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**Analysis of stock status and related indicators for key shark species of the Western
Central Pacific Fisheries Commission**

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1 Introduction

Sharks are typically caught as bycatch in the Pacific tuna fisheries, though some directed and/or mixed species fisheries also exist. The status of the shark species designated as key shark species in 2011 (blue, mako, thresher, silky oceanic whiteip sharks) in the Western and Central Pacific Ocean (WCPO) **ADD REF** underwent a comprehensive review in 2011 (Clarke et al., 2011). That review presented a number of indicators to inform on the status of the stock of these shark species and their response to fishing pressure. Given the paucity of data availability for shark species compared to target species, the indicators they developed were based on the type of information typically available from operational-level data for industrial purse-seine and longline fleets.

The current study updates key indicators and extends previous analyses to include hammerhead, porbeagle and whale sharks.

In this report, we present information on the geographic range of catches for each of the species considered; temporal trends in catch composition and catch rates, and key biological indicators of fishing pressure such as mean size and sex ratio by species. Whale sharks are assessed separately due to the unique nature of their interactions with fisheries in the WCPO. The analyses are based on Secretariat of the Pacific Community - Oceanic Fisheries Programme (SPC-OFP) data holdings for sharks taken in longline and purse seine fisheries in the WCPO. Our analysis generally follows the framework first developed and described in the Shark Research Plan presented to the sixth meeting of the Western and Central Pacific Fisheries Commission’s (WCPFC) Scientific Committee (SC6; Clarke and Harley 2010).

1.1 Report layout

This report is necessarily large. To assist the reader it has been structured along the following lines. Following a brief description of the available data in section 2, each of the four indicator analyses are described and results summarized in sections 3-6. Section 7 presents a consideration of the feasibility of conducting a formal stock assessment for each of the shark species discussed in this report. In Section 8, we review the impact of recent shark management measures and, in section 9,

recommend future work to extend and improve the indicator analysis approach. Conclusions arising from our analysis of stock indicators are summarized in section 10. Finally, section 11 discusses the management implications arising from the results of the work presented here.

2 Description of Data

The primary source of catch information regarding sharks is the SPC-held observer database which, despite low coverage in all regions (Table 1 %Observer coverage by region), has a substantial amount of information regarding operational characteristics as well as fate and condition data on captured sharks. Our measure of observer coverage is defined by "observed hooks set" and is used here because it is a "common currency" and allows for the standardisation of observer coverage rates when undertaking analyses. In addition to the observer data, SPC holds operational logsheet and aggregate data on shark catches by longline fisheries. The operational data submitted to the SPC are at a higher spatial resolution than the aggregate data, and are useful for catch estimation, but in practice their utility is limited by the lack of data provision by species for shark (Table 2 Logsheet coverage by region % that ID sharks to species), especially in equatorial regions where the majority of the longline effort occurs. This study covers the time period 1995-2014. While some observer and logbook data exist for years prior to 1995, the majority of records either do not report shark catch or list it as a general category 'shark'. At the time of analysis, sufficient data for 2014 was available both in logsheets and the observer data, notable exceptions from the observer database for 2014 are Australia and the United States whose most recent contributions were in 2011.

Aggregate coverage rates are on par with the coverage rates of the operational logsheet data sets, although coverage differs greatly by region (Table 3). Historical coverage rates are poor partly because prior to February 2011 sharks were not amongst the species for which data provision was required (WCPFC 2013); since that time, data provision for the 13 species designated by WCPFC as key shark species is mandatory. Under CMM 2007-01, required levels of Regional Observer Programme (ROP) coverage in longline fisheries are set to rise to 5% from June 2012 in most areas, but annual average values have been 1% in recent years (for the entire WCPO). With some notable exceptions (e.g. northeast and southwest of Hawaii), most observed sets occurred within Exclusive Economic Zones (EEZs). A thorough examination of the SPC-held fisheries data and its utility for shark related analyses can be found in Clarke et al. (2011).

Building on the work of Clarke et al (2011), this indicator analysis uses the six WCPFC statistical areas as defined in the 2010 WCPFC bigeye tuna stock assessment (Figure 1). As noted in Clarke et al. (2011), these regions are somewhat arbitrarily assigned to the key shark species. However, given the fact that the predominant source of fishing mortality for these species is the longline fishery targeting tropical tunas (as well as billfishes and occasionally sharks), these regions adequately capture the important characteristics of the fisheries. Therefore, for purposes of comprehension and comparison to the previous analysis, we opted to keep the same regions. **Mention that current BET stock assessment uses different region and that the current set also captures key pattern like eastern end of Japanese fleet for region 1.**

2.1 Longline Fishery Data

Put this somewhere: With the exception of 2014 total effort in the longline fleet has increased, throughout the study period (1995-2014) to approximately 800 million hooks annually with nearly

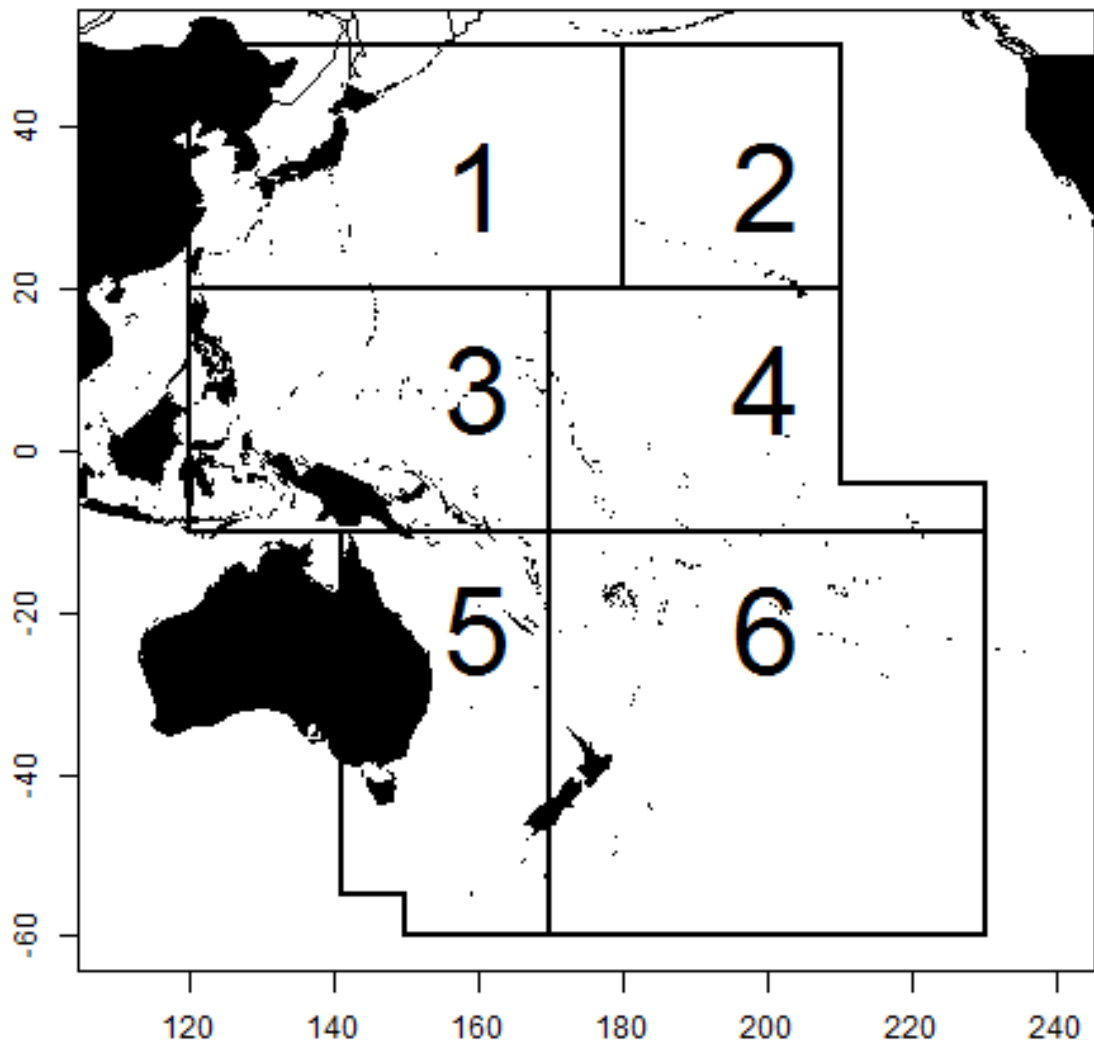


Figure 1: Map of WCPO and regions used for the analysis.

half occurring in regions 3 and 4.

Ideally, indicator analyses would be based on operational-level data as its higher spatial resolution permits more comprehensive and nuanced analyses, however SPC's operational level data is geographically limited with respect to provision of shark data. Figure 2 illustrates the geographic distribution of sets for which SPC holds operational data (blue dots) and sets with at least one recorded shark are overplotted (in orange). However, this picture is somewhat misleading as only 41% of the operational-level sets plotted recorded any sharks. This is in contrast to the observer data in which 93% of the sets recorded at least one shark (overplotted in red).

This is not necessarily due to misreporting. Prior to February 2011, sharks were not amongst the species for which data provision was required (WCPFC 2011); since that time data provision for the 13 species designated by WCPFC as key shark species has been mandatory. Figure 2 does not distinguish between key shark species and other shark species because only 16% of the reported sets recorded any species-specific shark catches. Clarke et al. (2011b) note that most historical species-specific shark catch data are provided by a small number of flag States.

Given the relatively low level of coverage in the operational-level logsheets, a more complete characterization of the longline fishery requires the use of the SPC-held aggregated (5x5 degree grid) data. Effort and reported shark catch data by flag at the aggregated level have a lower degree of spatial resolution but in most cases are raised to represent the entire WCPO longline fishery. Sets with observers present onboard, are shown for comparison (Figure 3) but have a finer degree of spatial resolution due to observer record keeping. Following CMM 2007-01, required levels of Regional Observer Programme (ROP) coverage in longline fisheries were set to rise to 5% in June 2012 but annual average values have been on the order of 1-2%.

A comparison of longline effort by flag and the number of sharks recorded in logsheets was constructed (Figure 4) by showing the top four fishing nations (in the WCPO as a whole) and aggregating the rest of the flag states to another group. If the fishing practices and reporting practices were more or less consistent across flags the numbers of sharks reported would be proportional, by flag, to the effort.

Comprehensive data on shark catches at high spatial resolution are available from observer data held by the SPC-OFP but, as described above, the overall coverage of these data is low, and less than the required levels of ROP coverage. In addition, a comparison of longline effort and longline observer coverage (Figure 5) reveals that the latter is disproportional by region and flag and thus cannot be considered representative of the fishery as whole.

Another aspect of the low data coverage problem is that of temporal representativeness on a month/year basis of the observed effort. A comparison of the annual proportion observed by month - on a regional basis - shows significant fluctuations in the relative coverage of the observer data compared to the logbook data (Figure 6).

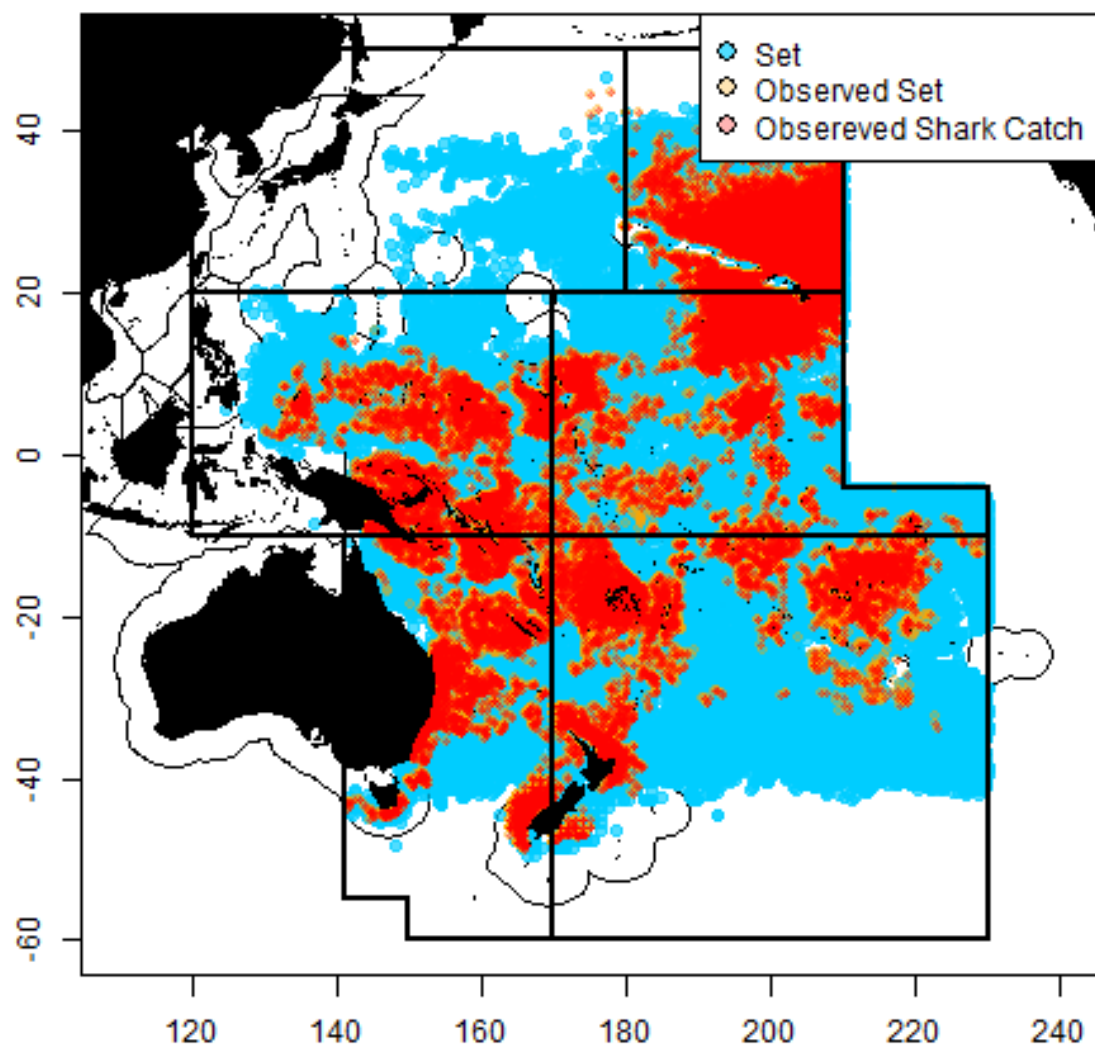


Figure 2: Map of WCPO and observed effort.

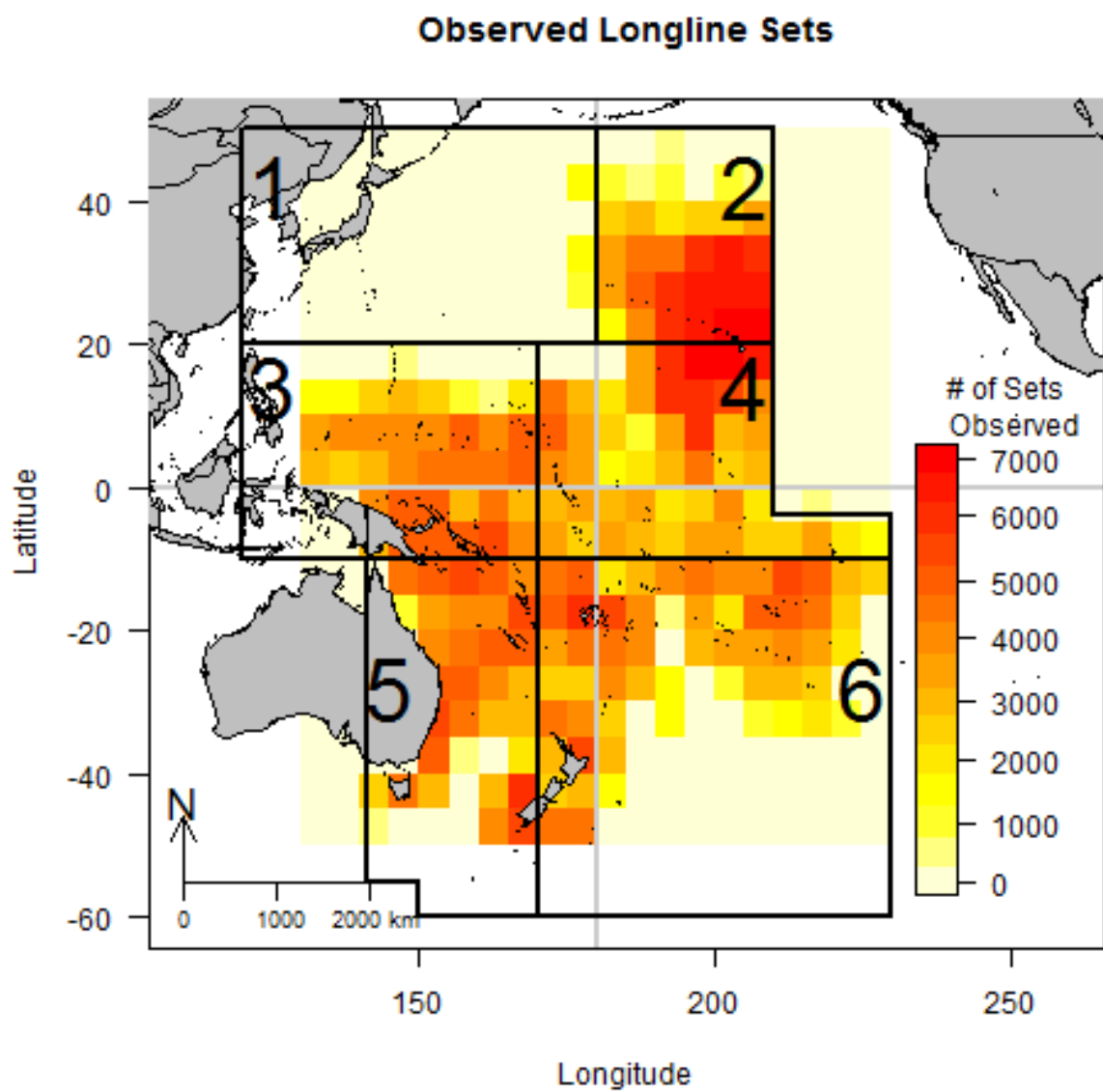
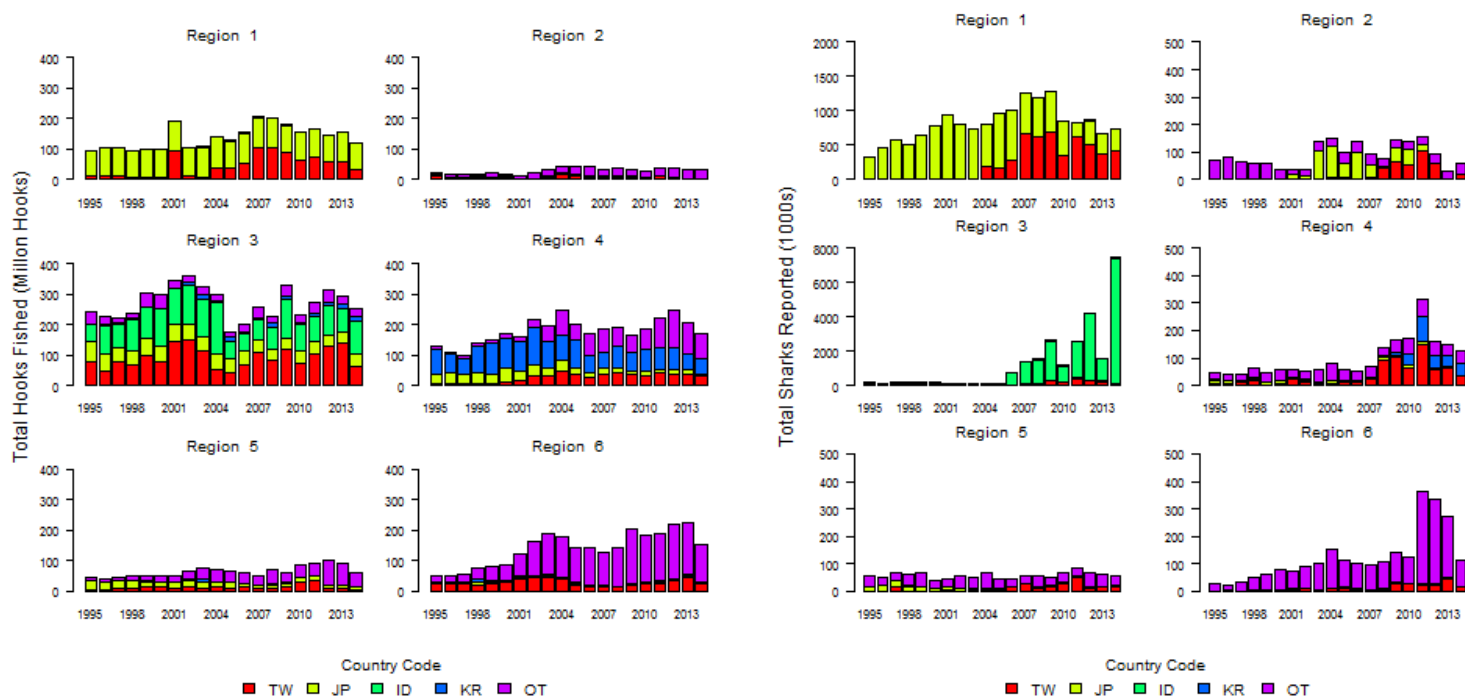


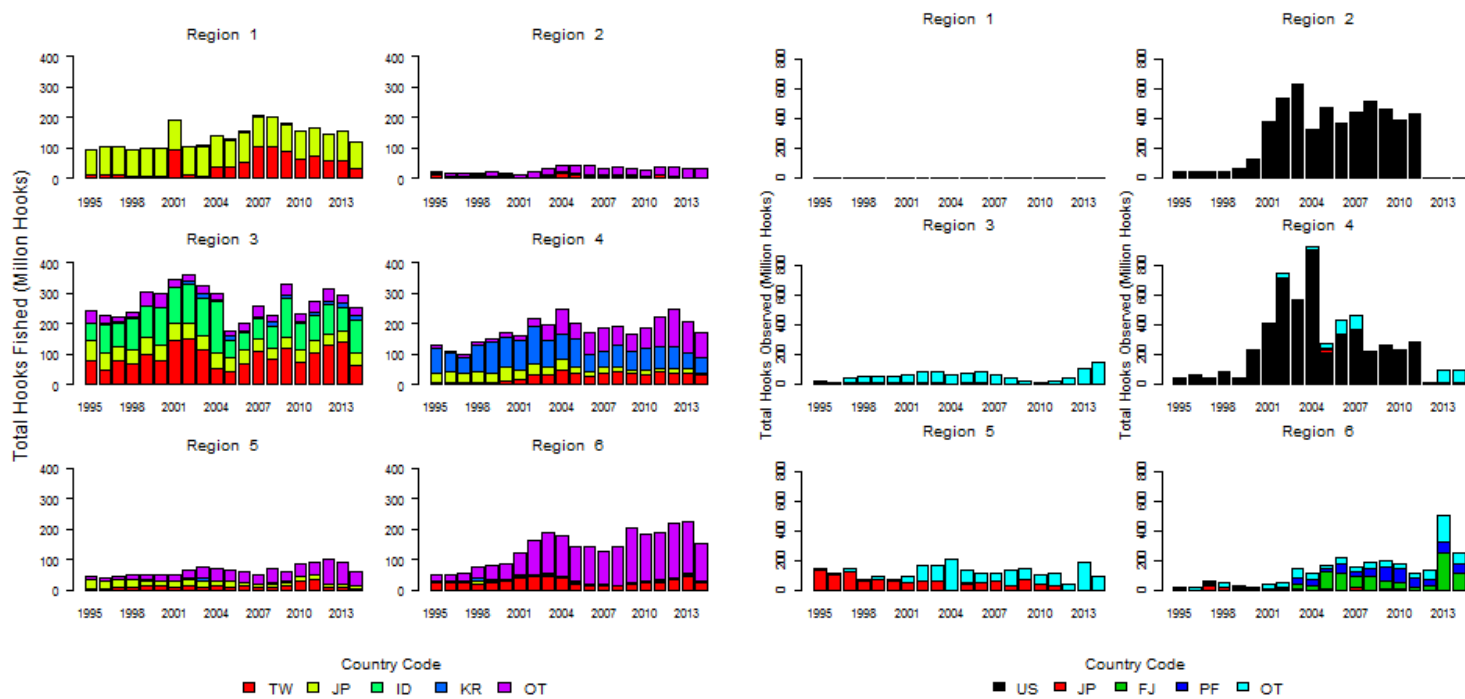
Figure 3: Longline observed sets by 5x5 square



(a) Longline effort.

(b) Reported total shark catch.

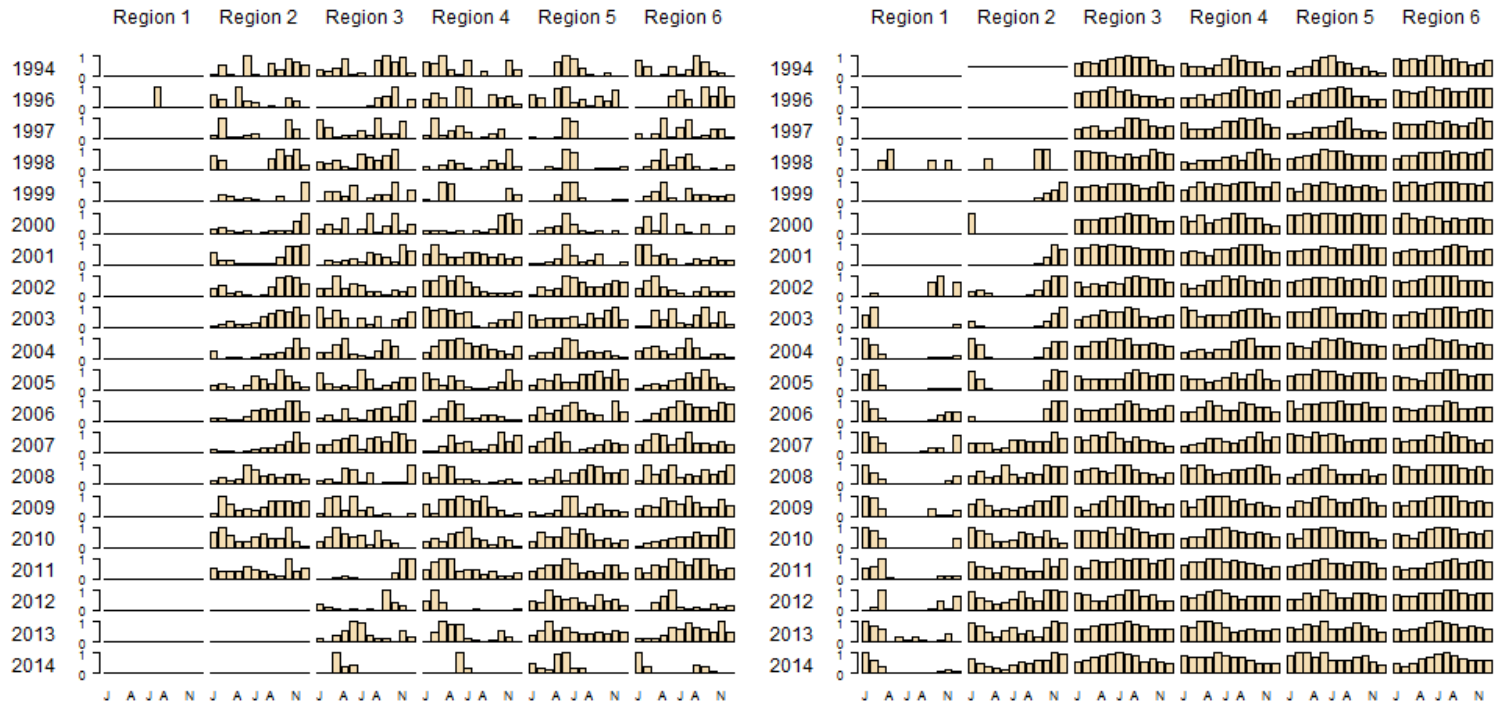
Figure 4: Longline effort by flag and the number of sharks reported in logsheets



(a) Longline effort.

(b) Observer coverage.

Figure 5: Longline effort by flag and the extent of observer coverage



(a) Longline effort.

(b) Observer coverage.

Figure 6: Longline effort by flag and the extent of observer coverage

2.2 Purse Seine data

Similar to the longline fishery, SPC-OFP holds logsheet data on shark catches by purse seine fisheries at both the operational and aggregate levels. However, operational-level coverage for the purse seine fishery (87%) is considerably higher than for the longline fishery (23%). This factor, in combination with the more limited geographic range of the purse seine fishery, contributes to more representative operation-level coverage in the purse seine fishery than in the longline fishery.

Following implementation of the WCPFC ROP on 1 January 2010, in combination with prior observer coverage commitments by Parties to the Nauru agreement (PNA) members, 100% purse seine observer coverage is now required (except for vessels fishing exclusively in one Exclusive Economic Zone (EEZ)). Historical observer coverage in the purse seine fishery has varied between EEZs. Coverage rates were low, generally less than 10%, for the years 1995-2002, with coverage increasing to 10-18% for the years 2003-2009. Recent (2010-2013) annual averages are between 42-56% in total.

While observer coverage of the purse seine fishery is not uniformly representative (Figure 7, orange points), it is more representative than observer coverage of the longline fishery, owing to both higher coverage levels and the more limited geographic range of the fishery (Lawson 2011). Regions 3 and 4 contain 98% of the operational-level reported purse seine sets, and 99% of observed sets and are thus the only regions for which purse seine analyses will be meaningful. Shark interactions are recorded in just 2.5% of purse-seine operational logsheets (Figure 7, red points), a value far lower than the 41% recorded in longline operational-level logsheet. As a result, it is not possible to assess the number of shark interactions by set or the species involved using purse seine logsheet data.

A comparison by flag of purse seine effort and the number of purse seine sets reporting at least one shark interaction was constructed for associated (floating object) and unassociated (free-swimming) sets based on aggregated logsheet data (Figure 8). For each panel, flags were ranked by number of sets and the top four flags were plotted separately with all remaining flags aggregated into an "Other" category. Although estimated shark catches in the purse seine fishery are considerably lower than shark catches in the longline fishery (SPC 2008, Lawson 2011), it would still be expected that purse seine shark interactions are proportional to purse seine effort. However, from the discrepancies observed between the left and right panels, it appears that some major fishing nations are not submitting or are under-reporting their shark interactions.

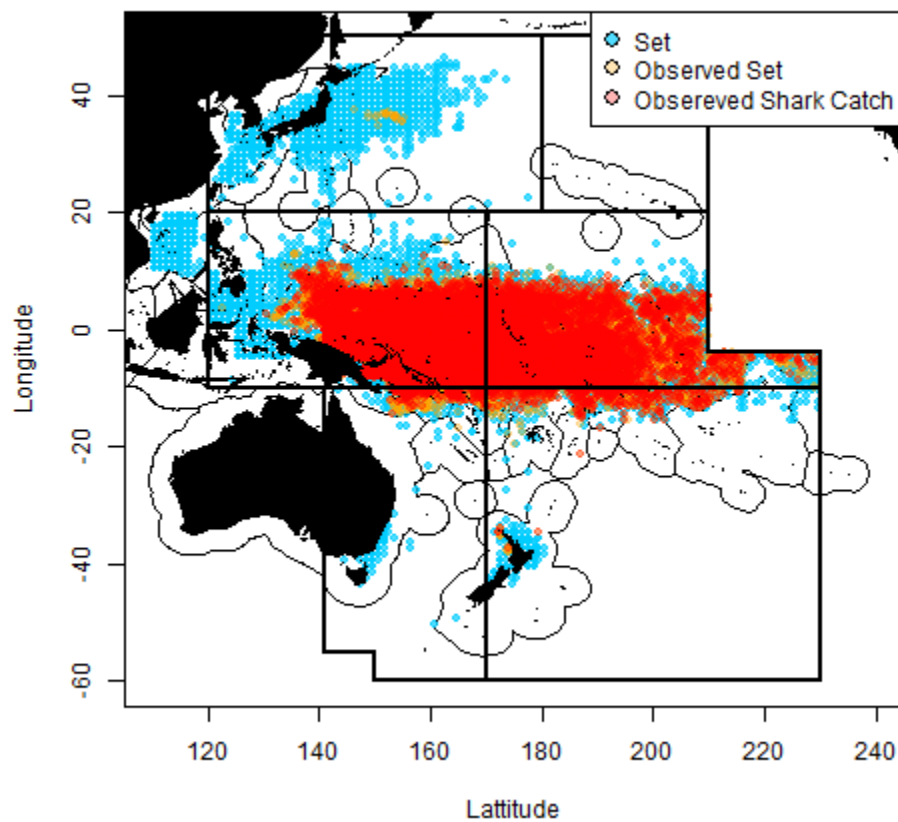
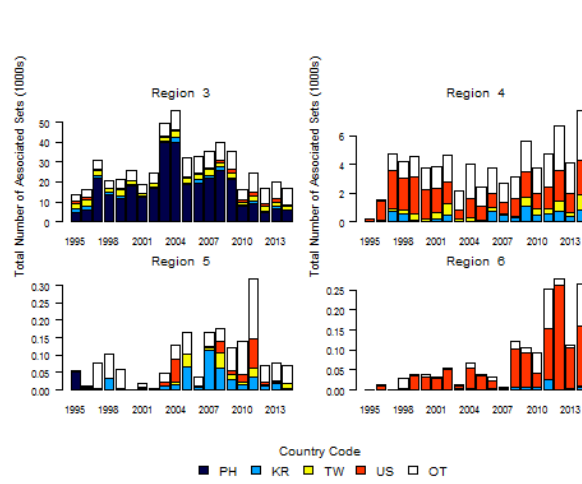
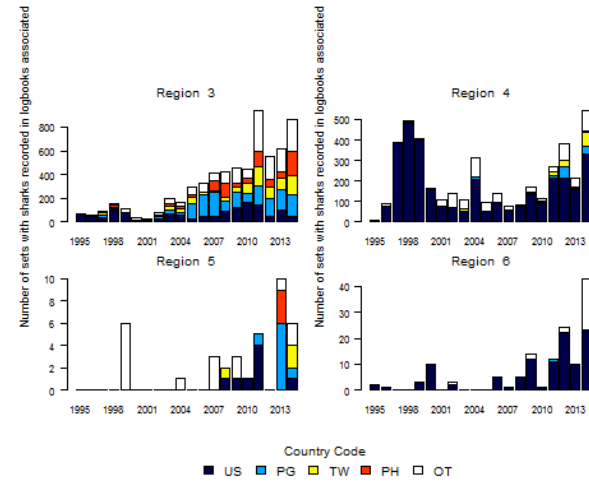


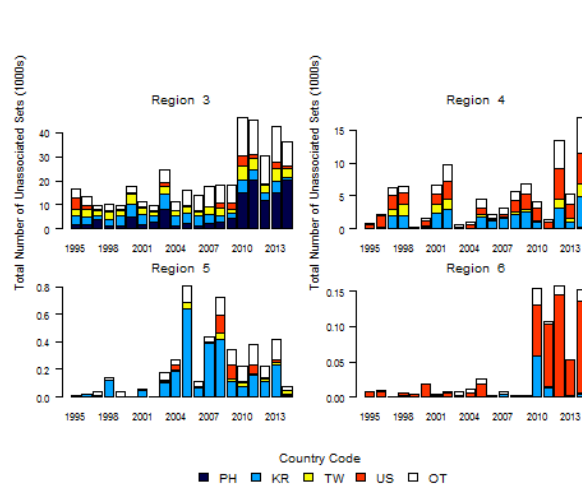
Figure 7: Absolute percent difference in effort between reported (logsheet) effort and observed effort.



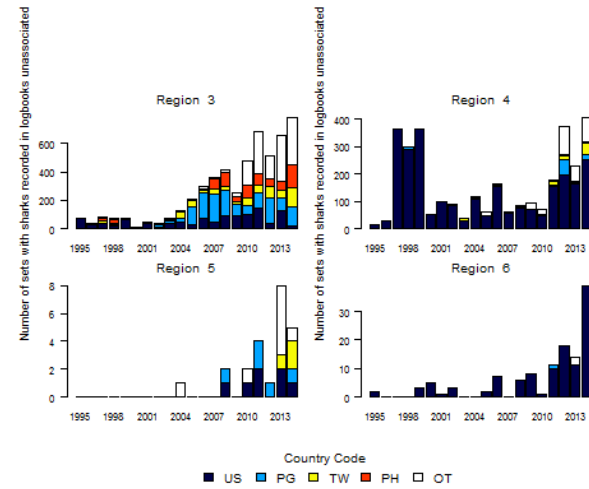
(a) Longline effort.



(b) Observer coverage.



(c) Longline effort.



(d) Observer coverage.

Figure 8: Longline effort by flag and the extent of observer coverage

3 Distribution Indicator Analyses

3.1 Introduction

Distribution indicators consider patterns in the geographic distribution of species catch. Spatial trends in fisheries data need to be interpreted carefully since they originate from a biased sampling design (Walters, 2003). If assessed carefully, however, they can provide useful insight into spatial and temporal trends in species distribution as well as highlight areas of strong interactions between a species and fisheries. In addition, changes in stock abundance might be reflected in distribution (?), with increases and decreases in abundance resulting in range expansions and contractions, respectively. Such patterns have been reviewed at length in the terrestrial literature (?) but less often for marine applications due to the paucity of historical data (but see ?). **FIX.** The indicators presented below are based on observer data and thus patterns in fishing effort and/or observer coverage may bias the results. These results should therefore be taken as an initial indication of the location and intensity of interactions between these species and WCPO longline fisheries. They can be updated over time to determine if the spatial patterns change or temporal trends develop. More complex methodologies might also be applied to remove potential sampling biases.

Potentially need to add back some of these. These indicators examine the geographic range of each species and the habitat usage (in terms of geography only; oceanographic variables are not considered) by different life stages (adult/juvenile) and sexes based on fishery interaction data. Spatial analysis of fish occurrences can be useful in identifying range contractions or expansions which may be linked to fishing activities (Worm and Tittensor 2011). In addition, since many pelagic shark species are known to exhibit sex- and age- specific distribution patterns (Camhi et al. 2008, Mucientes et al. 2009) spatial analysis can highlight areas which are important to key life stages (e.g. presence of adult females and juveniles may indicate pupping grounds; presence of juveniles only may indicate nursery grounds).

3.2 Methods

In this study, we calculated four Distribution Indicators:

- Species-occurrence. This indicator summarizes the occurrence of a species in any longline set monitored by an observer. A positive value at any given location simply indicates that the species in question was observed at least once, without regard to annual frequency or fishing effort.
- Proportion-presence. This indicator provides a rough indicator of the frequency of occurrence of each shark species in each region and trends in presence over time. Using observer data, the indicator is computed by dividing the total number of sets with at least one occurrence by the total number of sets in each region/year combination.
- High-CPUE. This indicator is intended to illustrate which regions and years have shown relatively high CPUE values for the different species. The index is constructed, again on the basis of observed longline sets, by computing mean CPUE within each $5^{\circ} \times 5^{\circ}$ cell within each of the six regions, and then calculating the proportion of cells within a region that are above a specific threshold. For this analysis, the threshold was set at 1 shark per 1000 hooks for blue shark and at 1 shark per 5000 hooks for the other species.

- **Catch-Hotspot.** This indicator is an extension of the Species-occurrence and Proportion-presence indicators, and is intended to illustrate the possible presence of variable species catch hotspots. All observed data sets are totalled within $1^\circ \times 1^\circ$ cells over four separate five-year (pentad) periods. The proportion of observed sets containing at least one species occurrence within that cell/pentad cell is then computed and mapped. This Catch-Hotspot indicator provides better temporal resolution than the Species-occurrence indicator and better spatial resolution than the Proportion-presence indicator in helping to identify the distributional patterns of each shark species.

3.3 Results

The four sets of Distribution Indicators are grouped in Appendix A, as follows: Species occurrence (Figures ?? to ??), Proportion-presence (Figure ??), High-CPUE (Figure ??), Hot spot analysis (Figures ?? to ??). Species-specific results below reference these sets of figures.

3.3.1 Blue Shark

Blue sharks are the most common and widely reported shark bycatch species in the WCPO longline fisheries. They are found to occur through the range of longline fishing and have the highest proportion-presence rate in virtually all years and regions among the shark species analysed in this report. Both the Proportion-presence and High-CPUE time series show distinct downwards trends from the late 1990s to the present in most regions (3, 5, and 6). The Catch-hotspot indicator shows consistently high occurrence of blue shark in longline fishery around the Hawaiian Islands with occurrence generally declining to the south, before again increasing in frequency around 20°S .

3.3.2 Mako Shark

Mako sharks are one of the most commonly captured shark species in the longline fisheries of the WCPO. Mako sharks have been encountered in longline sets in all regions that observers have sampled. The largest, most consistent, hotspots have included waters in Region 5 between Australia and New Zealand. Spatially, there are differing trends over time in the Proportion-presence and High-CPUE indicators. The north and west regions (2 and 3) show stable or slightly increasing rates (though data for region 2 is lacking for years 2012-2014) whereas the south Regions (5 and 6) show steadily declining rates.

3.3.3 Silky Shark

Silky sharks are commonly encountered in Regions 3 through 6 and at a very low rate in Region 2. Neither the Proportion-presence nor High-CPUE indicators illustrate sustained temporal trends in occurrence. The region with the greatest proportion of High-CPUE occurrence is Region 3. The Catch Hotspot indicator also illustrates a consistency in both the temporal and spatial encounter of the LL fishery with silky sharks.

3.3.4 Oceanic Whitetip Shark

Oceanic whitetip sharks also occur with regular frequency in observed longline sets through most of the WCPO longline fisheries. In the five regions where they are commonly encountered (Region 1 contains few observed sets) the trend in both Proportion-presence and High-CPUE has been steadily downward since the mid-1990s, with some of the decline in rates exceeding 80%. Catch-hotspots for oceanic whitetip sharks have been in the central Pacific, particular the region surrounding the junction of Regions 3, 4, 5, and 6.

3.3.5 Thresher Shark

Thresher sharks have been found in observed longline sets in most regions of the WCPO with the possible exception of the area around French Polynesia. Catch-hotspots have been north of the equator, especially in Region 4. Both the Proportion-presence and High-CPUE time series show indistinct temporal trends though Regions 3 and 4 have dropped considerably over the past five years.

3.3.6 Hammerhead Shark

Among the shark species analysed in this report, hammerhead sharks have the lowest encounter rates (measured as Proportion-presence) and appear to be patchily distributed. The regions with the apparent largest presence of hammerhead sharks is the Northeast (Hawaiian Islands) and Southwest (Papua New Guinea, Australia east coast). Due to the low encounter rates, little inference can be made regarding temporal trends in occurrence.

3.3.7 Porbeagle Shark

Porbeagle sharks have historically only been encountered in the southern region of the WCPO, essentially only south of 20 ° S (Regions 5 and 6). A decrease in the spatial and temporal occurrence of porbeagle in observed sets is evident in the three Distribution Indicators other than Species-occurrence. The porbeagle catch-hotspots have shrunk both in size and intensity over the four pentads; the Proportion-presence and High-CPUE time series for Regions 5 and 6 have declined as much as 90% over the past 15 years.

3.4 Conclusions

With the exception of blue shark the high-CPUE indicator more or less steady trends for all species in all regions, however this analysis was hampered by the lack of data throughout the region for species.

Intrepretation of the distribution indicators is complicated by the influence of changes in fishing effort, potential changes in community composition, obsservational coverage and operational factors influencing selectivity and catchability (e.g. depth and leader material). As such, these indicators are best used for identifying the areas in which species-fishery interactions take place, and as supporting information for interpreting other patterns and trends.

4 Observed Species Composition Indicator Analyses

4.1 Introduction

The species composition of the catch, as recorded by longline and purse seine observers, was examined to identify any apparent changes over time. This type of analysis reinforces the species-specific fishery interaction information above, but supplies more detail on interactions by separating longline sets by depth and purse seine sets by type of school association. Another important reason for examining catch composition indicators is to assess changes in the percentage of unidentified shark species over time. Improvements in the observers' ability to identify sharks could contribute to increasing occurrences of species-specific records in the observer database and could bias temporal trends.

While this analysis provides information on the relative proportions of the key species within the observer samples, estimation of total catch composition and quantity is complicated by issues of observer sample coverage and representativeness (see Section 2) and is the subject of a separate analysis (Lawson 2011). Regardless of whether catch composition indicators are based on observer samples or the entire catch, changes in species composition over time can suggest relative population increases or depletions. However, species-specific catch rate analyses should be performed to directly assess whether actual abundances for individual species have changed (see Section 5).

Longline

With just a few exceptions, blue shark catch dominates the longline shark bycatch. In Regions 2, 4, 5, and 6, blue sharks have average 60-90% of shark bycatch; in Region 4 the proportion of blue shark has dropped from around 60% in the late 1990s to 10-15 in recent years. The second most common observation of shark species, in terms of numbers, is silky shark which have constituted a majority of shark bycatch in Region 3 since the early 2000s and have been on the order of 5-10% in other regions. We note that there appears to be a sudden increase in the proportion of silky shark catch for Region 4 in years 2012-2104. In fact, this reflects the absence of observer data from the U.S. longline fleet operating around Hawaii which constituted the large majority of longline sets in that region dating back to the start of the time series. As evidenced by the small number of observed sets shown for years 2012-2014, the shark composition data for these years in Region 4 are quite likely very unrepresentative. Several of the other shark species constitute up to 10% of the shark bycatch in certain regions and time periods: porbeagle in Regions 5 and 6, oceanic white

tip sharks in Regions 3, 4, and 6 and thresher sharks in regions 3 and 4. The estimated proportion of unidentified sharks is quite low in all regions, which may reflect indicate that the composition of shark bycatch in tuna fisheries is composed of the mostly the species listed as key shark species.

Division of the longline shark bycatch into shallow and deep sets revealed several differences in the assemblage of sharks caught at depth. Regions 3, 5, and 6 each have relatively large number of observed sets (Regions 1, 2 and 4 have essentially no observed sets in one or the other depth characterization) so we restrict our comparison to those Regions. In the southern Regions (5 and 6), blue shark and porbeagle comprise as much as 95% of the longline shark catch; the deep water sets contain a much more diverse array of species with silky, thresher, oceanic whitetip and mako sharks occurring in substantial numbers. Differences in shark composition in Region 3 are much more subtle than Regions 5 and 6; hammerhead and oceanic white tip sharks are more common in deep sets while silky sharks are a bit more common in shallow sets.

Purse Seine

Plots of the catch composition as recorded by observers in the purse seine fishery indicate that unlike for longlines, a non-negligible portion of the sharks recorded in the first half of the time series (1995-2003) were not identified to species (i.e. UID; Figure 9). As discussed in Section 2, this is probably a function of the practical difficulties in recording purse seine-caught sharks which are not hauled onboard, but the problem appears to have been resolved in recent years. Overall, approximately 70% of the observer-recorded catch was silky shark; the next most abundant species was oceanic whitetip shark which comprised 7% of the records. The numbers of sets shown in the lower panels illustrate that associated sets comprised 67% of the observer samples in Region 3 and 59% of the samples in Region 4, but recorded 88% and 93% of the sharks respectively. It is also noted that oceanic whitetip sharks were observed in substantial numbers only in associated sets and only until 2004-2005.

4.2 Conclusions

The Species Composition indicators reveal that shark bycatch differs substantially between longline and purse seine fishing in the WCPO.

Blue sharks are the most prevalent longline caught shark, but there are substantial regional and depth variations. Several species are commonly caught more frequently in deeper sets; porbeagle form a sizable component of the shallow sets in Regions 5 and 6 and silky shark is the second most common longline caught shark.

urse seine shark bycatch is much less variable and is dominated by silky sharks, particularly over the past decade when the number of observed sets increased greatly and composition data may have become more representative. In virtually all regions and years, silky shark comprises more than 95% of the shark bycatch, with minor numbers of hammerhead and oceanic whitetip sharks occurring. Oceanic white tip sharks appear to have been more common prior to 2000, their percentage contribution to the overall shark cath has not been more than 20% in regions 3 and 4 for over a decade, which is stark contrast to the first ten years of the study period.

The observed longline catch composition plots illustrate that blue shark dominate in most regions. An exception to this pattern is Region 3 where silky sharks, primarily from shallow sets, are the

most frequently observed species. Although there are some minor differences in species composition between observed shallow and deep sets in other regions (e.g. Regions 2 and 4), these may be related to sampling representativeness. Analysis of observed purse seine shark catches reveals that silky sharks predominate with the majority of these found in associated sets. In previous years, oceanic whitetip shark was the second-most commonly identified shark in associated sets but this species has been only rarely observed in recent years. Substantial numbers of sharks caught by purse seines were unidentified until 2002-2003.

5 Catch Per Unit Effort indicator analyses

5.1 Introduction

Note: The current analysis does not construct inputs to use for stock assessments or catch estimates. Our goal is to highlight general trends in population abundance over time, to be interpreted together with other indicators as outlined above. We recommend that catch rates standardization for stock assessments or catch estimates be conducted independently.

Catch-per-unit-effort data (CPUE) are commonly used as an index of abundance for marine species. However, multiple factors—fishing technique, season, bait type, etc.—can alter the relationship between CPUE and abundance, especially in complex fisheries systems comprising of several fleets and spanning large spatial and temporal scales. Nominal catch rates must thus be standardized to account for changes in the relative prevalence of these factors over time. This is typically done *via* the use of models in the GLM family, which allows us to model the relationship of CPUE *vs.* a set of explanatory variables to be standardized against, but these variables must be defined for each observation. The dataset used in the current analysis provides many such candidate variables, but, given the diversity of observer programs represented, few had enough coverage to be retained in the final models. The available variables are described in Table ?? (see also Table 2 in ? for an overview of the use of variables in shark CPUE standardizations).

CPUE data for species such as sharks often have a large proportion of observations (sets) with zero catch, while at the same time also including instances of large catches (‘long tails’). These uncommon instances of high catches can occur when areas of high shark densities are accidentally encountered, but also when fishing vessels engage in anecdotal shark targeting behaviour. The co-existence of both high proportions of zero catches *and* long tails results in over-dispersed data, and is typical of bycatch species (Ward and Myers, 2005). These features are challenging to account for from a statistical point of view, and have been reviewed at length in the literature on by-catch analyses (Bigelow et al. 2002; Campbell 2004; Ward and Myers 2005; Minami et al. 2007).

Error distributions for by-catch species have been discussed at length in previous publications as these data are notoriously hard to model properly due to the high proportion of zeroes (?). We achieved significant improvements in model diagnostics by allowing multiple parameters in the error distribution to be fit. This is because accounting for the large amount of zeroes in shark CPUE catch data often comes at the expense of modelling large catch events, since the dispersion parameter which controls the length of the tail is assumed to be constant over all factors. This is especially a problem when the mean of the distribution is close to zero or one, as in those instances the probability of getting large events is mostly controlled by the dispersion parameter (unlike when the mean is larger and the tail is not as pronounced). However, whenever conditions are good for sharks or targeting takes place, larger catch events can happen and not modelling them properly means we are missing important drivers. Typically, this can be seen as a bump in the right-hand side of qqnorm plots. This approach is similar in spirit to the zero-inflated-neg-bin that has been advocated by multiple authors (brodziak) but is less computationally intensive. The main advantage of the zero inflated approach is that these techniques can model the overdispersion in both the zeros and the counts as opposed to just the counts (negative binomial) and deal with overdispersion better than other models (such as the quasi-Poisson). A drawback of the zero inflated approach is that it is data intensive and the models often fail to converge.

Further, catch data for non-target species (and sharks in particular) often contain large numbers

of observed zeros as well as large catch values which need to be explicitly modelled. More on data issues: Recent work by [Clarke et al. \(2011\)](#) noted gaps in observer data in terms of time and space continuity, reporting rate, and identification with respect to sharks.

Standardized CPUE series for the longline bycatch fisheries were developed using generalized linear models. We did not generate indices from purse-seine observer data. The number of hooks in a longline set was used as a measure of effort. See also [Clarke et al., \(2011, 2011b\)](#), [Walsh and Clarke \(2011\)](#), [Rice and Harley \(2013\)](#) for past work on shark CPUE standardization in the Western Central Pacific.

5.2 Methods

5.2.1 Stock definition for the purpose of the analysis

Silky and oceanic white tip sharks are observed mainly in the equatorial waters in the purse seine fishery (Figure ??), and from about -25° S to 25° N in the longline fishery (Figure 1). Silky and oceanic white tip sharks have been assessed (??) as a single stock in the WCPO, and are presented in this analysis as a single stock. Thresher, mako and blue sharks occur more frequently in cold, temperate waters, and generally believed to be separated into northern and southern stocks. For instance, blue sharks in the North Pacific have been subject to multiple stock assessments as a single stock (?). These temperate species will thus be analysed as individual stocks. Porbeagle sharks are only found in the southern hemisphere and will also be analysed as a single stock. Hammerheads

To further define the expected geographic range, we defined a coarse climate ‘envelope’ based on sea surface temperature. This aid in distinguishing between zero catches in areas where the species does not occur from zero catches in areas where the species occurs but was not caught. Temperature data were downloaded from the GODAS database (?) and matched to the observer data on a set by set basis. The temperature range of a species was defined as the 2.5 and 97.5th quantiles of temperature for cells with catches. Only cells which median annual temperature were retained as part of the range. **REWORK.** Note that this is a minimal filter and it was only used to exclude the most improbable cells from which a species could be seen. Looked at range of SST where positive catches occurred, selected cells where median falls within this range.

5.2.2 Data trimming

Data were cleaned following the general method outlined in Appendix section ??. Records from the US observer programs (Hawaii and American Samoa) were excluded from the analysis as they were only available up to 2011. Records from the Papua New Guinea observer program were removed as vessels in the fleet frequently target sharks. We also removed records from any observer programs for which we had less than 100 sets. Extreme catch events greater than the 97.5th quantile were also removed. Finally, year effects were only estimated if there were at least 50 sets observed in that year.

Although a much smaller proportion of the overall dataset (6.5% of the sets), the targeting sets represent significant shark catch (82% of the total silky shark catch). Therefore the dataset was examined with respect to variables relating to whether sharks were the intentional target of the set.

Shark targeting sets were deemed to be sets where the observer had marked that the set was intentionally targeting sharks of any species, **whether shark bait was used, or whether shark lines were used**. We also removed the data from the PGOB because of frequent shark targeting.

The results of these filtering rules are listed by species in Table ??.

5.3 Additional categorical variables

1. Day category 2. HPBCAT

5.4 Overview of GLM Analyses

5.4.1 Notes on error distributions:

The **filtered datasets** were standardized using generalized linear models (McCullagh and Nelder 1989) using the software package R (www.r-project.org). Multiple assumed error structures were tested including the delta lognormal approach (DLN) (Lo et al. 1992, Dick 2006, Stefansson 1996, Hoyle and Maunder 2006), zero-inflated poisson and negative binomial models, the tweedie distribution (cite), and negative binomial models with mu and sigma modelled. Due to its superior performance both in run time and model diagnostics, we retained the latter and only present those results here. The negative binomial (Lawless 1987): is typically more robust to issues of overdispersion (overdispersion can arise due to excess zeros, clustering of observations, or from correlations between observations) was also used. This model has been advocated as a model that is more robust to overdispersion than the Poisson distribution (McCullagh and Nelder 1991), and is appropriate for count data (Ward and Myers 2005), but does not expressly relate covariates to the occurrence of excess zeros (Minami et al. 2007).

5.4.2 Procedure for model selection

Because flag and observer programs are highly correlated, we used observer program as an explanatory categorical variable as it tended to explain a higher proportion of the data when used on its own than flag (except in the case of XXXX and XXXX where flag explained the most). We also explored adding an interaction between year and observer program, as for some species of less mobile sharks we could expect to see local trends in annual abundance that are reflected in the observer program data. We checked for the relevance of including interactions early in the model selection process **but did not proceed with an interaction for the remaining of the model selection**.

5.4.3 Calculation of year indices and confidence intervals

Year effects could be extracted as is from the model output as there were no interactions between year and other variables, and year was not included as an explanatory variable for the σ models. Confidence intervals were computed with the function `confint` in `gamlss`.

5.5 Results

Blue shark (*Prionace glauca*), north Pacific Both the standardized and nominal CPUEs of blue shark in the north Pacific show a declining trend starting in 1999 and 1998, respectively. Data points for 2011 and 2012 are unavailable due to low sample size.

Blue shark (*Prionace glauca*), south Pacific Both the standardized and nominal CPUEs for blue shark in the south Pacific show declines in the initial 1995-2003 and late 2010-2015 periods, with relatively stable CPUEs between 2004 and 2009.

Mako shark (*Isurus oxyrinchus* and *Isurus paucus*) in the north Pacific The standardized and nominal CPUEs share the same trajectories (Figure ??), but on a slightly different scale for the first 6 years (1995-2001). The largest difference in the nominal and standardized CPUE is in the final year, where the standardized CPUE declines sharply in contrast to the nominal, but years 2011 and 2012 were excluded from the standardization due to poor sample sizes (Figure ??).

Mako shark (*Isurus oxyrinchus* and *Isurus paucus*) in the south Pacific The standardized CPUEs show a more stable trend in relative abundance than the nominal CPUEs, although both have low points in 2002 and 2014. In addition, the standardized CPUE peaks in 2010, whereas the nominal is the highest in 1996.

Oceanic whitetip shark (*Carcharhinus longimanus*) The standardized oceanic whitetip shark trend decreases steadily over 1995-2014. The standardized trend shows a slightly steeper decline than the nominal, with the most noticeable departure from the nominal being the large decrease from 2013-2014 in the standardized CPUE.

Silky shark (*Carcharhinus falciformis*) Standardized silky shark trends in the WCPO showed high inter-annual variability with an initial decline from 1995-2000 followed by a slight increase until 2010, followed by a steep decline. This mirrors the trends seen in the nominal CPUE, albeit with a lesser variability.

Thresher sharks (*Alopias superciliosus*, *vulpinus*, & *pelagicus*) Standardized CPUE values for thresher sharks were similar to the nominal CPUE except for additional variability in the nominals. They both rise for the first 6 years of the series (1995-2001) but diverge afterwards. For the years 2002-2014, the standardized CPUE is less variable showing a slightly decreasing CPUE from 2003-2011. The last three years of both the standardized and nominal CPUEs show a steep decline. The CPUE from the thresher complex (bigeye, common and pelagic) is difficult to interpret as the second most commonly reported thresher species is the general “thresher shark” category.

Hammerhead sharks (*Sphyrna mokarran*, *lewini*, *zygaena*, & *Eusphyra blochii*) Standardized CPUE for the hammerhead complex shows a large increase from the 3rd to the 6th year of the study period (1997-2001), with a relatively stable CPUE thereafter (2002-2013, regions 3 and 5 in the longline database). Similar to the thresher shark complex, the CPUE series representing the hammerhead complex are difficult to interpret because more than half of the observations in the study period (1995-2014) were made to a generic “hammerhead” category.

Porbeagle shark (*Lamna nasus*) The standardized CPUE for porbeagle shark was close quite similar to the nominal CPUE, showing an increase in the first three years of the time series, followed by a decline from 1999 to 2003, and a monotonic increase thereafter.

5.6 Conclusions

Variable name	Symbol	Explanation	% records present
Year	β_Y	Require to estimate year effect	100
Month	β_M	Captures seasonal variability	100
Observer program	β_O	Country hosting the observer program	100
Vessel flag	β_F	Note: correlated with observer program	100
Hooks-beween-floats	β_{HBF}	Indicator of catchability for surface-dwelling species	
Shark bait			
Number of shark lines			
Lighsticks			
Shark target		Sharks explicitly defined as targets?	
SST	SST	Moon frac	

5.7 Model structure by species

in appendix: summarize proportion of data removed for each species (temperature, observer, quantile), e.g. North Mako: removing HW removes a lot of data!! check for catches...

5.8 Model diagnostics

Used quantile residuals.

5.9 Conclusions

The signals from the nominal CPUE data can be heavily influenced by factors other than abundance and therefore a procedure to standardize CPUE data for changes in factors that do not reflect changes in abundance is usually recommended.

Table 1: Summary of model structures retained for CPUE standardization of each species

Species	Model μ	model σ	% deviance
Blue shark, northern stock	year + program + HPBCAT2 + month + sharkbait	program + HPBCAT2 + month	—
Blue shark, southern stock	year + flag + HPBCAT2 + month + sharkbait		
Mako, southern stock	year + program + HPBCAT2 + month + sharkbait	program + month	
Mako, northern stock	year + program + month + sharkbait	HPBCAT2	
Oceanic white tip	year + program + HBPCAT2 + month + sharkbait	program	
Thresher sharks	year + program + HPBCAT2 + month	program + HBPCAT2	
Hammerheads	year + program + HPBCAT2 + month + sharkbait	sharkbait	
Oceanic whitetip shark	year + program + HBPCAT2 + month + sharkbait	program	
Silky shark	program + year + HPBCAT2 + month + sharkbait	program + sharkbait + month	
Porbeagle	year + flag + HPBCAT2 + month	flag + month	

Table 2: AIC improvement over null model for BSH.north from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
yy	319.76	216.04
program_code	212.51	198.47
flag	105.54	195.94
mm	56.57	52.05
daycat	11.17	19.95
HPBCAT2	10.07	53.88
sharkbait	8.29	10.80
HPBCAT	8.20	54.58

Table 3: AIC improvement over null model for BSH.south from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
flag	11043.90	4626.32
program_code	9971.76	4152.00
HPBCAT2	6048.07	2829.18
daycat	4346.51	2116.94
yy	2943.03	1860.51
mm	2803.40	749.34
HPBCAT	2709.55	2295.09
sharkbait	298.24	8.37

Table 4: AIC improvement over null model for FAL from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
program_code	2401.27	1256.90
flag	2084.24	1052.85
yy	745.86	265.08
daycat	240.04	82.13
HPBCAT	202.88	42.80
HPBCAT2	201.02	41.61
sharkbait	62.96	33.48
mm	22.92	31.98

Table 5: AIC improvement over null model for HHD from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
program_code	385.38	-4.39
flag	384.82	98.17
HPBCAT2	151.90	10.83
HPBCAT	102.78	-1.37
daycat	66.76	4.51
yy	33.71	31.08
mm	26.11	3.39
sharkbait	15.37	21.94

Table 6: AIC improvement over null model for MAK.north from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
yy	68.41	42.54
flag	41.17	-72.56
program_code	37.21	8.88
daycat	14.17	0.75
mm	6.12	-15.83
sharkbait	4.87	-1.39
HPBCAT	-1.18	1.10
HPBCAT2	-1.18	8.03

Table 7: AIC improvement over null model for MAK.south from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
flag	2405.90	543.71
program_code	2007.09	656.44
HPBCAT2	1477.37	269.01
daycat	544.87	70.17
yy	535.65	359.67
mm	473.91	251.28
HPBCAT	310.63	186.70
sharkbait	55.88	5.94

Table 8: AIC improvement over null model for OCS from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
program_code	999.45	192.55
yy	792.33	181.77
flag	627.40	69.86
HPBCAT2	71.93	-3.52
sharkbait	70.89	4.42
daycat	53.56	0.70
HPBCAT	50.80	-1.94
mm	28.96	11.17

Table 9: AIC improvement over null model for POR from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
yy	1007.71	376.45
flag	602.59	825.49
daycat	328.52	374.34
program_code	265.33	223.13
mm	241.27	383.30
HPBCAT2	39.12	165.32
HPBCAT	9.18	149.03
sharkbait	-0.85	-0.85

Table 10: AIC improvement over null model for THR from a single explanatory variable

Variable	AIC.diff	AIC.diff.sigma
program_code	3583.25	1213.50
flag	2832.48	934.07
yy	1049.10	434.79
mm	111.10	32.01
HPBCAT	13.59	256.75
HPBCAT2	12.85	264.39
sharkbait	7.09	25.92
daycat	0.27	280.76

6 Biological indicator analyses

6.1 Introduction

Trends in a standardized measure of fish size can indicate changes in the age and size composition of the population, in particular, a decrease in size is expected in a population under exploitation (Goodyear 2003). Previous analysis (Clarke et al. 2011) examined trends in median length of the key WCPFC shark species and found significant declines in most combinations of spatial strata and sex for blue and mako sharks, as well as silky sharks. The magnitude of such change can, in theory, provide information on the level of exploitation that a fish stock is experiencing (Francis and Smith 1995). As the size of sharks differs by sex, it is important to examine indicators on a sex-specific basis where possible.

In addition to identifying trends in size, length data can be used to assess whether the catch sample is sexually mature by comparing to species-specific lengths at maturity from the literature. Length is a better measure of size than weight because the former does not fluctuate with reproductive or other seasonal factors. As noted in Francis et al. (2014), median length is preferred over mean length as the median is less likely to be influenced by outliers.

The sex ratio of a shark population may also be a useful indicator of its status. Heavy exploitation could lead to a preferential loss of females because they tend to be larger and older than males. Thus, if the median length in a population declines, the sex ratio may also have been impacted. Additionally, male and female sharks often segregate spatially (Mucientes et al. 2009), and this has been reported in highly migratory ("HMS") sharks in New Zealand waters, e.g. in the South region, females dominate the blue shark catch while males dominate the mako shark catch (Francis 2013). If fishing activity is concentrated in areas favoured by one sex, then an imbalance in the sex ratio could be created.

In this section we analyse trends in median length and the proportion of females over time.

6.2 Methods

Shark sex identification data from observer samples were aggregated by year and region to assemble estimates of trends in sex ratio. The percent of female sharks by region and year are illustrated in Appendix Figure ??.

For the nominal length analysis, length data from observer samples in longline and purse seine were assembled by region and year. Observed length data from the purse seine fishery was limited to silky and oceanic whitetip sharks in regions 3 and 4, as sex is generally not recorded. Length measurements were generally recorded as fork length; in those instances that data was recorded in total length, measurements were converted to fork length using conversion factors given in Table ??. Those $5^\circ \times 5^\circ$ cells for which the sample size was less than 20 individuals were removed from the analysis. Due to small longline fishery sample sizes for longfin makos, and for bigeye, common and pelagic threshers, results for makos (two species plus unidentified) and threshers (three species plus unidentified) were grouped. Length at maturity data for shortfin mako, bigeye thresher, and scalloped hammerhead were chosen to represent each group, respectively, as both observer data and literature sources were greatest for these species. While length at maturity and conversion factors might be expected to vary by region within the WCPO, insufficient data were available to support regional analysis. The median lengths, with 5th and 95th percentiles, were plotted for both sexes

and all regions in Appendix Figures ?? to ?? (for the longline species) and Figures ?? and ?? (for purse seine species). Length at maturity is included in each plot for purposes of comparison with median length.

In addition to the nominal analysis, and in order to account for potential influences on shark size due to changes in sampling effort, fork lengths from the longline fishery were standardized. This was accomplished using a GLM based on a normal distribution with factors year and $5^\circ \times 5^\circ$ cell. The estimated model coefficients were used to predict shark lengths for each year for an arbitrarily chosen cell lying near the centre of each region. To more adequately capture the population trends, this analysis was carried out at stock level (north (Regions 3 and 4 combined) and south (Regions 5 and 6 combined)) for blue and mako sharks and regional level (Regions 3 to 6 combined) for silky, oceanic whitetip, hammerhead, thresher and porbeagle. Additionally, visualization of trends in the annual change in standardized length was facilitated by fitting a loess smoother through the annual GLM coefficients. Difficulties with standardization precluded the development of GLMS on purse seine length data. The results of the standardization are illustrated in Appendix Figures ?? to ??

Time trends over the duration of each standardized length time series were estimated by fitting linear models to the annual GLM coefficients. Linear model fits were produced separately for each species, sex, and stock. The slope coefficients, which is the estimated annual change in length per year, are plotted in Figure ???. One important caveat when interpreting the results is that linear models generalize the direction and magnitude of the trend over the entire time series. Therefore, a size trend that rises at the start of the time series and decreases in the later part of the time series may be characterized as having no trend through time.

6.3 Results

6.3.1 Sex-ratio

The proportion of observed females showed no clear trends over the entire study period for any of the sharks. Fine scale analysis is difficult due to lack of continuous data and small annual sample sizes in the most recent years. The sex ratio of blue shark in region 5 has been skewed in favor of females for the entire data period. With the exception of blue shark in region 5 there is nothing to suggest that incidental catchability (availability) is greater for either sex for all species.

6.3.2 Median length

Blue shark females showed declining trends in regions 5 and 6, with stable trends in regions 2, 3, and 4 5. Male blue sharks exhibited similar trends with nearly all the observed blue sharks in region 5 being immature in recent years.

Both male and female silky sharks showed declining trends in length in the core areas (regions 3 and 4) as well as region 5. The majority of the silky sharks observed were immature throughout the study period. The only area that showed increases in observed median length were regions 6 for males of both species.

Length data for hammerhead sharks is largely limited to region 3 during the time period 1998-2008, during this time the majority of the observed sharks were immature. The limited length data in

other regions indicates that the hammerhead sharks available to the longline fishery are mainly immature.

Male mako sharks showed the same trends as blue sharks with stable trends in regions 2, 3 and 4, with slightly declining trends in regions 5 and 6. Immature males were more commonly observed in regions 5 and 6 throughout the study. Observed female and male were approximately the same size in all regions and showed relatively stable. As female length at maturity is at a much larger size than for males, the observed median length of females was considerably lower than length at maturity.

The trends in length for both female and male oceanic whitetip sharks were relatively stable in the core area (regions 3 and 4), with the majority of the observed sharks being immature.

Porbeagle sharks were only observed in regions 5 and 6, where nearly every female and the majority of the male sharks were immature. Increasing median length for both sexes was observed in region 5 since 2007; Region 6 showed no consistent trends.

The majority of observed thresher sharks occurred in region 4 where the lengths of both male and female sharks were relatively stable throughout the time period. Observed female thresher sharks were predominantly immature while male thresher sharks did not show any clear bias towards maturity.

6.3.3 Standardized length

Possible trends in length over time are more evident in the standardized length plots when overplotted with a loess smoother. For the great majority of species, sex and stock, standardized lengths have decreased over time. The only exceptions are for the northern stock of mako (both species) and porbeagle females, which have essentially remained the same size. The slope coefficients fitted to annual GLM coefficients show a decrease of around 0.2 to 0.4 cm/year for most of the other time series. Southern male blue sharks showed the greatest decline in standardized length, with a negative slope coefficient of 0.6 cm/year.

6.4 Conclusions

This Biological Indicators section examined trends in sex ratio, median length and standardized length. The principal findings were as follows:

- Sex ratio of sharks in longline catches is approximately equal for all species and regions with the exception of blue sharks in Region 5, which are predominantly female.
- Observed length was investigated by plotting the nominal median length trends and length at maturity at the regional level. This indicated that the majority of the observed hammerhead, silky, thresher, oceanic whitetip and porbeagle sharks were immature. Observed blue sharks were mainly immature in regions 5 and 6 and mainly mature in region 2.
- The results of the length standardization indicate declines in most regions for most species based on a linear model fit to the standardized annual lengths, with annual declines of 0.2-0.4 cm/yr.

- The largest decline was seen for the southern stock of male mako sharks which have declined by 0.6 cm/yr By contrast, slight increases in mean standardized length were seen for northern mako sharks (both sexes)

7 Feasibility of Stock Assessments

Fisheries stock assessments are designed to provide stock status and management information via a population model that is scaled to the available data. Traditionally the data requirements include landings record or estimates of catch, abundance indices and biological information. For stocks that are not traditionally managed and considered bycatch (i.e. sharks), there are often short data series and data gaps for many species, estimates of removals are often highly uncertain and data poor methods or other alternatives may be more appropriate than full stock assessments. Here we consider each of the key shark species and the viability of a stock assessment or other population level study to provide stock status and management information.

Blue shark (*Prionace glauca*) in the north Pacific This species has been the subject of multiple stock assessments using both basic Bayesian production models and length based methods (SS3 and MFCL), there is sufficient data to develop reliable inputs for abundance indices and removals. Particular challenges exist for estimating catch and indices of abundance in areas where fishing behaviour has shifted towards targeting of sharks.

Blue shark (*Prionace glauca*) in the south Pacific An analysis of the potential catch and CPUE series to support a stock assessment of blue shark in the south Pacific Ocean was presented at the SC9 (WCPFC-SC9-2013/SA-WP-04) and noted that in general the data exist to complete a stock assessment, however all data sets (observer, logsheet, aggregate) share the same characteristics of poor coverage with respect to space, time, or species identification. This study analysed only data from the WCPO convention area in the south Pacific, and it is likely that blue shark in the south Pacific are well mixed and would support a single south Pacific wide stock assessment. Although fisheries data in the south eastern Pacific exist, the data have not been analysed and no indication as to whether they would support a south Pacific wide stock assessment can be given.

Mako shark (*Isurus oxyrinchus* and *Isurus paucus*) in the north Pacific The shark working group of the International Statistical Committee is currently working on an INDICATOR-BASED ANALYSIS OF THE STATUS OF SHORTFIN MAKO SHARK IN THE NORTH PACIFIC OCEAN. Preliminary results indicate that the indices of abundance, length information and size frequency data exist, though the extent to which this data can represent the entire north Pacific is unclear, there are connecting trends in abundance and problems with both shortfin and longfin mako being recorded as simply 'mako' shark. .

Mako shark (*Isurus oxyrinchus* and *Isurus paucus*) in the south Pacific Although no detailed study of the available data for mako sharks has been undertaken, this indicator analysis combined with the fact that mako sharks are often caught in the same fisheries as blue shark would indicate that sufficient data exist for a basic length based stock assessment in the southern portion of the WCPO.

Oceanic whitetip shark (*Carcharhinus longimanus*) Oceanic whitetip sharks in the WCPO were most recently assessed in 2012 (SC8) and at that time there was sufficient data to support an assessment for the period 1995-2009. In recent years longline observer coverage has dropped in the WCPO as observers have moved to purse seine vessels. At the same time increased reporting by species in the operational level logsheets has increased. It is unclear as to what the effect of these changes in data availability would have on a stock assessment, but given the exceptionally poor stock status based on the last assessment, another assessment is likely not to result in a significant change to stock status, so delaying a new assessment

would be prudent.

Silky shark (*Carcharhinus falciformis*) Silky sharks in the WCPO were most recently assessed in 2013 (SC9) and similar to oceanic whitetip, at that time there were sufficient data to support an assessment for the period 1995-2009. In recent years longline observer coverage has dropped in the WCPO as observers moved to purse seine vessels. At the same time increased reporting by species in the operational level logsheets has increased. It is unclear as to what the effect of these changes in data availability would have on a stock assessment, however silky sharks continue to be the most commonly observed shark in region 3 for both longline and purse seine, as well as in region 4 for purse seine. These factors indicate that a stock assessment of silky sharks is feasible.

Thresher shark (*Alopias superciliosus, vulpinus, & pelagicus*) Thresher sharks are mainly present in the longline observer data in region 4. They are represented by three species but often identified only as 'Thresher'. Catch rate analysis by species is constrained by limited data in space and time and would be better performed by species but was constrained due to limited data and produced no clear trends for the group. A limited stock assessment for all combined species is possible, though the results would be difficult to interpret on a species specific level, and therefore would have limited ability to inform management decisions.

Hammerhead Sharks (*Sphyrna mokarran, lewini, zygaena & Eusphyra blochii*) Observations of hammerhead sharks are virtually non-existent in the purse seine database and mainly limited to regions 3 and 5 in the longline database. Further complicating the analysis is that more than half of the observations in the study period (1995-2014) were recorded as generic 'hammerhead' category. A stock assessment for this species is not feasible given the current data.

Porbeagle Sharks (*Lamna nasus*) Porbeagle sharks are generally considered a wide ranging oceanic species, in the Pacific they are distributed throughout the southern temperate and cold waters. Observed catch of porbeagle sharks are mainly limited to the Australian and New Zealand EEZs, however, other data do exist, such as operational logsheet data and potentially observer data from the CCSBT. Given the current SPC data holdings limited analysis for the WCPO would be feasible, but it is likely that other organisations could undertake a Southern Ocean wide assessment.

Whale Shark (*Rhincodon typus*) Whale sharks are observed in small numbers in the purse seine fishery, however, large data gaps exist from some key areas. A formal stock assessment for them is unlikely to be successful at this time, however, with prolonged and complete observer coverage one may become possible in future.

8 Impact of Recent Shark Management Measures

A general Conservation and Management Measure (CMM) aimed at managing sharks within the WCPFC was developed in 2006 (CMM2006-05). This measure was subsequently updated and refined in 2008 (CMM2008-06), 2009 (CMM2009-04) and 2010 (CMM2010-07), in addition specific measures have been developed for oceanic whitetip sharks (CMM2011-04); whale sharks (CMM2012-04) and silky sharks (CMM2013-08). The general shark measure has evolved over the years but currently requires accurate reporting of key shark species, encourages live release of sharks and attempts to address issues of finning through a 5

The species specific measures all have a retention ban, reporting requirements and the whale sharks measure also prohibits specific targeting of purse seine sets on whale sharks. Notes on specific CMMs include;

CMM 2010-07 Conservation and Management Measure for Sharks This CMM was originally designed to encourage full utilization of retained sharks, among the components of this measure was the requirement that vessels shall have on board fins that total no more than 5The proportion of sharks that were finned was significantly reduced and the proportion discarded increased and has been approximately 80-100

CMM 2011-04 Conservation and Management Measure of Oceanic Whitetip Shark This CMM went into force on January 1, 2013, as such there should be a reduction in the proportion of retained and finned oceanic white tip sharks over the period 2013 and 2014. The measure aimed at the reduction in mortality of oceanic whitetip sharks in part because it was noted that the 5

CMM 2013-08 : Conservation and Management Measure for Silky Shark . This measure is specifically a no retention measure for silky sharks, and went into effect July 1 2014. We do not expect to see the impact of this measure as the most recent data are from December 2014.

Conservation and Management Measure 2014-05; Measures for longline fisheries targeting tuna and billfish, states:

CCMs shall ensure that their vessels comply with at least one of the following options:

1. do not use or carry wire trace as branch lines or leaders; or
2. do not use branch lines running directly off the longline floats or drop lines, known as shark lines.

This CMM goes into effect on July 1 2015so no assessment of it is possible at this stage. However the analysis carried out by SPC OFP (Rice and Harley 2012, Bromhead et al 2013, Canaco & Donovan 2014) in recent years showing the effect of wire trace and shark lines on the catch rate of sharks indicates that if the measure is adhered to it should reduce the catch rates of silky and oceanic whitetip sharks.

Of all the CMMs to have been passed the only ones we should see an impact from would be CMM2010-07 which stipulates the 5% fin to carcas ratio, and CMM 2011-04 which prohibits retention of oceanic whitetip. Overall there has been a trend in the purse seine fishery to greater discards and less finning, while retention and escape remain uncommon observations in the purse seine fishery. The largest change in the observations of shark fate in purse seine fisherys came in 2009, the year after CMM2010-07 (rather its predecessor) came into effect. In 2009 the proporiton of sharkse observed finned decreased by half and remained at low levels in the following years. This reduction in finning may be attributable to that CMM. Observations of oceanic white tip sharks in the longline fishery have shown that the CMM is not being strictly followed. Non-negligable proportions of oceanic whitetips are being retained, though there were no observations of oceanic whitetip sharks being finned in 2014. The analysis of this CMM in the purse seine fishery is hampered by the fact that there were no observatoons of oceanic whitetip sharks in 2014 (Figure ??). Proportionally more oceanic whitetip sharks were retained in 2013 (the first year of the CMM) than 2012, With respect to the purse seine fishery,the proportion of oceanic whitetip sharks that

were either finned or discarded increased, but the proportion retained decreased (Figure ??). It seems that this is only partially working.

9 Conclusions

This paper examines data held by the SPC-OFP for longline and purse seine fisheries in the WCPO to make inferences regarding the populations of key shark species in the WCPO. The data sets analysed - observer, logsheet and aggregated data - vary in coverage, representativeness and detail, and in general are not oriented at reporting information on bycatch species such as sharks. Logsheet data at the operational level is most useful in assessing shark catch and catch rates in the WCPO as a whole, however, such data are available in the longline fishery for 41% of the sets in 1995-2014 for the WCPFC Statistical Area as a whole, but there is little or no coverage in the northwest Pacific. Most of the operational-level longline logsheet sets (59

Operational-level coverage in the purse seine fishery is considerably higher (87%), but only 2.5% of purse seine operational-level logsheet sets reported any shark interactions. In both fisheries, most reported shark interactions are not species-specific, given these limitations, aggregated data (5° x 5° square) were used to characterize effort, observer coverage and re-reported shark catch by flag for both longline and purse seine fisheries. For longlines, this analysis showed clear evidence of non-/under-reporting of sharks by several major longline fleets. It also demonstrated that observer coverage is disproportional by region and flag and to an extent month thus they are not entirely representative of the fishery. Although the same non-/under-reporting patterns were observed in the purse seine aggregated data, observer coverage in the purse seine fishery is more representative by region and flag. Nevertheless observer data on purse seine-caught sharks are limited by the physical practicalities of on board sampling and the lower diversity of sharks encountered relative to the longline fishery.

With the exception of 2014 total effort in the longline fleet has increased, through the study period (1995-2014) to approximately 800 million hooks annually with nearly half occurring in regions 3 and 4. With the exception of blue shark the high-CPUE indicated more or less steady trends for all species in all regions, however, this analysis was hampered by the lack of data throughout the region for species. Notably the proportion of high-CPUE cells for blue shark was decreasing throughout the study period for regions 3, 5 and 6 with steady or slightly decreasing trends in region 3 and 4, region 1 was data deficient. Interestingly the percentage of positive sets for blue shark showed the opposite trend, increases in regions 3, 5 and 6 with flat trends in regions 2 and 5. For silky shark there seems to be a slight declining trend in the core regions of 3 and 4, while oceanic whitetip sharks show flat to slightly increasing trends throughout all of the regions. Porbeagle sharks in region 5 and 6 show slightly increasing to stable trends. Mako sharks show slightly increasing trends in region 5 and 6, stable trends in regions 3 & 4 and a slightly decreasing trend in region 2, though data is lacking for years 2012-2014. The proportion of positive sets for thresher sharks showed steady trends throughout the regions, however, region 4 where the majority of threshers were observed in recent years, an increase in the proportion of positive sets was evident. Hammerhead sharks had consistent, near zero proportion of positive sets.

The observed longline catch composition plots illustrate that blue shark continue to dominate the observed catch in most regions. An exception to this pattern is Region 3 where silky sharks, primarily from shallow sets, are the most frequently observed species. Although there are some minor differences in species composition between observed shallow and deep sets in other regions

(e.g. Regions 2 and 4), these may be related to sample representativeness. Note that declining trends in the number of sharks observed in all regions (except region 3) are partially a result of the reduction in observer coverage since 2010. In recent years more silky sharks have been observed in region 3 than prior to 2008, while the proportion of blue sharks observed during 2014 in regions 2-5 is one of the lowest on record. The analysis of observed purse seine shark catch revealed that silky sharks are the most common shark species observed with the majority of the catch occurring in associated sets. In previous years, oceanic whitetip shark was the second-most commonly identified shark in associated sets but this species is now rarely observed. Substantial numbers of sharks caught by purse seines were unidentified prior to 2002-2003.

The biological indicators showed that with a few exceptions (blue shark in region 5) the observed sex ratio in the longline fishery is approximately equal. Sex ratio analysis was not possible for the purse seine fishery. Observed length was investigated by plotting the nominal median length trends and length at maturity at the regional level. This indicated that the majority of the observed hammerhead, silky, thresher, oceanic whitetip and porbeagle sharks were immature. Observed blue shark were mainly immature in regions 5 and 6 and mainly mature in region 2. The results of the length standardization indicate declines in most regions for most species based on a linear model fit to the standardized annual lengths. These results mirror the larger scale population trends in length for the longline Fishery and the population level trends in silky and oceanic whitetip sharks in the purse seine Fishery. Overall the biological indicators showed that by in large the longline fishery is interacting with smaller immature sharks of both sexes. Of all the CMMs to have been passed the only ones we should see an impact from would be CMM2010-07 which stipulates the 5% fin to carcas ratio, and CMM 2011-04 which prohibits retention of oceanic whitetip. Overall there has been a trend in the purse seine fishery to greater discards and less finning, while retention and escape remain uncommon observations in the purse seine fishery. The largest change in the observations of shark fate in purse seine fisherys came in 2009, the year after CMM2010-07 (rather its predecessor) came into effect. In 2009 the proportion of sharks observed finned decreased by half and remained at low levels in the following years. This reduction in finning may be attributable to that CMM. Observations of oceanic white tip sharks in the longline fishery have shown that the CMM is not being strictly followed. Non-negligable proportions of oceanic whitetips are being retained, though there were no observations of oceanic whitetip sharks being finned in 2014. The analysis of this CMM in the purse seine fishery is hampered by the fact that there were no observations of oceanic whitetip sharks in 2014 (Figure ??). Proportionally more oceanic whitetip sharks were retained in 2013 (the first year of the CMM) than 2012, With respect to the purse seine fishery, the proportion of oceanic whitetip sharks that were either finned or discarded increased, but the proportion retained decreased (Figure ??). It seems that this is only partially working.

10 Research Recommendations and Management Implications

This indicator analysis provides informative insights into silky shark, oceanic whitetip, mako shark, blue shark, whale sharks and porbeagle sharks, but is somewhat limited in the amount of inference possible for hammerhead and thresher sharks largely due to lack of data. These species are not commonly caught in the primary fisheries in the WCPO, and are historically not well reported. Increased observer monitoring is vital to the continued understanding of the less common key shark species. Specific research recommendations include:

- Research to assess the discrepancy between shark reporting in logbooks and observer data.
- Silky shark and oceanic whitetip sharks have been declining under recent fishing pressure, and likely maintain their overfished status. The last assessment for both of these species used data from 1995-2009, at this point we could easily add another 5 years of data to these assessments, though this would be most useful for silky shark to understand how its stock status has changed in recent years in conjunction with the new CMM's. If the population of oceanic whitetip shark doubled or halved, it would still be overfished.
- The authors recommend that stock assessments be scheduled for blue sharks in the south Pacific, mako sharks, oceanic whitetip sharks (in the WCPO and Pacific wide) and silky sharks within the next five years.
- As the assessments generally start well into the catch histories of these species (e.g. the longline fisheries began in the 1950s but the assessment periods start in the 1990s), an investigation the initial depletion levels for assessed shark stocks should be undertaken. This would include developing catch histories for these species.
- Catch histories for all species, and an analysis of species composition of the catch for hammerhead and thresher sharks would also be informative and make some informative analyses possible in future.
- Assessing overall mortality rates is an important component of assessing the stocks. We currently have no informative data on post-release mortality rates of silky, oceanic whitetip and whale sharks. As all three species have non-retention management arrangements post-release survival rates are essential for monitoring the effectiveness of these measures. This work will also require an update to the way the observers collect release information and an update of the observer forms and data collection procedures will be required.
- The authors recommend that this be undertaken again in 2-3 years with a stock assessment for BSH in the south Pacific, and another silky shark assessment in the Indian.

Acknowledgements

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A Figures

A.1 Distribution Indicator Analyses: Figures

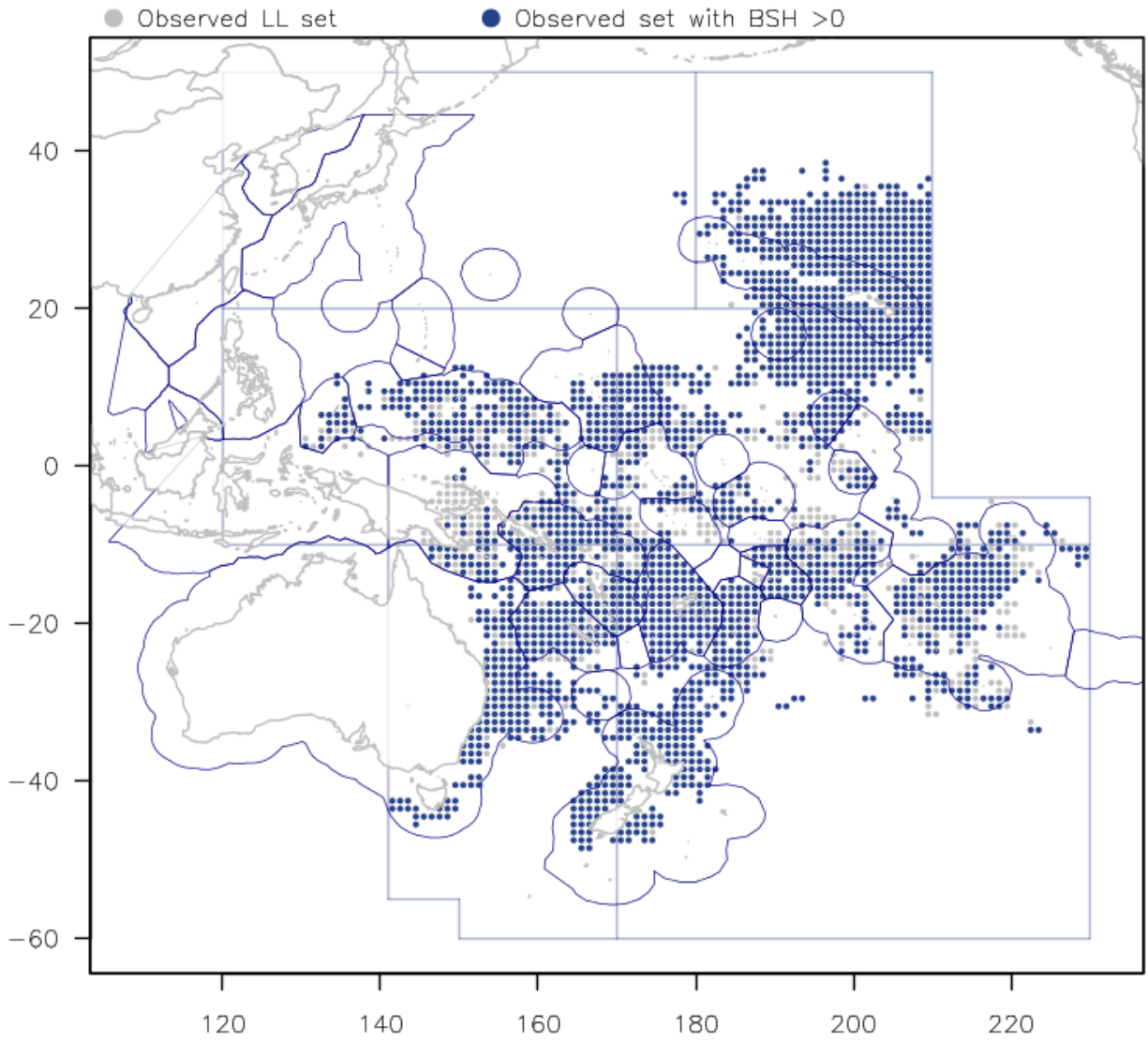


Figure 9: for the WCPFC convention area.

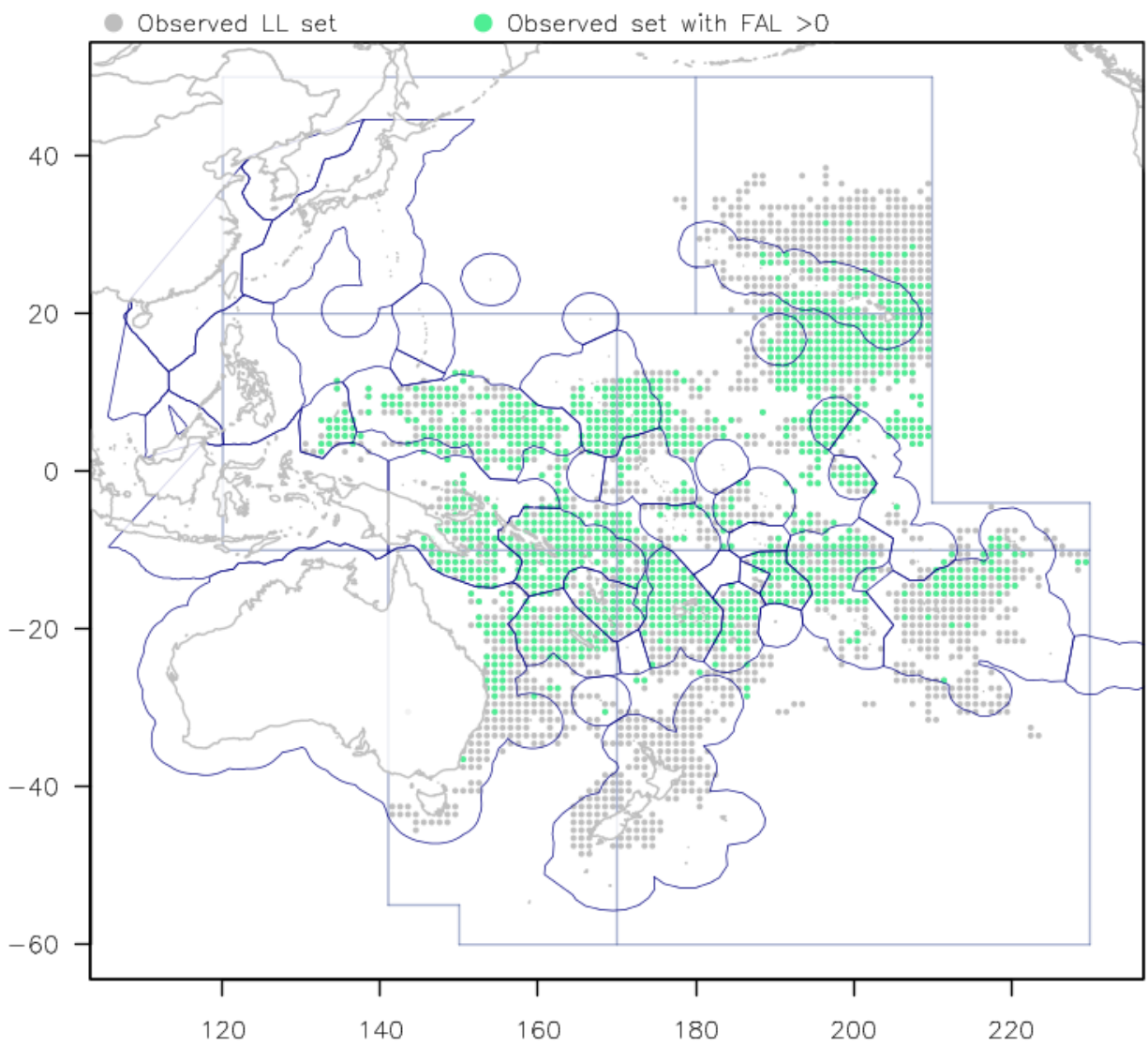


Figure 10: for the WCPFC convention area.

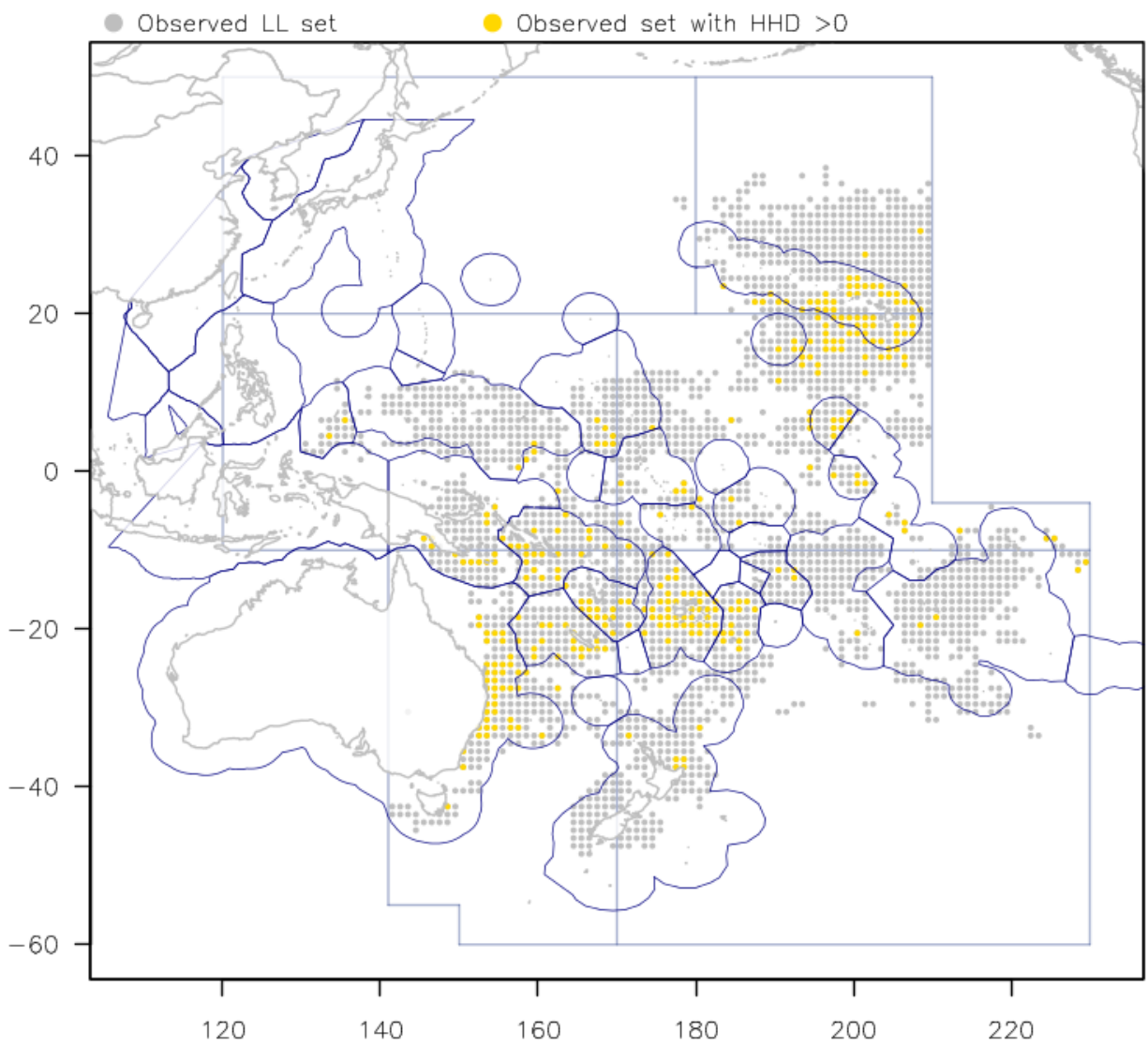


Figure 11: for the WCPFC convention area.

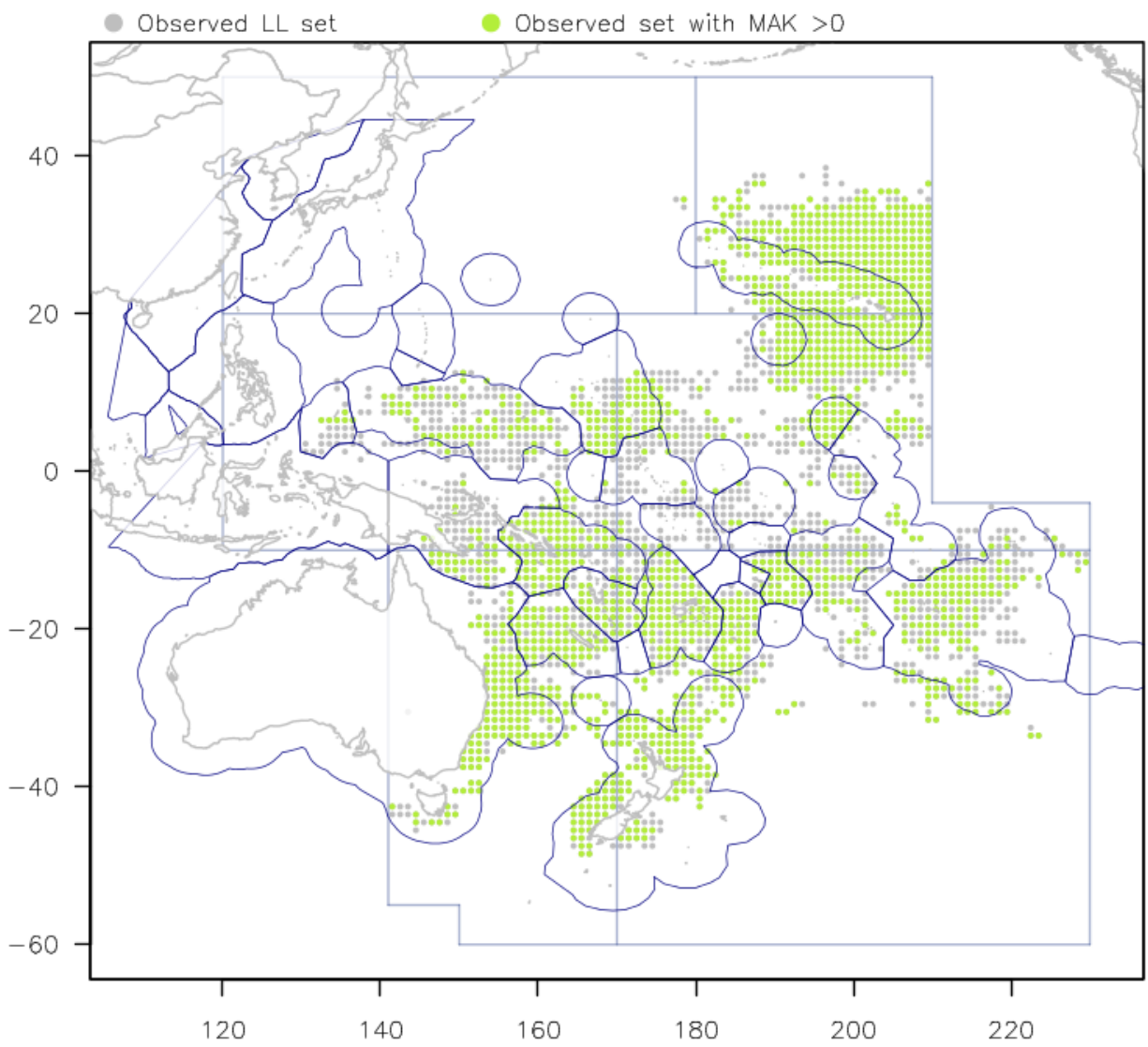


Figure 12: for the WCPFC convention area.

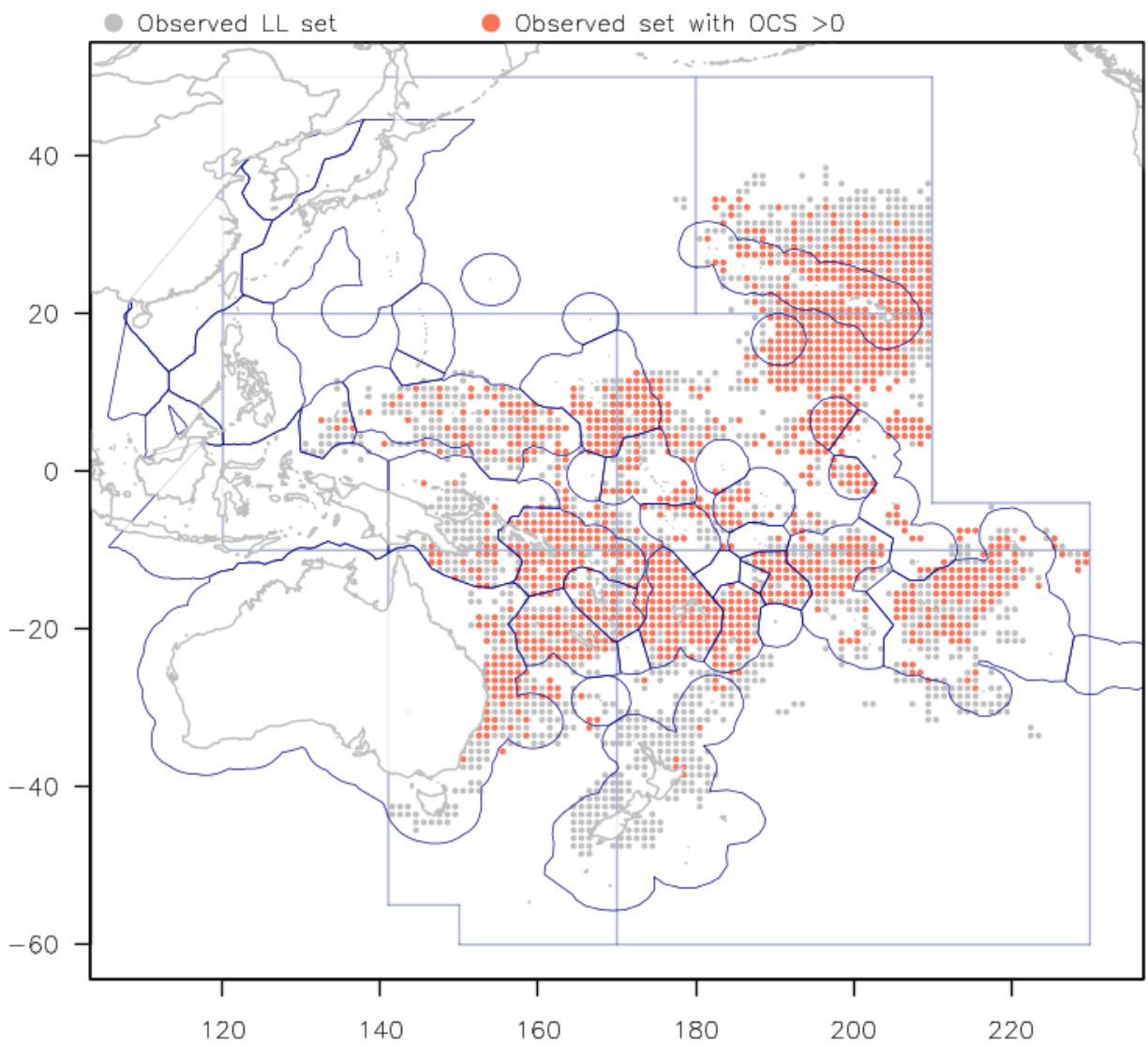


Figure 13: for the WCPFC convention area.

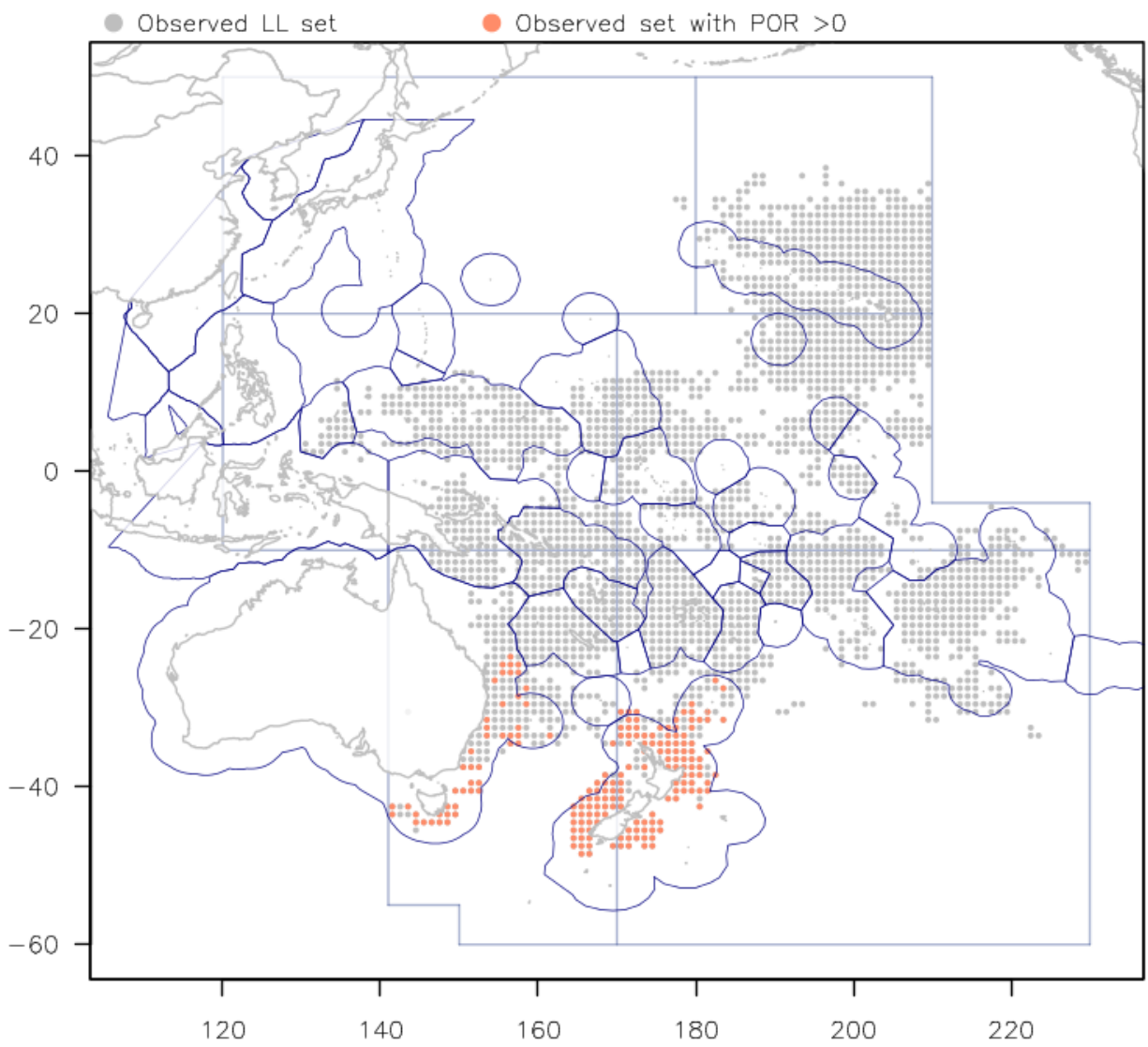


Figure 14: for the WCPFC convention area.

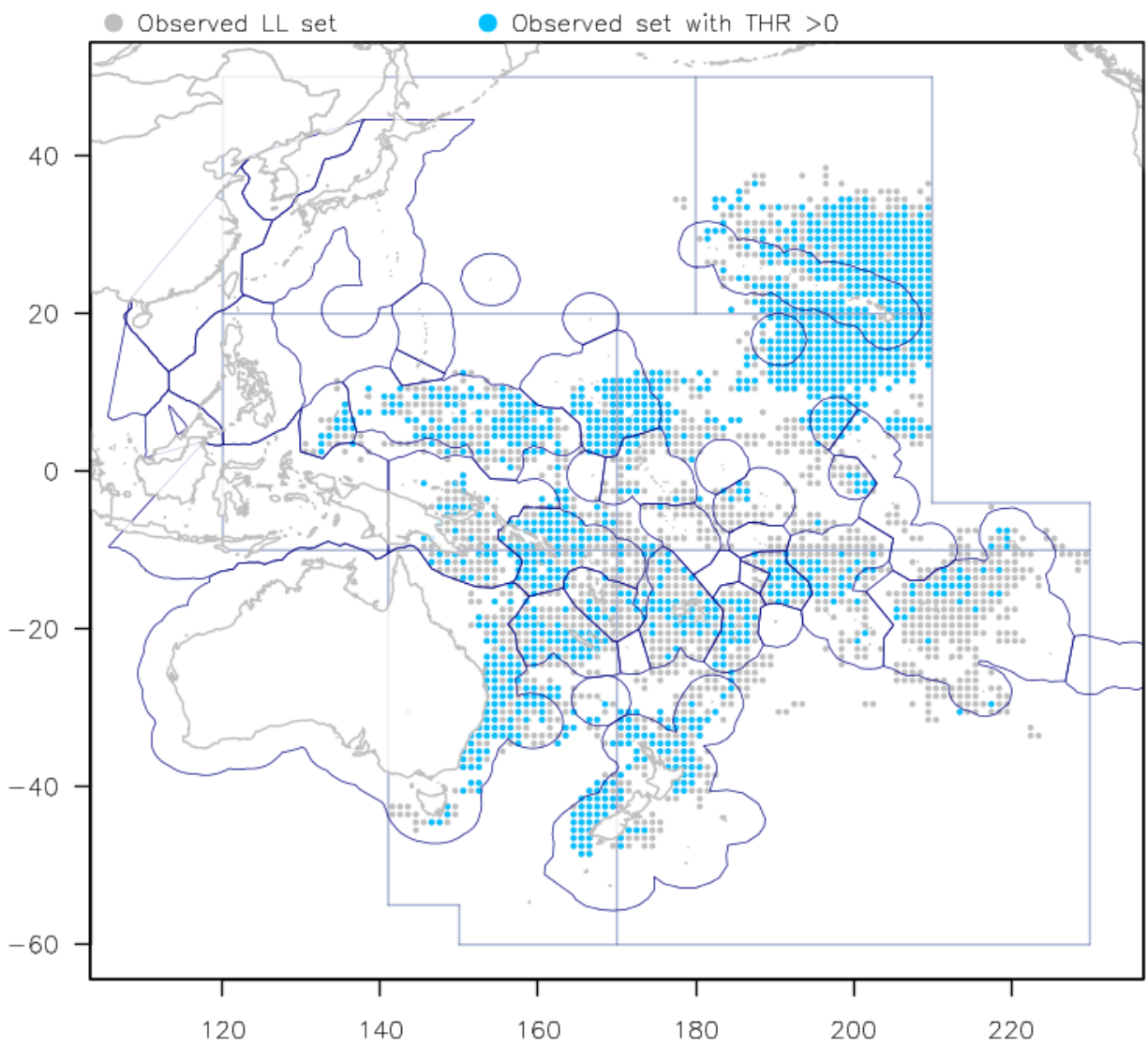


Figure 15: for the WCPFC convention area.

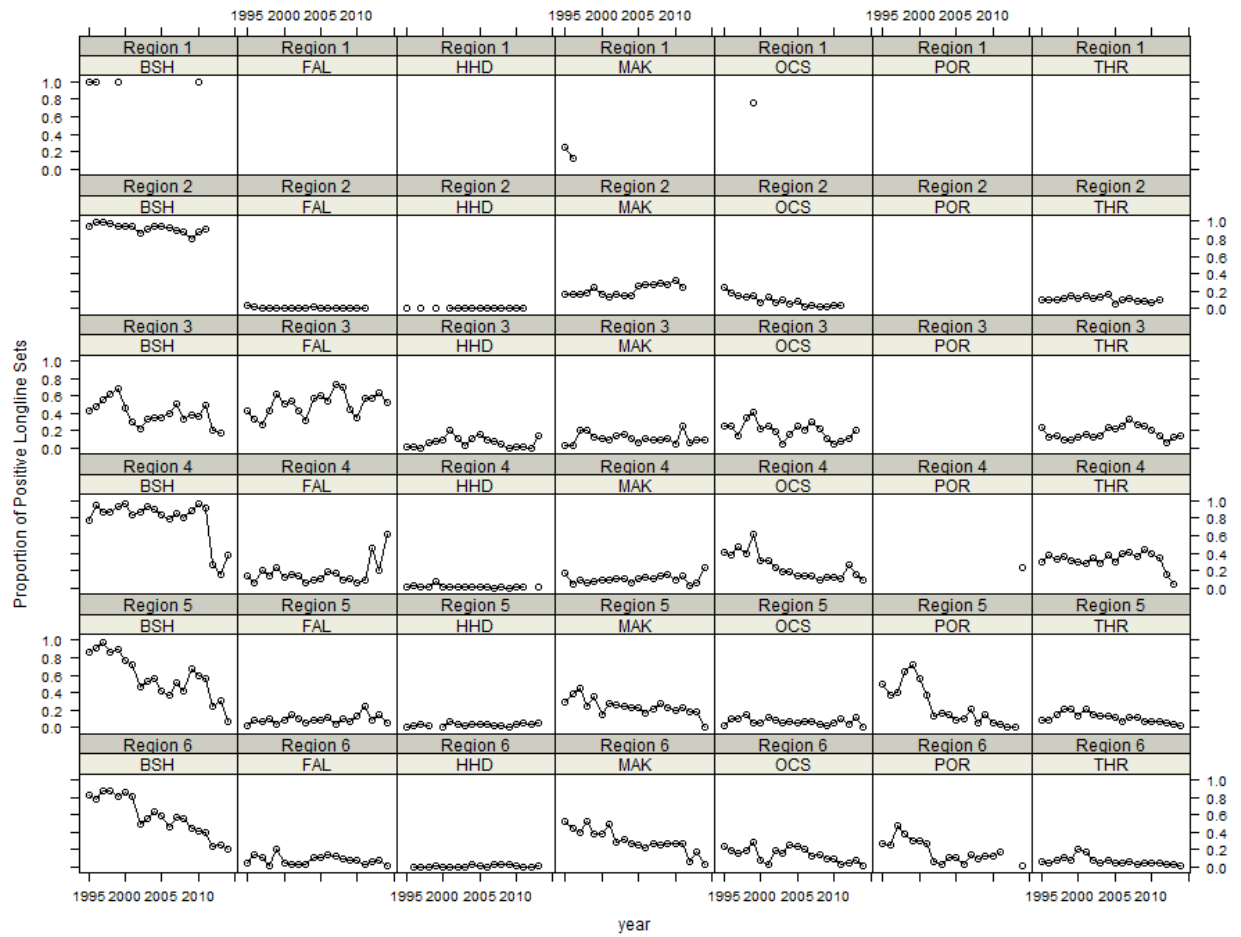


Figure 16: for the WCPFC convention area.

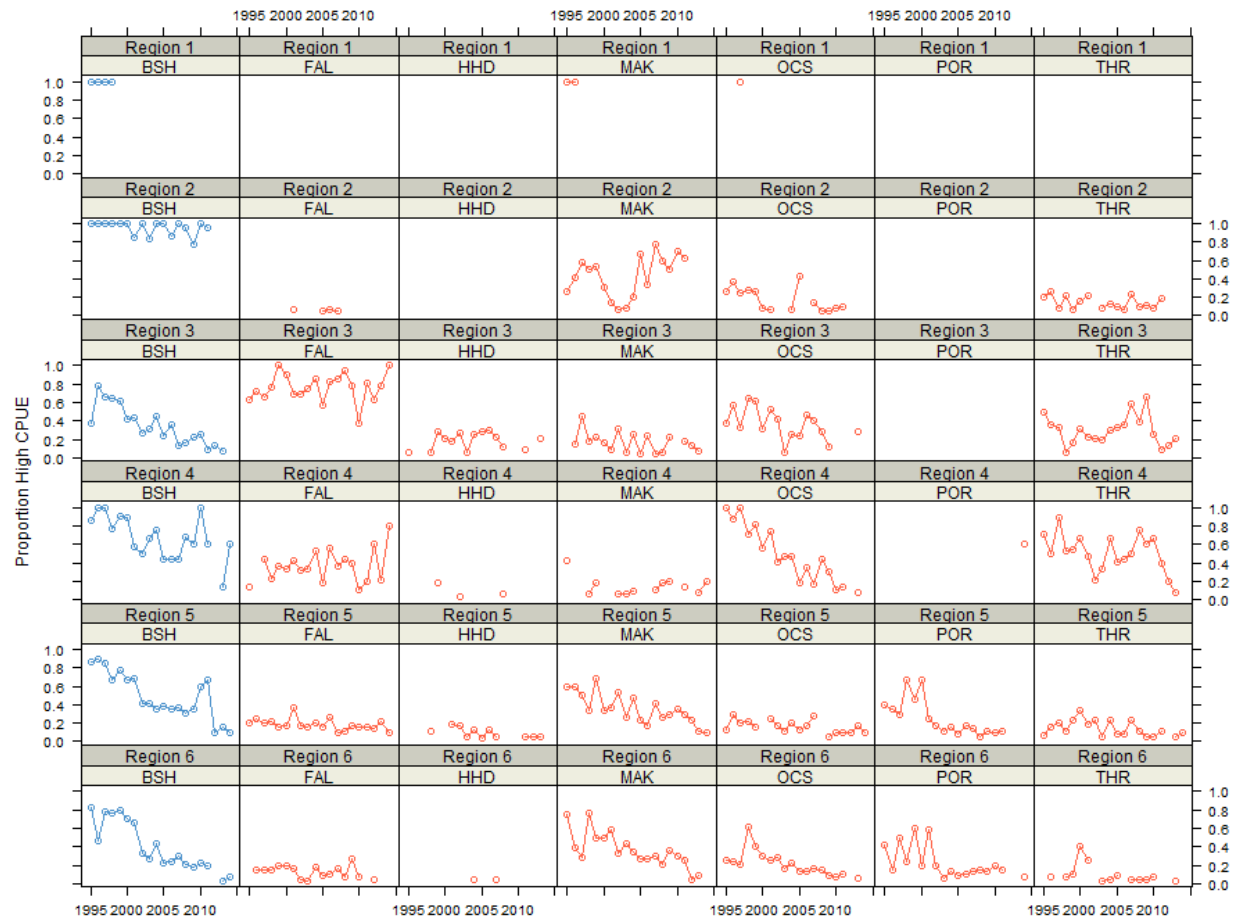


Figure 17: for the WCPFC convention area.

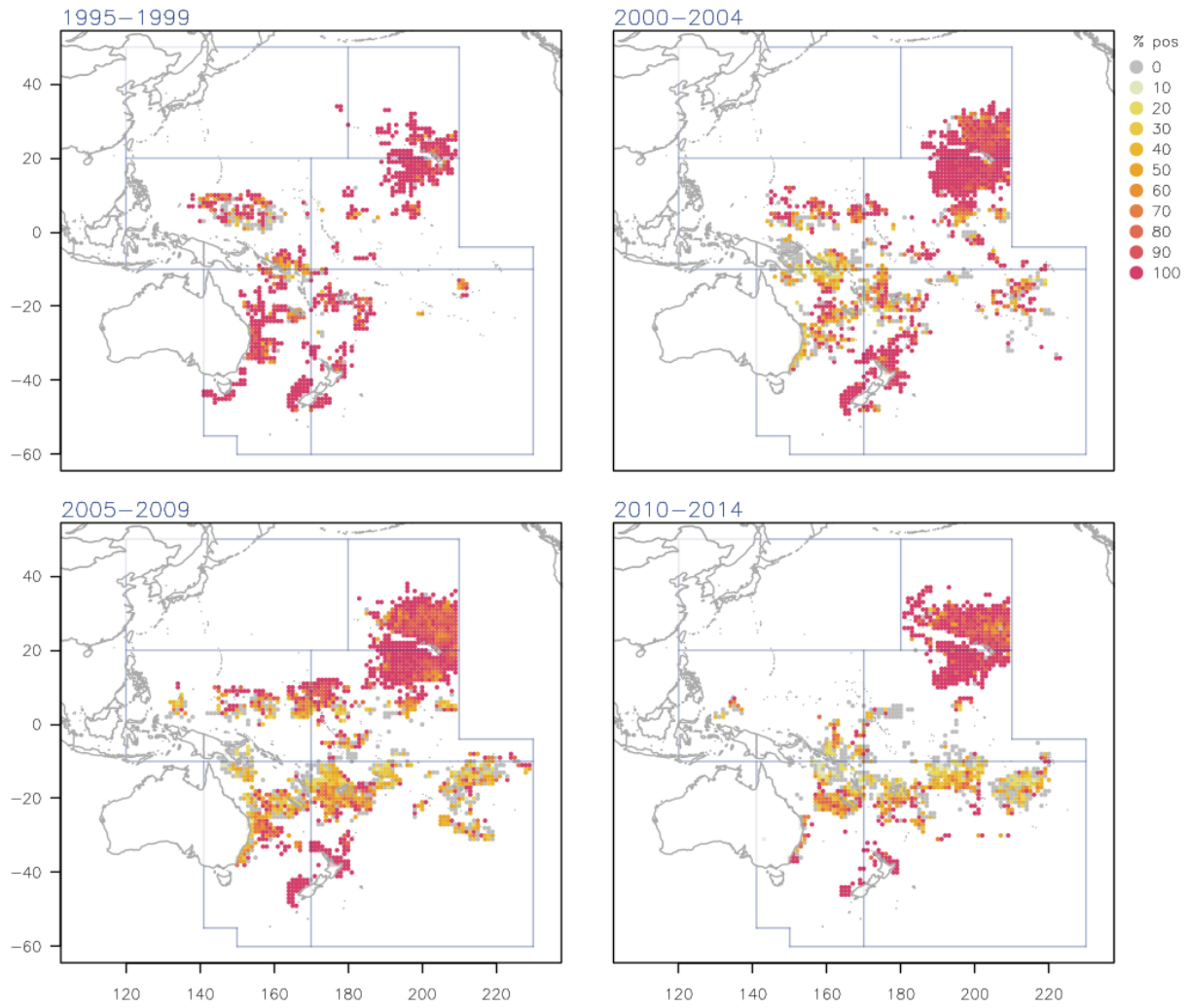


Figure 18: for the WCPFC convention area.

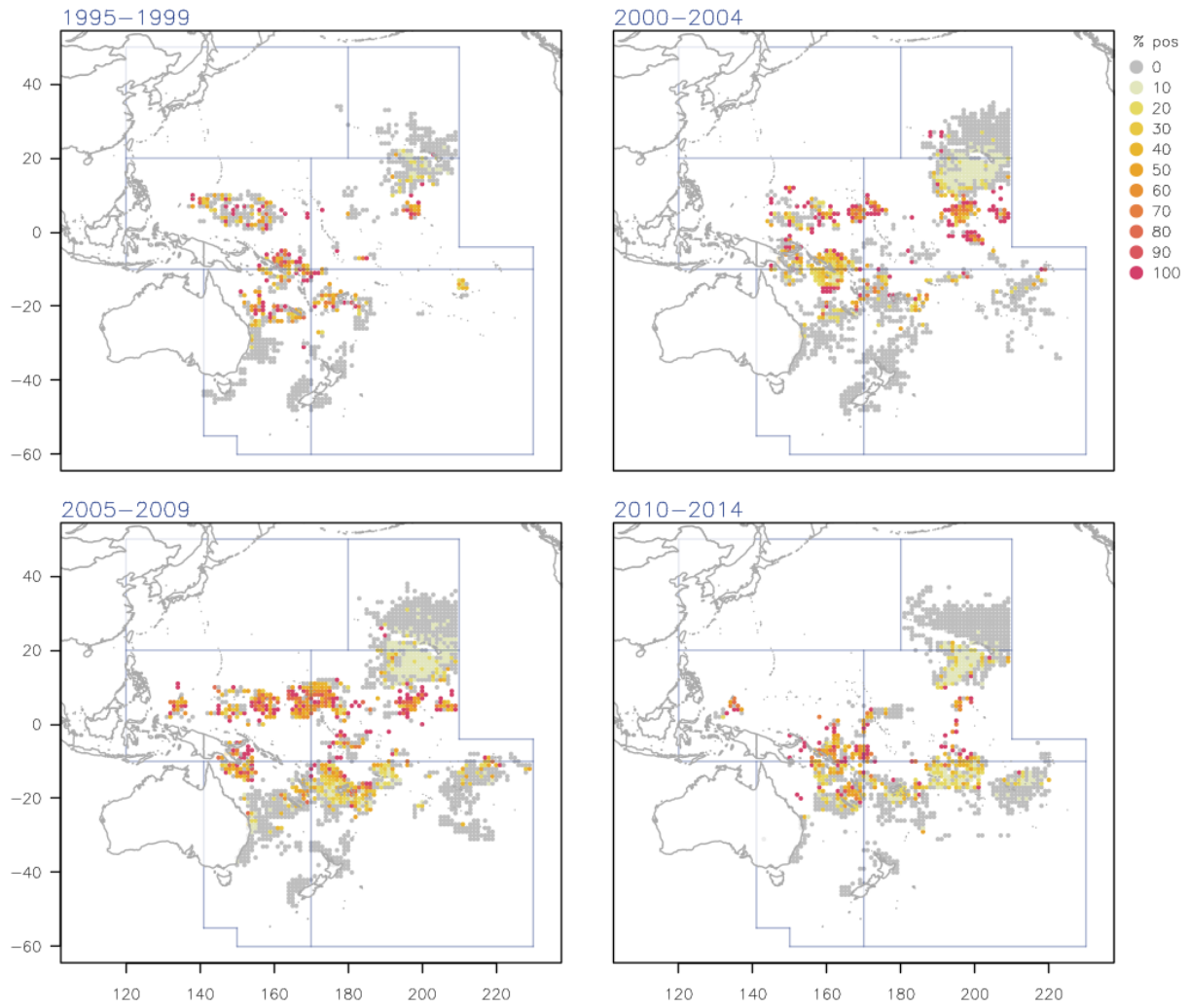


Figure 19: for the WCPFC convention area.

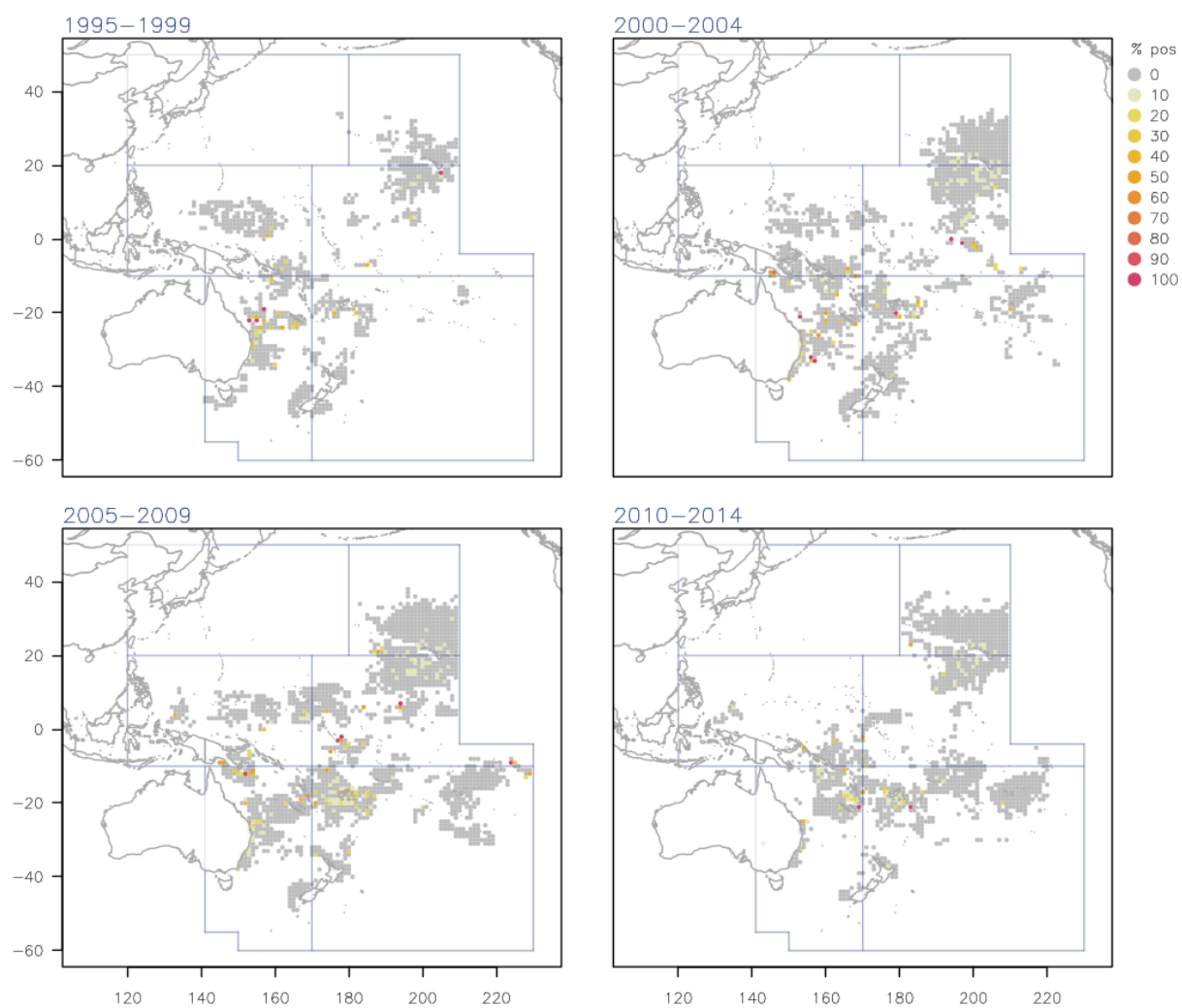


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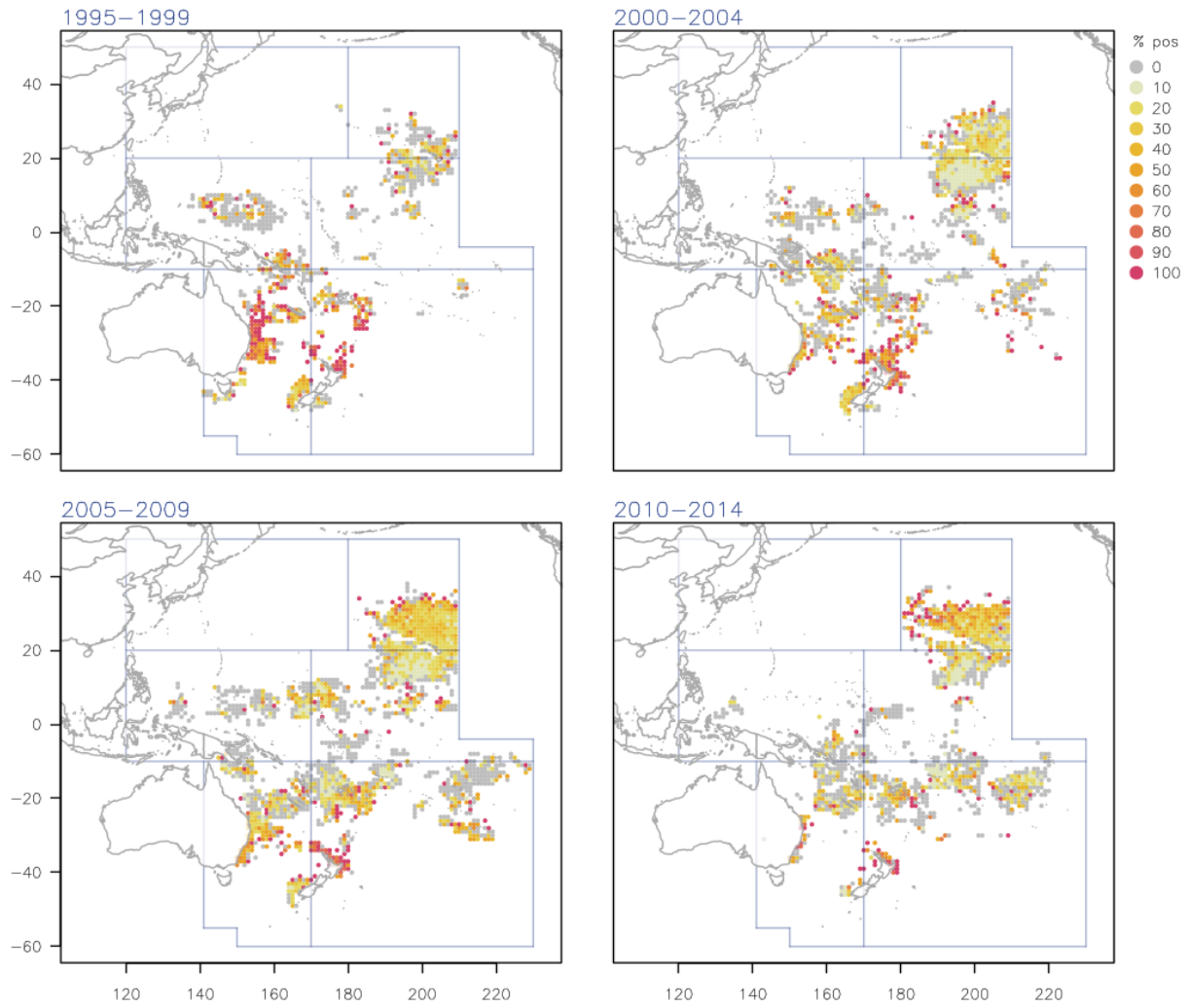


Figure 21: for the WCPFC convention area.

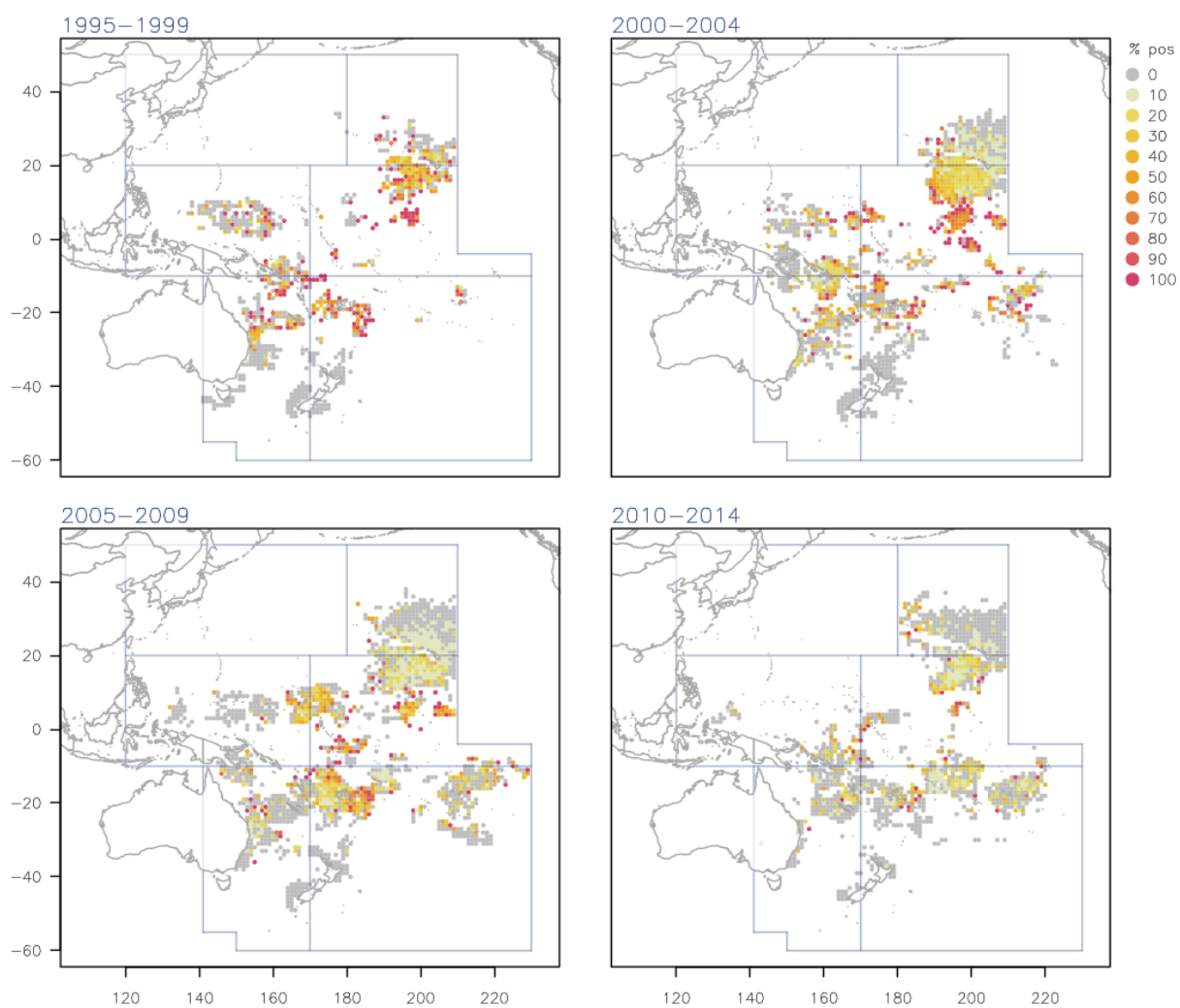


Figure 22: for the WCPFC convention area.

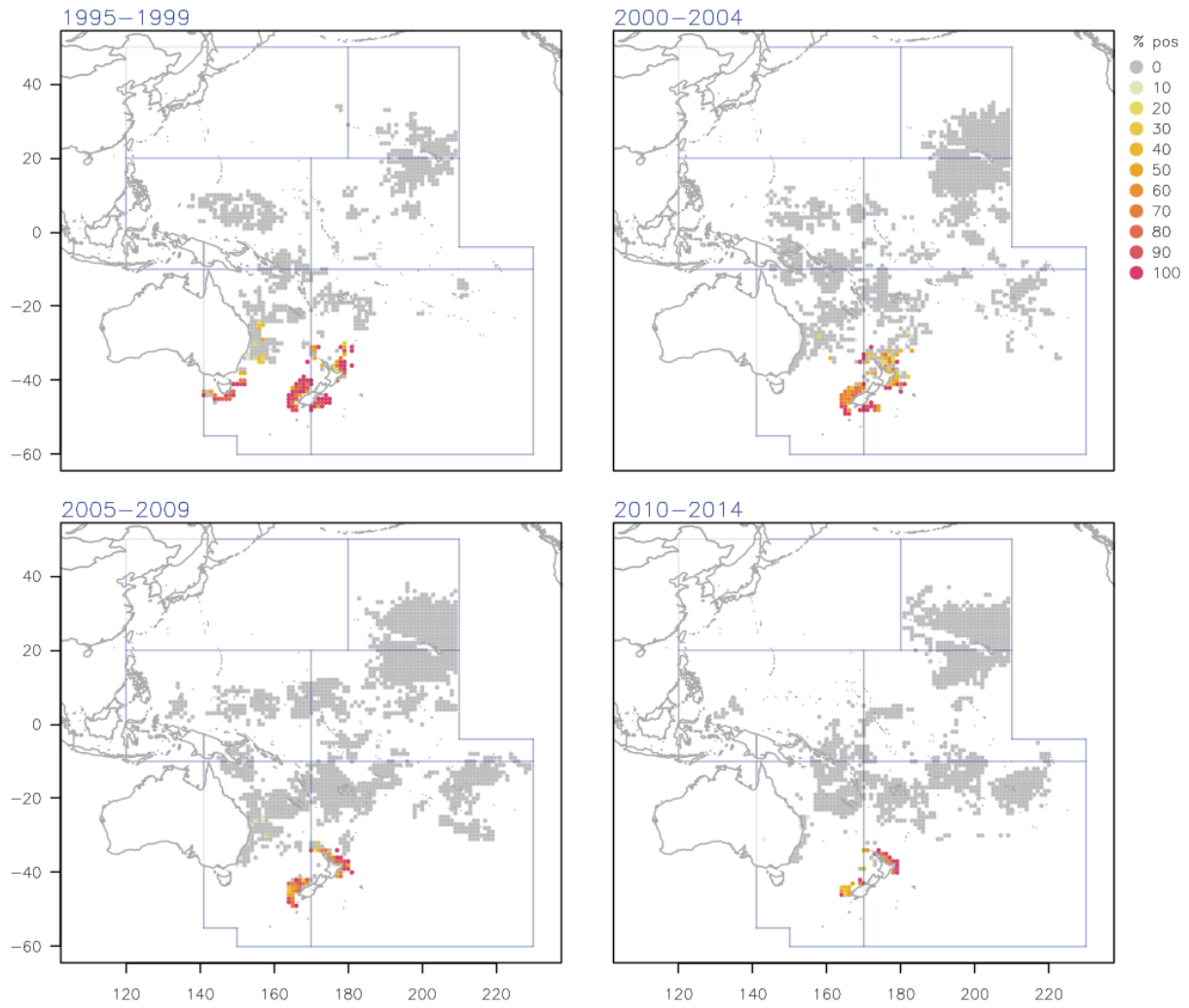


Figure 23: for the WCPFC convention area.

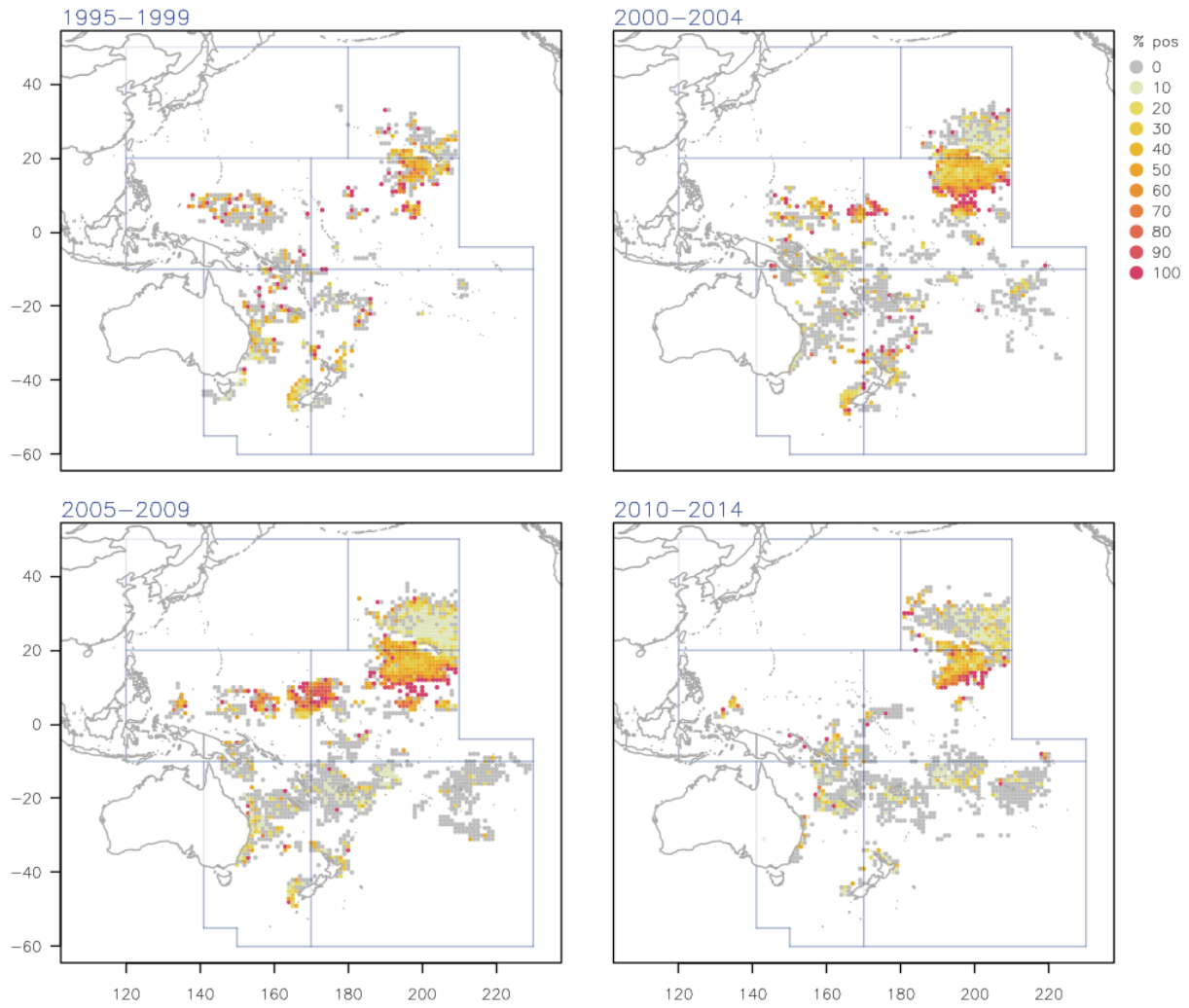


Figure 24: for the WCPFC convention area.

A.2 Species Composition Indicator Analyses: Figures

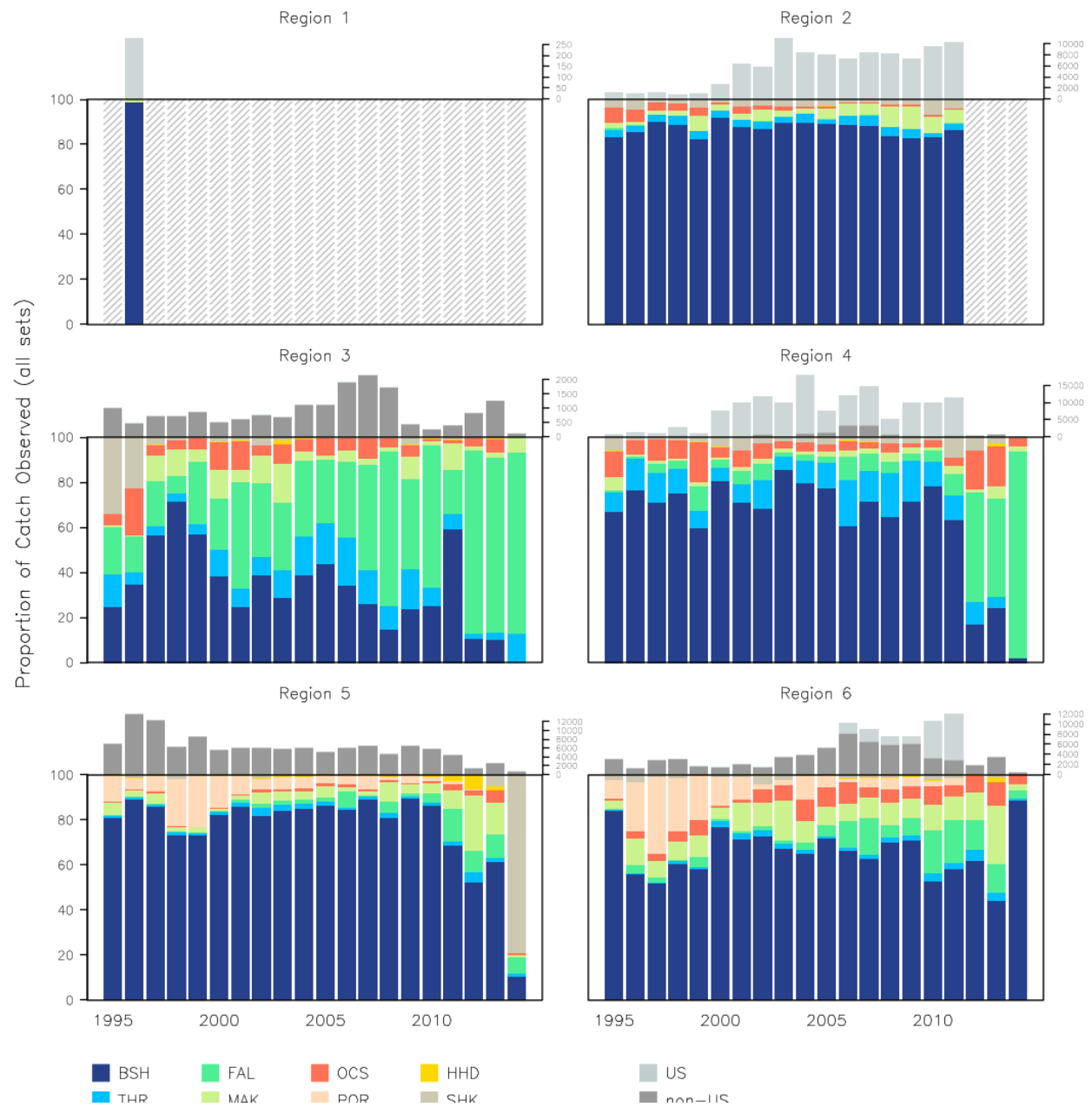


Figure 25: for the WCPFC convention area.

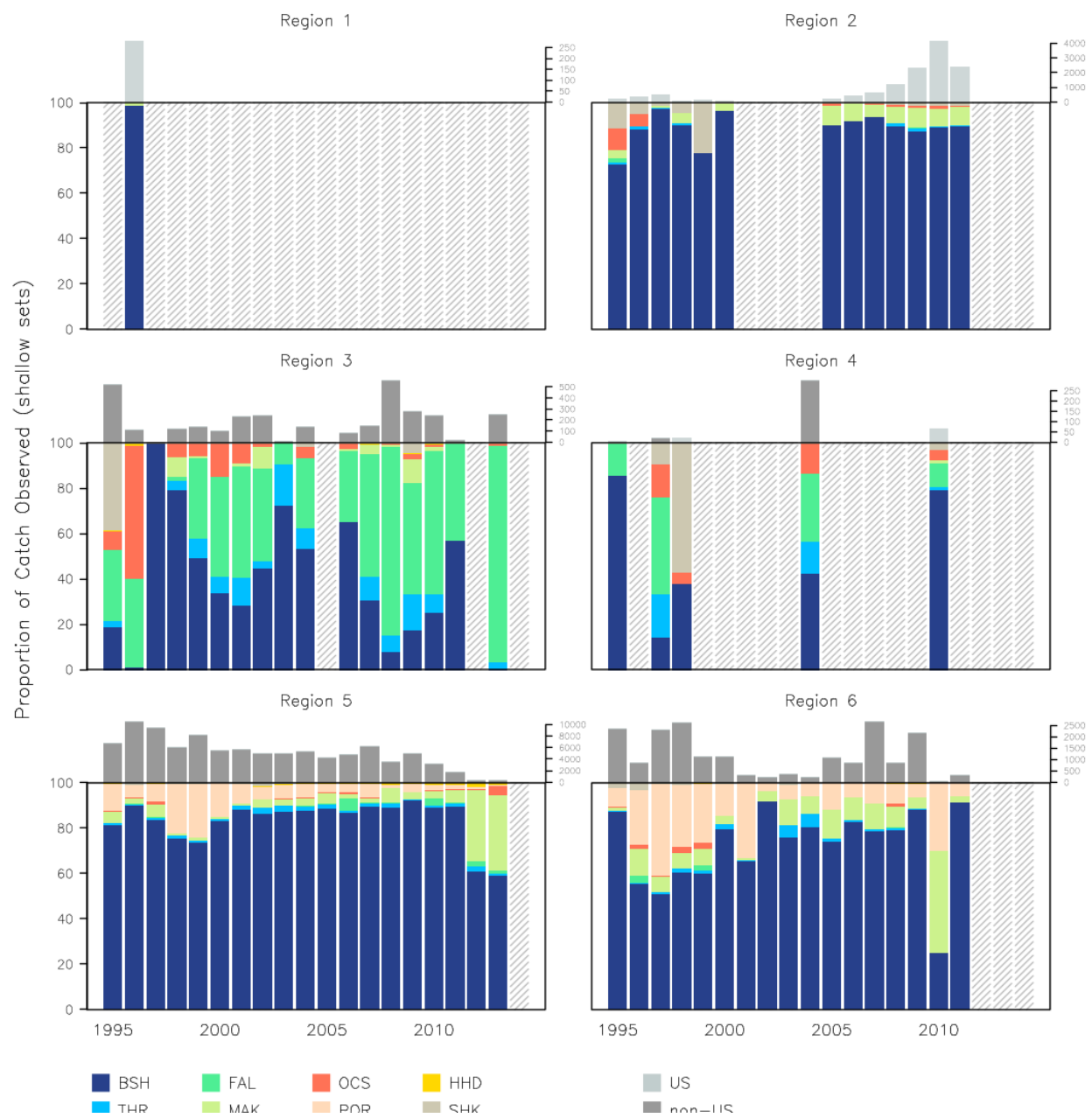


Figure 26: for the WCPFC convention area.

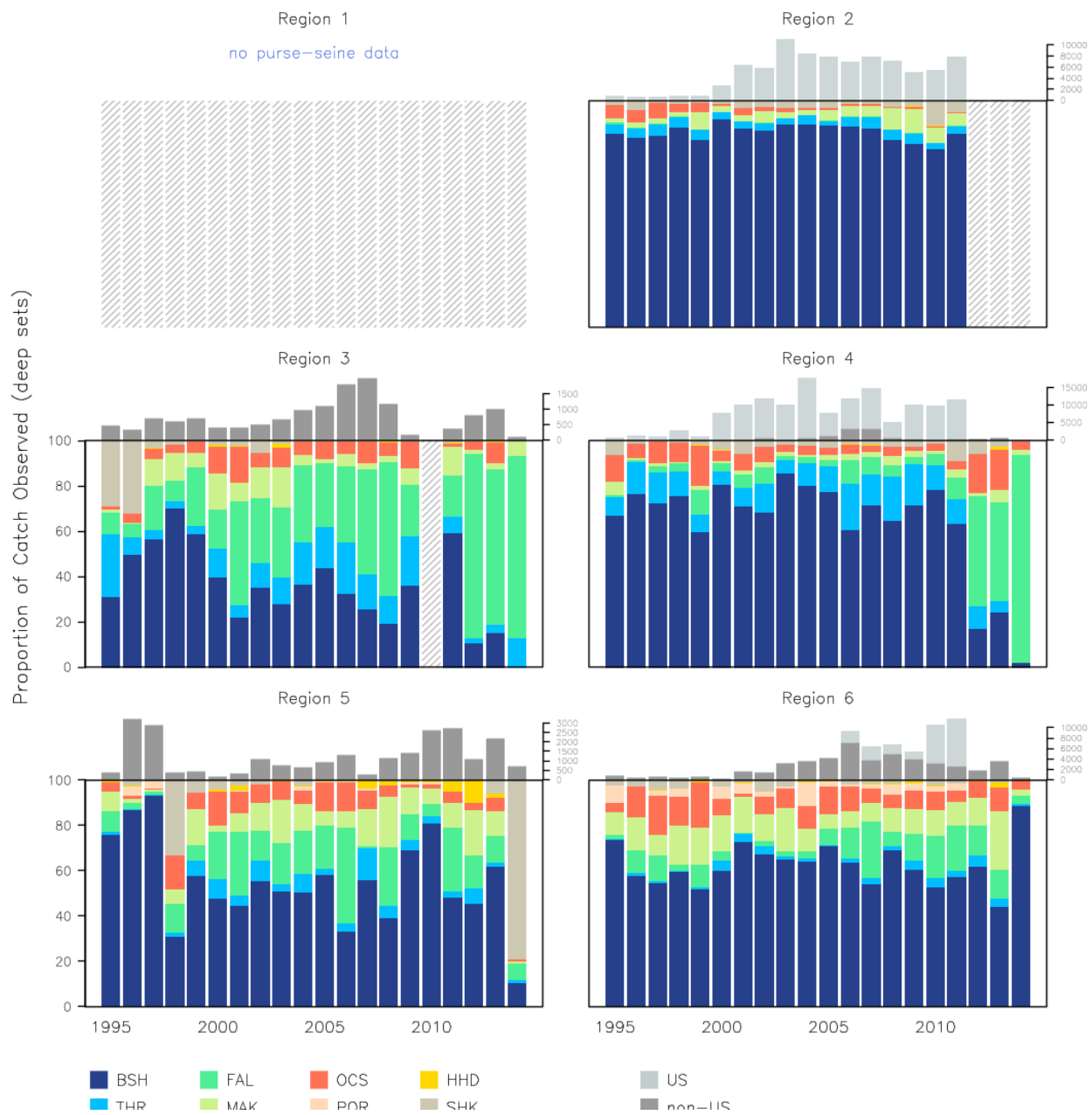


Figure 27: for the WCPFC convention area.

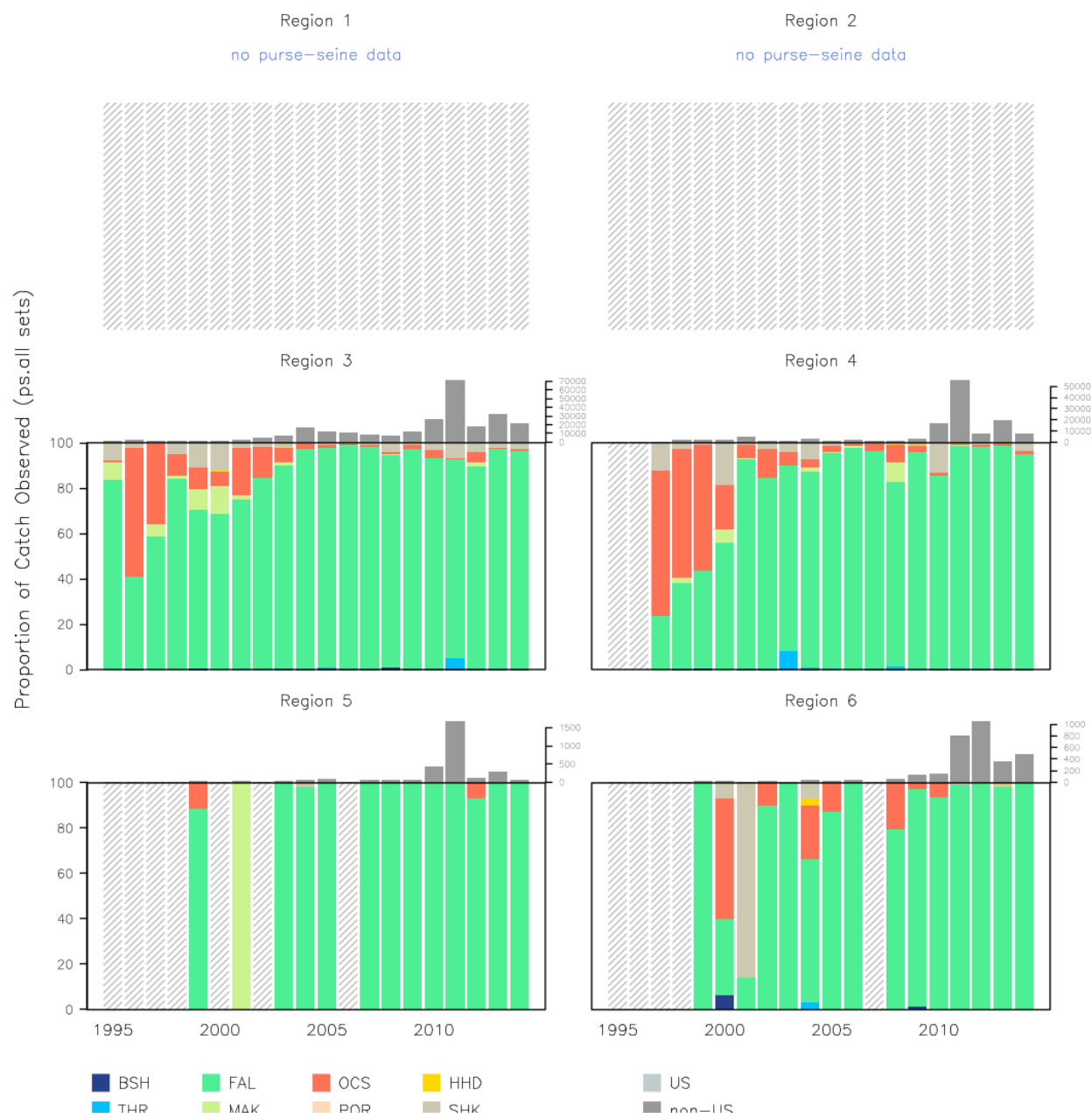


Figure 28: for the WCPFC convention area.

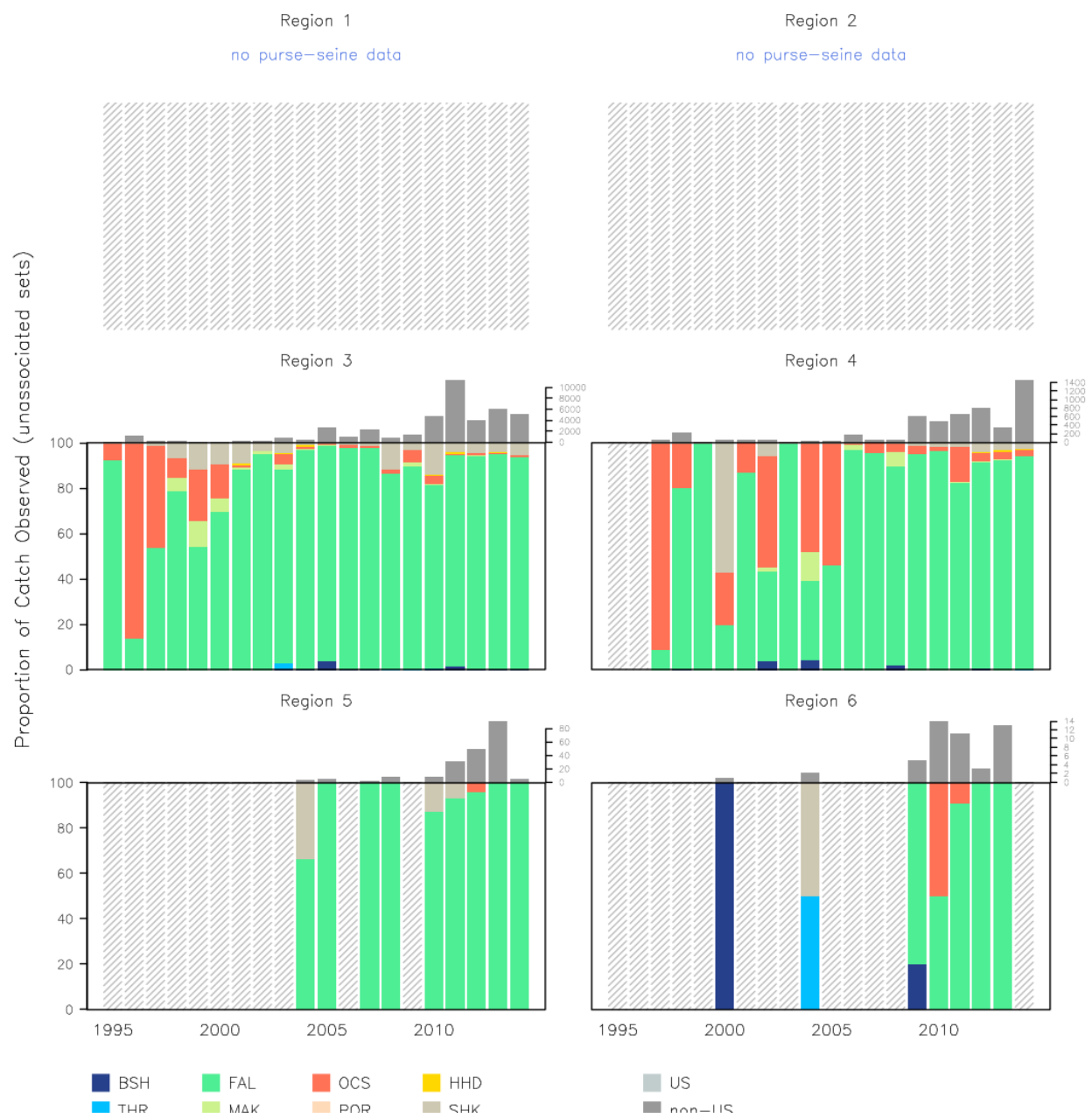


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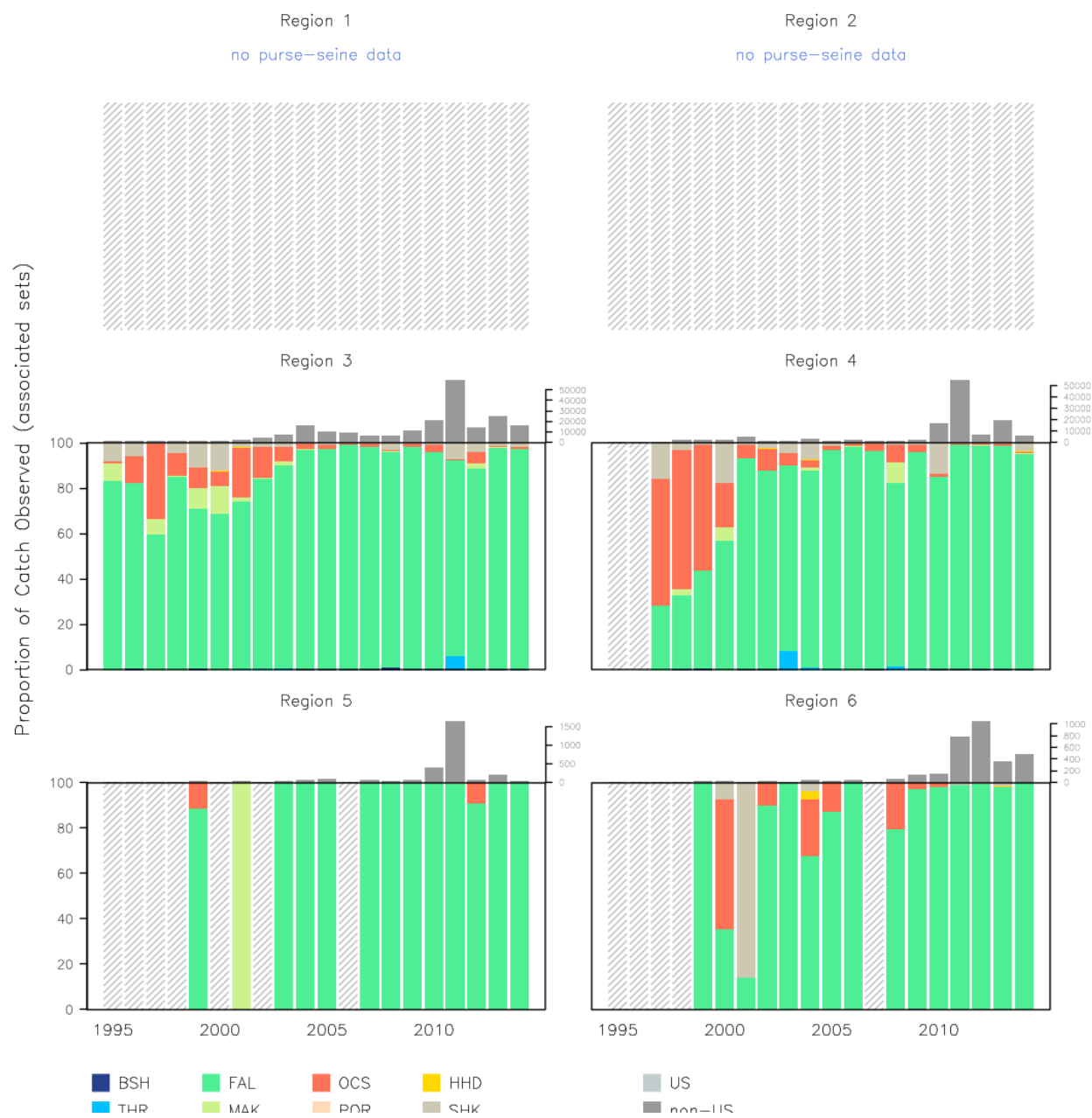


Figure 30: for the WCPFC convention area.

A.3 CPUE Indicators. Model diagnostics and extra plots

Blue Shark model diagnostics and extra plots

Silky Shark model diagnostics and extra plots

Oceanic Whitetip Shark model diagnostics and extra plots

Thresher Shark model diagnostics and extra plots

B Tables

Table 11: Sources of information used in defining length at maturity and converting between total length (TL) and fork length (FL) measurement standards. TL measurements which fell outside the range of data used to construct the FL-TL conversion equations were excluded from the analysis.

Species	Length at Maturity	Reference(s)	Conversion
Blue	Males: 168 FL (200 TL)		
Females: 168 FL (200 TL)	Nakano and Stevens (2008)	$FL=0.8313(TL)+1.39$	Skomal and
Mako (shortfin mako)	Males: 180 FL		
Females: 275 FL	Francis and Duffy (2005)	$FL=0.911(TL)+0.821$	Francis and
Oceanic whitetip	Males: 138 FL (168 TL)		
Females: 144 FL (175 TL)	Seki et al. (1998)	$FL = 0.822(TL)+0$	Seki et al. (
Silky	Males: 175 FL (212 TL)		
Females: 173 FL (210 TL)	Joung et al. (2008)	$FL = 0.8388(TL)-2.651$	Kohler, Cas
Thresher (bigeye thresher)	Males: 168 FL (270 TL)		
Females: 203 FL (332 TL)	Smith et al. (2008)	$FL = 0.5598(TL) + 17.666$	Kohler, Cas
Hammerhead (scalloped hammerhead)	Males: 153 (198 TL)		
Females: 163 FL (210 TL)	Chen et al. 1990	$FL = 0.7756(TL) -0.3132$	Kohler et al.
Porbeagle	Males: 145 FL		
Females: 175 FL	Francis and Duffy (2005)	$FL = 0.893(TL) -6.943$	Francis and

Table 12: Percent of effort observed in the longline fishery by region.

	1	2	3	4	5	6
1995	0.00	0.01	0.00	0.00	0.03	0.00
1996	0.00	0.02	0.00	0.00	0.03	0.00
1997		0.02	0.00	0.00	0.03	0.01
1998		0.02	0.00	0.00	0.02	0.01
1999	0.00	0.02	0.00	0.00	0.02	0.00
2000		0.04	0.00	0.01	0.02	0.00
2001		0.15	0.00	0.02	0.02	0.00
2002		0.13	0.00	0.02	0.03	0.00
2003		0.11	0.00	0.01	0.02	0.01
2004		0.06	0.00	0.02	0.03	0.01
2005		0.13	0.00	0.01	0.02	0.01
2006		0.10	0.00	0.03	0.02	0.02
2007		0.14	0.00	0.03	0.02	0.01
2008		0.16	0.00	0.01	0.02	0.01
2009		0.16	0.00	0.02	0.03	0.01
2010	0.00	0.16	0.00	0.01	0.02	0.01
2011		0.12	0.00	0.01	0.02	0.01
2012			0.00	0.00	0.01	0.01
2013			0.00	0.00	0.02	0.02
2014			0.00	0.00	0.02	0.00

Table 13: Percent of Logsheets reporting sharks to species, longline fishery by region.

	Log%Report_Reg1	Log%Report_Reg2	Log%Report_Reg3	Log%Report_Reg4	Log%Report_Reg5	Log%Report_Reg6
1995			0.30	0.08	0.49	0.34
1996			0.26	0.14	0.47	0.35
1997			0.30	0.24	0.49	0.37
1998	0.00	0.00	0.27	0.13	0.33	0.28
1999		0.00	0.25	0.05	0.36	0.23
2000		0.00	0.28	0.07	0.37	0.32
2001		0.19	0.28	0.10	0.38	0.36
2002	0.00	0.31	0.48	0.10	0.39	0.43
2003	0.14	0.30	0.50	0.19	0.41	0.45
2004	0.24	0.31	0.47	0.24	0.45	0.55
2005	0.11	0.30	0.33	0.29	0.49	0.60
2006	0.26	0.55	0.37	0.18	0.49	0.56
2007	0.41	0.71	0.38	0.40	0.50	0.59
2008	0.23	0.75	0.41	0.45	0.45	0.55
2009	0.37	0.69	0.43	0.45	0.45	0.55
2010	0.24	0.74	0.50	0.61	0.46	0.52
2011	0.37	0.74	0.58	0.59	0.45	0.48
2012	0.55	0.71	0.35	0.42	0.35	0.42
2013	0.63	0.70	0.50	0.49	0.29	0.39
2014	0.90	0.76	0.57	0.58	0.19	0.26

Table 14: Millions of hooks fished in longline fishery by region.

	Hks_Reg1	Hks_Reg2	Hks_Reg3	Hks_Reg4	Hks_Reg5	Hks_Reg6
1995	97.10	24.10	240.00	127.00	46.50	49.50
1996	107.30	15.90	227.70	110.40	38.70	51.00
1997	102.50	16.30	220.30	100.40	46.10	55.40
1998	96.00	18.60	238.20	140.30	50.70	75.10
1999	102.00	21.10	305.10	148.50	51.20	81.10
2000	102.00	19.10	299.10	170.80	50.20	84.50
2001	190.80	14.70	345.40	160.30	49.80	124.10
2002	102.50	22.70	360.10	215.40	67.90	161.50
2003	107.60	31.10	323.10	195.70	78.20	190.30
2004	142.60	43.90	298.10	244.10	68.80	177.80
2005	130.80	40.90	176.30	202.90	65.90	144.50
2006	154.20	40.90	201.50	170.60	61.10	141.90
2007	204.80	34.80	256.20	184.50	52.40	125.50
2008	203.80	36.90	228.10	190.30	73.50	143.30
2009	181.40	34.70	326.00	163.60	60.00	203.50
2010	158.50	27.10	228.70	186.60	86.80	184.30
2011	167.30	38.20	274.50	221.50	90.30	186.70
2012	147.10	36.90	313.30	246.70	103.90	221.40
2013	154.80	31.10	290.30	205.50	89.10	224.20
2014	119.10	35.10	251.50	171.00	60.40	153.80