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An Indicator-based Analysis of Key Shark Species based on Data Held by SPC-OFP

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Abstract

Longline and purse seine logsheet and observer datasets held by SPC-OFP were examined to assess the stock status of eight WCPFC key shark species. Both longline and purse seine logsheet datasets suffer from missing shark catch records and a lack of species-specific recording, therefore the indicator analysis was based on observer data only. Shark data from the observer data sets are, however, also constrained by a lack of representativeness, particularly for the North Pacific, and for the purse seine fishery by the physical practicalities of onboard sampling.

Shark status indicators in four main classes were assessed: range based on fishery interactions, catch composition, catch rates and biological indicators of fishing pressure (e.g. median size, sex ratio). For blue sharks, which dominate longline catches in most regions, declines in catch rates were observed in nominal and standardized analyses for the northern hemisphere. In the southern hemisphere catch rates declined in the nominal analysis but increased in the standardized analysis in recent years. Both significant increases and decreases in blue shark size were identified. Data for makos in the northern hemisphere were comparatively sparse, although this species is known to be commonly found there. Catch rate analysis showed different trends in different regions and no significant size trends. Oceanic whitetip sharks were once commonly caught in both longline and purse seine fisheries in tropical waters but their presence in observer samples has become increasingly rare over time. Catch rate analyses of data from both longline and purse seine fisheries showed clear, steep declines in abundance. Declining median size trends for oceanic whitetip sharks were observed in all regions and sexes in both fisheries until samples became too scarce for analysis; these trends were significant in the core habitat areas in tropical waters. Silky sharks comprise the largest proportion of the shark catch in both longline and purse seine fisheries in the western tropical WCPO. Silky shark catch rates follow an upward then downward trajectory for both longline and purse seine fisheries. Most catches in both fisheries were juveniles and within the core habitat of the western tropical WCPO significant declines in median sizes were identified for both sexes in both fisheries. The three thresher species have divergent, but not necessarily distinct distributions which, in combination with low sample sizes, produced no clear catch trends for the group. A significant decrease in median size was identified for threshers in tropical areas, most of which are expected to be bigeye threshers.

1. Introduction

This paper presents an analysis of Secretariat of the Pacific Community – Oceanic Fisheries Programme (SPC-OFP) data holdings for sharks taken in longline and purse seine fisheries in the Western and Central Pacific Ocean (WCPO). The framework for the analysis is a series of indicators of fishing pressure and stock status that were first described in the Shark Research Plan presented to the sixth meeting of the Western and Central Pacific Fisheries Commission's (WCPFC) Scientific Committee (SC6; Clarke and Harley 2010). A preliminary indicator-based analysis of SPC data holdings was presented to the Commission in December 2010 (Clarke et al. 2010). The following paper contains an expanded range of indicators, and provides a more detailed and updated analysis of the indicators presented in the previous paper. It is designed to be one of a suite of papers describing the status of sharks in the WCPO which include:

- "Analysis of North Pacific Shark Data from Japanese Commercial Longline and Research/Training Vessel Records" (Clarke et al. 2011a);
- "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" (Walsh and Clarke 2011); and
- "Estimation of Catch Rates and Catches of Key Shark Species in Tuna Fisheries of the Western and Central Pacific Ocean using Observer Data" (Lawson 2011).

The findings of these four papers are integrated and used to discuss potential conservation and management measures in "A Status Snapshot of Key Shark Species in the Western and Central Pacific and Potential Management Options" (Clarke 2011).

The following paper is organized around indicators in four main categories presented for both longline and purse seine fisheries where data allow:

- Fishery Interactions – by species; and by species, sex and life stage;
- Catch Composition – by species; [2]
- Catch Rate – by species in nominal and standardized form by region and by 5x5 degree grid;
- Biological – median length versus length at maturity, trends in size, and sex ratio by species.

These indicators were selected for their potential to represent fishing-induced changes in the status of shark stocks. However, in most cases, the trends in a given indicator may be influenced by a number of factors (e.g. fishing effort (amount and distribution), selectivity or catchability) which do not necessarily reflect a change in the status of shark stocks. For example, a major decrease in the amount of a certain species in the catch may be due to a change in fishing practices rather than an actual decline in the abundance of that species. Removing potential sources of bias from indicators is a complicated and time-consuming task which, in this analysis, was only attempted for some of the catch rate and biological indicators. Even with perfectly standardized indicators, a complete and accurate picture of shark stock status is best obtained using a stock assessment model, as is planned for the next step in the Shark Research Plan. Meanwhile, indicators such as those presented here, when examined as a set and

[2] Estimates of shark catches are provided in Lawson (2011).

considered under a preponderance of evidence approach, can provide for early identification of trends of concern. Identification of similar trends in other datasets, such as those analysed in the complementary papers cited above, would further amplify concerns and could provide a basis for conservation and management measures prior to the availability of the stock assessment results.

The shark species included in this indicator-based assessment are the original eight key shark species designated at the time the Shark Research Plan was formulated: blue (*Prionace glauca*); shortfin (*Isurus oxyrinchus*) and longfin (*I. paucus*) mako; oceanic whitetip (*Carcharhinus longimanus*); silky (*C. falciformis*); and bigeye (*Alopias superciliosus*), common (*A. vulpinus*) and pelagic (*A. pelagicus*) threshers. WCPFC7 increased the number of key shark species from eight to 13 (adding porbeagle (*Lamna nasus*) and scalloped (*Sphyrna lewini*), smooth, (*S. zygaena*), great (*S. mokarran*) hammerheads and winghead (*Eusphyra blochii*)), but maintained the focus of the Shark Research Plan on the original eight species until further funding is made available (WCPFC 2010a). In response to a request from SC6, a proposed process for the nomination of key shark species and for determining whether such species should be designated for data provision and/or assessment is provided in Clarke (2011b).

2. Data Description

As described in Clarke et al. (2010), for the purposes of shark indicator assessment, the WCPFC Statistical Area was delineated into six regions based on the regions used in WCPFC bigeye tuna stock assessments. Although these boundaries are somewhat arbitrarily applied to sharks, longlines are the primary gear type catching sharks in the Convention Area (Clarke and Harley 2010) and the WCPO bigeye tuna-targeting fisheries are longline fisheries. Therefore, delineation of shark regions based on the current understanding of operational characteristics of the bigeye-tuna targeting longline fishery provides a reasonable starting point for further analysis. The original boundary between Regions 1 and 2 was fixed at 170^{o}E, however, analysis of Japanese commercial and research/training vessel shark data (Clarke et al. 2011a) identified a block of longline effort in the northwest Pacific extending to 180^{o}E. As Japanese longliners are expected to comprise the majority of the fishing effort for sharks in Region 1, and to avoid biasing analyses for Region 2 by including a fleet that primarily operates in Region 1, the boundary between Regions 1 and 2 was moved to 180^{o}E (Figure 1).

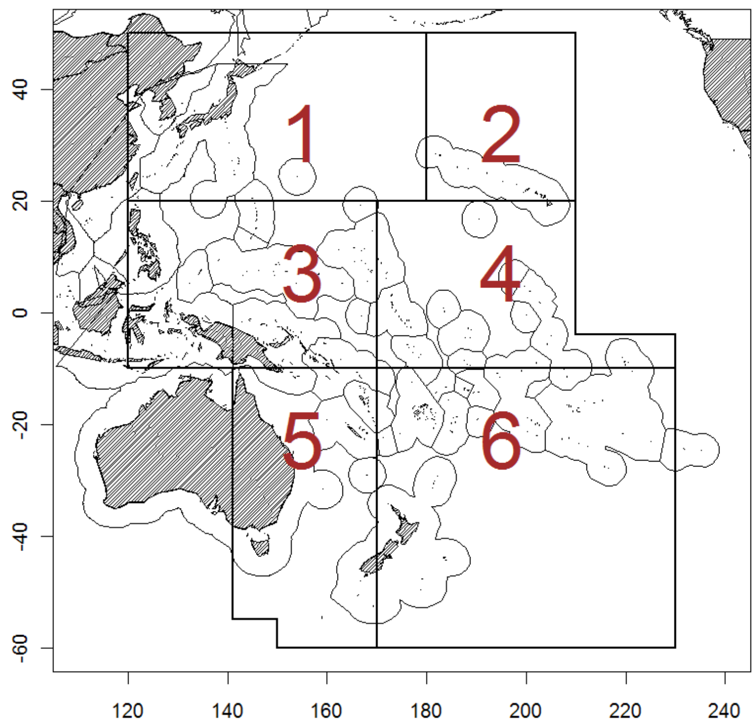

Figure 1. Regional boundaries applied in the indicator-based analysis of SPC-held shark data from longline and purse seine fisheries.

2.1 Longline Fishery Data

SPC holds logsheet data on shark catches by longline fisheries at the operational and aggregate levels. Due to its higher spatial resolution, operational-level data would in theory be preferred for indicator analysis but in this case its geographic coverage is limited due to lack of data provision (Figure 2, all points). The sparseness of operational-level data in the northwest Pacific is immediately apparent, and although coverage in other areas appears well-distributed, operational-level data are in fact only available for ≤35% of the catch in 1995-2009 for the WCPFC Statistical Area as a whole.

Sets for which at least one shark of any type was recorded in operational-level logsheet data held by SPC-OFP are distributed widely throughout the study area (Figure 2, pink points). However, this picture is somewhat misleading due to overplotting as only 37% of the operational-level sets plotted recorded any sharks[3]. Part of the reason for this is that prior to February 2011 sharks were not amongst the species for which data provision was required (WCPFC 2011); since that time data provision for the 13 species designated by WCPFC as key shark species is mandatory. This plot does not distinguish between key shark species and other shark species because only 12% of the sets shown here recorded any species-specific shark catches. Most historical species-specific shark catch data are provided by a small number of flag States (Clarke et al 2011b).

[3] In contrast to this figure, 87% of observed longline sets in the WCPFC Statistical Area reported at least one shark per set.

Sets which were documented by observers were plotted as the upper-most plot layer (Figure 2, orange points)[4]. Under CMM 2007-01, required levels of Regional Observer Programme (ROP) coverage in longline fisheries are set to rise to 5% in June 2012 but annual average values from 2005-2008 have been <1%. With some notable exceptions (e.g. northeast and southwest of Hawaii), most observed sets occurred within Exclusive Economic Zones (EEZs).

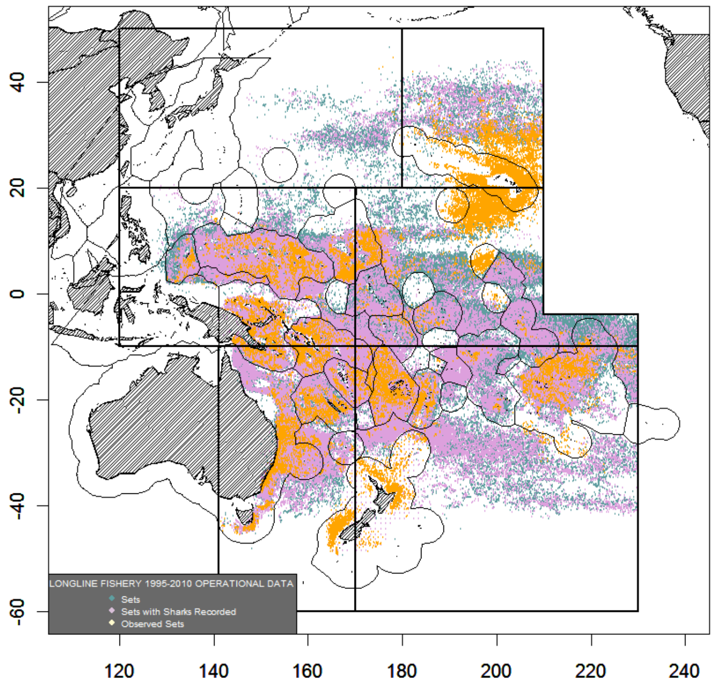

Figure 2. SPC-OFP logsheet data holdings for longline fisheries at the operational level (may be rounded to the nearest 1x1 degree square), 1995-2010, showing location of logsheet-reported sets (green), overplotted by sets for which at least one shark of any species was recorded on the logsheet (pink) and then overplotted by sets for which an observer was present (orange). Data as of 1 July 2011.

Given the relatively low level of coverage in the operational-level logsheets, a more complete characterization of the longline fishery requires the use of aggregated (5x5 degree grid) data. Effort and reported shark catch data by flag at the aggregated level have a lower degree of spatial resolution but in most cases are raised to represent the entire WCPO longline fishery (Figures 3 and 4). Observed sets (i.e. observer present onboard) by flag are shown for comparison but have a finer degree of spatial resolution due to observer recordkeeping.

A comparison by flag of longline effort and the number of sharks recorded was constructed by identifying the top ten flags in each panel and aggregating all remaining flags into an "Other" category (Figure 3). If shark catches are assumed to be proportional to longline effort, and if shark catch reporting practices are similar among flags, it would be expected that the same proportions by flag would be observed in both left and right panels of Figure 3. It has already been demonstrated that there are spatial and species-specific data gaps in the operational-level logsheet data and these gaps are necessarily carried through into the aggregated data. Figure 3 highlights that there is clearly non-reporting and under-reporting of sharks by flag as there are several major longline fishing countries (left panel) which report no or minimal shark catches (right panel). Among these major longline fishing

[4] Observer data submitted by Australia and New Zealand for 2009-2010 have not yet been entered into the database.

countries there are both cases for which the data may exist but have not been provided, and cases for which the data may never have been collected. Although data provision requirements for the key shark species are now in place (WCPFC 2011), this will not necessarily remedy the historical data gaps (i.e. if the data were never collected) and will not necessarily provide a complete picture of shark catches (i.e. as only reporting of key shark species is required). Also, although estimates of discards are required to be reported (WCPFC 2011) the extent of compliance with this requirement is unknown.

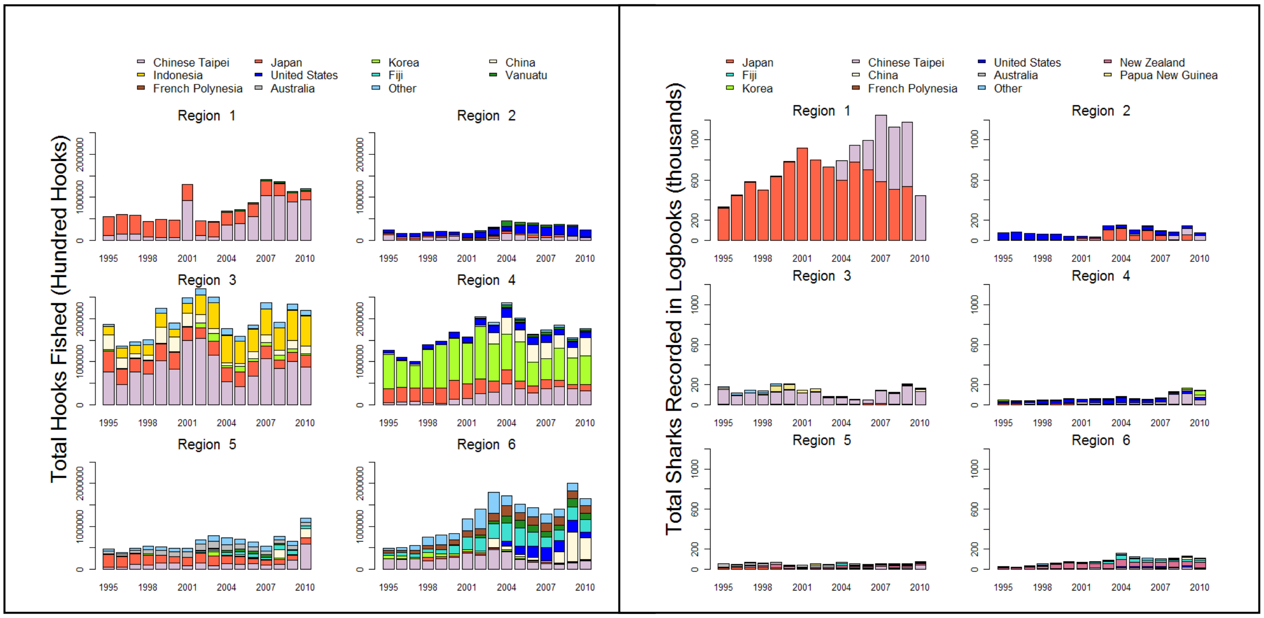

Figure 3. Comparison by region and flag of longline logsheet effort (left panel, in hundreds of hooks) and total sharks recorded on logsheets (right panel, in number of sharks), using aggregated (5x5 degree square) data, for six regions of the WCPFC Statistical Area. Data as of 13 July 2011.

Comprehensive data on shark catches at high spatial resolution are available from observer data held by the SPC-OFP but, as described above, the overall coverage of these data is low. In addition, a comparison of longline effort (Figure 3, left panel) and longline observer coverage (Figure 4) reveals that the latter is disproportional by region and flag and thus cannot be considered representative of the fishery as whole. Another aspect of the low data coverage problem is that a large proportion of the observed effort (37%) derives from United States-flagged vessels in Regions 2 and 4 and due to domestic legal constraints these observer data exist but have not been provided to the SPC-OFP database since 2004[5]. Data from Australia's and New Zealand's observer programmes for 2009-2010 have been submitted but are not yet available in the database for analysis.

[5] It is understood that the US intends to provide longline observer data from April 2010. See Walsh and Clarke (2011) for an analysis of the full US observer database (1995-2010) for silky and oceanic whitetip sharks.

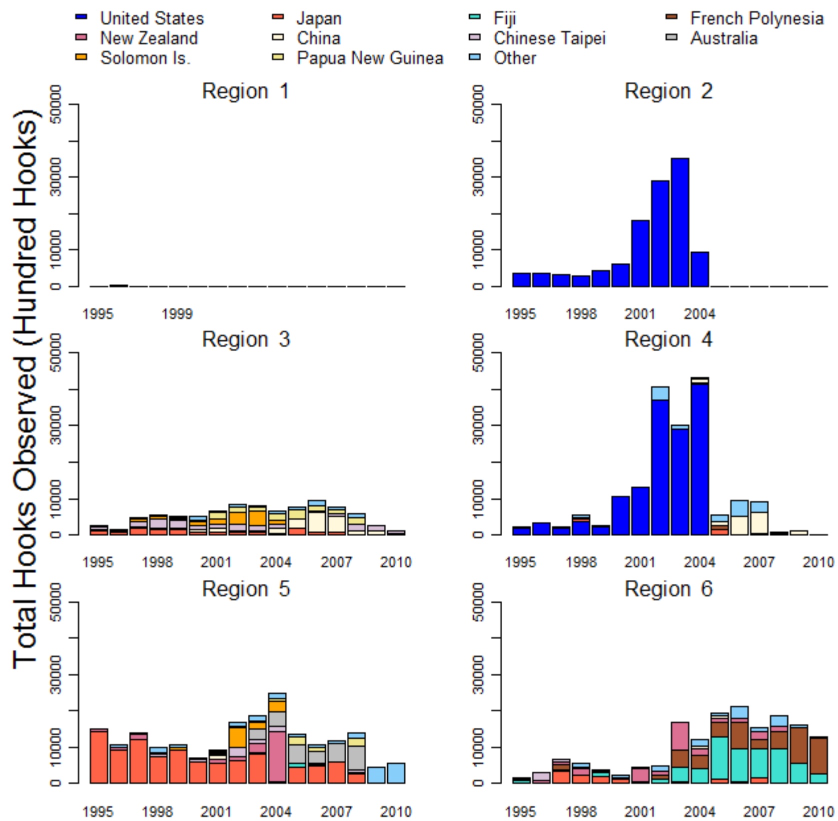

Figure 4. Total number of hooks observed (in hundred hooks) by flag based on longline observer records held by the SPC-OFP, for six regions of the WCPFC Statistical Area. Data as of 1 July 2011.

2.2 Purse Seine Fishery Data

As for the longline fishery, SPC-OFP holds logsheet data on shark catches by purse seine fisheries at the operational and aggregate levels, but operational-level coverage for the purse seine fishery (>80%) is considerably higher than for the longline fishery (≤35%). 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 (Figure 5, green points) than in the longline fishery.

With implementation of the WCPFC ROP on 1 January 2010, in combination with prior observer coverage commitments by Parties to the Nauru Agreement (PNA) members, 100% purse seine observer coverage is now required (except for vessels fishing exclusively in one exclusive economic zone (EEZ). Historical observer coverage in the purse seine fishery has varied between EEZs. Coverage has exceeded 20% in Papua New Guinea but has been generally less than 10% in most other areas (Hampton 2009) with annual averages of 13-16% in 2005-2009. Although observer coverage of the purse seine fishery is not perfectly representative (Figure 2, orange points), the higher coverage levels and the more limited geographic range of the fishery result in more representative observer coverage for purse seines than for longlines (Lawson 2011 (Appendix Figure A2)). 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.

In contrast to the longline operational-level logsheet data in which 37% of recorded sets reported at least one shark, only 2% of purse seine operational-level logsheet sets reported any shark interactions[6] (Figure 5, pink points). Due to inconsistent recording practices it is not possible to assess the number of shark interactions by set or the species involved using purse seine logsheet data.

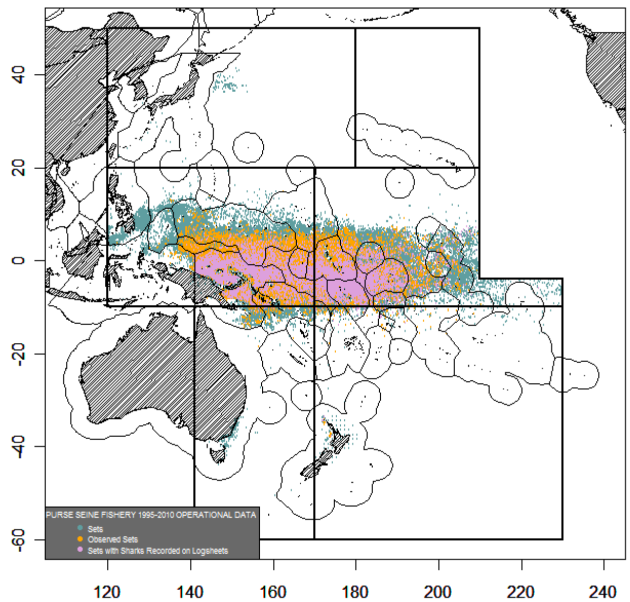

Figure 5. SPC-OFP logsheet data holdings for purse seine fisheries at the operational level (may be rounded to the nearest 1x1 degree square), 1995-2010, showing location of logsheet-reported sets (green), overplotted by sets for which an observer was present (orange), and then overplotted by sets recording at least one shark interaction (pink). Data as of 1 July 2010.

A comparison by flag of purse seine effort and the number of purse seine sets reporting at least one shark interaction was constructed for associated (floating object) and unassociated (free-swimming) sets based on aggregated logsheet data (Figure 6). For each panel, flags were ranked by number of sets and the top ten flags were plotted separately with all remaining flags aggregated into an "Other" category. Although estimated shark catches in the purse seine fishery are considerably lower than shark catches in the longline fishery (SPC 2008, Lawson 2011), it would still be expected that purse seine shark interactions are proportional to purse seine effort. However, from the discrepancies observed between the left and right panels in Figure 6, it appears that some major fishing nations are not submitting or are under-reporting their shark interactions. For example, the majority of the shark interactions in the right panels are reported by the US which only comprises about 12% of the effort in the left panels. This comparison also indicates that according to logsheets, shark interactions occur at a lower frequency in unassociated sets.

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[6] For the purpose of this analysis a shark interaction in the purse seine fishery was defined as a non-zero value recorded for sharks in either number and/or weight, and/or a non-zero value of sharks retained or discarded.

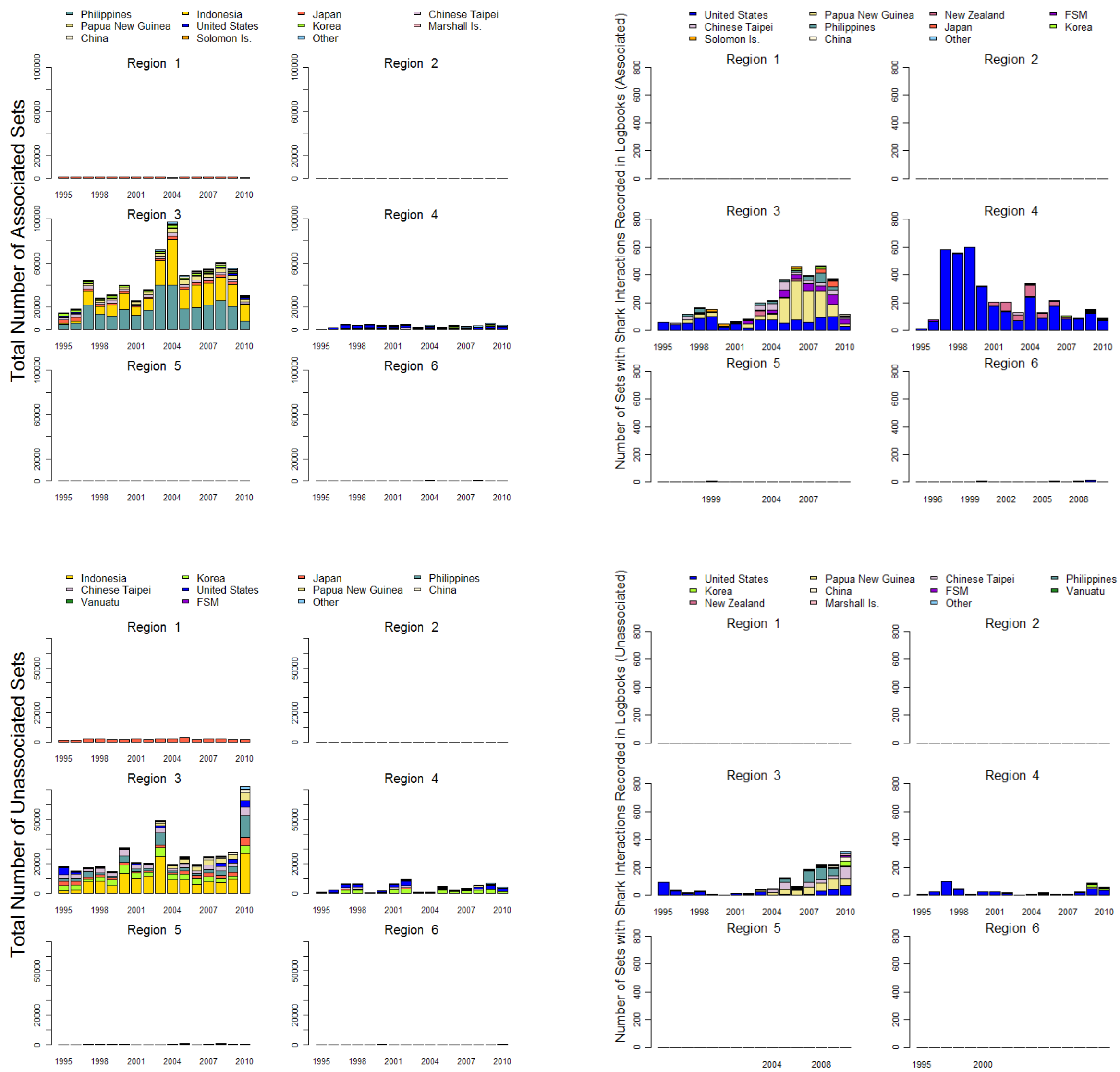

Figure 6. Comparison by region and flag of purse seine effort (in sets) and total sharks recorded on logsheets (in number of sets recording at least one shark interaction), for associated and unassociated sets using aggregated (5x5 degree square) data for six regions of the WCPFC Statistical Area. Data as of 1 July 2011.

Although there is a preponderance of observer records from Papua New Guinea, and from vessels fishing under the Federated States of Micronesia and US multilateral arrangements, observer coverage in the purse seine fishery (Figure 7) is more evenly distributed by flag than is observer coverage in the longline fishery. As discussed above the percentage of coverage by observers on purse seiners is also higher and more representative than observer coverage of the longline fishery. These factors suggest that analysis of purse seine observer data will be informative for sharks, however, practical difficulties in identifying and sampling purse seine-caught sharks which are not brought on board, and the lower shark species diversity encountered in purse seine hauls[7], works against this.

[7] SPC (2008) was able to estimate purse seine catches for only three species of sharks: silky, oceanic whitetip and whale sharks.

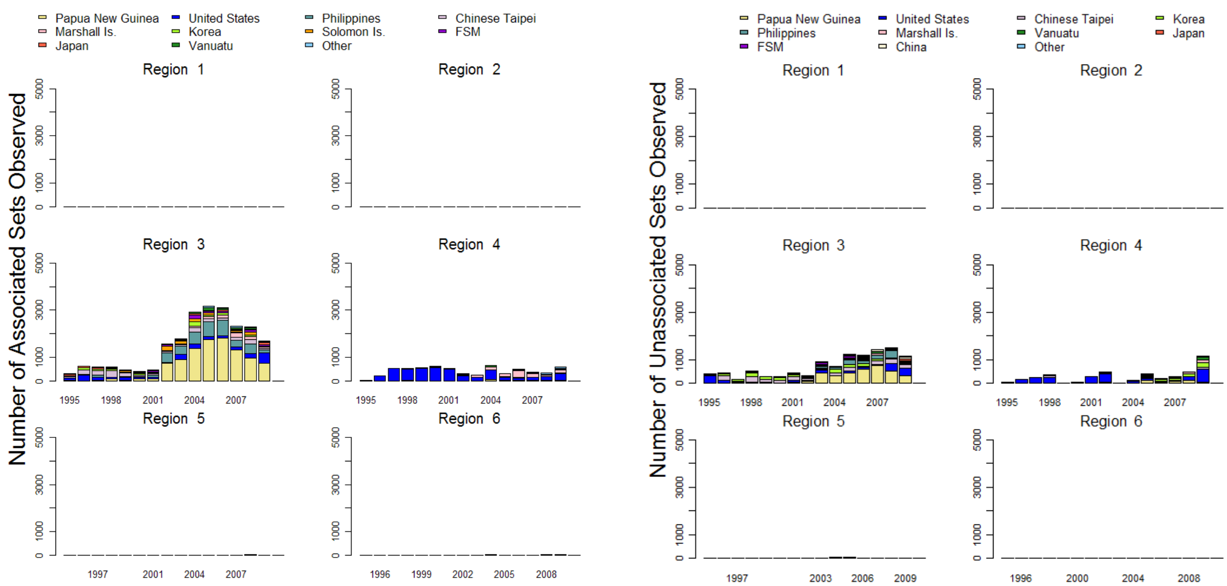

Figure 7. Number of associated and unassociated purse seine sets observed by region and flag based on purse seine observer records held by the SPC-OFP, for six regions of the WCPFC Statistical Area. Data as of 1 July 2011.

This brief introduction to the datasets available to support this indicator-based analysis of SPC shark data holdings has highlighted the following key points:

- Operational-level longline logsheet data have an overall coverage of only ≤35% and have major gaps in coverage for certain areas, particularly the northwest Pacific.
- Aggregated longline logsheet data provide better coverage but lack the spatial resolution essential for some analyses.
- Both operational-level and aggregated longline logsheet data are substantially handicapped by non-reporting, under-reporting and/or lack of species-specific reporting of shark catches.
- Longline observer data coverage is low (typically <1%) and not representative of the WCPO longline fishery as a whole.
- Purse seine logsheet data at the operational level achieves reasonable coverage of the fishery (>80%) but does not provide useful shark data due to lack of reporting or under-reporting of shark interactions.
- Purse seine observer coverage has recently averaged ~15% (2005-2009) and is now mandated at 100%. Observer-derived purse seine shark data are however limited by the physical practicalities of onboard sampling and by the lower diversity of sharks species encountered in this fishery.

Due to the major limitations of logsheet data, the indicator analyses presented in the remainder of this document rely primarily on observer data. The caveats associated with observer data outlined above should be considered when interpreting the results.

3. Indicators of Range based on Fishery Interactions

These indicators examine the geographic range of each species and the habitat usage (in terms of geography only; oceanographic variables are not considered) by different life stages (adult/juvenile) and sexes based on fishery interaction data. Spatial analysis of fish occurrences can be useful in identifying range contractions or expansions which may be linked to fishing activities (Worm and Tittensor 2011). In addition, since many pelagic shark species are known to exhibit sex- and age- specific distribution patterns (Camhi et al. 2008, Mucientes et al. 2009) spatial analysis can highlight areas which are important to key life stages (e.g. presence of adult females and juveniles may indicate pupping grounds; presence of juveniles only may indicate nursery grounds). Both indicators presented below are based on observer data and thus patterns in fishing effort and/or observer coverage may bias the results. These results should therefore be taken as an initial indication of the locations of interactions between these species, sexes and life history stages and the WCPO longline and purse seine fisheries. They can be updated over time to determine if patterns change, and can perhaps be subject to further development to remove sampling biases.

3.1 Fishery Interaction Patterns by Species

Longline and purse seine observer data held by SPC-OFP were plotted at the 1x1 degree scale for approximately 5-year intervals beginning in 1980 for longline and 1993 for purse seine (Annex 1). Although a separate plot was produced for each of the eight WCPFC key shark species there is expected to be some degree of mis-identification for at least the more difficult to distinguish species (i.e. longfin mako, common and pelagic threshers, Galapagos sharks mis-identified as silky sharks, etc.) resulting in either a positive or negative bias. In each plot, the presence of the species is indicated by a coloured point such that the oldest records are in the palest shades and the more recent records are superimposed in darker shades. It should be noted that these maps are not expected to cover the entire distribution of each species as they are based on only those locations for which there was a set conducted and the species was recorded by an observer. Furthermore, while patterns such as a halo of pale points around a darkly shaded core area might suggest a range contraction, such patterns may also be explained by changes in fishing effort and/or observer coverage.

The following points were noted from the plots:

- Blue sharks are frequently encountered in the longline fishery throughout WCPO including in equatorial areas. A concentration of historical (pale) points in the Australian EEZ is likely linked to catches of blue sharks by the Japanese longline fishery operating there at that time and to the closure of that fishery in 1997 (Stevens 1992, AFMA 2008). Blue sharks are only rarely encountered in the purse seine fishery.
- Shortfin makos are also frequently encountered in the longline fishery throughout the WCPO including in tropical areas, but longfin makos are rarer and primarily encountered between 20^{o} N and S latitude. These patterns correspond to the known ranges of these species in the literature (Compagno et al. 2005). Neither species is frequently encountered in the purse seine fishery.
- Oceanic whitetip sharks are found throughout WCPO between 30^{o} N and S latitude. This species is also commonly encountered in the purse seine fishery, particularly in areas just south of the equator.

- Silky sharks have a similar distribution to oceanic whitetips but appear to be concentrated in a narrower latitudinal band between 20° N and S latitude. Silky sharks interact with purse seine fisheries over nearly the entire geographic range of the fishery.
- The most frequently encountered thresher shark is the bigeye thresher which shows a particular area of interaction with longline fisheries south of Hawaii. The common thresher is most often encountered by longline fisheries off Australia and New Zealand. Like the common thresher, the pelagic thresher is infrequently encountered. The pelagic thresher is most often found near 10° N latitude. These ranges of the thresher species are also known from the literature (Compagno et al. 2005). All of the thresher species interact only rarely with purse seine fisheries.

3.2 Fishery Interaction Patterns by Life History Stage and Sex

Using a subset of the longline observer data (i.e. those records containing length and sex data), patterns of occurrence by life history stage and sex were explored (Annex 2). Data for each shark in each cell where it was observed were partitioned into four subsets: adult females, adult males, juvenile females and juvenile males. The lengths at maturity in fork length, and any conversion factors applied to convert measurements given in total length or pre-caudal length, are shown in Table 1. The number of occurrences of each sex-life history stage combination were then tallied for each 5x5 degree cell and screened to remove cells for which the sample size was less than 20 individuals. Due to small 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 and bigeye thresher were chosen to represent each group, respectively, as both observer data and literature sources were greatest for these species. While length at maturity and conversion factors might be expected to vary by sub-region within the WCPO, insufficient data were available to support sub-regional analysis.

Table 1. 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.

	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)

The maps in Annex 2 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). In order to account for seasonal changes, four-panel plots are presented separately for mid-year (May-July) and year-end (November-January); sharks sampled in other months were excluded from the analysis.

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

- Adult blue sharks were more common than juveniles in the waters off Hawaii and at latitudes of 20^{o} S this corresponds to the blue shark mating ground proposed by Nakano (1994); the highest proportion of juvenile blue sharks was found in mid-year (May-July) samples in the southern extremities of the WCPO.
- Juvenile makos of both sexes were most frequently observed in mid-year (May-July) samples in the southern extremities of the WCPO.
- The observed distributions of adult and juvenile oceanic whitetip and silky sharks are similar but samples of silky sharks were particularly skewed toward juveniles in tropical waters.
- Thresher sample sizes were small but were mainly comprised of juveniles in tropical areas.

3.3 Summary of Fishery Interaction Indicator Findings

Interpretation of fishery interaction indicators is complicated by the influence of changes in fishing effort, and perhaps other operational factors influencing selectivity and catchability (e.g. depth and leader material). Furthermore, samples sizes for length and sex information are quite limited for some species. 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. Indicators of Catch Composition

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

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

4.1 Observed Catch Composition in the Longline Fishery

As expected, blue sharks dominated the shark records from the longline fishery, comprising on average 69-91% of the observed catch in Regions 2, 4, 5 and 6 for 1995-2010 (Figure 14, top panel). In Region 3 silky sharks were the most frequently encountered sharks comprising 64% of the observed catch in 1995-2010. Small numbers of mako and oceanic whitetip sharks were recorded in temperate and tropical areas respectively. Thresher sharks, predominantly bigeye threshers, comprised on average 12% of the observed catch in Region 4 but were rarely recorded in other regions. The non-key species observed in Regions 5 and 6 were primarily composed of porbeagles, 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.

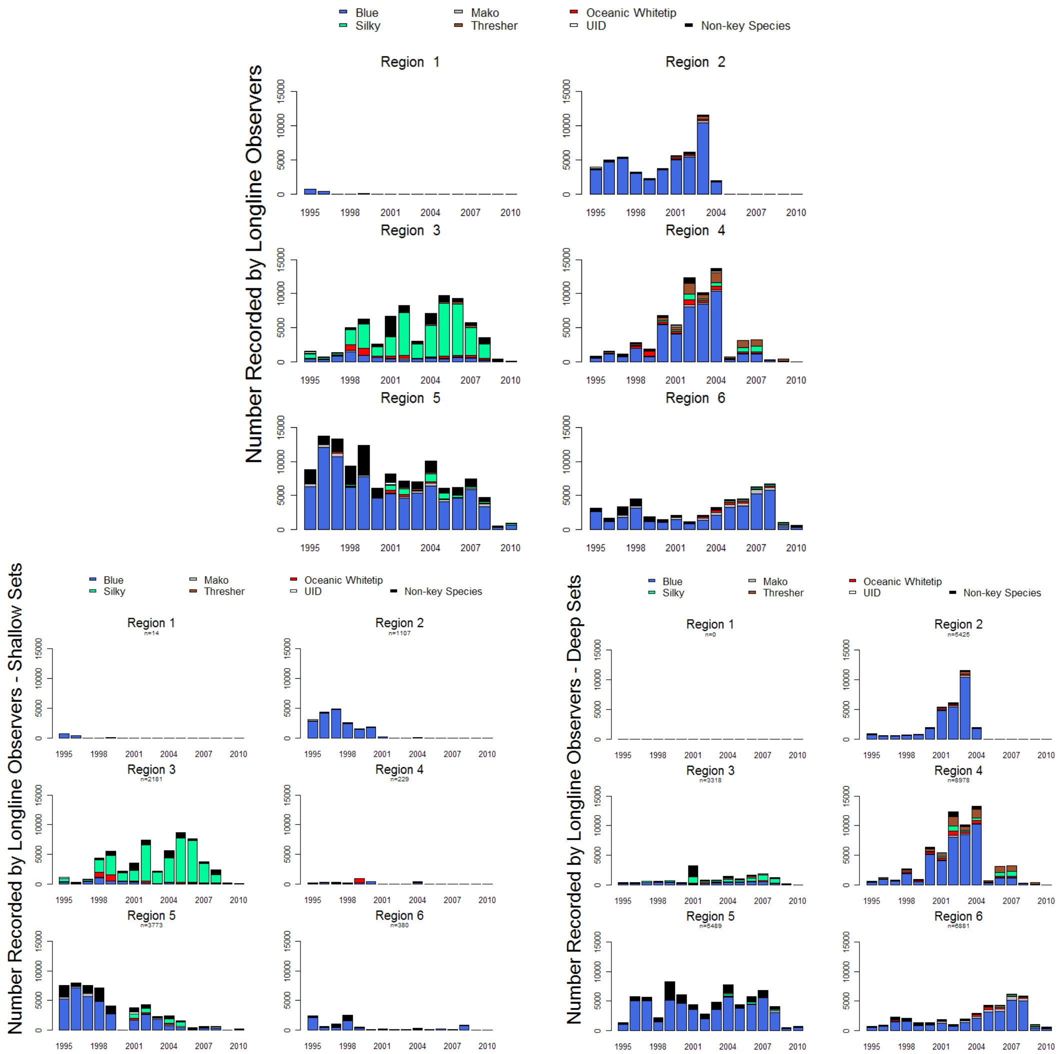

Figure 8. Number of sharks recorded by longline observers in Regions 1-6 during 1995-2010 for all sets combined (top panel), shallow (hooks per basket <10, bottom left panel) and deep sets (hooks per basket ≥10, bottom right panel). Key sharks are shown by species (blue, oceanic whitetip, silky) and genus (makos, threshers) with unidentified (UID) sharks and non-key species as groups.

Species composition is plotted by set depth in the lower panel of Figure 8, using hooks per basket as a proxy variable to separate shallow (<10 hooks per basket) from deep sets (≥10 hooks per basket). This comparison illustrates that although there were more deep sets conducted in Region 3 than shallow sets (n=3,318 versus n=2,181), most of the silky sharks in Region 3 are caught in the shallow sets. The vast majority of sets in Regions 4 and 6 were deep sets and it is these sets which produced the catches of blue and thresher sharks. Shifts in Regions 2 and 5 from shallow to deep sets may reflect changes in fishery regulations in Australia (AFMA 2008) and the US (Walsh et al. 2009), but both types of sets catch primarily blue sharks.

4.2 Observed Catch Composition in the Purse Seine Fishery

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

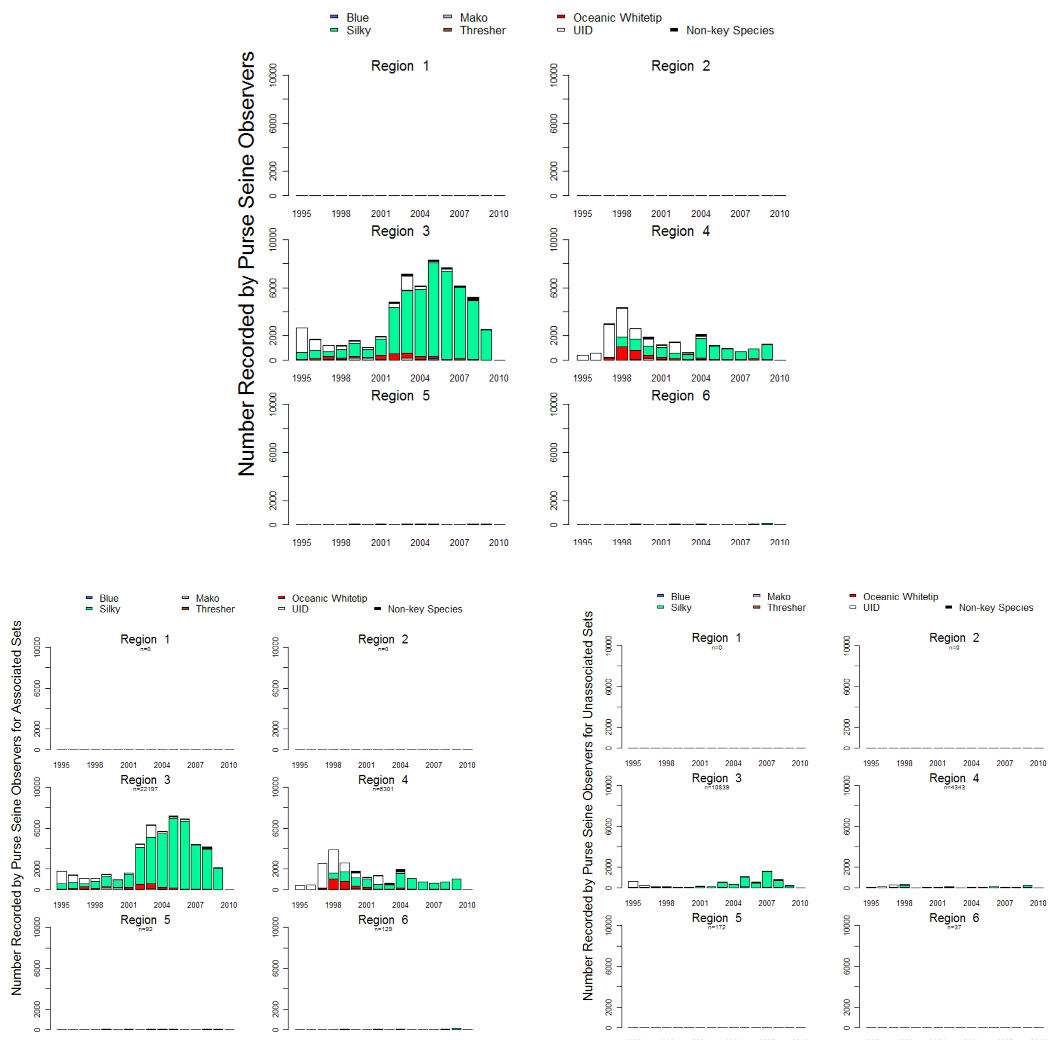

Figure 9. Number of sharks recorded by purse seine observers in Regions 1-6 during 1995-2010 for all sets combined (top panel), associated sets (bottom left panel) and unassociated sets (bottom right panel). Key sharks are shown by species (blue, oceanic whitetip, silky) and genus (makos, threshers) with unidentified (UID) sharks and non-key species as groups.

4.3 Summary of Catch Composition Findings

The observed longline catch composition plots illustrate that blue shark dominate in most regions. An exception to this pattern is Region 3 where silky sharks, primarily from shallow sets, are the most frequently observed species. Although there are some minor differences in species composition between observed shallow and deep sets in other regions (e.g. Regions 2 and 4), these may be related to sampling representativeness. Analysis of observed purse seine shark catches reveals that silky sharks predominate with the majority of these found in associated sets. In previous years, oceanic whitetip shark was the second-most commonly identified shark in associated sets but this species has been only rarely observed in recent years. Substantial numbers of sharks caught by purse seines were unidentified until 2002-2003.

5. Indicators of Catch Rate

Catch rate is one of the most commonly used indicators of population status in fisheries science. Catch rate series are also an important input to most stock assessment models. In its simplest form calculation of nominal catch per unit effort (i.e. dividing the catch per species by the number of hooks fished) can provide some insight into population trends. However, such nominal catch rates can be easily skewed if changes in fishing effort (e.g. shifts to different areas or depths) or changes in selectivity (e.g. use of different fishing gear or setting practices), are not taken into account. Standardization using statistical models is usually carried out to remove such potential biases where possible, but unknown influences may still remain, e.g. due to lack of relevant operational information.

This section presents nominal catch rates for observer data from longline and purse seine fisheries, and standardized catch rates for observer data from longline fisheries. For this indicator-based analysis the priority was given to standardization models which could be applied consistently across the five shark groups and which could be used to predict annual catch rate values with confidence intervals. Several different models were explored including delta-lognormal models in generalized linear form, generalized additive form, and generalized estimating equations; and overdispersed (quasi) Poisson models in generalized linear form. In addition to testing a number of covariates for significance, different forms of these covariates (continuous, categorical, splines, etc) were also tested. Due to observed overdispersion in the data, the generalized quasi-Poisson models were considered to provide the consistently best results and are presented here with diagnostics used to evaluate the fit of the models to the data. The quasi-Poisson standardization models can be taken as a starting point for stock assessment abundance indices but it is possible that they may be out-performed on a species by species basis by other models, particularly if different subsets of data are used or alternative covariates are applied (e.g. the addition of oceanographic factors).

Results for blue, oceanic whitetip and silky shark are presented by species, but mako and thresher sharks are analysed at the genus-level due to lack of species-specific data. For consistency, nominal results for all five shark groups are presented for every region, but in some cases sample sizes appear to be insufficient to generate reliable results and these cases should be interpreted with caution. It should also be noted that the dataset for 2010 is incomplete. As with all indicator analyses based on observer data, the issues of sample size and representativeness discussed in Section 2 have a bearing on their interpretation. A discussion of potential biases in this analysis is presented in Section 5.5.

5.1 Nominal Catch Rates in the Longline Fishery

Nominal catch rates were plotted for each shark by region and year to provide a preliminary indication of abundance trends for the five shark groups (Figures 10 and 11). Catch rates were also computed by depth (i.e. shallow (<10 hooks per basket) and deep (≥10 hooks per basket) subsets) (Annex 3). In Regions 4 and 6, almost all of the sets were deep, but in the other regions (2, 3 and 5) the percentage of shallow sets was non-negligible (17-41%). Species-region combinations for which the catch rates differed markedly between shallow and deep subsets are noted below.

Nominal catch rates for blue sharks show a decline in Regions 2, 3 and 5 for all data combined (Figure 10) as well as for shallow and for deep sets. For all data combined, nominal blue shark catch rates in Regions 4 and 6 are also declining. Trends in nominal catch rates for makos are not clear for Regions 3, 4 and 5 and the apparent decline in Region 2 is found only in shallow sets. In Region 6 mako nominal catch rate trends are driven by declines in deep sets which comprise 95% of the observed sets.

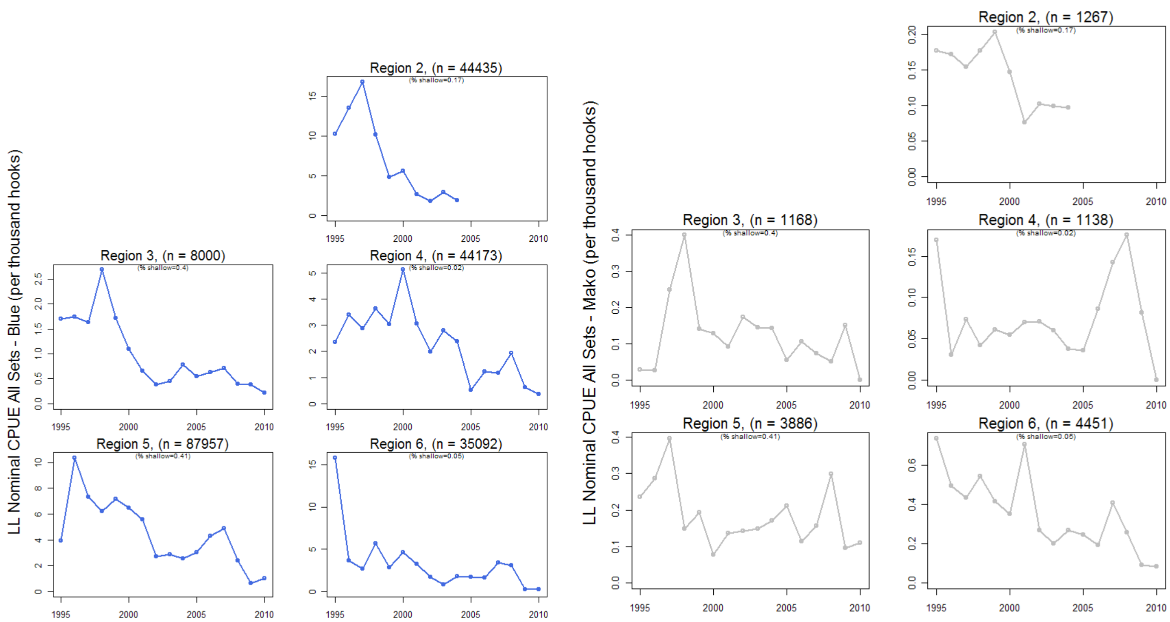

Figure 10. Nominal longline catch rates by region and year by blue (left) and mako (right) sharks. The number of sharks represented in each panel ("n") and the percentage of sets that were shallow sets is annotated.

Catch rates for oceanic whitetip sharks in Regions 3 and 4 (i.e. the core habitat) suggest declines but also contain some high annual values (i.e. 1999) which interrupt the trends (Figure 11). The steep decline in Region 2 should be interpreted in light of the lower frequency of fishery interactions with oceanic whitetips in this area (see Annex 1). Annual nominal catch rate values for silky sharks vary considerably such that overall there is no clear trend for their core habitat area (Regions 3 and 4). However, steep declines from peak abundances in 2006-2008 are observed in subsequent, recent years in these areas. Nominal catch rates series for thresher sharks suggest a decline in Regions 2, and in the latter half of the time series in Regions 5 and 6, driven by data from deep sets. It should be noted however that the areas of highest abundance for threshers are elsewhere (Regions 3 and 4). Based on the fishery interaction maps in Annex 1, threshers in Region 2 are likely to be bigeye or pelagic threshers whereas those in Regions 5 and 6 are likely to be common or pelagic threshers (assuming no mis-identification).

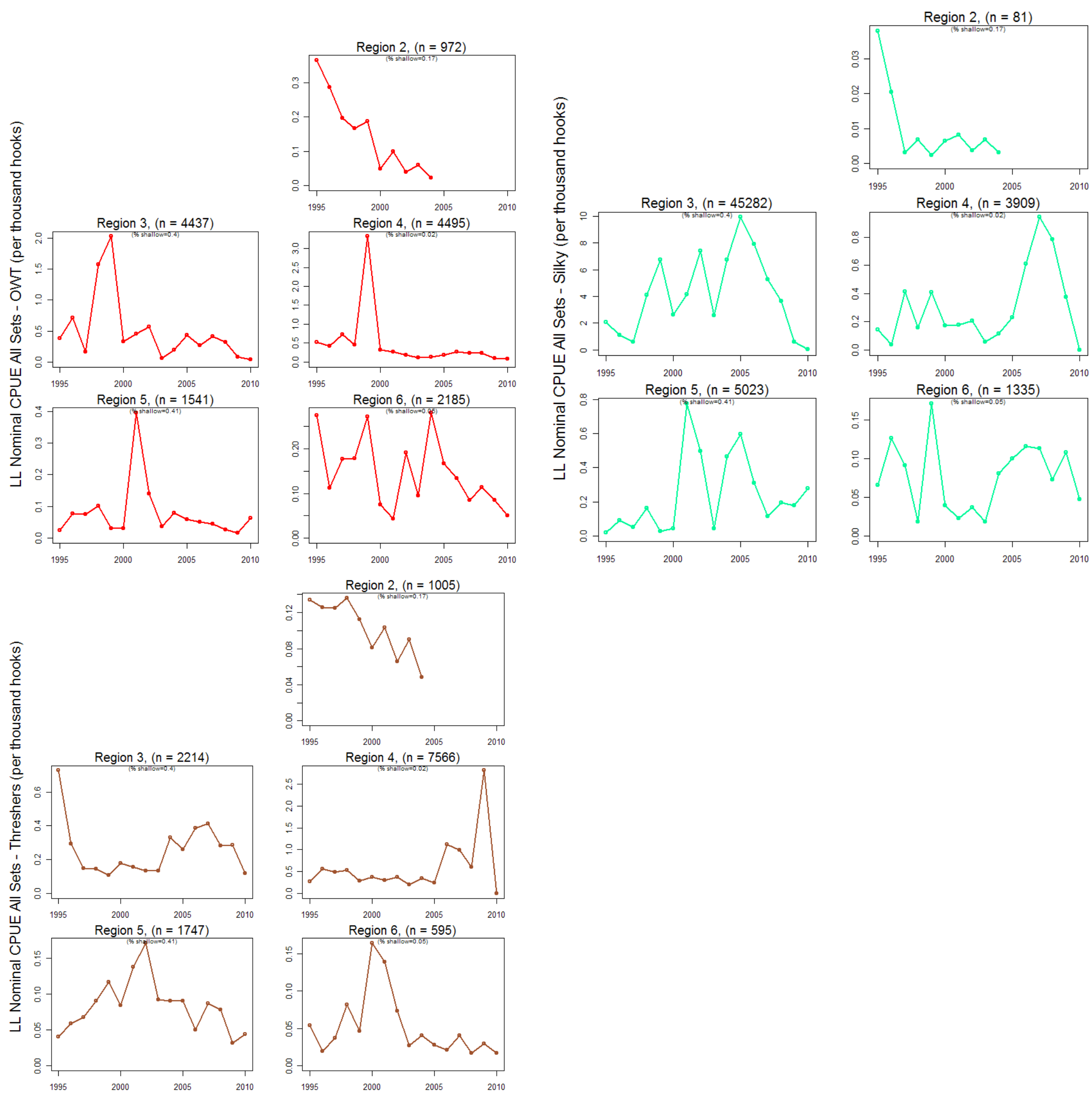

Figure 11. Nominal longline catch rates by region and year by oceanic whitetip (upper left), silky (upper right) and thresher (lower left) sharks. The number of sharks represented in each panel is annotated as "n" and the percentage of sets that were shallow sets is annotated.

In order to explore the influence of latitude on shark catches, nominal catch rates and the percentage of sets with zero catch were plotted by 10 degree latitudinal band from 50° S to 50° N (Annex 4). Each plot shows the number of sets included (i.e. the sample size in each band), the number of sharks represented (i.e. a function of shark abundance and sample size in each band), and the percentage of deep sets (≥10 hooks per basket). The declining trends for blue shark shown in Figure 10 are found throughout the latitudinal bands with the exception of the 30-40° S band. Similar to Figure 10, mako catch rates do not show clear trends by latitude except for the 10-30° S bands where catch rates have declined and zero catches have increased. Oceanic whitetip sharks were mainly found between 30° N and 30° S and exhibit a trend of increasing zero catches and declining catch rates in most bands within this range. Silky sharks are distributed across a narrower latitudinal band between 10° N and 20° S, and while there is evidence for an increase in zero catch sets in the 10-20° S band, the other panels in this range show no clear trend. The different distributions of the three thresher species likely contribute to widely varying trends in thresher catch rates and zero catches by latitudinal band.

5.2 Nominal Catch Rates in the Purse Seine Fishery

Nominal catch rates for the purse seine fishery in Regions 3 and 4 were computed on the basis of number of sharks per set regardless of set type (Figure 12) and for associated and unassociated set types separately (Annex 5). The relatively rare occurrences of blue, mako and thresher sharks in the purse seine observer database can be attributed to the lack of overlap between the fishing grounds and the habitat of these species and/or the lack of selectivity of the gear types for these species. The low sample sizes for these species suggest that these nominal catch rate trends are not useful for characterizing stock abundance for blues, makos and threshers. In contrast, sample sizes for oceanic whitetip and silky sharks are large and more indicative of abundance trends as Regions 3 and 4 overlap their core habitats. Both regions show declining trends: for oceanic whitetip since the early 2000s and for silky since the mid 2000s. The pattern of decline differs between species however, as oceanic whitetip catch rates have declined to very low, near zero values whereas the silky catch rates are similar to low rates recorded earlier in the time series. The analysis by set type (Annex 5) shows approximately ten times more sharks in the sample ("n", a function of both catch and sample size), and two times higher catch rates, in the associated sets versus the unassociated sets.

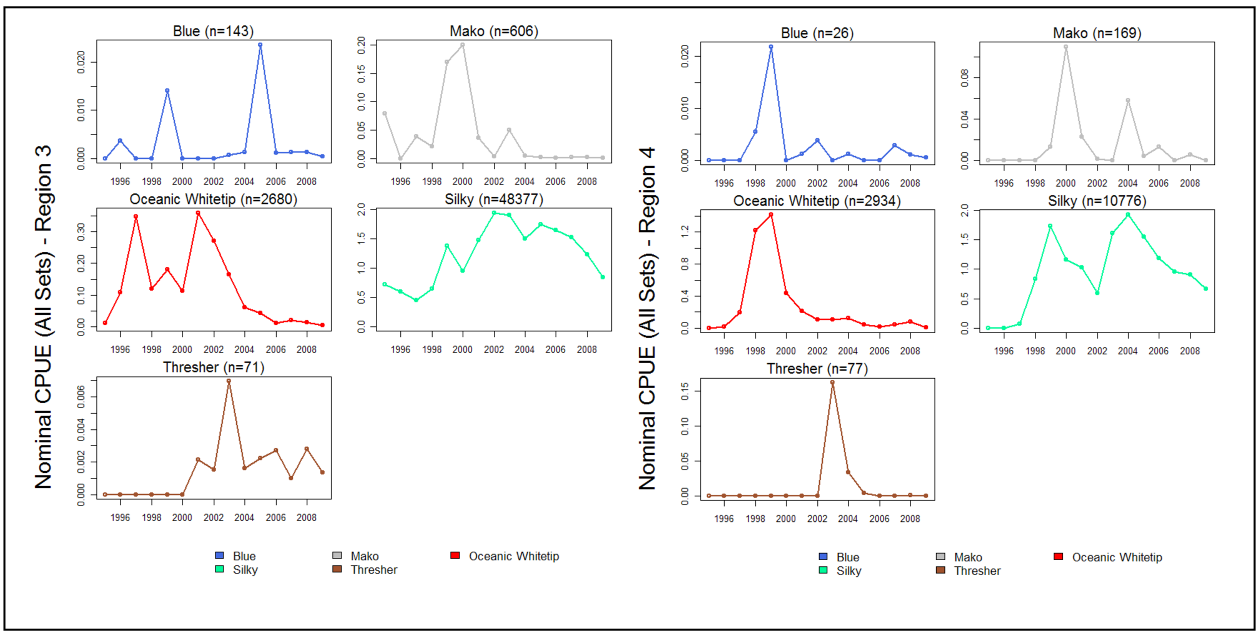

Figure 12. Nominal catch rates of key shark species for all purse seine sets in Region 3 (left) and Region 4 (right), 1995-2009. The number of sharks represented in each panel is annotated as "n".

5.3 Standardized Catch Rates in the Longline Fishery

Longline observer data on catch and effort were used to produce standardized estimates of catch rate by applying a generalized linear model with a quasi-Poisson distribution to allow for overdispersion in the data. Based on observations of different nominal catch rate patterns in northern and southern latitudinal bands for blue and makos, datasets for these species were divided at the equator and run separately.

The response variable in the model was the number of sharks caught per set. Each analysis began with a model containing a standard set of covariates including year, month, hooks per basket, vessel, flag State, time of day at setting, use of shark lines, use of shark bait, whether the set was targeting sharks (as assessed by the observer), latitude, longitude, and total hooks. All but the last three covariates were structured as factors (categories), and latitude and longitude were allowed an interaction term. The total number of hooks was included in the model as a polynomial variable with the degrees of freedom of splines set to five based on an examination of the distribution of hook data. This base model was then evaluated for collinearity using variance inflation factors and marginal testing using analysis of variance to determine which covariates were statistically significant in the model without being highly correlated with other covariates. The base model was then refined using these results and a quasi-AIC (Akaike Information Criterion) statistic to iteratively select the most appropriate combination of covariates. The results of the model selection in terms of the covariates, the overdispersion parameter and the percentage of null deviance explained are presented in Table 2.

Table 2. Covariates resulting from model selection in the quasi-Poisson generalized linear models applied to longline observer data. Statistical significance is indicated with asterisks: ***≤0.001; **≤0.01; *≤0.05; (*)>0.05 (see Annex 6 for details). The quasi-Poisson overdispersion parameter is also shown along with the percentage of the null deviance explained by each model.

Model:	Blue Shark North	Blue Shark South	Mako North	Mako South	Oceanic Whitetip	Silky	Thresher
Covariates:							
Year	X***	X***	X***	X***	X***	X***	X***
Month	X***	X***	X***	X***	X***	X***	X***
Hooks per Basket	X***	X*			X***	X***	X(*)
Vessel Flag State	X***	X***	X***	X***	X***	X***	X***
Time of Day	X***	X***	X***	X(*)	X***	X***	X***
Shark Lines	X***				X***	X***	
Shark Bait		X**			X***	X***	
Shark Targeting				X**	X***	X***	X***
Latitude	X***	X***	X***	X**	X***	X(*)	X***
Longitude	X***	X*	X***	X***	X***	X***	X***
Lat x Lon Interaction	X***	X***	X(*)	X***	X***	X***	X***
Hooks	X***	X***	X***	X***	X***	X***	X***
Overdispersion	4.84	11.55	1.39	2.14	2.26	4.66	2.58
% Null Deviance explained	39%	61%	7%	22%	42%	78%	24%

Model diagnostics for each of the seven models (i.e. two each for blue and mako sharks) are given in Annex 6. It should be noted that the Pearson residuals, the density histograms of residuals and the Q-Q plots all use residuals which have been scaled or standardized to account for overdispersion following methods given in Zuur et al. (2009). In the case of the density histogram of residuals and the Q-Q plot this standardization allows for valid comparisons to the normal distribution.

Based on consideration of the percentage of null deviance explained, the significance of terms in the model, and residuals diagnostics, reasonable model performance was attained for blue (north and south), oceanic whitetip and silky sharks. Poorer performance was observed for makos (north and south) and threshers and thus it is suggested that further work will be necessary to verify the reliability of the standardized catch rate trends presented below. For these species, and also for the oceanic whitetip, the relatively low values of the overdispersion parameter (<2.6, where values >1 indicate overdispersion) suggest that while application of the quasi-Poisson model appears valid, it may not be the optimal formulation of the model for these data.

One advantage of using the quasi-Poisson was the relative simplicity of calculating realistic confidence intervals for the catch rate index. In many catch rates series, the coefficient for each year in the model is used as the mean value for that year in the series (or plot) and the standard error of the coefficient is used to represent the uncertainty in the estimate. However, such an approach by definition produces symmetrical confidence intervals and is highly influenced by sample size such that very large sample sizes often produce extremely tight and unrealistic measures of variability. For the quasi-Poisson models, annual mean catch rates were predicted by fixing the covariates at median or otherwise common (i.e. for factors) values and fixing the number of hooks at 1000. Confidence intervals were generated using the R software 'predict' and 'confint' functions. This results in a time series of actual predicted values of catch per 1000 hooks and their confidence intervals rather than a derived index of relative values.

The model results for blue shark show different standardized catch rate trends in the northern and southern hemispheres (Figure 13). In the northern hemisphere catch rates decline after 1998 but rise again in 2006-2007 to nearly the previous level before dropping to a local minimum in 2008 (2010 data are incomplete). In the southern hemisphere, the standardized catch rate is opposite in trend to the nominal catch rate; it shows an increase from 2004-2008 followed by a sharp decline in 2009. The slope of linear models fit to the year coefficients for the North and South Pacific blue shark standardization models showed an overall trend of -0.14 for the North (p-value = 0.003) and a non-significant result for the South.

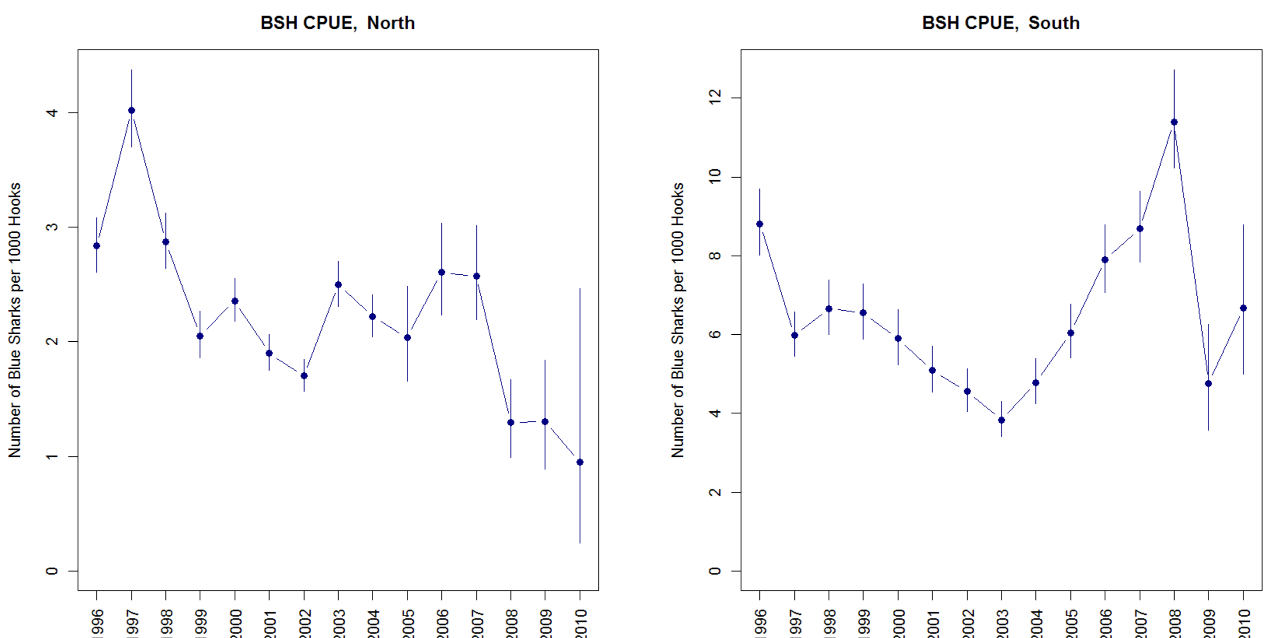

Figure 13. Catch rates for blue shark in the northern and southern hemispheres of the WCPO standardized using a quasi-Poisson formulation of a generalized linear model. For a summary of covariates see Table 2 and for further model details see Annex 6.

For makos in both hemispheres the catch rate trends are highest early in the time series and decline to a variable, but substantially lower level in the late 2000s (Figure 14). Although these standardized trends are more easily interpreted than the nominal indices in Section 5.2.1, poor model performance for makos (Annex 6) cautions against relying heavily on these results. The slope of linear models fit to the year coefficients for the North and South Pacific mako shark standardization models showed an overall trend of -0.08 for the North (p-value = 0.002) and a non-significant result for the South.

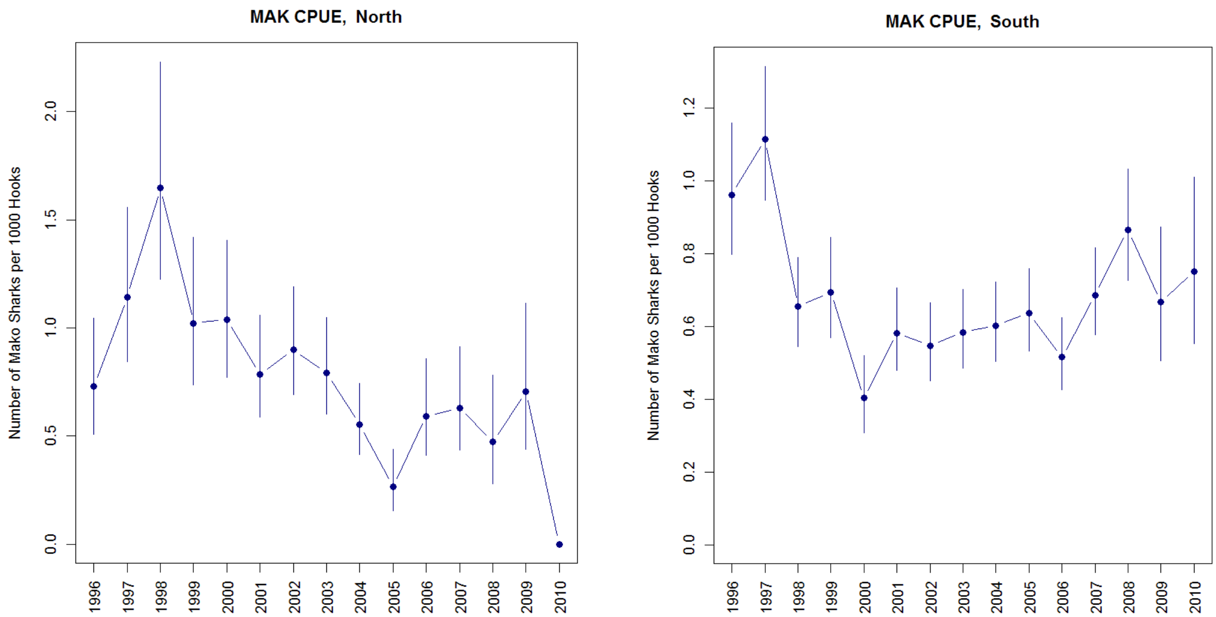

Figure 14. Catch rates for mako shark in the northern and southern hemispheres of the WCPO standardized using a quasi-Poisson formulation of a generalized linear model. For a summary of covariates see Table 2 and for further model details see Annex 6. Note the mean and the confidence interval for 2010 in the northern hemisphere are very near zero.

The standardized catch rates for oceanic whitetip shark show the most obvious pattern of decline: annual values in recent years have decreased to one-tenth of those observed in 1996-1998 with little uncertainty in the estimates (Figure 15). Standardized silky shark catch rates rise in the first half of the time series and decline in the second half with no significant difference between the early and recent annual values (Figure 15; excluding 2010). Although the uncertainty in the silky shark model is greater (i.e. wider confidence intervals on annual estimates), both the oceanic whitetip and silky shark models performed reasonably well and are likely to have produced reliable results (Annex 6). The slope of linear models fit to the year coefficients for the oceanic whitetip and silky shark standardization models showed an overall trend of -0.11 for the oceanic whitetip (p-value < 0.001) and a non-significant result for the silky shark.

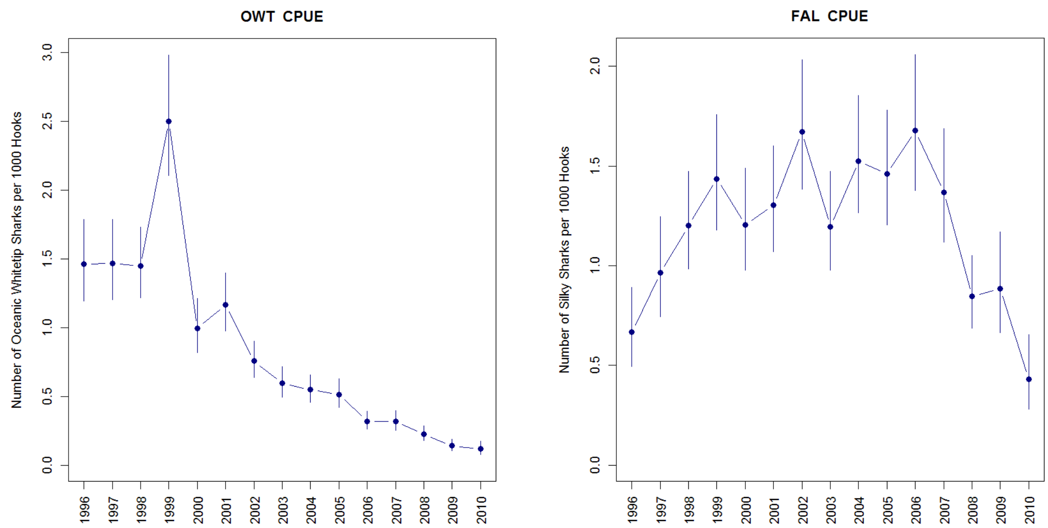

Figure 15. Catch rates for oceanic whitetip and silky sharks in the WCPO standardized using a quasi-Poisson formulation of a generalized linear model. For a summary of covariates see Table 2 and for further model details see Annex 6.

Estimates of catch rates for thresher sharks for 1996-2008 show no trend with nearly all confidence intervals overlapping each other (Figure 16). The final two values in the series, 2009 and 2010, are characterized by wide confidence intervals indicating higher uncertainty. This result, in combination with poor model diagnostics (Annex 6), suggests that further work may be necessary to identify a reliable catch rate trend for thresher species. The slope of a linear model fit to the year coefficients for the thresher shark standardization model showed a non-significant result.

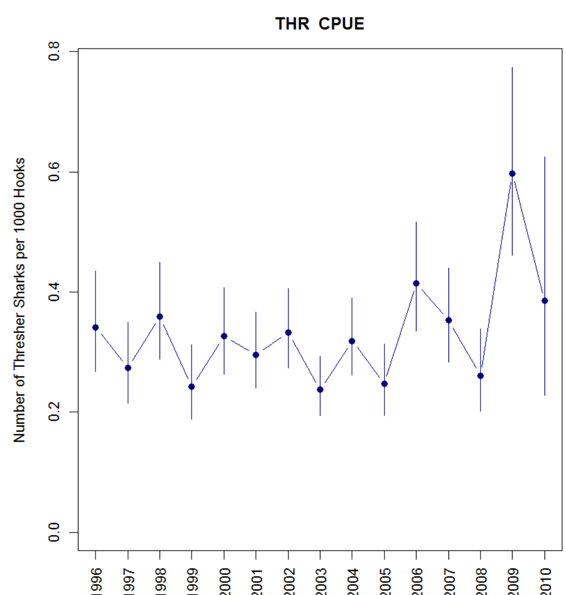

Figure 16. Catch rates for thresher sharks in the WCPO standardized using a quasi-Poisson formulation of a generalized linear model. For a summary of covariates see Table 2 and for further model details see Annex 6.

5.4 Spatial Patterns of Catch Rate in the Longline Fishery

As a final means of examining catch rates, spatial patterns in the longline fishery were examined using the results of the quasi-Poisson model described in Section 5.3 and gridded maps showing the estimated relative (within species/genus) catch rate for each of the five shark groups (Figure 17). The darker areas on these maps indicate the areas of higher catch rates and show a temperate distribution for blue and mako sharks, a tropical distribution for oceanic whitetip and silky sharks, and mixed pattern for thresher sharks, most likely reflecting habitat preferences of the three thresher species.

For the temperate species, existing information including distribution plots (Annex 1) would suggest that patterns of abundance and thus patterns of catch rates for blue and mako sharks would be similar and hemispherically symmetric. However, higher catch rates for both sharks were found more often in the southern hemisphere, with very few areas of high catch rates identified in the North Pacific, particularly for makos. Comparison to results in Lawson (2011), which applied a different method to the same data, shows a similar pattern for makos. For blue shark, however, Lawson (2011) was able to extrapolate for the data-poor northwest Pacific to predict the highest relative catch rates there. For comparison, plots of catch rates from Lawson (2011) are reproduced in Figure 18.

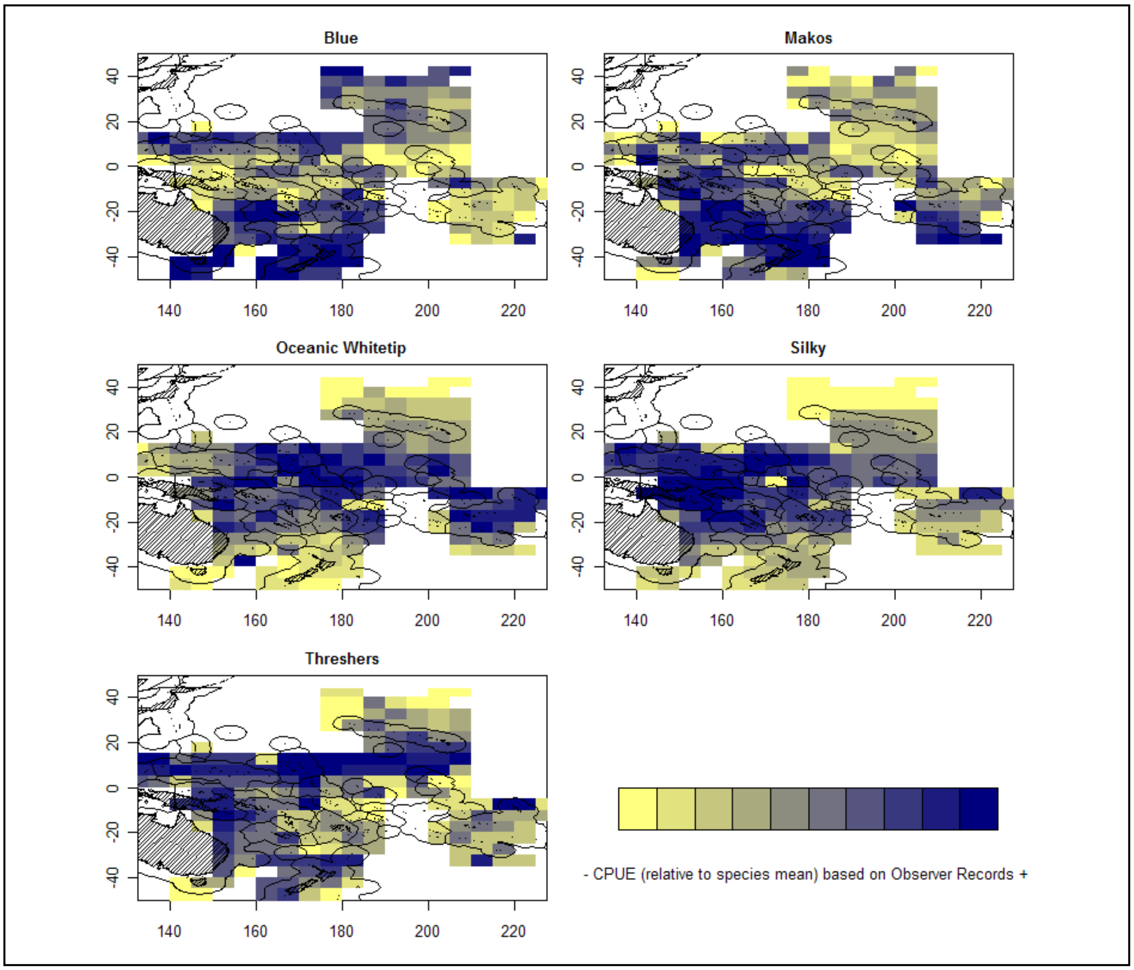

Figure 17. Relative estimates of abundance based on catch rate data standardized using a quasi-Poisson generalized linear model parameterized as shown in Table 2.

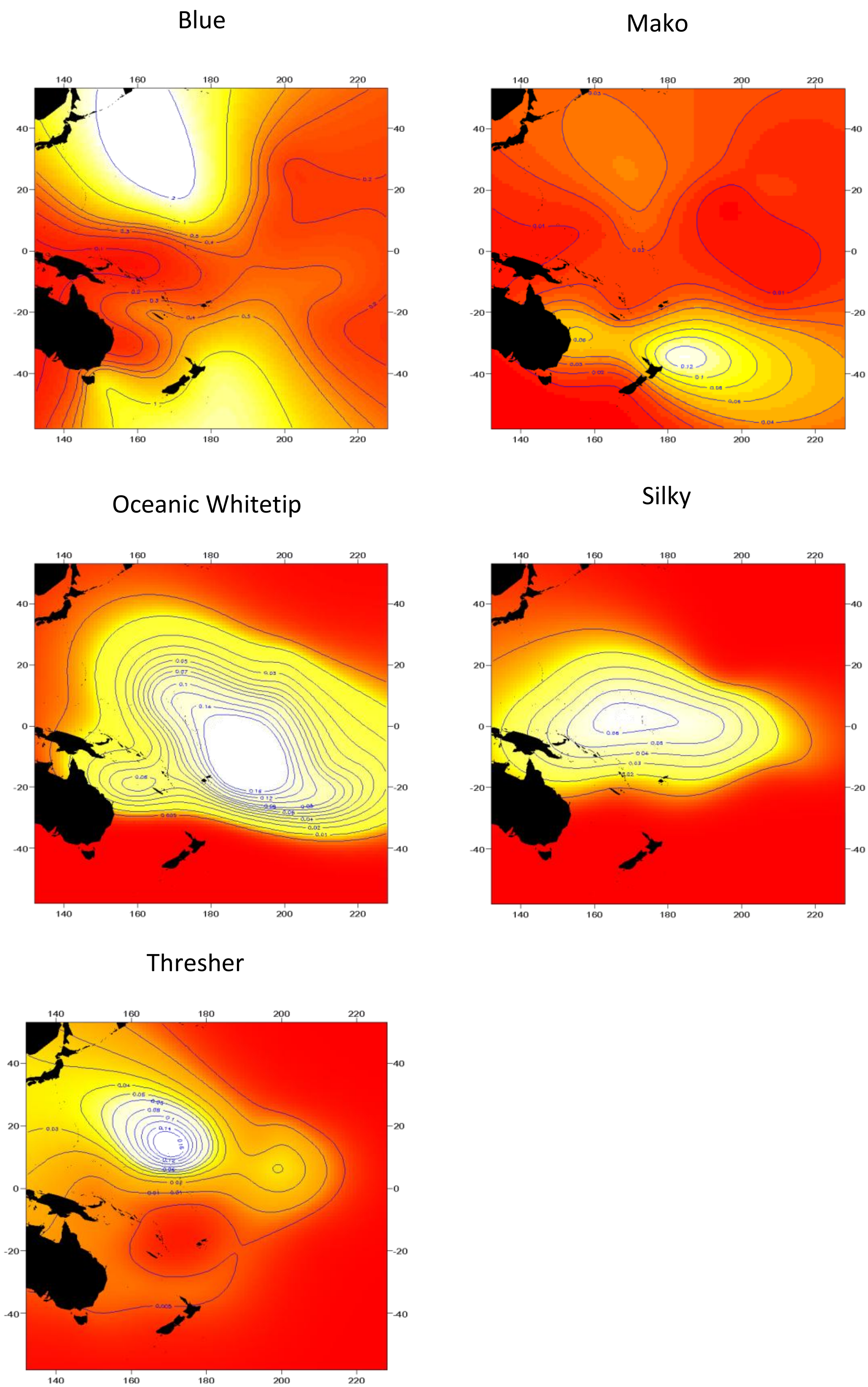

Figure 18. The effect of latitude and longitude on catch rates (sharks per 100 hooks) of key shark species and genera derived from a delta-lognormal model of catch per unit effort with splines (see Lawson (2011) for details).

Tropically distributed species such as the oceanic whitetip and silky sharks are less influenced by the data gaps in the observer data sets. Both methods (Figures 17 and 18) predict the highest abundances in the central Pacific near the equator, with the center of the silky shark distribution slightly to the west of the center of the oceanic whitetip distribution. Similarly, both methods show high abundances of thresher sharks at ~15^{o} N and a local concentration of threshers (probably common threshers) north of New Zealand.

5.5 Potential Biases in the Analysis of Shark Catch Rates

A number of potential biases can complicate this analysis of catch rates based on observer data. 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). Many of these biases are introduced in Section 2 of this paper, and others are described in Clarke et al. (2010) and Clarke (2011a). The following discussion summarizes the issues by region and considers their implications for interpretation of the catch rate findings presented in this paper.

In Region 1, Clarke et al. (2011a) found evidence of shark targeting since the late 1990s. This targeting behavior is a critical influence on catch rate trends in the northwest WCPO, but there are almost no observer data available for Region 1, and no catch rate analysis is presented here for Region 1.

In Region 2, biases arise for some fleets from the 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; and the unavailability of US observer data since 2004. Most of the observer data for the North Pacific, and all of the observer data for Region 2, available for this analysis derived from US fishing operations. In order to account for these potential biases, catch rates were standardized using flag, year, area and hooks per basket (set depth) covariates (among others) which attempted to remove the influence of these factors on catch rates. For blue shark, the species with the greatest abundance in Region 2 (see Figure 8), the standardized catch rates for the North Pacific show two periods of substantial decline, 1997-1999 and 2007-2008. Neither of these periods corresponds to the timings of potential bias factors. Furthermore, it is noted that an analysis of the Hawaii longline fishery observer data from deep sets only from 1996-2006 also found a decline in blue shark catch rates (Polovina et al. 2009), as did Clarke et al. (2011a) for the Japanese research and training vessel data in the waters surrounding Hawaii from 1992-2008.

Potential biases in Regions 3 and 4 are mainly associated with changes in shark recording practices of observers. For example, it is possible that the observed increase in silky shark catch rates in the purse seine fishery from 1998-2004 (Figure 12) may be due to increased species-specific recording of silky sharks or increased recording of sharks which are not brought onboard. The purse seine observed species composition plots in Figure 9 suggest that species-specific recording is not an issue. However, non-and under-reporting of sharks by observers prior to 1995, and the gradual correction of this problem after 1995, may have contributed to the increase in catch rates observed for both oceanic whitetip and silky sharks through the mid 2000s. For these reasons, sharply increasing catch rates in the early part of the time series, particularly for purse seine fisheries, may be suspect and should be accorded less weight than more recent records.

Potential biases in Region 5 are many. These issues consist of the suspension of the Japanese distant water longline fishery in the Australia EEZ in 1997[8], the imposition of a trip limit for sharks and a ban on finning by Australia in 2000, and the banning of wire leaders by Australia in 2005. Another bias may arise from the changes in observer coverage resulting from the closure of the Japanese fishery in the Australian EEZ. Although these effects may have been removed or partially removed by the standardization models for blue and mako sharks in the South Pacific, these factors may be responsible for the observed declines in catch rates after 1997 (Figures 13 and 14; Lawson 2011). In both cases, however, catch rates in the South Pacific rose again after these changes took place, mainly driven by the fisheries in Region 5 (Figure 10).

There are only two major potential biases known for Region 6: banning of shark fishing (except for makos) by French Polynesia in 2006 and implementation of a quota management system covering blue, mako and porbeagle sharks by New Zealand in 2004. Both might be expected to suppress catch rates but nominal catch rates for Region 6 increased slightly after this time (Figure 10) as did overall catch rates for the South Pacific (Figure 13 and 14).

One last major potential bias is not region-specific. This arises from the apparent decline in the usage of wire leaders in longline fisheries since 2004 (Clarke et al. 2010). The most effective way of eliminating this potential bias would be to include the use of wire leaders as a factor in catch rate standardization models. Since the amount of available data is at present too limited to allow this, it is recommended that longline observers collect better data on gear characteristics so that future catch rate analyses can account for this factor.

5.6 Summary of Catch Rate Findings

After examining this analysis of catch rates for potential biases, the findings can be summarized as follows:

- Blue shark abundance appears to have decreased in North Pacific temperate waters based on nominal and standardized longline catch rates.
- While there is some evidence for similar declines in blue shark abundance for the South Pacific (nominal catch rates), standardized longline catch rates show an increasing trend since 2003.
- It is difficult to draw conclusions about mako shark abundance trends because of variable patterns in nominal catch rates and poor performance of the standardization model for longline data; these problems are particularly apparent in the North Pacific and may relate to a lack of data for this area.
- Oceanic whitetip sharks show clear, steep declines in abundance based on standardized longline catch rates with low uncertainty in annual estimates and robust model performance; similar patterns are observed in the nominal purse seine analyses as well as in the standardized purse seine catch rate trends in Lawson (2011).
- Silky shark abundances increase in the early part of the time series and decrease in recent years to previous levels; similar patterns are observed in the nominal purse seine analysis.
- Catch rate trends for threshers are ambiguous due to poor performance of the standardization model for longline data and varying patterns in the nominal longline analyses possibly reflecting variation in the status and distribution of the three thresher species among areas.

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[8] This fishery was reported by Stevens (1992) to have had sustained catch rates of over 400 sharks per day during some periods of operation.

6. Biological Indicators of Fishing Pressure

The final type of indicator assessed in this study deals with trends in biological characteristics of the stock which may arise as responses to fishing pressure. In theory there are many such biological parameters (e.g. growth, survival and fecundity rates and their inputs), but few are measured by observers on a routine basis. For sharks, the two most useful biological parameters available in the observer database are length and sex. Indicators related to these parameters are described in the following sections. As with many of the indicators discussed in this study, there may be causal factors other than fishing pressure, particularly if trends are not fully standardized to remove other effects such as changes in fishing effort. Therefore, these indicators should not be interpreted in isolation but rather as part of an array of information that as a whole can indicate issues of concern.

6.1 Median Length versus Maturity

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). 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. Length, rather than weight, is preferred as a standardized measure of size because it is not as likely to fluctuate with reproductive or other seasonal factors. The median is preferred over the mean as it is less likely to be influenced by outliers. 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.

For the nominal analysis, length data from both longline and purse seine fisheries recorded in total length were converted to fork length using conversion factors given in Table 1 (see Section 3.2). Literature-based length at maturity values are also shown in Table 1. Those 5x5 degree cells for which the sample size was less than 20 individuals were removed from the analysis. In the purse seine dataset, sexes were not usually recorded and only oceanic whitetip and silky sharks in Regions 3 and 4 had sufficient data for analysis (Figure 19). Results of the nominal analysis of size data for the longline fishery are shown in Annex 7. 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 and bigeye thresher were chosen to represent each group, respectively, as both observer data and literature sources were greatest for these species. While length at maturity and conversion factors might be expected to vary by region within the WCPO, insufficient data were available to support regional analysis.

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 (only) were standardized. This was accomplished using a generalized linear model based on a normal distribution with factors year and 5x5 degree 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. As the model was unable to estimate coefficients for those species, sex, region and year combinations which were not adequately supported by the data, results were only produced for Regions 3-6.

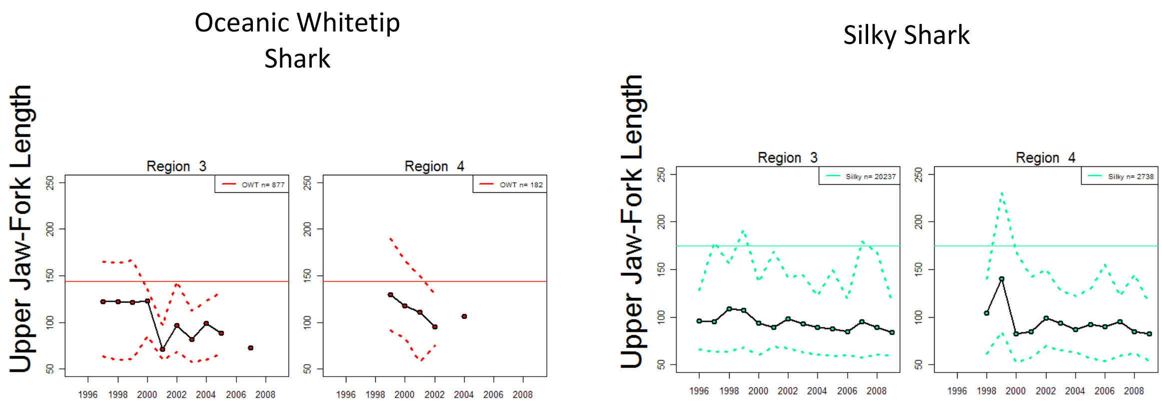

Figure 19. Median length (in fork length) for both sexes (combined) of oceanic whitetip and silky sharks in Regions 3 and 4 based on samples taken from the purse seine fishery, 1996-2009. The 5th and 95th percentiles of the data are shown with dashed lines. Size at maturity is represented by the solid horizontal line. The sample size is shown in the inset to each plot.

In order to the summarise the trends from the length data further, linear models were fit to the year coefficients produced by the standardization models applied to lengths recorded in longline and purse seine samples. The slopes of these linear models were used to identify significant trends in median lengths over time. Models were run separately for each species, sex, region and fishery and a p-value of 0.05 was used to indicate a trend significantly different from zero (Annexes 8 and 9). One important caveat when interpreting the results is that linear models generalize the direction and magnitude of the trend over the entire time series. Therefore, a size trend that rises at the start of the time series and decreases in the later part of the time series may be characterized as having no trend through time. A summary of the results of the linear model fits by species, sex and region is shown in Figure 20.

Blue sharks show varying trends in median size depending on region and sex with most trends toward decreasing size (Figure 20). There have been declines in median lengths for blue sharks in the longline fishery for both sexes in Regions 3 and 5, and males in Region 6, with the trends of males in Regions 3 and 6 being statistically significant (Annexes 7 and 8). Increases were estimated for some regions and sexes, but only females in region 4 had a statistically significant increase. Nominal median lengths in the longline fishery usually fell just above or below the length at maturity depending on the year, except for Region 5 where both male and female median lengths were usually below and Region 2 where both male and female median lengths were consistently above (Annex 7).

Summarized mako size trends were similar to those observed for blue shark with most but not all trends toward decreasing size (Figure 20). Sample sizes for mako shark lengths from the longline fishery were limited in all but Regions 5 and 6. Although median size trends were mostly decreasing, no significant trends were apparent in either the nominal or the standardized results for longline fisheries in these regions (Annexes 7 and 8). While male mako shark median lengths appear to be at or near the length at maturity, the entire 90% confidence interval for female mako sharks lies below the length at maturity (Annex 7). While this result appears to suggest that most female makos in Regions 5 and 6 are immature, it could also argue that more research is required into length at maturity in shortfin mako, e.g. some studies in other oceans indicate female length at maturity as low as 165 cm FL (180 cm TL; Snelson 2008).

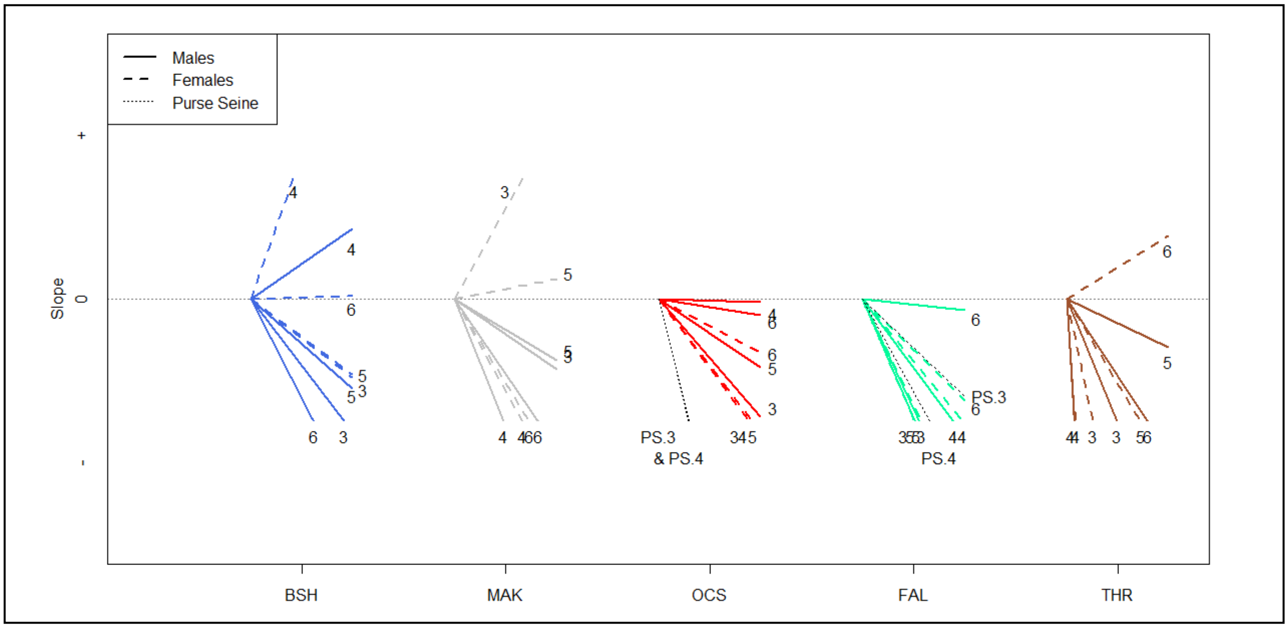

Figure 20. Diagram showing the slopes of linear models fit to year coefficients produced by standardization models of lengths recorded in longline observer samples in Regions 3 through 6, and purse seine observer samples in Regions 3 and 4 (OCS and FAL only, sexes combined), for blue (BSH), mako (MAK), oceanic whitetip (OCS), silky (FAL) and thresher (THR) sharks. Positive and negative slopes lie above and below the dotted line, respectively, with the angle corresponding to the magnitude of the slope. The lengths of the lines are arbitrary.

No positive trends in median size were observed for oceanic whitetip sharks (Figure 20). Length samples for this species were greatest in Region 3 for both longline and purse seine fisheries. In the longline fishery, the estimated trends in median length were declining for both sexes for all regions, with statistically significant trends for females in Regions 3 and 4. Regional medians were near the length at maturity (138 cm for males and 144 cm for females) in the longline fishery. In the purse seine fishery, oceanic whitetip median lengths were smaller than in the longline fishery, and few of the sampled sharks were mature. Both Regions 3 and 4 show decreasing sizes in the nominal data since 2000 with the trend being statistically significant for Region 3 (Figure 19).

Similar to oceanic whitetip sharks, no positive trends in median size were observed for silky sharks (Figure 20). In the longline fishery standardized trends were declining for both sexes in all regions, with statistically significant trends for both sexes in Regions 3 and 5, i.e. the western WCPO. Most longline silky shark samples from the core habitat area (Region 3) were immature, as were many of the individuals sampled from longline catches in Regions 4-6 (Annex 7). Silky sharks sampled from purse seine fisheries in Regions 3 and 4 were also usually immature (Figure 19) and there was a statistically significant decline in the nominal median lengths in Region 3 (Annex 9).

Like blue and mako sharks, threshers showed mostly negative trends in median sizes (Figure 20). Thresher length samples were only available from longline fisheries and were generally few in number. Most thresher median lengths were slightly below the length at maturity but application of a single length at maturity for the most commonly recorded thresher species (bigeye threshers) to the two other rarer species is an approximation that caveats this interpretation (Annex 7). Although samples were limited, standardized results show decreasing median size trends, particularly for females in Region 3 and for males and females in Region 4, both of which showed significant declines (Annex 8).

6.2 Sex Ratios

In addition to plotting median lengths, sex ratios in the form of percent female, were plotted for longline fisheries. Fish sex was not recorded for purse seine biological samples of sharks. The fact that sharks are known to segregate by sex (Camhi et al. 2008, Mucientes et al. 2009) complicates interpretation of sex ratio data by region, as changes in fishing effort within a region could in theory lead to major shifts in sex ratios if habitat boundaries do not correspond closely to regional boundaries. In the absence of such influences, major changes in the sex ratio of the catch and/or a consistently high or low ratio could indicate differential impacts by sex which could upset reproductive patterns.

The sex ratio analysis is limited by small sample sizes in some regions for some species, but generally shows that the percentage of females varies from 40-60% in most years and regions (Figure 21). Exceptions to this include a high percentage of male blue sharks in Region 2 (probably adult), a high percentage of female blue sharks in Region 5 (probably juvenile) and a high percentage of male mako sharks in Region 5 (probably adult; Figure 21 and Annex 7). There are no strong trends observed over time for any species, sex or region.

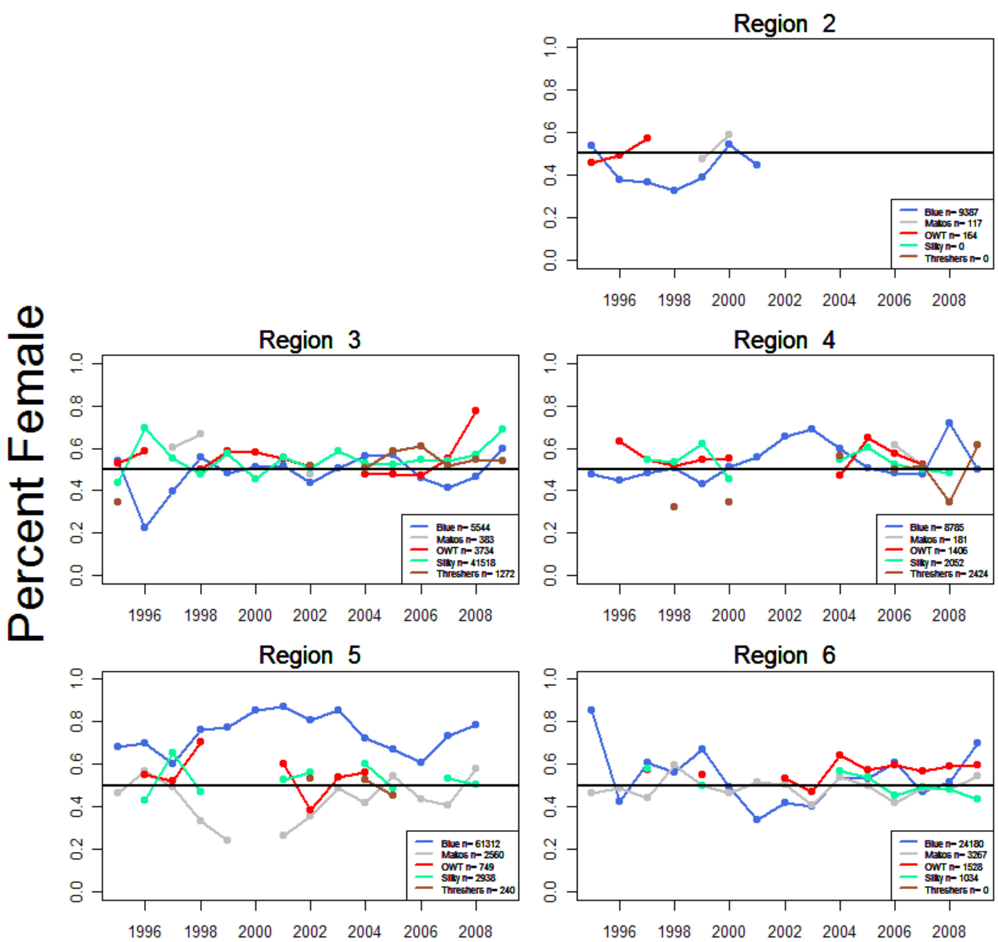

Figure 21. Percentage of sharks sampled by longline observers which were female for five shark groups in Regions 2-6 of the WCPO Statistical Area, 1995-2009. The sample size by shark group and by region is annotated in each panel.

6.3 Summary of Biological Indicator Findings

The results of this analysis of biological indictors can be summarized as follows:

- Blue shark median lengths for males show significant declines for Regions 3 and 6, but a significant increase for females in Region 4.
- Mako shark median length trends are mostly declining, but no significant trends were identified.
- Oceanic whitetip median lengths from the longline fishery show declines for all regions and sexes, but the only statistically significant declines were for females in the core habitat area (Regions 3 and 4). Purse seine samples clearly indicated catches of juveniles with smaller sizes since 2000 in both regions, and trends were significant in Region 3.
- Very few mature silky shark individuals were sampled by either longline or purse seine fisheries observers. Median lengths from the longline fishery show declines for all regions and both sexes, with statistically significant declines identified for the core habitat area (Region 3) as well as for Region 5. Purse seine samples also indicate declining lengths with a significant trend in Region 3.
- Thresher size samples were limited but median lengths show significant decreases in standardized longline data for Regions 3 (females only (but males' p-value is marginally significant at 0.052)) and 4 (both sexes). Differences in length at maturity between the three species may be responsible for the large number of samples which appear to be immature based on length at maturity for bigeye thresher.
- There have been no apparent, consistent trends in sex ratios for any shark group or region over time.

7. Conclusions

This paper examines shark data held by the SPC-OFP for longline and purse seine fisheries in the WCPO in the form of vessel logsheets and observer data. While logsheet data at the operational level is most useful in assessing shark catches and catch rates, such data are available in the longline fishery for ≤35% of the sets in 1995-2009 for the WCPFC Statistical Area as a whole, and there is little or no coverage in the northwest Pacific. Most of the operational-level longline logsheets sets (63%) did not record any sharks. Operational-level coverage in the purse seine fishery is considerably higher (80%), but only 2% 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 in operational-level data, aggregated data (5x5 degree square) were used to characterize effort, observer coverage and reported shark catches 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 fishing countries. It also demonstrated that observer coverage is disproportional by region and flag and thus not representative. 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 is limited by the physical practicalities of onboard sampling and the lower diversity of sharks encountered relative to the longline fishery.

Despite the identified shortcomings in the longline and purse seine observer data, these data formed the basis for an assessment of a number of shark status indicators in four main classes: range based on fishery interactions, catch composition, catch rates and biological indicators of fishing pressure (e.g. median size, sex ratio). The key findings of the indicator analysis are summarized by species as follows:

- Blue shark: This species is frequently encountered in the longline fishery throughout the WCPO but is rarely encountered in the purse seine fishery. It dominates longline catches in all regions except for Region 3. Although it is known as one of the most prolific shark species (Cortés 2002), declines in blue shark catch rates were observed in nominal and standardized longline catches in the northern hemisphere and these could not be linked to any known changes in fishery operations or observer coverage. Blue shark nominal catch rates declined in the southern hemisphere but standardized catch rates rose from 2003-2008. Significant declines in median lengths were identified for Regions 3 and 6, but biological sample sizes for the North Pacific were too limited for meaningful analysis.

- Mako sharks: These sharks (shortfin and longfin makos) were disproportionally observed in the South Pacific, although they are known from other datasets to be common in the North Pacific (Compagno et al. 2005, Semba et al. 2009, 2011). Makos comprised a very small proportion of the longline catch and were even less common in the purse seine fishery. Catch rate analysis showed different trends in different regions, and poor performance of the standardization model perhaps due to a lack of data, particularly in the North Pacific. There were no significant size trends for makos.

- Oceanic whitetip shark: This species ranges between 30°N and S and is commonly caught by both longline and purse seine fisheries, however, records in both fisheries have become increasingly rare over time. A robust model standardizing catch rates for longline observer data demonstrates clear, steep declines in abundance with similar patterns suggested by nominal catch rates in the purse seine fishery and standardized purse seine catch rates in Lawson (2011). Declining median size trends were observed in all regions and sexes in both longline and purse seine fisheries until samples became too scarce for analysis. These trends were significant in for females in the longline fishery (Regions 3 and 4), and for the purse seine fishery (Region 3), for core habitat areas.

- Silky shark: This species' distribution appears concentrated between 20°N and S latitude and it is the predominant shark species caught in WCPO longline and purse seine fisheries in Region 3. These findings as well as fishery interaction and catch rate plots suggest that silky sharks are more abundant in the western equatorial WCPO than in eastern areas. Standardized longline catch rate trends, as well as nominal purse seine catch rate trends, follow an upward then downward trajectory with similar catch rate values in early and recent years of the time series. Most catches in both fisheries are juveniles. Significant declines in median size were identified for both sexes in both fisheries in the core habitat within Region 3.

- Thresher sharks: The three species in the thresher family have divergent, but not necessarily distinct, distributions and interact with longline fisheries throughout the WCPO. Threshers comprise a notable portion of the longline catch only in Region 4, and mainly in deep sets. Catch rate analysis would be better performed by species but was constrained due to limited data and produced no clear trends for the group. Significant decreasing size trends were identified in tropical regions which most likely reflect trends in bigeye thresher.

The indicators assessed in this study provide initial signals of the status of key shark species in the Pacific to the extent possible given available data. Other datasets such as research and training vessel and commercial logbook data held by Japan (see Clarke et al. 2011a), and recent longline observer data held by the United States (see Walsh and Clarke 2011), provide essential supplementary information for the North Pacific. Estimates of WCPO shark catches based on SPC-held observer data (Lawson 2011) and an analysis of shark-related mitigation measures (Clarke 2011a) also supplement this analysis. All of this information can be taken into account when planning for the upcoming WCPFC shark stock assessments beginning in late 2011 (Clarke et al. 2011b). These stock assessments will integrate biological and fishery information in species-specific models which will provide more details on current stock status and can be used to evaluate management options.

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ANNEX 1

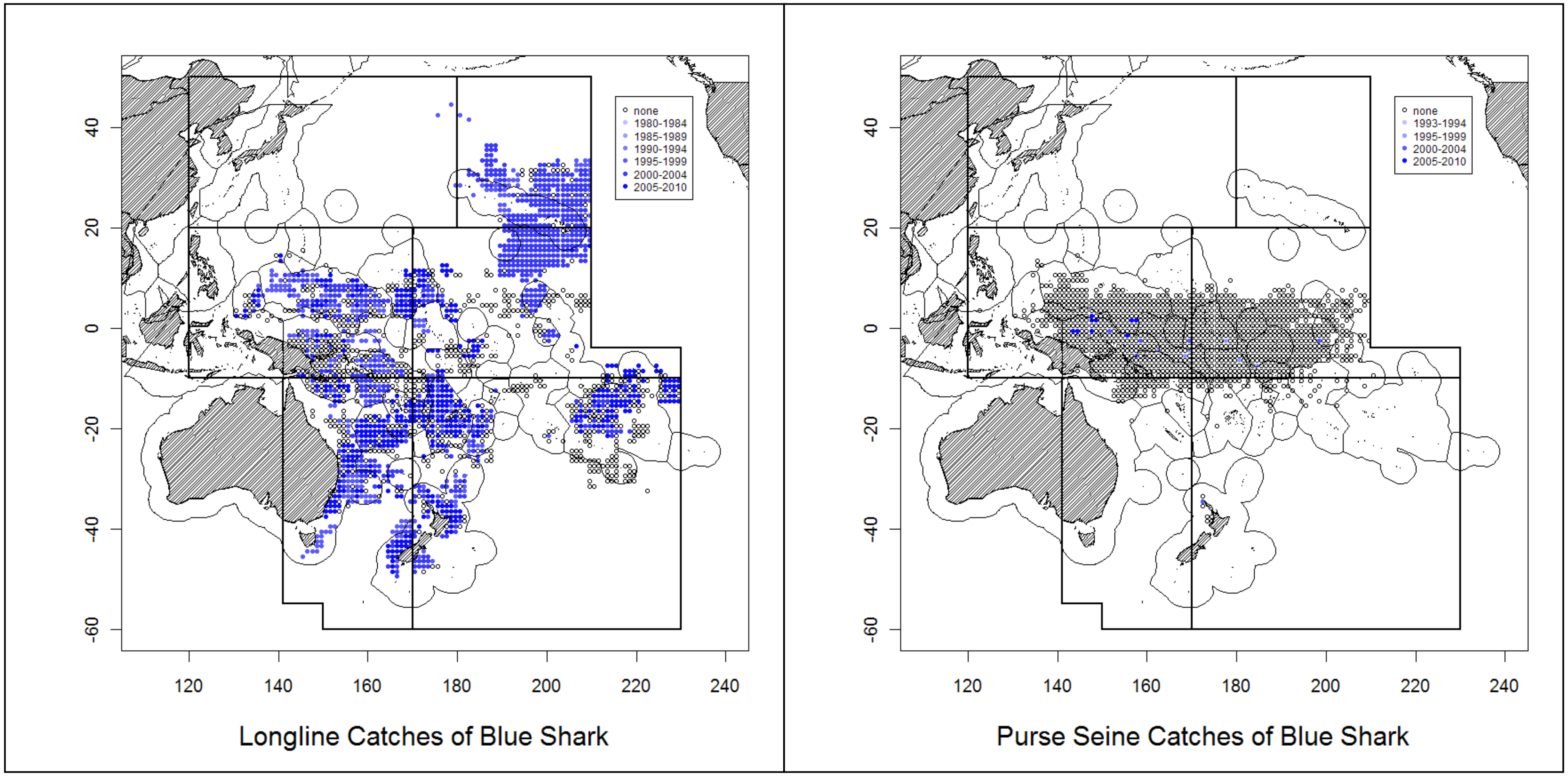


Figure A1. Fishery interaction maps for blue (BSH) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

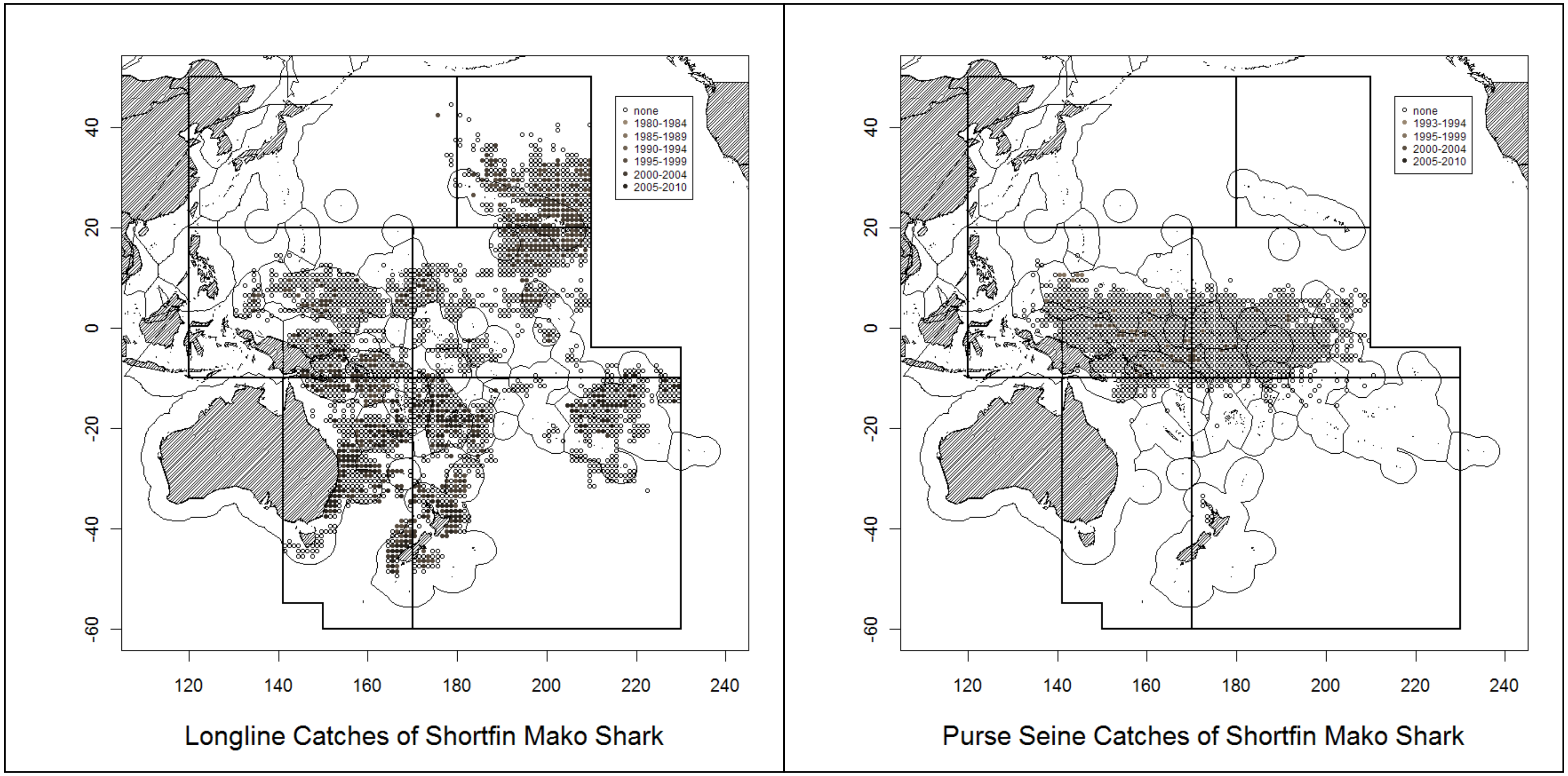


Figure A1 (cont.) Fishery interaction maps for shortfin mako (SMA) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

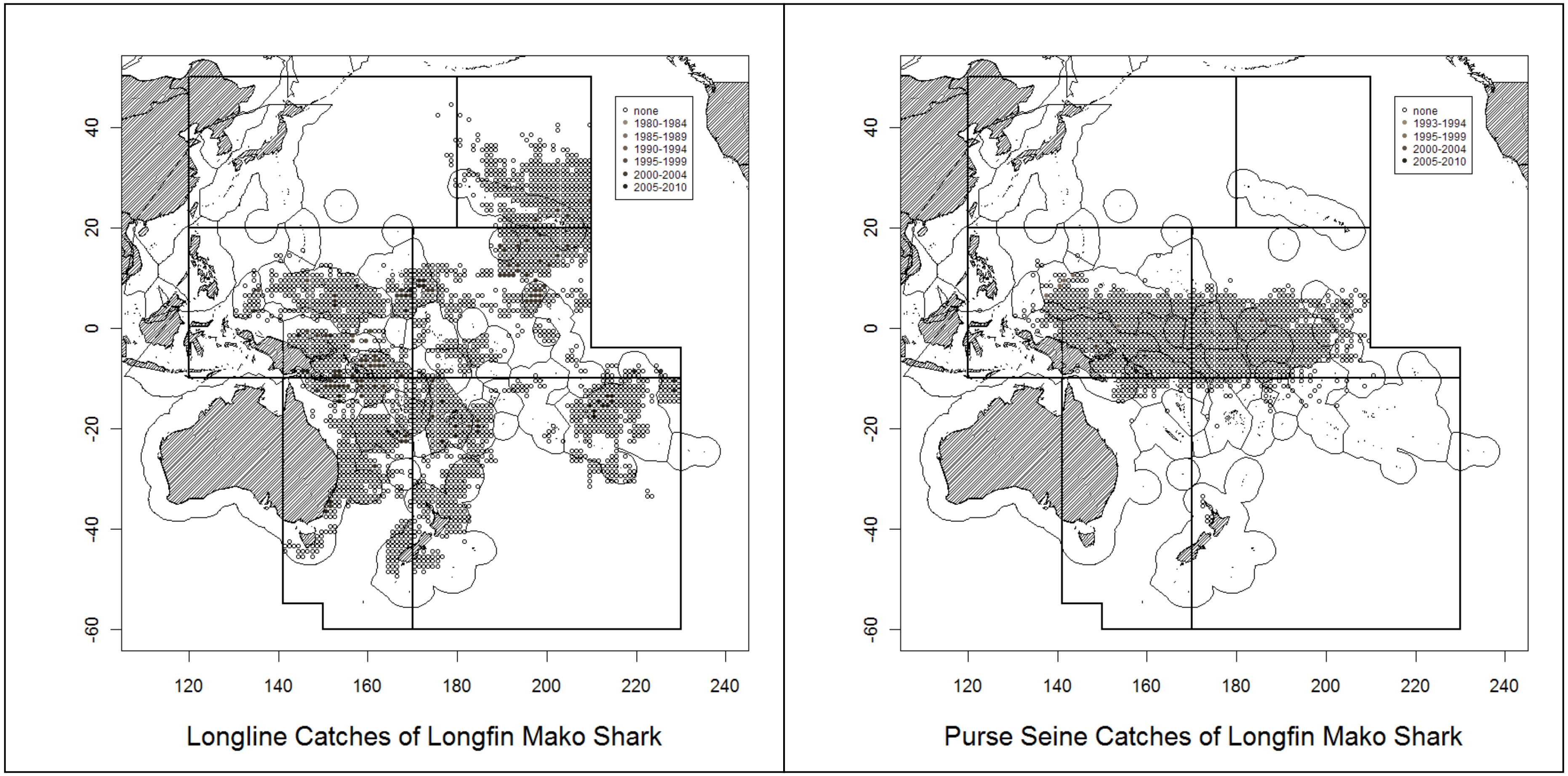


Figure A1 (cont.) Fishery interaction maps for longfin mako (LMA) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

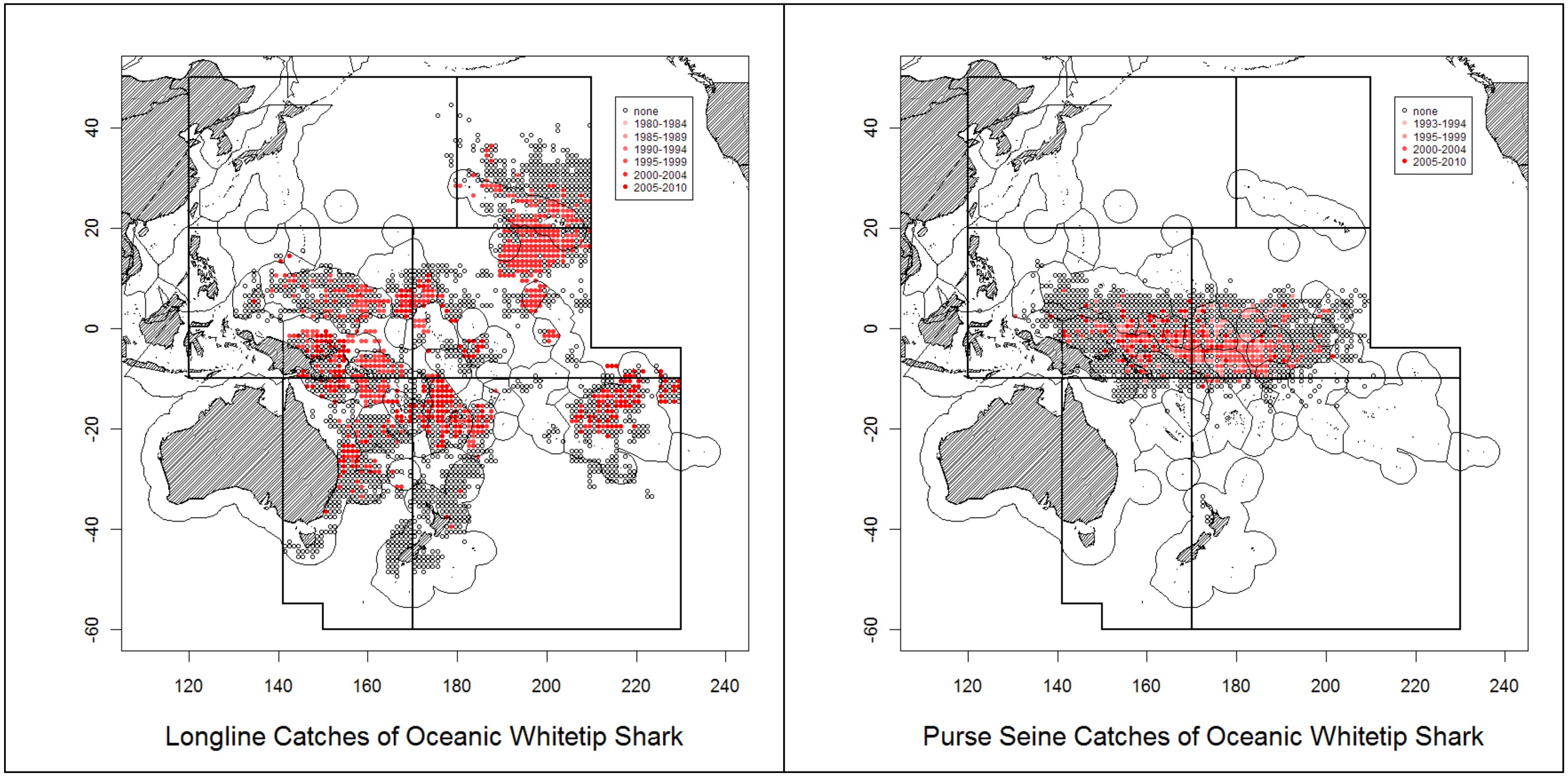


Figure A1 (cont.) Fishery interaction maps for oceanic whitetip (OCS) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

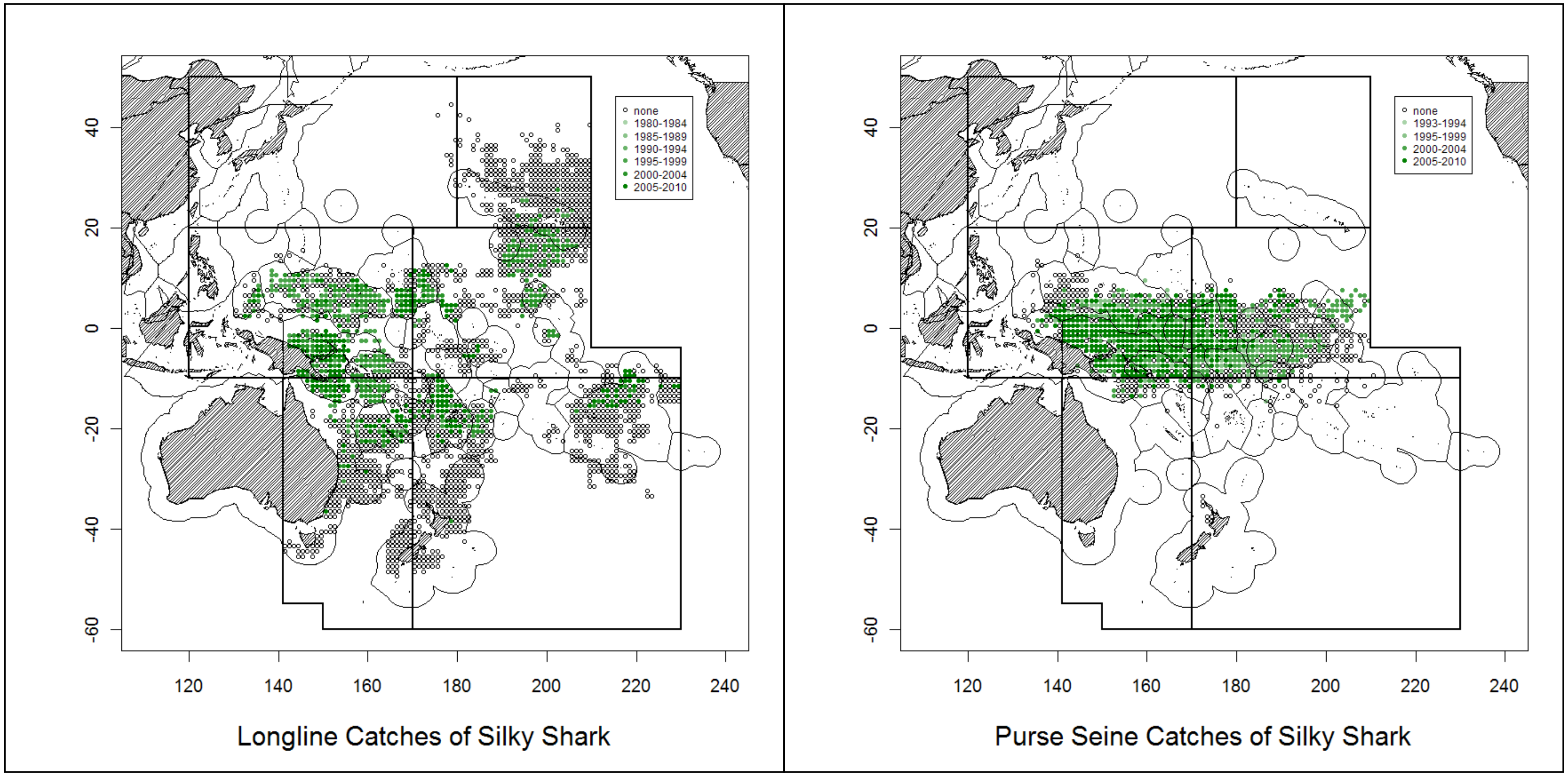


Figure A1 (cont.) Fishery interaction maps for silky (FAL) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

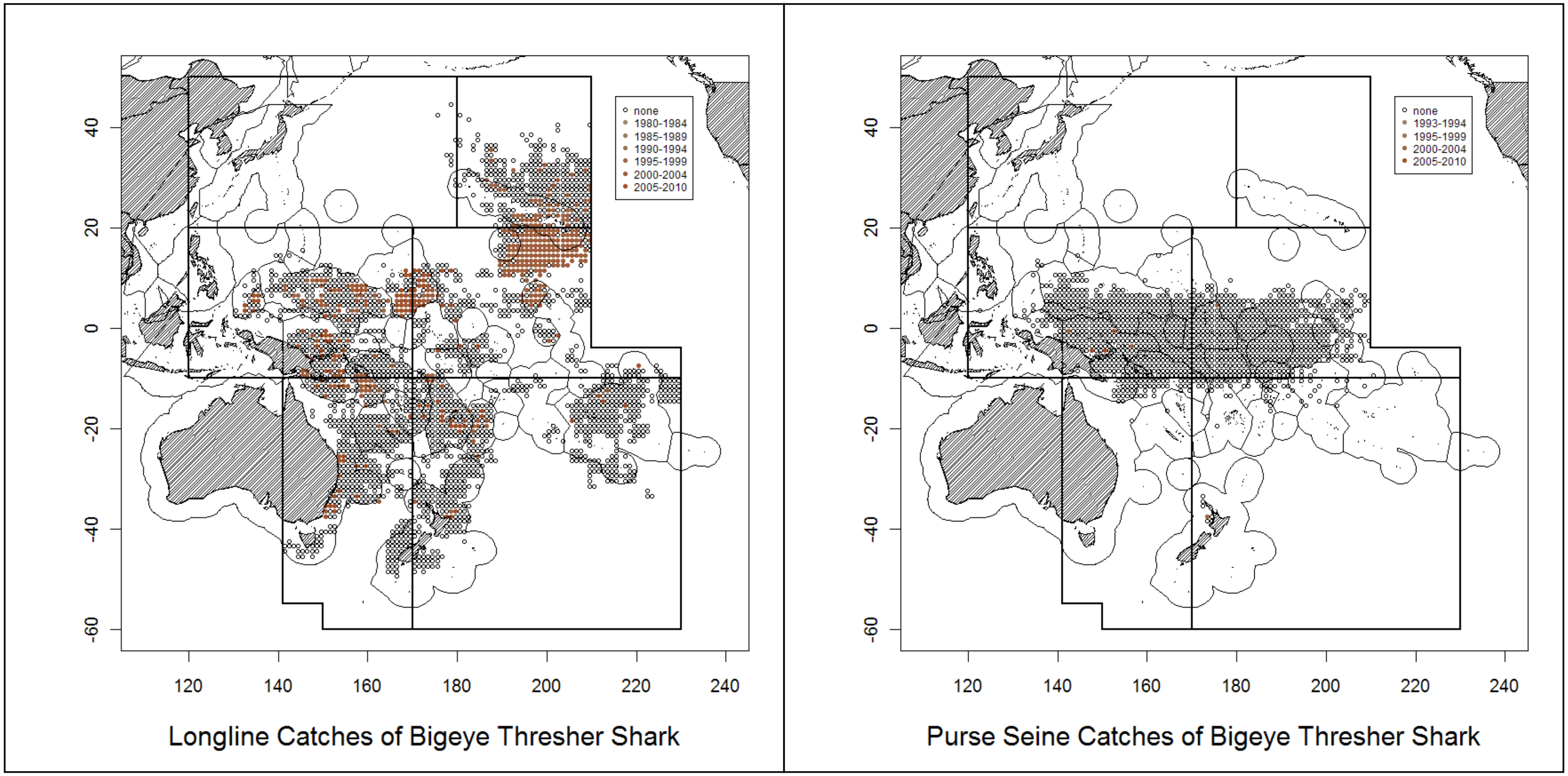


Figure A1 (cont.) Fishery interaction maps for bigeye thresher (BTH) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

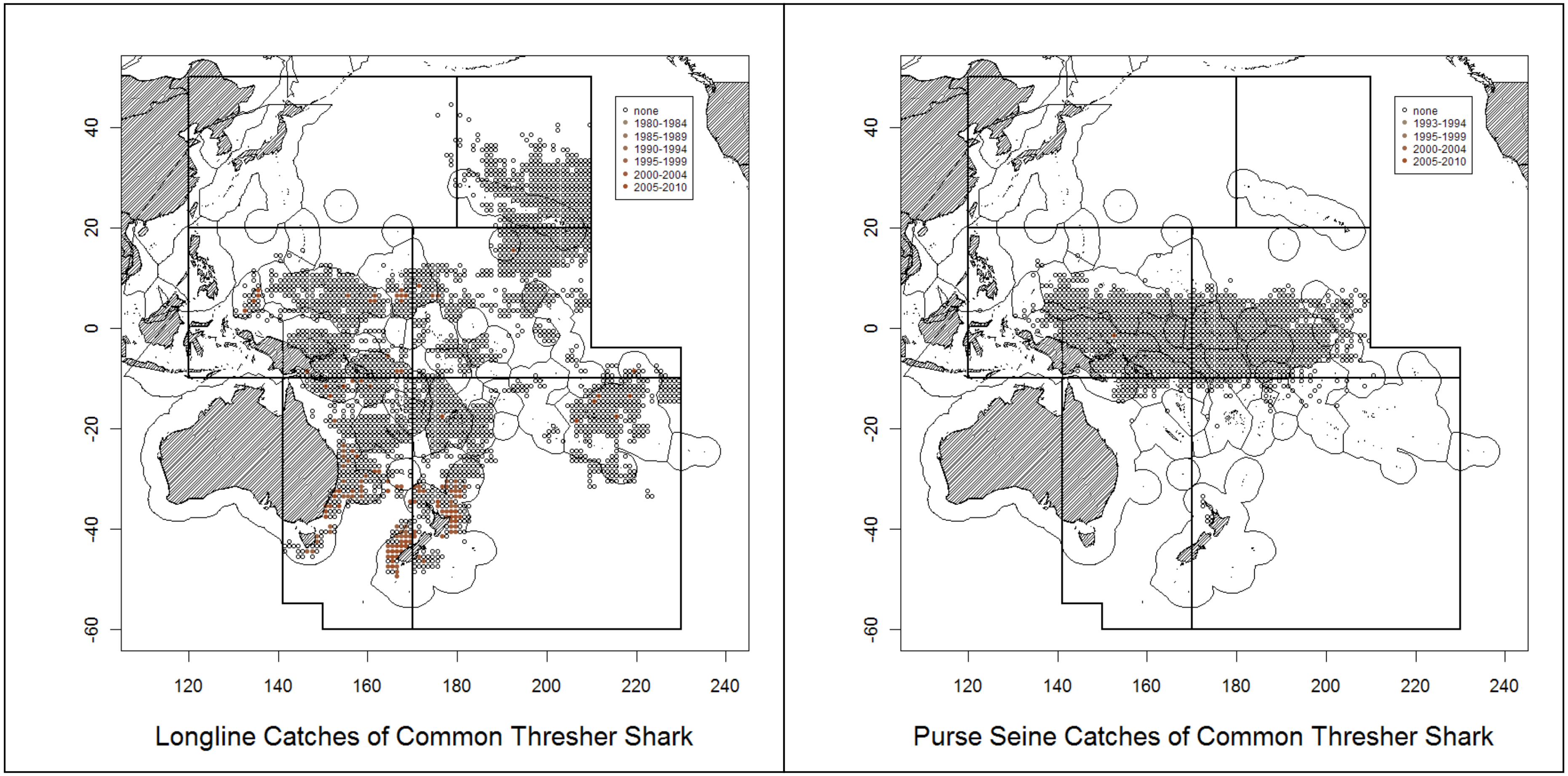


Figure A1 (cont.) Fishery interaction maps for common thresher (ALV) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

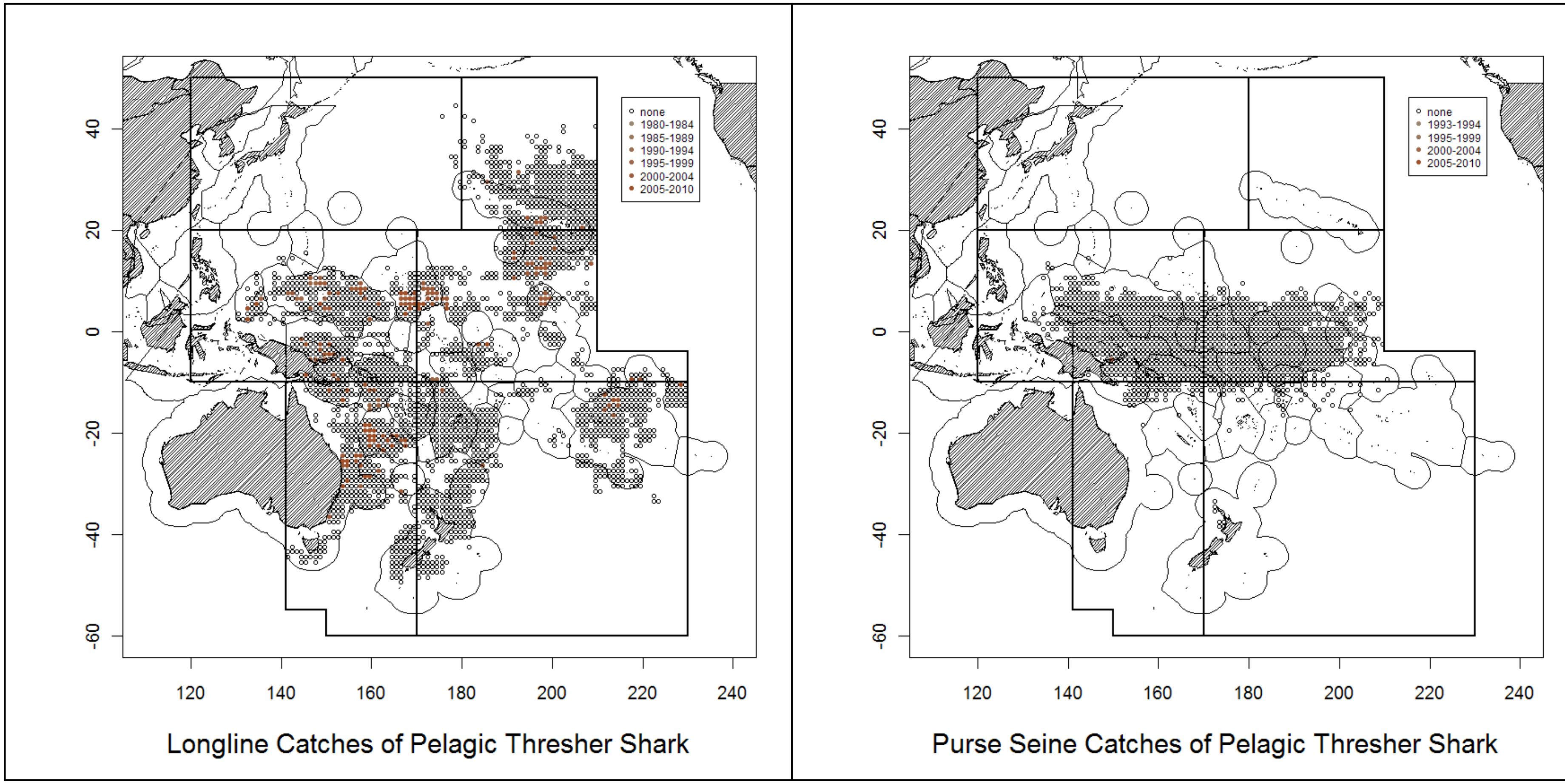


Figure A1 (cont.) Fishery interaction maps for pelagic thresher (PTH) sharks based on observer records from the WCPO longline (1980-2010) and purse seine fisheries (1993-2010). Colored circles represent positive catches (points are shaded by year with more recent catches in the darkest shades) and empty circles represent zero catch.

ANNEX 2

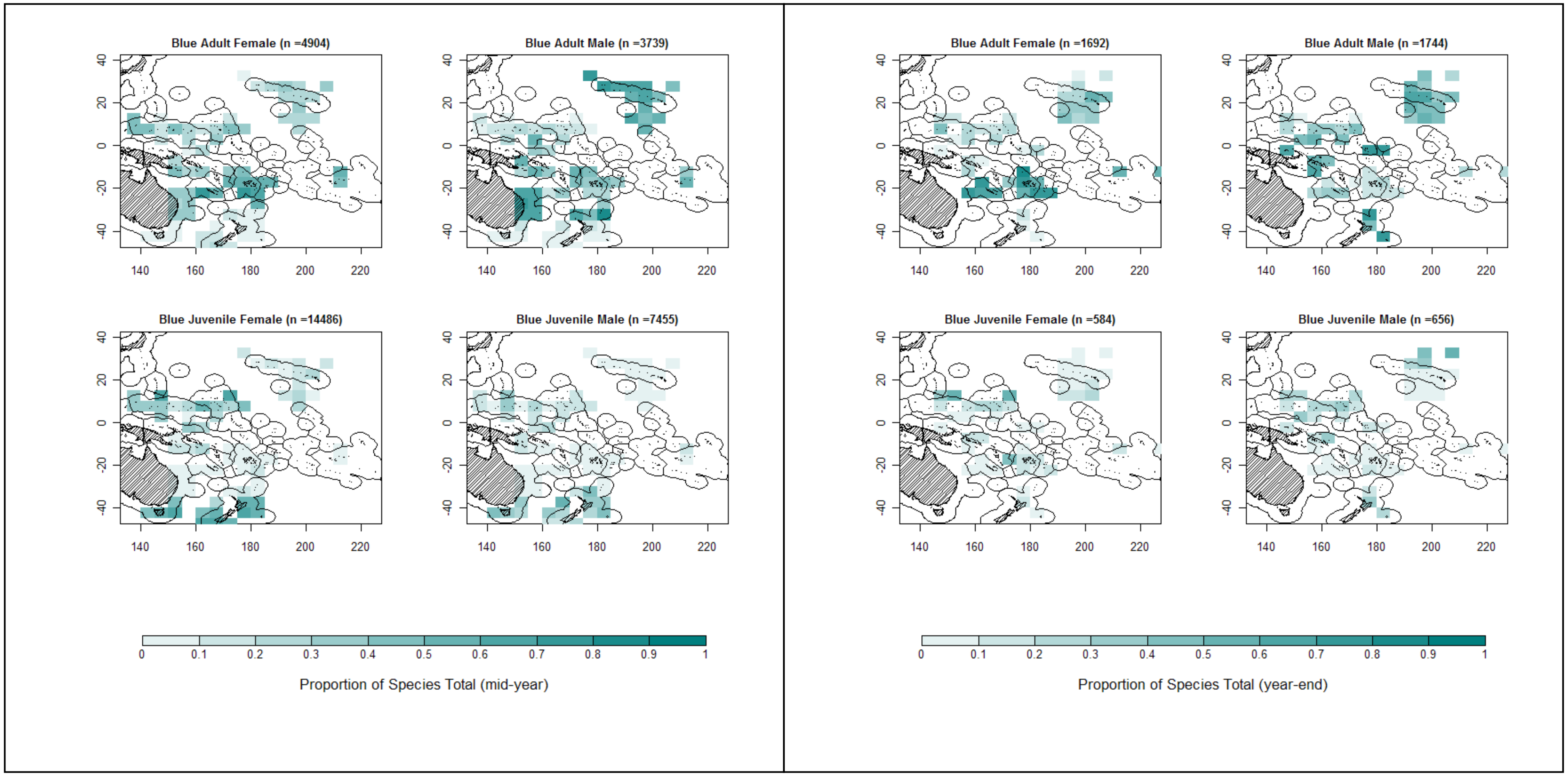


Figure A2. Proportion of blue sharks observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year (left panel) and year-end (right panel) periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with <20 individuals from the analysis.

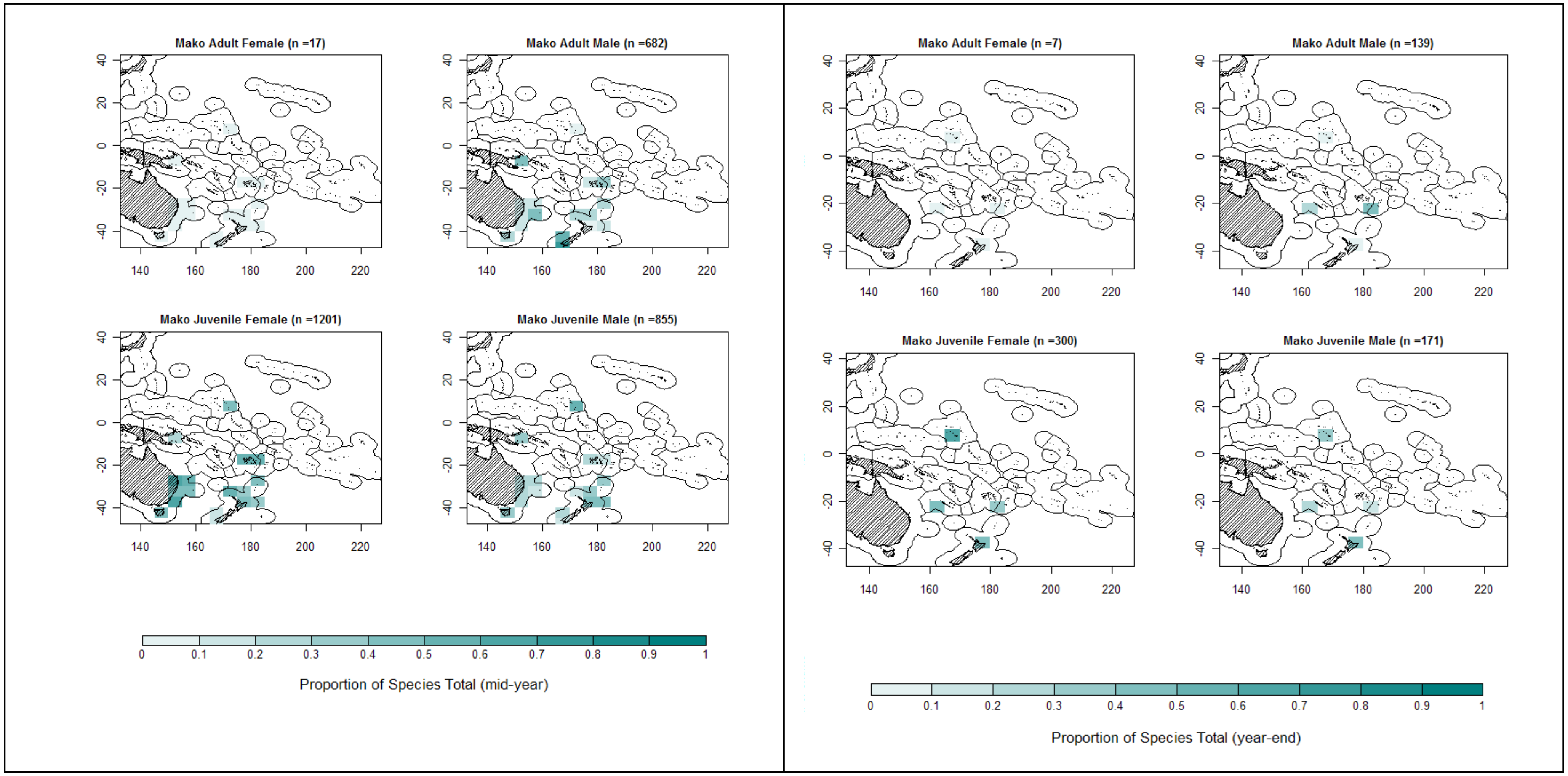


Figure A2 (cont.) Proportion of mako sharks observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year and year-end periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with <20 individuals from the analysis. Due to small sample sizes shortfin and longfin mako records were combined.

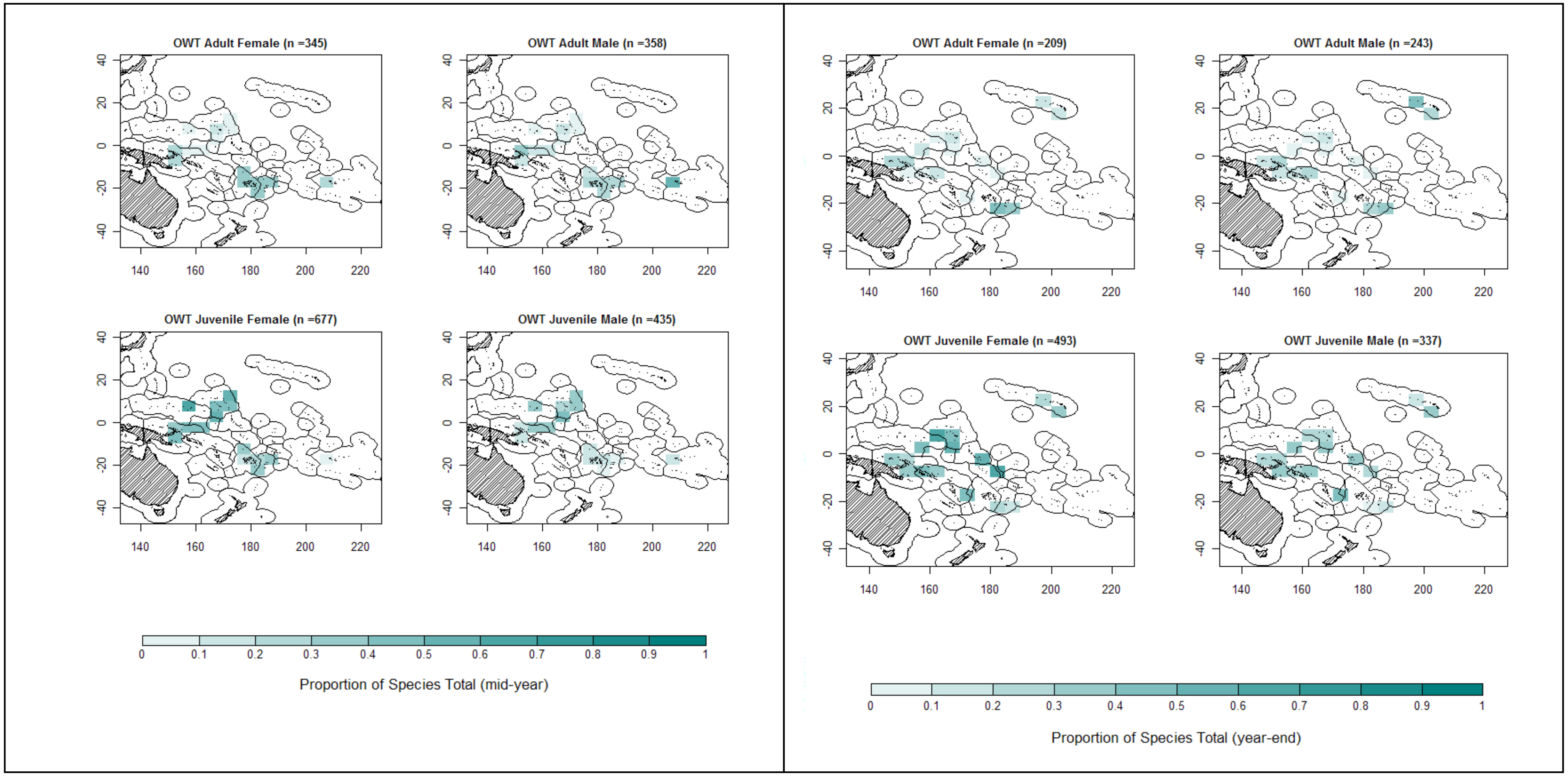


Figure A2 (cont.) Proportion of oceanic whitetip sharks observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year and year-end periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with <20 individuals from the analysis.

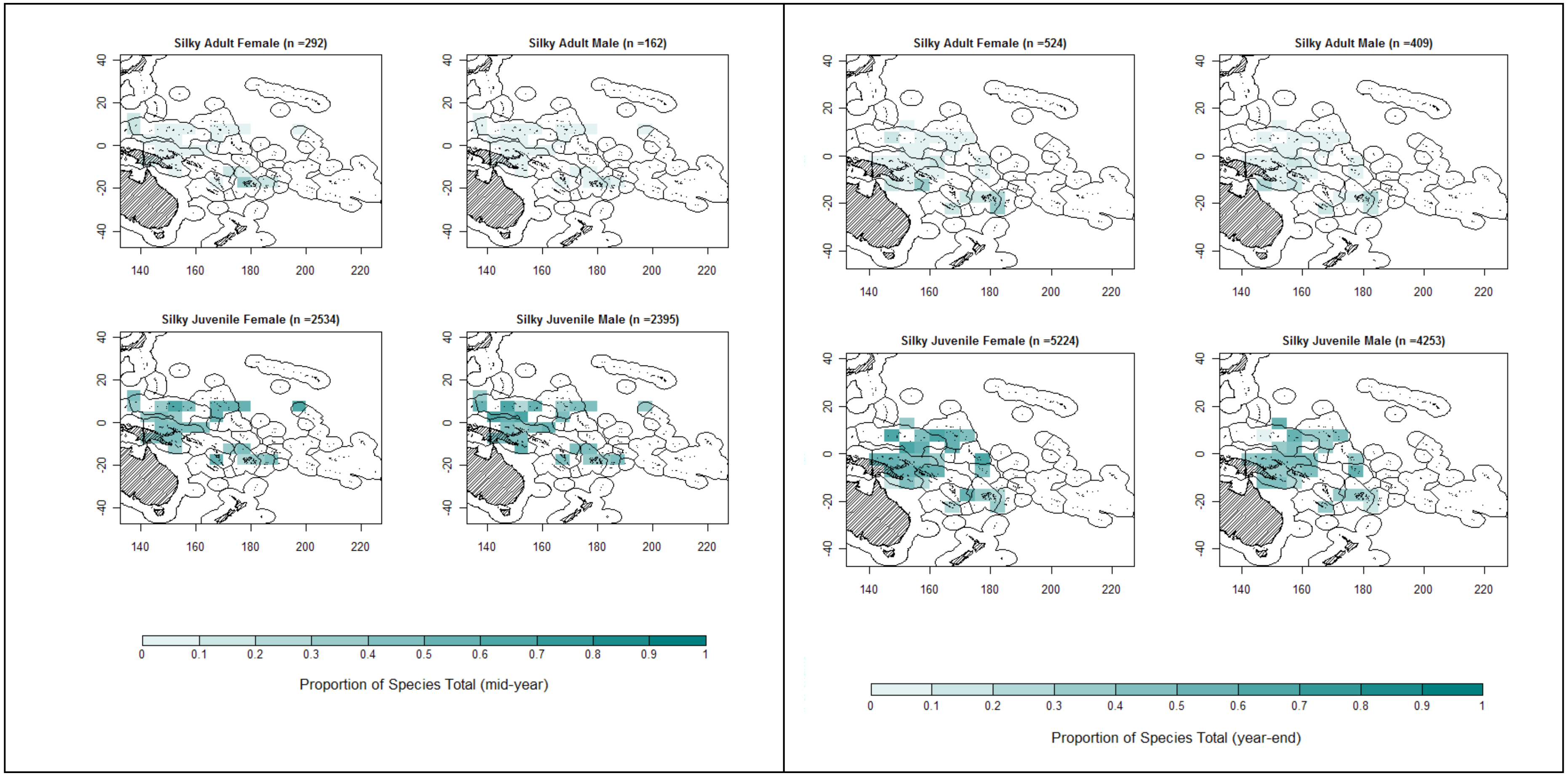


Figure A2 (cont.) Proportion of silky sharks observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year and year-end periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with <20 individuals from the analysis.

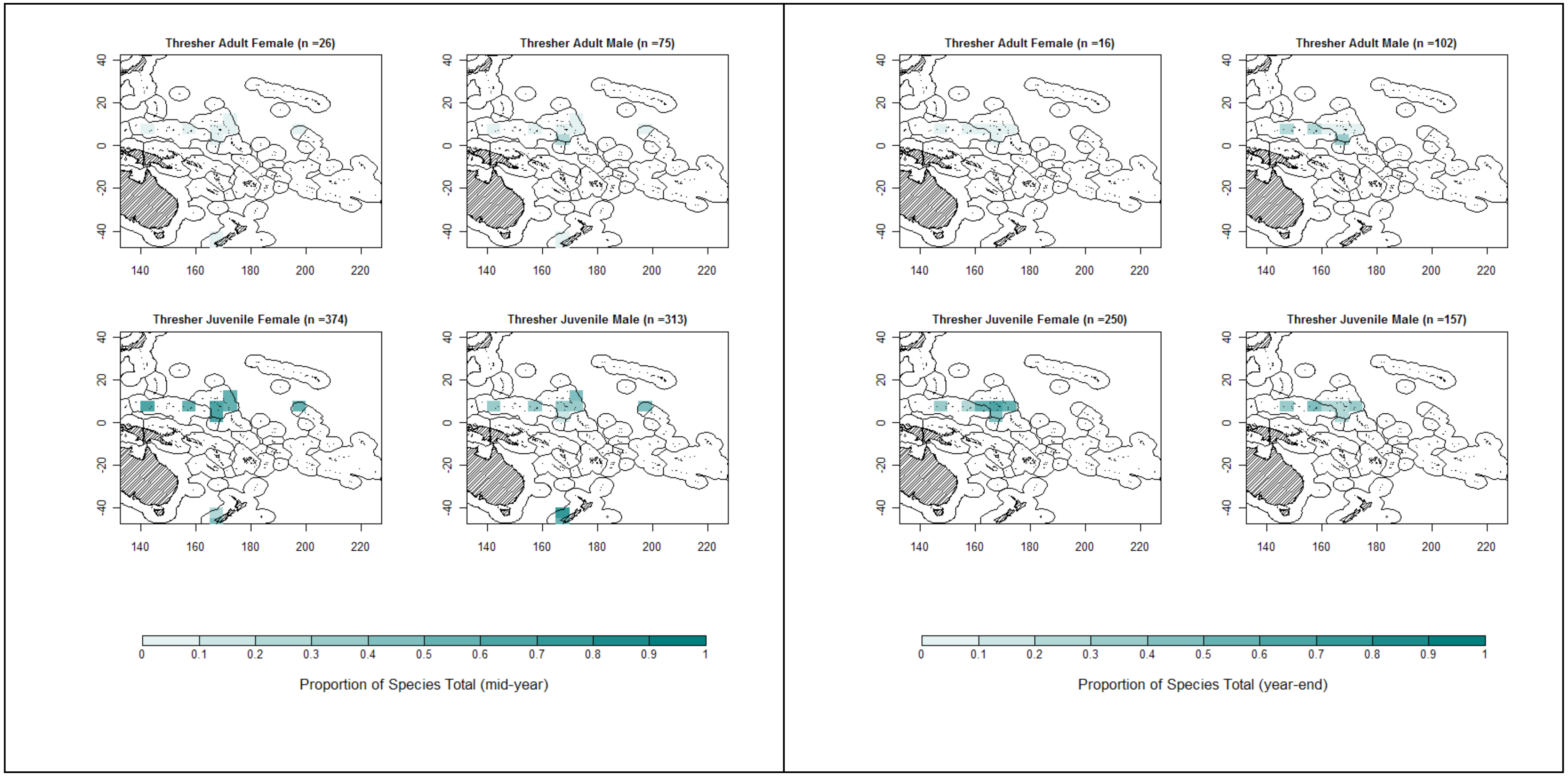


Figure A2 (cont.) Proportion of thresher sharks observed in each 5 x 5 degree cell which were adult females, adult males, juvenile females and juvenile males for mid-year and year-end periods. Darker cell shading indicates higher proportions observed. Samples sizes shown are those before removing cells with <20 individuals from the analysis. Due to small sample sizes bigeye, common and pelagic thresher records were combined.

ANNEX 3

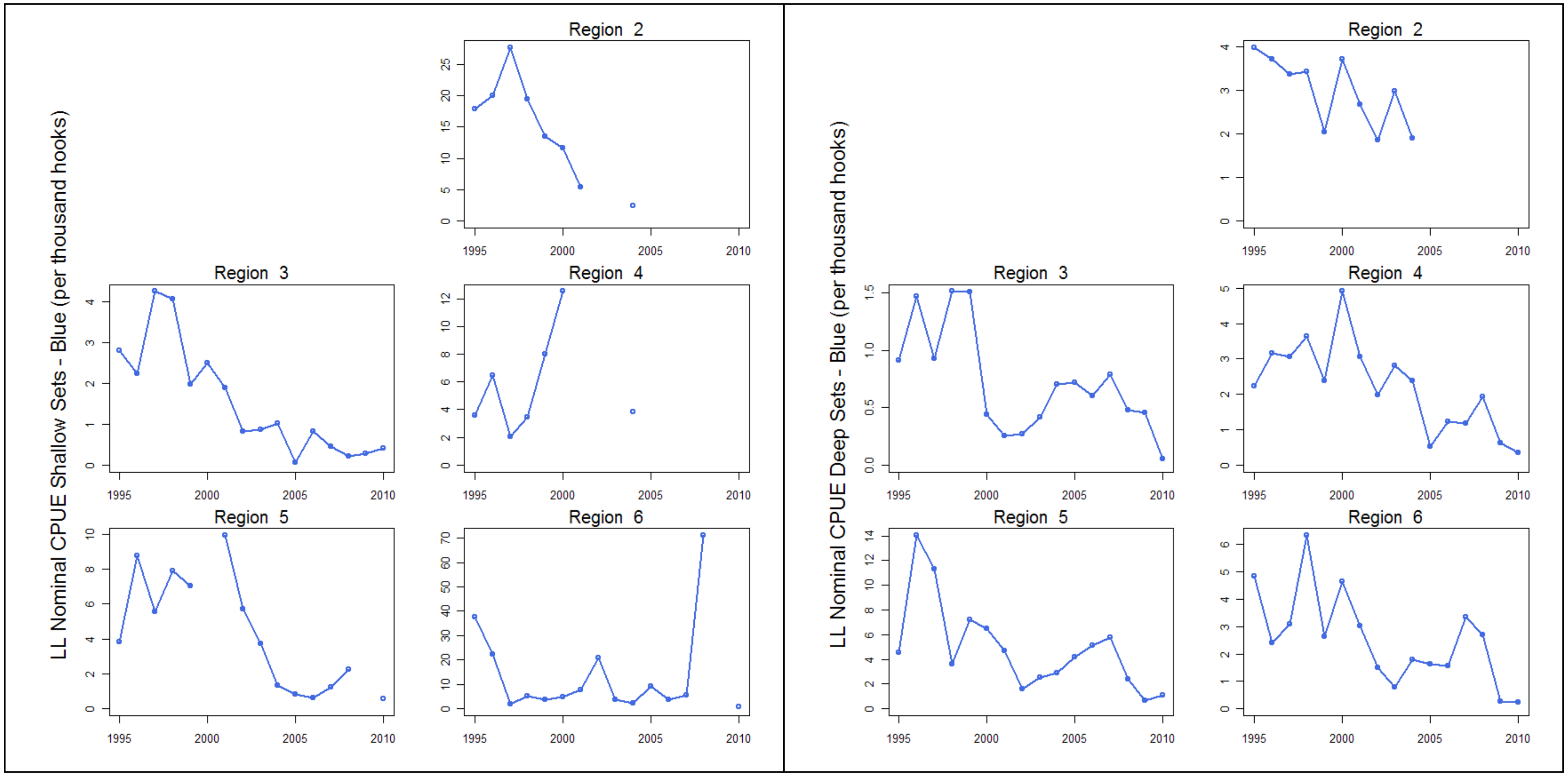


Figure A3. Nominal catch rates by region and year for blue sharks by shallow (<10 hooks per basket) and deep (≥10 hooks per basket) sets.

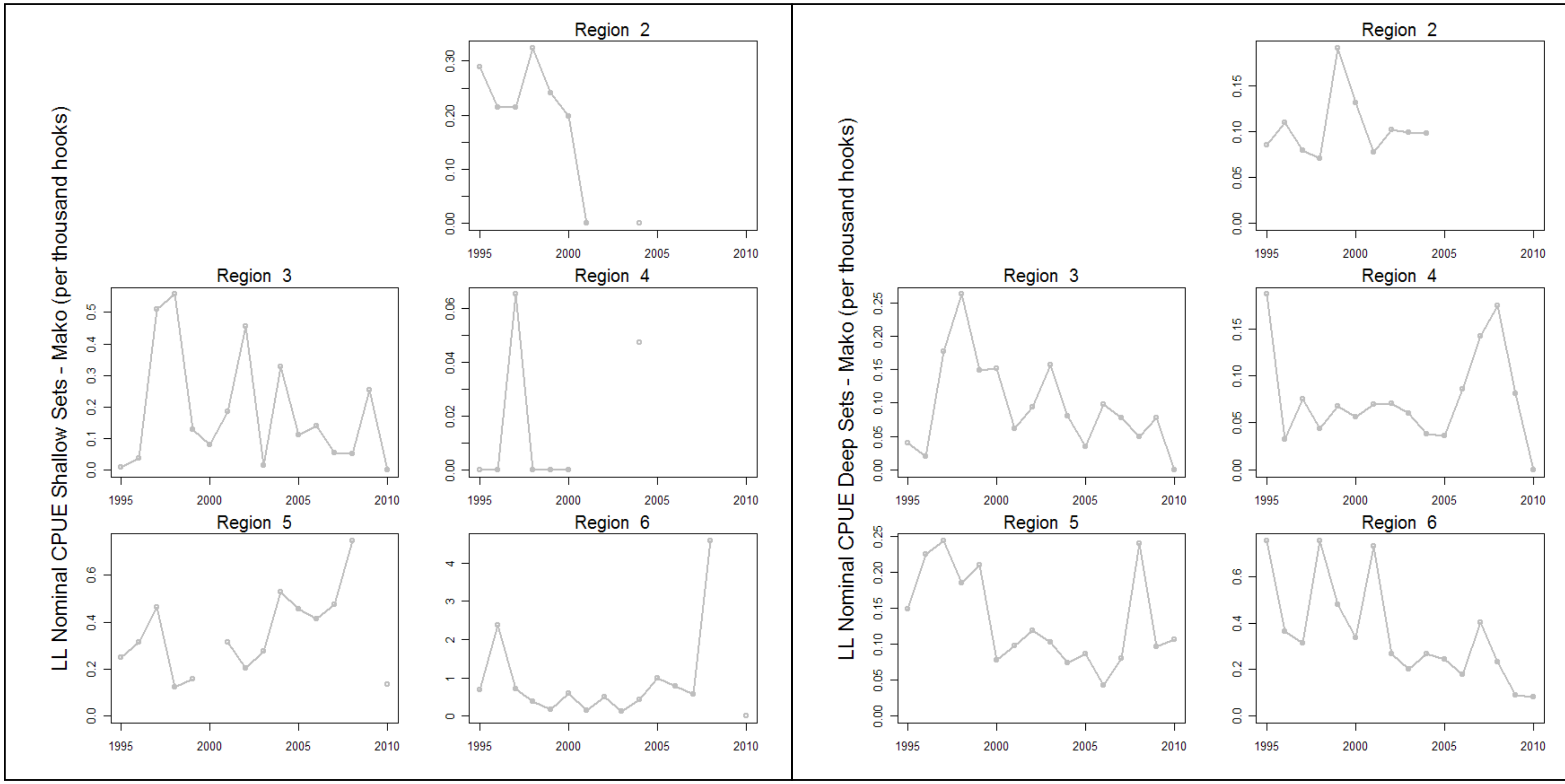


Figure A3 (cont.) Nominal catch rates by region and year for mako sharks by shallow (<10 hooks per basket) and deep (≥10 hooks per basket) sets.

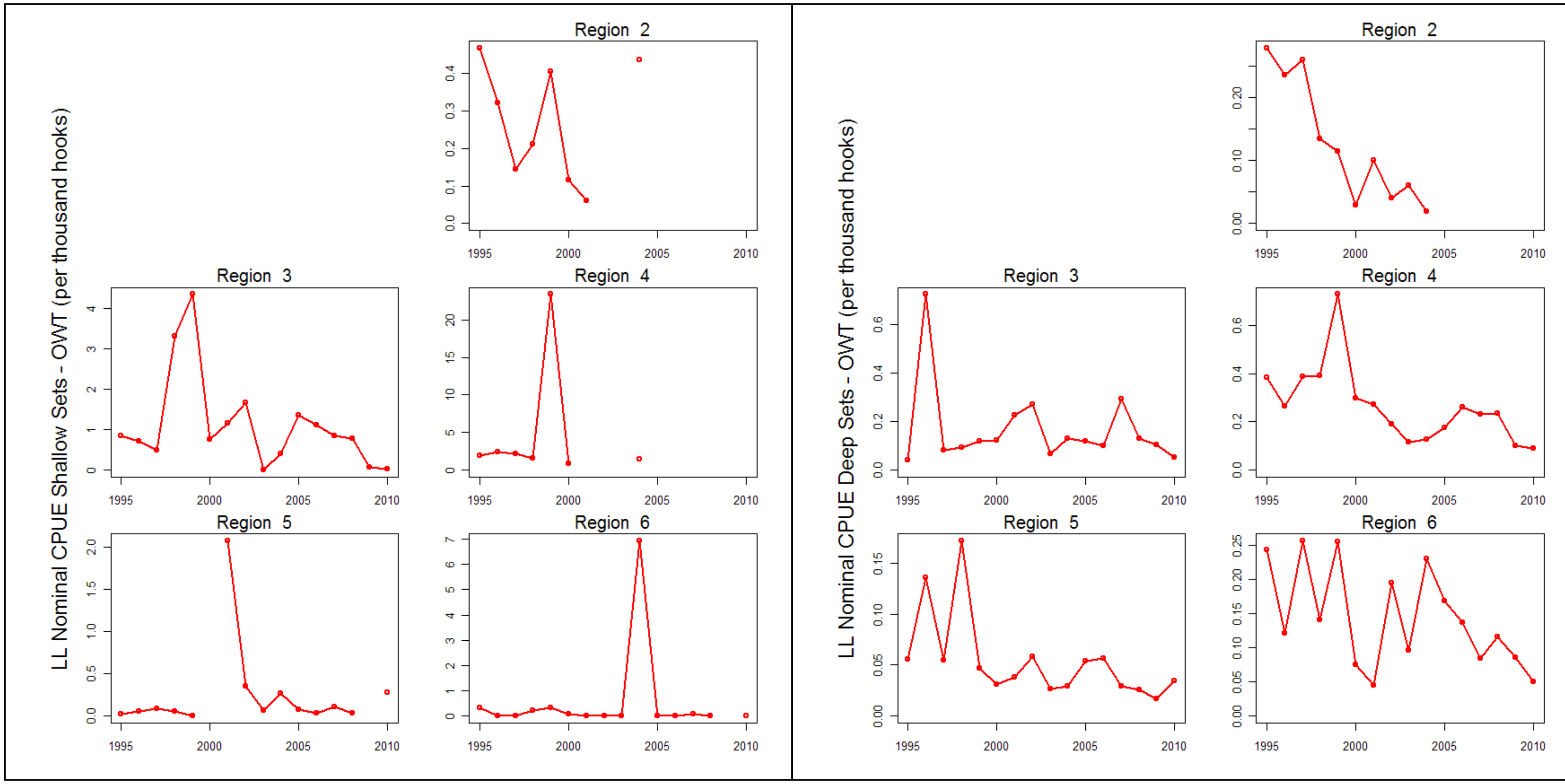


Figure A3 (cont.) Nominal catch rates by region and year for oceanic whitetip sharks by shallow (<10 hooks per basket) and deep (≥10 hooks per basket) sets.

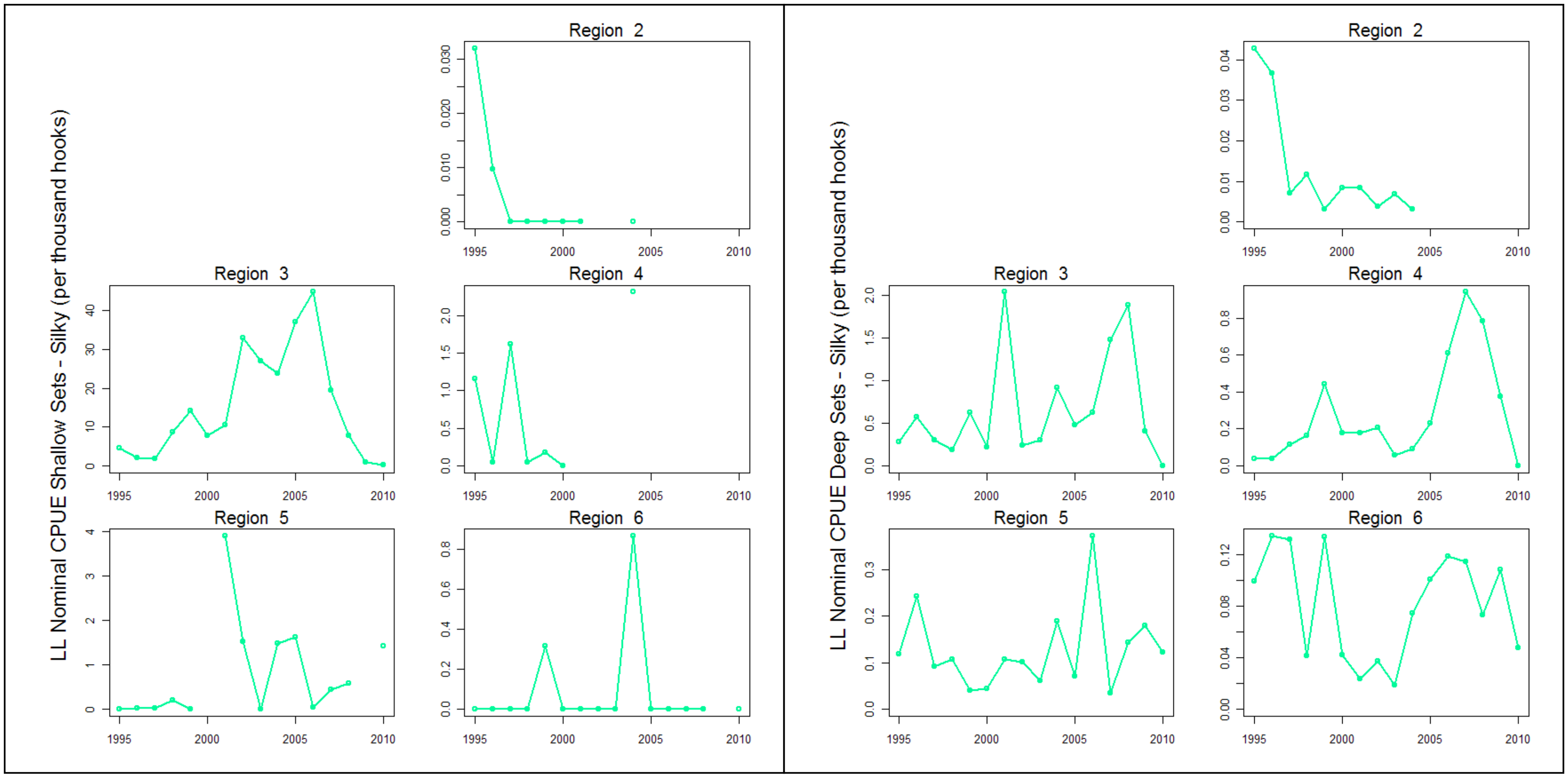


Figure A3 (cont.) Nominal catch rates by region and year for silky sharks by shallow (<10 hooks per basket) and deep (≥10 hooks per basket) sets.

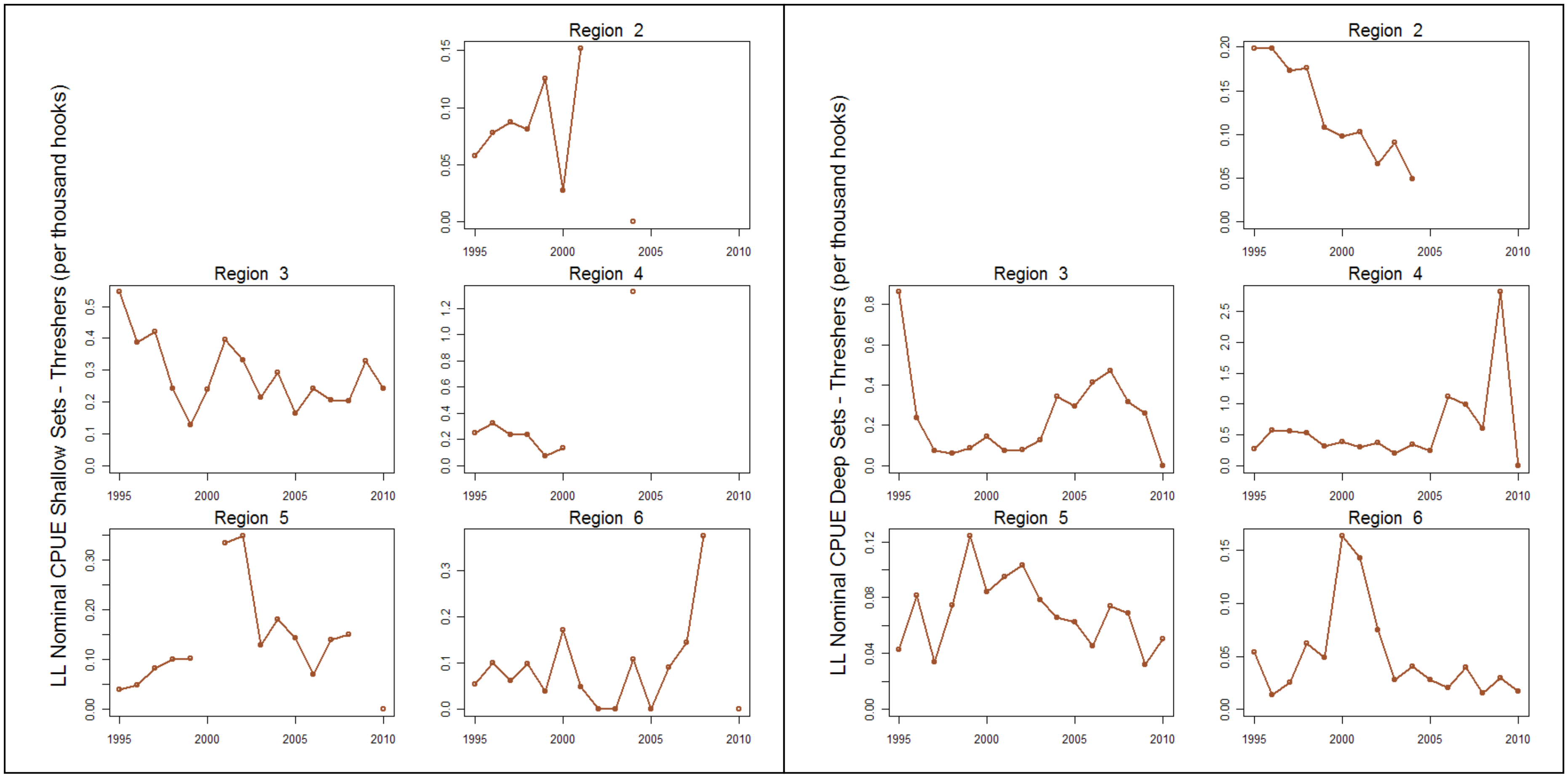


Figure A3 (cont.) Nominal catch rates by region and year for thresher sharks by shallow (<10 hooks per basket) and deep (≥10 hooks per basket) sets.

ANNEX 4

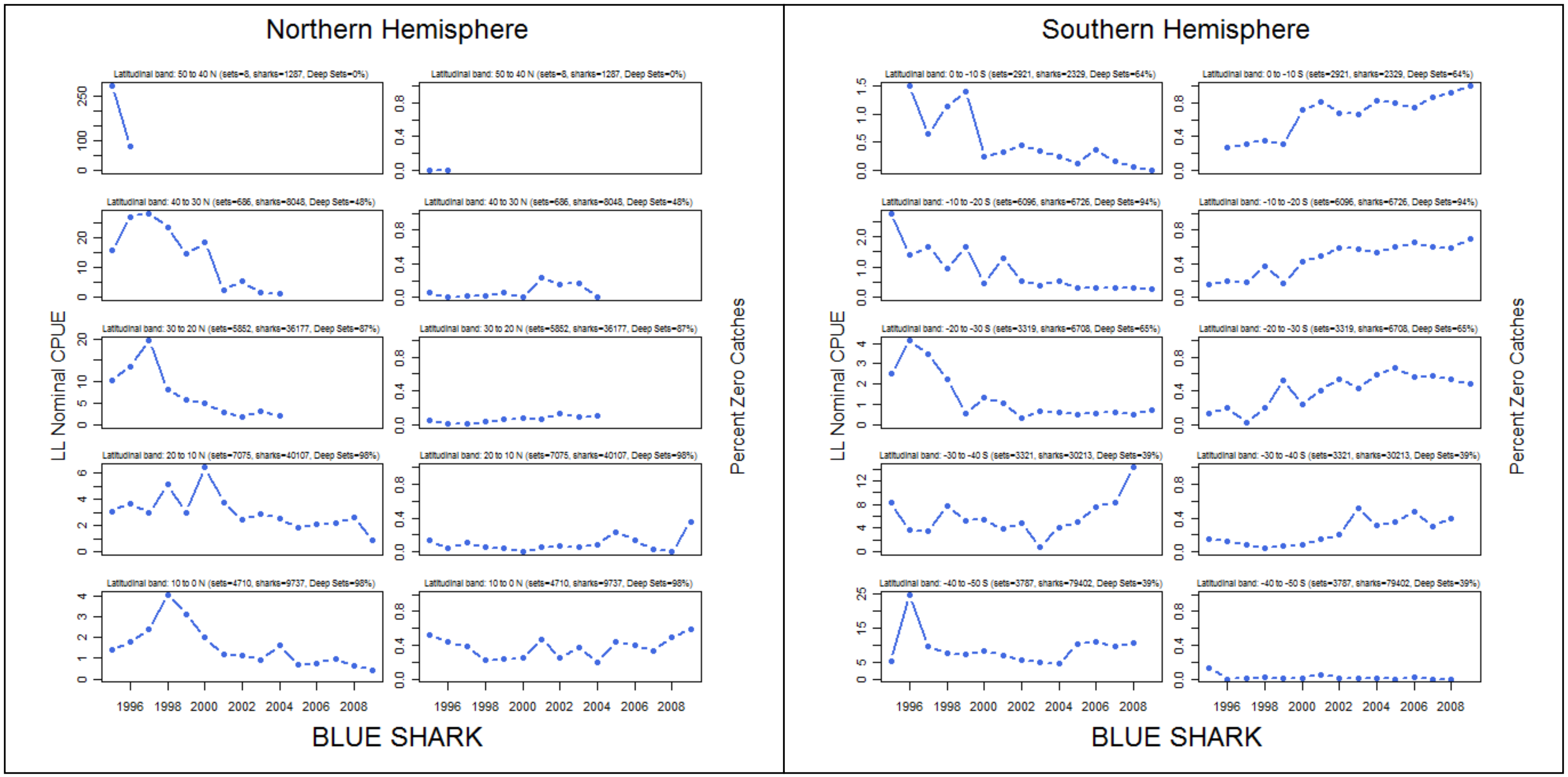


Figure A4. Paired plots of nominal catch rates (left) and proportion of sets with zero catch (right) for blue sharks in 10° latitudinal bands for the northern and southern hemispheres. Each panel shows the number of sets represented, the number of sharks represented and the percentage of sets that were fished deep (i.e. with ≥10 hooks per basket).

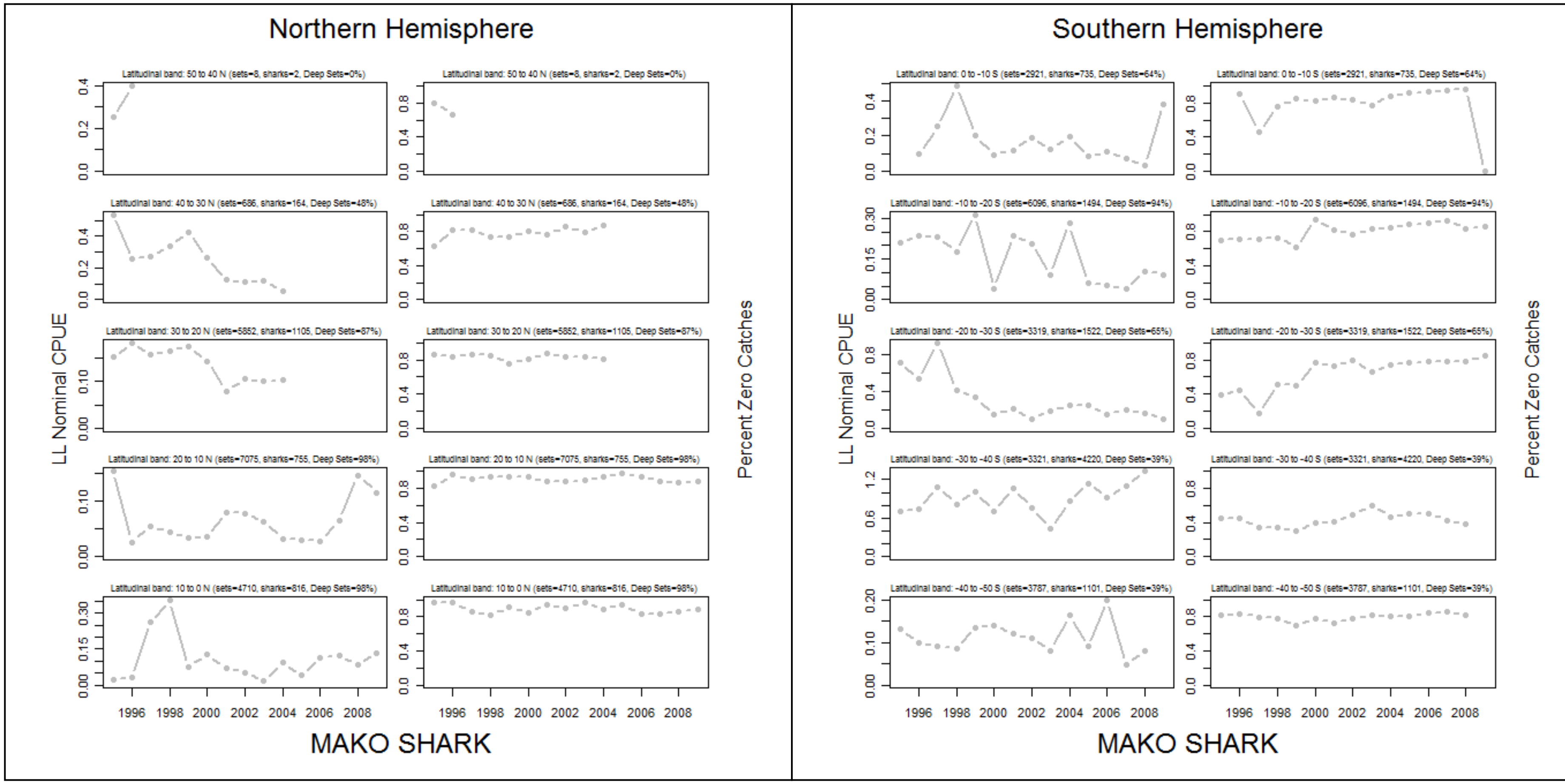


Figure A4 (cont.) Paired plots of nominal catch rates (left) and proportion of sets with zero catch (right) for mako sharks in 10° latitudinal bands for the northern and southern hemispheres. Each panel shows the number of sets represented, the number of sharks represented and the percentage of sets that were fished deep (i.e. with ≥10 hooks per basket).

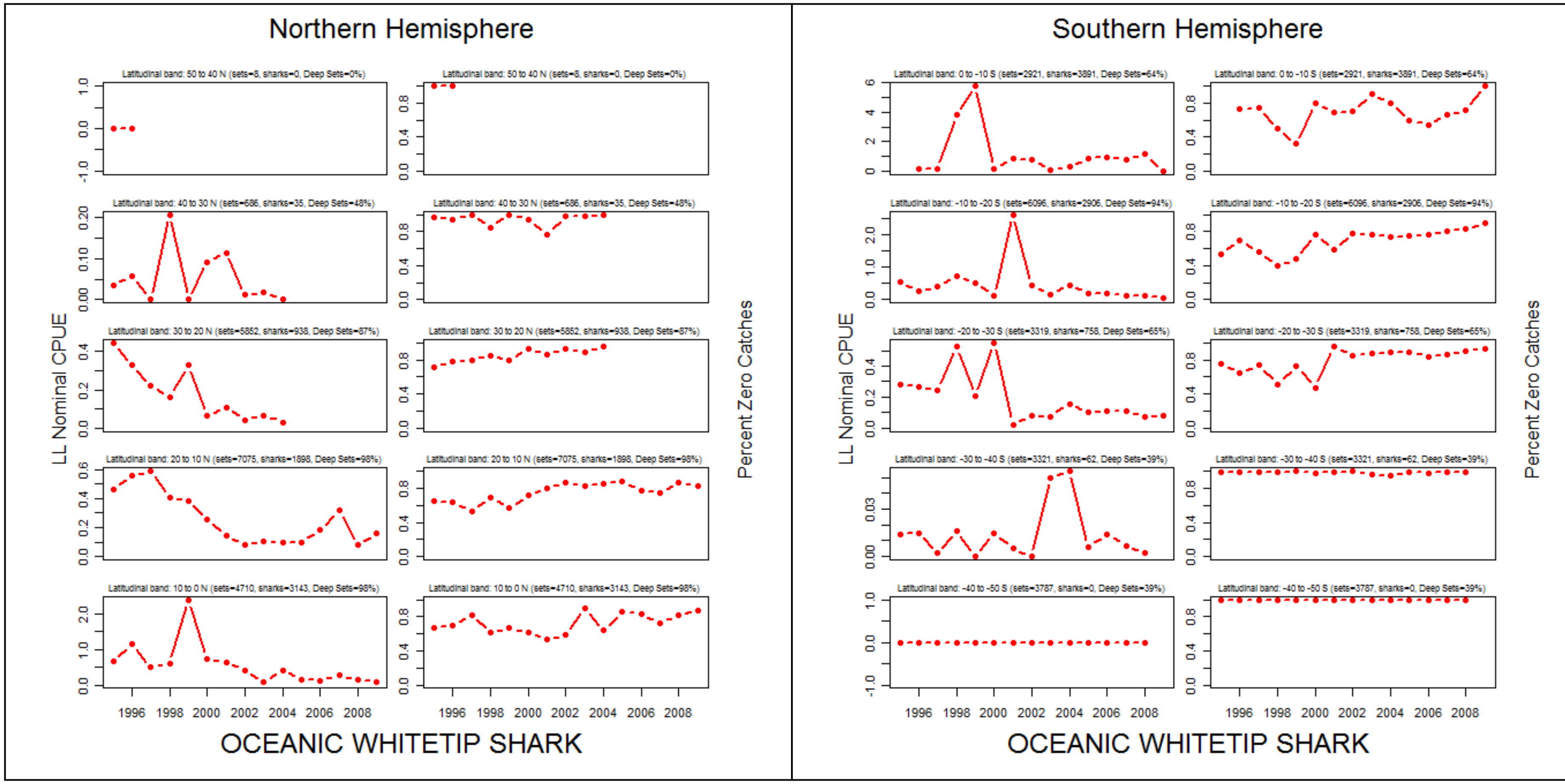


Figure A4 (cont.) Paired plots of nominal catch rates (left) and proportion of sets with zero catch (right) for oceanic whitetip sharks in 10° latitudinal bands for the northern and southern hemispheres. Each panel shows the number of sets represented, the number of sharks represented and the percentage of sets that were fished deep (i.e. with ≥10 hooks per basket).

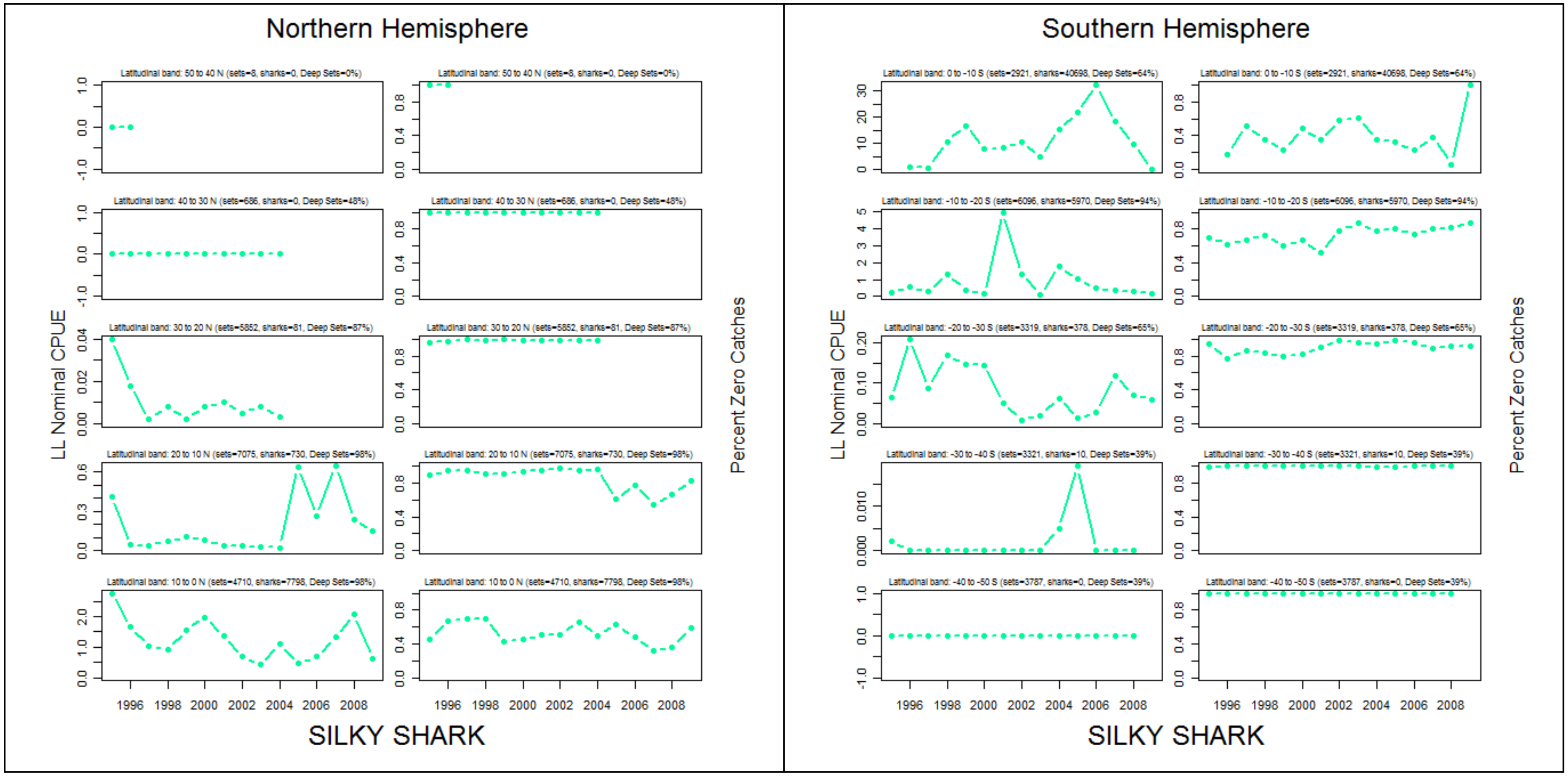


Figure A4 (cont.) Paired plots of nominal catch rates (left) and proportion of sets with zero catch (right) for silky sharks in 10^{o} latitudinal bands for the northern and southern hemispheres. Each panel shows the number of sets represented, the number of sharks represented and the percentage of sets that were fished deep (i.e. with ≥10 hooks per basket).

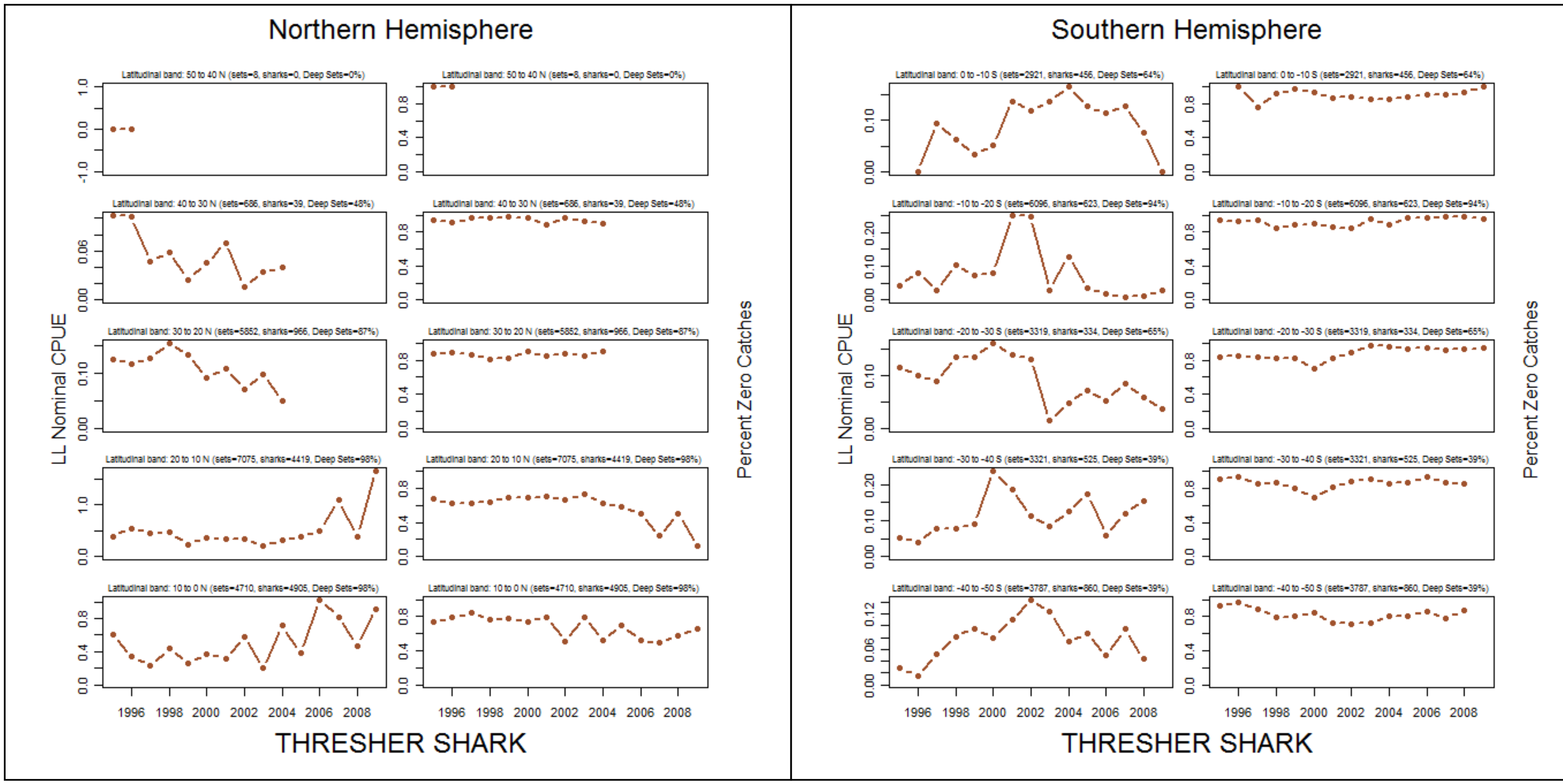


Figure A4 (cont.) Paired plots of nominal catch rates (left) and proportion of sets with zero catch (right) for thresher sharks in 10° latitudinal bands for the northern and southern hemispheres. Each panel shows the number of sets represented, the number of sharks represented and the percentage of sets that were fished deep (i.e. with ≥10 hooks per basket).

ANNEX 5

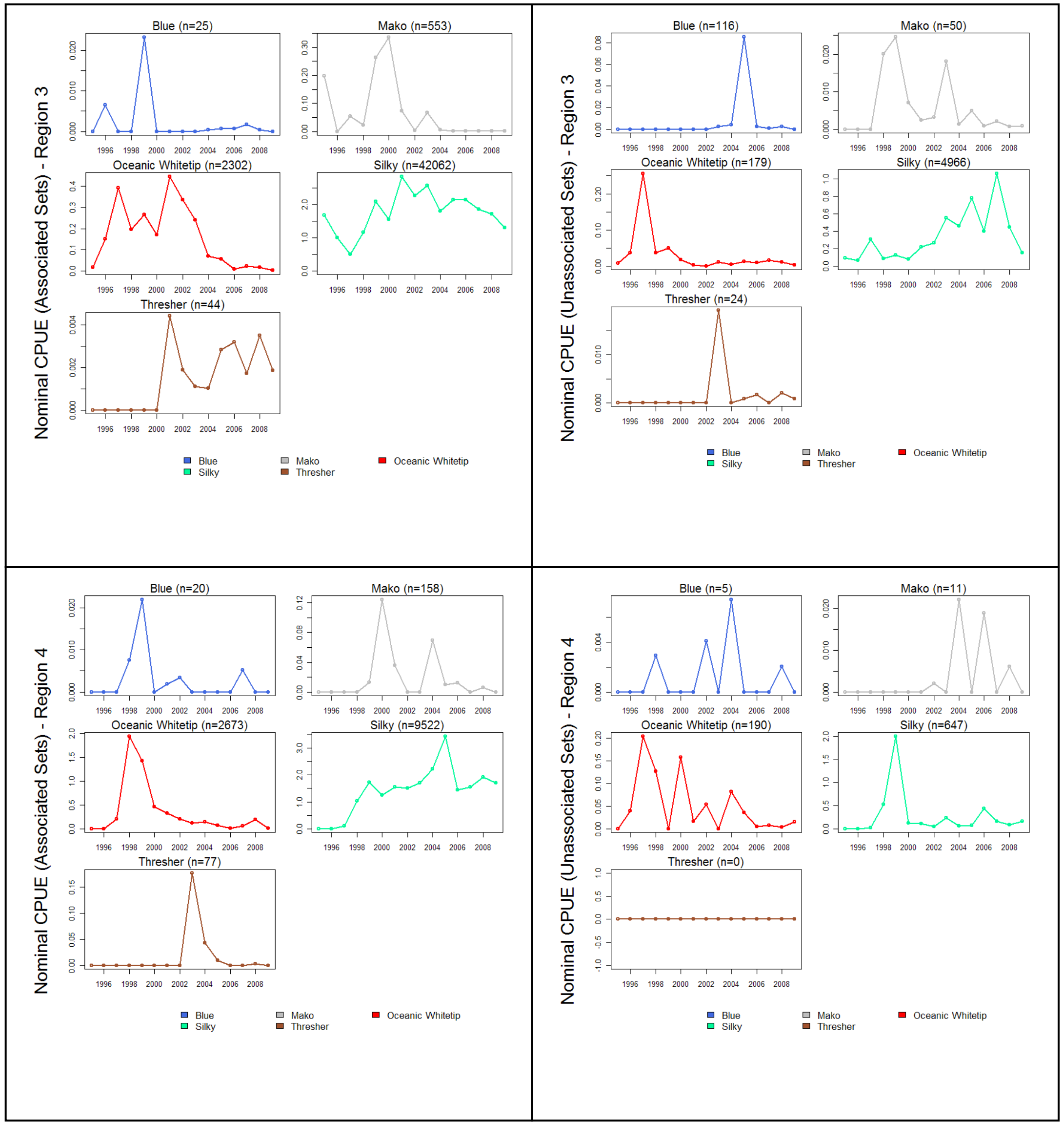
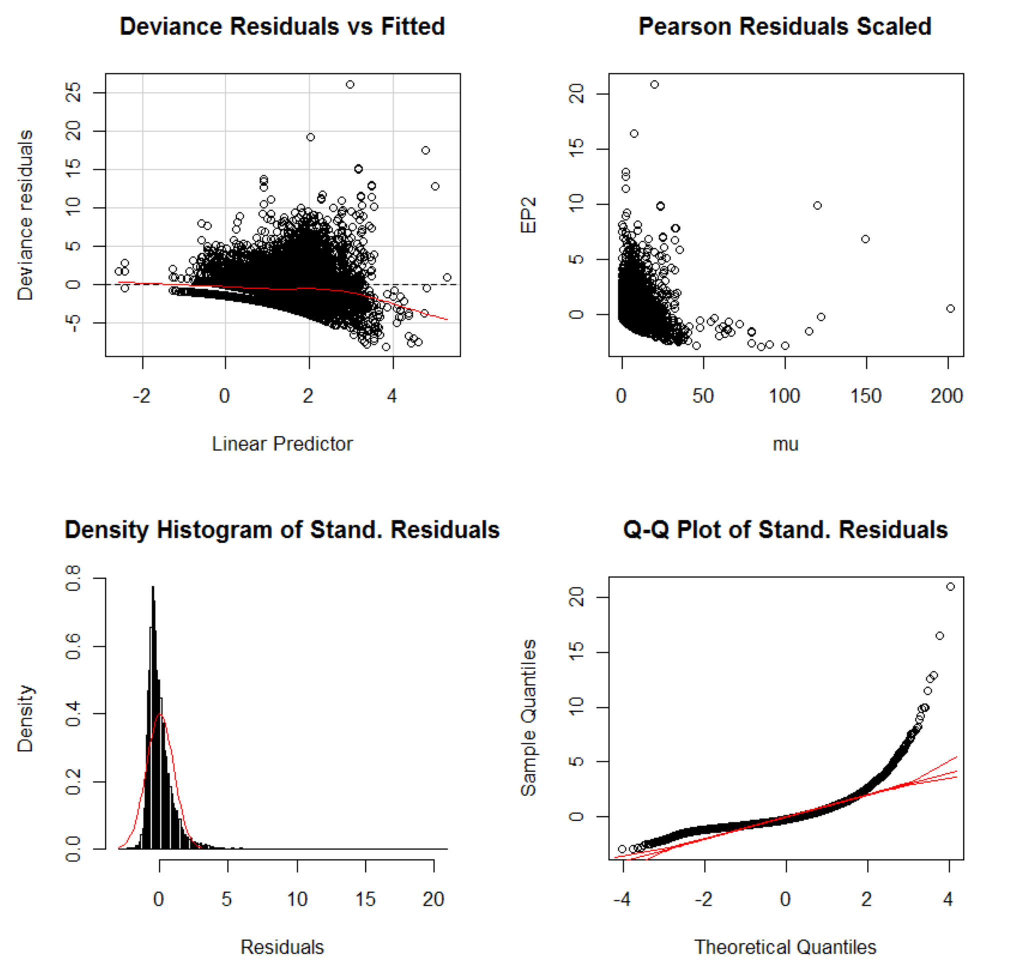


Figure A5. Nominal catch rates (number of sharks per set) for associated (left) and unassociated (right) purse seine sets in Regions 3 (upper) and 4 (lower), 1995-2009. The number of sharks represented in each panel is annotated as "n".

ANNEX 6. Diagnostics for the longline catch rate standardization models discussed in Section 5.3.

```
> summary(QPModBlue) (NORTH)

Call:
glm(formula = blue ~ yy + mm + HPBCAT + flag_id + TIMECAT + SHKLINE +
   (lat1 * lon1) + ns(log(hook_est), df = 5), family = quasipoisson,
   data = shk)

Deviance Residuals:
   Min      1Q   Median      3Q     Max
-8.0037  -1.6192  -0.5528   0.7177  26.1071

Coefficients:
                       Estimate Std. Error t value          Pr(>|t|)
(Intercept)            -4.5107799  0.5138730  -8.778          < 2e-16 ***
yy1996                  0.0783561  0.0423391   1.851         0.064232 .
yy1997                  0.4275609  0.0426124  10.034          < 2e-16 ***
yy1998                  0.0910170  0.0431438   2.110         0.034905 *
yy1999                 -0.2451318  0.0506216  -4.842 0.0000012931155740 ***
yy2000                 -0.1062746  0.0402642  -2.639         0.008312 **
yy2001                 -0.3216736  0.0422314  -7.617 0.0000000000000273 ***
yy2002                 -0.4324550  0.0411096 -10.520          < 2e-16 ***
yy2003                 -0.0484596  0.0400021  -1.211         0.225748
yy2004                 -0.1667726  0.0420879  -3.962 0.0000744583216510 ***
yy2005                 -0.2520218  0.1031672  -2.443         0.014581 *
yy2006                 -0.0067667  0.0786056  -0.086         0.931401
yy2007                 -0.0182814  0.0806321  -0.227         0.820639
yy2008                 -0.7043382  0.1330248  -5.295 0.0000001205412119 ***
yy2009                 -0.6995670  0.1858769  -3.764         0.000168 ***
yy2010                 -1.0178838  0.5736445  -1.774         0.076011 .
mm2                     0.0882190  0.0354004   2.492         0.012710 *
mm3                    -0.2442411  0.0389736  -6.267 0.0000000003767432 ***
mm4                    -0.2548521  0.0383286  -6.649 0.0000000000303220 ***
mm5                    -0.3332646  0.0398865  -8.355          < 2e-16 ***
mm6                     0.0042064  0.0394295   0.107         0.915043
mm7                    -0.0282709  0.0420521  -0.672         0.501412
mm8                     0.0976124  0.0388323   2.514         0.011956 *
mm9                     0.4181616  0.0365216  11.450          < 2e-16 ***
mm10                    0.4018648  0.0348442  11.533          < 2e-16 ***
mm11                    0.4075752  0.0346491  11.763          < 2e-16 ***
mm12                    0.1534956  0.0380699   4.032 0.0000555424791804 ***
HPBCATS                 0.2755552  0.0670906   4.107 0.0000402214023278 ***
flag_idFM               0.3477909  0.0706196   4.925 0.0000008516766609 ***
flag_idJP               0.3360877  0.0798136   4.211 0.0000255573065957 ***
flag_idKR              -0.1929200  0.1336271  -1.444         0.148835
flag_idPF              -1.6790495  1.0676529  -1.573         0.115816
flag_idTW               0.3539488  0.0765810   4.622 0.0000038287329925 ***
flag_idUS               1.3557014  0.0930950  14.563          < 2e-16 ***
TIMECAT2                0.4111493  0.0820000   5.014 0.0000005380680219 ***
TIMECAT3                0.2696566  0.0832566   3.239         0.001202 **
TIMECAT4                0.4320826  0.1078062   4.008 0.0000614908750559 ***
TIMECAT5                1.0536648  0.0707491  14.893          < 2e-16 ***
TIMECAT6                0.7731672  0.0768167  10.065          < 2e-16 ***
SHKLINE1                0.4172560  0.0743374   5.613 0.0000000201751503 ***
lat1                    0.6172161  0.0218368  28.265          < 2e-16 ***
lon1                    0.0220263  0.0028787   7.651 0.0000000000000209 ***
ns(log(hook_est), df = 5)1  0.0559778  0.0655575   0.854         0.393186
```

```
ns(log(hook_est), df = 5)2  0.1985479  0.0615167   3.228          0.001251 **
ns(log(hook_est), df = 5)3  0.1605399  0.0669241   2.399          0.016457 *
ns(log(hook_est), df = 5)4  0.5485571  0.1233501   4.447 0.0000087531194446 ***
ns(log(hook_est), df = 5)5  1.0573579  0.1131135   9.348           < 2e-16 ***
lat1:lon1                  -0.0030915  0.0001118 -27.645           < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for quasipoisson family taken to be 4.844091)

    Null deviance: 119566  on 18212  degrees of freedom
Residual deviance:  73190  on 18165  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 6

Analysis of Deviance Table (Type II tests)

Response: blue
                          LR Chisq Df Pr(>Chisq)
yy                          741.09 15  < 2.2e-16 ***
mm                          991.30 11  < 2.2e-16 ***
HPBCAT                       17.20  1  3.356e-05 ***
flag_id                     353.28  6  < 2.2e-16 ***
TIMECAT                     433.92  5  < 2.2e-16 ***
SHKLINE                      30.03  1  4.262e-08 ***
lat1                         84.53  1  < 2.2e-16 ***
lon1                       1197.39  1  < 2.2e-16 ***
ns(log(hook_est), df = 5)   162.56  5  < 2.2e-16 ***
lat1:lon1                   768.02  1  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

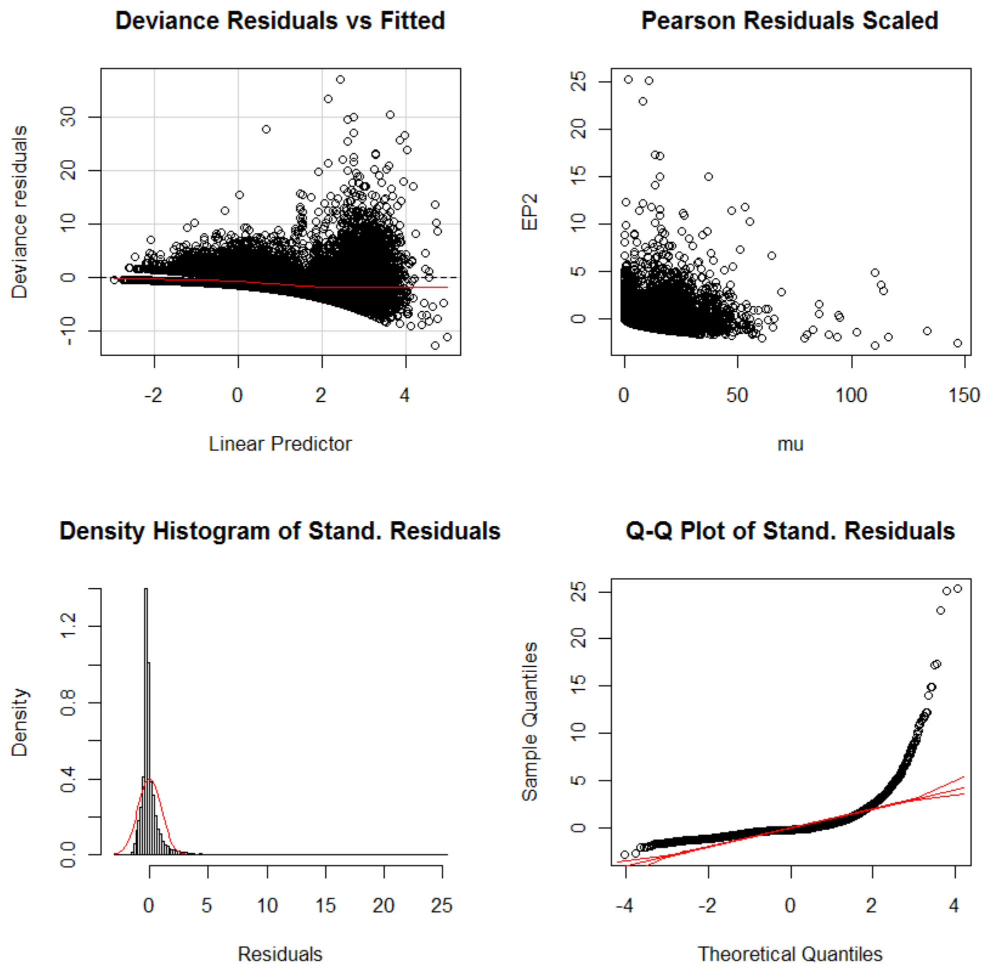


Diagnostics for Quasi-Poisson model of blue sharks in the North Pacific

Blue South

```
> sum.QPModBlue

Call:
glm(formula = blue ~ yy + mm + HPBCAT + flag_id + TIMECAT + sharkbait +
    (lat1 * lon1) + ns(log(hook_est), df = 5), family = quasipoisson,
    data = shk)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-12.540   -1.589   -0.906    0.486   37.007

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)    -1.037e+01  1.240e+00  -8.362  < 2e-16 ***
yy1996          7.147e-01  4.861e-02  14.703  < 2e-16 ***
yy1997          3.278e-01  4.836e-02   6.778 1.25e-11 ***
yy1998          4.344e-01  5.244e-02   8.285  < 2e-16 ***
yy1999          4.182e-01  5.399e-02   7.746 9.97e-15 ***
yy2000          3.129e-01  6.071e-02   5.155 2.57e-07 ***
yy2001          1.659e-01  5.855e-02   2.833 0.004620 **
yy2002          5.544e-02  6.025e-02   0.920 0.357505
yy2003         -1.167e-01  5.833e-02  -2.002 0.045342 *
yy2004          1.030e-01  6.116e-02   1.684 0.092254 .
yy2005          3.389e-01  5.738e-02   5.907 3.55e-09 ***
yy2006          6.047e-01  5.533e-02  10.929  < 2e-16 ***
yy2007          7.012e-01  5.247e-02  13.363  < 2e-16 ***
yy2008          9.730e-01  5.552e-02  17.525  < 2e-16 ***
yy2009          9.886e-02  1.430e-01   0.691 0.489303
yy2010          4.360e-01  1.435e-01   3.039 0.002379 **
mm2            -1.258e-01  1.036e-01  -1.214 0.224726
mm3            -2.861e-02  1.008e-01  -0.284 0.776548
mm4             3.341e-01  8.676e-02   3.851 0.000118 ***
mm5             4.941e-01  8.470e-02   5.834 5.51e-09 ***
mm6             6.730e-01  8.348e-02   8.062 7.97e-16 ***
mm7             7.146e-01  8.445e-02   8.461  < 2e-16 ***
mm8             2.365e-01  9.171e-02   2.579 0.009909 **
mm9            -3.694e-01  1.190e-01  -3.104 0.001914 **
mm10           -2.016e-01  1.288e-01  -1.565 0.117523
mm11           -3.080e-01  1.318e-01  -2.337 0.019470 *
mm12           -1.559e-01  1.248e-01  -1.249 0.211547
HPBCATS        -1.012e-01  4.245e-02  -2.383 0.017202 *
flag_idAU       9.787e-01  9.227e-01   1.061 0.288834
flag_idCK       3.367e-02  1.123e+00   0.030 0.976085
flag_idFJ       1.757e+00  9.158e-01   1.918 0.055063 .
flag_idJP       3.529e+00  9.184e-01   3.843 0.000122 ***
flag_idKR       3.077e+00  9.176e-01   3.354 0.000799 ***
flag_idNC       2.077e+00  9.218e-01   2.253 0.024246 *
flag_idNZ       3.295e+00  9.181e-01   3.589 0.000332 ***
flag_idPF       4.155e-01  9.176e-01   0.453 0.650641
flag_idPG       1.762e+00  9.345e-01   1.886 0.059346 .
flag_idSB       2.559e+00  9.251e-01   2.766 0.005672 **
flag_idTO       1.877e+00  9.185e-01   2.044 0.040997 *
flag_idTW       2.949e+00  9.223e-01   3.197 0.001389 **
flag_idVU       8.495e-01  1.028e+00   0.827 0.408526
flag_idWS       6.749e-01  1.287e+00   0.525 0.599897
TIMECAT2        2.578e-01  4.269e-02   6.038 1.59e-09 ***
```

```
TIMECAT3                 8.495e-02  7.724e-02   1.100 0.271383
TIMECAT4                -5.266e-02  1.122e-01  -0.469 0.638759
TIMECAT5                 3.325e-01  4.259e-02   7.807 6.14e-15 ***
TIMECAT6                 1.585e-01  3.459e-02   4.584 4.60e-06 ***
sharkbaitYES             2.710e-01  9.529e-02   2.844 0.004458 **
lat1                    -2.226e-01  2.070e-02 -10.756  < 2e-16 ***
lon1                     3.676e-02  4.433e-03   8.293  < 2e-16 ***
ns(log(hook_est), df = 5)1  6.792e-01  1.001e-01   6.789 1.17e-11 ***
ns(log(hook_est), df = 5)2  7.050e-01  1.144e-01   6.164 7.25e-10 ***
ns(log(hook_est), df = 5)3 -2.085e-01  7.566e-02  -2.755 0.005869 **
ns(log(hook_est), df = 5)4  2.425e+00  2.372e-01  10.225  < 2e-16 ***
ns(log(hook_est), df = 5)5  1.544e+00  1.196e-01  12.905  < 2e-16 ***
lat1:lon1                1.030e-03  1.266e-04   8.135 4.36e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for quasipoisson family taken to be 11.5539)

    Null deviance: 348272  on 19228  degrees of freedom
Residual deviance: 135431  on 19173  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 6

Analysis of Deviance Table (Type II tests)

Response: blue
                          LR Chisq Df Pr(>Chisq)
yy                          811.87 15  < 2.2e-16 ***
mm                          588.92 11  < 2.2e-16 ***
HPBCAT                        5.67  1   0.017293 *
flag_id                    1571.86 14  < 2.2e-16 ***
TIMECAT                      90.21  5  < 2.2e-16 ***
sharkbait                     7.78  1   0.005281 **
lat1                        526.11  1  < 2.2e-16 ***
lon1                          4.31  1   0.037858 *
ns(log(hook_est), df = 5)   258.00  5  < 2.2e-16 ***
lat1:lon1                    65.25  1  6.586e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '1
```

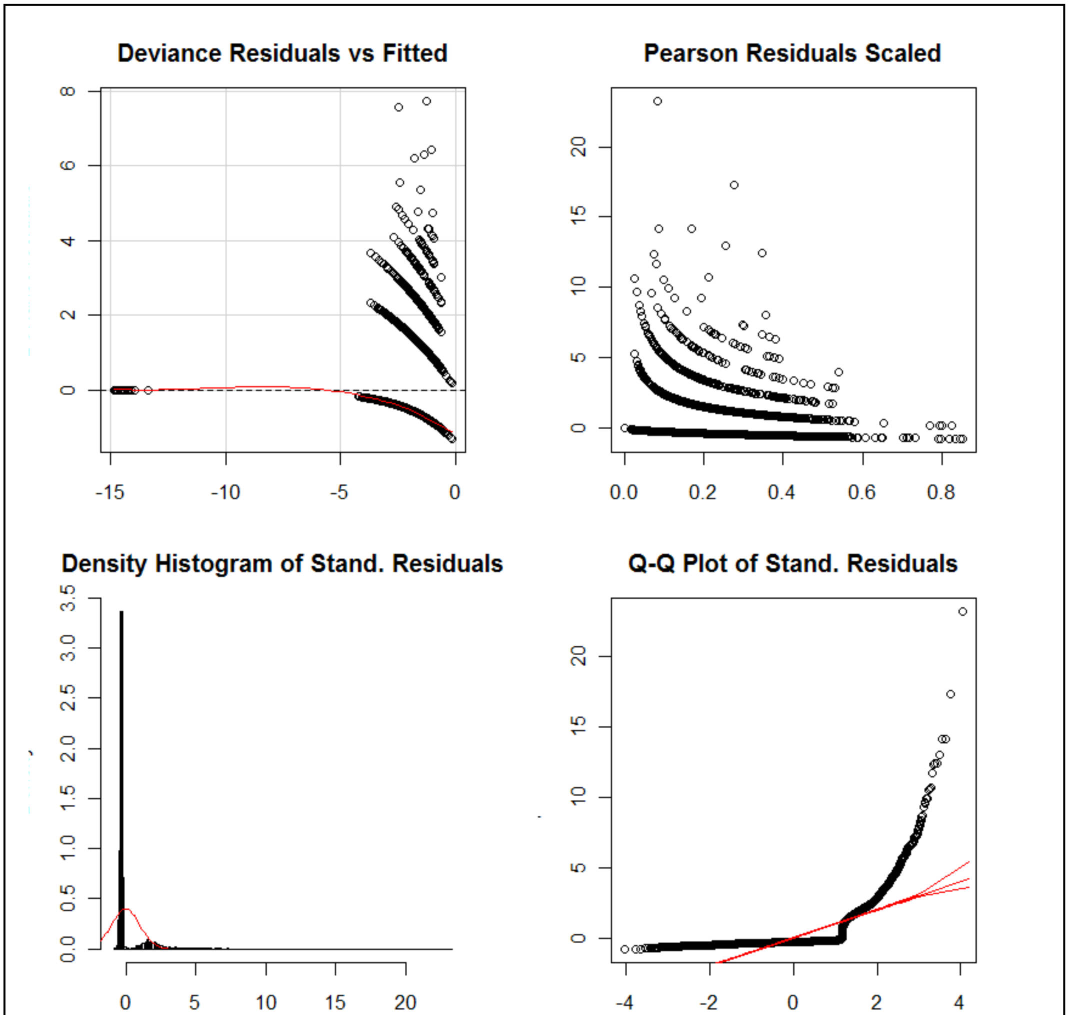


Diagnostics for Quasi-Poisson model of blue sharks in the South Pacific

Mako North

```
> sum.QPModMako

Call:
glm(formula = mako ~ yy + mm + flag_id + TIMECAT + (lat1 * lon1) +
   ns(log(hook_est), df = 5), family = quasipoisson, data = shk)

Deviance Residuals:
   Min      1Q   Median      3Q      Max
-1.3049  -0.5940  -0.4869  -0.3759   7.7242

Coefficients:
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)             -2.964e+00  1.217e+00  -2.436 0.014865 *
yy1996                  -2.558e-01  1.831e-01  -1.397 0.162293
yy1997                   1.910e-01  1.560e-01   1.224 0.220855
yy1998                   5.567e-01  1.522e-01   3.657 0.000256 ***
yy1999                   7.952e-02  1.664e-01   0.478 0.632688
yy2000                   9.483e-02  1.527e-01   0.621 0.534493
yy2001                  -1.836e-01  1.491e-01  -1.231 0.218368
yy2002                  -4.707e-02  1.387e-01  -0.339 0.734322
yy2003                  -1.772e-01  1.412e-01  -1.255 0.209338
yy2004                  -5.350e-01  1.498e-01  -3.572 0.000355 ***
yy2005                  -1.267e+00  2.644e-01  -4.794 1.65e-06 ***
yy2006                  -4.649e-01  1.884e-01  -2.468 0.013585 *
yy2007                  -4.049e-01  1.887e-01  -2.146 0.031852 *
yy2008                  -6.879e-01  2.626e-01  -2.619 0.008825 **
yy2009                  -2.913e-01  2.370e-01  -1.229 0.219036
yy2010                  -1.340e+01  1.780e+02  -0.075 0.940014
mm2                      3.285e-03  9.819e-02   0.033 0.973311
mm3                      4.087e-01  9.233e-02   4.427 9.63e-06 ***
mm4                      1.201e-01  1.003e-01   1.197 0.231322
mm5                     -3.371e-01  1.134e-01  -2.972 0.002962 **
mm6                     -5.184e-01  1.333e-01  -3.889 0.000101 ***
mm7                     -4.591e-01  1.263e-01  -3.636 0.000278 ***
mm8                     -6.855e-01  1.220e-01  -5.621 1.93e-08 ***
mm9                     -9.460e-01  1.222e-01  -7.743 1.02e-14 ***
mm10                    -7.466e-01  1.106e-01  -6.752 1.50e-11 ***
mm11                    -5.710e-01  1.076e-01  -5.309 1.12e-07 ***
mm12                    -1.521e-01  1.016e-01  -1.497 0.134415
flag_idFM               -1.512e-01  1.451e-01  -1.042 0.297419
flag_idJP               -1.982e-01  1.799e-01  -1.102 0.270540
flag_idKR               -1.377e+00  2.895e-01  -4.757 1.98e-06 ***
flag_idPF               -7.459e-01  2.849e+02  -0.003 0.997912
flag_idTW                5.940e-01  1.723e-01   3.448 0.000565 ***
flag_idUS               -1.849e+00  2.157e-01  -8.573  < 2e-16 ***
TIMECAT2                 2.316e-01  2.012e-01   1.151 0.249684
TIMECAT3                 1.168e-01  2.052e-01   0.569 0.569290
TIMECAT4                -9.637e-02  2.717e-01  -0.355 0.722822
TIMECAT5                -1.839e-01  2.071e-01  -0.888 0.374437
TIMECAT6                -7.465e-01  2.657e-01  -2.810 0.004966 **
lat1                    -4.601e-02  6.319e-02  -0.728 0.466577
lon1                     7.584e-03  6.841e-03   1.109 0.267656
ns(log(hook_est), df = 5)1  8.760e-02  1.893e-01   0.463 0.643543
ns(log(hook_est), df = 5)2  1.886e-01  1.978e-01   0.953 0.340365
ns(log(hook_est), df = 5)3  5.149e-01  1.935e-01   2.661 0.007805 **
ns(log(hook_est), df = 5)4  5.863e-01  4.407e-01   1.330 0.183388
```

```
ns(log(hook_est), df = 5)5  1.005e+00  4.000e-01   2.512 0.012000 *
lat1:lon1                  5.733e-04  3.207e-04   1.788 0.073869 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for quasipoisson family taken to be 1.391354)

    Null deviance: 12360  on 18212  degrees of freedom
Residual deviance: 11512  on 18167  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 12

Analysis of Deviance Table (Type II tests)

Response: mako
                          LR Chisq Df Pr(>Chisq)
yy                         136.476 15  < 2.2e-16 ***
mm                         284.222 11  < 2.2e-16 ***
flag_id                     85.660  6  2.410e-16 ***
TIMECAT                     29.521  5  1.832e-05 ***
lat1                       161.644  1  < 2.2e-16 ***
lon1                        15.715  1  7.364e-05 ***
ns(log(hook_est), df = 5)   34.987  5  1.513e-06 ***
lat1:lon1                    3.185  1     0.0743 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



Diagnostics for Quasi-Poisson model of mako sharks in the North Pacific

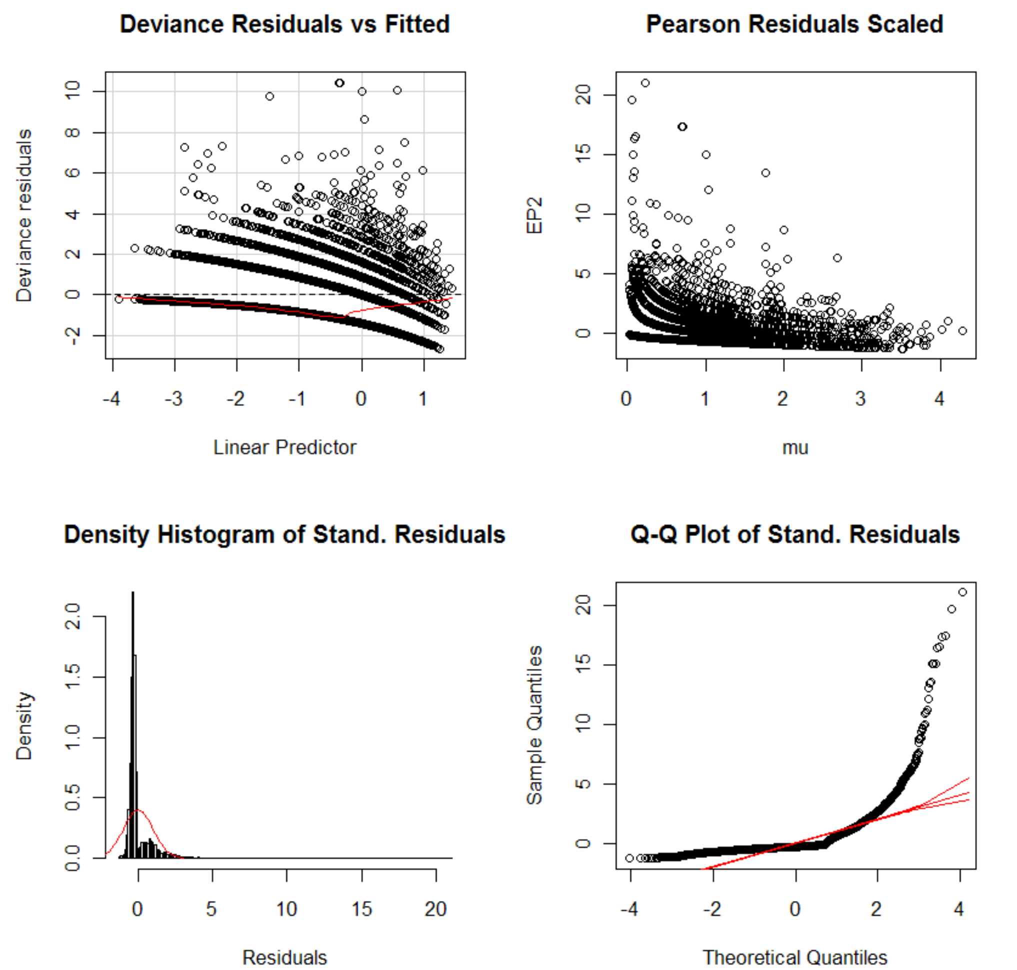
Mako South

```
> sum.QPModMako

Call:
glm(formula = mako ~ yy + mm + flag_id + TIMECAT + target + (lat1 *
   lon1) + ns(log(hook_est), df = 5), family = quasipoisson,
   data = shk)

Deviance Residuals:
   Min       1Q   Median       3Q      Max
-2.6519  -0.8884  -0.6429  -0.2934  10.4475

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)    4.521951   0.986981   4.582 4.64e-06 ***
yy1996         0.027143   0.094838   0.286 0.774728
yy1997         0.173936   0.083431   2.085 0.037102 *
yy1998        -0.356260   0.094143  -3.784 0.000155 ***
yy1999        -0.299566   0.100887  -2.969 0.002988 **
yy2000        -0.843690   0.133344  -6.327 2.55e-10 ***
yy2001        -0.475520   0.098724  -4.817 1.47e-06 ***
yy2002        -0.536509   0.098755  -5.433 5.62e-08 ***
yy2003        -0.472812   0.093351  -5.065 4.12e-07 ***
yy2004        -0.440616   0.091427  -4.819 1.45e-06 ***
yy2005        -0.386917   0.090465  -4.277 1.90e-05 ***
yy2006        -0.597117   0.097517  -6.123 9.35e-10 ***
yy2007        -0.311253   0.088820  -3.504 0.000459 ***
yy2008        -0.079267   0.089736  -0.883 0.377067
yy2009        -0.339600   0.139746  -2.430 0.015103 *
yy2010        -0.221306   0.153340  -1.443 0.148969
mm2           -0.215248   0.115945  -1.856 0.063403 .
mm3            0.193663   0.108792   1.780 0.075073 .
mm4           -0.044445   0.104587  -0.425 0.670874
mm5            0.141617   0.100930   1.403 0.160597
mm6            0.508056   0.096342   5.273 1.35e-07 ***
mm7            0.912962   0.093451   9.769  < 2e-16 ***
mm8            0.710086   0.098616   7.201 6.22e-13 ***
mm9            0.686139   0.102212   6.713 1.96e-11 ***
mm10           0.444110   0.111616   3.979 6.95e-05 ***
mm11           0.315638   0.114704   2.752 0.005933 **
mm12           0.134852   0.119498   1.128 0.259130
flag_idAU      0.842288   0.442531   1.903 0.057011 .
flag_idCK     -2.414686   0.844944  -2.858 0.004270 **
flag_idFJ     -0.325868   0.428028  -0.761 0.446472
flag_idJP      0.919556   0.438605   2.097 0.036047 *
flag_idKR      0.665083   0.439196   1.514 0.129961
flag_idNC     -0.052527   0.440678  -0.119 0.905122
flag_idNZ      0.779953   0.435279   1.792 0.073173 .
flag_idPF     -1.231916   0.429017  -2.871 0.004090 **
flag_idPG     -1.317706   0.456383  -2.887 0.003890 **
flag_idSB      0.371419   0.437068   0.850 0.395449
flag_idTO      0.199375   0.428513   0.465 0.641742
flag_idTW      0.386809   0.437417   0.884 0.376544
flag_idVU     -1.295385   0.574872  -2.253 0.024249 *
flag_idWS     -1.525383   1.114960  -1.368 0.171295
TIMECAT2       0.061078   0.063748   0.958 0.338018
TIMECAT3       0.018599   0.082682   0.225 0.822021
```

```
TIMECAT4                -0.020670   0.088334  -0.234 0.814990
TIMECAT5                -0.008658   0.062766  -0.138 0.890289
TIMECAT6                -0.103931   0.051473  -2.019 0.043487 *
targetYES                0.265032   0.081209   3.264 0.001102 **
lat1                     0.456137   0.026494  17.217  < 2e-16 ***
lon1                    -0.035519   0.004752  -7.475 8.05e-14 ***
ns(log(hook_est), df = 5)1 -0.061443   0.113975  -0.539 0.589828
ns(log(hook_est), df = 5)2  0.064480   0.139732   0.461 0.644475
ns(log(hook_est), df = 5)3 -0.598754   0.119374  -5.016 5.33e-07 ***
ns(log(hook_est), df = 5)4  0.749540   0.325344   2.304 0.021243 *
ns(log(hook_est), df = 5)5  0.236805   0.391302   0.605 0.545072
lat1:lon1               -0.002730   0.000160 -17.069  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for quasipoisson family taken to be 2.137417)

    Null deviance: 29339  on 19228  degrees of freedom
Residual deviance: 22868  on 19174  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 6
```

Analysis of Deviance Table (Type II tests)

```
Response: mako
                          LR Chisq Df Pr(>Chisq)
yy                          198.49 15  < 2.2e-16 ***
mm                          430.87 11  < 2.2e-16 ***
flag_id                     606.50 14  < 2.2e-16 ***
TIMECAT                       6.97  5   0.222558
target                       10.40  1   0.001257 **
lat1                          7.16  1   0.007464 **
lon1                        145.32  1  < 2.2e-16 ***
ns(log(hook_est), df = 5)    75.65  5  6.799e-15 ***
lat1:lon1                   290.36  1  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

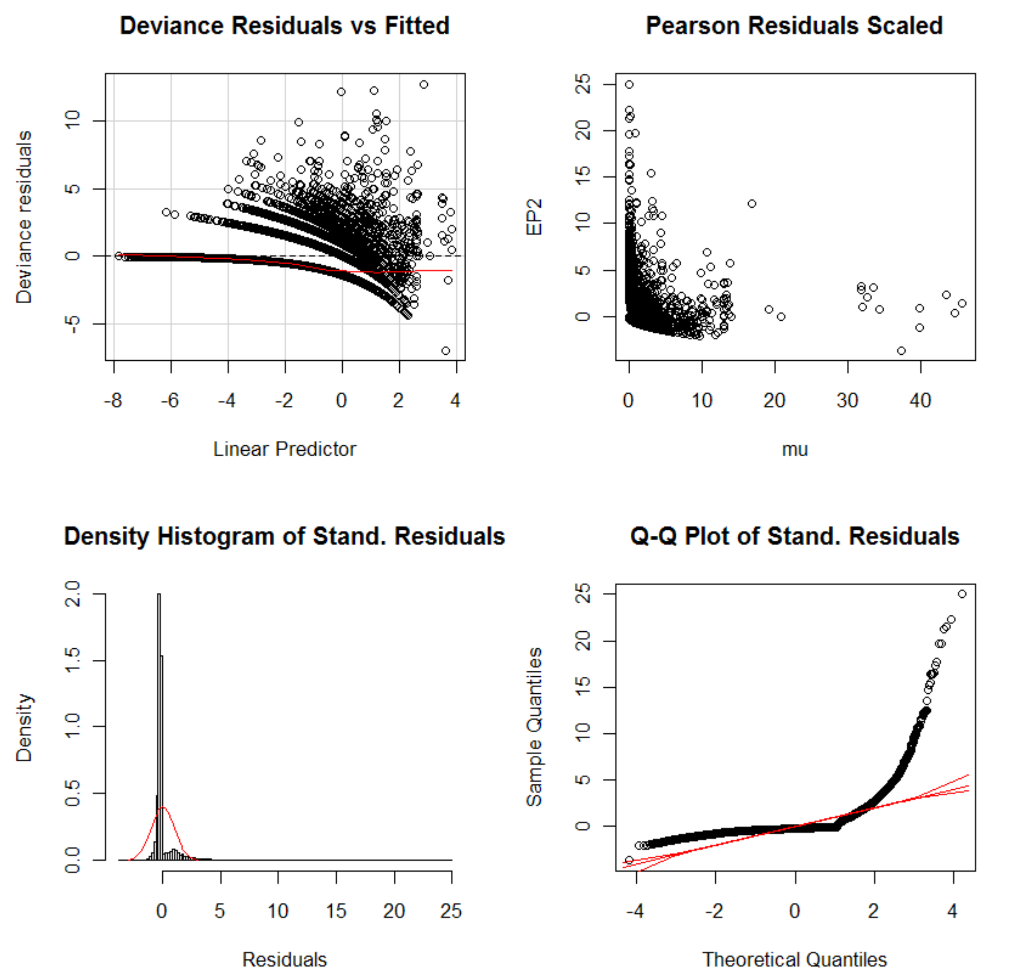


Diagnostics for Quasi-Poisson model of mako sharks in the South Pacific

Oceanic Whitetip

```
> sum.QPModOWT

Call:
glm(formula = owt ~ yy + mm + HPBCAT + flag_id + TIMECAT + SHKLINE +
    (lat1 * lon1) + sharkbait + target + ns(log(hook_est), df = 5),
    family = quasipoisson, data = shk)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-6.9839  -0.7065  -0.4660  -0.1987  12.7284

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)        -6.218e+00  5.067e-01 -12.272  < 2e-16 ***
yy1996              3.692e-03  1.029e-01   0.036 0.971379
yy1997              7.729e-03  1.007e-01   0.077 0.938835
yy1998             -4.062e-03  9.016e-02  -0.045 0.964069
yy1999              5.416e-01  8.831e-02   6.133 8.71e-10 ***
yy2000             -3.785e-01  9.979e-02  -3.793 0.000149 ***
yy2001             -2.217e-01  9.154e-02  -2.422 0.015421 *
yy2002             -6.542e-01  8.921e-02  -7.333 2.30e-13 ***
yy2003             -8.955e-01  9.628e-02  -9.301  < 2e-16 ***
yy2004             -9.756e-01  9.133e-02 -10.681  < 2e-16 ***
yy2005             -1.042e+00  1.016e-01 -10.262  < 2e-16 ***
yy2006             -1.512e+00  1.042e-01 -14.513  < 2e-16 ***
yy2007             -1.520e+00  1.116e-01 -13.622  < 2e-16 ***
yy2008             -1.863e+00  1.189e-01 -15.677  < 2e-16 ***
yy2009             -2.336e+00  1.490e-01 -15.679  < 2e-16 ***
yy2010             -2.510e+00  2.018e-01 -12.439  < 2e-16 ***
mm2                -1.308e-01  6.543e-02  -1.998 0.045698 *
mm3                -5.539e-01  6.874e-02  -8.057 8.06e-16 ***
mm4                -3.423e-01  6.632e-02  -5.160 2.48e-07 ***
mm5                -7.616e-02  6.271e-02  -1.214 0.224606
mm6                -3.543e-01  7.269e-02  -4.874 1.10e-06 ***
mm7                -1.174e-01  7.028e-02  -1.671 0.094789 .
mm8                -2.913e-01  7.174e-02  -4.060 4.91e-05 ***
mm9                -1.855e-01  6.506e-02  -2.851 0.004357 **
mm10               -6.293e-01  6.745e-02  -9.330  < 2e-16 ***
mm11               -6.971e-01  6.797e-02 -10.256  < 2e-16 ***
mm12               -7.207e-01  7.021e-02 -10.265  < 2e-16 ***
HPBCATS             4.554e-01  6.013e-02   7.573 3.72e-14 ***
flag_idAU           1.753e+00  3.751e-01   4.674 2.96e-06 ***
flag_idCK          -2.796e+00  1.117e+00  -2.503 0.012311 *
flag_idCN           1.476e+00  3.409e-01   4.331 1.49e-05 ***
flag_idFJ           1.098e+00  3.421e-01   3.211 0.001324 **
flag_idFM           1.301e+00  3.595e-01   3.619 0.000296 ***
flag_idGU           2.213e+00  3.869e-01   5.718 1.08e-08 ***
flag_idJP          -2.462e-01  3.604e-01  -0.683 0.494430
flag_idKI           1.616e+00  9.374e-01   1.724 0.084682 .
flag_idKR           1.250e+00  3.428e-01   3.648 0.000265 ***
flag_idMH           1.322e+00  5.888e-01   2.245 0.024786 *
flag_idNC           1.550e+00  3.695e-01   4.194 2.74e-05 ***
flag_idNZ          -2.884e+00  4.879e-01  -5.910 3.44e-09 ***
flag_idPF          -1.052e+00  3.459e-01  -3.040 0.002365 **
flag_idPG           1.489e+00  3.467e-01   4.294 1.76e-05 ***
flag_idPW           9.673e-02  1.546e+00   0.063 0.950117
```

```
flag_idSB                1.981e+00  3.442e-01   5.754 8.78e-09 ***
flag_idTO                1.066e+00  3.415e-01   3.120 0.001808 **
flag_idTW                1.559e+00  3.434e-01   4.540 5.65e-06 ***
flag_idUS                1.700e+00  3.397e-01   5.006 5.59e-07 ***
flag_idVU                7.257e-01  4.548e-01   1.596 0.110528
flag_idWS                3.094e-01  5.230e-01   0.592 0.554082
TIMECAT2                -2.537e-01  6.255e-02  -4.055 5.02e-05 ***
TIMECAT3                -1.891e-01  6.772e-02  -2.792 0.005243 **
TIMECAT4                -7.561e-02  7.095e-02  -1.066 0.286548
TIMECAT5                -3.881e-01  7.066e-02  -5.493 3.99e-08 ***
TIMECAT6                -9.367e-01  1.046e-01  -8.957  < 2e-16 ***
SHKLINE1                 7.471e-01  6.018e-02  12.415  < 2e-16 ***
lat1                     4.391e-01  1.626e-02  27.013  < 2e-16 ***
lon1                     2.557e-02  1.816e-03  14.084  < 2e-16 ***
sharkbaitYES             8.194e-01  4.847e-02  16.904  < 2e-16 ***
targetYES                1.345e+00  4.954e-02  27.160  < 2e-16 ***
ns(log(hook_est), df = 5)1  4.921e-01  9.524e-02   5.167 2.39e-07 ***
ns(log(hook_est), df = 5)2  4.227e-01  1.110e-01   3.808 0.000140 ***
ns(log(hook_est), df = 5)3 -2.623e-02  1.525e-01  -0.172 0.863425
ns(log(hook_est), df = 5)4  1.577e+00  3.171e-01   4.975 6.55e-07 ***
ns(log(hook_est), df = 5)5  7.444e-01  4.989e-01   1.492 0.135683
lat1:lon1               -2.555e-03  8.832e-05 -28.933  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasipoisson family taken to be 2.263809)

    Null deviance: 63632  on 37773  degrees of freedom
Residual deviance: 37006  on 37709  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 7

Analysis of Deviance Table (Type II tests)

Response: owt
                          LR Chisq Df Pr(>Chisq)
yy                         1334.96 15  < 2.2e-16 ***
mm                          322.68 11  < 2.2e-16 ***
HPBCAT                       58.05  1  2.553e-14 ***
flag_id                    1159.84 21  < 2.2e-16 ***
TIMECAT                     130.45  5  < 2.2e-16 ***
SHKLINE                     151.94  1  < 2.2e-16 ***
lat1                        106.21  1  < 2.2e-16 ***
lon1                        138.23  1  < 2.2e-16 ***
sharkbait                   285.13  1  < 2.2e-16 ***
target                      747.62  1  < 2.2e-16 ***
ns(log(hook_est), df = 5)    69.86  5  1.094e-13 ***
lat1:lon1                   793.05  1  < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

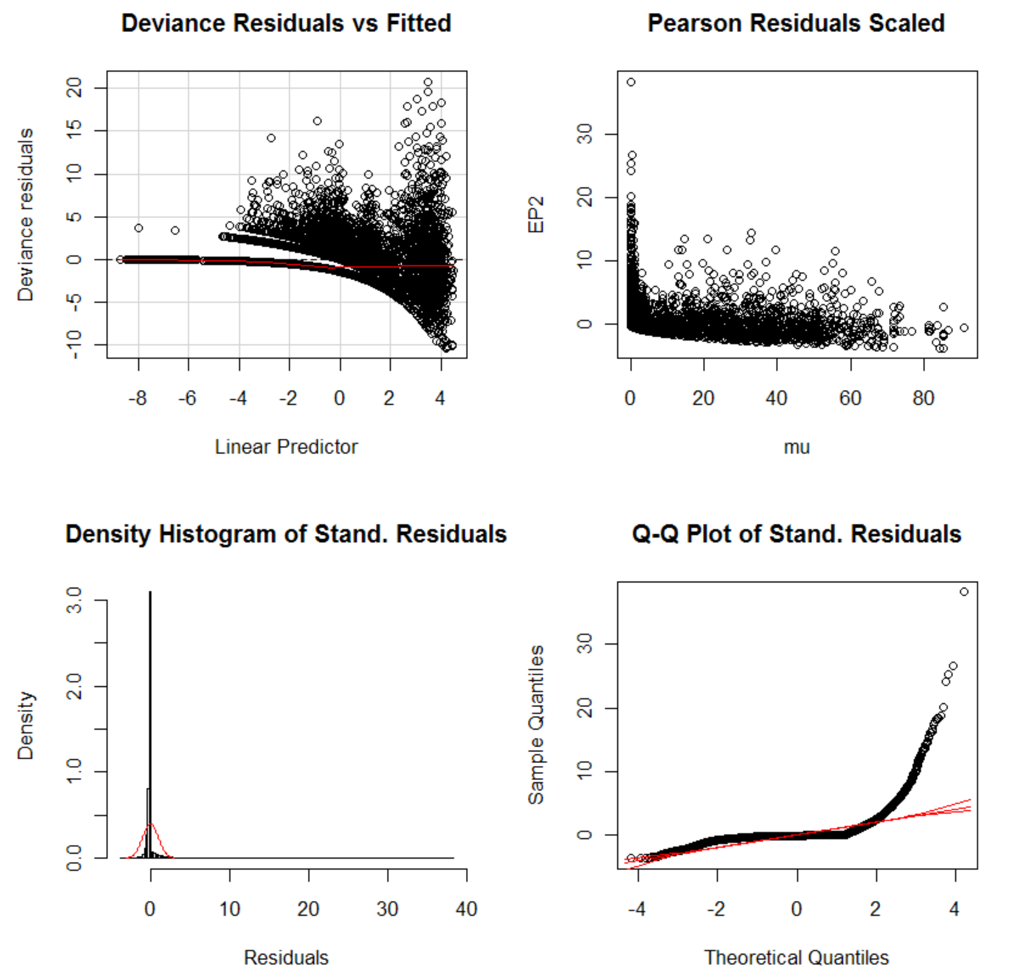


Diagnostics for Quasi-Poisson model of oceanic whitetip sharks

Silky

```
> sum.QPModFAL

Call:
glm(formula = silky ~ yy + mm + HPBCAT + flag_id + TIMECAT +
    SHKLINE + (lat1 * lon1) + sharkbait + target + ns(log(hook_est),
    df = 5), family = quasipoisson, data = shk)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-10.3371  -0.6303  -0.3983  -0.2492  20.7394

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)       0.446198   0.737915   0.605 0.545399
yy1996           -0.593540   0.149512  -3.970 7.21e-05 ***
yy1997           -0.224460   0.130841  -1.716 0.086260 .
yy1998           -0.006056   0.102381  -0.059 0.952833
yy1999            0.172455   0.101574   1.698 0.089549 .
yy2000           -0.002863   0.107105  -0.027 0.978675
yy2001            0.077451   0.102259   0.757 0.448815
yy2002            0.324465   0.097814   3.317 0.000910 ***
yy2003           -0.009524   0.104913  -0.091 0.927667
yy2004            0.233809   0.097785   2.391 0.016805 *
yy2005            0.189287   0.099415   1.904 0.056917 .
yy2006            0.329333   0.102091   3.226 0.001257 **
yy2007            0.125113   0.104956   1.192 0.233249
yy2008           -0.355074   0.108819  -3.263 0.001104 **
yy2009           -0.312169   0.143527  -2.175 0.029637 *
yy2010           -1.027547   0.216787  -4.740 2.15e-06 ***
mm2              -0.106187   0.049127  -2.161 0.030666 *
mm3              -0.048169   0.051462  -0.936 0.349270
mm4              -0.194780   0.051521  -3.781 0.000157 ***
mm5              -0.359150   0.056405  -6.367 1.95e-10 ***
mm6              -0.466592   0.067285  -6.935 4.14e-12 ***
mm7              -0.016971   0.058591  -0.290 0.772089
mm8              -0.098845   0.049463  -1.998 0.045685 *
mm9              -0.109037   0.049265  -2.213 0.026886 *
mm10              0.072035   0.052044   1.384 0.166327
mm11             -0.153608   0.055445  -2.770 0.005601 **
mm12             -0.224175   0.056052  -3.999 6.36e-05 ***
HPBCATS           0.481531   0.050139   9.604  < 2e-16 ***
flag_idAU        -1.311295   0.700214  -1.873 0.061117 .
flag_idCK        -1.102432   1.264644  -0.872 0.383360
flag_idCN         2.452203   0.657008   3.732 0.000190 ***
flag_idFJ         1.051174   0.659451   1.594 0.110941
flag_idFM         2.336122   0.661679   3.531 0.000415 ***
flag_idGU         2.168265   0.707303   3.066 0.002174 **
flag_idJP        -0.252089   0.670366  -0.376 0.706885
flag_idKI         0.857650   1.101660   0.779 0.436275
flag_idKR         2.673563   0.659621   4.053 5.06e-05 ***
flag_idMH         2.981825   0.738940   4.035 5.46e-05 ***
flag_idNC         1.112801   0.673436   1.652 0.098456 .
flag_idNZ        -5.561882   1.658431  -3.354 0.000798 ***
flag_idPF        -0.903302   0.676906  -1.334 0.182062
flag_idPG         2.803472   0.658762   4.256 2.09e-05 ***
flag_idPW         0.714786   1.413785   0.506 0.613152
flag_idSB         1.863760   0.661543   2.817 0.004846 **
```

```
flag_idTO               0.189039   0.671728   0.281 0.778388
flag_idTW               2.419342   0.658250   3.675 0.000238 ***
flag_idUS               2.501011   0.664253   3.765 0.000167 ***
flag_idVU               1.344546   0.695468   1.933 0.053207 .
flag_idWS               1.058811   0.944980   1.120 0.262525
TIMECAT2                0.139648   0.069846   1.999 0.045576 *
TIMECAT3                0.267533   0.071083   3.764 0.000168 ***
TIMECAT4                0.436105   0.067686   6.443 1.19e-10 ***
TIMECAT5                0.345310   0.068424   5.047 4.52e-07 ***
TIMECAT6                0.183287   0.078185   2.344 0.019070 *
SHKLINE1                0.285278   0.033405   8.540  < 2e-16 ***
lat1                    0.381664   0.017593  21.694  < 2e-16 ***
lon1                   -0.020716   0.001678 -12.345  < 2e-16 ***
sharkbaitYES            1.164979   0.037192  31.323  < 2e-16 ***
targetYES               0.868910   0.035979  24.150  < 2e-16 ***
ns(log(hook_est), df = 5)1 -0.196358   0.079149  -2.481 0.013111 *
ns(log(hook_est), df = 5)2  0.930549   0.097810   9.514  < 2e-16 ***
ns(log(hook_est), df = 5)3 -1.708302   0.188641  -9.056  < 2e-16 ***
ns(log(hook_est), df = 5)4  1.946978   0.381152   5.108 3.27e-07 ***
ns(log(hook_est), df = 5)5  1.693877   0.726897   2.330 0.019796 *
lat1:lon1              -0.002341   0.000107 -21.878  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasipoisson family taken to be 4.665208)

    Null deviance: 327273  on 37773  degrees of freedom
Residual deviance:  71980  on 37709  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 8

Analysis of Deviance Table (Type II tests)

Response: silky
                    LR Chisq Df Pr(>Chisq)
yy                    370.30 15     <2e-16 ***
mm                    165.27 11     <2e-16 ***
HPBCAT                 96.16  1     <2e-16 ***
flag_id              1702.92 21     <2e-16 ***
TIMECAT                90.48  5     <2e-16 ***
SHKLINE                72.37  1     <2e-16 ***
lat1                    1.91  1     0.1674
lon1                  169.89  1     <2e-16 ***
sharkbait            1058.65  1     <2e-16 ***
target                586.69  1     <2e-16 ***
ns(log(hook_est), df = 5)   332.18  5     <2e-16 ***
lat1:lon1             430.23  1     <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

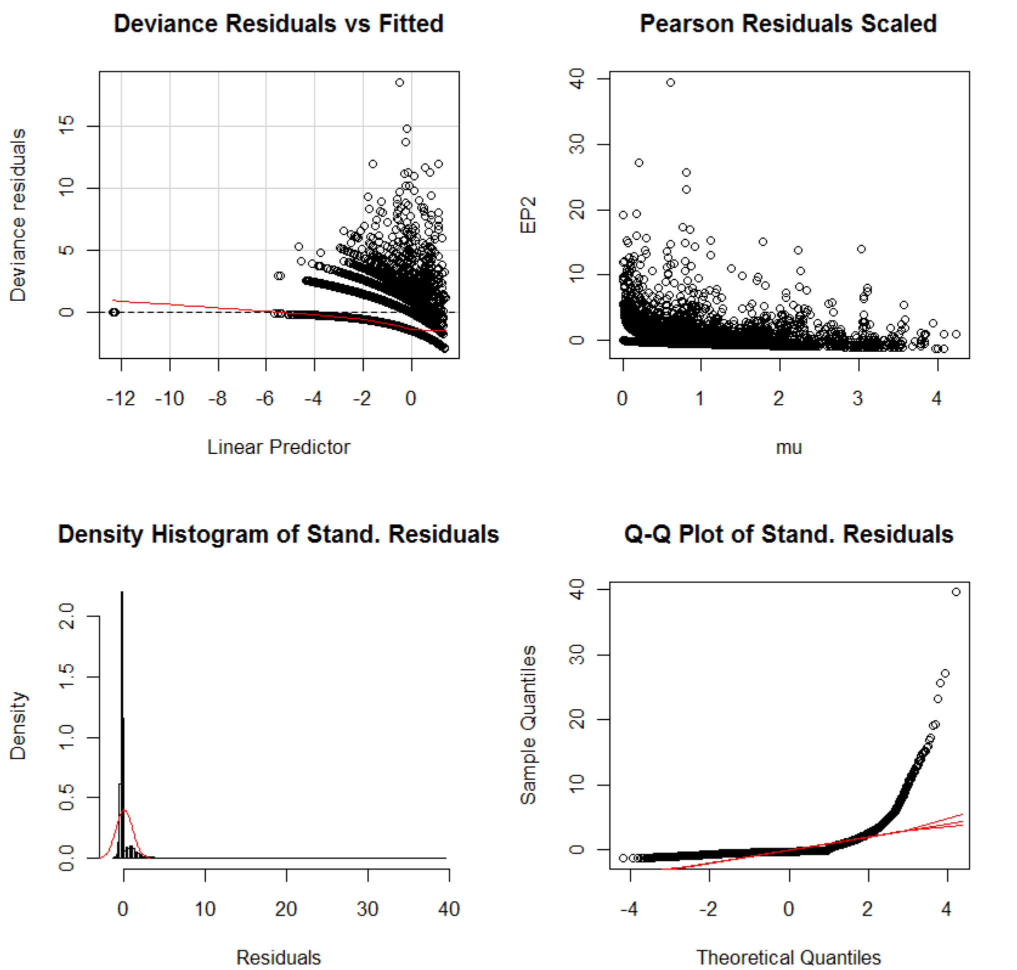


Diagnostics for Quasi-Poisson model of silky sharks

Thresher

```
> sum.QPModTHR

Call:
glm(formula = thresher ~ yy + mm + HPBCAT + flag_id + TIMECAT +
    target + (lat1 * lon1) + ns(log(hook_est), df = 5), family = quasipoisson,
    data = shk)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.8528  -0.7733  -0.5421  -0.2573  18.5046

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)       -4.956e+00  7.256e-01  -6.831 8.55e-12 ***
yy1996             6.784e-02  1.237e-01   0.548 0.583402
yy1997            -1.518e-01  1.243e-01  -1.221 0.222077
yy1998             1.190e-01  1.134e-01   1.050 0.293799
yy1999            -2.728e-01  1.277e-01  -2.136 0.032703 *
yy2000             2.270e-02  1.115e-01   0.204 0.838616
yy2001            -7.438e-02  1.077e-01  -0.691 0.489773
yy2002             4.114e-02  1.007e-01   0.409 0.682794
yy2003            -2.939e-01  1.044e-01  -2.817 0.004856 **
yy2004            -2.300e-04  1.014e-01  -0.002 0.998190
yy2005            -2.554e-01  1.215e-01  -2.102 0.035524 *
yy2006             2.632e-01  1.100e-01   2.394 0.016685 *
yy2007             1.008e-01  1.118e-01   0.901 0.367393
yy2008            -1.998e-01  1.329e-01  -1.503 0.132936
yy2009             6.278e-01  1.315e-01   4.774 1.81e-06 ***
yy2010             1.896e-01  2.564e-01   0.739 0.459611
mm2               -1.952e-01  8.270e-02  -2.360 0.018257 *
mm3                4.827e-01  7.029e-02   6.866 6.70e-12 ***
mm4                2.879e-01  7.309e-02   3.939 8.18e-05 ***
mm5                3.220e-01  7.153e-02   4.502 6.76e-06 ***
mm6                2.909e-01  7.530e-02   3.863 0.000112 ***
mm7                2.174e-01  7.866e-02   2.763 0.005724 **
mm8               -7.820e-02  8.500e-02  -0.920 0.357578
mm9               -2.615e-02  8.302e-02  -0.315 0.752790
mm10              -3.423e-01  8.539e-02  -4.009 6.10e-05 ***
mm11              -7.286e-02  8.071e-02  -0.903 0.366683
mm12               6.597e-04  8.262e-02   0.008 0.993630
HPBCATS            3.009e-02  7.957e-02   0.378 0.705301
flag_idAU          2.104e+00  5.426e-01   3.877 0.000106 ***
flag_idCK         -8.248e-01  1.248e+00  -0.661 0.508675
flag_idCN          3.190e+00  5.175e-01   6.165 7.14e-10 ***
flag_idFJ         -7.656e-01  5.458e-01  -1.403 0.160726
flag_idFM          3.015e+00  5.212e-01   5.784 7.36e-09 ***
flag_idGU          3.681e+00  5.524e-01   6.663 2.73e-11 ***
flag_idJP          1.729e+00  5.261e-01   3.286 0.001017 **
flag_idKI          1.583e+00  8.082e-01   1.959 0.050173 .
flag_idKR          1.103e+00  5.394e-01   2.045 0.040880 *
flag_idMH          2.028e+00  6.572e-01   3.085 0.002035 **
flag_idNC          4.289e-01  5.570e-01   0.770 0.441266
flag_idNZ          1.059e+00  5.273e-01   2.009 0.044541 *
flag_idPF         -1.939e+00  5.507e-01  -3.521 0.000431 ***
flag_idPG          1.637e+00  5.362e-01   3.053 0.002270 **
flag_idPW         -9.622e+00  1.319e+02  -0.073 0.941838
```

```
flag_idSB                1.343e+00  5.348e-01   2.511 0.012055 *
flag_idTO                2.682e-01  5.450e-01   0.492 0.622633
flag_idTW                1.999e+00  5.261e-01   3.800 0.000145 ***
flag_idUS                3.139e+00  5.139e-01   6.107 1.02e-09 ***
flag_idVU               -1.434e+00  1.261e+00  -1.137 0.255452
flag_idWS               -1.918e-01  1.245e+00  -0.154 0.877574
TIMECAT2                 1.336e-01  9.121e-02   1.465 0.142914
TIMECAT3                 1.129e-02  9.667e-02   0.117 0.907043
TIMECAT4                 1.123e-01  1.221e-01   0.919 0.357971
TIMECAT5                -1.722e-01  1.057e-01  -1.630 0.103173
TIMECAT6                 1.979e-01  9.633e-02   2.054 0.039987 *
targetYES                4.979e-01  5.988e-02   8.315  < 2e-16 ***
lat1                     3.000e-01  1.589e-02  18.874  < 2e-16 ***
lon1                     1.129e-03  2.471e-03   0.457 0.647799
ns(log(hook_est), df = 5)1  1.464e+00  1.532e-01   9.555  < 2e-16 ***
ns(log(hook_est), df = 5)2  1.752e+00  1.704e-01  10.283  < 2e-16 ***
ns(log(hook_est), df = 5)3  6.146e-01  1.686e-01   3.646 0.000267 ***
ns(log(hook_est), df = 5)4  3.019e+00  4.224e-01   7.147 9.03e-13 ***
ns(log(hook_est), df = 5)5  1.057e+00  4.820e-01   2.194 0.028256 *
lat1:lon1               -1.766e-03  8.762e-05 -20.155  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for quasipoisson family taken to be 2.576681)

    Null deviance: 53900  on 37773  degrees of freedom
Residual deviance: 40914  on 37711  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 10


Analysis of Deviance Table (Type II tests)

Response: thresher
                          LR Chisq Df Pr(>Chisq)
yy                          148.16 15  < 2.2e-16 ***
mm                          256.47 11  < 2.2e-16 ***
HPBCAT                        0.14  1     0.7052
flag_id                    1943.31 21  < 2.2e-16 ***
TIMECAT                      29.78  5  1.628e-05 ***
target                       64.90  1  7.878e-16 ***
lat1                         53.09  1  3.194e-13 ***
lon1                         18.70  1  1.530e-05 ***
ns(log(hook_est), df = 5)   145.74  5  < 2.2e-16 ***
lat1:lon1                   409.71  1  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



Diagnostics for Quasi-Poisson model of thresher sharks

ANNEX 7

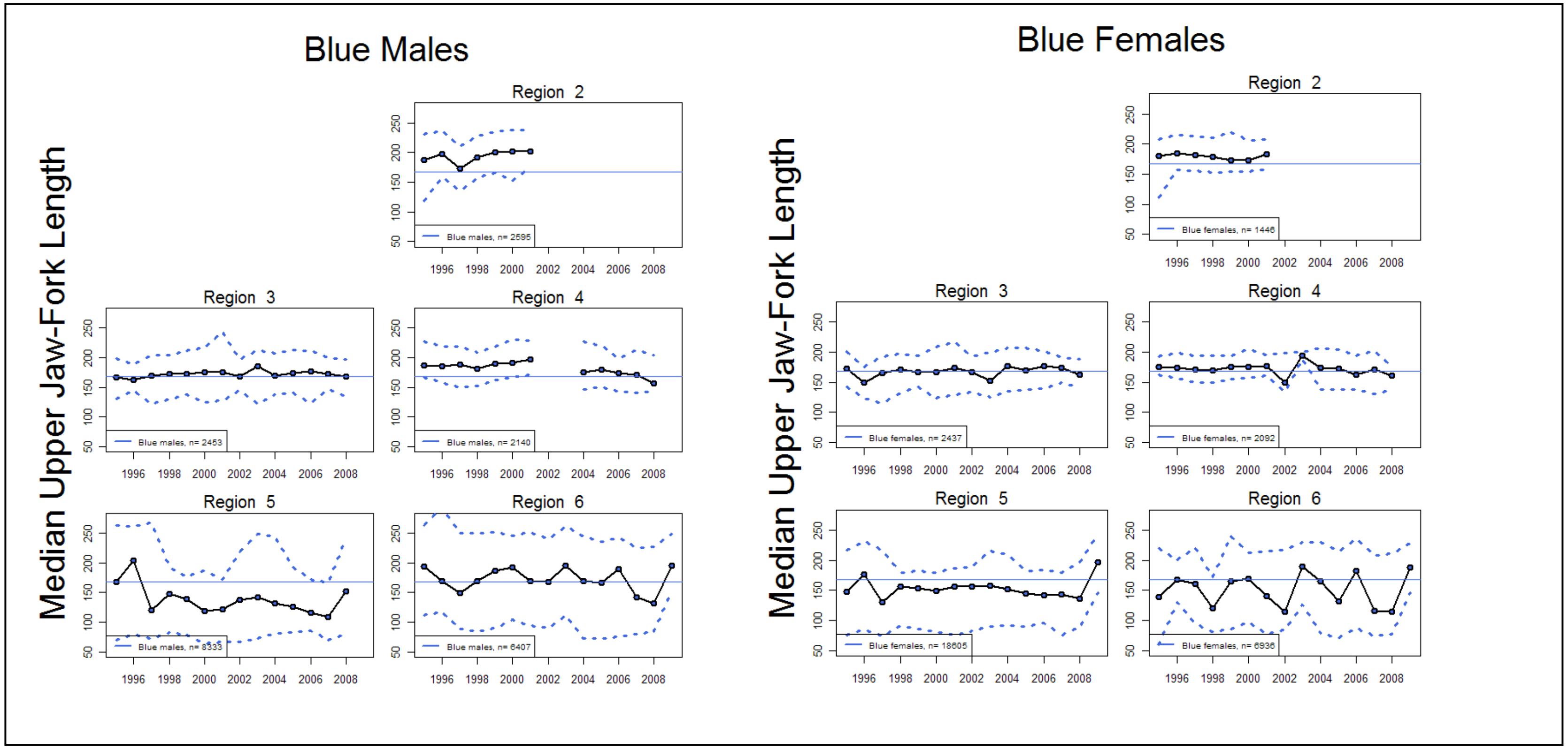


Figure A7. Median length (in fork length in cm) for male (left panel) and female (right panel) blue sharks by region from longline observer data, 1995-2009. The 5th and 95th percentiles of the data are shown with dashed lines. The sample size is shown in the inset to each plot. Size at maturity is represented by the solid horizontal line.

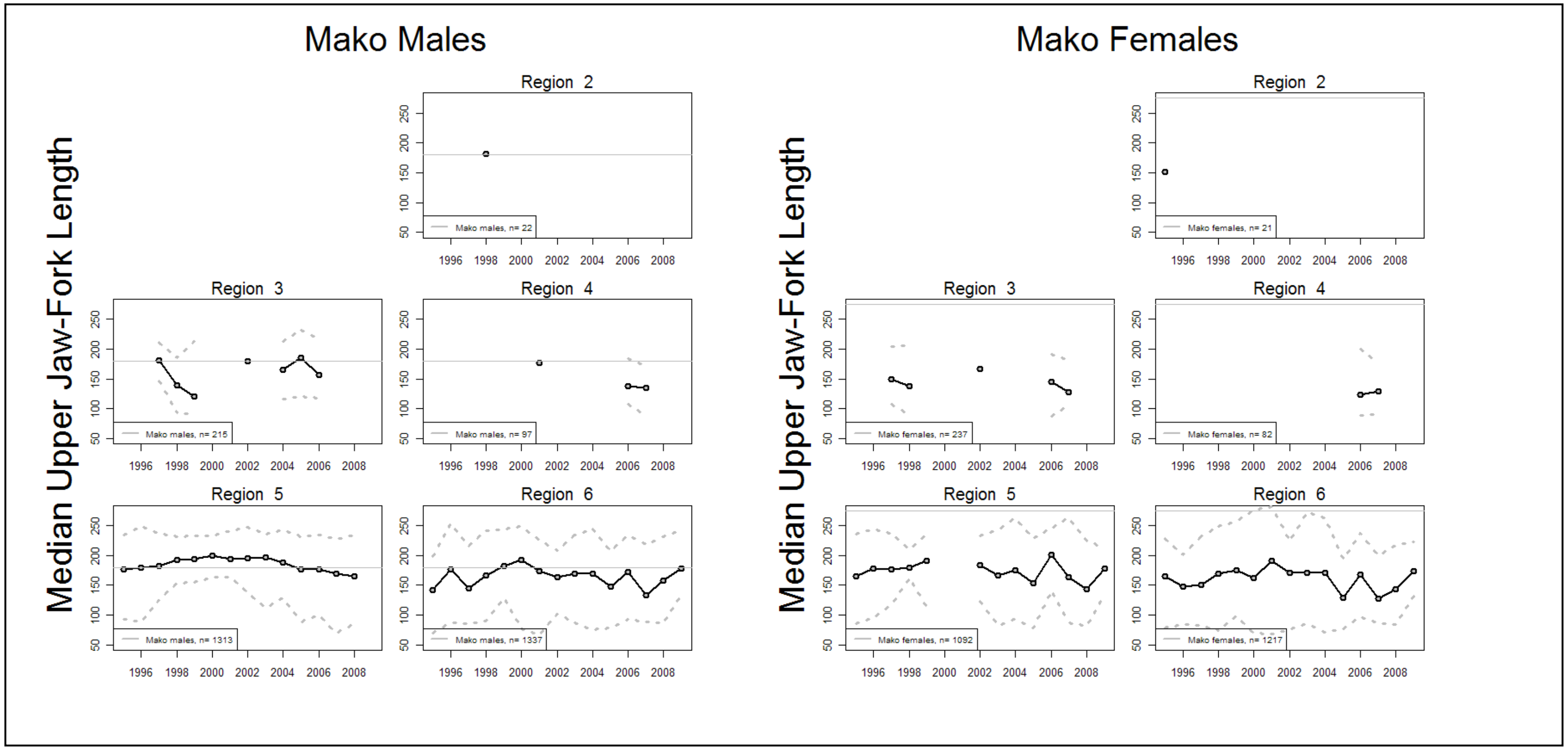


Figure A7 (cont.) Median length (in fork length in cm) for male (left panel) and female (right panel) mako sharks by region from longline observer data, 1995-2009. The 5th and 95th percentiles of the data are shown with dashed lines. The sample size is shown in the inset to each plot. Size at maturity is represented by the solid horizontal line.

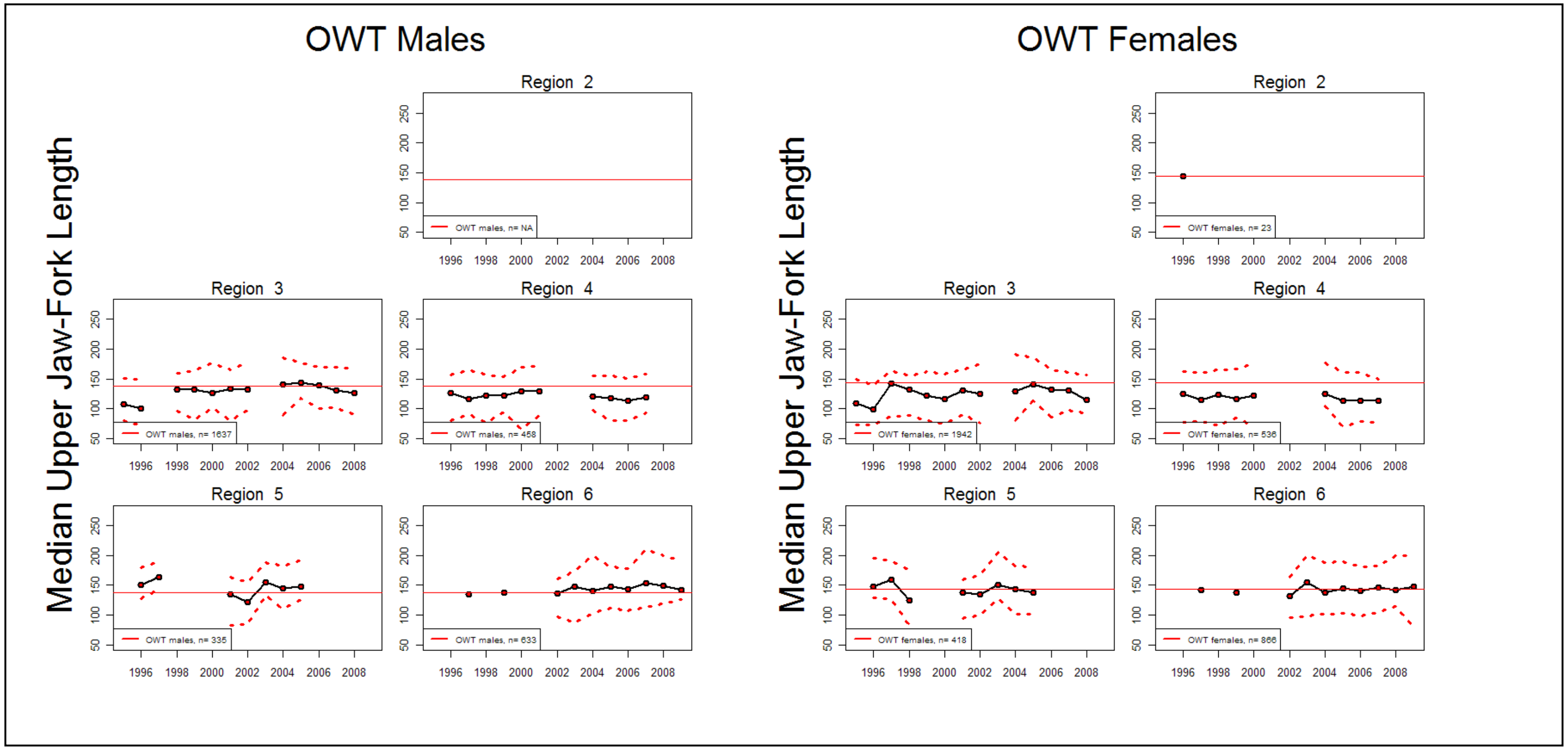


Figure A7 (cont.) Median length (in fork length in cm) for male (left panel) and female (right panel) oceanic whitetip sharks by region from longline observer data, 1995-2009. The 5th and 95th percentiles of the data are shown with dashed lines. The sample size is shown in the inset to each plot. Size at maturity is represented by the solid horizontal line.

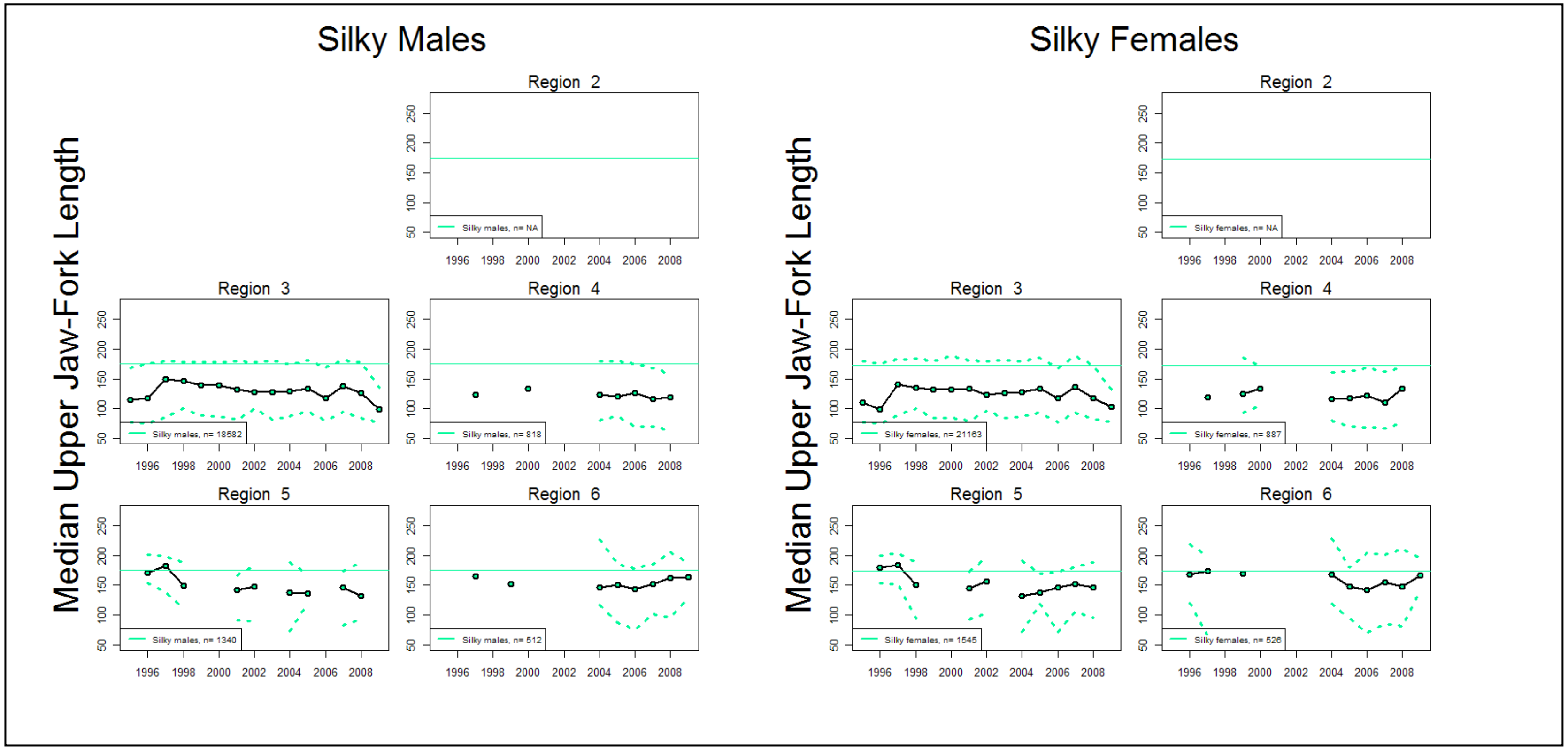


Figure A7 (cont.) Median length (in fork length in cm) for male (left panel) and female (right panel) silky sharks by region from longline observer data, 1995-2009. The 5th and 95th percentiles of the data are shown with dashed lines. The sample size is shown in the inset to each plot. Size at maturity is represented by the solid horizontal line.

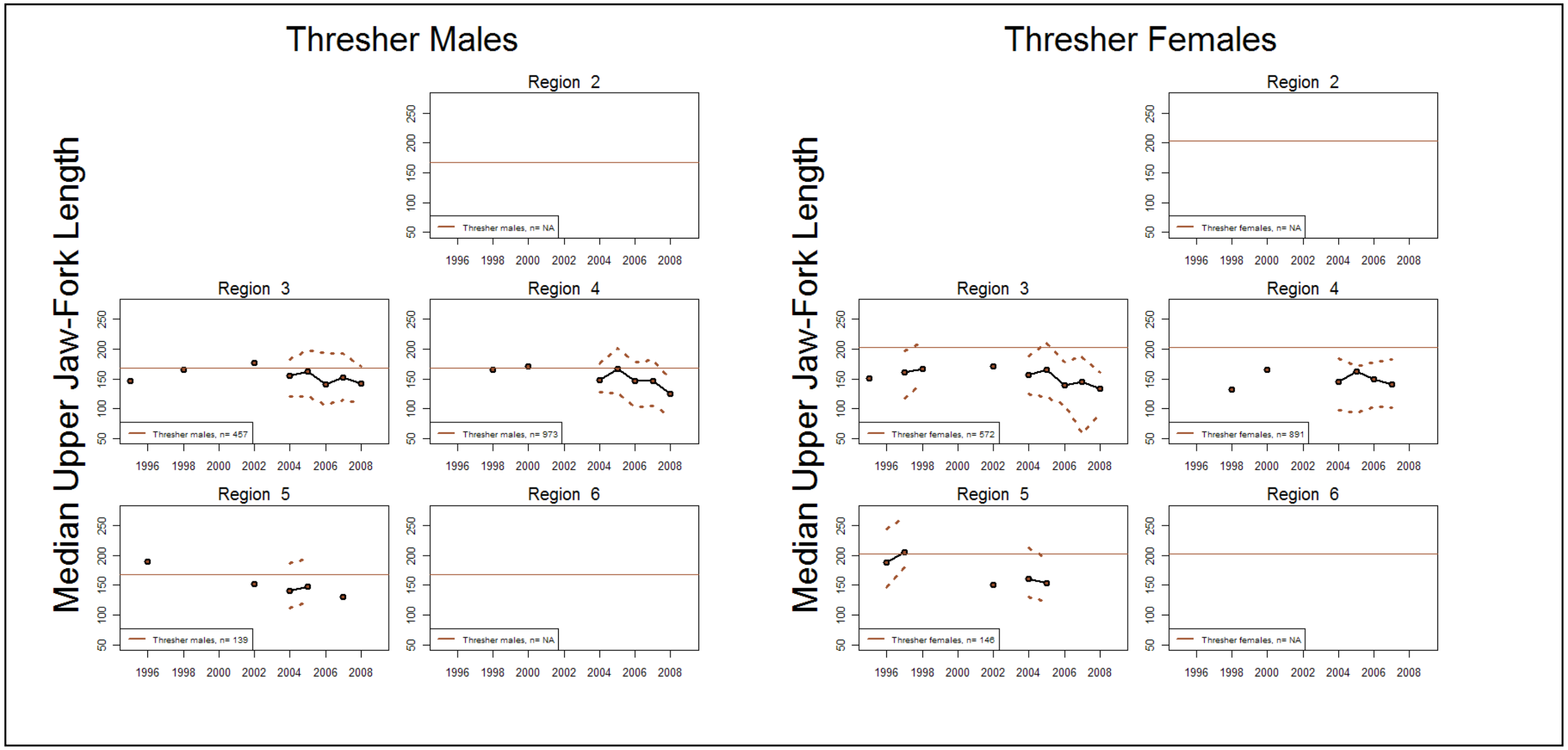


Figure A7 (cont.) Median length (in fork length in cm) for male (left panel) and female (right panel) thresher sharks by region from longline observer data, 1995-2009. The 5th and 95th percentiles of the data are shown with dashed lines. The sample size is shown in the inset to each plot. Size at maturity is represented by the solid horizontal line.

Figure A8. Results of linear model fits to predicted (standardized) median sizes for male (=1) and female (=2) blue (BSH), mako (MAK), oceanic whitetip (OCS), silky (FAL) and thresher (THR) sharks measured by observers on longline vessels in Regions 3-6. Significant results (p≤0.05) are shaded.

Region	Species	Sex	Slope	p-value
3	BSH	1	-1.627	0.014
3	BSH	2	-0.963	0.082
4	BSH	1	0.86	0.35
4	BSH	2	3.523	0.018
5	BSH	1	-1.097	0.209
5	BSH	2	-0.917	0.086
6	BSH	1	-2.42	0.002
6	BSH	2	0.035	0.973
3	FAL	1	-2.91	0
3	FAL	2	-2.59	0.003
4	FAL	1	-1.689	0.308
4	FAL	2	-1.523	0.103
5	FAL	1	-2.688	0.018
5	FAL	2	-2.923	0.012
6	FAL	1	-0.141	0.899
6	FAL	2	-1.24	0.225
3	MAK	1	-0.866	0.539
3	MAK	2	2.224	0.036
4	MAK	1	-3.111	0.04
4	MAK	2	-2.265	0.117
5	MAK	1	-0.75	0.171
5	MAK	2	0.246	0.827
6	MAK	1	-1.826	0.14
6	MAK	2	-2.053	0.075
3	OCS	1	-1.439	0.123
3	OCS	2	-1.684	0.032
4	OCS	1	-0.039	0.948
4	OCS	2	-1.628	0.046
5	OCS	1	-0.832	0.305
5	OCS	2	-1.627	0.093
6	OCS	1	-0.195	0.849
6	OCS	2	-0.653	0.41
3	THR	1	-3.027	0.052
3	THR	2	-5.837	0.01
4	THR	1	-20.724	0.003
4	THR	2	-16.97	0.01
5	THR	1	-0.591	0.466
5	THR	2	-2.066	0.119
6	THR	1	-1.884	0.35
6	THR	2	0.771	0.808

Figure A9. Results of linear model fits to (nominal) median sizes for both sexes of oceanic whitetip (OCS) and silky (FAL) sharks measured by observers on purse seine vessels in Regions 3 and 4. Significant results ($p \leq 0.05$) are shaded.

Region	Species	Slope	p-value
3	OCS	-5.08	0.009
4	OCS	-5.108	0.141
3	FAL	-1.192	0.008
4	FAL	-2.271	0.085