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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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Notes by Laura
Missions for Joel
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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. Mention study period chosen here 1995-2014 .

Add table of species names

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. They generally follow 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

Adjust section numbers for whale shark

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 5), 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 6), 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 - NO SUCH TABLE CURRENTLY?!?). 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. We note that the current bigeye tuna assessment utilizes a set of regions that differs from those used here, however as the change mostly consisted of subdividing a few of the large regions, and to maintain comparability with previous analyses, we opted to work with the six-region set as is.

2.1 Longline Fishery Data

Longline fishing effort in the WCPO has increased steadily over the study period (1995-2014) to approximately 800 million hooks, with nearly half of the effort occurring in Regions 3 and 4 (Table 7). 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 (**?**); 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 (5° × 5° 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.

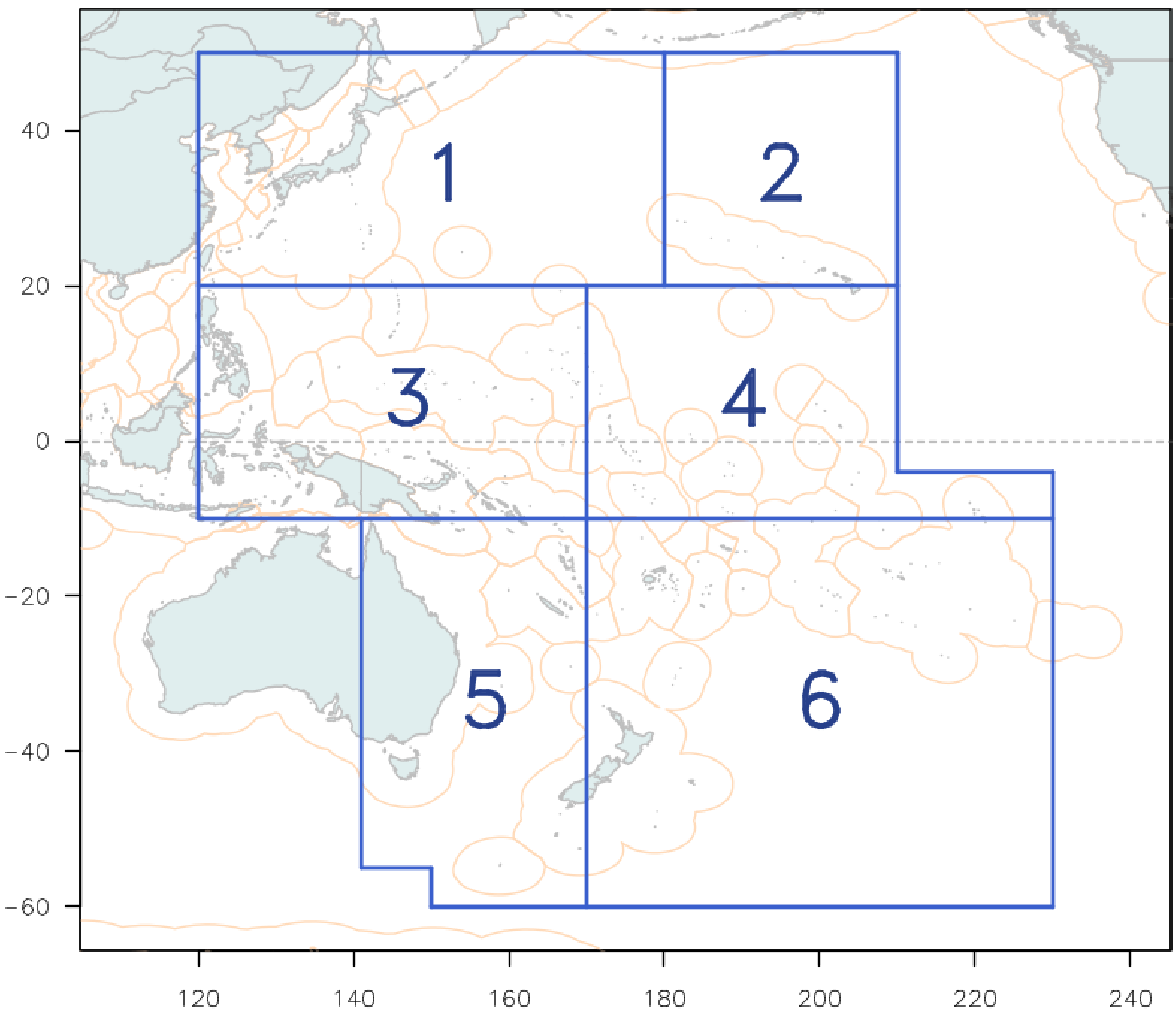


Figure 1: Map of WCPO and regions used for the analysis.

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 much 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 number of sets 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).

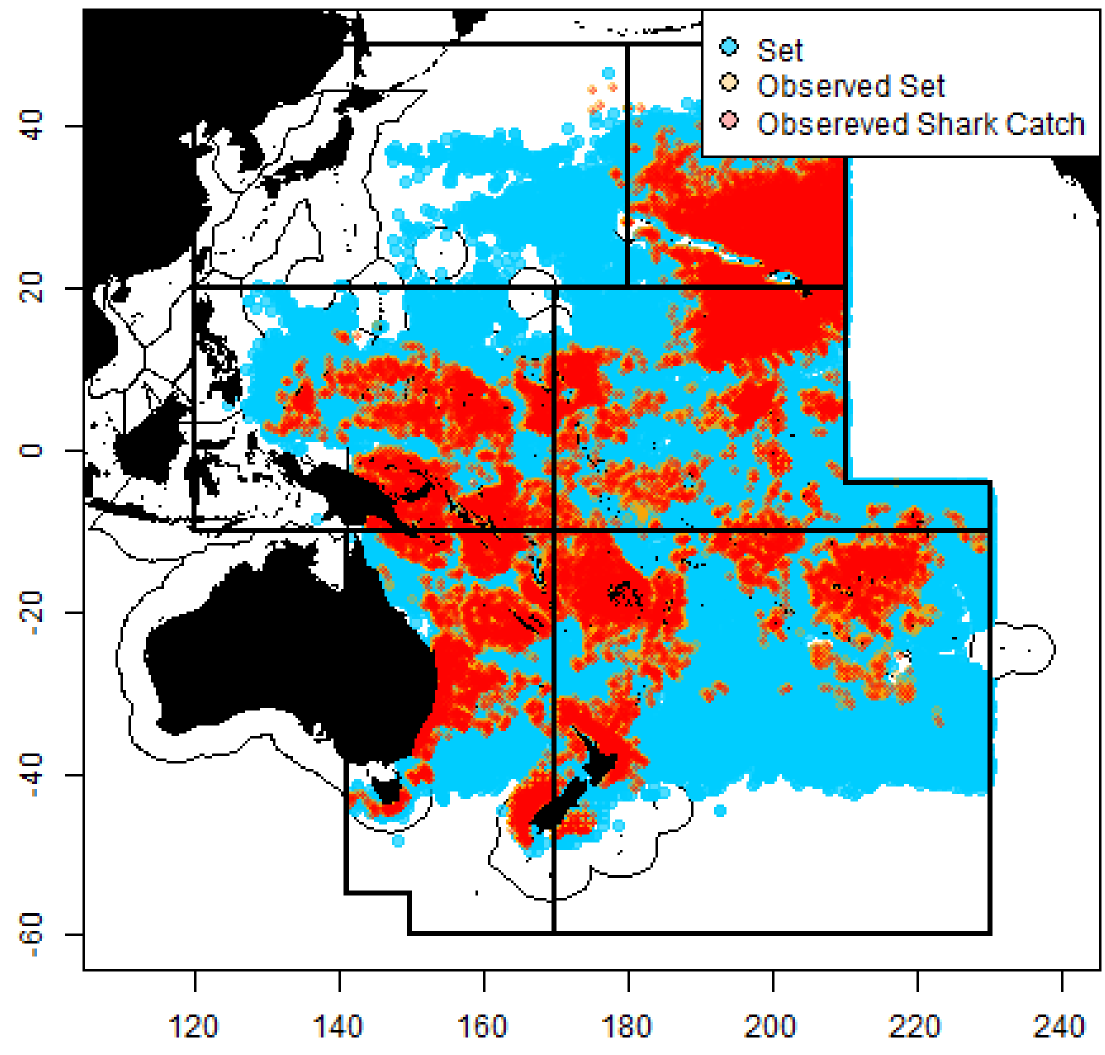


Figure 2: Map of WCPO and observed effort.

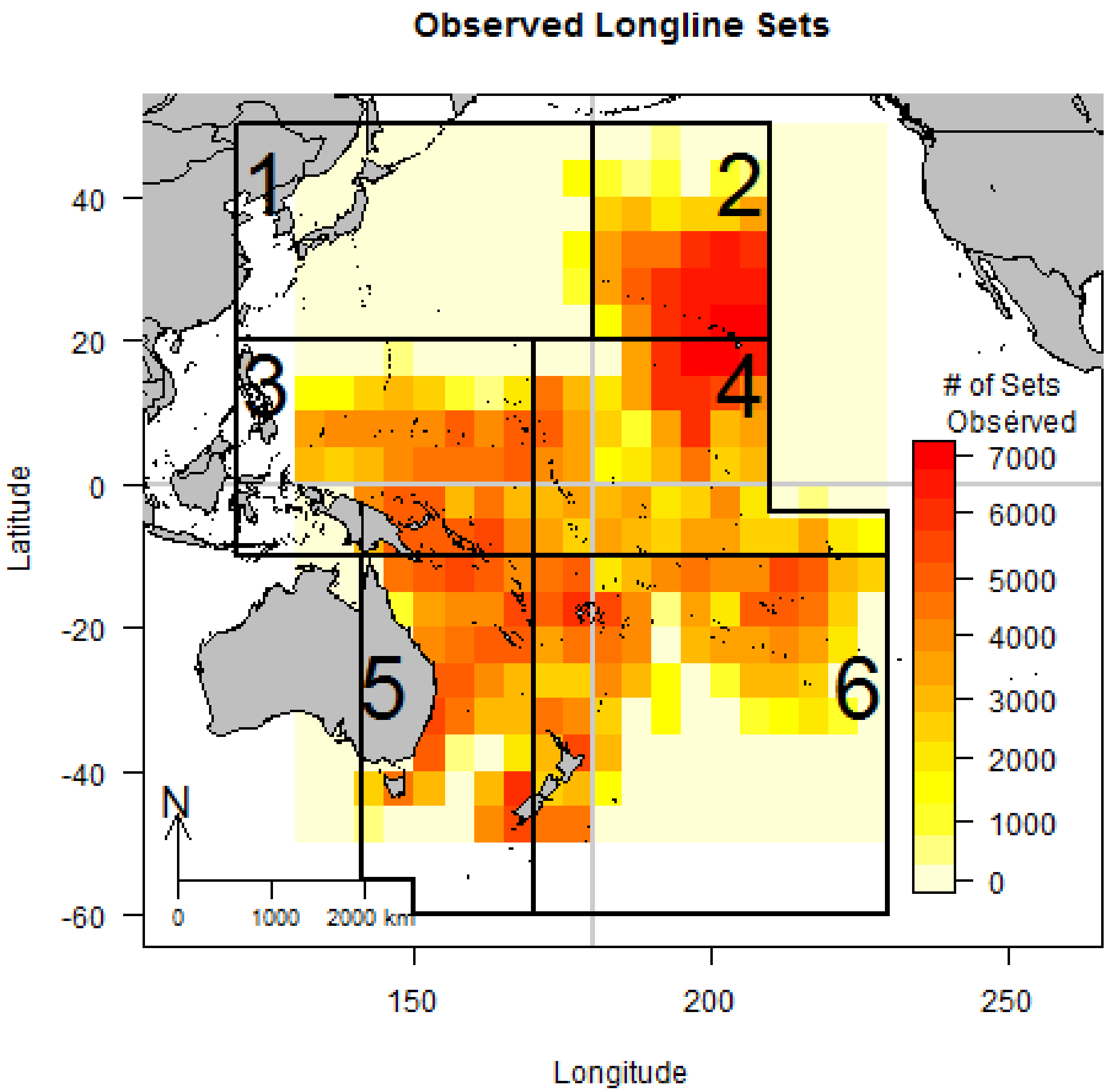
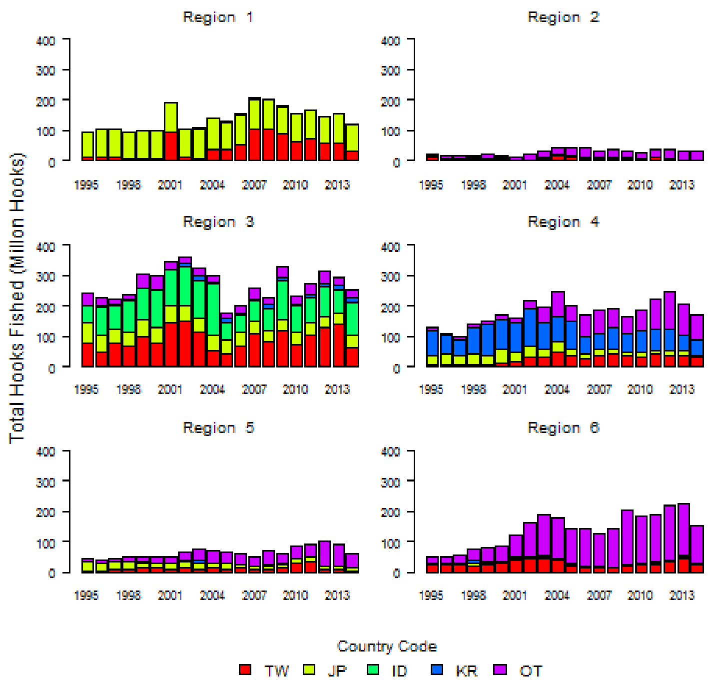
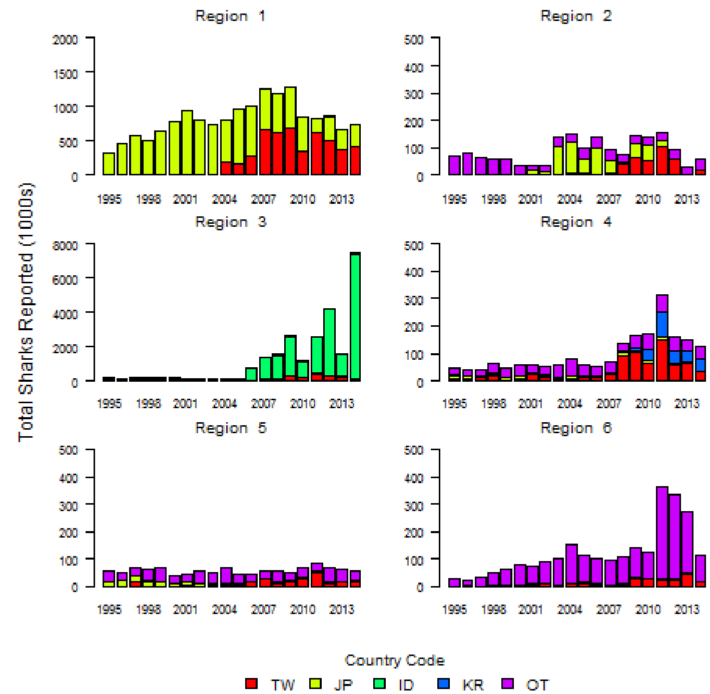


Figure 3: Longline observed sets by 5° x 5° square

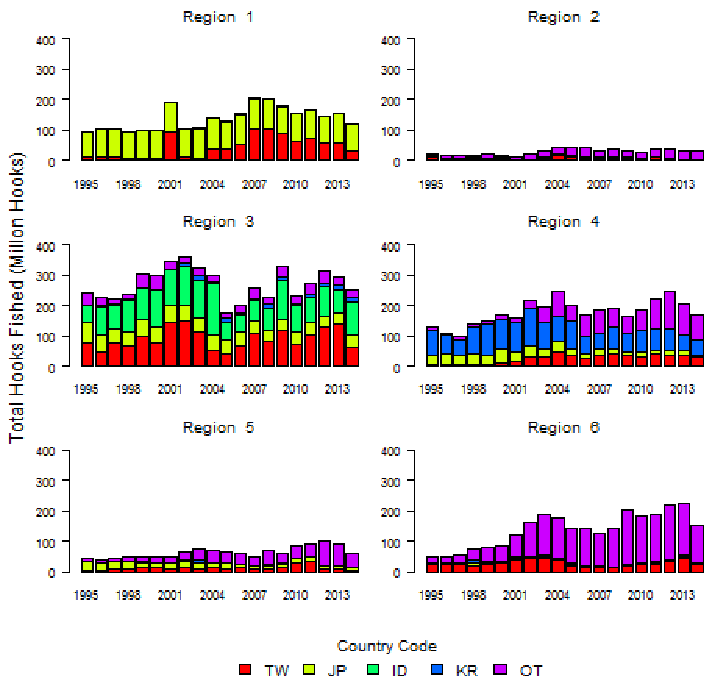


(a) Longline effort.

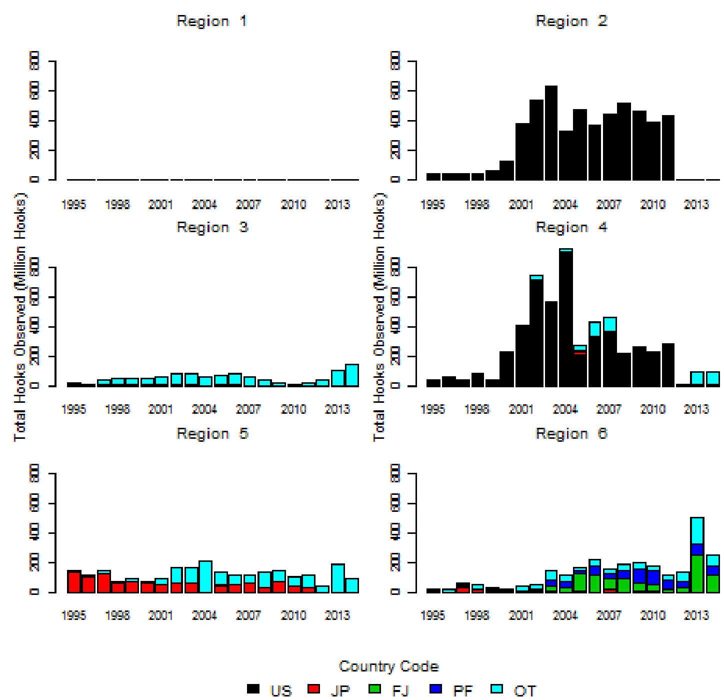


(b) Reported total shark catch.

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

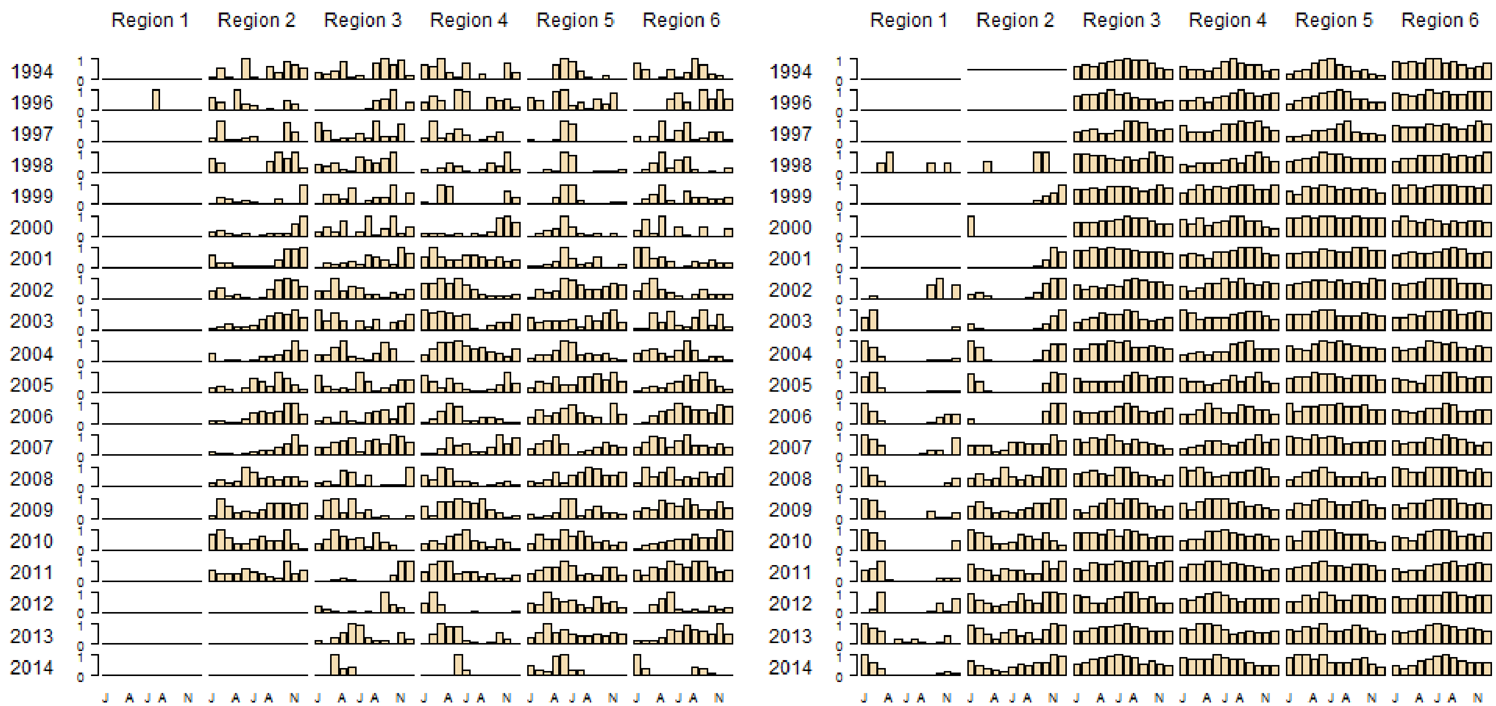


(a) Longline effort.



(b) Observer coverage.

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



(a) Longline effort.

(b) Observer coverage.

Figure 6: Monthly breakdown of longline effort by region 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.

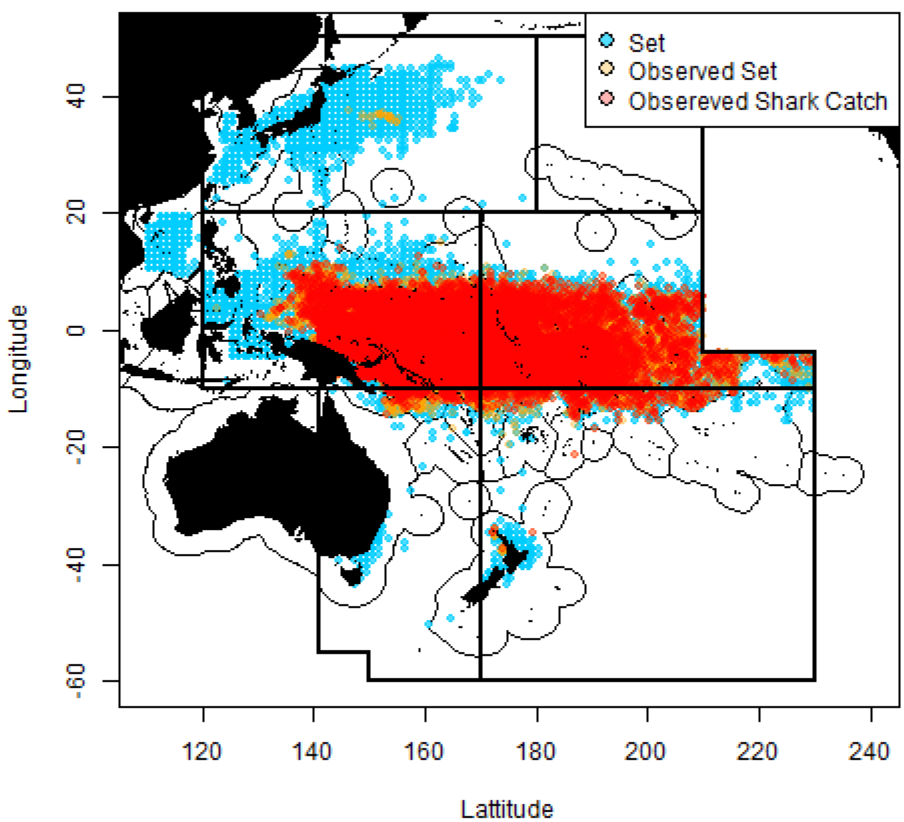
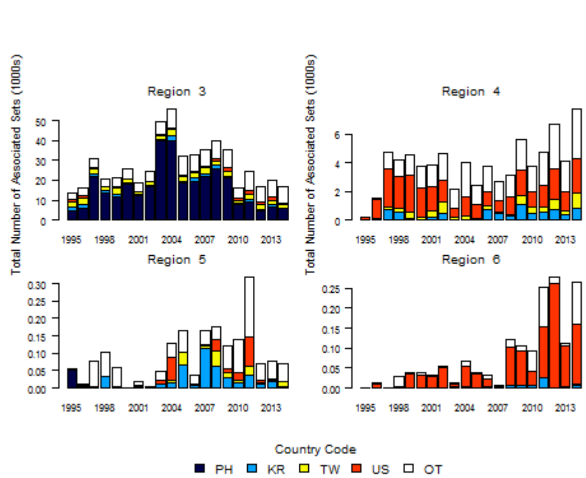
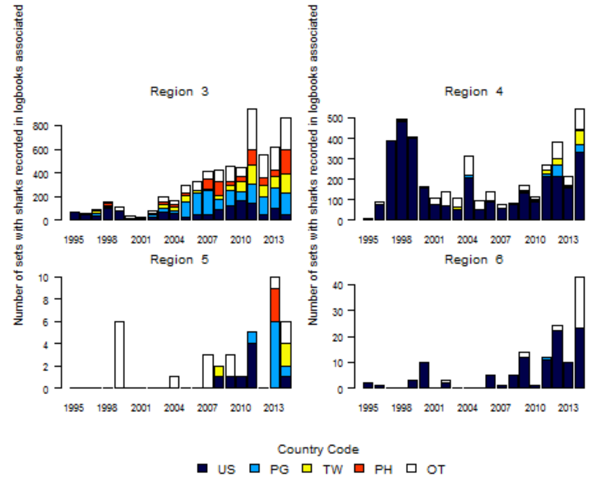


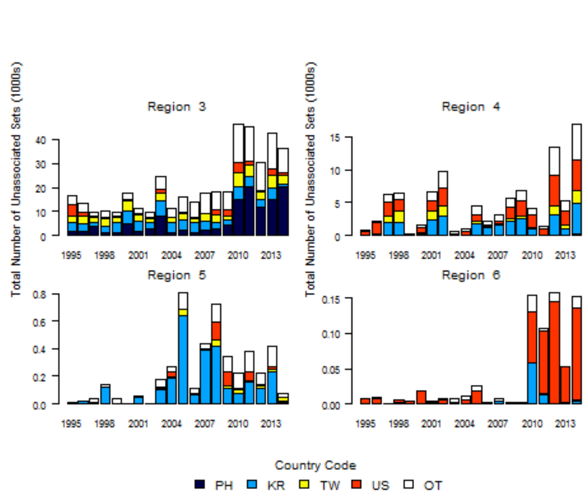
Figure 7: Absolute percent difference in effort between reported (logsheet) effort and observed effort.



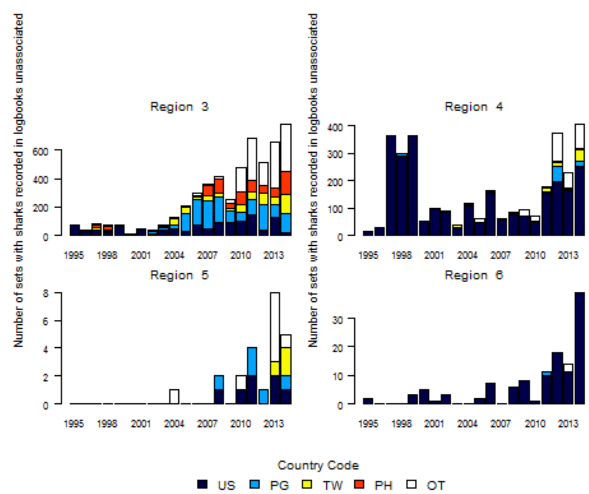
(a) Longline effort.



(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 ?). 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 interpreted as potential indicative of the location and intensity of interactions between these species and WCPO longline fisheries. These indicators can be updated over time to determine if the spatial patterns change or temporal trends change. More complex methodologies might also be applied to remove potential sampling biases.

Potentially need to add back some of these, but move to biological indicator section? 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° × 1° 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

these figure labels to be changed in figure input The four sets of Distribution Indicators are grouped in Appendix A, as follows: Species occurrence (Figures 9 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

Add general statement for other 3 indicators: With the exception of blue shark, the high-CPUE indicator showed a more or less steady trends for all species in all regions.

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

Joel: do you recall if the two paragraphs below were directly copied from another report?
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).

4.1.1 Longline

Link to figures, change labels as needed in figure input 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 other species of 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. Replaced unidentified with other species of sharks. Check if needs to be replaced elsewhere

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. Any trends over time?

4.1.2 Purse Seine

#Not sure why this is highlighted... Steven? Joel?
#Link to figures 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 XXX). 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 the regions where they occur (i.e. Regions 5 and 6) and silky shark is the second most common longline caught shark.

Purse 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.

#Not sure why this is highlighted... Steven? Joel?

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

This text could be smoothed over, paragraphs 3-5 need to be merged. *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 2 (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 resuls 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 if 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 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

Review: high priority text is rough Tables to be moved to the end of the document

5.2.1 Stock definition for the purpose of the analysis

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 minimum and maximum of the monthly mean sea surface temperatures (SST) of cells with positive catches for that species (see Table 1). SST was measured as the temperature predicted by GODAS at the 5 meters depth. Only cells for which all mean monthly temperatures fell within this range were retained.

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 97.5^{th} 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: sunset and sunrise were calculated
2. HPBCAT: based on data exploration two types explored: either shallow or deep (with shallow <= 10), or HPBCAT2 shallow, intermediate and deep, with intermediate between 10 and 15 ... in general hpbcat2 had slighlty better aic (in tables at the end)

5.4 Overview of GLM Analyses

5.4.1 Notes on error distributions:

some repeat from intro, gah 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

Laura or Joel to fix – fitted model with only one covariate (aics listed in table at end)
– all models included year effects and flag or program
– looked at other covariates in order of proportion explained on their own based on tables
– added covariate on MU ONLY (mean) until AIC showed decline < 10 (arbitrary....)
– then added other covariate on sigma based on aic table for sigma (at end also), and including as few as possible to improve long-tail fit — this is what made the difference to the qqnorm in most cases

Because flag and observer programs are highly correlated, we used either one or the other as an explanatory categorical variable, based on the proportion of variance it explained and whether model diagnostics were impacted. 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 proceeded 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 the R package `stats` CITE .

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 superciliousus, 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.

Table 1: Summary of temperature ranges by species used as filters for cells to retain in the CPUE analysis.

Species	Minimum T(° C)	Maximum T(° C)
Blue shark	10	30
Hammerhead sharks	13	30
Mako sharks	11	30
Oceanic whitetip shark	18	30
Porbeagle shark	10	26
Silky shark	18	30
Thresher sharks	11	30

Table 2: Description of variables used in CPUE standardization

Variable name	Symbol	Explanation	% records present
Year	β_Y	Required 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			
Shark target		Sharks explicitly defined as targets?	
SST	SST	100	
Day category		Day or night, before or after sunrise/sunset?	100

5.6 Model diagnostics

The quality of model fit was assessed by inspecting the residuals as well as simulating data from the fitted GLM model and comparing the simulated to the observed. Quantile residuals (Dunn and Smyth, 1996) were used instead of the traditional deviance or Pearson's residuals. Quantile residuals overcome many of the problems encountered for count-based GLMs and greatly facilitate model diagnostics. More specifically we aimed to improve fit to both the zeros and high catch events. Diagnostics were very satisfactory for all stocks except that of southern blue shark for which high catch events were still not well modelled, presumably due to unaccounting targeting by some fleets. Key diagnostics are included in Figures XXX to XXX .

5.7 Conclusions

re-read: high priority 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.

Analyzing and interperting CPUE trends for highly mobile species on a population level based on a small subset of the actual encounters with the fishery can be difficult, a number of potential biases can complicate this analysis These biases arise either from changes in the fisheries themselves (e.g. operational or gear changes) or from changes in observer coverage of these fisheries (e.g. observer data not provided for some years) or from the species interactions with natural occuring forcing factors (e.g. el nino). Many of these issues and their potential effect on sharks are documented in the previous report (Clarke et al 2011). Briefly the issues can be broken down into four main areas:

Despite these obsticals, analysis of the catch rate (both nominal and standardizes) of the key species revealed that ;

Blue shark CPUE is declining in the notrh and south pacific based on the nominal and standardized CPUE.

Oceanic white tip continue to decline throughout the tropical waters of the WCOP

Silky shark cpue exhibits hi fluctiuations throughout the study period.

The thresher shark complex appears to be in decline though the last years data point is based on relatively few data.

Mako shark in the south pacific may have been declining for the last five years however the last data point is based on relativly few data points.

Mako in the north Pacific is similarily plauged by data deficiencies missing dta for years 1996, 2003, 2011, and 2012. Despite this the trend looked relatively stable between 2000 and 2010, however no infrence is possible for the lst 4 years.

Porbeagle shark CPUE experienced a large decrease early on in the study period followed by a fluctuating but increasing CPUE trend.

Table 3: Summary of number of records removed by filter type for each species before GLM analyses. HW/AS and PG refer to the Hawaai/American Samoa and the Papua New Guinea observer programs. OB sampling refers to records removed from observer programs with few records. See summary in section 5.2

Species	Hemisphere	SST range	max quantile	HW/AS	PG	OB sampling	# rows left
Blue shark, south	41276	1234	309	3449	571	21	19660
Blue shark, north	25244	0	805	36818	0	35	3618
Hammerhead sharks	0	4999	12	41072	571	21	19845
Mako sharks, south	41276	1419	130	3359	571	21	19744
Mako sharks, north	25244	0	97	37536	0	35	3608
Oceanic whitetip shark	0	10266	171	38532	570	21	16960
Porbeagle shark	41276	18038	78	0	0	122	7006
Silky shark	0	10266	127	38563	563	21	16980
Thresher sharks	0	1419	290	40860	571	21	23359

Table 4: 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	

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.

need intro statement about utility of life history stage maps

In this section we analyse trends in median length, proportion of females over time, and patterns of life history by sex.

6.2 Methods

Shark sex identification data from oberver 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 8. Those 5° x 5° 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 (Table 8). While length at maturity and conversion factors might be expected to vary by region within the WCPO, insuficient 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° x 5° 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 standarized 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 anual 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.

Patterns of occurrence by life history stage by sex were explored using the same dataset developed for the standardized length analyses. Analyses were conducted for each species across sex (male and female) and maturity (adult/juvenile), giving four plots of the proportionality of each sex:maturity stage. The analyses were carried out for the entire time series, stratified by season, May-July (mid year) and November -January(year-end); sharks sampled in other months were excluded from the analysis. The life history stage and sex maps are illustrated in Appendix Figures **??** to **??**. The maps were produced by shading each cell based on the proportion of individuals observed in each of the four subsets with darker colours indicating higher proportions. For example, if all of the silky sharks observed in a given cell were adult females the adult female panel would show a darkly shaded cell whereas the other three panels would show only the lightest shading (i.e. even zero proportions receive the lightest colour shading).

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 dificult due to lack of continous data and small annual sample sizes in the most recent years. The sex ratio of blue shark in region 5 has 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 (availabilty) 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 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 shaks 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 throuhout 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 Standarized length

Possible trends in length over time are more evident in the stardarized length plots when overplotted with a loess smoother. For the great majority of species, sex and stock, standardized lengths have decreaed 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.

6.3.4 Life history stage and sex

The following points were noted from the life stage and sex distribution plots:

- In the south Pacific adult blue sharks and especially females were presesnt in the waters of New Caledonia and Fiji throughout the year, with higher proportions of adults present south of 20° only in the mid year.
- Adult blue sharks were more common than juveniles in the waters off Hawaii and at latitudes of 20° S this corresponds to the blue shark mating ground proposed by Nakano (1994); the highest proportion of juvenile blue sharks was found in mid-year (May-July) samples in the southern extremities of the WCPO.
- Juvenile silky sharks are present throughout the year in the waters between 10° north and 10° south, especially in waters around Papua New Guinea and the Solomon Islands
- Juvenile hammerhead sharks were most commonly observed in the adjoining seas of Papua New Guinea and the Solomon Islands' territorial waters. Adult hammerheads were uncommly observed in the same areas.
- Juvenile makos of both sexes were most frequently observed in the year end around the waters of southern Hawaii and during mid-year (May-July), the waters around southern Australia New Zealand and to a extent Fiji.
- The observed distributions of oceanic whitetip are similar across sex and seasonality, with respect to maturity they are quite similar with adults occuring more in the north of Hawaii.
- Thresher sample sizes were small and were mainly comprised of juveniles in tropical areas (especially off southern Hawaii) where they were seen year round. Large proportions of juveniles were observed in waters off New Zealand during the mid-year.

6.4 Conclusions

This Biological Indicators section examined trends in sex ratio, median length, standardized length and life history stage and sex. 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 investegated by plotting the nomial 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, 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 Whale Sharks

reread: medium priority #This whole section, figure and table labels need to be fixed

Text from Joel, could be merged in section intro? Whale shark interactions are generally reported only by the purse seine fishery. These observations are subject to considerable spatial and temporal heterogeneity and likely to have been affected by changes in observer coverage and reporting practices in recent years. The fate of whale sharks following interactions is also uncertain and information on key biological processes are limited. Given the current SPC data holdings only limited analysis for whale sharks in the WCPO is considered to be feasible.

For the purposes of this report, information on whale sharks has been retained in a separate section. For other key shark species the analyses described in this report have focussed on longline interactions with additional information from purse seines for some species in equatorial regions. For whale sharks, there are almost no interactions with longline gear. Whale shark interactions occur almost exclusively with purse seine fishing gear where tuna schools associated with whale sharks are either specifically targeted or else whale sharks are subsequently discovered to be associated with schools that were previously thought to be free school tuna aggregations.

The background to the original work by Harley et al. (2013) (for a full description of the analysis) was initiated from a request at WCPFC9 to add whale sharks to the list of key shark species and subsequently a conservation and management measure was adopted (CMM-2012-04). This work is an update of the work produced by Harley et al. (2013) to include data up to 2014 looking at the spatial and temporal distribution of whale sharks in the western and central Pacific Ocean based on observer data collected from purse seine vessels (OFP, 2014). It is important to note that this study focused on the occurrence of whale shark interactions with purse seine free school sets in contrast to the other key shark species (in this document) interactions with longline sets.

7.1 Data and Methods

The observer data used in the analysis comprised all observed purse seine sets held by SPC for the last twelve years (2003-2014). Prior to the agreement of 100% observer coverage in 2010, the observer data are not representative of the entire fleet with a strong bias towards US vessels, Pacific Islands fleets (under the FSM Arrangement) and those vessels fishing in the waters of Papua New Guinea.

Nevertheless, they represent over 200,000 observed sets over the past ten years (Table 1). To determine if a set encountered a whale shark in some way we used three criteria 1) was the set labelled as a whale shark associated set as recorded on the observer PS-2 form; 2) whether the set caught a whale shark, from the observer PS-3 form; or 3) was an interaction reported, from the observer GEN-2 form.

As has been noted previously (Harley et al. 2013) not all whale shark associated sets necessarily result in the encirclement of the whale shark, and many of the whale shark interactions come from sets that were reported by the observer as a free school set because the whale shark was not noticed until after the set was made.

The majority of the analysis in this paper relates to modelling the distribution of sets, whale shark records, and the 'encounter rate' (whale shark records per set) at 1×1 ° square resolution. It is important to note here, that the observer data are restricted in its coverage of the WCPO purse seine fishery with no coverage for the domestic purse seine within EEZ fisheries in Indonesia and the Philippines or the Japanese purse seine fisheries that operate in the North. Any hotspots identified in this paper are not necessarily the areas of highest density of whale sharks in the WCPO or even the equatorial part of the convention area.

this table needs a caption

Year	All Sets	Whale shark associated sets	Whale shark encounters
2003	3655	18	36
2004	5339	17	39
2005	6254	29	54
2006	6171	37	91
2007	6064	43	80
2008	6364	40	84
2009	10919	42	89
2010	32006	112	259
2011	30777	157	259
2012	32683	135	328
2013	41680	188	340
2014*	26386	127	217

CMM 2012-04 came into effect January 1st 2014, whale shark associated sets reported here may include whale shark target sets and some inadvertent catch where the shark was noticed during brailing.

As has been noted previously (SPC-OFP, 2011; Harley et al. 2013) not all whale shark associated sets necessarily result in the encirclement of the whale shark, and many of the whale shark interactions come from sets that were reported by the observer as a free school set because the whale shark was not noticed until after the set was made.

7.2 Results

Nine hundred and forty-five observed sets were recorded as whale shark sets (criteria 1 above) and a further 931 sets met either criteria 2 or 3 (Table 1). This gave 1876 records of whale sharks from just over 200,000 observed sets. The data coverage increased dramatically in 2010 with the introduction of 100% observer coverage so overall the data are biased toward recent years. The percentage of all sets that recorded some form of whale shark interaction has been just under 1% except for the period 2006-2008 when it increased to just less than 1.5% (Figure 1).

Aside from 2006 which had a large spike in the occurrence of whale sharks in free schools sets (2.5%), there has been a general decline in the occurrence of whale sharks in free school sets with a mean of around 1% until 2009 (ignoring 2006) and just under 0.5% from 2010-2014 the last four years (Figure 2). The pattern of whale shark distribution with fishing effort is very similar with the largest densities found in the Bismark and Solomon seas (Figure 3). However the range of observations were found scattered across the western equatorial Pacific Ocean. In terms of the encounter rate there were some isolated areas where the rate of records per observed set were high but these were generally areas with low observed whale shark records, but even [relatively] lower observed effort. These areas included the south eastern corner of the Papua New Guinea EEZ in the Solomon Sea, the southwest corner of the EEZ of the Federated States of Micronesia, and some small parts of the Gilbert, Phoenix, and Line Islands groups.

7.3 Discussion

Further to the work discussed by Harley et al. (2013) there have been no significant differences in the fishery for the past 2 years. However, key areas of work have been identified within the shark research plan (see Brouwer and Harley, 2015). In summary these include:-

- Updating the catch history.
- Stock discrimination.
- Development of a standardised CPUE index.
- Observer form re-development process should include distinguishing between target whale shark sets and inadvertent catch.

Furthermore, with reference to Clarke (2015) who suggests that it is difficult to make inference about purse seine interaction and whale sharks from 2014 observer data and that these data are under-estimates. This was also the conclusion from the report conducted by SPC (SPC-OFP, 2011) which suggested that the proportion of whale-shark associated sets should be higher than that reported by observers. This is because more than two-thirds (73% in both 2007-2009 and 2010) of the sets where whale sharks were encountered in the net (i.e. "interactions") were not recorded as a "whale shark-associated" set type. One of the main reasons for this is that the whale shark may be not visible at the time of setting and so the set is recorded as another set type (e.g. "unassociated, feeding on baitfish"). Subsequently, the observer discovers the animal in the net during the brailing process, and records it as an interaction.

We therefore recommend revision of the observer data forms as soon as possible in order to distinguish between target whale shark sets and inadvertent catch so as to determine an accurate level of risk to whale shark mortality in the WCPO from purse seining.

8 Feasibility of Stock Assessments

Steven: can you confirm that you have incorporated SB's feedback here? 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 indicated 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 it 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 superciliousus, 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.

9 Impact of Recent Shark Management Measures

reread: high priority — make sure edits from Steve B. incorporated 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 measure 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 fining through a 5% fin to carcass ratio. In addition, CMM2014-05 was developed to limit the use of wire traces and shark lines in tuna and billfish target longline sets.

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 5% of the weight of sharks on board up to the first point of landing. This CMM replaced Conservation and Management Measure 2009-04, which was similar and an extension of CMM 2008-06, which was an extension of CMM 2006-05, which originally went into force on January 1st 2008. Observer records indicate a change in the observed practices of dealing with sharks in the purse seine fishery from the year 2008 to 2009 (Figure **??**, bottom panel). The proportion of sharks that were finned was significantly reduced and the proportion discarded increased and has been approximately 80-100% from 2009-2014. During this time the coverage of the purse seine fleet increased significantly, so the dramatic decrease in the proportion finned may partly be an artefact of a more extensive sample of the fleet, thought the CMM likely had some impact in the changes of handling sharks. Observer data for the key shark species in the longline fishery indicates that the years preceding the CMM were similar (with respect to the fate of sharks) as to those after, with an increase in the number of sharks retained (carcass along with fins as per the CMM) evident in recent years.

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.

Repeated from above?!? 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 hammpered by the fact that there were no observatoons of occeanic 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 Conclusions

This paper examines data held by the SPC-OFP for longline and purse seine fisheries in the WCPO to makes 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%) did not record sharks, in contrast XX% observer data for longline did, possible explanations for this discrepancy include underreporting of sharks or that the observer data are not representative of the fishing methods/areas/time periods of the longline fleet as a whole.

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-ported 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 indicat 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 thought 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 fshery. 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 popuation trends in length for the longline Fishery and the popoulation 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. This paragraph repeated later on... need to be fixed. 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 hammpered by the fact that there were no observatoons of occeanic 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.

11 Research Recommendations and Management Implications

This indicator analysis provides informative insights into silky shark, oceanic whtitetip, 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 wat 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 intrim.

Acknowledgements

Thank you to Kelly Shark for her constructive criticism.

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A Tables

Need more consistent section names for appendix...?!? there are tables later on too. Maybe name this after the first section? Check with Rob beforehand. Also table captions on top please.

	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 5: Percent of effort observed in the 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 6: Percent of Logsheets reporting sharks to species, 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

Table 7: Millions of hooks fished in longline fishery by region.

Species	Length at Maturity	Reference(s)
Blue	Males: 168 FL (200 TL) Females: 168 FL (200 TL)	Nakano and Stev
Mako (shortfin mako)	Males: 180 FL Females: 275 FL	Francis and Duff
Oceanic whitetip	Males: 138 FL (168 TL) Females: 144 FL (175 TL)	Seki et al. (1998)
Silky	Males: 175 FL (212 TL) Females: 173 FL (210 TL)	Joung et al. (200
Thresher (bigeye thresher)	Males: 168 FL (270 TL) Females: 203 FL (332 TL)	Smith et al. (200
Hammerhead (scalloped hammerhead)	Males: 153 (198 TL) Females: 163 FL (210 TL)	Chen et al. 1990
Porbeagle	Males: 145 FL Females: 175 FL	Francis and Duff

Table 8: 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.

B Figures

review: medium priority, read over all captions

B.1 Distribution Indicator Analyses: Figures

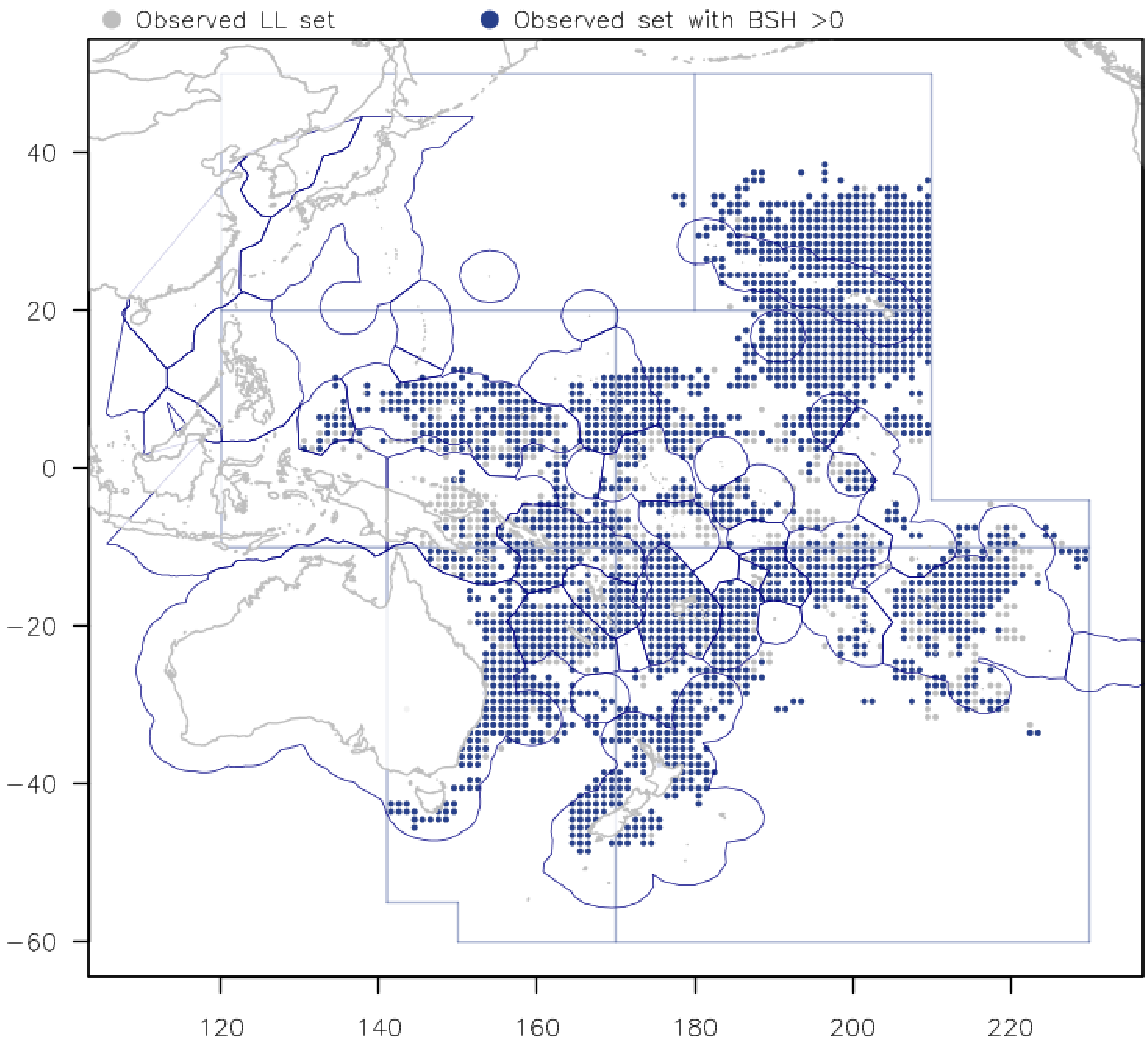


Figure 9: Distribution of observed LL sets (grey) and observed longline sets for which catches of blue shark were made during the study period within the WCPFC convention area.

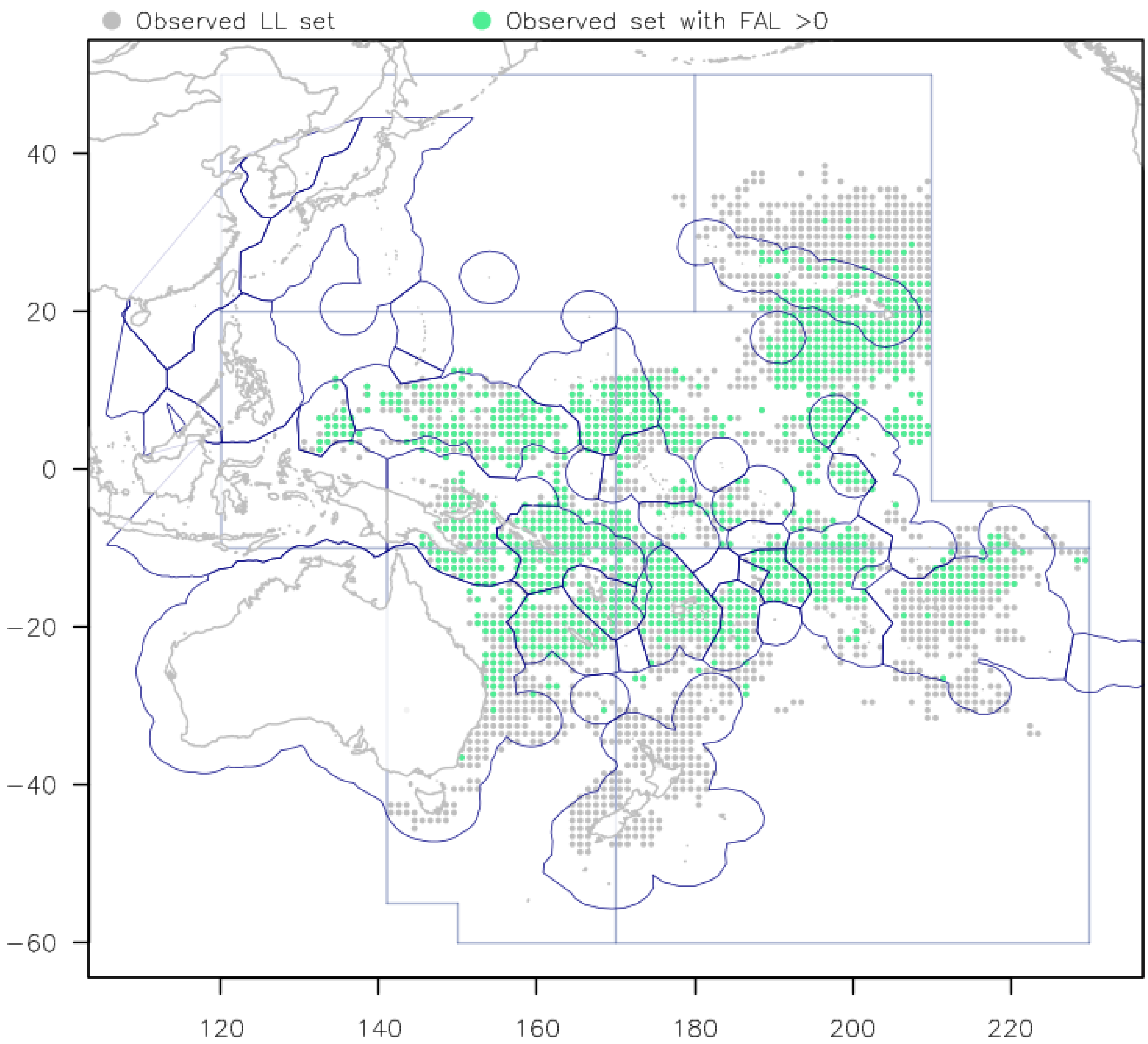


Figure 10: Distribution of observed LL sets (grey) and observed longline sets for which catches of silky shark were made during the study period within the WCPFC convention area.

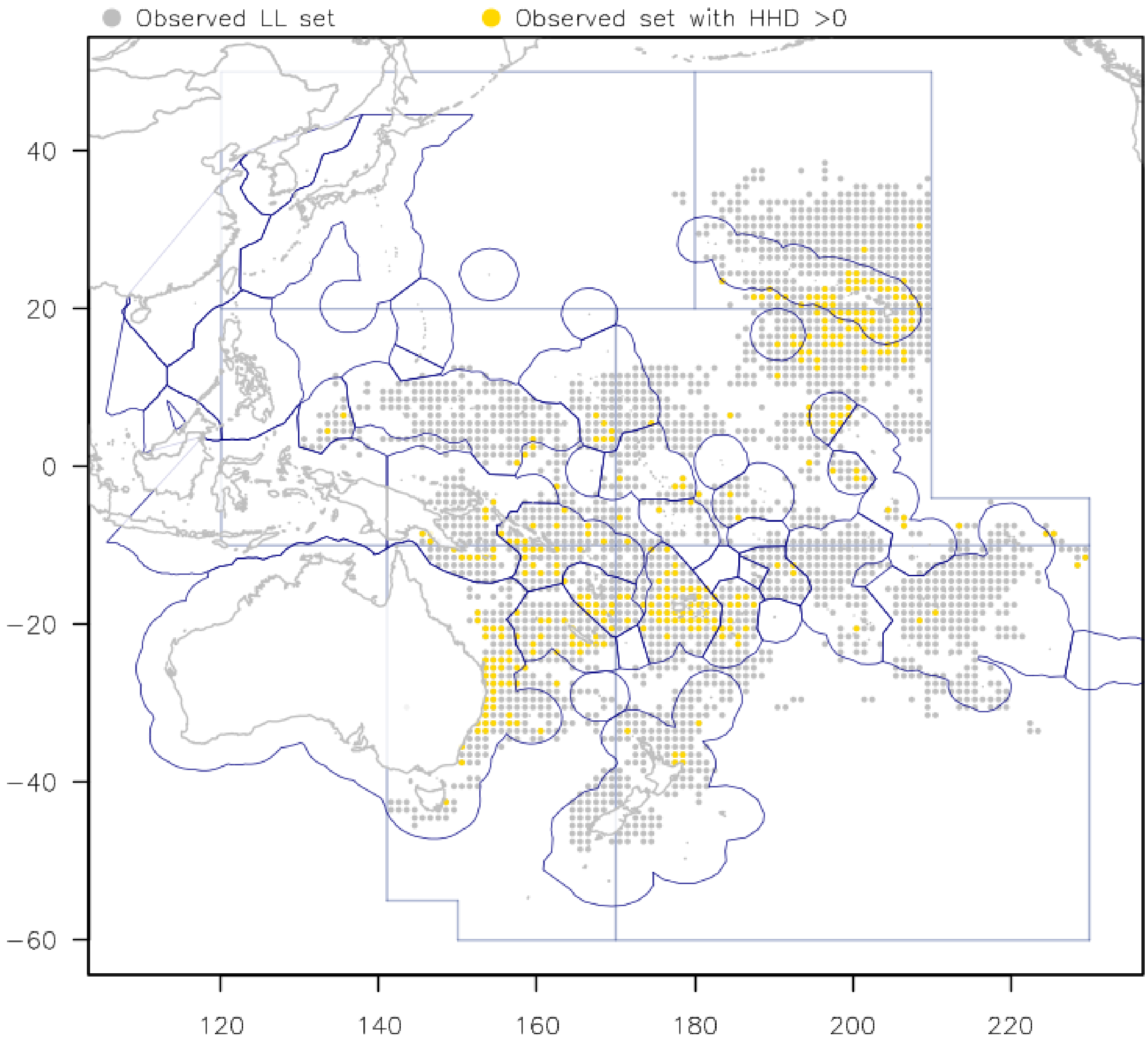


Figure 11: Distribution of observed LL sets (grey) and observed longline sets for which catches of hammerhead shark were made during the study period within the WCPFC convention area.

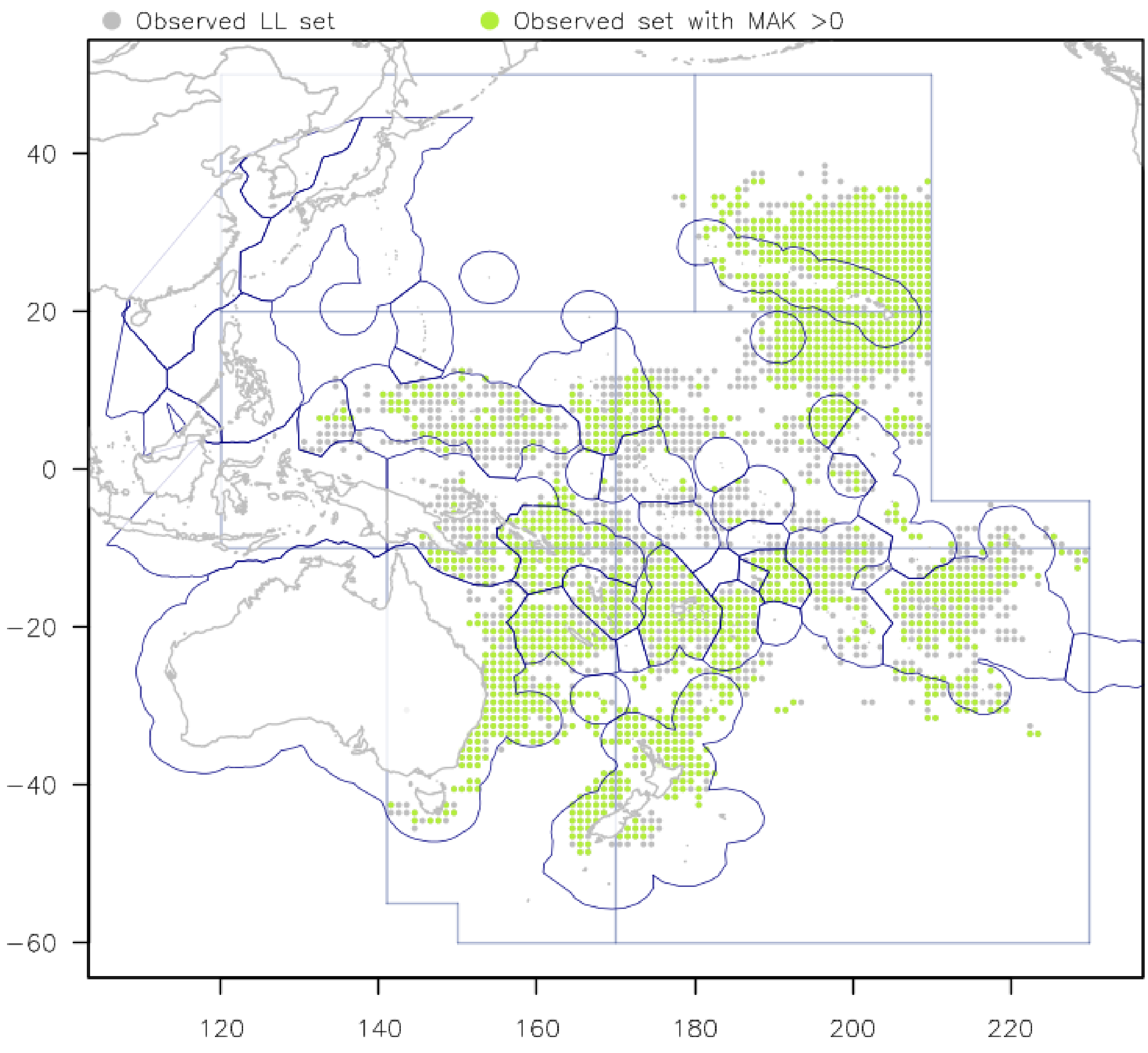


Figure 12: Distribution of observed LL sets (grey) and observed longline sets for which catches of mako shark were made during the study period within the WCPFC convention area.

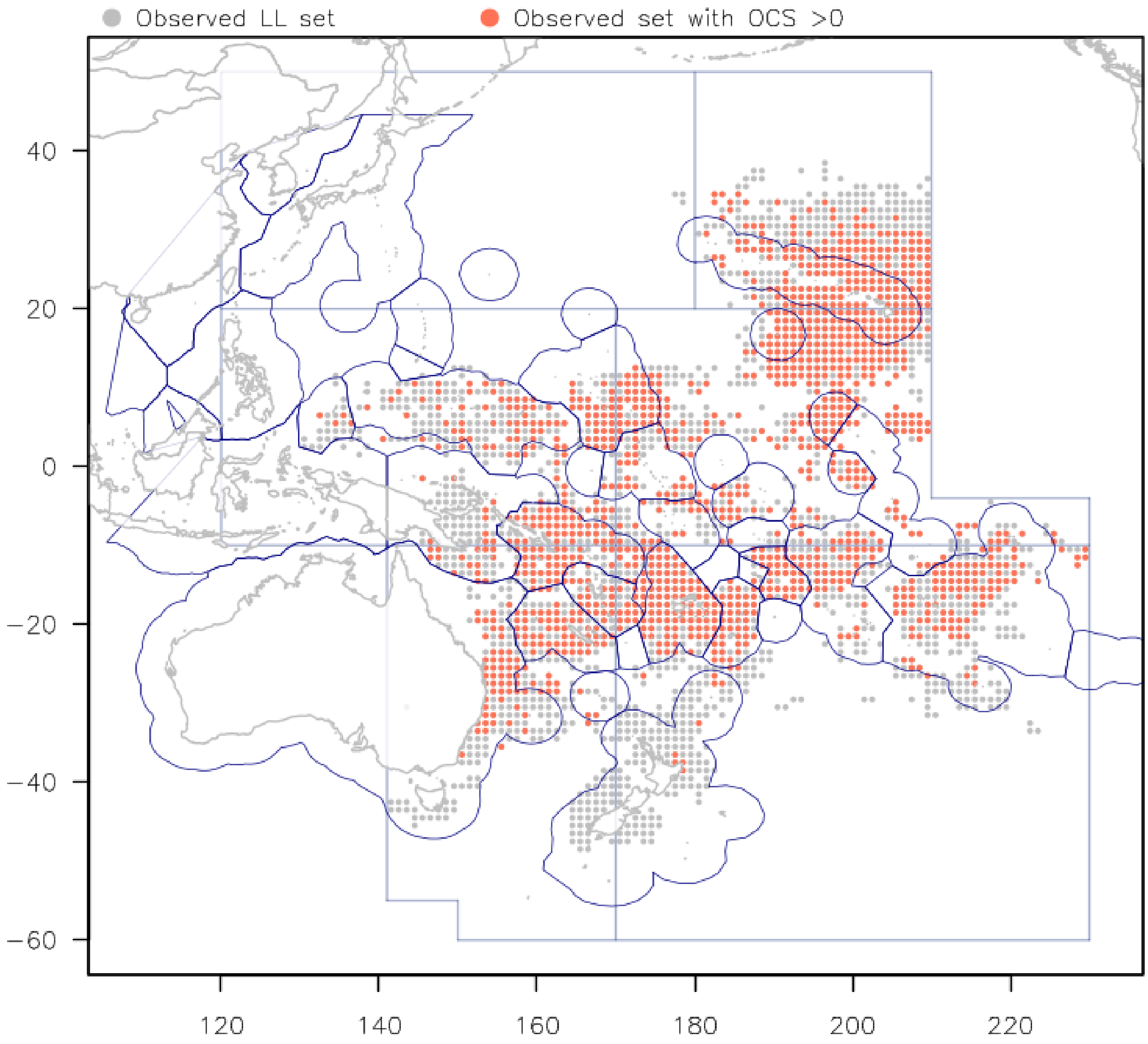


Figure 13: Distribution of observed LL sets (grey) and observed longline sets for which catches of oceanic whitetip shark were made during the study period within the WCPFC convention area.

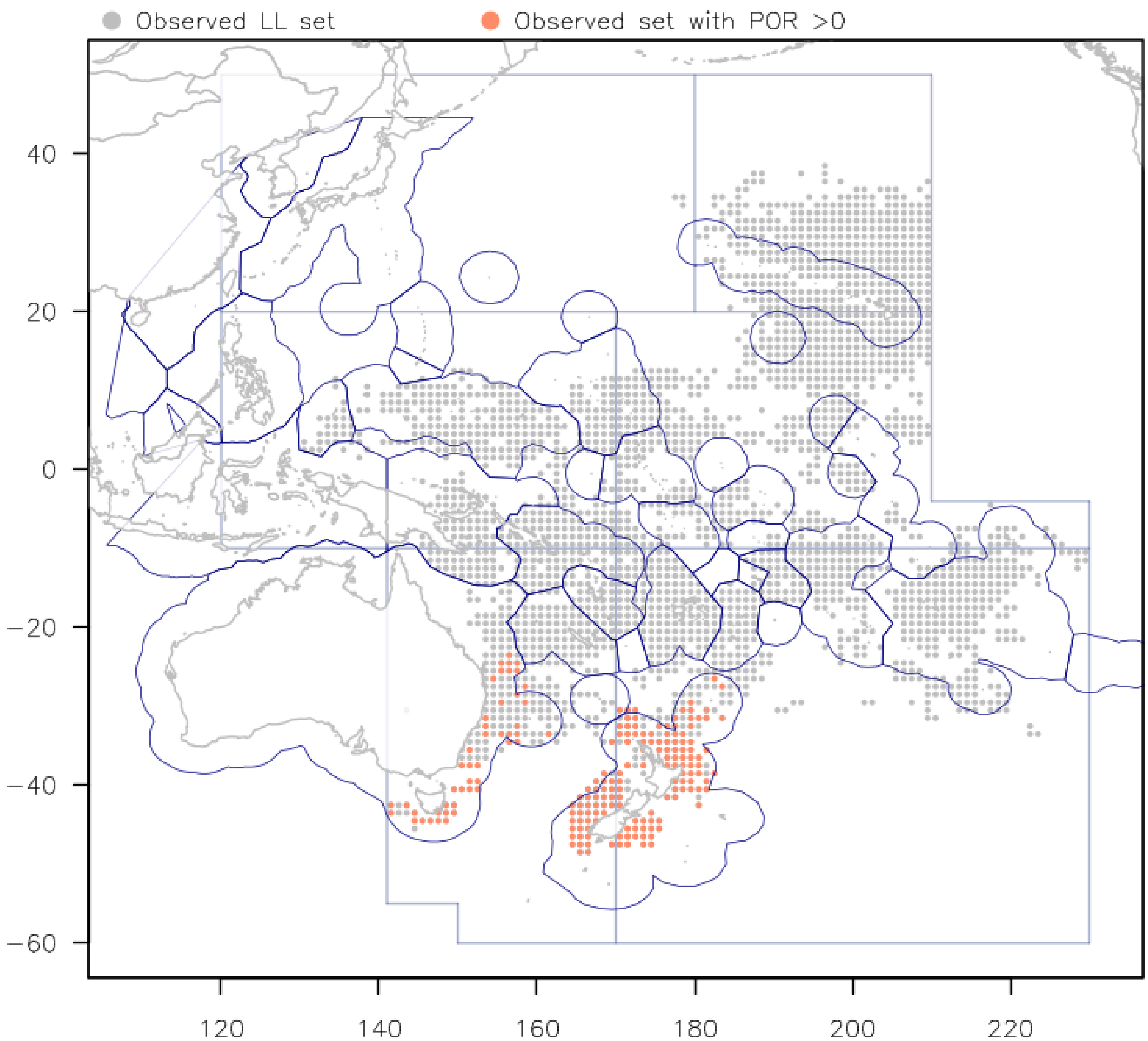


Figure 14: Distribution of observed LL sets (grey) and observed longline sets for which catches of porbeagle shark were made during the study period within the WCPFC convention area.

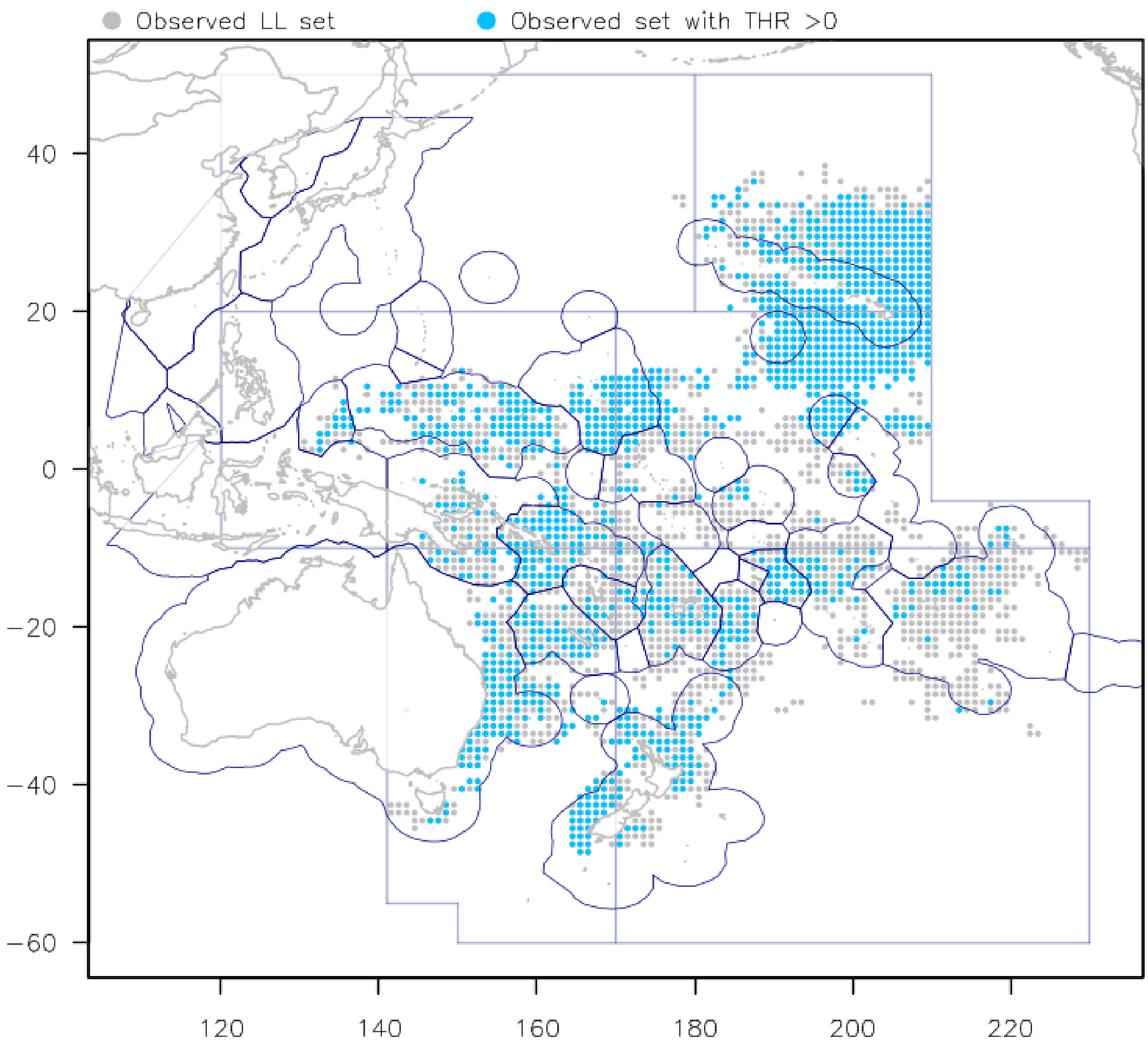


Figure 15: Distribution of observed LL sets (grey) and observed longline sets for which catches of thresher shark were made during the study period within the WCPFC convention area.

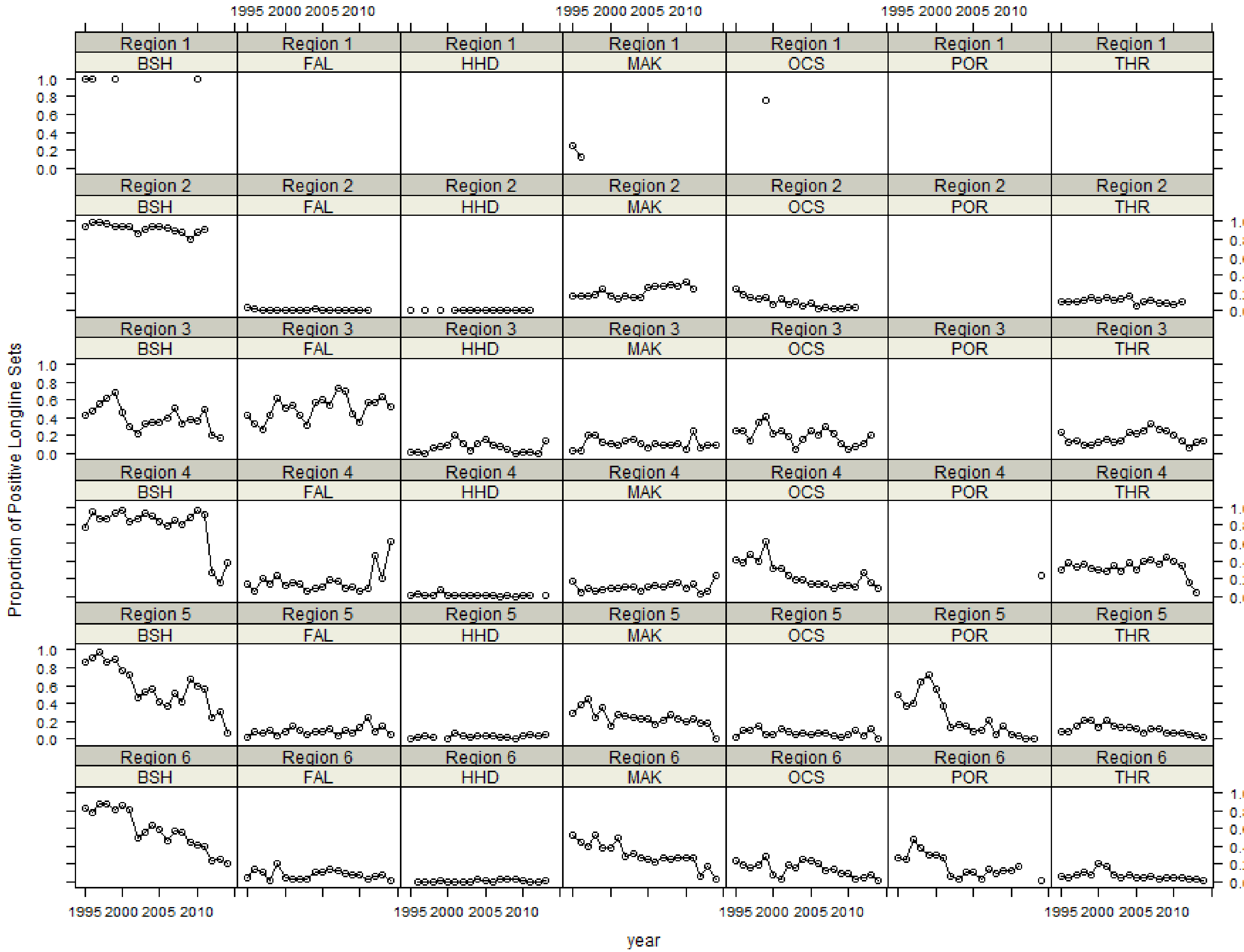


Figure 16: The proportion of longline sets for which one or more sharks were caught by region and year.

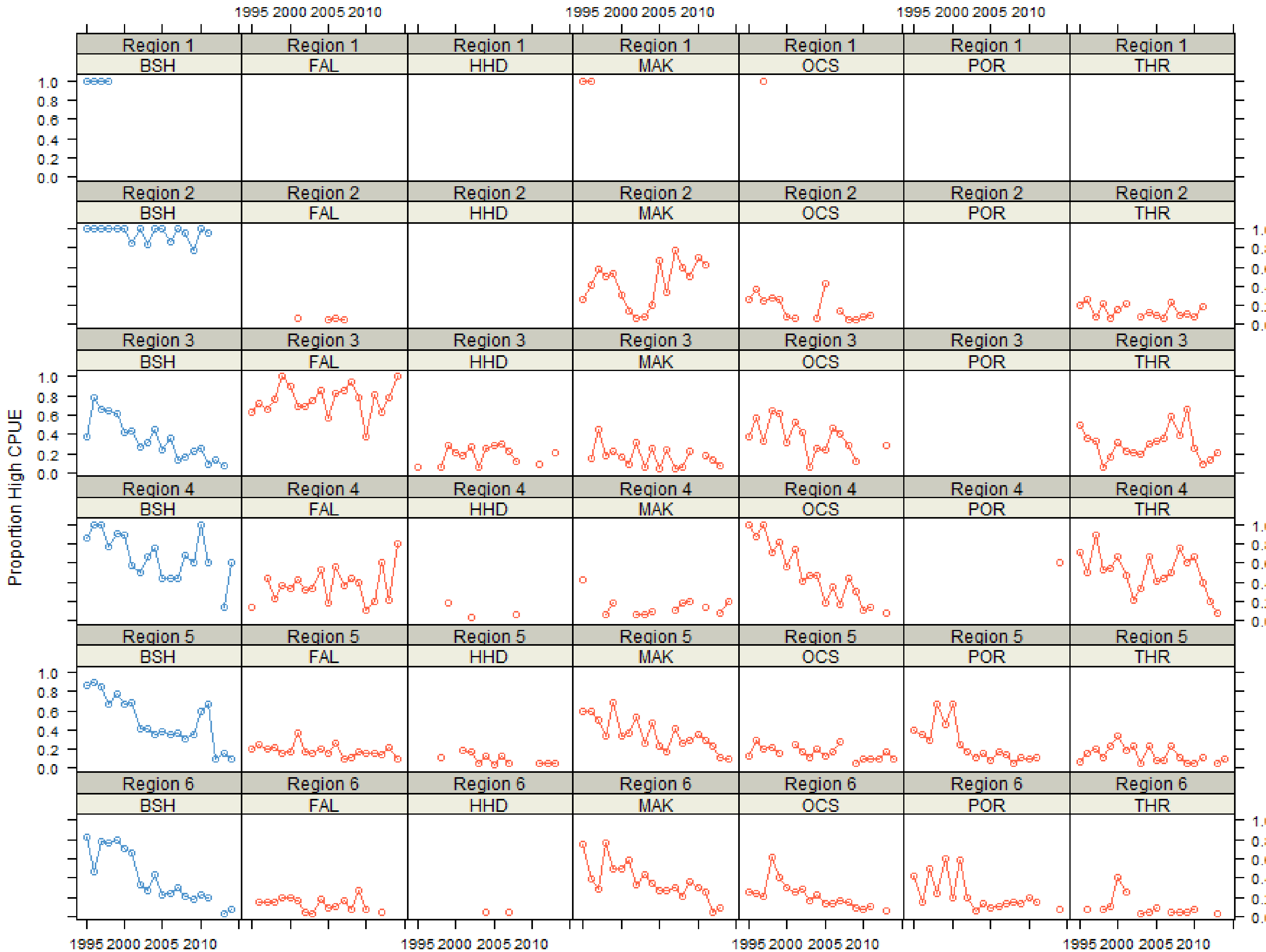


Figure 17: Proportion of longline sets with high CPUE by species and region. High CPUE is defined as sets with more than 1 shark per 1000 hooks (for blue shark, blue lines) or more than one shark per 5000 hooks (all other species, red lines).

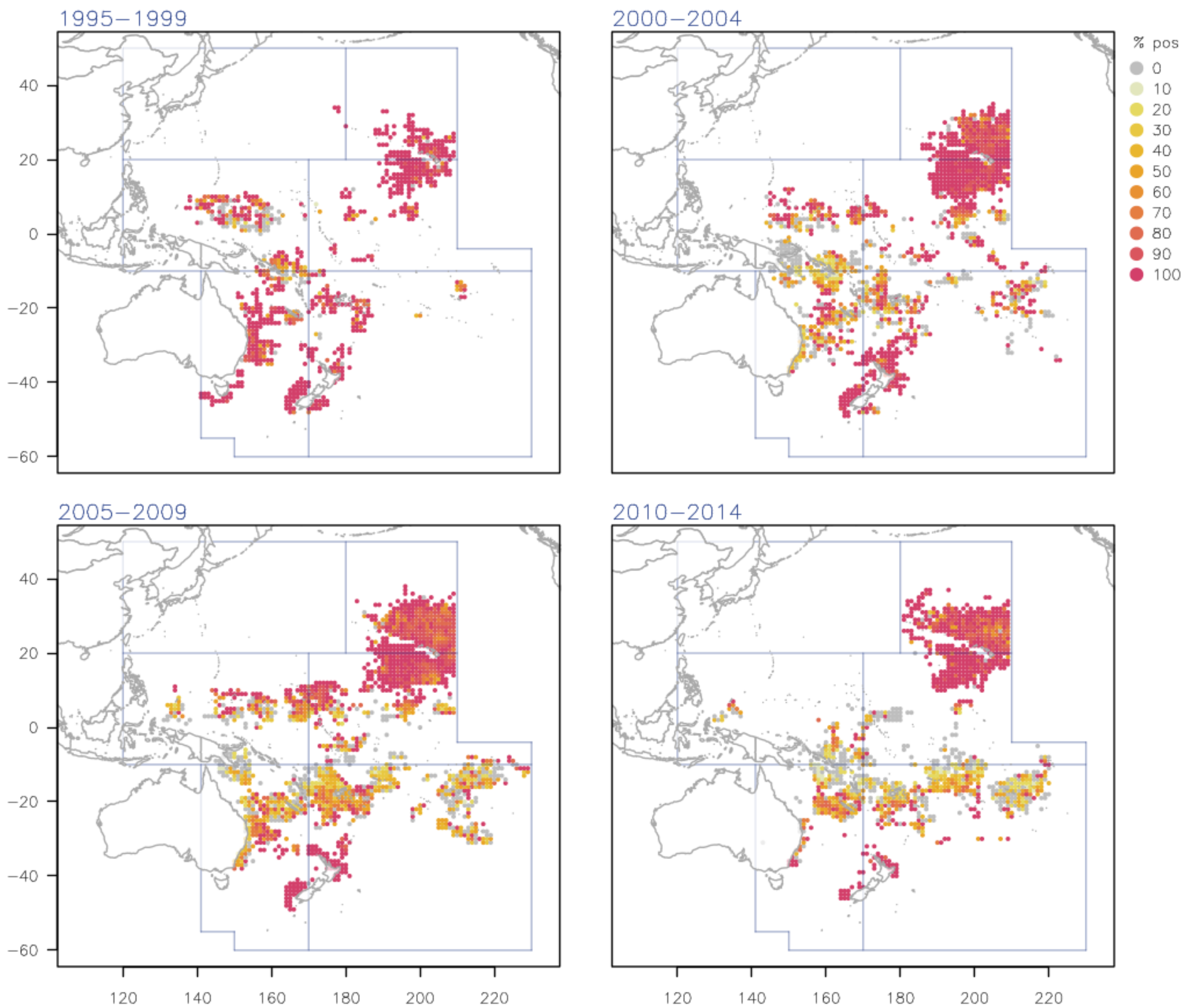


Figure 18: Spatial distribution of the proportion of longline sets for which one or more blue shark were caught for each five year period between 1995 and 2014.

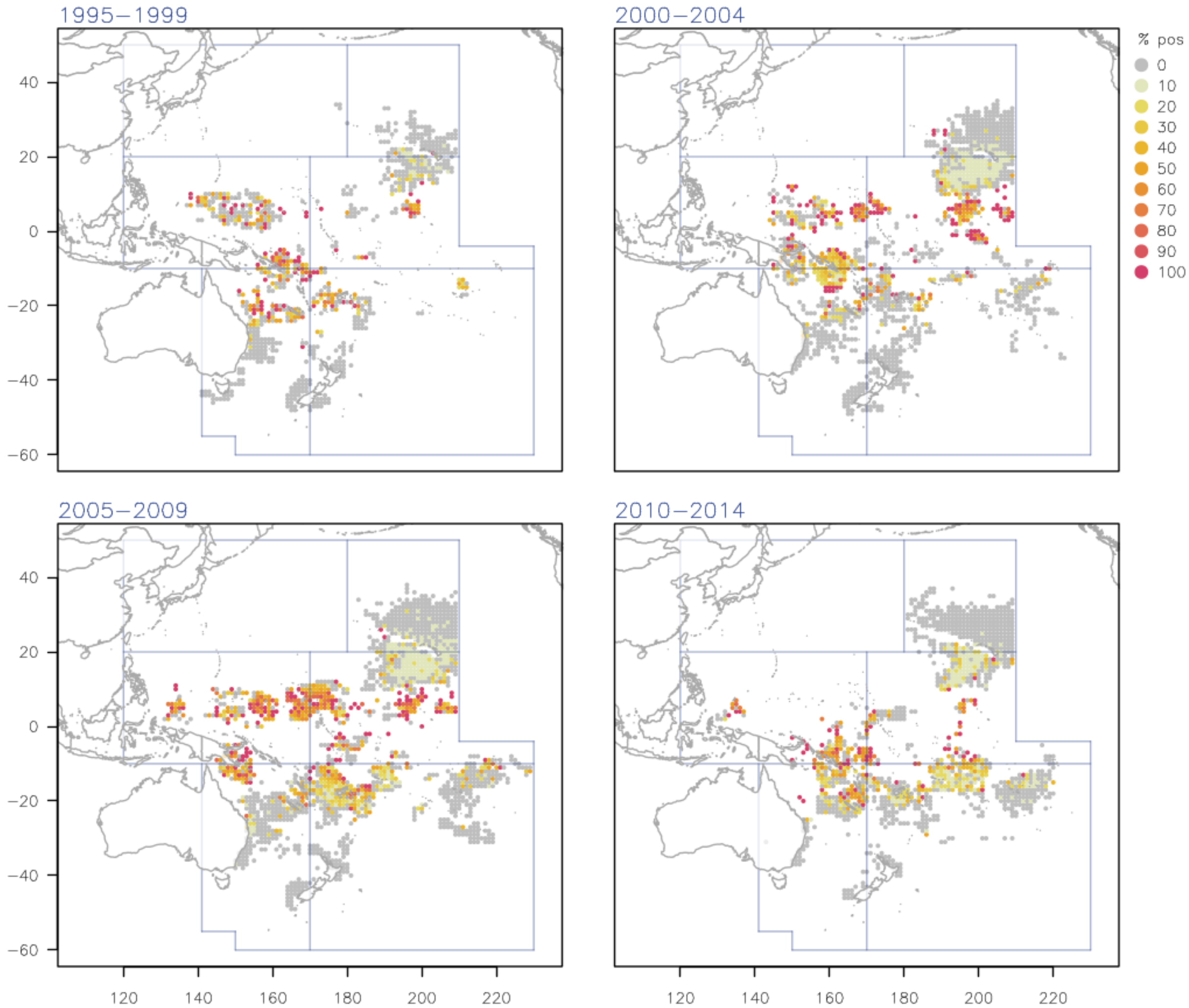


Figure 19: Spatial distribution of the proportion of longline sets for which one or more silky shark were caught for each five year period between 1995 and 2014.

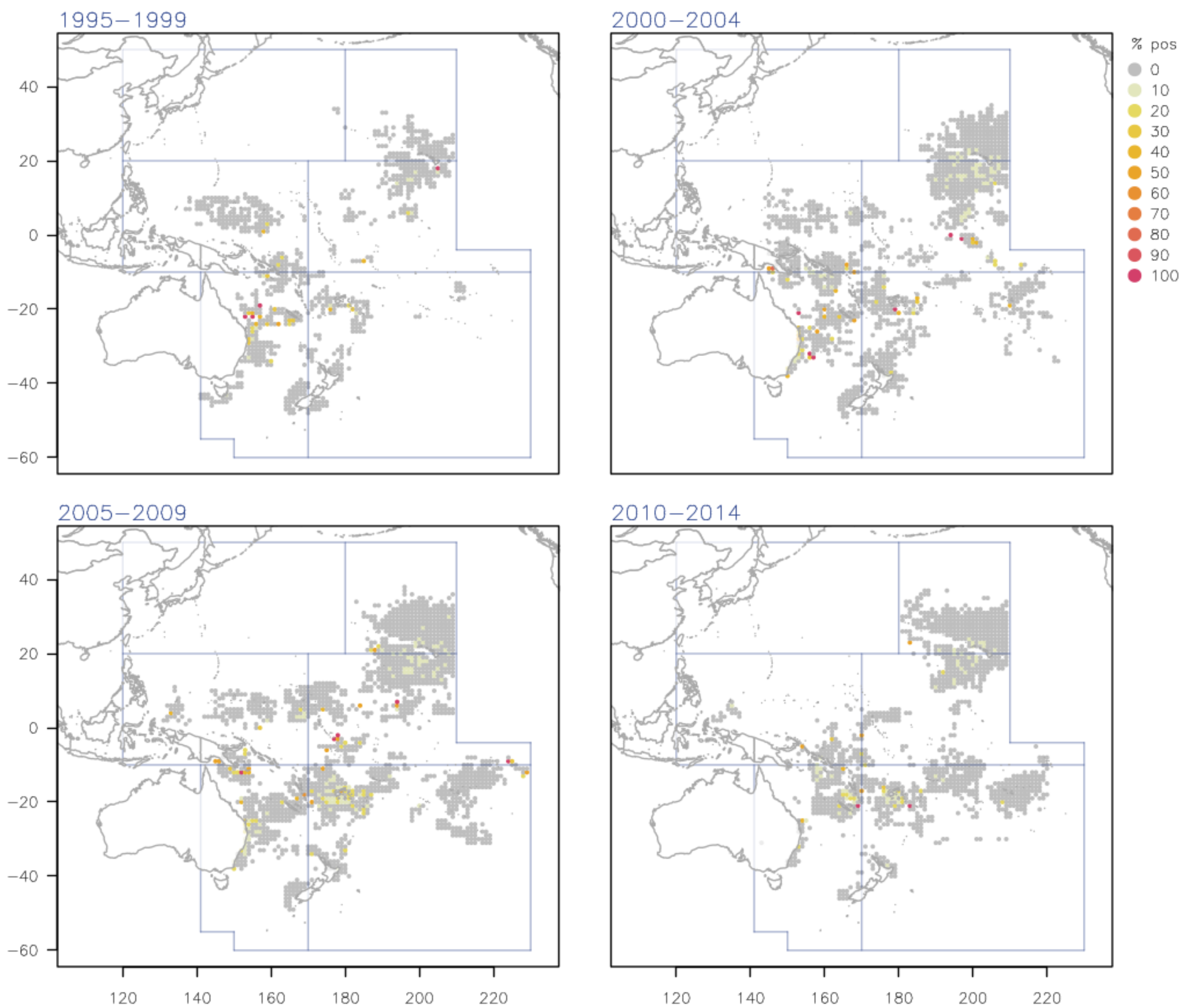


Figure 20: Spatial distribution of the proportion of longline sets for which one or more hammerhead shark were caught for each five year period between 1995 and 2014.

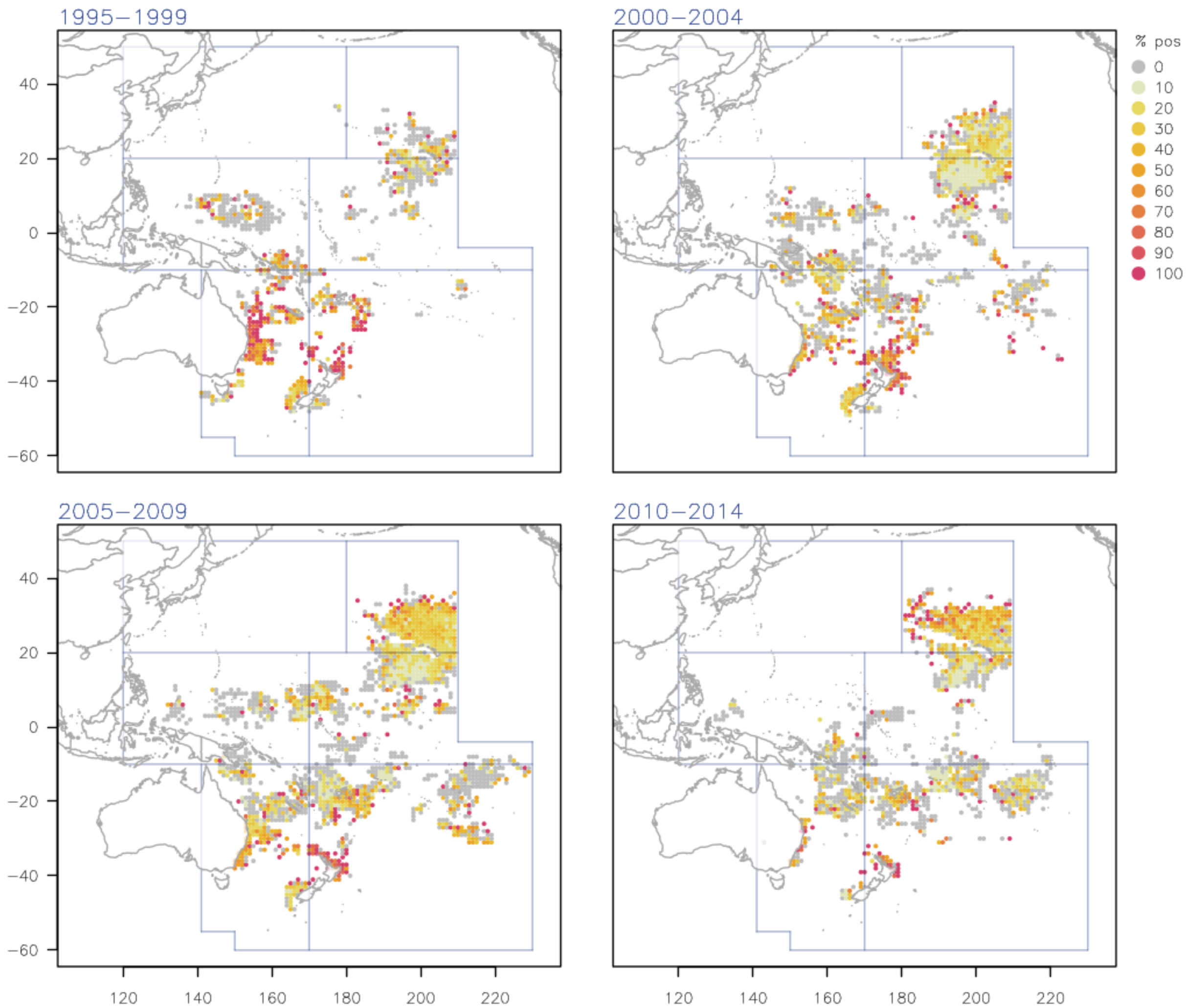


Figure 21: Spatial distribution of the proportion of longline sets for which one or more mako shark were caught for each five year period between 1995 and 2014.

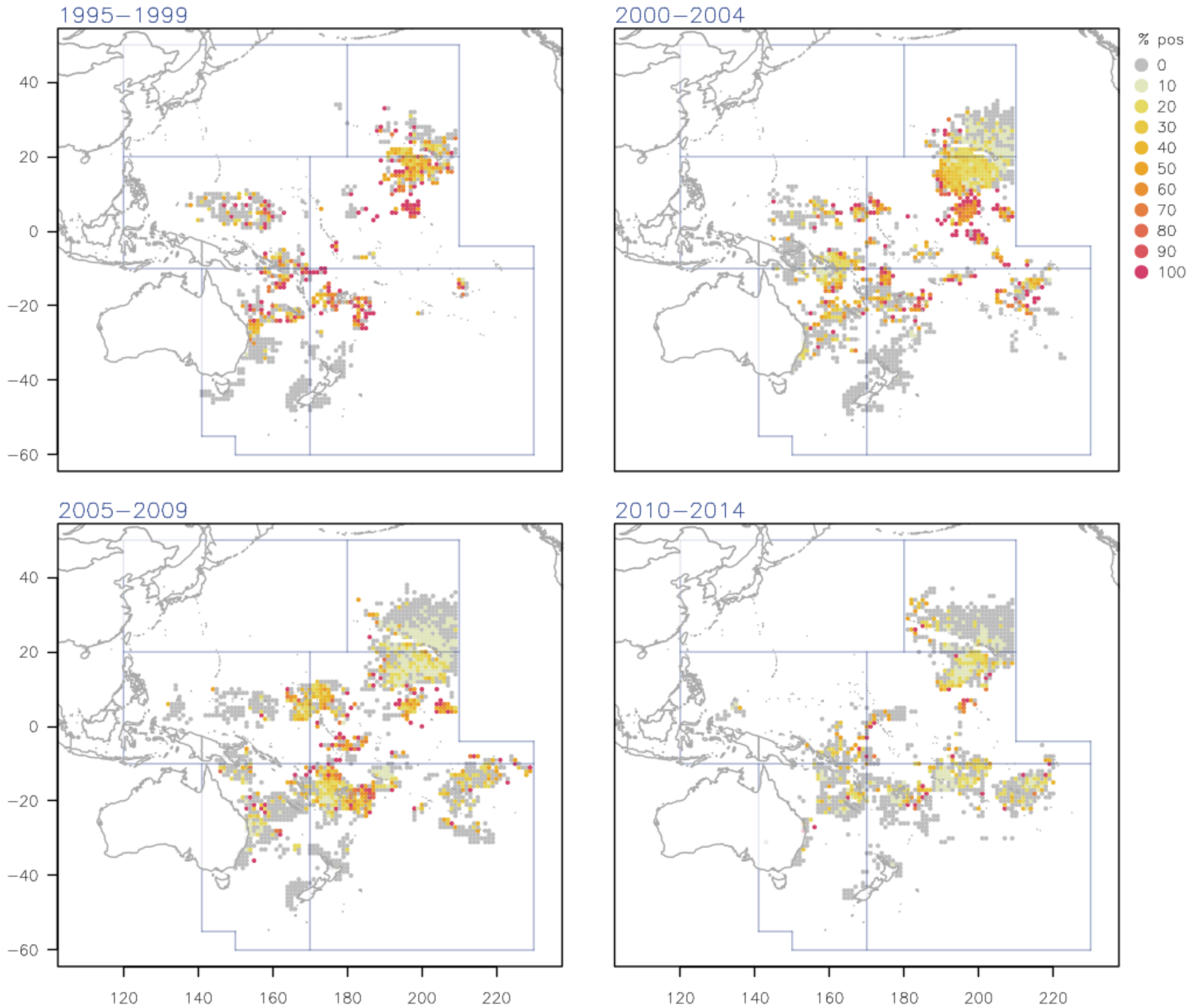


Figure 22: Spatial distribution of the proportion of longline sets for which one or more oceanic whitetip shark were caught for each five year period between 1995 and 2014.

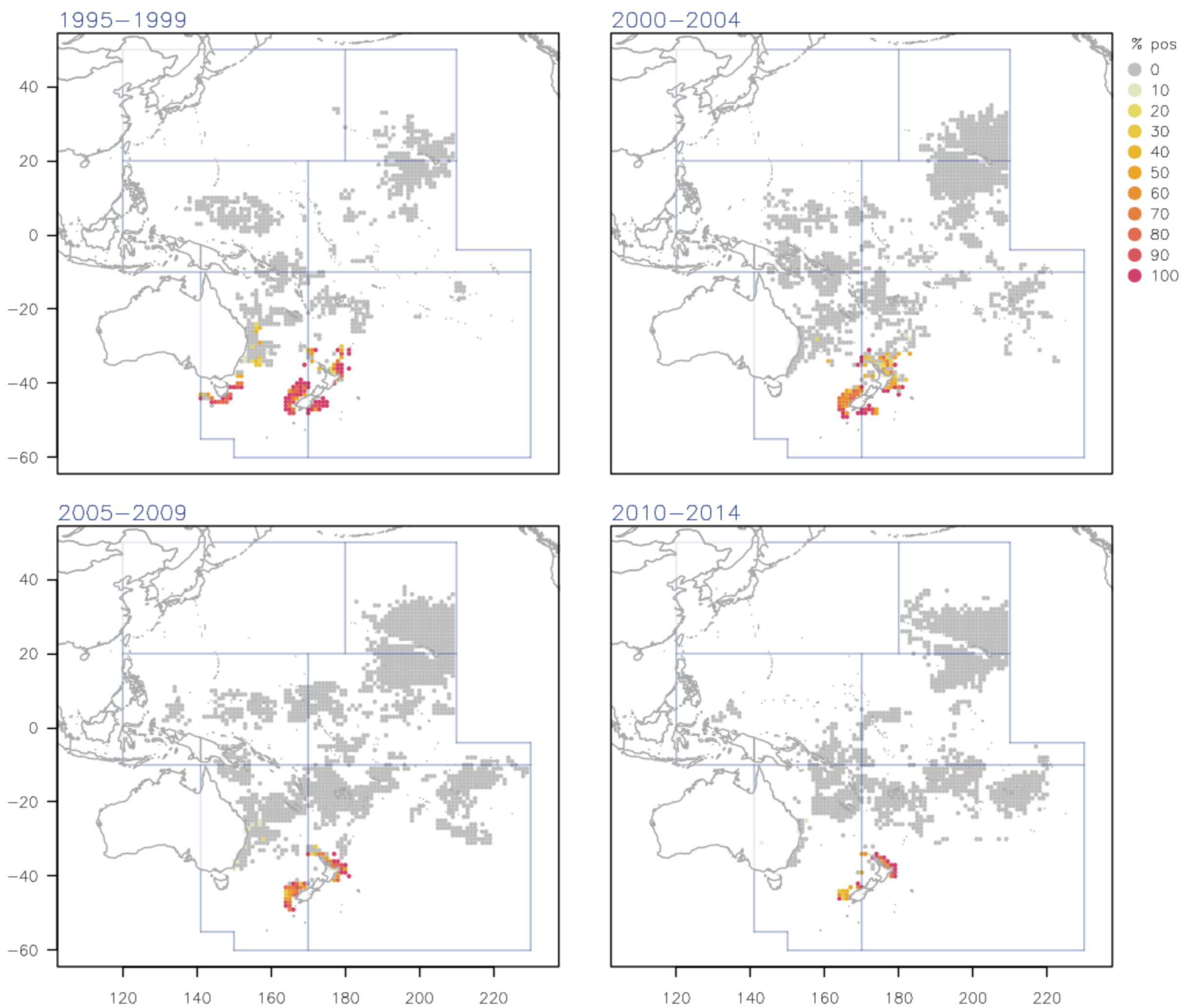


Figure 23: Spatial distribution of the proportion of longline sets for which one or more porbeagle shark were caught for each five year period between 1995 and 2014.

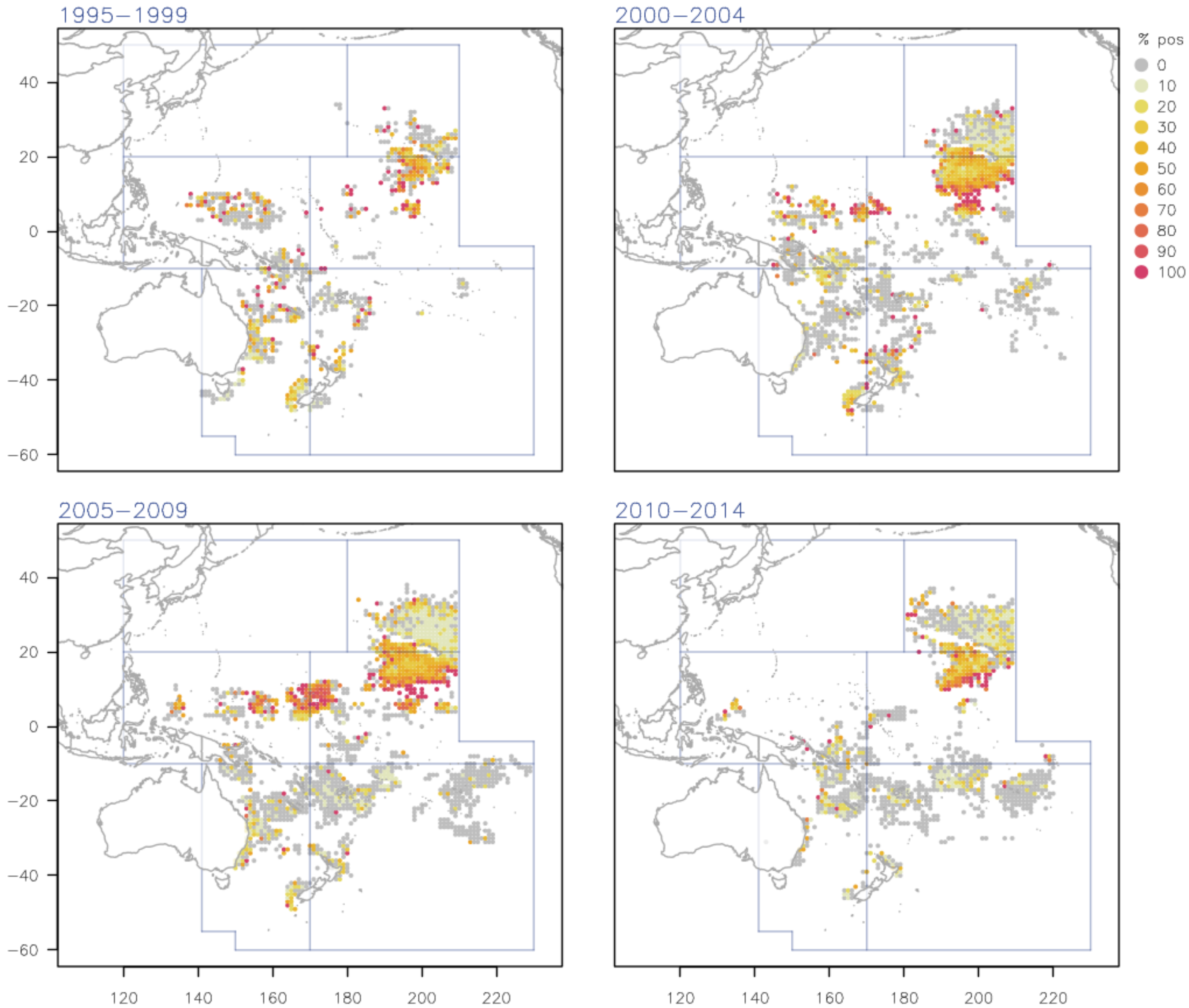


Figure 24: Spatial distribution of the proportion of longline sets for which one or more thresher shark were caught for each five year period between 1995 and 2014.

B.2 Species Composition Indicator Analyses: Figures

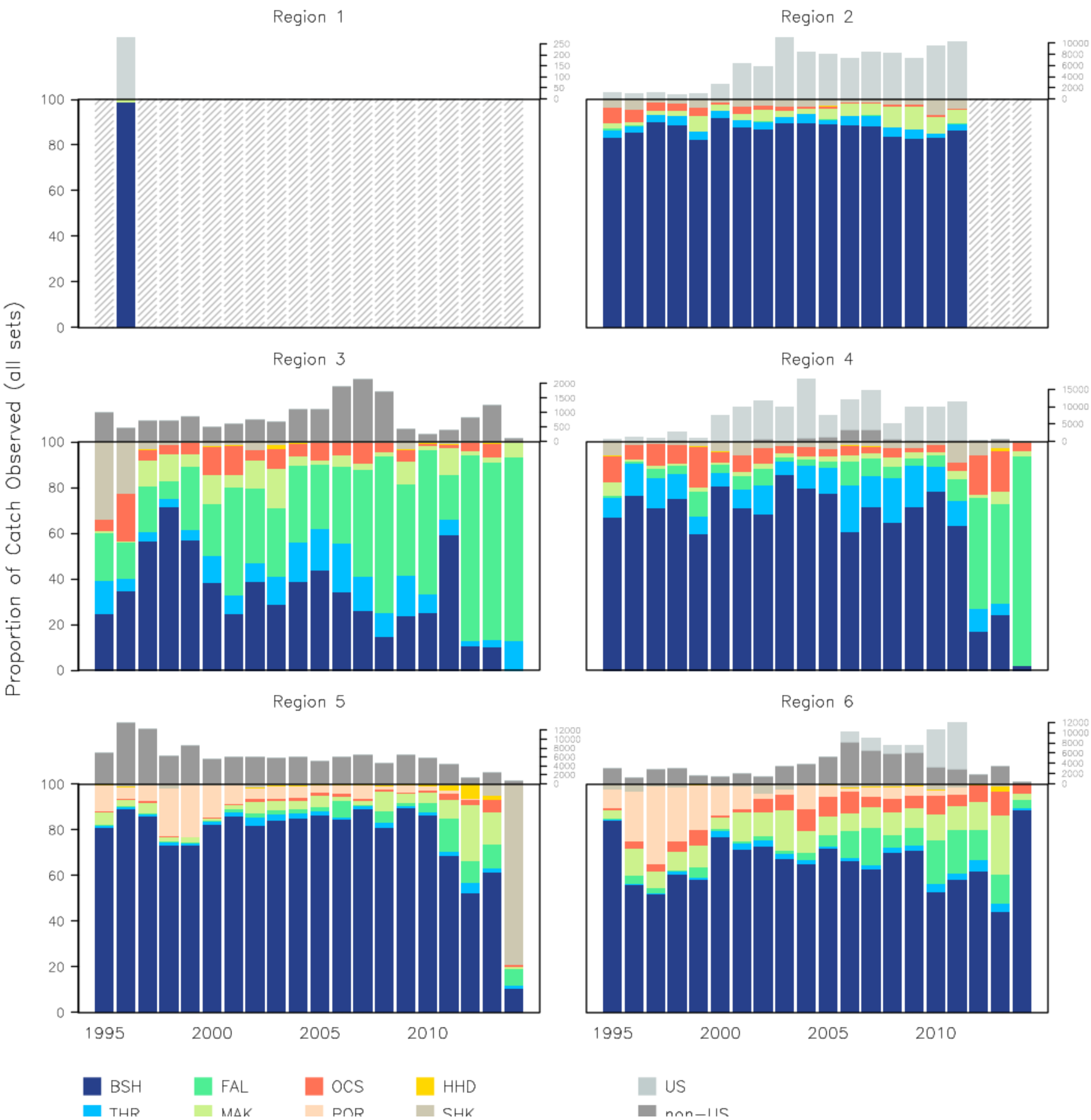


Figure 25: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for all longline sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each species in the catch.

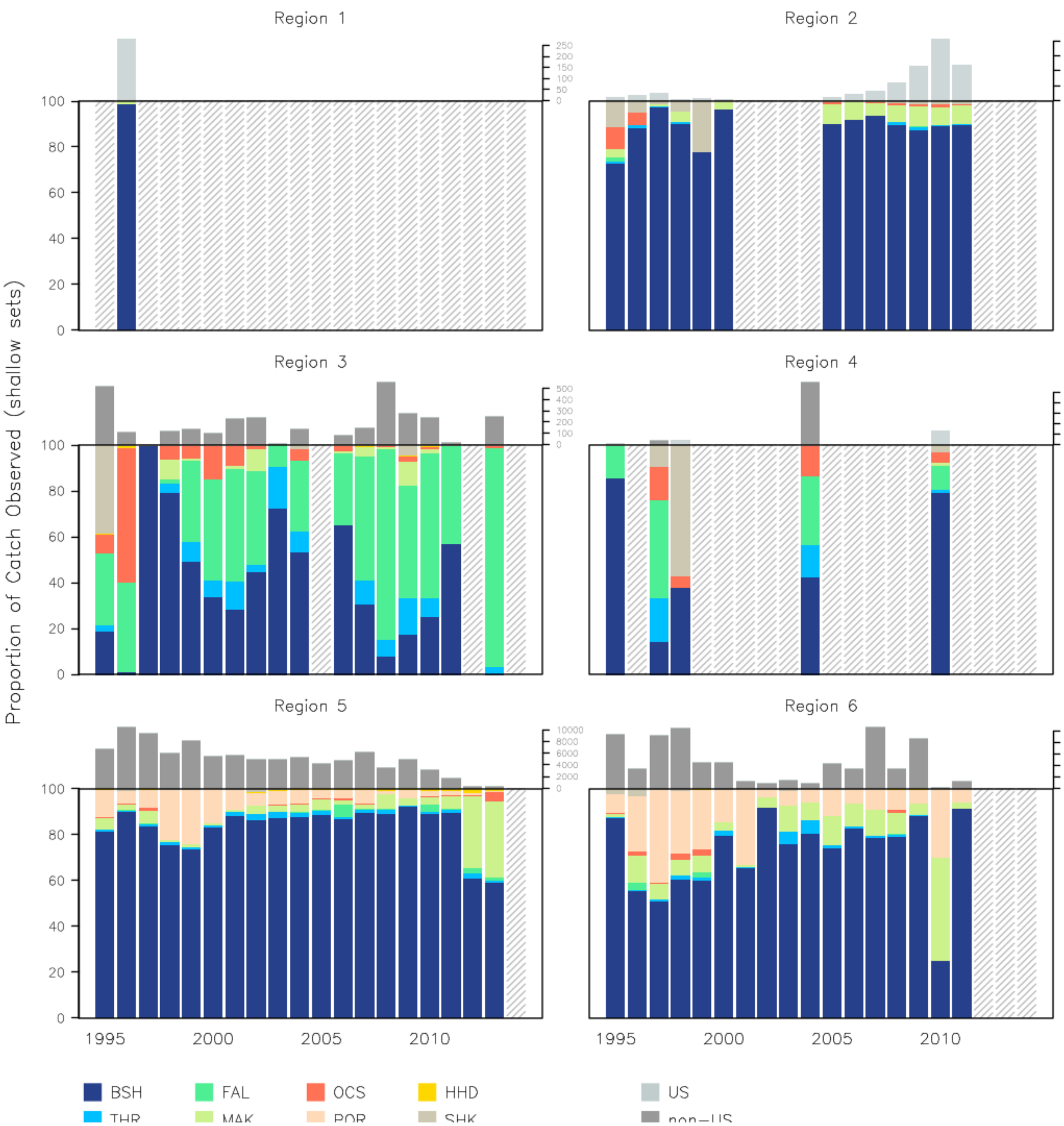


Figure 26: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for shallow longline sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each species in the catch.

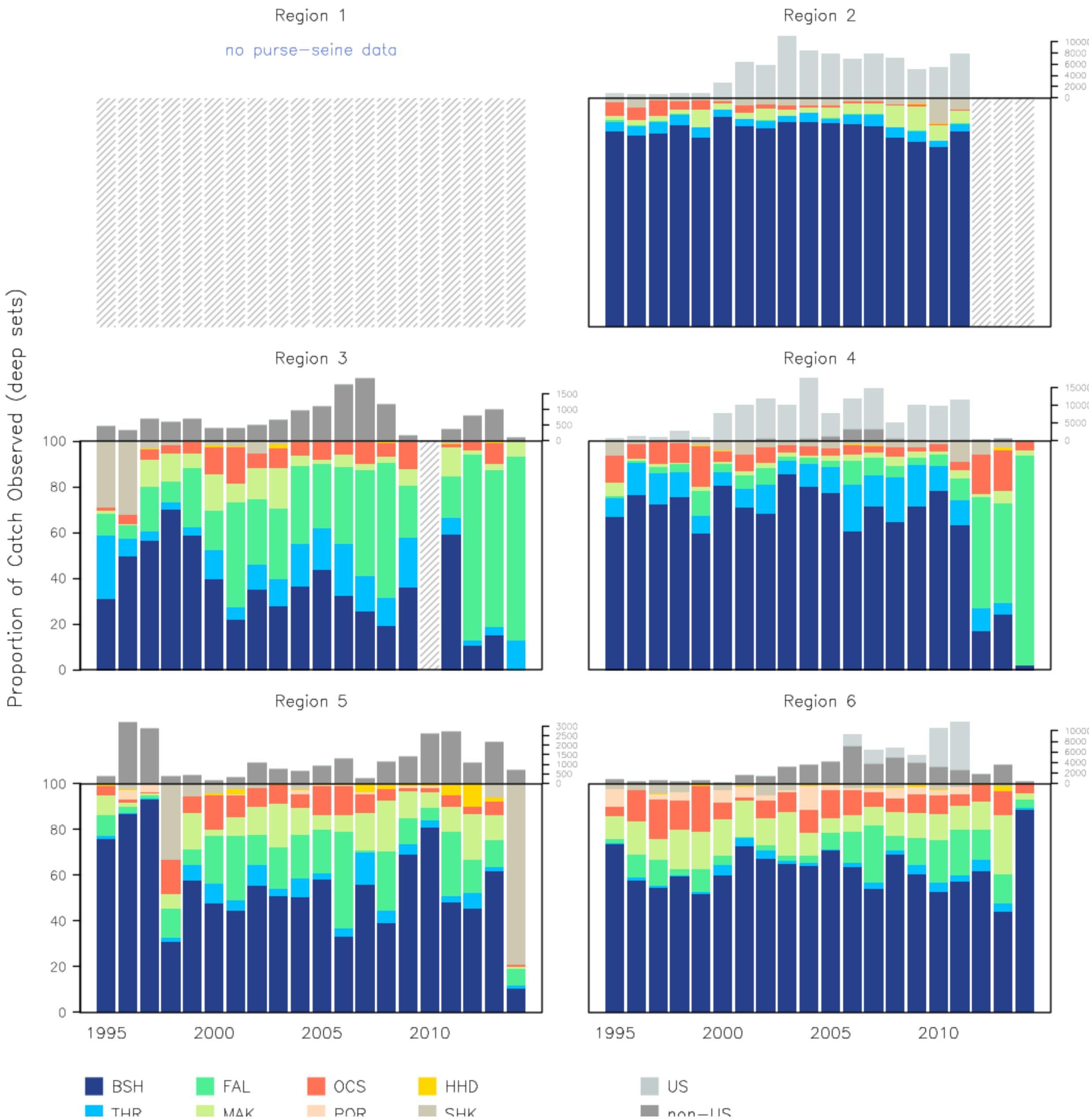


Figure 27: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for deep longline sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each species in the catch.

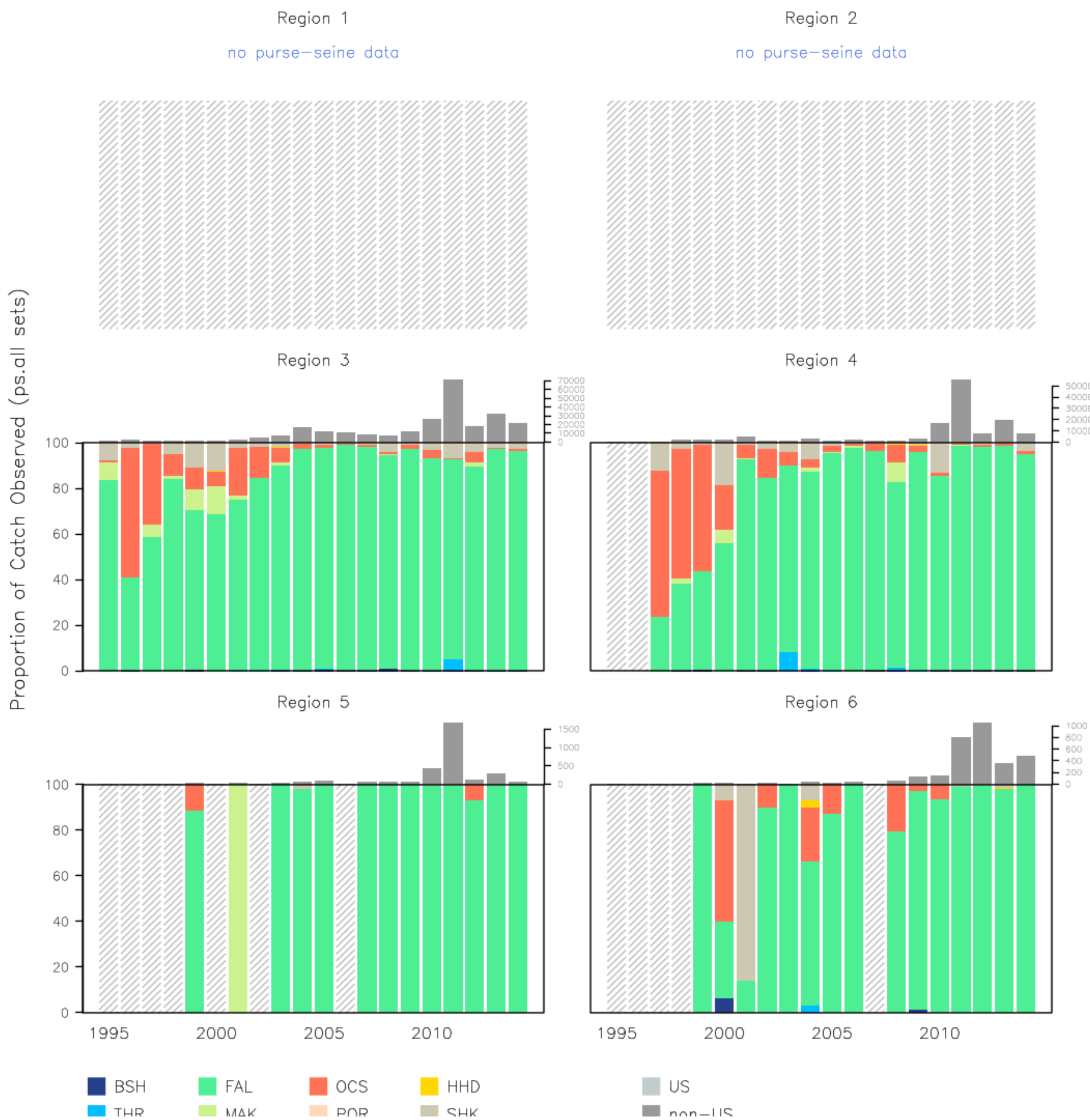


Figure 28: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for all purse seine sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each species in the catch.

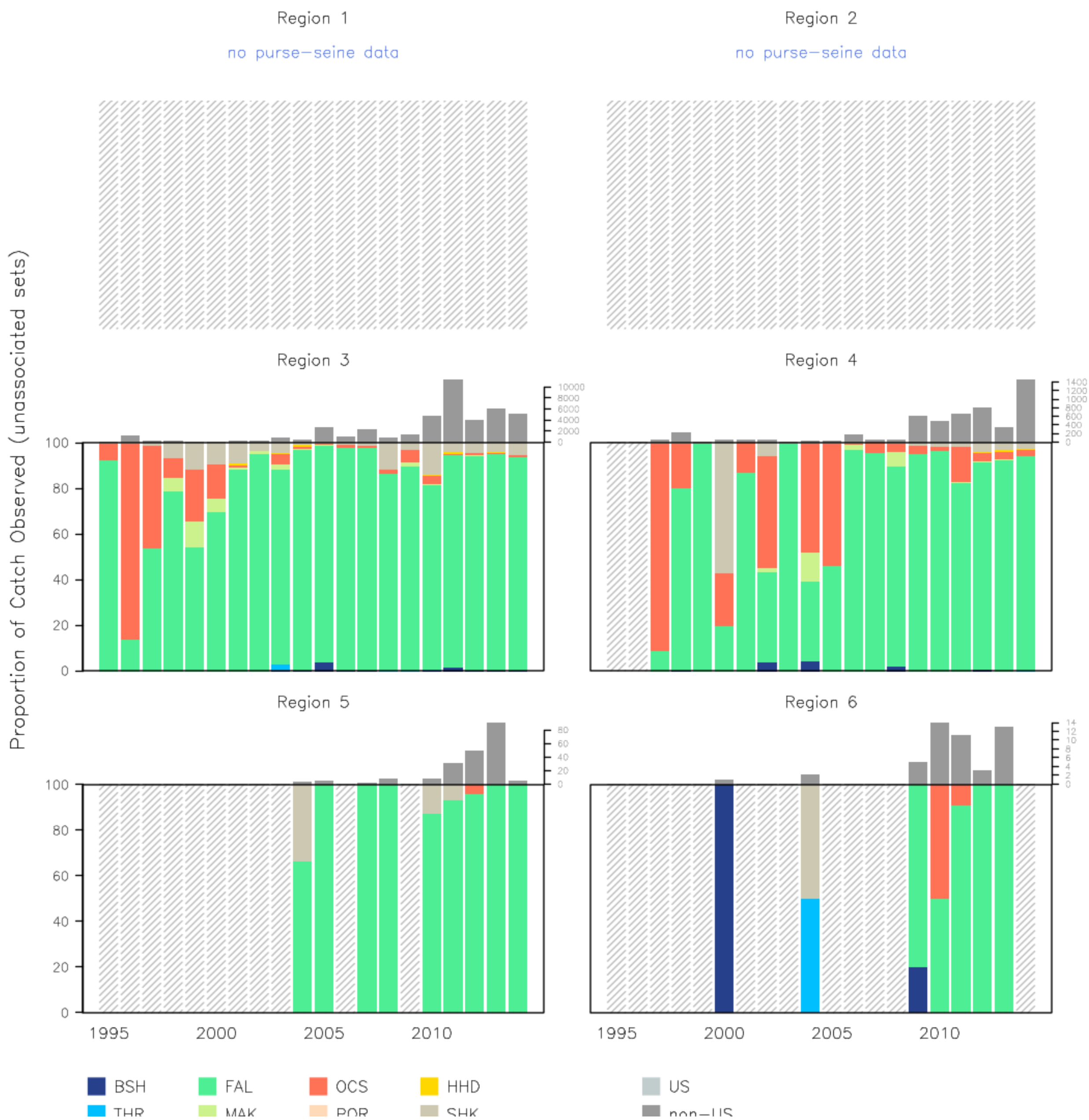


Figure 29: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for unassociated purse seine sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each species in the catch.

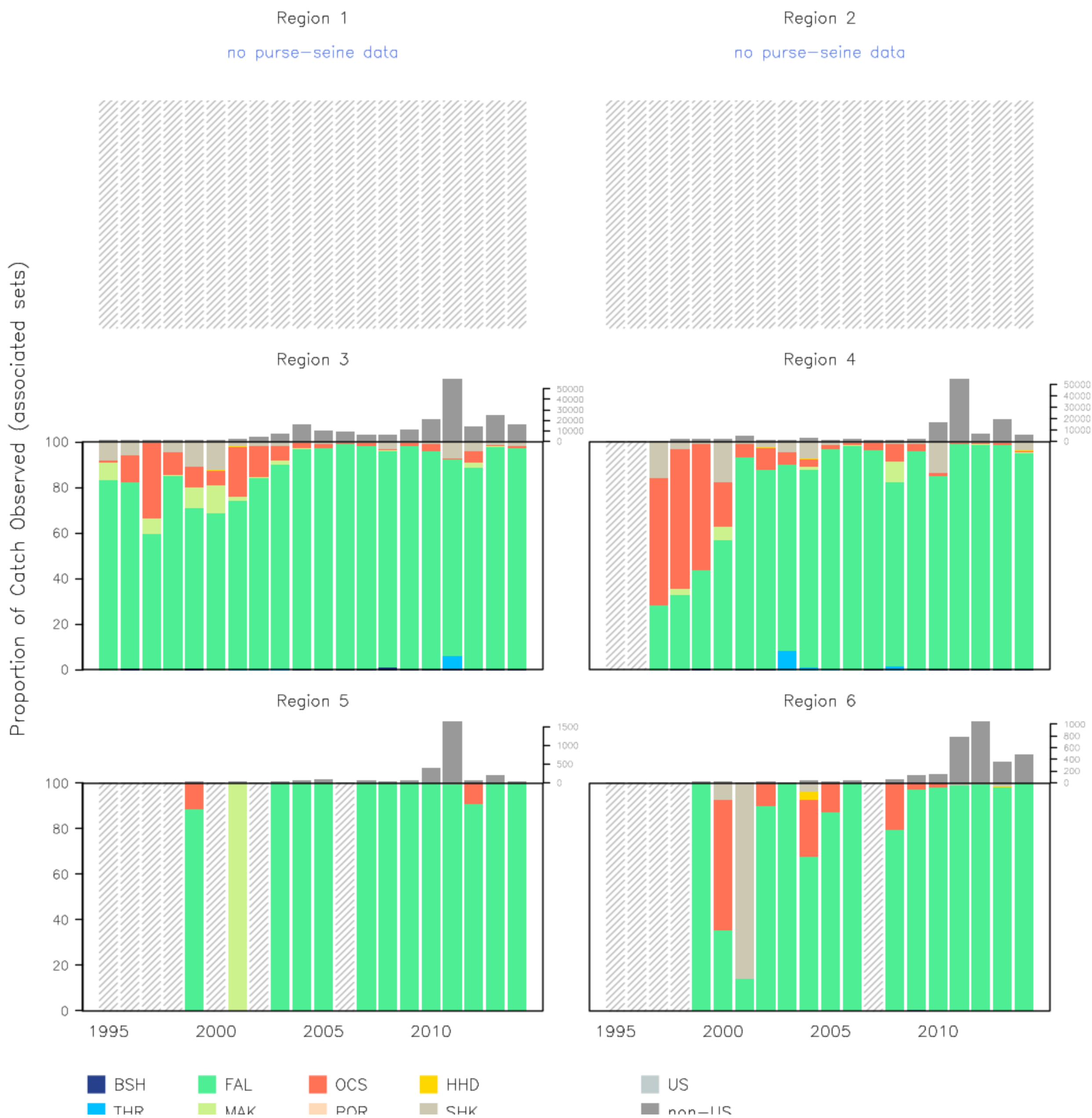


Figure 30: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for all associated seine sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each species in the catch.

B.3 CPUE Indicators. Model diagnostics and extra plots

B.3.1 Nominal CPUE

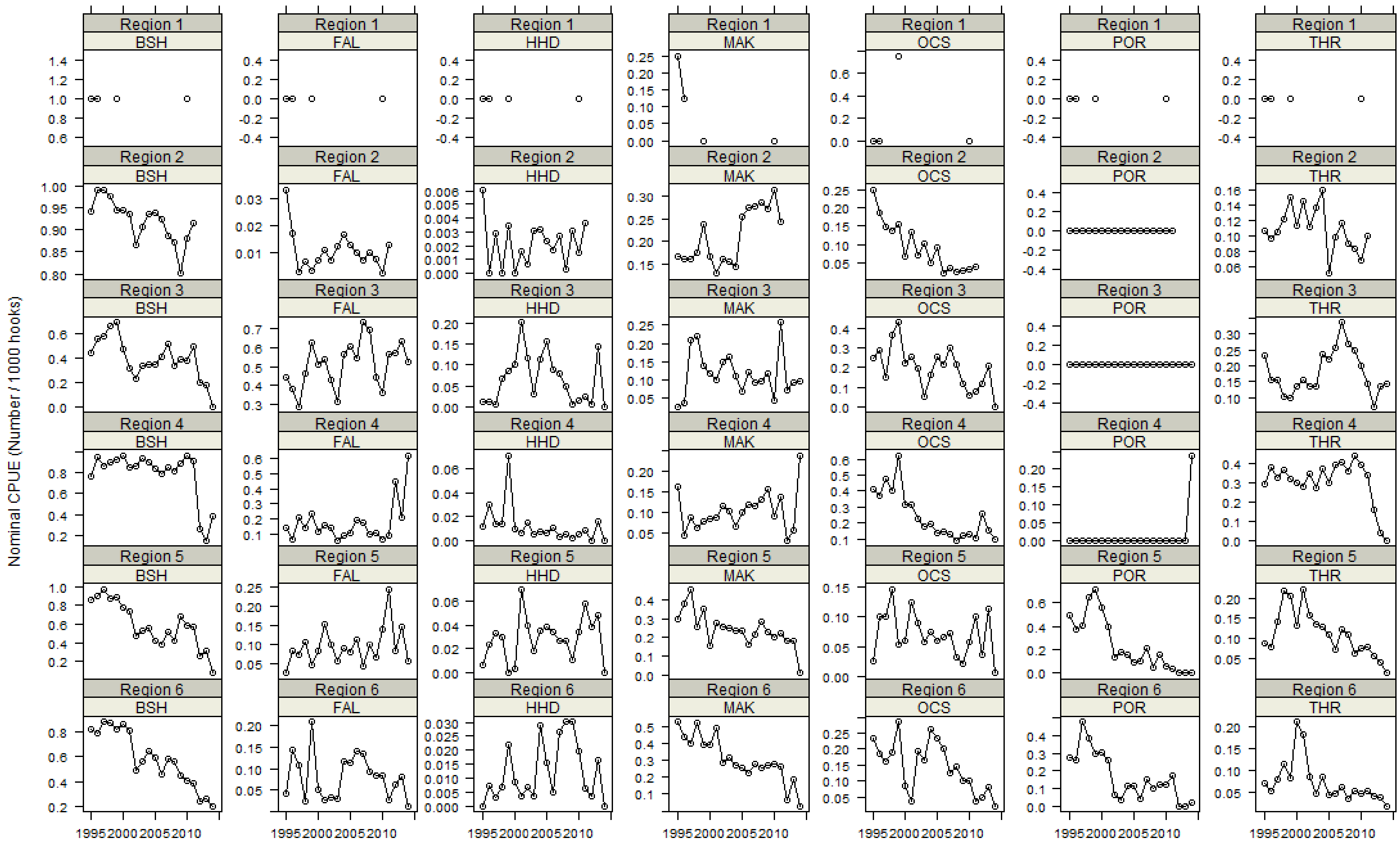


Figure 31: Nominal CPUE (numbers/1000 hooks) by species and region for sharks caught by longline.

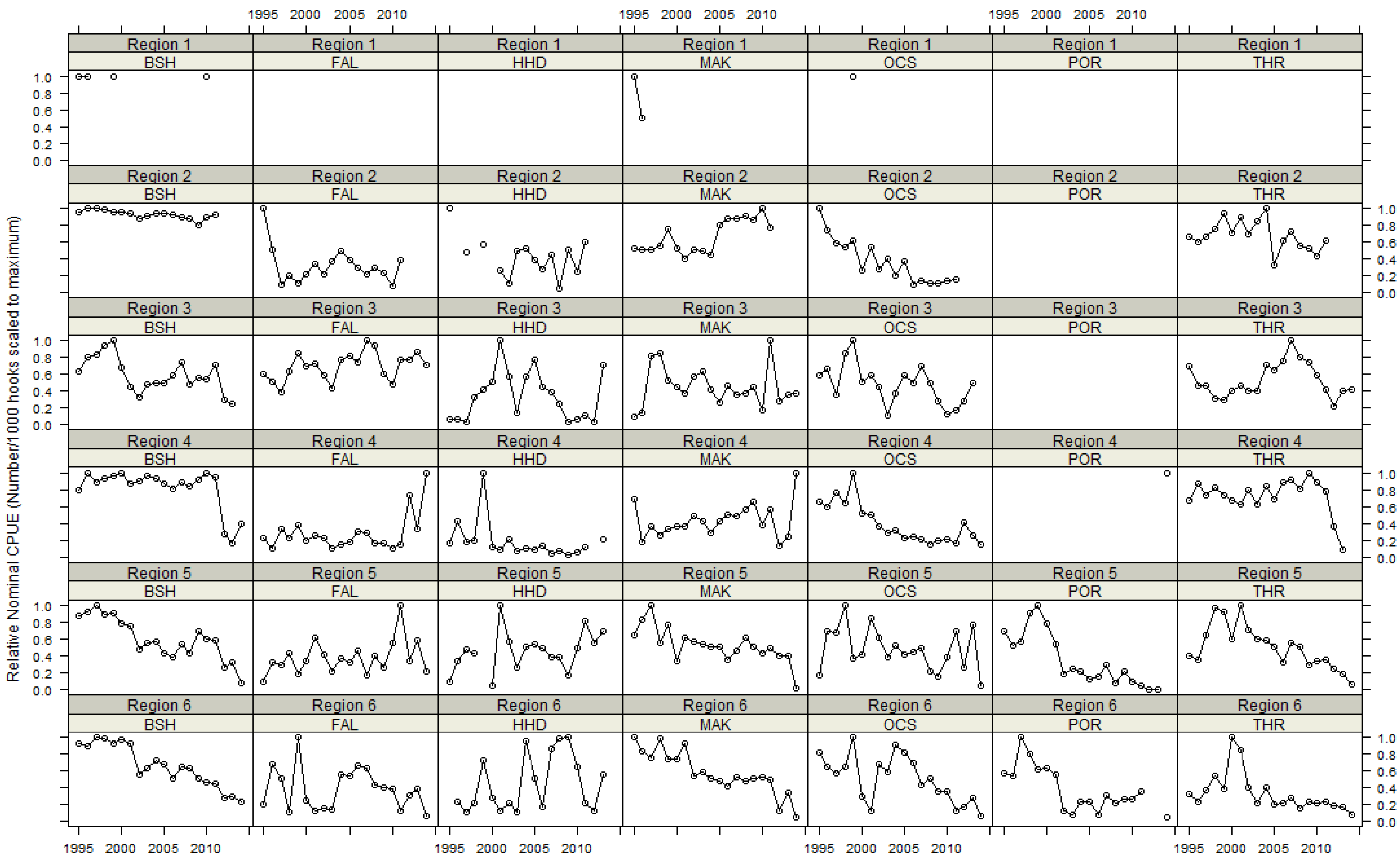


Figure 32: Relative nominal CPUE (numbers/1000 hooks standardised to a maximum value of 1) by species and region for sharks caught by longline.

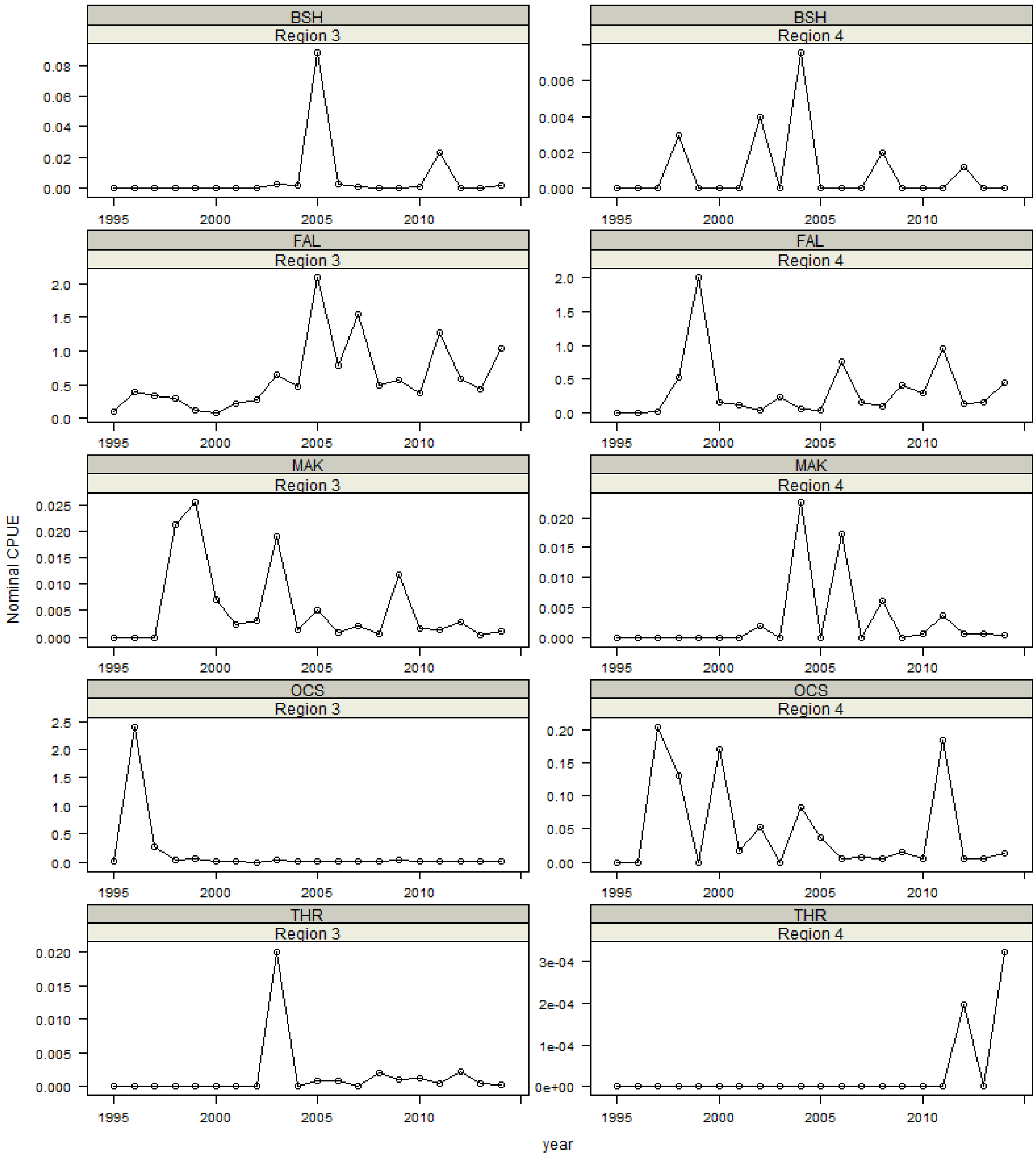


Figure 33: Nominal CPUE (numbers/1000 hooks) by species and region for sharks caught by purse seine (unassociated sets).

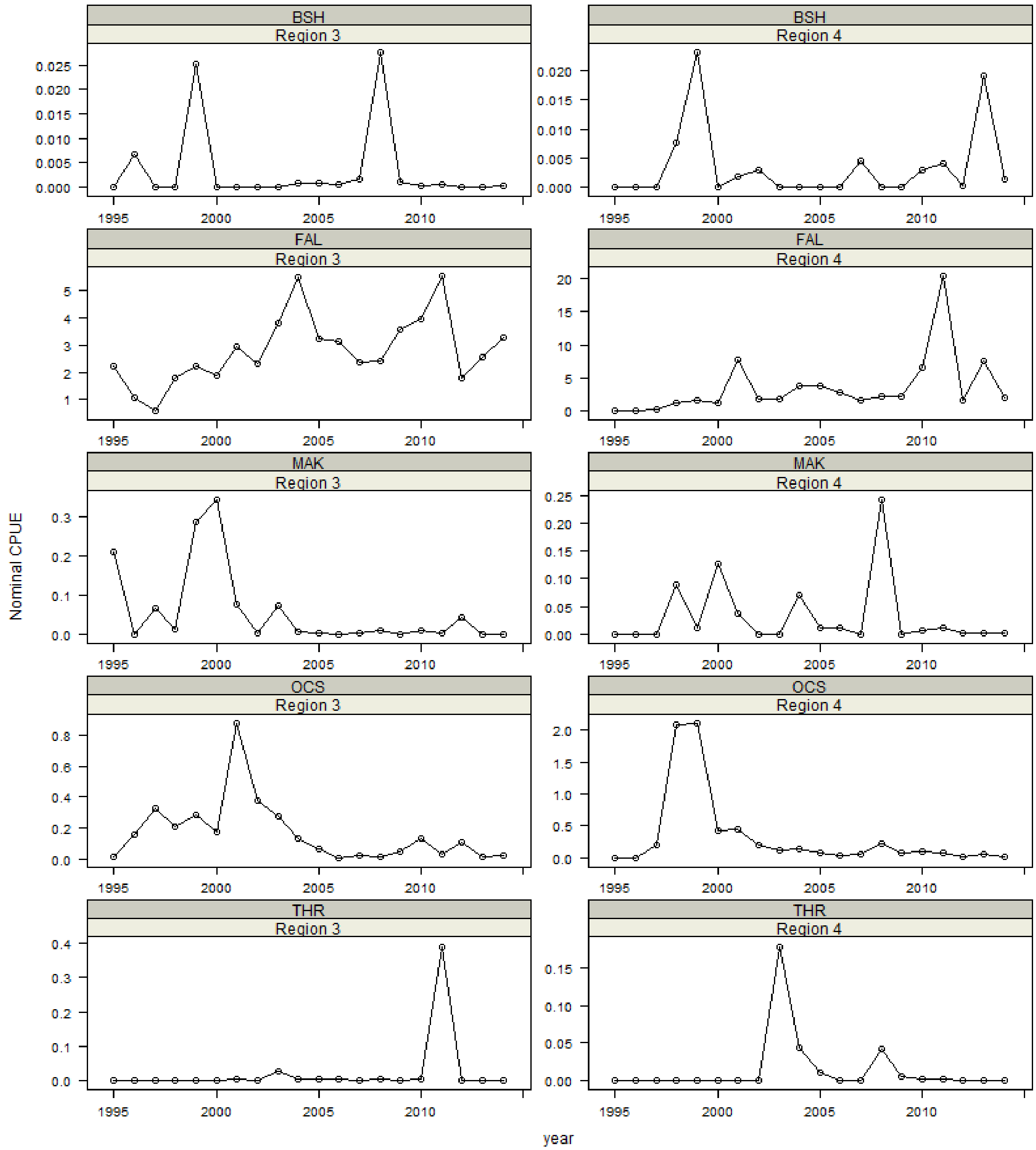


Figure 34: Nominal CPUE (numbers/1000 hooks) by species and region for sharks caught by purse seine (associated sets).

B.3.2 Standardised CPUE

Figure 35: Nominal and standardised CPUE for blue shark in the northern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

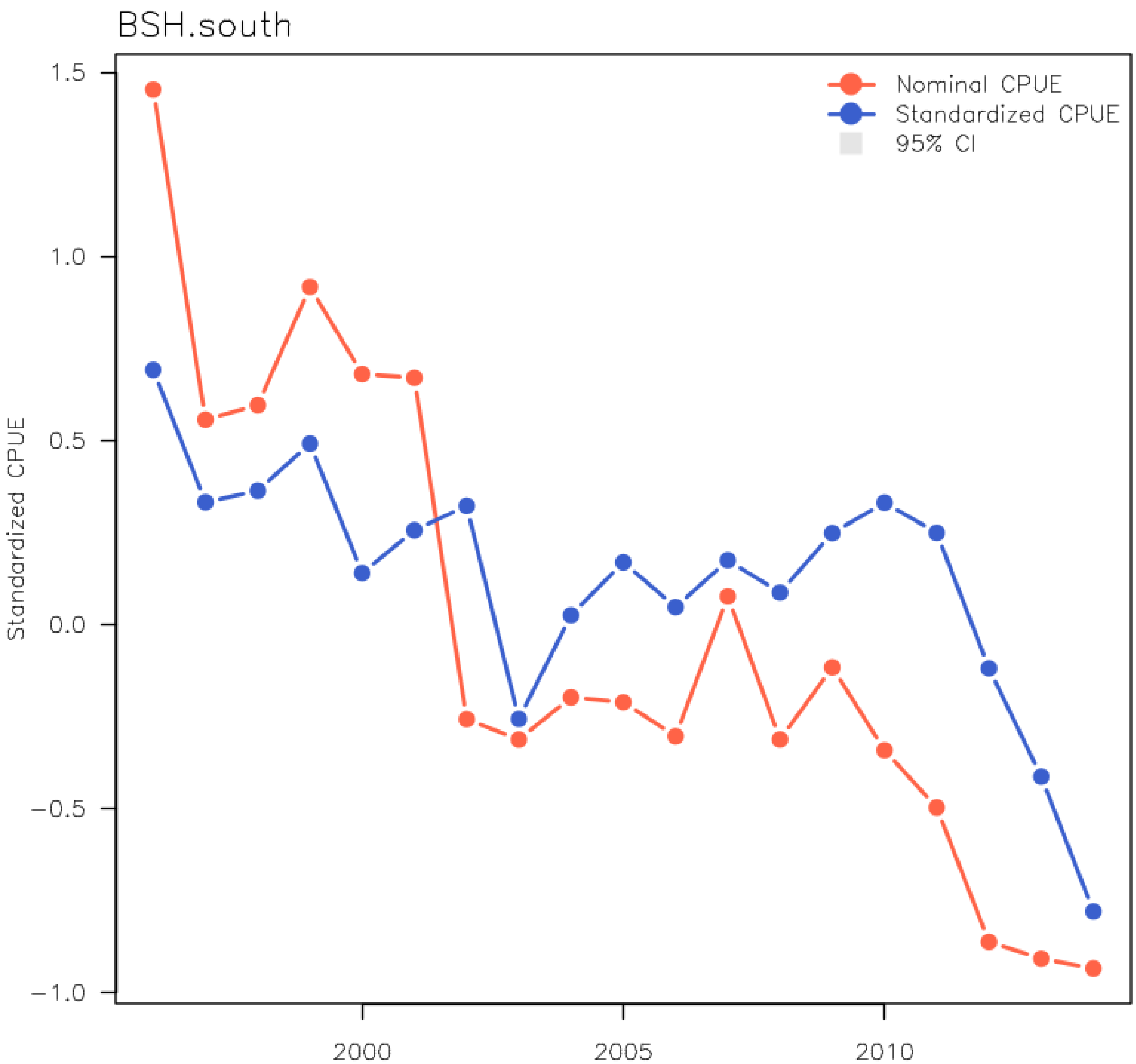


Figure 36: Nominal and standardised CPUE for blue shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

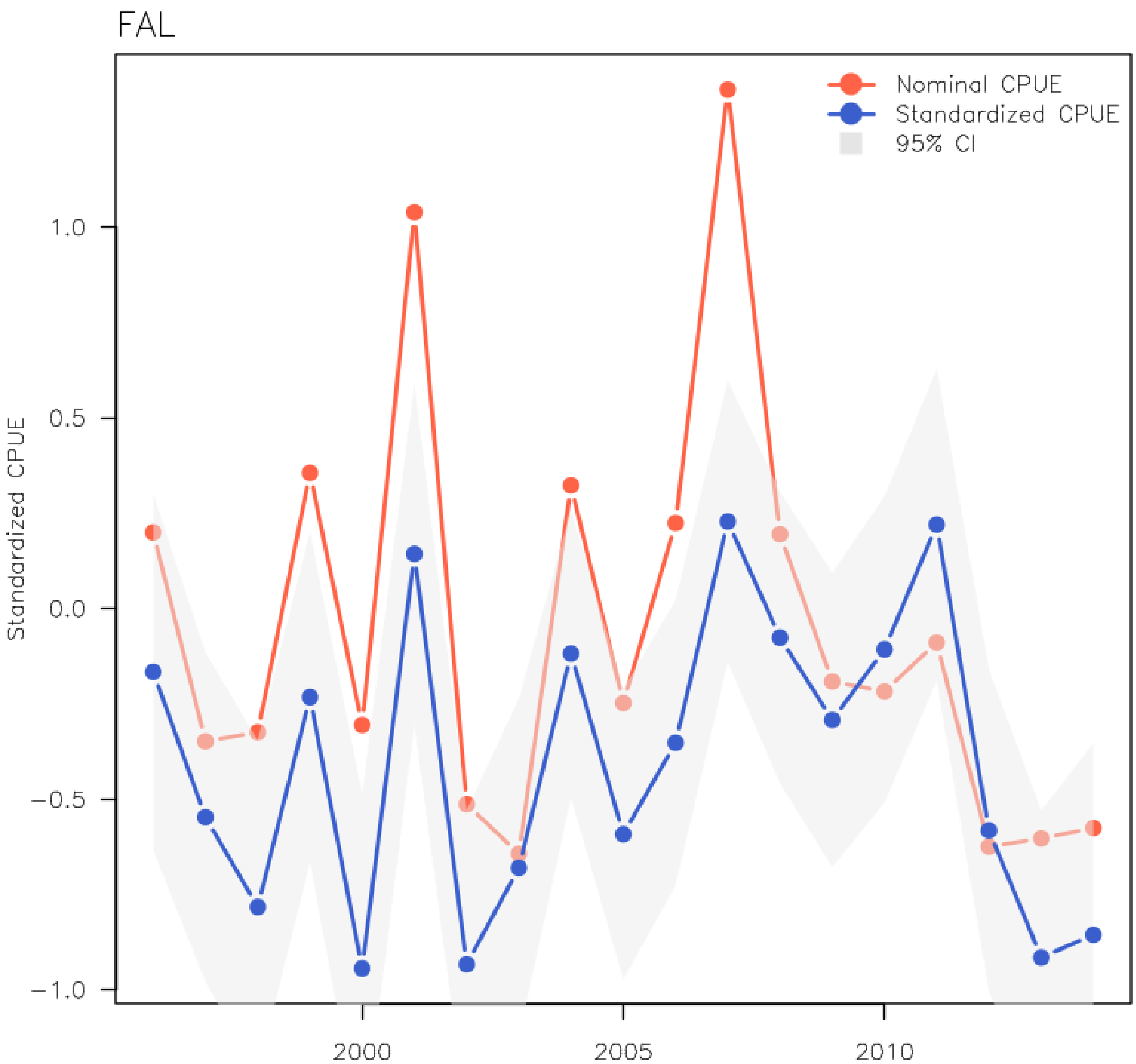


Figure 37: Nominal and standardised CPUE for silky shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals..

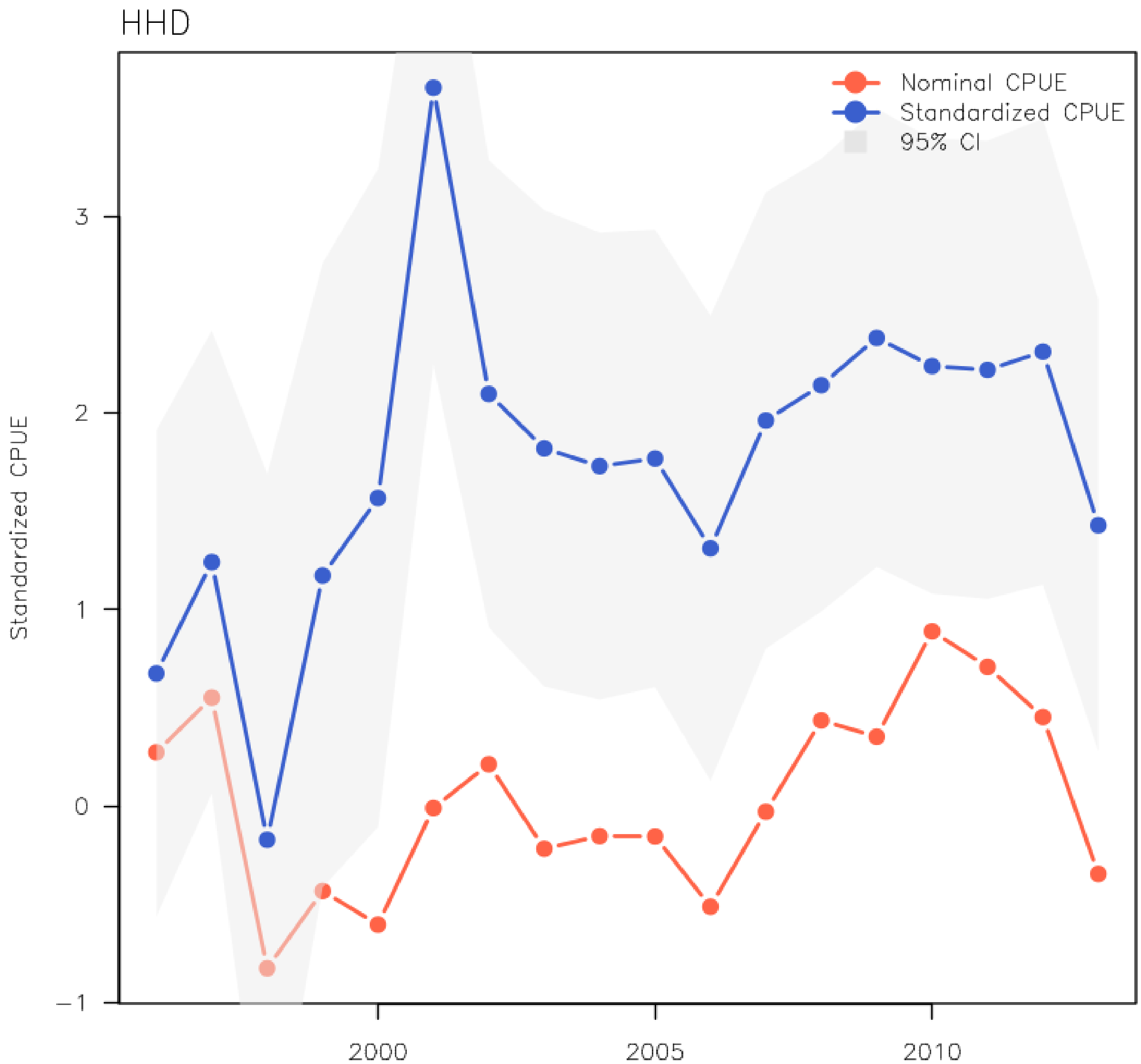


Figure 38: Nominal and standardised CPUE for hammerhead shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

Figure 39: Nominal and standardised CPUE for mako shark in the northern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

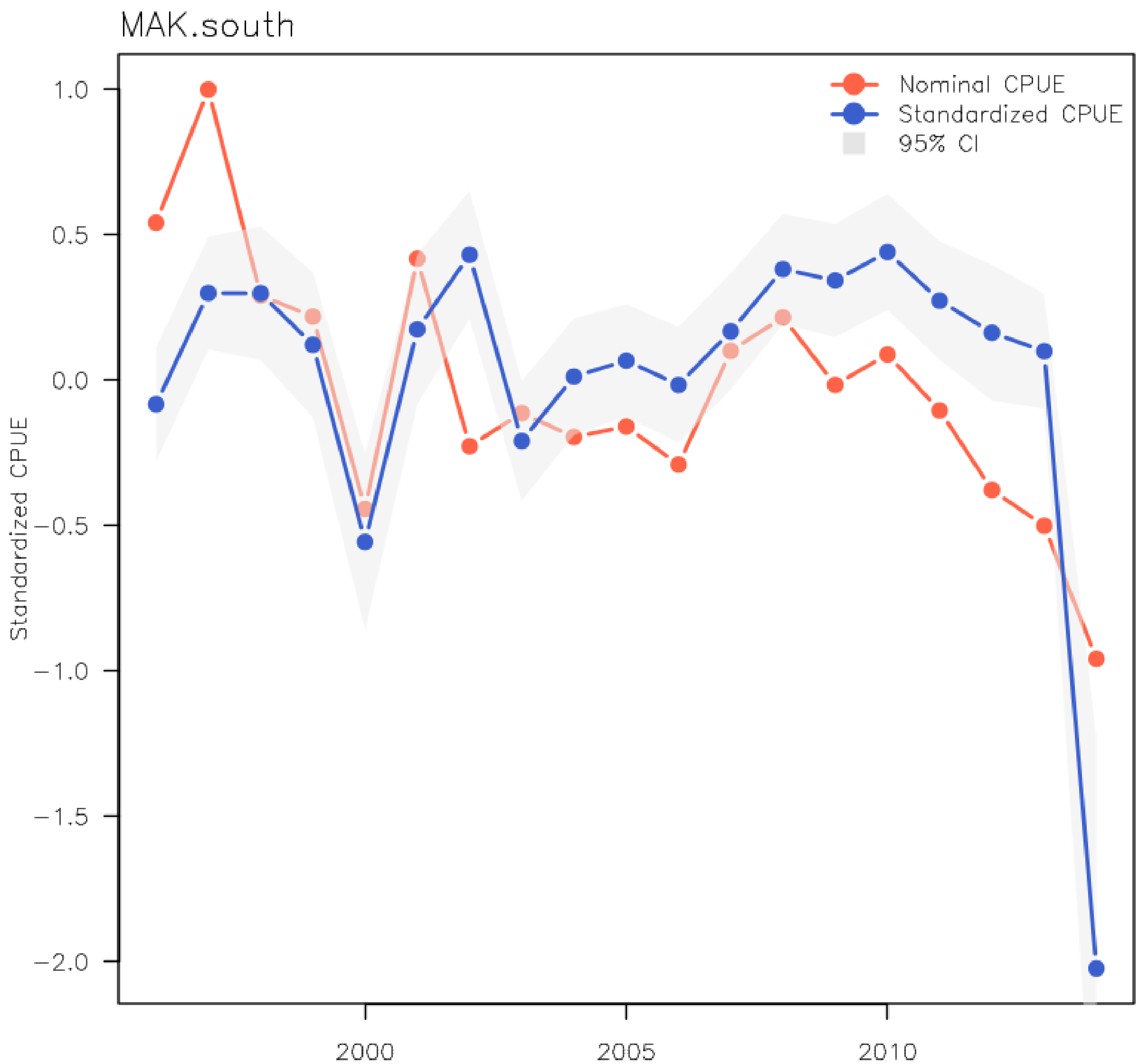


Figure 40: Nominal and standardised CPUE for mako shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals..

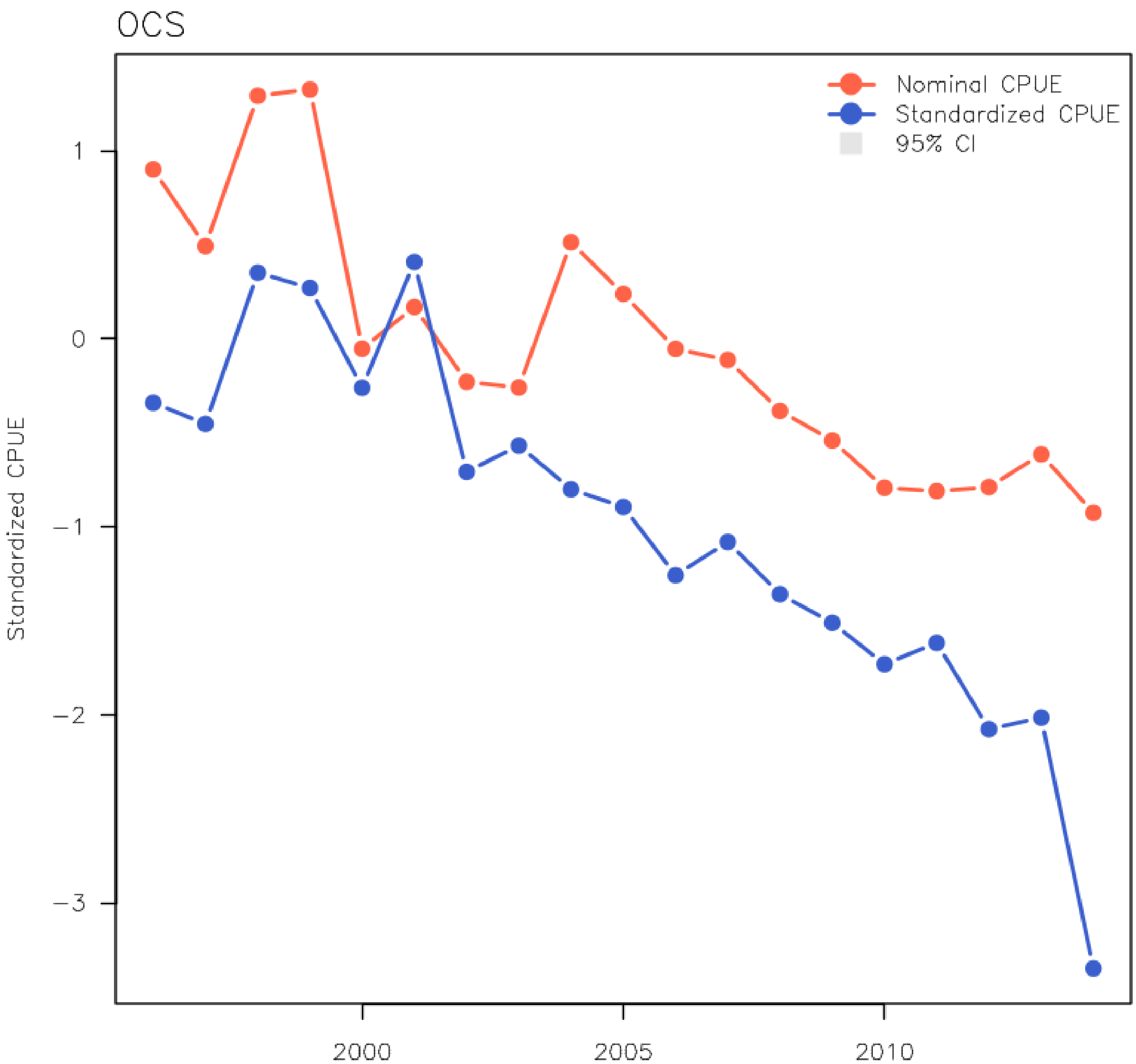


Figure 41: Nominal and standardised CPUE for oceanic whitetip sharks in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals..

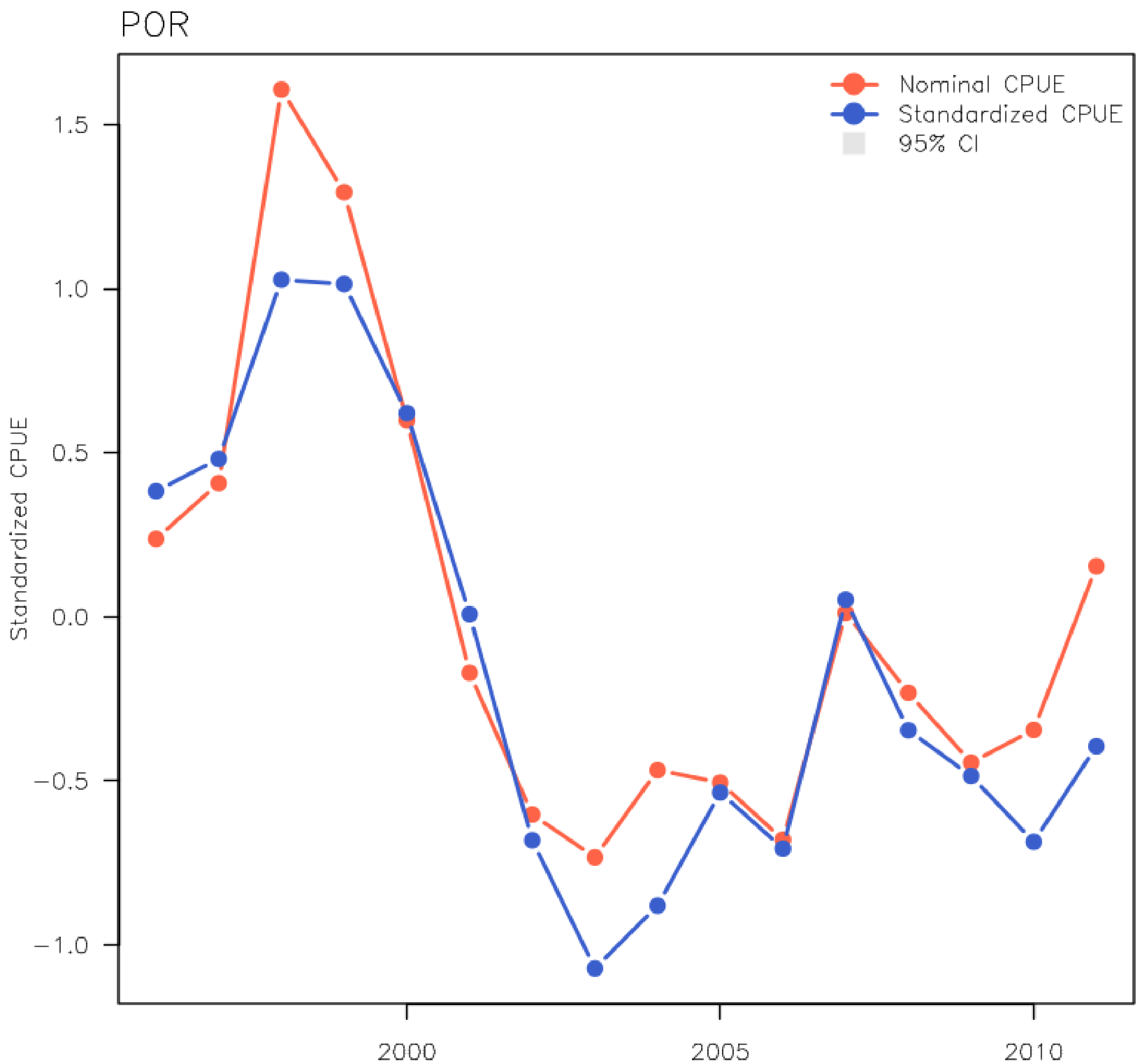


Figure 42: Nominal and standardised CPUE for porbeagle shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

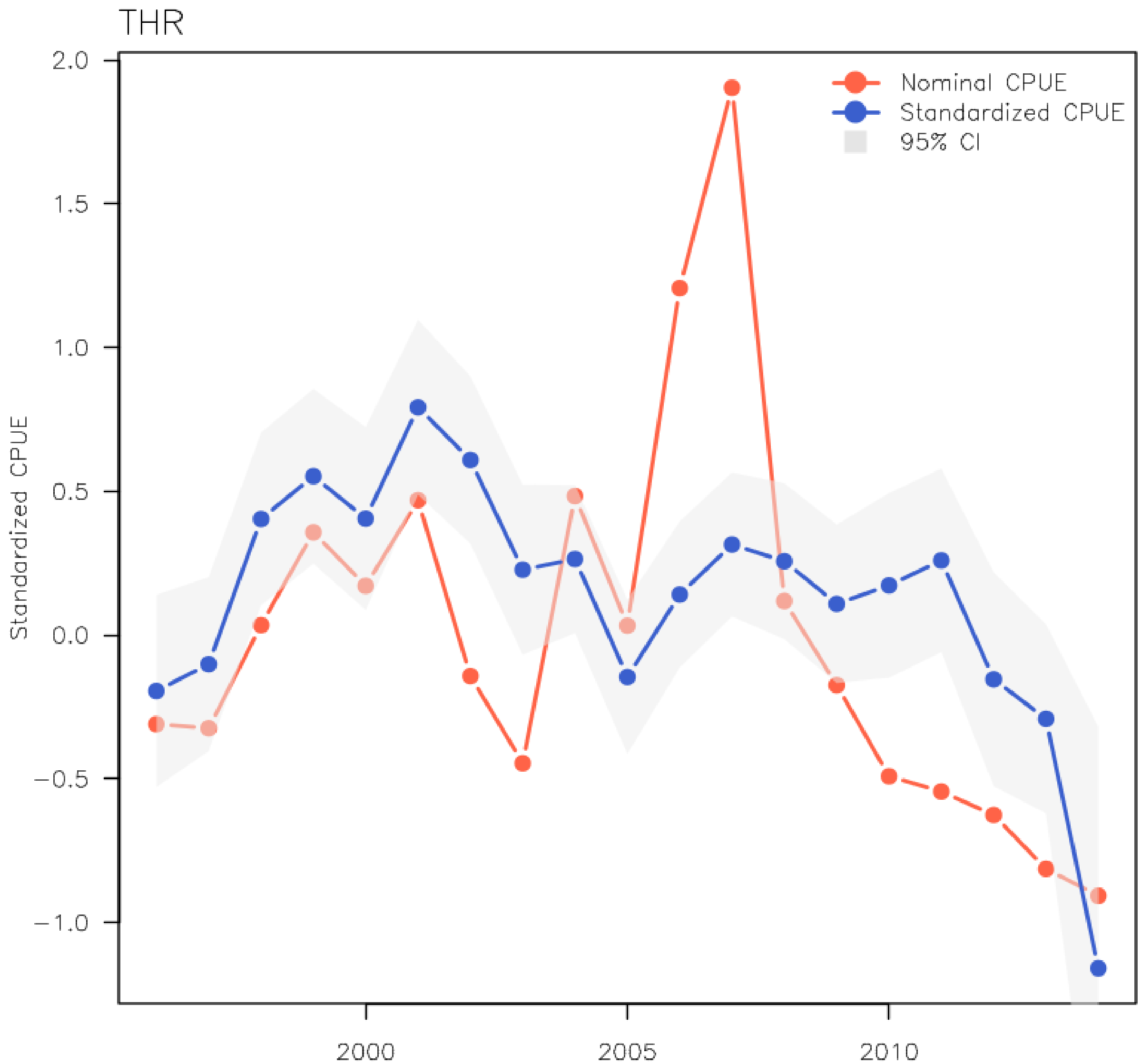
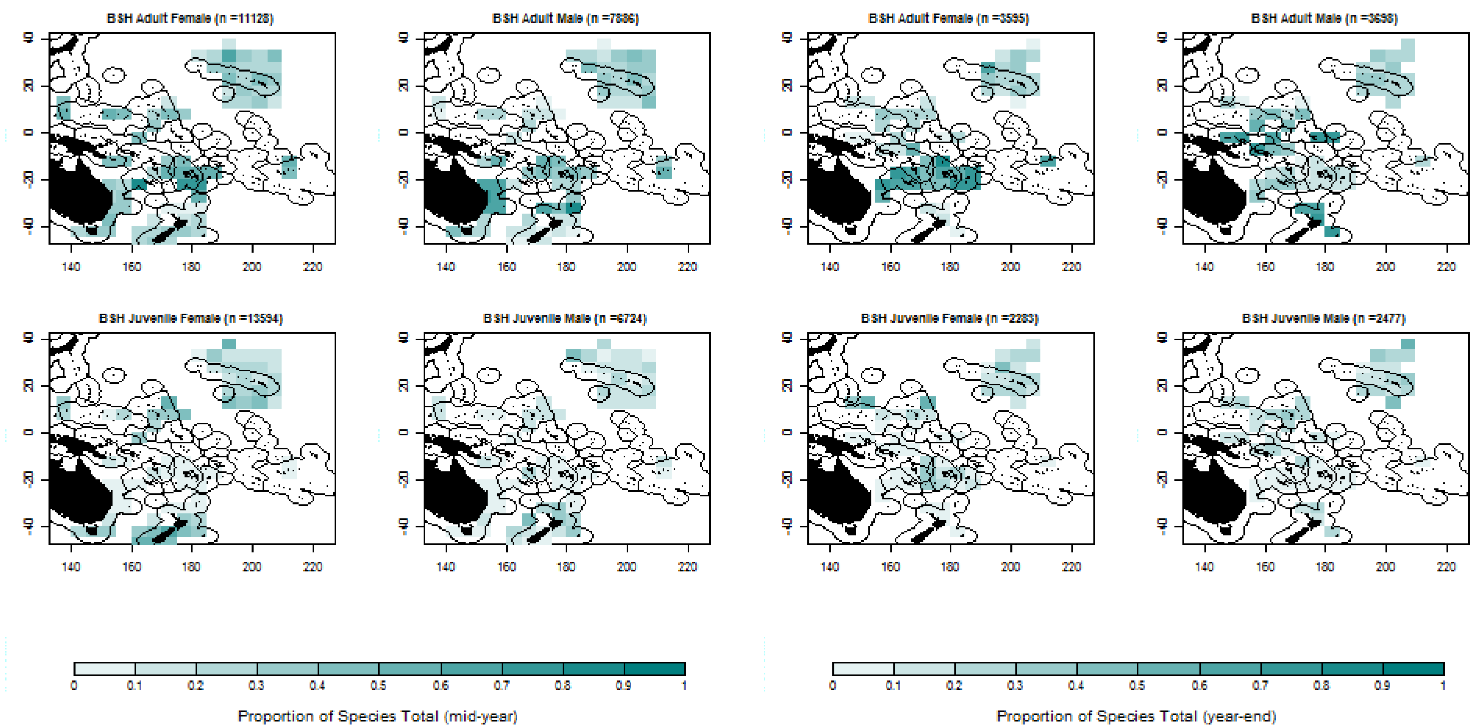


Figure 43: Nominal and standardised CPUE for thresher shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

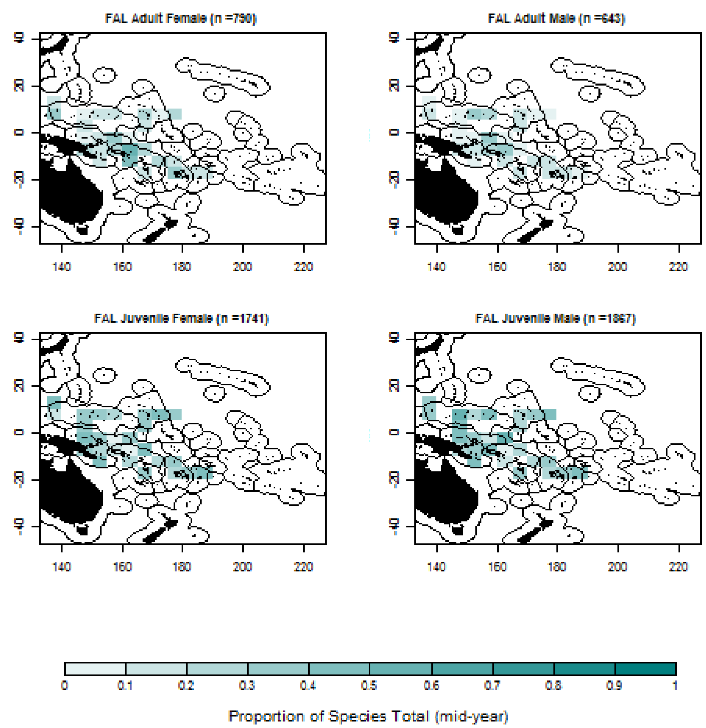
B.4 Biological Indicators



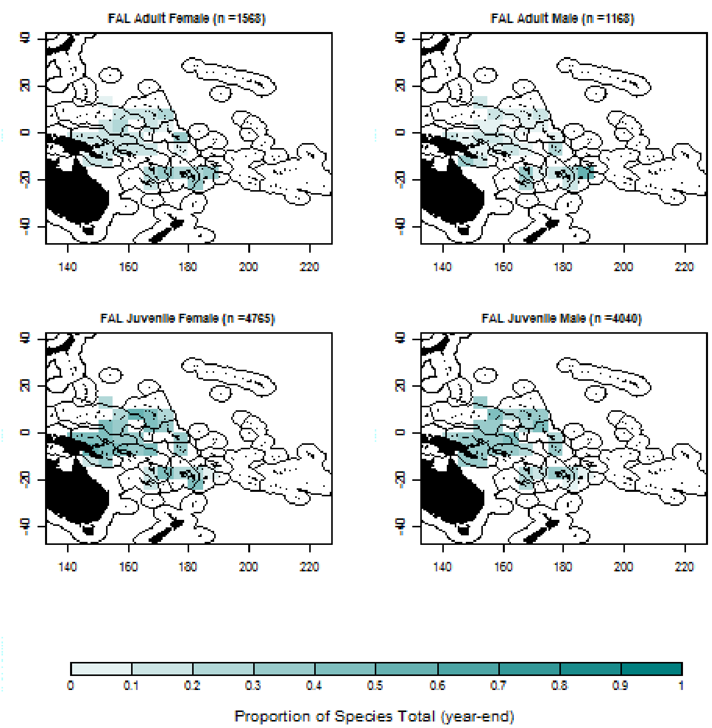
(a) Mid-year estimates.

(b) End of year estimates.

Figure 44: Blue Shark: Proportion of male and female as adults and juveniles in longline catches

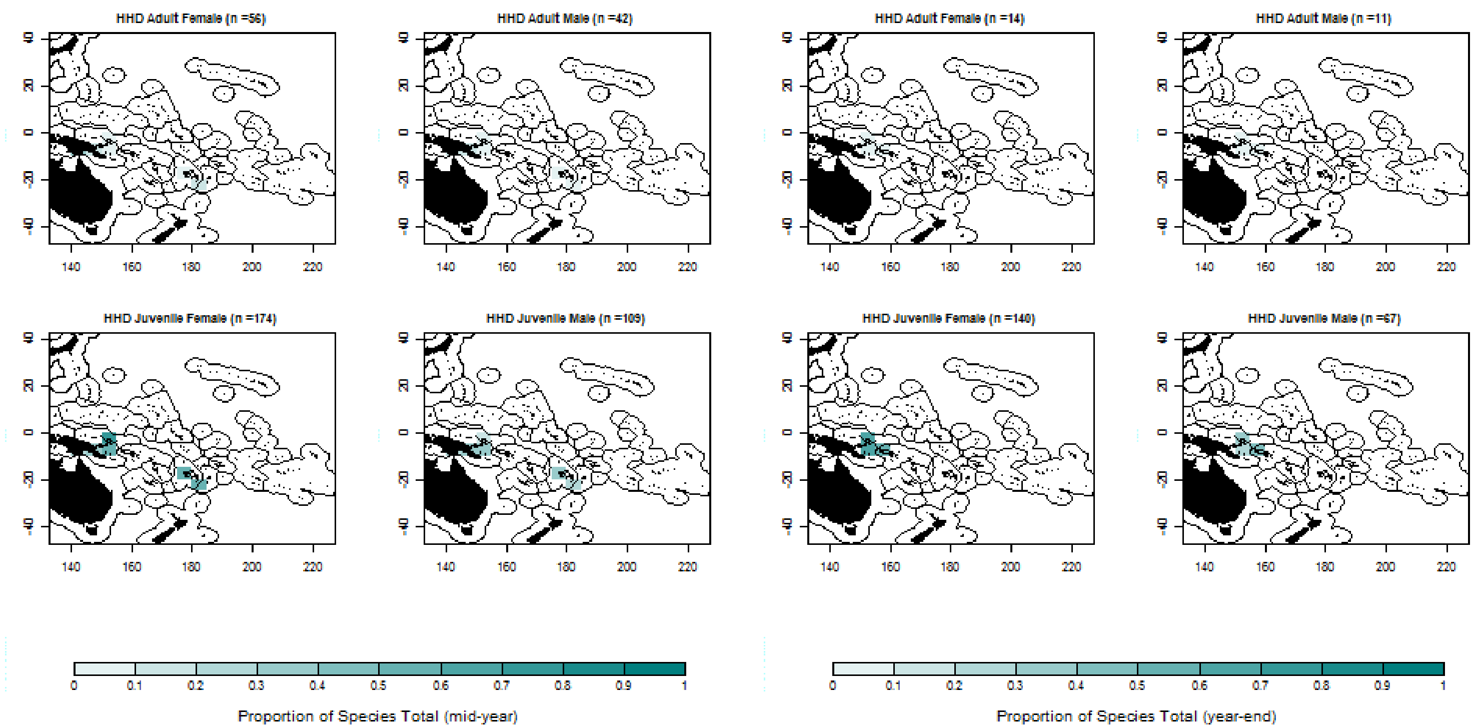


(a) Mid-year estimates.



(b) End of year estimates.

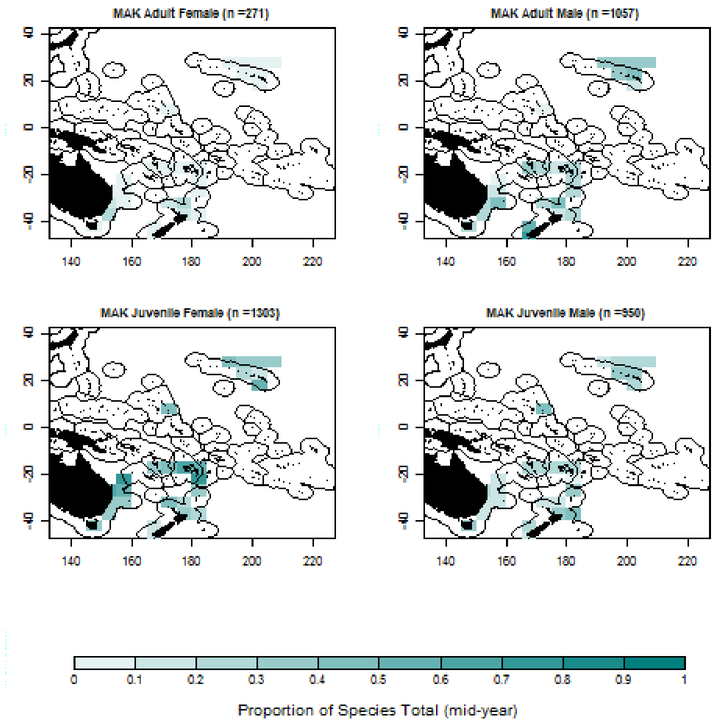
Figure 45: Silky Shark: Proportion of male and female as adult and juvenile in longline catches



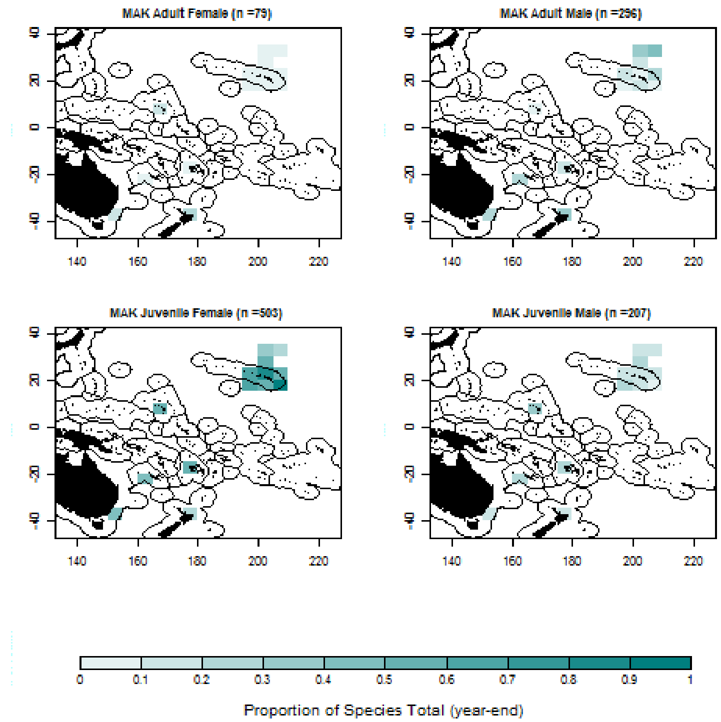
(a) Mid-year estimates.

(b) End of year estimates.

Figure 46: Hammerhead Shark: Proportion of male and female as adult and juvenile in longline catches

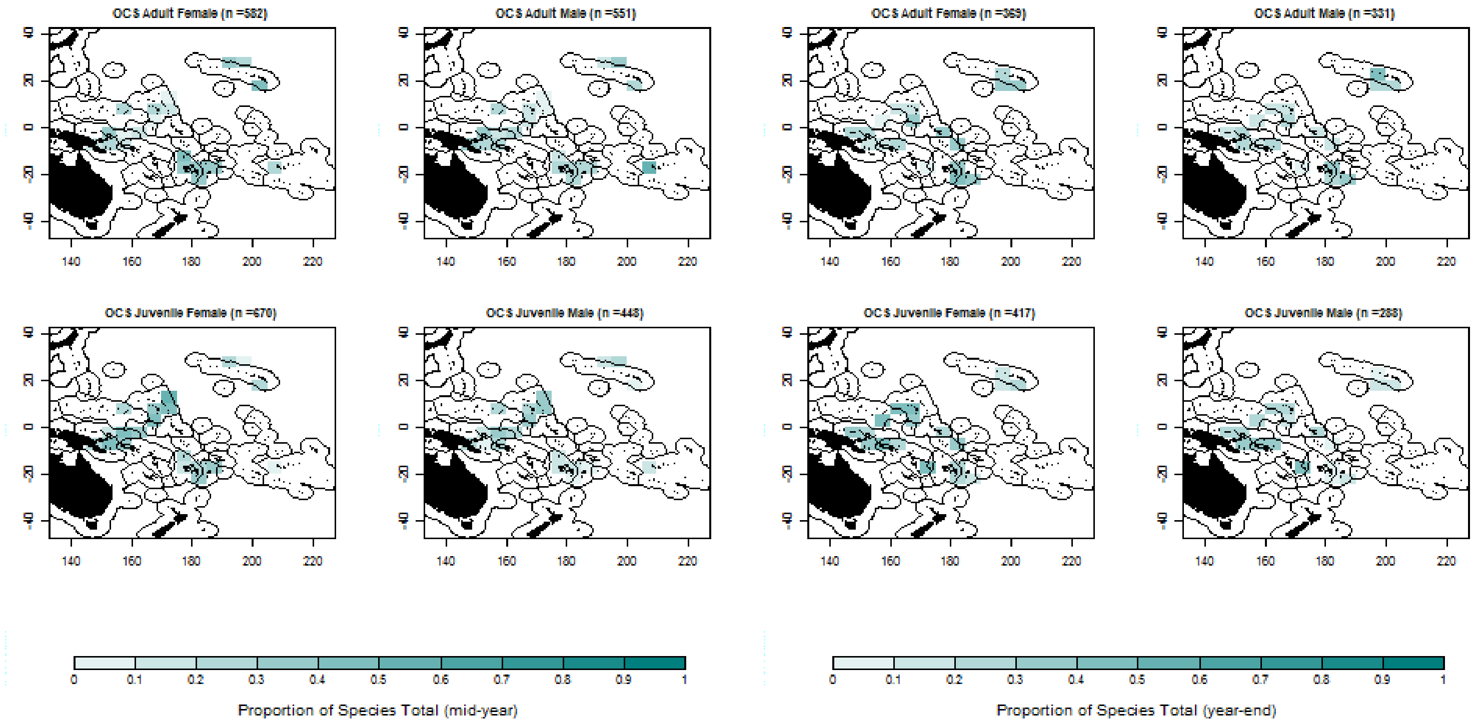


(a) Mid-year estimates.



(b) End of year estimates.

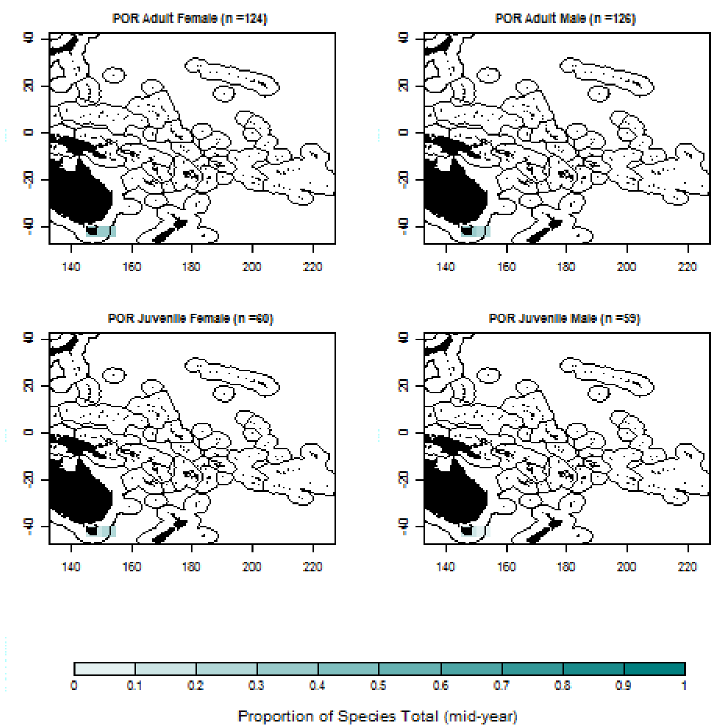
Figure 47: Mako Shark: Proportion of male and female as adult and juvenile in longline catches



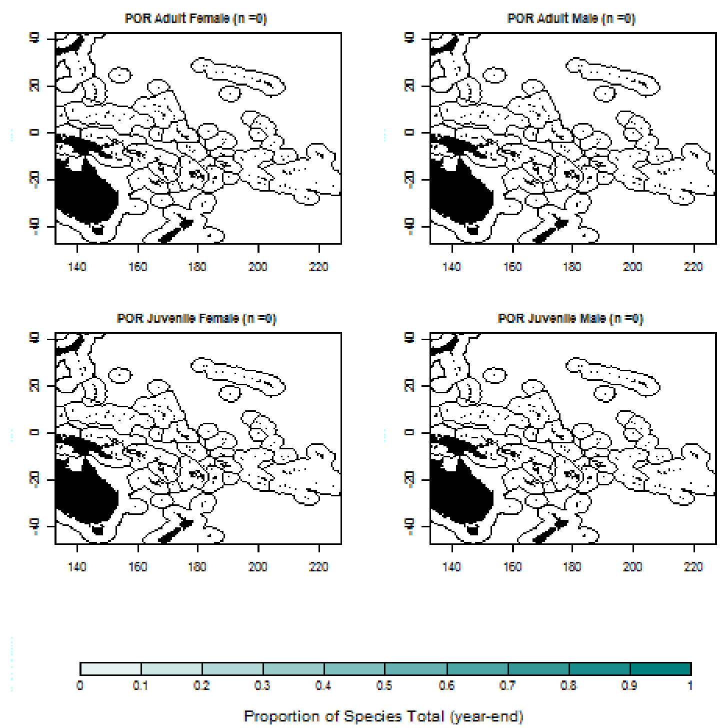
(a) Mid-year estimates.

(b) End of year estimates.

Figure 48: Oceanic Whitetip Shark: Proportion of male and female as adult and juvenile in longline catches

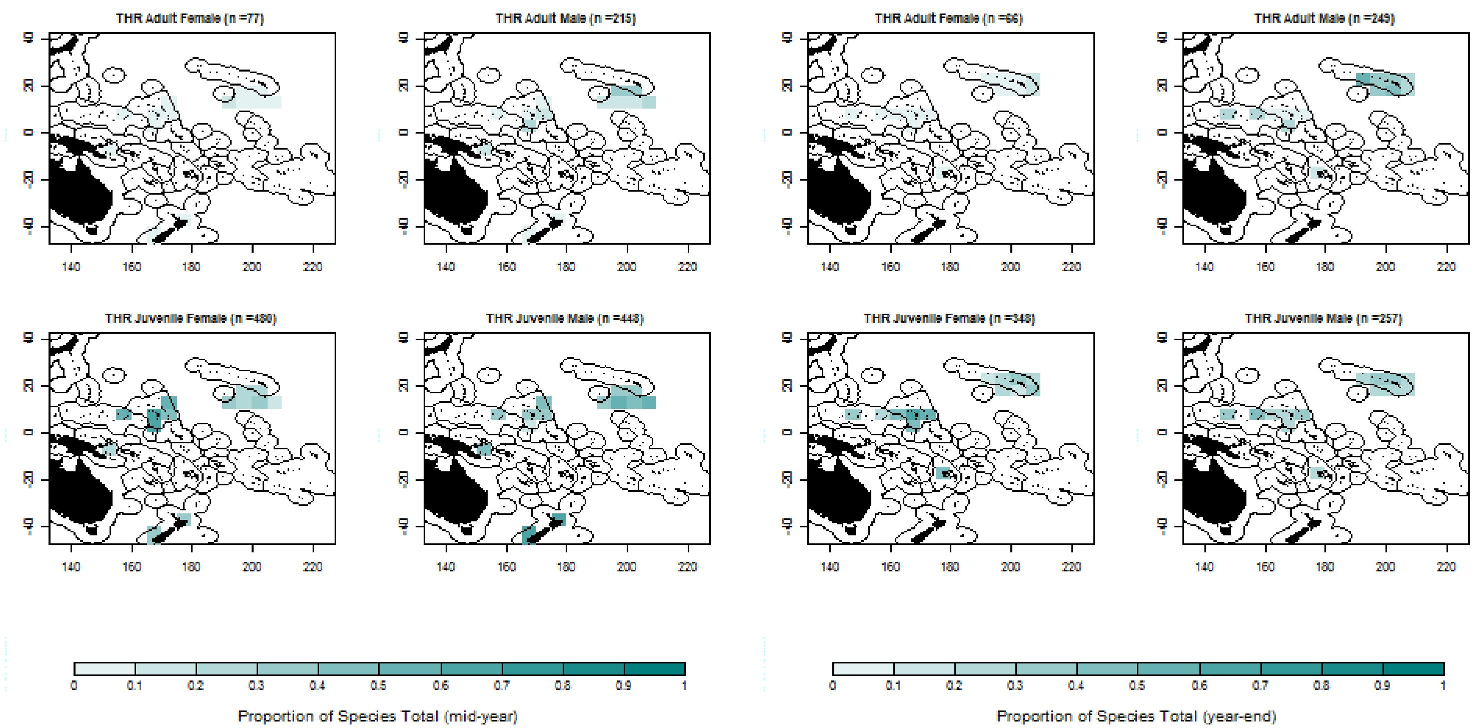


(a) Mid-year estimates.



(b) End of year estimates.

Figure 49: Porbeagle Shark: Proportion of male and female as adult and juvenile in longline catches



(a) Mid-year estimates.

(b) End of year estimates.

Figure 50: Thresher Shark: Proportion of male and female as adult and juvenile in longline catches

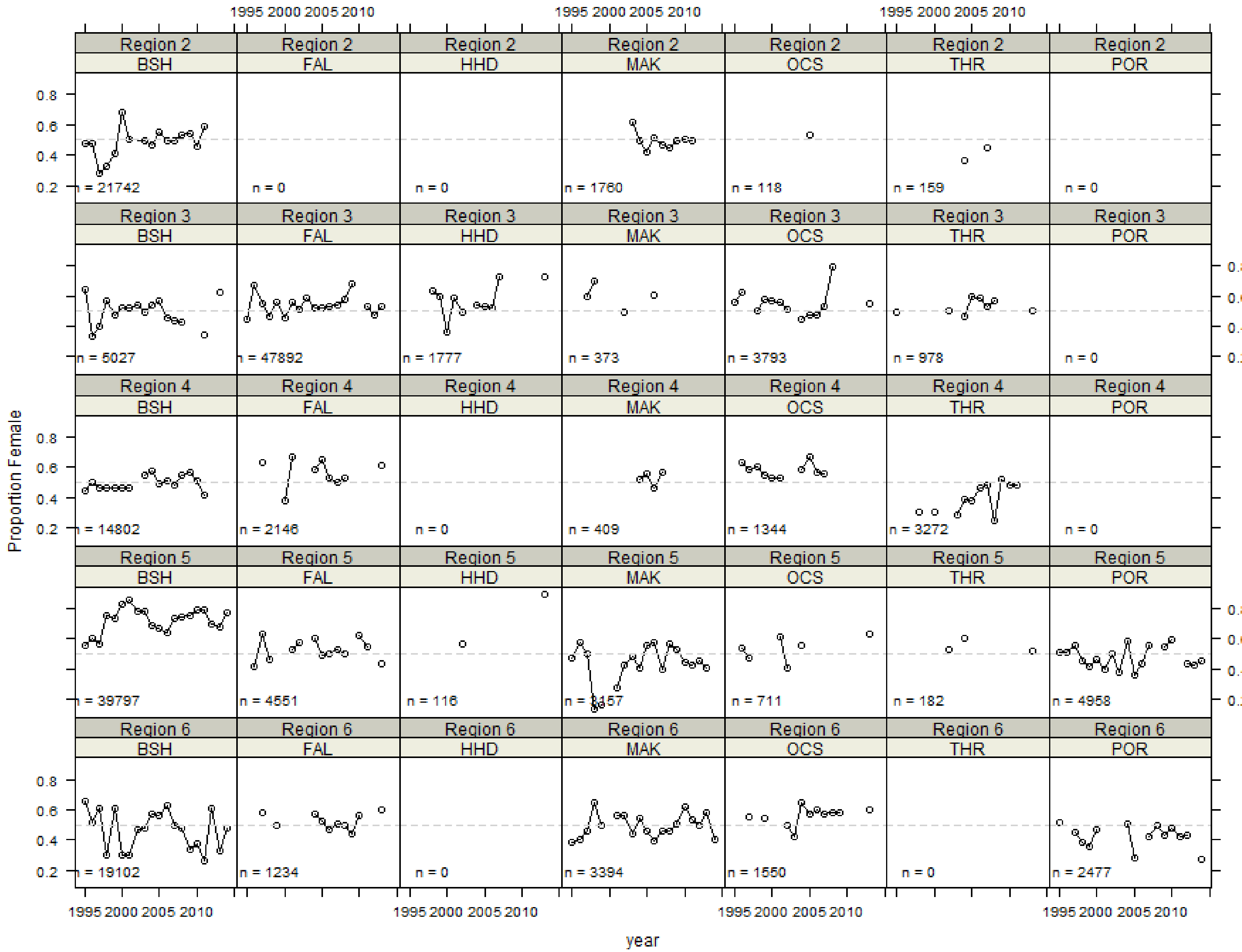


Figure 51: Sex ratio (proportion female) of shark species caught by longline gear in the WCPO. The number of samples available for each sex and region is also shown.

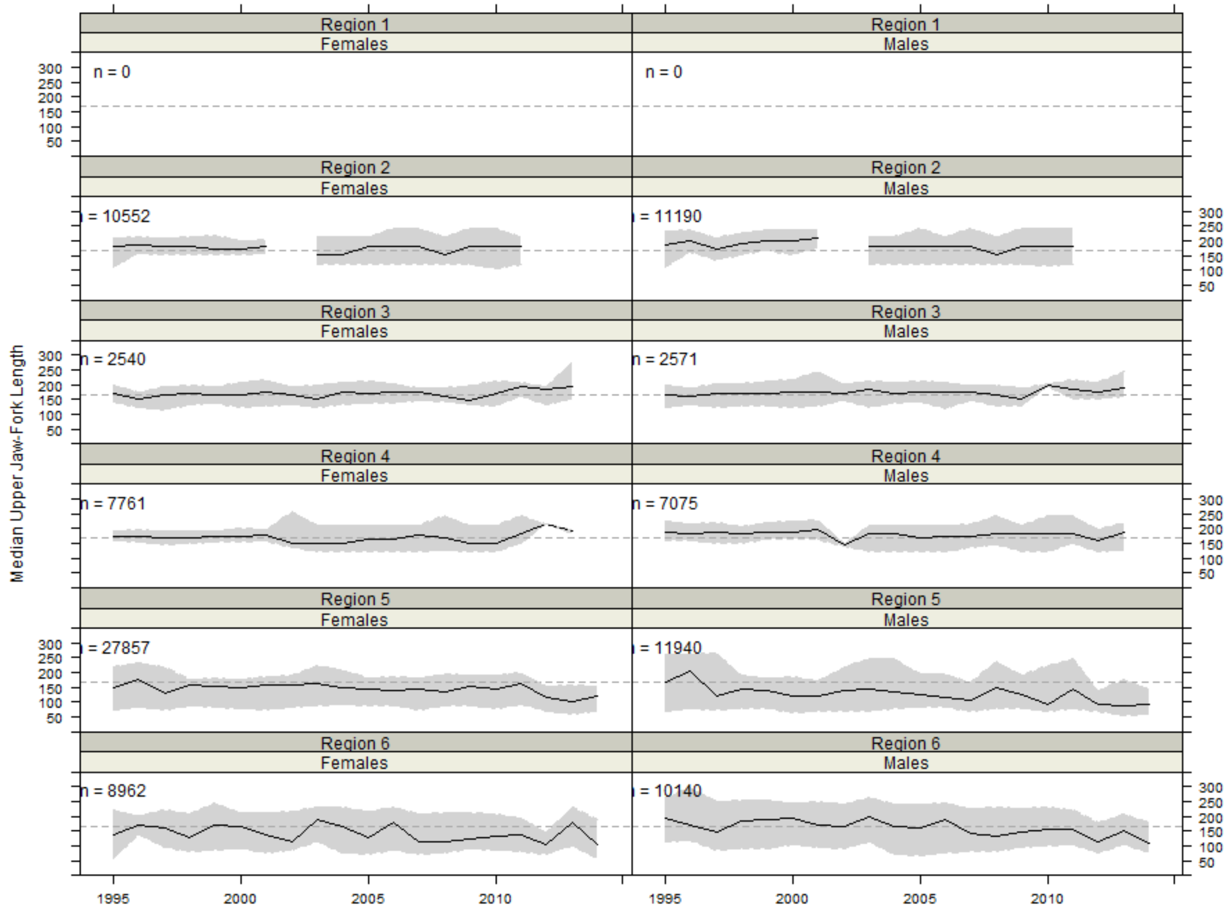


Figure 52: Blue shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

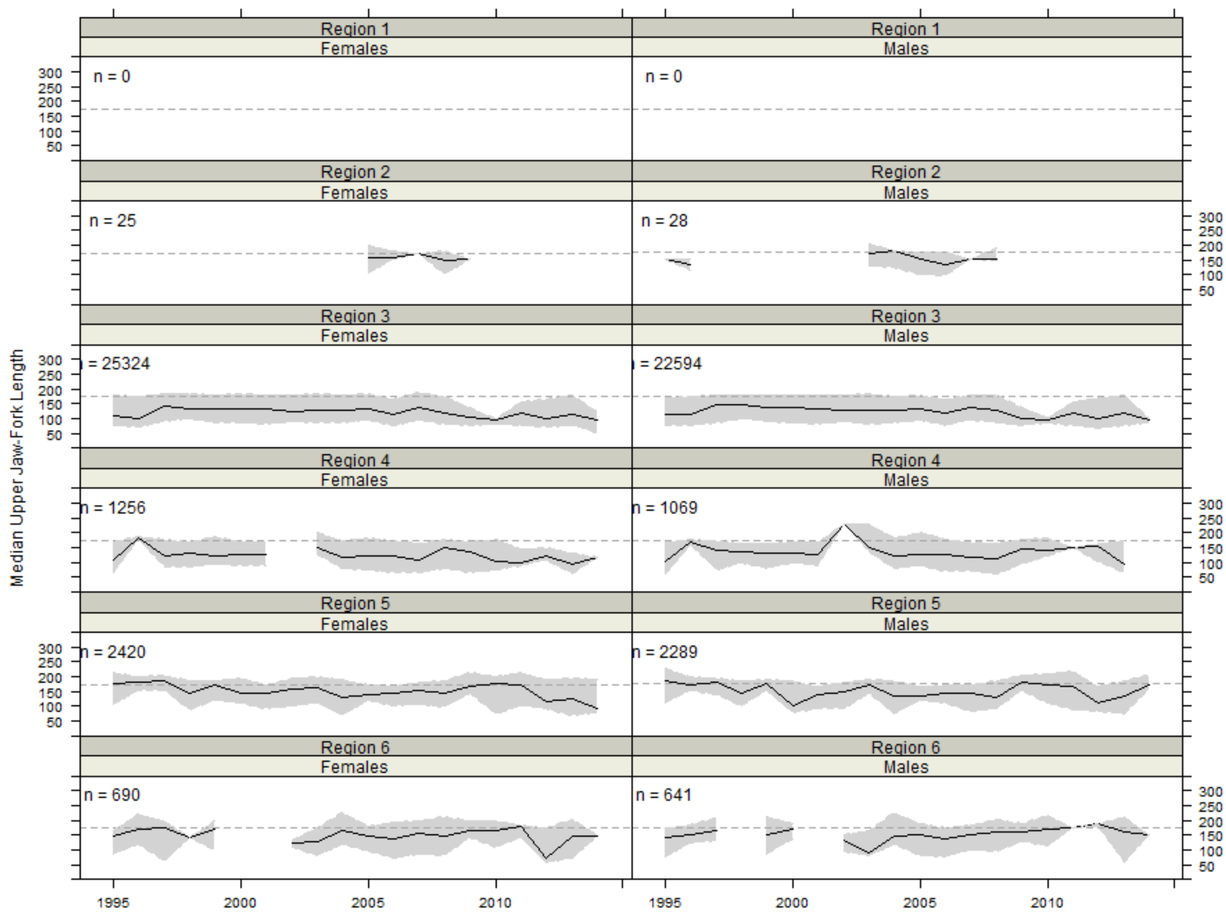


Figure 53: Silky shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

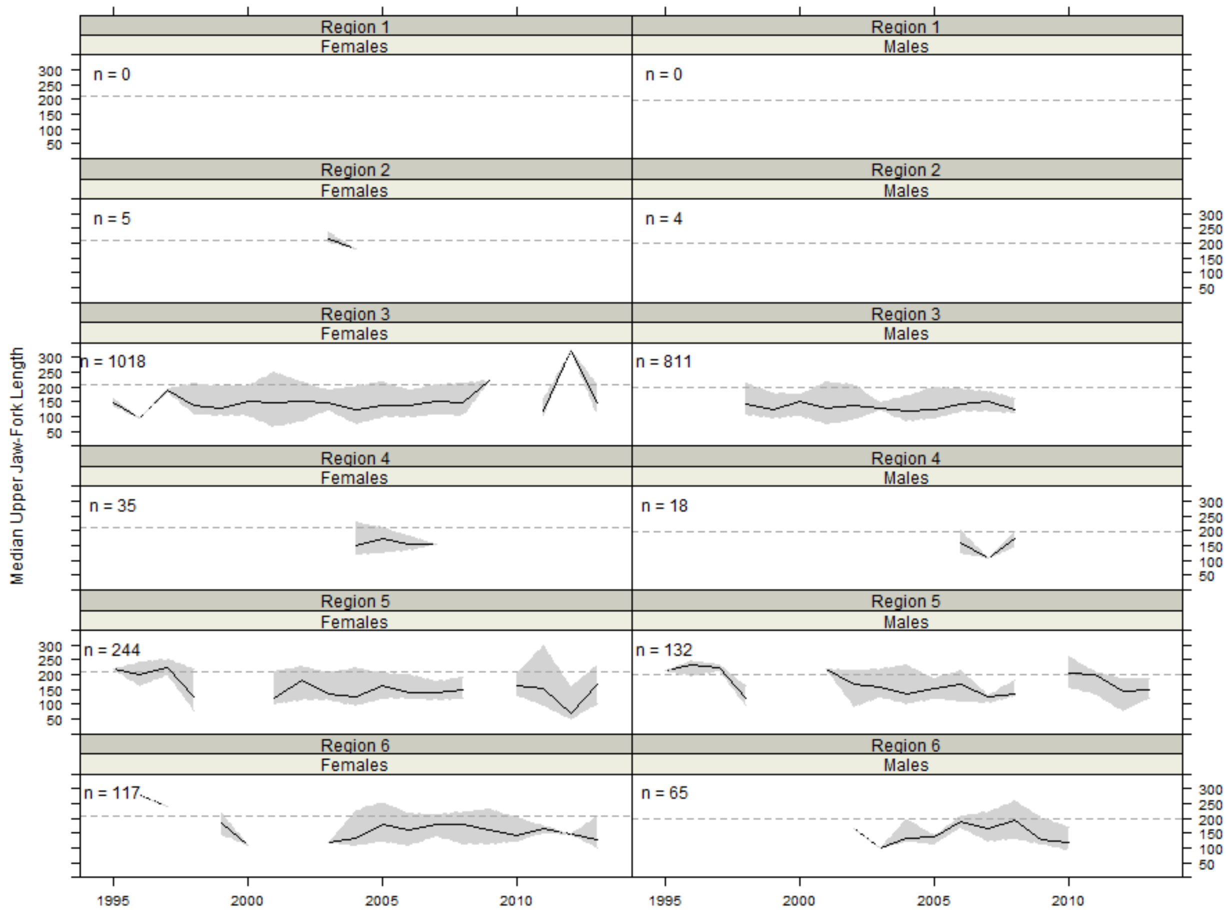


Figure 54: Hammerhead shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

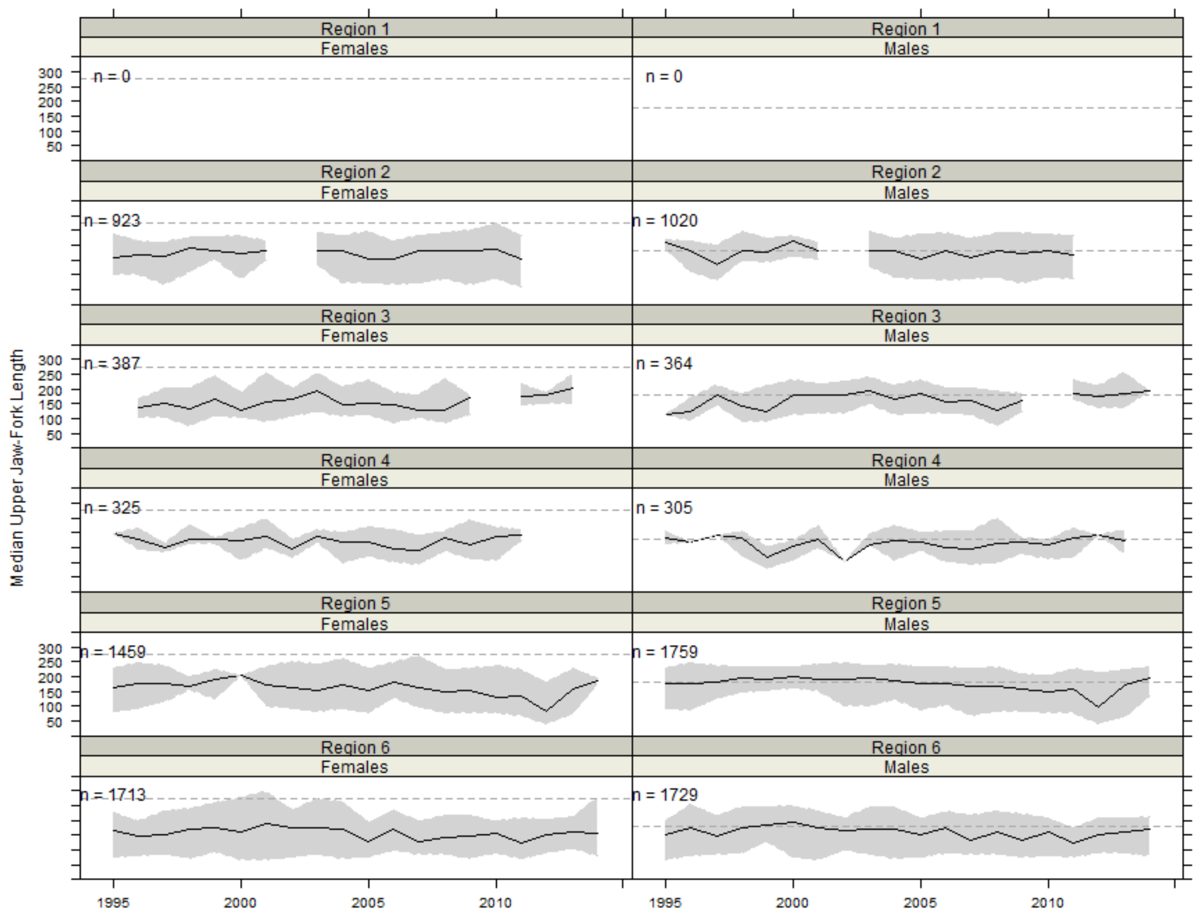


Figure 55: Mako shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

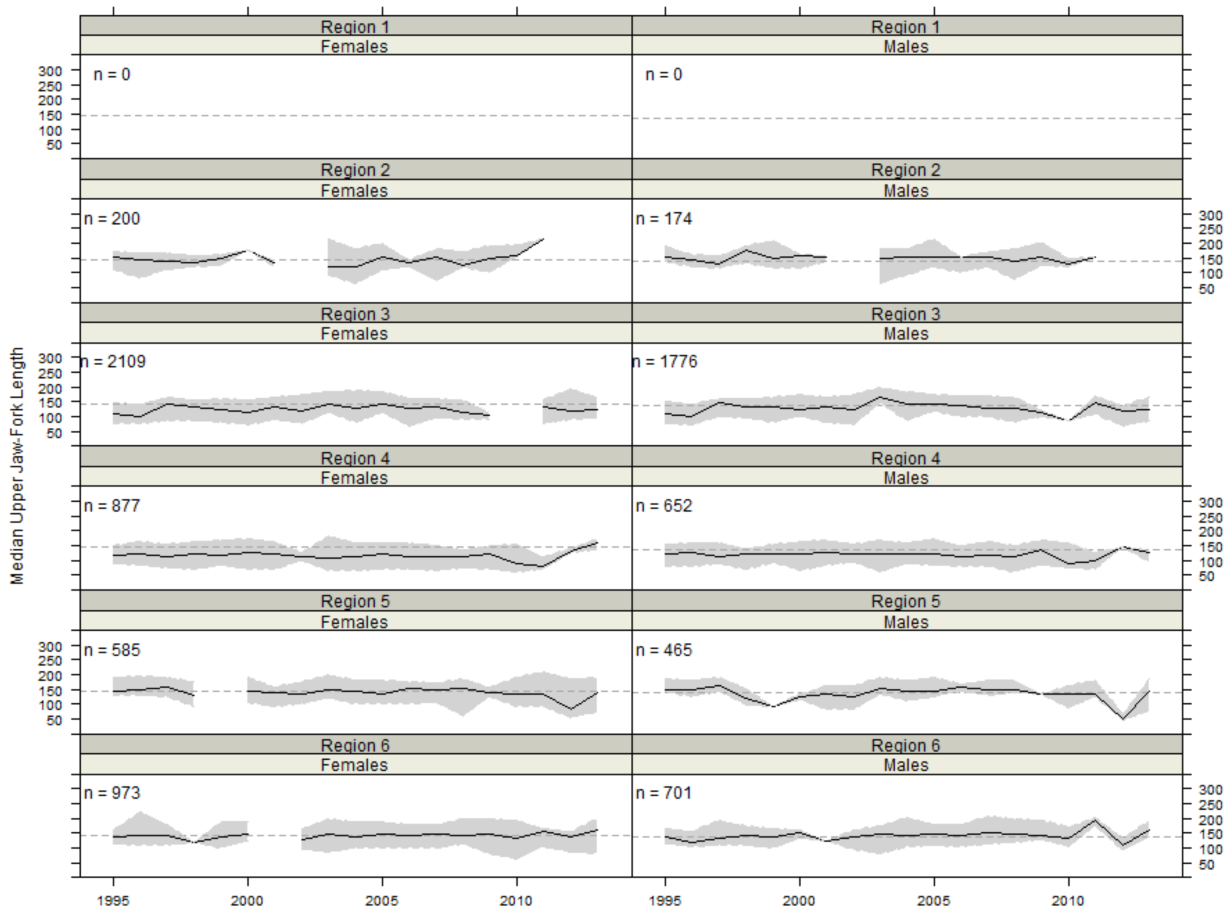


Figure 56: Oceanic Whitetip shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

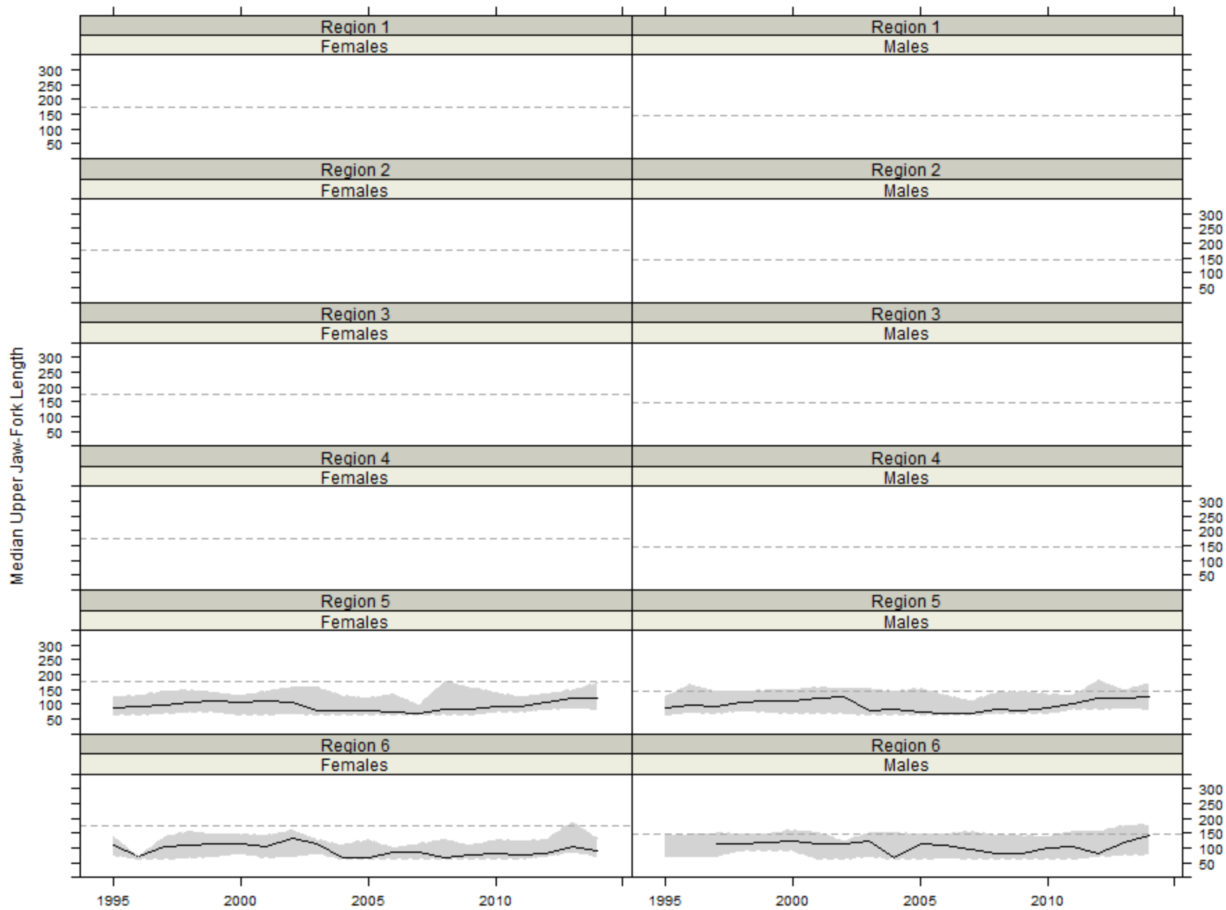


Figure 57: Porbeagle shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

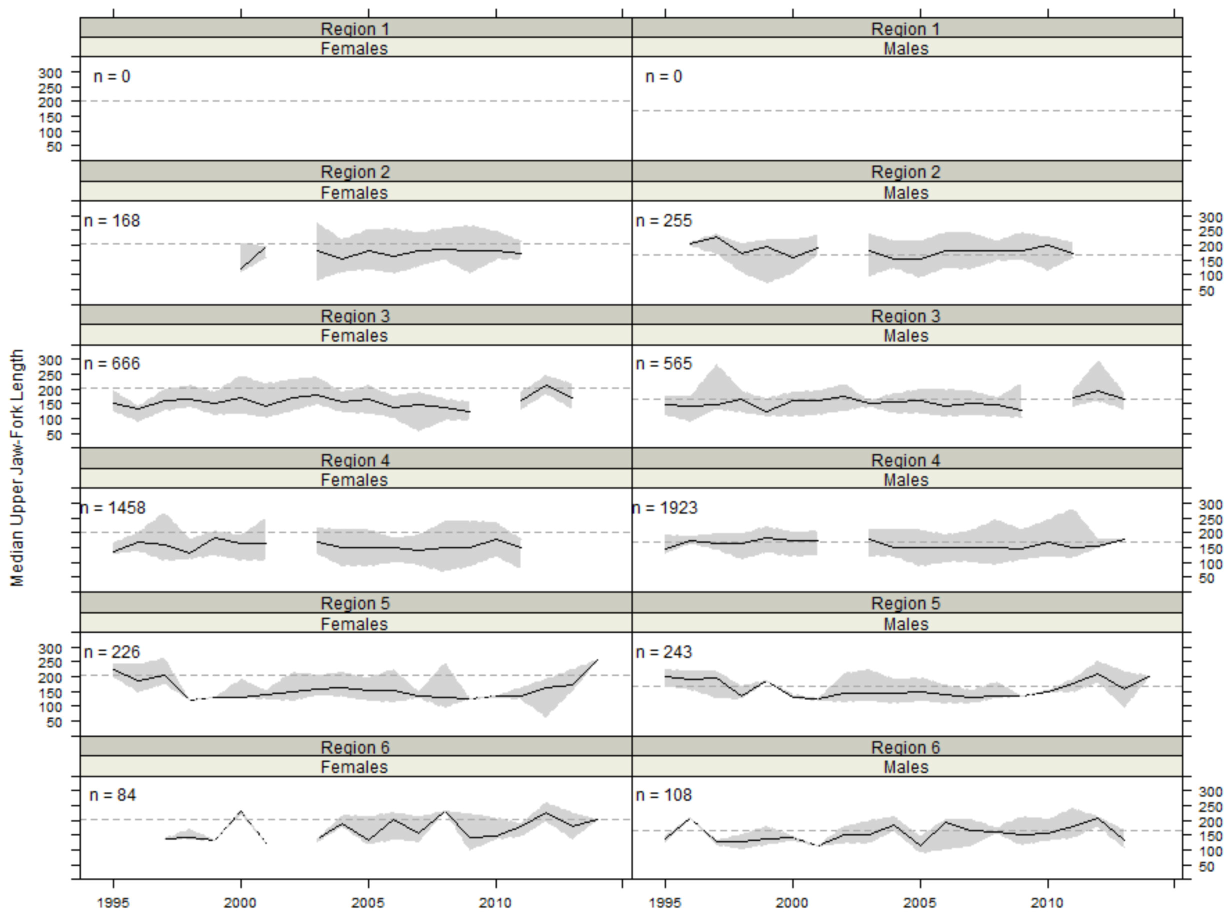


Figure 58: Thresher shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

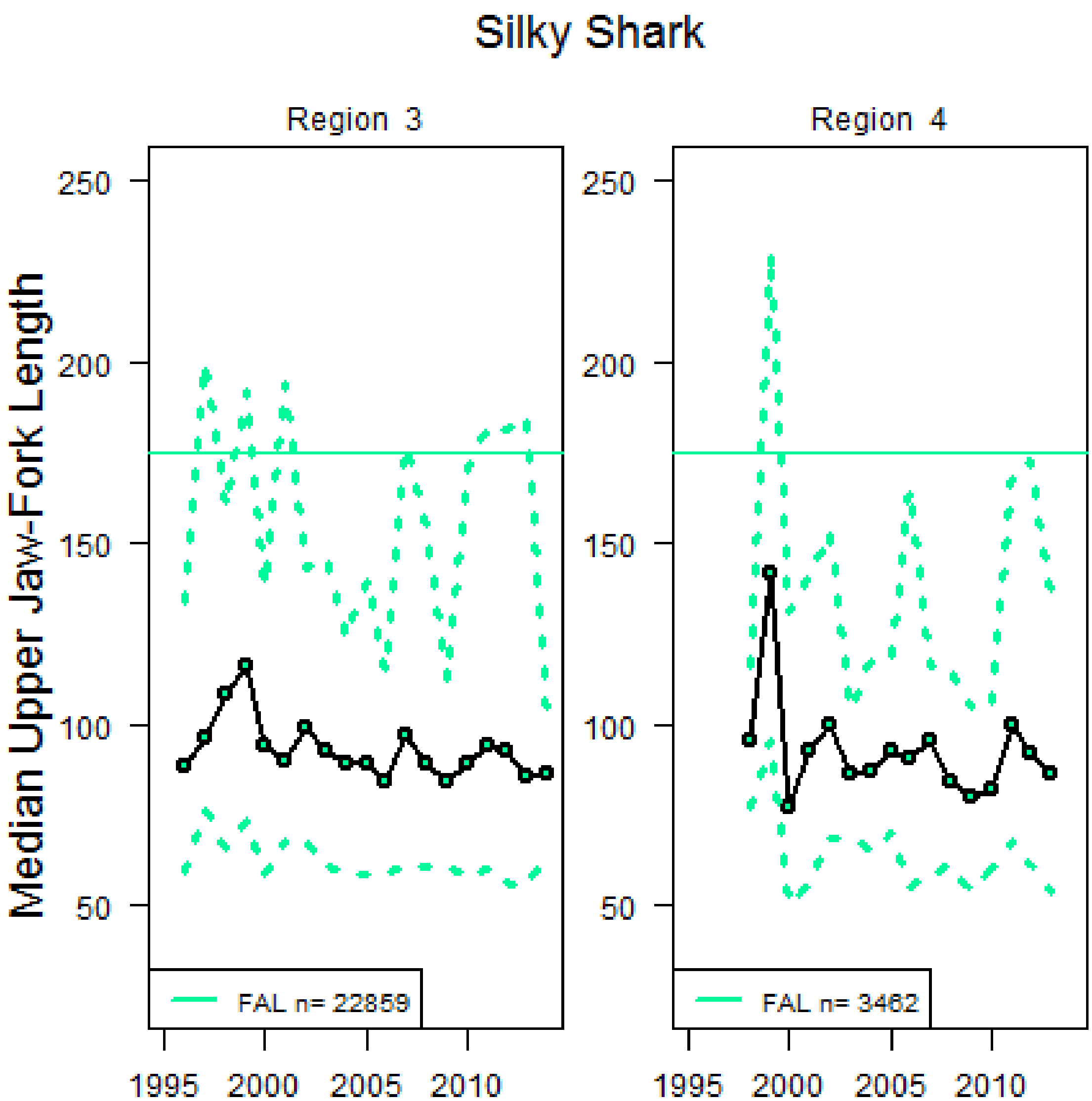


Figure 59: Silky shark: median upper jaw fork length by year and region for males and females caught by purse seine. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

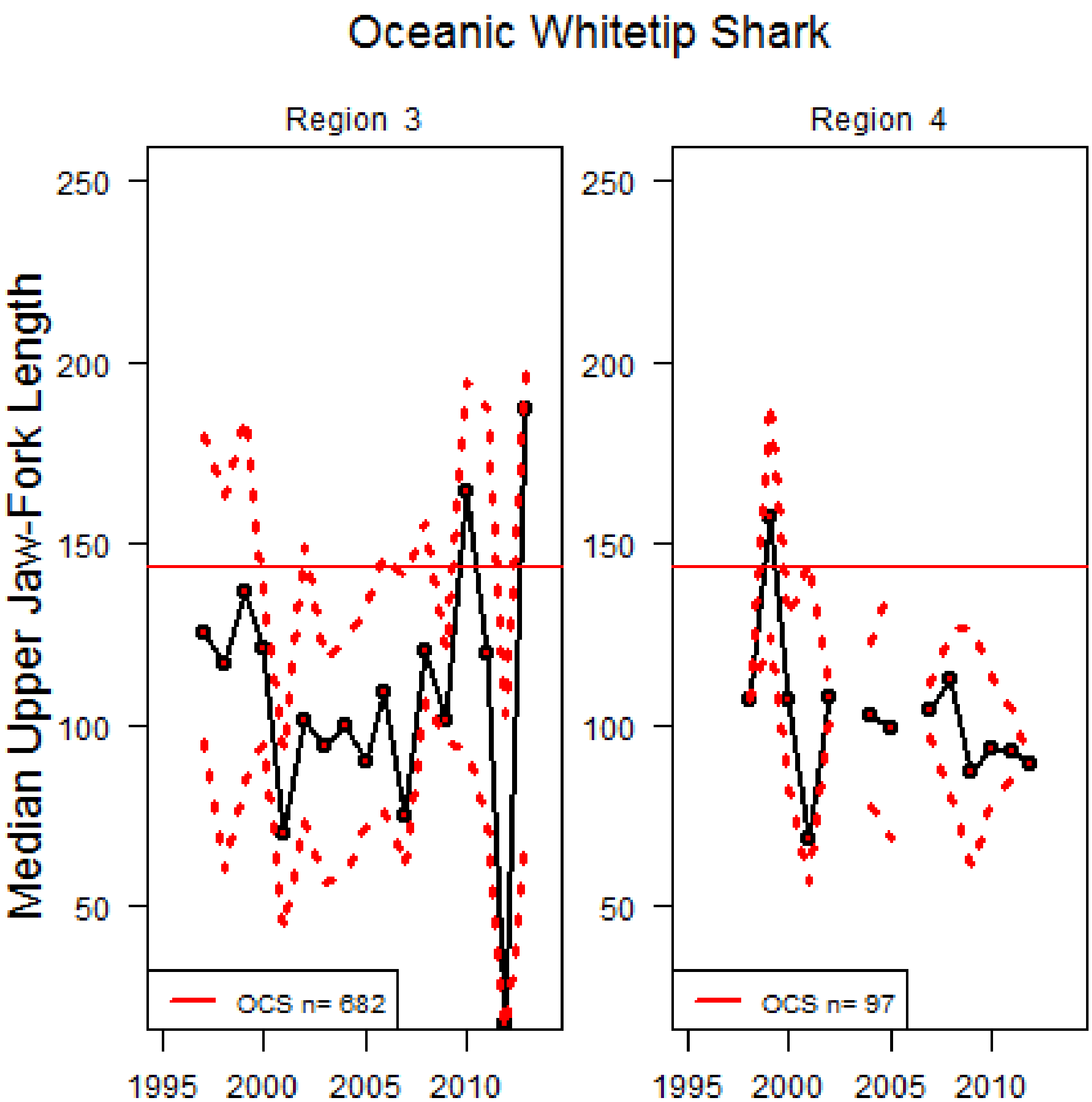


Figure 60: Oceanic whitetip shark: median upper jaw fork length by year and region for males and females caught by purse seine. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

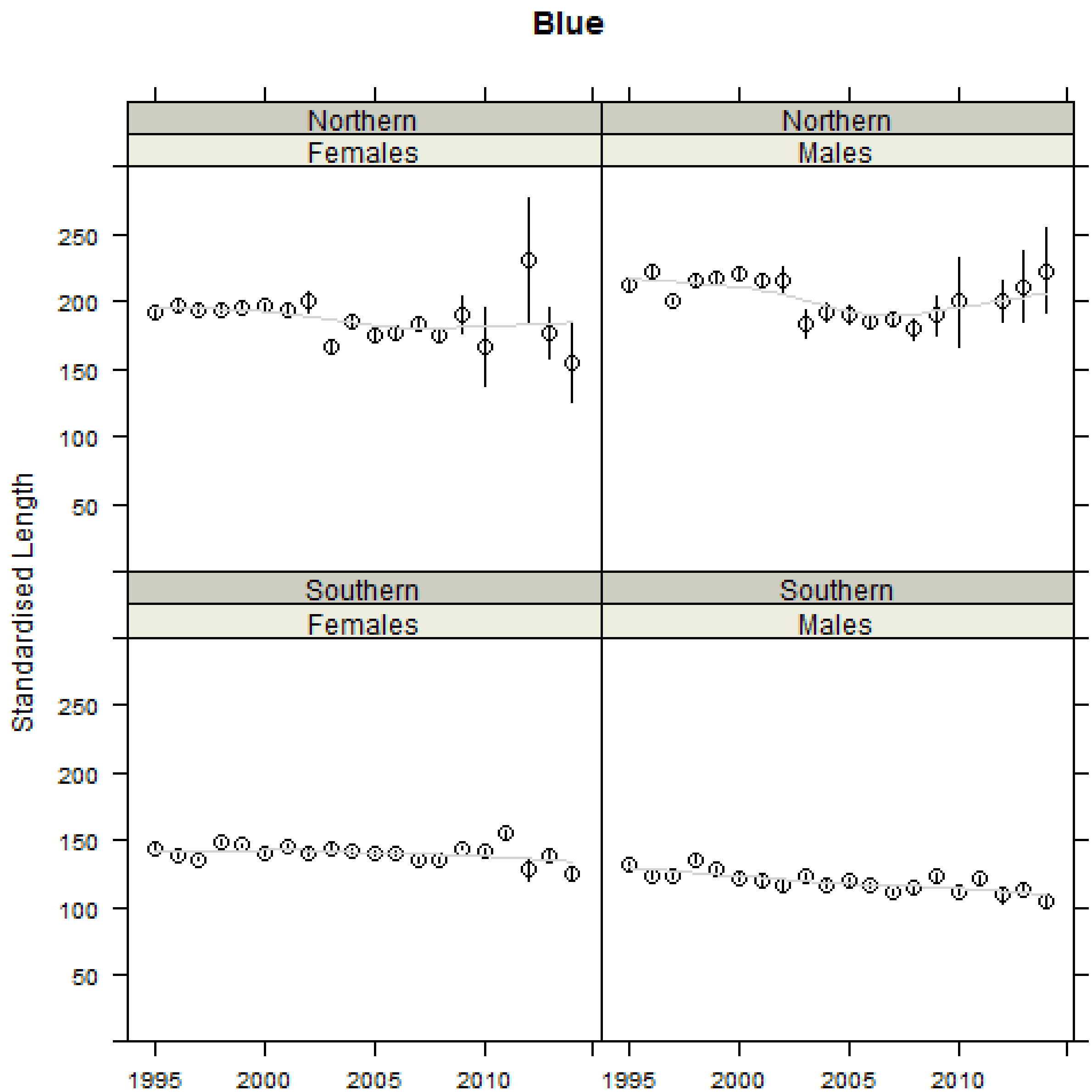


Figure 61: Blue shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

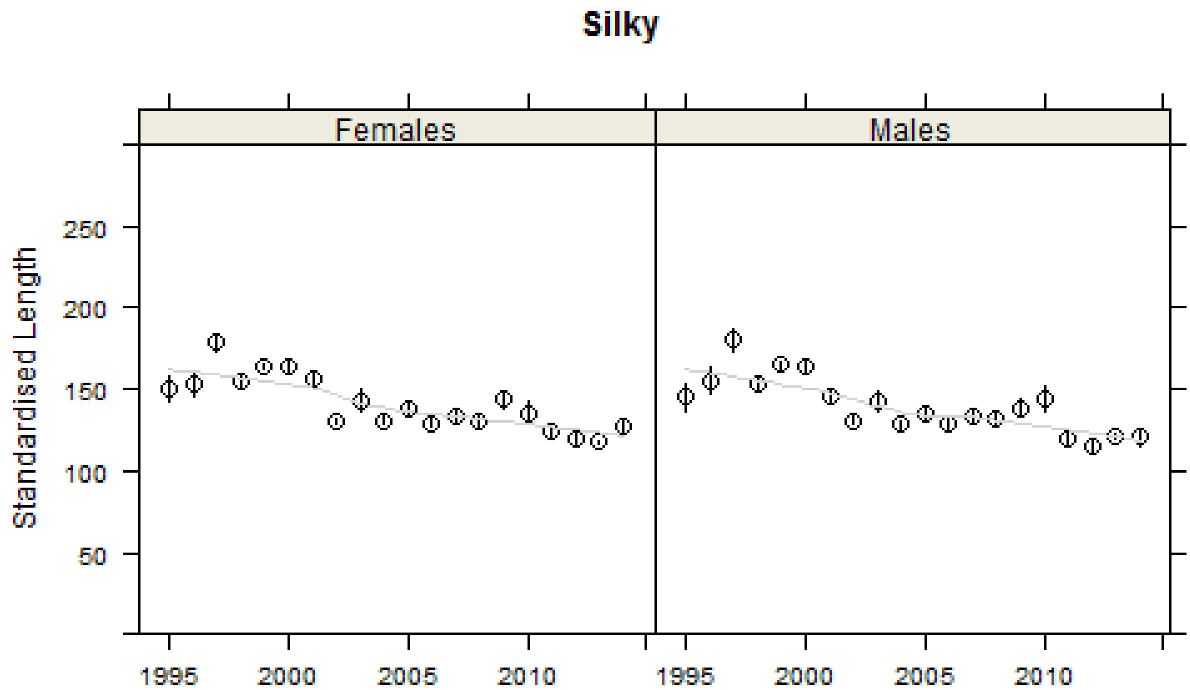


Figure 62: Silky shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

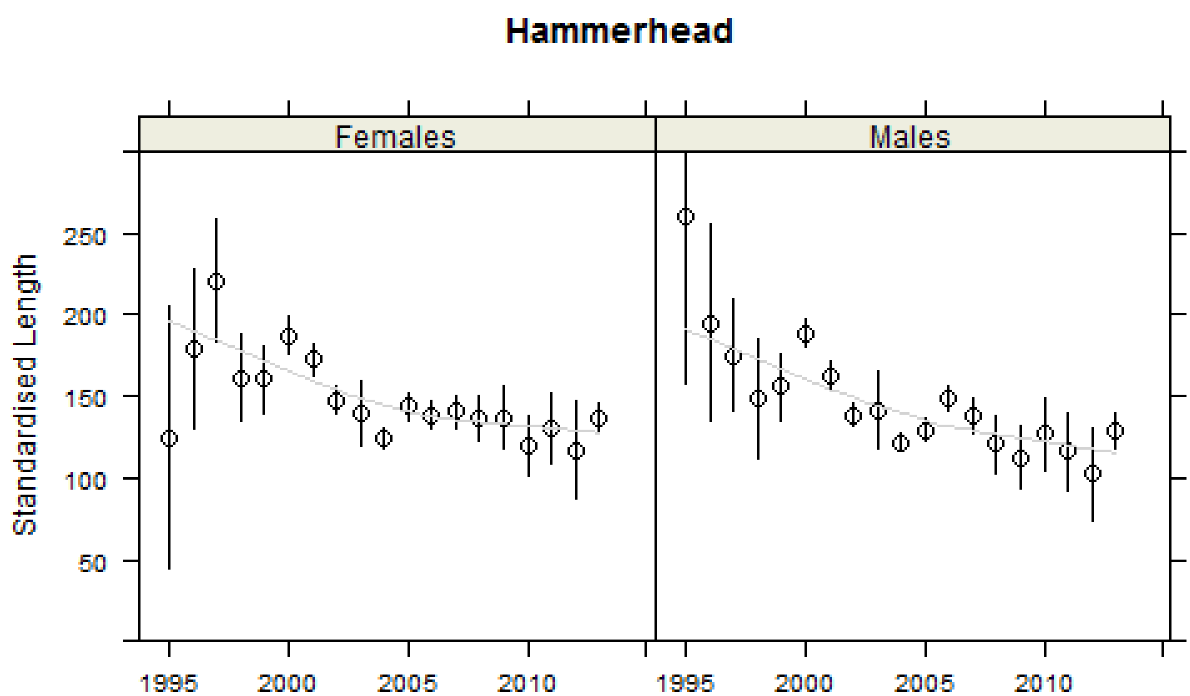


Figure 63: Hammerhead shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

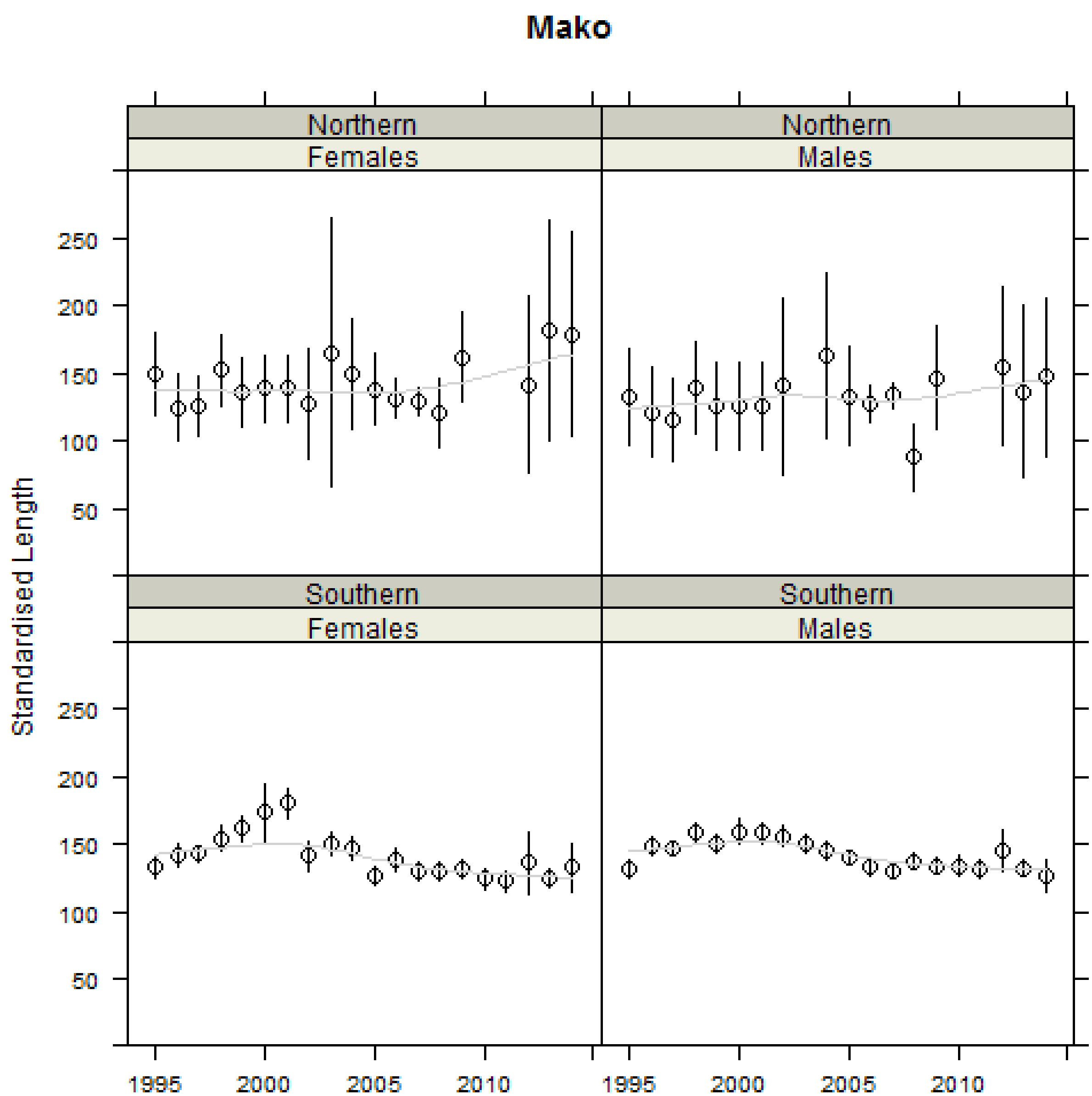


Figure 64: Mako shark: standardised length for male and females. Light grey line shows a lowess smoother.

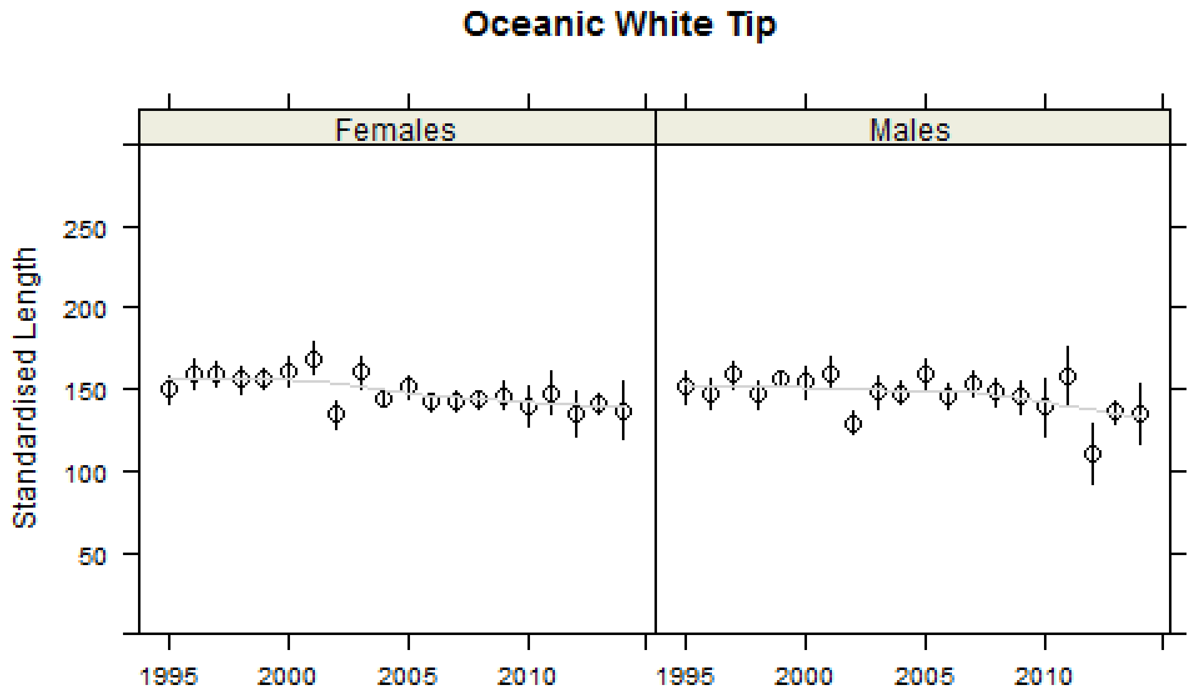


Figure 65: Oceanic Whitetip shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

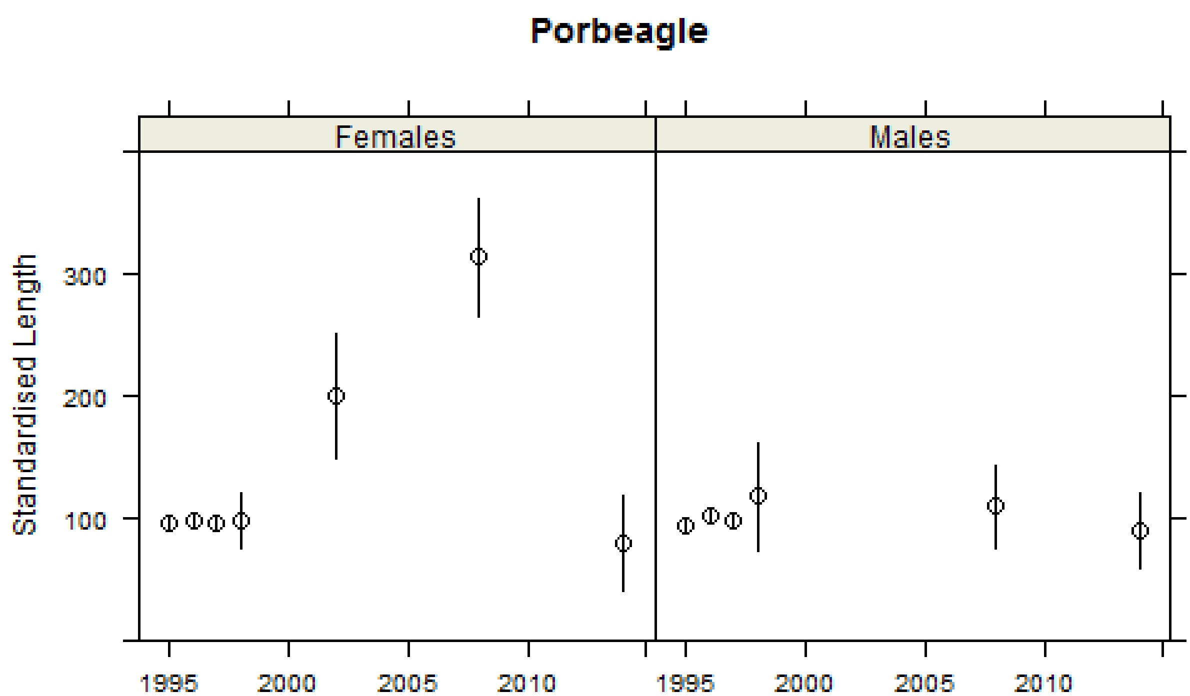


Figure 66: Porbeagle shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

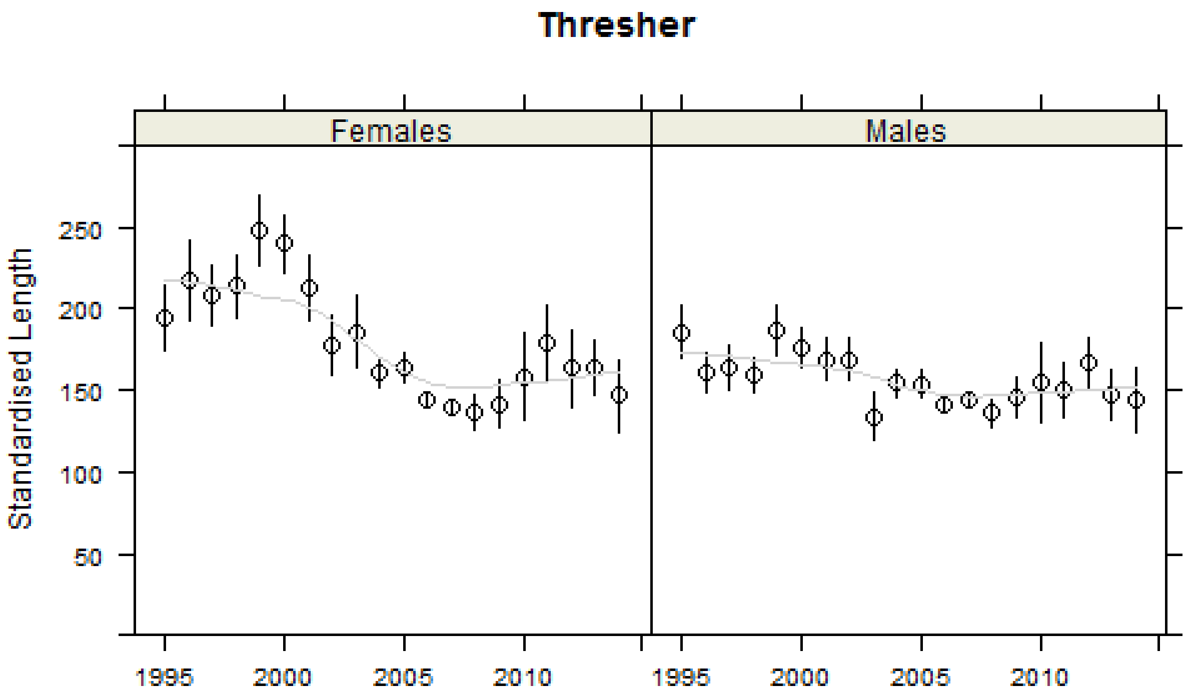


Figure 67: Thresher shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

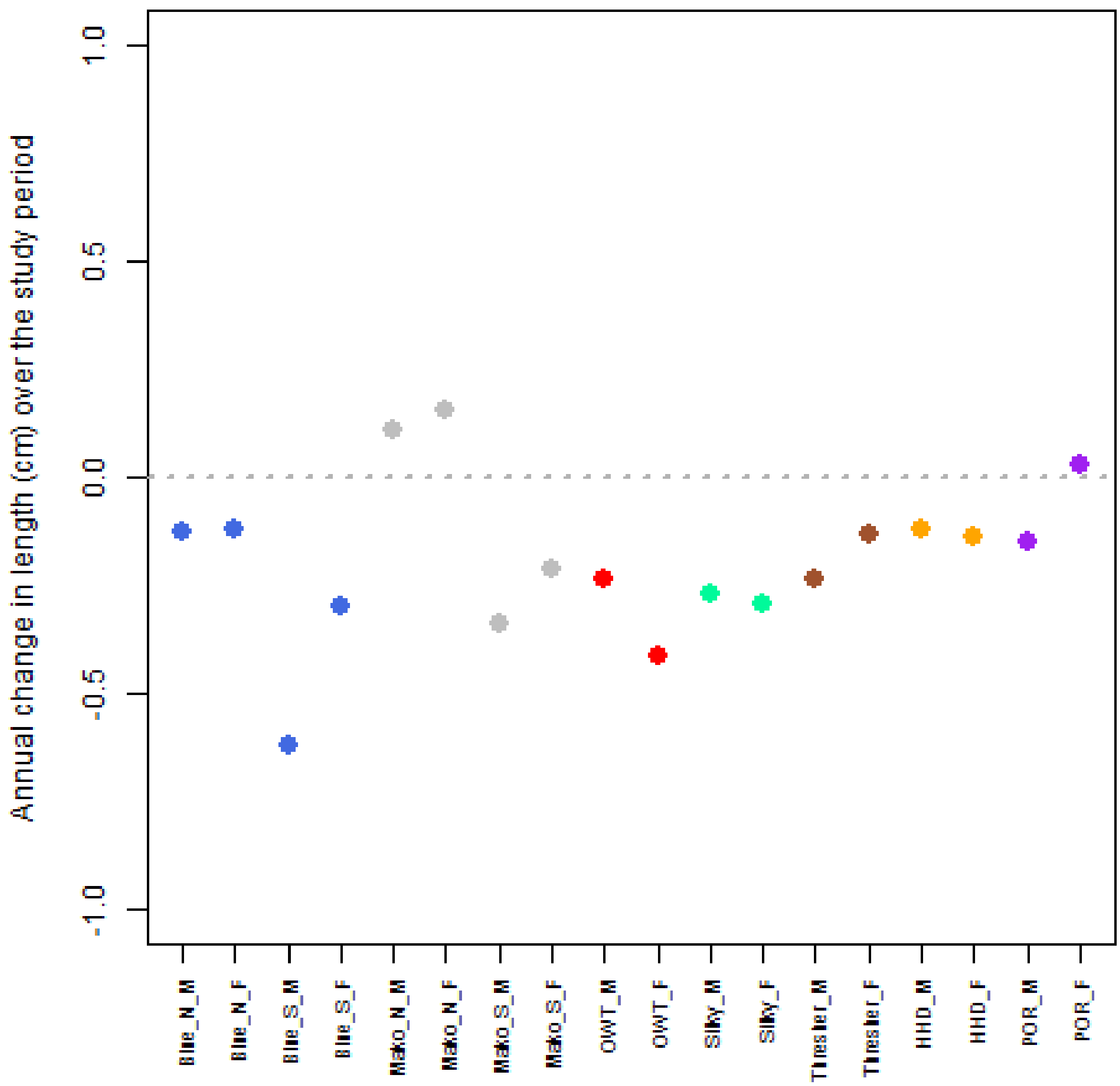


Figure 68: Annual change in length (cm) over the study period as derived from the year effect of a GLM fitted to the sex and species specific data shown in figures 71 to 77

C Whale Shark Figures

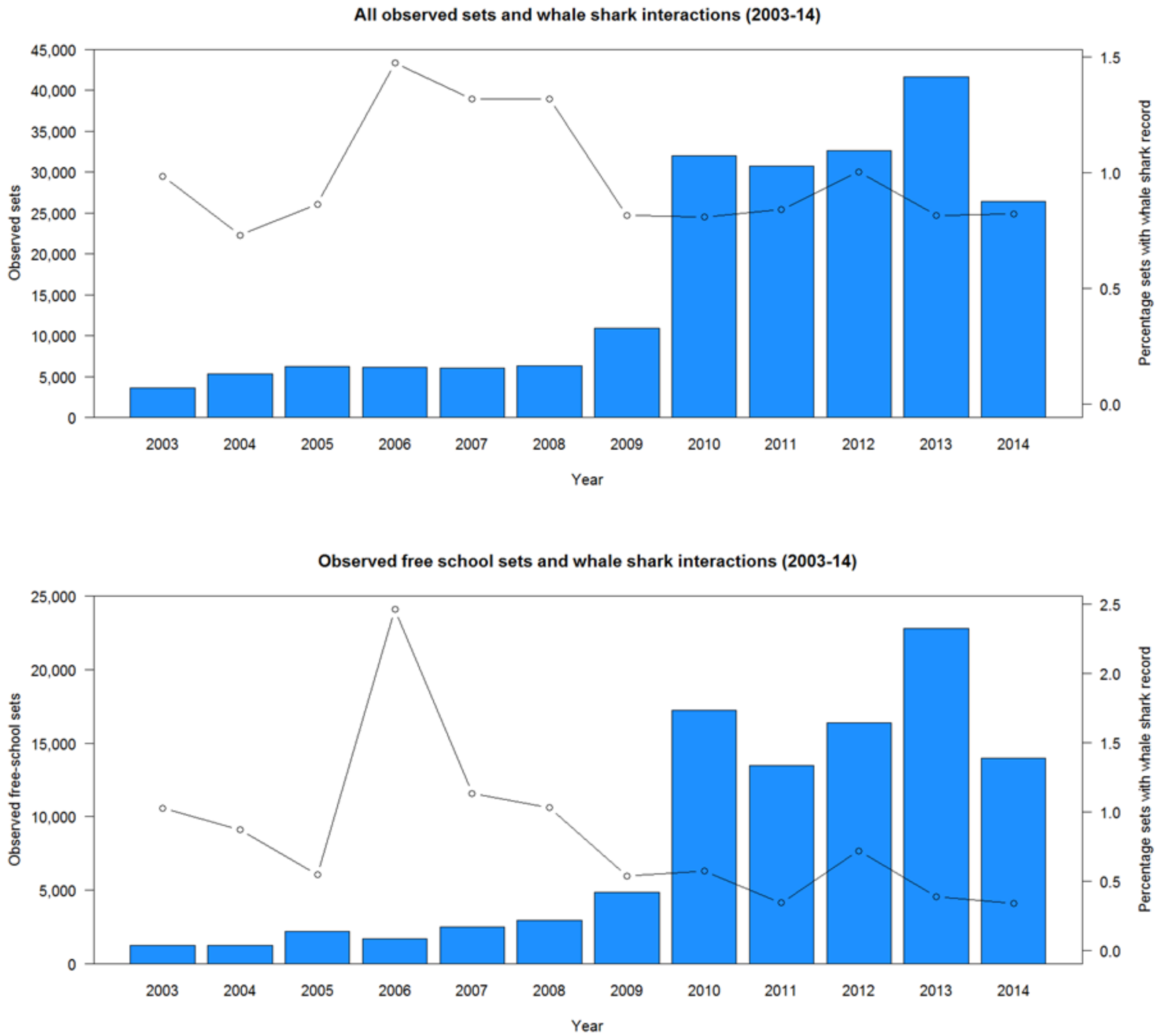


Figure 69: Annual number of observed free school sets (bars) and proportion of sets with some form of whale shark interaction (see text for criteria).

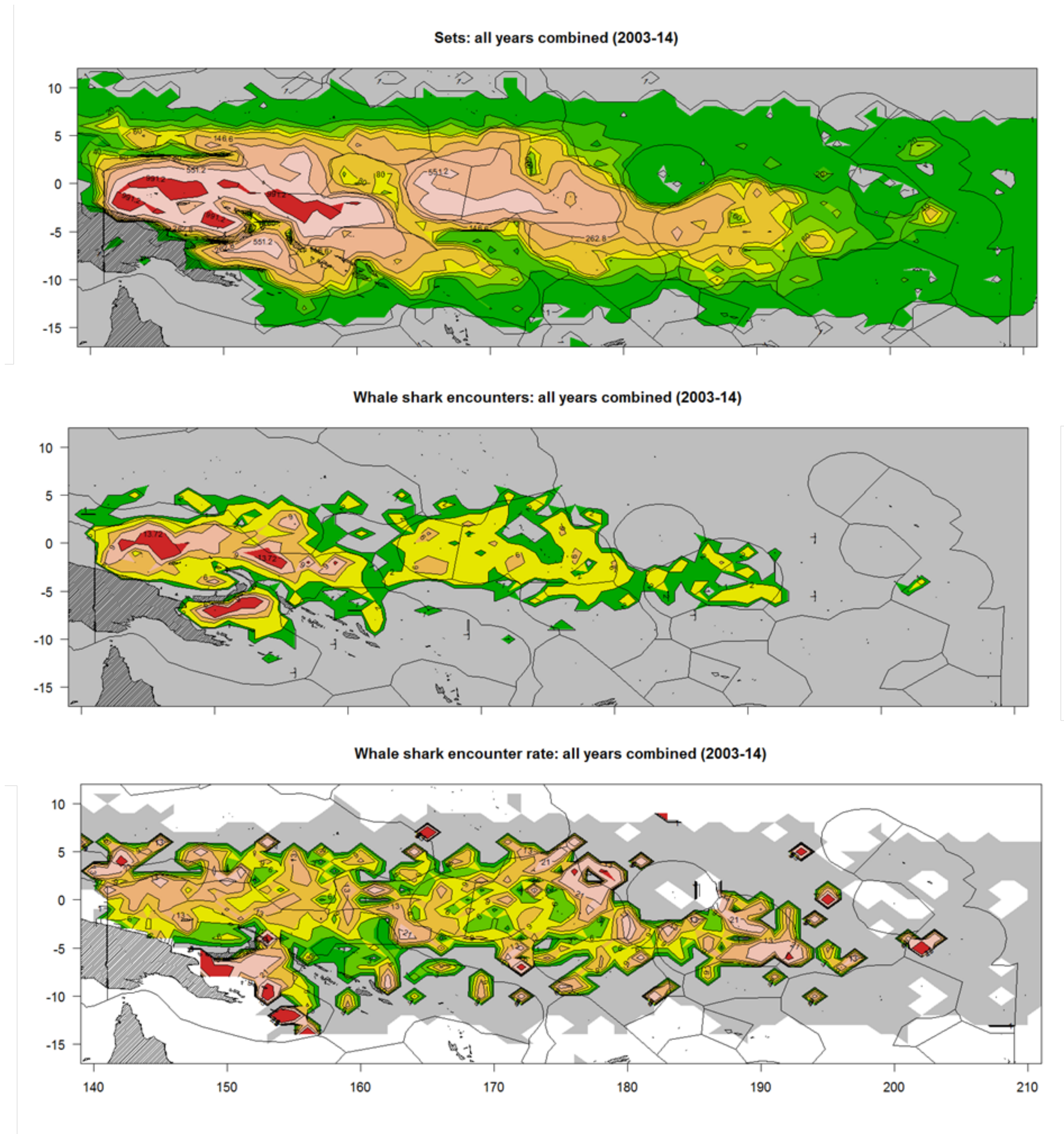


Figure 70: Contour plots based on 1 x 1 degree square data for all years combined of purse seine sets (top), whale shark records (middle – see text for criteria), and encounter rates (bottom — simply whale shark records divided by total sets for each 1 x1 degree square). Grey represents zeros, white are NA's (e.g. zero whale sharks divided by zero sets), and the scale increases from green to yellow to orange to pink to red.

C.1 Management Considerations

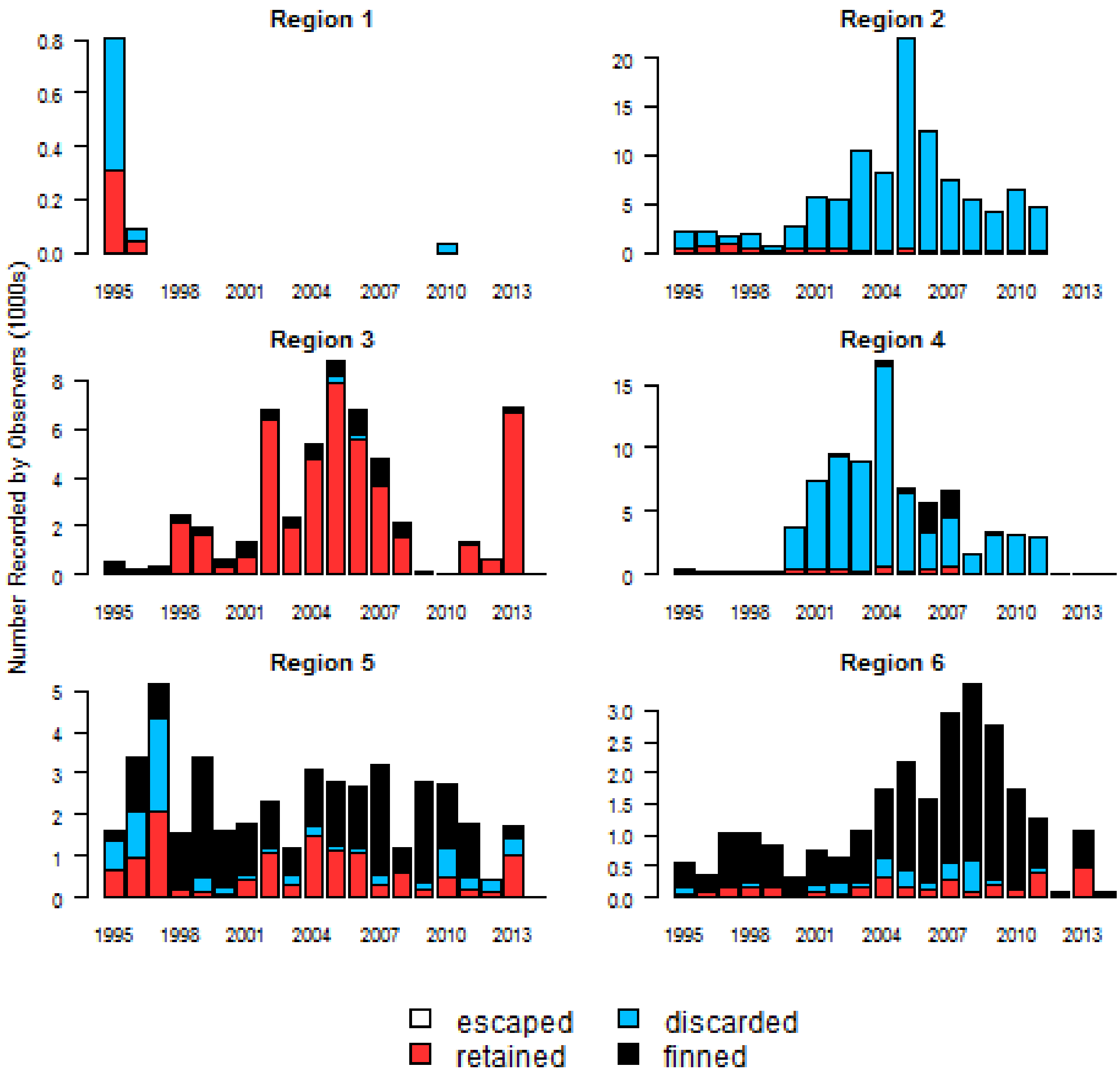


Figure 71: Fate of observed sharks caught by longline in the WCPO (total numbers for all species combined).

D Model Diagnostics

D.0.1 CPUE Standardisation Diagnostics

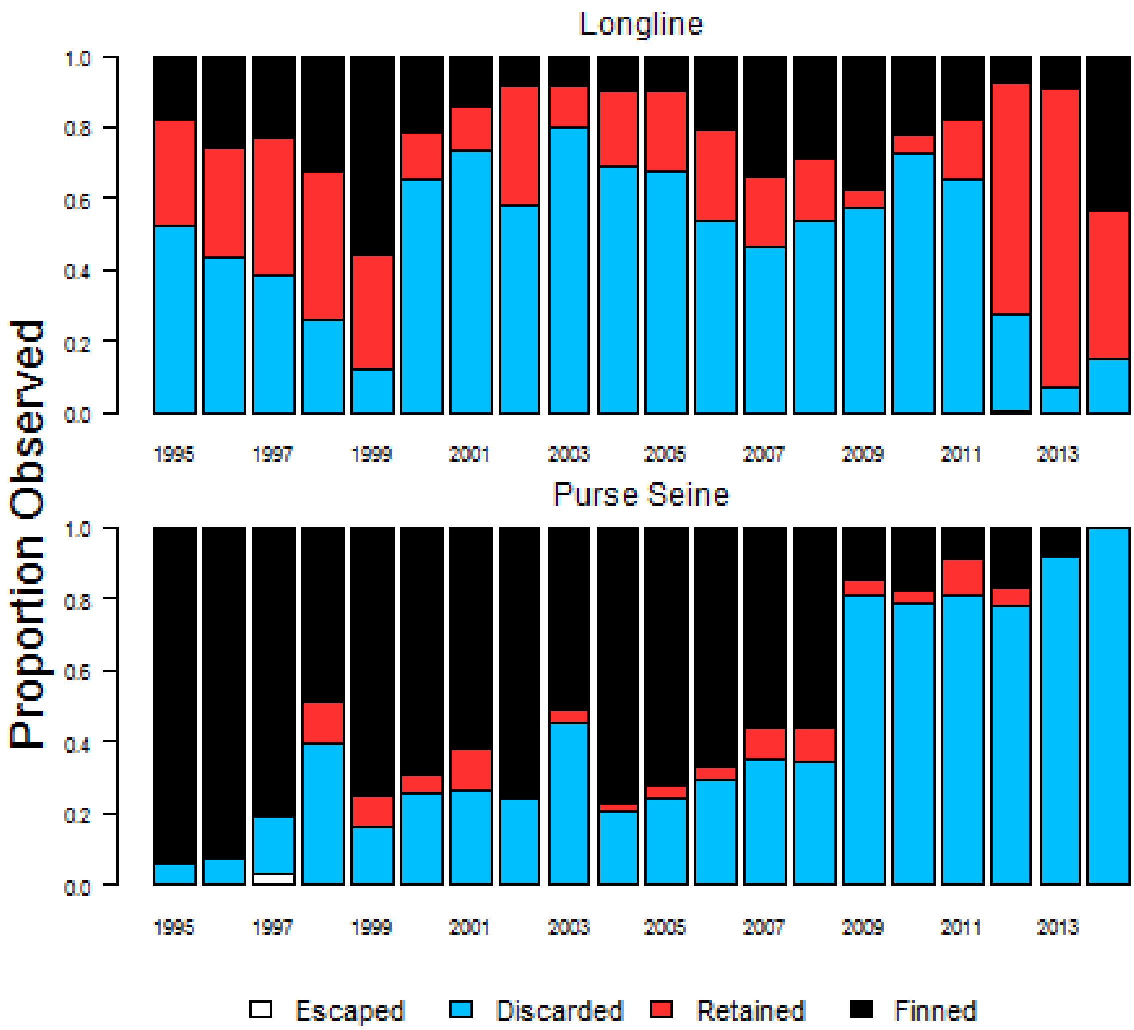


Figure 72: Fate of observed sharks caught by longline in the WCPO (proportion by number for all species combined).

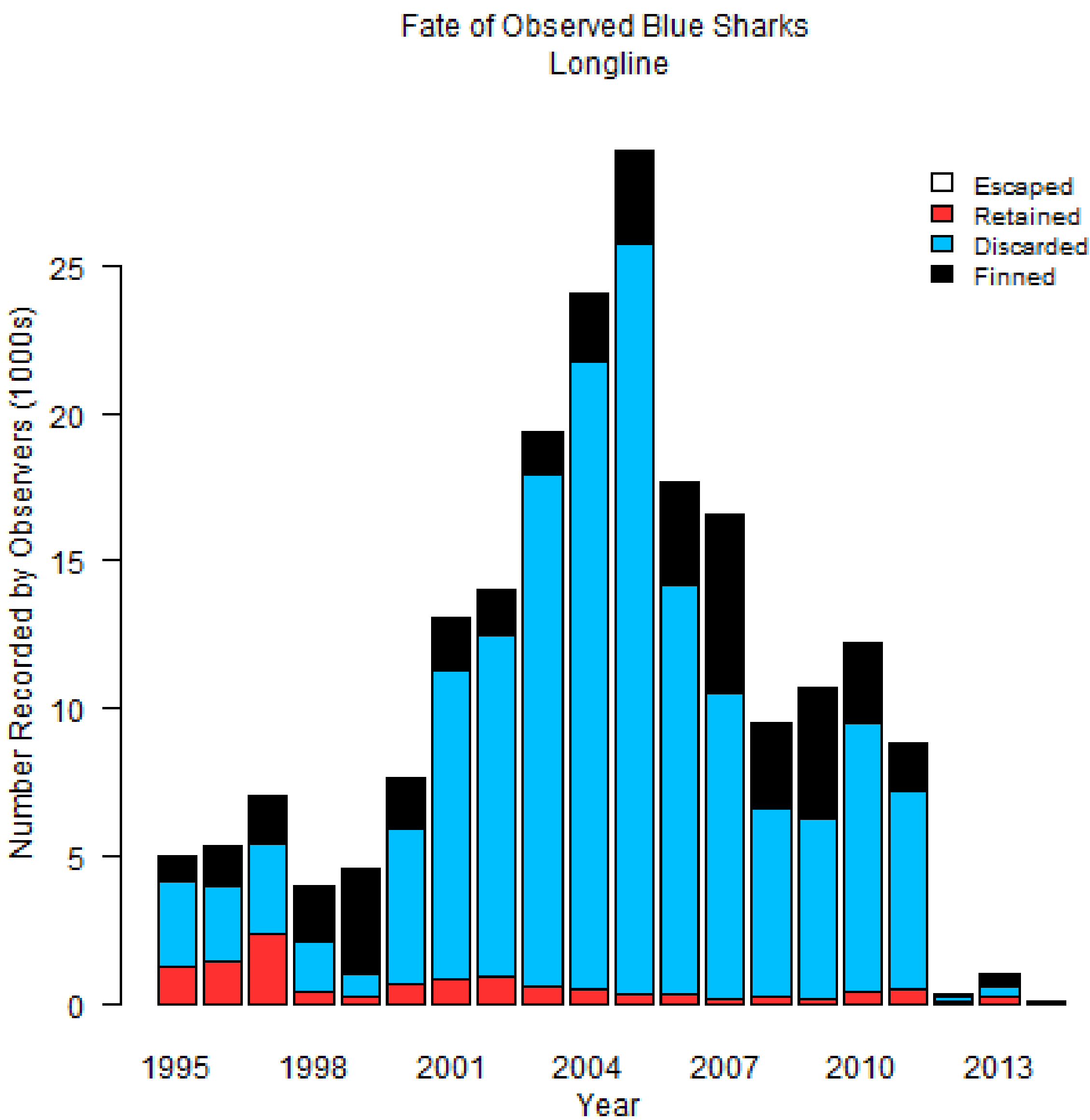


Figure 73: Fate of observed blue sharks caught by longline in the WCPO.

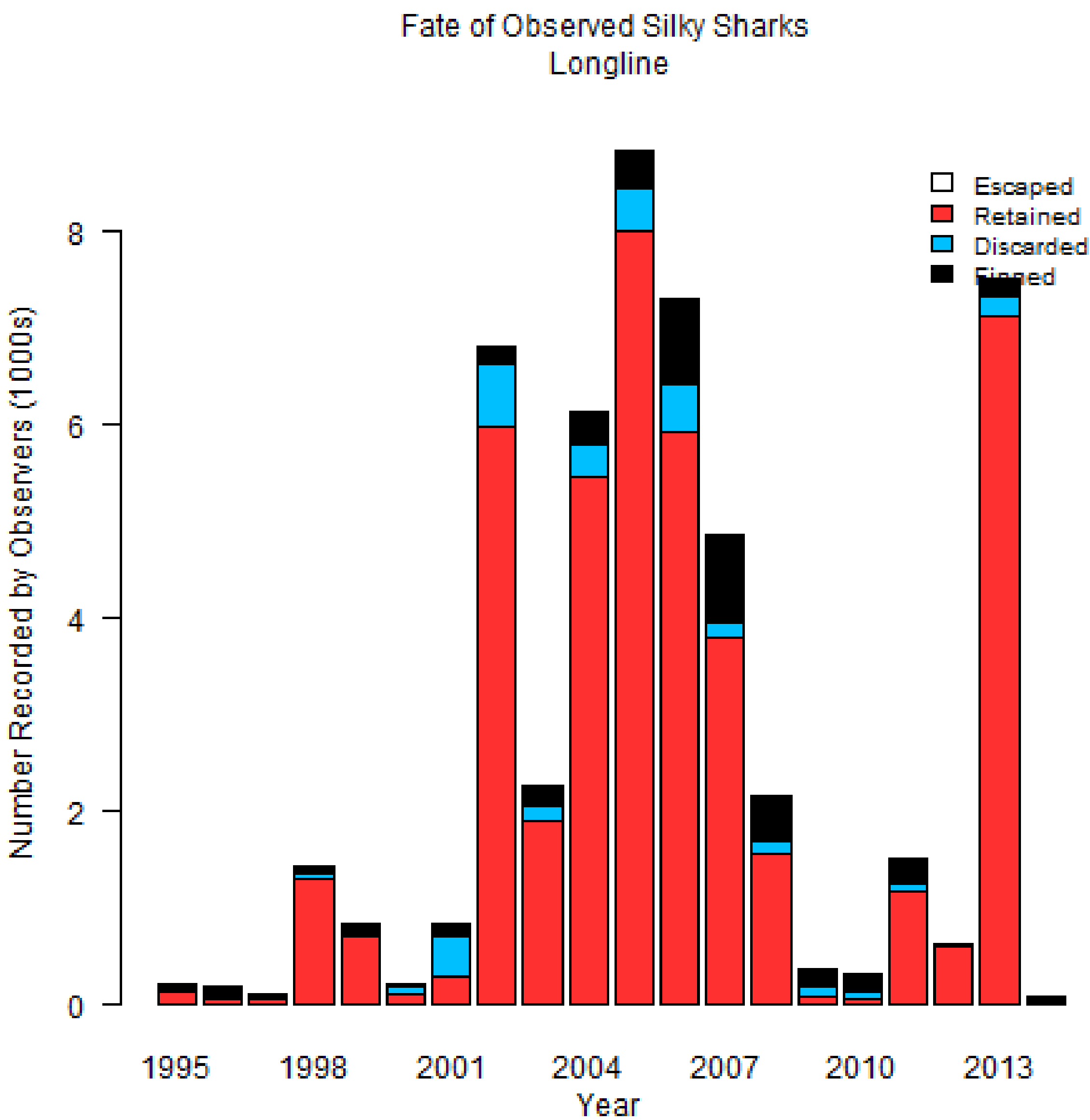


Figure 74: Fate of observed silky sharks caught by longline in the WCPO.

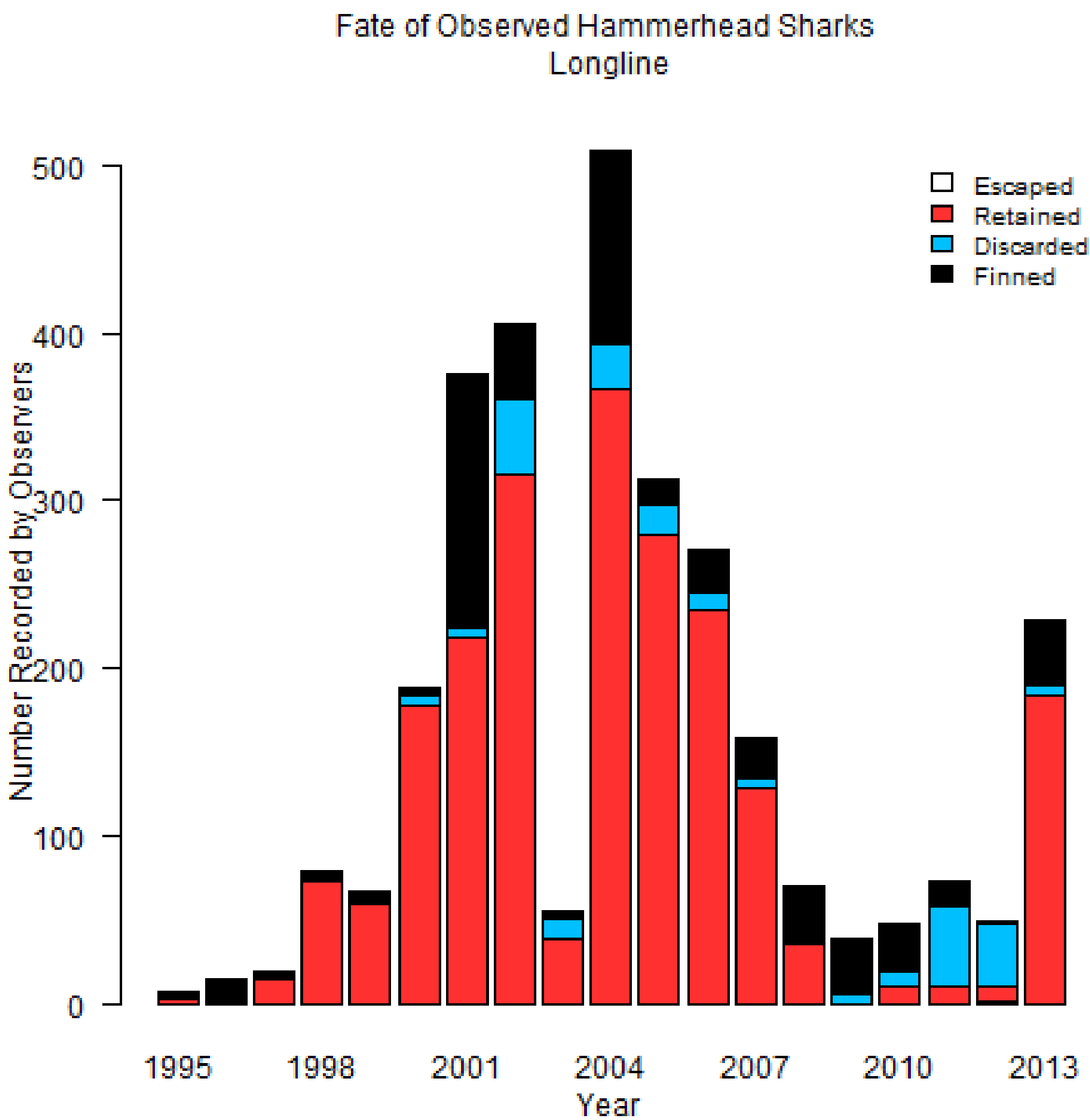


Figure 75: Fate of observed hammerhead sharks caught by longline in the WCPO.

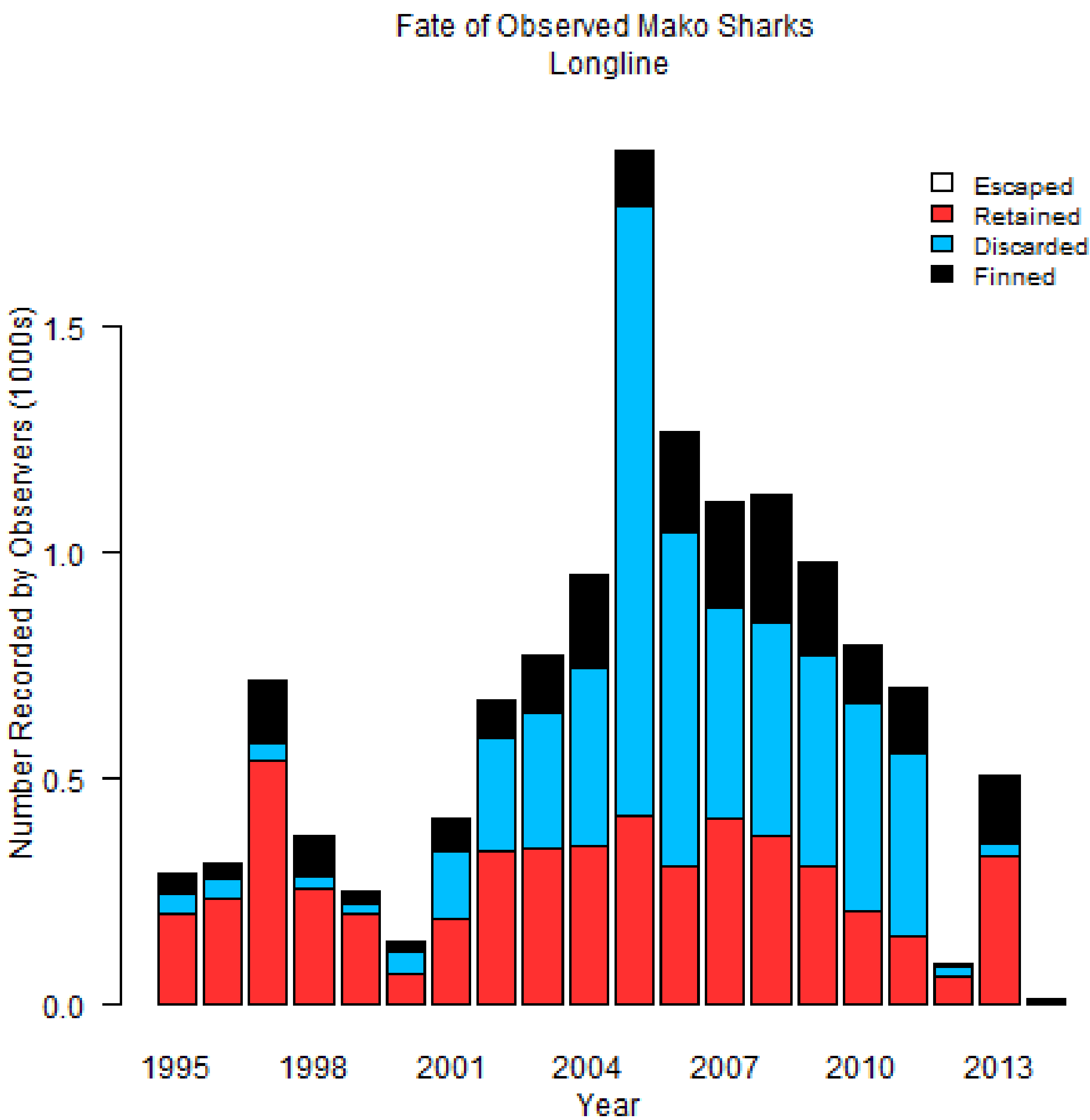


Figure 76: Fate of observed mako sharks caught by longline in the WCPO.

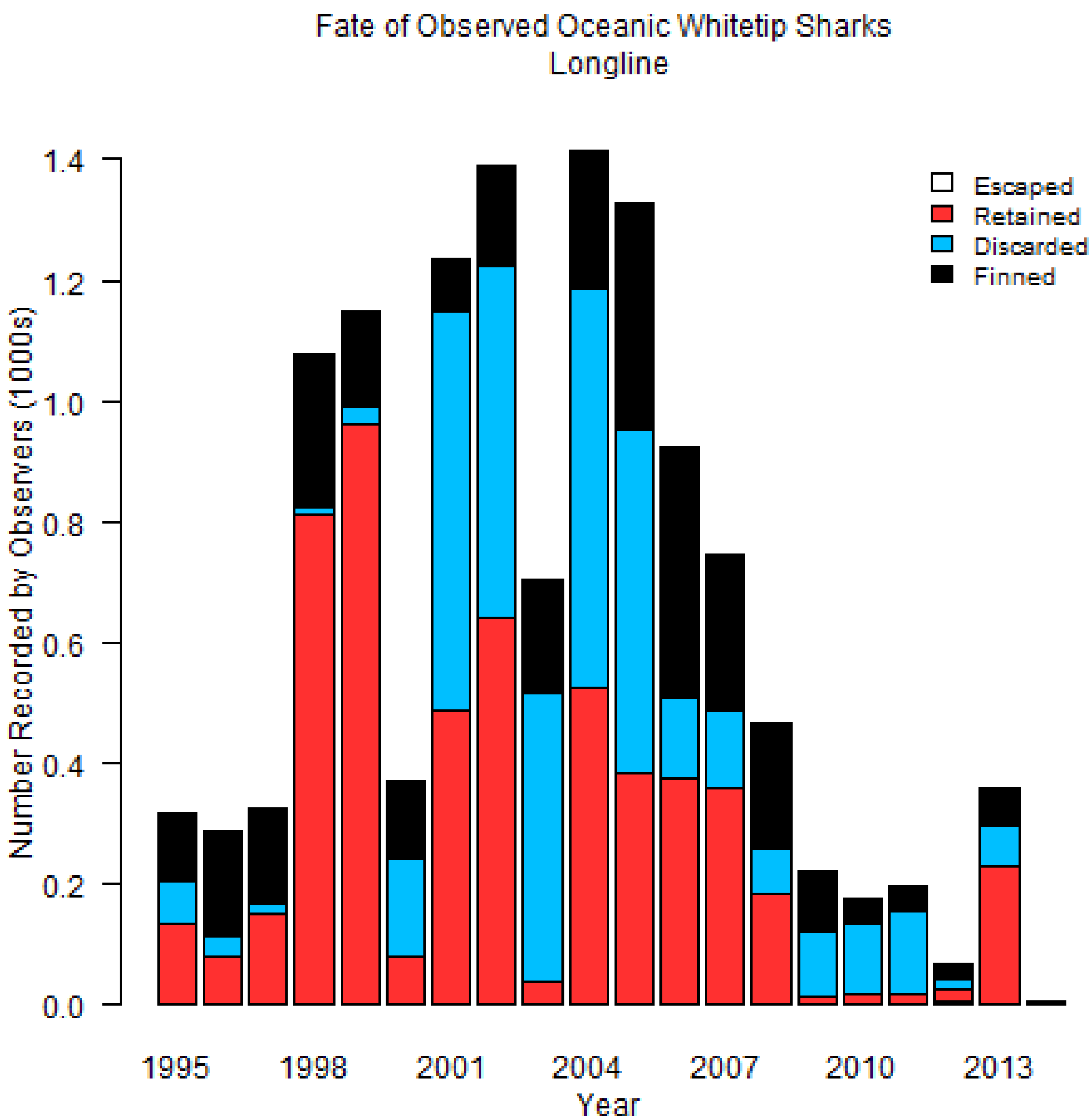


Figure 77: Fate of observed oceanic whitetip sharks caught by longline in the WCPO.

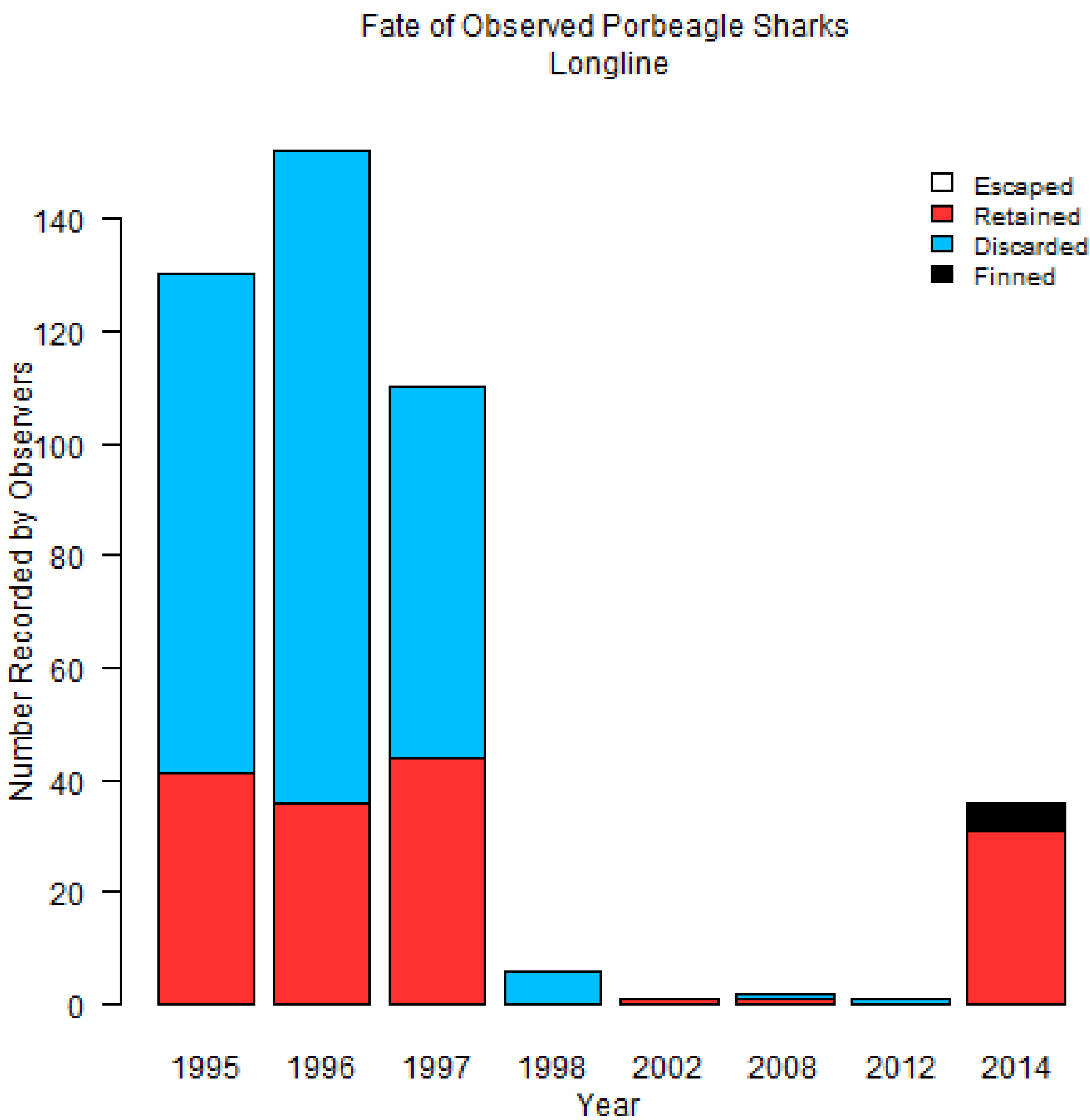


Figure 78: Fate of observed porbeagle sharks caught by longline in the WCPO.

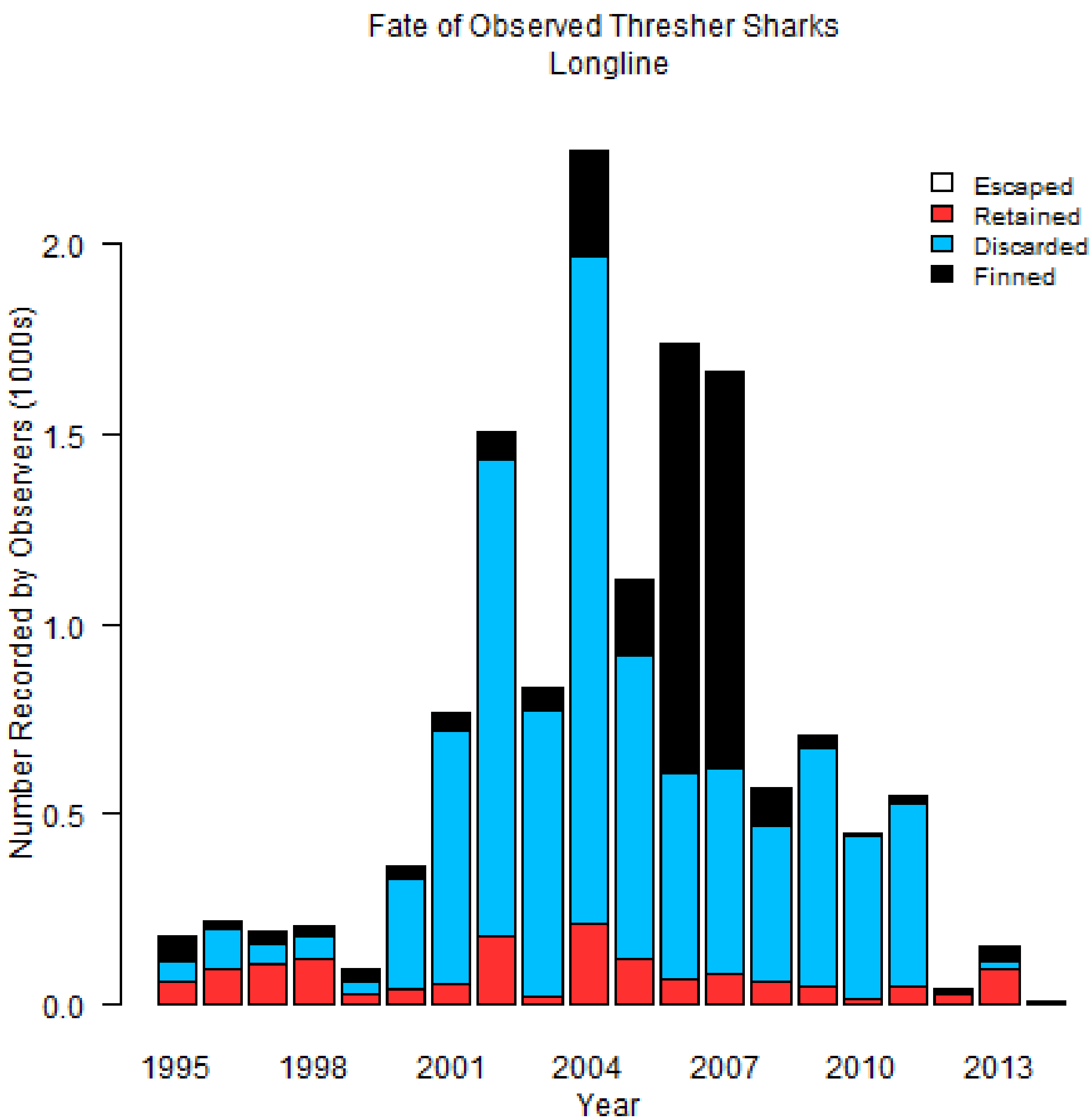


Figure 79: Fate of observed thresher sharks caught by longline in the WCPO.

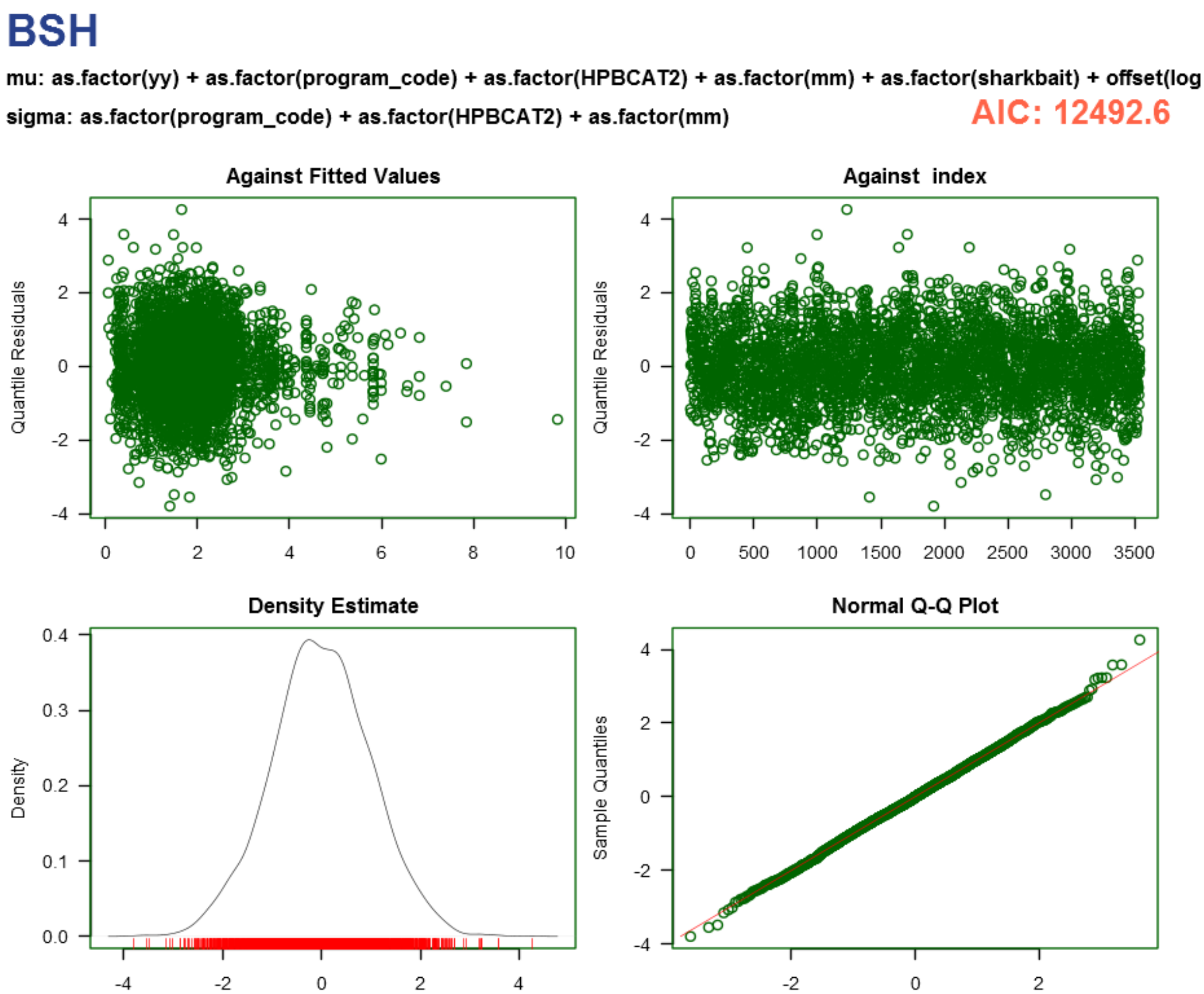


Figure 80: [CPUE indicators, model diagnostics for blue shark (north) CPUE standardization via negative binomial model.

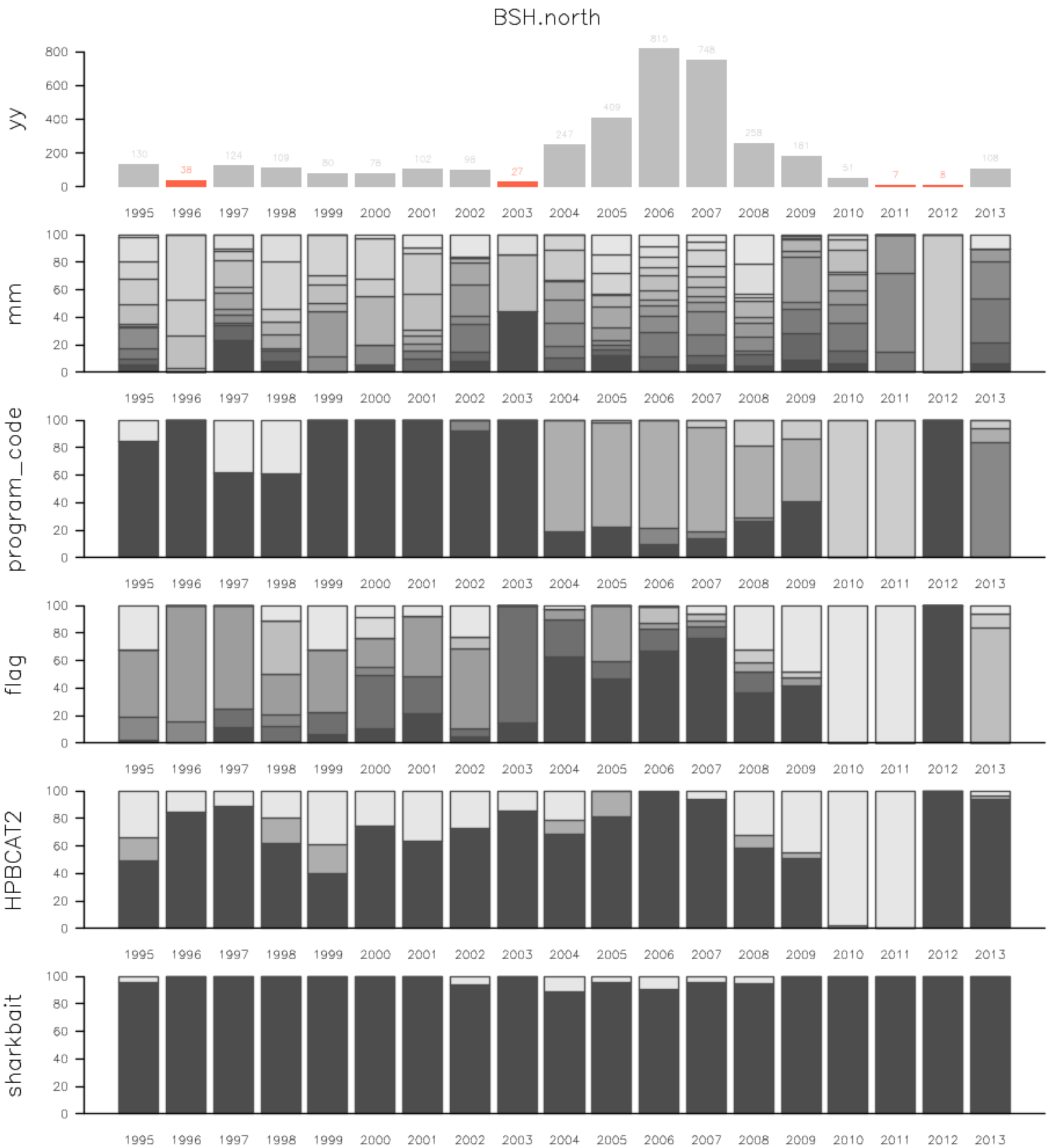


Figure 81: [CPUE indicators, model diagnostics for blue shark (north) CPUE standardization via negative binomial model.

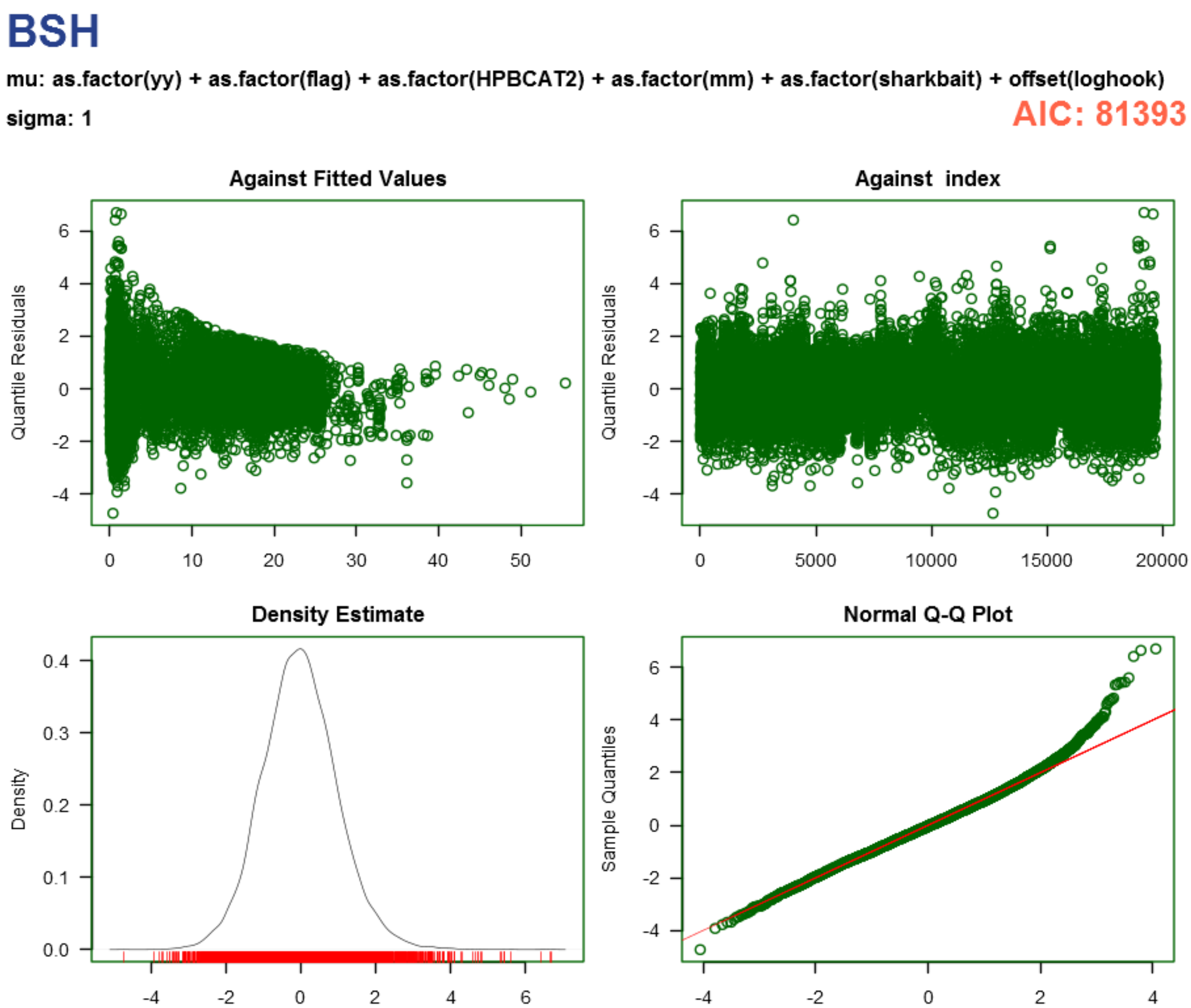


Figure 82: [CPUE indicators, model diagnostics for blue shark (south) CPUE standardization via negative binomial model.

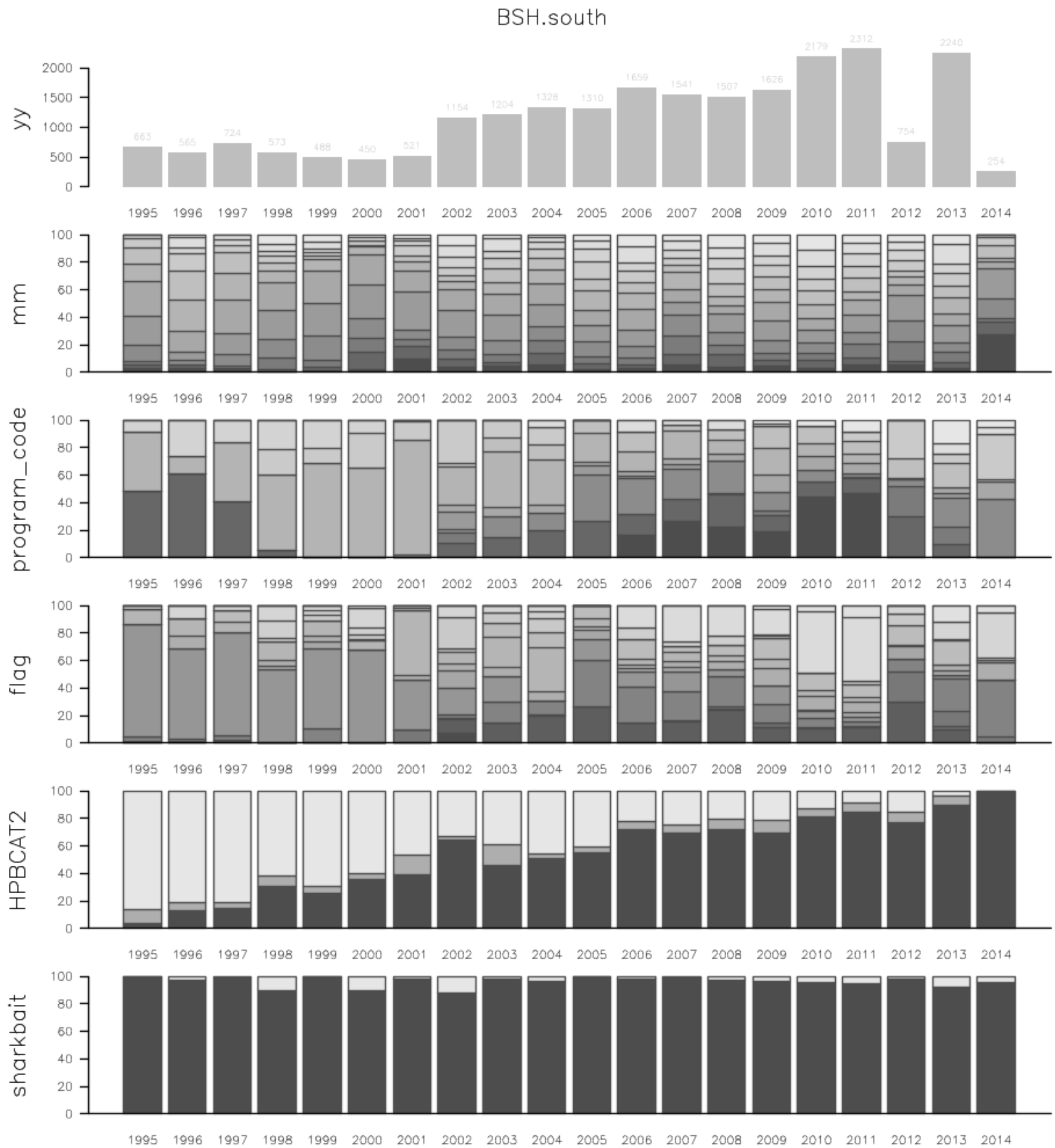


Figure 83: [CPUE indicators, model diagnostics for blue shark (south) CPUE standardization via negative binomial model.

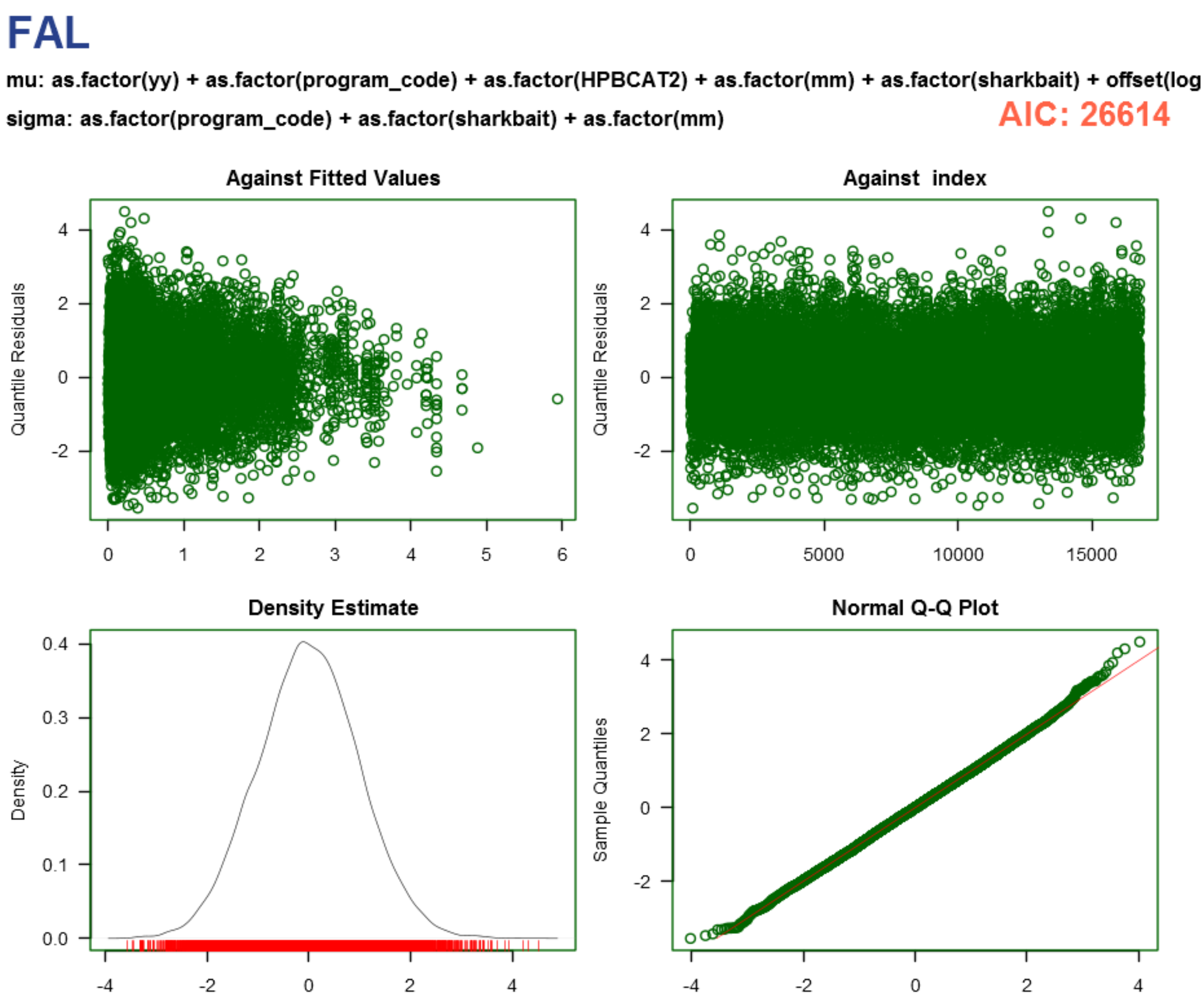


Figure 84: [CPUE indicators, model diagnostics for silky shark CPUE standardization via negative binomial model.

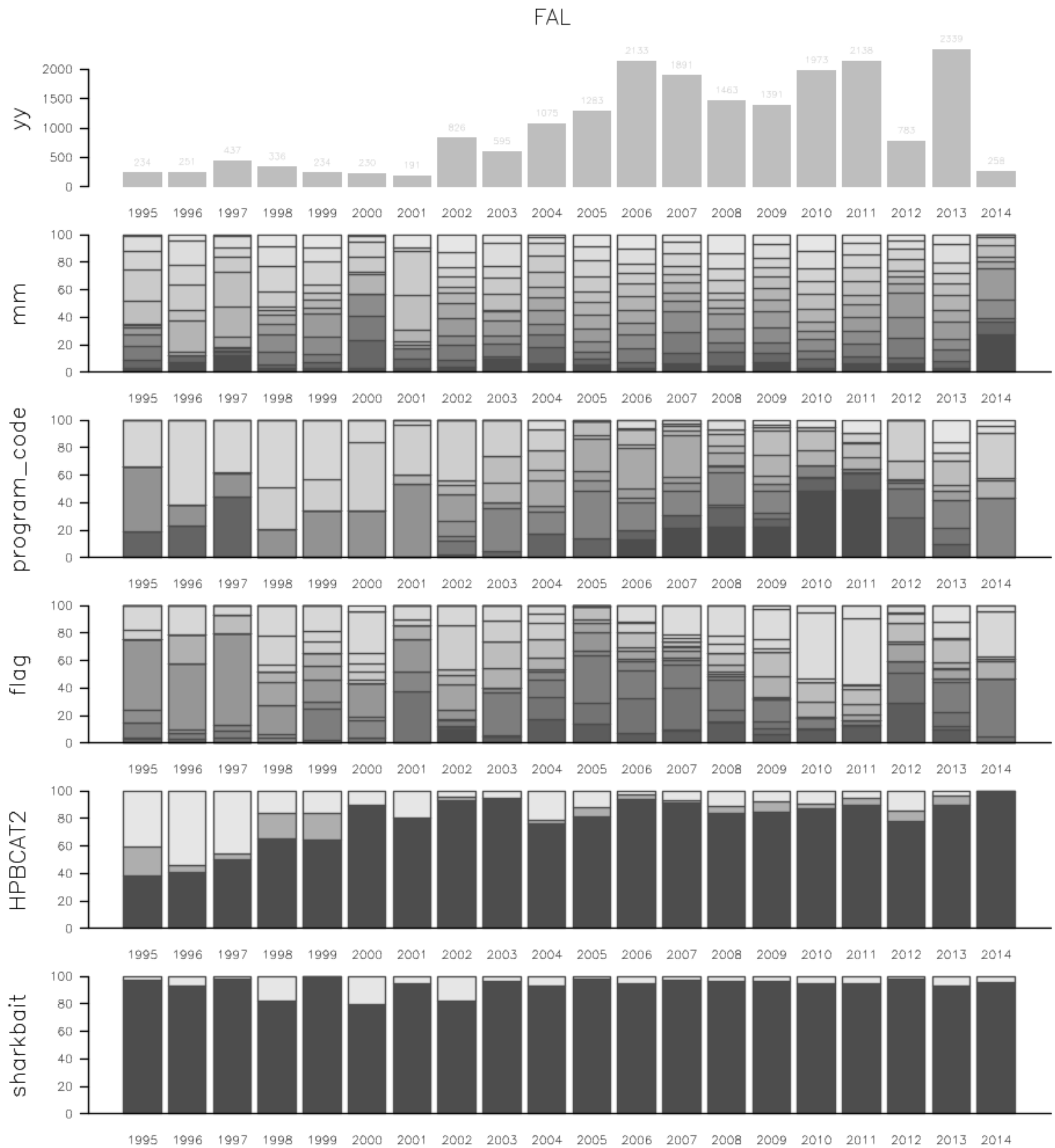


Figure 85: [CPUE indicators, model diagnostics for silky shark CPUE standardization via negative binomial model.

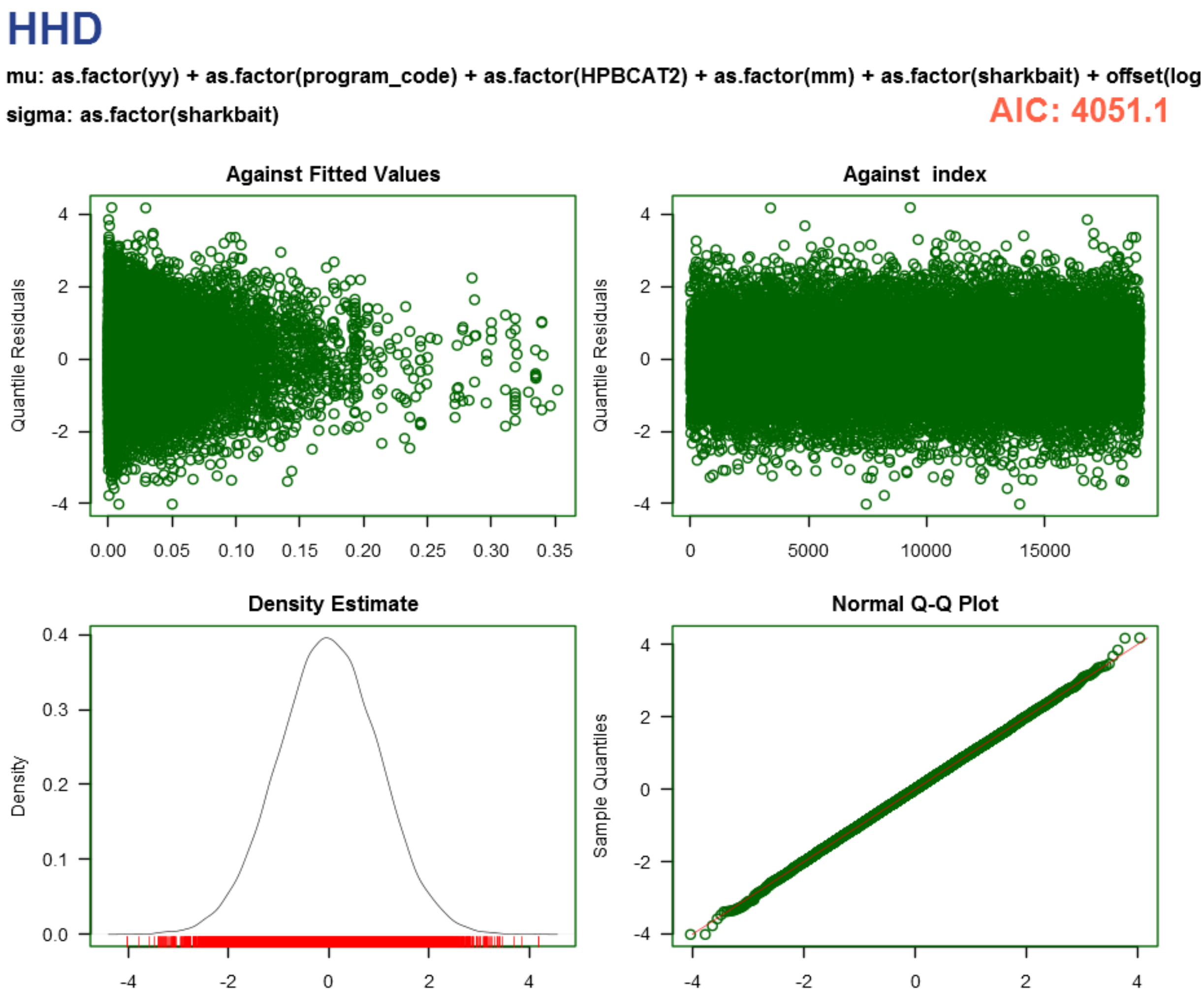


Figure 86: [CPUE indicators, model diagnostics for hammerhead shark CPUE standardization via negative binomial model

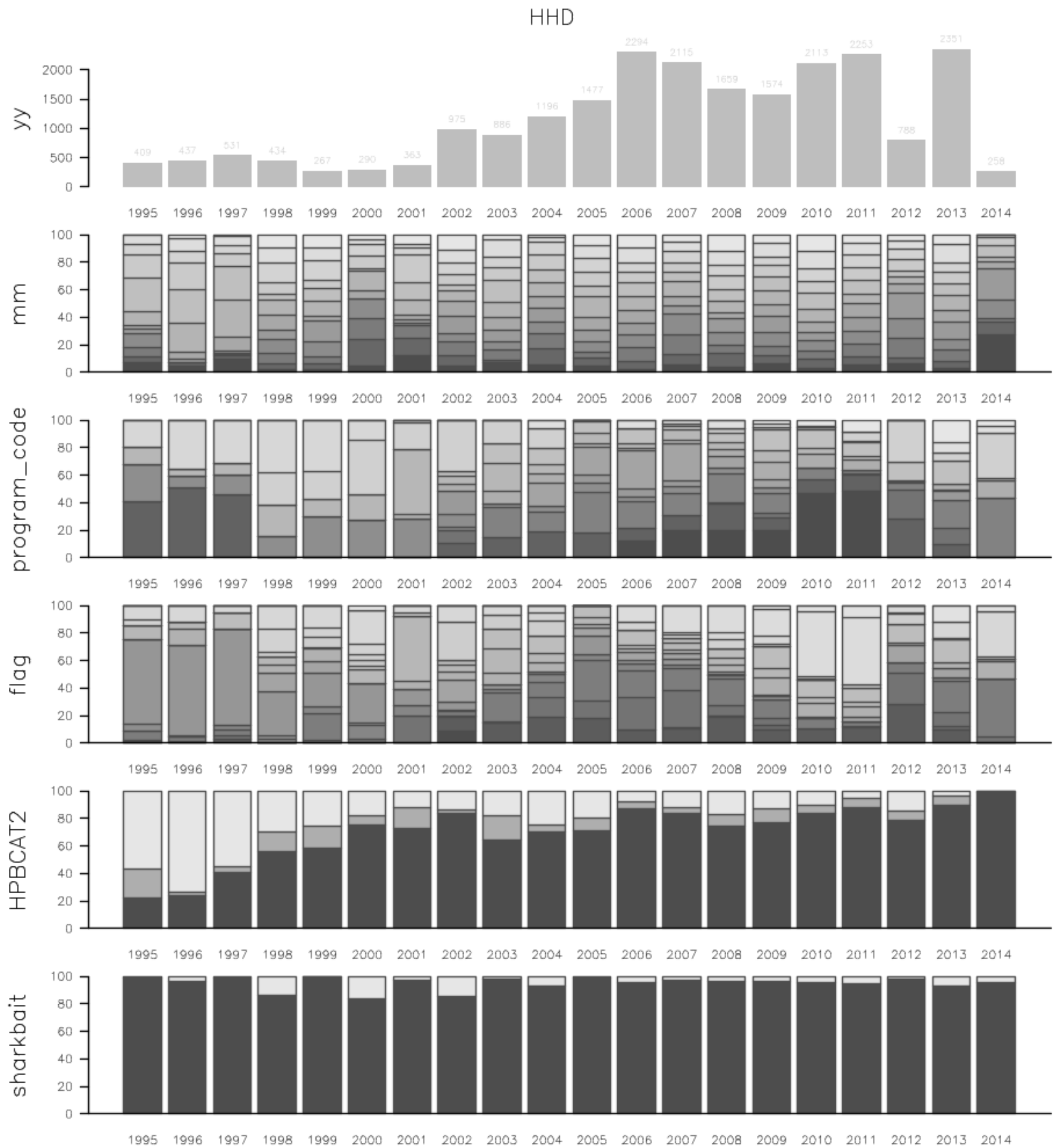


Figure 87: [CPUE indicators, model diagnostics for hammerhead shark CPUE standardization via negative binomial model

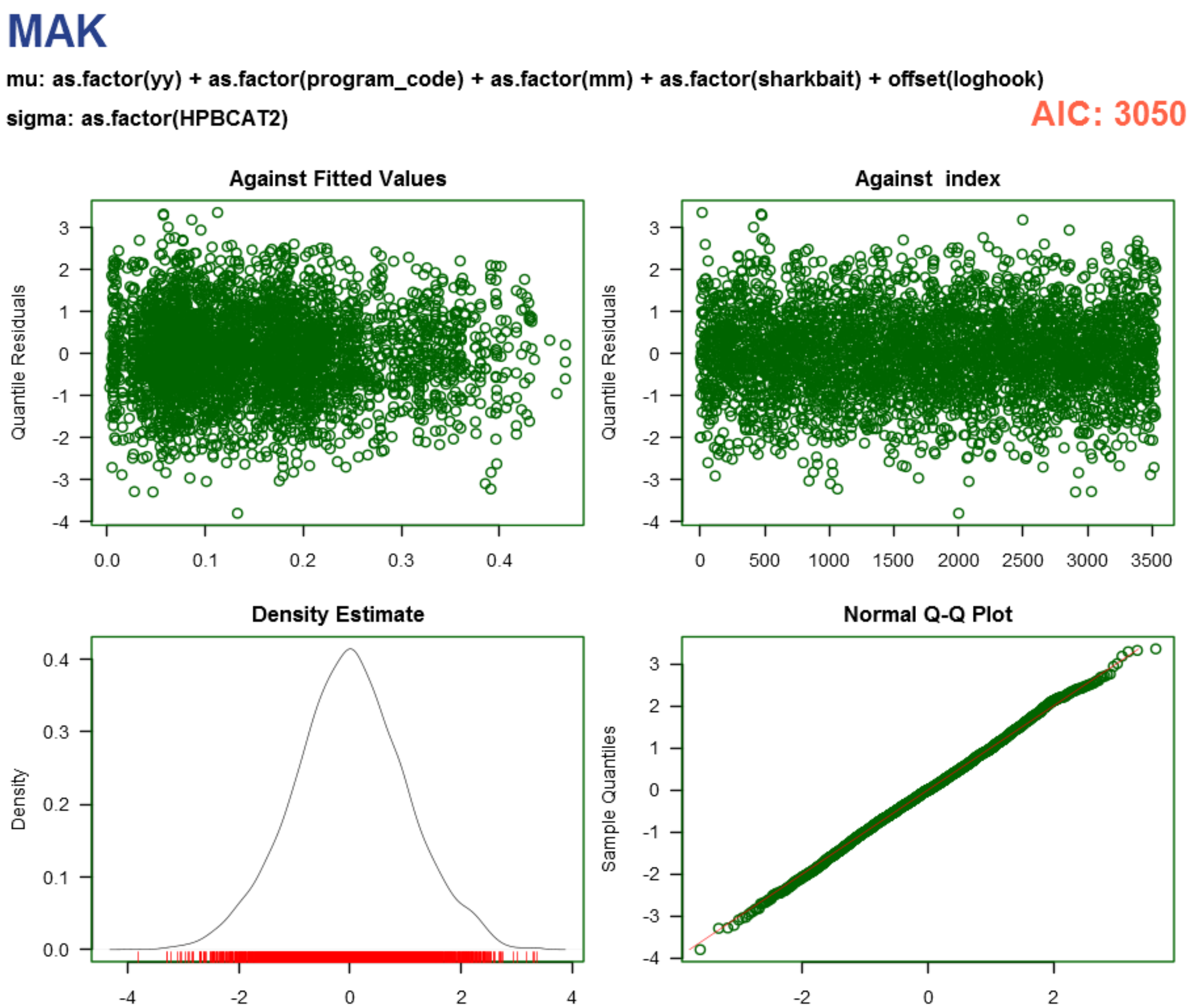


Figure 88: [CPUE indicators, model diagnostics for mako shark (northern hemisphere) CPUE standardization via negative binomial model.

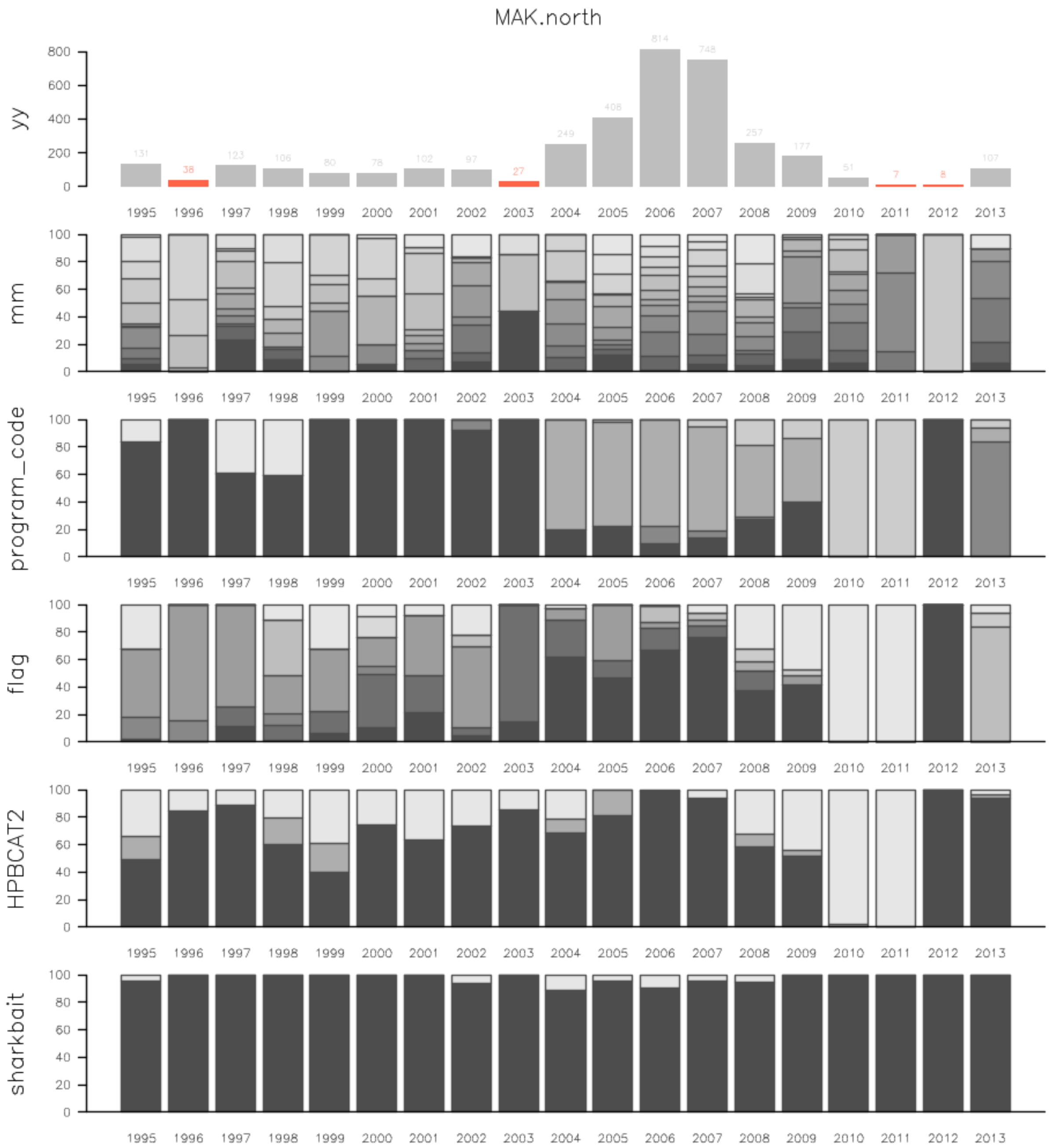


Figure 89: [CPUE indicators, model diagnostics for mako shark (northern hemisphere) CPUE standardization via negative binomial model.

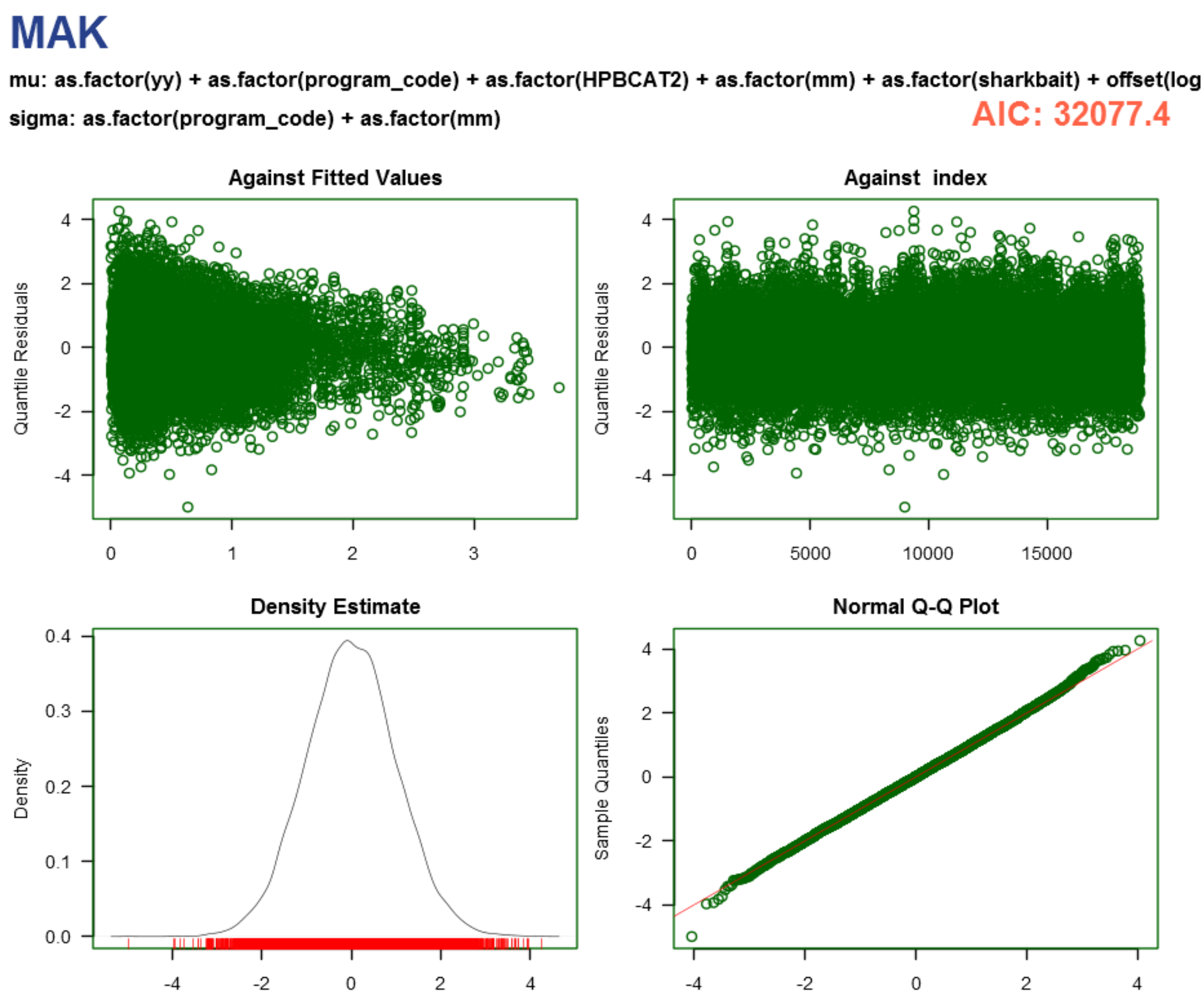


Figure 90: [CPUE indicators, model diagnostics for mako shark (southern hemisphere) CPUE standardization via negative binomial model.

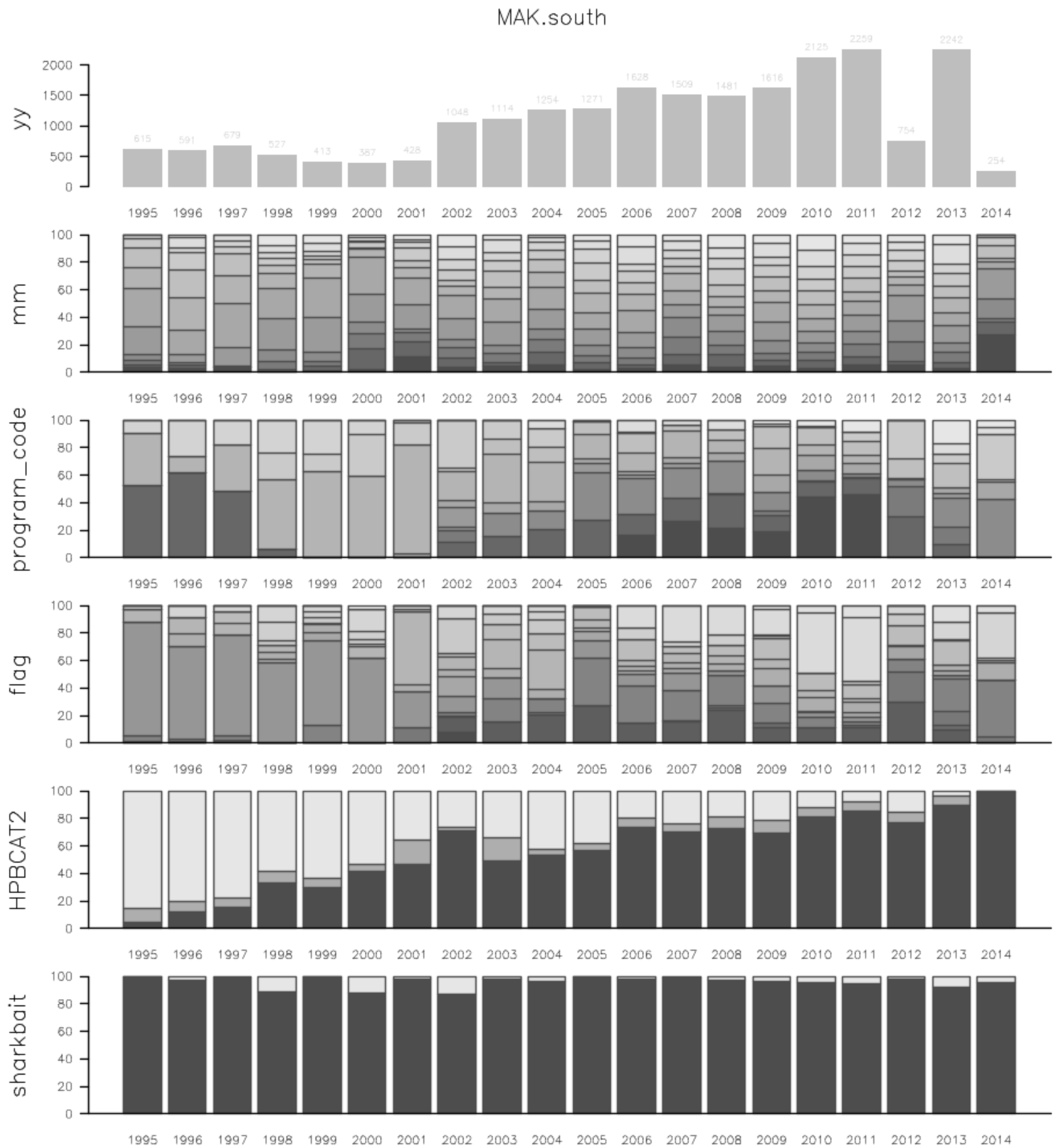


Figure 91: [CPUE indicators, model diagnostics for mako shark (southern hemisphere) CPUE standardization via negative binomial model.

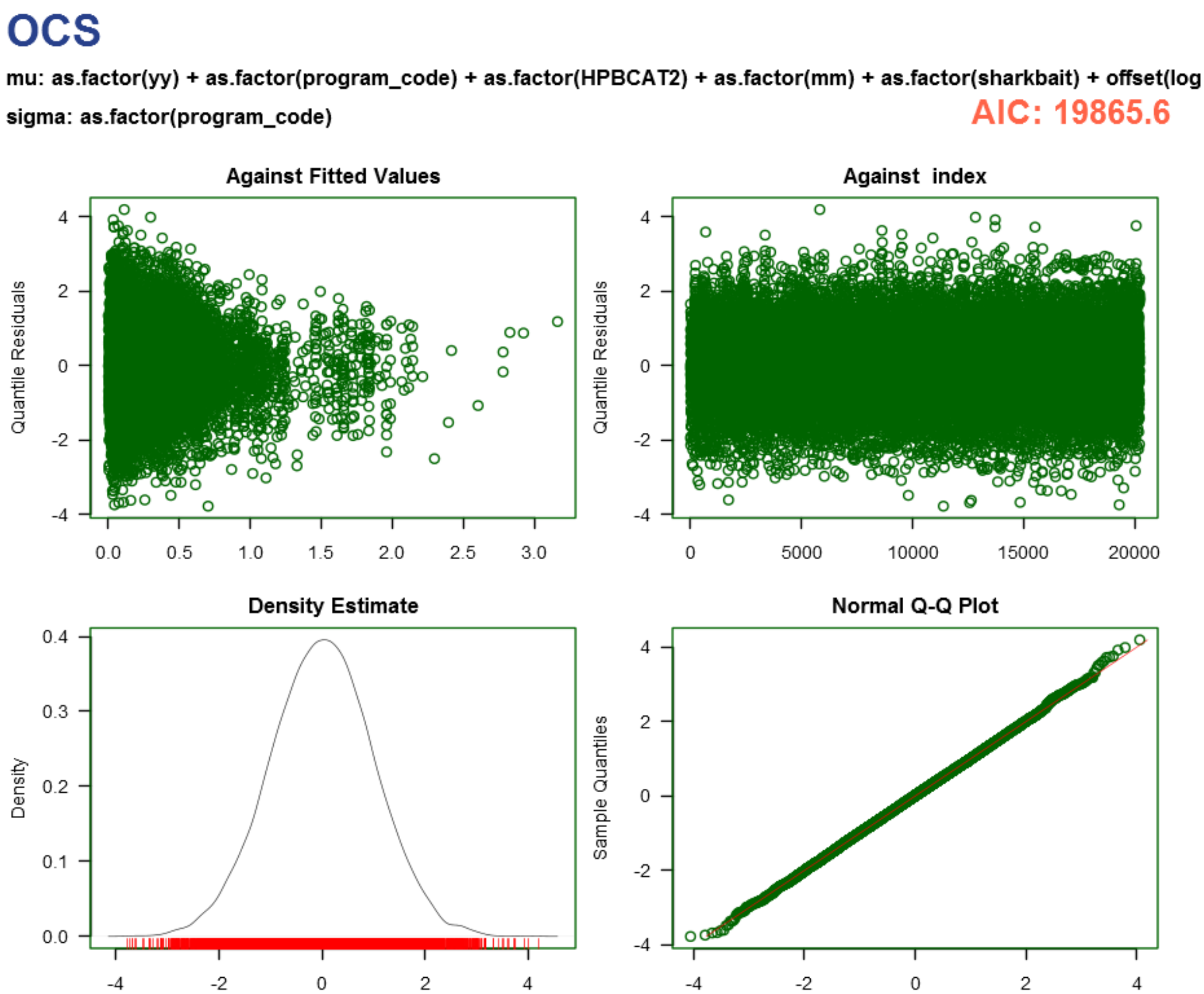


Figure 92: [CPUE indicators, model diagnostics for oceanic whitetip shark CPUE standardization via negative binomial model.

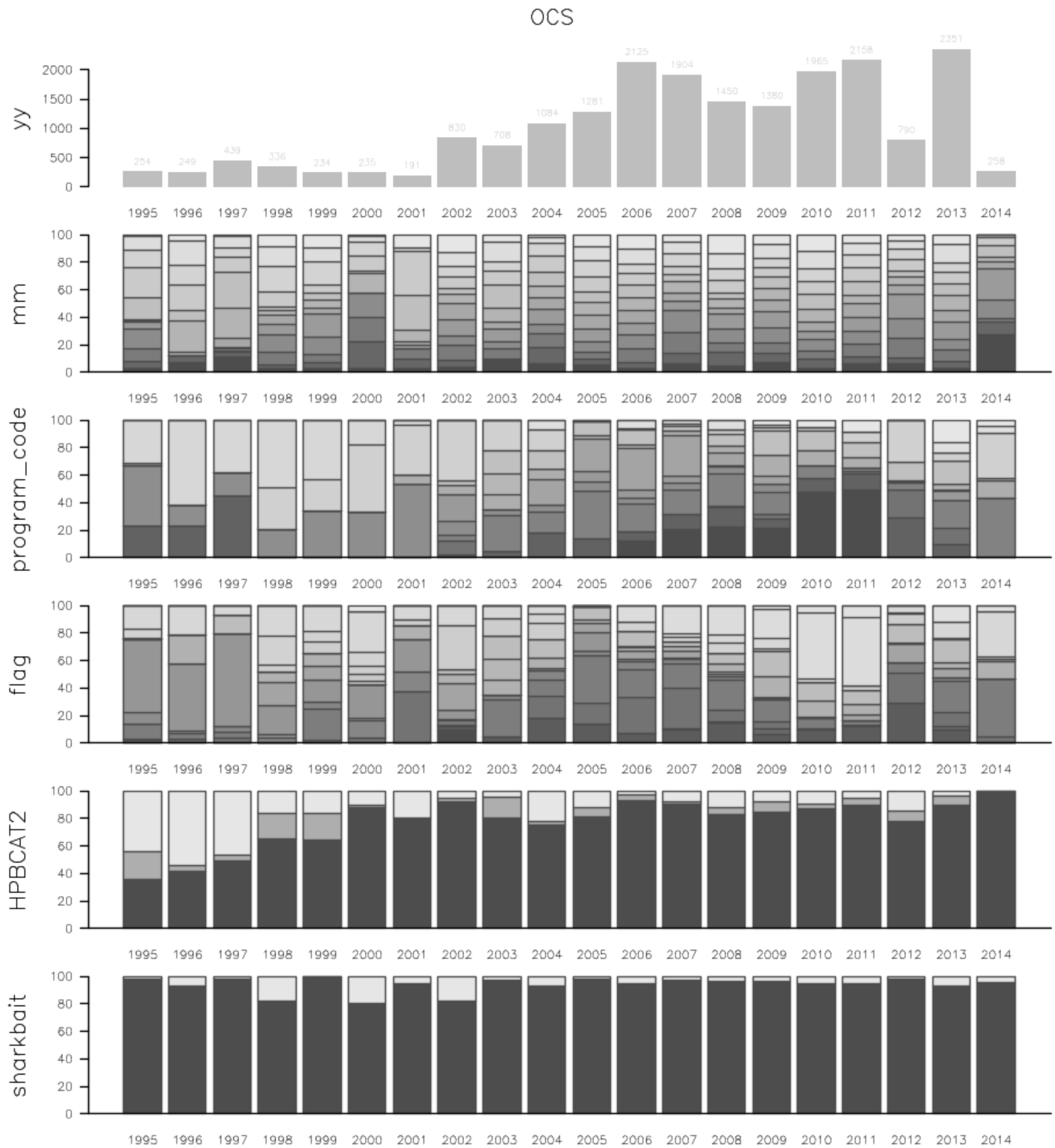


Figure 93: [CPUE indicators, model diagnostics for oceanic whitetip shark CPUE standardization via negative binomial model.

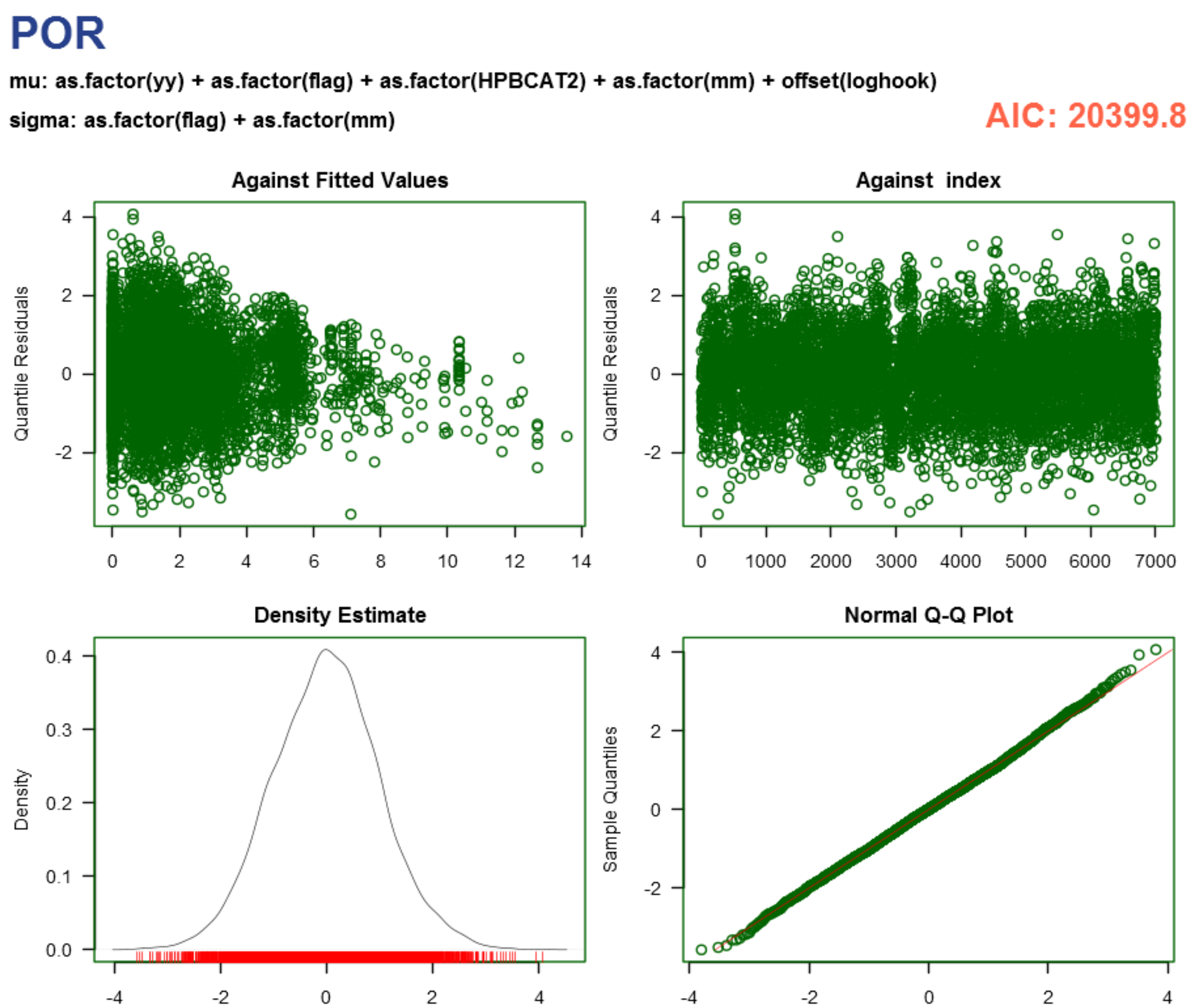


Figure 94: f[CPUE indicators, model diagnostics for porbeagle shark CPUE standardization via negative binomial model.

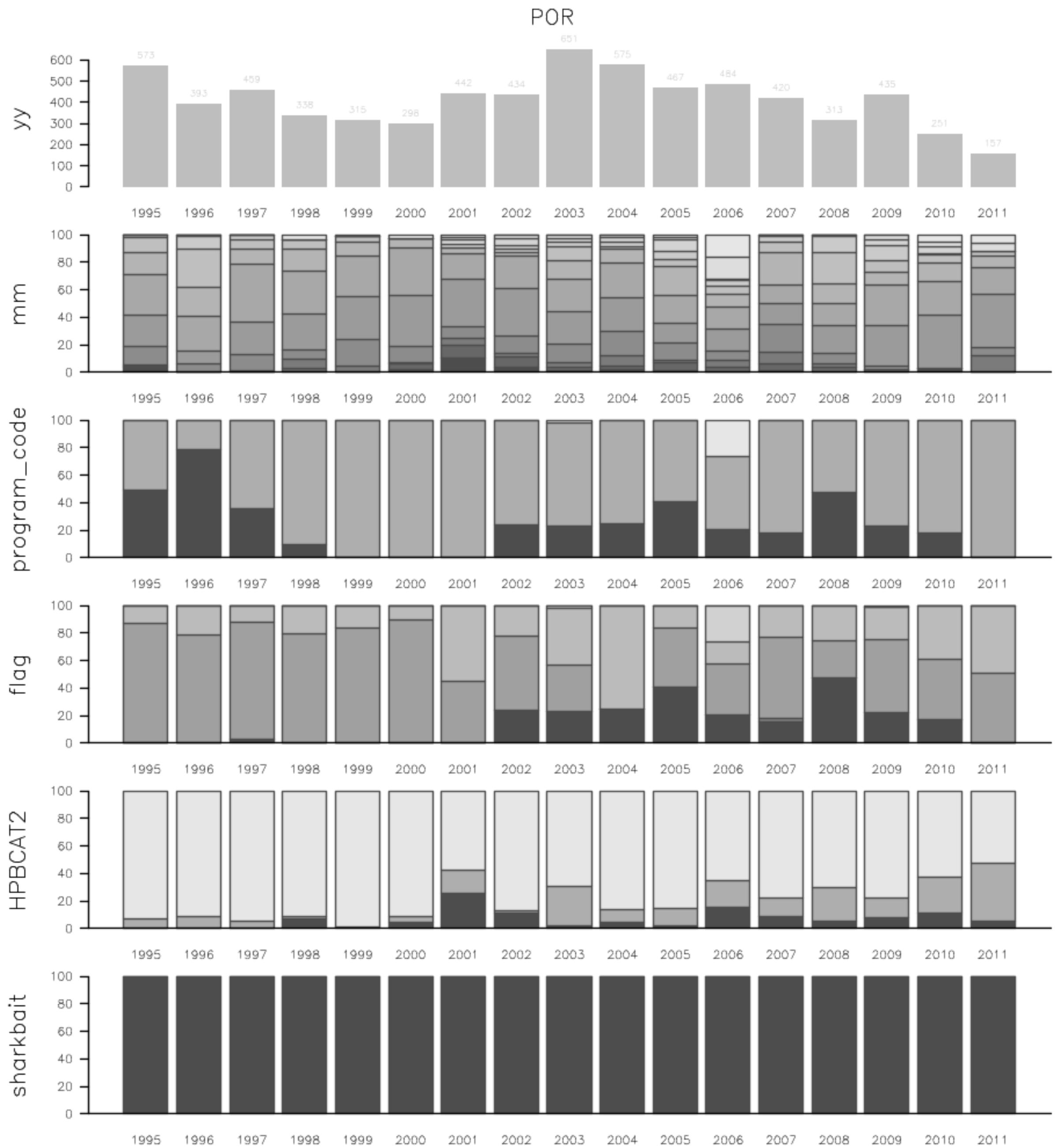


Figure 95: f[CPUE indicators, model diagnostics for porbeagle shark CPUE standardization via negative binomial model.

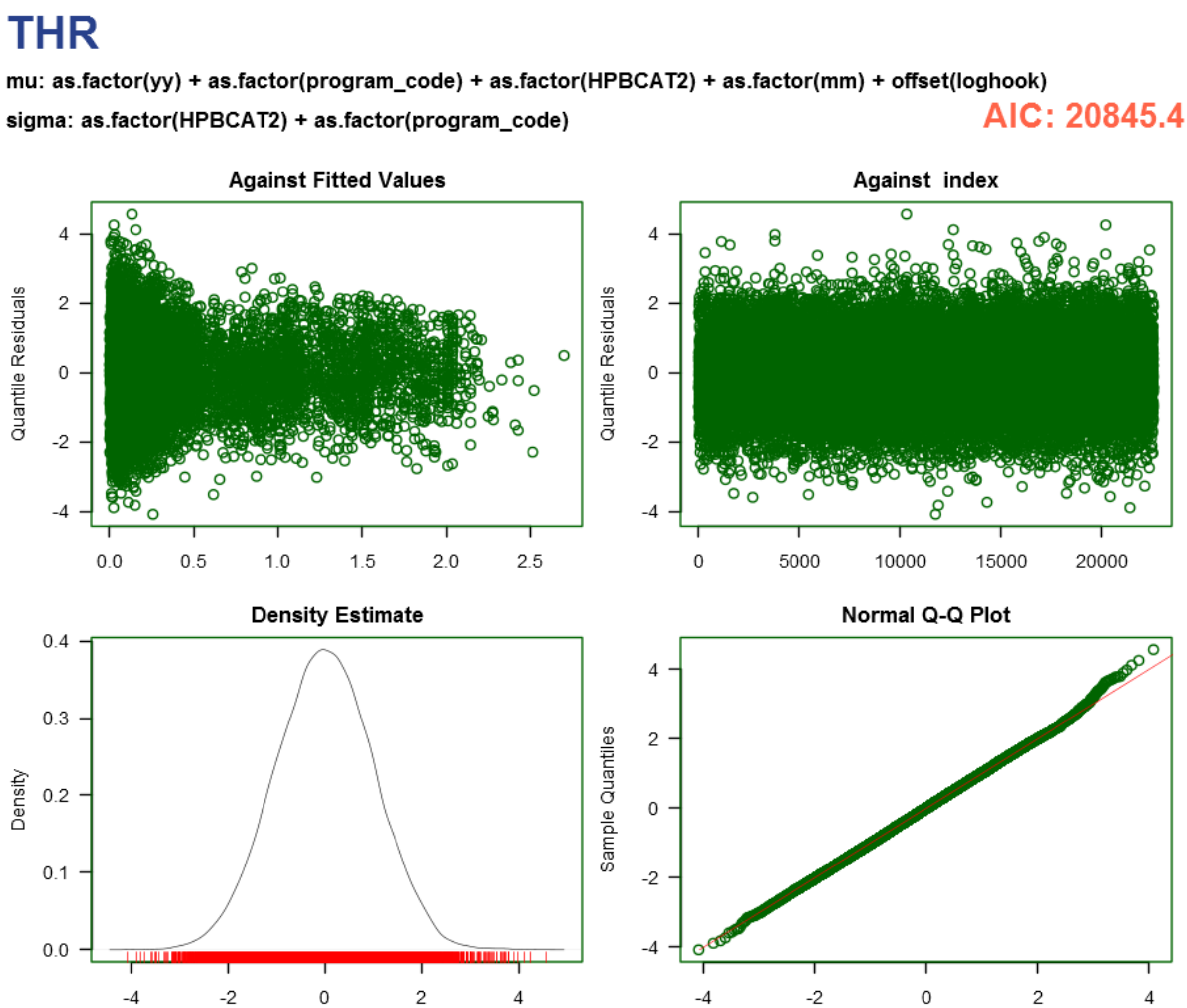


Figure 96: [CPUE indicators, model diagnostics for silky thresher CPUE standardization via negative binomial model.

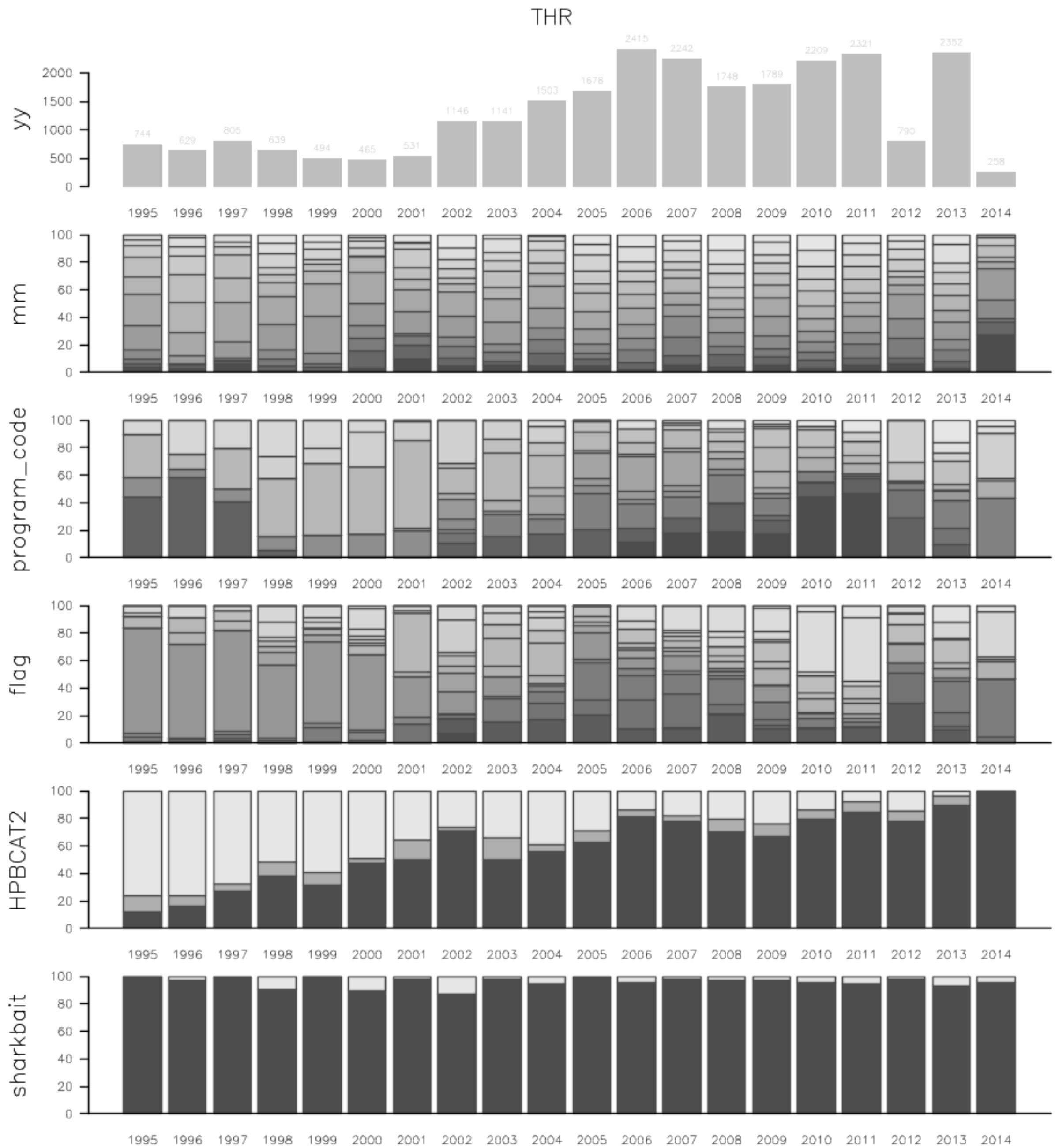


Figure 97: [CPUE indicators, model diagnostics for silky thresher CPUE standardization via negative binomial model.

Table 9: 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 10: 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 11: 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 12: 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 13: 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 14: 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 15: 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 16: 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 17: 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