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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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Joel Rice[1],Laura Tremblay-Boyer[2], Robert Scott[2], Steven Hare[2], and Alex Tidd[2]

[1]Joel Rice Consulting Ltd.
[2] Oceanic Fisheries Programme, Secretariat of the Pacific Community

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This revision includes the following changes:

- Section 1 and executive summary: We have indicated that available 2014 observer data have been included where possible, but that these data are incomplete and care should be made taking certain inferences from these data;
- Section 2.1: the last sentence of the first paragraph was incomplete and has been corrected;
- Section 2.2: We have referred to the Williams et al. (2015) ST-IP-02 on ROP data management;
- Section 7.1: removed a duplicated paragraph – "*As has previously noticed ....*";
- Section 7.2: changed reference to 'bias' for recent trends and to representative;
- Section 7.3: In response to subsequent discussions with trainers of purse seine observers and members of the FFA/SPC Data Collection Committee, we have expanded upon the recommendation for whale sharks (Section 7.3) and also included this recommendation in the Executive Summary, and Sections 10 and 11;
- Section 10 and Table 11: We have added a synthesis table which pulls together the major indicator analyses;
- Section 11: made the south Pacific blue shark assessment recommendation consistent with that in the Executive Summary; and
- Table 12: Table caption expanded.

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Executive Summary

In this report we present, for seven of the fourteen key shark species, information on the geographic range of catches; temporal trends in catch composition and catch rates; and key biological indicators of fishing pressure such as mean size and sex ratio. Whale sharks are assessed separately due to the unique nature of their interactions with WCPO fisheries. The analysis generally follows the framework first developed and described in the Shark Research Plan (Clarke and Harley, 2010).

This analysis provides indicative trends for silky shark, oceanic whitetip, mako shark, blue shark, whale sharks and porbeagle sharks, but more limited inferences are possible for hammerhead and thresher shark species complexes, 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.

Where possible we have included observer data for 2014, but note that these data are incomplete and certain inferences from these data should be made with caution.

Species occurrence indicators show that five of the seven species are encountered across the breadth of the WCPFC region. The exceptions are hammerheads, which are distributed more patchily, and porbeagle which are restricted to the region south of 20°S. The proportion-presence and High-CPUE indicators showed relatively steady trends for most species in all regions. However, for blue shark and oceanic whitetip sharks both indicators show declines as great as 80% in the equatorial and south Pacific regions.

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, and silky shark are the second most common. There are substantial regional and depth variations. Several species are caught more frequently in deeper sets, while porbeagle form a sizeable component of the shallow sets in the regions where they occur (i.e., Regions 5 and 6). Purse seine shark bycatch has much lower species diversity and is dominated by silky sharks, which generally comprise more than 95% of the shark bycatch. Minor numbers of hammerhead and oceanic whitetip sharks also occur.

CPUE indicators indicate that blue shark CPUE is declining in both the north and south Pacific. Oceanic whitetip continue to decline throughout the tropical waters of the WCPO. Silky shark CPUE exhibits high fluctuations throughout the study period. CPUE for the thresher shark complex, and Mako sharks in the south Pacific, appear to be in decline, though the last years' data points are based on relatively few data. Mako in the north Pacific is subject to missing data for some years; trends in CPUE appeared relatively stable between 2000 and 2010, but no inference is possible for the last 4 years. Porbeagle shark CPUE experienced a large decrease early on in the study period followed by a fluctuating but increasing CPUE trend.

Biological Indicators show that the sex ratio of sharks in longline catch is approximately equal for all species and regions, with the exception of blue shark in Region 5, which are predominantly female. 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 mature in Region 2. Declines in standardised annual lengths are apparent in most regions for most species, 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 annual standardised length were seen for northern mako sharks (both sexes).

Recommendations to the Scientific Committee

Based on the indicators examined in this analysis, we invite the SC to consider the following recommendations when considering future research priorities:

- Increased observer monitoring is vital to provide improved information for all shark species to support development of stock assessments as well as gather fishery information necessary to monitor the impact of CMMs.
- 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. While updated assessments may be warranted for both stocks, this would appear most useful for silky shark to understand how its stock status has changed in recent years in conjunction with the new CMMs.
- Stock assessments for blue sharks in the south Pacific, mako sharks, oceanic whitetip sharks (in the WCPO and Pacific wide) and silky sharks should be scheduled within the next five years. Given the marked CPUE declines for blue shark in the south Pacific this should be the highest priority.
- For currently unassessed stocks, the development of catch histories would enable more informative analyses in future. For hammerhead and thresher sharks the analysis of catch species composition would be similarly useful.
- For silky, oceanic whitetip and whale sharks, information on post release mortality rates is needed to monitor the effectiveness of existing non-retention management measures. This work requires an update to the information collected by observers with respect to shark releases; to this end an update to observer forms and data collection procedures will be required.
- A similar indicator analysis be undertaken for relevant key shark species again in 2-3 years, with a stock assessment for blue shark in the south Pacific, and another silky shark assessment conducted in the interim.
- Develop a time series of whale shark interactions and mortalities, taking into account potential changes in reporting and observer coverage.
- Examination of observer data/journals for 2014 to determine whether distinction between compliance/non-compliance with the whale shark CMM is possible.

1 Introduction

Sharks are typically caught as bycatch in the Pacific tuna fisheries, though some directed and/or mixed species fisheries also exist. The Western and Central Pacific Fisheries Commission (WCPFC) has 14 designated key shark species (Table 1). Initially the list included blue shark, oceanic whitetip shark, mako sharks and thresher sharks. Silky, porbeagle (south of 30° S), hammerhead sharks (winghead, scalloped, great, and smooth) and whale sharks were added later. The status of the five of these species (blue, mako, thresher, silky, and oceanic whitetip sharks) in the Western and Central Pacific Ocean (WCPO) was reviewed in 2011 (Clarke et al., 2011; Clarke, 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 sharks compared to target species, the indicators developed were based on data from logsheets and observer records from industrial purse-seine and longline vessels.

The current study updates key indicators and extends the analyses to include hammerhead, porbeagle and whale sharks. 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, data for 2014 were available both in logsheets and the observer data, however, the most recent observer data for Australia and the United States were in 2013 and 2011 respectively. We note that observer data for 2014 are incomplete and certain inferences from these data should be made with caution.

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. 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 (Clarke and Harley, 2010).

Table 1: Species and species groupings included in the analysis

Species label	Scientific Name
Blue shark	*Prionce glauca*
Hammerhead sharks	*Sphyrna mokarran, S. lewini, S. zygaena and, Eusphyra blochii*
Mako sharks	*Isurus oxyrinchus, I. paucus*
Oceanic whitetip shark	*Carcharhinus longimanus*
Porbeagle shark	*Lamna nasus*
Thresher sharks	*Alopias superciliousus, A. vulpinus and A. pelagicus*
Whale shark	*Rhincodon typus*

1.1 Report layout

This report is necessarily large. To assist the reader it has been structured along the following lines.

- Section 1 - Introduction
- Section 2 - brief description available data
- Sections 3-6 - each of the four indicator analyses are described and results summarized
- Section 7 - an overview of stock status indicators for whale sharks, as they have a rather unique interaction with the WCPO tuna fisheries
- Section 8 - a consideration of the feasibility of conducting a formal stock assessment for each of the shark species discussed in this report
- Section 9 - review of the impact of recent shark management measures
- Section 10 - conclusions arising from our analysis of stock indicators are summarized
- Section 11 - discussion on research recommendations to improve on the indicator analysis as well as management implications arising from the results of the work

2 Description of Data

The primary source of data is the SPC-held observer database which, despite low coverage in all regions (Table 2) has substantial information regarding fleet operational characteristics as well as fate and condition data of 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 longline logsheet (operational) and aggregated shark catch data. The operational data submitted to the SPC are at a higher spatial resolution than the aggregate data, and are useful for catch estimation, but their utility is limited by the lack of data provision by species for sharks (Table 3), especially in equatorial regions where the majority of the longline effort occurs.

Aggregate data coverage is on par with the logsheet data, although coverage differs greatly by region. 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 14 species designated by WCPFC as key shark species is mandatory however, thresher and hammerhead sharks are each considered as a species complex for reporting purposes. Under CMM 2007-01, 5% observer coverage by the Regional Observer Programme (ROP) has been required since June 2012 in longline fisheries, but annual average values have been $\leq$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).

This indicator analysis uses six 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, billfish and occasionally sharks, these regions adequately capture the important characteristics of the fisheries. Therefore, for comparison to the previous analysis, we opted to retain regional structure.

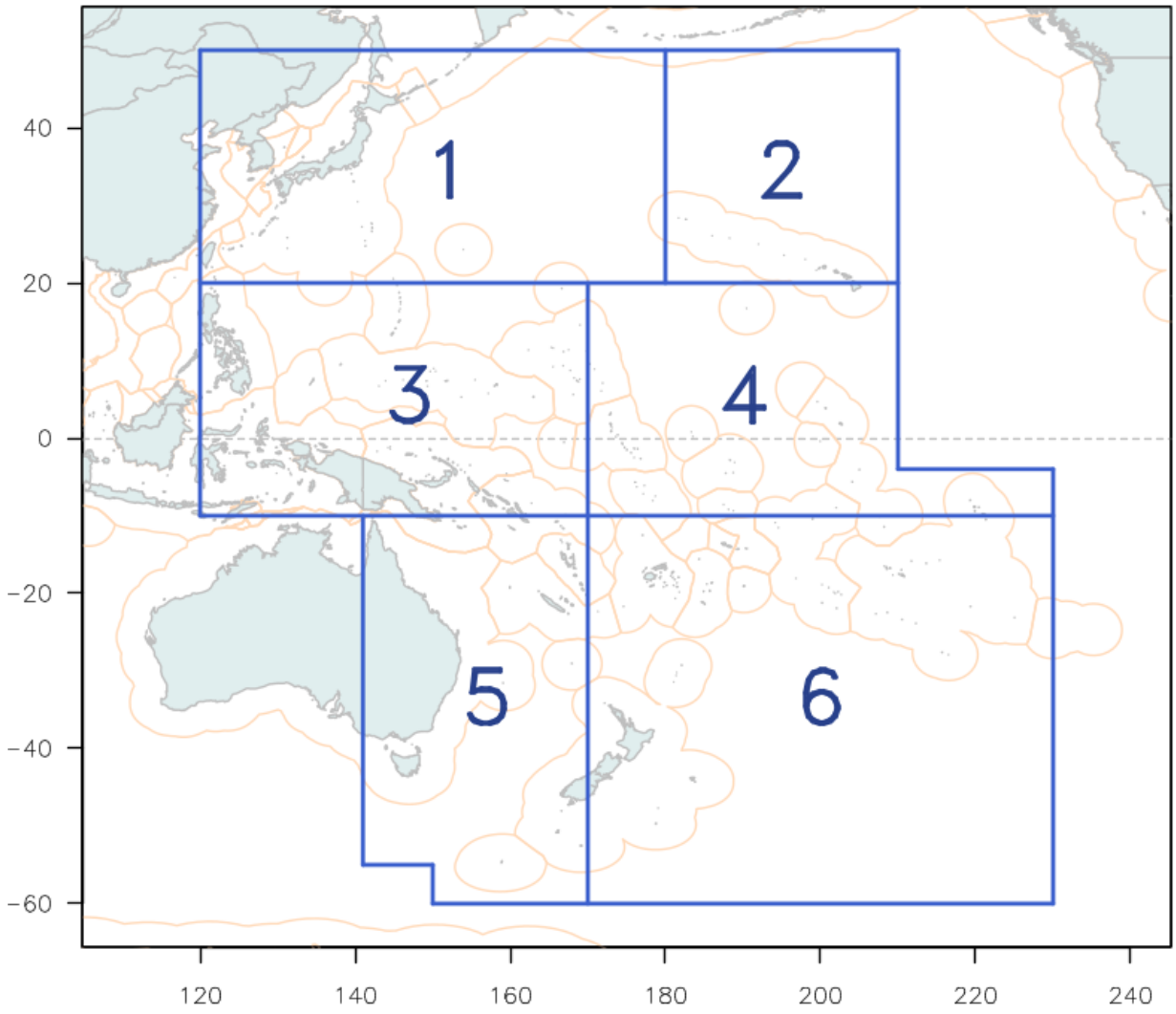


Figure 1: Map of the WCPO and regions used for the analysis.

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 4). Ideally, indicator analyses would be based on operational-level data as its higher spatial resolution permits more comprehensive and nuanced analyses, however SPC's operational level data are geographically limited and not consistent with the spatio-temporal distribution of the fleet. Figure 2 illustrates the geographic distribution of longline logsheet data held by SPC (blue points). However, this picture is somewhat misleading as only 41% of the sets plotted recorded sharks. This is in contrast to the observer data (orange points) in which 93% of the sets recorded at least one shark (red points).

This discrepancy is not necessarily due to misreporting. Prior to February 2011, sharks were not amongst the species for which data provision was required (WCPFC, 2011); since that time data provision for the 14 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 (2011) 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 data, a more complete characterisation of the longline fishery requires the use of the aggregated ($5° \times 5°$ grid) data. Effort and reported shark catch 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.

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 catch 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.

Due to the low data coverage, the observed sets are not spatio-temporarily representative of the fishing 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).

Prior to all of the analyses performed in this report, the longline dataset was groomed according to the filters outlined in Table 5.

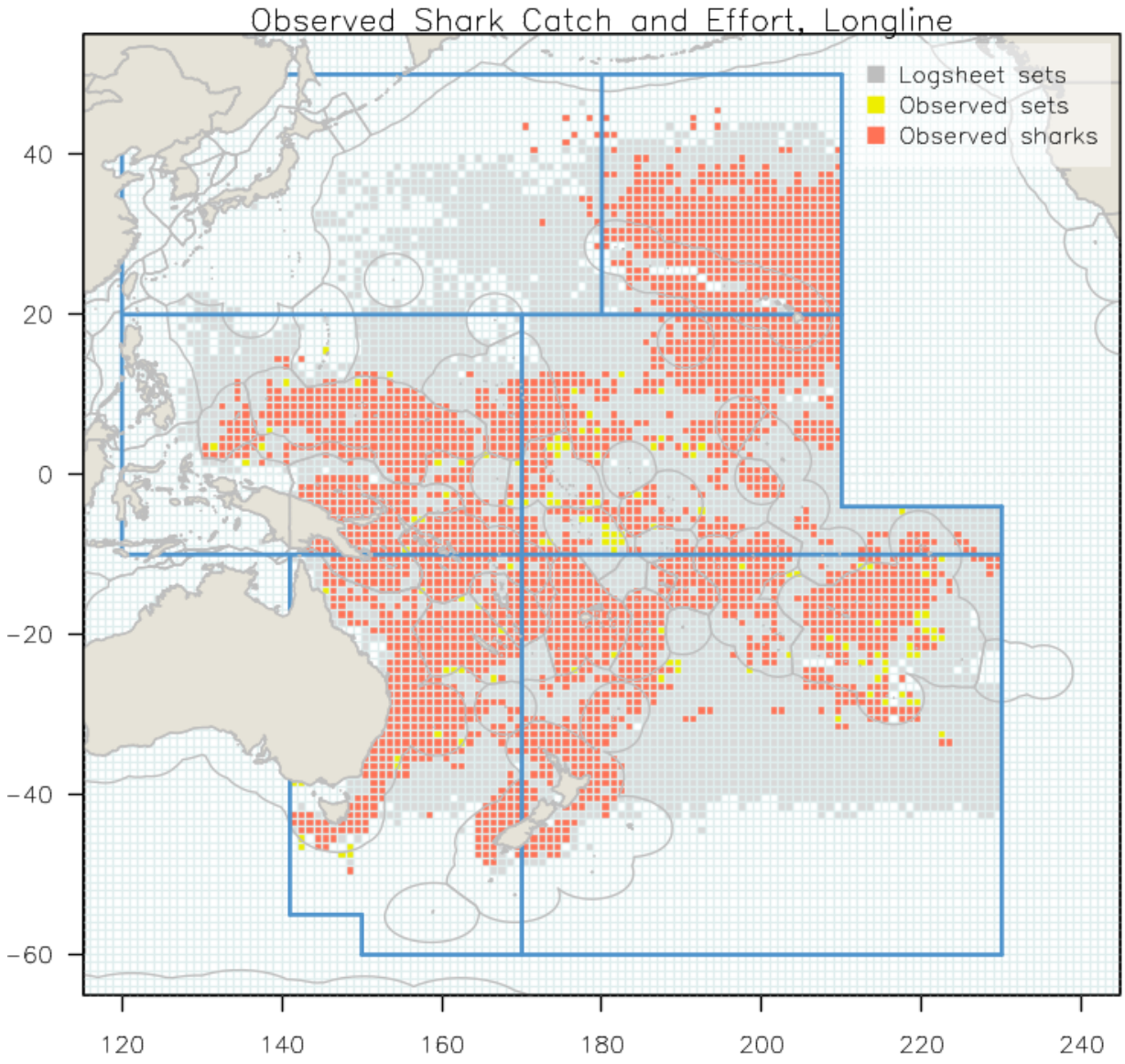


Figure 2: Reported sets (blue points), observed sets (orange points) and observed shark catch (red points) in the longline fisheries of the WCPO, from 1995-2014.

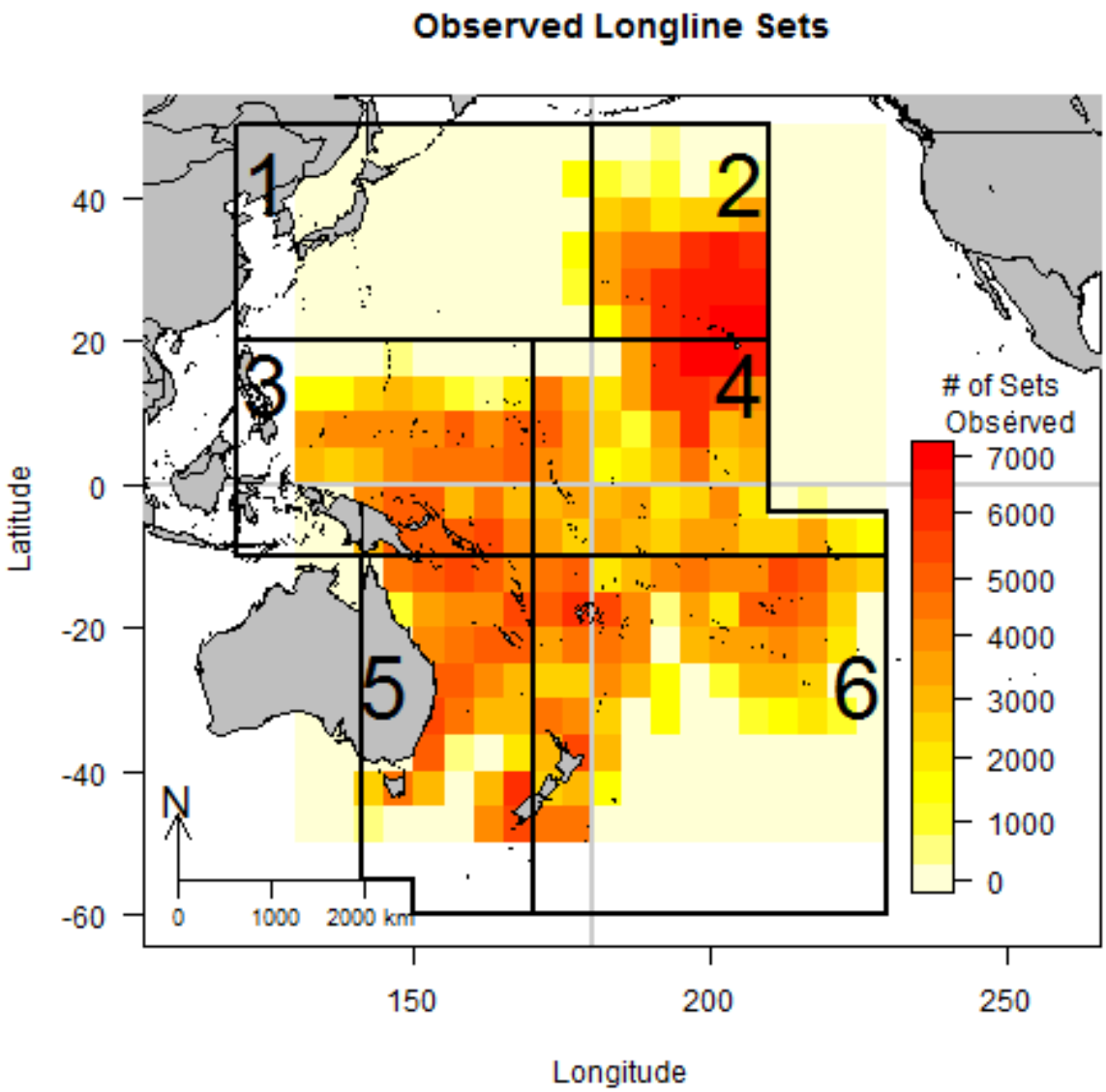
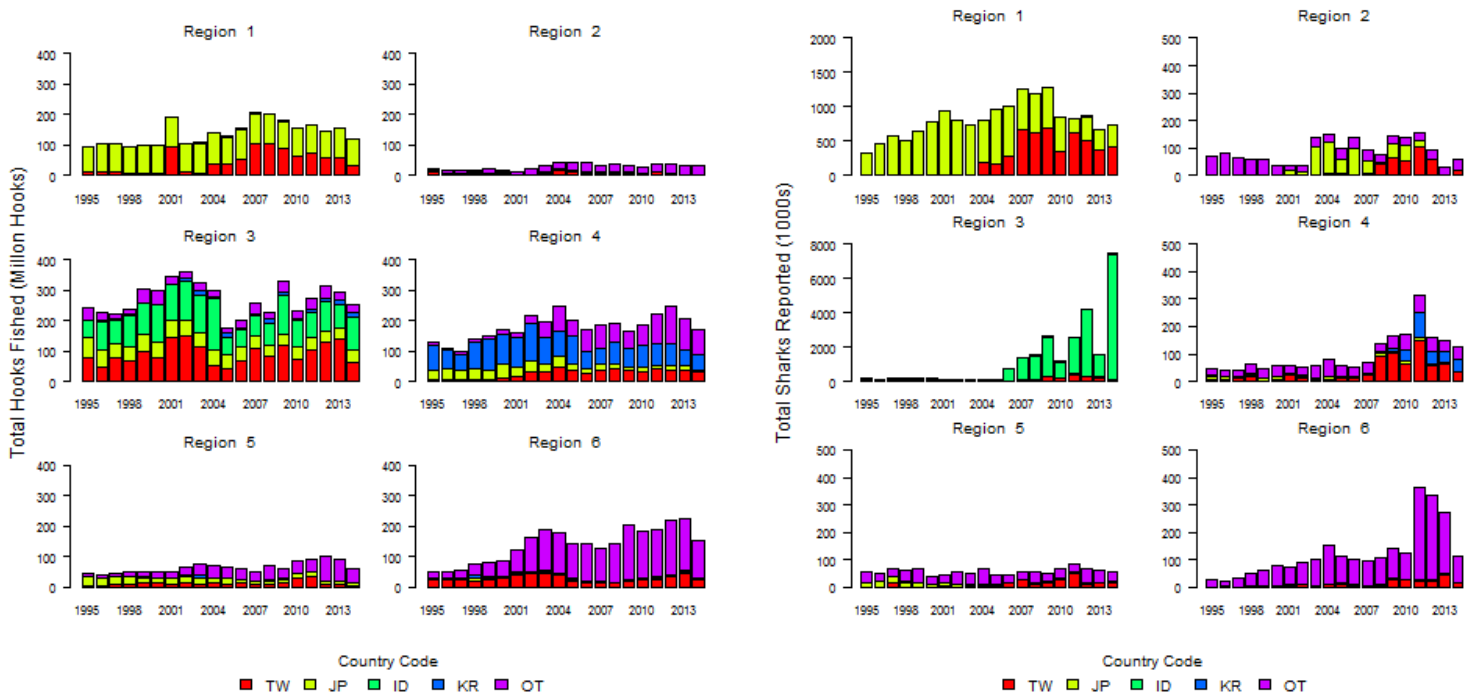


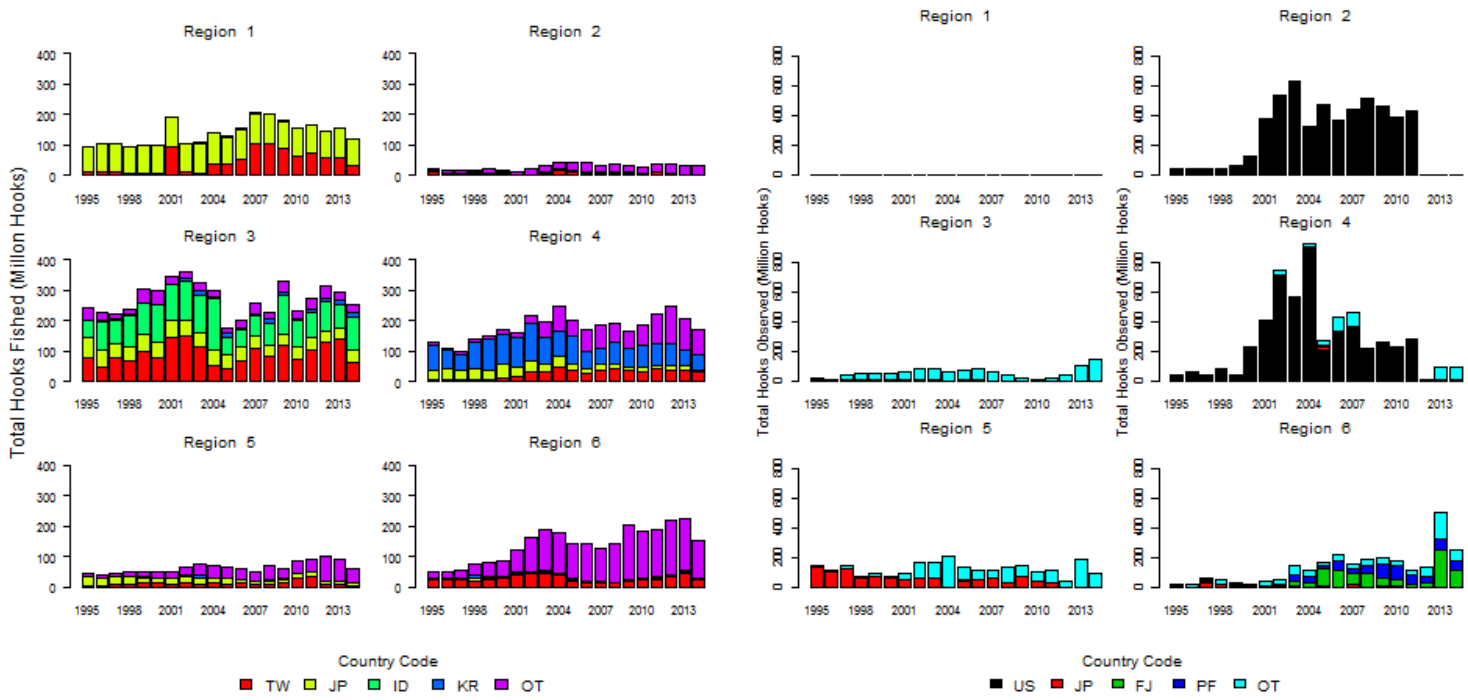
Figure 3: Longline observed sets by 5° × 5° square



(a) Longline effort.

(b) Reported total shark catch.

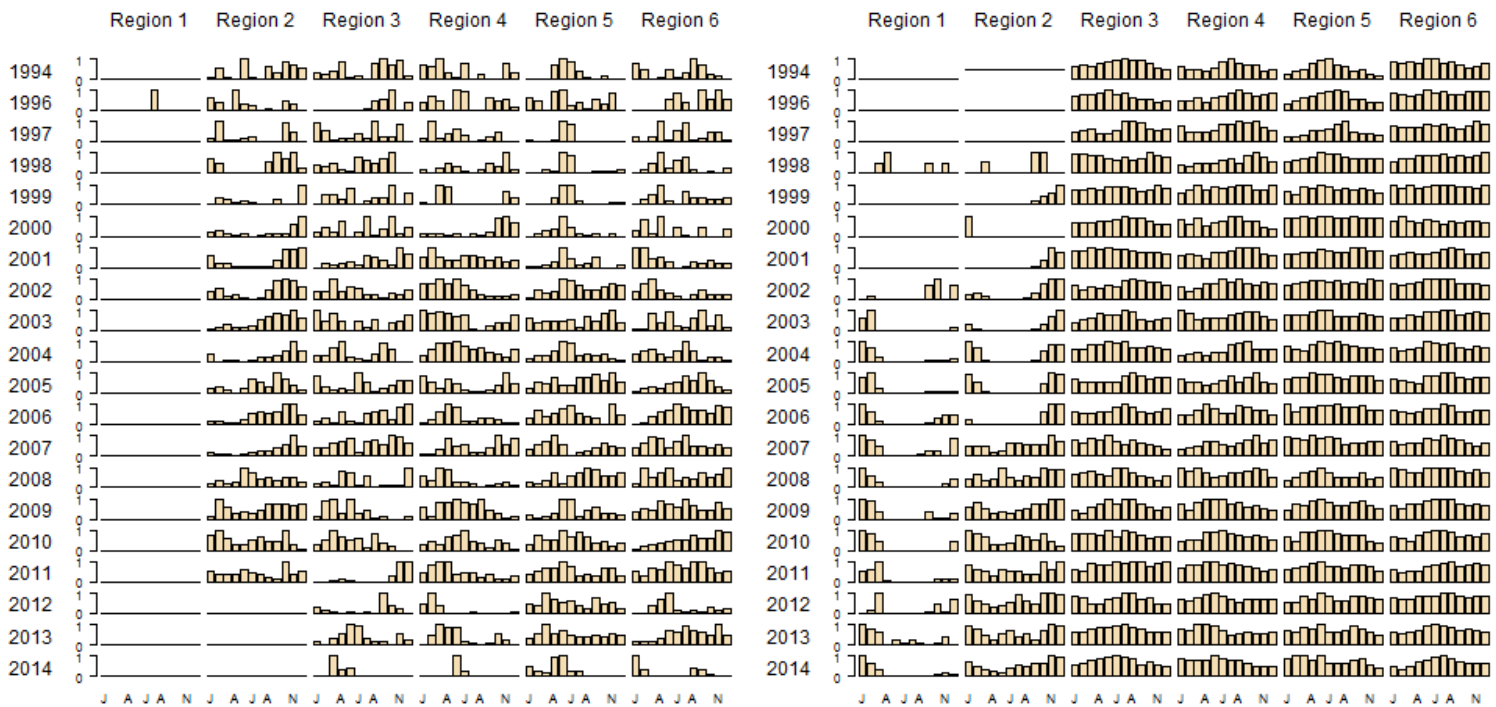
Figure 4: Longline effort by flag and the number of sharks reported in logsheets



(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 catch 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. 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% for logsheet sets / observed sets, but see Williams et al. (2015) for a more detailed analysis of purse seine observer coverage.

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 logsheets (Figure 7, red points), a value far lower than the 41% recorded in longline 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 (Fish Aggregating Device [FAD]) and unassociated (free school) sets based on aggregated 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 catch in the purse seine fishery are considerably lower than the longline fishery (Lawson, 2011; SPC, 2008), it would still be expected that purse seine shark interactions are proportional to purse seine effort. However, from the discrepancies between observed and reported catch, it appears that some major fishing nations are not submitting or are under-reporting shark interactions.

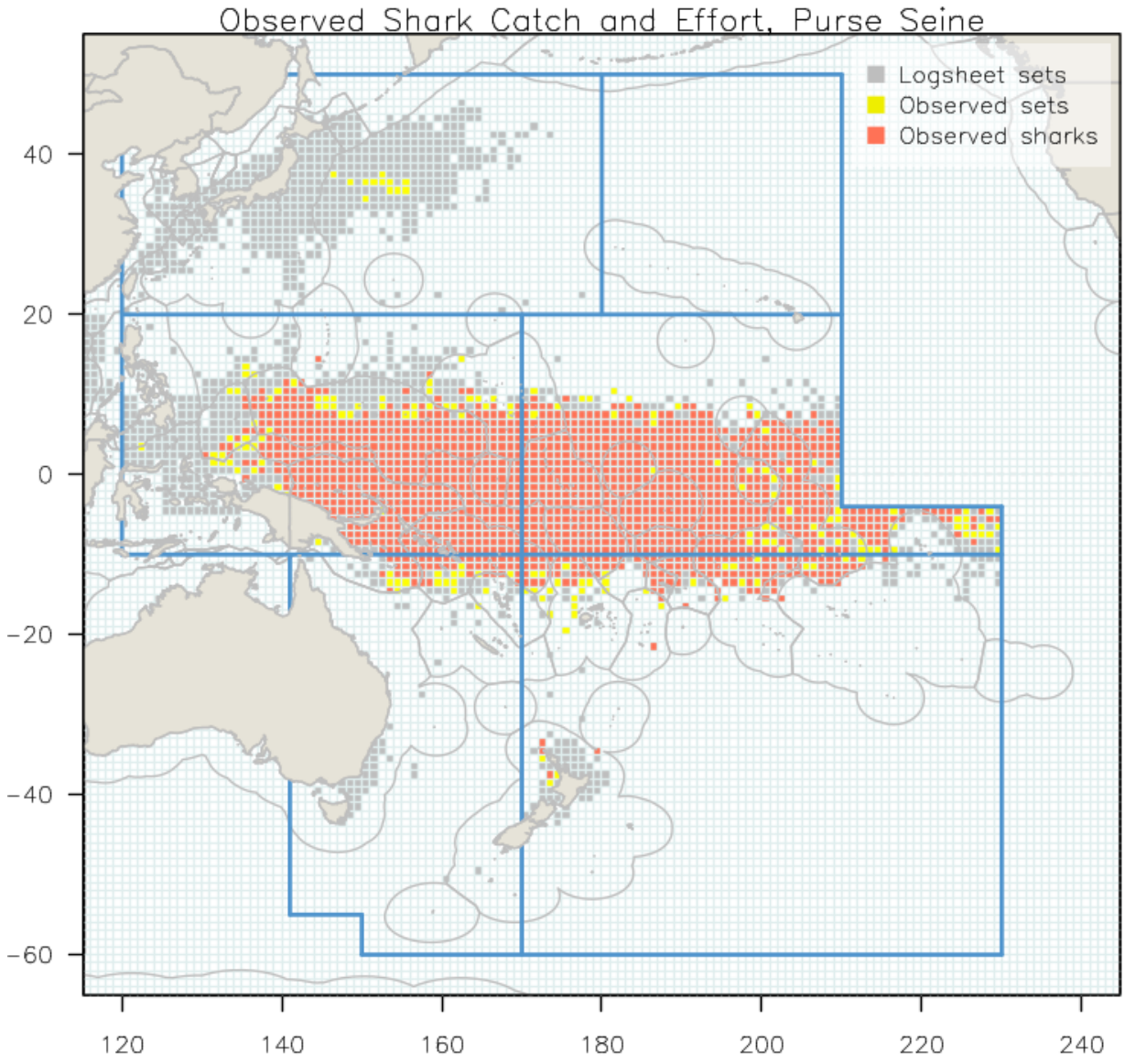
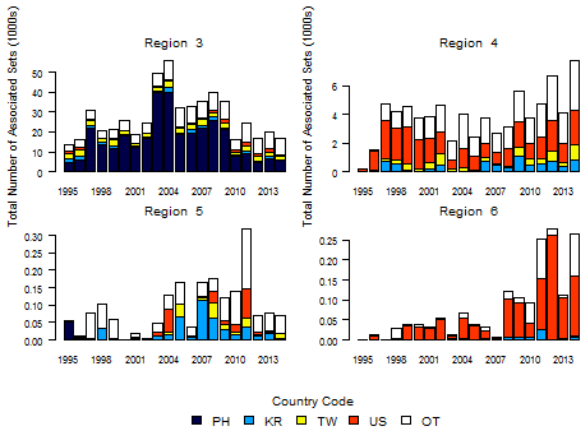
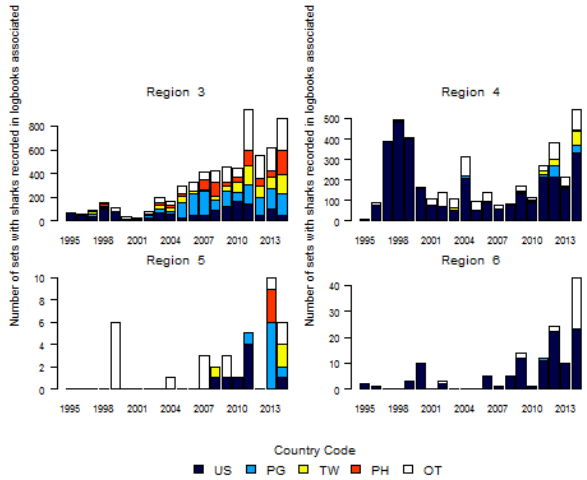


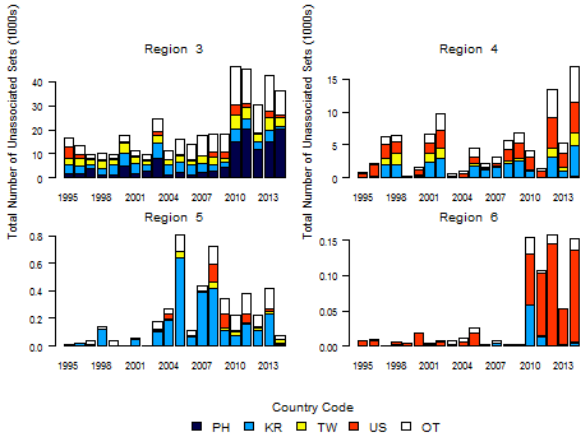
Figure 7: Absolute percent difference in effort between reported (logsheet) effort and observed effort.



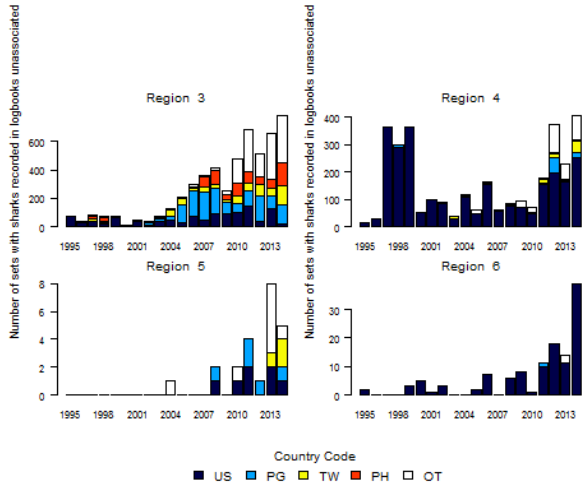
(a) Purse seine effort (Associated).



(b) sharks reported from associated sets.



(c) Purse seine effort (Unassociated).



(d) Sharks reported from unassociated sets.

Figure 8: Purse seine effort by flag and the number of sharks reported for associated and unassociated sets.

3 Distribution Indicator Analyses

3.1 Introduction

Distribution indicators consider patterns in the geographic distribution of catch. Spatial trends in fisheries data need to be interpreted carefully since they originate from biased design (Walters, 2003). If assessed carefully, however, they can provide useful insight into spatial and temporal trends in 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(MacCall, 1990), with increases and decreases in abundance resulting in range expansions and contractions, respectively. Such patterns have been reviewed at length in the terrestrial literature (Borregaard and Rahbek, 2010), but less often for marine applications due to the paucity of historical data (but see Worm and Tittensor, 2011). 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.

3.2 Methods

In this study, we calculated four Distribution Indicators:

- Species-occurrence. This indicator summarises 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 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 are totalled within $1^\circ \times 1^\circ$ cells over four separate five-year (pentad) periods. The proportion of observed sets containing at least one species occurrence within that cell/pentad cell is then computed and mapped. This provides better temporal resolution than the Species-occurrence indicator and better spatial resolution than the Proportion-presence indicator in helping to identify the distributional patterns of each shark species.

3.3 Results

The four sets of Distribution Indicators are grouped in Appendix B.1, as follows: Species occurrence (Figures 9 to 15), Proportion-presence (Figure 16), High-CPUE (Figure 17), Hot spot analysis (Figures 18 to 24). Species-specific results below reference these sets of figures.

3.3.1 Blue Shark

Blue sharks are the most common and widely reported shark species in WCPO longline fisheries. They 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 there. 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). Regions 2 and 4 show less distinct temporal trends. 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 longline 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 declining steadily 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

The Species occurrence indicators show that all seven species examined here, with the exception of porbeagle and hammerheads, are encountered across the breadth of the WCPFC region; hammerheads are distributed more patchily while porbeagle are restricted to the region south of 20°S. With the exception of blue shark and oceanic whitetips, the Proportion-presence and High-CPUE indicators showed a more or less steady trends for all species in all regions. for those two species, both indicators have shown declines as great as 80% in Regions 3 through 6.

Interpretation of the distribution indicators, particularly the Catch-Hotspot indicators, is complicated by the influence of changes in fishing effort, potential changes in community composition, observational 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

Changes in the species composition of the catch can be one of the most direct indicators of fishing induced changes to fish assemblages over time. Additional information on potential changes can be inferred by examining catch data on a finer basis, e.g., by separating longline sets by depth and purse seine sets by type of school association. We rely on observer sampling of individual sets for such analyses. Additionally, by examining time series of catch composition we can ascertain whether there has been a decline in the percentage of unidentified sharks; improvements in observers' ability to identify sharks to the species level can help resolve or identify potential regional and temporal trends in abundance.

We compile the observer data to provide information on the relative proportion of key species in observer sample. Nevertheless, it is an ongoing issue that observer sampling may not be representative of total catch composition due to issues of uneven coverage and low sample sizes. Those issues are covered in detail in Lawson (2011). However, these data represent the best that we have and temporal/spatial changes in relative species composition can help identify population increases or decreases. More direct species-specific analyses, such as summarised in section 5, should be performed to assess the veracity of identified abundance changes.

Species Composition Indicator Figures are illustrated in Appendix B.2 for longline (Figures 25 to 27) and purse seine (Figures 28 to 30).

4.1.1 Longline

With just a few exceptions, blue shark catch dominates the longline shark bycatch. In Regions 2, 4, 5, and 6, blue sharks have average 60-90% of shark bycatch; in Region 4 the proportion of blue shark has dropped from around 60% in the late 1990s to 10-15% in recent years. The second most common observation of shark species, in terms of numbers, is silky shark which have constituted a majority of shark bycatch in Region 3 since the early 2000s and have been on the order of 5-10% in other regions. We note that there appears to be a sudden increase in the proportion of silky shark catch for Region 4 in years 2012-2104. This reflects the absence of observer data from the U.S. longline fleet operating around Hawaii rather than a chance in species composition. 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 unrepresentative. Several of the other key 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 other, or non-key species, observed in Regions 5 and 6 were primarily composed of roughskin dogfish (*Centroscymnus owstoni*) and tope shark (*Galeorhinus galeus*), and in Region 3 were primarily composed of unidentified hammerhead, grey reef (*Carcharhinus amblyrhynchos*) and blacktip (*Carcharhinus limbatus*) sharks. Unidentified sharks comprised no more than 1.6% of the recorded sharks in any of the regions.

Division of the longline shark bycatch into shallow (<11 hooks per basket) and deep (>=11 hooks per basket) 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 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. There was no strong indication of temporal trends specific to deep or shallow sets.

4.1.2 Purse Seine

The majority of purse seine caught sharks have been identified to species in observer samples since the late 1990s. Prior to that, it is likely that practical difficulties, such as sharks not being hauled aboard, resulted in non-identification. Sample sizes were small during that time period making it difficult to generalize trends before 2000. Overall, silky shark comprise at least 70%, and often more than 90%, of the sharks captured in purse seine sets; both in associated and unassociated sets. Oceanic whitetip and hammerhead sharks have also been caught in notable.

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 sizeable 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 specious 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 catch 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.

5 Catch Per Unit Effort indicator analyses

5.1 Introduction

Catch-per-unit-effort (CPUE) data are commonly used as indices 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 therefore be standardized to account for changes in these factors over time. This is typically done using General Linear Models (GLM), which allow us to model the relationship between CPUE and a set of explanatory variables. The dataset used in this analysis provided many 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 7 (see also Table 2 in Francis et al. (2014) for an overview of the use of variables in shark CPUE standardisations).

CPUE data for sharks often have a large proportion of observations (sets) with zero shark catch, while while some sets have large catch. These instances of high catch can occur when areas of high shark densities are accidentally encountered or when fishers target sharks. The co-existence of both high proportions of zeros and high catch results in over-dispersed data, typical of bycatch species. These features are challenging to account for from a statistical point of view, and have been reviewed at length in the literature on bycatch analyses (Bigelow et al., 2002; Campbell, 2004; Ward and Myers, 2005; Minami et al., 2007).

Zero-inflated approaches have been advocated as best suited to model over-dispersion in both zeros and positive counts (Brodziak et al., 2013). A drawback of the zero inflated approach is that it is data intensive and models fail to converge. In addition, in practice it tends to be more successful at modelling the extra zeroes than the 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 σ, unlike when the mean is larger and the tail is not as pronounced. However, whenever conditions are good for sharks and/or targeting takes place, larger catch events can happen and not modelling those properly implies that we are missing important drivers of catch. Typically, this can be diagnosed as a departure from the one-to-one line on the right-hand side of quantile-quantile plots. Here we achieved significant improvements in model diagnostics by keeping a negative binomial distribution but allowing both the mean μ and σ parameters to be modelled against covariates (Rigby and Stasinopoulos, 2005). This approach is much less computationally intensive than zero-inflated models, and yielded excellent diagnostics with these data.

5.2 Methods

Standardised CPUE series for the longline bycatch fisheries were developed using generalised linear models using longline catch and effort data. The number of hooks in a longline set was used as a measure of effort. See also Clarke et al. (2011); Clarke (2011), Walsh and Clarke (2011), Rice and Harley (2012) for past work on shark CPUE standardisation in the Western and Central Pacific Ocean (WCPO).

5.2.1 Stock definition for the purpose of the analysis

Silky and oceanic whitetip sharks have each been assessed (Rice and Harley, 2012, 2013) as single stocks 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 stock unit. These temperate species are thus analysed as individual stocks. In the Pacific porbeagle sharks are only found south of 20°S and were analysed as a single stock. Hammerhead sharks for the purpose of this analysis (and throughout the report) are considered to be a single stock.

5.2.2 Data Preparation

To further define the expected geographic range, we defined a coarse climate 'envelope' based on sea surface temperature. This aided in distinguishing between zero catch in areas where the species does not occur from zero catch in areas where the species occurs but was not caught. Temperature data were downloaded from the GODAS database (`www.cdc.noaa.gov/data/gridded/data.godas.html`) 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 catch for that species (see Table 6). The temperature predicted by GODAS at the 5 meters depth at set time/day was used for the SST value. Only cells for which all mean monthly temperatures fell within this range were retained.

Data were cleaned following the filters outlined in Table 5. 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 any observer programs for which we had less than 100 sets were removed. Extreme catch events greater than the 97.5^{th} quantile of the nominal CPUE were also removed. Finally, year effects were only estimated if there were at least 50 sets observed in that year (by species and population). Records from the Papua New Guinea observer program were removed as vessels in the fleet frequently target sharks. Additional filters are listed by species in Table 8.

5.3 Overview of GLM Analyses

5.3.1 Notes on error distributions:

The filtered datasets were standardised using generalized linear models (McCullagh and Nelder, 1989) with the software package R (`www.r-project.org`, R Core Team 2013) and the package `gamlss` (Rigby and Stasinopoulos, 2005). Initially, multiple assumed error structures were tested including the delta lognormal approach (DLN) Lo et al. (1992); Dick (2006); Stefansson (1996), zero-inflated poisson and negative binomial models, the tweedie distribution (Shono, 2008) and negative binomial models with mu and σ modelled. Due to its superior performance both in run time and model diagnostics, we retained the latter and only present those results here.

5.3.2 Procedure for model selection

Initial model exploration began via fitting each model (species and population) with only one covariate and evaluating the explanatory power of that covariate *via* AIC (AIC values are listed in tables listed in Tables 13 to 21. Model fitting proceeded by fitting additional covariates in order of the proportion of deviance explained on their own. Only those covariates showing a change in AIC of 10 or greater were kept in the model.

If model diagnostics indicated a departure from the assumed error structure, covariates were added to σ until the model mis-specification was resolved. Covariates were added based on the principle of a minimally efficient design and beginning with those covariates for which the AIC σ table (Tables 13 to 21) indicated had the most explanatory power.

The addition of explicitly modelling the σ greatly improved the model diagnostics in most cases where the Q-Q norm plot indicated a misspecification in the tail of the assumed distribution. The objective of the CPUE standardisations were to produce CPUE values that accounted for changes in catch rate not due to changes in abundance over time, in this case the time step was an annual time step, therefore year effects were included in each model. All models also included either flag or observer program code, because flag and observer program are often highly correlated, one or the other as an explanatory categorical variable, based on the proportion of variance it explained and whether model diagnostics were impacted. Interaction between year and observer program was also modeled in part to account for potential changes in individual program practices (e.g. reporting to species, banning shark fishing) within a particular program. Additionally modelling year and program may account for localised trends in annual abundance, or sampling effort that are reflected in the program specific observer data. Other interaction effects were investigated early in the model selection process but discarded due to low explanatory power.

5.3.3 Model diagnostics

Model selection included examination of diagnostics including quantile residuals (Dunn and Smyth, 1996), normal quantile-quantile plots, plots of the residuals residuals vs fitted factors, residuals vs. explanatory factors as well as an overall summary. 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 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. Specifically we aimed to improve fit to both the zeros and high catch events. Diagnostics were satisfactory for all stocks except that of blue shark in the south Pacific for which high catch events were still not well modelled, presumably due to unaccounted targeting by some fleets. Key diagnostics are included in Figures 80 to 97.

5.3.4 Calculation of year indices and confidence intervals

Year effects could be extracted directly 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`.

5.4 Results

Nominal CPUE by species and region for longline sets are shown in Figures 31 and 32 and for associated and unassociated purse seine sets in regions 3 and 4 in Figures 33 and 34 respectively. Plots of nominal and standardised CPUE on a species by species basis are shown in Figures 35 to 43.

Blue shark (*Prionace glauca*), north Pacific Both the standardised 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 standardised 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 complex (*Isurus oxyrinchus* and *I. paucus*) in the north Pacific The standardised and nominal CPUEs share the same trajectories (Figure 39), but on a slightly different scale for the first 6 years (1995-2001). The largest difference in the nominal and standardised CPUE is in the final year, where the standardised CPUE declines sharply in contrast to the nominal, but years 2011 and 2012 were excluded from the standardisation due to poor sample sizes (Figure 90).

Mako shark complex (*Isurus oxyrinchus* and *I. paucus*) in the south Pacific The standardised 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 standardised CPUE peaks in 2010, whereas the nominal is the highest in 1996.

Oceanic whitetip shark (*Carcharhinus longimanus*) The standardised oceanic whitetip shark trend decreases steadily over 1995-2014. The standardised 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*) Standardised 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 shark complex (*Alopias superciliousus, A. vulpinus, and A. pelagicus*) Standardised 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 thereafter. For 2002-2014, the standardised CPUE is less variable, decreasing slightly from 2003-2011. The last three years of both the standardised and nominal CPUEs show a steep decline. The CPUE from the thresher complex is difficult to interpret as the second most commonly reported thresher species is the general "thresher shark" category.

Hammerhead shark complex (*Sphyrna mokarran, S. lewini, S. zygaena, and Eusphyra blochii*) Standardised 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 recorded into the generic

"hammerhead" category.

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

5.5 Conclusions

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

Analysing and interpreting 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 occurring forcing factors (e.g. El Niño). 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 three main areas:

Targeting: There is evidence of shark targeting and mixed shark/tuna or shark/billfish fisheries in many regions including regions 1, 3 and 4.

Changes in regulations: Changes in regulations that will impact CPUE indices include: banning of shark finning by US vessels and in US waters in 2000; the closure of the shallow set component of the Hawaii longline fishery for three years beginning 2001; banning of finning by Australia in 2000; banning of wire leaders by Australia in 2005; and the banning of shark fishing (except for makos) by French Polynesia in 2006.

Changes in data availability: Since the implementation of the WCPFC ROP on 1 January 2010 100% observer coverage has been required on the purse seine fleet. In practice this reduced the number of observers on longline vessels as they were transferred to the purse seine fleet. This created discontinuities in the observer coverage for some species.

Despite these obstacles, analysis of the catch rate (both nominal and standardised) of the key species revealed that:

- Blue shark CPUE is declining in the north and south pacific based on the nominal and standardised CPUE.
- Oceanic whitetip continue to decline throughout the tropical waters of the WCPO.
- Silky shark CPUE exhibit high fluctuations throughout the study period.
- The thresher shark complex appears to be declining though the last data point is based on relatively few data and may exaggerate the trend in the last year.
- Mako shark in the south Pacific may have been declining for the last five years, however, 2014 is based on relatively few data and may therefore be unreliable. Mako in the north Pacific is similarly plagued by data deficiencies with not enough data to estimate year effects in 1996,

2003, 2011, and 2012. Despite this, the trend looked relatively stable between 2000 and 2010, however, no inference is possible for the last 4 years.

- Porbeagle shark CPUE experienced a large decrease until 2003 and has increased since then.

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 by a size selective fishery could lead to a preferential loss of females because, for most species, 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. In additional, male and female sharks often segregate spatially (Mucientes et al., 2009). This has been reported in highly migratory ("HMS") sharks in New Zealand waters, where female blue sharks dominate the catch in the south while for mako sharks males dominate the catch (Francis et al., 2014). If fishing activity is concentrated in areas favoured by one sex, then an imbalance in the sex ratio could be created.

Life history and stage 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. Many pelagic shark species are known to exhibit sex- and age- specific distribution pattern (Camhi et al., 2008; Mucientes et al., 2009) thus spatial analyses can highlight areas which are important to key life stages such as spawning or recruitment.

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

6.2 Methods

Shark sex identification data from observer samples were aggregated by year and region to assemble estimates of trends in sex ratio. The percent of female sharks by region and year are illustrated in Appendix Figure 44.

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 where data were recorded as total length, measurements were converted to fork length using conversion factors given in Table 10.

Those $5^\circ \times 5^\circ$ cells for which the sample size was less than 20 individuals were removed from the analysis. Due to small longline fishery sample sizes for longfin makos, and for bigeye, common and pelagic threshers, results for makos (two species plus unidentified) and threshers (three species plus unidentified) were grouped. Length-at-maturity data for shortfin mako, bigeye thresher, and scalloped hammerhead were chosen to represent each group, respectively, as both observer data and literature sources were greatest for these species (Table 10). While length at maturity and conversion factors might be expected to vary by region within the WCPO, insufficient data were available to support regional analysis. The median lengths, with 5th and 95th percentiles, were plotted for both sexes and all regions in Appendix Figures 45 to 51 (for the longline species) and Figures 52 and 53 (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 standardised. This was accomplished using a GLM based on a normal distribution with factors year and $5^\circ \times 5^\circ$ cell. The estimated model coefficients were used to predict shark lengths for each year for an arbitrarily chosen cell lying near the centre of each region. To more adequately capture the population trends, regions in the north and south were pooled (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 standardised 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 54 to 60.

Time trends over the duration of each standardized length time series were estimated by fitting linear models to the annual GLM coefficients. Linear model fits were produced separately for each species, sex, and stock. The slope coefficients, which is the estimated annual change in length per year, are plotted in Figure 61. One important caveat when interpreting the results is that linear models generalise 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 characterised as having no trend through time.

Patterns of occurrence by life history stage by sex were explored using the same dataset developed for the standardised 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 62 to 68. 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 (Figure 44). Fine scale analysis is difficult due to lack of continuous data and small annual sample sizes in the most recent years. The sex ratio of blue shark in region 5 has has been skewed in favour of females for the entire data period. With the exception of blue shark in region 5 there is nothing to suggest that incidental catchability (availability) is greater for either sex for all species.

6.3.2 Median length

The following points were noted from the observer median length (Figures 45 to 53):

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 throughout the study period were immature. The only area that showed increases in observed median length were regions 6 for males of silky and blue sharks.

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

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

6.3.3 Standarized length

Possible trends in length over time are more evident in the standardised length plots (Figures 54 to 60) when overlaid with a loess smoother. For the majority of species, sex and stock, standardized lengths have decreased over time. The only exceptions are for the northern stock of mako (both species) and porbeagle females, which have essentially remained the same size. The slope coefficients fitted to annual GLM coefficients show a decrease of around 0.2 to 0.4 cm/year for most of the other time series. Male blue sharks in the south Pacific 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 (Figures 62 to 68):

- Adult blue sharks in the south Pacific particularly females were present in the waters of New Caledonia and Fiji throughout the year, with higher proportions of adults present south of 20°S only in the mid-year.
- Adult blue sharks were more common than juveniles in the waters off Hawaii and at latitudes of 20°S which 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°N and 10°S, particularly 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 observed rarely 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) in the waters around southern Australia New Zealand and to an extent in Fiji.
- The observed distributions of oceanic whitetip are not influenced by sex maturity or seasonality, mostly they occur 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:

- The sex ratio of sharks in longline catch is approximately equal for all species and regions with the exception of blue sharks in Region 5, which are predominantly female.
- Observed length was investigated by plotting the nominal median length trends and length-at-maturity at the regional level. This indicated that the majority of the observed hammerhead,

silky, thresher, oceanic whitetip and porbeagle sharks were immature. Observed blue 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 standardised length were seen for northern mako sharks (both sexes)

7 Whale Sharks

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.

Observations of whale sharks 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.

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 (SPC, 2011).

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 12). To determine if a set encountered a whale shark in some way we used three criteria 1) if the set was 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 analyses in this section relate 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 their coverage of the WCPO purse seine fishery with no coverage for the domestic purse seine operations 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.

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 12). 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 more representative in 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 69). Values for 2014 should be treated with caution as observer data are incomplete and there may be some changes in observer reporting (see below).

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 encounter rate of around 1% until 2009 (ignoring 2006) and just under 0.5% from 2010-2014 the last four years (Figure 70). The pattern of whale shark distribution with fishing effort is very similar with the largest densities found in the Bismark and Solomon seas (Figure 70). 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 (Brouwer and Harley, 2015). In summary these include:

- Develop a time series of whale shark interactions and mortalities;
- Stock discrimination.
- Development of a standardised CPUE index.
- Examination of observer data/journals for 2014 to determine whether distinction between compliance/non-compliance with the whale shark CMM is possible.

It has been suggested (Clarke, 2015) that it is difficult to make accurate inferences about purse seine interactions with whale sharks from 2014 observer data as these data are likely under-estimates. This was also the conclusion from the report conducted by SPC (SPC, 2011) which suggested that the proportion of whale-shark associated sets is 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.

Advice from regional observer trainers suggests that the implementation of the FAD closure, and whale shark measures (noting that a whale shark set is also considered a FAD set), has led to a change in the reporting of school association for sets that encounter a whale shark, where the whale shark may not have been visible (to the observer at least) prior to the set commencing. Therefore, the designation of a set as a whale shark associated set by an observer does not necessarily indicate that the whale shark was visible to the observer, and/or the crew, prior to the set commencing and therefore cannot alone be used as an indication of non-compliance with the whale shark CMM.

We note that changes have been made to the GEN-2 form from 2015 specifically to provide further details on the time of sighting of whale sharks relative to the start of the set, to address this issue. In terms of considering compliance with the whale shark CMM in 2014, we recommend a detailed review of available 2014 observer data/journals prior to TCC11 to determine whether distinction between compliance/non-compliance with the whale shark CMM is possible.

8 Feasibility of Stock Assessments

Fisheries stock assessments are designed to provide stock status and management information via a population model that is scaled to the available data. Traditionally the data requirements include landings records 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 are 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 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 to SC9 (WCPFC-SC9-2013/SA-WP-04) which 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 *I. 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 in Region 3 for both longline and purse seine, as well as in Region 4 for purse seine. These factors indicate that a stock assessment of silky sharks is feasible.

Thresher shark (*Alopias superciliousus, A. vulpinus, & A. 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, S. lewini, S. 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

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 finning 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.

Figures relating to the fate of longline and purse seine caught sharks are illustrated in Appendix D (Figures 71 to 79)

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 (Figures 71 and 72).

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% fin to carcass requirement doesn't necessarily lead to a reduction in mortality, as a result this measure was designed to prohibit the retention (and finning) of oceanic whitetip.

Observations of oceanic white tip sharks in the longline fishery have generally indicated reduction in the proportion finned since the mid-2000s (Figure 77). However, proportionally more oceanic whitetip sharks were retained in 2013 (the first year of the CMM). 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 77). It seems that this measure is partially successful.

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 at this stage.

CMM 2014-05 : Measures for longline fisheries targeting tuna and billfish. This CMM 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 2015 so 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; Caneco et al., 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.

Among the CMMs to have been passed to date only CMM2010-07 (5% fin to carcass ratio) and CMM 2011-04 (prohibits the retention of oceanic whitetip sharks) have been in effect long enough to assess the potential impact. The CMM 2013-08 (prohibits the retention of silky shark) and CMM 2014-05 have not been in effect long enough and have not yet come into effect, respectively.

Observations of shark fate from the purse seine fishery indicate a trend, over the study period, towards greater discards and less finning, while retention and escape remain uncommon observations. The largest change in the observations of shark fate in purse seine fisheries came in 2009, the year after CMM2010-07 came into effect. In 2009, the proportion of sharks observed finned decreased by half and remained at low levels in the following years of this study. This reduction in finning may be attributable to that CMM. In longline fisheries the percentage of key shark species that were finned reduced from 2010-2013, the last year of the study saw an increase in finning and a decrease in the number of sharks retained. Corresponding with the decrease in finning from 2010-2013 was an increase in retention, which would be the expectation if fishers were beginning to retain the carcass to adhere to CMM 2010-07 (the 5% fin to carcass rule). Analysis of this available observed data from 2014 indicates an increase in the proportion of key sharks observed finned. Caution must be taken with regards to extrapolation of the observer data set to the fishery level due to many factors including change in coverage and missing data in recent years.

With respect to CMM 2011-04, observations from the longline fishery have shown that the CMM is not being strictly followed.

Non-negligible proportions of oceanic whitetips are being retained or finned. both in number and proportionally more oceanic whitetip sharks were retained in 2013 (the first year of the CMM) than 2012 in the longline fishery. Analysis of this measure in recent years is complicated due to the reduction in numbers of oceanic whitetips observed, the recent change in observer coverage and the absence of data from both the United States for the years 2012-2014 and Australia in 2014 in the

longine fishery. The analysis of this CMM in the purse seine fishery is hampered by the fact that there were no observations of oceanic whitetip sharks in 2014 (Figure 77). In 2013 the proportion of oceanic whitetip sharks that were either finned or discarded in the purse seine fishery,increased, but the proportion retained decreased (Figure 77).

10 Conclusions

This report presents a number of data summaries and analyses. To facilitate reference to the key conclusions of the work, we index them by report category. A synthesis table (Table 11) provides a general overview of the results for each category of the indicator analysis.

Logsheet coverage

This paper analyses data held by the SPC-OFP for longline and purse seine fisheries in the WCPO to make inferences regarding the populations of key shark species in the WCPO. The data sets analysed - observer, logsheet and aggregated data - vary in coverage, representativeness and detail, and in general are not oriented at reporting information on bycatch species such as sharks. Logsheet data at the operational level are most useful in assessing shark catch and catch rates in the WCPO as a whole, however, while such data are available in the longline fishery for only 41% of the sets between 1995 and 2014 for the WCPFC Statistical Area as a whole, 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 93% of observed longline sets recorded at least shark. Possible explanations for this discrepancy include under-reporting of sharks or that the observer data are not representative of the fishing methods/areas/time periods of the longline fleet as a whole.

Observer coverage

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° × 5° square) were used to characterize effort, observer coverage and reported shark catch by flag for both longline and purse seine fisheries. For longlines, this analysis showed clear evidence of non-/under-reporting of sharks by several major longline fleets. It also demonstrated that observer coverage is disproportional by region and flag and, to an extent, month thus they are not entirely representative of the fishery. Although the same non-/under-reporting patterns were observed in the purse seine aggregated data, observer coverage in the purse seine fishery is more representative by region and flag. Nevertheless, observer data on purse seine-caught sharks are limited by the physical practicalities of on board sampling and the lower diversity of sharks encountered relative to the longline fishery.

Distribution Indicators

With the exception of 2014, total effort in the longline fleet has increased through the study period (1995-2014) to the current effort level of approximately 800 million hooks annually; nearly half this effort occurs in regions 3 and 4. With the exception of blue sharks, the high-CPUE indicators show more or less steady trends for all species in all regions. This analysis, however, was hampered by the lack of data throughout the region for species. Most 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 2 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 Regions 5 and 6 show slightly increasing to stable trends. Mako sharks show slightly increasing trends in Regions 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.

Species Composition Indicators

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.

CPUE Indicators

Several issues related to changes in targeting practice, regulations and distribution of observer coverage greatly complicate CPUE analysis of shark catch rates. Despite these obstacles, our analysis suggests the following trends: blue shark CPUE is declining in the north and south pacific; oceanic whitetip sharks continue to decline throughout the tropical waters of the WCPO; thresher sharks appear to be in decline but the data are sparse; silky and mako sharks show no strong trends; Porbeagle shark CPUE experienced a large decrease early in the study period followed by a fluctuating but increasing CPUE trend.

Biological Indicators

The biological indicators showed that with a few exceptions (blue shark in Region 5) the observed sex ratio in the longline fishery is approximately equal. Sex ratio analysis was not possible for the purse seine fishery. Observed length was investigated by plotting the nominal median length trends and length at maturity at the regional level. This indicated that the majority of the observed hammerhead, silky, thresher, oceanic whitetip and porbeagle sharks were immature. Observed blue shark were mainly immature in regions 5 and 6 and mainly mature in Region 2. The results of the length standardization indicate declines in most regions for most species based on a linear model fit to the standardized annual lengths. These results mirror the larger scale population trends in length for the longline fishery and the population level trends in silky and oceanic whitetip sharks in the purse seine fishery. Overall the biological indicators showed that by and large the longline fishery is interacting with smaller immature sharks of both sexes.

Whale sharks

We note that there may have been changes over time in how certain whale shark interactions have been reported. Nevertheless there is scope to develop time series of whale shark interactions and mortalities by combining information across various observer forms. Further we recommend examination of observer data/journals for 2014 to determine whether distinction between

compliance/non-compliance with the whale shark CMM is possible.

Impact of recent shark management measures

Observations of shark fate from the purse seine fishery indicate a trend, over the study period, towards greater discards and less finning, while retention and escape remain uncommon observations. In longline fisheries the percentage of key shark species that were finned reduced from 2010-2013, the last year of the study saw an increase in finning and a decrease in the number of sharks retained. Corresponding with the decrease in finning from 2010-2013 was an increase in retention, which would be the expectation if fishers were beginning to retain the carcass to adhere to CMM 2010-07 (the 5% fin to carcass rule). Non-negligible proportions of oceanic whitetips are being retained or finned. Both in number and proportionally, more oceanic whitetip sharks were retained in 2013 than 2012 in the longline fishery.

11 Research Recommendations and Management Implications

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

- Research to assess the discrepancy between shark reporting in logbooks and observer data.
- Silky shark and oceanic whitetip sharks have been declining under recent fishing pressure, and likely maintain their overfished status. The last assessment for both of these species used data from 1995-2009, at this point we could 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. Given the marked CPUE declines for blue shark in the south Pacific this should be the highest priority.
- 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 what 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 interim.
- Develop a time series of whale shark interactions and mortalities, taking into account potential changes in reporting and observer coverage.
- Examination of observer data/journals for 2014 to determine whether distinction between compliance/non-compliance with the whale shark CMM is possible.

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References

Bigelow, K., Hampton, J., and Miyabe, N. (2002). Application of a habitat-based model to estimate effective longline fishing effort and relative abundance of Pacific bigeye tuna (*Thunnus obesus*). *Fisheries*, 11(3):143–155.

Borregaard, M. K. and Rahbek, C. (2010). Causality of the relationship between geographic distribution and species abundance. *Quarterly Review of Biology*, 85(1):3–25.

Bromhead, D. B., Rice, J., and Harley, S. J. (2013). Potential approaches to mitigate bycatch of oceanic whitetip and silky sharks from longline fisheries. WCPFC-SC9-2013/EB-WP-02, Pohnpei, Federated States of Micronesia, 6–14 August 2013.

Brouwer, S. and Harley, S. J. (2015). Draft shark research plan: 2016-2020. WCPFC-SC11-2015/EB-WP-01, Pohnpei, Federated States of Micronesia, 5–13 August 2015.

Camhi, M., Valenti, S., Fordham, S., Fowler, S., and Gibson, C. (2008). The Conservation Status of Pelagic Sharks and Rays: Report of the IUCN Shark Specialist Group Pelagic Shark Red List Workshop. IUCN Species Survival Commission Shark Specialist Group. Newbury, UK.

Campbell, R. A. (2004). CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research*, 70:209–227.

Caneco, B., Donovan, C., and Harley, S. J. (2014). Analysis of WCPO longline observer data to determine factors impacting catchability and condition on retrieval of oceanic white-tip, silky, blue, and thresher sharks. WCPFC-SC10-2014/EB-WP-01, Majuro, Republic of the Marshall Islands, 6–14 August 2014.

Clarke, S. (2011). A status snapshot of key shark species in the western and central pacific and potential mitigation options. WCPFC-SC7-2011/EB-WP-04.

Clarke, S. (2015). Understanding and mitigating impacts to whale sharks in purse seine fisheries. WCPFC-SC11-2015/EB-WP-03, Pohnpei, Federated States of Micronesia, 5–13 August 2015.

Clarke, S. and Harley, S. J. (2010). A proposal for a research plan to determine the status of the key shark species. WCPFC-SC6-2010/EB-WP-01, Nuku'alofa, Tonga, 10–19 August 2010.

Clarke, S., Harley, S. J., Hoyle, S. D., Rice, J., and Clarke, S. C. (2011). An indicator-based analysis of key shark species based on data held by SPC-OFP. WCPFC-SC7-2011/EB-WP-01, Pohnpei, Federated States of Micronesia, 9–17 August 2011.

Dick, E. (2006). Delta-glm [1.7,2]. Santa Cruz, CA, USA, NOAA.

Dunn, K. P. and Smyth, G. K. (1996). Randomized quantile residuals. *Journal of Computational and Graphical Statistics*, 5:1–10.

Francis, M. P., Clarke, S. C., Griggs, L., and Hoyle (2014). Indicator based analysis of the status of new zealand blue, mako and porbeagle sharks. New Zealand Fisheries Assessment Report 2014/69, Ministry for Primary Industries.

Harley, S. J., Williams, P., and Rice, J. (2013). Spatial and temporal distribution of whale sharks in the western and central pacific ocean based on observer data and other sources. WCPFC-SC9-2013/EB-WP-01, Pohnpei, Federated States of Micronesia, 6–14 August 2013.

Lawson, T. (2011). Estimation of catch rates and catches of key shark species in tuna fisheries of the Western and Central Pacific Ocean using observer data. WCPFC-SC7-2011/EB-IP-02, Pohnpei, Federated States of Micronesia, 9–17 August 2011.

Lo, N. C., Jacobson, L. D., and Squire, J. L. (1992). Indices of Relative Abundance from Fish Spotter Data based on Delta-Lognormal Models. *Canadian Journal of Fisheries and Aquatic Sciences*, 49:2515–2526.

MacCall, A. (1990). *Dynamic geography of marine fish populations.* Univ. Washington Press., Seattle, US.

McCullagh, P. and Nelder, J. (1989). *Generalized Linear Models.* Chapman and Hall, London.

Minami, M., Lennert-Cody, C., Gaoc, W., and Roman-Verdesoto, M. (2007). Modeling shark by-catch: The zero-inflated negative binomial regression model with smoothing. *Fisheries Research*, 84:210–221.

Mucientes, G., Queiroz, N., Sousa, L., Taroso, P., and Sims, D. (2009). Sexual aggregation of pelagic sharks and the potential threat from fisheriies. *Biology Letters*, 5:156–159.

Nakano, H. (1994). Age, reproduction and migration of blue shark in the North Pacific Ocean. *National Research Institute of Far Seas Fisheries Bulletin*, 31:141–256.

R Core Team (2013). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria.

Rice, J. and Harley, S. J. (2012). Stock assessment of oceanic whitetip sharks in the western and Central Pacific Ocean. WCPFC-SC8-2012/SA-WP-06, Busan, Republic of Korea, 7–15 August 2012.

Rice, J. and Harley, S. J. (2013). Updated stock assessment of silky sharks in the western and Central Pacific Ocean. WCPFC-SC9-2013/SA-WP-03, Pohnpei, Federated States of Micronesia, 6–14 August 2013.

Rigby, R. A. and Stasinopoulos, D. M. (2005). Generalized additive models for location, scale and shape,(with discussion). *Applied Statistics*, 54(3):507–554.

Shono, H. (2008). Application of the Tweedie distribution to zero-catch data in CPUE analysis. *Fisheries Research*, 93:154–162. doi:10.1016/j.fishres.2008.03.006.

SPC (2008). Estimates of annual catches in the WCPFC statistical area. WCPFC-SC4-2008/ST-IP-1, Port Moresby, Papua New Guinea, 11–22 August 2008.

SPC (2011). Summary information on whale shark and cetacean interactions in the tropical WCPFC purse seine fishery. Technical Report WCPFC8-2011-IP-01, Pohnpei, Federated States of Micronesia, 9–17 August 2011.

Stefansson, G. (1996). Analysis of groundfish survey abundance data: Combining the glm and delta approaches. *ICES Journal of Marine Science*, 53:577–588.

Walsh, W. A. and Clarke, S. C. (2011). Catch data for oceanic whitetip and silky sharks from fishery observers document changes in relative abundance in the Hawaii-based longline fishery in 1995–2010. WCPFC-SC7-2011/EB-WP-03, Pohnpei, Federated States of Micronesia, 9–17 August 2011.

Walters, C. (2003). Folly and fantasy in the analysis of spatial catch rate data. *Canadian Journal of Fisheries and Aquatic Sciences*, 60(12):1433–1436.

Ward, P. and Myers, R. (2005). A method for inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. *Canadian Journal of Fisheries and Aquatic Sciences*, 62(5):1130–1142.

WCPFC (2011). Conservation and Management Measure for oceanic whitetip sharks. Conservation and Management Measure 2011–04, Eighth Regular Session of the WCPF Commission, Guam, USA, 26–30 March 2012.

Williams, P. G., Tuiloma, I., and Falasi, C. (2015). Status of ROP data management. WCPFC-SC11-2015/ST-IP-02, Pohnpei, Federated States of Micronesia, 5–13 August 2015.

Worm, B. and Tittensor, D. P. (2011). Range contraction in large pelagic predators. *Proceedings of the National Academy of Sciences*, 108(29):11942–11947.

A Tables

Table 2: Percent of effort observed in the longline fishery by region.

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

Table 3: Percent of Logsheets reporting sharks to species, longline fishery by region.

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

Table 4: Millions of hooks fished in longline fishery by region.

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

Table 5: Filtering rules used to clean the longline observer dataset

# records at start	103700
Record filter	**# rows removed**
Duplicated set IDs	589
Missing values for HBF, hooks, lon and lat	7385
Sets declared as targeting sharks	1517
Sets with hooks > 1000	14404
Sets with HBF < 5 or > 40	3300
Sets outside of study regions	4774
Sets in years < 1995 and > 2014	4511
# records left	66520

Table 6: 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 7: Description of variables used in CPUE standardization

Variable name	Symbol	Explanation
Year	β_Y	Required to estimate year effect
Month	β_M	Captures seasonal variability
Observer program	β_O	Country hosting the observer program
Vessel flag	β_F	Note: correlated with observer program
Hooks-between-floats	β_{HBF}	Indicator of catchability for surface-dwelling species
Shark target		Sharks explicitly defined as targets?
SST	SST	100
Day category		Day or night, before or after sunrise/sunset?

Table 8: 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 9: Summary of model structures retained for CPUE standardization of each species

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

Table 10: Sources of information used in defining length at maturity and converting between total length (TL) and fork length (FL) measurement standards. TL measurements which fell outside the range of data used to construct the FL-TL conversion equations were excluded from the analysis.

Species	Length at Maturity	Reference(s)	Conversion Factor(s)	Reference(s)
Blue	Males: 168 FL (200 TL) Females: 168 FL (200 TL)	Nakano and Stevens (2008)	FL=0.8313(TL)+1.39	Skomal and Natanson (2003)
Mako (shortfin mako)	Males: 180 FL Females: 275 FL	Francis and Duffy (2005)	FL=0.911(TL)+0.821	Francis and Duffy (2005)
Oceanic whitetip	Males: 138 FL (168 TL) Females: 144 FL (175 TL)	Seki et al. (1998)	FL =0.822(TL)+0	Seki et al. (1998)
Silky	Males: 175 FL (212 TL) Females: 173 FL (210 TL)	Joung et al. (2008)	FL = 0.8388(TL)-2.651	Kohler, Casey and Turner (1996)
Thresher (bigeye thresher)	Males: 168 FL (270 TL) Females: 203 FL (332 TL)	Smith et al. (2008)	FL = 0.5598(TL) + 17.666	Kohler, Casey and Turner (1996)
Hammerhead (scalloped hammerhead)	Males: 153 (198 TL) Females: 163 FL (210 TL)	Chen et al. 1990	FL = 0.7756(TL) -0.3132	Kohler et al. 1996
Porbeagle	Males: 145 FL Females: 175 FL	Francis and Duffy (2005)	FL = 0.893(TL) -6.943	Francis and Duffy (2005)

Table 11: Synthesis of indicator results for each of the seven shark species by indicator category and region. Dots are colour coded to identify the direction of trends in each indicator (red - decreasing; green - increasing; yellow - stable; grey - insufficient data). Blank entries remain where the species is caught in relatively very low numbers.

	Distribution						Composition												CPUE						Biological					
							Longline						Purse Seine																	
Region	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Blue	●	●	●	●	●	●	●	●	●	●	●	●							●	●	●	●	●	●	●	●	●	●	●	●
Silky	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Hammerheads	●	●	●	●	●	●	●	●	●	●	●	●							●	●	●	●	●	●	●	●	●	●	●	●
Mako	●	●	●	●	●	●	●	●	●	●	●	●							●	●	●	●	●	●	●	●	●	●	●	●
Oceanic whitetip	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Porbeagle					●	●					●	●											●	●					●	●
Threshers	●	●	●	●	●	●	●	●	●	●	●	●							●	●	●	●	●	●	●	●	●	●	●	●

Table 12: Summary of whale shark observations and purse seine sets. We note that 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.

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

B Figures

B.1 Distribution Indicator Analyses: Figures

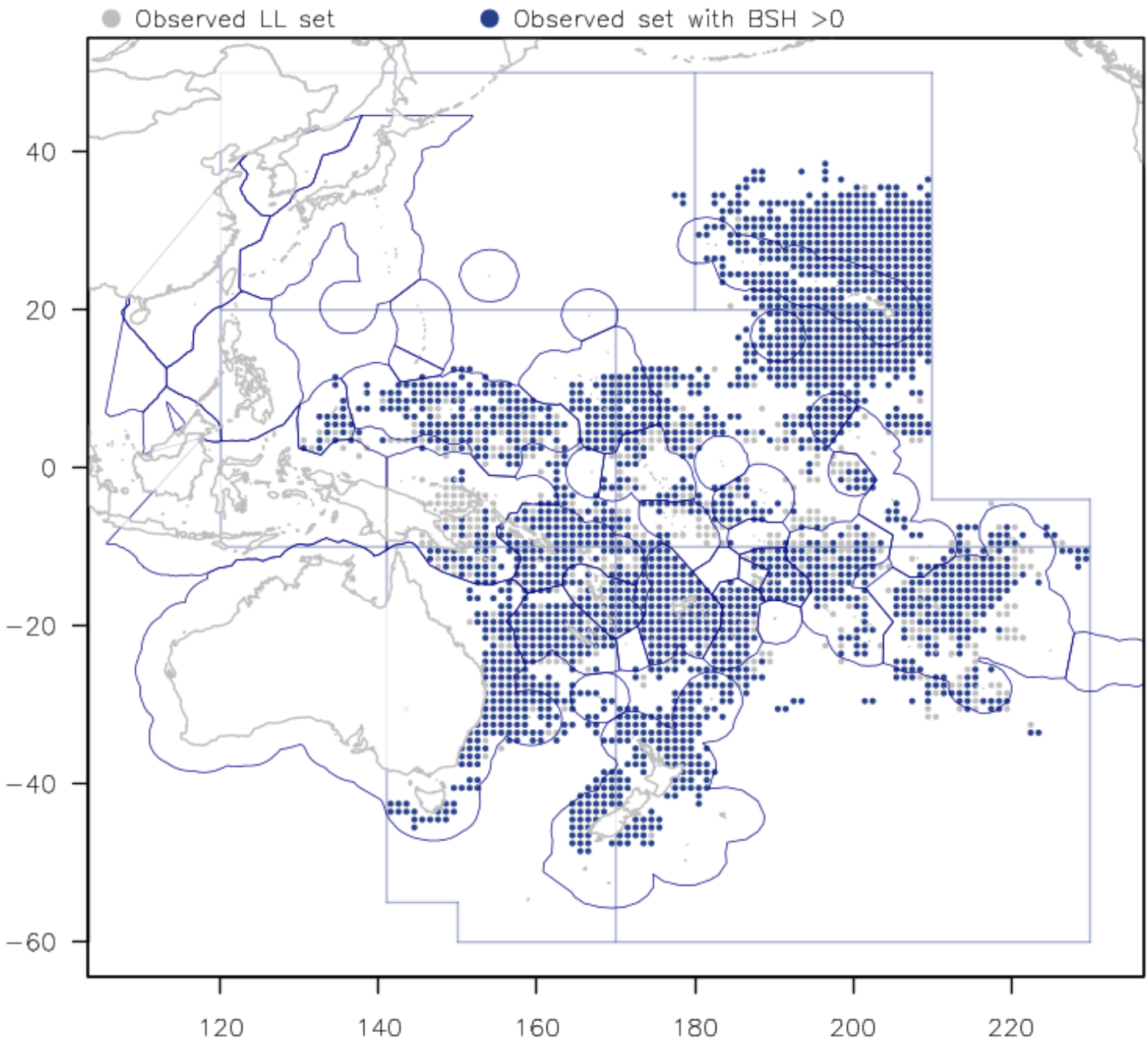


Figure 9: Distribution of observed LL sets (grey) and observed longline sets for which catches of blue shark were made during the study period within the WCPFC convention area.

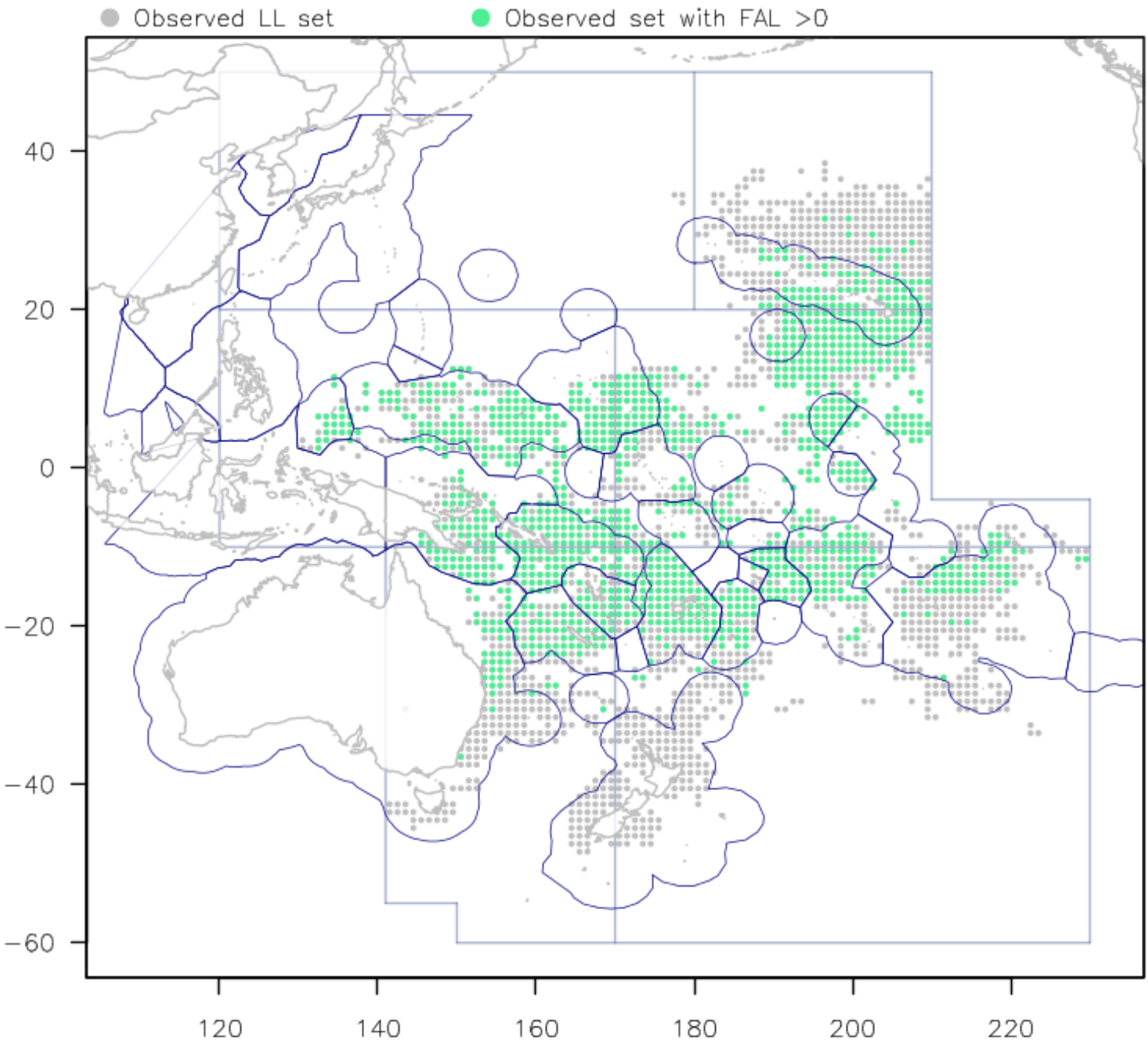


Figure 10: Distribution of observed LL sets (grey) and observed longline sets for which catches of silky shark were made during the study period within the WCPFC convention area.

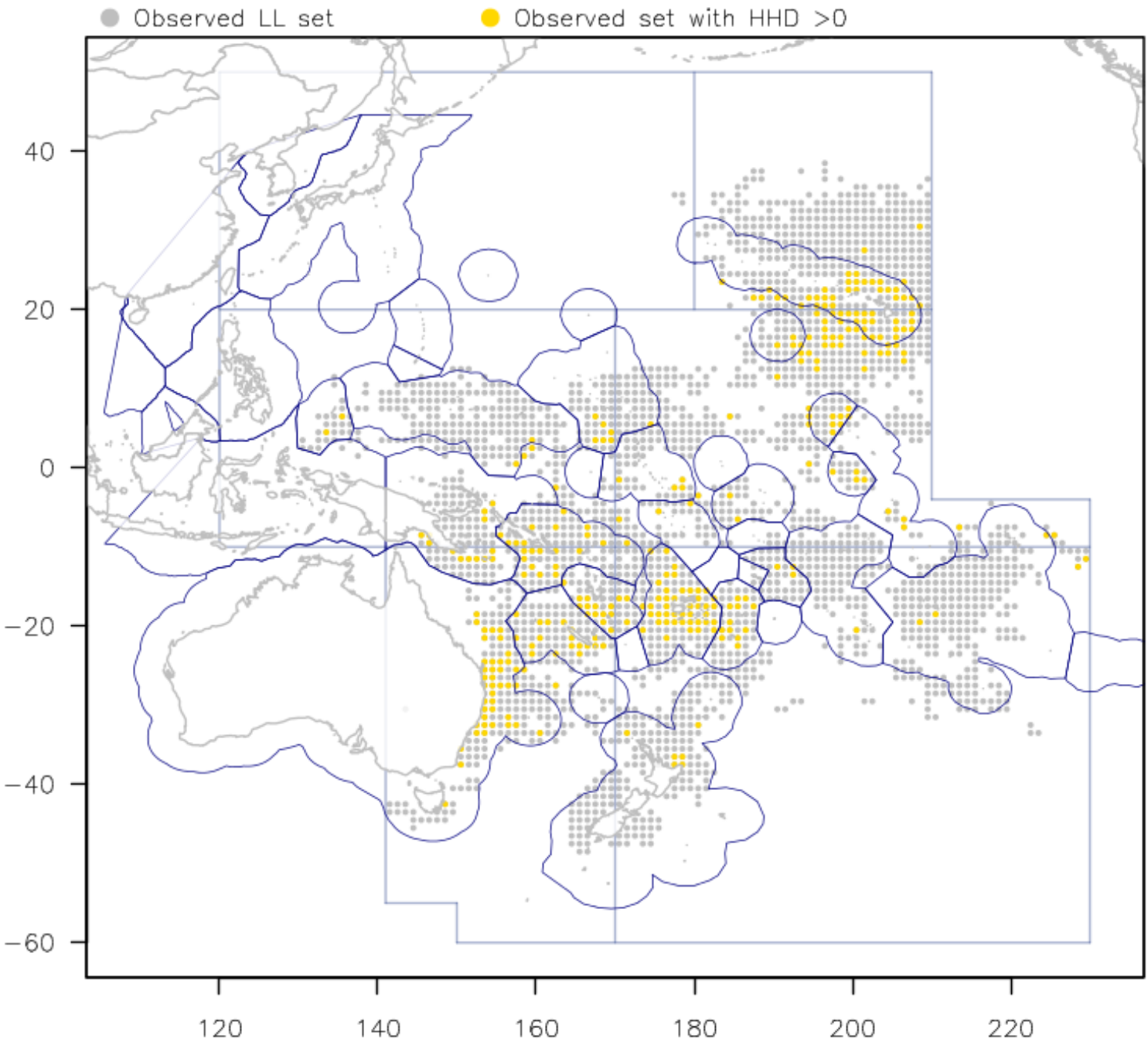


Figure 11: Distribution of observed LL sets (grey) and observed longline sets for which catches of hammerhead shark were made during the study period within the WCPFC convention area.

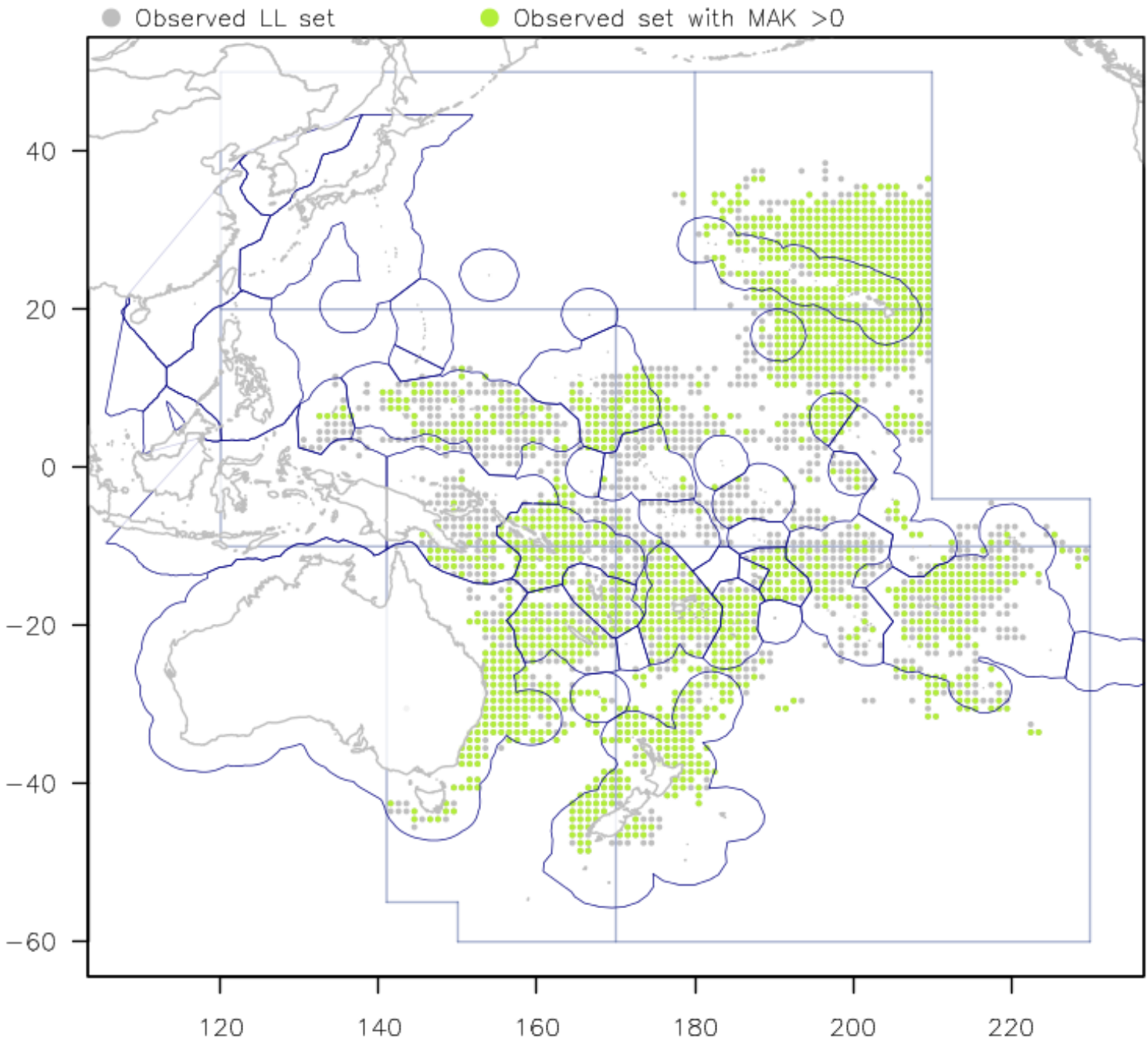


Figure 12: Distribution of observed LL sets (grey) and observed longline sets for which catches of mako shark were made during the study period within the WCPFC convention area.

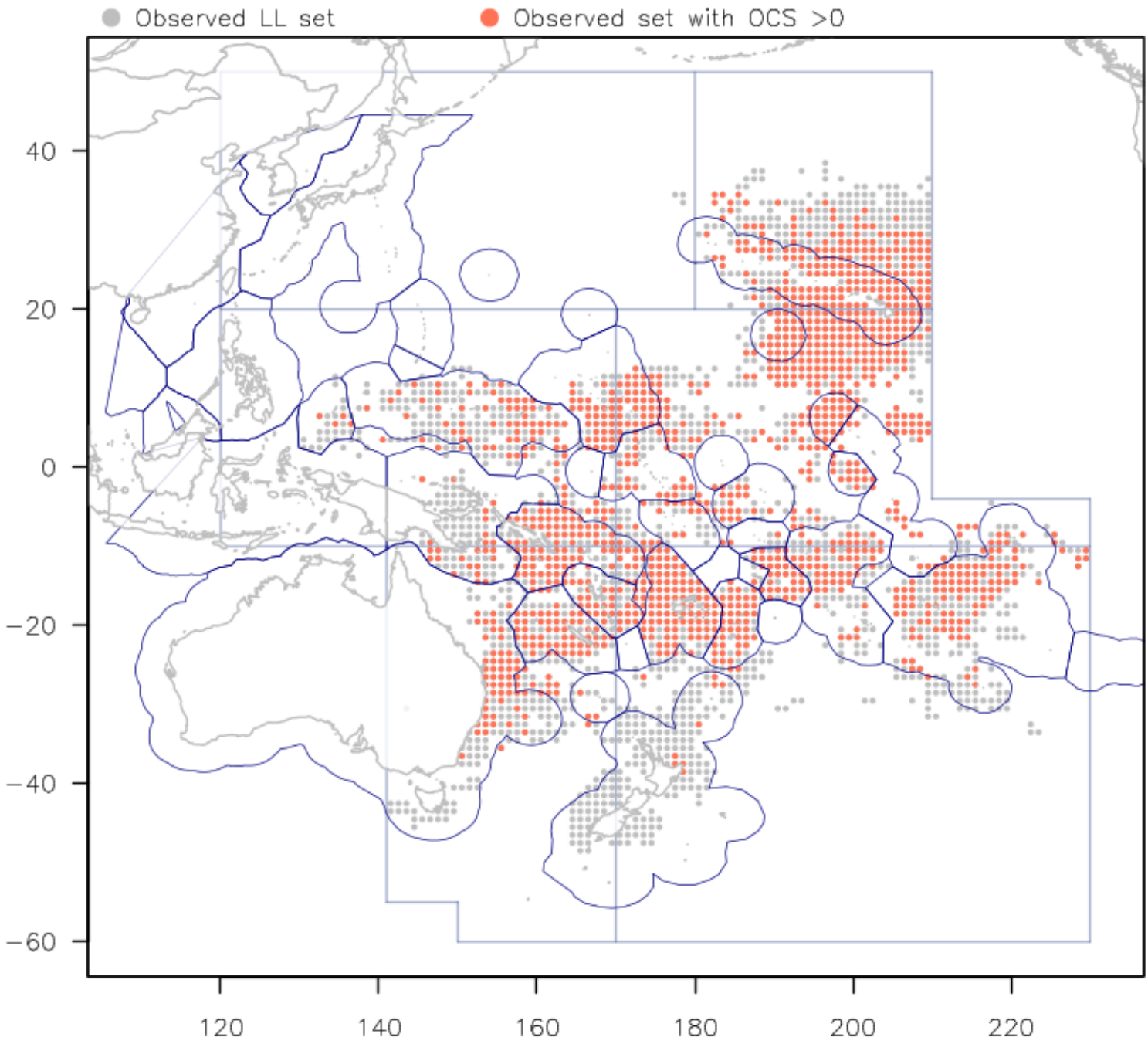


Figure 13: Distribution of observed LL sets (grey) and observed longline sets for which catches of oceanic whitetip shark were made during the study period within the WCPFC convention area.

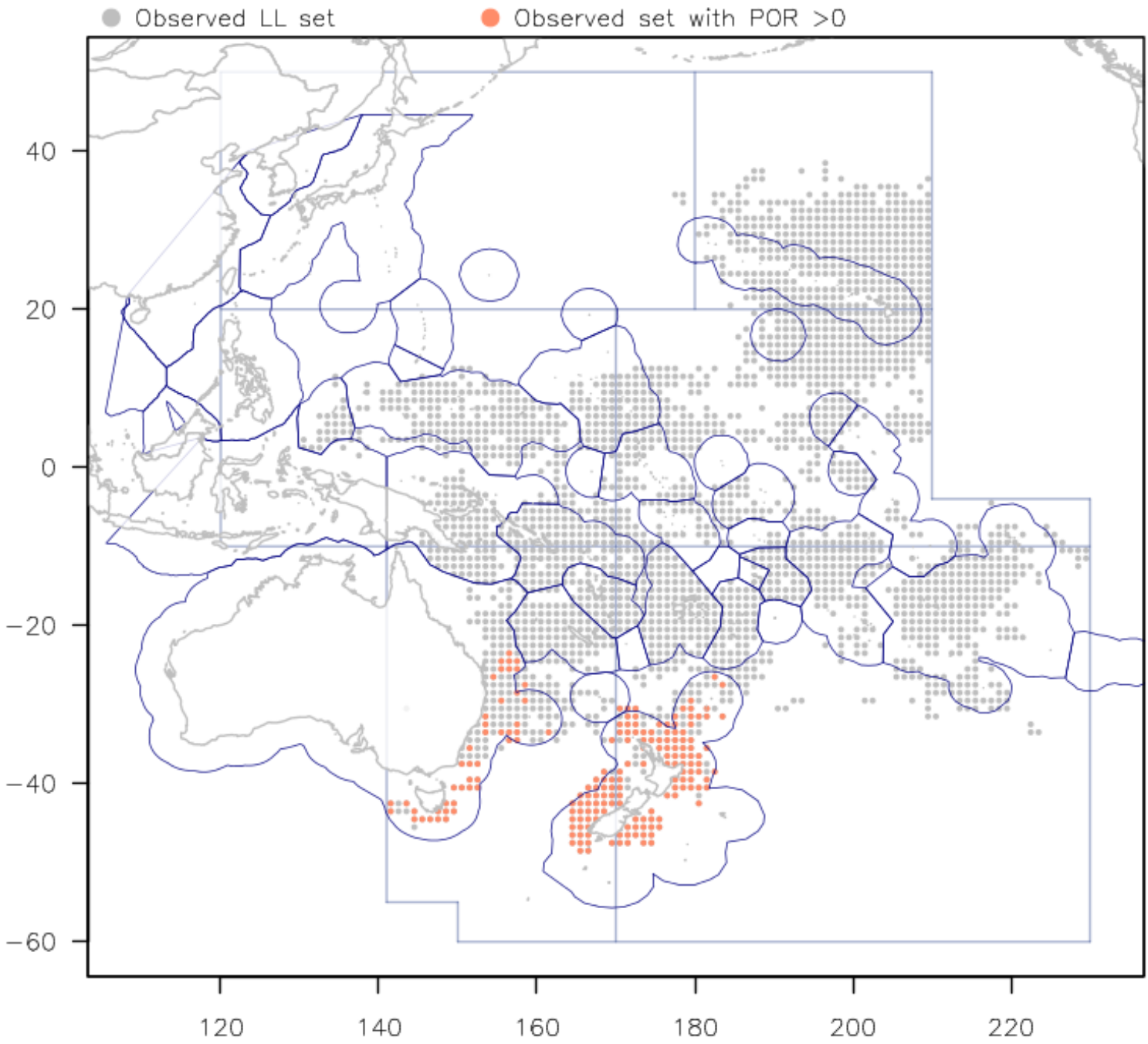


Figure 14: Distribution of observed LL sets (grey) and observed longline sets for which catches of porbeagle shark were made during the study period within the WCPFC convention area.

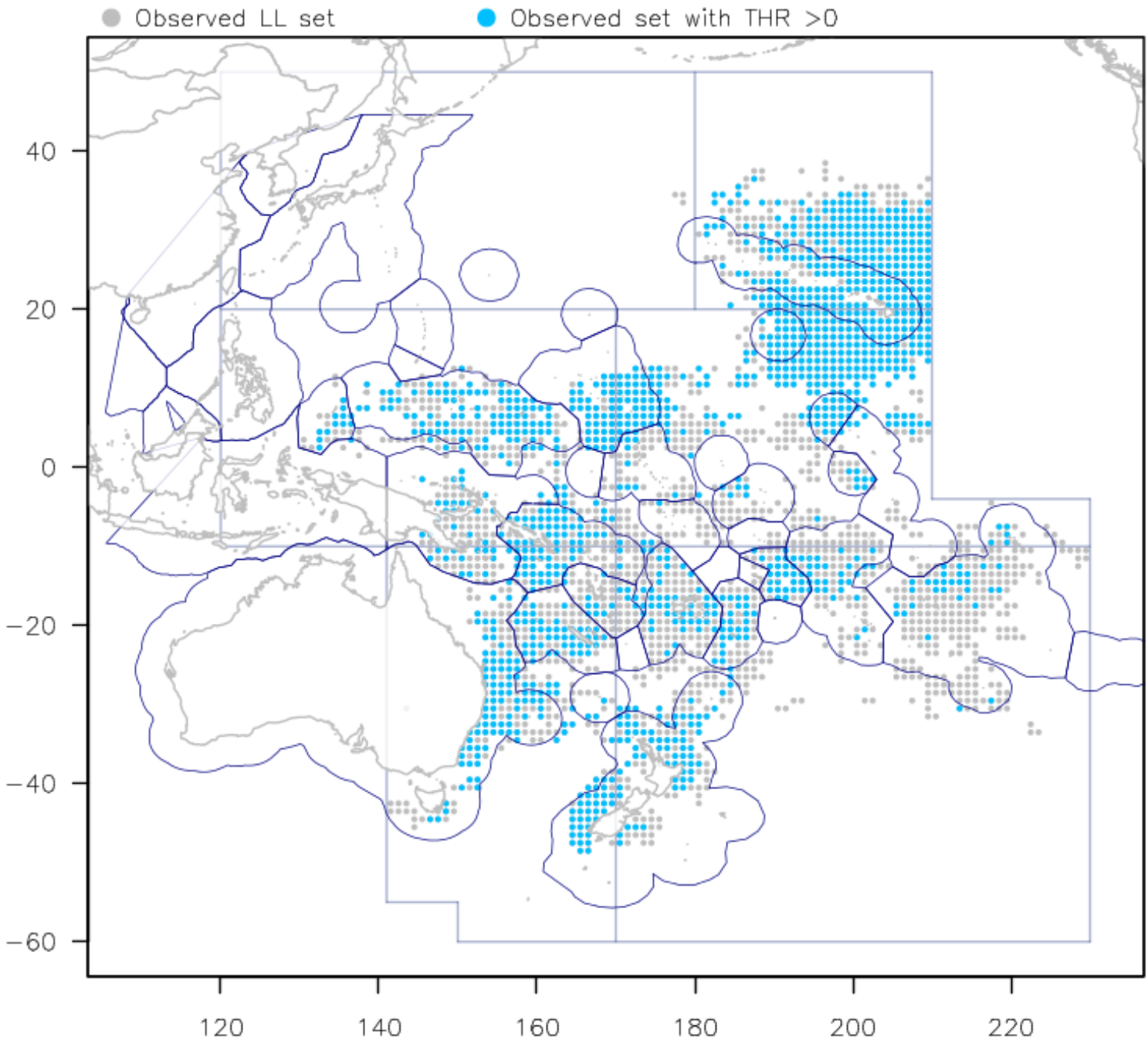


Figure 15: Distribution of observed LL sets (grey) and observed longline sets for which catches of thresher shark were made during the study period within the WCPFC convention area.

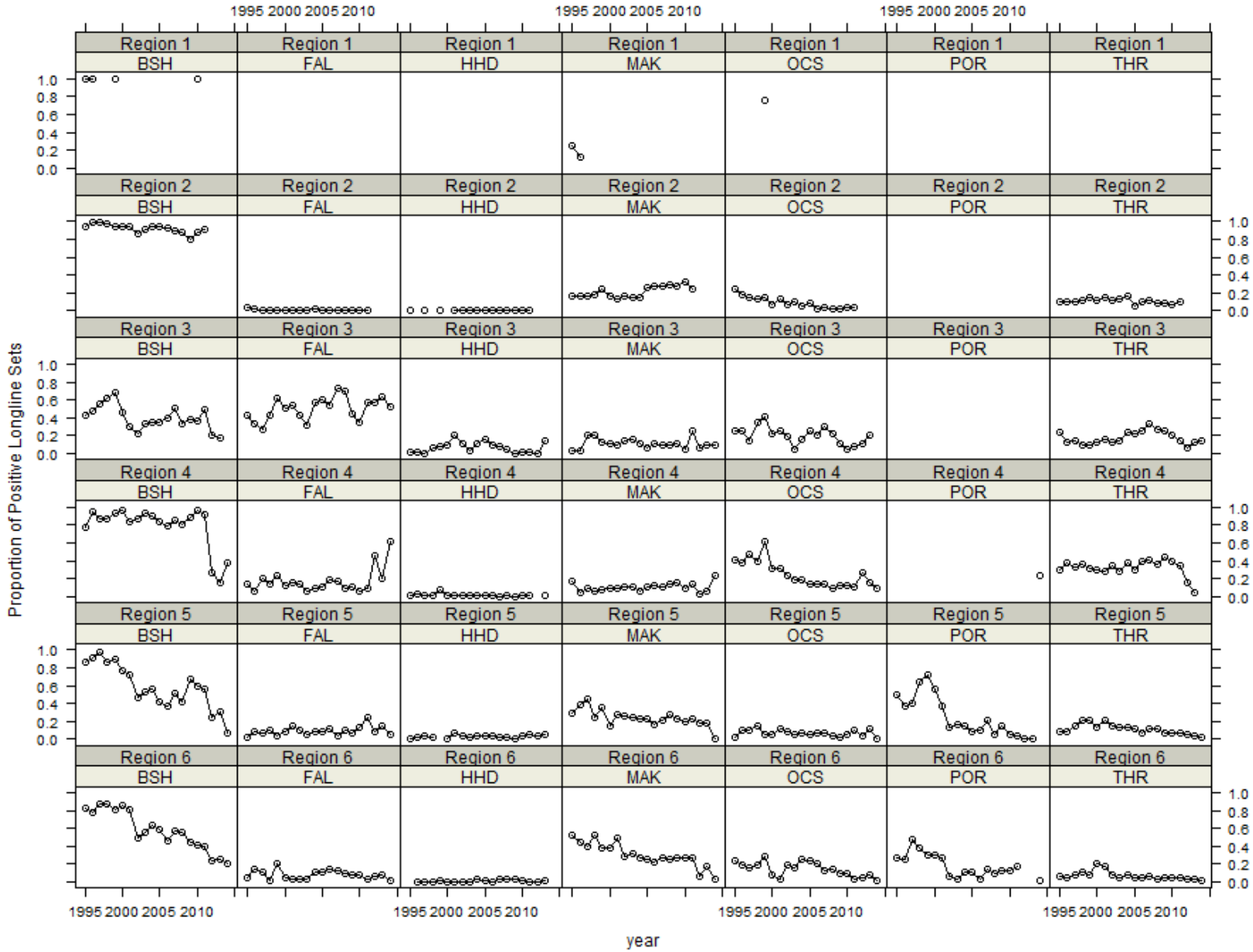


Figure 16: The proportion of longline sets for which one or more sharks were caught by region and year.

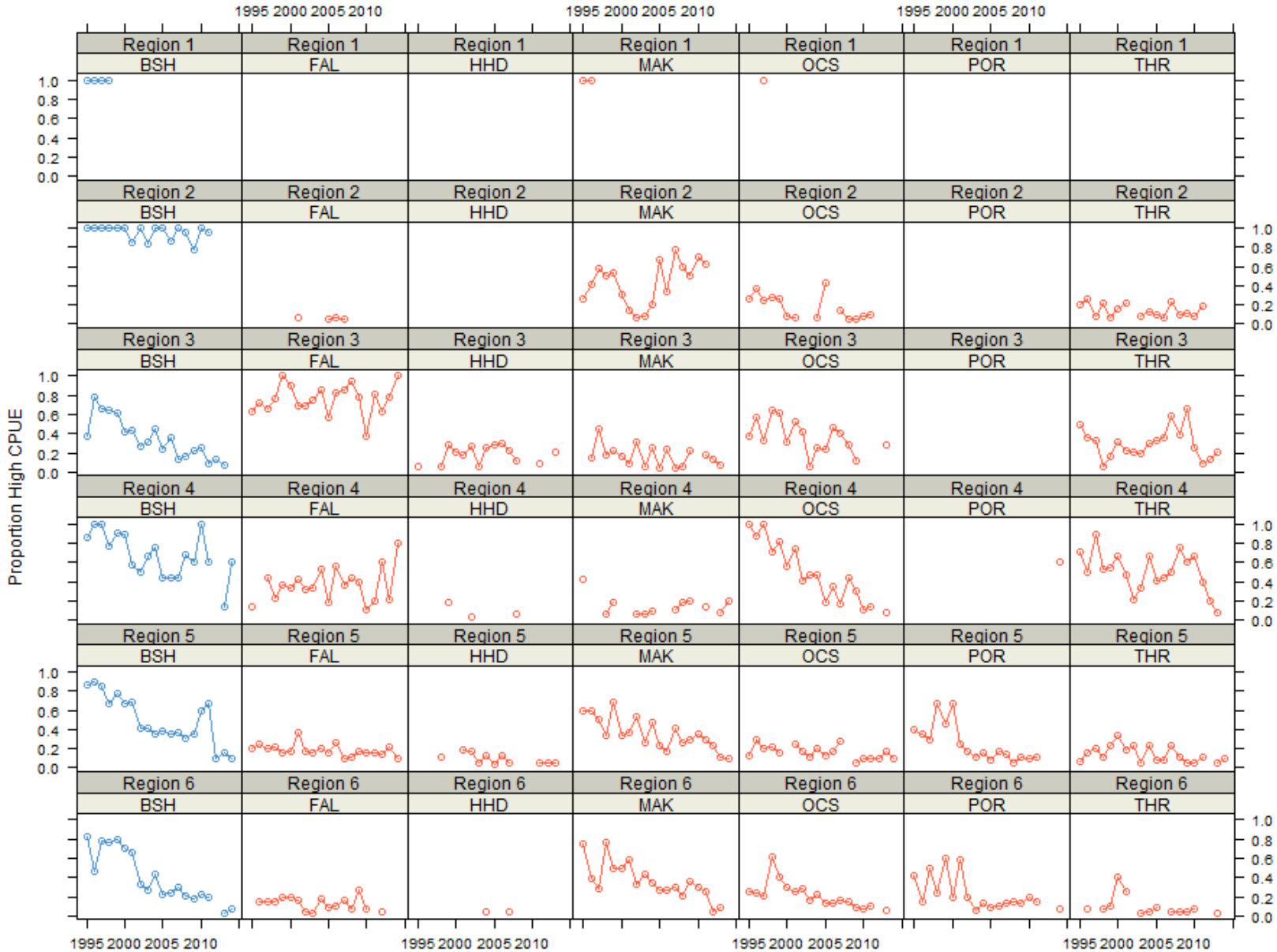


Figure 17: Proportion of longline sets with high CPUE by species and region. High CPUE is defined as sets with more than 1 shark per 1000 hooks (for blue shark, blue lines) or more than one shark per 5000 hooks (all other species, red lines).

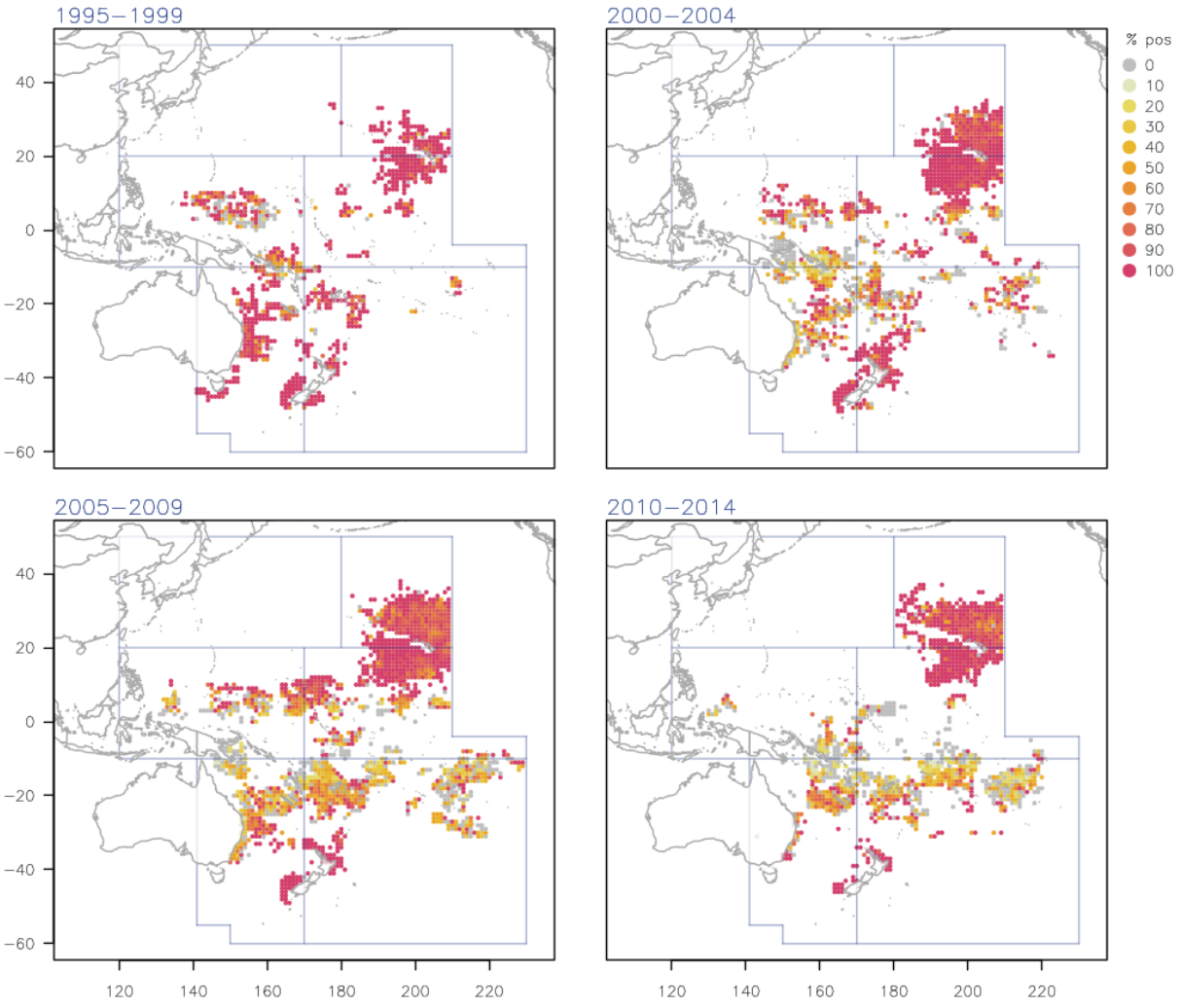


Figure 18: Spatial distribution of the proportion of longline sets for which one or more blue shark were caught for each five year period between 1995 and 2014.

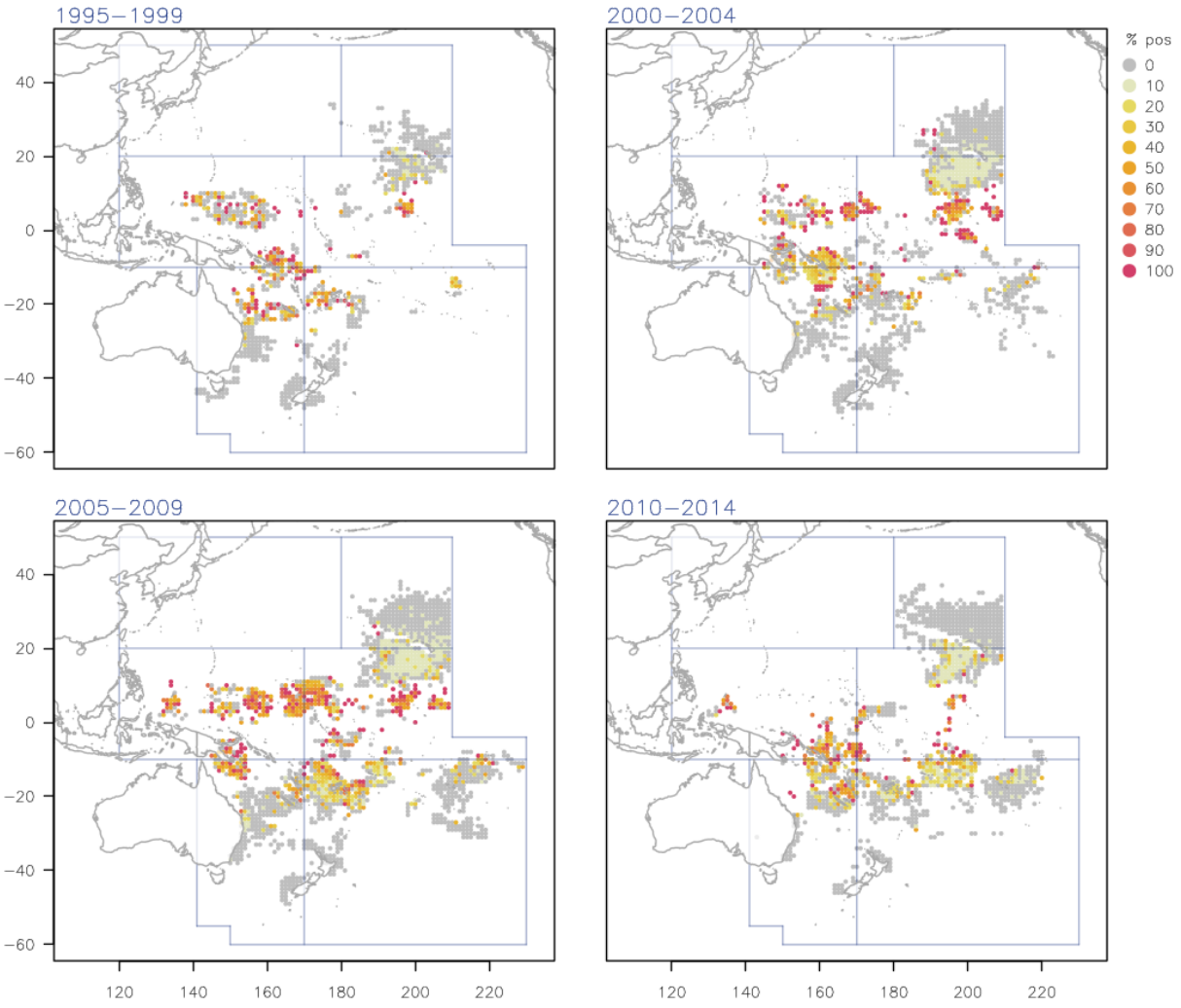


Figure 19: Spatial distribution of the proportion of longline sets for which one or more silky shark were caught for each five year period between 1995 and 2014.

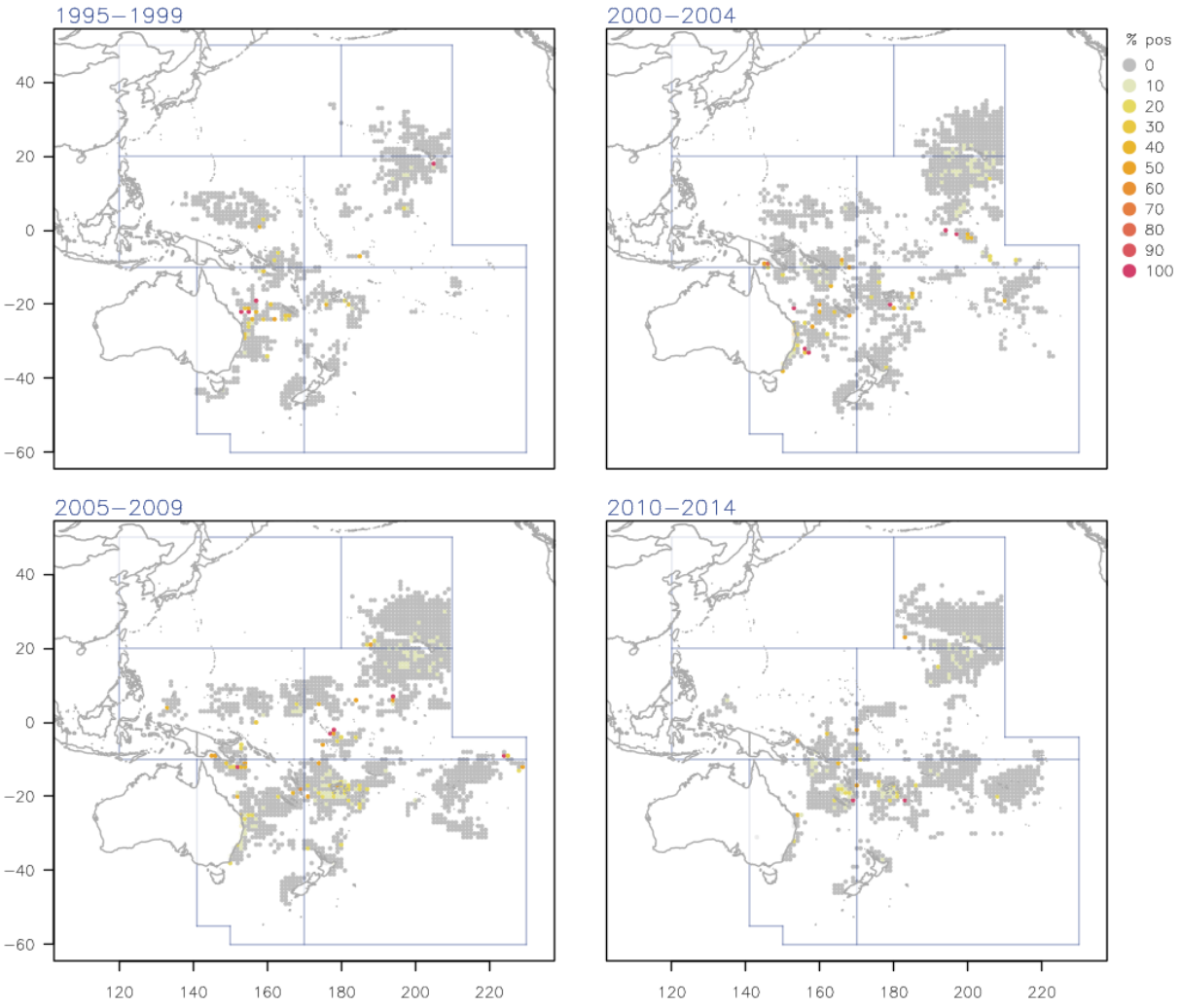


Figure 20: Spatial distribution of the proportion of longline sets for which one or more hammerhead shark were caught for each five year period between 1995 and 2014.

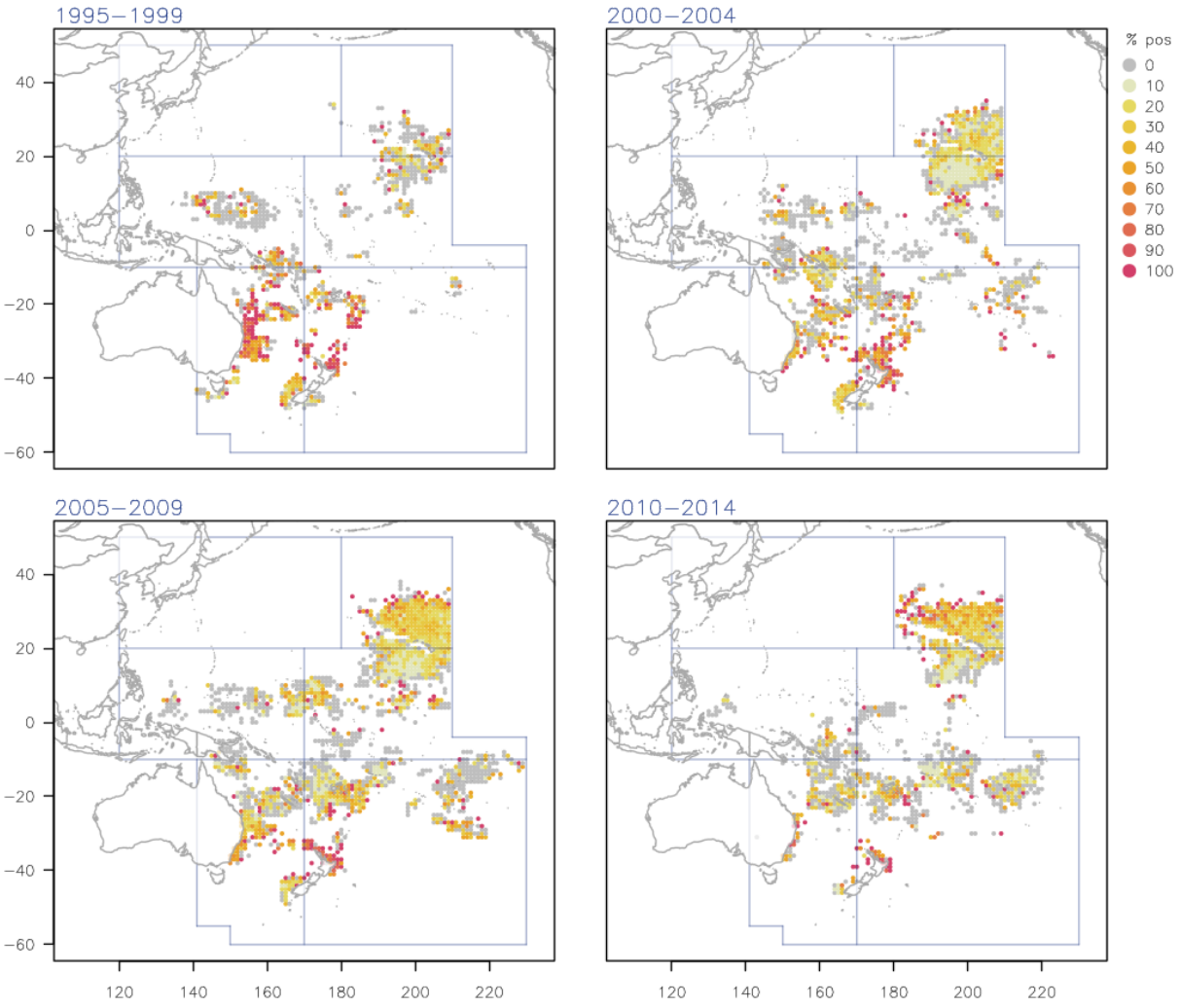


Figure 21: Spatial distribution of the proportion of longline sets for which one or more mako shark were caught for each five year period between 1995 and 2014.

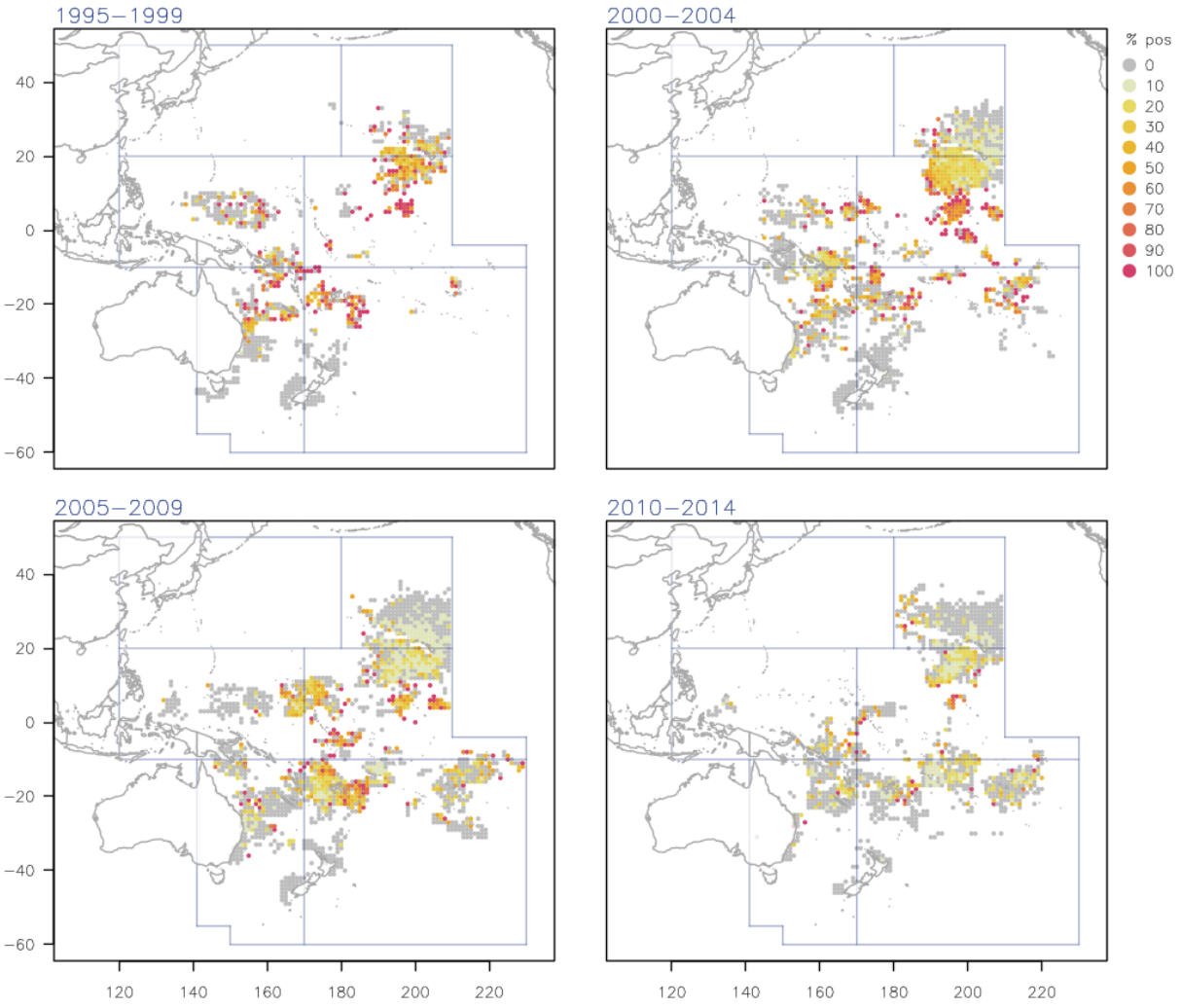


Figure 22: Spatial distribution of the proportion of longline sets for which one or more oceanic whitetip shark were caught for each five year period between 1995 and 2014.

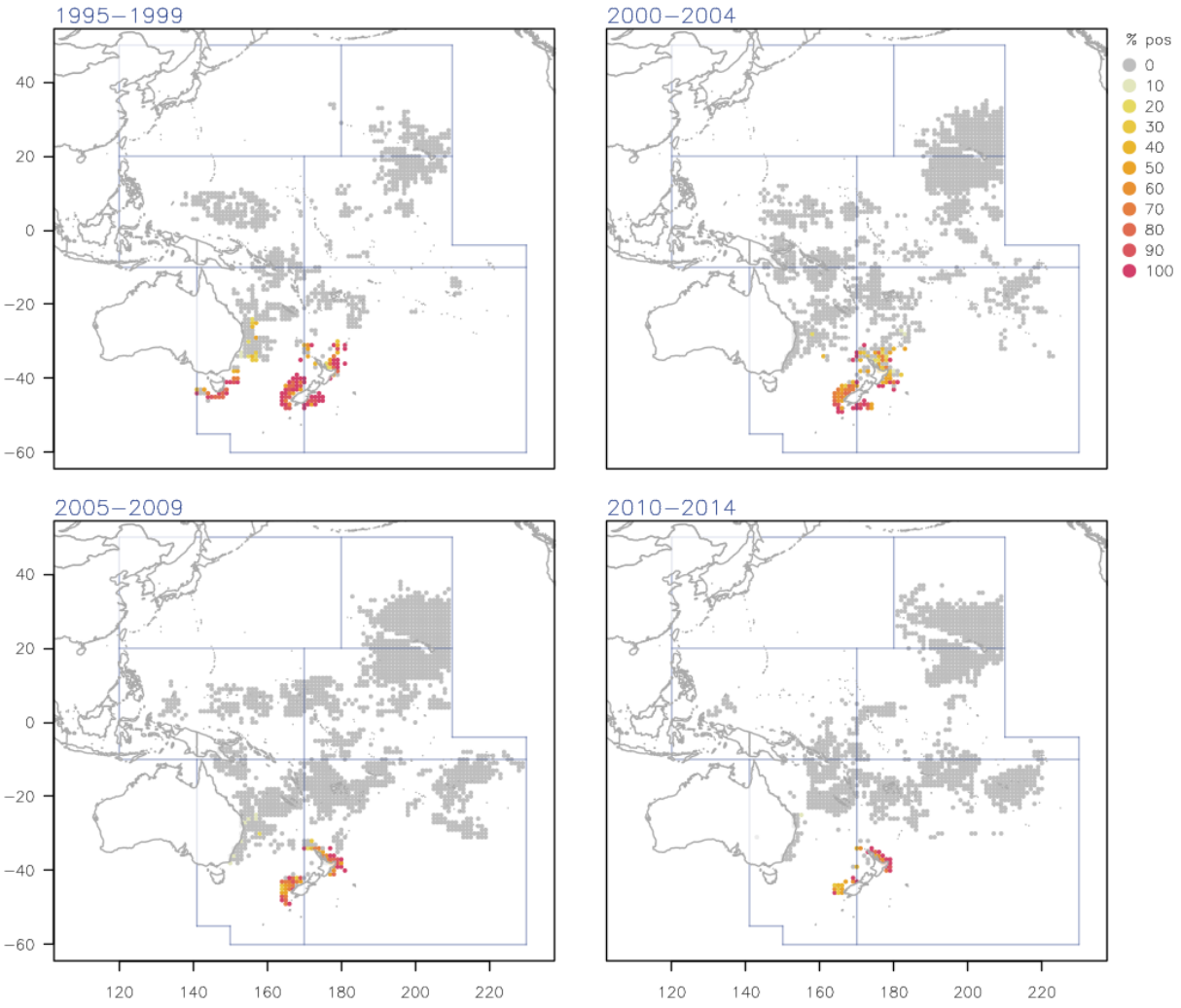


Figure 23: Spatial distribution of the proportion of longline sets for which one or more porbeagle shark were caught for each five year period between 1995 and 2014.

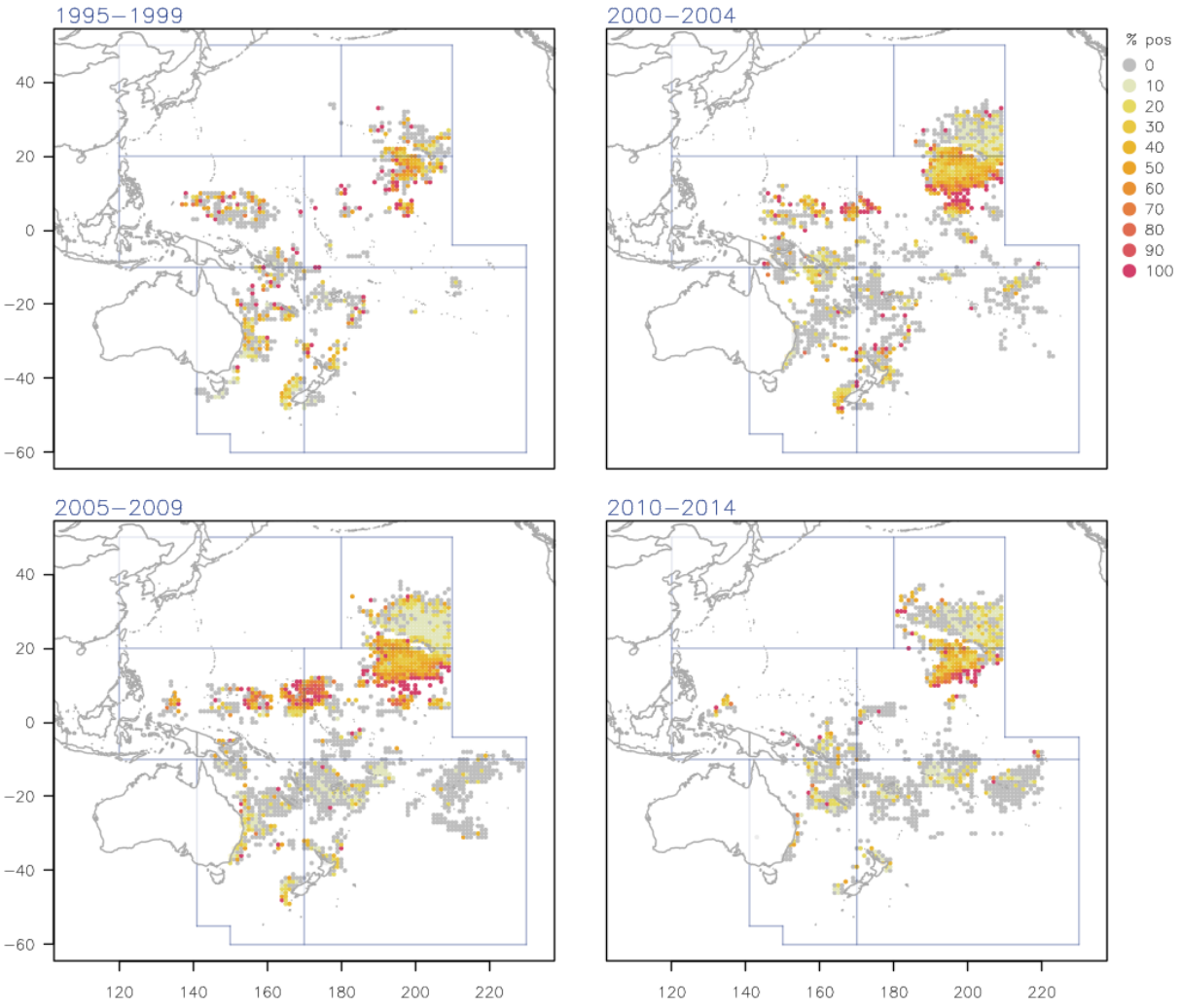


Figure 24: Spatial distribution of the proportion of longline sets for which one or more thresher shark were caught for each five year period between 1995 and 2014.

B.2 Species Composition Indicator Analyses: Figures

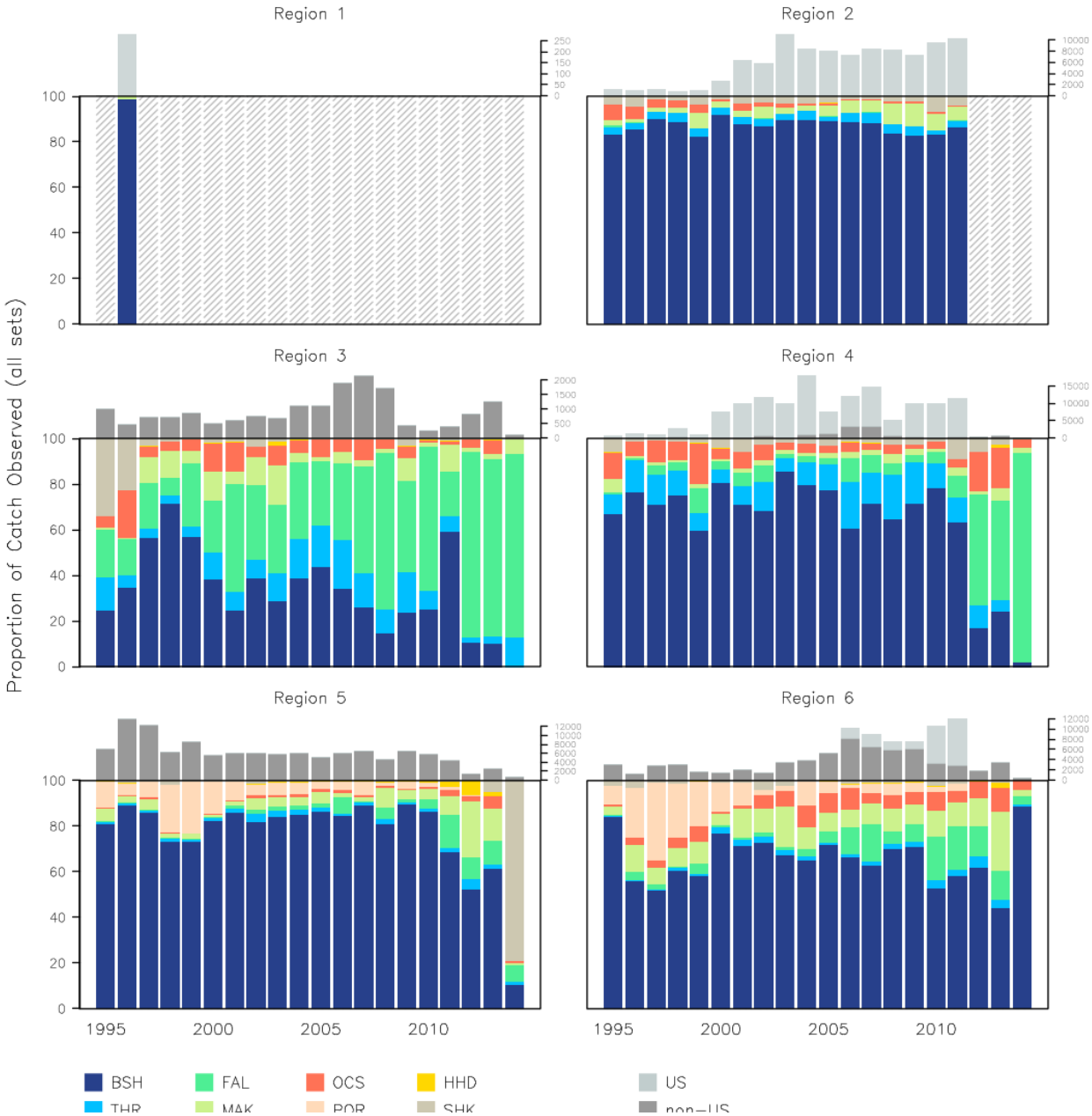


Figure 25: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for all longline sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each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

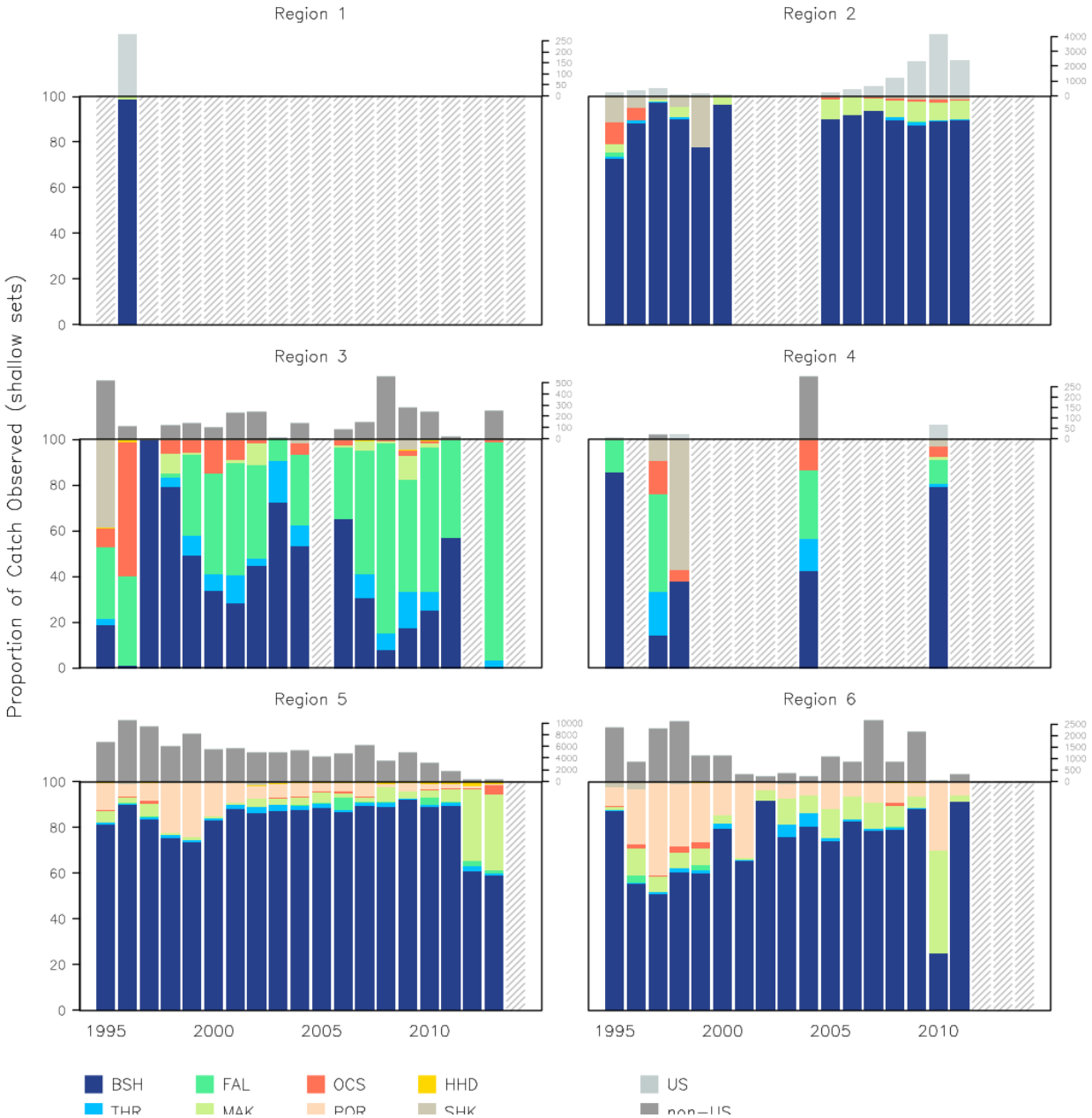


Figure 26: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for shallow longline sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of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

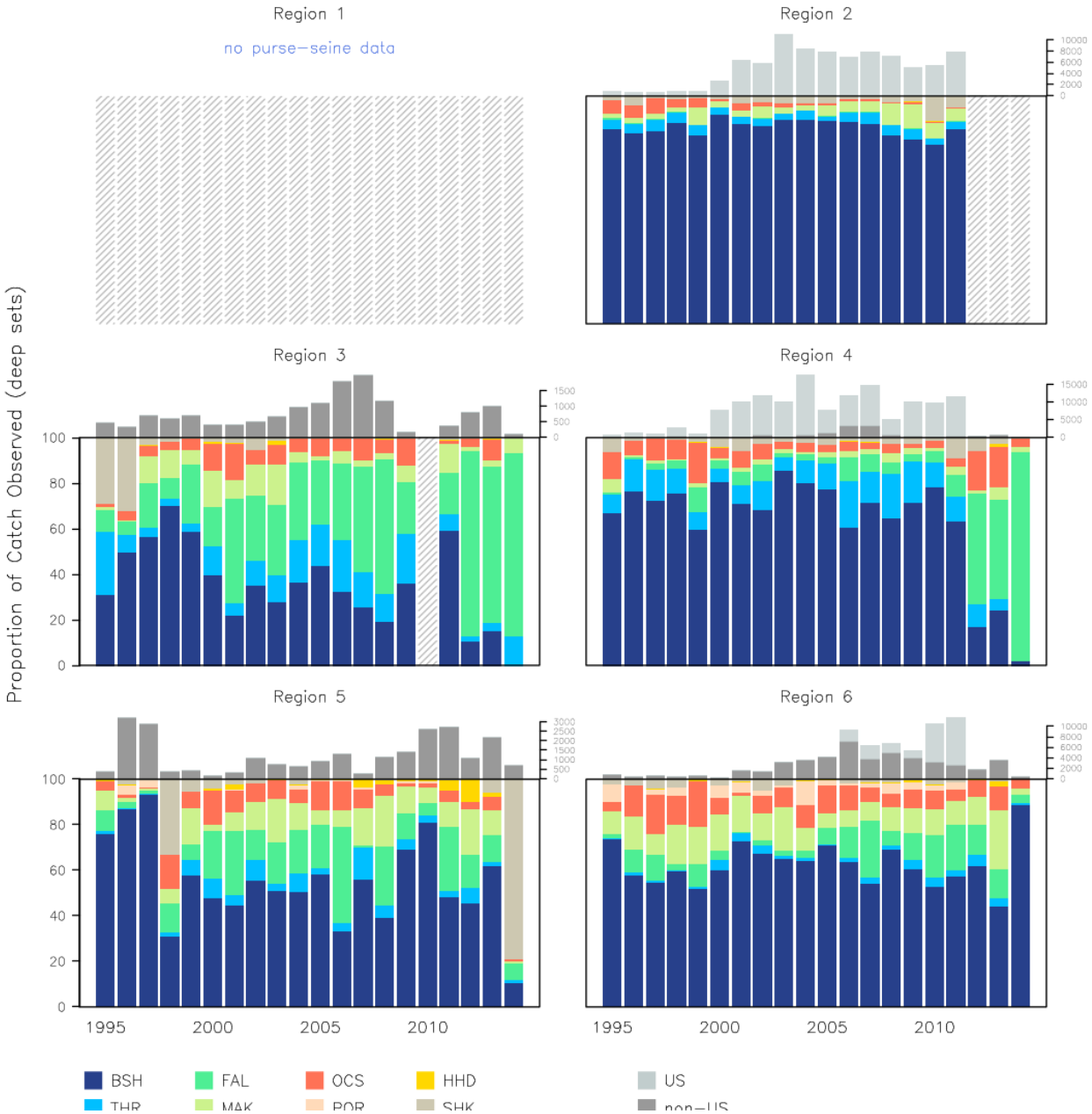


Figure 27: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for deep longline sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each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

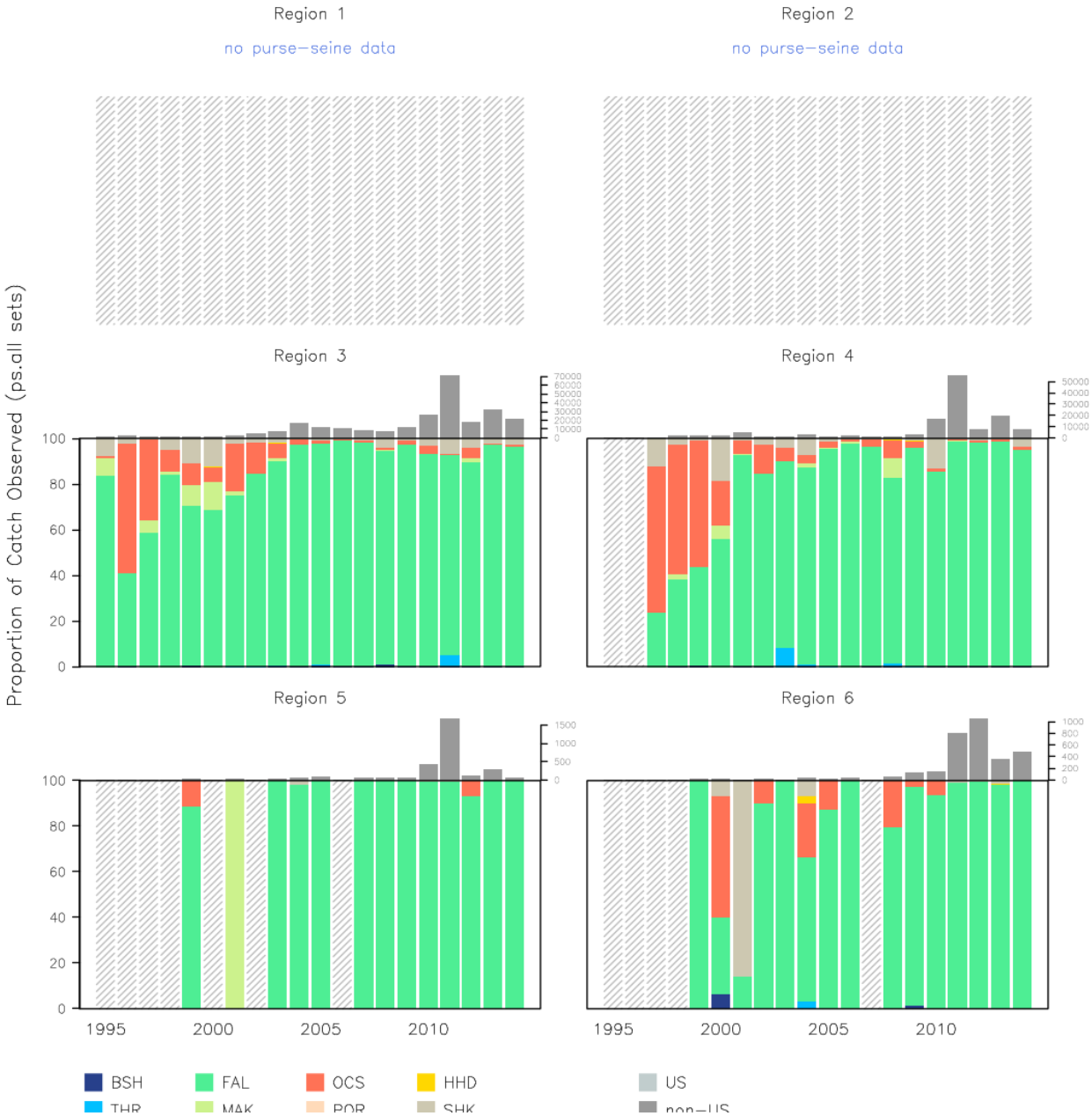


Figure 28: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for all purse seine sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage of each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

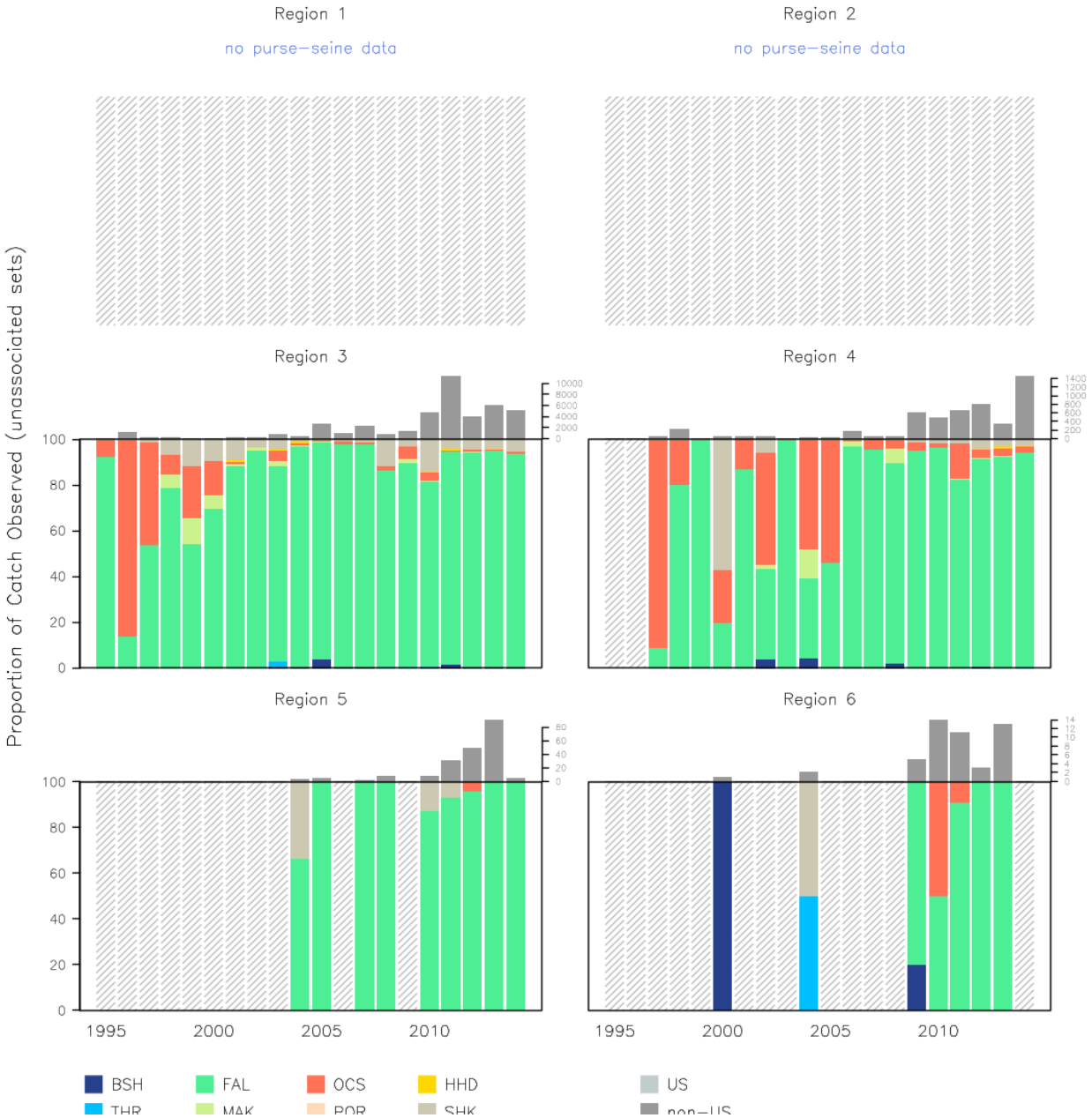


Figure 29: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for unassociated purse seine sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage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

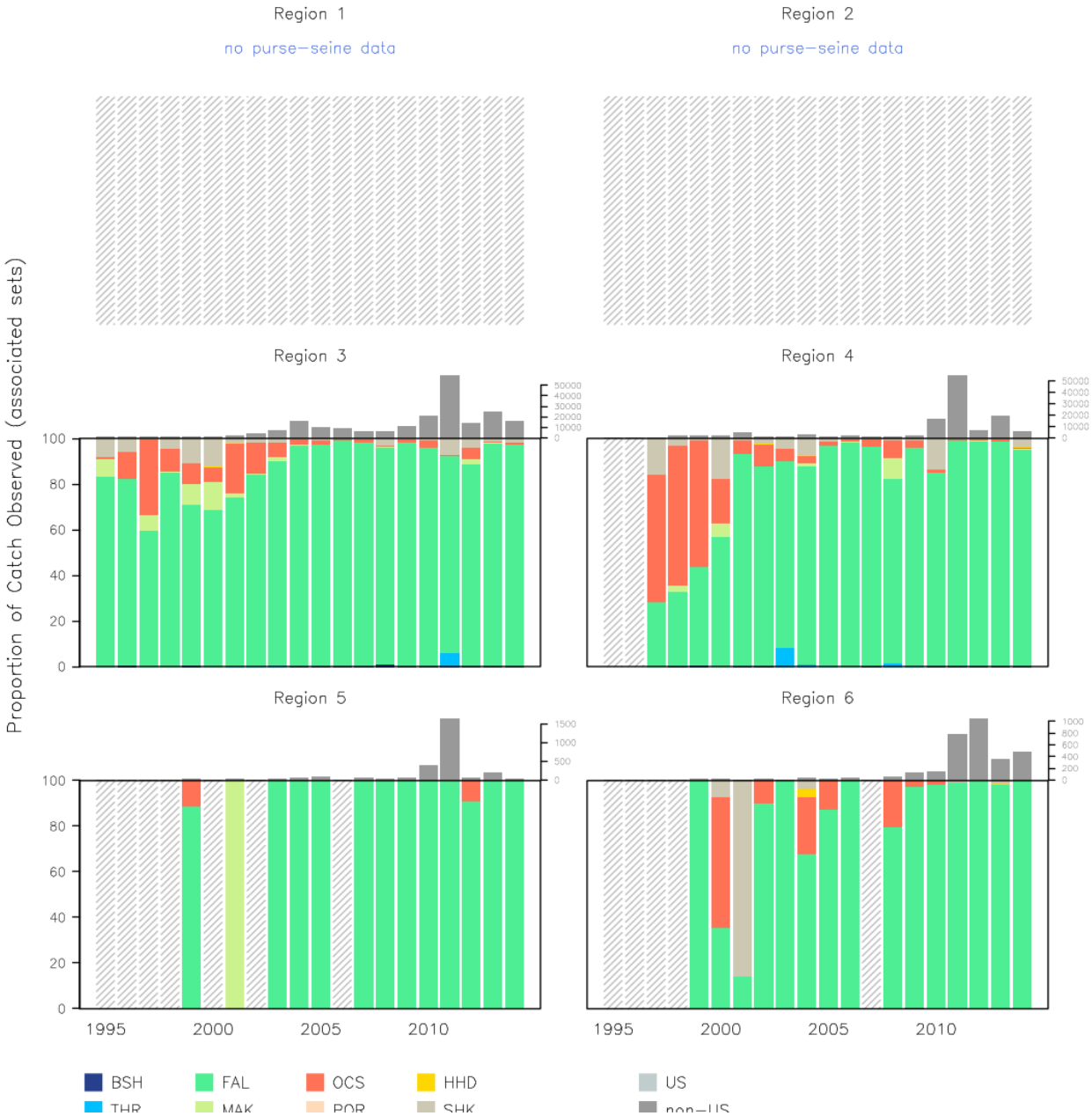


Figure 30: Species compositon plots by year, region and species showing the proportion of each species observed in the catch for all associated seine sets. Grey bars in the upper panel of each plot indicate the total number of all sharks caught. Coloured bars in the main panel indicate the percentage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

B.3 CPUE Indicators. Model diagnostics and extra plots

B.3.1 Nominal CPUE

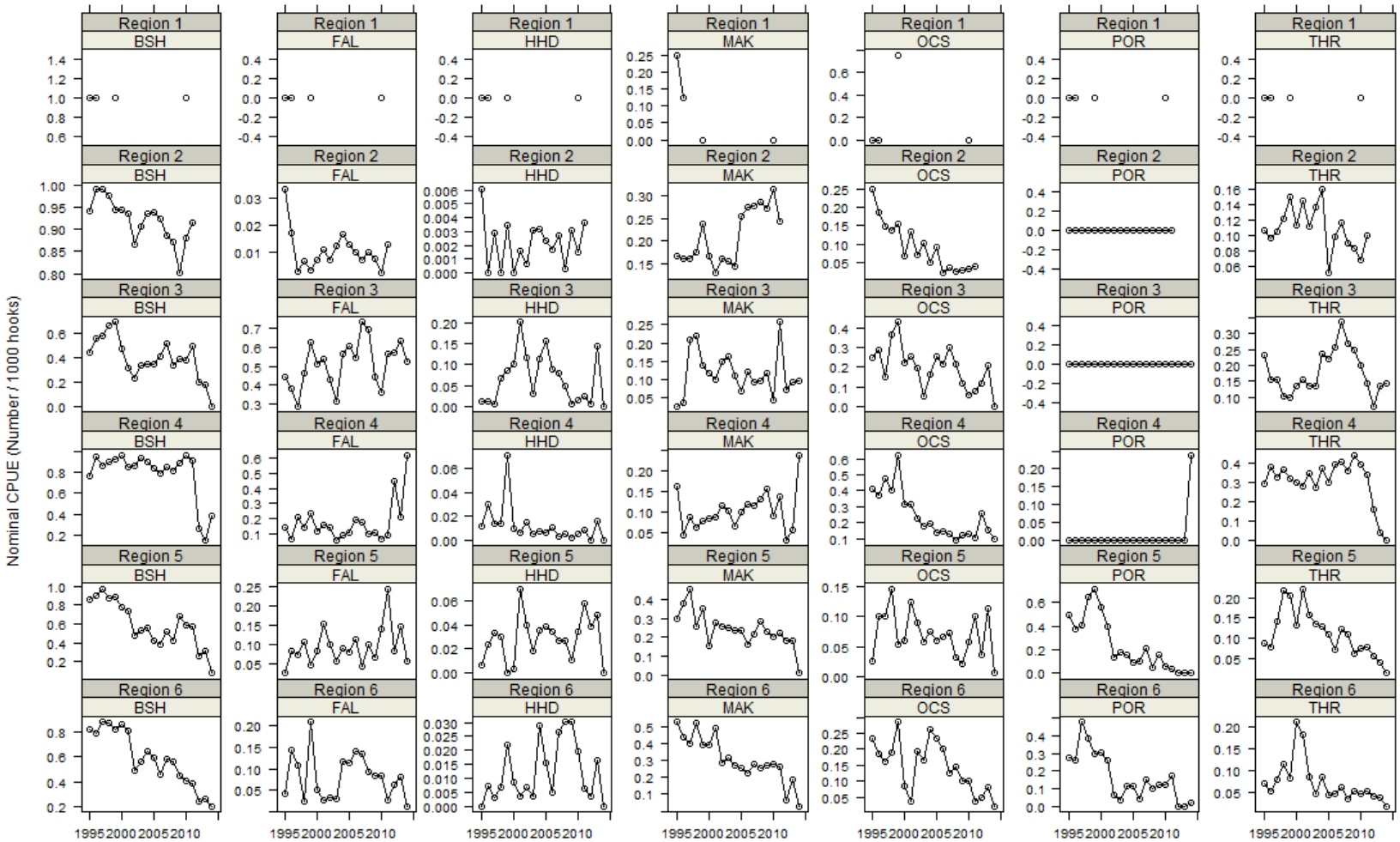


Figure 31: Nominal CPUE (numbers/1000 hooks) by species and region for sharks caught by longline.

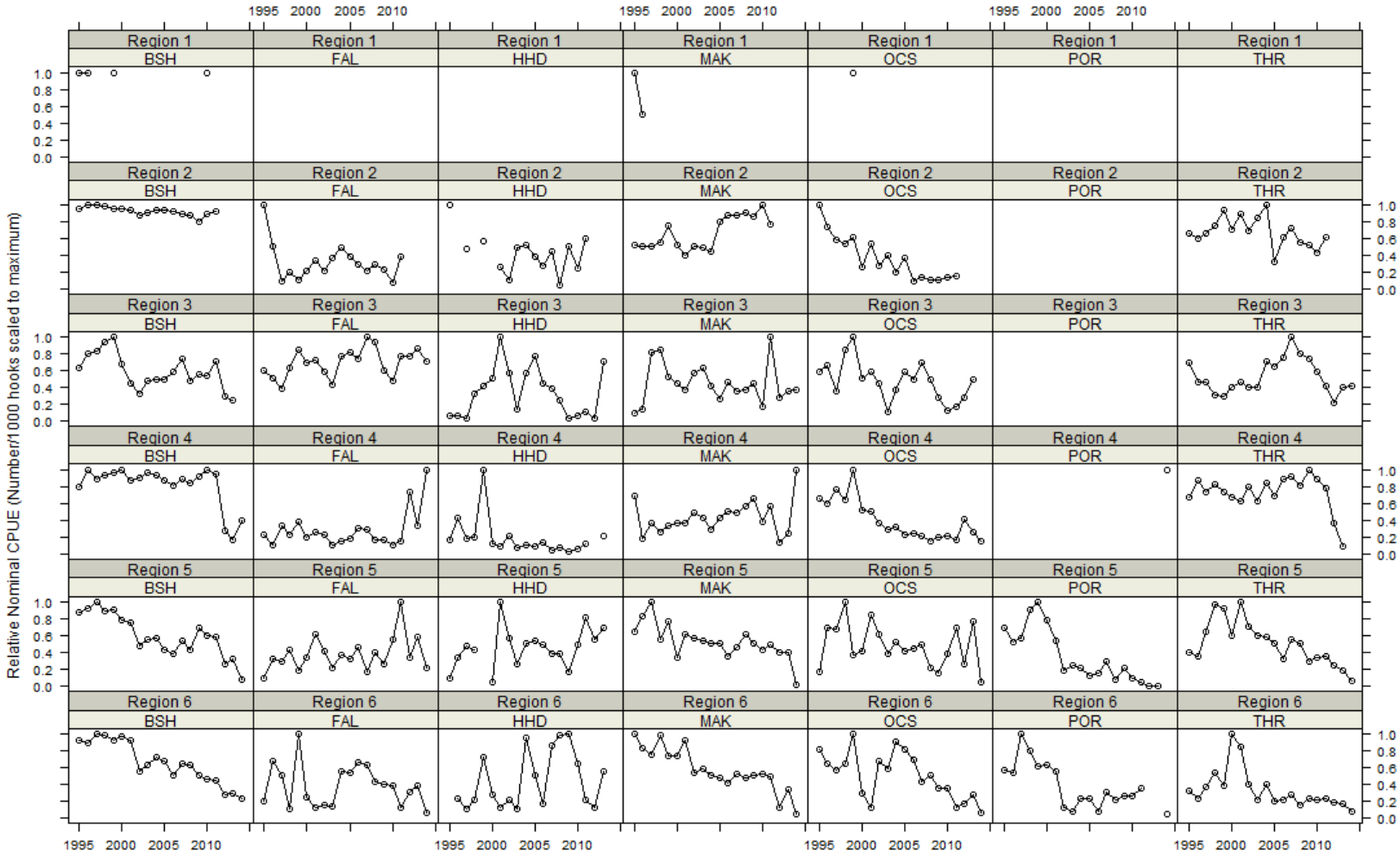


Figure 32: Relative nominal CPUE (numbers/1000 hooks standardised to a maximum value of 1) by species and region for sharks caught by longline.

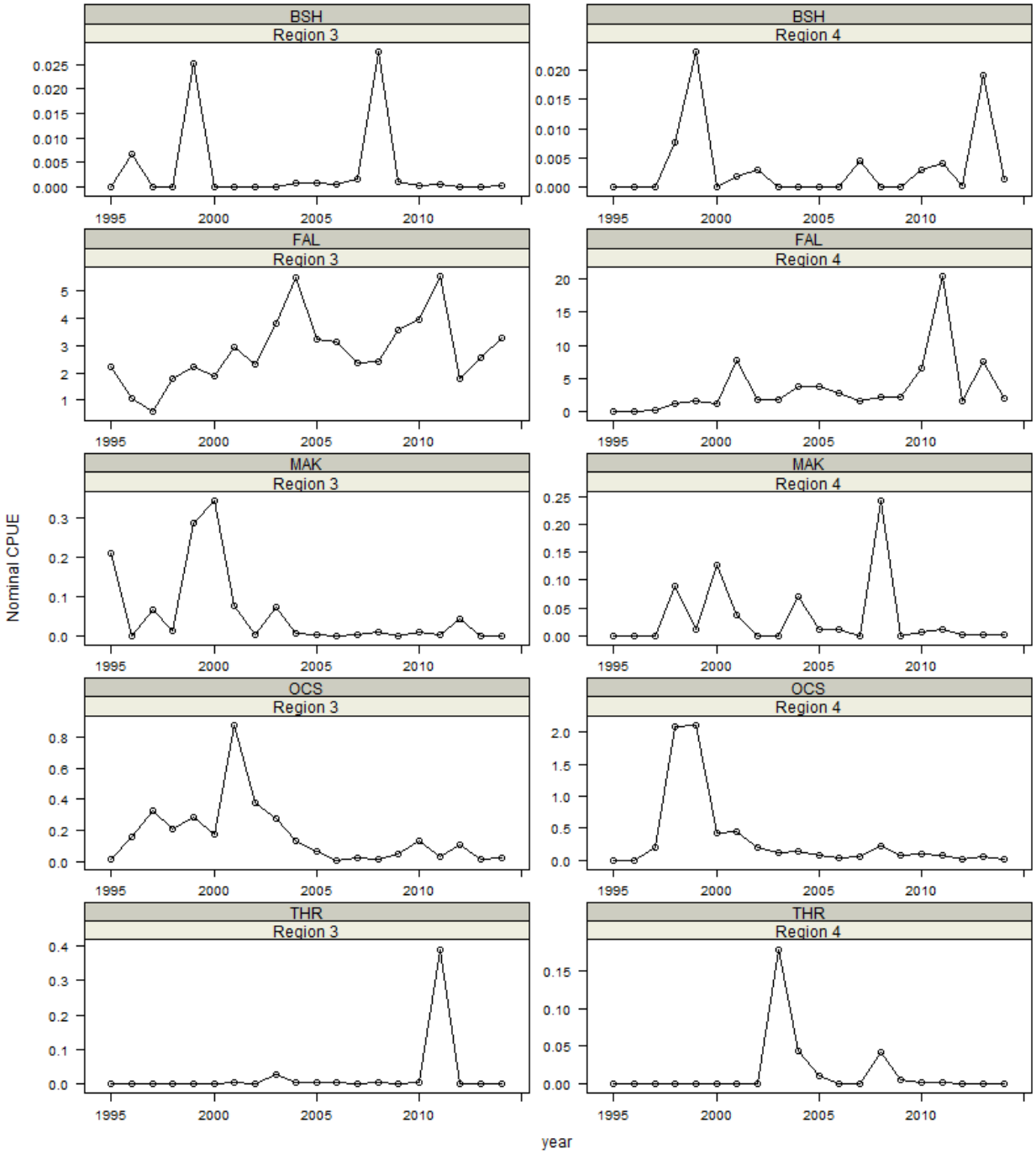


Figure 33: Nominal CPUE (numbers/1000 hooks) by species and region for sharks caught by purse seine (associated sets).

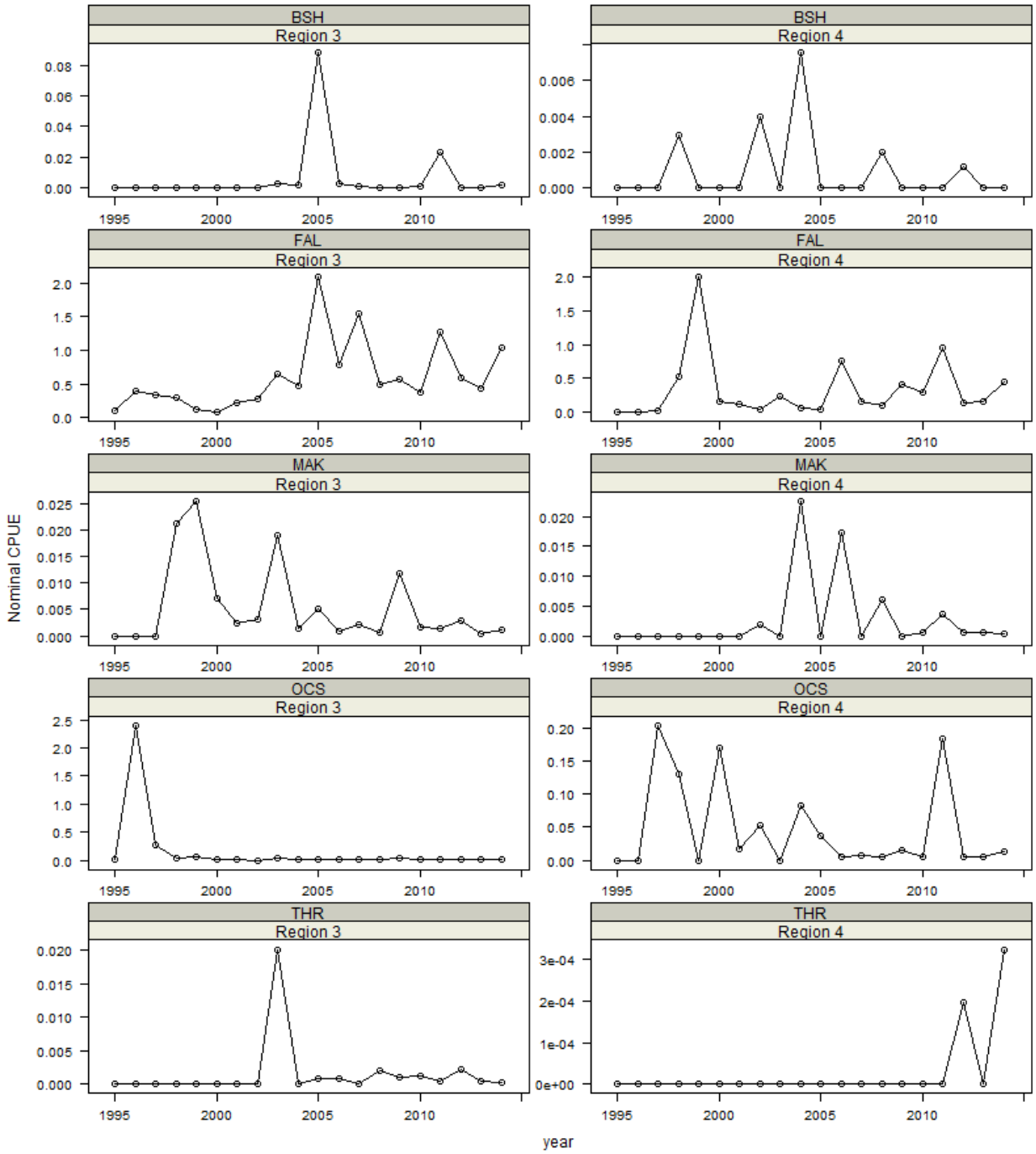


Figure 34: Nominal CPUE (numbers/1000 hooks) by species and region for sharks caught by purse seine (unassociated sets).

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.

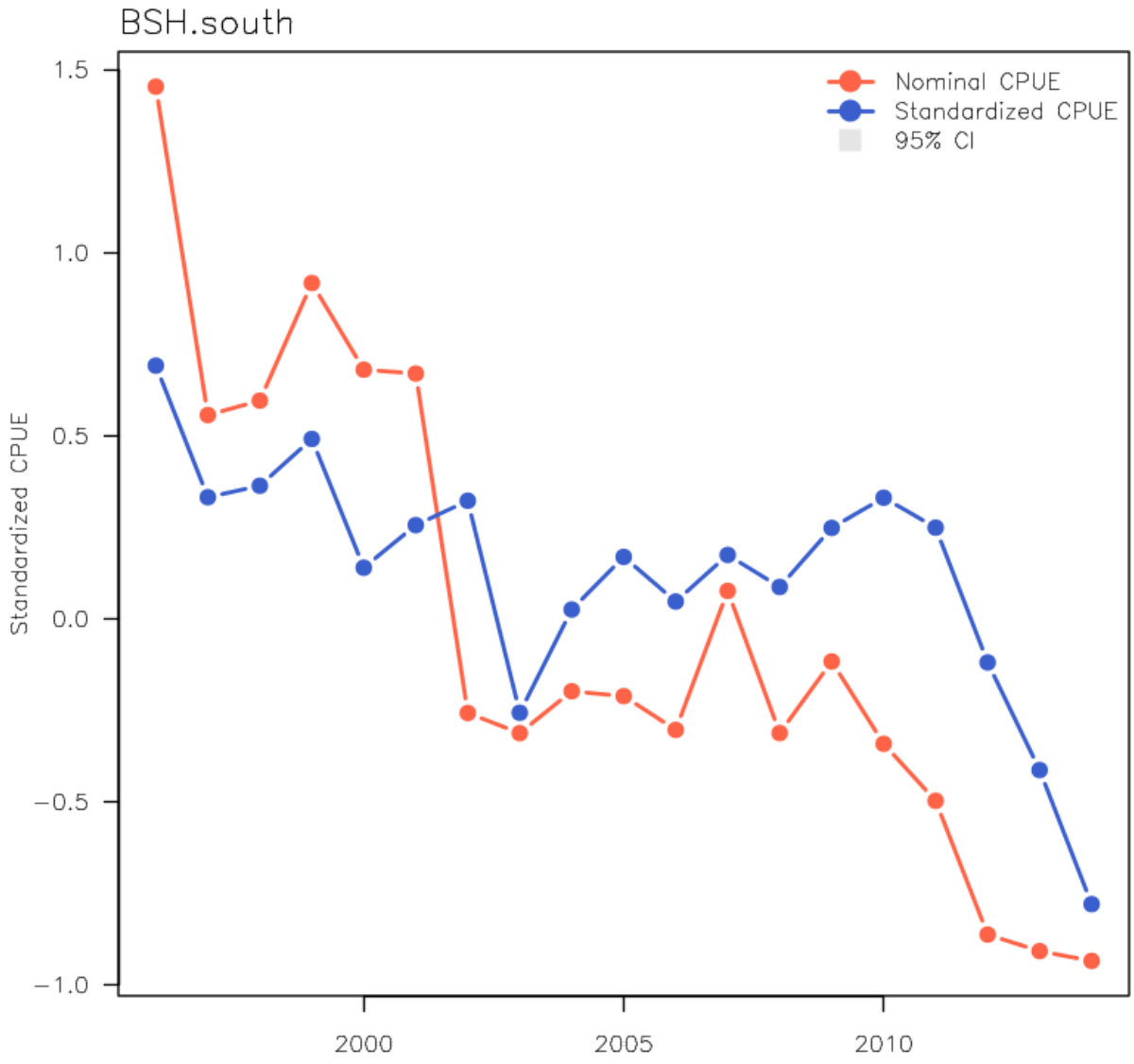


Figure 36: Nominal and standardised CPUE for blue shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

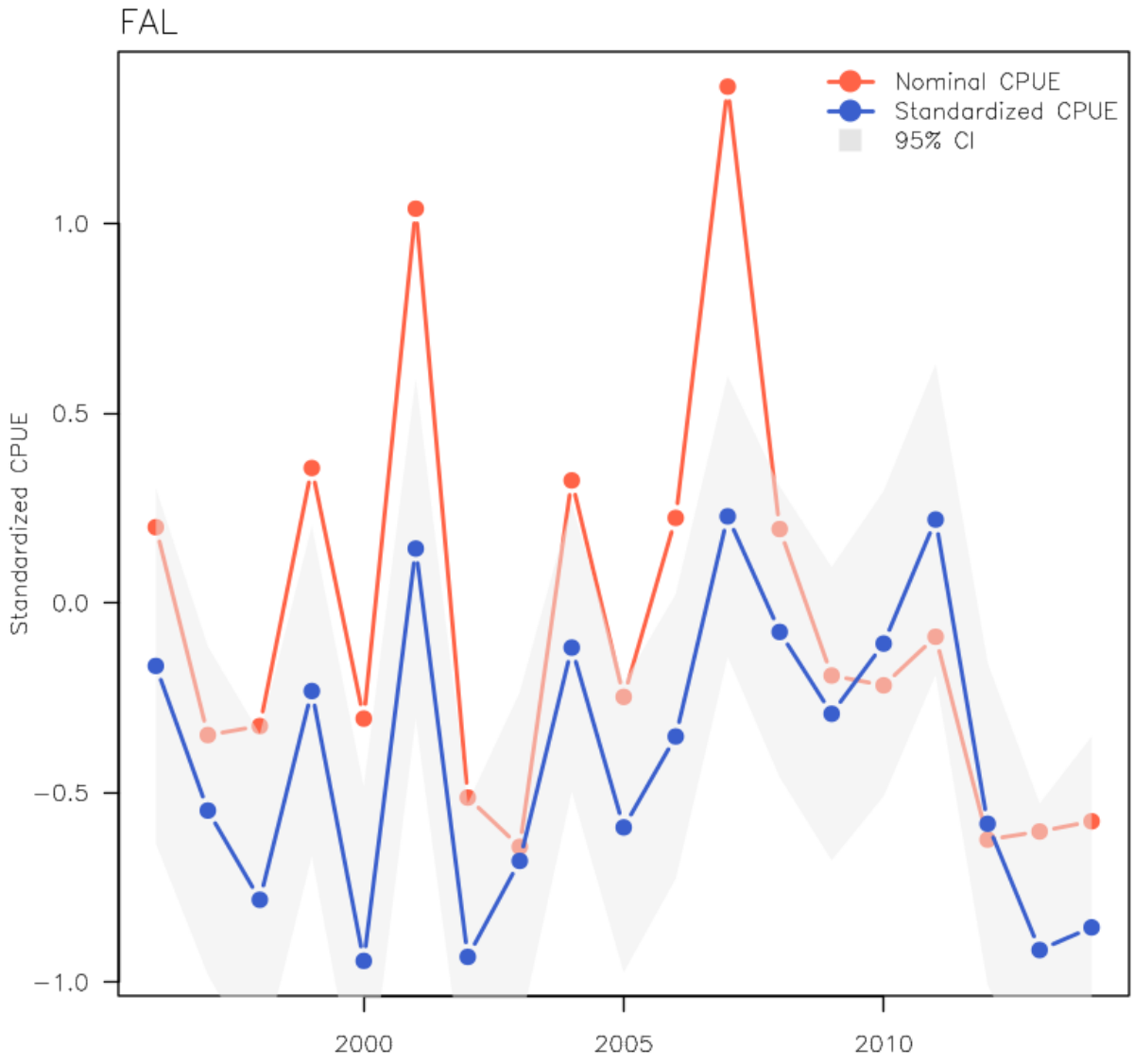


Figure 37: Nominal and standardised CPUE for silky shark. Grey shaded area indicates the limits of the 5% and 95% confidence intervals..

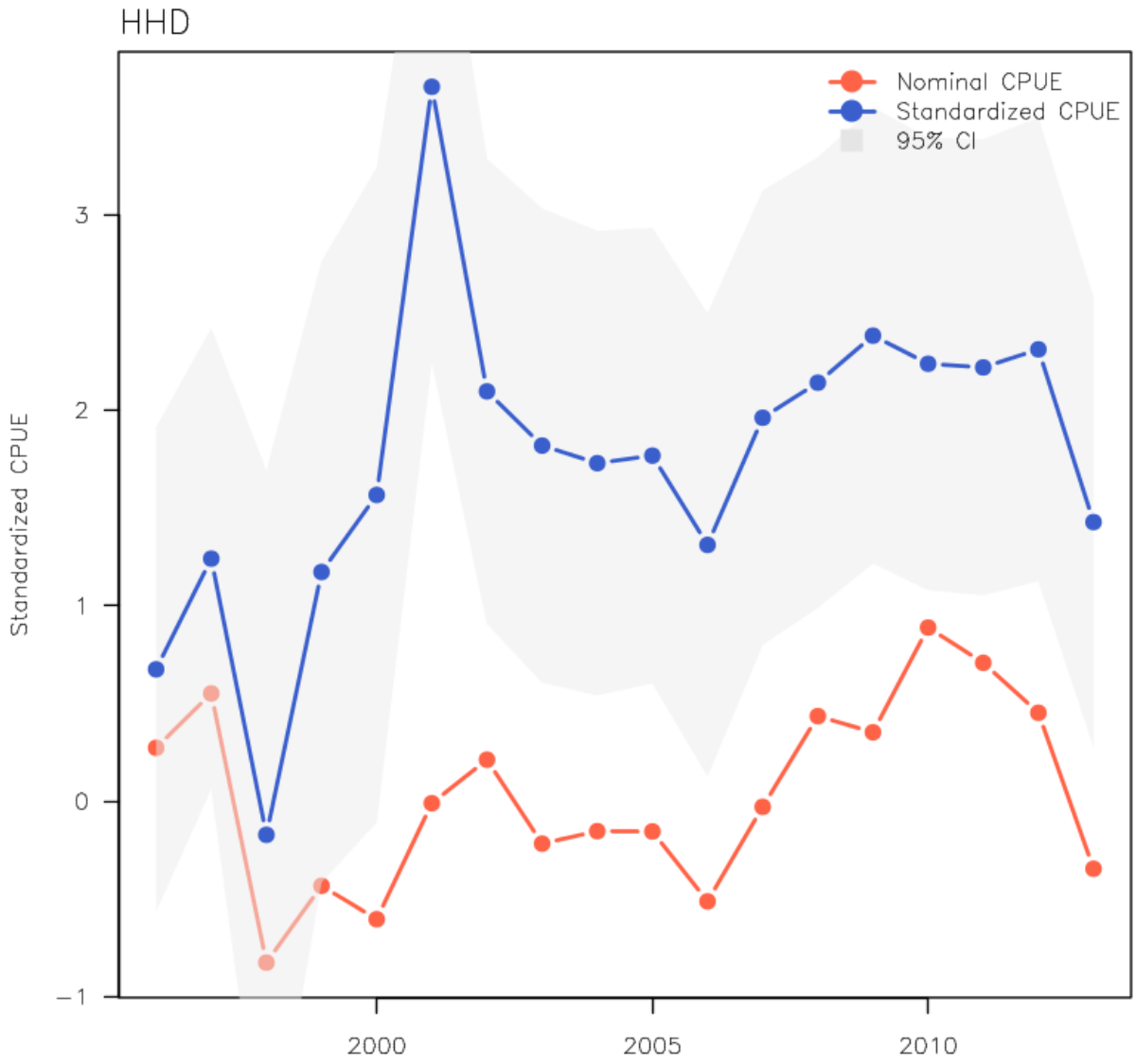


Figure 38: Nominal and standardised CPUE for hammerhead shark. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

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.

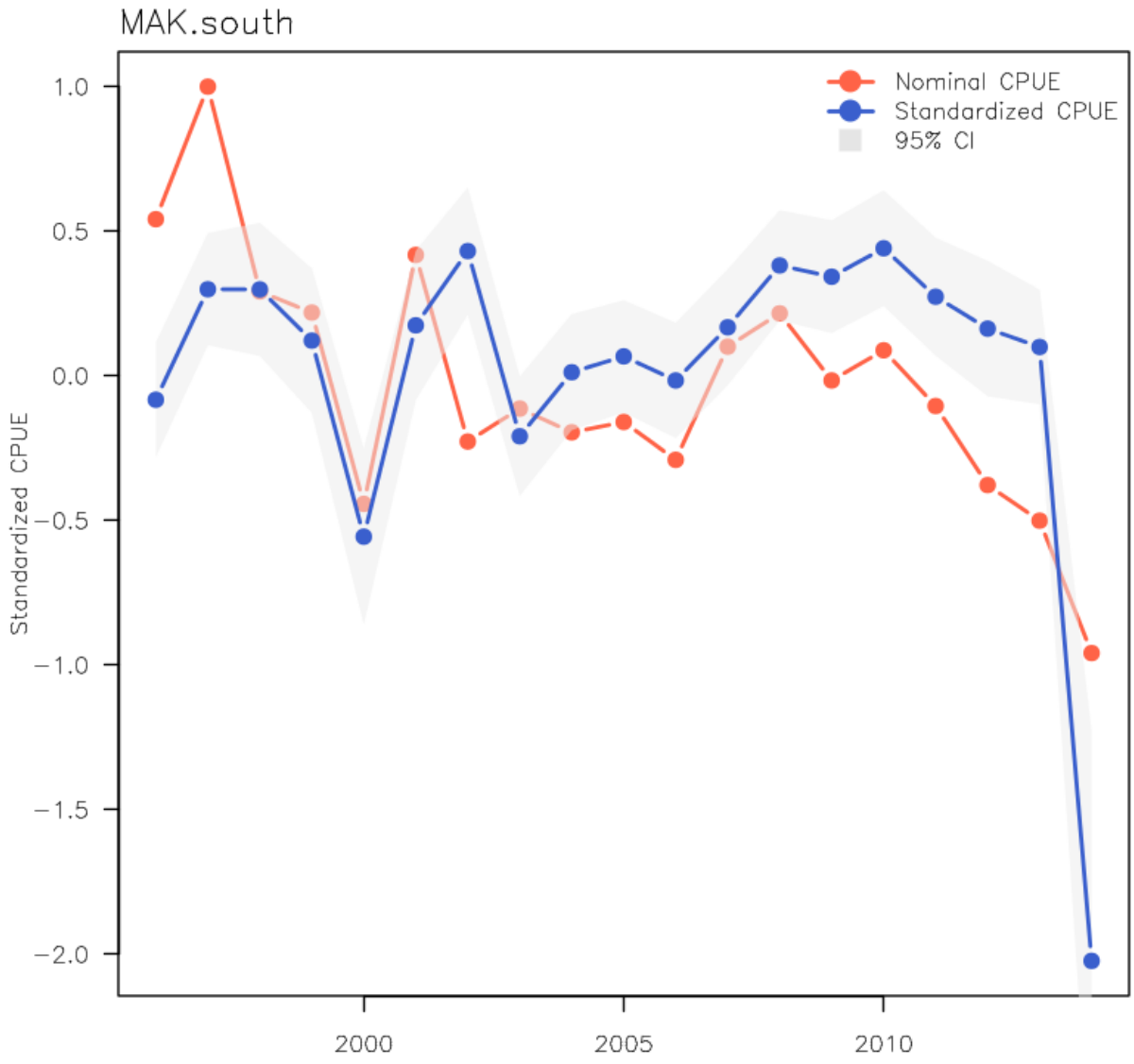


Figure 40: Nominal and standardised CPUE for mako shark in the southern hemisphere. Grey shaded area indicates the limits of the 5% and 95% confidence intervals..

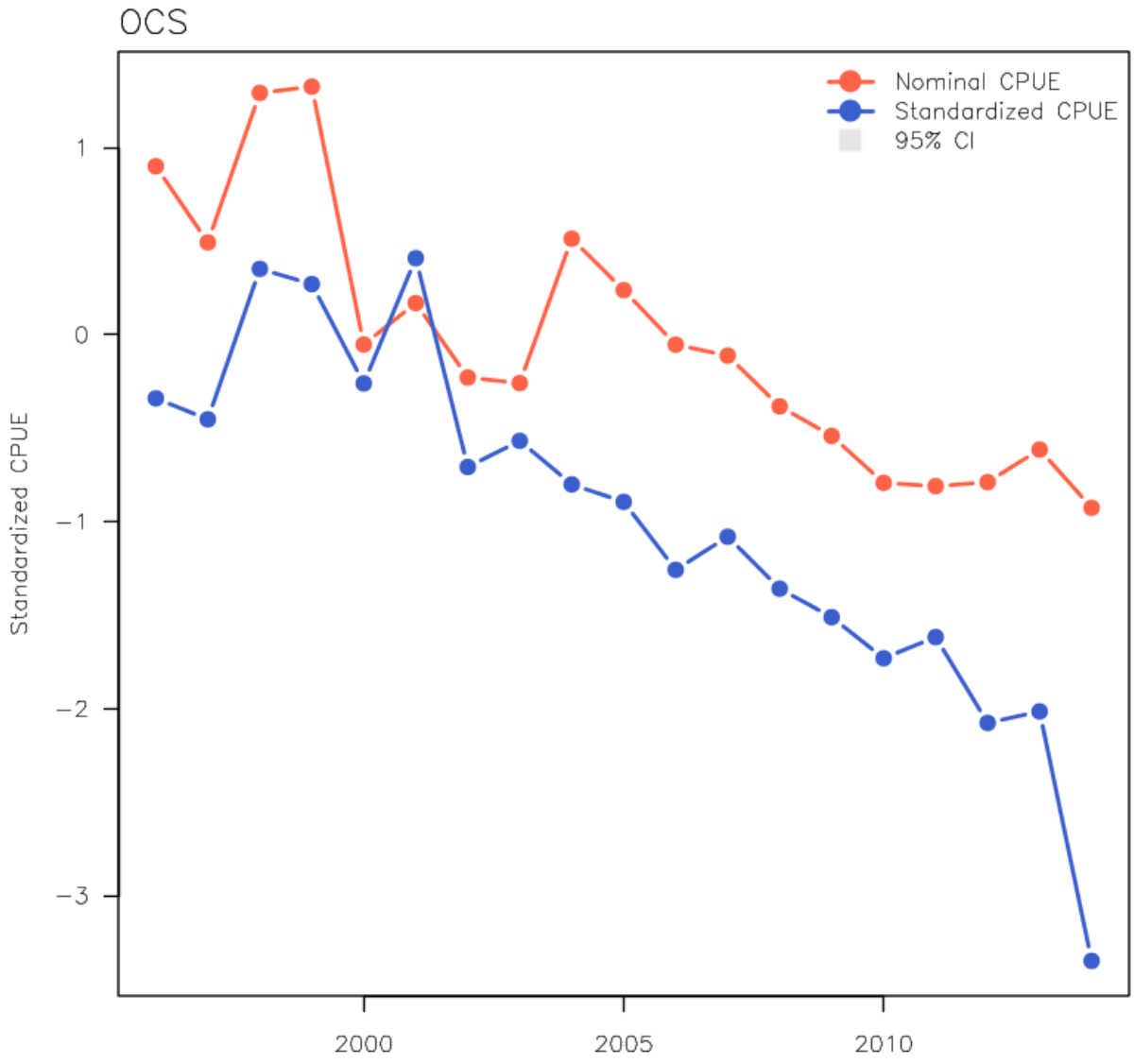


Figure 41: Nominal and standardised CPUE for oceanic whitetip sharks. Grey shaded area indicates the limits of the 5% and 95% confidence intervals..

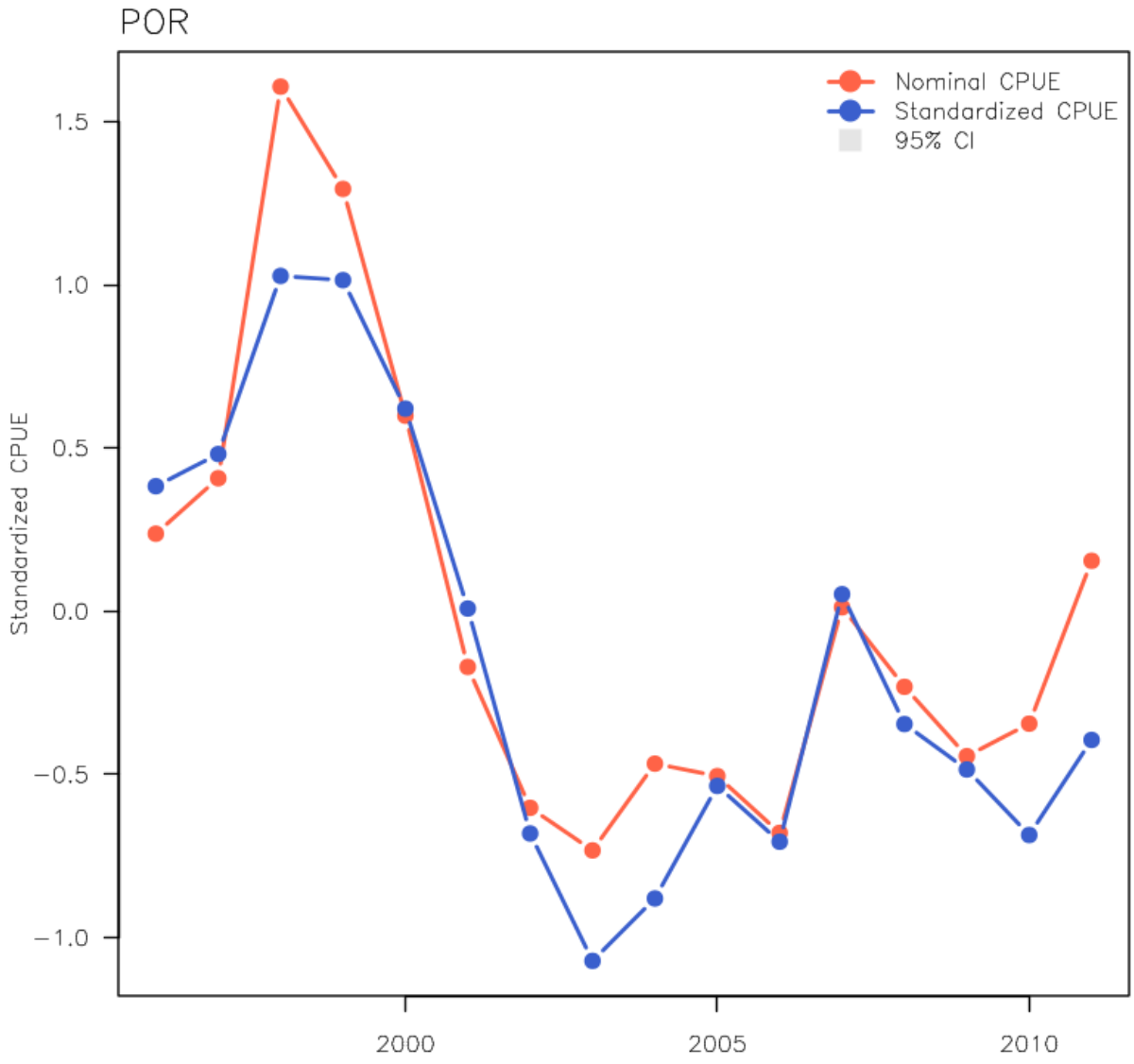


Figure 42: Nominal and standardised CPUE for porbeagle shark. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

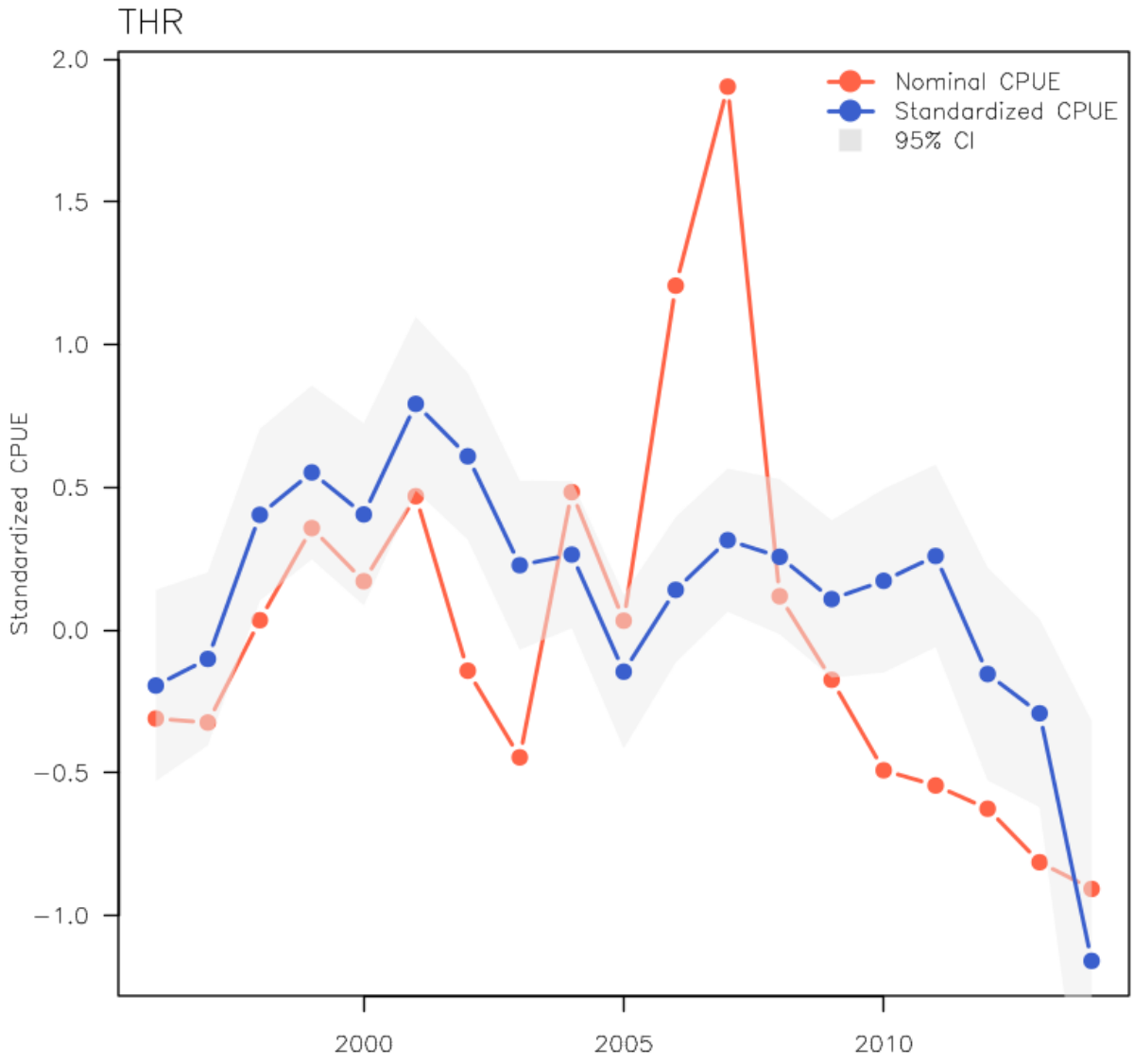


Figure 43: Nominal and standardised CPUE for thresher shark. Grey shaded area indicates the limits of the 5% and 95% confidence intervals.

B.4 Biological Indicators

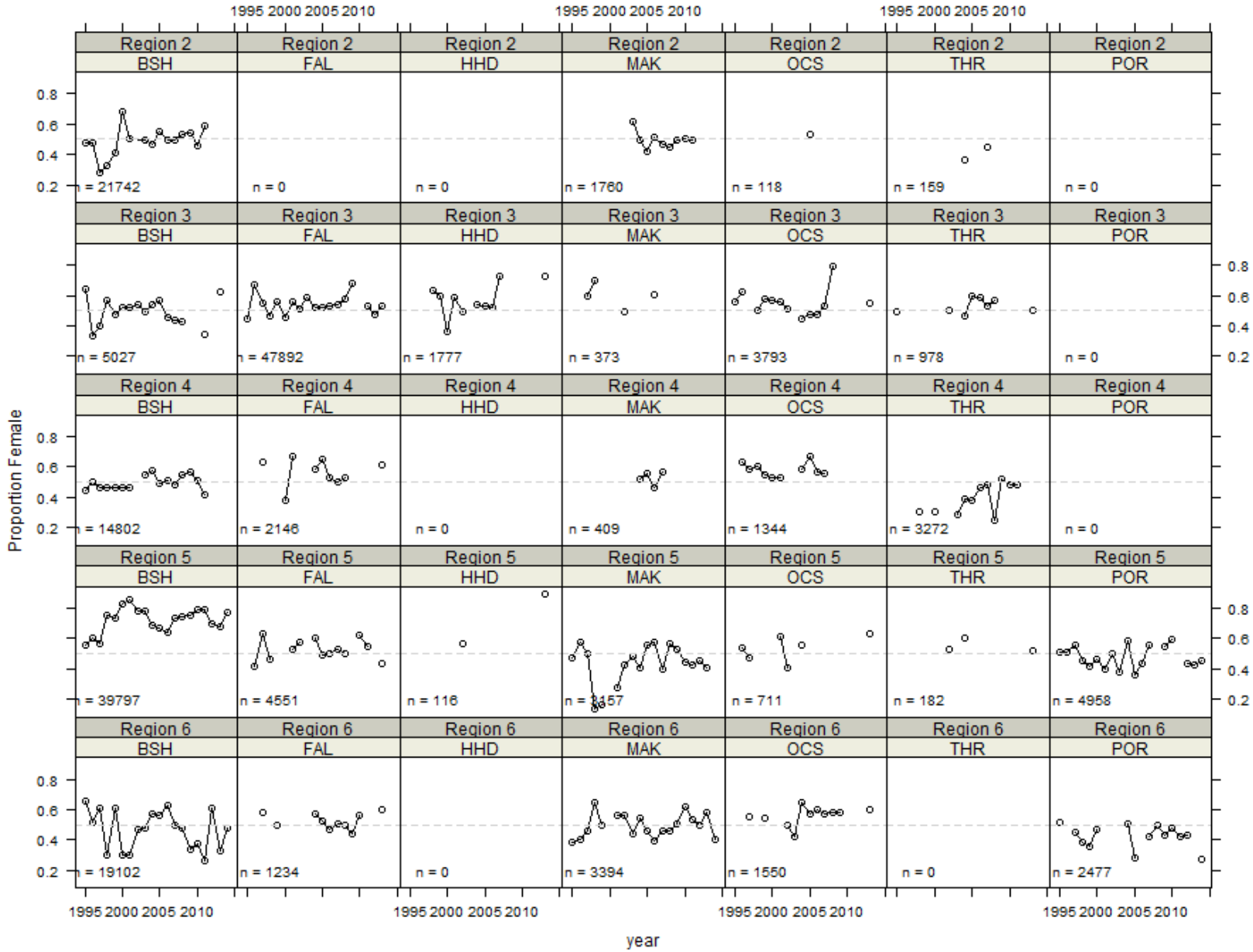


Figure 44: Sex ratio (proportion female) of shark species caught by longline gear in the WCPO. The number of samples available for each sex and region is also shown.

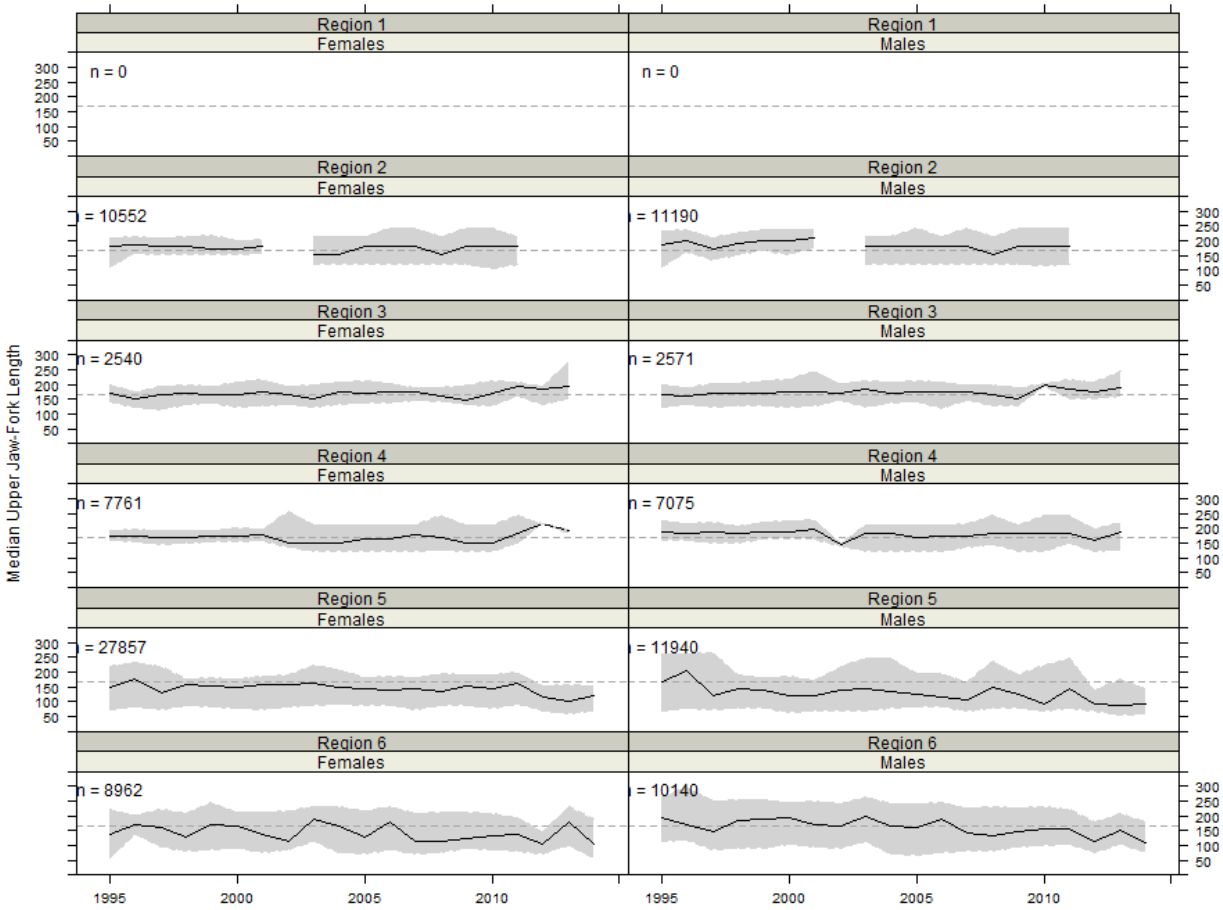


Figure 45: Blue shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

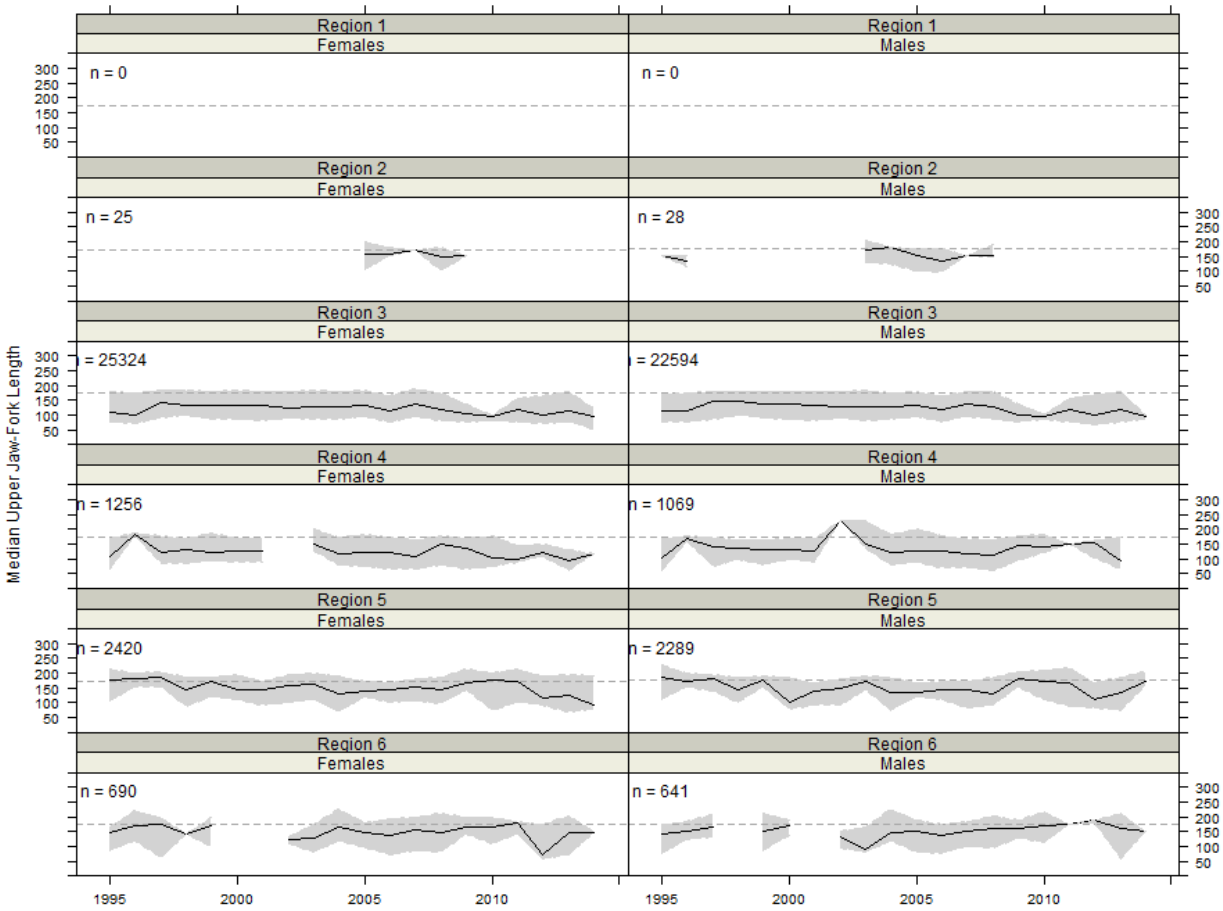


Figure 46: Silky shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

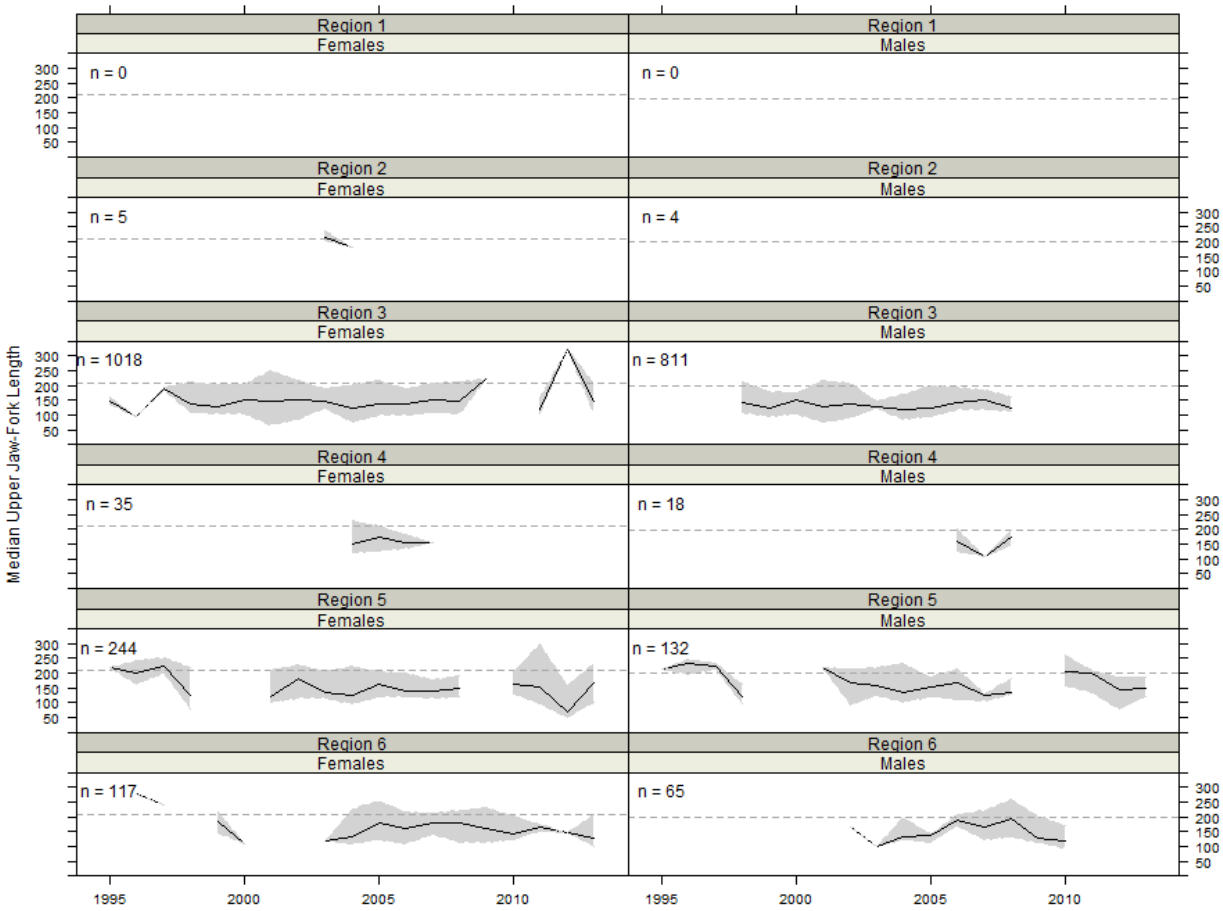


Figure 47: Hammerhead shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

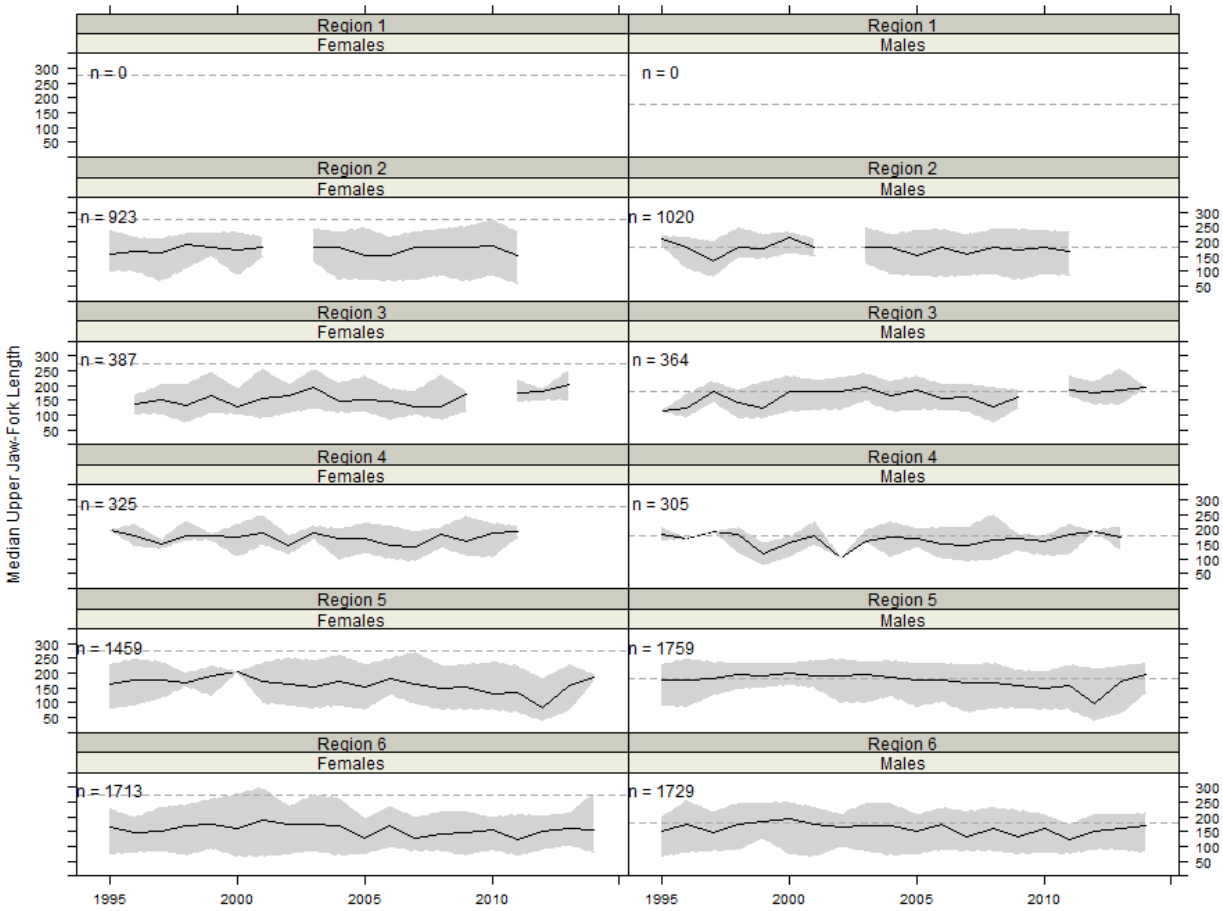


Figure 48: Mako shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

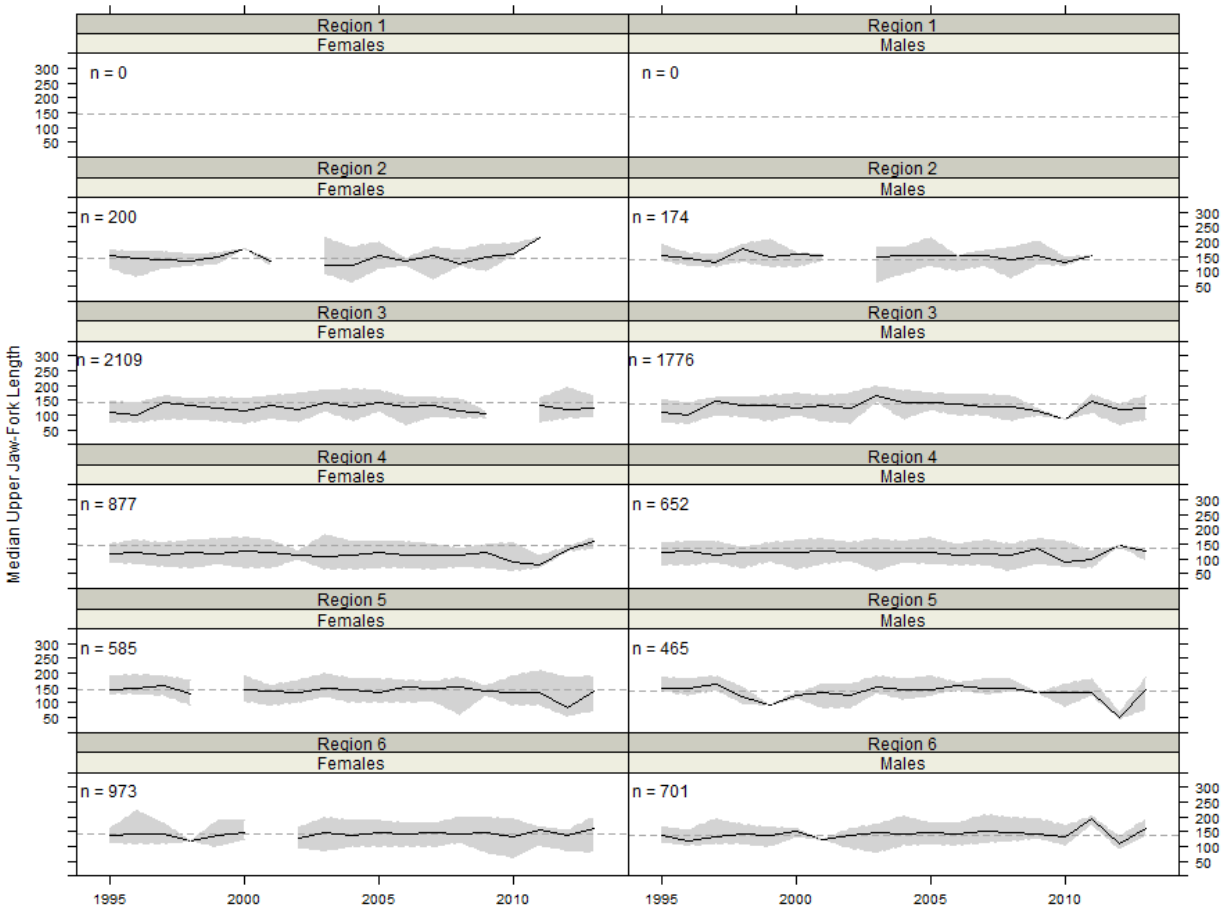


Figure 49: Oceanic Whitetip shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

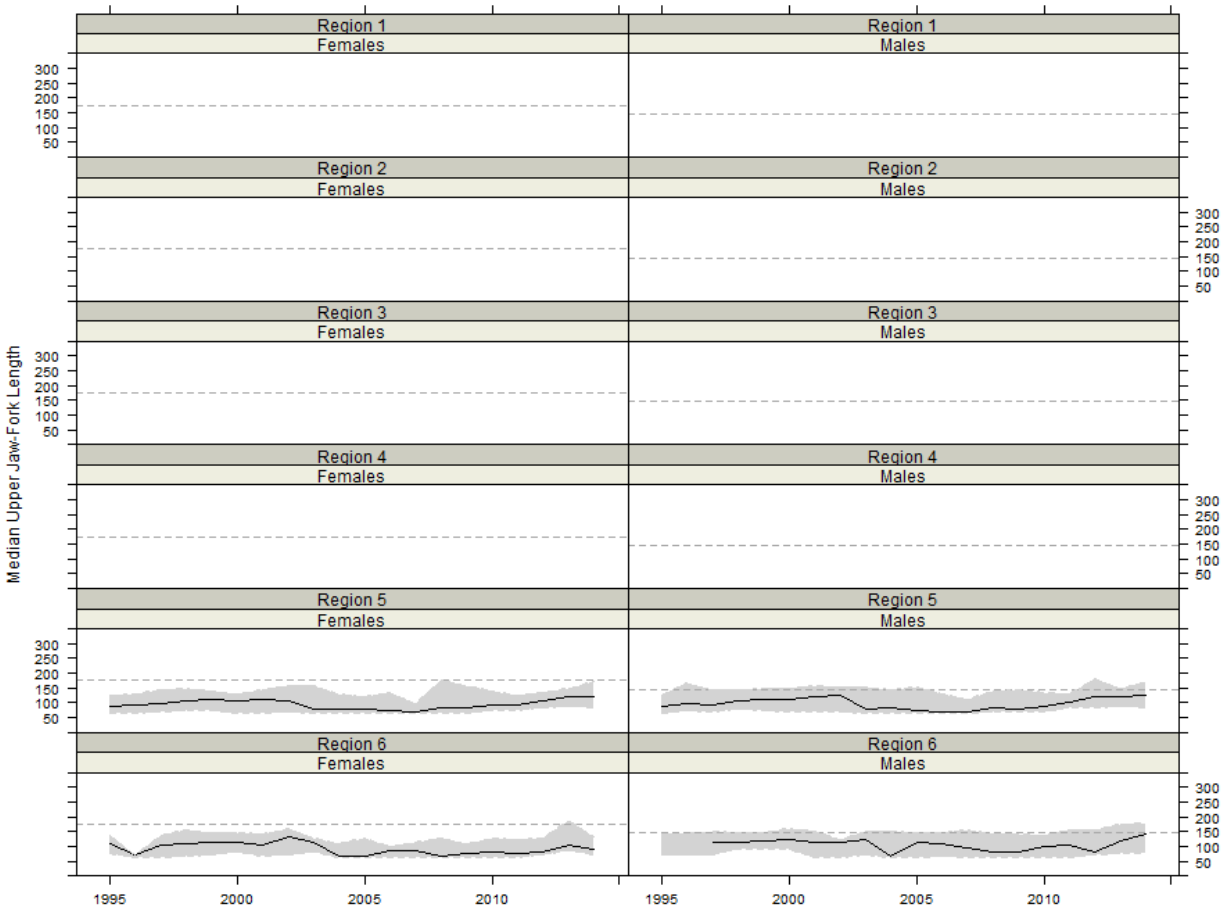


Figure 50: Porbeagle shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

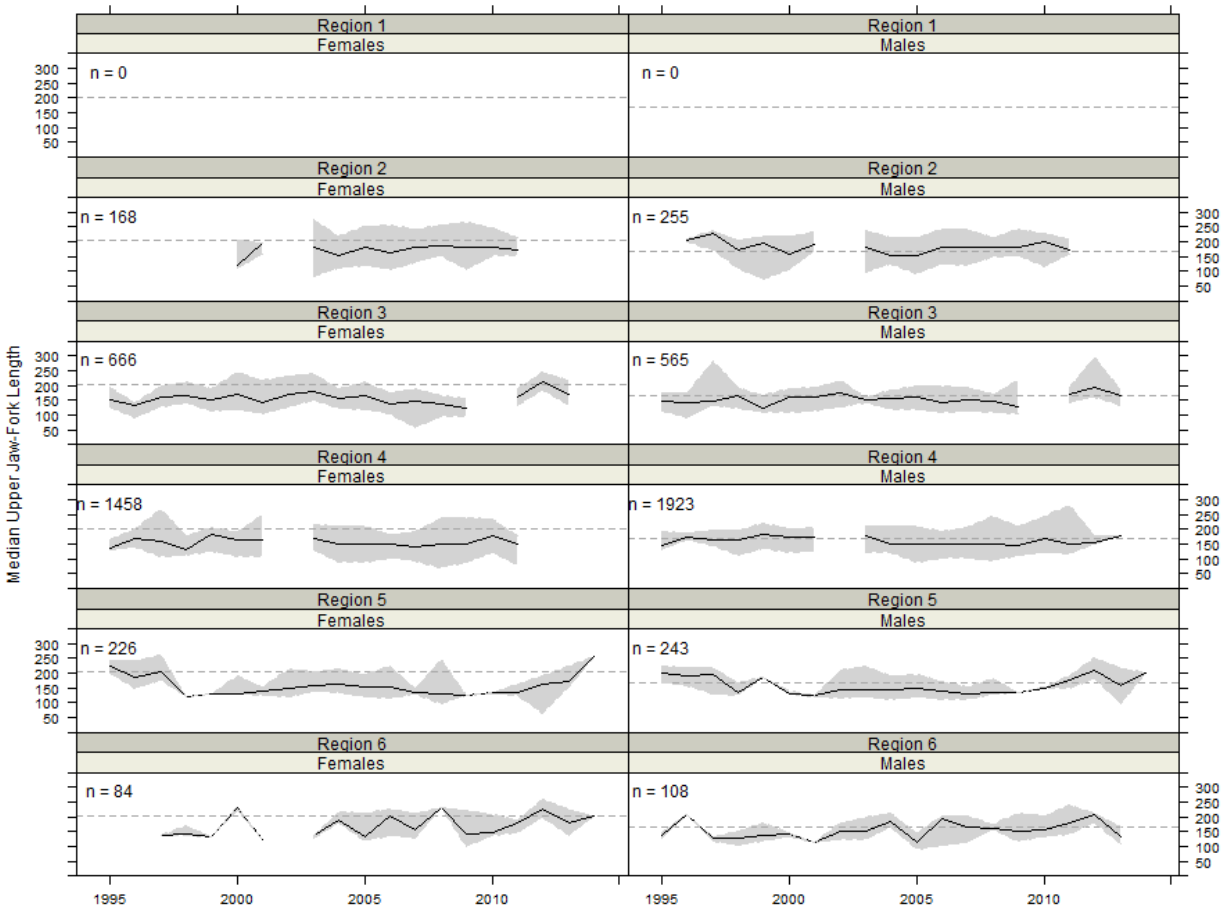


Figure 51: Thresher shark: median upper jaw fork length by year and region for males and females. Solid line shows median values, greyed area shows the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

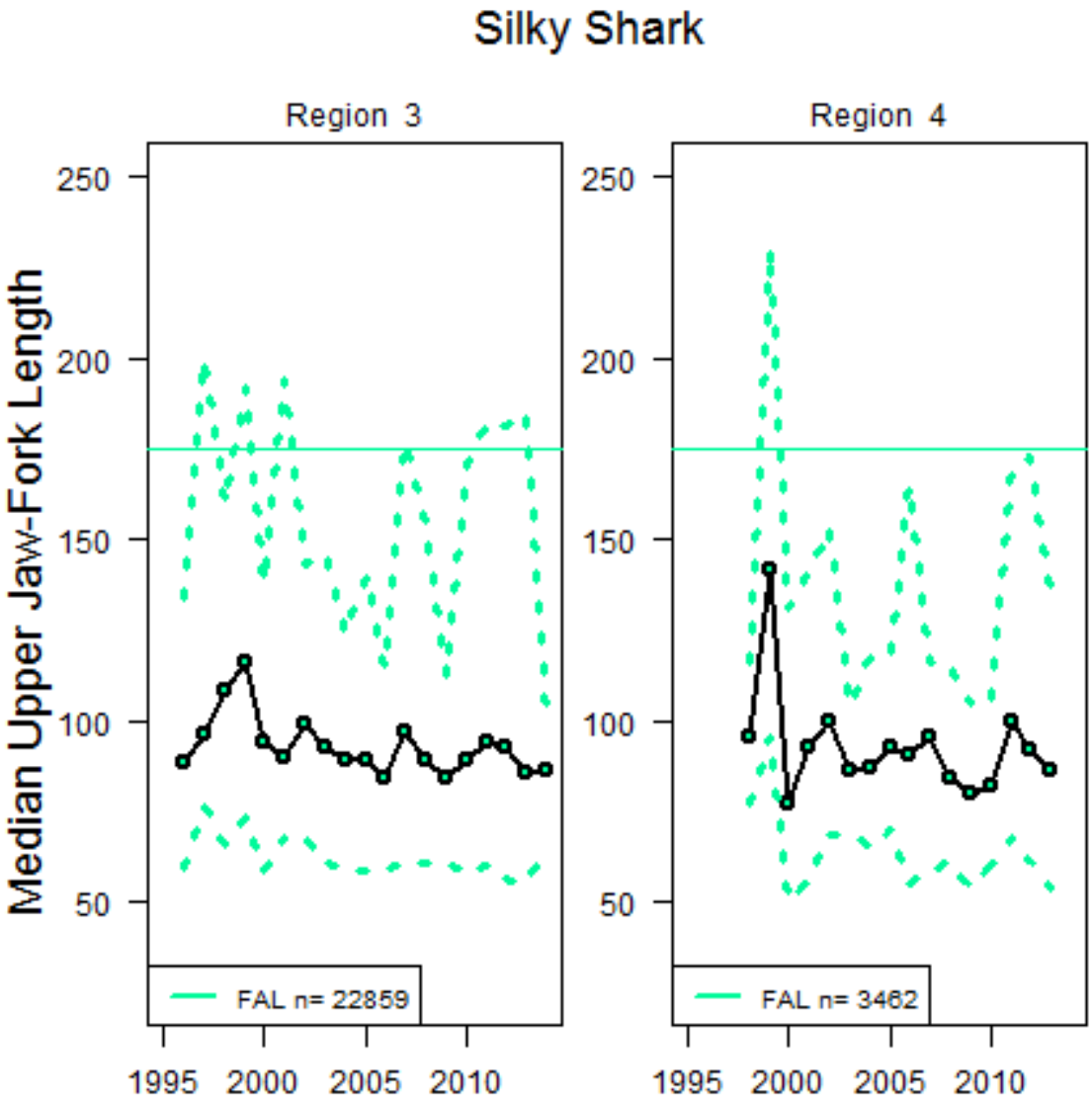


Figure 52: Silky shark: median upper jaw fork length by year and region for both sexes combined, observed in the purse seine fishery. Solid black line shows median values, dashed lines show the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

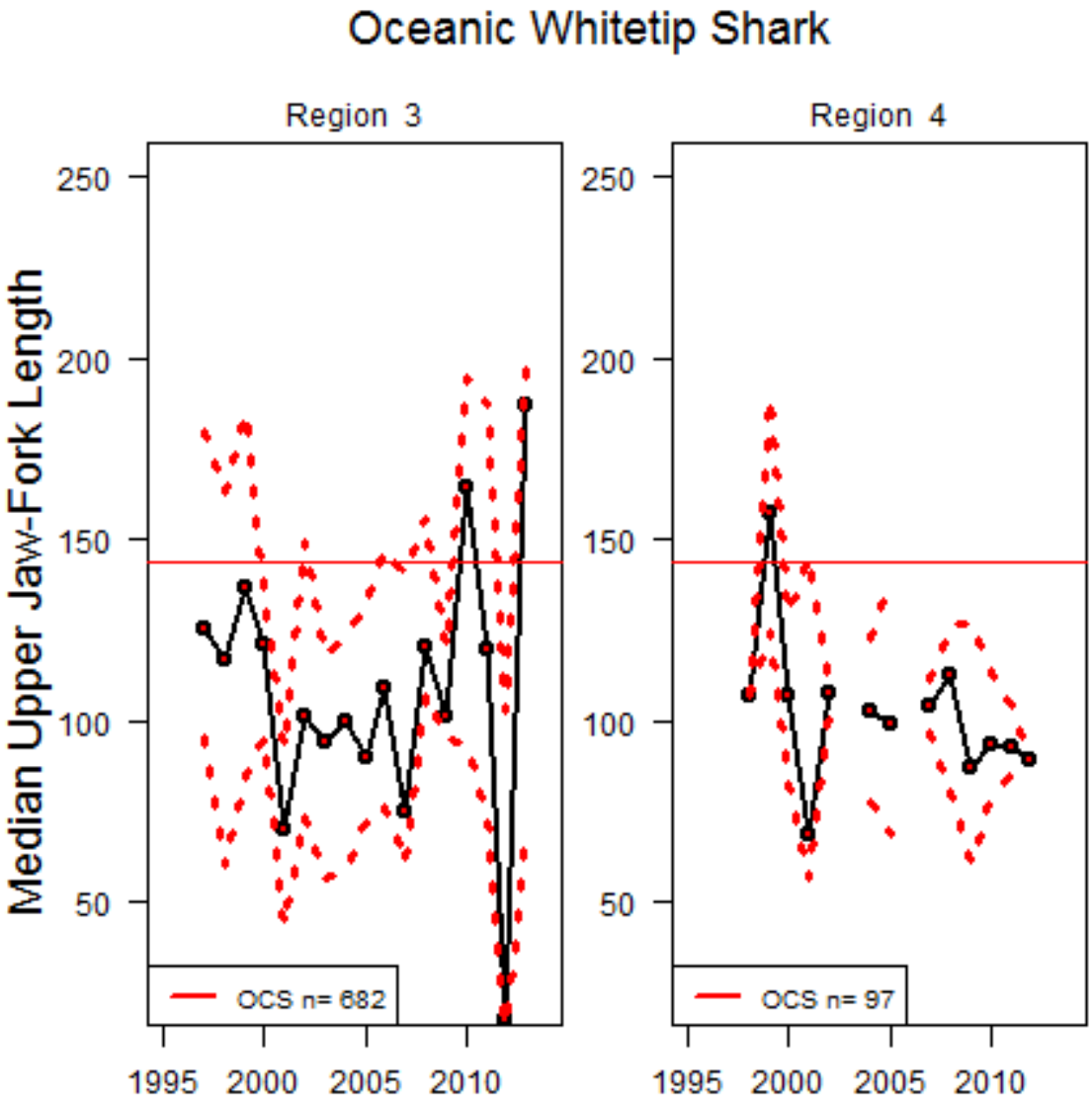


Figure 53: Oceanic whitetip shark: median upper jaw fork length by year and region for both sexes combined, observed in the purse seine fishery. Solid black line shows median values, dashed lines show the limits of the 5th and 95th percentiles. The number of samples available for each sex and region is also shown.

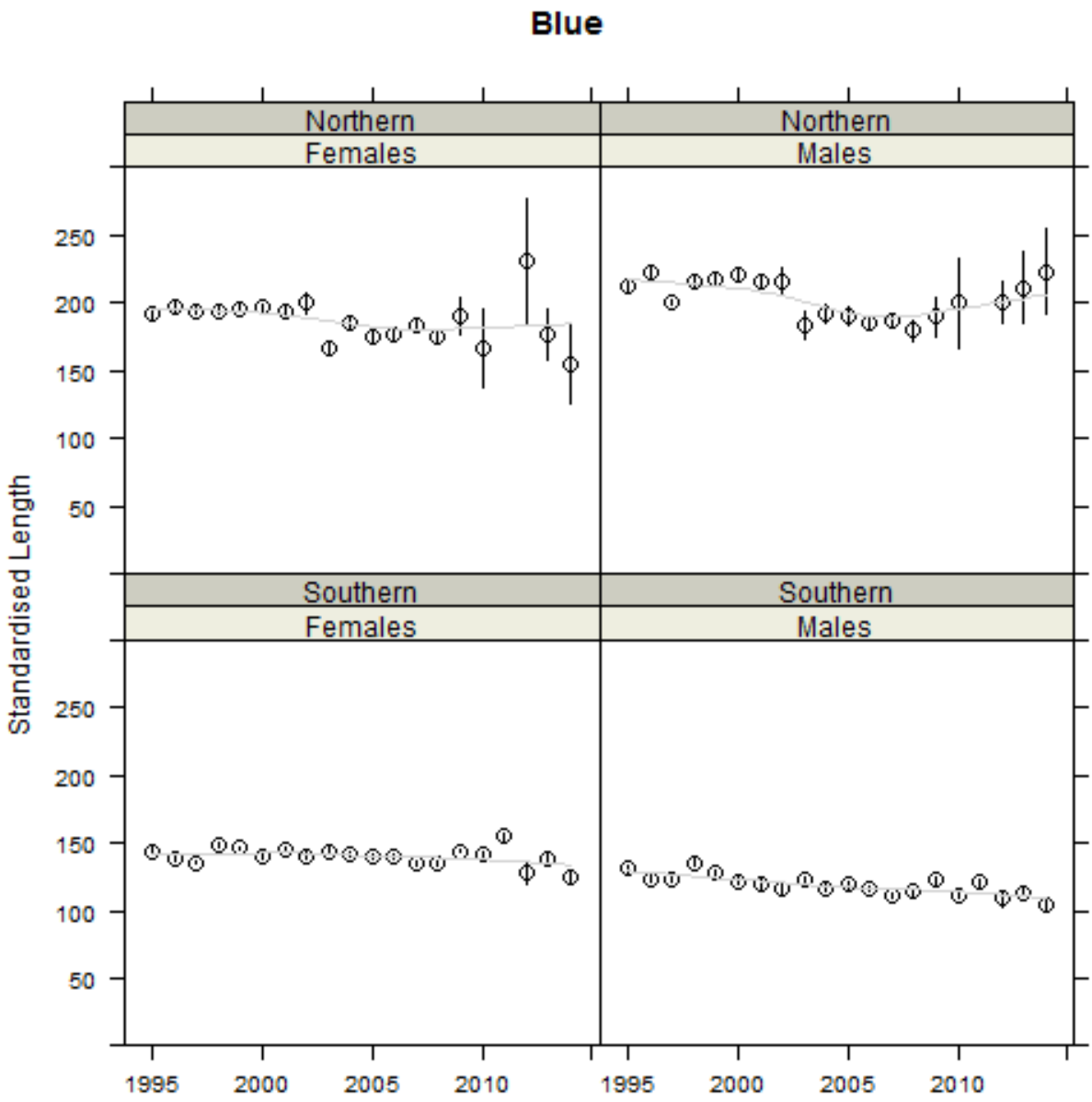


Figure 54: Blue shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

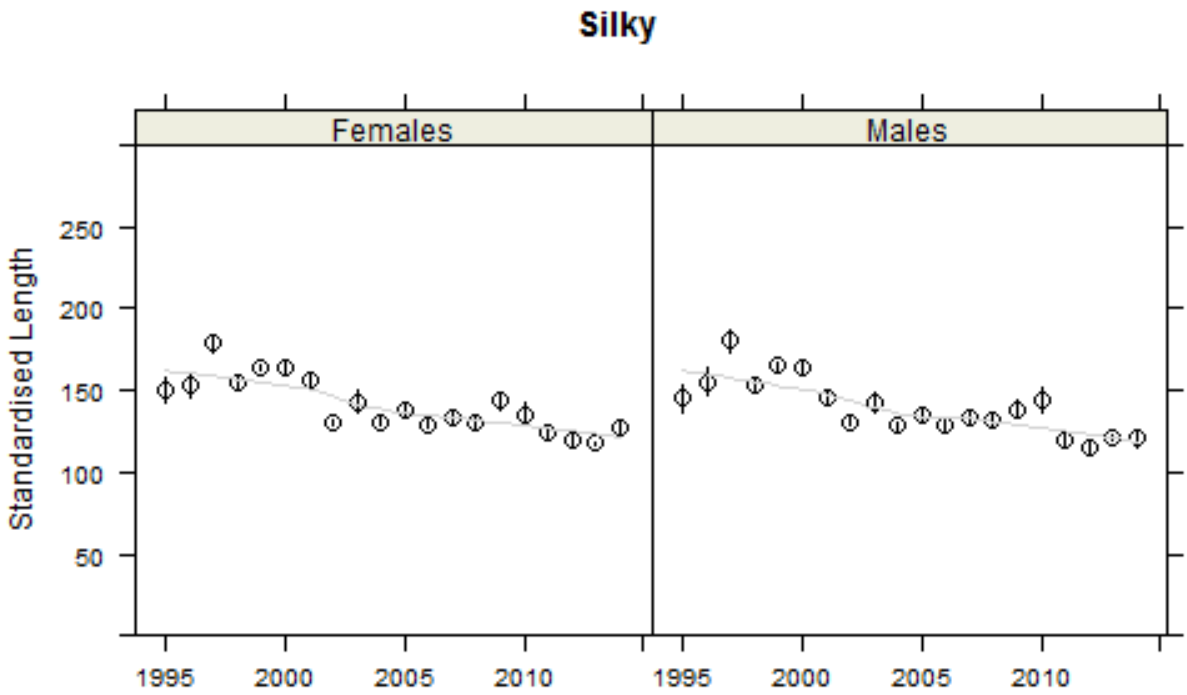


Figure 55: Silky shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

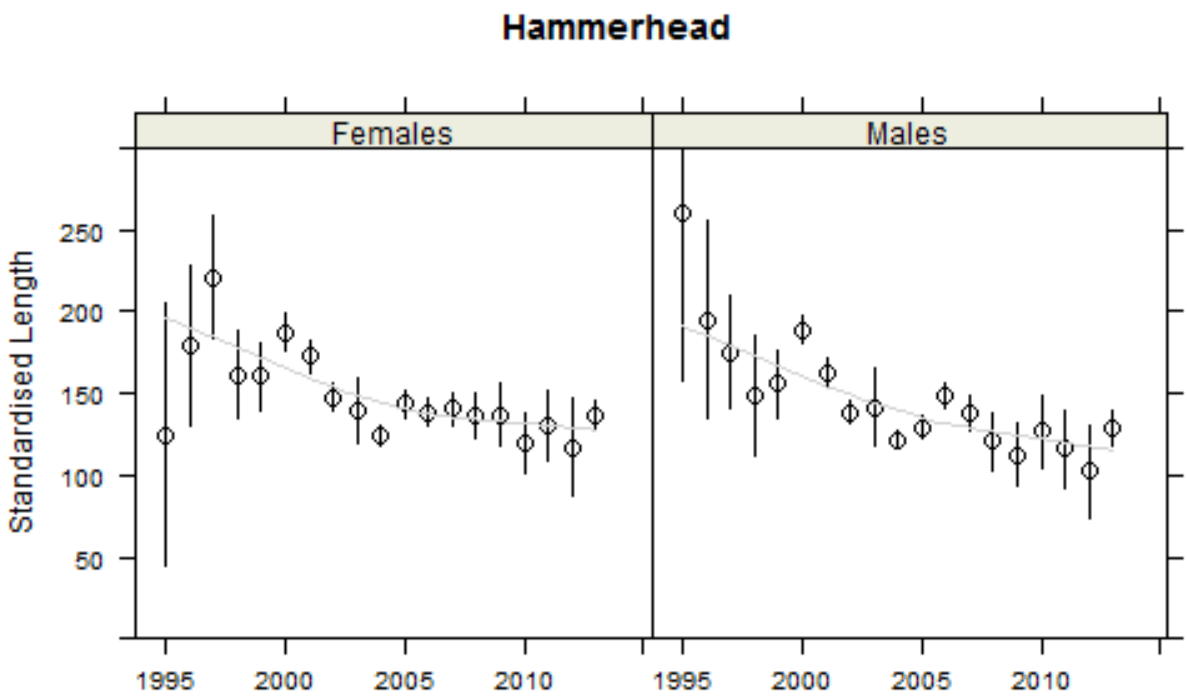


Figure 56: Hammerhead shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

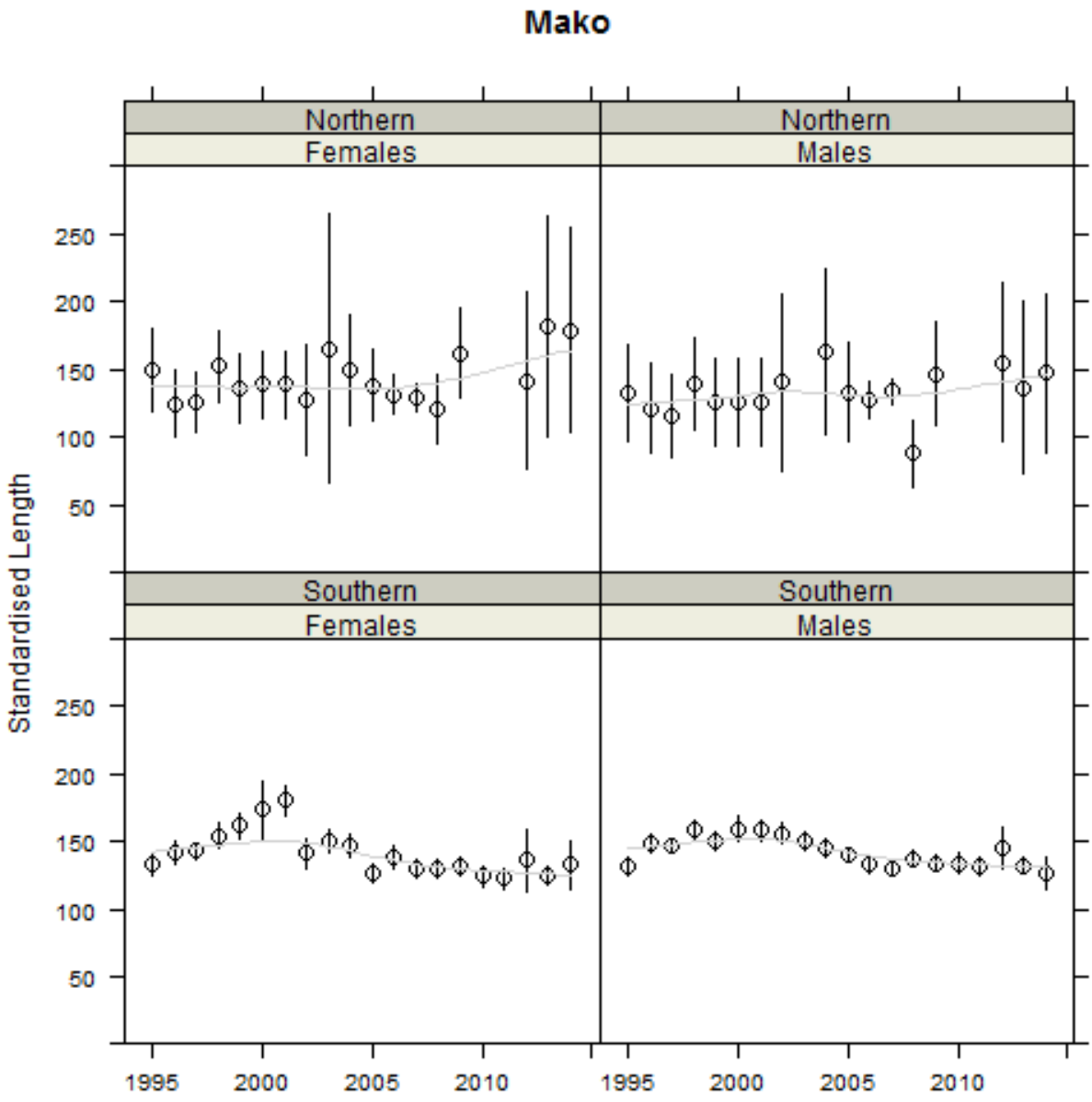


Figure 57: Mako shark: standardised length for male and females. Light grey line shows a lowess smoother.

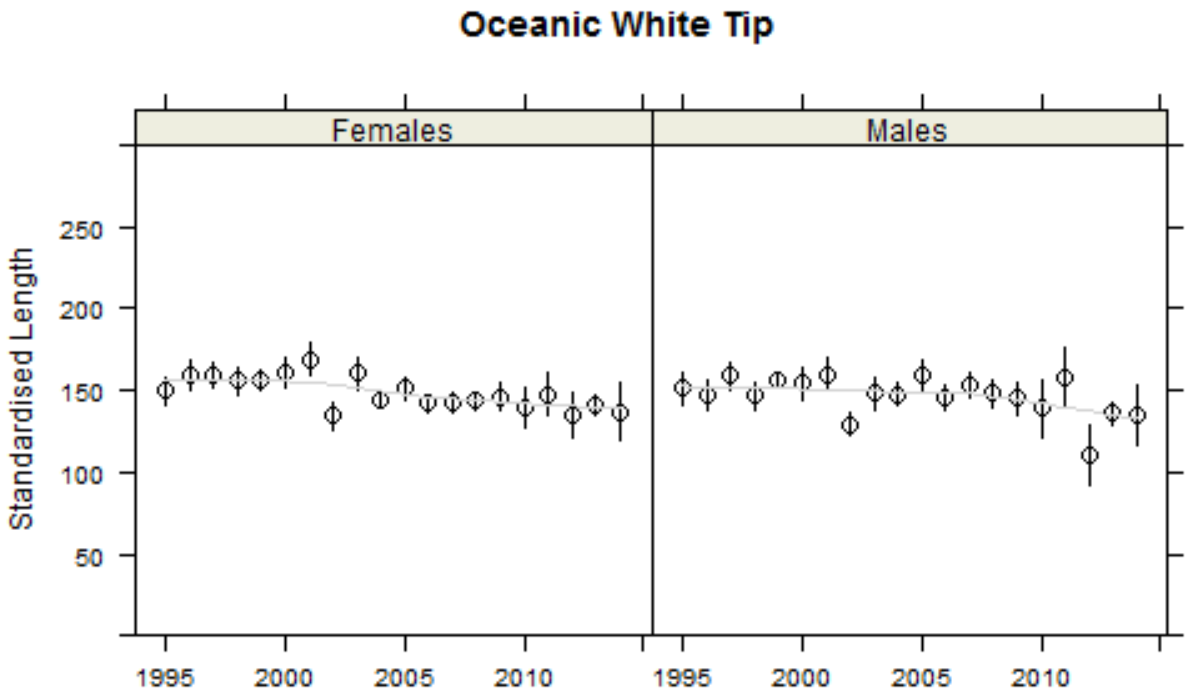


Figure 58: Oceanic Whitetip shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

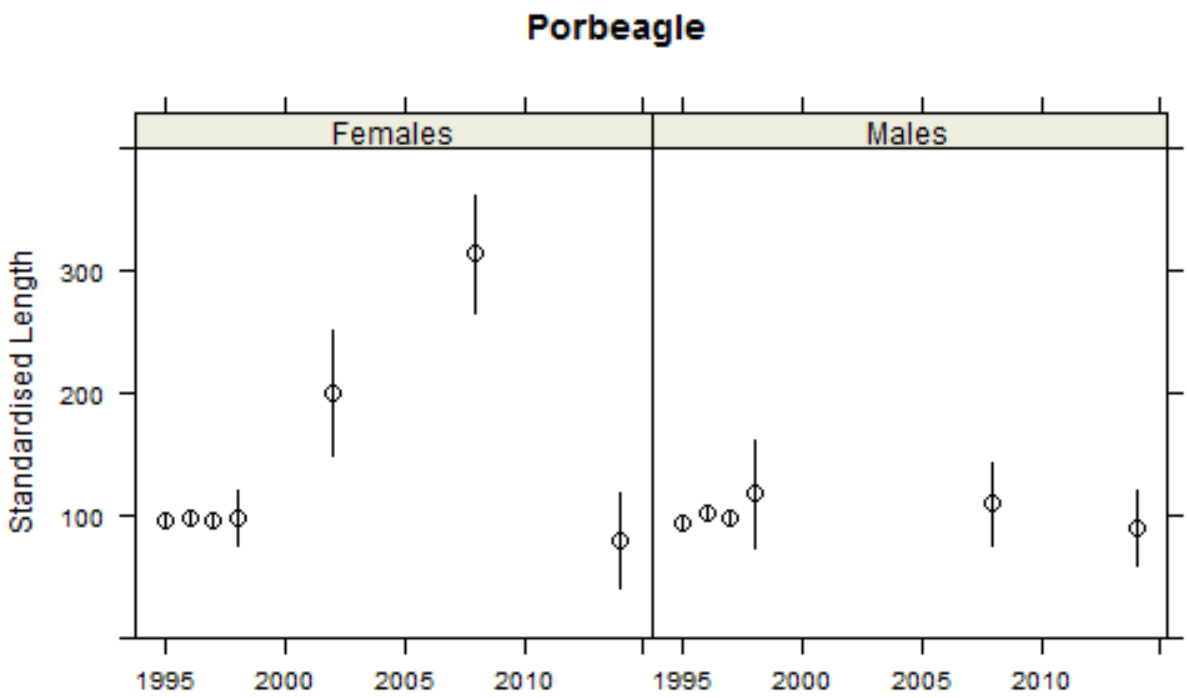


Figure 59: Porbeagle shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

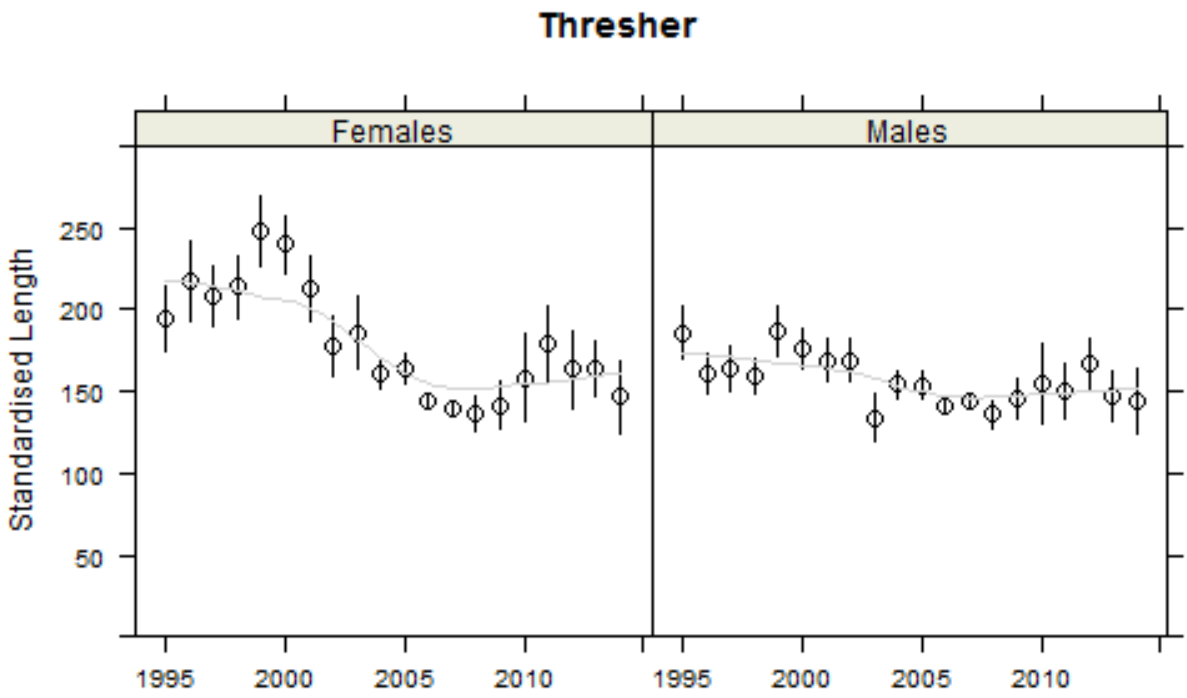


Figure 60: Thresher shark: standardised length for male and females for longline data. Light grey line shows a lowess smoother.

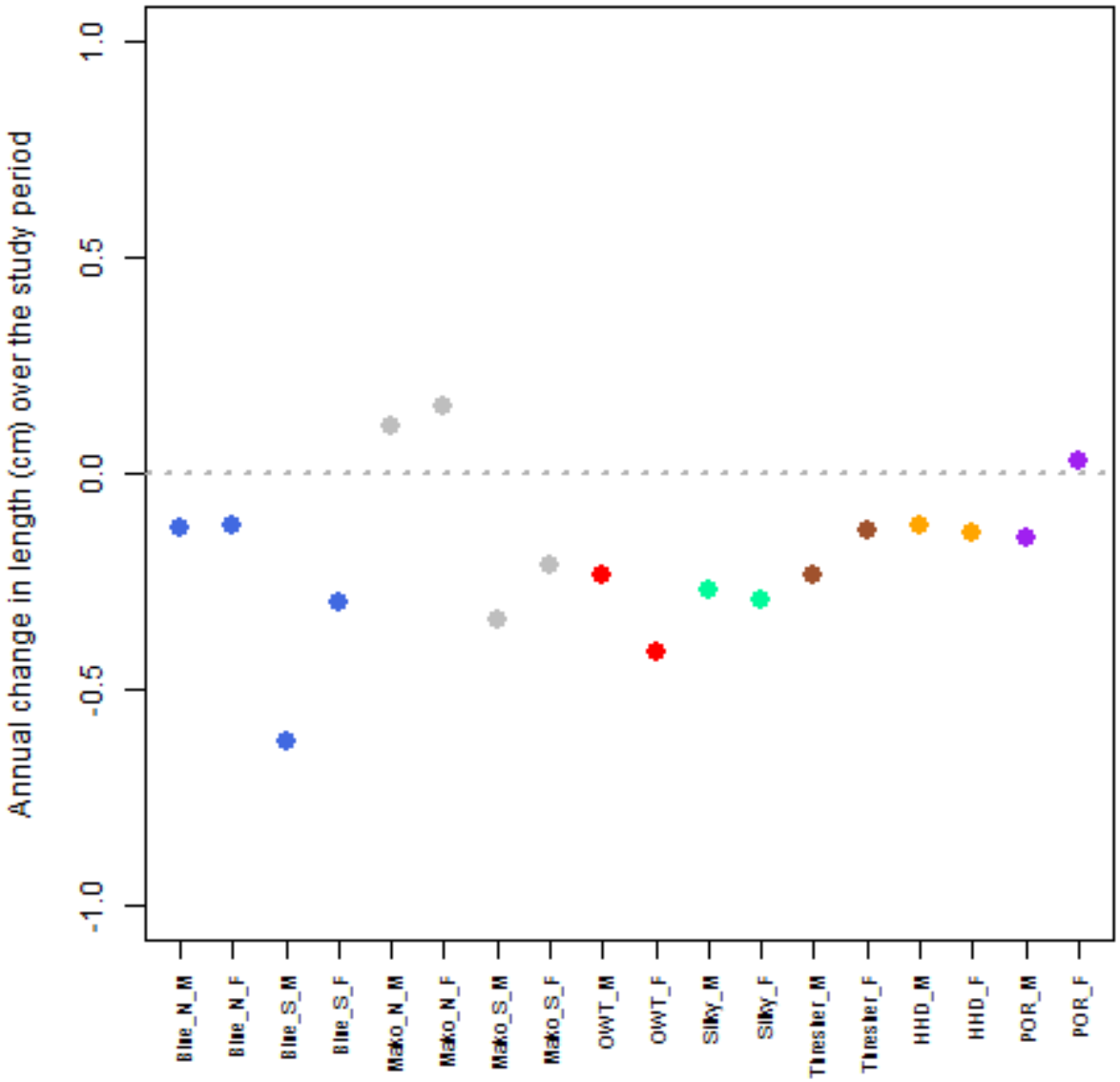
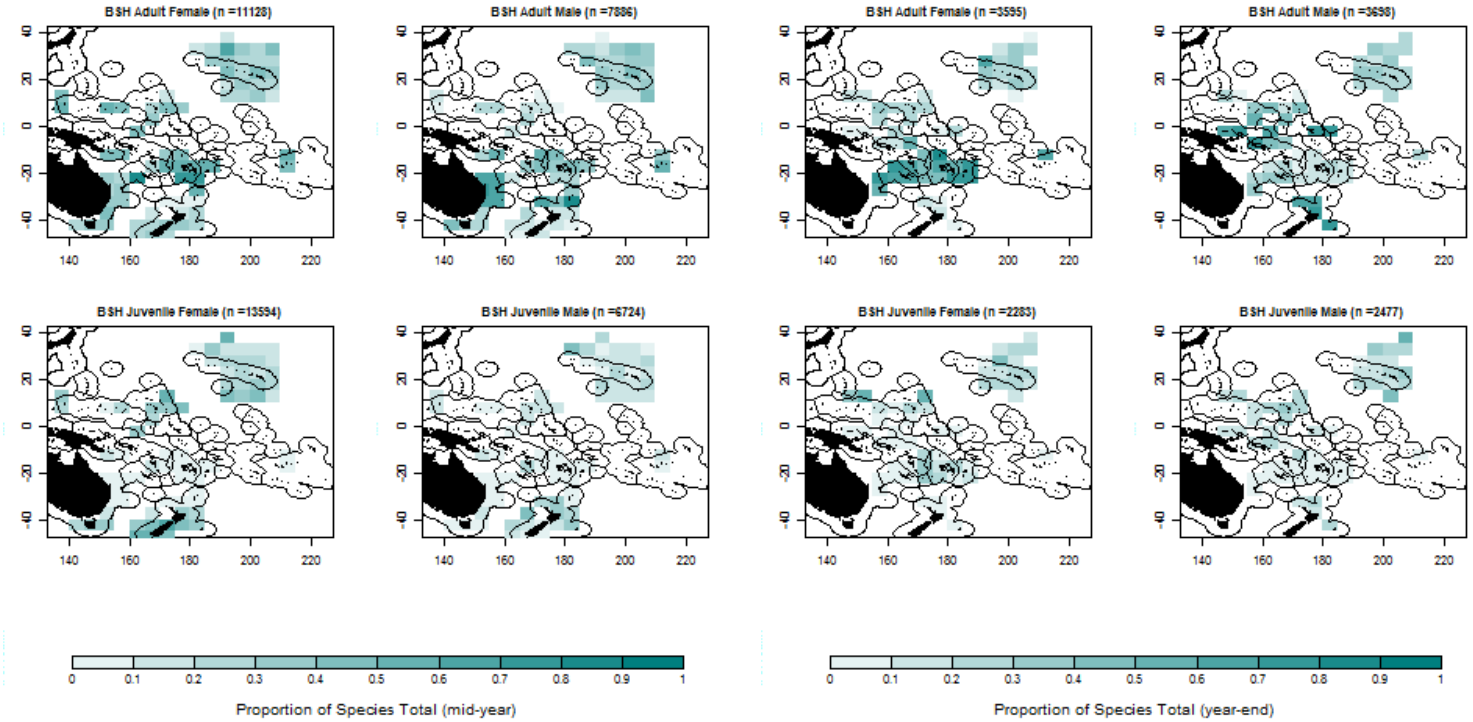


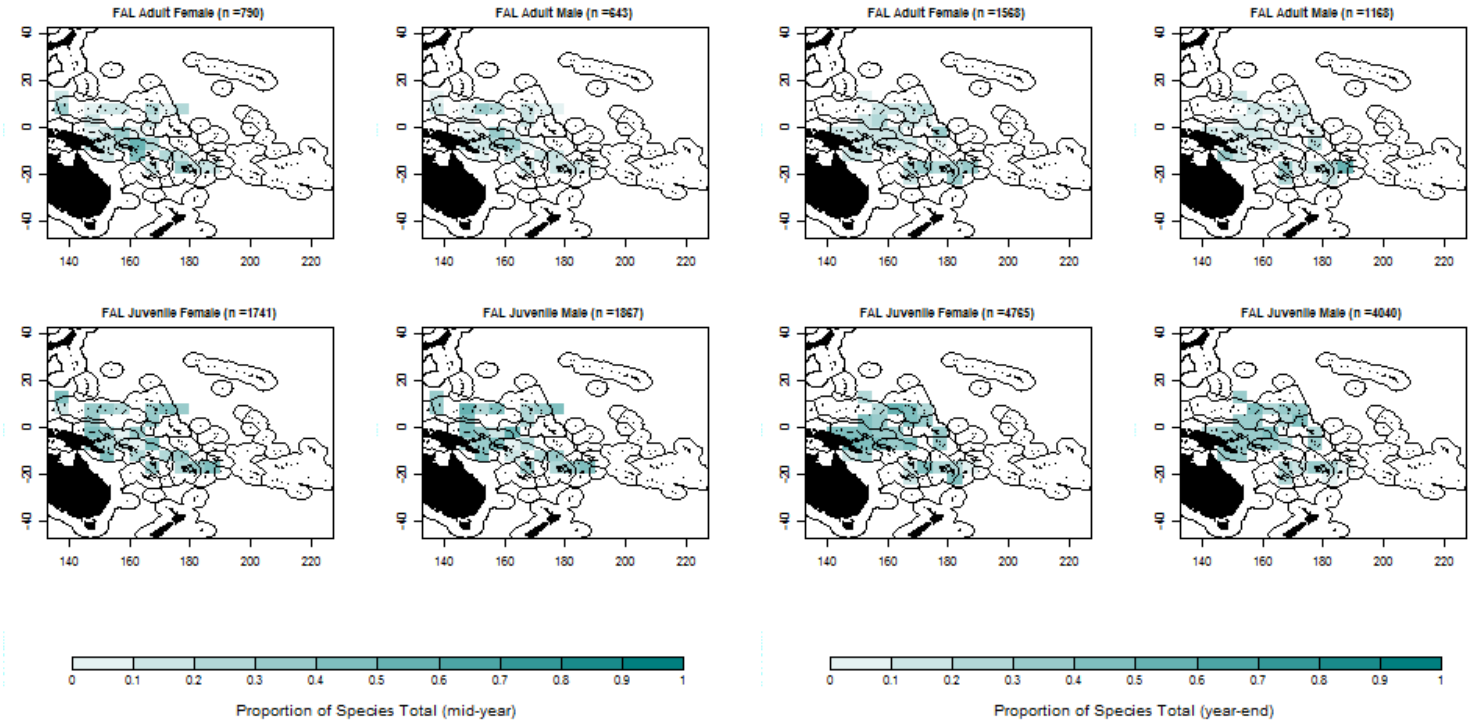
Figure 61: Annual change in length (cm) over the study period as derived from the year effect of a GLM fitted to the sex and species specific data shown in figures 71 to 77



(a) Mid-year estimates.

(b) End of year estimates.

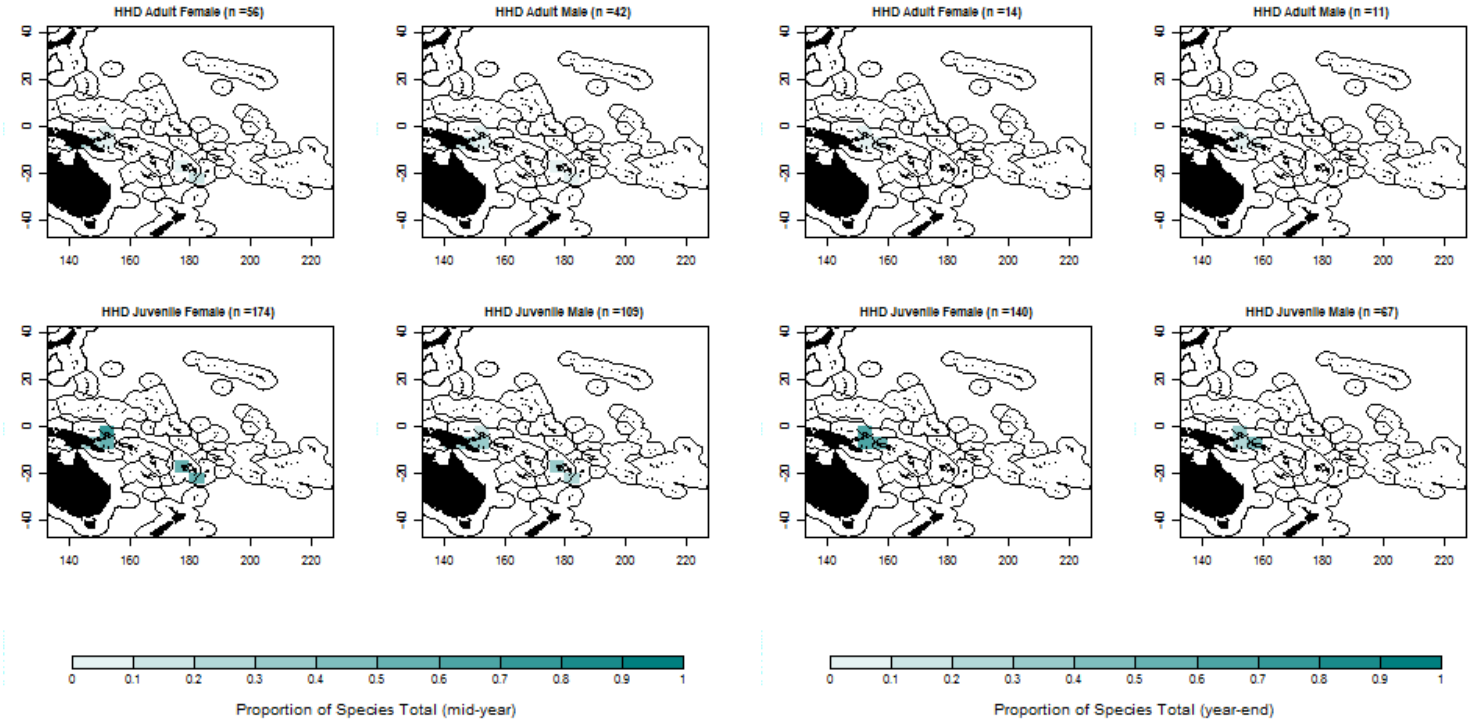
Figure 62: Blue Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.



(a) Mid-year estimates.

(b) End of year estimates.

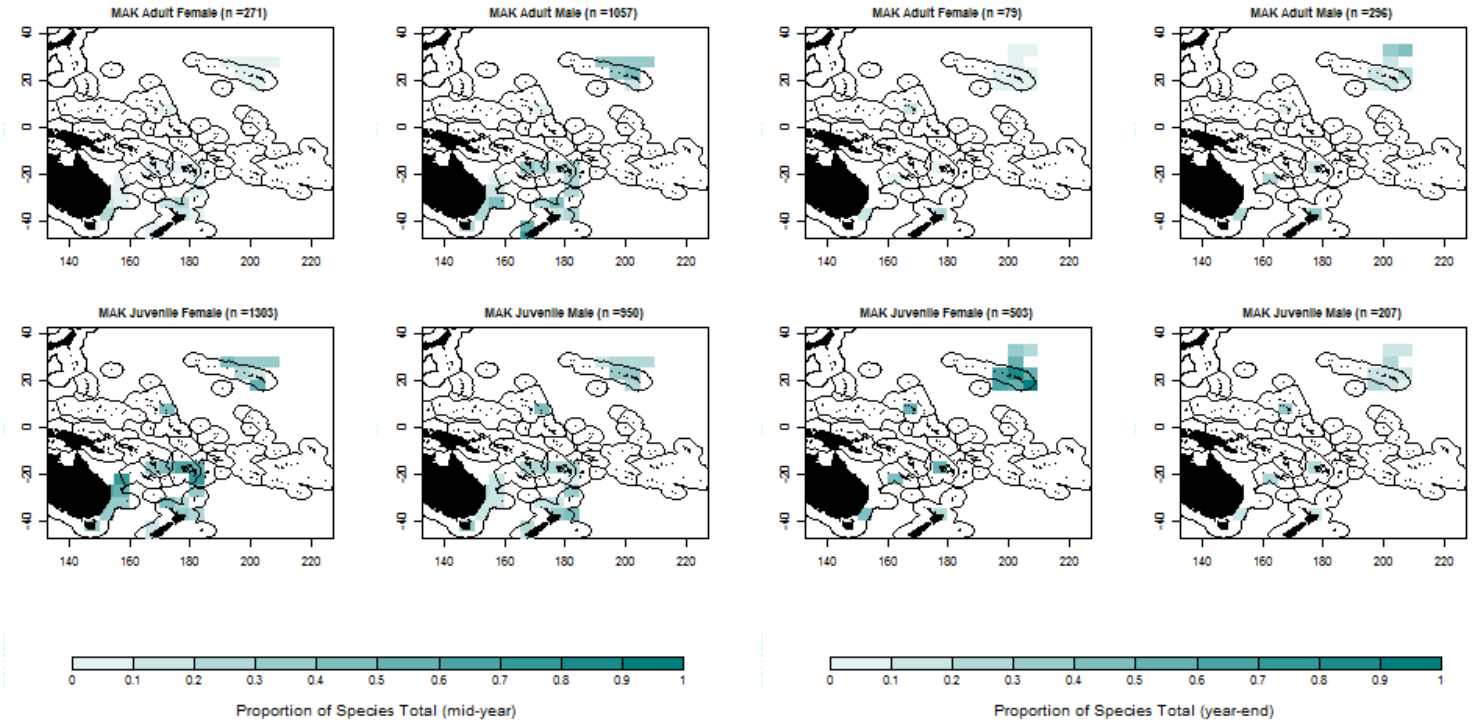
Figure 63: Silky Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.



(a) Mid-year estimates.

(b) End of year estimates.

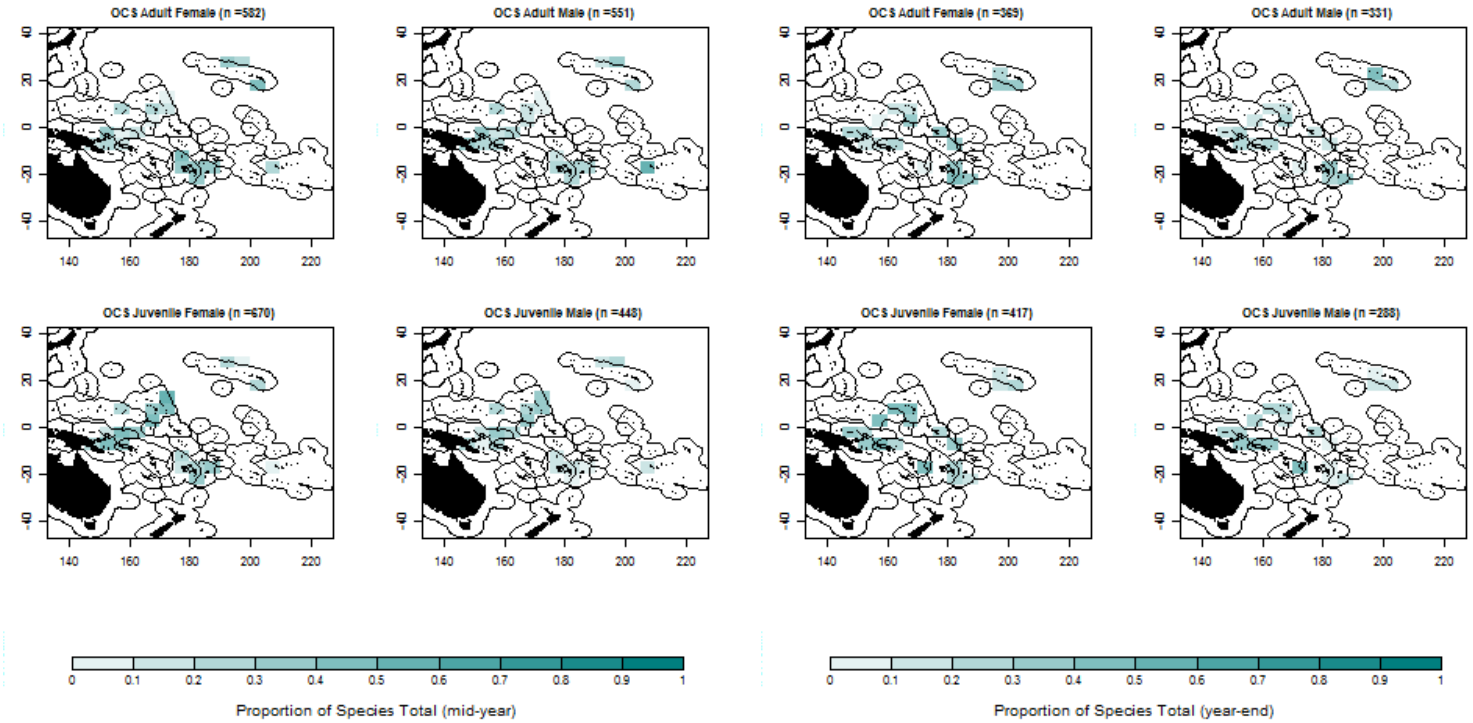
Figure 64: Hammerhead Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.



(a) Mid-year estimates.

(b) End of year estimates.

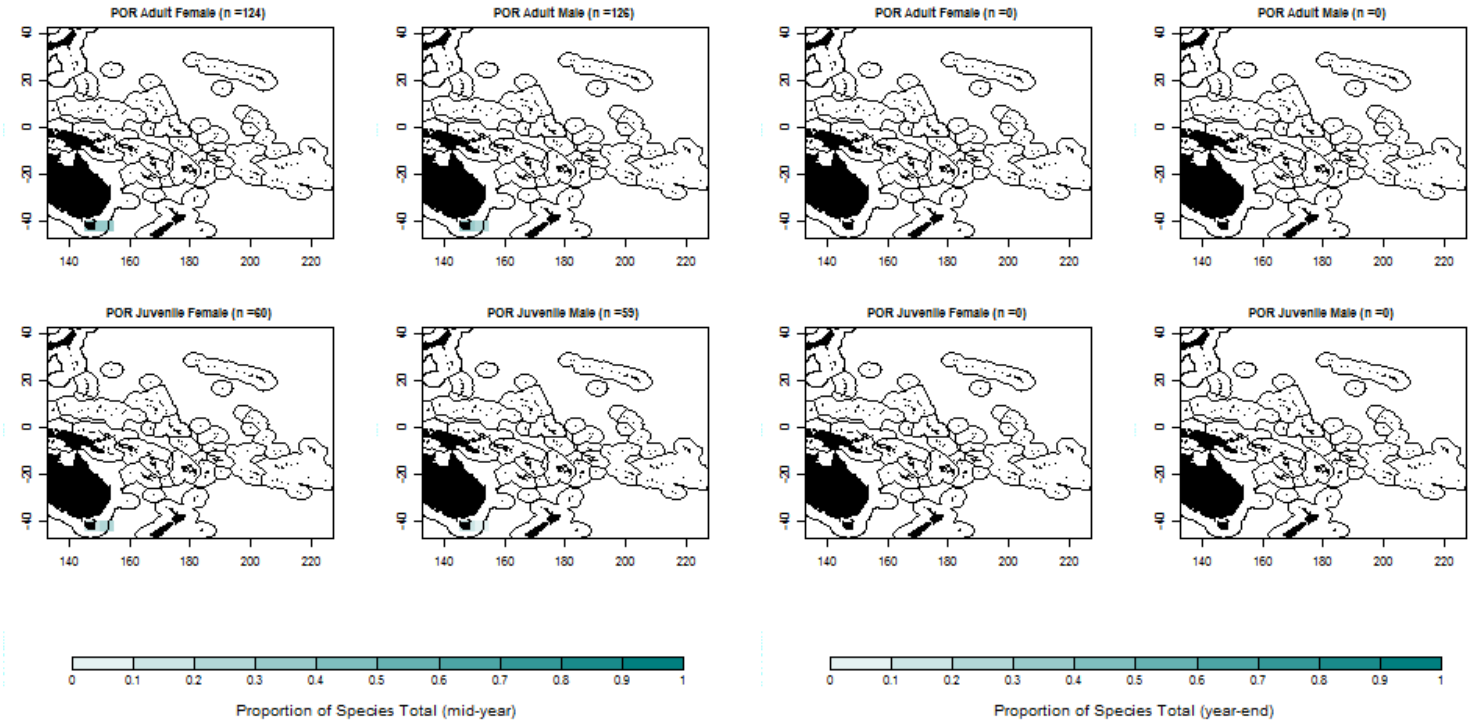
Figure 65: Mako Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.



(a) Mid-year estimates.

(b) End of year estimates.

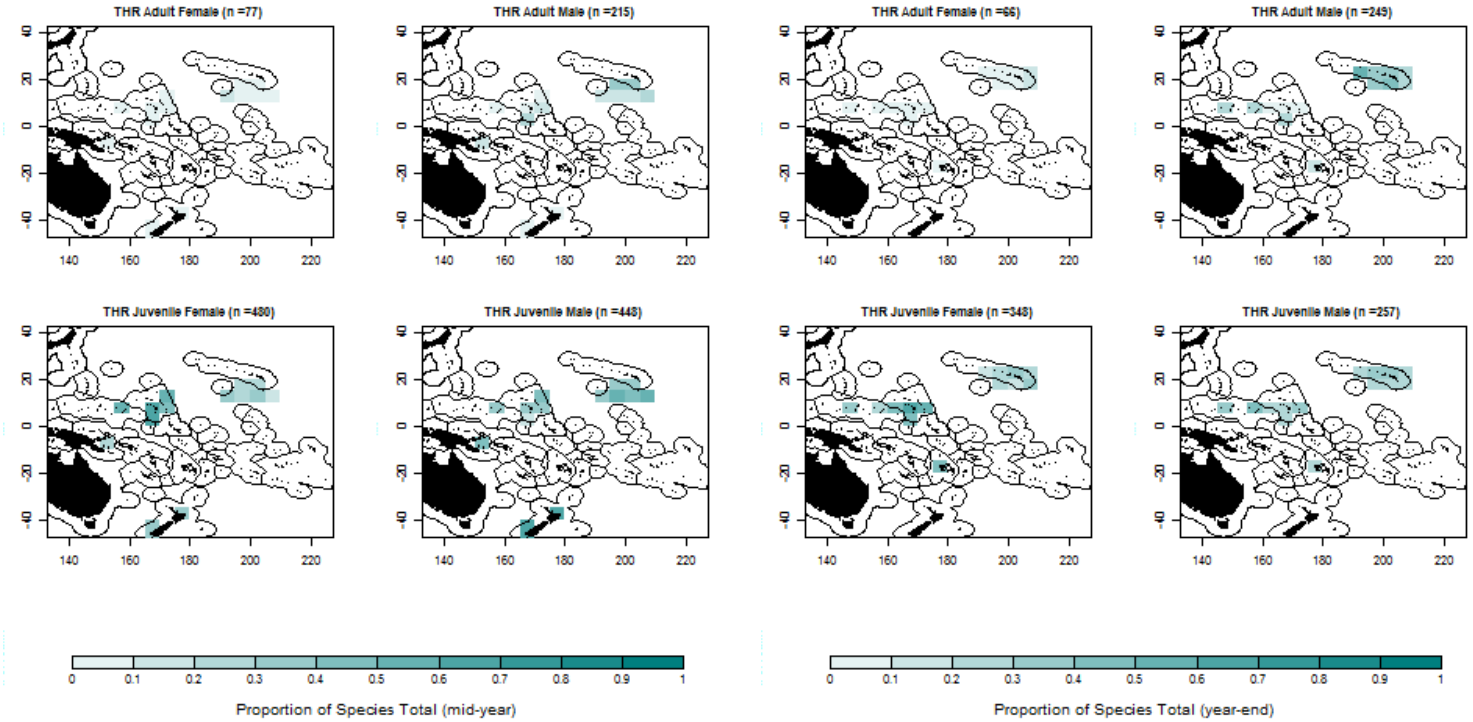
Figure 66: Oceanic Whitetip Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.



(a) Mid-year estimates.

(b) End of year estimates.

Figure 67: Porbeagle Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.



(a) Mid-year estimates.

(b) End of year estimates.

Figure 68: Thresher Shark: Proportion observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with less than 20 individuals from the analysis.

C Whale Shark Figures

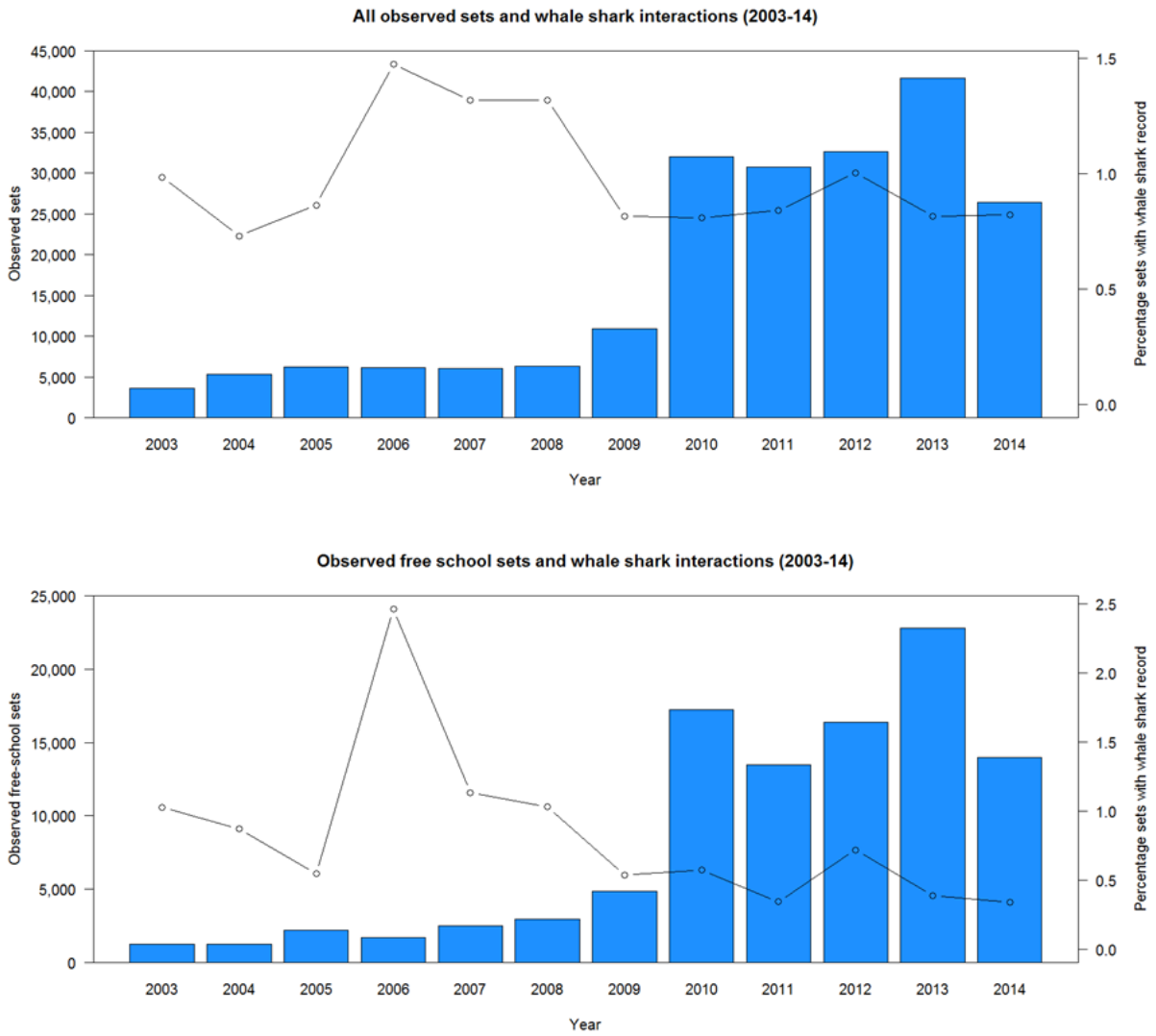


Figure 69: Annual number of observed free school sets (bars) and proportion of sets with some form of whale shark interaction (see text for criteria).

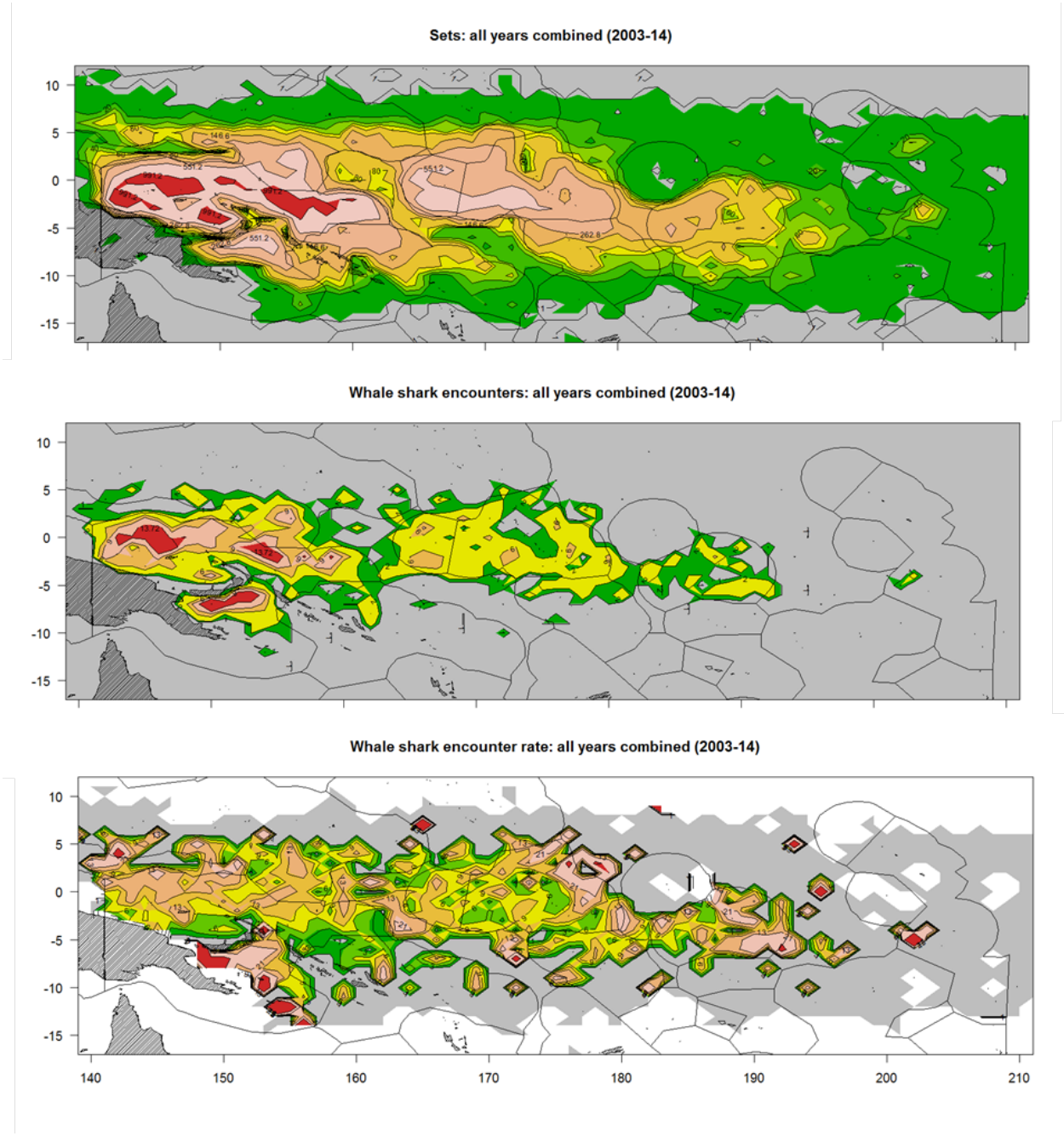


Figure 70: Contour plots based on 1 × 1 degree square data for all years combined of purse seine sets (top), whale shark records (middle – see text for criteria), and encounter rates (bottom — simply whale shark records divided by total sets for each 1 x1 degree square). Grey represents zeros, white 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.

D Management Consideration Figures

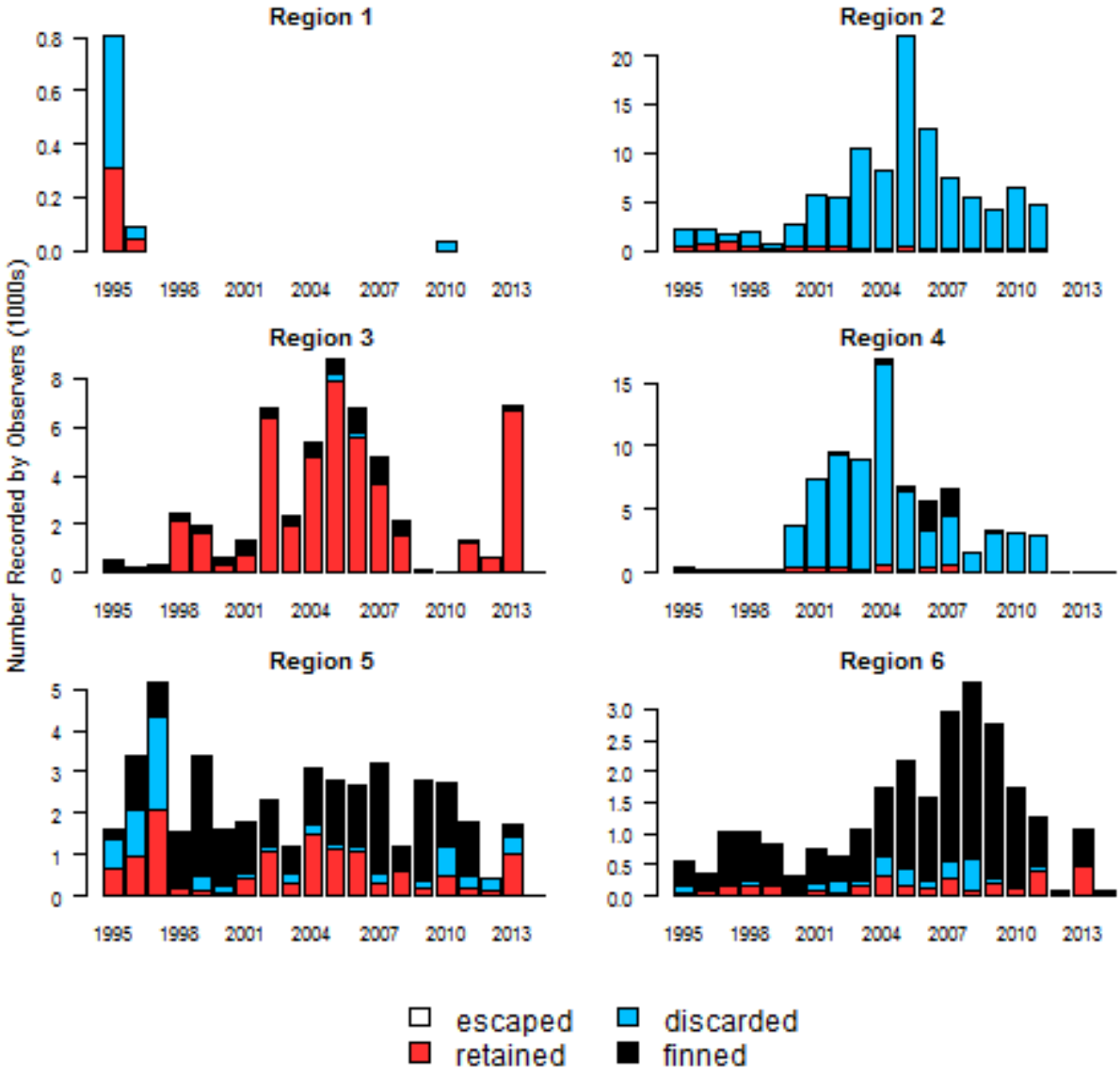


Figure 71: Fate of observed sharks caught by longline in the WCPO (total numbers for all species combined).

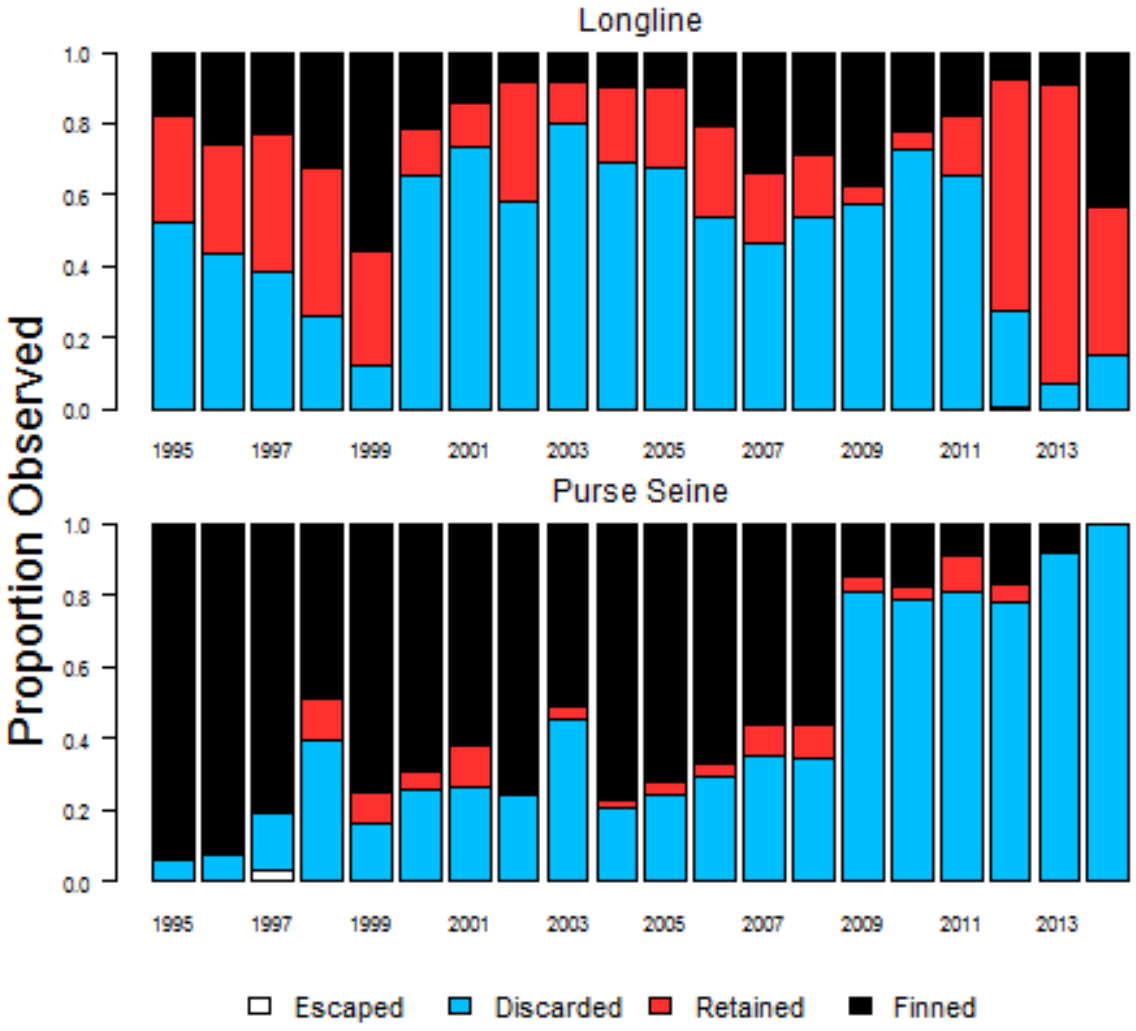


Figure 72: Fate of observed sharks caught by purse seine (top) and longline (bottom)in the WCPO (proportion by number for all species combined).

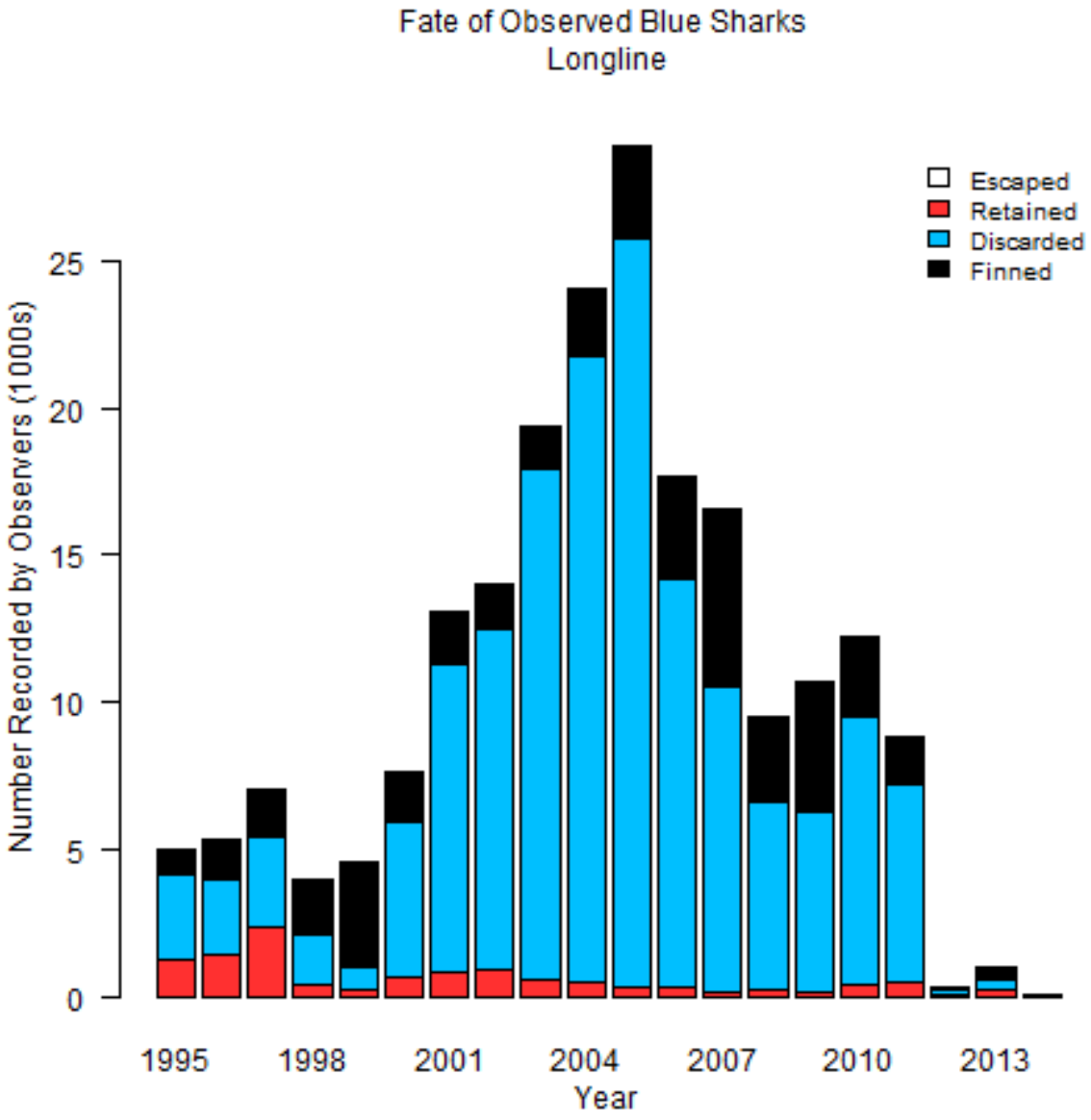


Figure 73: Fate of observed blue sharks caught by longline in the WCPO.

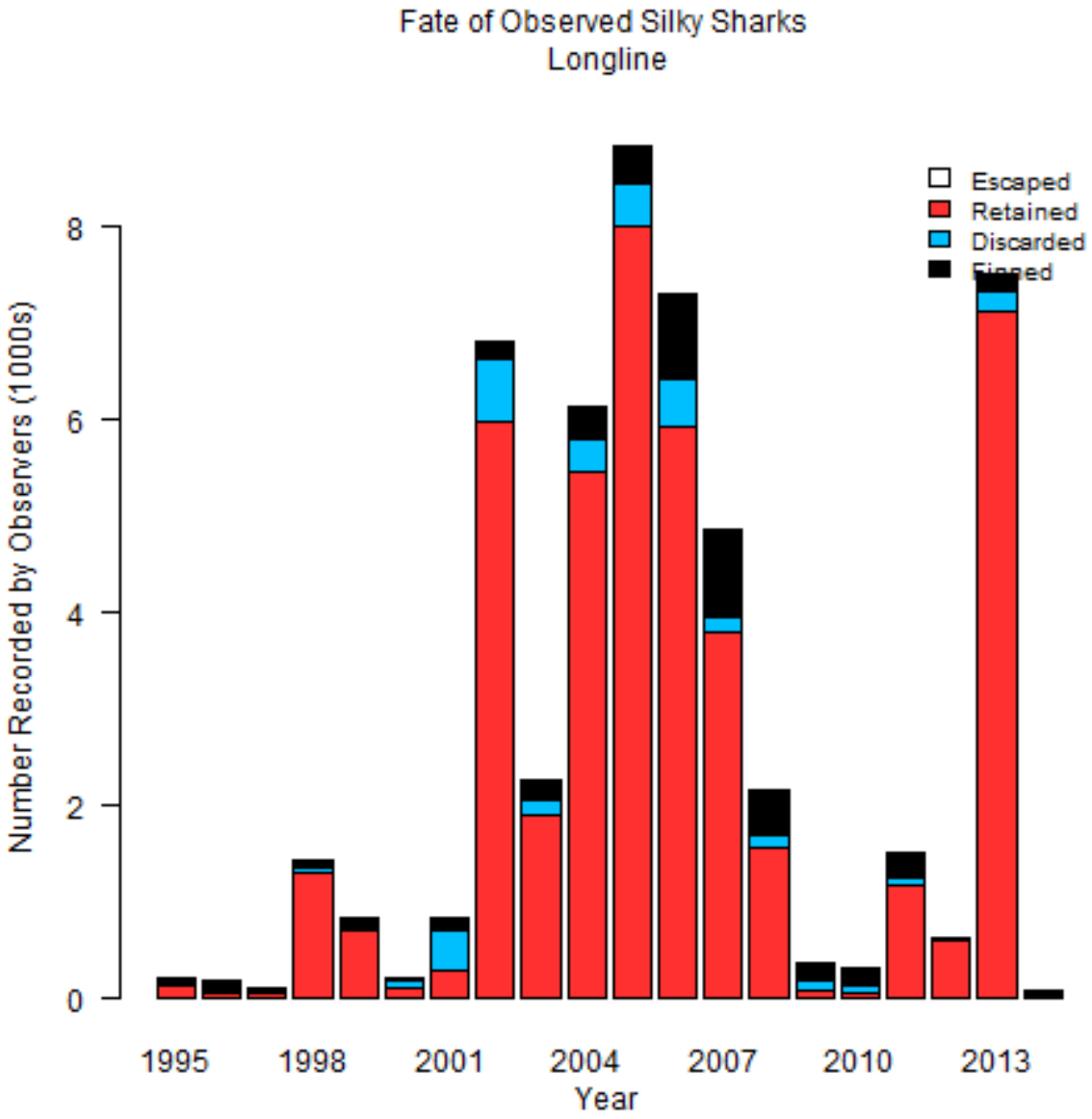


Figure 74: Fate of observed silky sharks caught by longline in the WCPO.

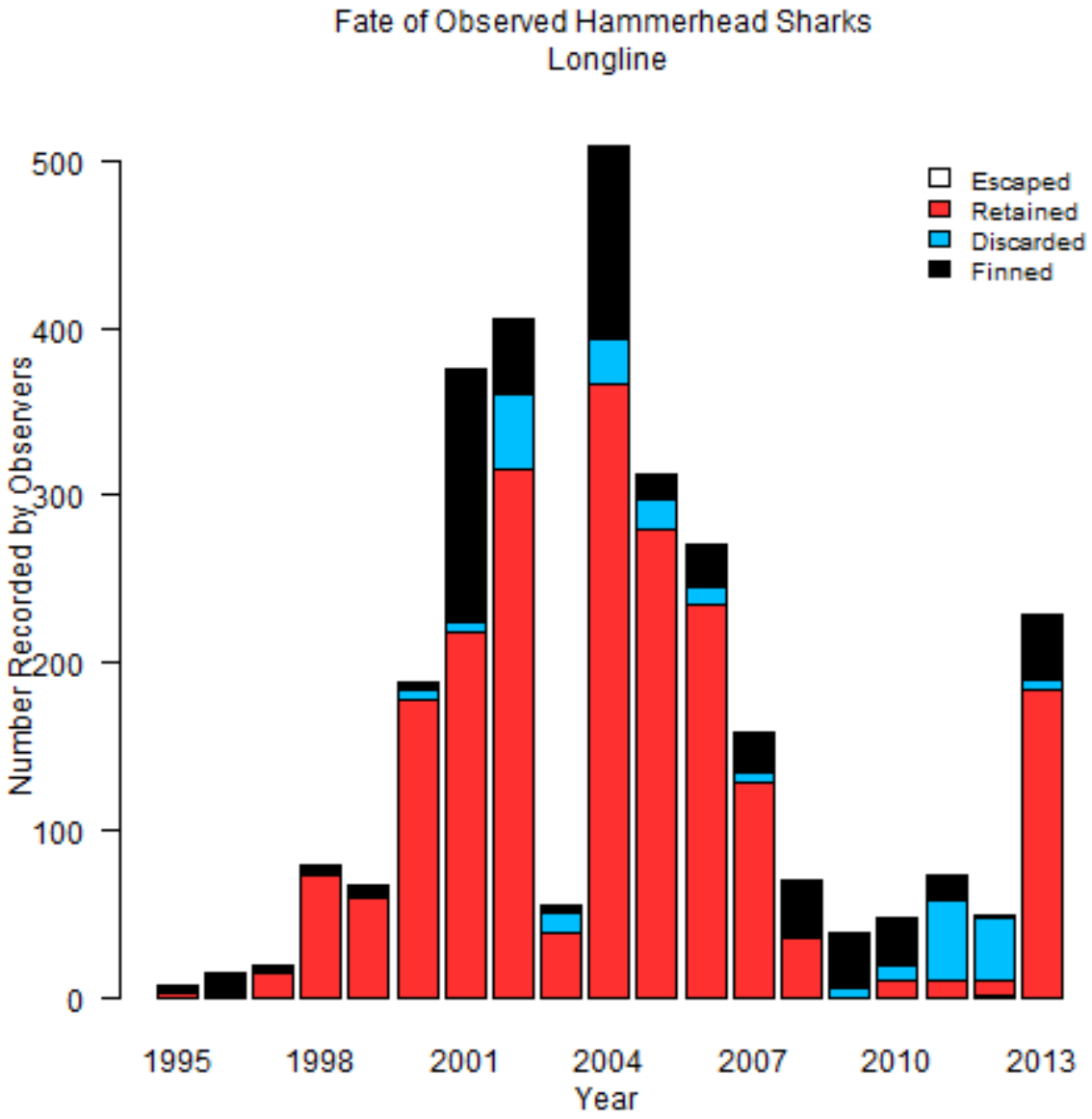


Figure 75: Fate of observed hammerhead sharks caught by longline in the WCPO.

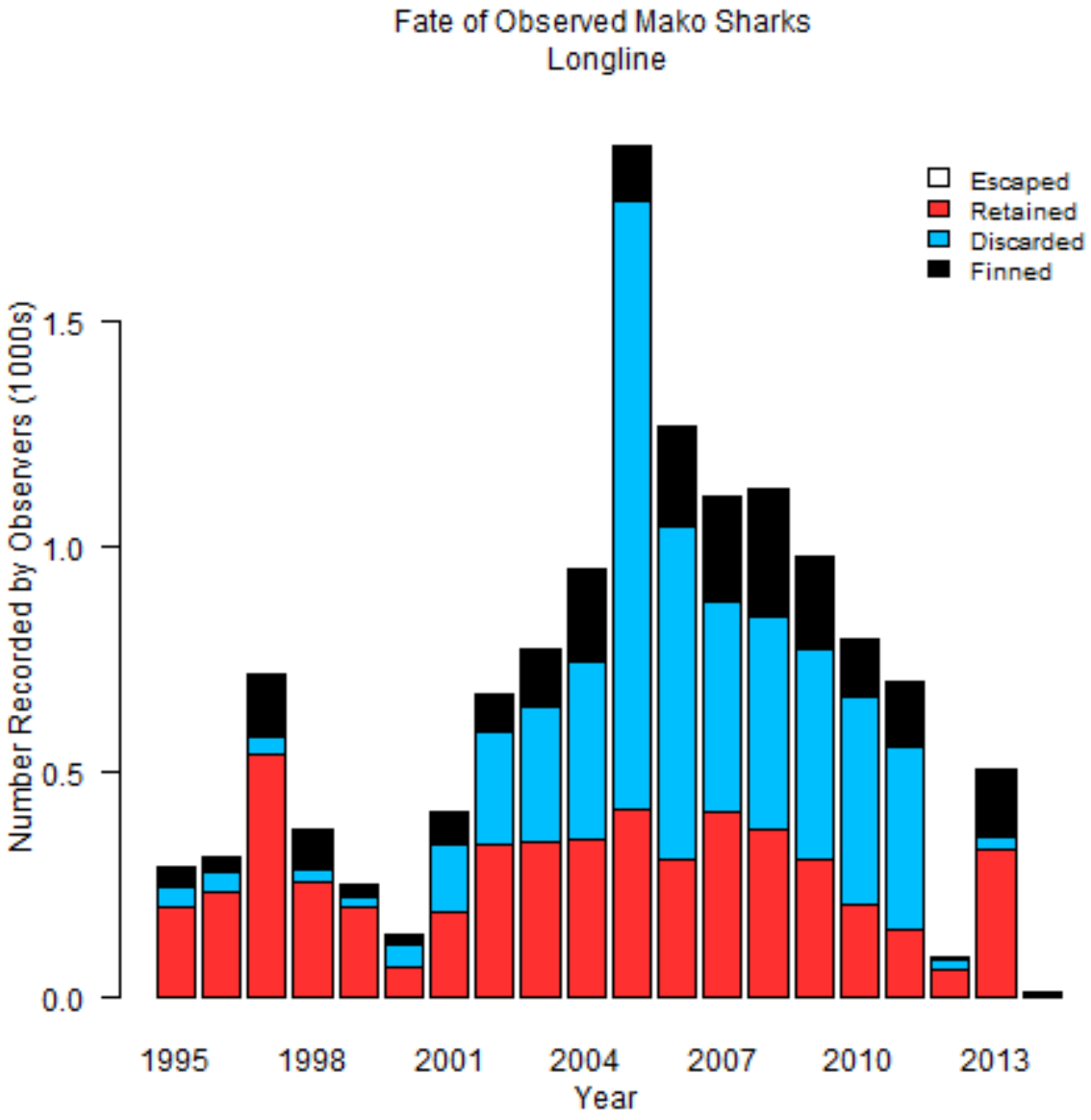


Figure 76: Fate of observed mako sharks caught by longline in the WCPO.

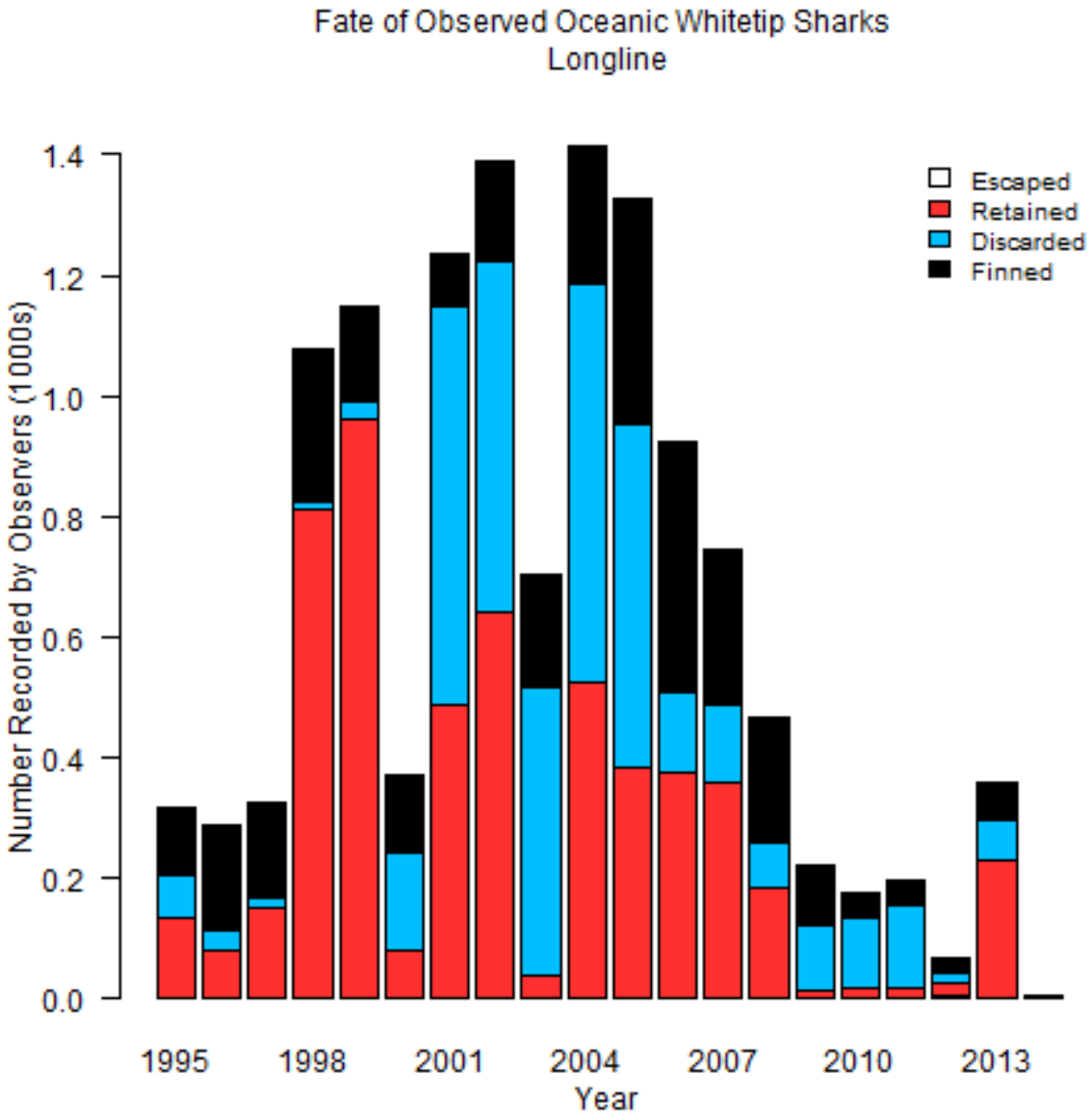


Figure 77: Fate of observed oceanic whitetip sharks caught by longline in the WCPO.

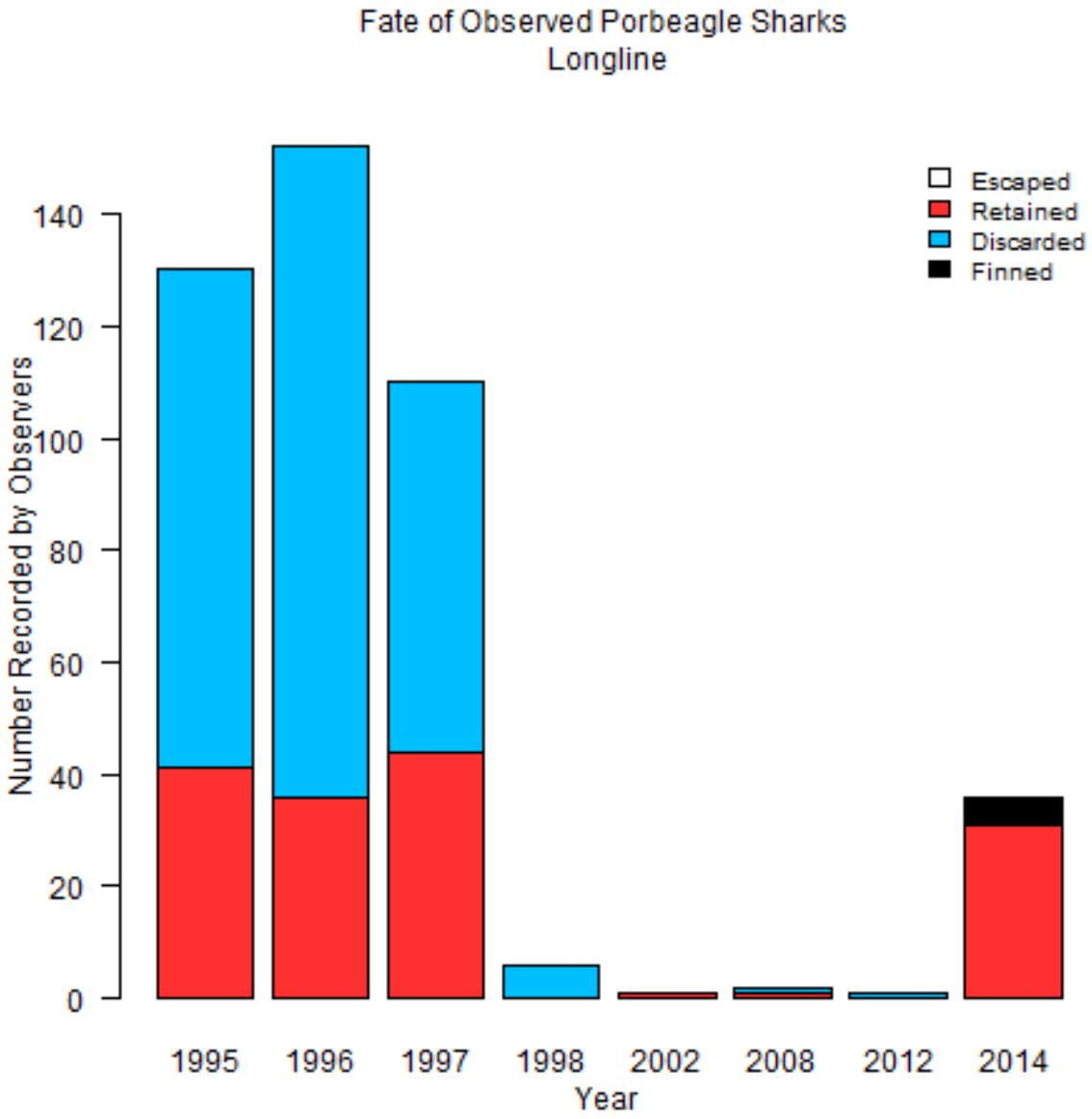


Figure 78: Fate of observed porbeagle sharks caught by longline in the WCPO.

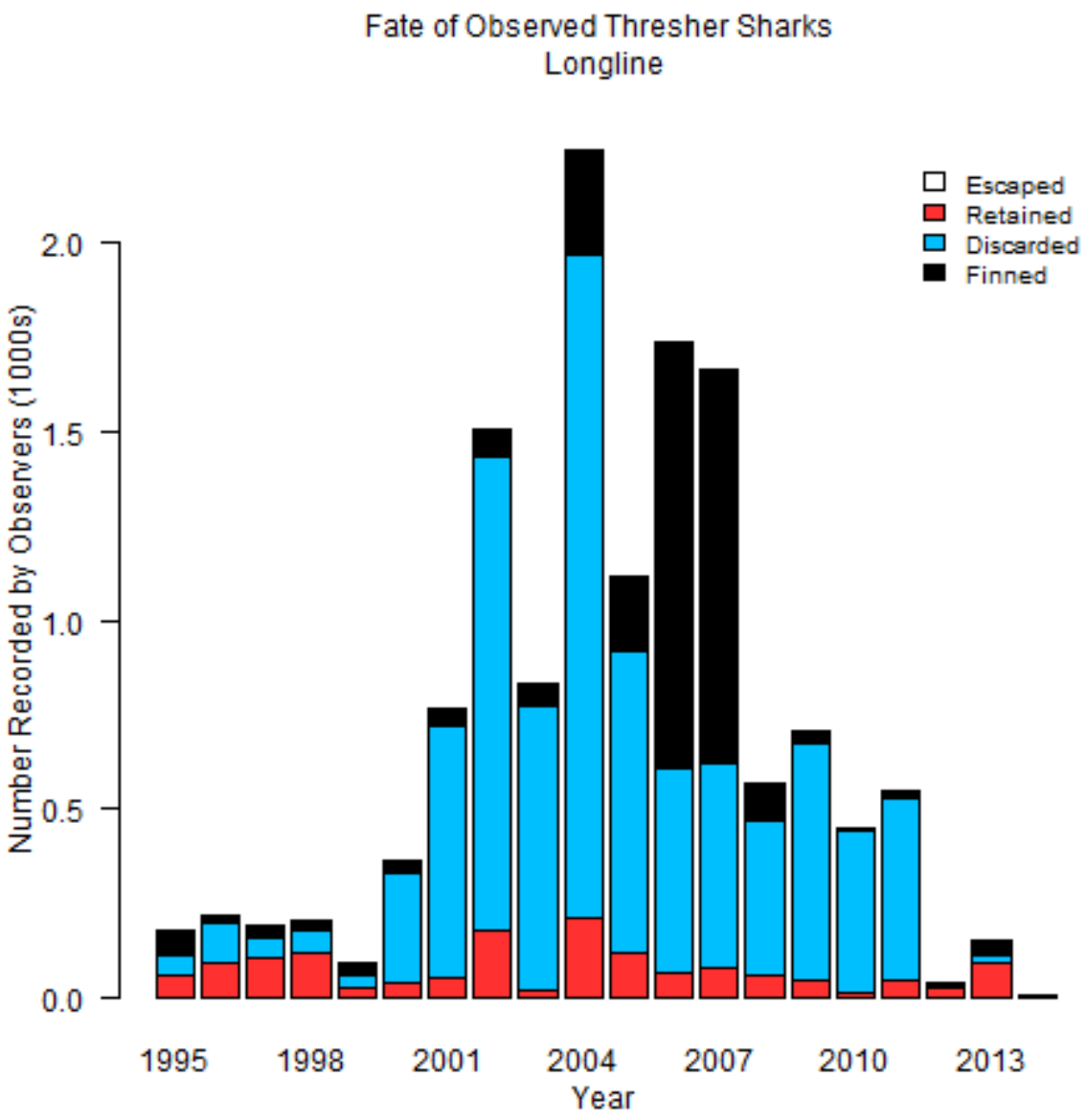


Figure 79: Fate of observed thresher sharks caught by longline in the WCPO.

E Model Diagnostics

E.0.1 CPUE Standardisation Diagnostics

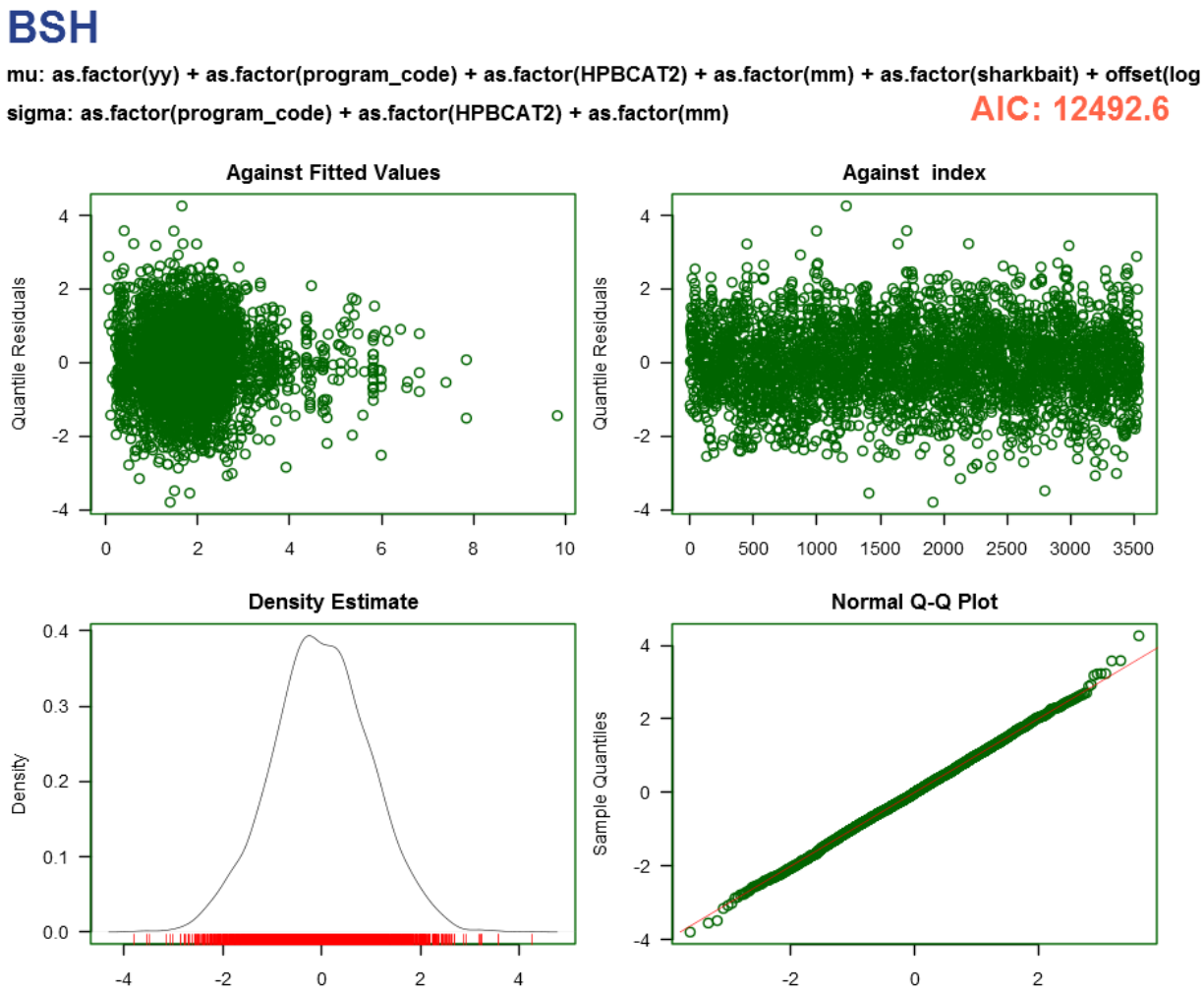


Figure 80: CPUE indicators, model diagnostics for blue shark (north) CPUE standardization via negative binomial model.

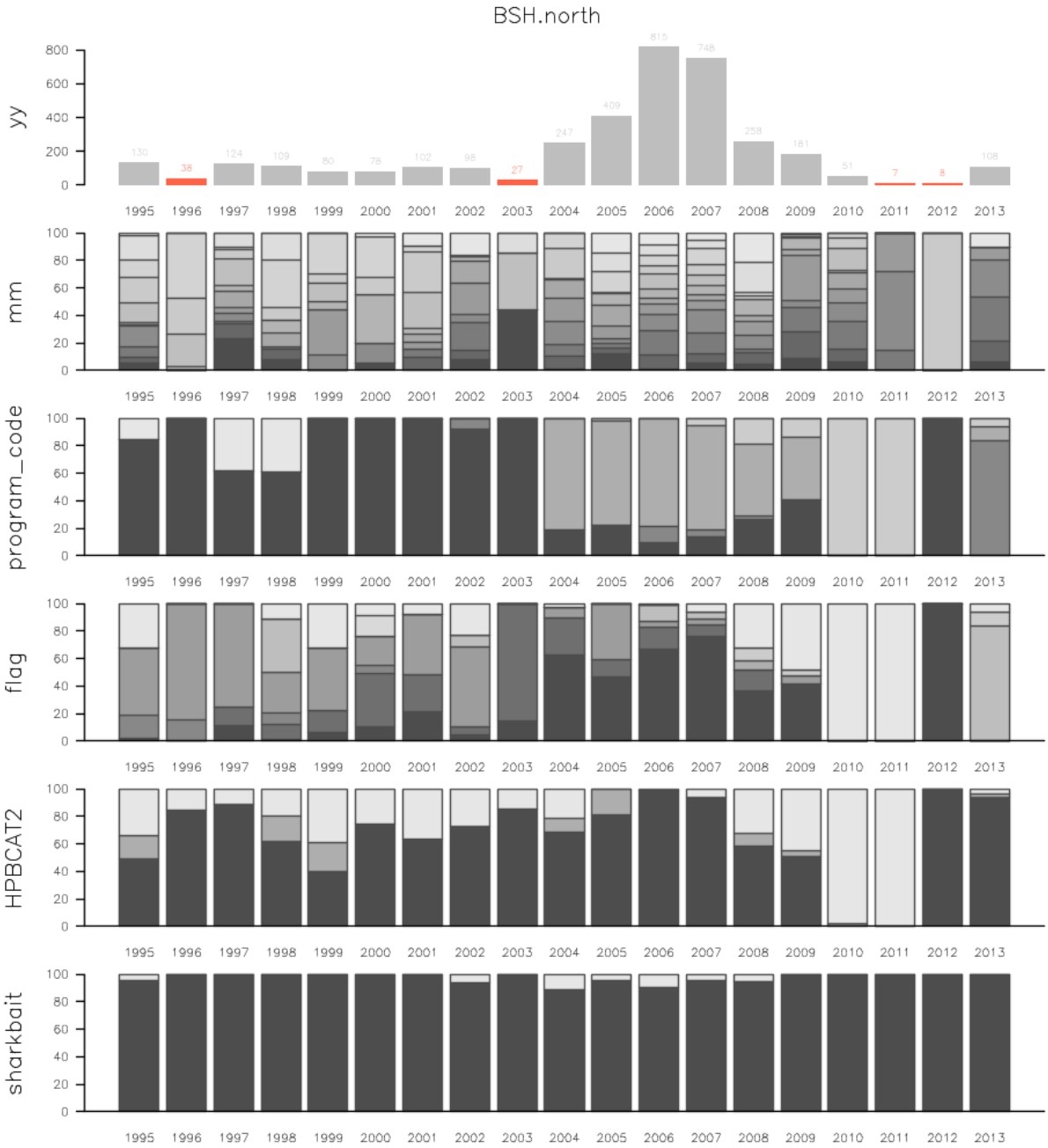


Figure 81: CPUE indicators, model diagnostics for blue shark (north) CPUE standardization via negative binomial model.

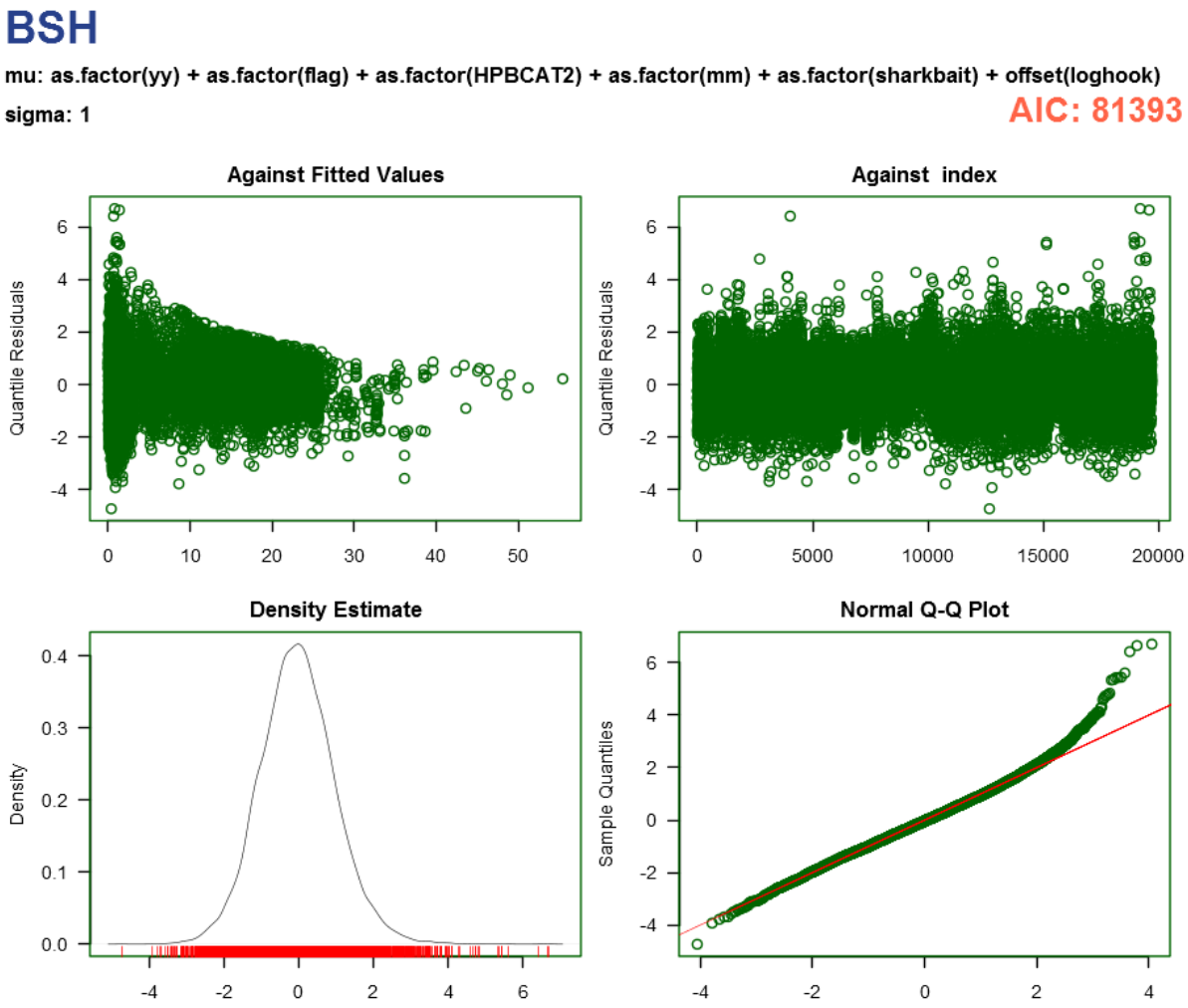


Figure 82: CPUE indicators, model diagnostics for blue shark (south) CPUE standardization via negative binomial model.

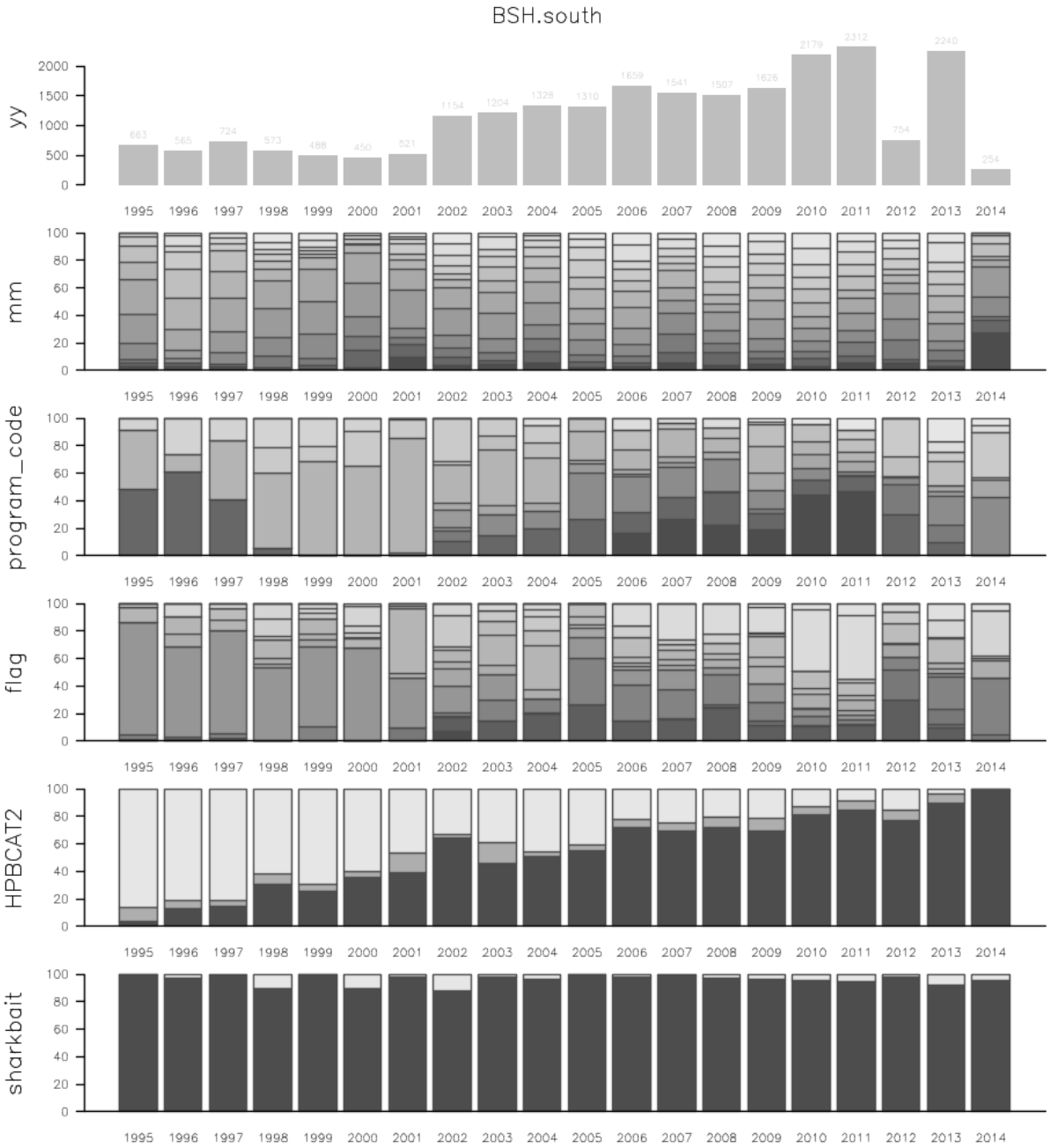


Figure 83: CPUE indicators, model diagnostics for blue shark (south) CPUE standardization via negative binomial model.

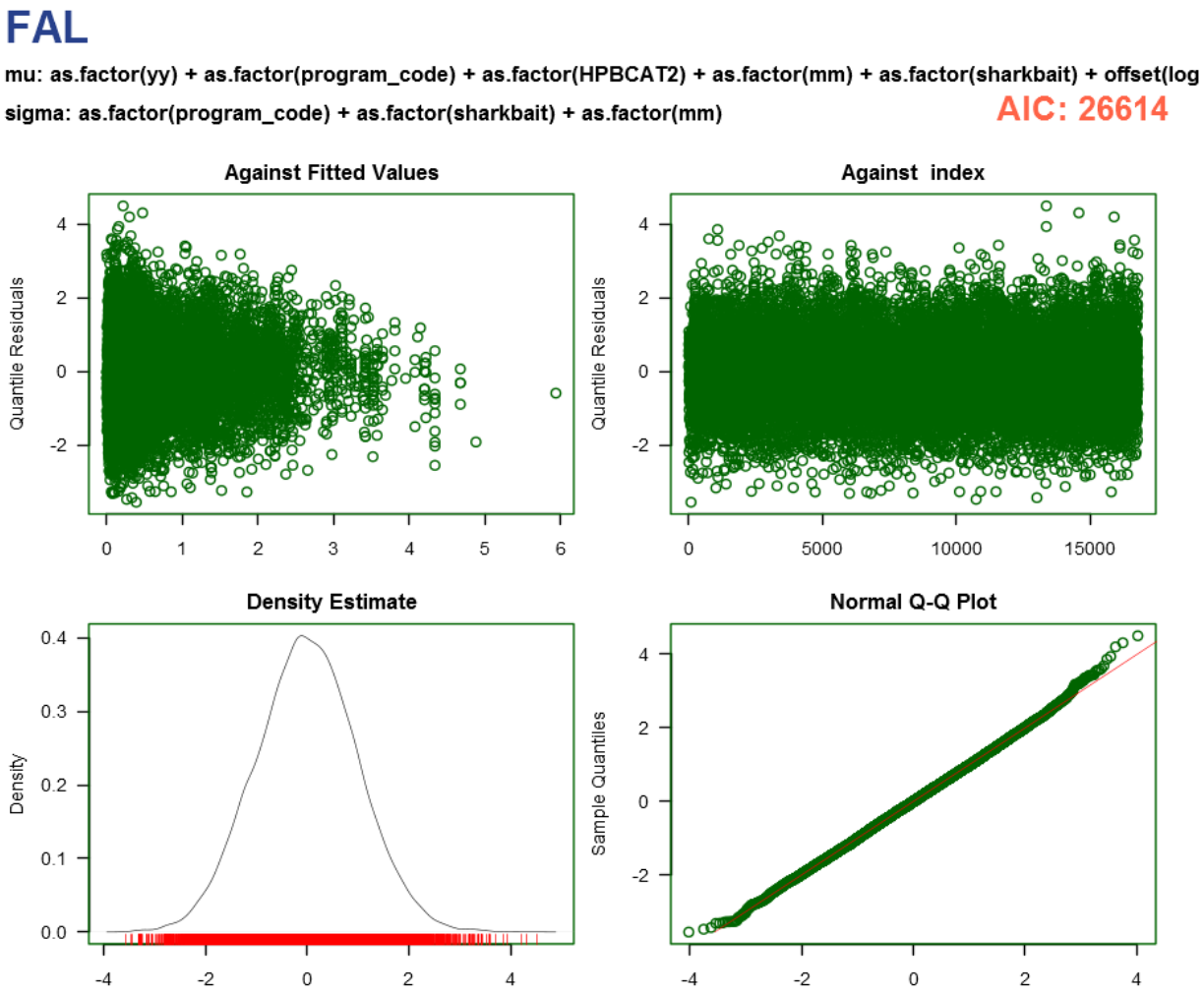


Figure 84: CPUE indicators, model diagnostics for silky shark CPUE standardization via negative binomial model.

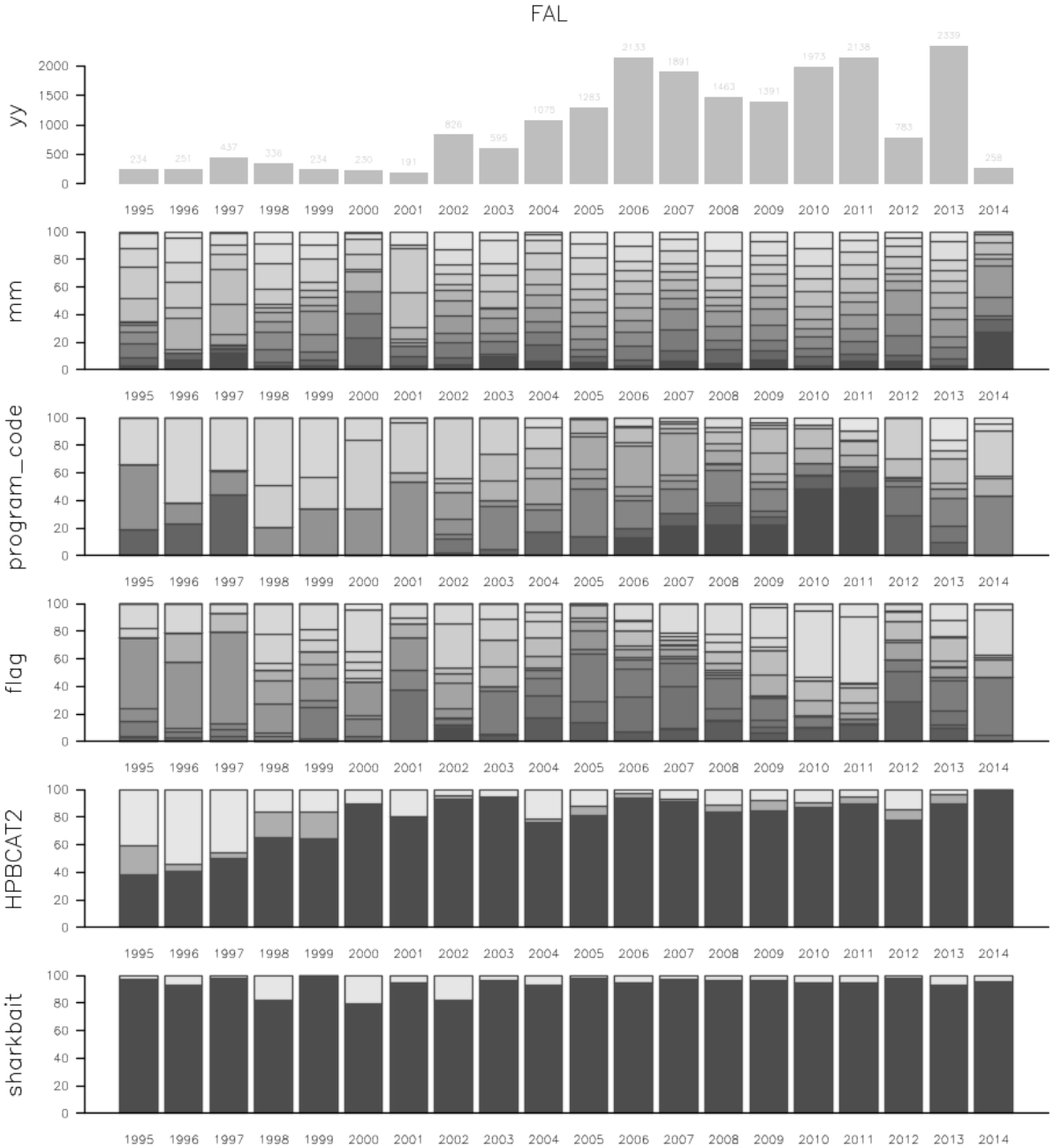


Figure 85: CPUE indicators, model diagnostics for silky shark CPUE standardization via negative binomial model.

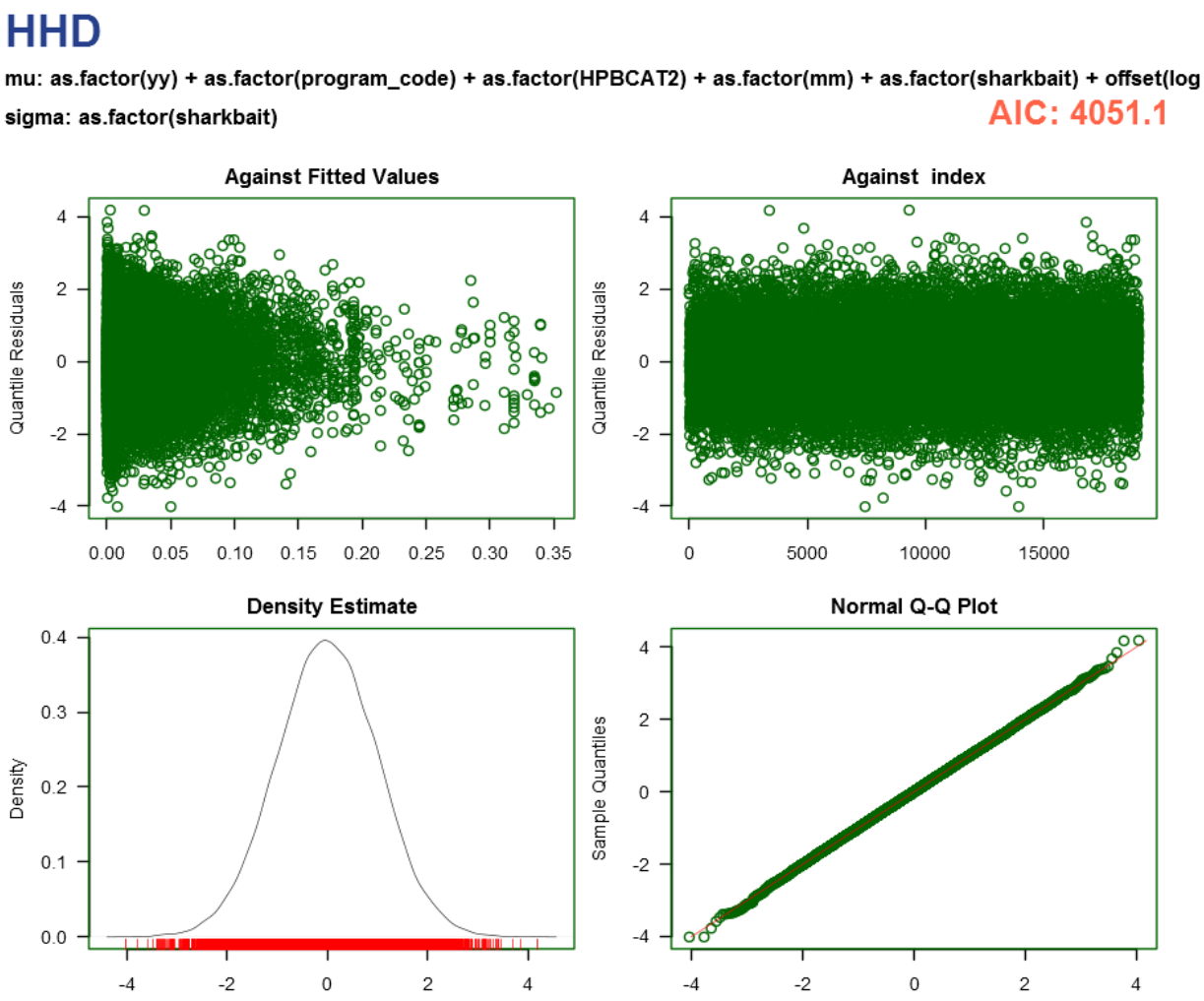


Figure 86: CPUE indicators, model diagnostics for hammerhead shark CPUE standardization via negative binomial model

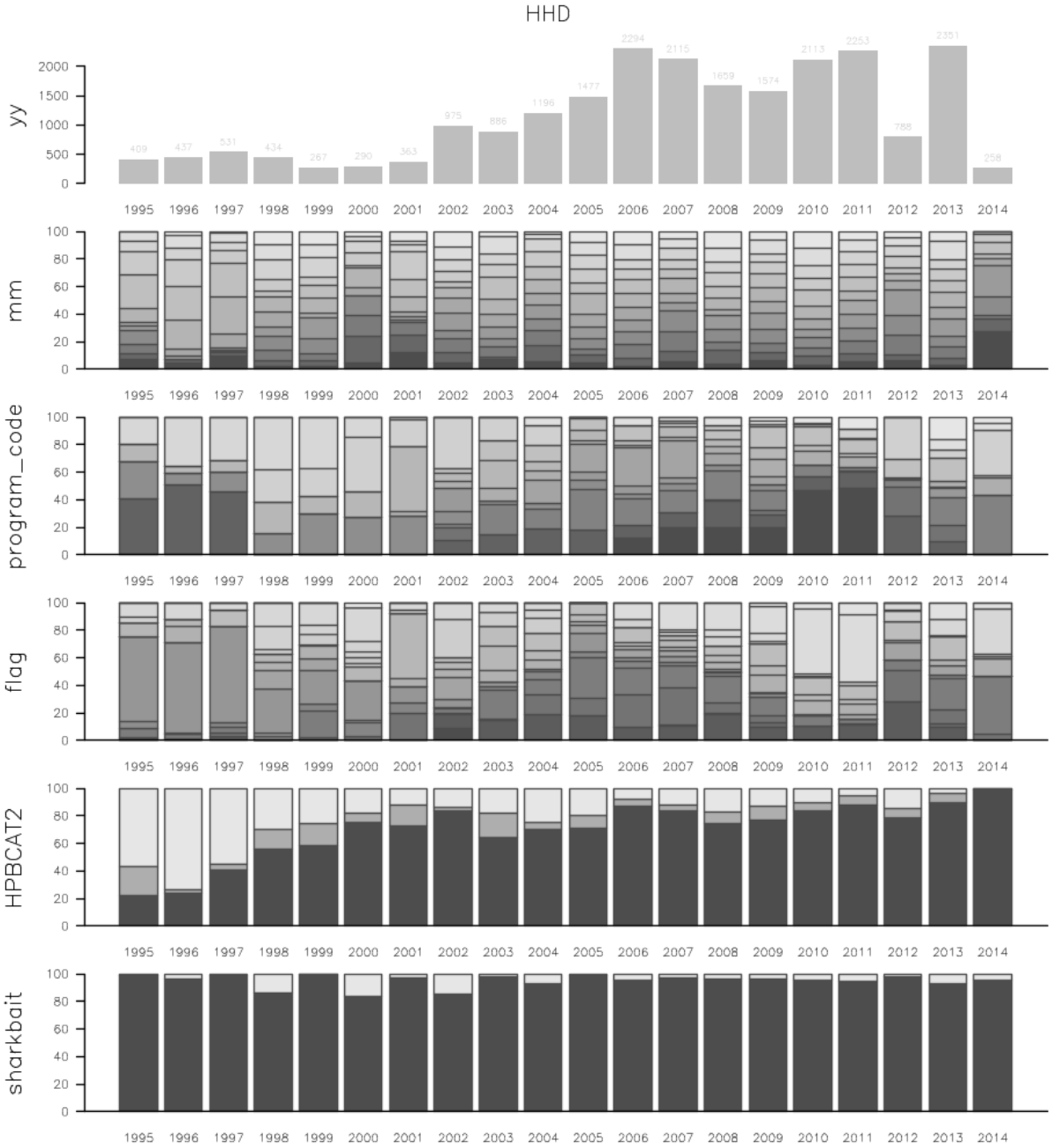


Figure 87: CPUE indicators, model diagnostics for hammerhead shark CPUE standardization via negative binomial model

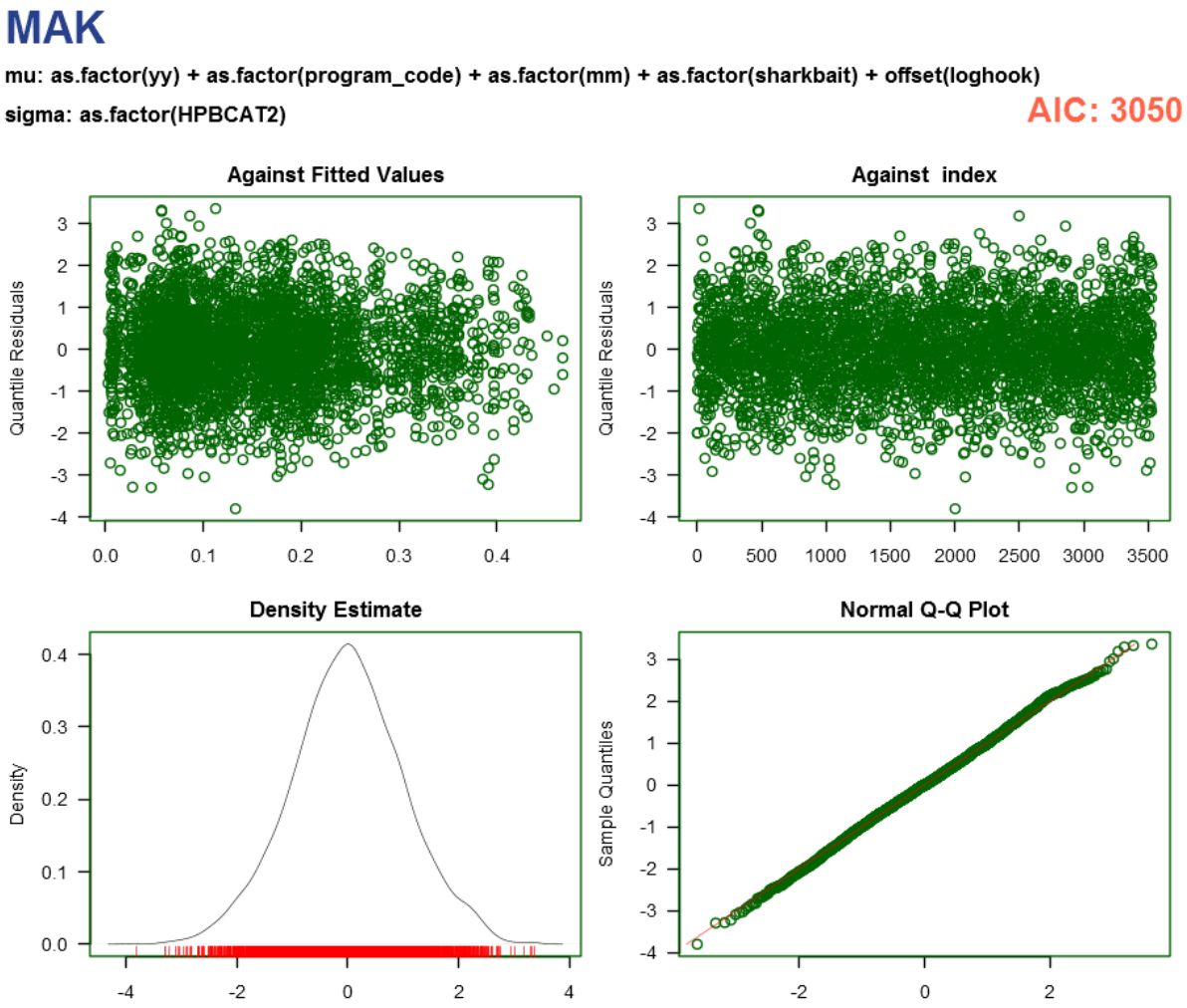


Figure 88: CPUE indicators, model diagnostics for mako shark (northern hemisphere) CPUE standardization via negative binomial model.

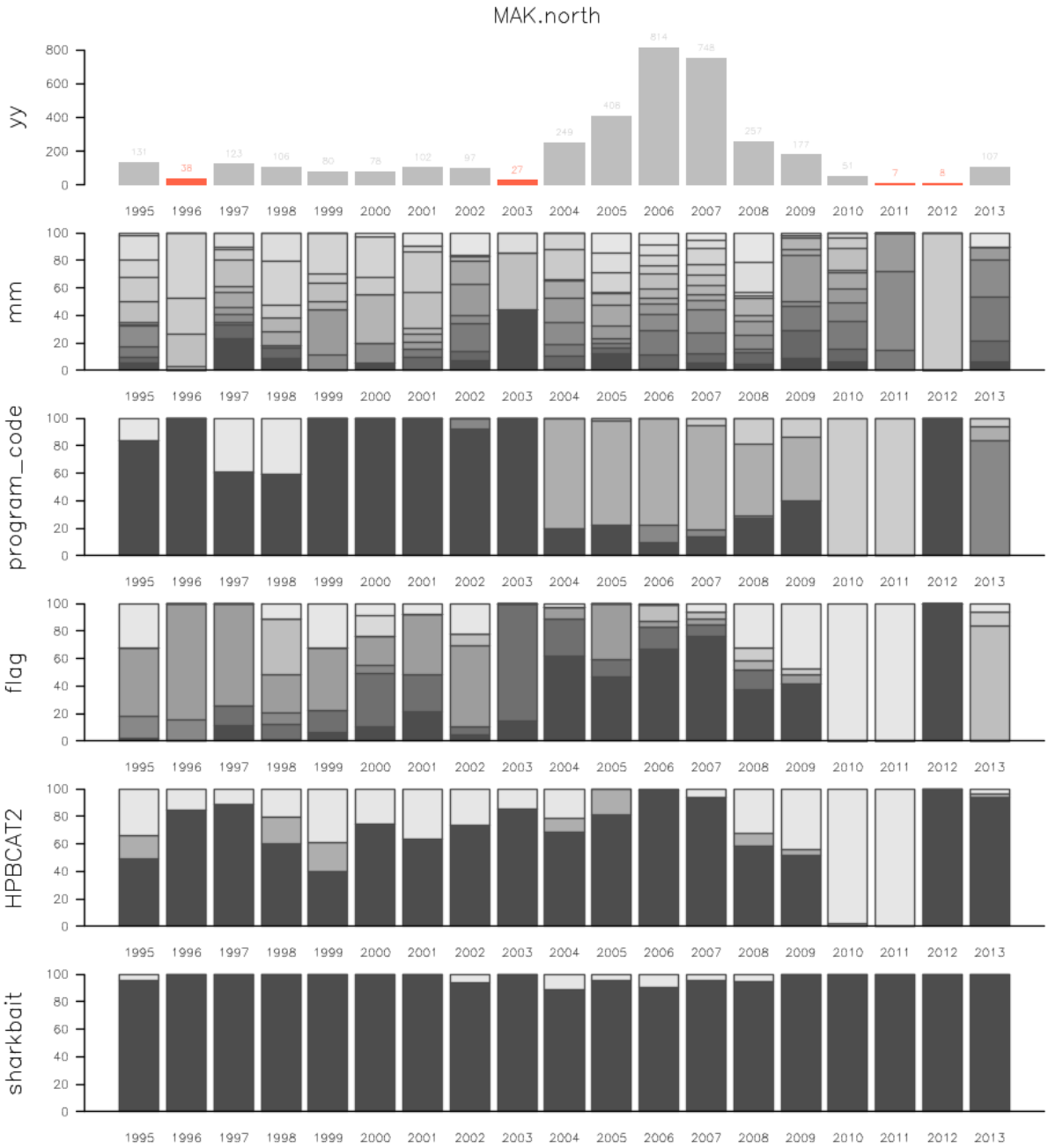


Figure 89: CPUE indicators, model diagnostics for mako shark (northern hemisphere) CPUE standardization via negative binomial model.

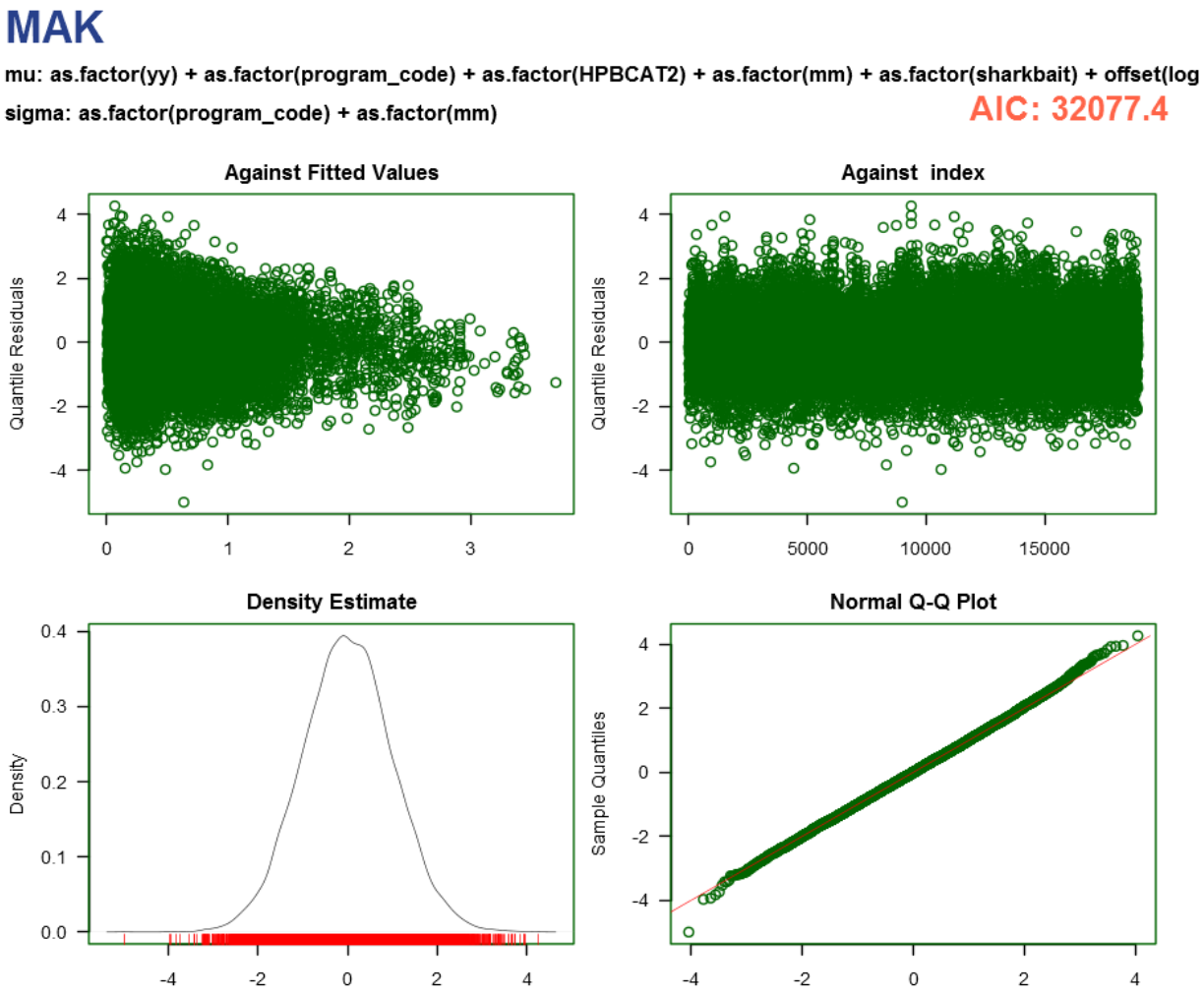


Figure 90: CPUE indicators, model diagnostics for mako shark (southern hemisphere) CPUE standardization via negative binomial model.

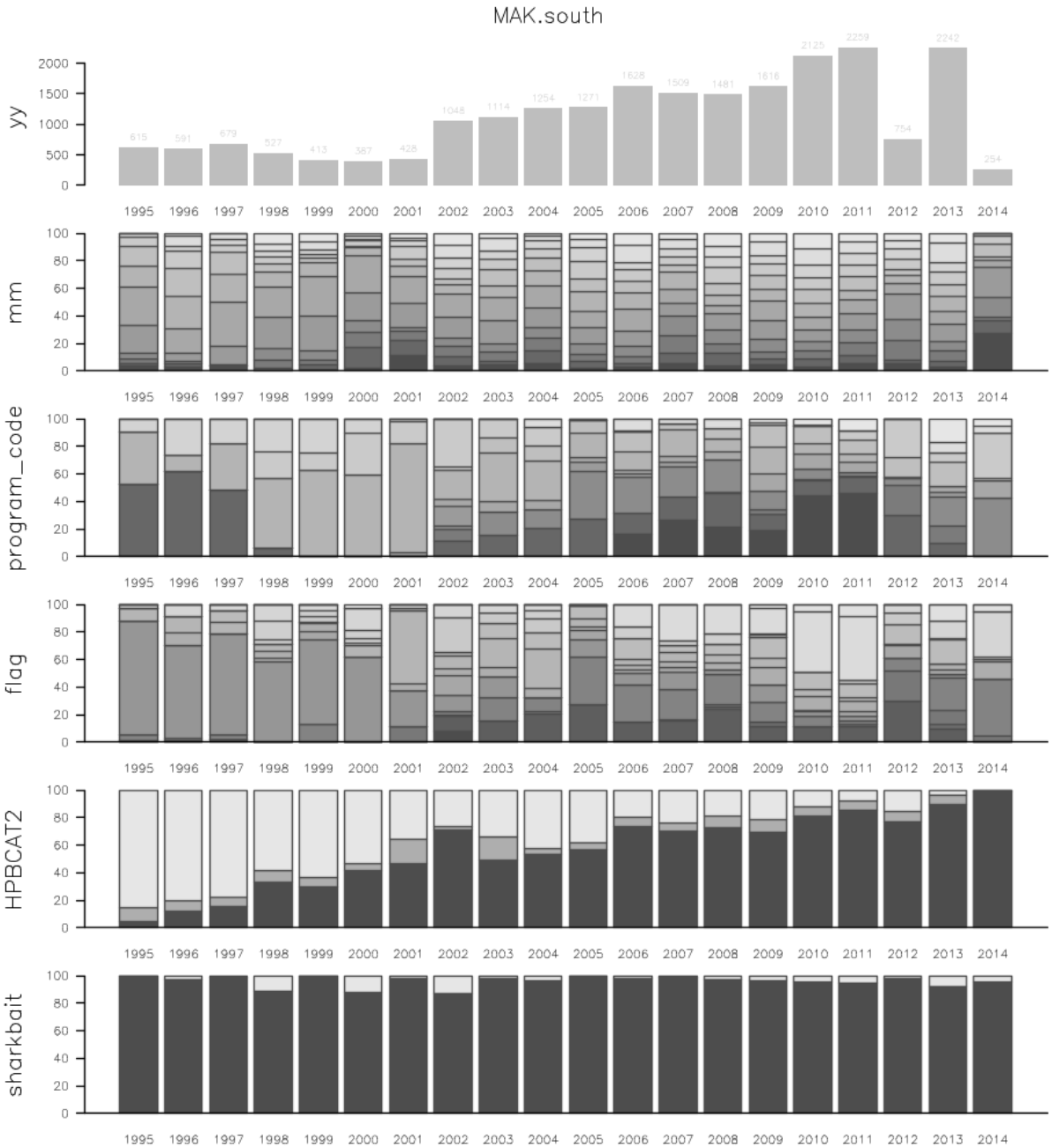


Figure 91: CPUE indicators, model diagnostics for mako shark (southern hemisphere) CPUE standardization via negative binomial model.

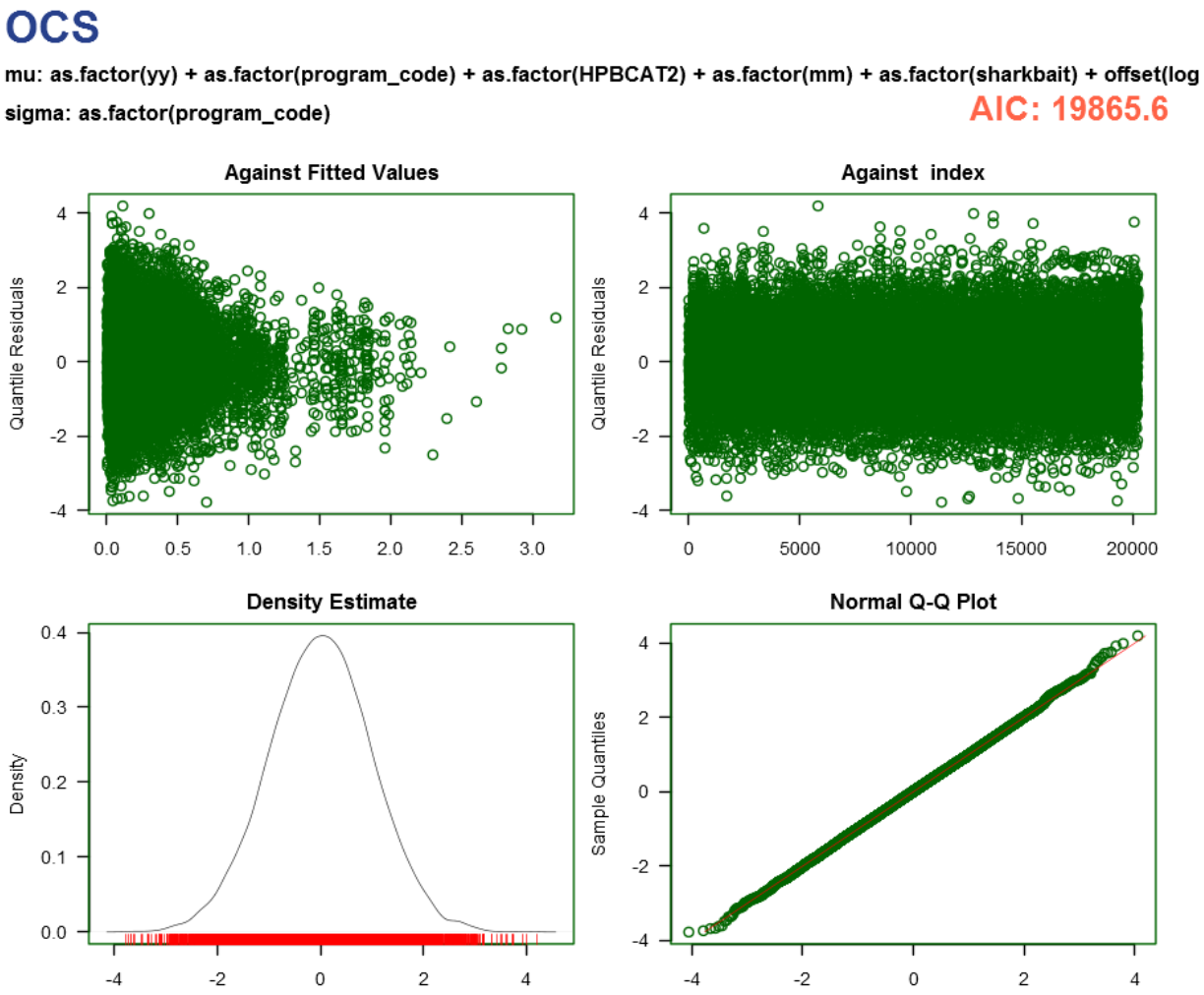


Figure 92: CPUE indicators, model diagnostics for oceanic whitetip shark CPUE standardization via negative binomial model.

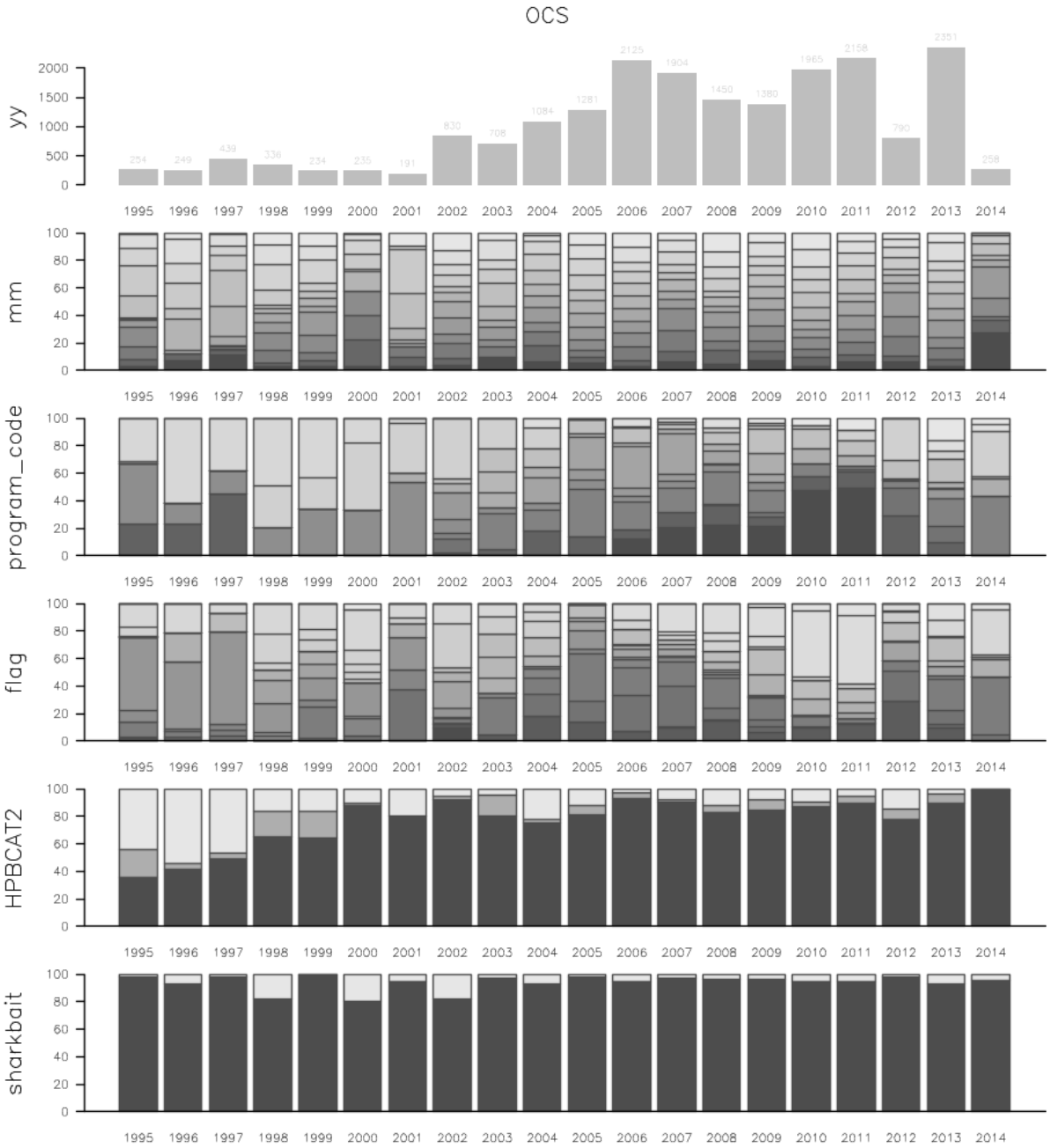


Figure 93: CPUE indicators, model diagnostics for oceanic whitetip shark CPUE standardization via negative binomial model.

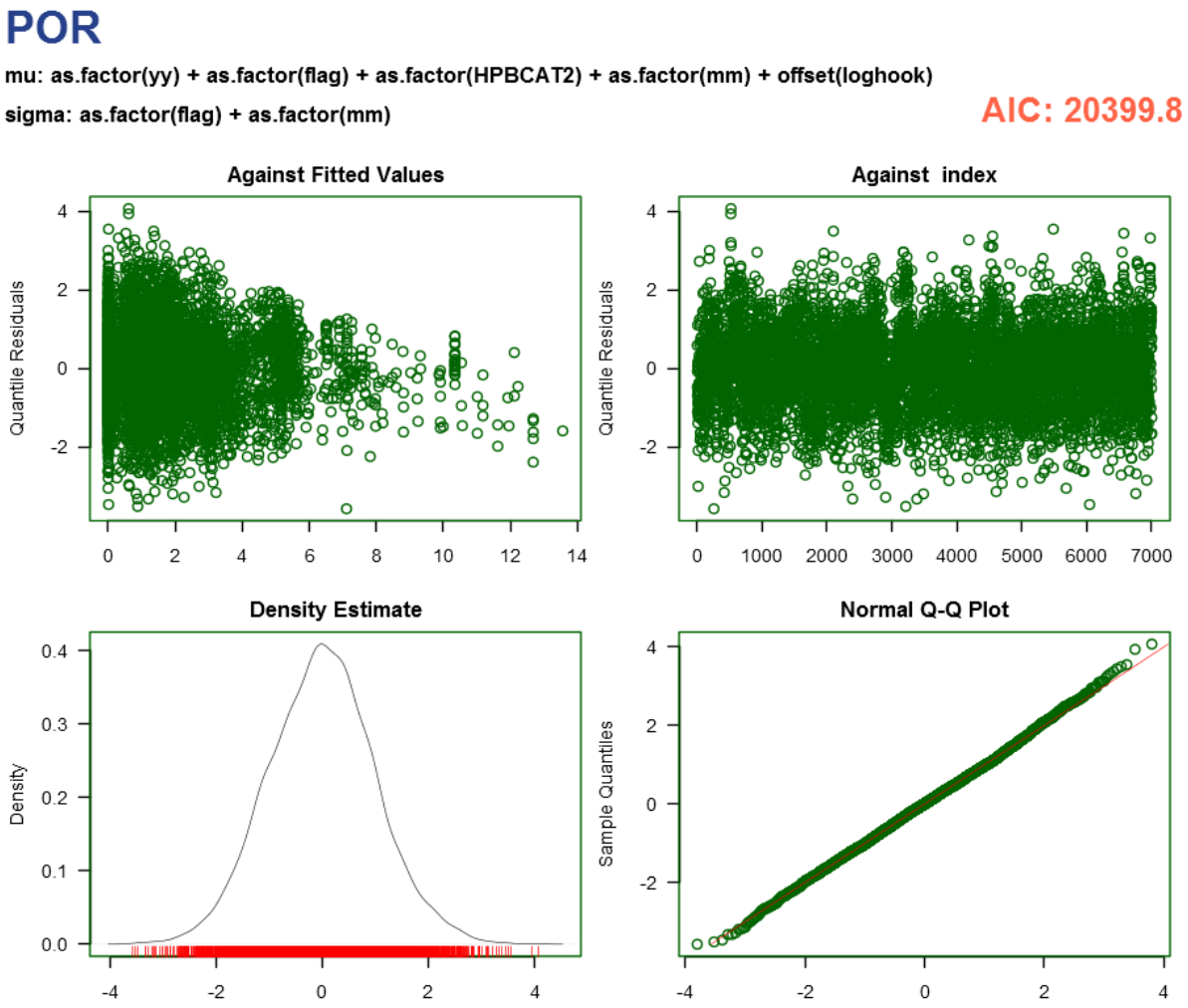


Figure 94: CPUE indicators, model diagnostics for porbeagle shark CPUE standardization via negative binomial model.

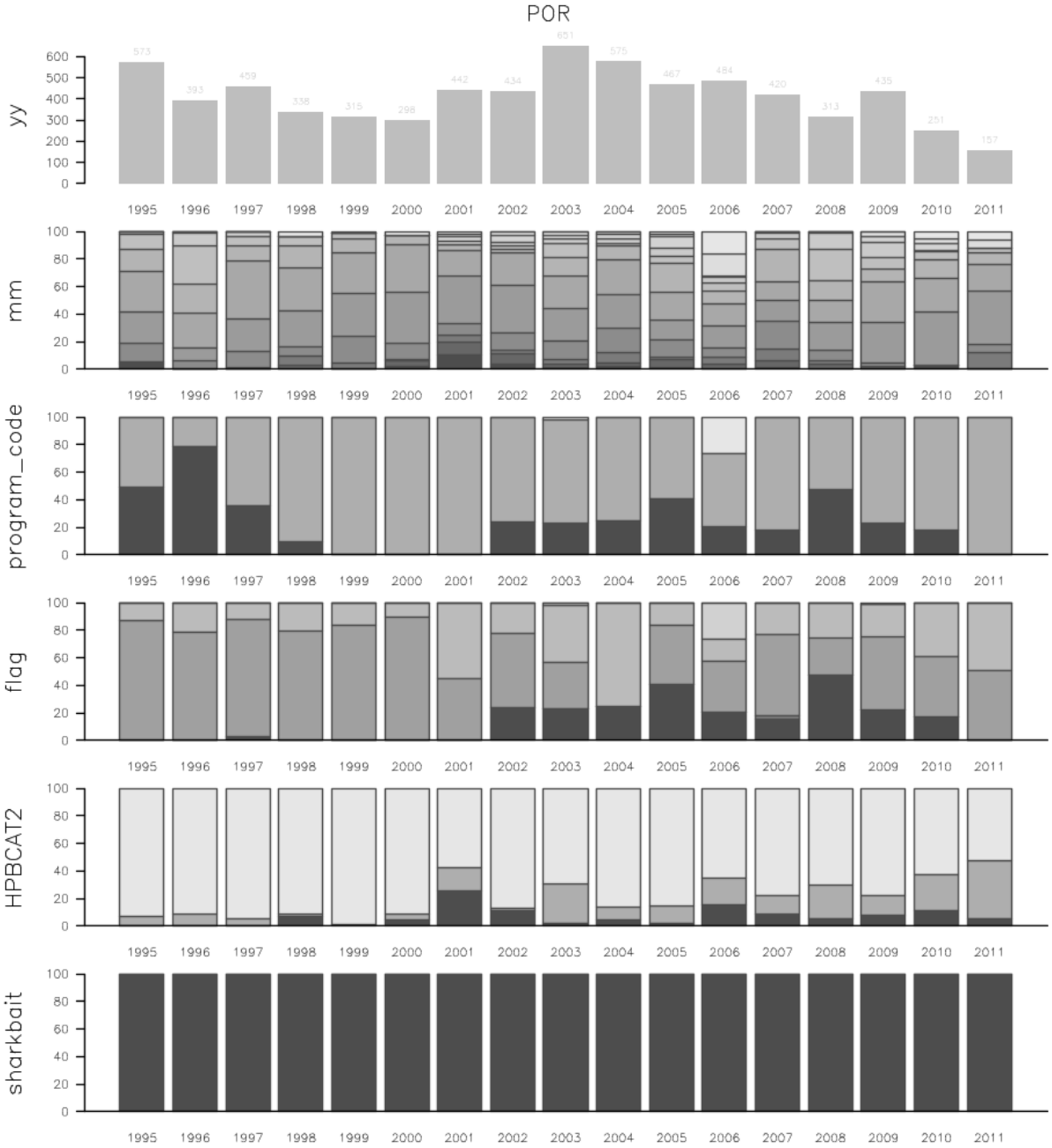


Figure 95: CPUE indicators, model diagnostics for porbeagle shark CPUE standardization via negative binomial model.

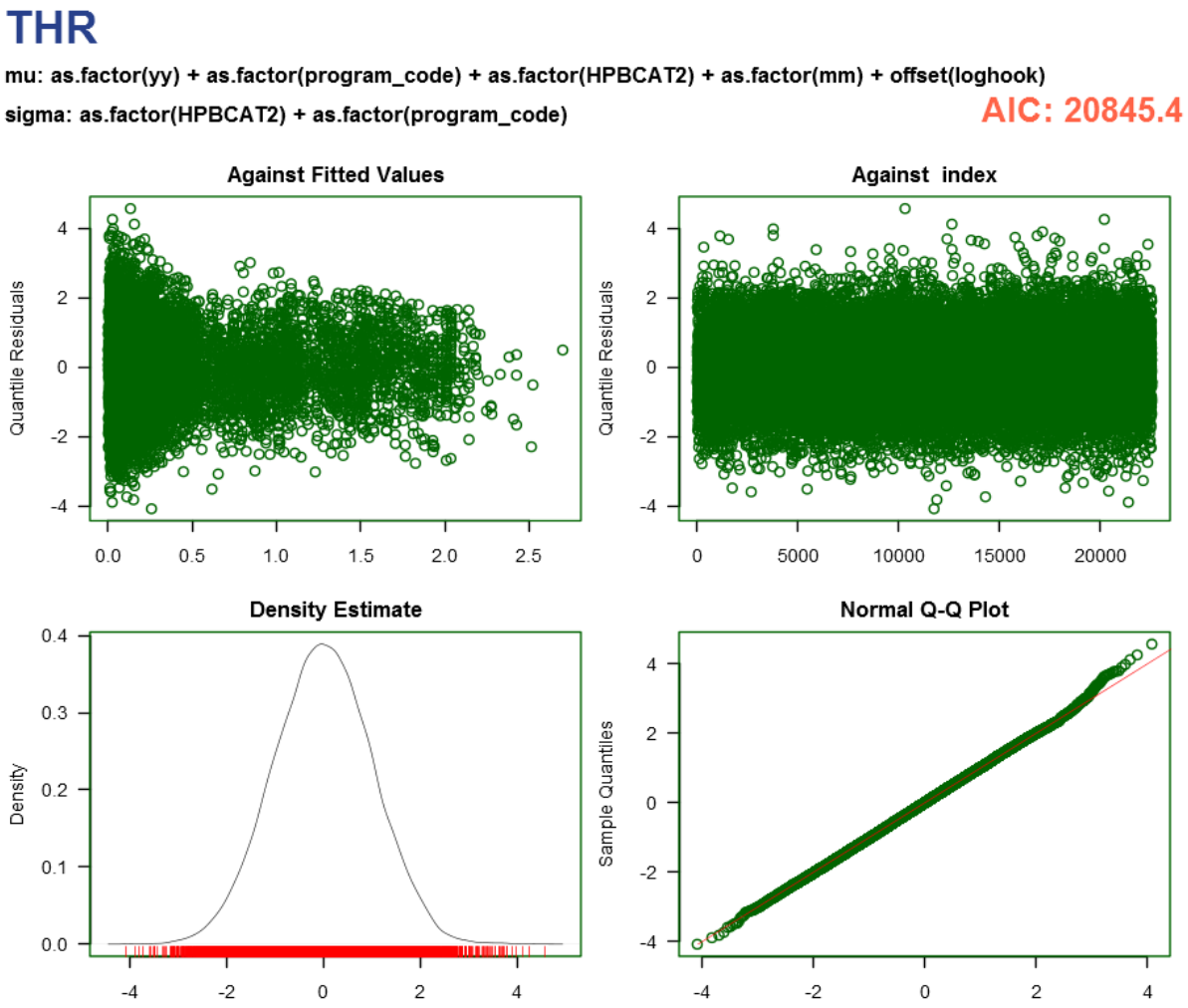


Figure 96: CPUE indicators, model diagnostics for thresher CPUE standardization via negative binomial model.

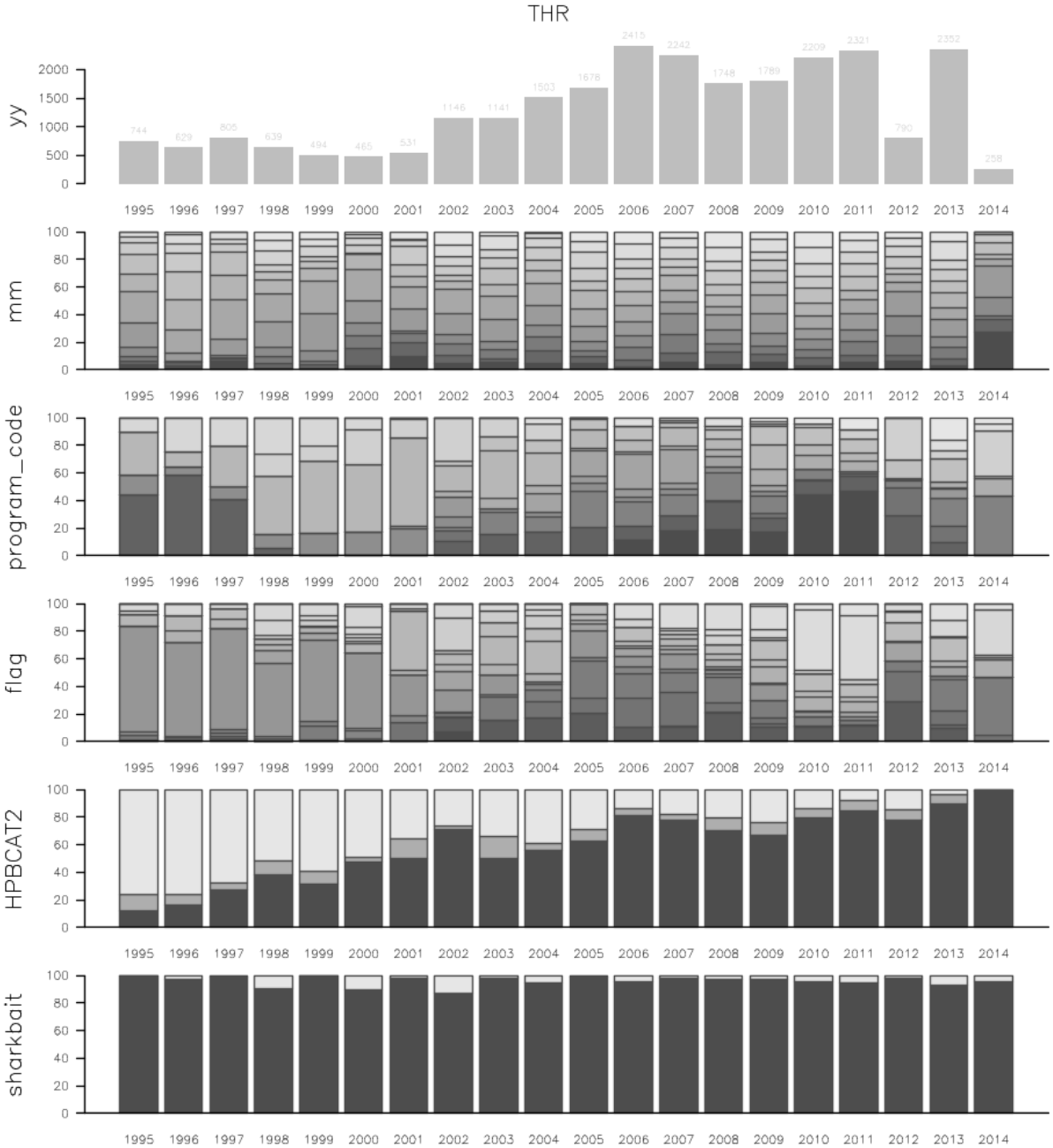


Figure 97: CPUE indicators, model diagnostics for thresher CPUE standardization via negative binomial model.

Table 13: 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 14: 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 15: 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 16: 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 17: 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 18: 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 19: 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 20: 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 21: 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