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Examination of purse seine catches of bigeye tuna

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Executive Summary

Bigeye tuna in the Western and Central Pacific Ocean (WCPO) region is currently assessed as experiencing overfishing and its adult biomass is below the adopted limit reference point. The assessment indicates that longline fishing and purse seine fishing on FADs have similar levels of impact on the stock.

As 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. This paper examines the nature of bigeye tuna interactions in the purse seine fishery with a focus on areas that might support consideration of management measures. We focus primarily on the component of the fishery based on Fish Aggregating Devices (FADs) as around 90% of bigeye tuna taken in the purse seine fishery is taken this way.

Examination of the spatial distribution of bigeye tuna catches indicated strong contrast in the nature of interactions within the WCPO: the western part of the WCPO can be characterized by high effort and high catches, with a small amount of bigeye tuna in most sets and bigeye tuna catches being relatively unimportant in the overall context of this part of the fishery; while for the central Pacific Ocean (CPO) there is a relatively low amount of effort, but high bigeye tuna CPUE, and bigeye tuna represents a significant and likely economically important component of the catch. In many respects the central Pacific is far more similar to the Eastern Pacific Ocean (EPO). This dichotomy in the nature of interactions represents the key challenge for the Western and Central Pacific Fisheries Commission (WCPFC) in managing bigeye tuna purse seine interactions.

In the CPO, bigeye tuna are generally taken in more than 80% of FAD sets and in some areas it is higher than 90%. This frequency of occurrence declines as you move to the west, but even there the rate of occurrence is 30–40% of FAD sets. Areas where FAD sets are dominated by bigeye tuna, i.e., where at least 50% of the total tuna catch is comprised of bigeye tuna, are represented by localized regions towards the east of the WCPO, where 20–30% of FAD sets can be dominated by bigeye tuna. In the main (western) part of the fishery closer to 5% of FAD sets are dominated by bigeye tuna.

Considering the period 2010–13, 9–14 vessels were responsible for 25% of the bigeye tuna purse seine catch and 34–43 vessels were responsible for 50% of the catch. We examined what differences might exist between those 'top' vessels with high bigeye tuna catches versus the rest of the fleet. There was no strong difference in the regions of the WCPO fished, but perhaps more effort by the top vessels occurs to the east of High Seas Pocket 2 (HSP2) than for the rest of the fleet. Nevertheless the top vessels fished throughout the extent of the fishery, i.e., there is effort for top vessels in all the areas fished by the rest of the fleet. For the top vessels, bigeye tuna comprised 12% of their total tuna catch (i.e., all set types) versus 4% for the rest of the fleet. Top vessels also had a much higher reliance on FADs (60% versus 43%), more of their FAD sets contain bigeye tuna (62% versus 42%), and more of their FAD sets are dominated by bigeye tuna (9% versus 3%).

Further this same percentage (9% versus 3%) also applied to the percentage of annual catch that came from bigeye tuna dominated sets.

We found that 22–28% of total purse seine-caught bigeye tuna were taken in sets dominated by bigeye tuna. While this is lower than the 43% of total purse seine bigeye tuna catch from dominated sets found previously for the EPO, it still provides some scope for benefits to bigeye tuna from pre-set identification of such schools and then incentives for fishers to not set on such aggregations.

We invite the WCPFC Scientific Committee (WCPFC-SC) to consider the results described here and determine if, at this time, there are any results which should immediately be brought to the attention of decisions makers and whether future work of this nature be added to the work plan of the WCPFC-SC. If yes, we invite WCPFC-SC to define what priority it might have compared to other activities.

1 Introduction

While bigeye tuna only make up 3.8% of total tuna catches in purse seine fishing in the Western and Central Pacific Ocean (WCPO) (Harley et al., 2015), these catches have a significant impact on the stock – similar to that of the regions longline fisheries (Harley et al., 2014). Bigeye tuna biomass is currently estimated to be below the Limit Reference Point (LRP) of $20\% SB_{F=0}$ recently adopted by the Western and Central Pacific Fisheries Commission (WCPFC). Overfishing of the bigeye tuna stock is also occurring with fishing mortality estimated to be in excess of F_{MSY} (Harley et al., 2014). Specific management measures to address purse seine catches of bigeye tuna have been a feature of management measures adopted by both the Parties to the Nauru Agreement (Parties to the Nauru Agreement, 2010) and the Western and Central Pacific Fisheries Commission (Western and Central Pacific Fisheries Commission, 2008, 2014).

The purpose of this paper is to look more closely at the nature of the bigeye tuna catches in the WCPO purse seine fishery to help further inform discussions of potential management options that might rebuild the stock and remove overfishing. We focus on the purse seine fishery that fishes on Fish Aggregating Devices (FADs) as it is well known that this mode of purse seine fishing has the greatest purse seine impact (90% of bigeye tuna catch) on bigeye stocks (Fonteneau et al., 2005; Lawson, 2013; Harley et al., 2015).

While this paper will show that bigeye tuna can not be viewed as 'bycatch' (i.e., unintended and unwanted) or 'by-product' (unintended, but retained and sold), we have followed some of the basic philosophy for examining a bycatch issue. Hall (1996) proposed that addressing bycatch issues requires an examination of the problem against various factors: e.g., time, space, and level of control that fisherman might have to restrict interactions. The more that the catch of bigeye can be seen to be 'concentrated' in a particular way, e.g., time or space, the greater the opportunity for management measures that can efficiently reduce fishing impacts on bigeye while minimizing undesirable impacts on the overall fishery. This is similar to the basis for the analyses described by Harley and Suter (2007) and we repeat many of these analyses, this time for the WCPO.

The paper provides summaries of existing data and basic analyses that are potentially of value to the management process. We examine the distribution of bigeye tuna catches in space, the distribution of catches across sets, the distribution of catches across vessels in the fleet, and the importance to the overall purse seine fishery of bigeye tuna and specific fishing grounds within the WCPO. We use these to to define hot-spots for bigeye tuna, and examine whether catches come from a small number of sets with large catches or a larger number of sets with small catches. We take the opportunity to make some comparisons between the results found here for the WCPO, and the findings for the Eastern Pacific Ocean (EPO) from analyses described in this paper and those undertaken previously (e.g., Harley et al., 2004; Harley and Suter, 2007).

The analyses described here are not considered to be exhaustive or definitive – rather a digestible starting point for a more thorough analysis of this issue.

2 Methods

A critical aspect of any analysis of bigeye tuna catches from purse seine data is the determination of the most appropriate sources of data to be used to construct the catch estimates. Without careful consideration of assumptions used in constructing purse seine data, it is possible for 'data assumptions' to lead to incorrect conclusions. In this sense, a 'best' catch data set for inclusion in a stock assessment might not be the best data set to use to examine fine-scale catch hot-spots (Harley and Lawson, 2010).

It has long been recognized that there are biases in the catch species composition in purse seine logsheet data, particularly in the separation of bigeye and yellowfin tuna (Lawson and Williams, 2005). It has also recently been shown that there are problems in the reporting of skipjack catches in many fleets (Hampton and Williams, 2011). Therefore it is only the total of the three tuna species that is used from logsheets (Lawson, 2013); the observer species composition information obtained from small samples taken from every brail is then used to partition this total into species catch estimates. However, it has also been shown that there are some 'selection bias' problems with observer grab samples, with spill samples demonstrated to be better in this regard (Lawson, 2013), though the extent of this effect is relatively small when compared to the problem of logsheet reporting (Hampton and Williams, 2015).

Taking into account known data issues and data availability, we generated two data sets for use in the analyses described in this paper. Descriptions of these data sets and the accompanying analyses are provided in the sections below.

2.1 Spatial analyses of patterns in raised aggregate purse seine data

To perform spatial analyses we used raised (to total estimated purse seine catch) catch and effort data aggregated to 1°x 1°, month and flag. For the WCPO, these represent our best estimates of purse seine catches and are based on analyses of observer grab sampling, logsheets, vessel monitoring data, port sampling data, and corrections derived from paired grab / spill sample experiments (Lawson, 2013). Due to an absence of accurate effort data, we excluded the domestic purse seine fisheries for Indonesia and the Philippines. Data for the EPO were provided by the Inter-American Tropical Tuna Commission (IATTC). We will refer to this as the SBEST (purse Seine BEST estimates) data set. This data set was used for identification of spatial hot-spots and to examine the impact of 'closure' scenarios.

Hot-spot identification

A critical part of analyzing the 'problem' is the investigation of spatial 'hot-spots' for bigeye purse seine interactions. We used three criteria to define spatial hot-spots using SBEST data for 2010–2013: 1) average annual bigeye tuna catch; 2) CPUE in catch per set for FAD sets; and 3) proportion of bigeye tuna in the total tuna catch from FAD sets. Hot-spots were defined as those 1°x 1°squares that had values above the 90th percentile of each of the three calculated quantities. These hot-spots were not contiguous, but it would be possible to design algorithms to construct a contiguous hot-spot area based on these individual 1°x 1°squares.

It should be noted that the SBEST data set is available for a much longer time period than used here, and the patterns in catches and hot-spots would change if different time periods were used. We analysed only the most recent years to enable comparisons with the Observer data set analyses (see below).

Closure calculations

Noting that the hot-spots identified using the SBEST data are not contiguous and therefore unlikely to inform a practical management measure using spatial closures, we have not undertaken dynamic modelling (e.g., including effort transfer and fish movements – see Sibert et al., 2012 for an example of such approaches) of the 'closed areas'. We calculated the bigeye and total tuna catch from identified hot-spot 1°x 1°squares. Simply stated, calculations aimed to identify the potential reductions in overall bigeye tuna catches if 1) no catch was taken in these areas and the effort was not redeployed elsewhere, and 2) the fish within the hot-spot were not later caught outside the hot-spot area. The impact on overall tuna catches was also examined, to evaluate the potential impact on the purse seine fishery as a whole. The analysis is perhaps best viewed as measuring the importance of bigeye hot-spots to the purse seine fishery as a whole.

2.2 Analyses of the set by set purse seine data

The SBEST (raised and aggregated) data set does not allow examination of bigeye catches at the level of an individual vessel set (e.g., operational level) so we constructed a second data set to provide information on catches at the vessel level and variability in bigeye catches across sets. This WCPO set-by-set data set used the total estimated tuna catch from the logsheet and the size and species composition from the observer grab samples from that set to provide an estimate of the catch by species for the set. We will refer to this as the Observer data set. While it does not include any correction for potential grab sample bias (after Lawson, 2013) we believe the approach used here is probably not unreasonable as a first step to construct estimates at the set level (see Hampton and Williams, 2015; Hare et al., 2014).

Using the length-frequency data collected through the observer grab sampling, and applying a length-weight relationship, we also constructed an Observer data set where bigeye tuna set catches were divided into fish >10 kg and <10 kg.

Analysis of the Observer data set was restricted to the years 2010-2013 due to the reliance on observer grab samples to estimate the catches of the three tropical tunas at the set level. These analyses can inform discussion of catch limits that might be applied to individual vessels (see below). It should be noted that as data coverage is not 100% of activity[2], it represents a minimum estimate for vessel specific bigeye tuna catches. For the period 2010–13 total bigeye tuna FAD catches in Observer data set were 58–73% of the comparable SBEST estimates.

The set-by-set data were used for estimation of individual vessel limits, identification of 'top' bigeye tuna catching vessels, and the occurrence and impact of sets where bigeye was the dominant component of the catch.

Individual vessel limits

Using the observer data set, we calculated the annual bigeye tuna catch for each vessel. As noted above, with logsheet and grab sample data coverage less than 100% of all sets, these estimates should be seen as preliminary minimum estimates. We then considered a range of hypothetical individual vessel bigeye catch limit levels and, using the data for 2010–13, calculated the reduction in overall catch for each year that could have occurred if a vessel took either their estimated catch or the limit – whichever was lower. We also counted the number of vessels to which the limit would have applied.

[2] This could be due to missing logsheet or observer records, or data may not yet have been processed and loaded into regional databases

Top bigeye tuna catching vessels

In order to further examine the differences in bigeye catches among vessels, we divided the fleet into vessels falling within the 'top' bigeye tuna catching vessel category, and the 'rest' category. The 'top' fleet was comprised of any vessel which was in the top 10 vessels for bigeye tuna catch in any year from 2010–13.

Dominant bigeye tuna aggregations

Using the observer data set we calculated the proportion of bigeye tuna in each set and then examined specifically those sets where catch was more that 50% bigeye tuna. We then calculated the proportion of total annual bigeye and total tuna catch levels which came from sets where the proportion of bigeye tuna was greater than 50%.

3 Results

Here we will describe separately analyses for each of the two data sets. First, we describe the spatial characterization of purse seine FAD bigeye tuna catches based on raised aggregate catch and effort data (SBEST) and then we describe analyses undertaken using the Observer set by set data where we examine catch variation across both the fleet and individual sets.

3.1 Spatial analyses of patterns in raised aggregate purse seine data

For the recent period (2010–13), the area of highest bigeye tuna catches has been in the west of the Convention area, with one hot-spot south of High Seas Pocket 1 (HSP1) and west of High Seas Pocket 2 (HSP2) covering the waters of Papua New Guinea and the Solomon Islands, and a second to the east of HSP2 covering the waters of Nauru, the Gilbert group in Kiribati, and the northern part of Tuvalu (Figure 1).There are also lesser catch hot-spots in Kiribati's Phoenix and Line Islands Groups and the surrounding Eastern High Seas (EHS). When one compares this to the overall Pacific (Figure 1) we can see that bigeye tuna purse seine catches are higher in the west than the east, but catches in the east are generally more spread out, though there is a hot-spot area west of the Galápagos Islands.

Figure 2 provides annual plots of the distribution of bigeye catch on FADs for 2006–13. Generally the pattern observed for 2010–13 is consistent, but in 2006 and 2009 the region of higher bigeye catches extends further east to represent a near continuous band.

Broadly the patterns of bigeye catch in the WCPO cover the distribution of FAD effort (Figure 3), though there is more catch in the central Pacific than one might expect given the effort levels there. The reason for this is clearly shown in the plots of bigeye FAD CPUE (mt/set) presented in Figure 4. Considering only the WCPO first, the far east (around 150° W, equivalent to 210 in the figure) has an area of very high CPUE and there is a gradient of declining CPUE to the west (Figure 4). For the entire Pacific Ocean, the area of highest CPUE covers a wide area in the central Pacific with CPUE declining to the far west and the far east.

The final element of the spatial distribution of catch from the SBEST data examined was the 'importance' of bigeye tuna to the FAD catches as measured by the proportion of the FAD catch made up by bigeye tuna (Figure 5). In the central region of the WCPO, bigeye tuna comprise more than 20% of the total FAD catch and this declines rapidly to the west, declining to around 10% by 170° E and reducing further to the western extreme. In the EPO, the proportion of bigeye tuna in FAD catches is much higher – exceeding 40-50% of the total tuna catch in some areas.

The information in Figures 1, 4, and 5 provides a set of criteria for defining three bigeye interaction hot-spots. In the left-hand panels of Figure 6 we provide the full SBEST WCPO catch, CPUE, and catch proportion distributions. The right-hand panels present the same information restricted to 1°x 1°squares at or above the 90th percentile (red) and those cells between 50% and 90% (dark blue). For the 'closure' analysis we defined our hot-spots based on those 1°x 1°squares at or above the 90th percentile. We calculated the bigeye and total tuna catch from these hot-spot areas. This analysis shows the importance of these regions for both potential bigeye conservation and the overall purse seine fishery. Removing effort from the catch hot-spot areas reduced WCPO bigeye catches by 56%, and total tuna catches by 57% (Table 1). Examining the results where hot-spots were based upon CPUE or catch proportions produced different results from the use of average annual catch. Removal of effort from hot-spot areas based on those two calculations reduced bigeye catch by 13-14% while reducing total tuna catches by 3%.

3.2 Analyses of the set by set Observer purse seine data

The observer data had lower coverage than SBEST, so these data were more variable in some respects, as can be seen by comparing the calculated proportion of bigeye tuna in the catch from the observer data set (Figure 7; top panel) and SBEST (Figure 6; lower left panel). However the broad patterns were similar. In the central Pacific, bigeye tuna are taken in more than 80% of FAD sets and in some areas higher than 90% of FAD sets (Figure 7; middle panel). This frequency of occurrence declines to the west, but even there the rate of occurrence is 30–40%. In some small regions to the east of the WCPO, 20–30% of FAD sets can be dominated (at least 50%) by bigeye tuna (Figure 7; bottom panel). In the main part of the fishery (to the west of the WCPO), closer to 5% of FAD sets are dominated by bigeye tuna.

There is often some debate about whether all bigeye purse seine catch could be viewed as detrimental or whether management actions should primarily focus on minimizing catches of 'small' bigeye tuna. We next examine whether there are differences in the spatial distribution of these two different sizes classes (above and below 10kg) of bigeye tuna in Figure 8. There is some evidence to suggest that more larger bigeye tuna are found east of HSP2 than west, but there is considerable overlap.

Bigeye tuna catch estimates at the individual vessel level were used to rank vessels from highest to lowest in terms of their bigeye tuna catch, and then were plotted as the cumulative catches versus vessel numbers (Figure 9). Considering the period 2010-13, 9–14 vessels were responsible for 25% of the bigeye tuna catch in a given year and 34–43 vessels were responsible for 50% of the catch.

From this vessel-level analysis, we developed hypothetical analyses regarding a range of individual vessel bigeye tuna catch limits (Table 2). In Table 2 we present results based on data for 2013, but results for other years were undertaken and gave similar conclusions. A low limit of 200 mt per vessel per annum could reduce bigeye tuna catch by 42% and would be expected to impact 76 vessels or 31% of the fleet in our data set for 2013. An intermediate limit of 600 mt would affect far fewer vessels (14 and 6%, respectively), but only yield modest (11%) reductions in bigeye tuna catches, while a limit of 1000 mt would only impact four vessels (i.e., four purse seine vessels caught more than 1000 mt of bigeye tuna in 2013) and only result in a 5% bigeye tuna catch reduction. We note that the absolute limit numbers should be viewed with particular caution as the availability of paired observer and logsheet data was not 100%, but general conclusions regarding the trade-off between the catch reduction achieved and proportion of the fleet affected are likely to be generally robust.

We examined what differences might exist between those 'top' vessels which catch the most bigeye tuna (defining 'top' as a vessel within the top 10 bigeye catching vessels at least once in the period 2010–13) versus the rest of the fleet. This gave 31 vessels, with two being in the top 10 three times and five being represented twice. A first comparison of the distribution of the fishing effort of top vessels versus the rest (Figure 10) indicates that there is no strong difference in the regions fished, but perhaps more effort by the top vessels occurs to the east of HSP2 than for the rest of the fleet. Nevertheless, the top vessels are represented throughout the extent of the fishery, i.e., the effort by top vessels is found in all areas for which there is effort from the rest of the fleet so there are likely both vessel and spatial effects occurring. Comparing various aspects of the fishing of top vessels versus the rest, for top vessels bigeye tuna comprise 12% of their total tuna catch (i.e., all set types) versus 4% for the rest of the fleet (Table 3). Top vessels also have a much higher reliance on FADs (60% versus 43% of their fishing effort), more of their FAD sets contain bigeye tuna (62% versus 42%), and more of their FAD sets are dominated by bigeye tuna (9% versus 3%). Further, this same percentage (9% versus 3%) also applies to the percentage of annual catch that comes from bigeye tuna dominated sets.

Following Harley and Suter (2007), we next examined how bigeye tuna catches were distributed across sets, i.e., whether bigeye tuna were taken in small amounts in a large number of sets, or large amounts in a small number of sets (Figure 11). Examining data for 2010–13 we found that 22–28% of bigeye tuna catch came from FAD sets where bigeye tuna comprised at least 50% of the total tuna catch (i.e., bigeye tuna dominated). These bigeye tuna dominated sets were only responsible for 1–2% of skipjack tuna catches and 3–5% of the total tuna catch. The data therefore suggests significant portion of the bigeye tuna catch is taken in large amounts in a small number of sets, but this decreases spatially as you move from the CPO to the western WCPO.

Finally, we looked at bigeye tuna catches from FAD sets against the total tuna catch in the set to see if there was any relationship between school size and bigeye tuna catch. If the bigeye tuna catch curve descends faster than the total tuna catch curve (Figure 12) then proportionally more bigeye tuna are taken in small sets. For reference, we calculated the proportions based on sets of 50 mt or less and 30 mt or less (not presented) and found similar patterns. Aside from 2012, there is no evidence that more bigeye tuna are taken in small sets than medium or large sets, but the pattern in 2012 warrants further examination.

4 Discussion

The current status of bigeye tuna in the WCPO is of concern and has resulted in considerable attention from the WCPFC in management of the longline and purse seine fishery. In this paper we have focused on gaining a better understanding of purse seine fishery interactions. We hope these analyses will support the the consideration of management measures for that segment of the WCPO fleets that maximizes the benefits for bigeye tuna while minimizing the negative impacts on the overall purse seine fishery.

Understanding how bigeye tuna catches might be 'concentrated' in some way may provide the basis for developing management measures and here we have examined patterns of bigeye tuna catches spatially, across sets, and across vessels. Many of the analyses conducted here follow similar analyses for the EPO (e.g. Harley and Suter, 2007).

4.1 Hot spots and closures

We examined hot-spots of bigeye tuna catch based on three criteria and found that for the WCPO, there is a spatial separation between the areas of highest catches and areas of highest CPUE. There is a strong contrast in the nature of interactions with bigeye tuna within the WCPO: the western part of the WCPO can be characterized by high catches being the product of high levels of effort with a small amount of bigeye tuna in most sets – catches being relatively unimportant in the overall context of the fishery; the central Pacific shows low amounts of effort with high CPUE and bigeye tuna representing a significant and likely economically important component of the catch. In many respects, the central Pacific Ocean is far more similar to the EPO. This dichotomy in the nature of interactions represents the key challenge for the WCPFC to manage bigeye tuna purse seine interactions.

Marine reserves or spatial management have been widely proposed as tools to manage not only demersal or near-shore fisheries resources, but also highly mobile or highly migratory fish stocks whose ranges cross both EEZs and High Seas (Sibert et al., 2012; White and Costello, 2014; Sumaila et al., 2015). In the EPO closed areas have been used to manage fisheries impacts on bigeye tuna (Harley and Suter, 2007). Within the WCPFC convention area, the two High Seas pockets (HSP1 and HSP2) have been closed to almost all purse seine activity since 2009 (Western and Central Pacific Fisheries Commission, 2008, 2014), but these closures are not specifically directed at conserving bigeye tuna. Considering the hot spots for bigeye tuna identified in this paper, closing the area of greatest bigeye tuna catches does not seem feasible as this essentially represents the core of the purse seine fishery. We have identified areas in the central Pacific – the far east of the WCPFC convention area – predominately covering the EEZ of Kiribati and the eastern High Seas, where bigeye tuna CPUE is high and this species comprises a large proportion of the catch. It is noteworthy that two bodies of water within this region receive no fishing effort – the United States EEZs of Howland Baker and Jarvis, and more recently a large part of the Phoenix Islands within the Kiribati EEZ (Phoenix Island Protected Area, 2015). The management of High Seas areas where bigeye tuna CPUE is high has been of concern to several countries and there have been proposals in recent years to close the eastern High Seas to purse seine fishing specifically as a measure for bigeye tuna (Dr Transform Aqorau, CEO of the Parties to the Nauru Agreement, *personal communication*).

Given the greater coverage of EEZs of the WCPFC purse seine tuna fishing grounds when compared to other oceans, and significant differences in the fishing grounds of different fleets, attention to socioeconomic impacts and the distribution of conservation burden borne by different parties (e.g., Hanich and Ota, 2013) may be important if closed areas are to be considered. Finally, for any formal analysis of closed areas, assumptions about what will happen to displaced effort are crucial (Harley and Suter, 2007; Sibert et al., 2012) and we have not considered this in analyses presented here. This of course does not mean that spatial management cannot occur until such analyses are undertaken, but if such action was considered, effort redistribution should be a key focus in the development of such a measure.

We note that we have not examined the temporal / seasonal timing of bigeye tuna purse seine catches in this analysis. It is difficult to do this in an unbiased manner as the implementation of FAD closures by the PNA and WCPFC in the third quarter of the year since 2009 restricts our understanding of what the seasonality of bigeye tuna catches might be given the current status of the stock and overall levels of effort in the fishery.

4.2 Vessel limits

We have examined how bigeye tuna catches vary across the fleet and such an analysis could support consideration of individual vessel limits. Such approaches have been proposed for the EPO (Harley et al., 2004), but not adopted. Implementation of such approaches within the WCPFC would require more intensive catch monitoring, as current catch sampling programmes are directed at providing the best stock level catch estimates and may not necessarily be of sufficient accuracy at the individual set/trip/vessel level. Implementation of such limits will require decisions on allocation principles, and may require estimation of catch histories, and other scaling factors might be considered to take into account the different sizes of vessels operating in the fishery, as is done within the PNA Vessel Days Scheme (Parties to the Nauru Agreement, 2010).

4.3 Between set variability

The variation in bigeye across sets could motivate further analysis to determine factors leading to higher bigeye tuna and thus avoidance/mitigation practices that might be implemented in conjunction with, or independent to, vessel limits. We found that 22–28% of purse seine caught bigeye tuna were taken in sets dominated by bigeye tuna. While this is lower than the 43% bigeye tuna catch from dominated sets found by Harley et al. (2004) for the EPO, it still provides some scope for benefits to bigeye tuna from pre-set identification of such schools and then incentives for fishers to not set on such aggregations.

The acoustic target strength of skipjack, bigeye, and yellowfin tunas varies for fish of a given size (Bertrand et al., 1999; Fuller and Schaefer, 2014), and there is growing evidence that fisherman, using advanced acoustic technology on their vessels do have some ability to predict the species composition of an aggregation prior to setting. The same does not currently seem to apply to sonar technology deployed on smart FADs. Therefore we see that as a potential important area for future research. We remain mindful that for the regions where bigeye tuna is found in high proportions of the catch, while it might be possible to identify bigeye tuna dominated aggregations, bigeye tuna can not be seen as unimportant bycatch, rather it likely represents an important and valuable component of the catch.

Dagorn et al. (2012) found the ratio of bycatch to tuna was inversely related to school size, i.e., bycatch comprised a high proportion of total catch in sets on smaller tuna aggregations when compared to sets on large tuna aggregations. This implied that avoidance of small tuna aggregations could lead to more ‘clean’ fishing. Using the data that was available to us, we examined whether this might also apply to bigeye tuna, but from our data at least there is no evidence to suggest that bigeye tuna catches vary with overall aggregation size.

4.4 Potential future work

This paper presented an initial examination of some of the features of the purse seine catches of bigeye tuna in WCPFC fisheries to support consideration of potential management measures. These investigations have identified several potential areas for further research and we invite the

WCPFC-SC to consider these and suggest any other specific analyses which they feel would be of value to the Commission's consideration of bigeye tuna management:

- Examination of contiguous hot-spot areas and consistency of hot-spots through time;
- Closed area simulations including scenarios of effort reallocation and total versus FAD restrictions;
- Further examination of the top vessels fishing behavior compared to the rest of the fleet;
- Quantitative analysis to attempt to separate vessel and area effects;
- Comparison of species composition of FAD sets versus time of set in relation to sunrise;
- Generation of raised estimates of catch and effort at the vessel level. Generation of 'best' estimates at the vessel/set level could be constructed through logsheet, observer, and VMS reconciliations to ensure all effort is considered and some substitution or statistical modelling for missing or imprecise grab samples[3];
- Improved species composition estimates at the individual set level, e.g., through hierarchical modelling of sets within the same temporal/spatial strata and/or other data sources; and
- Examination of bigeye tuna catches in unassociated or free schools.

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[3]This analysis is not of management *per se*, but would likely support consideration of a range of management measures.

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Table 1: Proportion of bigeye tuna and total tuna purse seine catches from the 1x1 degree squares that have values above the 90th percentile for different hotspot identification criteria

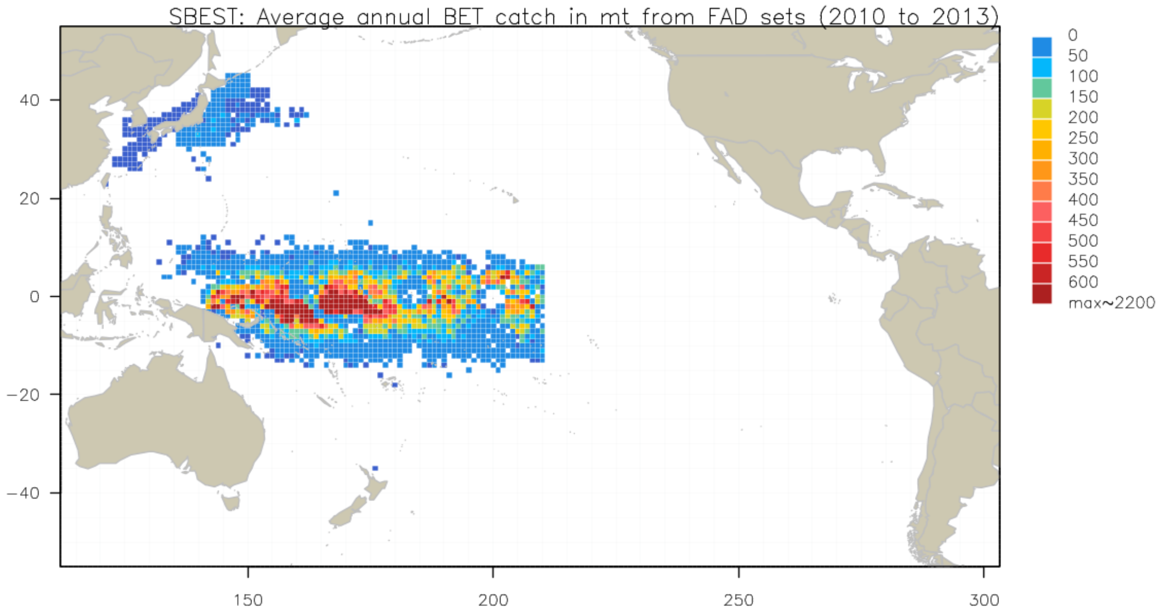
Hotspot criteria	% Bigeye reduction	% Tuna reduction
Total bigeye catch	56	57
Bigeye FAD set CPUE	14	3
Bigeye FAD set Proportion	13	3

Table 2: Simple evaluation of potential vessel limits based on observed bigeye catch data in 2013 (as an example only - values are also available for 2010–12)

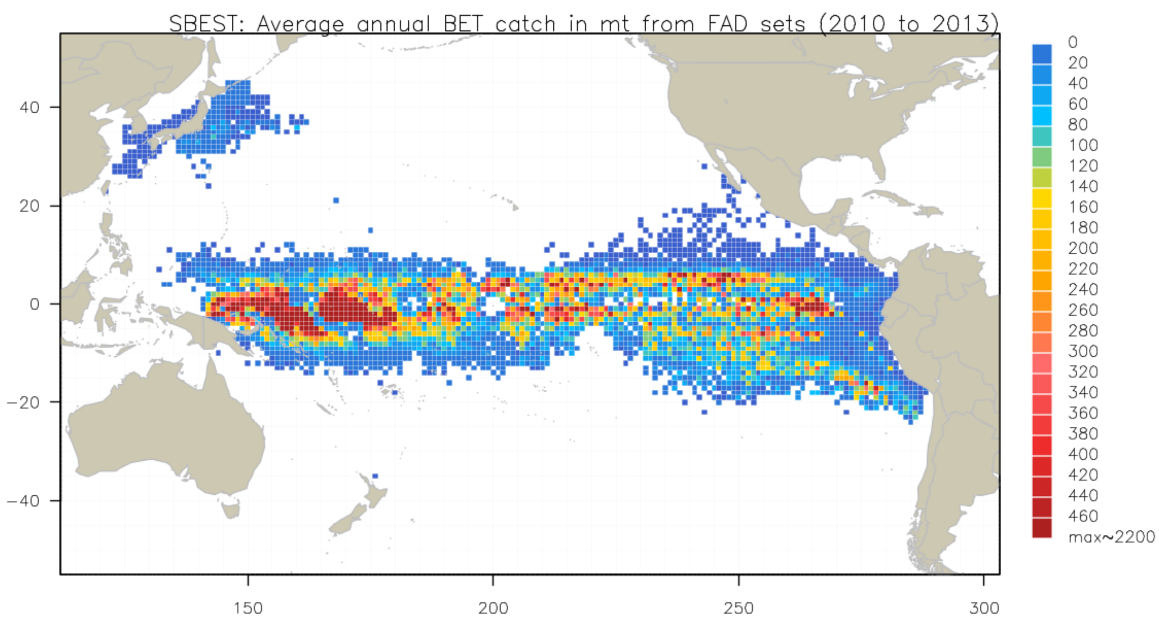
Limit	% Bigeye catch reduction	Number vessels affected	% vessels affected
200	42	76	31
400	21	33	13
600	11	14	6
800	8	8	3
1000	5	4	2

Table 3: Comparison of some features of catch and effort for those vessels that were in the top 10 bigeye catching vessels at least once in the period 2010–13 versus the rest of the fleet. Analysis is based on observer data.

	Bigeye catching vessels	
Criteria	top	rest
Average annual number of vessels	27	237
Average annual total tuna catch (mt)	119,719	702,227
Average annual total bigeye catch (mt)	14,484	30,131
Bigeye proportion of total tuna	0.12	0.04
Proportion effort on FADs	0.6	0.43
Proportion FAD sets with bigeye	0.62	0.42
Proportion FAD sets with >50% bigeye	0.09	0.03
Proportion of bigeye from bigeye dominated sets	0.34	0.21
Proportion of tuna from bigeye dominated sets	0.09	0.03

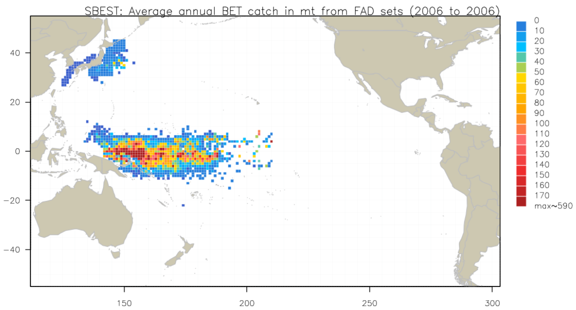


(a) WCPO

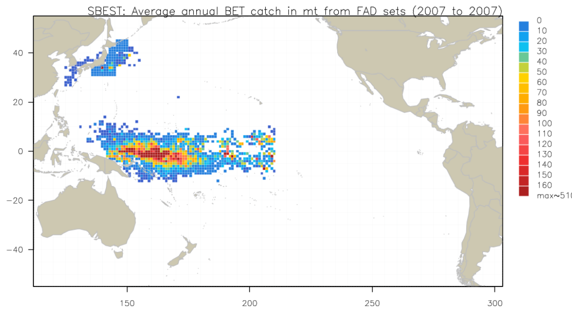


(b) Pacific Ocean

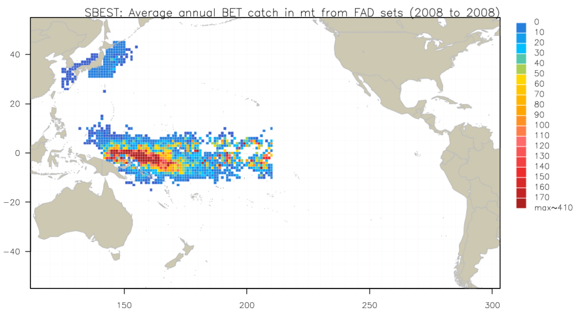
Figure 1: Average annual bigeye tuna catches from FAD sets for 2010–13. Note that colour scales are deliberately different.



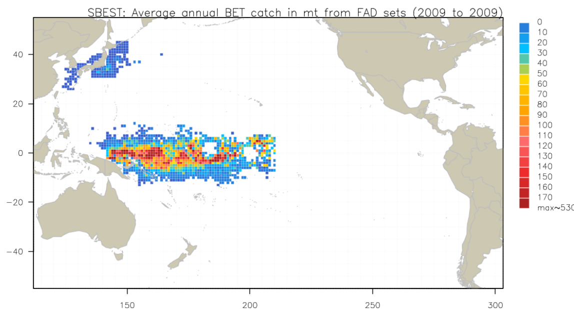
(a) 2006



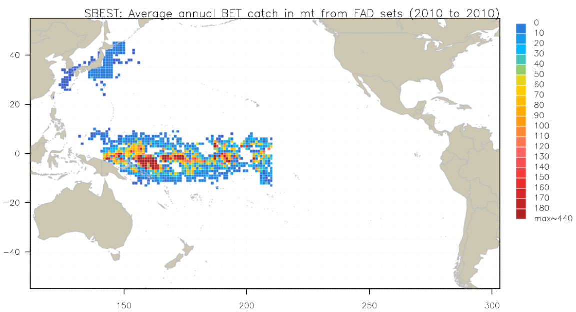
(b) 2007



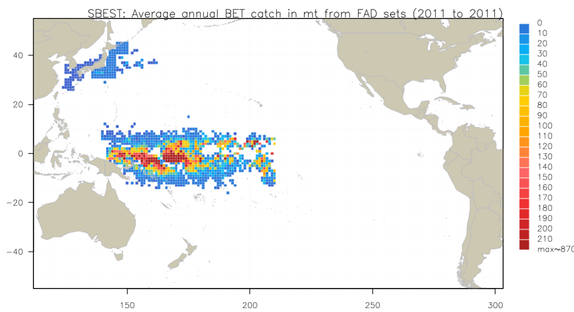
(c) 2008



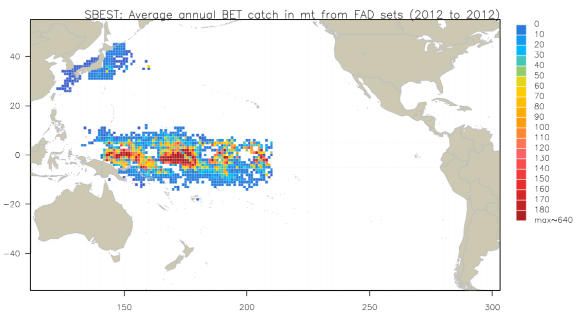
(d) 2009



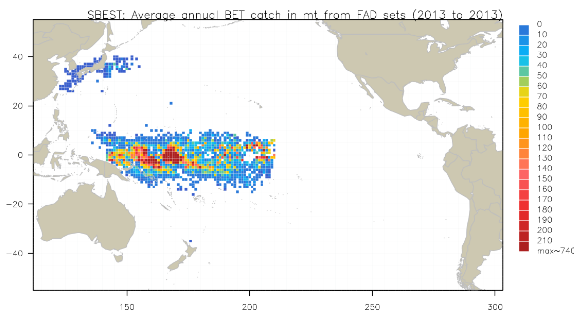
(e) 2010



(f) 2011

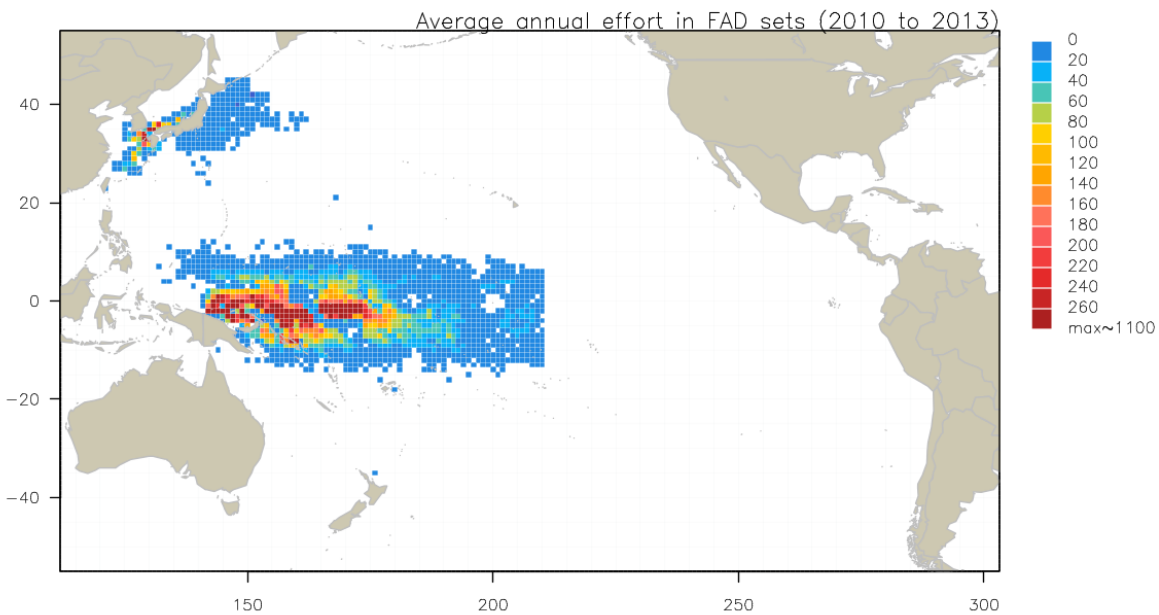


(g) 2012

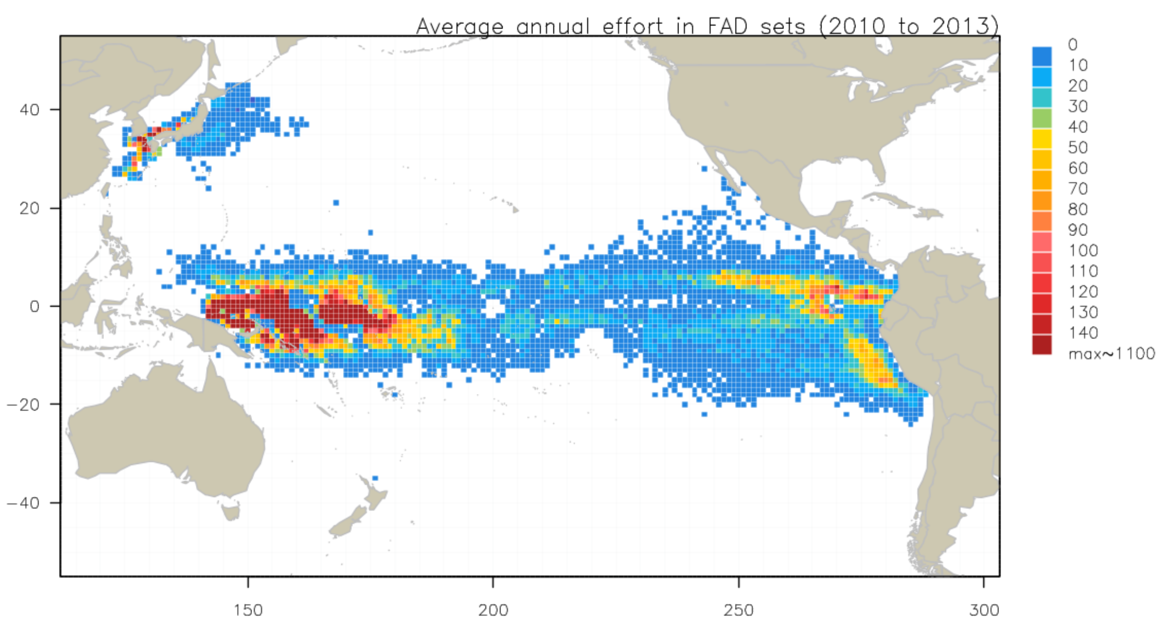


(h) 2013

Figure 2: Annual distribution of bigeye FAD catches in the WCPO (2006–13). Note the scales on each panel are different.

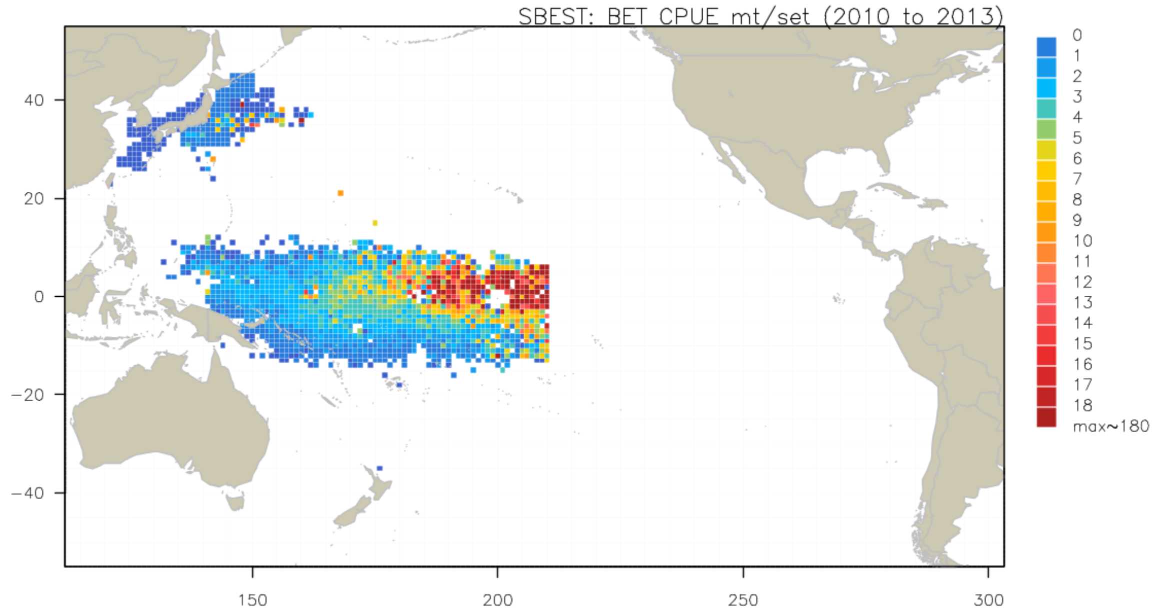


(a) WCPO

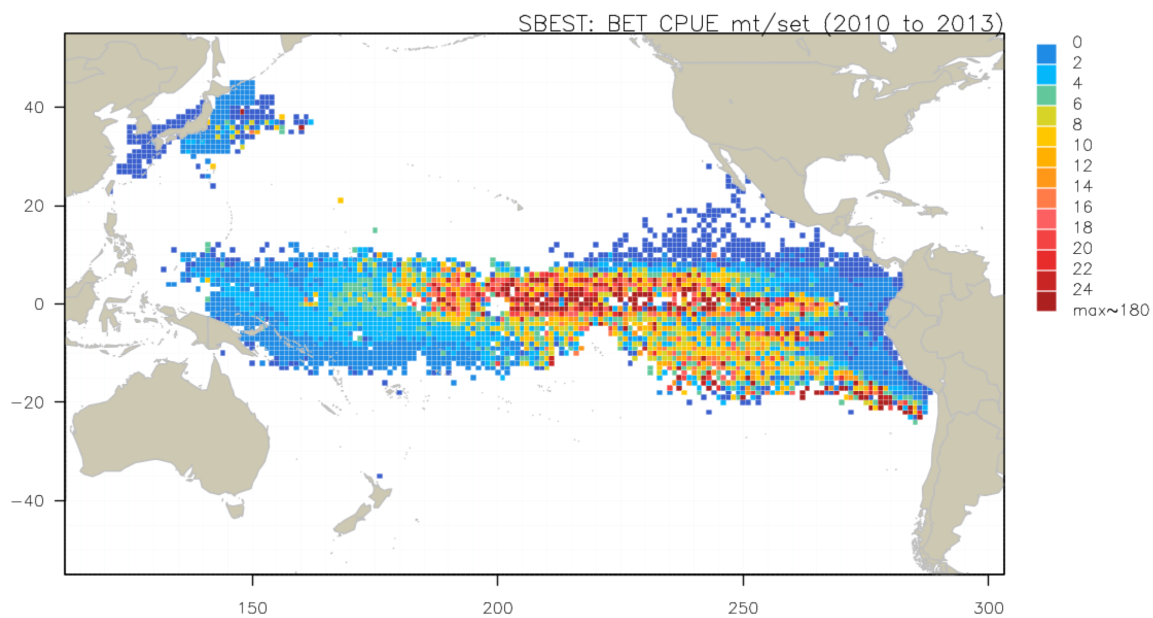


(b) Pacific Ocean

Figure 3: Average annual number of FAD sets for 2010–13. Note that colour scales are deliberately different.

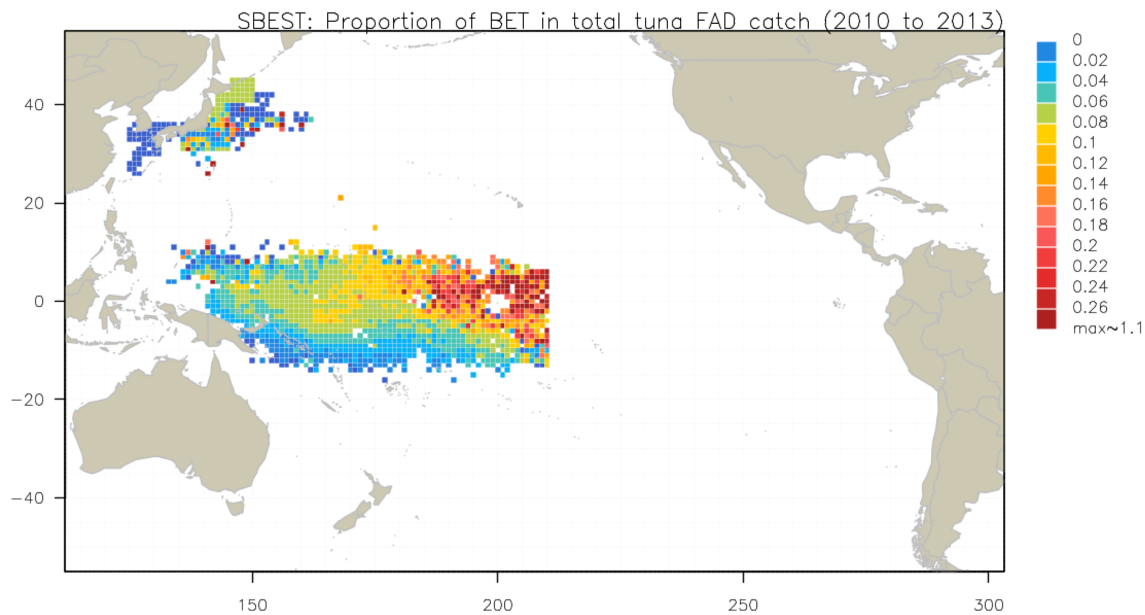


(a) WCPO

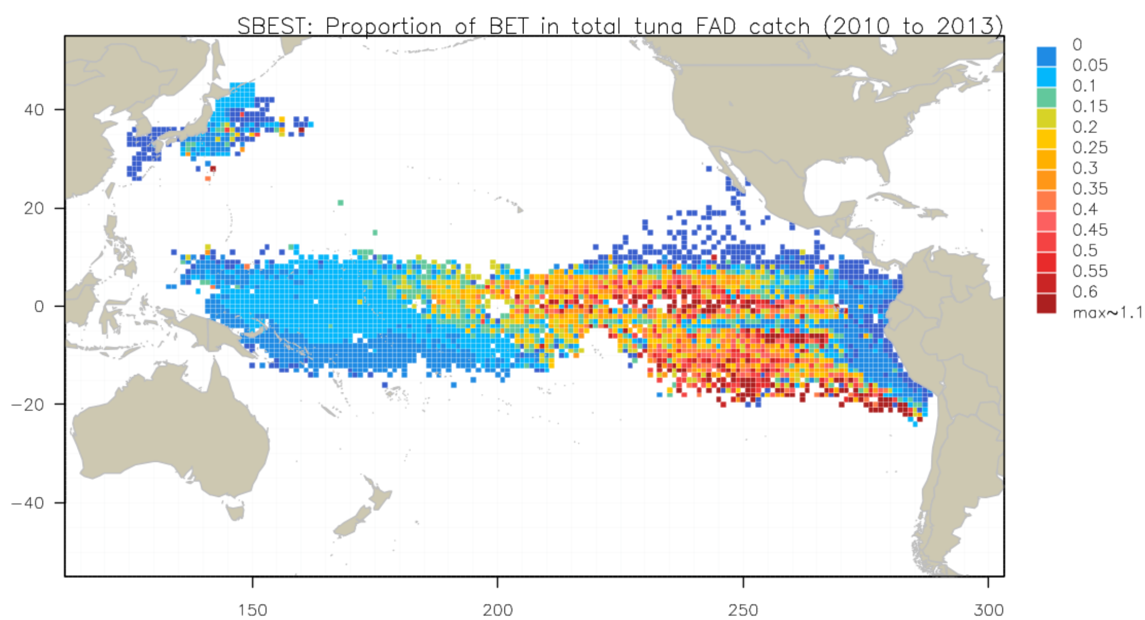


(b) Pacific Ocean

Figure 4: Average annual bigeye tuna CPUE (mt per set) from FAD sets for 2010–13. Note that colour scales are deliberately different.

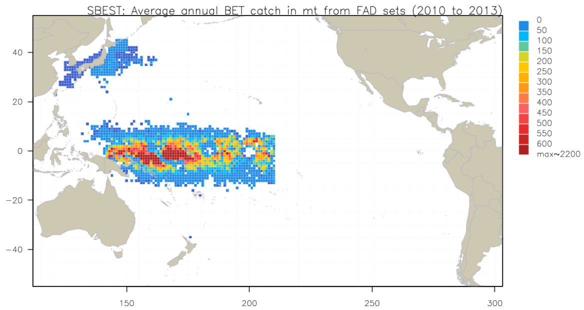


(a) WCPO

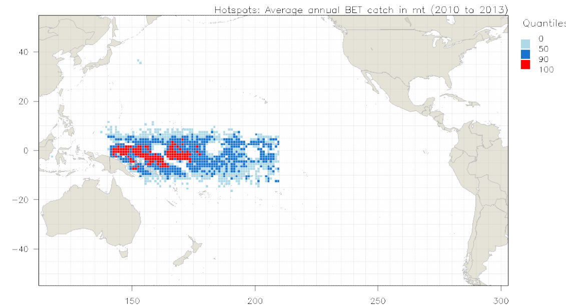


(b) Pacific Ocean

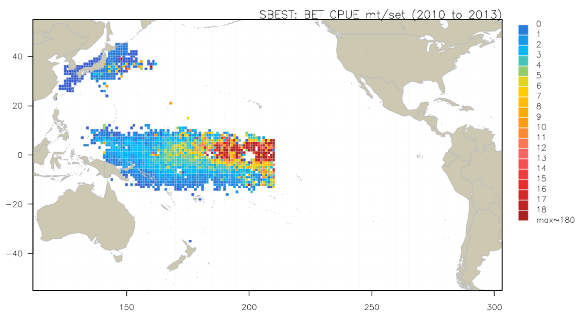
Figure 5: Proportion of bigeye tuna in total tuna FAD set catches for 2010–13. Note that colour scales are deliberately different.



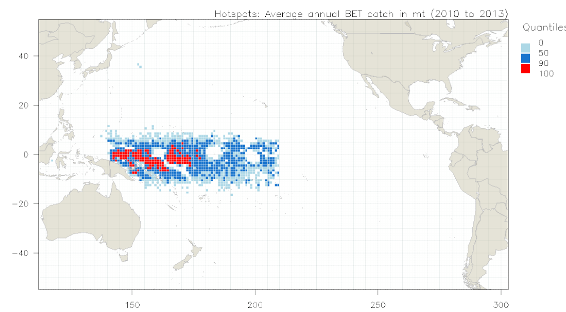
(a) Catch – distribution



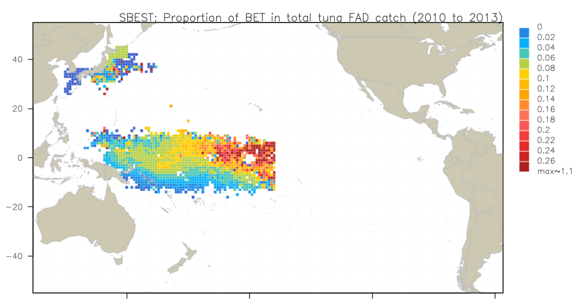
(b) Catch – hot spots



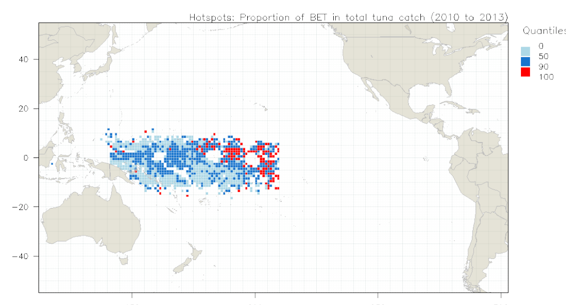
(c) CPUE – distribution



(d) CPUE – hotspots

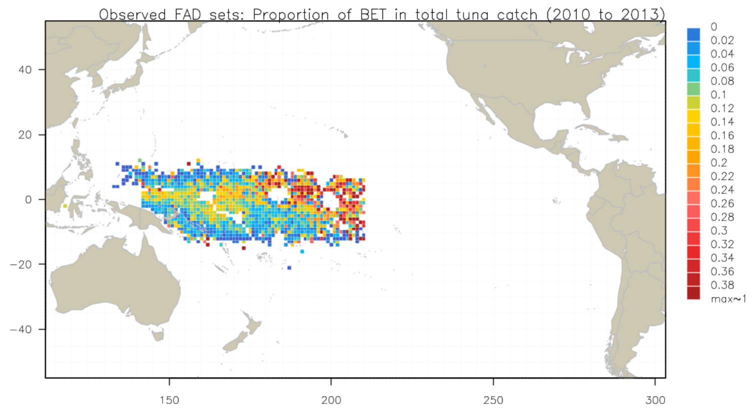


(e) Proportion – distribution

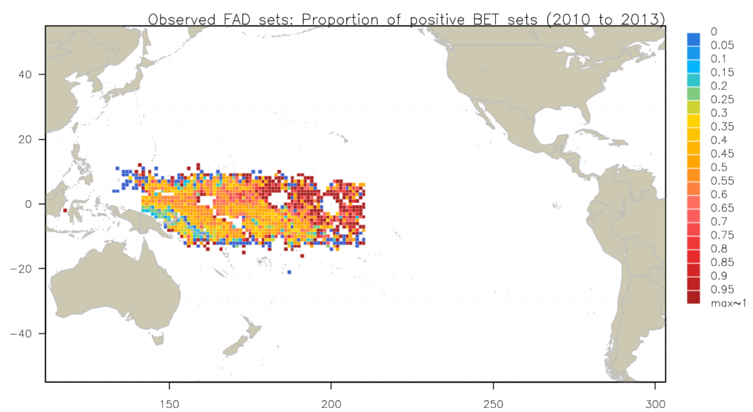


(f) Proportion – hotspots

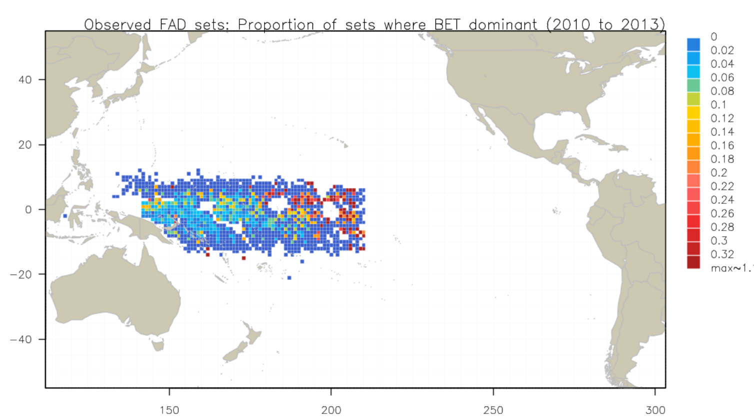
Figure 6: Distribution of metrics chosen for the hot spot analysis (left) and the 1x1 cells above the 90th percentile for each (right).



(a) Proportion of BET in catch

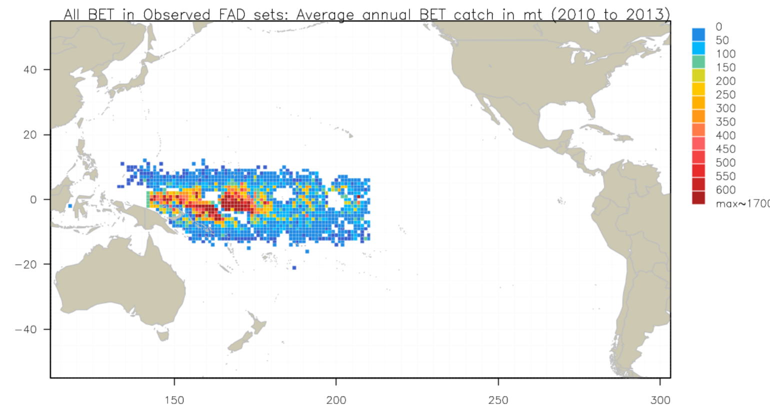


(b) Proportion of sets to catch BET

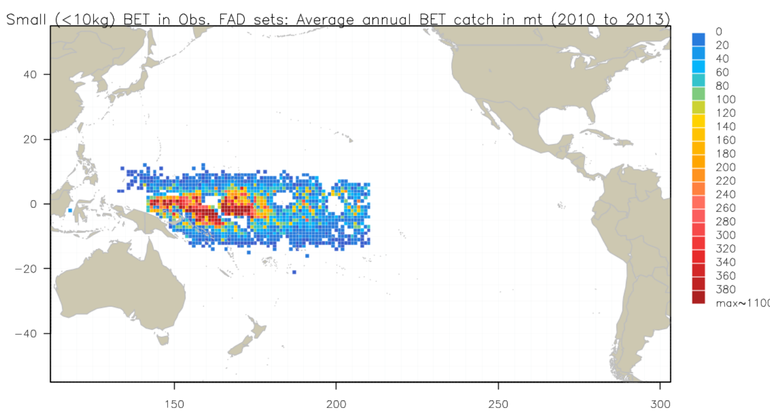


(c) Proportion of sets dominated (at least 50%) by BET

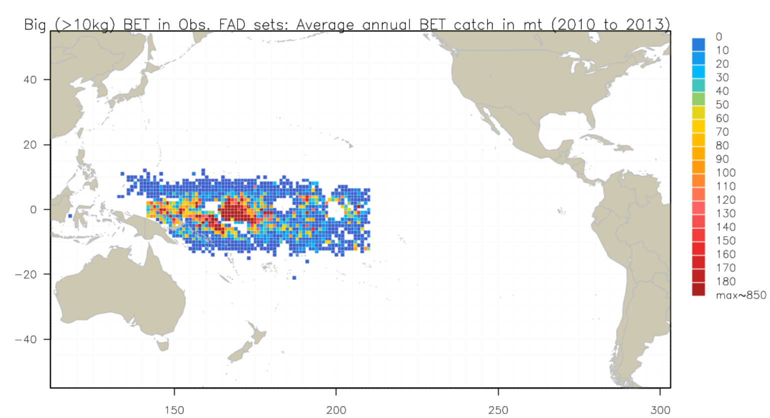
Figure 7: Occurrence of bigeye tuna in observed FAD set catches for 2010–13.



(a) All BET



(b) Small BET (< 10kg)



(c) Large BET (> 10kg)

Figure 8: Comparison of the distribution of catch of BET by size for the period 2010–13.

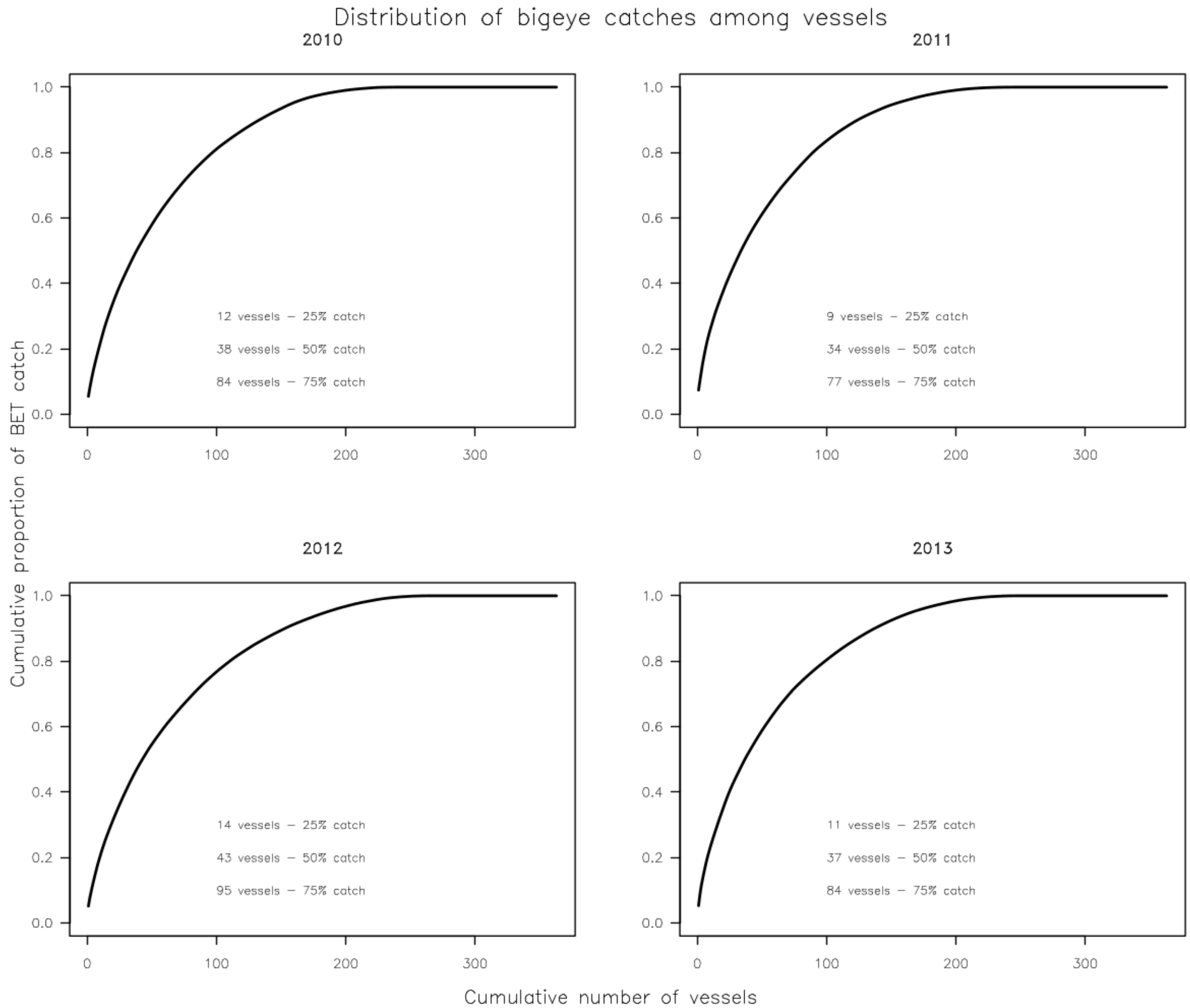
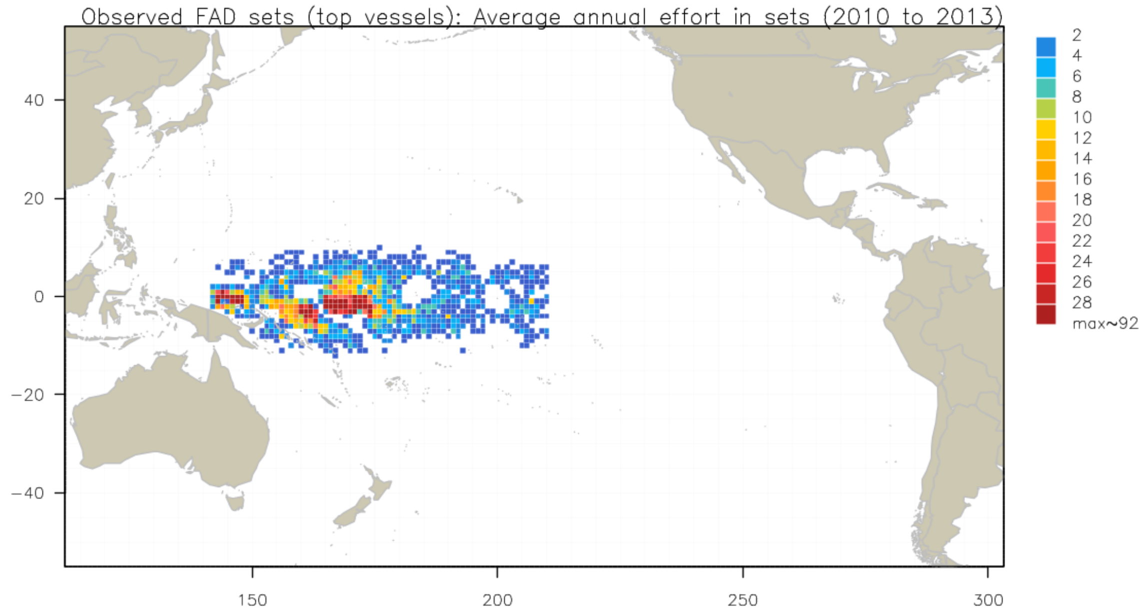
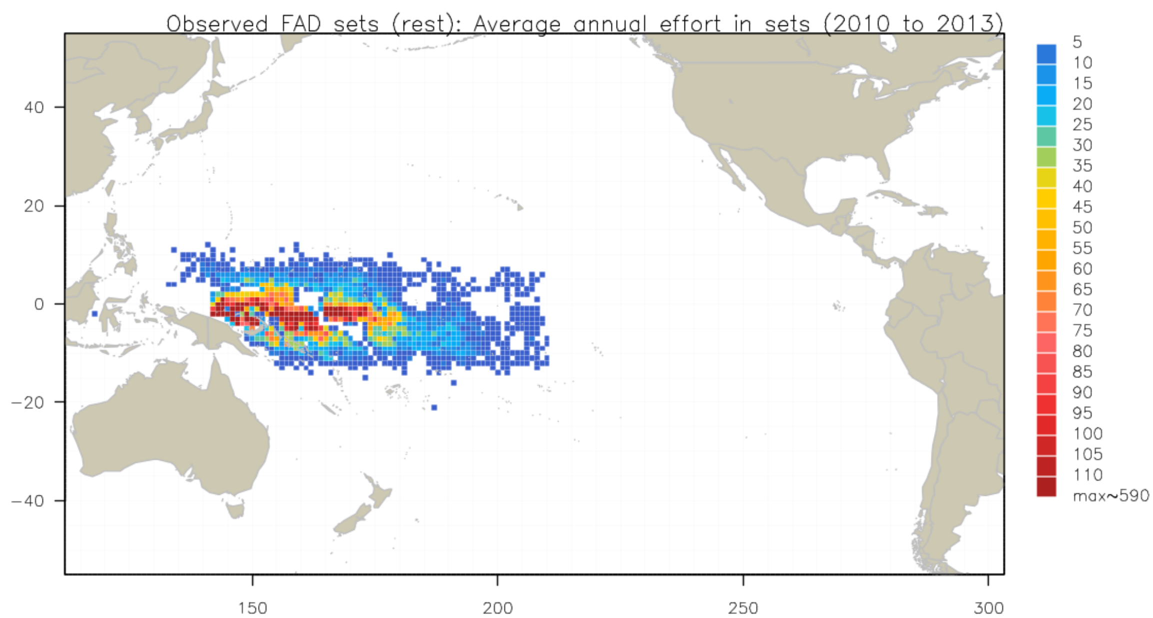


Figure 9: Cumulative number of vessels versus cumulative observed FAD set bigeye catches for 2010–13 where vessels are ranked from highest to lowest bigeye catch. For reference the number of vessels responsible for 25, 50, and 75% of the annual bigeye catches are presented



(a) Top vessels



(b) Remainder of fleet

Figure 10: Distribution of FAD sets for the top bigeye catching vessels and the rest of the fleet over the period 2010–13. Note that the colour scales are deliberately different for each panel.

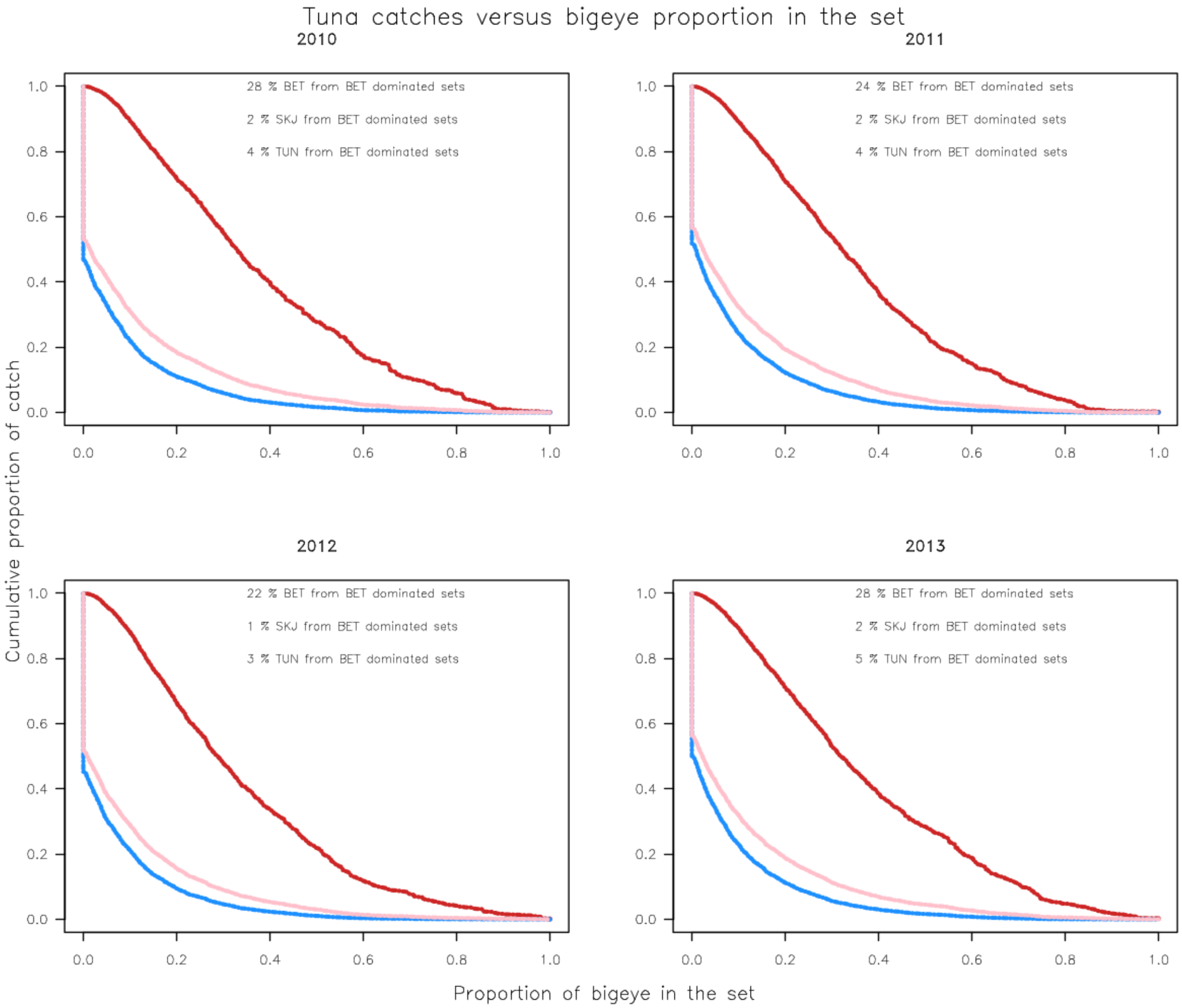


Figure 11: Proportion of bigeye tuna in the set versus proportion of observed FAD catches of bigeye (red), skipjack (blue), and total tuna (pink) taken in sets with at least that proportion. For reference the proportion of observed catch from FAD sets that have more than 50% bigeye are presented.

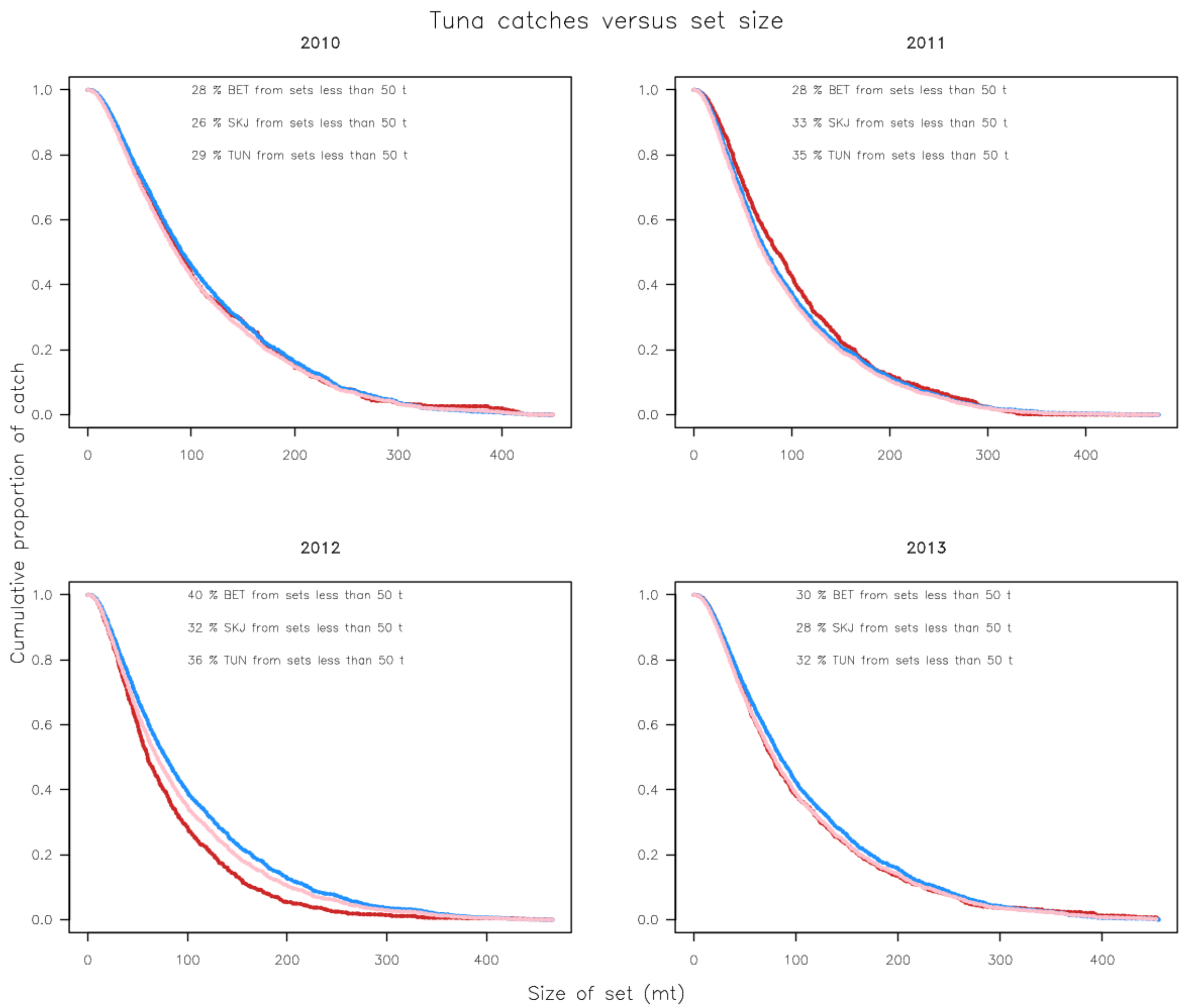
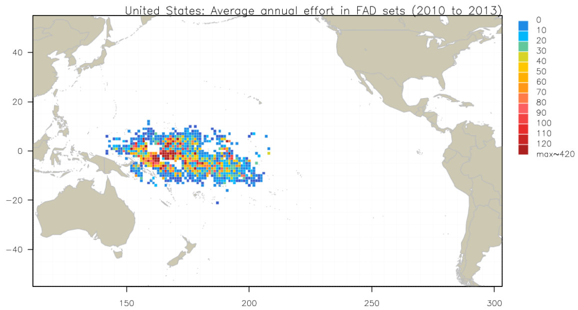
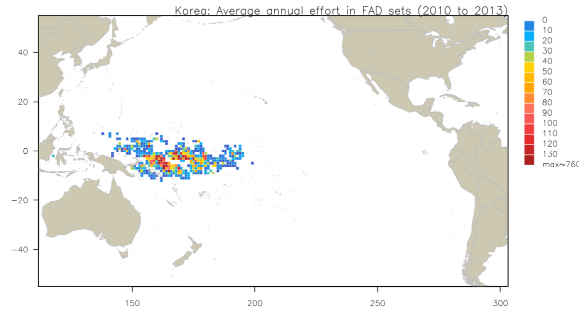


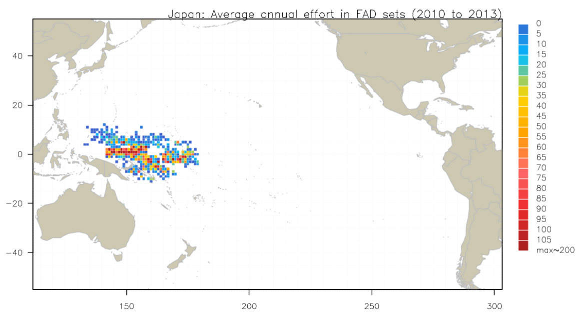
Figure 12: Set size versus proportion of catches of bigeye (red), skipjack (blue), and total tuna (pink) that were taken in sets smaller than that set size for years 2010–13. For reference the proportion of observed catch from FAD sets that are less than 50 mt are presented.



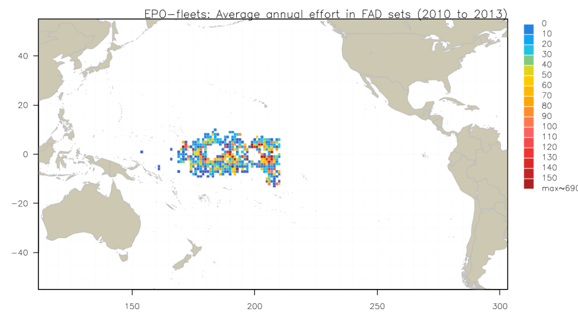
(a) United States



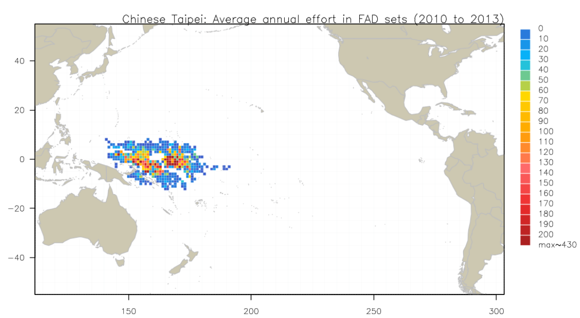
(b) Republic of Korea



(c) Japan



(d) EU and Latin American



(e) Chinese Taipei

Figure 13: Distribution of FAD fishing effort for 2010–13 for major purse seine fleets. Note that the colour scales are deliberately different for each panel.