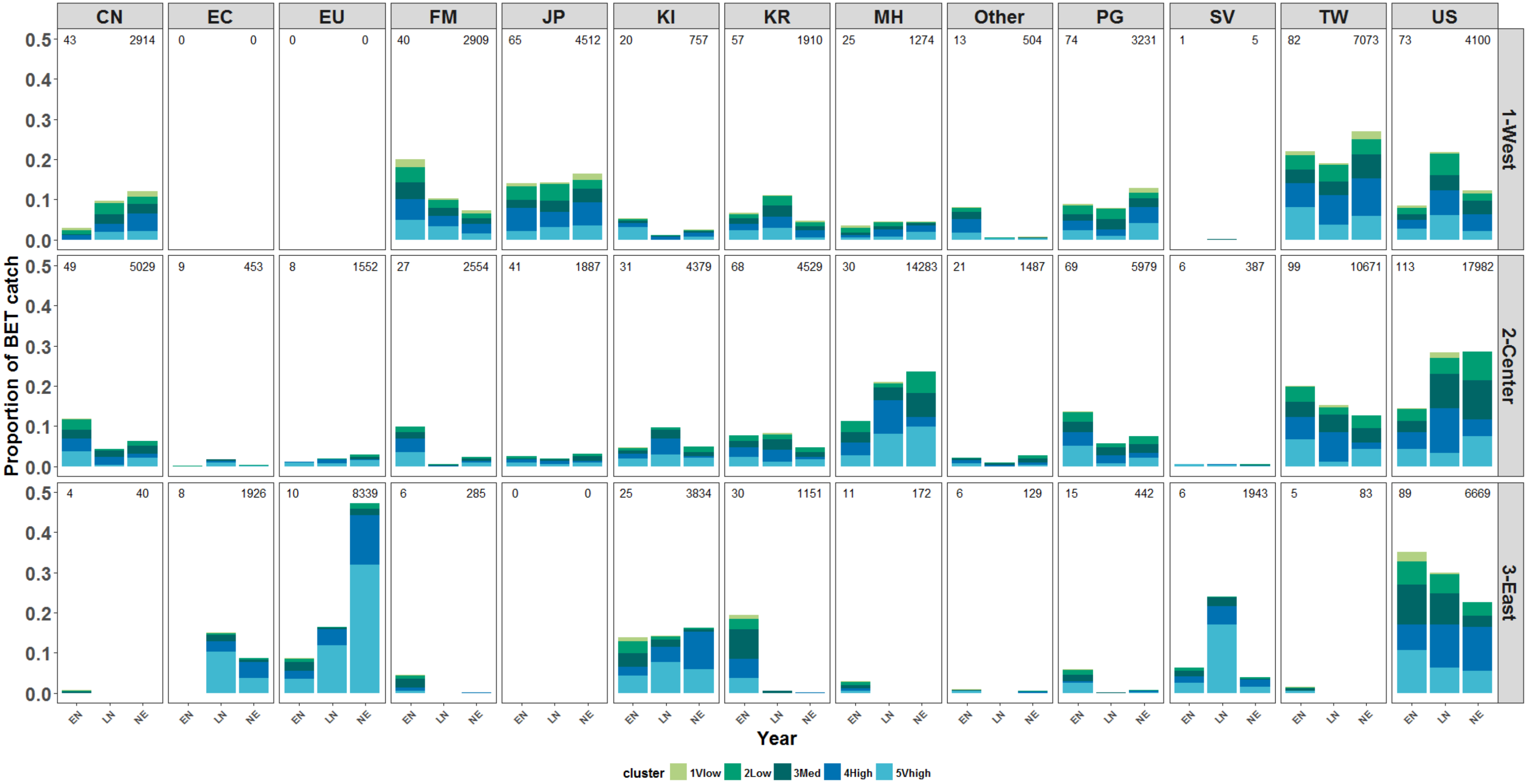


Figure A7. Proportion of BET catch by area and ENSO period captured by each purse seine fleet. Numbers in each box represent the number of vessel operating by fleet in each area (left) and total BET catch by fleet (right). Other fleets = VU, TV, PH, NZ, SB.

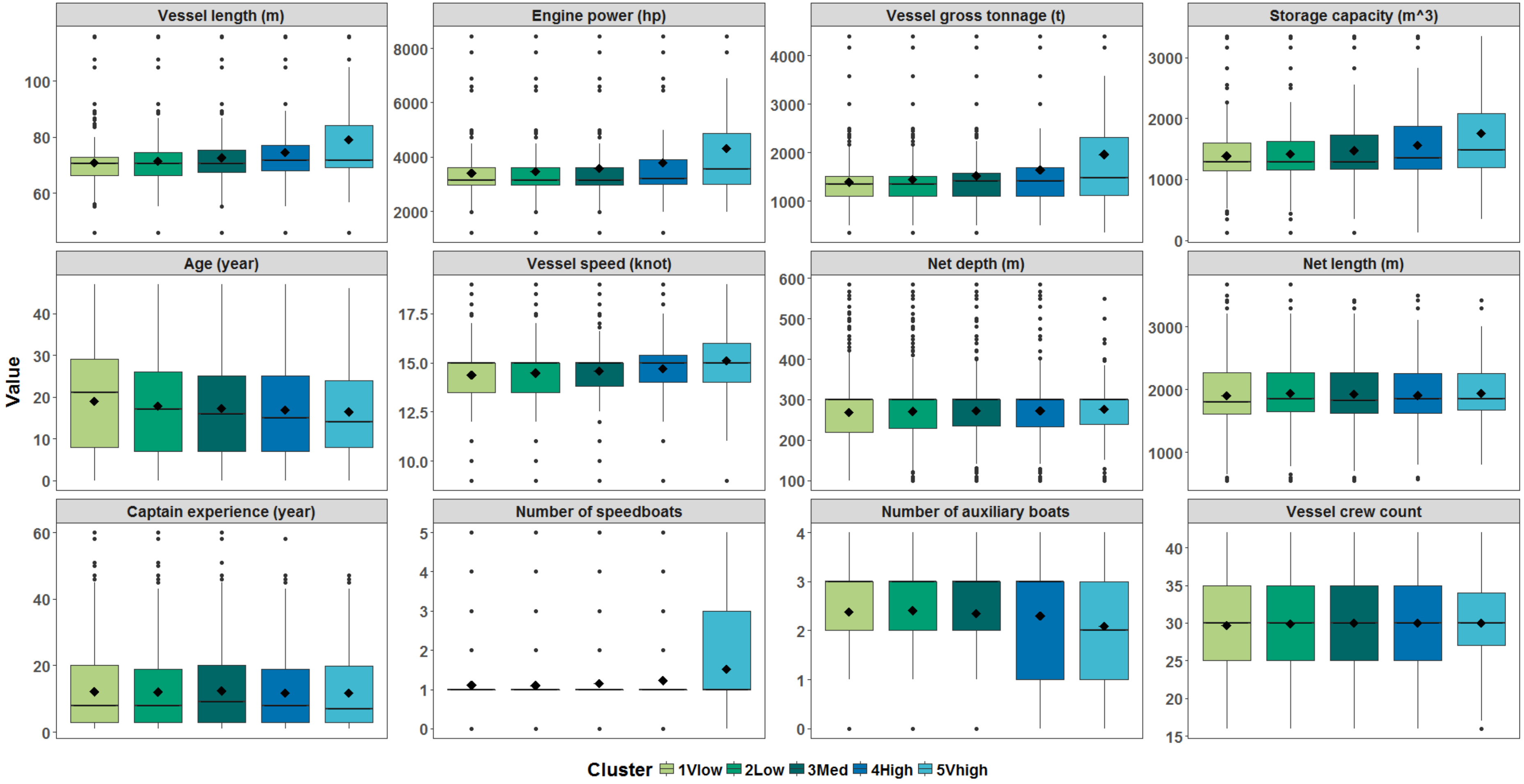


Figure A8. Characteristics of vessels with sets in each bigeye catch cluster, from the general clustering analysis.

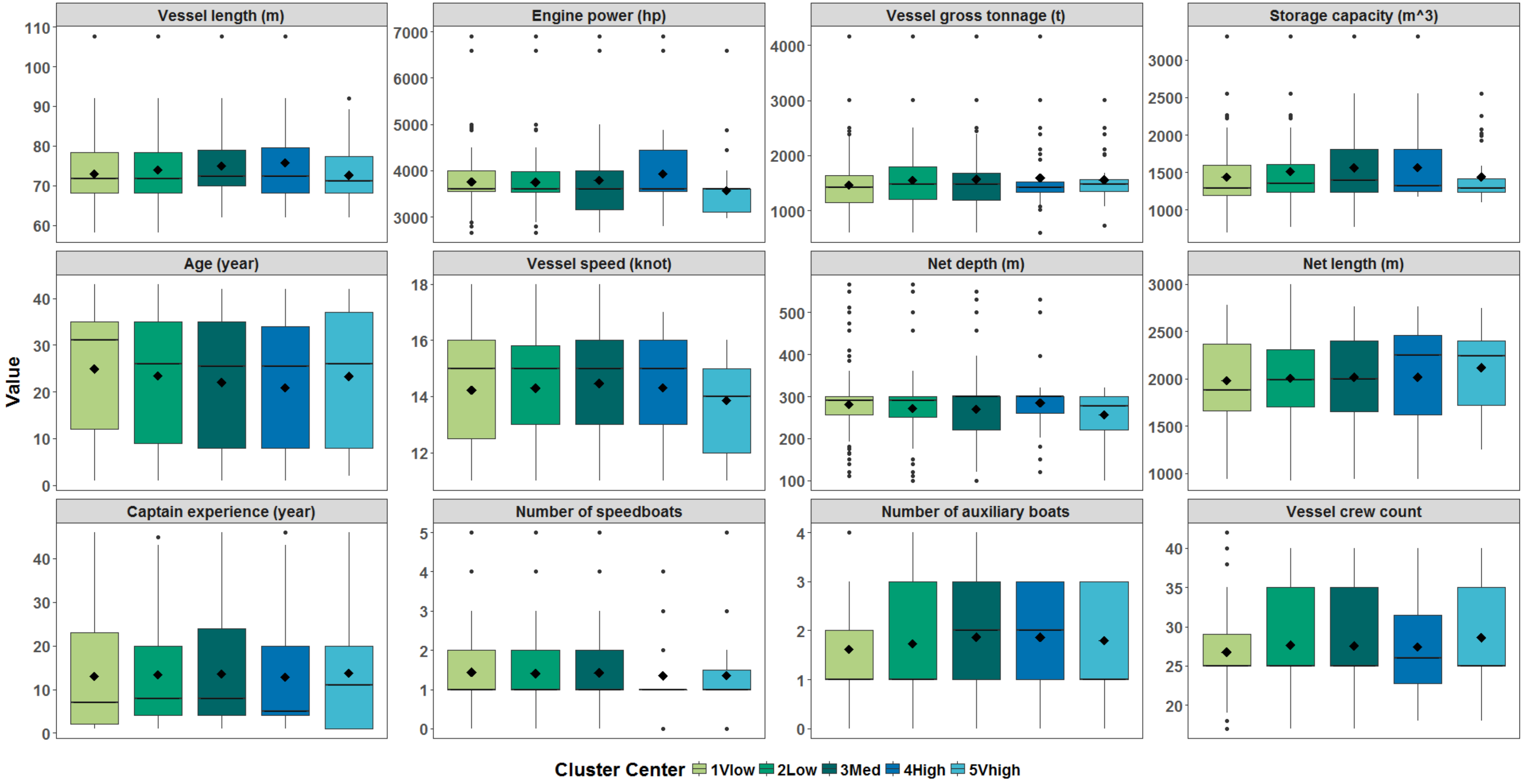


Figure A9. Characteristics of vessels with sets in each bigeye catch cluster, from clustering in the eastern area in 2015 and 2016.

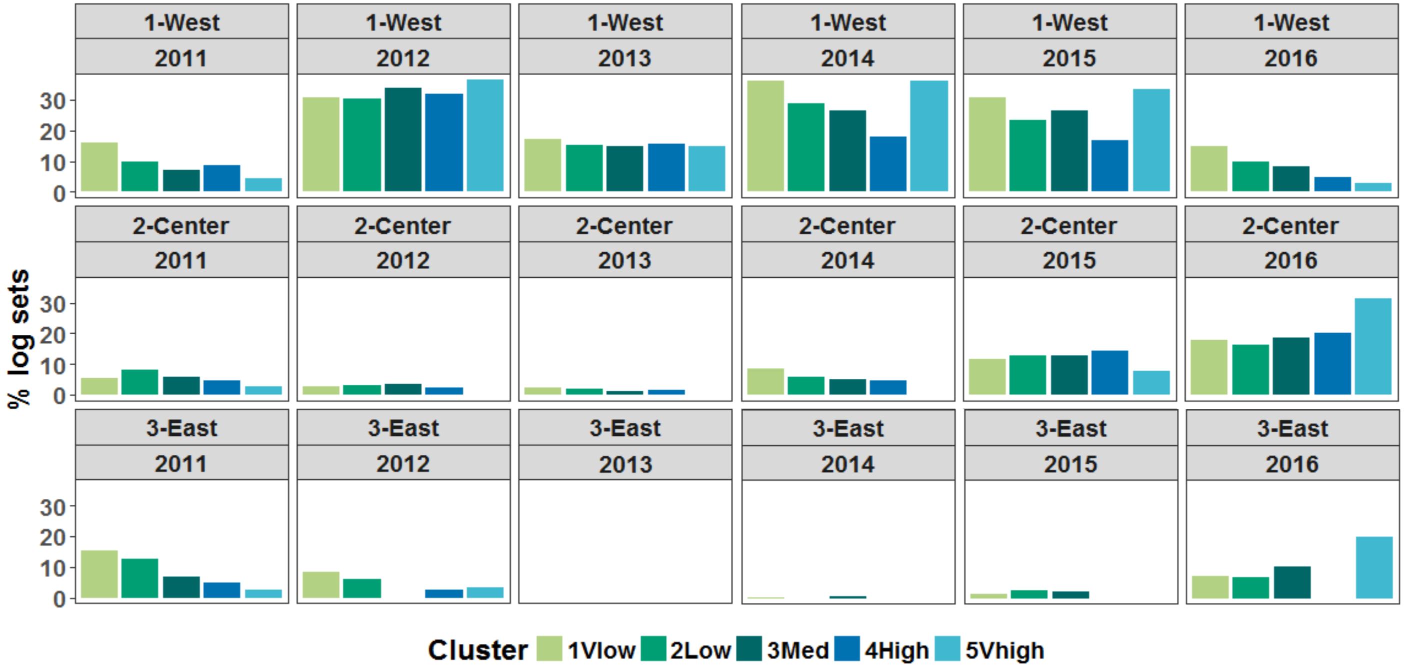


Figure A10. Percentage of logs among all associated sets by area and year.

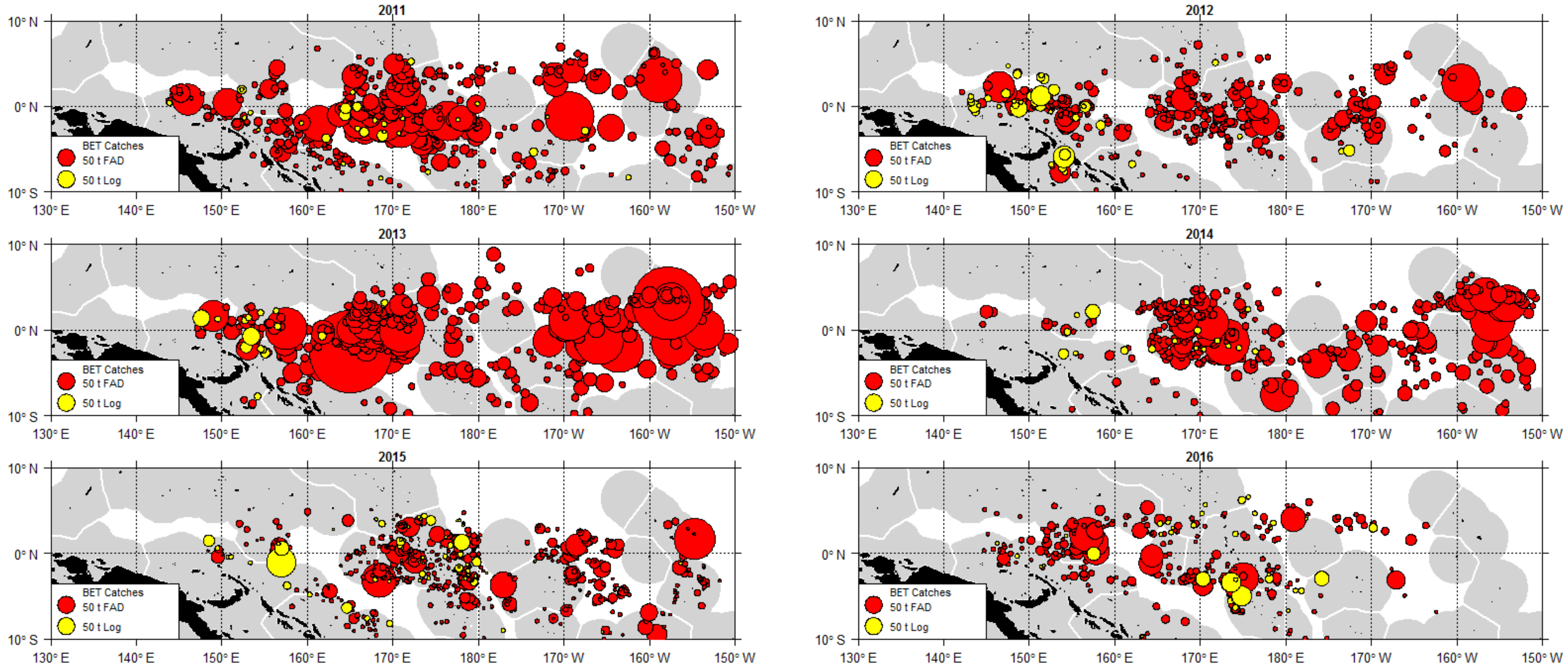


Figure A11. Spatial distribution of drifting constructed FAD and log sets by year in the high and very high clusters, pooled.

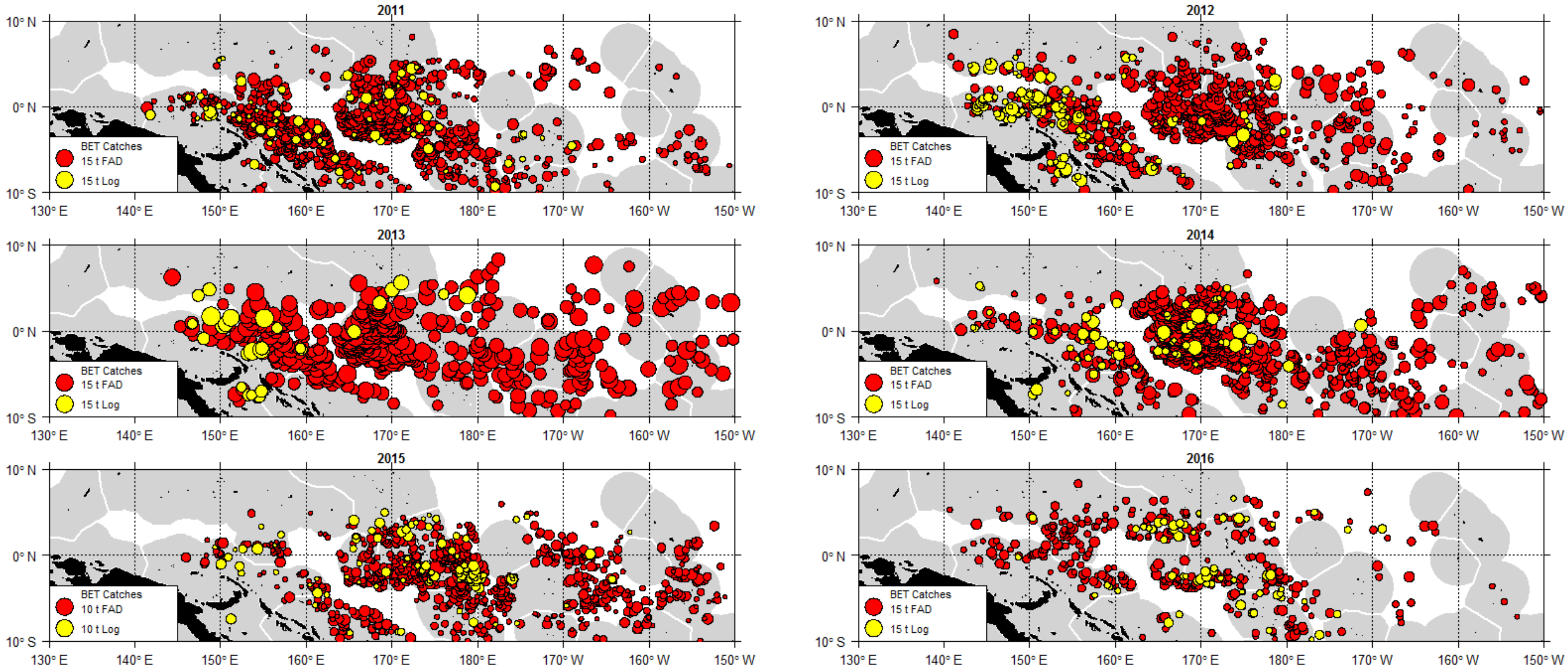


Figure A12. Spatial distribution of drifting constructed FAD and log sets by year in the medium cluster.

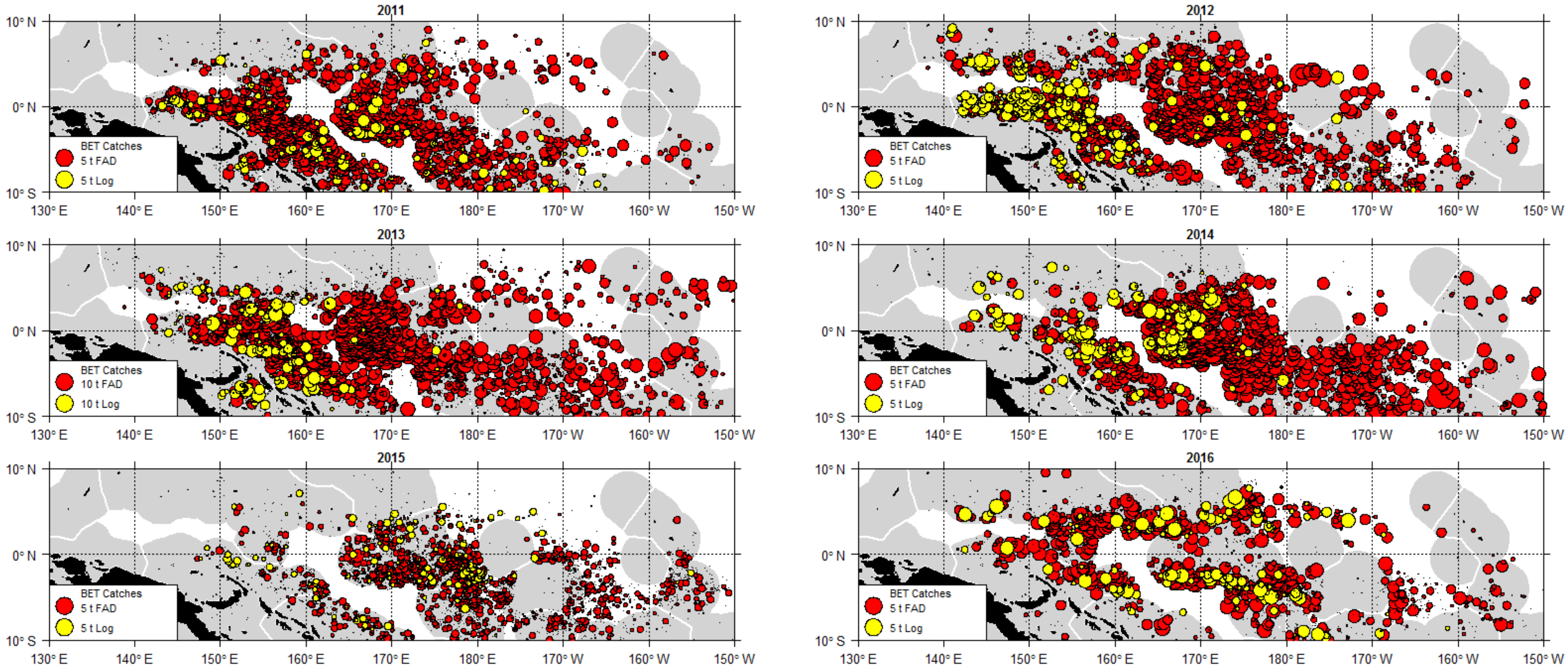


Figure A13. Spatial distribution of drifting constructed FAD and log sets by year in the low and very low clusters, pooled.

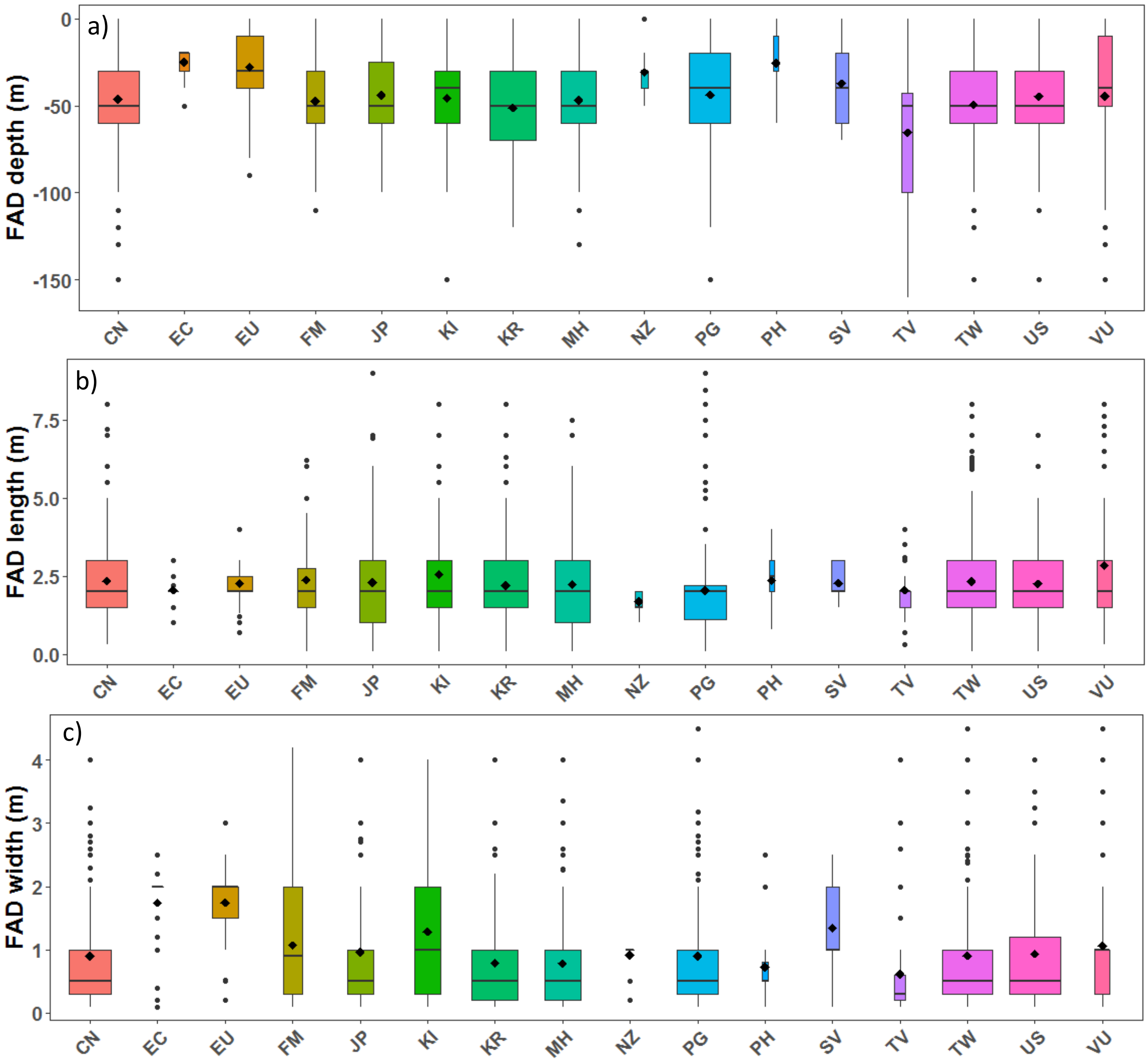


Figure A14. Drifting constructed FAD depth (a), length (b) and width (c) by fleet. The width of the bars is proportional to the number of sets by fleet.

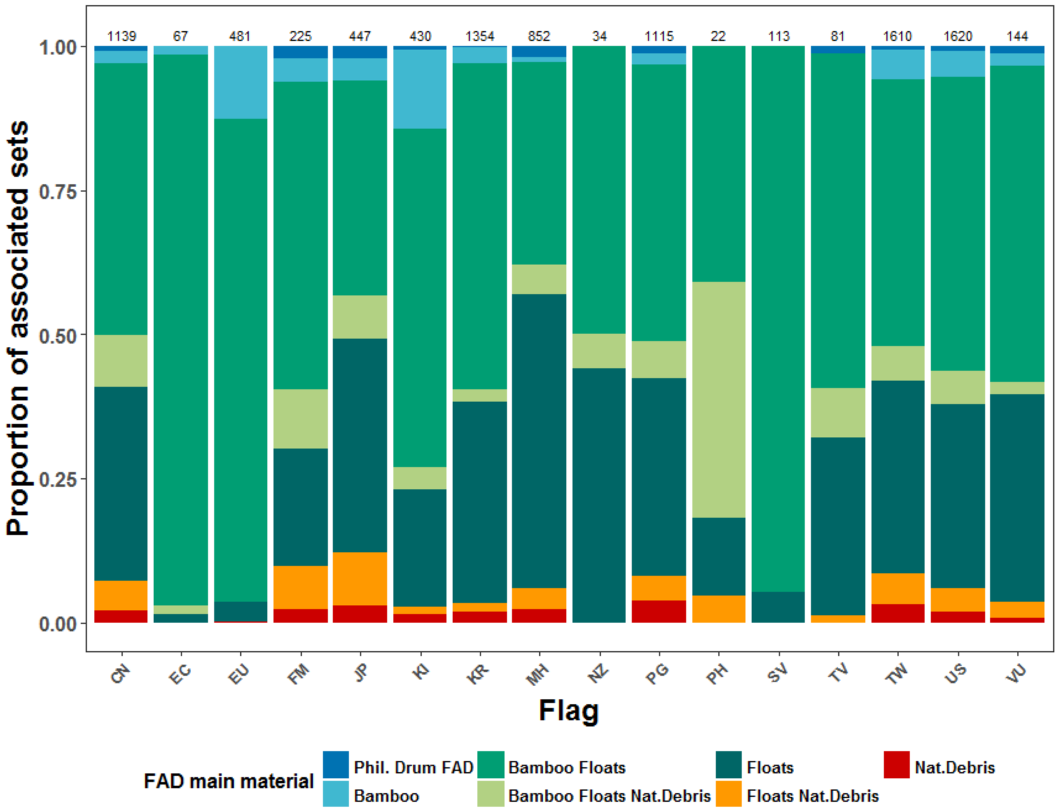


Figure A15. Drifting constructed FAD main material by fleet. Numbers are the number of sets with information on FAD material recorded by observer.

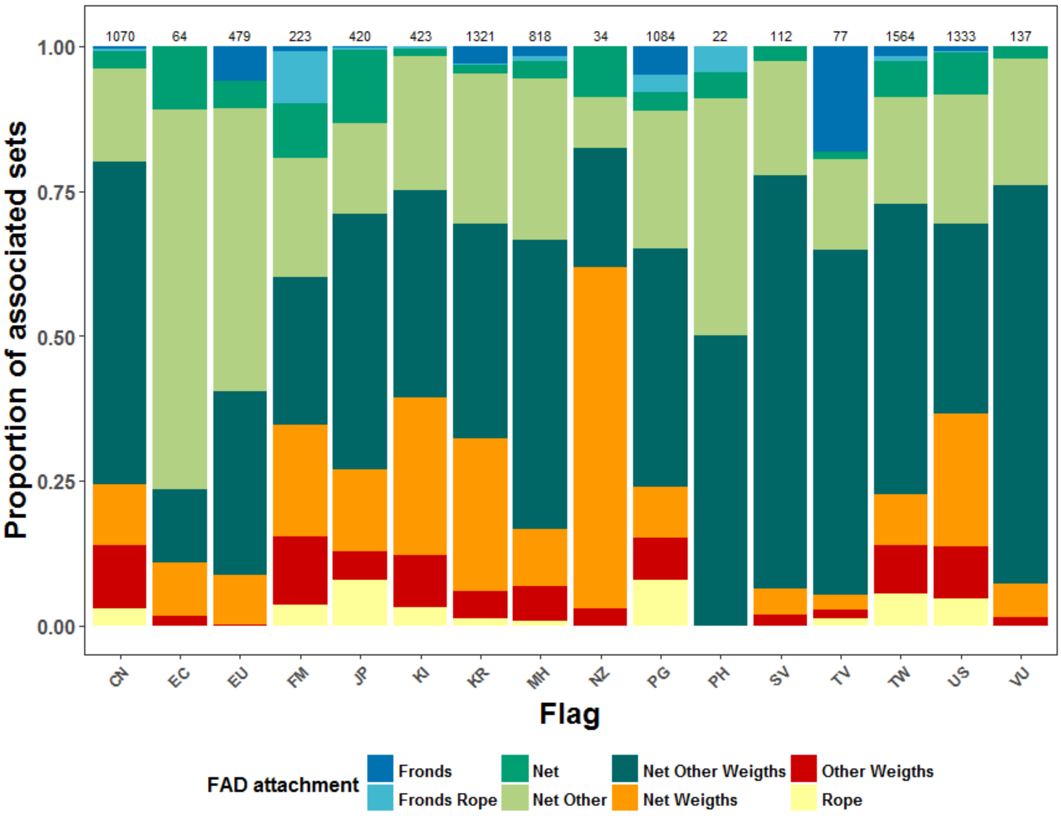


Figure A16. Drifting constructed FAD attachment by fleet. Numbers indicate the number of sets with information on FAD material recorded by observer.

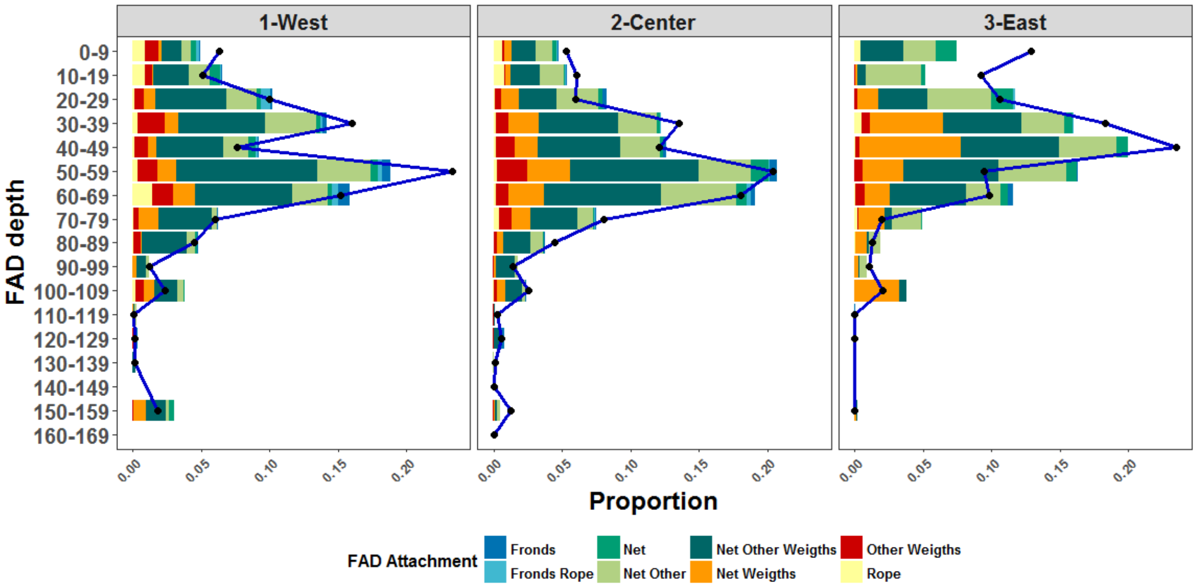


Figure A17. Proportion of drifting constructed FAD by depth and attachment category, blue lines represent the proportion of bigeye catch by drifting FAD depth class and by area.

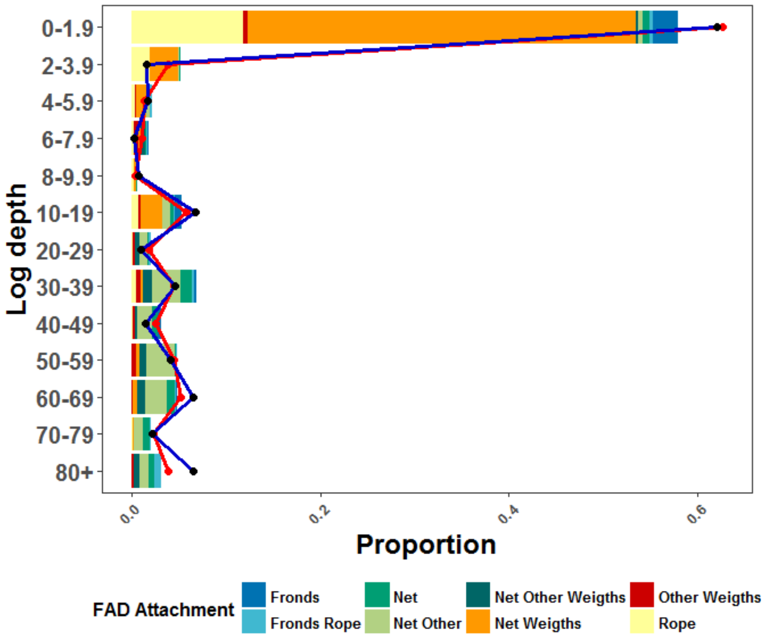


Figure A18. Proportion of log by depth and attachment category, the blue line represents the proportion of bigeye catch by log depth category and by area and red line the proportion of total catch.

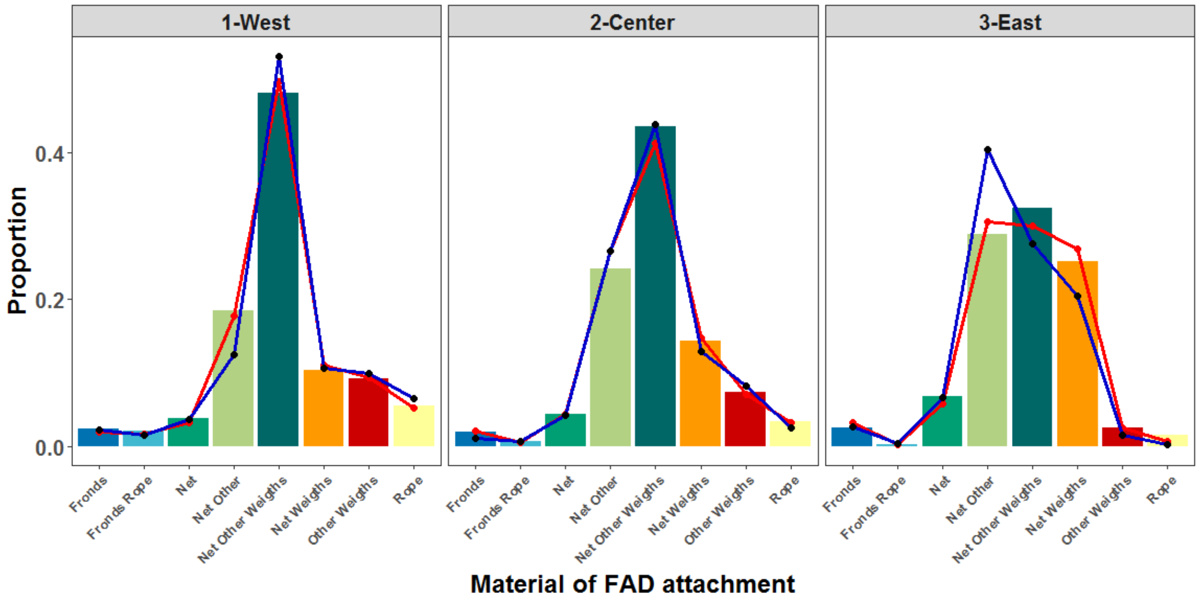


Figure A19. Proportion of drifting constructed FAD by attachment category, blue lines represent the proportion of bigeye catch by FAD depth category and by area and red lines the proportion of total catch.

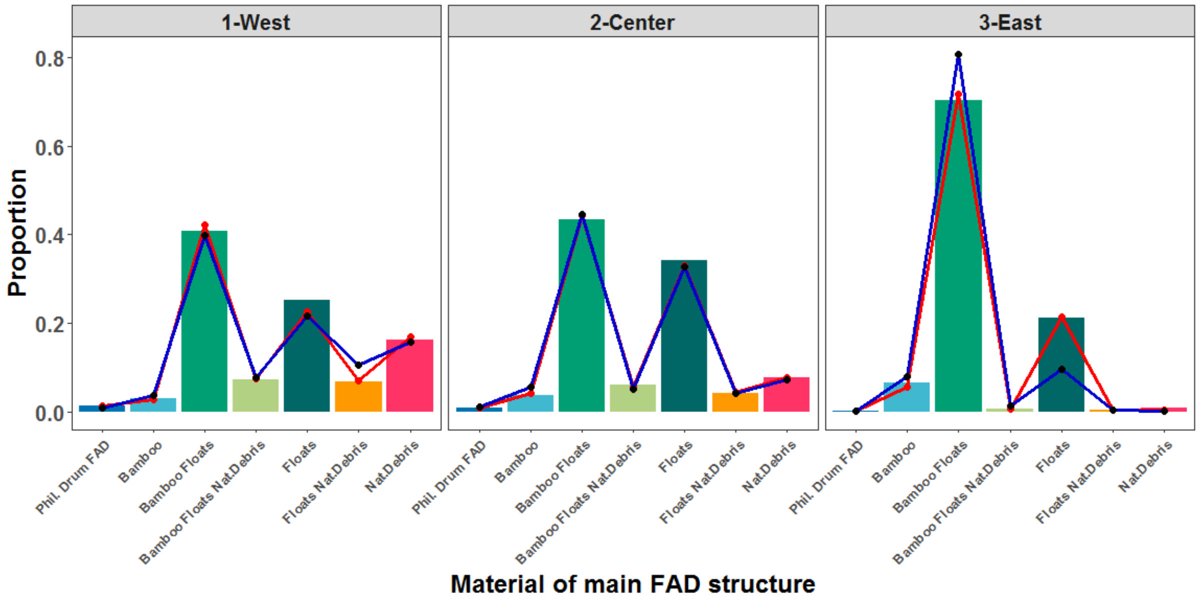


Figure A20. Proportion of drifting constructed FAD by main structure category, blue lines represent the proportion of bigeye catch by FAD depth category and by area and red lines the proportion of total catch.

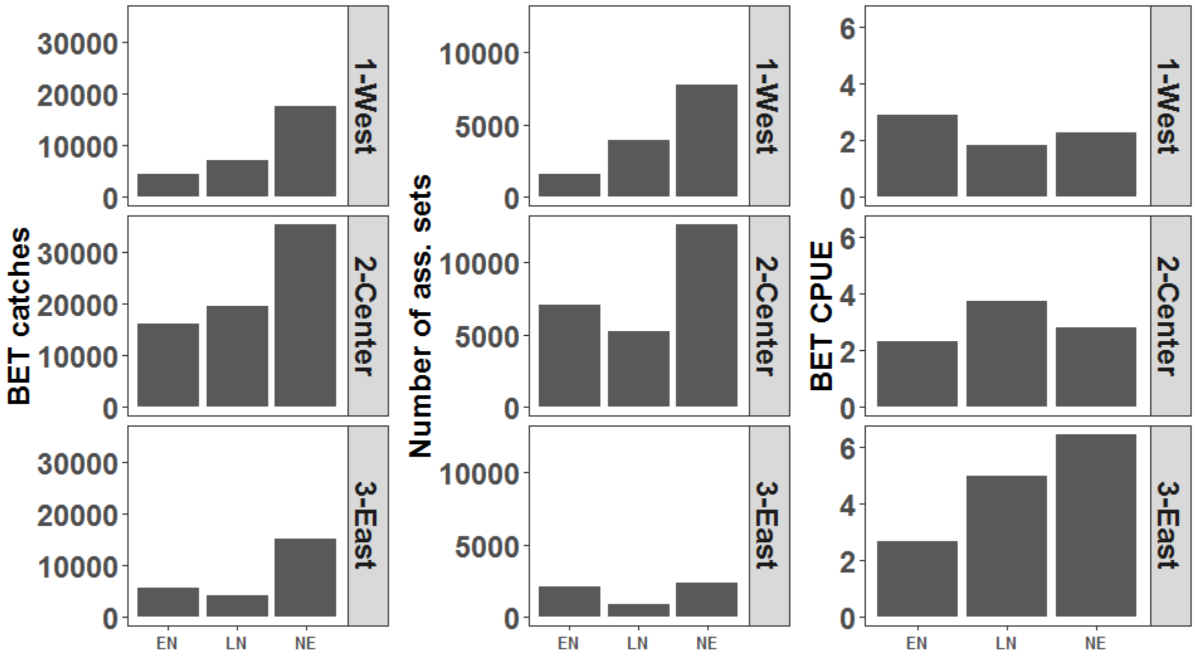


Figure A21. Total bigeye tuna catch, number of associated sets and bigeye CPUE by area and ENSO period (EN = El Niño, LN = La Niña, NE = Neutral).

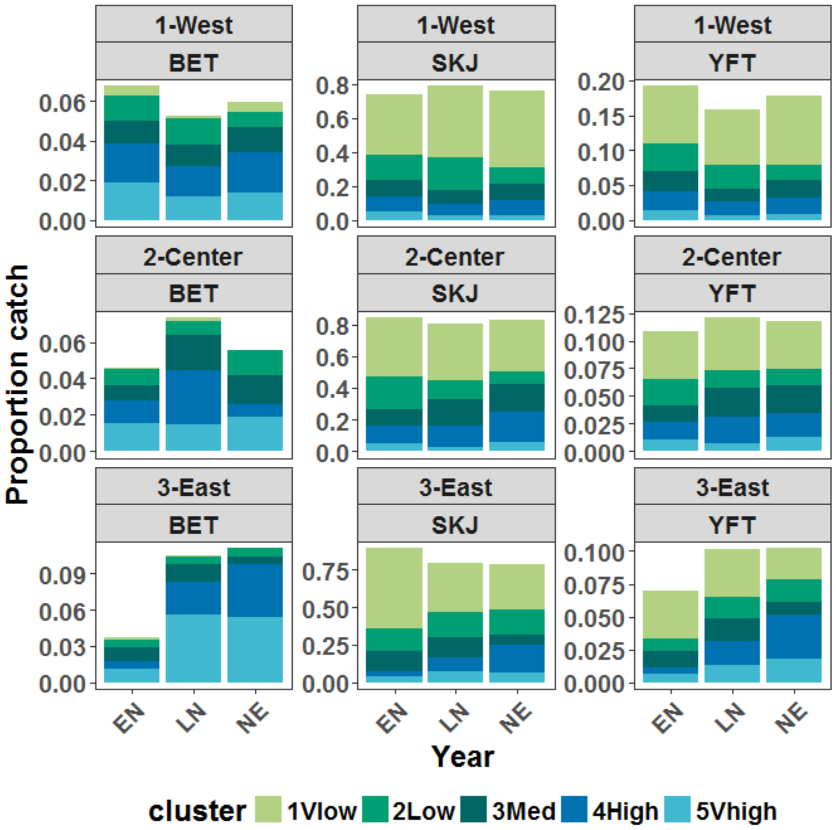


Figure A22. Proportion of each species catch over the total catch by area and ENSO period. EN = El Niño (2015), LN = La Niña (2011), NE = neutral (2012, 2013, 2014 and 2016).

Table A3. Tuna catch from the top vessels catching ~10; 25 and 50% of the overall bigeye tuna catch by year.

	Year	% BET	% SKJ	% YFT	% Total	% Ass. sets	Number of vessels
Top vessels 10% bigeye catch	2011	9.14	4.38	3.94	4.67	2.36	1
	2012	8.69	2.64	3.45	3.07	1.80	2
	2013	7.48	2.00	2.25	2.43	1.45	1
	2014	9.89	2.32	2.37	2.75	1.76	2
	2015	8.16	3.53	4.22	3.80	3.34	4
	2016	7.89	3.51	3.66	3.78	3.38	2
Top vessels 25% bigeye catch	2011	24.02	11.53	12.49	12.61	8.31	7
	2012	24.85	9.30	11.38	10.39	8.74	11
	2013	24.89	9.89	10.18	11.01	8.33	8
	2014	24.31	8.62	9.98	9.67	7.92	10
	2015	24.96	14.68	16.71	15.31	12.25	15
	2016	24.14	11.90	15.18	13.01	11.35	9
Top vessels 50% bigeye catch	2011	49.82	28.10	29.12	29.87	23.62	25
	2012	49.85	30.63	29.21	31.49	29.16	30
	2013	49.09	28.11	28.42	29.66	24.11	23
	2014	49.21	25.82	31.81	27.83	27.01	29
	2015	49.38	29.85	32.94	30.99	28.60	34
	2016	49.86	28.72	32.99	30.46	29.02	25

Table A4. List of top vessels in at least two years or/and catching more than 3% of the bigeye tuna in the WCPO per year. Numbers indicate the percentage of bigeye / total tuna catch made by the vessel considered over total bigeye / tuna catch in associated sets of the tropical WCPO. Light grey indicates vessel being classified as "top vessel"; dark grey indicates bigeye catch > 3% of the total associated bigeye catch in the WCPO.

Vessel number	Flag	Length (m)	2011	2012	2013	2014	2015	2016
1	KI	80+	9.1 / 4.7	5.5 / 1.9	2.4 / 1.3	2.0 / 0.8	1.6 /1.1	
2	US	71-75	2.8 / 1.3	1.6 / 1.0	1.2 / 0.9	2.1 / 0.9	1.5 / 0.6	
3	MH	71-75	1.3 / 0.9	1.4 / 1.0	1.3 / 1.7	1.1 / 1.0		2.5 / 2.0
4	MH	71-75	4.1 / 1.9	1.2 / 0.7	1.2 / 1.0	1.3 / 0.9		
5	EU	80+	2.9 / 1.1	3.1 / 1.1	2.0 / 2.4	2.0 / 1.1		
6	MH	61-65	2.8 / 1.9	1.5 / 1.2	1.5 / 1.6	1.5 / 1.2		
7	MH	71-75		1.0 / 1.4	1.4 / 1.2	2.0 / 1.2		1.3 / 1.3
8	US	71-75	1.9 / 1.6	1.1 / 1.2			1.3 / 0.4	
9	EU	80+		2.7 / 0.6	7.5 / 2.4	7.2 / 1.7		
10	MH	61-65	1.9 / 0.7		2.6 / 1.5	1.7 / 0.9		
11	MH	71-75	1.8 / 1.4	1.3 / 1.2		2.1 / 1.4		
12	JP	61-65		1.5 / 0.8		1.0 / 0.6	1.8 /0.3	
13	CN	66-70		1.4 / 1.0		1.2 / 1.1	1.2 / 1.1	
14	TW	66-70		1.4 / 1.5	2.0 / 1.1	1.4 / 1.3		
15	TW	71-75				1.5 / 0.8	1.5 / 1.3	1.4 / 1.4
16	PG	71-75				1.4 / 0.6	1.4 / 0.4	2.0 / 0.7
17	US	66-70		1.3 / 1.2	1.9 / 1.7		1.8 / 1.1	
18	US	71-75	2.3 / 1.7	1.4 / 1.1				
19	SV	80+	2.1 / 0.9			2.7 / 1.1		
20	US	76-80	1.7 / 1.3					1.9 / 0.8
21	KR	76-80	1.2 / 0.7				1.6 / 1.3	
22	MH	71-75	1.2 / 0.4		3.2 / 1.4			
23	KR	71-75	1.1 / 0.7				1.2 / 0.9	
24	US	66-70		2.3 / 1.5	1.8 / 1.7			
25	US	80+		1.6 / 0.6	1.6 / 1.0			
26	US	71-75		1.3 / 1.2			1.1 / 0.7	
27	EU	80+			3.5 / 1.6	2.3 / 0.6		
28	KI	66-70				1.7 / 1.0		1.5 / 1.2
29	CN	71-75				1.8 / 1.0		1.7 / 0.8
30	KI	66-70				1.1 / 0.8		1.5 / 1.2
31	FM	80+				1.0 / 0.7		3.1 / 2.1
32	TW	71-75					1.4 / 1.2	1.6 / 1.0
33	FM	76-80					1.2 / 0.4	3.7 / 1.3
34	EU	80+			3.5 / 1.1			
35	MH	71-75			2.3 / 1.7			
36	MH	71-75			2.2 / 1.1			
37	EC	80+			1.8 / 0.8			
38	US	80+			1.7 / 1.0			
39	TW	71-75				1.2 / 1.1		4.2 / 2.5
40	FM	66-70						3.3 / 1.4
41	PG	61-65						3.2 / 1.3

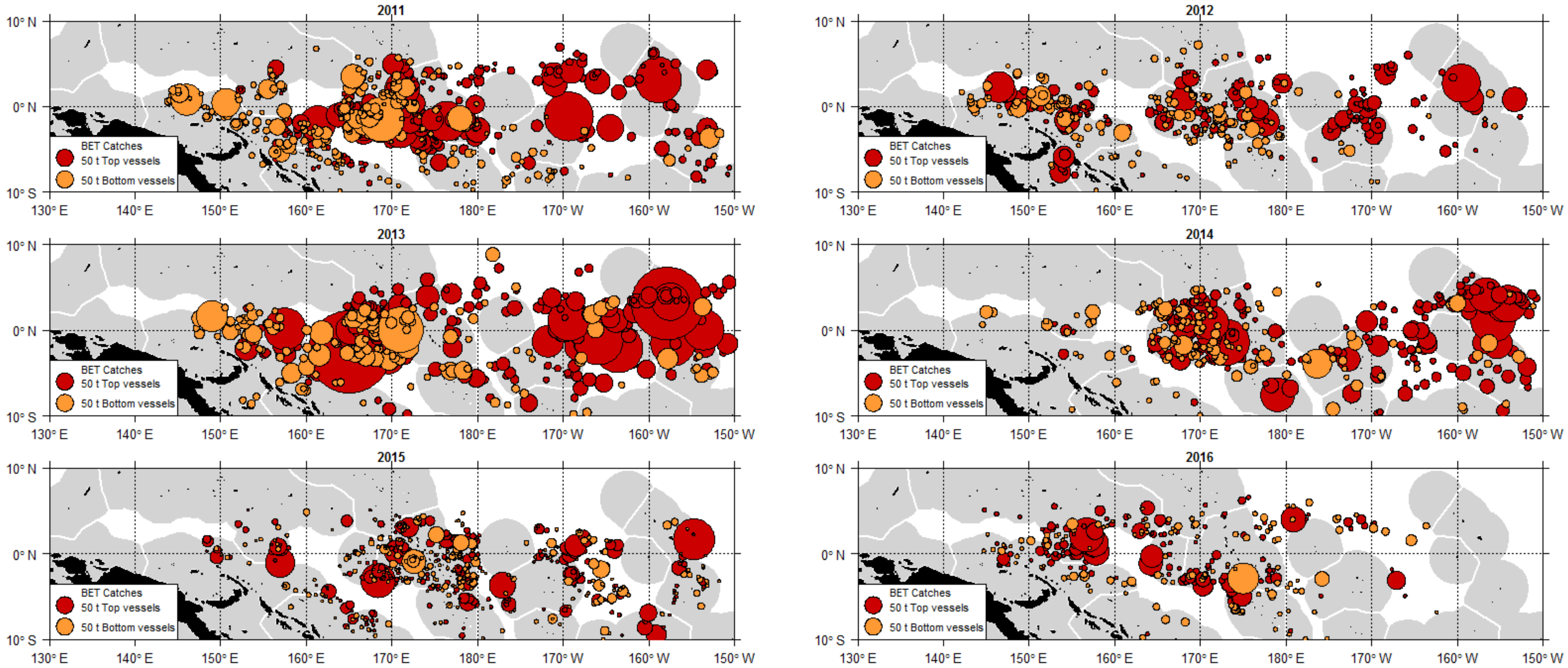


Figure A23. Top vs bottom vessel sets in High and Very high bigeye catch clusters, pooled.

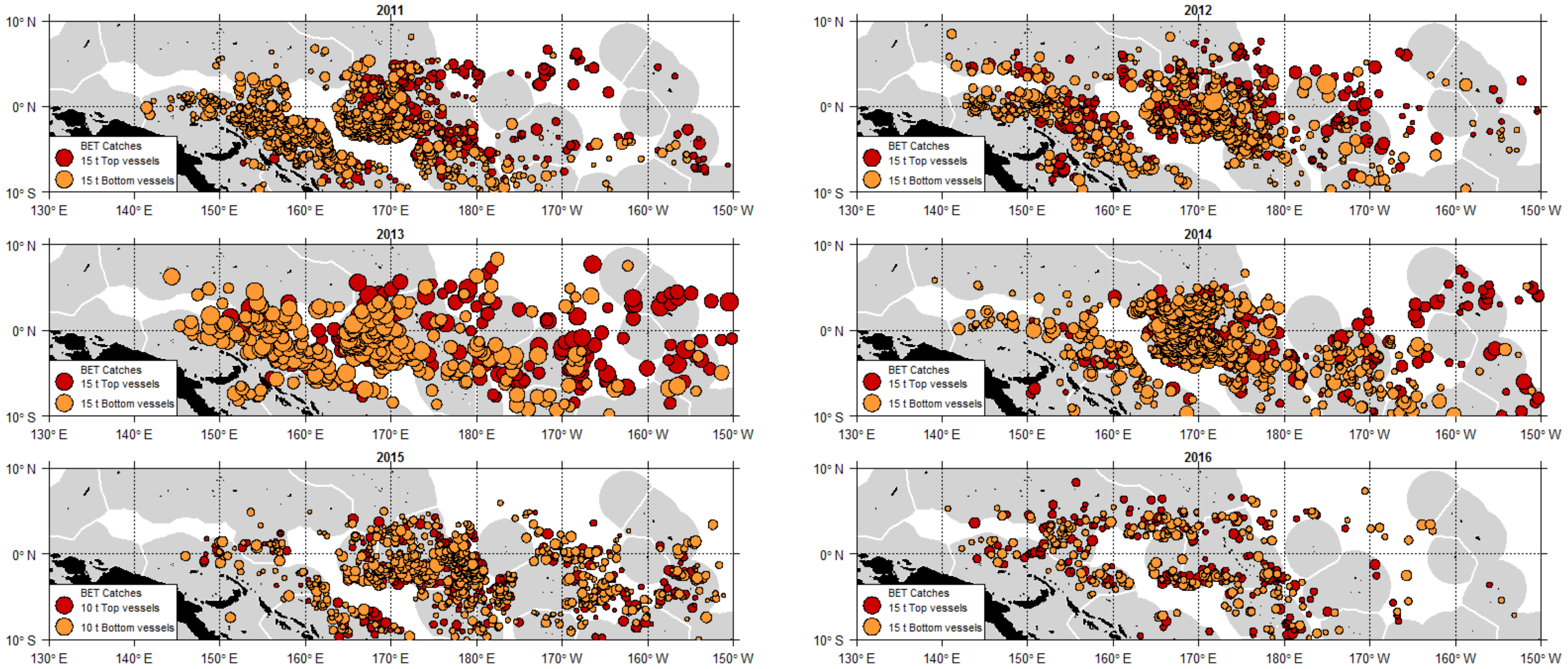


Figure A24. Top vs bottom vessel sets in Medium bigeye catch cluster. Note that in the Western and Central areas, due to the high number of sets, sets performed by top vessels may be hidden by those performed by bottom vessels.

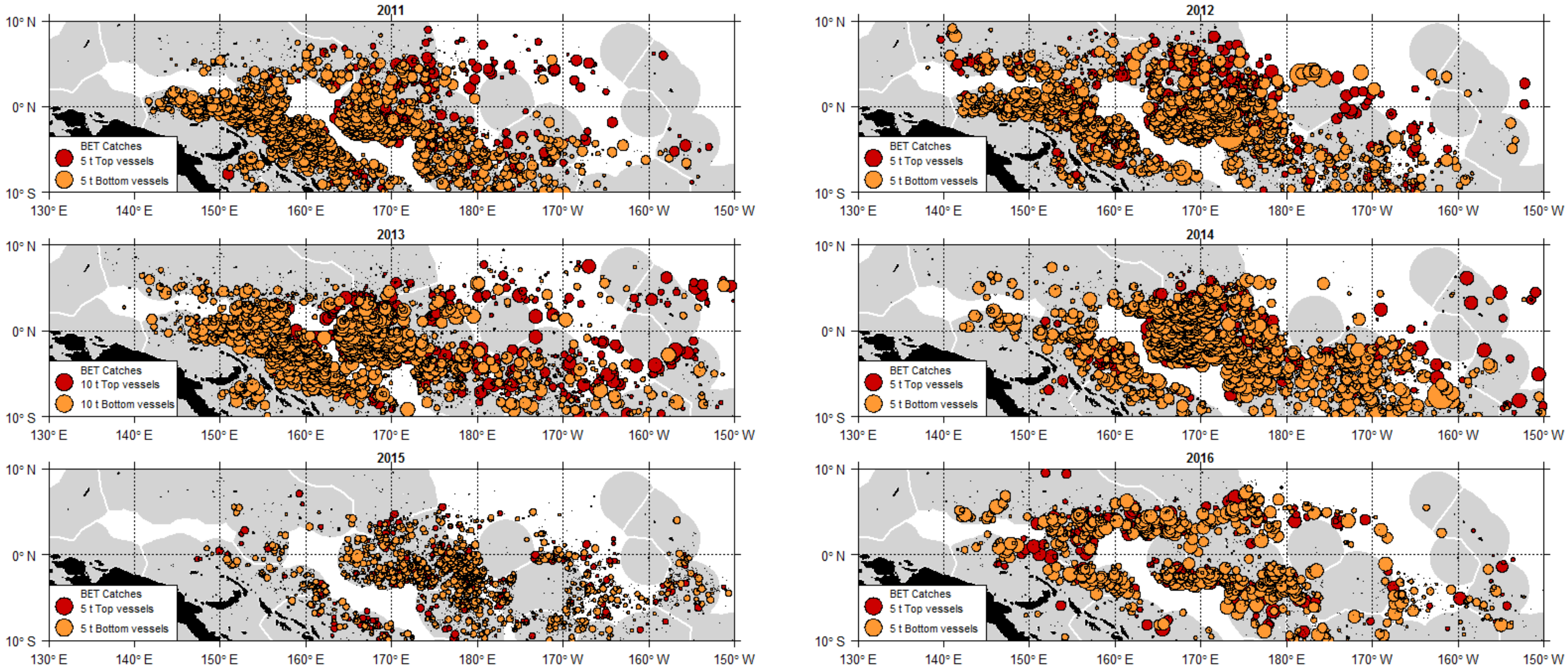


Figure A25. Top vs bottom vessel sets in Low and Very low bigeye catch clusters, pooled. Note that in the Western and Central areas, due to the high number of sets, sets performed by top vessels may be hidden by those performed by bottom vessels.

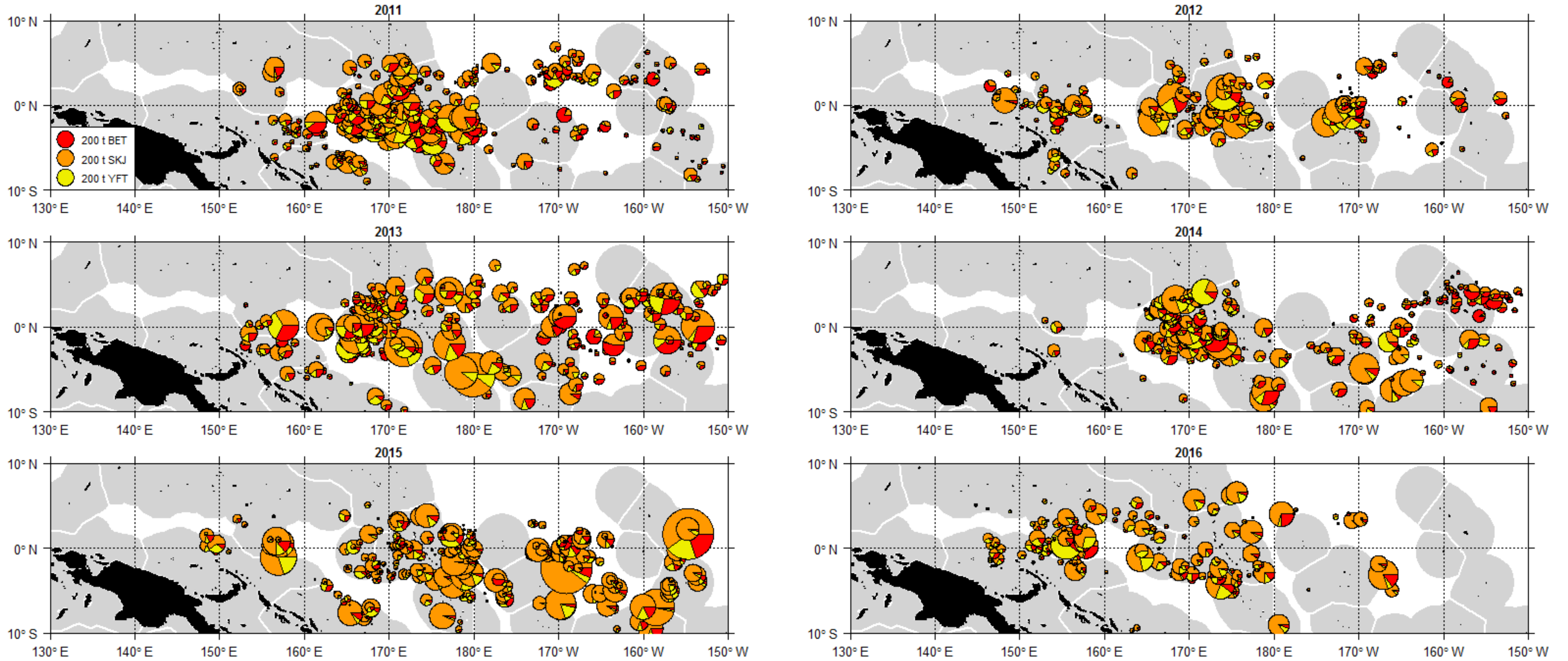


Figure A26. Proportion of catch by species in sets included in High and Very High clusters (pooled) and from top vessels.

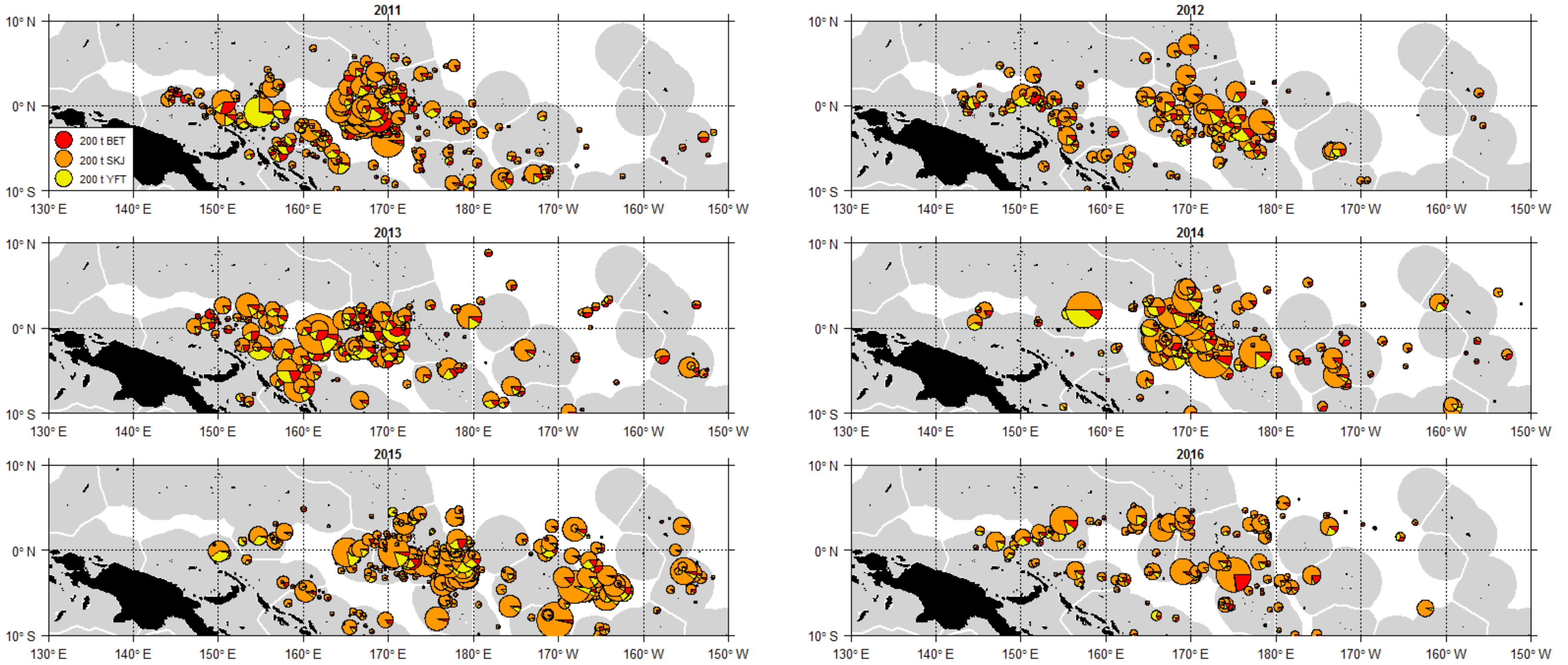


Figure A27. Proportion of catch by species in sets included in High and Very High clusters (pooled) and from bottom vessels.

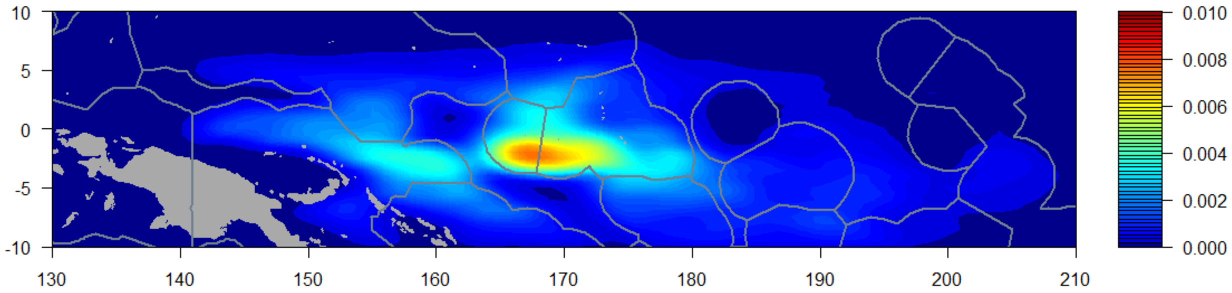


Figure A28. Smoothed kernel distribution of effort (associated sets) from 2011–2016 for each 0.5° cell.

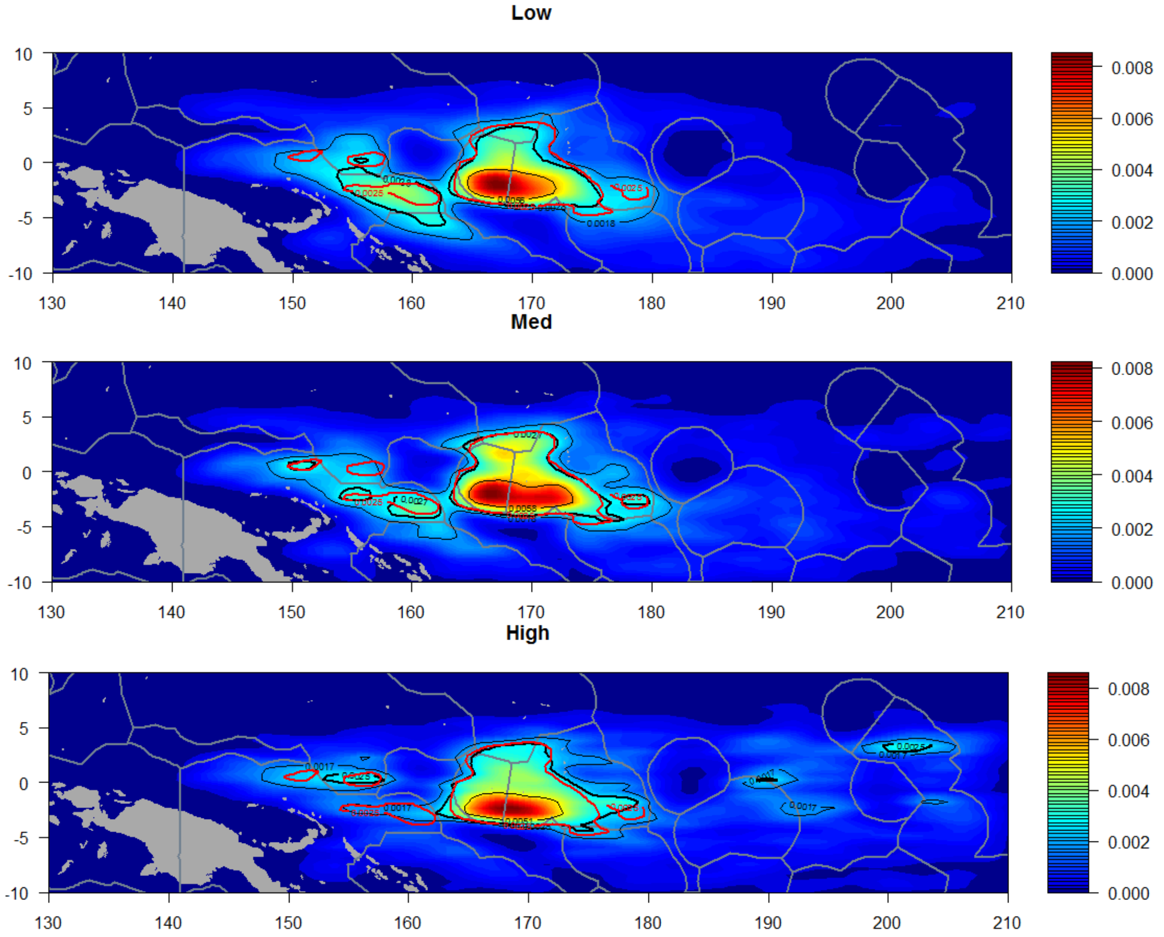


Figure A29. Smoothed kernel distribution of proportion of BET catch for each cluster from 2011– 2016 for each 0.5° cell. Black lines represent quantile 0.99 of proportion, quantile 0.95 and quantile 0.90 for each cluster, and the red line represents the quantile 0.95 for all data (see Figure 20).

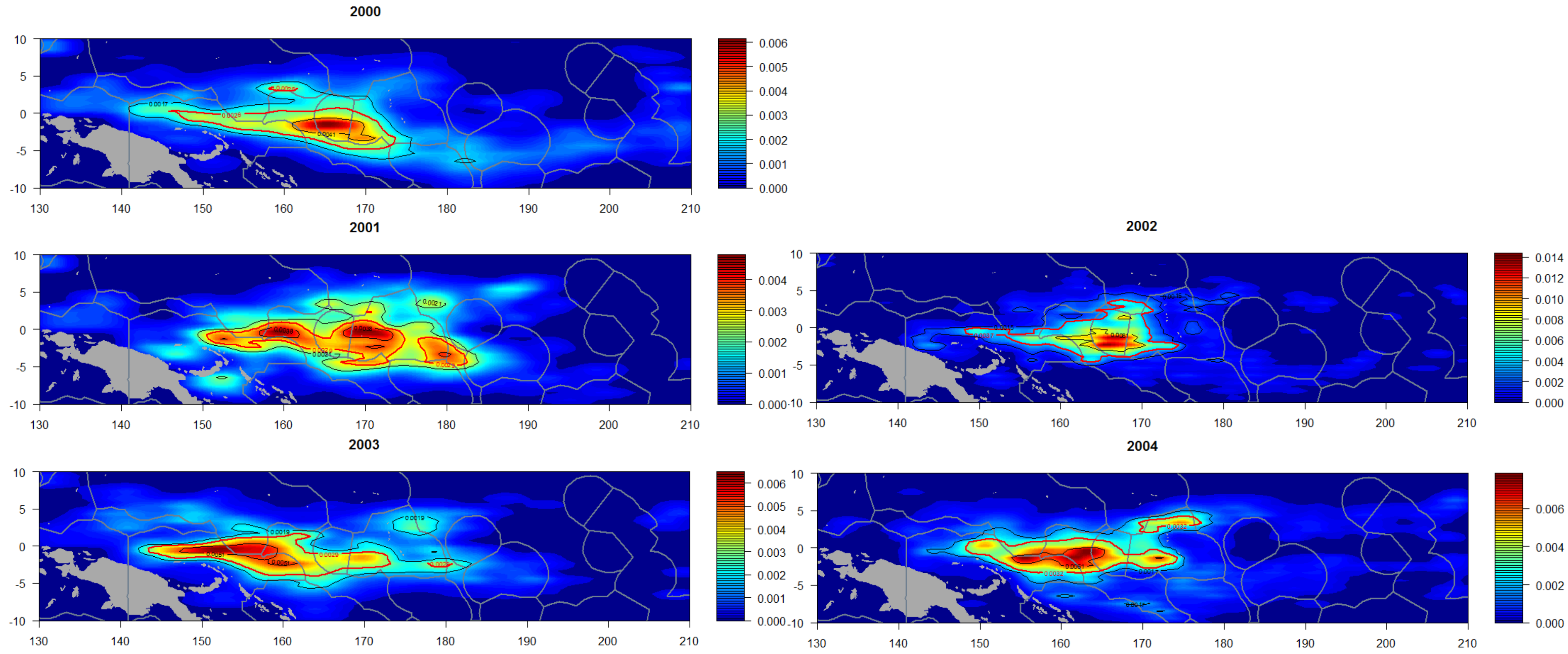


Figure A30. (Part 1) Smoothed kernel distribution of proportion of BET catch for each year for each 0.5° cell using S-BEST data (corrected and aggregated logsheet data). Black lines represent quantile 0.99 of proportion and quantile 0.90 and the red line quantile 0.95 by year.

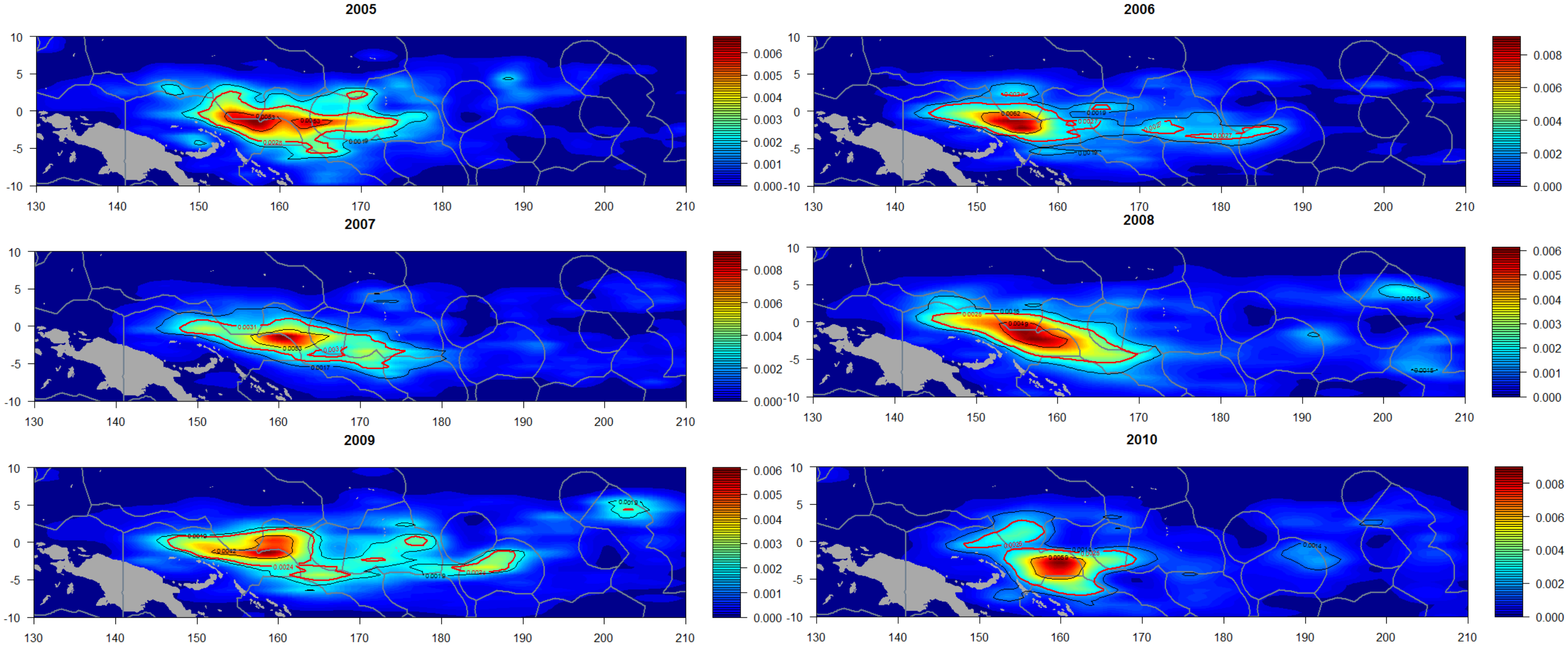


Figure A30. (Part 2) Smoothed kernel distribution of proportion of BET catch for each year for each 0.5° cell using S-BEST data (corrected and aggregated logsheet data). Black lines represent quantile 0.99 of proportion and quantile 0.90 and the red line quantile 0.95 by year.

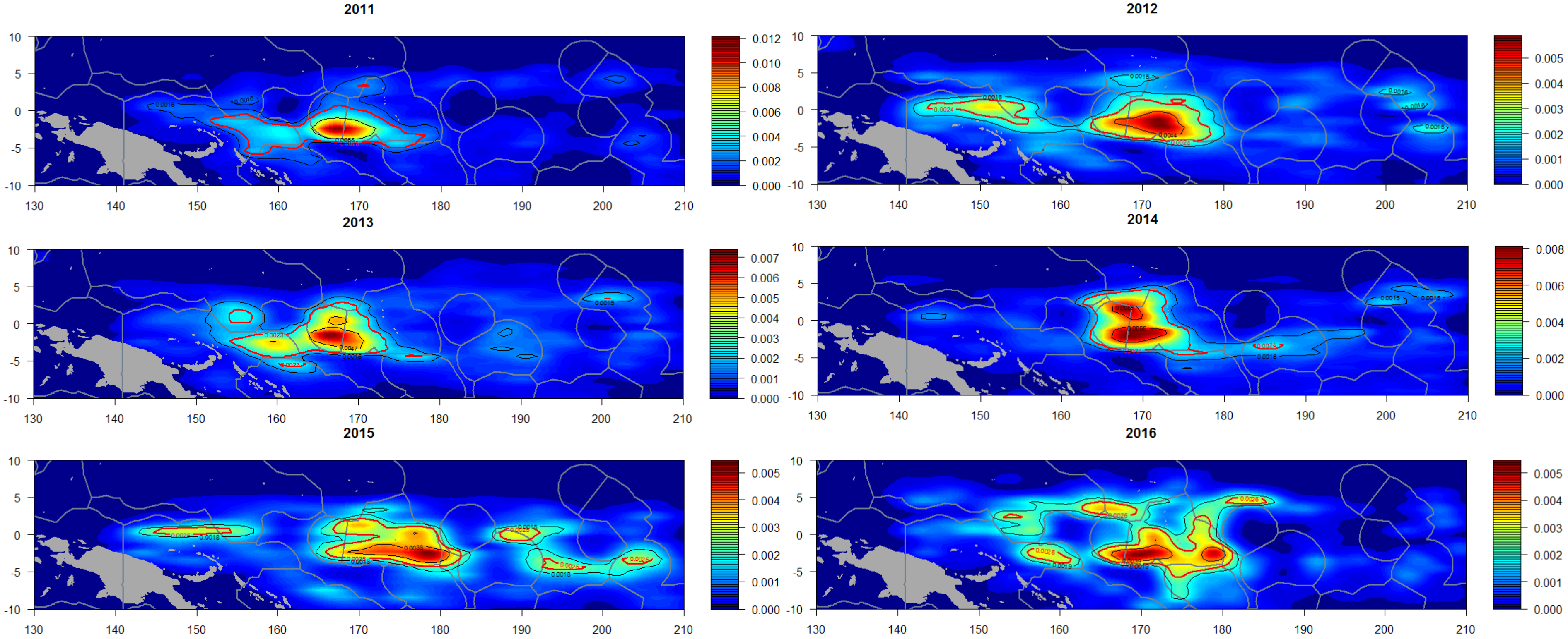


Figure A30. (Part 3) Smoothed kernel distribution of proportion of BET catch for each year for each 0.5° cell using S-BEST data (corrected and aggregated logsheet data). Black lines represent quantile 0.99 of proportion and quantile 0.90 and the red line quantile 0.95 by year.

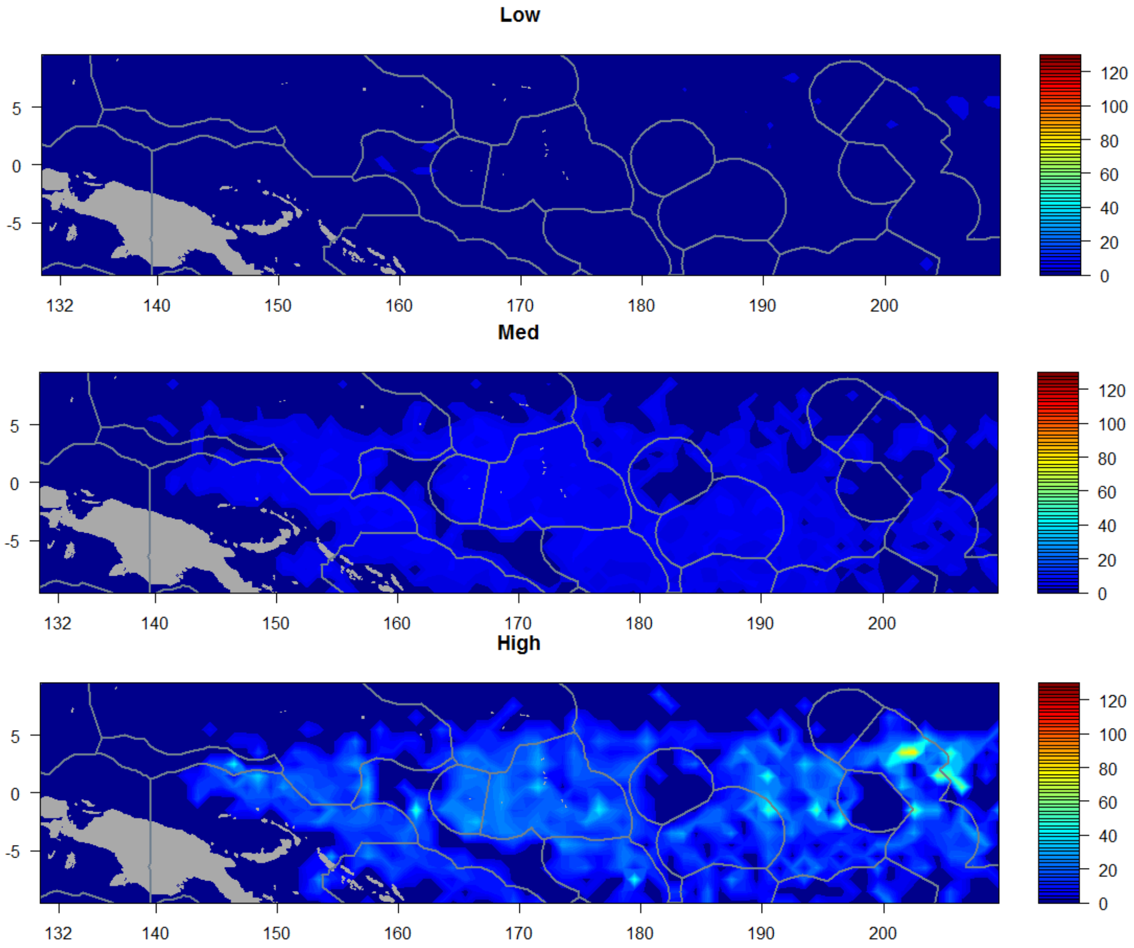


Figure A31. Smoothed kernel distribution of BET CPUE for each cluster from 2011–2016 for each 0.5° cell.

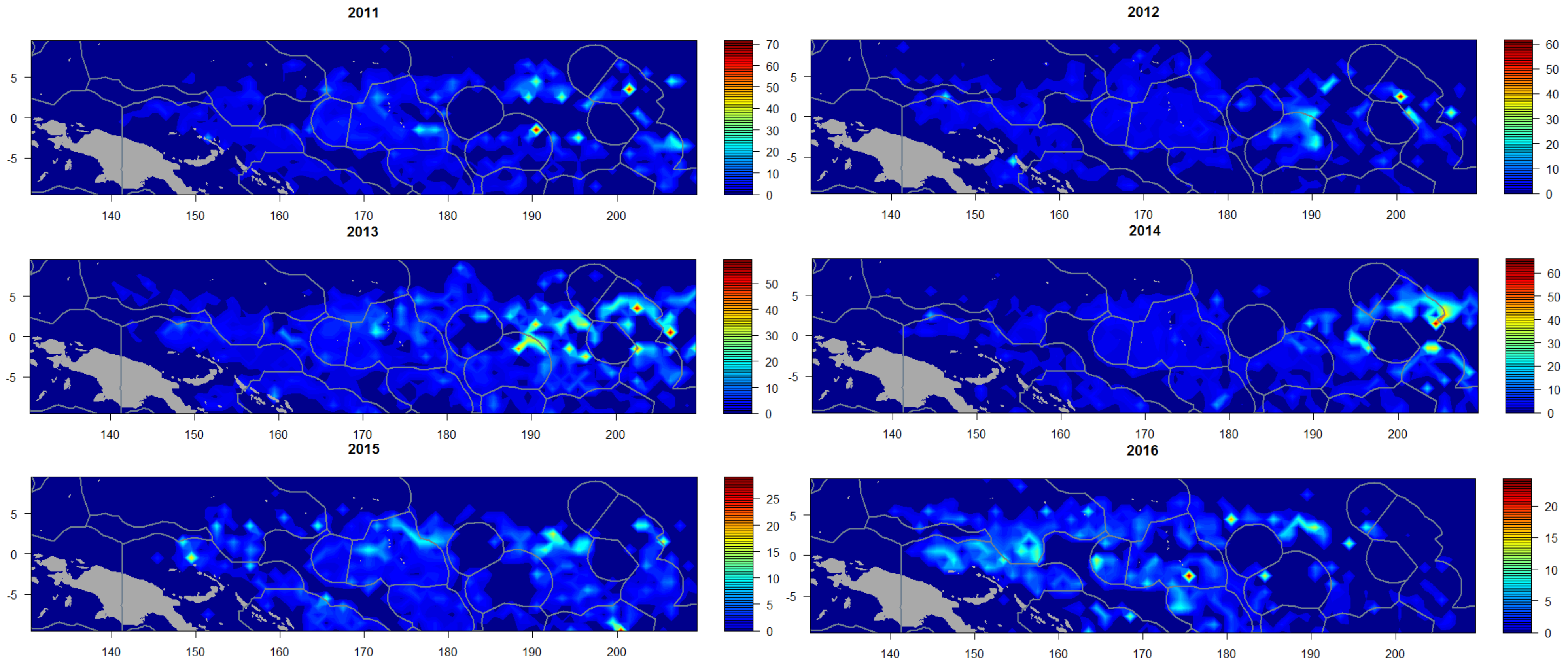


Figure A32. Smoothed distribution of CPUE by year for each 0.5° cell.

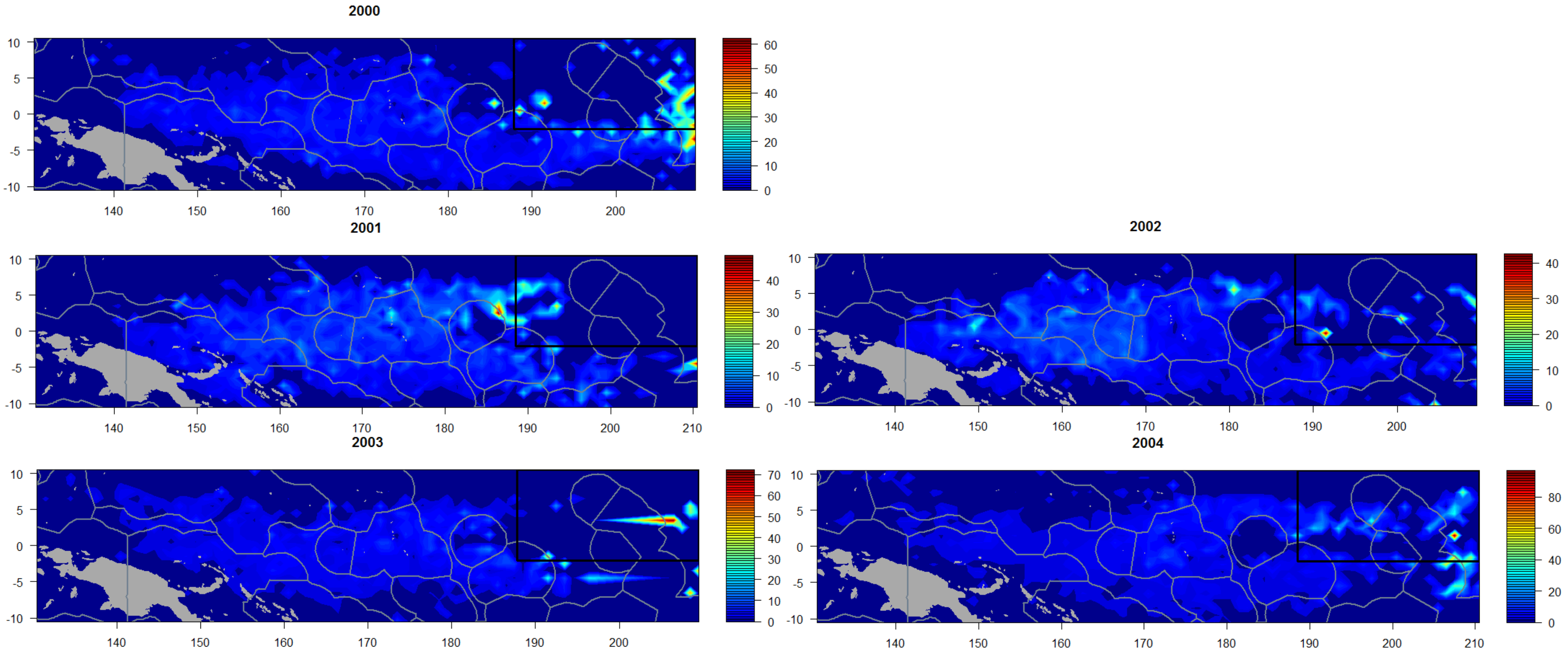


Figure A33. (Part 1) Smoothed distribution of CPUE by year for each 0.5° cell using S-BEST data (corrected and aggregated logsheet data).

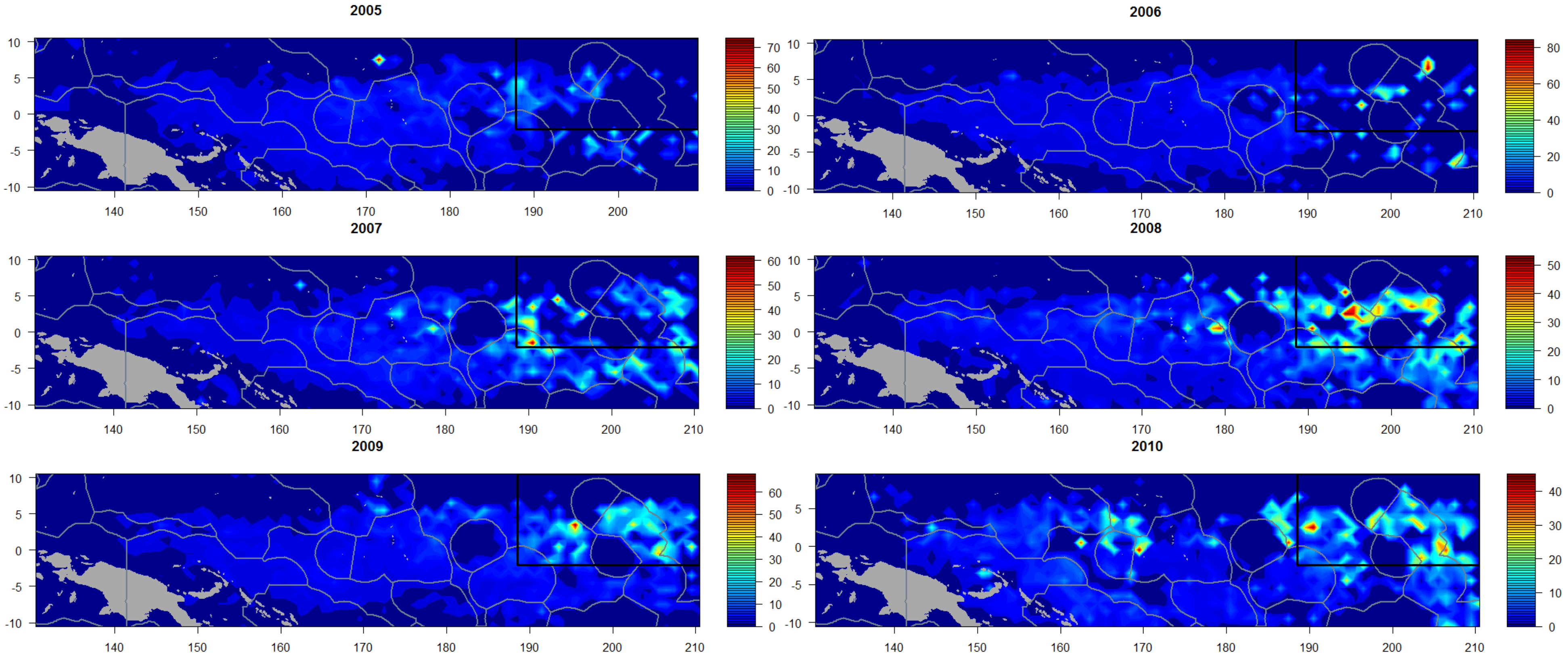


Figure A33. (Part 2) Smoothed distribution of CPUE by year for each 0.5° cell using S-BEST data (corrected and aggregated logsheet data).

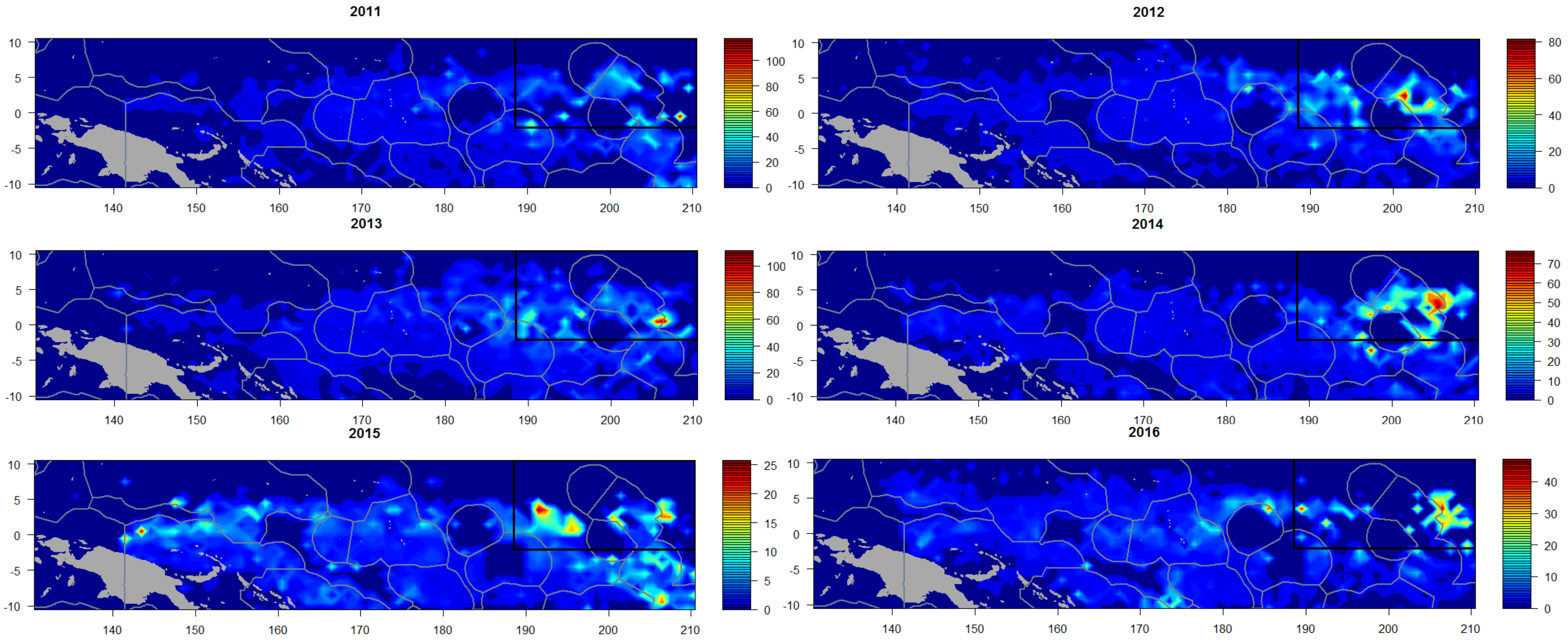
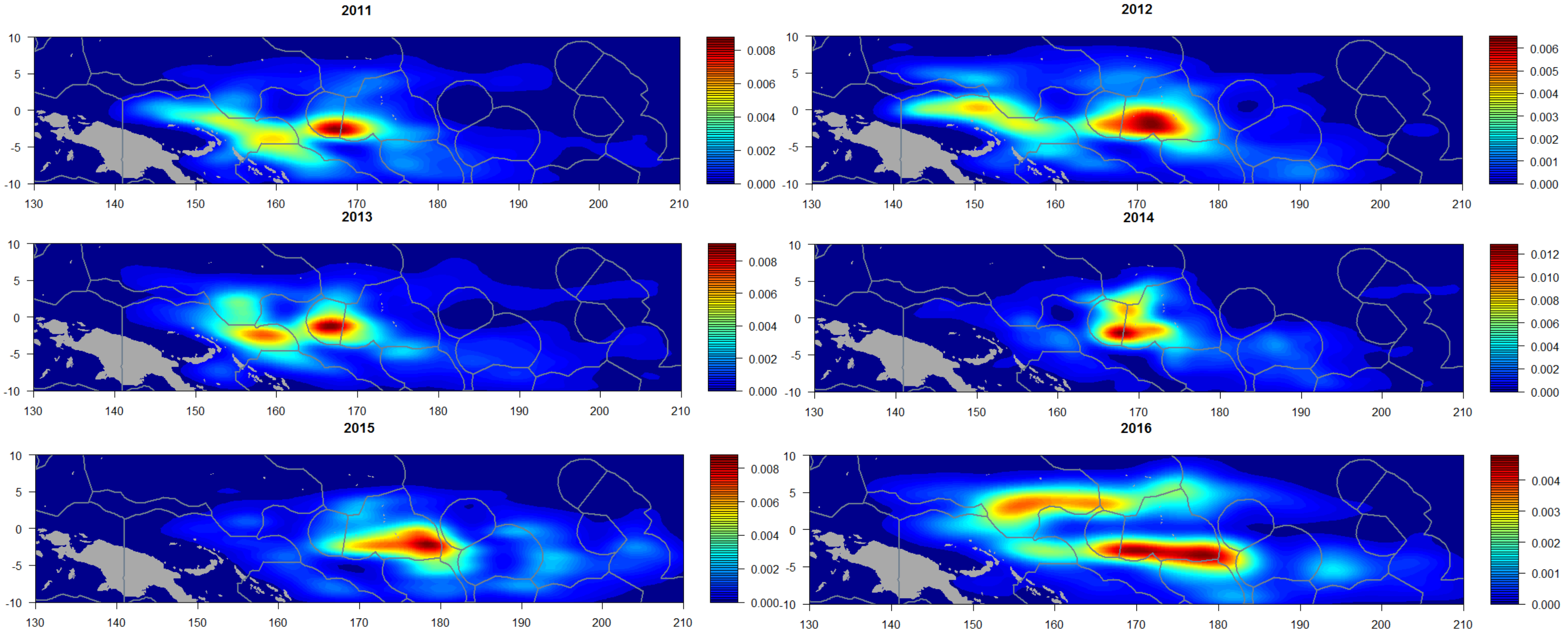


Figure A33. (Part 3) Smoothed distribution of CPUE by year for each 0.5° cell using S-BEST data (corrected and aggregated logsheet data).


2011

2012

2013

2014

2015

2016

Figure A34. Smoothed kernel distribution of proportion of effort (number of associated set) by year for each 0.5° cell.

Table A5. Percentage of tuna catch performed within the catch and CPUE hotspots per year using S-BEST data (corrected and aggregated logsheet data). Rows highlighted in grey corresponds to the same period as the analyses performed in this study using observer visual estimates data.

	Catch hotspot					CPUE hotspot				
Year	% BET	% SKJ	% YFT	% total catch	% ass. set	% BET	% SKJ	% YFT	% total catch	% ass. set
2000	23.09	21.95	19.84	21.40	12.01	4.72	0.73	2.19	1.50	0.63
2001	23.58	23.36	18.90	22.24	16.29	2.03	0.98	1.23	1.15	0.53
2002	38.36	36.21	34.69	36.06	23.80	1.96	1.44	1.12	1.41	0.79
2003	21.65	16.48	18.66	17.37	8.95	1.22	0.37	0.40	0.43	0.09
2004	25.66	20.46	20.09	20.77	17.54	4.55	0.76	3.20	1.67	1.44
2005	23.78	20.46	18.42	20.18	16.77	4.80	1.91	2.69	2.31	1.55
2006	19.60	17.69	15.87	17.48	18.65	3.45	0.94	0.56	1.02	0.55
2007	22.24	19.85	17.75	19.61	16.90	6.93	1.28	2.21	1.74	1.38
2008	15.85	14.61	14.04	14.58	12.48	9.78	2.48	3.07	3.06	1.42
2009	15.32	14.54	14.19	14.52	13.43	13.83	3.78	3.37	4.25	2.40
2010	23.03	22.57	24.50	22.93	20.98	12.13	6.13	4.24	6.27	3.67
2011	35.12	31.65	28.32	31.39	25.14	7.11	2.44	2.83	2.90	1.32
2012	29.07	31.11	25.80	30.16	26.39	10.87	2.18	2.93	2.89	1.74
2013	31.47	33.73	29.99	32.87	28.04	12.66	4.10	5.19	4.98	2.82
2014	38.37	40.94	43.76	41.18	39.88	11.42	2.73	2.45	3.26	1.94
2015	24.23	21.51	28.06	22.51	26.33	11.48	10.43	6.77	10.00	6.35
2016	26.61	25.18	26.35	25.45	23.93	4.13	1.47	1.27	1.62	1.09

Table A6. CPUE (t / set) of each tuna species by area and year.

	West			Center			East		
Year	BET	SKJ	YFT	BET	SKJ	YFT	BET	SKJ	YFT
2011	2.0	24.5	5.8	3.8	40.8	6.3	7.8	38.1	6.4
2012	2.1	29.1	5.4	2.1	39.5	4.9	4.3	36.2	5.7
2013	2.2	31.5	7.8	3.8	44.2	7.1	8.5	46.8	6.7
2014	2.0	26.6	6.3	2.6	41.1	5.7	4.6	52.4	4.6
2015	2.7	26.3	8.4	2.2	42.7	5.4	2.7	68.9	5.3
2016	3.3	35.8	7.8	2.8	45.0	5.8	1.9	36.9	3.8

Table A7. CPUE (t / set) of large (length >90m) vessels and smaller vessels in the "CPUE hotspot area" (172°W–150°W and 2°S–10°N), the rest of the Eastern area and the Center.

	East "CPUE hotspot" area						East rest of the area						Center		
	Vessels <= 90m			Vessels > 90m			Vessels <= 90m			Vessels > 90m			Vessels > 90m		
Year	BET	SKJ	YFT	BET	SKJ	YFT	BET	SKJ	YFT	BET	SKJ	YFT	BET	SKJ	YFT
2011	10.0	38.3	4.7	17.6	61.5	11.9	4.3	33.5	5.2	10.2	31.1	6.6	10.8	59.0	10.6
2012	8.9	23.5	4.9	17.2	59.1	13.5	1.5	33.6	4.3	10.6	41.1	9.9	4.8	41.9	6.8
2013	16.1	38.0	7.5	19.6	51.4	18.4	3.8	42.8	4.0	11.1	68.1	8.7	9.5	76.0	10.5
2014	11.4	41.0	5.2	29.0	45.6	11.4	1.7	51.3	3.8	9.8	68.4	7.1	9.3	67.4	6.1
2015	4.5	70.3	6.6	6.3	29.3	6.2	2.0	67.5	4.8	4.7	93.7	6.3	6.1	101.4	5.8
2016	6.4	34.8	7.0				1.0	37.4	3.1						

Table A8. Percentage of large (>10kg) bigeye captured by large (length >90m) vessels and smaller vessels in the "CPUE hotspot area" (172°W–150°W and 2°S–10°N), the rest of the Eastern area and the Center, when recorded by observers.

Year	% sets with bigeye size class recorded	West	Center		East 'CPUE hotspot' area		East rest of the area	
		<=90m	<=90m	>90m	<=90m	>90m	<=90m	>90m
2011	0.5	9.31	7.44	7.65				3.75
2012	10.5	9.94	7.28	7.31	13.86	19.49	11.22	20.24
2013	24.3	9.33	12.20	12.28	16.34	14.98	14.75	15.31
2014	24.2	6.74	10.29	10.40	10.20	17.70	10.80	19.64
2015	26.9	10.00	10.70	10.72	17.04	10.00	8.03	5.10
2016	29.4	9.19	12.14	12.15	15.39		6.33	