SCIENTIFIC COMMITTEE
FOURTEENTH REGULAR SESSION
Busan, Korea
8-16 August 2018

Pacific-wide Silky Shark (*Carcharhinus falciformis*) Stock Status Assessment

WCPFC-SC14-2018/SA-WP-08

Common Oceans (ABNJ) Tuna Project[1]

[1] Coordinated by the Western and Central Pacific Fisheries Commission, implemented by the Food and Agriculture Organization of the United Nations, and funded by the Global Environment Facility

Pacific-wide Silky Shark (*Carcharhinus falciformis*) Stock Status Assessment

Covering Note on Stock Status and Conservation Advice

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The Western and Central Pacific Fisheries Commission (WCPFC) was the first, and to date the only, tuna regional fisheries management organization (t-RFMO) to complete a stock assessment for the silky shark, *Carcharhinus falciformis*. The first WCPFC assessment for this species was completed in 2013 and subsequently became the basis for the WCPFC's silky shark no-retention measure (CMM2013-08) which took effect on 1 July 2014. The International Commission for the Conservation of Atlantic Tunas (ICCAT) and the Inter-American Tropical Tuna Commission (IATTC) adopted silky shark no-retention measures in 2011 and 2016, respectively. The Indian Ocean Tuna Commission (IOTC) has not yet adopted any conservation and management measure for this species.

Silky shark was listed on Appendix II of the Convention on the Conservation of Migratory Species (CMS) in 2014, and on Appendix II of the Convention on International Trade in Endangered Species (CITES) in 2017. Both proposals cited the WCPFC's 2013 stock assessment as one of the major bases for finding that threats to silky sharks were sufficiently significant to warrant listing. The IUCN Red List has classified the silky shark as "vulnerable", again with strong reference to the WCPFC's 2013 stock assessment.

This study to update the stock status of the silky shark is one of four Common Ocean (ABNJ) Tuna Project-supported assessments, all of which are required to be conducted on a Pacific-wide scale. Through collaboration with IATTC Secretariat scientists, this study was not only able to update the time series of data included in the previous assessment with new data (i.e. from 2010-2016), it also incorporated a long catch rate time series and large size composition datasets from the Eastern Pacific Ocean (EPO). Using the same modelling software (Stock Synthesis) and the same life history parameters, this new assessment has confirmed that a number of the CPUE indices used in both the 2013 Western and Central Pacific Ocean (WCPO) assessment, as well as in the current assessment, are closely correlated with prevailing oceanographic conditions and thus may not represent reliable indices of abundance. Previous studies of EPO catch rate indices also show correlation with oceanographic conditions, and a previous attempt to assess silky sharks in the EPO was unsuccessful in fitting the sharp decline in catch rates in the late 1990s. The present study shows that WCPO and EPO regional catch rate indices are in conflict and linking these indices in a Pacific-wide model is not able to resolve that conflict given the current level of understanding of regional stock structure and movement dynamics. These estimation issues undermine confidence in any conclusions drawn from the currently available data and preclude definitive findings on the acceptability of current stock biomass levels and fishing mortality rates.

This assessment has improved our understanding of the complexity of the regional structure and the influence of oceanographic conditions on Pacific silky sharks. However, these insights also caveat previous findings which did not take these factors into account. Precautionary management actions were taken on the basis of the prior stock assessment and these appear justified: there are several indications that silky shark biomass has substantially declined and fishing mortality has considerably increased over the last two decades. This new expanded and more informed assessment model now better acknowledges the uncertainties, and also provides a basis for clear recommendations for data and methodological improvements.

SC14 is invited to consider whether to:

- Recognise that previous management decisions for WCPO silky sharks were based on the best available science at the time;
- Endorse the results of this assessment as the currently best available science concerning the stock status of silky shark at the Pacific basin scale and at the regional scale for the WCPO;
- Accept that due to various uncertainties in this Pacific-wide assessment, estimates of management quantities such as SB/SB_0 and F/F_{MSY} are unreliable and should not be used as the basis for management advice;
- Acknowledge that the assessment model, though not sufficiently robust to estimate management quantities, suggests that WCPO and EPO silky shark biomass has substantially declined and fishing mortality has considerably increased over the last two decades;
- Maintain the no-retention measure for WCPO silky sharks (CMM2013-08) as a precautionary approach until such time as reliable stock status advice is available;
- Call for data improvement initiatives as outlined in the assessment as follows:
    - Ensure that observers are able to see and accurately record which sharks are caught, and to better code their condition at release;
    - Implement tagging programmes to improve understanding of silky shark movement dynamics and population structure, as well as post-release mortality;
    - Direct future shark assessments to explicitly incorporate oceanographic indices and explore their effects;
    - Increase longline observer coverage to avoid continuing problems with unrepresentative sampling and highly variable catch rate indices;
    - Collaborate with IATTC, NOAA and other partners toward a more robust Pacific-wide assessment model for silky sharks.
- Recommend that this silky shark assessment be revisited under the WCPFC Shark Research Plan no later than 2021.

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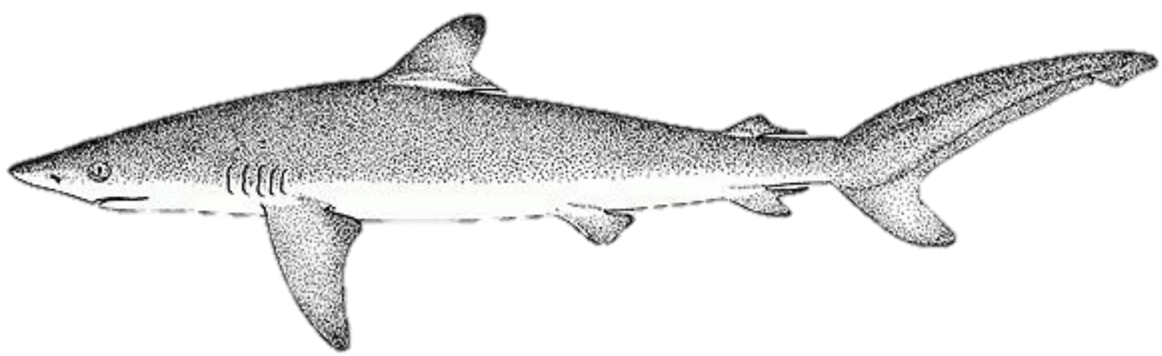

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Abstract

This collaborative assessment revisits the existing silky shark (*Carcharhinus falciformis*) assessments for the Western and Central Pacific (WCPO) and the Eastern Pacific (EPO) Oceans using, for the first time, a Pacific-wide model structure. The aim of the study is to improve stock assessment methods, increase understanding of data strengths and weaknesses, and further explore silky shark stock status. Joint data preparation began in February 2017 and involved standardization of observer data from purse seine associated set fisheries to produce indices of abundance for the WCPO and EPO. Catch rate indices were also prepared for the WCPO purse seine unassociated fishery, the Hawaii deep set longline fishery and the WCPO longline fishery. These analyses in combination with catch reconstructions reported in Clarke (2018) and size composition analyses were used in an integrated analysis involving the Stock Synthesis (SS) model. The results highlight considerable conflicts between the key data sets and are not considered sufficiently robust to provide an assessment of the stock status of Pacific Ocean silky shark. In particular, the WCPO catch rate indices remain short, variable and potentially unrepresentative of stock abundance indices, and are strongly correlated with prevailing oceanographic conditions. A Pacific-wide model was unable to fit both WCPO and EPO CPUE indices simultaneously despite attempts to account for basin-scale movement dynamics, recruitment variability, alternative regional structures and environmental covariates. On the basis of existing information, estimates of current stock depletion and fishing mortality are unreliable and should not be used as the basis for management advice. Nevertheless, there are several indications that Pacific Ocean silky shark populations are likely to have declined considerably over the last two decades in response to the increased levels of catch. Correspondingly, fishing mortality rates are likely to have increased considerably over the same period, and this is a concern given the low productivity of silky sharks. Although this Pacific-wide model did not successfully integrate all of the signals from the expansive range of the silky shark, it has provided critical new insights into the potential connectivities between regions and the relationships between these connectivities and oceanographic conditions. A new appreciation of these relationships now calls for caution in interpreting previous results which were based on simpler, regional paradigms, but it also points the way toward gaining a deeper understanding of the real mechanisms structuring Pacific silky shark populations.

1 Introduction

Under the Common Oceans (Areas Beyond National Jurisdiction (ABNJ)) Tuna Project, the Western and Central Pacific Fisheries Commission (WCPFC), with support from the United Nations Food and Agriculture Organization (FAO), is executing a programme of shark and bycatch work. One of the components of this work involves shark assessment and management and funding has been provided to conduct four shark stock assessments on the condition that they be pan-Pacific in nature. Two of these stock status assessments (Pacific-wide bigeye thresher shark (Common Oceans (ABNJ) Tuna Project 2017a) and Southern Hemisphere porbeagle shark (Common Oceans (ABNJ) Tuna Project 2017b)) were presented to SC13 in August 2017.

It was agreed at SC12 in August 2016 that the third ABNJ Pacific-wide shark stock status assessment would be for the silky shark (*Carcharhinus falciformis*) (see SC12 Summary Report, Attachment H). This species has been identified by both WCPFC and the Inter-American Tropical Tuna Commission (IATTC) as being depleted and in need of management, and was recently listed on the Convention on International Trade in Endangered Species (CITES). In the Western and Central Pacific Ocean (WCPO), silky shark was previously assessed by Rice & Harley (2013), which used data through 2009. By updating that work this study provides useful information on WCPO stock status and helps to evaluate the WCPFC no-retention measure for this species (CMM 2013-08). Silky shark is also a priority shark research topic for the IATTC (Resolution C-16-05) in the Eastern Pacific Ocean (EPO). A stock assessment was attempted for the EPO but the model was unable to fit the main index of abundance adequately, and therefore the results were not reliable since both relative trends and absolute scale were compromised (IATTC 2014). By conducting a Pacific-wide assessment the current study has the potential to elucidate basin-wide patterns for this highly migratory species and address some of the challenges faced in both previous assessments, thereby facilitating future assessments.

An interim product containing data preparatory work was submitted to SC13 in August 2017 (Clarke 2017). This paper focused on describing and exploring four key WCPO datasets: the WCPO longline observer dataset (consisting of both Regional Observer Programme (ROP) and SPC member's observer data accessed by permission), the United States observer dataset, the Japan observer dataset, and the ROP purse seine observer dataset. The sections of Clarke (2017) describing these datasets have been incorporated into this paper as **Annex A**. Contributions to the assessment from IATTC in the form of a Scientific Advisory Committee working paper in May 2017 (Lennert-Cody et al. 2017) are attached as **Annex B**. The main body of this paper presents work since SC13 including standardization of catch per unit effort indices for the WCPO longline, United States longline and WCPO Regional Observer Programme (ROP) purse seine datasets, as well as stock assessment modelling setup and results. A new working paper on Pacific-wide silky shark catch estimates derived from shark fin trade data is submitted to SC14 to support the assessment (Clarke 2018).

2 Background and Scoping of the Assessment

The silky shark inhabits both coastal and offshore waters and is one of the world's most abundant and widely distributed sharks (Bonfil 2008). Based on life history data through 2001, Bonfil (2008) suggested that there are distinct populations of silky shark in the EPO versus the WCPO. This hypothesis rests on observations of smaller sizes at maturity for both males and females in the EPO, but it was noted that sample sizes were limited and length measurements can differ between studies. In parallel, Bonfil (2008) stated that the Pacific population structure is unknown and that Pacific islands may serve as a link between the two edges of the ocean basin. One recent population genetics study suggests there is evidence for separate WCPO and EPO populations, but it could not definitively reject the hypothesis of panmixia (Galván-Tirado et al. 2013). Other research by the United States National Oceanic and Atmospheric Administration (J. Hyde, NOAA-SWFSC, unpublished data) suggested a Pacific stock boundary running eastward through the WCPO at the equator until it approaches the South American coast where it dips southward to 20^{o}S. Adding further uncertainty to delineating a Pacific-wide assessment model, recent research indicates important differences in silky shark life history parameters amongst five regions within the Pacific (M. Grant, James Cook University, unpublished data).

Despite the lack of understanding of the genetic, biological or environmental factors that may be structuring the Pacific silky shark population, it was clear that further exploration of these issues would benefit from a Pacific-wide approach. Nevertheless, data access arrangements needed to follow the data confidentiality procedures adopted by each data holder, and in this sense data preparation for the largest datasets was necessarily spatially structured by the jurisdictional boundaries of the WCPFC and IATTC.

Cooperation between the WCPFC and IATTC Secretariats was initiated through an exchange of letters in February 2017 proposing to share purse seine observer data between the two

Secretariats' nominated staff for the purpose of the silky shark assessment only. This type of arrangement is provided for under a 2009 Memorandum of Cooperation on Exchange and Release of Data between WCPFC and IATTC (WCPFC 2009). WCPFC Circular 2017/20, issued on 21 March 2017, finalized the data sharing arrangement and specified that WCPFC would only make available to IATTC staff ROP purse seine observer data. WCPO non-ROP data was not used in the study due to data unavailability. Available longline data from WCPFC member countries (under both the ROP and through bilateral arrangements with the Common Oceans (ABNJ) Tuna Project) was used in the study, subject to data confidentiality arrangements agreed with the data holders, but was not shared with IATTC staff. Furthermore, the data confidentiality arrangements for all datasets precluded provision of the data to outside consultants. As a result, the ABNJ Technical Coordinator-Sharks and Bycatch (TCSB) undertook the data preparation work for all datasets except for the Eastern Pacific Ocean (EPO) purse seine fishery which was undertaken by IATTC staff.

Both sides have built upon on their previous work relating to silky sharks in their regions. In the EPO, IATTC attempted a stock assessment for silky shark over a multi-year period (IATTC 2014) and has updated an index of abundance based on the purse seine fishery in every year since then (Aires-da-Silva et al. 2014, 2015; Lennert-Cody et al. 2016, 2017, 2018). In the WCPO, a stock assessment was undertaken in 2013 (Rice & Harley 2013) with follow-up studies updating the abundance index (Rice et al. 2015) and evaluating the effects on silky sharks of a ban on shark lines and wire leaders (Harley & Pilling 2016). Most of the WCPO studies have primarily focused on the longline fishery, however, one study considered the effects on silky shark bycatch of shifts in purse seine fishing effort between free school and floating object sets (Peatman & Pilling 2016). Catch estimation studies by Lawson (2011) and Peatman et al. (2017, 2018) have provided catch estimates for longline- and purse seine-caught silky sharks based on observer data.

3 Overview of Key Data Sets

The silky shark is the most frequently encountered shark in the tropical WCPO purse seine fishery and the second most frequently encountered shark in the tropical and sub-tropical WCPO longline fishery (Lawson 2011). It also the most common shark caught in both the EPO purse seine and longline fisheries (IATTC 2018, Siu et al. 2017). Given their potentially important contribution to fishing mortality on the silky shark stock, it was necessary to compile data from both purse seine and longline fisheries.

For the WCPO fisheries a number of non-public domain datasets were accessed for this study including (**Annex A**):

- Longline observer data maintained by SPC as part of the WCPFC Regional Observer Programme accessible to the TCSB via the WCPFC Secretariat, as well as non-public domain longline observer data maintained by SPC on behalf of Australia, the Cook Islands, the Federated States of Micronesia, Fiji, French Polynesia, the Republic of the Marshall Islands, New Caledonia, New Zealand, Samoa, Solomon Islands, Tonga and Vanuatu and accessible to the TCSB through data confidentiality agreements with each country for use in the Common Oceans (ABNJ) Tuna Project ("WCPO LL observer data");
- United States longline observer data provided directly to the TCSB for use in the Common Oceans (ABNJ) Tuna Project under a data confidentiality agreement ("US LL observer data");
- Japan longline observer data provided to the TCSB under a data confidentiality agreement specific to this assessment ("Japan LL observer data"); and

- Purse seine observer data maintained by SPC as part of the WCPFC Regional Observer Programme accessible to the TCSB via the WCPFC Secretariat ("ROP PS observer data").

For the EPO fisheries, observer placement on purse seine vessels dates back to the 1970s with observer coverage of ~100% on trips by Class 6 seiners (those larger than 363 t capacity) since 1992 (Scott et al. 2016). Quantitative data on shark bycatch began to be collected in 1993 (Román-Verdesoto & Orozco-Zöller 2005). The IATTC Secretariat coordinates the regional purse seine observer programme, including managing all of the data, and the Secretariat regularly makes use of these data for scientific analyses. As mentioned above, the IATTC has produced papers estimating a silky shark index of abundance from Class 6 purse seine fishery observer data on floating object sets for several years. These papers provide some background on biological data collection and spatial distribution of bycatch rates (Aires-da-Silva et al. 2014, 2015; Lennert-Cody et al. 2016, 2017, 2018).

In contrast to the EPO purse seine fishery, national authorities coordinate the EPO longline observer programmes (Wiley et al. 2017). In the longline fisheries managed by IATTC, observer coverage of 5% has been required since January 2013 for vessels larger than 20 m (IATTC Resolution C11-08). However, the vast majority of longline observer data provided to the IATTC Secretariat to date is highly summarized rather than at the operational (set-by-set) level required for stock assessments (Wiley et al. 2017). As a consequence, it is difficult for scientists to obtain reliable indices of abundance from longline fisheries for either tunas or sharks in the EPO (Griffiths & Duffy 2017). No observer data from EPO longline fisheries were available for use in this study. IATTC is currently working to compile a database of existing shark data from Central American countries under the Common Oceans (ABNJ) Tuna Project (Siu & Aires-da-Silva 2016, Aires-da-Silva et al. 2016, Siu et al. 2017). In addition, a pilot port sampling study is underway with the aim to obtain information on gear types, estimate the order of magnitude of catches, and document unloading strategies (IATTC 2017).

4 Modelling Methods and Data Inputs

This study uses the Stock Synthesis (SS) stock assessment model (version 3.24Z) as described in Methot & Wetzel (2013). The SS modelling software was used in the previous WCPO and EPO silky shark stock assessments (IATTC 2014, Rice & Harley 2013). Therefore, the use in the current assessment modelling enables direct comparisons with the results of the previous studies.

The Pacific-wide model was comprised of two regions: the WCPO and the EPO (Figure 1). The regional structure was based on the approximate administrative boundaries of the WCPFC and IATTC and the configuration of the available data. The following section describes the catch histories, indices of abundance, and size composition data used in the assessment for each region. This is followed by a description of the SS model set up including the life history parameter inputs.

4.1 Datasets and their preparation

4.1.1 Catch Histories

The SS model requires a time series (i.e. annual values) of the total removals of silky sharks by each fleet considered in the model. As silky shark is a WCPFC key shark species, its catches are required to be reported to the WCPFC as part of each WCPFC member's annual data submissions (WCPFC 2017a). While it would be possible to simply use these reported catches to produce the necessary catch series, there would be several major problems with this approach. The first of these is under-reporting. Silky sharks were made a key shark species under CMM 2009-04 which means that the first required annual reporting was for 2010. Some silky shark catches were reported as far back as 1995 but the numbers are extremely sparse (WCPFC 2017b). In periods prior to the WCPFC's prohibition on shark finning (CMM 2006-05, effective January 2008), the number of sharks recorded in logbooks is likely to be low relative to the actual number of sharks killed. Even with reporting requirements now in place, logbook records are expected to grossly underestimate the true number of total removals. One reason for this is that in purse seine fisheries the potentially large number of silky sharks caught combined with the process of brailing and sorting may make it difficult to fully enumerate the catch. In both longline and purse seine fisheries, no-retention measures in place in since 1 July 2014 (WCPFC CMM 2013-08) (and also various no-retention and catch limits in place in the EPO since 1 January 2017 (IATTC Res. 2016-06)), create a situation where discarded silky sharks are less likely to be recorded in logbooks than retained ones, even if there are requirements to report both (see below). All of these factors combined argue strongly against the use of logbook reported silky shark catches as input for stock assessment catch series.

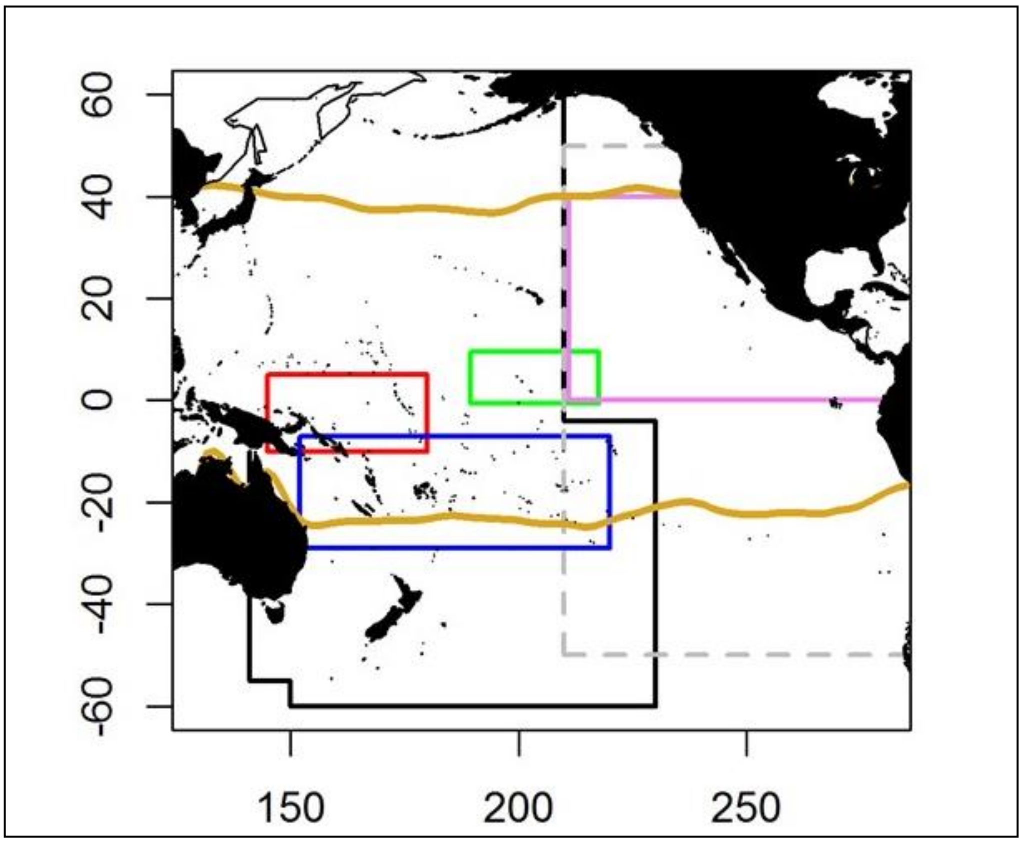


Figure 1. Pacific Ocean showing the boundaries of the Western and Central Pacific Fisheries Commission Convention Area (black) and the Inter-American Tropical Tuna Commission Convention Area (gray dashed). Fishing grounds included in various catch per unit effort standardization analyses used in this study are shown with rectangles: Eastern Pacific purse seine associated fishery northern grounds (pink; Lennert-Cody et al. 2017), Western Central Pacific purse seine associated and unassociated core area (red; Lennert-Cody et al. 2017 and this study), South Pacific longline core area (blue; this study), and Hawaii-based deep set longline fishery core area (green; this study). Indicative (FAO 2018) northern and southern ranges of the distribution of the silky shark are shown in gold (though it is noted that substantial catches of silky sharks were found south of this range in observer records examined in the present study).

One alternative is to estimate catches from observer data. This analysis was undertaken for WCPO longline and purse seine fisheries by Lawson (2011) and Rice (2012) and used in the 2013 WCPO assessment (Rice & Harley 2013). Both extrapolated observed silky shark catch rates across the entire WCPO using available, but often unrepresentative, observer data, and then multiplied these catch rates by fishing effort. The two studies differed because Rice (2012):

i. had more data available but filtered it more conservatively to effectively exclude more of the zero catches in habitats (based on temperature) where silky sharks would not be expected to be present;
ii. used a slightly different formulation of the catch rate model; and
iii. derived a separate catch series for a "shark targeting" longline fleet.

The 2013 WCPO assessment used the Lawson (2011) catch histories as the base case and the Rice (2012) catch histories as sensitivity test.

Recently Peatman et al. (2017, 2018) have updated the Lawson (2011) and Rice (2012) catch histories using a similar approach, i.e. estimating total catches using observed catch rates and effort data. However, a major difference with these later estimates is that they are based on extrapolation by strata (year, quarter, gear) and focus only on tropical waters (20°N to 20°S). This suggests that the Peatman et al. (2017, 2018) estimates would be lower than the Lawson (2011) and Rice (2012) estimates which covered the entire WCPO, even though the tropical distribution of the silky shark would tend to mediate these differences somewhat. Another difference is that Peatman et al. (2017, 2018) consider that the reliability of observer data collected prior to 2003 to be low and so they do not estimate for previous years.

When interpreting the Peatman et al. (2017, 2018) estimates (i.e. 2003-2016) it is important to consider potential biases arising from the recent implementation of the WCPFC's no retention measures for silky sharks on 1 July 2014 (WCPFC CMM 2013-08). Observers are required to record every shark that they see but under the WCPFC's no-retention measure for silky sharks (and also for oceanic whitetip sharks) there are informal reports that a greater number of sharks are being cut free before the observer can see them, often at quite some distance from the vessel. This situation could result in a larger number of sharks being recorded in a general "shark unidentified" category (if the observer sees that it was some kind of shark) or no record at all (if the observer cannot see anything). For this reason, there is higher level of uncertainty in observer-based catch estimates under no-retention conditions. In the WCPO, this pertains not only to the period after implementation of the WCPFC shark no-retention measures but also potentially in several WCPFC members' national waters where retention is prohibited for all shark species (since approximately 2011; Ward-Paige 2017).

In summary, for the WCPO, available observer-based catch estimates prior to 2003 are considered unreliable and after 2011 have a higher degree of uncertainty. As the remaining nine-year time series is extremely short for the purposes of stock assessment, alternative catch series such as those based on trade records can be particularly useful. Trade-based estimates were prepared through 2006 (Clarke 2009), updated through 2009 (Rice 2013) and through 2016 for this stock assessment as described in Clarke (2018). A summary of the comparison in that paper between the most recent trade-based estimates and historical estimates based on observer data is provided in Figure 2.

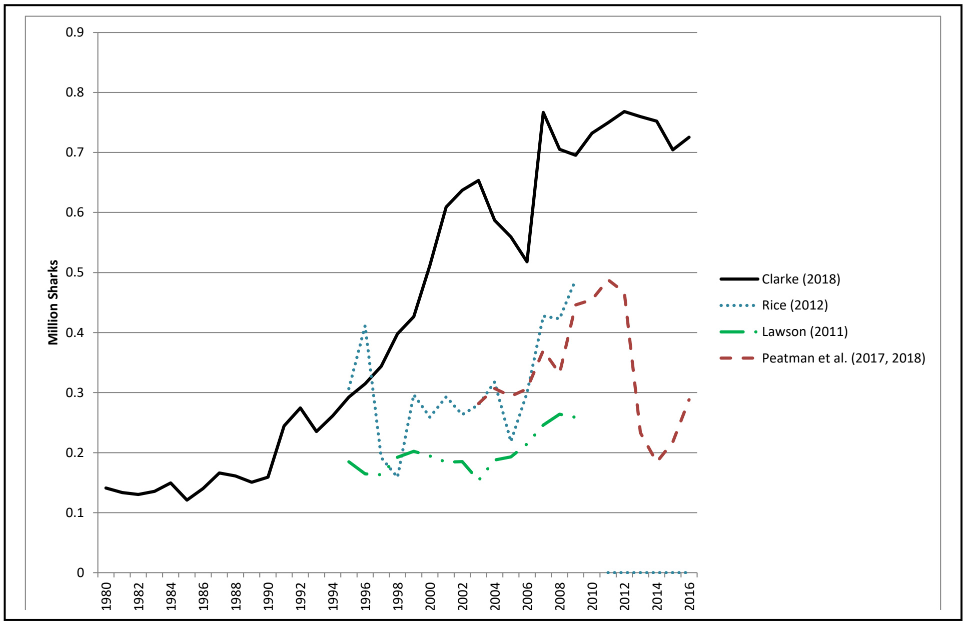


Figure 2. Silky shark catch estimates (combined longline and purse fisheries) for the Western and Central Pacific Ocean from various studies, 1980-2016 (Clarke 2018).

Peatman et al. (2017, 2018) only estimated for the tropical WCPO but produced figures similar to those of Rice (2012) which estimated for the entire WCPO. Similarities between Lawson (2011), Rice (2012) and Peatman et al. (2017, 2018) are expected because all of these studies are based on WCPO observer data. The Clarke (2018) estimates are independent of observer data and are based on traded volumes of shark fins proportioned to the WCPO based on target species catch statistics. Nevertheless they show a similar trend of increase to the observer-based series from the mid-2000s until 2011-2012—the period of greatest reliability in the data. The trade-based records are consistently and considerably higher than the highest of the other estimates during this period but this might be expected given that the trade-based methods account for the potentially large catches in Southeast Asia, whereas the observer-based methods excluded catches by Indonesia, Vietnam, domestic Philippine, and temperate purse seine vessels. It should be noted that the trade-based series also has higher uncertainty in the values starting in 2012 due to market trends and changes in customs statistics systems (see Clarke (2018) Section 2.1.2).

Alternative trade-based catch histories were also prepared for the Eastern Pacific Ocean in both number of sharks and biomass. In the 2013 EPO silky shark stock assessment catch histories were constructed from national fleet summaries based on available statistics and expert judgment for both northern and southern areas (IATTC 2014). The catch series for the northern stock, which comprises the majority of the catch, spans 1993-2010 and varies from a low of just over 10,000 t to a high of slightly more than 16,000 t. Catches from the southern stock annually add another 2,000 t or less until 2003 and less than 1,000 t annually thereafter. The EPO assessment acknowledged the substantial uncertainty in these estimates but there is a remarkable consistency between these estimates and the EPO estimates produced by the trade-based methodology (Clarke 2018). Both datasets show an increase in the early 2000s to approximately 15,000 t, followed by a sharp decline to approximately 11,000 t in 2006 and then a quick recovery and steady increase to approximately 17,000 t at the end of the series (Figure 3). Comparing silky shark catches between the WCPO and EPO, maximum annual estimates for the western portion (39,000 t) are approximately double those for the eastern portion (17,000 t).

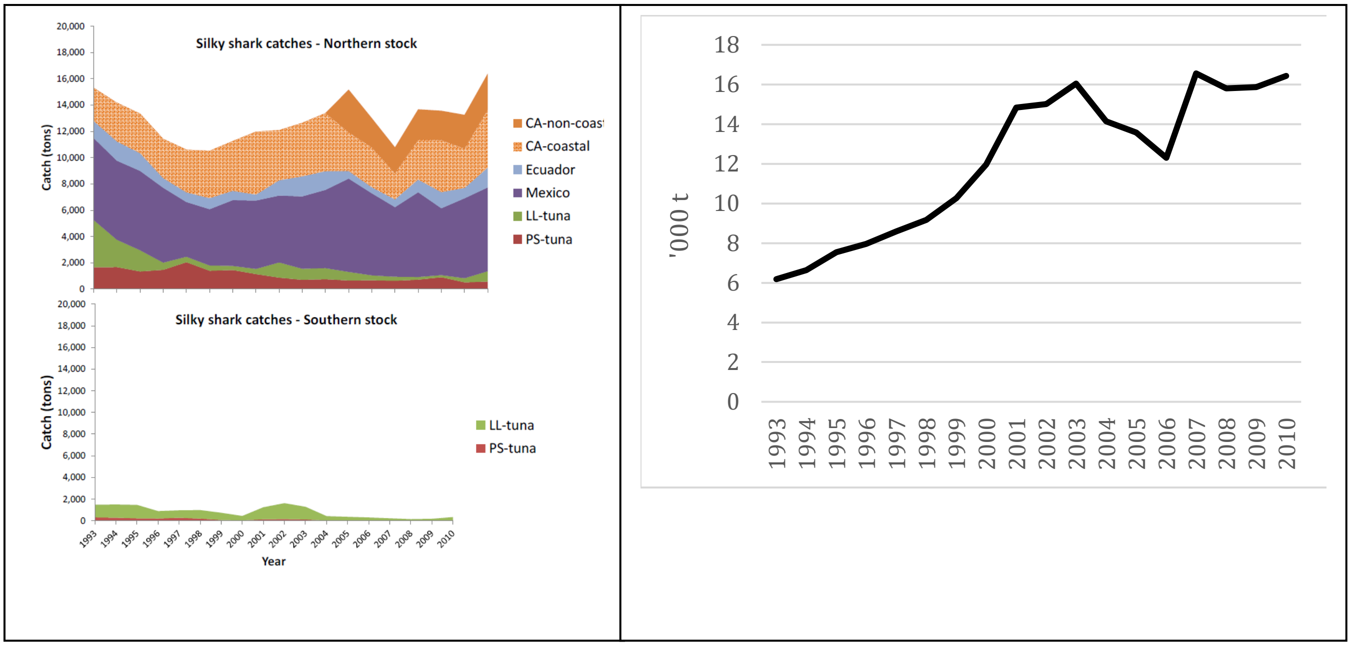


Figure 3. Silky shark catch estimates (combined longline and purse fisheries) for the EPO from IATTC (2014, left) and Clarke (2018, right) for 1993-2010.

The trade-based catch series have several advantages over the other available estimates, not least of which they span a long time period and apply a consistent methodology for the WCPO and EPO. However, as they derive from trade statistics, rather than being tied to specific fisheries, another step is required to partition the WCPO and EPO catches by fleet as required for the SS model. For this purpose, annual catch ratios between fleets in each region were calculated from previous studies and applied to the trade-based figures (Table 1). For the WCPO, the first step was to partition the Clarke (2018) WCPO catches for 2003-2016 by an annual ratio of purse seine to longline silky shark catches derived from summing Peatman et al. (2017, 2018) estimates for purse seine and longline fisheries. Subsequently, the WCPO purse seine catches for 2003-2016 were split into associated and unassociated fisheries based on annual catches estimated for each by Peatman et al. (2017). For years prior to the Peatman et al. (2017, 2018) estimates (i.e. 1995-2003), WCPO purse seine and longline catches were split by ratios derived from Lawson (2011)[1]. However, as Lawson (2011) does not provide purse seine associated and unassociated catches separately for this earlier period, the ratio of associated to unassociated set catch for 2003 from Peatman et al. (2017) was applied as a constant to the 1995-2002 purse seine splits.

For the main model scenarios, the total EPO catch was assigned to the composite EPO_LL fishery with an additional, notional catch allocated to the EPO PS fisheries. The notional PS catch, consisting of 10,000 silky sharks per year each for the EPO PS associated and unassociated fisheries, was essentially a "place holder" in the absence of actual catch values. Subsequently, a single model option was conducted that correctly allocated the reported catches of silky shark to the PS fishery based on the IATTC annual catch estimates of silky shark (IATTC 2018). These catch

[1] Rice (2012) estimated catches for target and non-target longline fisheries but those splits were not applied here. Lawson (2011) estimates were selected over those of Rice (2012) for the longline-purse seine split for 1995-2003 as Lawson (2011) was the base case in the Rice & Harley (2013) assessment.

estimates indicated that the EPO purse seine fishery represents 5-10% of the estimated annual EPO silky shark catch (Table 1).

Table 1. Total WCPO and EPO silky shark catches (in thousand sharks) estimated from trade-based records. WCPO catch splits were obtained by applying ratios from previous studies; EPO PS catch splits were first assumed and then replaced with actual reported values (see text for details).

	Total WCPO	WCPO LL	WCPO PS-Unasso	WCPO PS-Asso	Total EPO	Assumed EPO PS-Asso +Unasso Catch	Reported EPO PS-Asso+Unasso Catch (IATTC 2018)
1995	292,500	254,830	5,161	32,510	147,500	20,000	4,738
1996	314,800	267,816	6,437	40,548	161,000	20,000	6,683
1997	343,800	284,564	8,115	51,120	173,700	20,000	9,643
1998	398,000	341,281	7,770	48,948	185,400	20,000	9,320
1999	426,600	352,384	10,168	64,048	207,800	20,000	8,374
2000	512,000	429,393	11,317	71,290	242,200	20,000	9,094
2001	609,100	493,054	15,898	100,148	295,500	20,000	16,017
2002	637,200	488,983	20,306	127,911	299,100	20,000	15,347
2003	653,500	553,930	13,641	85,929	319,600	20,000	15,877
2004	587,100	472,538	6,301	108,261	282,000	20,000	13,885
2005	559,400	454,251	12,828	92,321	270,300	20,000	22,644
2006	518,100	425,736	7,943	84,421	245,100	20,000	26,054
2007	766,600	660,244	14,358	91,998	327,800	20,000	25,201
2008	705,200	599,976	14,626	90,597	313,000	20,000	31,161
2009	695,300	628,530	6,677	60,093	314,300	20,000	23,253
2010	732,200	681,887	10,515	39,798	325,600	20,000	26,473
2011	749,500	669,706	13,485	66,309	349,100	20,000	20,146
2012	768,300	708,074	11,563	48,663	355,200	20,000	12,976
2013	759,800	624,548	26,104	109,149	350,600	20,000	16,145
2014	752,200	549,159	45,887	157,154	340,000	20,000	28,163
2015	704,500	573,913	24,550	106,037	330,700	20,000	38,038
2016	725,400	570,000	47,086	108,314	341,100	20,000	32,151

4.1.2 Indices of Abundance

Five indices of abundance were prepared for this stock assessment based the structure of the fishery and the availability of catch rate data:

- WCPO purse seine fishery, associated (also referred to as "object") sets
- EPO purse seine fishery, associated sets
- WCPO purse seine fishery, unassociated (also referred to as "free school") sets
- Hawaii deepset longline fishery
- WCPO longline fishery

Standardization of the first two catch rate series was undertaken jointly by the TCSB and scientists from the IATTC Secretariat and reported in Lennert-Cody et al. (2017) (**Annex B**). This work was recently accepted for publication in Fisheries Oceanography (Lennert-Cody et al. (in press)) and the standardization work is not further discussed in this report. Standardization of the remaining three catch rate series is described below.

4.1.2.1 WCPO purse seine fishery, unassociated (free school) sets

The previous WCPO silky shark assessment (Rice & Harley 2013) standardized unassociated (free school) purse seine sets using data from 1995-2009. However it is not clear whether this index of abundance was used as one of the sensitivity tests in the study (i.e. CPUE 5 and CPUE 6 runs were based on purse seine catch per set, but whether in the associated or unassociated fishery is not specified). Rice & Harley (2013) note that the unassociated purse seine fishery catches somewhat larger silky sharks than does the associated fishery: 45% of the catch in the unassociated fishery was less than 150cm total length (TL) compared to 93% in the associated fishery. They also note the number of sets with zero catch of silky sharks was much higher in the unassociated fishery, although no details are provided. Their standardization model was formulated as a delta-lognormal and used covariates year, cell (5^ox5^o grid) and flag (Rice 2013; Figure 4).

Standardization of the WCPO purse seine unassociated dataset was undertaken for the present study with the aim of maximizing consistency with the standardization of the WCPO purse seine associated set fishery by Lennert-Cody et al. (2017). The unassociated (i.e. school types "unassociated" or "feeding on baitfish") dataset was filtered as follows:

- Only data from 2004-2015 were retained;
- Only sets with the area between 145^o-180^oE and 5^oN to 10^oS were retained as a core area of the fishery;
- Only sets with recorded catch of tunas were retained (i.e. "skunk" sets were excluded to avoid biases associated with non-functional sets);
- Vessels flagged to China, Ecuador, Spain, New Zealand, Philippines, El Salvador and Tuvalu were excluded as there were not consistent operations throughout the range of years assessed and since it was considered that flag was a potentially important covariate the model would not run with missing data for the above mentioned fleets.

This filtering left n=47,631 sets available for modelling. Based on the large number of sets with zero silky shark catch (n=43,847 or 92%) and the relatively overdispersed nature of the catches in sets that caught silky sharks (i.e. 127 sets with more than 30 silky sharks recorded) a zero-inflated negative binomial (ZINB) model was theoretically preferred (similar to the associated purse seine fishery catch rate standardization of Lennert-Cody et al. 2017). This model was fit using R package 'pscl' rather than the EM algorithm of Minami et al. (2007) used by Lennert-Cody et al. (2017) but the underlying ZINB model structure is the same. Covariates for both components of the ZINB 'pscl' model were those available in the observer dataset and included year, month, latitude, longitude, time of day of the set, the amount of tuna caught (in log scale) and flag as follows:

Zeroinfl(FALnumb ~ yearfact + monthfact + s(lat) + s(lon) + s(timeofset) + log.tunakg + flagfact | yearfact + monthfact + s(lat) + s(lon) + s(timeofset) + log.tunakg + flagfact, dist="negbin", link="logit", data = UNAset)

The statistical significance of some of the covariates varied between the two components of the model, i.e. the binomial (presence/absence) and the count (numbers of sharks caught) models. Covariates year, month, longitude and amount of tuna caught were highly significant ($p < 0.001$) in both models, whereas latitude was less significant ($p < 0.05$) in both models. In contrast, time of day of the set was a highly significant predictor ($p < 0.001$) only in the binomial portion of the model, and flag was a highly significant predictor ($p < 0.001$) in the count portion of the model (**Annex C**). The most important diagnostics for the ZINB model are plots of observed versus fitted values and Pearson residuals (Zuur et al. 2009). These diagnostics for the unassociated fishery suggest that even with a ZINB model structure the rare, large catches are not well predicted (**Annex C**). Measures of significance, collinearity and null deviance explained are not available for the ZINB model.

Confidence intervals calculated from the ZINB model were unstable therefore zero-inflated Poisson (ZIP) and quasi-Poisson (QP) models were also run. As the ZIP and QP model estimated year coefficients are very similar to those from the ZINB, the QP confidence intervals can be taken as a proxy for the ZINB confidence intervals for interpretive purposes (i.e. confidence intervals are not input to the SS model). Annual nominal estimates (computed as the number of silky sharks divided by the number of sets), and ZINB, ZIP and QP model-predicted estimates (obtained using the R predict() function), along with the confidence intervals for the QP model (obtained using the R predict() function with a confidence interval on the annual estimate obtained using the R confint() function), are shown in Figure 4.

The WCPO associated set purse seine standardized series from Lennert-Cody et al. (2017) shows some similarities, particularly with respect to the peak in 2011, but the WCPO unassociated series shows relatively little trend in other years compared to the associated series. Although this fishery is of some interest given that it tends to interact with both large and small silky sharks (see Section 4.1.3) it is difficult to standardize due to the extremely high number of zero catch records and some rare but very high catches (e.g. 29 observed sets with ≥100 silky sharks). These factors in combination with its relatively short timespan and general lack of trend suggest it should not have a large influence on the stock assessment results.

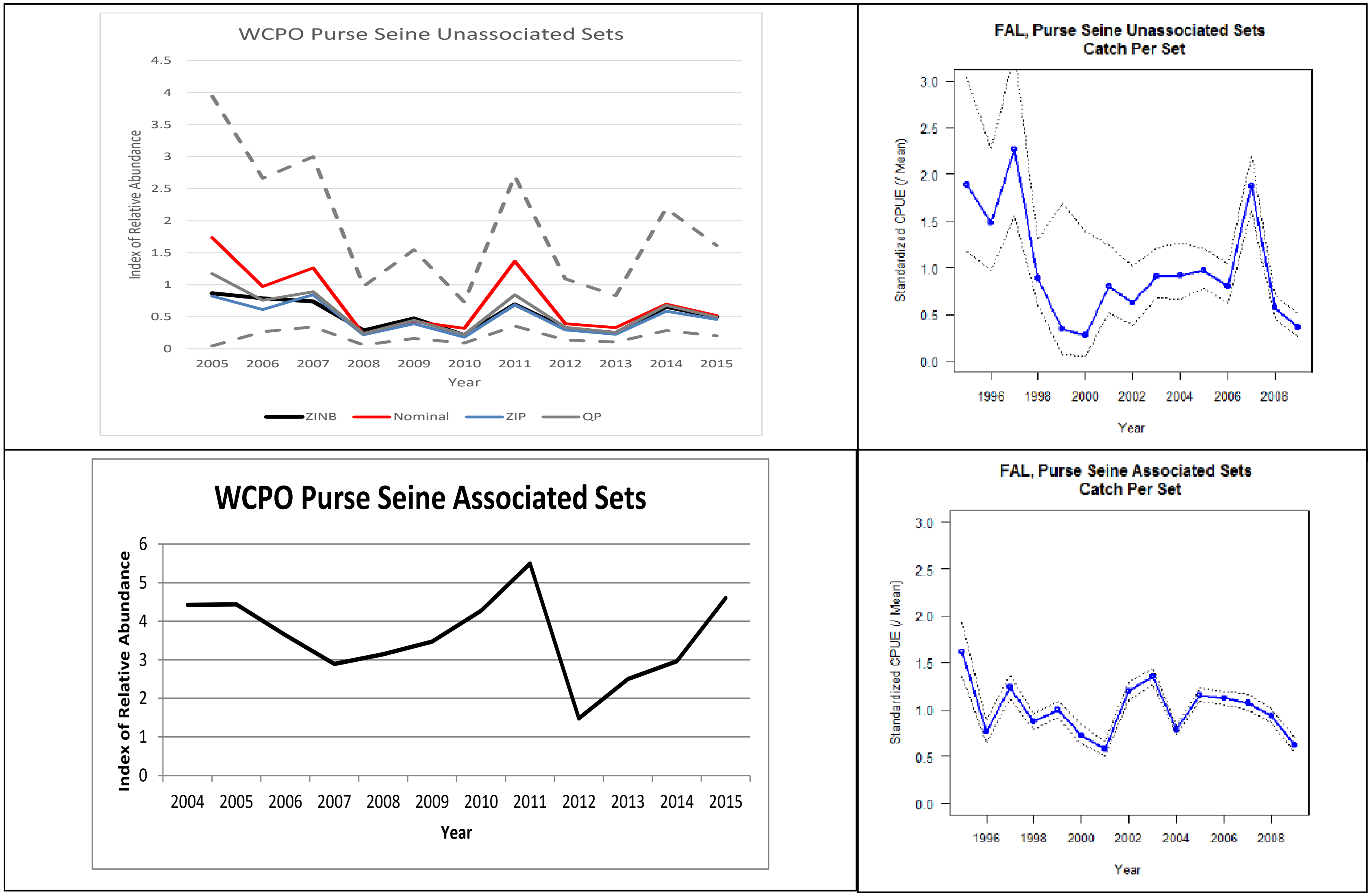


Figure 4. Nominal and standardized (zero-inflated negative binomial (ZINB), and zero-inflated Poisson (ZIP) and quasi-Poisson (QP, with 95% confidence intervals shown with dashed lines) catch per unit effort time series for the unassociated purse seine fishery (top left), and standardized catch series for the associated purse seine fishery in the WCPO (Lennert-Cody et al. 2017, bottom left). The right panels show the standardized catch rates for WCPO unassociated and associated purse seine fisheries used in the previous assessment (Rice 2013) for comparison.

4.1.2.2 Hawaii longline fishery

This dataset was standardized by Walsh & Clarke (2011) and used in the Rice & Harley (2013) silky shark stock assessment. Walsh & Clarke (2011) used data from the Hawaii-based longline fishery in 1995-2010, and both delta-lognormal and quasi-Poisson modelling approaches. Covariates included year, hooks between floats (HBF) and distance from land for both models. The dataset was filtered to use sets from 0-10^{o}N in the deep sector (≥15 HBF) only as most of the silky shark catch was taken in these operations. Although the study notes that the models have low explanatory power, they conclude that silky shark abundance has remained fairly stable since 2000, before which time sample sizes were very small (Figure 5).

For the present study, the abundance index of Walsh & Clarke (2011) was updated with data available through 2014 (see **Annex A**). The dataset provided by NOAA for this study did not include the distance to land variable however, upon request, NOAA staff provided sea surface temperature (SST) data for each set. Working with these available data the following filters were applied:

- Only data from the Hawaii-based fishery was retained;
- Only data from 2000-2014 were retained;
- In line with Walsh & Clarke (2011) only sets between the equator and 10^{o}N, and with ≥15 HBF, were retained.

A tree model (R package 'tree') was used to explore the potential significance of the following variables in the model: year, month, latitude, longitude, HBF and SST. The tree model indicated that only year, latitude and SST are significant. Since 42% of the sets remaining in the dataset reported zero catch of silky sharks, and most positive catches ranged from 1 to 13 sharks, an overdispersed Poisson model was selected. An additional 81 sets were removed due to missing SST values leaving a total of n=1,530 sets available for modelling.

The following model was fit to the data:

glm(formula = FAL ~ yearfact + s(lat1) + s(SST) + offset(loghooks), family = quasipoisson, data = Walshdat)

and the overdispersion parameter is 4.44 (compared to the Walsh & Clarke (2011) value of 4.98) indicating that overdispersion should be taken into account. In this model some of the year coefficients are statistically significant and latitude and SST are statistically significant at $p<0.05$. Model diagnostics indicate some problems with the fit to the data (**Annex C**).

Nominal and quasi-Poisson year coefficients are shown in Figure 5. It should be noted that the lower bound of the confidence level for 2005 could not be estimated due to only n=12 observed sets (only one of them catching one silky shark) in that year. Both this analysis and the previous one show increased catch rates in 2003, 2006 and 2008, and this analysis suggests the fluctuation continued with additional peaks in 2011 and 2014. Neither analysis was able to explain the variation through standardization using any of the available covariates. It is noted that the peak in 2011 and subsequent drop in 2012 shown in the updated analysis of the Hawaii longline fishery corresponds to the pattern shown above for the unassociated and associated WCPO purse seine fishery (see Figure 4). Walsh & Clarke (2011) note that most of the sharks taken by the Hawaii longline fishery appear to be immature and therefore it should be considered that the abundance trends in this fishery are influenced by the oceanographic patterns identified as influencing small silky sharks in Lennert-Cody et al. (2017, in press).

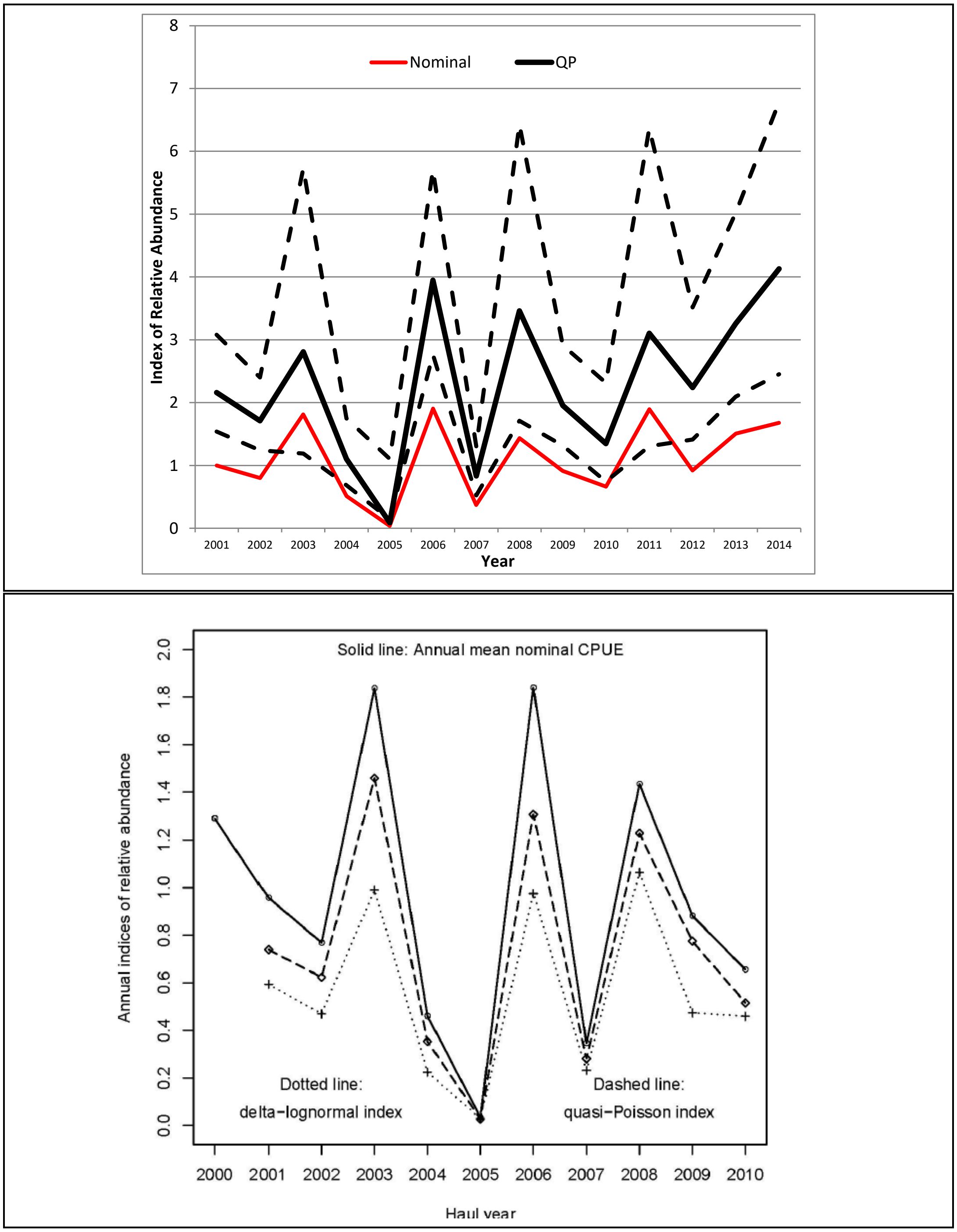


Figure 5. Nominal and standardized quasi-Poisson model (QP; with 95% confidence intervals shown with dashed lines) catch per unit effort time series for the Hawaii longline fishery in this study (top) and by Walsh & Clarke (2011).

4.1.2.3 WCPO longline fishery

Standardized catch rates from this dataset formed the basis of the Rice & Harley (2013) silky shark stock assessment. For that study data from a "target" shark longline fishery was standardized separately by segregating data from vessels operating in Papua New Guinea (PNG) and the Solomon Islands that declared that they targeted sharks. The analysis acknowledged that the series was the most spatially restricted of those included in the assessment and suffered from relative data deficiencies at the beginning and end of the time series (Rice 2013). The stock assessment notes that all runs that included the target longline CPUE series estimated a current total biomass in excess of 150 million tonnes—more than 18 times greater than the 2010 estimate of total biomass of bigeye, south Pacific albacore, skipjack and yellowfin tuna combined—leading the authors to conclude that those results were not plausible (Rice & Harley 2013). Sets that were not marked in observer records as "shark targeting" were standardized separately using a ZINB model and referred to as the longline "bycatch" series (Rice 2013; Figure 6). This non-target catch rate series was used as the reference case in the stock assessment (Rice & Harley 2013).

The issue of shark targeting was re-visited in 2015 as part of a shark indicators assessment (Rice et al. 2015). In the 2015 study a different standardization approach was applied. All sets from the PNG observer programme were removed from the dataset *a priori* because "vessels in the fleet frequently target sharks"[2]. After accounting for targeting in that way, records remaining in the dataset after the application of several other filters were standardized using a negative binomial model estimating both the mean and the variance. Nevertheless, the authors noted evidence of shark (or mixed species, including shark) targeting in many areas (Rice et al. 2015), presumably inferred from very high catch rates, that affected model performance in some cases.

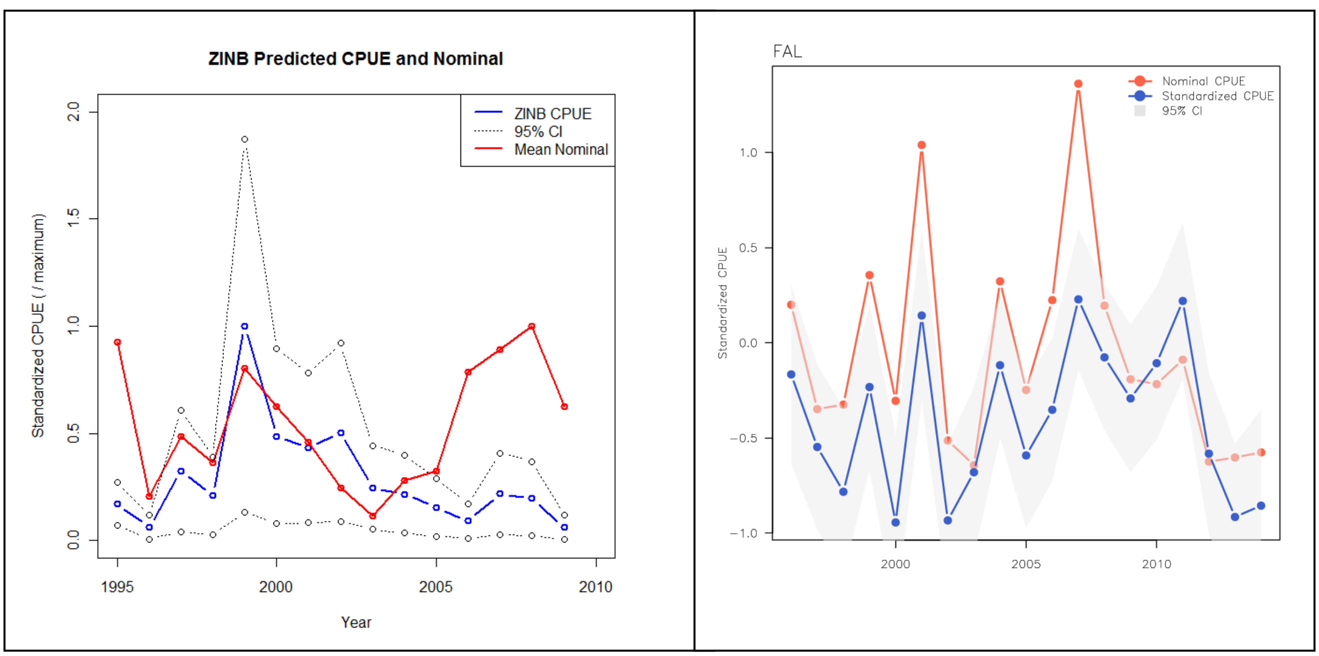


Figure 6. Nominal and standardized catch per unit effort time series for silky sharks from Rice (2013; the longline "bycatch" series used as the reference case in the last assessment) and Rice et al. (2015).

[2] The Papua New Guinea shark fishery closed in the first quarter of 2014 (NFA 2017).

The two series show quite different trends. In the 2013 analysis catch rates peaked in 1999, dropped by about half from 2000-2002, and then dropped again by half from 2003-2009. In the 2015 analysis the annual values fluctuate from 1996 until 2011 (the highest value in the series) and then decrease considerably in 2012-2014. Rice et al. (2015) suggest that part of this decrease may be attributable to lags in receiving and loading observer data for analysis in the most recent years which can lead to higher levels of uncertainty (see Williams et al. 2015).

For the present study extensive data cleaning was undertaken for the WCPO longline dataset resulting in removal of approximately 42% of the observed sets due to missing covariates, sets outside of the year range, or overlap with the US observer data described above and in **Annex A**. Further cleaning was required prior to the standardization modelling in order to ensure that the dataset was sufficiently balanced to allow estimation of the necessary parameters. The first step in this process was to filter the available 45,643 records to retain only sets from fisheries that had been operating consistently in silky shark habitat throughout 2002-2016. Sets from vessels flagged to American Samoa, China, the Federated States of Micronesia (FSM), Japan, Kiribati, Korea, Republic of the Marshall Islands (RMI), PNG, the Solomon Islands, Vanuatu and Samoa were excluded because observations were missing in multiple years, due either to lack of observer coverage or because these national programme data were not accessible to this study. New Zealand data were excluded as they were not expected to encounter silky sharks. Chinese Taipei data were excluded due to a balance issue: in 2012-2014 Chinese Taipei's observer data comprised 50-60% of the total observed sets and there was concern that these data could unduly bias the estimates in these years despite the inclusion of relevant covariates. These filters resulted in a dataset of n= 20,927 sets containing data from Australia, the Cook Islands, Fiji, New Caledonia, French Polynesia and Tonga.

Given their geographical location, most of these countries' observer data was expected to derive from areas of silky shark habitat, but as a further check, sets and silky shark catches were plotted by latitude in order to identify a core area where the majority of the catch was taken in the observed sets. Based on these plots, the core area boundaries were set at 7°S and 29°S and 152°E to 220°E. A total of 16,531 sets remained for analysis.

Considering the available covariates in the dataset, the covariates used in previous analyses (Rice 2013, Rice & Harley 2013), and consultation with IATTC, an initial model was selected with year, month, latitude, longitude, HBF, flag, tuna catch and swordfish catch as explanatory variables. Year, month and flag were modelled as factors. Latitude and longitude were rounded to the nearest 1 degree, and all covariates except the factors were specified as splines. The log of hooks observed was specified as an offset. The maximum catch of silky shark observed in the model was 16, and 91% of the records showed zero silky shark catch, therefore the zero-inflated Poisson (ZIP) was chosen as the preferred model. Flag was subsequently dropped from the model because it was confounded with latitude and longitude. The swordfish variable was also dropped as it did not contribute significantly to improving the model fit.

The following model was fit to the data:

zeroinfl(FAL ~ yearfact + monthfact + s(HBF) + s(lat1) + s(lon1) + s(tuna) + offset(loghooks) | yearfact + monthfact + s(HBF) + s(lat1) + s(lon1) + s(tuna) + offset(loghooks), dist="poisson", link="logit", data = SPLL)

In the final model, latitude, longitude and tuna catch were highly significant ($p<0.001$) in both the binomial (presence/absence) and count components. Month and HBF were less important but still significant in both portions of the model ($p<0.01$). A quasi-Poisson (QP) model was also fit to the data for the sake of estimating indicative 95% confidence intervals (obtained using the R predict() function with a confidence interval on the annual estimate obtained using the R confint() function). The year factor estimates of the ZIP and QP models are similar. The confidence intervals for the QP model are shown in Figure 7. The over-dispersion parameter for the QP model was 2.132 indicating that overdispersion is present. However, the model diagnostics reveal that the residuals from the model deviate from the distributional assumptions of the QP model (**Annex C**).

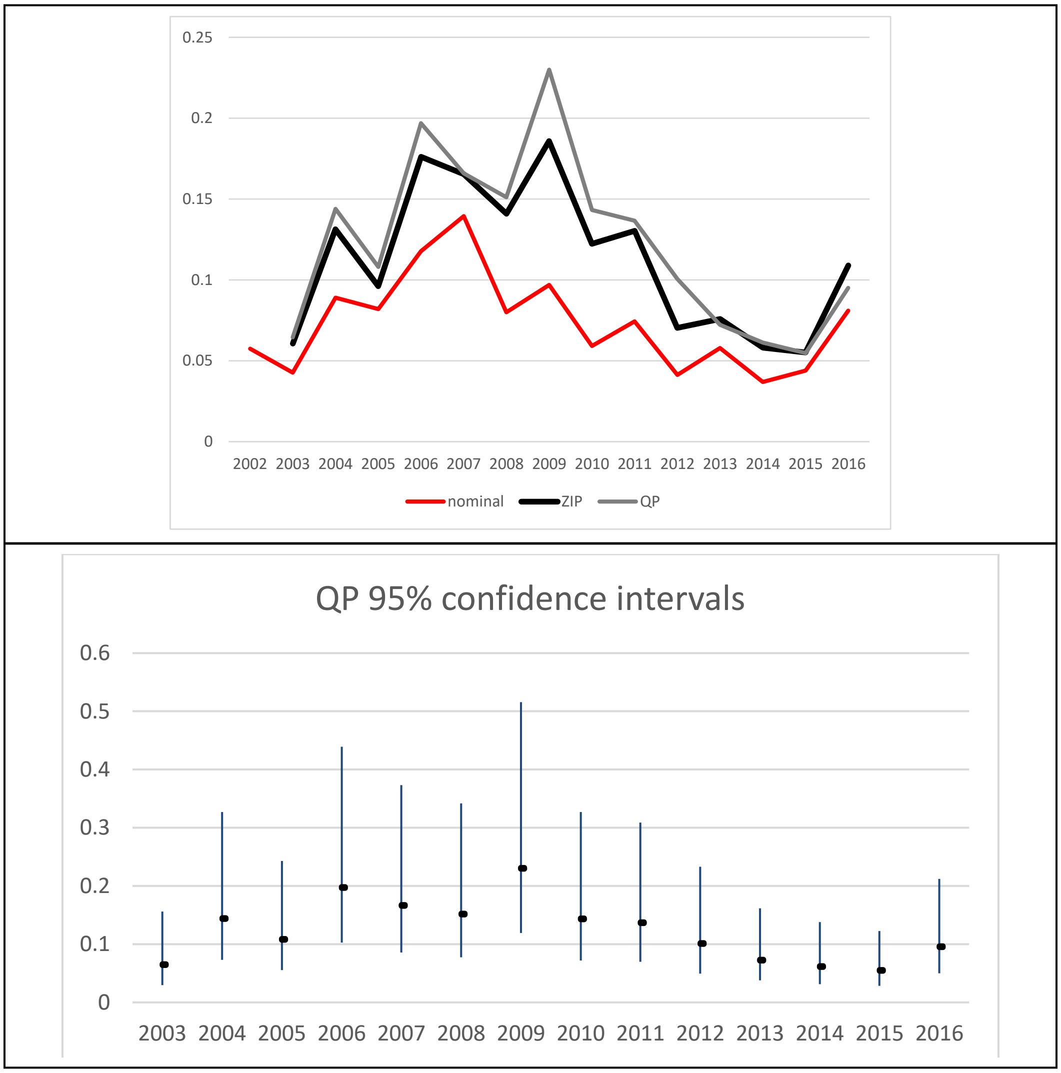


Figure 7. Nominal and standardized catch per unit effort time series for silky sharks applying ZIP and QP models to WCPO longline data (top panel). Indicative 95% confidence intervals from the QP model (bottom panel).

The standardized catch rate time series resemble the nominal series thus suggesting that available covariates are not able to explain the variation other than through the year factor. The indicative 95% confidence intervals suggest that the decrease in catch rates in 2012-2016, though producing the lowest median values since 2005, are not likely to be statistically significantly lower than the earlier values in the time series. It is likely that increased observer coverage in recent years has led to the reduction in uncertainty illustrated by the tighter confidence intervals. The nominal catch rate peak in 2007 (Figure 7) can also be seen in previous catch rate series (for example, Rice et al. 2015 (Figure 6)), but the updated standardization suggests that even higher values occurred in 2009. There is a peak in the nominal standardization of the full WCPO longline set in 2007 (**Annex A** (Figure A4)) and also in the unassociated purse seine fishery in 2007 (Figure 4) which may suggest that the fishing effort was skewed toward high silky shark catch rate areas in that year (i.e. but this is not seen in the standardized series because the standardization accounts for that skew). SST values were not available for this dataset and could have improved the standardization. However, SST was also not used in the previous standardizations of this catch rate time series (Rice 2012, Rice 2013, Rice et al. 2015) so this factor cannot be the source of the differences.

4.1.3 Size Composition

The final type of data prepared for the SS model was silky shark length frequencies collected by observers. Of the total number of lengths collected, some could not be accessed for this study due to data permissions and some were not used because they were collected on sets that were excluded from the catch rate standardization modelling described above.

In the WCPO, silky shark measurements have been taken since 1998 but the number of data points is low (<600 individuals) until 2004 (Figure 8). In the period 2004-2009 between 1000-2000 silky sharks were measured each year in the purse seine associated fishery, but few measurements were taken in the purse seine unassociated fishery. The number of measurements taken in the WCPO longline fishery were generally fewer than those in the purse seine associated fishery and more than those taken in the purse seine unassociated fishery. From 2010 onward sample sizes increased but the purse seine associated fishery continued to dominate the sampling with the exception of 2012 when over 4000 silky shark were measured in the WCPO longline fishery.

The sample sizes shown for the EPO fishery in Figure 8 are those lengths taken from sets used in the catch rate standardization modelling only, therefore, the actual number of length samples taken is higher than what is shown. Samples are only shown from 2005 onward as lengths were only recorded in size categories (i.e. small (< 90cm total length (TL) or <72cm fork length (FL)), medium (90-150cm TL or 72-122cm FL), large (>150cm TL or >122cm FL) prior to that time (Aires-da-Silva et al. 2014). All sample sizes shown are for the EPO purse seine associated fishery. Sample sizes for the northern region of this fishery are between 2000-6000 silky sharks per year, whereas for the southern region, where silky shark catch is lower, sample sizes range from 1000-3000 per year.

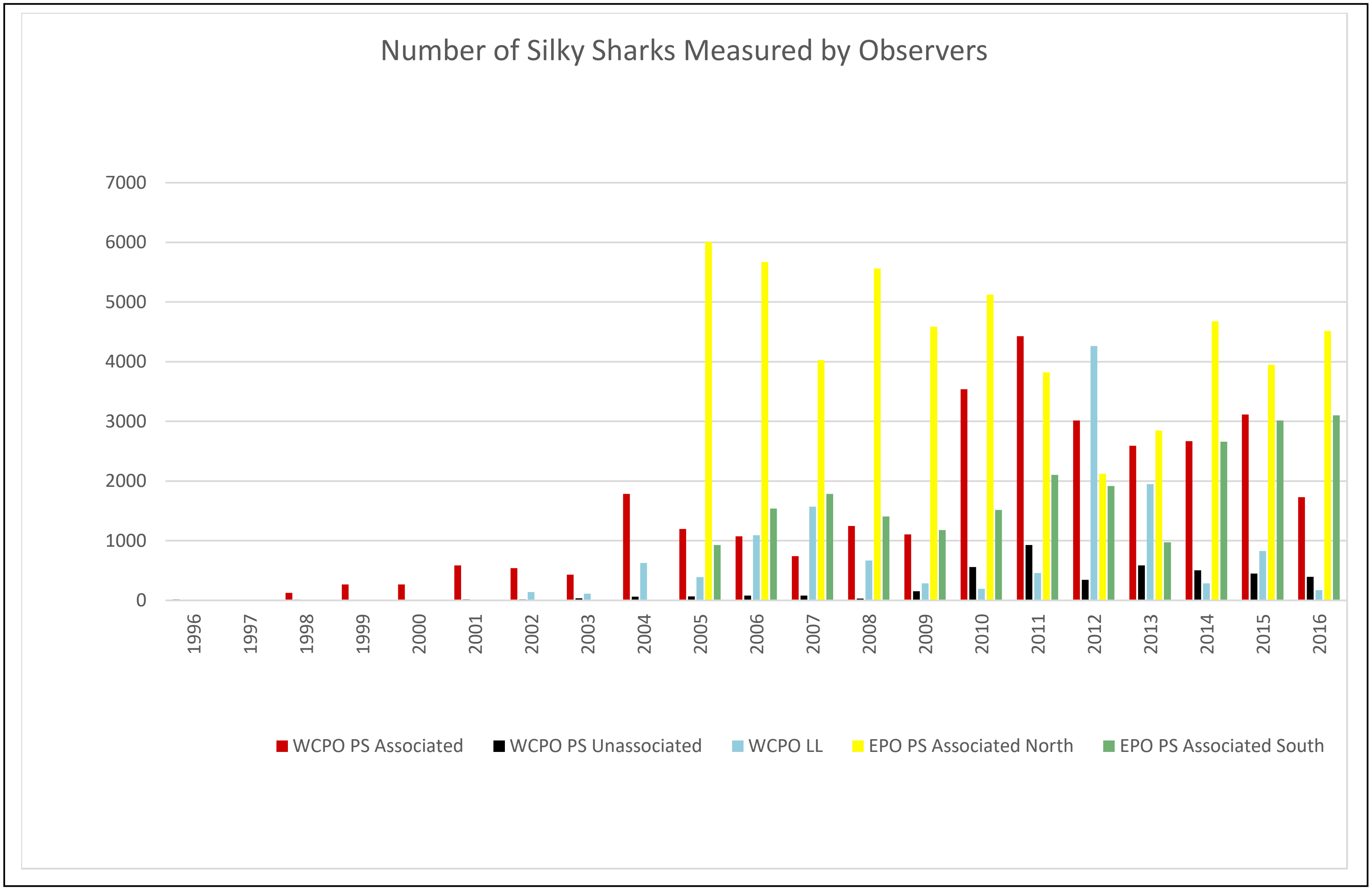


Figure 8. Sample sizes by year for measured silky sharks in various WCPO and EPO fisheries. The WCPO figures represent all the data available to this study. The EPO figures represent only those sharks measured on sets included in the catch rate standardization models.

The EPO purse seine associated length frequencies from those sharks used in the catch rate standardization models were made available for this study in 2 cm-binned summary format by sex and year for northern and southern regions (Figure 9).

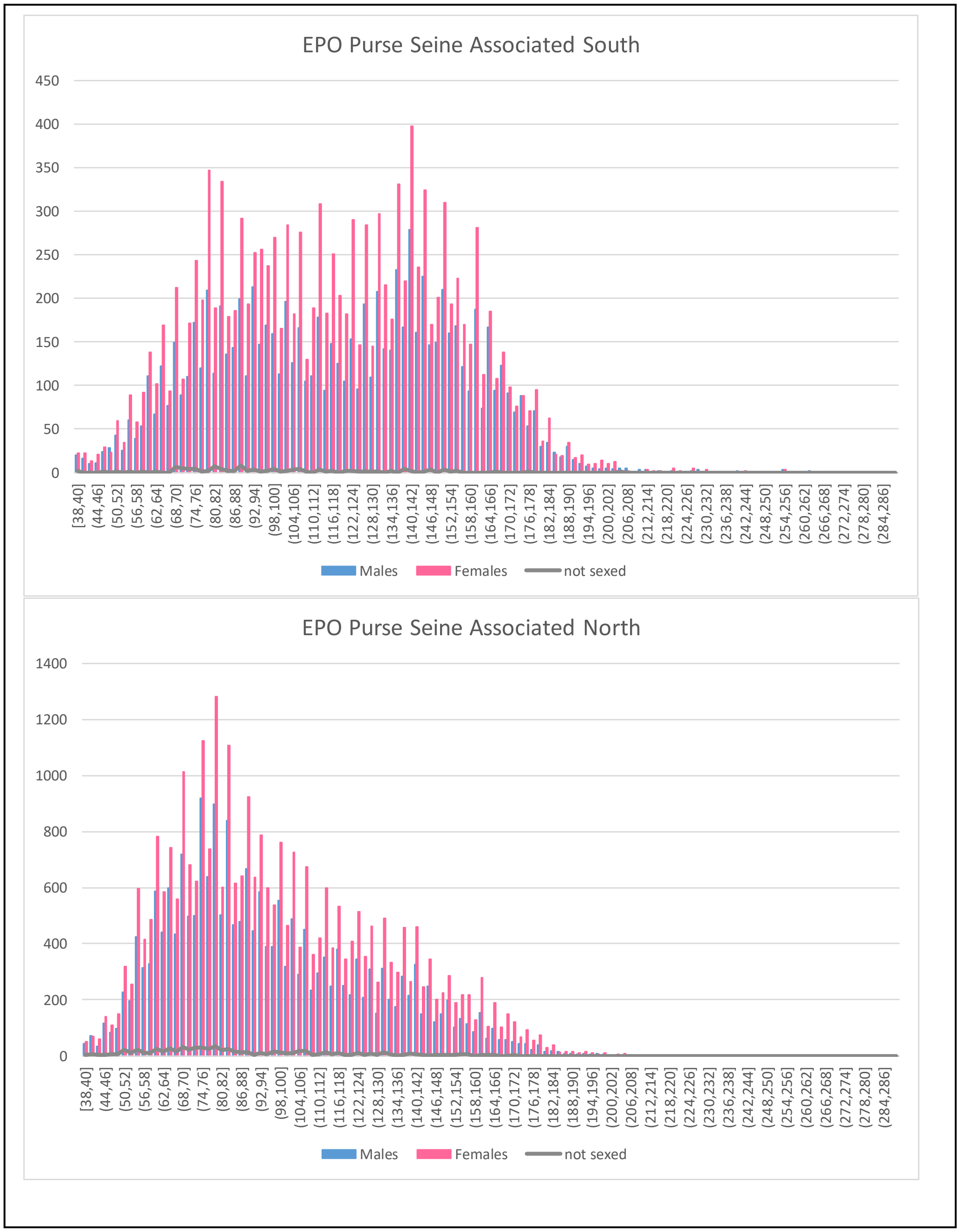


Figure 9. Length frequencies for male, female and unsexed silky sharks from the EPO purse seine associated fishery in the northern and southern regions (see Lennert-Cody et al. (2017) for regional definitions). Total sample sizes are n=52,909 for the northern region and n=22,126 for the southern region. All lengths are given in fork length.

A comparison between silky shark lengths in the WCPO and EPO purse seine associated fisheries was made in Lennert-Cody et al. (2017; **Annex B**). The conclusions from this analysis were as follows:

- Silky shark sizes in the WCPO purse seine associated fishery (145°-180°E and 5°N to 10°S) are similar to those in the EPO purse seine associated northern fishery, especially in the equatorial offshore region.
- In both areas, silky shark sizes are skewed toward smaller-sized individuals (most sharks <122cm FL).
- The EPO purse seine associated fishery in the southern region catches larger silky sharks than the other areas' fisheries.

The length frequency distributions for the WCPO fisheries vary depending on the underlying dataset. This study has more years of data available to it than did Rice & Harley (2013), but this study did not obtain access to the full dataset available to SPC and so may not have as many shark lengths available in some years. The length data used in Rice & Harley (2013; obtained from the SPC website[3]) is contrasted with the length data available to this study for WCPO purse seine associated and unassociated fisheries (unsexed), and for WCPO longline fisheries by sex (Figure 10). In each fishery, the Rice & Harley (2013) size composition shows a greater number of large sharks than found in the current datasets (blue lines versus yellow bars). Even if the dataset available to this study is restricted to the years used in the Rice & Harley (2013) assessment, the discrepancy remains (blue lines versus orange bars), therefore the difference is not due to differing time periods. This leaves open the possibility that differing data permissions are the reason for the discrepancy. In order to explore this possibility SPC was requested to generate histogram from their entire dataset, however, these 2017 SPC histograms still closely resembled the yellow bars in Figure 10.

Figure 10 also reveals the effects of recent years' data on overall size frequencies. In the case of the WCPO purse seine associated data, the truncation of the dataset available to this study at 2009 (to simulate the data available to Rice & Harley (2013) does not have a large effect the shape of the distribution (i.e. yellow versus orange bars). However, in the case of the WCPO purse seine unassociated data, more recent years seem to have encountered a greater number of larger sharks, whereas in the WCPO longline fishery more recent years seem to have encountered a greater number of smaller sharks.

One final preliminary evaluation of the length frequency inputs to the SS model requires examining the difference between the full dataset and the dataset resulting from using only silky sharks measured on sets used in the catch rate standardization models. As explained above this assessment is not possible for the EPO length compositions as only the reduced dataset was provided. For the WCPO datasets, the comparisons for the purse seine associated, purse seine unassociated and longline fisheries are shown in Figure 11. This figure highlights the fact that the WCPO PS associated fishery catches much smaller fish than the other WCPO fisheries. While the purse seine associated and unassociated length frequencies were similar between the full and modelled datasets, this was not the case for the longline fishery where the modelled dataset contained considerably larger silky sharks. This feature of the size composition was taken into consideration in specifying the selectivities for the various fisheries (see Figure 24).

[3] http://www.spc.int/Oceanfish/en/ofpsection/sam/sam/215-sharks-assessment-results#2013

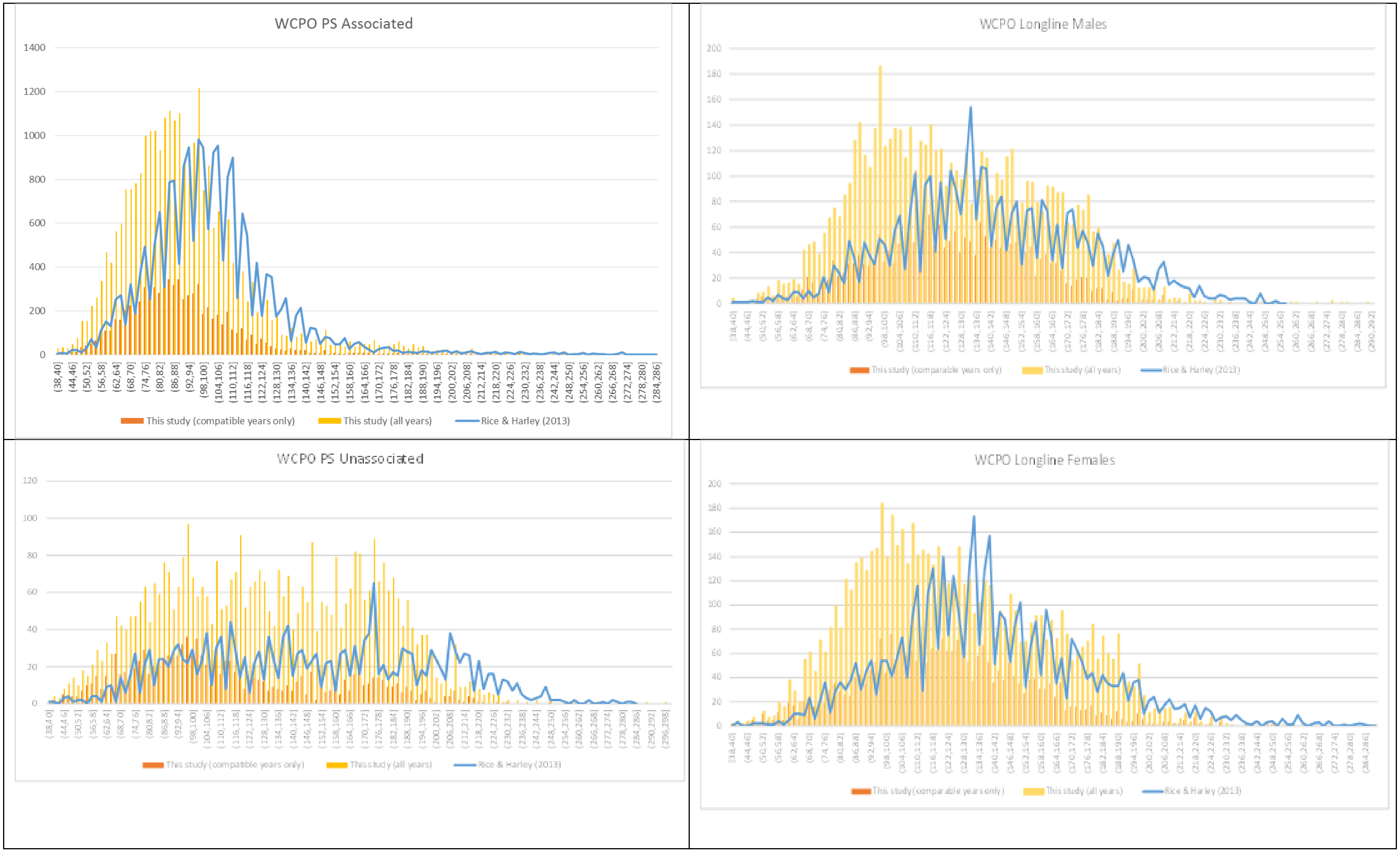


Figure 10. Length frequencies for measured silky sharks used in Rice & Harley (2013, blue lines) and in this study (all available lengths (yellow bars)) and only those lengths which match the years compiled for Rice & Harley (2013), i.e. "compatible years" (orange bars). All lengths are given in fork length (converted from TL as necessary).

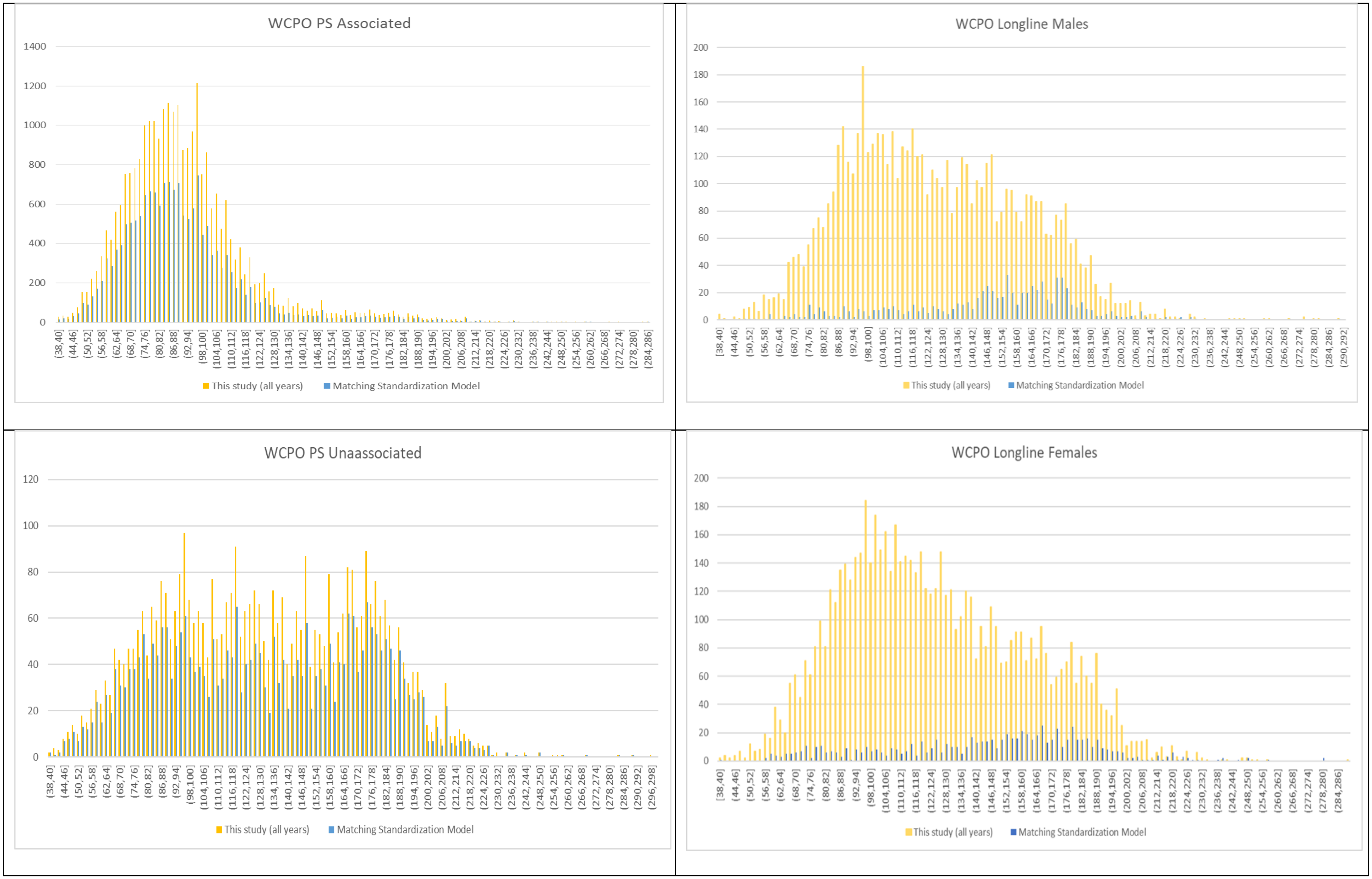


Figure 11. Size composition for full dataset available to this study compared to lengths taken from silky sharks caught in sets used in the catch rate standardization models for WCPO purse seine associated (unsexed), WCPO purse seine unassociated (unsexed) and WCPO longline fisheries (male and female). All lengths are given in fork length.

4.2 Model Configuration

The Pacific wide silky shark model was configured to provide a framework for evaluating the consistency of the various datasets available from the fishery. This framework enables a range of potential stock hypotheses and assumptions to be evaluated. The results may lead towards the development of a model (or range of models) that can be applied to assess the status of the stock.

4.2.1 Fisheries structure and input data sets

The Pacific-wide model was configured to encompass six fisheries:

- WCPO longline (WCPO_LL);
- WCPO purse seine associated sets (WCPO_PS_Assoc);
- WCPO purse seine unassociated sets (WCPO_PS_Unassoc);
- EPO purse seine associated sets (EPO_PS_Assoc);
- EPO purse seine unassociated sets (EPO_PS_Unassoc); and,
- EPO longline fishery (EPO_LL) representing a composite fishery incorporating all non-purse seine catches from the EPO.

Total catches (in numbers) are dominated by the catch from the two longline fisheries (WCPO_LL and EPO_LL). The EPO catch estimates provided in Section 4.1.1 were allocated exclusively to the EPO_LL fishery. Initially, EPO purse seine catches were not available for inclusion in the model. Instead, annual catches for the EPO purse seine fisheries were each assigned a low, nominal value. The magnitude of the notional purse seine catches was consistent with the catches included in the preliminary EPO stock assessment (IATTC 2014). Actual reported catches of silky shark from the EPO purse seine fishery were available towards the end of the project (IATTC 2018). For comparative purposes, a model option was conducted using the actual reported catches (see Table 7). The results from that model option were not appreciably different from the other model options and, on that basis, it was considered that the model results were insensitive to the range of catches assumed for the EPO purse seine fishery.

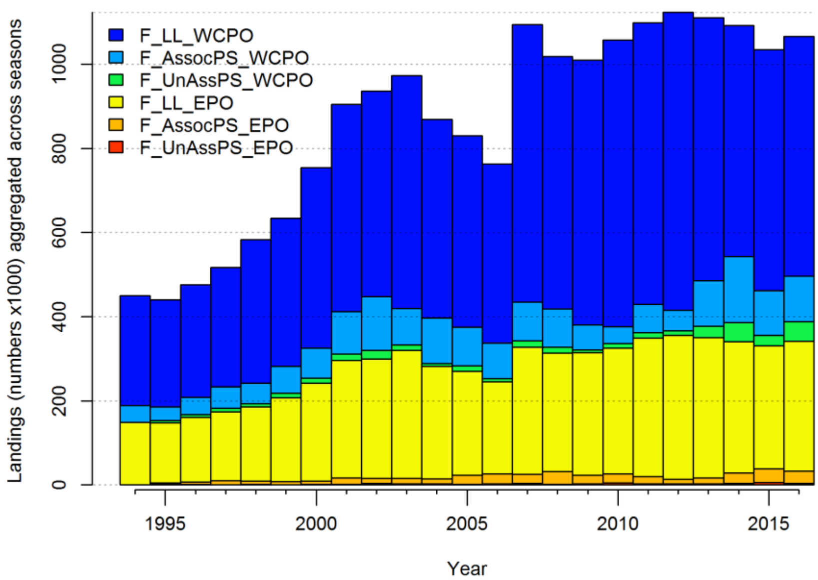


Figure 12. Annual estimated catches of silky sharks by fishery (numbers in thousands). The catches for 1994 are the assumed initial, equilibrium levels of catch.

CPUE indices have been derived from five observer data sets (Figure 13). For the WCPO, the primary CPUE indices are derived from South Pacific (SP) observer data from the longline fishery (SP_LL; see Section 4.1.2.3). The SP data set is a subset of the WCPO longline fishery (see Figure 11).

For the EPO, CPUE indices are available from the purse seine object fishery for three shark size categories (Lennert-Cody et al. 2017). The large (> 150 cm TL (>122 cm FL)) category CPUE indices are considered to be the most representative of trends in stock abundance and were the basis for the previous stock assessment in the EPO (IATTC 2014). Hence, these CPUE indices were included as the primary abundance index for the EPO region in the current assessment model (PSOBJ_EPO_Large).

Additional CPUE indices are available from the WCPO_PS_Assoc, WCPO_PS_Unassoc and Hawaii-based longline fishery (Lennert-Cody et al. 2017, Section 4.1.2.1 and Section 4.1.2.2, respectively). The WCPO_PS_Assoc CPUE and WCPO_PS_Unassoc indices represent limited time-series and were not considered sufficiently informative for monitoring stock abundance. The Hawaii-based longline fishery (HWLL) operates within a relatively small area of the WCPO close to the EPO boundary and, consequently, the HWLL CPUE indices are unlikely to be representative of trends in stock abundance throughout the WCPO region. Nonetheless, to enable evaluation, the three sets of indices were included within the WCPO region of the assessment model and associated with the relevant selectivity function (WCPO_PS_Assoc, WCPO_PS_Unassoc and the selectivity of the HWLL assumed equivalent to WCPO_LL). However, these CPUE indices did not contribute to the likelihood function of the base model (lambda 0) and, hence, did not influence estimation of model parameters.

Correlations between each set of CPUE indices were examined with lags in each series of -2, -1, 0, 1, 2, and 3 years. There is a moderate positive correlation (correlation coefficient 0.704) between the SP LL CPUE indices and the WCPO_PS_Unassoc CPUE indices two years later. Similarly, there is a moderate positive correlation (correlation coefficient 0.690) between the SP_LL CPUE indices and the PSOBJ_EPO_Large CPUE indices in the preceding year. However, the correlations between the sets of CPUE indices are not very compelling as they are based on a limited number of observations and there are inconsistencies between trends from the individual sets of CPUE indices (Figure 14). No other significant correlations amongst the sets of CPUE indices were detected.

Length composition data are available from the WCPO_LL (15 years), WCPO_PS_Assoc (21 years), WCPO_PS_Unassoc (20 years) and EPO_PS_Assoc (12 years) fisheries and associated with the SP_LL CPUE index (Table 2). The WCPO_LL length composition data are partitioned by sex, while the other data sets are for both sexes combined. The length data were provided based on fork length measurements aggregated by 2 cm length bin. The dimensions of the length bins were converted to total length using the equation of Joung et al. (2008).

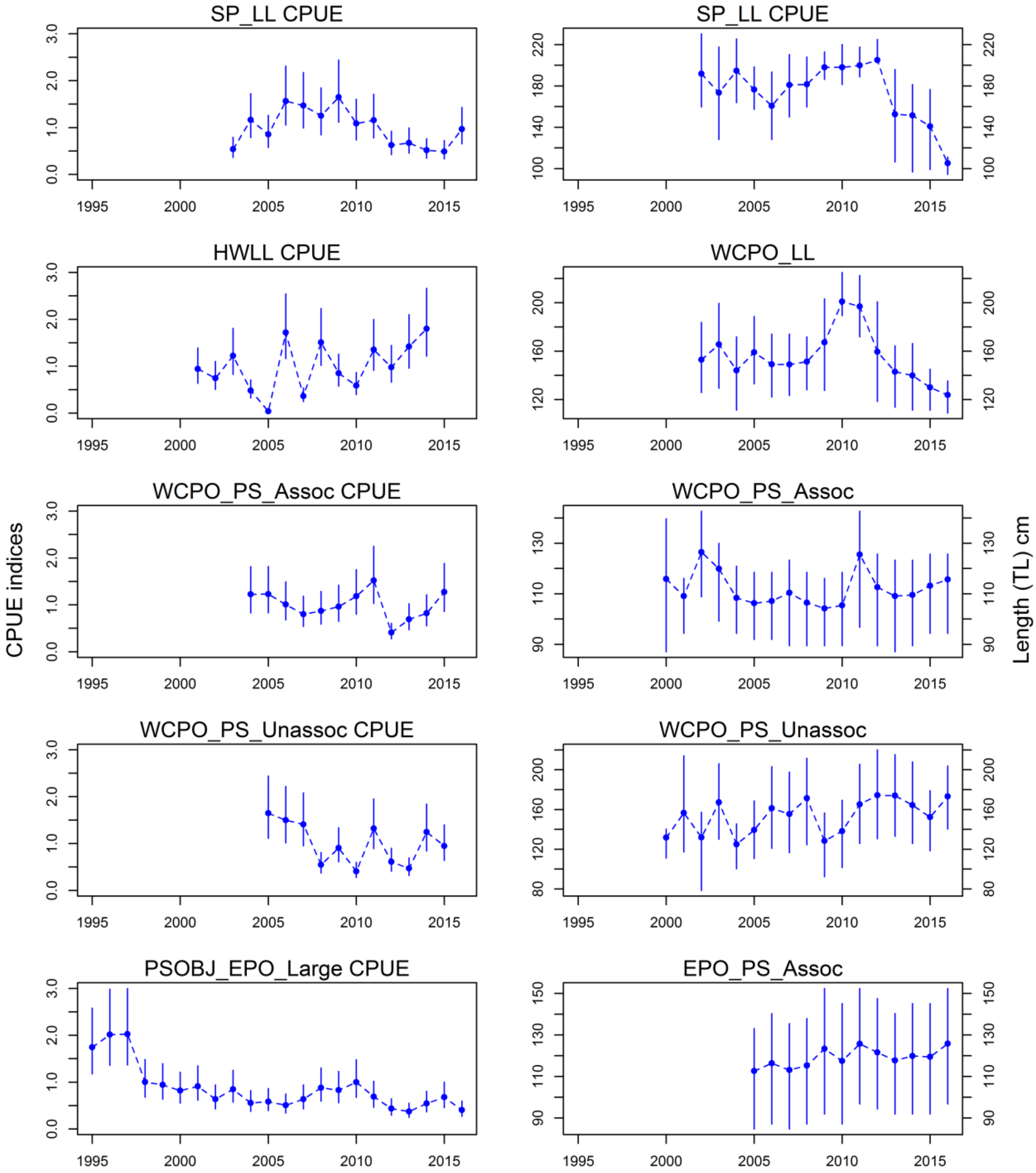


Figure 13. Annual trends in CPUE indices (left) and average lengths from fishery length compositions (right). The confidence intervals for the CPUE indices are based on an assumed CV of 20%. For the length data, the vertical bars represent the inter-quartile range.

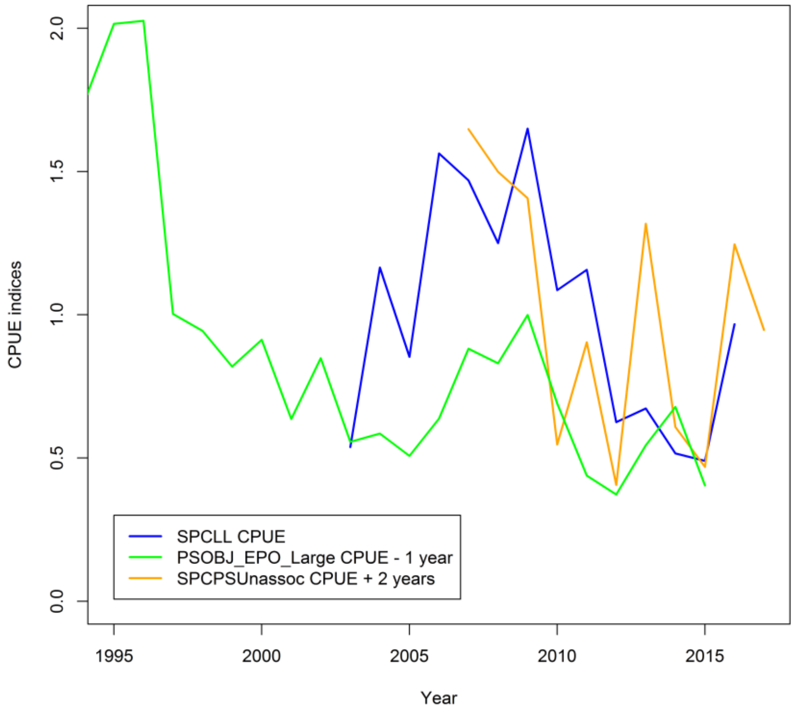


Figure 14. Comparison between those sets of CPUE indices that have a moderate degree of correlation (with relevant lag period).

Table 2. Summary of input data sets for assessment model. The relative weighting includes the Effective Sample Size (ESS) of length composition data and the coefficient of variation (CV) associated with the CPUE indices.

Data set	Model year(s)	# of obs (years)	Relative weighting
SP_LL CPUE	2003–2016	14	CV 20%
PSOBJ_EPO_Large	1995–2016	22	CV 20%
HWLL CPUE	2001–2014	14	Lambda 0
WCPO_PS_Assoc CPUE	2004–2015	12	Lambda 0
WCPO_PS_Unassoc CPUE	2005–2015	11	Lambda 0
Len Comp SP_LL CPUE	2002–2016	15	ESS 10
Len Comp WCPO_LL	2002–2016	15	ESS 10
Len Comp WCPO_PS_Assoc	1996–2016	21	ESS 10
Len Comp WCPO_PS_Unass	1997–2016	20	ESS 10
Len Comp EPO_PS_Assoc	2005–2016	12	ESS 10

There is considerable inter-annual variation in the some of the key data sets. Trends in the data sets were examined relative to a number of environmental indices that characterise the oceanographic conditions in the equatorial Pacific: Niño3.4, Niño1.2 and Trans-Niño-Index TNI (Figures 15-18). The Niño3.4 index represents the average equatorial SSTs across the equatorial Pacific, spanning the (150° W) boundary between the WCPO and EPO regions (Trenberth 2016; Figures 15 and 16). The Niño3.4 index is highly correlated with the Pacific Decadal Oscillation (PDO) index used in the analysis by Lennert-Cody et al. (in press). The Niño1.2 index represents the average SSTs derived from an area of the eastern equatorial Pacific (Figures 15 and 17). The TNI represents the difference in the SST anomalies between Niño1.2 and Niño4 (Figures 15and 18).

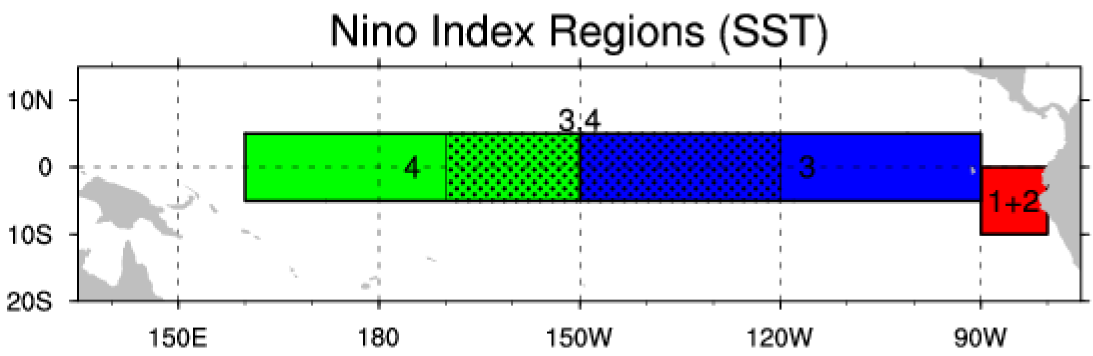


Figure 15. Niño Index Regions (from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni).

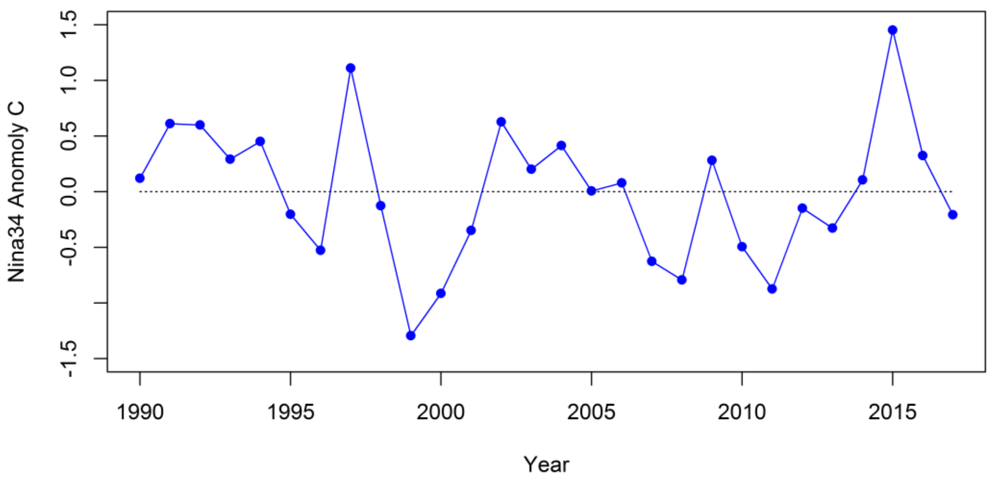


Figure 16. Annual average values of the Niño3.4 index. The indices are presented as deviations from the 1990-2017 time period.

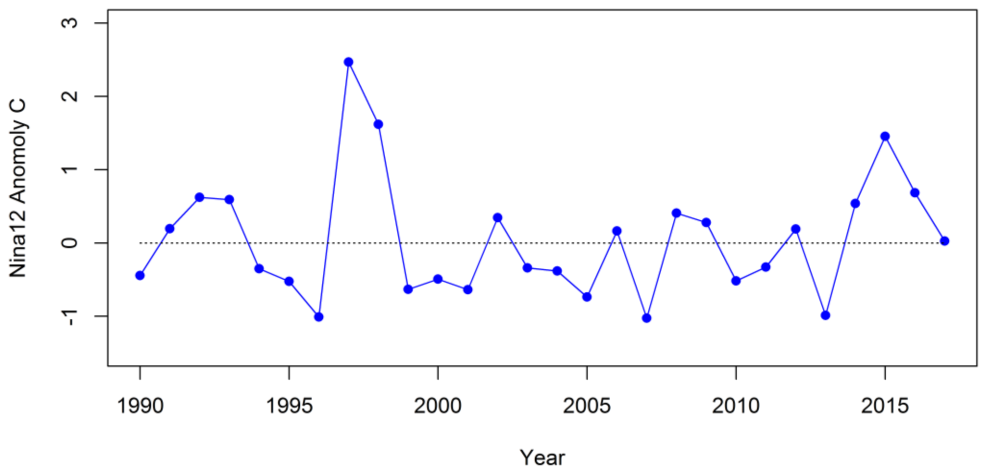


Figure 17. Annual average values of the Niño1.2 index. The indices are presented as deviations from the 1990-2017 time period.

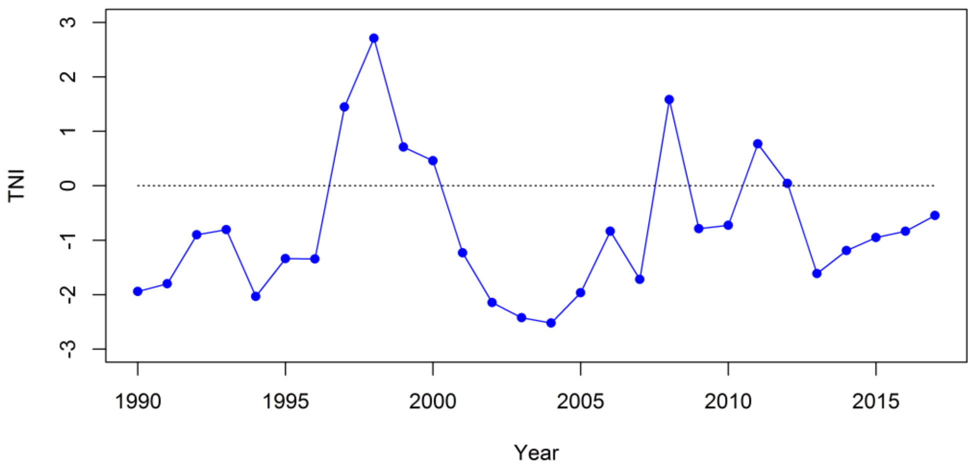


Figure 18. Annual average values of the TNI index.

The main observations from the comparison between the key data sets and the environmental indices are, as follows:

- SP_LL CPUE indices are negatively correlated (corr. coef. -0.66) with the Niño3.4 environmental index in the following year (lag 1 year) (Table 3 and Figure 19). There is also a weak negative correlation with fish size (mean length;
- Table 4) which may suggest that larger fish were less available to the composite longline fisheries during positive Niño3.4 conditions.
- There is a positive correlation between the WCPO_PS_Unassoc CPUE indices and Niño3.4 environmental index two years earlier (lag -2 years) (corr. coef. 0.784); i.e., positive Niño3.4 conditions followed by higher CPUE in WCPO_PS_Unassoc index two years later (Table 3 and Figure 20).
- There is a weak positive correlation between the PSOBJ_EPO_Large CPUE indices and the TNI in the preceding year (corr. coef. 0.55) and two years earlier (corr. coef. 0.60). The correlation is driven by the higher CPUE indices in the earlier years (1995-1997).
- There is a negative correlation (-0.695) between mean length of sharks sampled from the EPO PS fishery and Niño3.4 environmental index in the previous year (lag -1 year) (
- Table 4); i.e., negative Niño3.4 index is correlated with larger sharks in the EPO PS one year later. This could correspond to an increased predominance of smaller sharks following positive Niño3.4 conditions (El Niño conditions).

Table 3. Correlation coefficients between the five sets of CPUE indices and the annual Niño3.4 environmental index lagged by specified annual intervals (from 3 years to -4 years).

Year lag	CPUE index				
	SP_LL	HWLL	WCPO PSAssoc	WCPO PSUnassoc	PSOBJ_EPO Large
3	-0.329	0.313	-0.526	-0.255	-0.509
2	-0.509	0.094	-0.432	-0.379	-0.206
1	-0.663	0.405	-0.045	0.074	0.059
0	-0.358	-0.146	0.156	0.110	0.013
-1	-0.178	-0.311	0.467	0.345	-0.063
-2	0.323	0.023	0.429	0.784	0.156
-3	0.398	-0.342	-0.273	0.321	0.335
-4	0.625	0.113	-0.253	-0.078	0.423

Table 4. Correlation coefficients between average annual lengths from the fishery length compositions and the annual Niño3.4 environmental index lagged by specified annual intervals (from 3 years to -4 years).

Year lag	Fishery/CPUE				
	WCPO_LL	WCPO PS_Assoc	WCPO PS_Unassoc	EPO PS_Assoc	SP_LL CPUE
3	0.059	0.286	0.388	0.526	0.115
2	-0.346	0.265	0.176	-0.058	-0.348
1	-0.437	0.145	0.284	0.086	-0.502
0	-0.404	0.017	-0.333	0.041	-0.069
-1	0.034	-0.090	-0.008	-0.695	-0.307
-2	-0.167	-0.055	-0.043	-0.222	-0.064
-3	-0.195	-0.450	-0.149	-0.543	0.052
-4	-0.142	-0.433	0.098	-0.529	-0.282

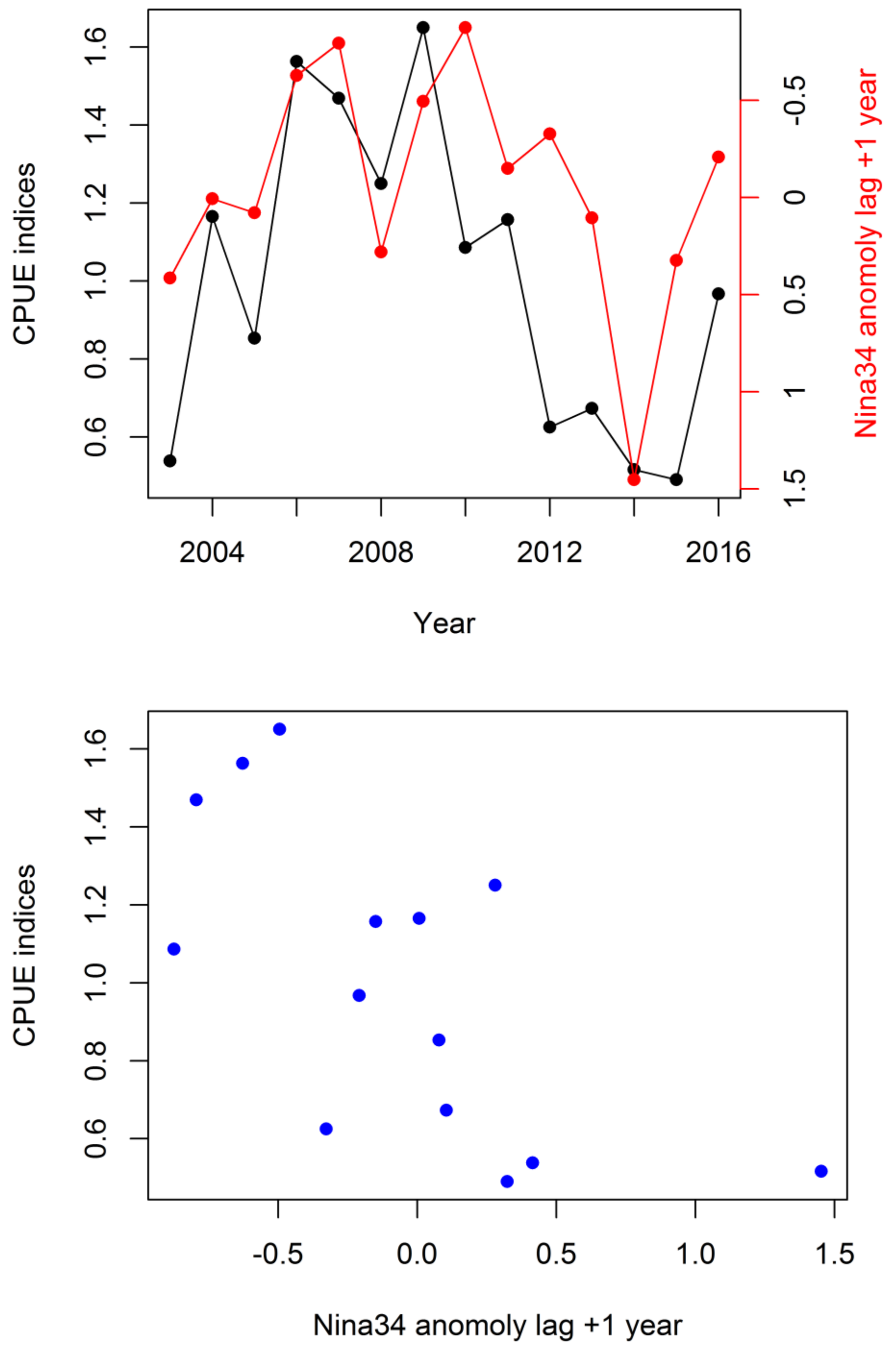


Figure 19. Comparison between SP_LL CPUE indices and the Niño3.4 index in the following year (+1 year).

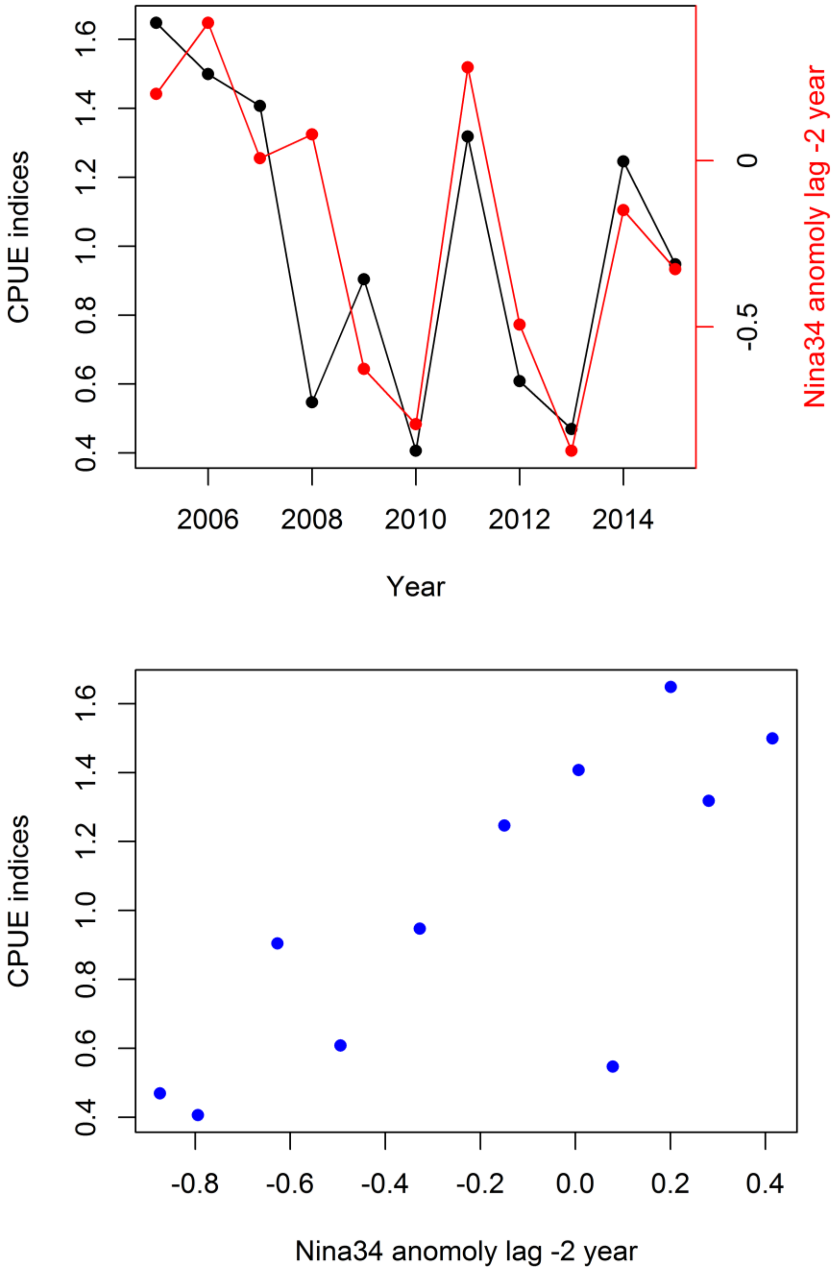


Figure 20. Comparison between WCPO_PS_UNASSOC CPUE indices and the Niño3.4 index from two years earlier (-2 year).

4.2.2 Biological parameters

Biological parameters were sourced from Clarke et al. (2015) and were equivalent to those used by Rice & Harley (2013). The key biological parameters for the assessment model are presented in Table 5. Following previous assessments, natural mortality (M) was assumed to be 0.18 for the base model options. Growth was parameterised using a sex-combined Von Bertalanffy growth function (Figure 21Figure 21.) and length-weight relationship (Figure 22) from Joung et al (2008). The variation in length-at-age was approximated by a constant CV of 8.5% of the mean length at age (Figure Figure 21. 21). The sexual maturity was length-based with 50% maturity at 215 cm (TL) (Joung et al. 2008) (Figure 23).

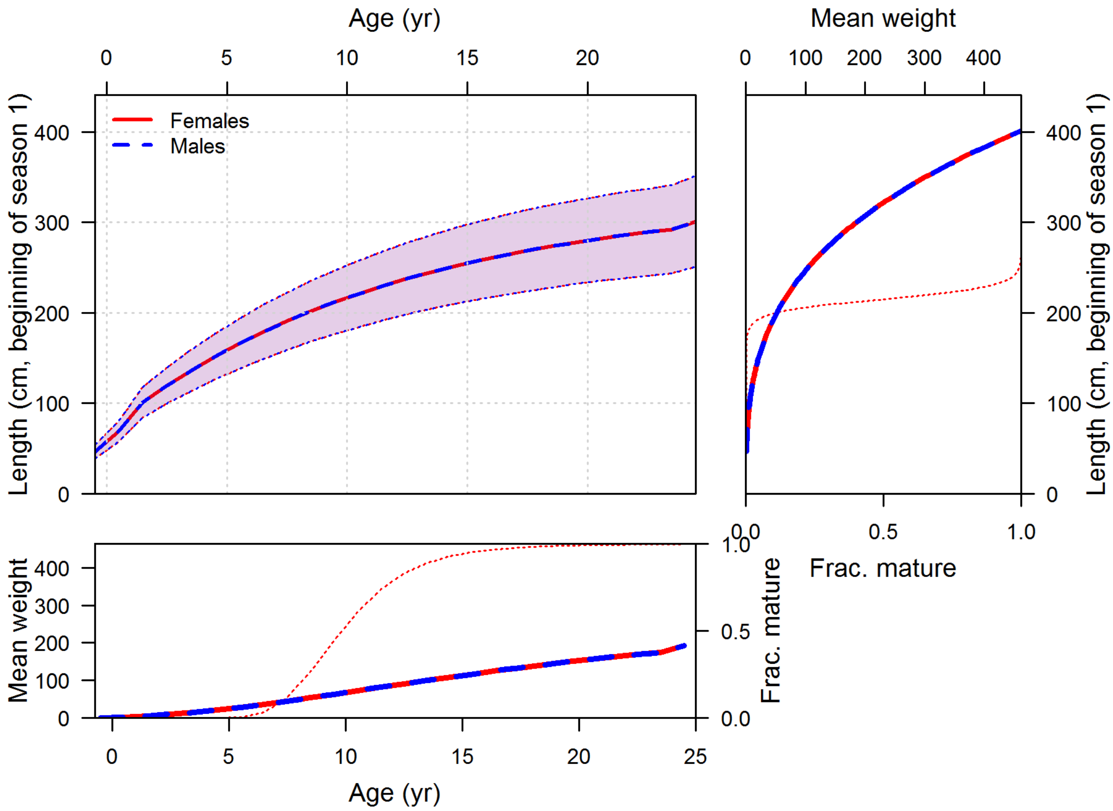


Figure 21. Silky shark growth function.

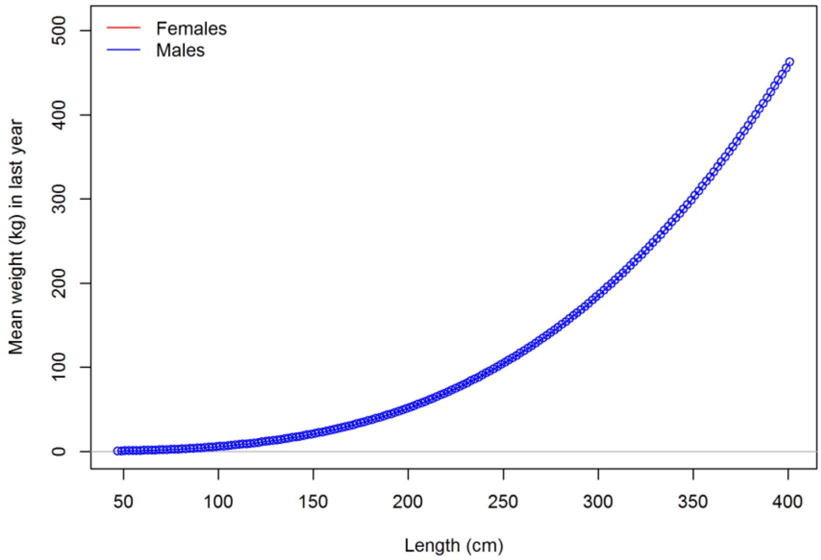


Figure 22. Length-weight relationship (both sexes combined).

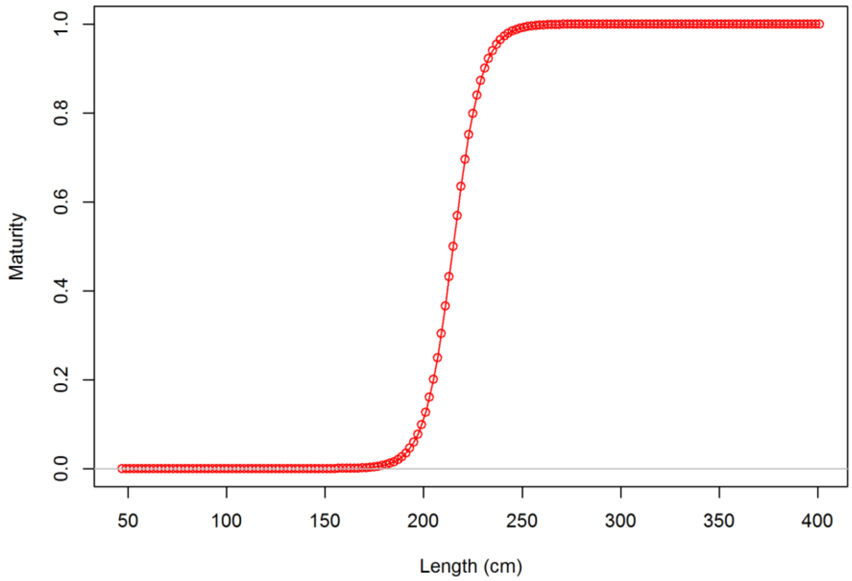


Figure 23. Length based maturity ogive for female silky sharks.

4.2.3 Model structural assumptions

The Pacific-wide model was comprised of two regions: the WCPO and the EPO. The regional structure was based on the approximate administrative boundaries of the WCPFC and IATTC and the configuration of the available catch statistics.

The assessment model was consistent with the initial year (1995) of the previous WCPO assessment model (Rice & Harley 2013). The initial population age structure (in 1995) is assumed to be in an exploited state and initial fishing mortality rates were estimated for the main fisheries operating at that time. The population was structured by sex and included 25 age classes, the oldest age class representing an aggregated "plus" group (25 years and older). The model population was structured into 2 cm TL bins with a minimum length of 46 cm, corresponding to the smallest sharks sampled from the commercial fisheries (however note that this is smaller than the assumed length at birth of 63.5 to 75.5 cm TL from Joung et al. 2008).

The model was structured with an annual time-step with four seasons (3 months). Recruitment was distributed evenly amongst the four seasons. Recruitment was distributed equally between the two sexes at birth (proportion females 0.5).

Recruitment is a function of the spawning biomass at the start of the year. Fecundity was based on the mature female biomass. A Beverton-Holt spawning stock-recruitment relationship (SRR) was assumed with steepness (h) fixed at 0.409. This was equivalent to the median value of steepness assumed by Rice & Harley (2013). Deviations from the SRR were not estimated. Recruitment variability is likely to be very low for shark species and the available length composition data do not exhibit strong modal structure that might indicate the presence of strong or weak cohorts in the population. Further, the length composition data from some fisheries may be influenced by changes in the spatial distribution of the sampling coverage (especially the WCPO LL fishery and SP_LL CPUE data sets) and, hence, these data may not adequately represent the trends in the length composition of the population over time.

The overall proportional distribution of recruitment between the two regions was estimated. The proportion of recruitment allocated between the two regions was allowed to vary between years (from 1995 to 2014). This assumption enabled the model to have considerable flexibility to fit differential trends in the main sets of CPUE indices by allowing the population distribution to vary over time (in addition to the movement parameterisation).

Each fishery and CPUE index was associated with a length-specific, sex invariant selectivity function. The length of fish comprising the SP_LL CPUE index were generally the largest fish sampled from the WCPO region and, consequently, a logistic selectivity function was estimated for the CPUE series. Separate double normal selectivity functions were estimated for the WCPO_LL, WCPO_PS_Assoc, WCPO_PS_Unassoc and EPO_PS_Assoc fisheries (Table 5). The selectivity of the EPO_PS_Unassoc fishery was assumed to be equivalent to the WCPO_PS_Unassoc fishery. For the PSOBJ_EPO_Large CPUE indices, selectivity was assumed to be knife-edged at 150 cm (TL) and selectivity was assumed to decline for larger sharks approximating the descending limb estimated for the EPO_PS_Assoc fishery (selectivity declining to approximate zero at about 300 cm TL). The selectivity function for the HWLL CPUE indices was assumed to be equivalent to the WCPO_LL fishery.

No length composition data were available from the EPO_LL fishery to inform the estimation of selectivity parameters. Initial model options assumed a logistic selectivity function for the EPO_LL fishery with 50% selectivity at 150 cm TL. A preliminary assessment of EPO silky shark estimated selectivity functions for the main longline fisheries (IATTC 2014) and those results indicated a domed shaped selectivity was more appropriate for the EPO_LL fishery. The sensitivity of the model results to the EPO_LL selectivity assumptions was investigated (*EPO_LLselect* model option).

The two main sets of CPUE indices (SP_LL and PSOBJ_EPO_Large) were both assigned a CV of 20% based on a qualitative evaluation of preliminary models. This level of precision was intended to allow the two sets of CPUE indices to have considerable influence on the model abundance trends in each region, while also reflecting the considerable inter-annual variation amongst the two sets of CPUE indices. For each CPUE index, catchability (q) was estimated as an uninformative scale parameter.

The three other sets of CPUE indices were included within the model input data, although these data were not included within the likelihood function (lambda 0) and, hence, did not influence the parameter estimation. Nonetheless, the inclusion of these CPUE data sets within the model enabled an evaluation of the consistency between the CPUE trends and the estimated population dynamics.

The length compositions were each assigned a moderate weighting (ESS 10) to ensure the size data were informative in the estimation of the selectivity parameters but have limited influence on the estimation of stock population dynamics (i.e., estimation of overall recruitment parameter $R0$).

Fishing mortality was modelled using a hybrid method that calculates the harvest rate using Pope's approximation then converts it to an approximation of the corresponding fishery specific F (see Methot & Wetzell 2013 for details). The annual catches from each fishery were taken instantaneously halfway through the year. In the base model, fishery catches were assumed to be known without error. Initial fishing mortalities were estimated for three fisheries for which there were significant catches at the start of the time-series (1995) (i.e., WCPO_LL, WCPO_PS_Assoc and EPO_LL). For these fisheries, annual initial, equilibrium catches were set at approximately the level of the 1995 catch.

There is evidence of movement of juvenile silky sharks between the western and eastern areas of the equatorial Pacific, influenced by prevailing oceanographic conditions (Lennert-Cody et al 2017, in press). Reciprocal movements between the two regions were parameterised to estimate movement coefficients for juvenile (2–7 years) and adult (14+ years) sharks; movement coefficients were interpolated for the intermediate age classes (8–13 years). The movement coefficients were parameterised with uninformative priors.

Table 5. Model parameters and priors for the base model.

Component	Parameters	Value, Priors	Notes
Biology	*M*	0.18	Fixed
	VB Growth	*k* = 0.0838 *L1yr* = 91 cm *L12yr* =233.9	Fixed
	CV length-at-age	0.085	Fixed
	Length-weight	*a* = 2.92×10^{-6} *b* = 3.15	Fixed
	Maturity (logistic)	Inflection 215 cm	Fixed
		Slope -0.138	
Recruitment	Ln*R0*	Uniform[3-15]	Estimated (1)
	B-H SRR steepness *h*	0.409	Fixed
	Regional recruitment	Norm(0.5,0.2)	Estimated (1)
	SigmaR *6R*	-	-
	Recruitment deviates	-	-
	Regional recruitment deviates		Estimated (20)
Movement	WCPO > EPO juvenile	Norm(0.44,0.4)	Estimated (4)
	WCPO > EPO adult	Norm(0.44,0.4)	
	EPO > WCPO juvenile	Norm(0.44,0.4)	
	EPO > WCPO adult	Norm(0.44,0.4)	
	Enviro link		Estimated (2,4)
Initial fishing mortality	WCPO_LL	Norm(0.1,0.2)	Estimated
	WCPO_PS_Assoc	Norm(0.05,0.2)	Estimated
	WCPO_PS_Unassoc	0	Fixed
	EPO_PS_Assoc	0	Fixed
	EPO_PS_Unassoc	0	Fixed
	EPO_LL	Norm(0.1,0.2)	Estimated
Selectivity			
WCPO_LL	Double Normal p1 – length at peak p2 – width of peak p3 – width of ascending limb p4 – width of descending limb p6 – selectivity at max length	 Norm(150,10) Norm (5,3) Norm(7,3) Fixed(10) Norm(0,5)	Estimated (4)
WCPO_PS_Assoc	Double Normal		Estimated (5)
	p1 – length at peak p2 – width of peak p3 – width of ascending limb p4 – width of descending limb p6 – selectivity at max length	Norm(95,5) Norm (5,3) Norm(6,3) Norm(7,3) Norm(-10,2)	
WCPO_PS_Unassoc	Double Normal		Estimated (5)
	p1 – length at peak p2 – width of peak p3 – width of ascending limb p4 – width of descending limb p6 – selectivity at max length	Norm(120,5) Norm(5,5) Norm(20,10) Norm(20,10) Norm(0,2)	
EPO_LL	Logistic parameterisation p1 – length at inflection p2 – width for 95% selection	 150 10	Fixed

Component	Parameters	Value, Priors	Notes
EPO_PS_Assoc	Double Normal		Estimated (4)
	p1 – length at peak p2 – width of peak p3 – width of ascending limb p4 – width of descending limb p6 – selectivity at max length	Norm(100,5) Fixed (-5) Norm(7,5) Norm(10,5) Norm(-10,2)	
SP_LL CPUE	Logistic parameterisation p1 – length at inflection p2 – width for 95% selection	 Norm(110,10) Norm(25,5)	Estimated (2)
PSOBJ_EPO_Large CPUE	Double normal p1 – length at peak p2 – width of peak p3 – width of ascending limb p4 – width of descending limb p6 – selectivity at max length	 Fixed (150) Fixed (-10) Fixed (-15) Fixed(8.5) Fixed(-10)	Fixed

The availability of smaller silky sharks in the EPO purse seine fishery fluctuates relative to the prevailing oceanographic conditions (Lennert-Cody et al. 2017, in press). Oceanographic conditions may be influential in the eastward and westward movements of silky sharks. Thus, a range of model options were configured to include environmental indices as a covariate to incorporate inter-annual variability in the estimation of movements between the two regions. The potential indices included the TNI, Niño3.4, and Niño1.2 indices parameterised with a range of different lags. The environmental covariates were included for reciprocal movements (WCPO to EPO *and* EPO to WCPO) or applied to a single direction (WCPO to EPO *or* EPO to WCPO).

There are three main components to the model likelihood objective function:

i. CPUE indices - the fit to the CPUE indices assuming a lognormal error structure;
ii. Length composition data set - the fit to the length composition data assuming a multinomial error structure; and
iii. Parameter priors - deviation of estimated parameter(s) from assumed prior distribution(s).

The formulation of the individual likelihood components is documented in Methot & Wetzell (2013). The estimation procedure minimises the negative log-likelihood of the objective function. The modelling framework was applied to evaluate the consistency between the various input data sets, particularly comparing the key sets of CPUE indices from each model region. A range of different scenarios were evaluated, especially related to regional structure, movement dynamics and initial conditions.

5 Model Results

The model development phase focused on the regional structure and the parameterisation of movement between the two regions. The performance of the models was appraised based on the fit to the two principal sets of CPUE indices (WCPO _LL and PSOBJ_EPO_Large). An initial model was configured with no movement between the two regions. The *NoMove* model provided a reasonable fit to the PSOBJ_EPO_Large CPUE indices, although the fit to the WCPO_LL CPUE indices was poor. The fit to the PSOBJ_EPO_Large CPUE indices was achieved via a strong temporal trend in the proportion of the overall recruitment allocated to the EPO region (via the estimated regional recruitment deviates).

The second step in the model development was to estimate movement between the two regions, without associated environmental covariates (*MoveNoEnviro*). The model resulted in an improvement in the total likelihood with an improvement in the fit to the length composition data sets, although there was a marked deterioration in the fit to the PSOBJ_EPO_Large CPUE indices. The improvement in the fit to the length composition data was attributable to a minor improvement in the fit to the WCPO _LL and SP_LL CPUE data sets. The fits to both sets of CPUE indices from the *MoveNoEnviro* model revealed trends in the residuals that are correlated with available environmental variables (Figure 24); the residuals from the SP_LL CPUE indices are negatively correlated with the Niño3.4 Index (1 year lag) (corr. coef. -0.60), while the residuals from the PSOBJ_EPO_Large CPUE indices are positively correlated with the Trans-Niño Index (1 year lag) (corr. coef 0.49).

The residual patterns informed the range of potential environmental covariates considered for inclusion in the parameterisation of movement. Most of the options considered the covariates to be incorporated in the estimation of movement from a single direction (from WCPO to EPO, *MoveEPO*; from EPO to WCPO, *MoveWCPO*), while the counter movement was estimated without an environmental covariate. Trials conducted using environmental covariates with both sets of movement parameters did not appreciably influence the results. A range of lag periods in the environmental index were also evaluated.

Overall, the model options with the best fit to the PSOBJ_EPO_Large CPUE indices included the TNI in the parameterisation of movement (Table 6). A reasonable fit to the WCPO_LL CPUE indices was obtained for a single model option that incorporated the Niño3.4 index in the estimation of movement from EPO to WCPO (Table 6 and also Figure 28). For the range of model options, there was a negative correlation between the likelihoods from the two sets of CPUE indices, indicating a conflict between the indices despite the range of environmental coefficients included in the movement parameterization (Table 6). This could relate to the assumptions regarding the selectivities of the respective CPUE indices (Figure 25). In addition, there is a deterioration in the fit to the length composition data (primarily from the WCPO) with an improvement in fit to the PSOBJ_EPO_Large CPUE indices, indicating that these data sets are also somewhat contradictory.

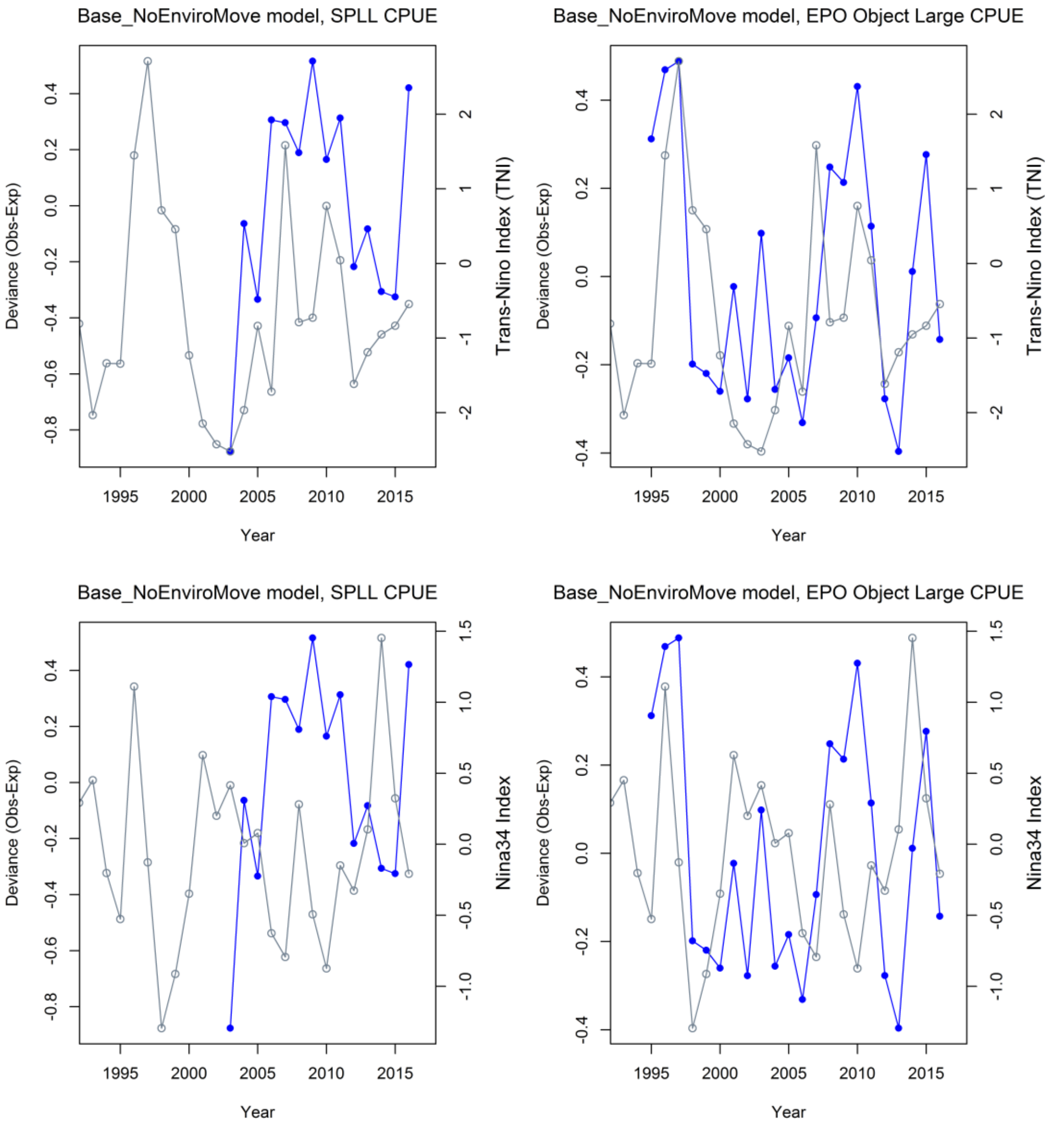


Figure 24. A comparison of the deviations from the fit to the SP_LL CPUE indices (left panels) and the PSOBJ_EPO_Large CPUE indices (right panels) (blue lines) with the annual average TNI (top panels) and Niño3.4 index (bottom panels) (grey lines).

Table 6. Model log likelihoods for selected model runs investigating different movement parameterisations. The likelihood values in italics were not included in the total likelihoods (i.e. lambda 0).

Name	Movement WCPO to EPO	Movement EPO to WCPO	Likelihood component					CPUE likelihoods		
			LF	Survey	Total	SP_LL	HWLL	WCPO PSasso	WCPO PSuna	EPOOBJ
NoMove	No movement	No movement	294.54	-18.96	285.28	1.98	*163.88*	*-3.85*	*10.10*	-20.94
MoveNoEnviro	no enviro covar	no enviro covar	282.86	-13.25	279.52	1.51	*167.59*	*-4.00*	*9.70*	-14.76
MoveEPOTNI1_ WCPONino341	TNI, lag -1 year	Nino34, lag -1 year	280.43	-13.72	278.04	-1.55	*168.54*	*-3.65*	*11.96*	-12.17
MoveEPOTNI1	TNI, lag -1 year	no enviro covar	282.16	-13.31	279.07	0.55	*168.16*	*-3.98*	*9.96*	-13.86
MoveEPOTNI2	TNI, lag -2 year	no enviro covar	285.14	-15.96	278.19	2.28	*164.60*	*-4.30*	*9.35*	-18.24
MoveEPOTNI	TNI no lag	no enviro covar	282.80	-14.60	278.50	0.92	*165.53*	*-3.98*	*10.30*	-15.52
MoveEPOTNI_ WCPOTNI1	TNI no lag	TNI, lag -1 year	288.20	-19.96	279.41	1.73	*166.19*	*-2.68*	*10.57*	-21.69
MoveEPONino34x1	Nino34, lag +1 year	no enviro covar	282.71	-13.17	279.62	1.54	*167.07*	*-4.00*	*9.81*	-14.71
MoveEPONino34	Nino34, no lag	no enviro covar	282.64	-13.76	279.19	1.22	*166.15*	*-4.03*	*10.15*	-14.97
MoveEPONino341	Nino34, lag -1 year	no enviro covar	283.89	-15.86	278.48	0.49	*165.73*	*-4.09*	*10.75*	-16.35
MoveEPONino342	Nino34, lag -2 year	no enviro covar	282.22	-14.74	277.78	-1.56	*171.58*	*-4.01*	*11.96*	-13.18
MoveWCPOTNI	no enviro covar	TNI no lag	286.64	-21.02	276.49	2.69	*164.86*	*-3.43*	*11.03*	-23.72
MoveWCPOTNI1	no enviro covar	TNI, lag -1 year	284.45	-15.84	279.15	1.58	*166.70*	*-4.15*	*10.31*	-17.42
MoveWCPOTNI2	no enviro covar	TNI, lag -2 year	282.01	-16.21	274.90	3.30	*168.95*	*-3.68*	*8.37*	-19.51
MoveWCPONino34	no enviro covar	Nino34, no lag	280.91	-13.31	278.59	0.20	*172.84*	*-4.40*	*9.37*	-13.51
MoveWCPONino341	no enviro covar	Nino34, lag -1 year	289.27	-16.49	283.11	-10.27	*175.45*	*1.14*	*22.29*	-6.22
MoveWCPONino342	no enviro covar	Nino34, lag -2 year	279.63	-16.89	273.73	-2.48	*166.49*	*-4.37*	*12.24*	-14.41

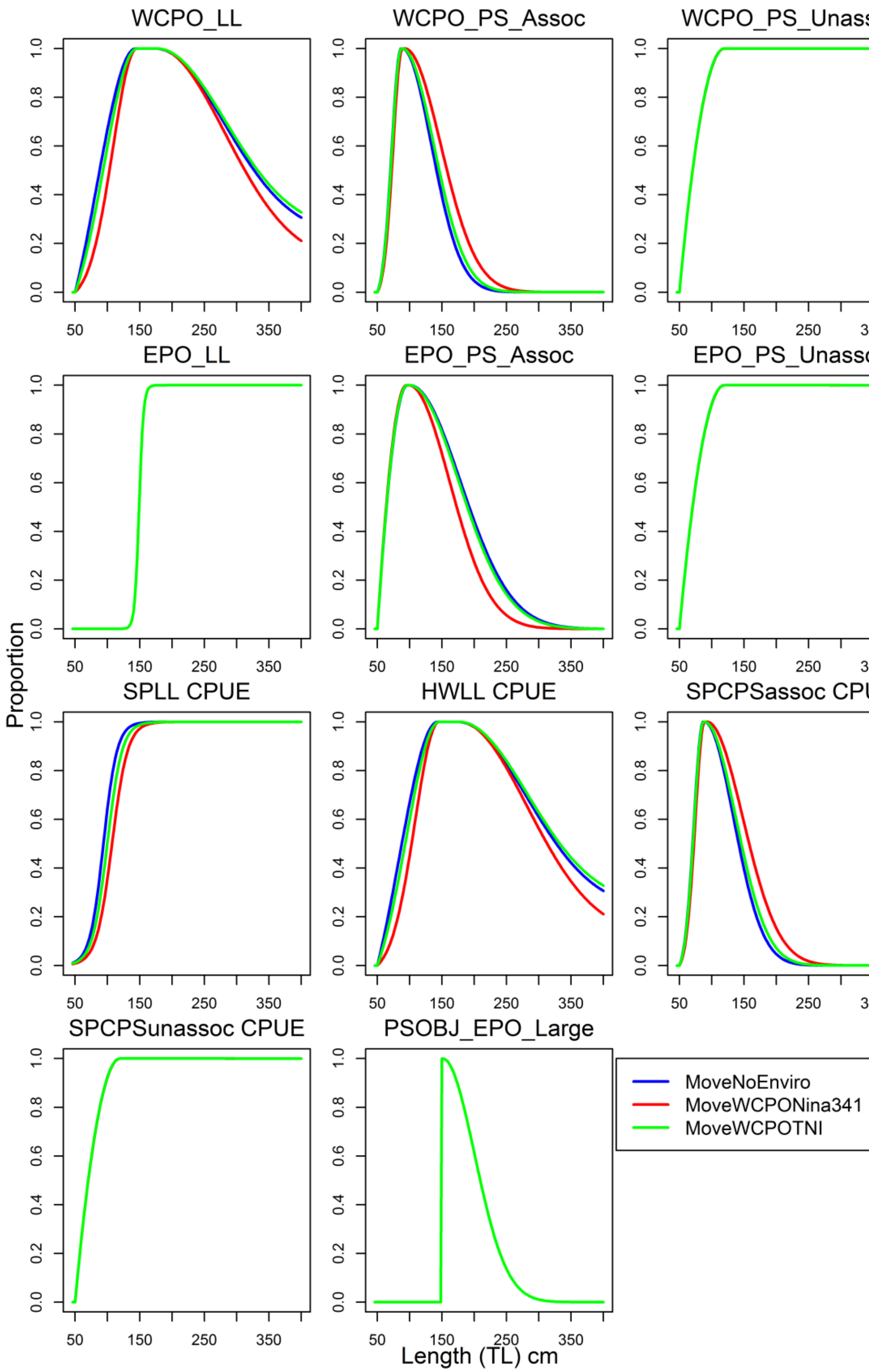


Figure 25: Selectivity functions for the fisheries and CPUE indices included in the three selected model options.

From the initial modelling results, no single model could be identified as a preferred model option. Instead, the results from three model options are compared to construct a range of the results: the baseline *MoveNoEnviro* model and the two models that provide the best individual fits to the WCPO_LL and PSOBJ_EPO_Large CPUE indices (*MoveWCPONino341* and *MoveWCPOTNI*, respectively).

The estimated selectivity functions are very similar for the three model options. For the WCPO_LL fishery, 50% selectivity was estimated at about 95 cm TL with full selectivity at about 120 cm TL and a declining selectivity for larger sharks (Figure 25). The selectivity for the WCPO_LL is considerably lower than assumed for the EPO_LL fishery (50% selectivity at 150 cm TL).

The selectivity of the WCPO_PS_Assoc fishery is dome-shaped with a peak selectivity at about 95 cm TL. The EPO_PS_Assoc fishery has a similar peak selectivity (100 cm TL) although the tail of the selectivity function is considerably broader, extending to about 300 cm TL (Figure 25). The unassociated purse seine fisheries are estimated to have a broad selection range.

The three model options assign a considerably different proportion of the overall recruitment to the WCPO region (relative to the EPO) (Figure 26). A lower proportion of the recruitment is allocated to the region that has the best fit to the relevant CPUE index; i.e., a good fit to the EPO CPUE index corresponds to a high overall proportion of recruitment to the WCPO (*MoveWCPOTNI*), while a good fit to the WCPO CPUE index corresponds to a high overall proportion of recruitment to the EPO (*MoveWCPONino341*). This suggests that the model can fit the trends in the CPUE indices better when the biomass in the respective region is lower. There are also strong temporal trends in the proportion of recruitment allocated to each region which differ between the three model options (Figure 26).

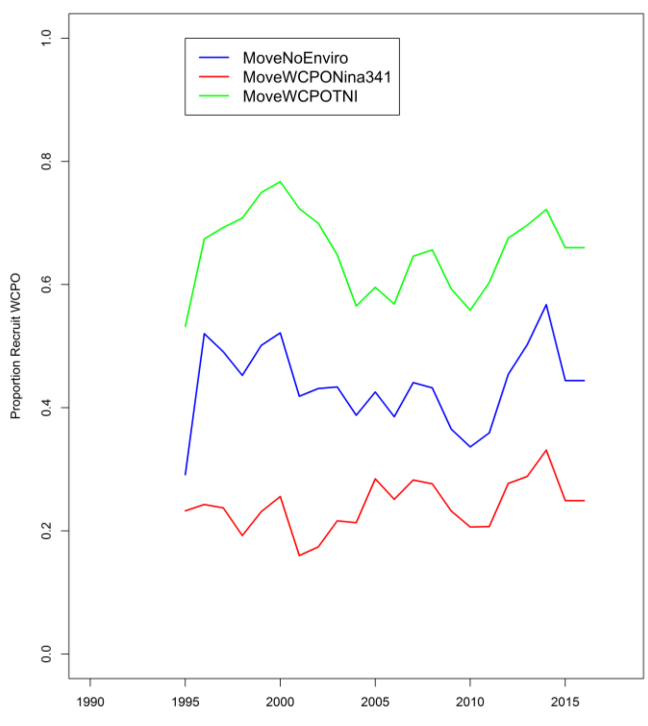


Figure 26. Estimated proportion of annual recruitment allocated to the WCPO region for the three comparative model options.

The three model options estimate very high rates of movement of adult sharks from WCPO to EPO regions, although the movement rates of juvenile sharks differ considerably between the *MoveWCPONino341* model (high) and the other two model options (negligible) (Figure 27). Estimated movement rates from the EPO tend to be relatively high and are strongly correlated with the respective environmental index.

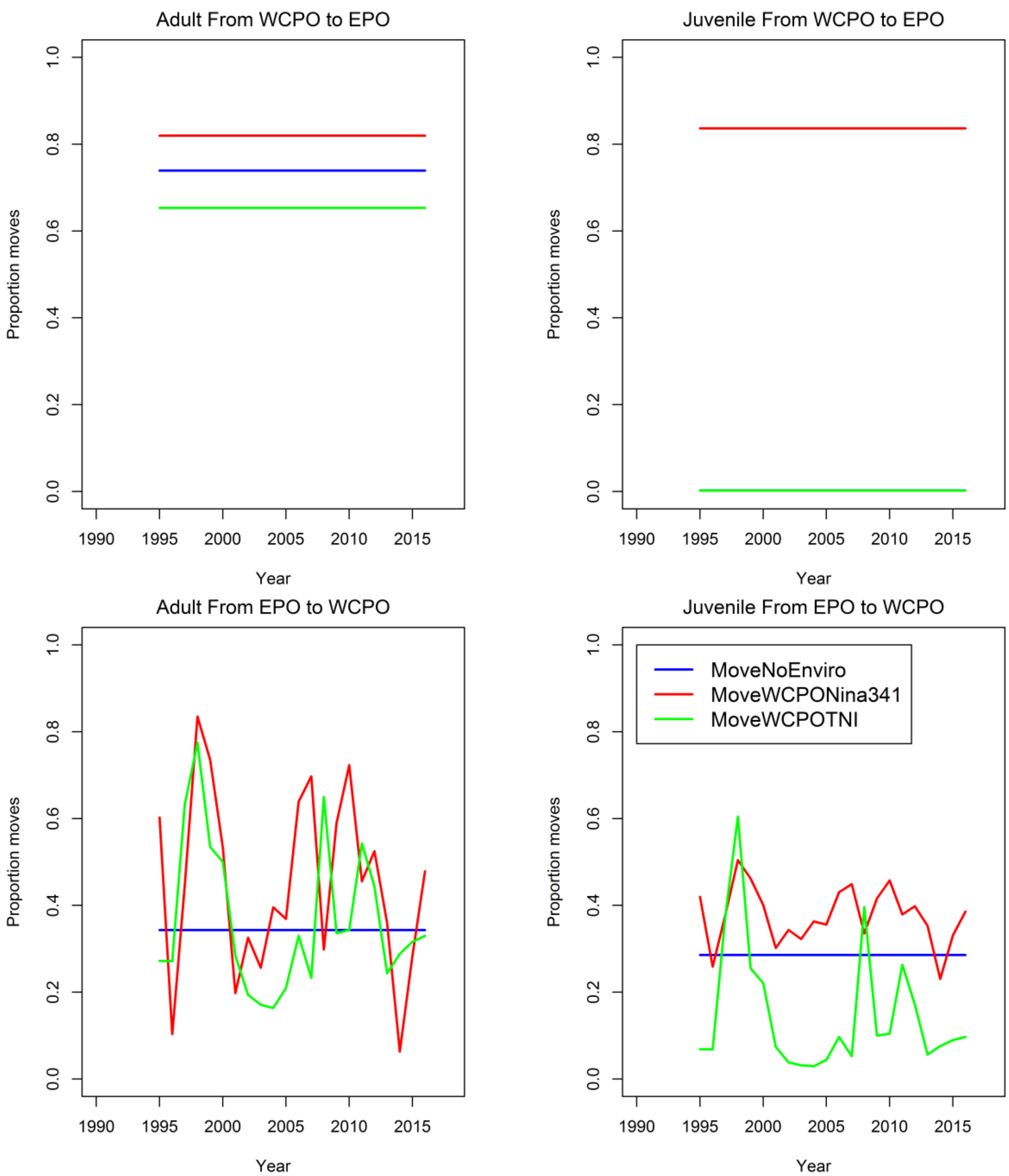


Figure 27. Estimated annual movement rates of juveniles (right panels) and adults (left panels) from WCPO (top panels) and from EPO (lower panels).

The net effect of the recruitment distribution and movement dynamics gives the model considerable flexibility to fit one or other of the sets of CPUE indices. However, the models are unable to simultaneously fit the two sets of CPUE indices (Figure 28Figure 28.). The fit to the secondary CPUE index is poor in both cases: the *MoveWCPOTNI* model option resulted in reasonable fits to the PSOBJ_EPO_Large CPUE indices and very poor fits to the WCPO_LL CPUE indices (similar to *MoveNoEnviro*), while the model options that incorporated Niño34 in the movement parameterisation resulted in a poor fit to the PSOBJ_EPO_Large CPUE indices and a moderate fit to the WCPO_LL CPUE indices.

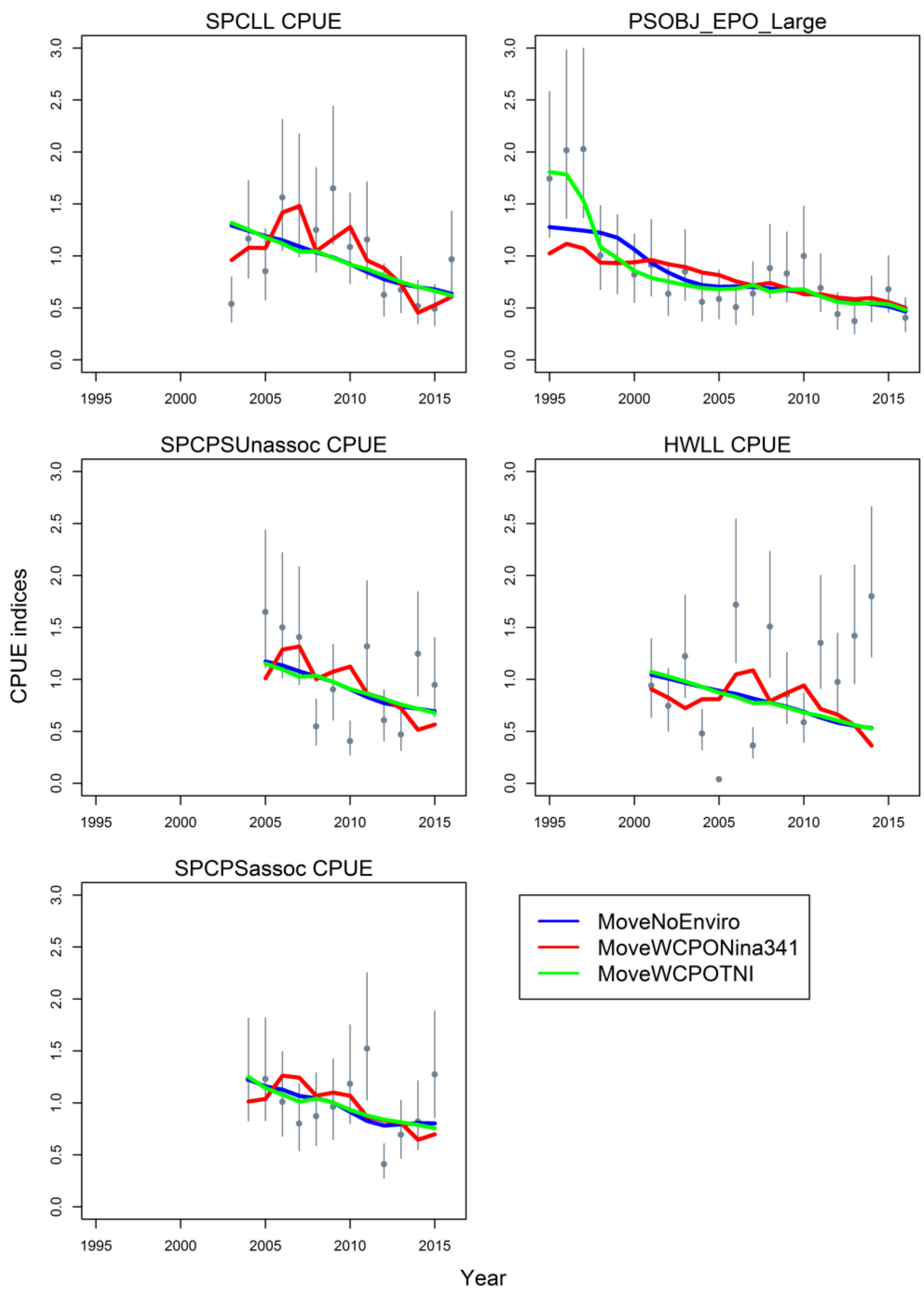


Figure 28. A comparison of the five sets of CPUE indices (points) and the corresponding trends in specific vulnerable biomass (in numbers) for the base model. Only the WCPO_LL and PSOBJ_EPO_Large indices are included in the model likelihood. The other two sets of indices are presented for comparative purposes. The confidence intervals represent 95% confidence intervals (assumed CV 20%).

Nonetheless, in both cases, residual patterns remained in the fits to the primary CPUE index indicating the models were unable to fully account for the variation in the observed CPUE (Figure 28).

The three model options estimated trends in stock abundance that were inconsistent with the three other sets of CPUE indices (HWLL, WCPOPSassoc and WCPOPSUnassoc). This indicates that the trends in CPUE from these three fisheries are inconsistent with the CPUE trends from both the SP_LL and the PS_Object_Large CPUE indices (Figure 28). The discrepancy is particularly pronounced for the HWLL CPUE indices (Figure 28). The indices fluctuate considerably inter-annually and are positively correlated (correlation coefficient 0.714) with the Niño3.4 index from the preceding year. The fluctuations in the CPUE indices also tended to precede the fluctuations in the EPO CPUE indices for small and medium sharks in the area adjacent to the HWLL fishery (Area 2 from Lennert-Cody et al. (2017, in press)).

The three models options provided a reasonable fit to the aggregated length composition data from the WCPO_LL fishery (Figure 29). However, there was a systematic lack of fit to the length composition data from the EPO Associated purse seine fishery for lengths less than 150 cm. This may be due to a conflict with the PSOBJ_EPO_Large CPUE indices which are derived for fish greater than 150 cm. The models also consistently over-estimate the length of fish caught by the WCPO_PS_Assoc fishery.

For each of the length composition data sets, there are strong temporal trends in the average size of fish sampled. These trends are not adequately accounted for by the models which have limited flexibility to account for variation in fish size (via age specific movement parameters and regional recruitment deviates) (Figure 30).

Down-weighting the length composition data did not resolve the conflict between the two primary sets of CPUE indices, although there was a considerable improvement in the fit to the PSOBJ_EPO_Large CPUE indices (relative to the *MoveNoEnviro* model) with a corresponding deterioration in the fit to the length data from the EPO_PS_Assoc fishery. Similarly, increasing the weighting assigned to the length composition data resulted in a considerable deterioration in the fit to the PSOBJ_EPO_Large CPUE indices.

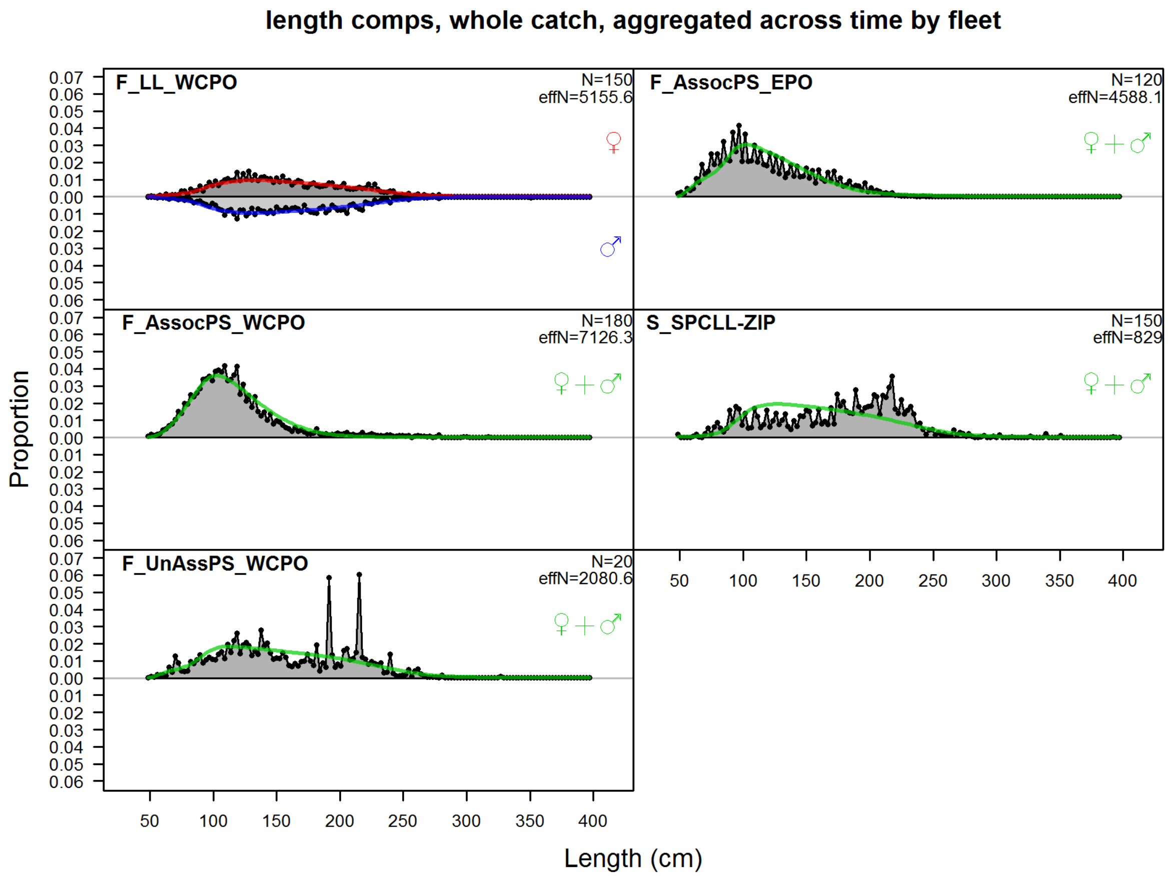


Figure 29. Observed (points) and predicted (line) proportions at length for the aggregated fishery length compositions from the base model (MoveNoEnviro).

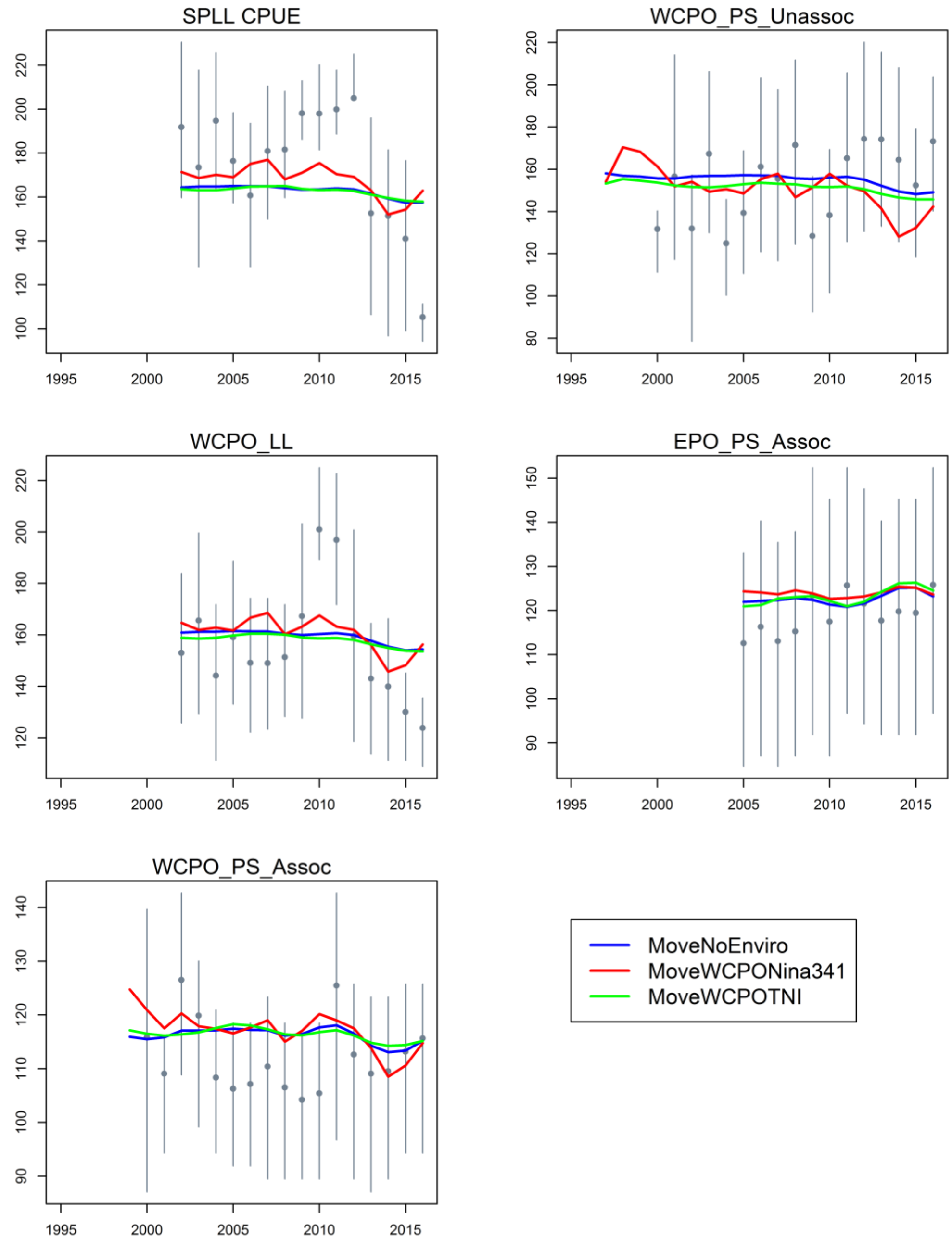


Figure 30. Comparison of the annual average length and interquartile range from the length compositions (grey points and segments) and the predicted average length from the three model options.

The three model options estimate substantially different levels of recruitment and total biomass between the two regions depending on the CPUE scenario (Figures . 1 and 32). As noted previously, the best fit to each of the primary CPUE indices was achieved when the level of biomass in the specific region (corresponding to the CPUE index) was low.

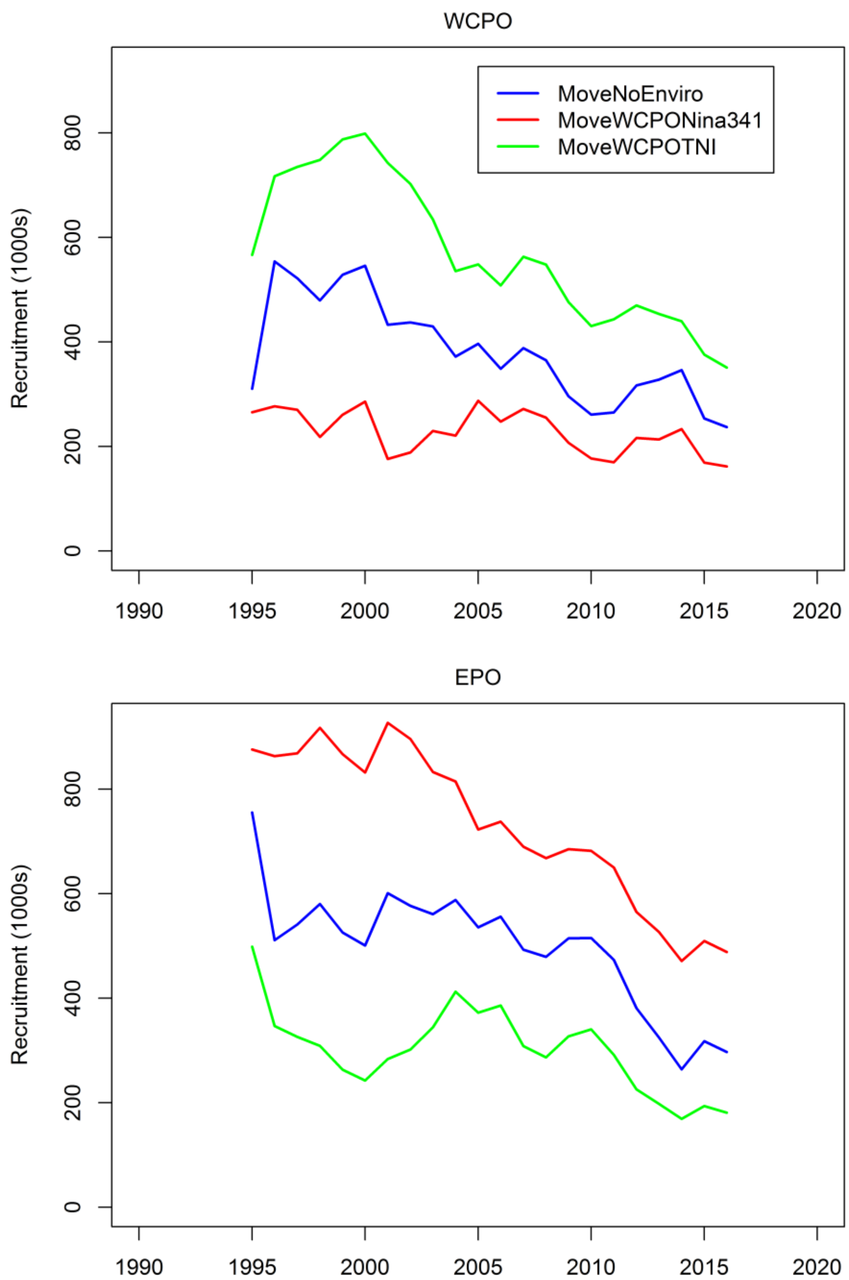


Figure 31. Annual recruitment for WCPO region (top) and EPO region (bottom) for the three model options.

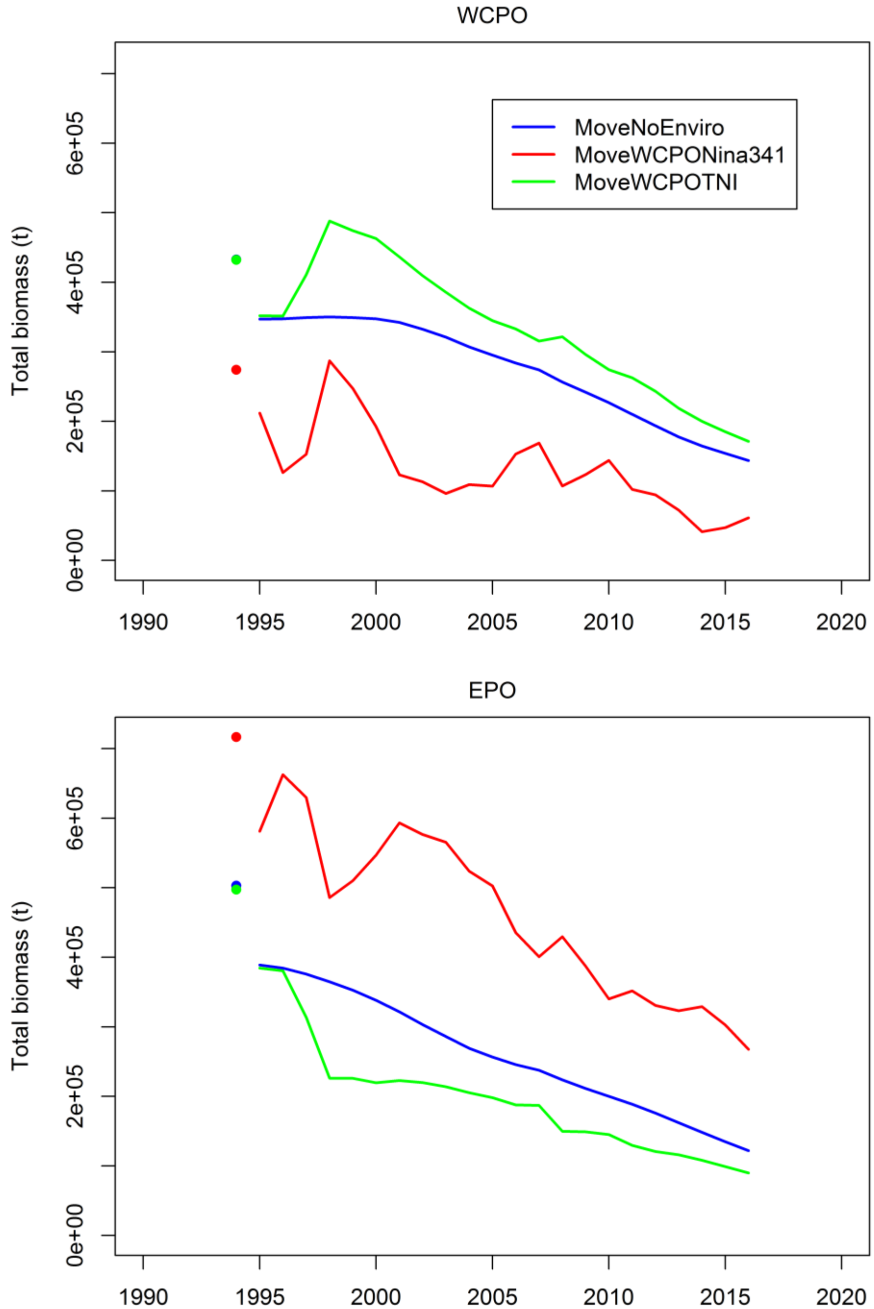


Figure 32. Annual total biomass for WCPO region (top) and EPO region (bottom) for the three model options. The points denote the virgin biomass level.

The total spawning biomass was comparable for the three model options (Figure 33). The initial (1995) biomass level was estimated at approximately 70% of the virgin biomass. The magnitude of the decline in biomass over the model period is related to the level of catch and the productivity of the stock (including the SRR) mediated by the two sets of CPUE indices. Given the high estimated mixing rates, the three model options yield very similar trends in stock biomass.

Recruitment is a direct function of the spawning biomass, given the assumed level of steepness of the SRR (Figure 34Figure 34.). Recruitment is predicted to have declined by about 50% over the model period, following the decline in spawning biomass. The stock recruitment relationship is based on a relatively low value of steepness (0.401) reflecting the low productivity of shark species. A model option that estimated the steepness parameter (without constraint) estimated a slightly lower value (h = 0.334) than assumed, although there was no appreciable change in the total likelihood of the model.

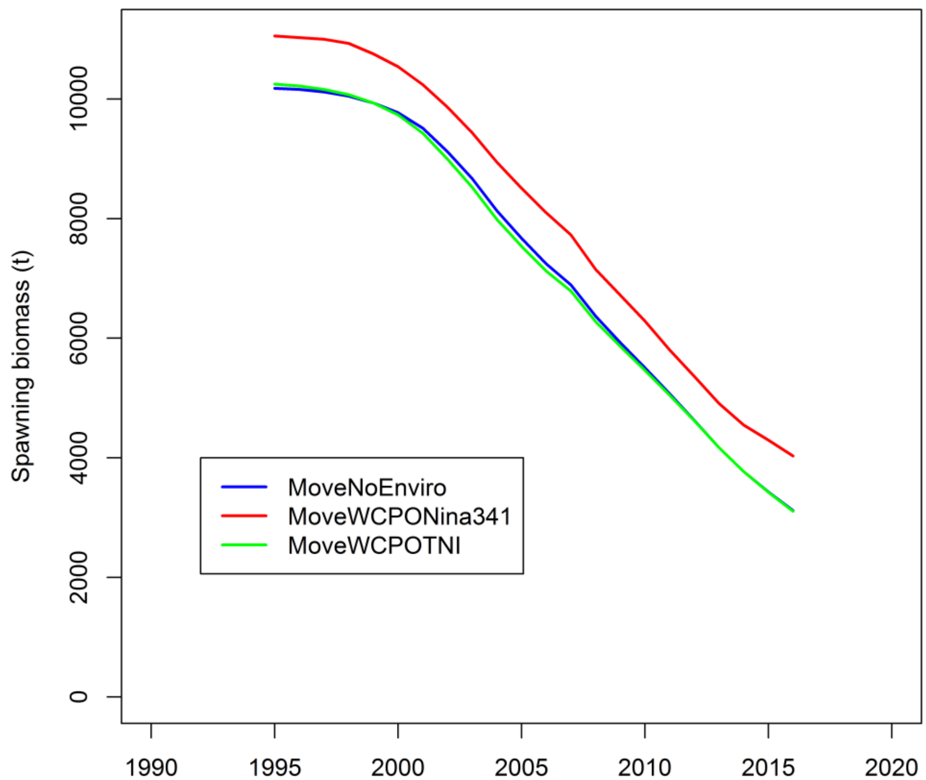


Figure 33. Annual spawning biomass for the Pacific Ocean (WCPO and EPO regions combined) for the three model options.

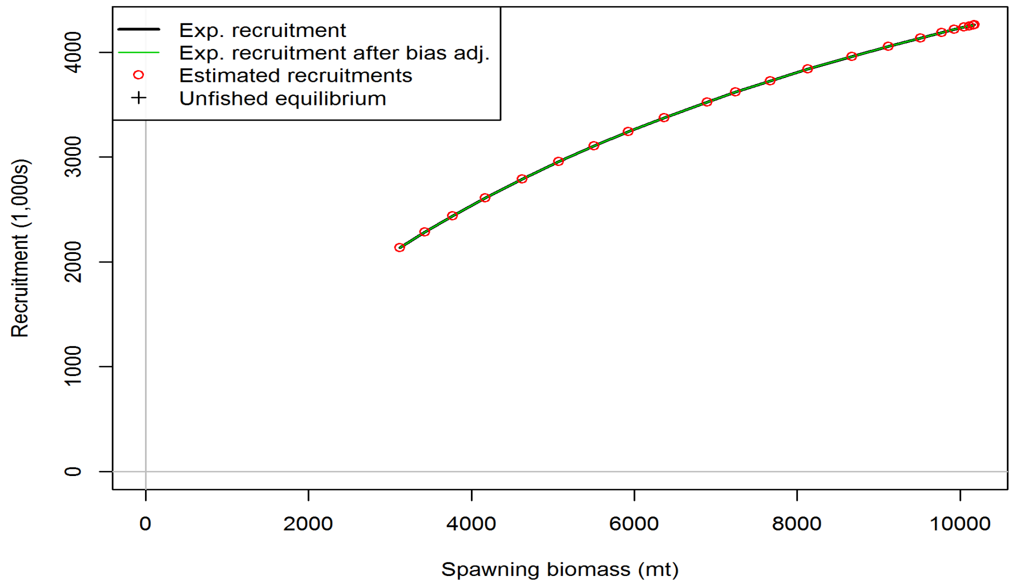


Figure 34. The stock-recruitment relationship from the MoveNoEnviro model.

The influence of the two sets of CPUE indices was examined by excluding each index from the model likelihood (relative to the *MoveNoEnviro* model). The model estimated substantially higher levels of depletion for the model option that retained the PSOBJ_EPO_Large CPUE indices (*CPUEexWCPO*) compared to the model option that retained the SP_LL CPUE indices (*CPUEexEPO*) (Figure 35Figure 35.). Neither model option provided a good fit to the respective CPUE series.

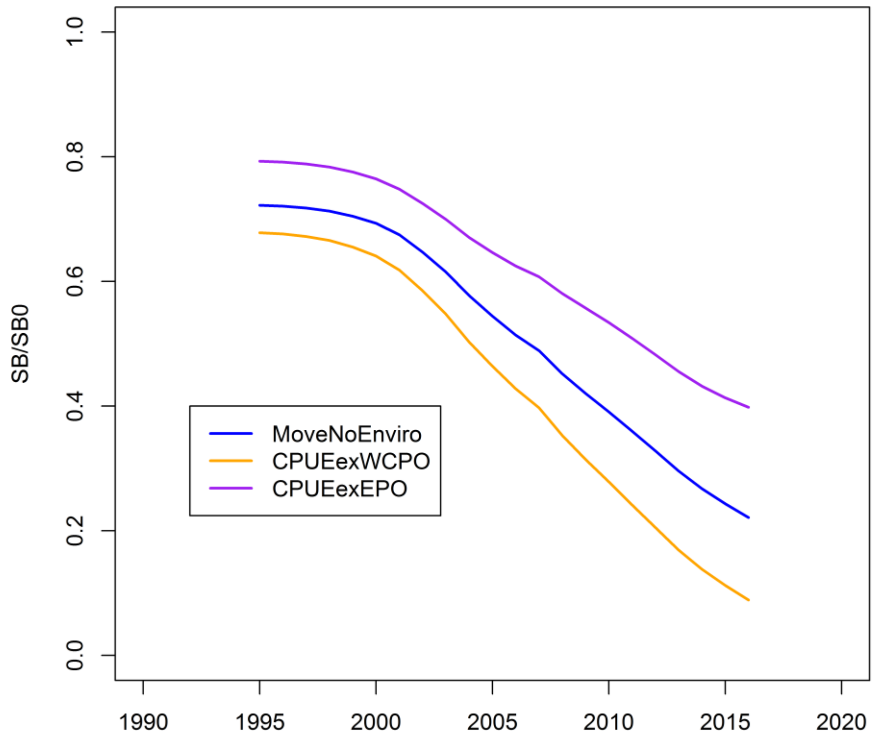


Figure 35. Comparison of the spawning biomass (relative to virgin spawning biomass) for model options that excluded the PSOBJ_EPO_Large CPUE indices (CPUEexEPO) compared to the model option that excluded the SP_LL CPUE indices (CPUEexWCPO).

A range of additional model options were investigated to explore the influence of the various data sets (Table 7). For comparative purposes, these model options were configured as changes from a single, base model *MoveNoEnviro*. The base model was selected as it did not exhibit the more extreme stock dynamics evident from the two options that included environmental covariates in the movement dynamics.

Table 7. Description of the model options, relative to the base model MoveNoEnviro.

Model option	**Description (from base model)**	**Rationale**
MoveNoEnviro	Base model for comparison, as described above.	
LFdownWt	Decrease weighting on length composition data (ESS 1) and relax selectivity assumptions.	Evaluate influence of LF data sets.
LFupWt	Increase weighting on length composition data (ESS 50).	Evaluate influence of LF data sets.
CPUEexWCPO	Exclude WCPO_LL CPUE indices from likelihood.	Evaluate relative influence of EPO and WCPO CPUE indices.
CPUEexEPO	Exclude PSOBJ_EPO_Large CPUE indices from likelihood.	Evaluate relative influence of EPO and WCPO CPUE indices.
SteepnessEst	Estimate steepness parameter of SRR.	
EPO_PScatch	Reduce total EPO PS catches to approximately 400 t per annum based on catch statistics from 2000-2010.	More consistent with available EPO catch estimates. Catches in base model options are too high.
EPO_LLselect	Double normal selectivity for the EPO LL fishery. Selectivity equivalent to the WCPO_LL fishery.	More consistent with the EPO LL selectivity estimated in the IATTC preliminary assessment.
ThreeRegion	Partition WCPO region into equatorial region and SW Pacific region. Fit to PS_Unassoc CPUE in WCPO equatorial region; WCPO_LL CPUE in SW region. All WCPO catch allocated to WCPO equatorial region. Movement between two WCPO regions and between EPO and equatorial WCPO.	Evaluation of an alternative regional structure.

For the *EPO_PScatch* model, the EPO catch history was amended to include the best available catch estimates for the EPO purse seine fisheries and reallocate the total EPO catch estimates between the fisheries, accordingly. There was no appreciable change in the fit to the key CPUE indices from the base model (Table 8).

Table 8. Model log likelihoods for the range of model options. The likelihood values in italics were not included in the total likelihoods (i.e. lambda 0).

Model option	Likelihood component			CPUE likelihoods				
	LF	Survey	Total	SP_LL	HWLL	WCPO PSass	WCPO PSuna	EPOOBJ
MoveNoEnviro	282.9	-13.25	279.5	1.51	*167.59*	*-4.00*	*9.70*	-14.76
MoveWCPOTNI	286.6	-21.02	276.5	2.69	*164.86*	*-3.43*	*11.03*	-23.72
MoveWCPONino341	289.3	-16.49	283.1	-10.27	*175.45*	*1.14*	*22.29*	-6.22
CPUEexEPO	276.3	-1.28	286.5	-1.28	*171.05*	*-4.04*	*7.85*	*4.08*
CPUEexWCPO	278.3	-14.69	274.9	*37.16*	*239.85*	*10.63*	*24.56*	-14.69
EPO_PScatch	283.3	-12.72	280.7	1.29	*166.85*	*-3.93*	*9.89*	-14.01
EPO_LLselect	282.9	-13.1	279.7	1.41	*169.37*	*-4.16*	*9.58*	-14.52
LFdownwt	52.5	-24.01	37.9	1.79	*157.65*	*-4.40*	*10.77*	-25.80
LFupwt	1244.3	1.51	1273.7	3.23	*184.04*	*-3.03*	*5.77*	-1.72
SteepnessEst	281.7	-12.61	279.4	1.60	*168.52*	*-3.72*	*9.70*	-14.22
ThreeRegion	288.2	-8.63	297.9	-2.65	*181.54*	*-3.79*	5.76	-11.75

The base model option assumed that the EPO_LL fishery had a logistic selectivity (i.e., large sharks were assumed to be fully selected by this fishery). Length composition data were available from the WCPO_LL fishery and the resulting estimates of selectivity indicated that the larger sharks were less vulnerable to the fishery. On that basis, an additional model option was configured with the selectivity of the EPO_LL fishery set to be equivalent to the WCPO_LL fishery (*EPO_LLselect*). Again, there was no appreciable change in the fit to the key CPUE indices from the base model (Table 8).

The configuration of the various datasets meant that there was limited potential to explore alternative spatial structures in the modelling framework. A trial model option was configured that partitioned the WCPO region into two separate regions: an equatorial region that included the two purse seine fisheries and the WCPO_LL fishery and a southern area that included the SP_LL CPUE indices only (*ThreeRegion*). No attempt was made to apportion the WCPO_LL catch between the two regions. Movement was estimated between the two WCPO regions. However, movement between the WCPO and EPO was configured to occur via the WCPO equatorial region only. Trends in abundance in the equatorial WCPO region were mediated by the WCPO_PSUnass CPUE indices. The fit to these CPUE indices was poor, while there was a slight deterioration in the fit to the CPUE indices from the EPO (Table 8). Additional model options that included both environmental covariates in the movement configuration of the *ThreeRegion* model did not appreciably improve the fit to the individual sets of CPUE indices.

Comparative estimates of biomass, depletion and *MSY* yields from the range of model options are presented in Table 9. None of these model options is considered sufficiently robust to provide reliable estimates of the stock status of silky sharks. Instead, the range of model options provide an indication of the influence of the various modelled data sets. For comparison with estimates of *MSY* yields, levels of current catch included in the model are about 38,000 t.

Table 9. Comparisons of model estimates of virgin biomass (SB_0 in tonnes), Maximum Sustainable Yield (MSY in tonnes), current (2016) biomass (relative to SB_0) and current (2016) fishing mortality relative to F_{MSY}. Standard errors are provided in brackets for selected options.

Model option	SB_0	MSY	SB_{2016}/SB_0	F_{2016}/F_{MSY}
MoveNoEnviro	14,096 (s.e. 851)	16,504 (s.e. 1193)	0.221 (s.e. 0.043)	4.01 (s.e. 0.71)
MoveWCPOTNI	14,005 (s.e. 942)	16,801 (s.e. 1544)	0.222 (s.e. 0.046)	4.15 (s.e. 0.83)
MoveWCPONino341	14,928 (s.e. 918)	17,031 (s.e. 1096)	0.270 (s.e. 0.044)	3.33 (s.e. 0.55)
CPUEexEPO	18,403	20,379	0.398	2.02
CPUEexWCPO	11,836	12,976	0.089	8.12
EPO_PScatch	13,346	15,666	0.222	3.95
EPO_LLselect	12,584	12,825	0.248	3.80
LFdownwt	14,591	16,196	0.315	2.99
LFupwt	15,567	17,182	0.294	2.94
SteepnessEst	15,824	13,062	0.250	5.23
ThreeRegion	14,622	16,418	0.271	3.32

6 Discussion

6.1 Stock Assessment Modelling Conclusions

- This study represents the first attempt to develop a Pacific wide population model for silky sharks. The exploratory analysis highlighted considerable conflicts between the key data sets, in particular, the models were unable to simultaneously fit the primary CPUE indices from the western and eastern Pacific regions (WCPO_LL and PSOBJ_EPO_Large).

- ***<u>These exploratory models are not considered sufficiently robust to provide an assessment of stock status for silky sharks in the Pacific Ocean as a whole or at either regional scale.</u>***

- The short-term (2-3 year), high interannual variation in the CPUE indices and correlation with environmental variables indicate that the CPUE indices are likely to be influenced by prevailing oceanographic conditions rather than changes in stock abundance. It is possible that the CPUE indices are more informative regarding long-term trends in stock abundance. However, the CPUE time-series is relatively short (only 14 years for the WCPO) and the overall trend may be influenced by the prevailing oceanographic conditions at the start and end of each CPUE series.

- Estimating basin scale movement dynamics was not adequate to account for the different trends in the CPUE indices from the two regions.

- Fitting the individual CPUE indices (WCPO_LL and PSOBJ_EPO_Large) was reliant on the inclusion of environmental covariates in the movement parameterisation. Good fits to the separate sets of CPUE indices occurred when corresponding regional biomass was estimated to be low. Low regional biomass values are less credible because they imply that fishing mortality rates for the main regional fishery (WCPO_LL or EPO_LL) are unrealistically high.

- The estimation of regional stock dynamics adds considerable complexity to the Pacific-wide assessment model. The data sets are limited and are unlikely to be particularly informative regarding the movement dynamics and regional recruitment variability. Despite the considerable freedom to fit the available data sets, the model could not resolve the differential trends in CPUE from the two regions.

- The estimated movement dynamics from the EPO to the WCPO were parameterised with environmental covariates that were consistent with the study by Lennert-Cody et al. (2017, in press). That study revealed a very strong correlation between the CPUE for small and medium sized sharks within the central equatorial region and the Pacific Decadal Oscillation (PDO). In the present study, the assessment models were not directly informed about changes in the relative abundance of juvenile sharks in the EPO. Instead, the models estimated movement parameters that were consistent with the variation in CPUE indices that represented changes in the abundance of larger sharks. These movement parameters moved larger sharks from the EPO in periods of lower SST and maintained the biomass in the EPO during periods of La Niña (positive Southern Oscillation Index) conditions. Incorporating the additional EPO CPUE indices for small and medium sized sharks is likely to inform the model regarding the movement of this component of the population.

- The observed variation in primary CPUE indices may not adequately represent the variation in biomass in the overall region, but rather the smaller areas that corresponds to the respective fisheries. The WCPO_LL fishery is primarily based on observer data from the non-equatorial South Pacific waters, while the EPO_PS_Object_Large CPUE index is from the northern equatorial area of the EPO. Significant catches of silky sharks occur outside of these two areas.

- The other sets of CPUE indices from the WCPO region (HWLL, WCPO_PSassoc and WCPO_PSunass) are also highly variable and correlated with environmental indices. This suggests that the availability of silky sharks to those fisheries was influenced by the prevailing oceanographic conditions. These additional sets of CPUE indices were not fitted directly in the assessment models. However, the trends in these CPUE indices were generally not consistent with the trends in stock biomass derived from the range of model options. This indicates that these CPUE indices are not compatible with the primary CPUE indices, given the structural assumptions of the model (especially spatial structure and movement).

- There is considerable variation in the length composition from some of the main fisheries, especially in the WCPO region. Some of the variation in the size of fish sampled from the fishery was also correlated with environmental indices. This may indicate that oceanographic conditions affect the distribution of different components of the population (juveniles and adults) in different ways. The variation in the length composition data sets may also be attributable to changes in the distribution of sampling coverage by the WCPO observer programmes. The range of model options did not adequately fit the annual trends in the length composition data sets. This indicates that the trends in the length compositions data are not consistent with the trends in stock abundance indexed by the primary sets of CPUE indices.

- Overall, the modelling results indicate that there is considerable conflict between the main CPUE indices and the additional CPUE indices and the associated length composition data. The deficiencies of the model may indicate that its structural assumptions are not valid and/or key data sets are not representative of the populations in each of the model regions. The regional structure of the current model was limited by the stratification of the silky shark catch estimates. Alternative spatial stratification of the model may be more appropriate. For example, the further spatial partitioning of the model population at the equator or the inclusion of an additional region in the central Pacific. Further refinement of the model's spatial structure may accommodate some of the spatial variability in the silky shark catch rates from the EPO purse seine fishery (Lennert-Cody et al. 2017; in press).

- The model estimates the level of depletion at the start of the model (in 1995) based on an assumed level of initial, equilibrium catch. The sensitivity of the assumptions regarding initial conditions was investigated during preliminary modelling. Those results indicated that the estimates of overall depletion (in 2016) were insensitive to the level of initial, equilibrium catch. The robustness of the estimate of overall depletion reveals that the model is strongly determined by the time-series of catch and

CPUE data and the recruitment dynamics prescribed by the low value of steepness of the SRR.

- There are insufficient data available to reliably estimate the SRR function (directly or indirectly) in the assessment and, consequently, the relationship was predetermined (Beverton-Holt) based on the previous WCPO assessment (Rice & Harley 2013). There is limited information available from other shark assessments to refine the SRR assumptions. The estimates of stock depletion will be strongly influenced by these assumptions.

- The model options estimated levels of current (2016) biomass at or below the SB_{MSY} level. These estimates are most strongly influenced by the PSOBJ_EPO_Large CPUE indices, especially the three higher CPUE index values at the start of the time series (1995-1997). Estimates of current catch are also considerably higher than the *MSY* estimates.

6.2 Scientific Recommendations

- Further development of the Pacific-wide model for silky sharks is required. The model development should consider a range of alternative regional structures and stratify the input data accordingly. The configuration of the model regional structure(s) should be informed by generalised circulation models for the Pacific Ocean. Further partitioning of the model structure would require information regarding the spatial distribution of the annual catches which may not be readily available for some of the key fisheries.

- Movement observations from tagging studies may provide additional information to refine the spatial configuration of the model and improve the parameterisation of the movement dynamics.

- The Pacific-wide model is limited by the relatively short time-series of CPUE indices from the WCPO region (SP_LL). The CPUE series should be routinely updated with the most recent data (from 2017). Data from earlier years have been evaluated and were considered to be inadequate to derive annual CPUE indices prior to 2002-2003. While it is not clear that higher or more representative levels of observer coverage in longline fisheries would have resolved all of the issues encountered in this study, the current low and unbalanced levels of coverage contributed to the considerable uncertainty in the results.

- Careful attention should be given to ways to improve observer data collection under silky shark no-retention measures. These measures not only have the potential to lead to underestimation of catch rates (particularly when sharks are cut free at a considerable distance from the vessel and are not recorded by species (or at all) by observers), they may also lead to unaccounted for mortality when sharks die after they are released. It is also possible that no-retention measures may change fleet targeting practices, and thus change catch rate patterns. Ways of ensuring that observers are able to see and accurately record what sharks are caught, and to better code their condition at release, should be incorporated into the WCPFC Regional Observer Programme as matter of urgency.

- Future iterations of the Pacific-wide model for silky sharks should incorporate additional data sets from the EPO fishery, including CPUE indices for small and medium sharks from the EPO purse seine fisheries as well as length composition data from the range of EPO longline and gill net fisheries. Such data may become available through the Common Oceans (ABNJ)-supported Central American port sampling project (IATTC 2017).

- Additional length composition data are required from the HWLL fishery. This fishery operates in the central region of the equatorial Pacific. The CPUE indices from the fishery are highly variable and may be indicative of the movements of silky sharks through the equatorial region. However, negligible length composition data have been collected from this fishery and, therefore, it is unknown which component of the population is monitored by the CPUE indices from the fishery.

- The current modelling investigated the sensitivity to a range of structural assumptions, including initial conditions, SRR steepness and recruitment variation. The model results were relatively insensitive to these assumptions. However, such factors should continue to be investigated during the future development of a silky shark assessment model. Further refinements of the assessment model could also investigate a range of additional factors, such as uncertainty in the catch history, sex specific selectivity, etc.

6.3 Stock Status Advice

- Of the two previous stock assessments of silky shark in the Pacific (Rice & Harley 2013, IATTC 2014), only the WCPO assessment was used to formulate stock status advice. That stock assessment covered the WCPO region only. Both that study and the present study incorporated a primarily South Pacific longline observer-derived CPUE index as an index of abundance for the WCPO region. Three recent standardized analyses of that observer data set (Rice 2013, Rice et al. 2015 and this study) have produced different abundance trajectories (see Section 4.1.2.3). This result highlights that WCPO longline observer coverage is low (2-3%) and unlikely to be representative of the overall fishing effort. Therefore, depending on how the data are subset and which covariates are used, CPUE analyses may not be able to account for biases arising from the underlying observer sampling scheme.

- Work by Lennert-Cody et al. (2017, in press) first identified that silky shark CPUE trends can be closely related to prevailing oceanographic conditions and thus may not represent reliable indices of abundance. The present study has further explored and confirmed these findings. In particular, a number of CPUE indices included in the 2013 WCPO assessment, i.e. the WCPO longline, the WCPO purse seine and the HWLL CPUE indices, have now been shown to be strongly correlated with the prevailing oceanographic conditions. This may have led to significantly biased estimates of stock status in the 2013 assessment.

- For the WCPO 2013 assessment, the fits to the individual sets of CPUE indices were not thoroughly evaluated. Instead, all sets of CPUE indices were considered to represent equally reliable indices of stock abundance (with the exception of the target longline CPUE indices which produced implausibly high estimates of total biomass). Conclusions about stock status were then drawn from the results of a grid of over 2500 scenarios with the reference case chosen randomly from the multiple highest weighted models.

While this type of grid approach can be robust, obtaining results from such a wide range of scenarios works best in data-rich situations. When time series are short, uncertain or contradictory, estimation shortcomings need to be over-ridden with fixed parameters and highly relaxed assumptions. The present assessment was operating with considerably more data, not only from the WCPO but also building in information from the EPO, but still encountered numerous model estimation issues with a much more limited suite of scenarios. It is these issues that undermine confidence in any conclusions drawn from the currently available data.

- A preliminary assessment of EPO silky sharks was undertaken by IATTC (IATTC 2014). However, the model results were not considered sufficiently robust due to the poor fit to the CPUE indices, particularly the inability of the model to fit the sharp decline in the CPUE indices in the late 1990s. The present study has also not been able to adequately account for the variation in the EPO CPUE indices in a Pacific-wide model due to the conflict with the SP_LL CPUE indices.

- The previous WCPO 2013 assessment primarily relied on an estimated catch history derived from observer data (Lawson 2011). Newer estimates (Rice 2012; Peatman et al. 2017, 2018) suggest that the older catch history considerably under-estimated actual catches; the trade-based estimates used in the present assessment suggest historical catch levels have been even higher (see Section 4.1.1). Changes in catch history will primarily influence the estimates of sustainable levels of catch (MSY catch), and the higher catch levels used in the present study thus suggest much higher levels of MSY catch for the entire Pacific Ocean (i.e. 15,000-20,000 t for the Pacific Ocean compared to 2,000 to 5,000 t for the WCPO from the 2013 assessment). At the same time, the absolute level of current catches assumed in the present study is also considerably higher (38,000 t per annum versus 5,000 to 15,000 t per annum in the 2013 assessment) and thus, although there are important differences between the two studies, the ratio of $F_{current}$ to F_{MSY} is similar.

- The estimated level of stock depletion is primarily informed by the principle CPUE indices included in the assessment model. Despite the differences between the WCPO LL CPUE series used in the 2013 WCPO assessment and the present assessment, both series –as well as the EPO PS associated series – indicate a decline in abundance between the mid 2000s (in some cases earlier) and the early 2010s.

- The current study estimated SB_{MSY} of about 0.40 SB_0 (which is consistent with SB_{MSY} /SB_0 = 0.39 from the 2013 WCPO assessment). The relatively high value of SB_{MSY} reflects the relatively low productivity of the stock, especially related to the low value assumed for steepness of the SRR (0.401; also consistent between the present and previous WCPO assessments).

- Regardless of the key concerns about reliability of the Pacific wide model results, the two sets of regional CPUE indices (SP_LL and PSOBJ_EPO_Large) reveal a general decline over the modelled time period as manifested in the estimates of stock depletion (Table 9). While the model estimates of depletion are not considered reliable, they do indicate that Pacific Ocean silky shark populations are likely to have declined considerably over the last two decades in response to the increased levels of catch. Correspondingly, fishing mortality rates are likely to have increased considerably over the same period. . The current model suggests that fishing mortality rates could be higher than the F_{MSY}

level ($F/F_{MSY} > 1$). However, due to various uncertainties in the assessment, the results are unreliable and should not be used as the basis for management advice.

- The reference points mentioned in this assessment are notional and reflect those presented in Rice & Harley (2013). No reference points have been adopted by either the WCPFC or IATTC for use in shark assessments. Work to develop limit reference points for sharks is currently underway in the WCPFC (Zhou et al. 2018).

- The Pacific wide model for silky sharks is not considered sufficiently robust to provide estimates of current stock status, primarily due to the inability of a range of model options to simultaneously fit the trends in the two sets of region-specific CPUE indices. This indicates that the differences in the trends between the two sets of CPUE indices were not adequately accounted for by the regional structure of the model and the associated movement dynamics. Although this Pacific-wide model did not successfully integrate all of the signals from the expansive range of the silky shark, it has provided critical new insights into the potential connectivities between regions and the relationships between these connectivities and oceanographic conditions. A new appreciation of these relationships now calls for caution in interpreting previous results which were based on simpler, regional paradigms, but it also points the way toward gaining a deeper understanding of the real mechanisms structuring Pacific silky shark populations.

7 Acknowledgements

The authors acknowledge the assistance of the Pacific Community (SPC) for the provision of datasets used in this study. Appreciation is extended to staff at NOAA's Pacific Islands Fisheries Science Center who facilitated longline observer data access and responded to queries regarding the datasets. The following WCPFC members and participating territories are also thanked for granting access to their non-ROP longline observer data under special data confidentiality arrangements: Australia, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Japan, Republic of the Marshall Islands, New Caledonia, New Zealand, Samoa, Solomon Islands, Tonga and Vanuatu. Nick Vogel and Marlon Román-Verdesoto of IATTC participated in helpful discussions of data interpretation issues. Finally, S. Clarke is grateful to IATTC Director Dr. Guillermo Compeán for the opportunity to work at the IATTC Secretariat in La Jolla, California during two periods in 2017.

This study is a product of the Global Environment Facility-funded, Food and Agriculture Organization of the United Nations-implemented Common Oceans (ABNJ) Tuna Project as a part of the shark and bycatch work conducted under an Execution Agreement by the Western and Central Pacific Fisheries Commission.

8 References

Aires-da-Silva, A., C. Lennert-Cody, M.N. Maunder and M. Román-Verdesoto. 2014. Stock status indicators for silky sharks in the Eastern Pacific Ocean (IATTC Document SAC-05-11a). Accessed online at https://www.iattc.org/Meetings/Meetings2014/MAYSAC/PDFs/SAC-05-11a-Indicators-for-silky-sharks.pdf

Aires-da-Silva, A., C. Lennert-Cody, M.N. Maunder, M. Román-Verdesoto and M.G. Hinton. 2015. Updated stock status indicators for silky sharks in the Eastern Pacific Ocean (1994-2014) (IATTC Document SAC-06-08ba). Accessed online at https://www.iattc.org/Meetings/Meetings2015/6SAC/PDFs/SAC-06-08b-Updated-indicators-for-silky-sharks.pdf

Aires-da-Silva, A., S. Siu, C. Lennert-Cody, C. Minte-Vera, M. Maunder, J.F. Pulvenis, J.C. Marrow, M.A. Hall, M.H. Román, L. Duffy, E.A. Altamirano Nieto, R. Belmontes, R. Deriso and G. Compeán. Challenges to collecting shark fishery data in the Eastern Pacific Ocean, and recommendations for improvement to data collection standards and procedures. IATTC Document SAC-07-06b(iii) Revised. Accessed online at https://www.iattc.org/Meetings/Meetings2016/SAC-07/PDFs/Docs/_English/SAC-07-06b(iii)_Results_–of-FAO-GEF-shark-project-2-REV-11-01-2016.pdf

Bonfil, R. 2008. The biology and ecology of the silky shark, *Carcharhinus falciformis*. Pp. 114-127 In: Sharks of the Open Ocean (eds. M. Camhi, E. Pikitch and E. Babcock), Blackwell Science, Oxford. 502 pp.

Clarke, S. 2009. An alternative estimate of catches of five species of sharks in the Western and Central Pacific Ocean based on shark fin trade data. WCPFC-SC5-2009/EB-WP-02. Accessed online at https://www.wcpfc.int/node/2123

Clarke, S. 2017. Western and Central Pacific Ocean data preparation to support a Pacific-wide re-assessment of the silky shark (*Carcharhinus falciformis*). WCPFC-SC13-2017/SA-IP-12. Accessed online at https://www.wcpfc.int/node/29536

Clarke, S. 2018. Historical Catch Estimate Reconstruction for the Pacific Ocean based on Shark Fin Trade Data (1980-2016). WCPFC-SC14-2018/SA-IP-09. Accessed online at https://www.wcpfc.int/meetings/14th-regular-session-scientific-committee

Clarke, S., R. Coelho, M. Francis, M. Kai, S. Kohin, K.M. Liu, C. Simpfendorfer, J. Tovar-Avila, C. Rigby and J. Smart. 2015. Report of the Pacific shark life history expert panel workshop, 28-30 April 2015. WCPFC-SC11-2015/EB-IP-13. Accessed online at https://www.wcpfc.int/system/files/EB-IP-13%20Workshop%20Shark%20Life%20History%20Expert%20Panel%202.pdf

Common Oceans (ABNJ) Tuna Project. 2017a. Pacific-wide sustainability risk assessment of bigeye thresher shark (*Alopias superciliosus*). WCPFC-SC13-2017/SA-WP-11. Accessed online at https://www.wcpfc.int/node/29524

Common Oceans (ABNJ) Tuna Project. 2017b. Southern Hemisphere porbeagle shark (*Lamna nasus*) stock status assessment. WCPFC-SC13-2017/SA-WP-12. Accessed online at https://www.wcpfc.int/node/29525

FAO (Food and Agriculture Organization of the United Nations). 2018. Aquatic Species Distribution Map Viewer: Silky Shark. Accessed online at www.fao.org/figis/geoserver/factsheets/species.html

Galván-Tirado, C., P. Díaz-Jaimes, F.J. García-de León, F. Galván-Magaña and M. Uribe-Alcocer. 2013. Historical demography and genetic differentiation inferred from the mitochondrial DNA of the silky shark (*Carcharhinus falciformis*) in the Pacific Ocean. Fisheries Research 147: 36-46.

Griffiths, S. and L. Duffy. 2017. A preliminary metadata analysis of large-scale tuna longline fishery data in the Eastern Pacific: a precursor to ecological risk assessment. Document SAC-08-07b. Accessed online at https://www.iattc.org/Meetings/Meetings2017/SAC-08/PDFs/Docs/_English/SAC-08-07b_Preliminary-metadata-review-for-the-high-seas-longline-fishery.pdf.

Harley, S. and G. Pilling. 2016. Potential implications of the choice of longline mitigation approach allowed within CMM 2014-05 (Rev 1). WCPFC-SC12-2016/EB-WP-06. Accessed online at https://www.wcpfc.int/node/27456

Hoyle, S.D., A.D. Langley and R.A. Campbell. 2014. Recommended approach for standardizing CPUE data from pelagic fisheries. WCPFC-SC-10/SA-IP-10. Accessed online at https://www.wcpfc.int/system/files/SC10-SA-IP-10%20Rec%20methods%20for%20standardizing%20CPUE%20data.pdf

Joung, S.J., C.T. Chen, H.H. Lee and K.M. Liu. 2008. Age, growth, and reproduction of silky sharks, *Carcharhinus falciformis*, in Northeastern Taiwan Waters. Fisheries Research 90 (1-3): 78–85.

IATTC (Inter-American Tropical Tuna Commission). 2014. A collaborative attempt to conduct a stock assessment for the silky shark in the Eastern Pacific Ocean (1993-2010): Update Report. IATTC Document SAC-05 INF-F. Accessed online at https://www.iattc.org/Meetings/Meetings2014/May/_English/SAC-05-INF-F-Assessment-of-silky-sharks.pdf

IATTC (Inter-American Tropical Tuna Commission). 2017. Workshop to Develop a Pilot Study for a Shark Fishery Sampling Program in Central America. Report of the Workshop, 25-27 September 2017. Accessed online at https://www.iattc.org/Meetings/Meetings2017/WRK-09-25-2017/_English/WRK-RPT_FAO-GEF-Shark-project-Sampling-Workshop.pdf

IATTC (Inter-American Tropical Tuna Commission). 2018. IATTC public domain data files for download: Shark EPO purse seine catch and effort aggregated by year, month, flag or set type, 1°x1° and Shark EPO longline catch and effort aggregated by year, month, flag, 5°x5°. Accessed online at https://www.iattc.org/Catchbygear/IATTC-Catch-by-species1.htm

Lawson, T. 2011. Estimation of catch rates and catches of key shark species in tuna fisheries of the Western and Central Pacific Ocean using observer data. WCPFC-SC7-2011/EB-IP-02. Accessed online at https://www.wcpfc.int/node/2777

Lennert-Cody, C., A. Aires-da-Silva, M.N. Maunder and M.H. Román. 2016. Updated stock status indicators for silky sharks in the Eastern Pacific Ocean (1994-2015). IATTC Document SAC-07-06b.i. Accessed online at https://www.iattc.org/Meetings/Meetings2016/SAC7/PDFfiles/SAC-07-06b(i)-Indicators-for-silky-shark.pdf

Lennert-Cody, C., S. Clarke, A. Aires-da-Silva, M.N. Maunder and M.H. Román. 2017. Updated stock status indicators for silky sharks in the Eastern Pacific Ocean (1994-2016), with oceanographic considerations. IATTC Document SAC-08-08a(i). Accessed online at https://www.iattc.org/Meetings/Meetings2017/SAC08/PDFs/SAC-08-08a(i)-Updated-indicators-for-silky-sharks.pdf

Lennert-Cody, C., A. Aires-da-Silva and M.N. Maunder. 2018. Updated stock status indicators for silky sharks in the Eastern Pacific Ocean (1994-2017). IATTC Document SAC-09-13. Accessed online at https://www.iattc.org/Meetings/Meetings2018/SAC-09/PDFs/Docs/_English/SAC-09-13-EN_Updated-purse-seine-indicators-for-silky-sharks-in-the-EPO.pdf

Lennert-Cody, C.A., S. Clarke, A. Aires-da-Silva, M. Maunder, P. Franks, M. Román, A. Miller and M. Minami (in press). The importance of environment and life stage on interpretation of silky shark relative abundance indices for the equatorial Pacific Ocean. Fisheries Oceanography.

Methot, R.D. and C.R. Wetzel. 2013. Stock synthesis: a biological and statistical framework for fish stock assessment and fishery management. Fish. Res. 142, 86–99.

Minami, M., C.E. Lennert-Cody, W. Gao and M. Roman-Verdesoto. 2007. Modeling shark bycatch: the zero-inflated negative binomial regression model with smoothing. *Fisheries Research* 84 (2): 210-221.

NFA (National Fisheries Authority of Papua New Guinea). 2017. Annual Report to the Commission, Part 1: Information on Fisheries, Research and Statistics, 2016. WCPFC AR-CCM-19 (Rev01). Accessed online at https://www.wcpfc.int/system/files/AR-CCM-19%20PNG%20%28Rev01%29.pdf .

Peatman, T. and G. Pilling. 2016. Monte Carlo simulation modelling of purse seine catches of silky and oceanic whitetip sharks. WCPFC-SC12-2016/EB-WP-03. Accessed online at https://www.wcpfc.int/node/27455

Peatman, T., V. Allain, S. Caillot, P. Williams and N. Smith 2017. Summary of purse seine fishery bycatch at a regional scale, 2003-2016. WCPFC-SC13-2017/ST-WP-05. Available online at https://www.wcpfc.int/system/files/ST-WP-05%20regional%20bycatch%20summary%20purse%20seine%20%28submitted%29.pdf

Peatman, T., V. Allain, S. Caillot, P. Williams and N. Smith. 2018. Summary of longline fishery bycatch at a regional scale, 2003-2017. WCPFC-SC14-2017/ST-WP-03. Accessed online at https://www.wcpfc.int/meetings/14th-regular-session-scientific-committee

Rice, J. 2012. Alternate catch estimates for silky and oceanic whitetip sharks in the Western and Central Pacific Ocean. WCPFC-SC8-2012/SA-IP-12. Available online at https://www.wcpfc.int/system/files/SA-IP-12-Alternative-Catch-Est-Silky-and-OWT-Sharks-WCPO.pdf

Rice, J. 2013. Catch and catch per unit effort of silky sharks in the Western and Central Pacific Ocean. WCPFC9-SC9-2013/SA-IP-02. Accessed online at https://www.wcpfc.int/system/files/SA-IP-02-Silky-shark-Catch-CPUE.pdf

Rice, J. and S. Harley. 2013. Updated Stock assessment of silky shark in the western and central Pacific Ocean. WCPFC-SC9-2013/SA-WP-03. Accessed online at https://www.wcpfc.int/node/3685

Rice, J., L. Tremblay-Boyer, R. Scott, S. Hare and A. Tidd. 2015. Analysis of stock status and related indicators for key shark species of the Western Central Pacific Fisheries Commission. WCPFC-SC11-2015/EB-WP-04-Rev 1. Accessed online at https://www.wcpfc.int/system/files/EB-WP-04%20shark%20indicators%20Rev%201.pdf

Román-Verdesoto, M. and M. Orozco-Zöller. 2005. Bycatches of sharks in the tuna purse-seine fishery of the eastern Pacific Ocean reported by observers of the Inter-American Tropical Tuna Commission, 1993–2004. Data Report II. Inter-American Tropical Tuna Commission. Accessed online at http://www.iattc.org/PDFFiles/DataReports/_English/No-11-2005-Marlon%20Román-Verdesoto%20and%20Mauricio%20Orozco-Zöller_Bycatches%20of%20sharks%20in%20the%20tuna%20PS%20fishery%20of%20the%20EPO%20reported%20by%20observers%20of%20the%20IATTC,%201993-2004.pdf

Scott, M.D., C.E. Lennert-Cody, T. Gerrodette, H.J. Skaug, C.V. Minte-Vera, J. Hofmeister, J. Barlow, S.J. Chivers, L.M. Duffy, R.J. Olson, A.A. Hohn, P.C. Fiedler, L.T. Ballance and K.A. Forney. 2016. Data available for assessing dolphin population status in the Eastern Tropical Pacific Ocean. Workshop on Methods for Monitoring the Status of Eastern Tropical Pacific Ocean Dolphin Populations, 18-20 October, 2016, La Jolla, California. Accessed online at www.iattc.org/Meetings/Meetings2016/DEL-01/PDFs/_English/DEL-01_Data-Available-for-Assessing-Dolphin-Population-Status-in-the-Eastern-Tropical-Pacific-Ocean.pdf

Siu, S. and A. Aires-da-Silva. 2016. An Inventory of Sources of Data in Central America on Shark Fisheries Operating in the Eastern Pacific Ocean – Metadata Report. IATTC Document SAC-07-

06b(ii). Accessed online at https://www.iattc.org/Meetings/Meetings2016/SAC-07/PDFs/Docs/_English/SAC-07-06b(ii)_Results-of-FAO-GEF-shark-project-1.pdf

Siu, S., A. Aires-da-Silva, C. Lennert-Cody and M.N. Maunder. 2017. Shark landing data available from longline fisheries in Central America: progress report. IATTC Presentation SAC-08-08a(ii). Accessed online at https://www.iattc.org/Meetings/Meetings2017/SAC-08/PDFs/Presentations/_English/SAC-08-08a-(ii)-PRES_Updated-results-of-FAO-GEF-shark-project.pdf

Trenberth, K. 2016. The Climate Data Guide: Nino SST Indices (Nino 1+2, 3, 3.4, 4; ONI and TNI). Last updated on 2 February 2016. Retrieved from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni.

Walsh, W.A. and S.C. Clarke. 2011. Analyses of Catch Data for Oceanic Whitetip and Silky Sharks reported by Fishery Observers in the Hawaii-based Longline Fishery in 1995–2010. WCPFC-SC7-2011/EB-WP-03. Accessed online at https://www.wcpfc.int/system/files/EB-WP-03%20%5BOceanic%20whitetip%20and%20silky%20sharks%20-%20catch%20data%20analysis%5D.pdf

Ward-Paige, C. 2017. A global overview of shark sanctuary regulations and their impact on shark fisheries. Marine Policy 82: 87-97.

WCPFC (Western and Central Pacific Fisheries Commission). 2009. WCPFC-IATTC Memorandum of Cooperation on the Exchange and Release of Data. Accessed online at https://www.wcpfc.int/doc/wcpfc-iattc-memorandum-cooperation-exchange-and-release-data

WCPFC (Western and Central Pacific Fisheries Commission). 2017a. Scientific Data to be provided to the Commission. Last revised in December 2017. Accessed online at https://www.wcpfc.int/system/files/Att%20G_Revised%20SciData%20decision.pdf

WCPFC (Western and Central Pacific Fisheries Commission). 2017b. WCPFC Data Catalogue (last updated 18 November 2017). Accessed online at https://www.wcpfc.int/wcpfc-data-catalogue-0.

Wiley, B., S. Griffiths, M. Hall, A. Aires-da-Silva, C. Lennert-Cody, S. Clarke, M. Maunder and L. Duffy. 2017. Establishing minimum data standards and reporting requirements for longline observer programs under Resolution C-11-08. Document SAC-08-07e. Accessed online at https://www.iattc.org/Meetings/Meetings2017/SAC-08/PDFs/Docs/_English/SAC-08-07e_Establishing-minimum-data-standards-and-reporting-requirements-for-longline-observer-programs-under-resolution-C-11-08.pdf

Williams, P., I. Tuiloma and C. Falasi. 2015. Status of Observer Data Management. WCPFC-SC11-2015/ST-IP-02 (Rev 1, 28 July 2015). Accessed online at https://www.wcpfc.int/system/files/ST-IP-02%20Status%20of%20ROP%20Data%20Management%20rev%201%20%2828%20July%202015%29_0.pdf

Zhou, S., R. Deng, S. Hoyle and M. Dunn. 2018. Identifying appropriate reference point for elasmobranchs within the WCPFC. WCPFC-SC14-2018/MI-WP-07. Accessed online at https://www.wcpfc.int/meetings/14th-regular-session-scientific-committee

Zuur, A.F., E.N. Ieno, N.J. Walker, A.A. Saveliev and G.M. Smith. 2009. Zero-truncated and zero-inflated models for count data. pp. 261-293 In *Mixed Effects Models and Extensions in Ecology with R*, pp. 261-293. Springer, New York, NY.

Annex A. Data description and exploration of WCPO data sets (excerpted from Clarke, S. 2017. Western and Central Pacific Ocean data preparation to support a Pacific-wide re-assessment of the silky shark (*Carcharhinus falciformis*). WCPFC-SC13-2017/SA-IP-12).

Description of Key Data Sets

A number of non-public domain datasets which are exclusively or mainly focused on WCPO fisheries were available to this study. These include:

- Longline observer data maintained by SPC as part of the WCPFC Regional Observer Programme accessible to the TCSB via the WCPFC Secretariat, as well as non-public domain longline observer data maintained by SPC on behalf of Australia, the Cook Islands, the Federated States of Micronesia, Fiji, French Polynesia, the Republic of the Marshall Islands, New Caledonia, New Zealand, Samoa, Solomon Islands, Tonga and Vanuatu and accessible to the TCSB through data confidentiality agreements with each country for use in the ABNJ Tuna Project ("SPC LL observer data");
- United States longline observer data provided directly to the TCSB for use in the ABNJ Tuna Project under a data confidentiality agreement ("US LL observer data");
- Japan longline observer data provided to the TCSB under a data confidentiality agreement specific to this assessment ("Japan LL observer data");
- Purse seine observer data maintained by SPC as part of the WCPFC Regional Observer Programme accessible to the TCSB via the WCPFC Secretariat ("SPC ROP PS observer data").

Each of these datasets is described and explored separately below.

1 SPC LL Observer Data

1.1 Data Description

These data were provided by SPC to the TCSB on 29 March 2017. They consist of two files: one file contains set-level information with one row per set ("Set Header", Table A1) and one file contains catch records for individual fish with one row per fish caught ("Catch", Table A2). The catch dataset contains all species in order to explore potential explanatory variables associated with the catch of target species. The field names for the data in each file are shown in Table A3; explanations of the fields and how they are collected can be found in SPC (2017a).

To link each catch record to its set characteristics, a unique identifier was created by combining set identifiers and trip identifiers in the set database. At this step there were 202 set records which shared a unique identifier with another set. As it was impossible to know which, if any, of these set records were correct, all 202 were removed. From the remaining number of sets (n=78,354), containing 23,824 silky sharks (FAL), the following number of sets (and FAL records) were removed sequentially:

- Removed due to missing lat/long information (2,464 sets and 70 FAL);
- Removed due to not being within the year range of sufficient observer coverage (10,902 sets and 3,564 FAL);
- Removed due to missing hooks fished values (3,420 sets and 43 FAL);
- Removed due to missing hooks between floats (70 sets and 3 FAL);
- Removed due to too many or too few hooks per set (720 sets and 285 FAL);
- Removed due to too many or too few hooks between baskets (344 sets and 27 FAL);

- Removed due to being outside the spatial boundaries of the assessment (3,734 sets and 8 FAL); and
- Removed due to originating from the Hawaii or American Samoa longline observer programme (11,048 sets and 778 FAL).

Removals related to missing values (hooks between floats, latitude, longitude and number of hooks fished) were necessary because these values are likely to be very important in the catch rate standardizations and missing values may interfere with coefficient estimation. Extreme values of hooks fished (i.e. <500 or >4500) were considered to represent abnormal fishing operations and were also thus removed. Similarly, sets recording fewer than four, or more than 45 hooks between baskets were considered dubious and were removed. Sets before 2002 and sets after 2016 were removed to avoid biases associated with poor observer coverage (prior to 2002) or incomplete reporting (2017). The spatial boundaries were defined based on the Pacific-wide tropical/semi-tropical distribution of the species as not extending more than 40^{o} north and south of the equator; the longitudinal distribution was based on the range within which there was observer coverage over most of the time series (130^{o}-230^{o}E longitude). Finally, sets from the Hawaii and American Samoa longline fisheries were removed because they are likely to be duplicated in the US longline observer dataset described below in Section 3.2.

A number of other filters applied or discussed in Rice et al. (2015) were considered but not applied as follows:

- sets from fisheries known to be targeting sharks (e.g. Papua New Guinea) and those sets for which the set header field target_shk_yn=yes (Table A3), were not removed *a priori* as it was considered that any shark targeting effect could be addressed through the catch rate standardization;
- removing sets from small national observer programs with < 100 sets each was not considered necessary as this analysis will not be using the observer program identifier in lieu of actual (lat/long) location (as Rice et al. 2015 did);
- removing records considered to be outside the sea surface temperature (SST) range of species was not done due to doubts about the certainty of silky shark's SST range and a preference to address habitat issues through a lat/long exclusion criterion and explanatory variables in the standardization model;
- removing records where the catch rate of FAL is greater than the 97.5th percentile of nominal mean CPUE for the dataset as a whole was not done because FAL may exhibit schooling behaviour and thus we might expect to see rare large catches.

In total 32,702 sets were removed from the analysis, containing 4,778 FAL, leaving 45,643 sets and 19,046 FAL. Nearly 86% of the sets recorded no catch of silky sharks. All catch and effort data were screened before plotting in accordance with the three-vessel rule (WCPFC 2007).

Table A1. Number of observed sets by flag and year extracted for this study (before filtering) from the SPC LL observer dataset. Year-flag combinations without any observations are shaded in blue.

SET	AS	AU	CK	CN	FJ	FM	GU	JP	KI	KR	MH	NC	NZ	PF	PG	PW	SB	TO	TW	US	VU	WS	TOTAL
1980	-	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17
1981	-	17	-	-	-	-	-	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	35
1982	-	10	-	-	-	-	-	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27
1984	-	10	-	-	-	-	-	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	19
1985	-	-	-	-	-	-	-	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18
1986	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
1987	-	4	-	-	-	-	-	36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40
1988	-	19	-	-	-	-	-	79	-	-	-	-	-	-	-	-	-	-	-	-	-	-	98
1989	-	60	-	-	-	-	-	106	-	-	-	-	-	-	-	-	-	-	-	-	-	-	166
1990	-	32	-	-	-	-	-	314	-	-	-	-	-	-	-	-	-	-	-	-	-	-	346
1991	-	43	-	-	-	-	-	877	-	7	-	-	-	-	-	-	-	-	-	-	-	-	927
1992	-	9	-	-	-	-	-	1,011	-	8	-	-	16	-	-	-	-	-	-	-	-	-	1,044
1993	-	-	-	18	-	-	-	1,459	-	5	-	-	-	-	-	-	-	-	35	-	-	-	1,517
1994	-	-	-	29	-	7	-	963	-	-	-	-	13	-	-	-	-	-	95	-	-	-	1,107
1995	-	-	-	28	-	2	23	644	-	-	-	-	80	-	-	-	-	-	39	-	2	-	818
1996	-	-	-	69	-	12	13	470	-	-	-	-	144	-	-	-	5	-	-	-	-	-	713
1997	-	13	-	67	-	27	8	653	-	-	-	-	136	-	-	-	-	-	57	-	-	-	961
1998	-	-	-	82	-	42	9	371	-	-	-	-	143	-	-	-	14	-	162	-	-	-	823
1999	-	10	-	65	-	20	-	358	-	25	-	-	74	-	-	-	41	-	138	-	-	-	731
2000	-	-	-	73	-	54	5	334	-	-	-	-	41	-	-	12	50	-	154	-	-	-	723
2001	-	115	6	122	-	27	-	265	-	-	-	12	276	-	-	-	65	-	53	-	-	14	955
2002	84	697	7	6	49	28	-	292	-	175	-	56	126	72	-	-	419	-	191	-	-	2	2,204
2003	-	644	40	35	195	23	-	257	-	39	-	81	268	172	-	-	283	-	126	-	-	2	2,165
2004	-	798	59	209	133	67	-	20	-	1	-	84	451	180	-	-	174	83	101	-	-	-	2,360
2005	-	944	60	191	443	61	-	366	-	106	-	37	138	136	-	-	-	11	-	-	-	9	2,502
2006	-	930	18	553	437	131	-	219	-	240	-	48	107	291	-	-	-	145	8	-	-	15	3,142
2007	-	455	12	576	339	62	-	275	-	107	-	61	160	93	-	-	-	56	9	-	-	-	2,205
2008	-	575	32	125	355	39	-	83	-	-	23	86	158	186	-	-	-	108	48	-	-	-	1,818
2009	-	402	54	80	236	-	-	244	-	-	8	211	174	434	-	-	-	33	71	-	59	-	2,006
2010	-	224	52	-	176	-	-	109	17	-	-	227	175	445	-	-	-	10	1	-	129	-	1,565
2011	-	317	58	-	334	-	-	80	-	145	-	172	160	351	-	-	63	-	23	-	260	7	1,970
2012	-	282	-	175	174	-	-	82	-	589	-	127	109	399	52	-	137	8	3,311	3,374	6	-	8,825
2013	-	277	159	272	963	61	-	129	-	877	11	102	98	453	-	-	54	-	7,371	3,957	515	16	15,315
2014	-	128	85	465	1,375	311	-	136	-	427	-	150	133	437	1	-	-	22	4,810	3,981	143	-	12,604
2015	-	66	129	330	1,991	151	-	133	50	550	-	103	141	342	-	-	-	51	1,071	-	211	20	5,339
2016	-	-	14	128	1,984	94	-	16	8	171	-	144	-	186	-	-	-	8	340	-	116	-	3,209
2017	-	-	-	8	18	-	-	-	-	-	-	13	-	-	-	-	-	-	-	-	-	-	39
TOTAL	84	7,098	785	3,706	9,202	1,219	58	10,444	75	3,472	42	1,714	3,321	4,177	53	12	1,305	535	18,214	11,312	1,441	85	78,354

Table A2. Number of FAL catch records (each record is one shark) by flag and year extracted for this study (before filtering) from the SPC LL observer dataset. Year-flag combinations without any observations are shaded in blue. Year-flag combinations with zero silky sharks recorded are shaded in red.

SET	AS	AU	CK	CN	FJ	FM	GU	JP	KI	KR	MH	NC	NZ	PF	PG	PW	SB	TO	TW	US	VU	WS	TOTAL
1980	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1981	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1982	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1984	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1985	NA	NA	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1986	NA	NA	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1987	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1988	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1989	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1990	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1991	NA	-	NA	NA	NA	NA	NA	-	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1992	NA	-	NA	NA	NA	NA	NA	-	NA	-	NA	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
1993	NA	NA	NA	-	NA	NA	NA	-	NA	-	NA	NA	NA	NA	NA	NA	NA	NA	-	NA	NA	NA	-
1994	NA	NA	NA	-	NA	-	NA	-	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	-	NA	NA	NA	-
1995	NA	NA	NA	57	NA	-	24	28	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	100	NA	-	NA	209
1996	NA	NA	NA	81	NA	-	43	-	NA	NA	NA	NA	-	NA	NA	NA	-	NA	NA	NA	NA	NA	124
1997	NA	-	NA	21	NA	4	6	55	NA	NA	NA	NA	-	NA	NA	NA	NA	NA	118	NA	NA	NA	204
1998	NA	NA	NA	96	NA	2	2	28	NA	NA	NA	NA	-	NA	NA	NA	6	NA	470	NA	NA	NA	604
1999	NA	-	NA	128	NA	11	NA	33	NA	2	NA	NA	-	NA	NA	NA	30	NA	1,151	NA	NA	NA	1,355
2000	NA	NA	NA	160	NA	20	-	30	NA	NA	NA	NA	-	NA	NA	3	31	NA	374	NA	NA	NA	618
2001	NA	2	-	273	NA	8	NA	27	NA	NA	NA	1	-	NA	NA	NA	18	NA	119	NA	NA	9	457
2002	11	8	-	-	5	6	NA	4	NA	12	NA	7	-	2	NA	NA	146	NA	126	NA	NA	-	327
2003	NA	-	-	16	44	4	NA	11	NA	14	NA	12	-	2	NA	NA	136	NA	65	NA	NA	-	304
2004	NA	18	-	366	31	137	NA	4	NA	-	NA	16	1	53	NA	NA	43	50	223	NA	NA	NA	942
2005	NA	41	-	204	163	101	NA	47	NA	16	NA	7	-	22	NA	NA	NA	2	NA	NA	NA	-	603
2006	NA	19	-	658	213	102	NA	14	NA	243	NA	-	-	15	NA	NA	NA	75	33	NA	NA	-	1,372
2007	NA	33	3	1,436	130	228	NA	13	NA	32	NA	-	1	35	NA	NA	NA	34	11	NA	NA	NA	1,956
2008	NA	27	4	182	118	61	NA	-	NA	NA	39	3	-	2	NA	NA	NA	11	391	NA	NA	NA	838
2009	NA	8	13	48	150	NA	NA	3	NA	NA	2	35	-	4	NA	NA	NA	19	133	NA	43	NA	458
2010	NA	9	2	NA	60	NA	NA	-	-	NA	NA	29	-	27	NA	NA	NA	-	-	NA	170	NA	297
2011	NA	11	13	NA	106	NA	NA	-	NA	83	NA	38	-	3	NA	NA	-	NA	77	NA	429	-	760
2012	NA	15	NA	60	63	NA	NA	-	NA	283	NA	8	-	5	1,711	NA	438	1	2,009	231	-	NA	4,824
2013	NA	27	96	37	148	19	NA	-	NA	413	-	5	-	6	NA	NA	13	NA	1,662	317	222	-	2,965
2014	NA	11	53	94	173	246	NA	-	NA	537	NA	5	-	19	-	NA	NA	2	266	230	64	NA	1,700
2015	NA	10	67	54	365	22	NA	-	1	989	NA	6	-	31	NA	NA	NA	1	81	NA	408	-	2,035
2016	NA	NA	-	4	318	16	NA	23	-	137	NA	61	NA	105	NA	NA	NA	-	14	NA	187	NA	865
2017	NA	NA	NA	-	-	NA	NA	NA	NA	NA	NA	7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	7
TOTAL	11	239	251	3,975	2,087	987	75	320	1	2,761	41	240	2	331	1,711	3	861	195	7,423	778	1,523	9	23,824

Table A3. Data types extracted for the SPC LL observer set and catch datasets.

Data Set	Fields Available
SPC LL Observer Dataset (Set Header)	year, obstrip_id, program_code, flag, vessel_id, vessel_name, l_set_id, set_start_date, set_start_time, set_end_time, haul_start_date, haul_start_time, soak_time, lat1d, lon1d, eez_code, tar_sp_code, target_tun_yn, target_swo_yn, target_shk_yn, hk_bt_flt, hook_set, hook_est, lightsticks, bask_set, bask_observed, nbshark_lines, bait1_sp_code, bait2_sp_code, bait3_sp_code, bait4_sp_code, bait5_sp_code, wire_trace, hook_type, sharktarget, sharkbait, moonfrac, sst
SPC LL Observer Dataset (Catch)	year, obstrip_id, l_set_id, catch_time, sp_code, sp_category, hk_bt_flt, hook_no, condition_land, condition_release, fate_code, length, len_code, sex_code

1.2 Data Exploration

The SPC longline observer dataset, after cleaning and filtering, is distributed with low coverage over a wide area as illustrated by a sample of plots of annual observed effort and annual total effort from 2004, 2009 and 2014 (Figure A1). Although the distribution and amount of effort fished remains remarkably constant throughout the 15-year period, the observed effort increased considerably between 2009 and 2014 both in quantity and range of areas covered. This is a positive development but it suggests that the observer dataset, in its nominal form, may be unbalanced over the time series as well as still unrepresentative of the total fishing effort on the stock. In addition to representing much less than 1% of the total effort, until recently much of the observed effort is concentrated in the Southern Hemisphere at or below 20°S and thus potentially outside much of the WCPO core habitat area for FAL. It should also be noted that Figure A1 does not include observer data provided for this study by the US and Japan, and thus there is better coverage for the North Pacific than this figure suggests. Some data are available for analysis but are not plotted in the figure due to the three vessel rule, in particular coverage north of Hawaii from the Chinese Taipei observer programme which has been providing data since 2012.

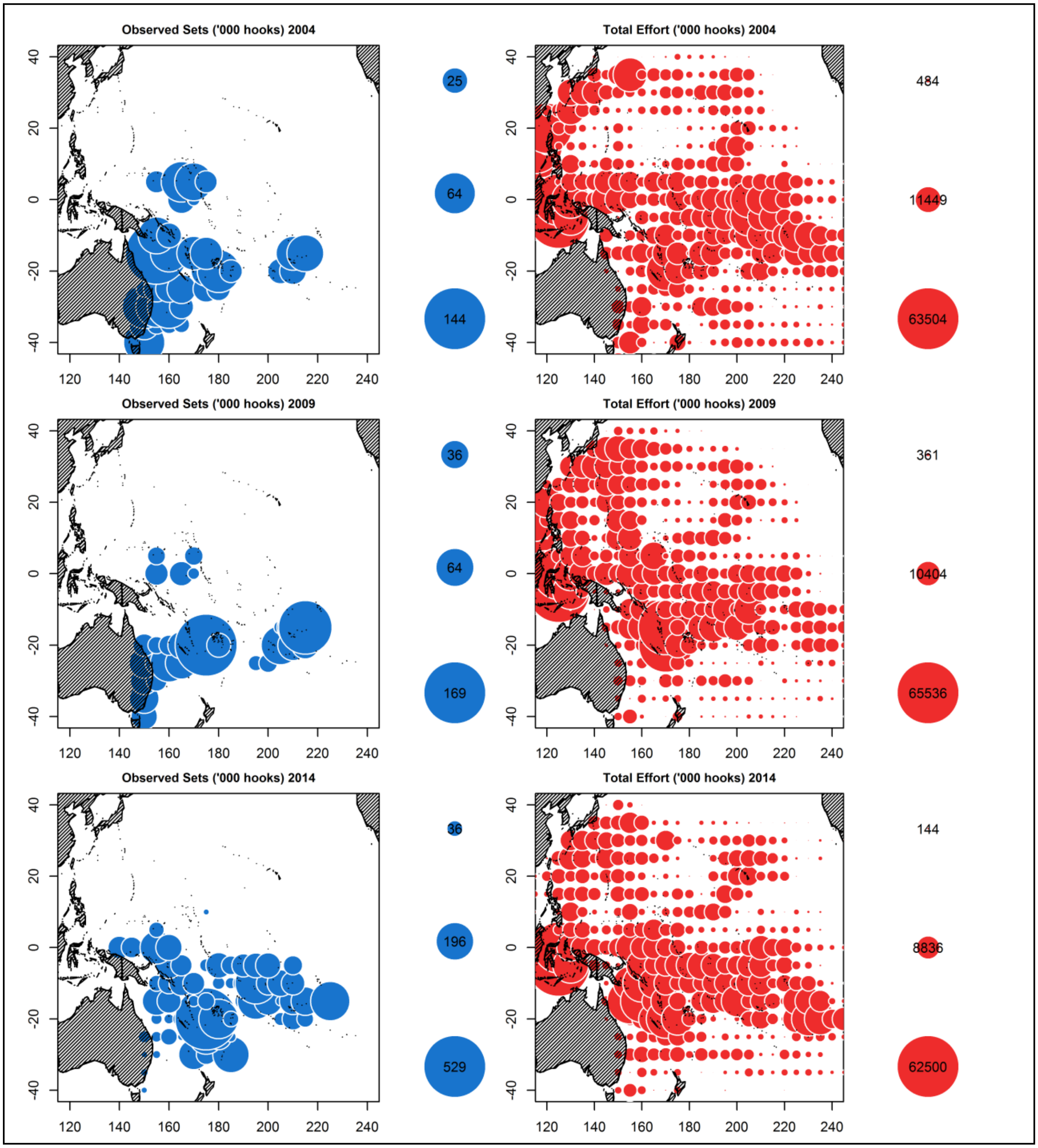


Figure A1. Distribution of observed effort relative to total effort (in thousand hooks) in the Pacific longline fishery (for comparison) for a sample of years (2004, 2009 and 2014) within the extracted SPC LL observer and CES effort datasets. The size of the circles is proportional to the number of hooks fished in each 5°x5° cell in thousands of hooks (10th, 50th and 90th percentiles given as a legend). Actual set locations are rounded southward and westward to the nearest 5°x5° grid point and may be plotted over land as a result.

Silky shark catch per unit effort (CPUE) by year and 5°x5° grid in the SPC LL observer dataset are shown in Figure A2. These nominal catch rate plots suggest that within the observed sets shown here the main centres of FAL abundance lie in near-equatorial waters between 20° N and 20° S. Within this dataset, areas of high CPUE are often found in or just east of the Papua New Guinea and Solomon Island exclusive economic zones (EEZs).

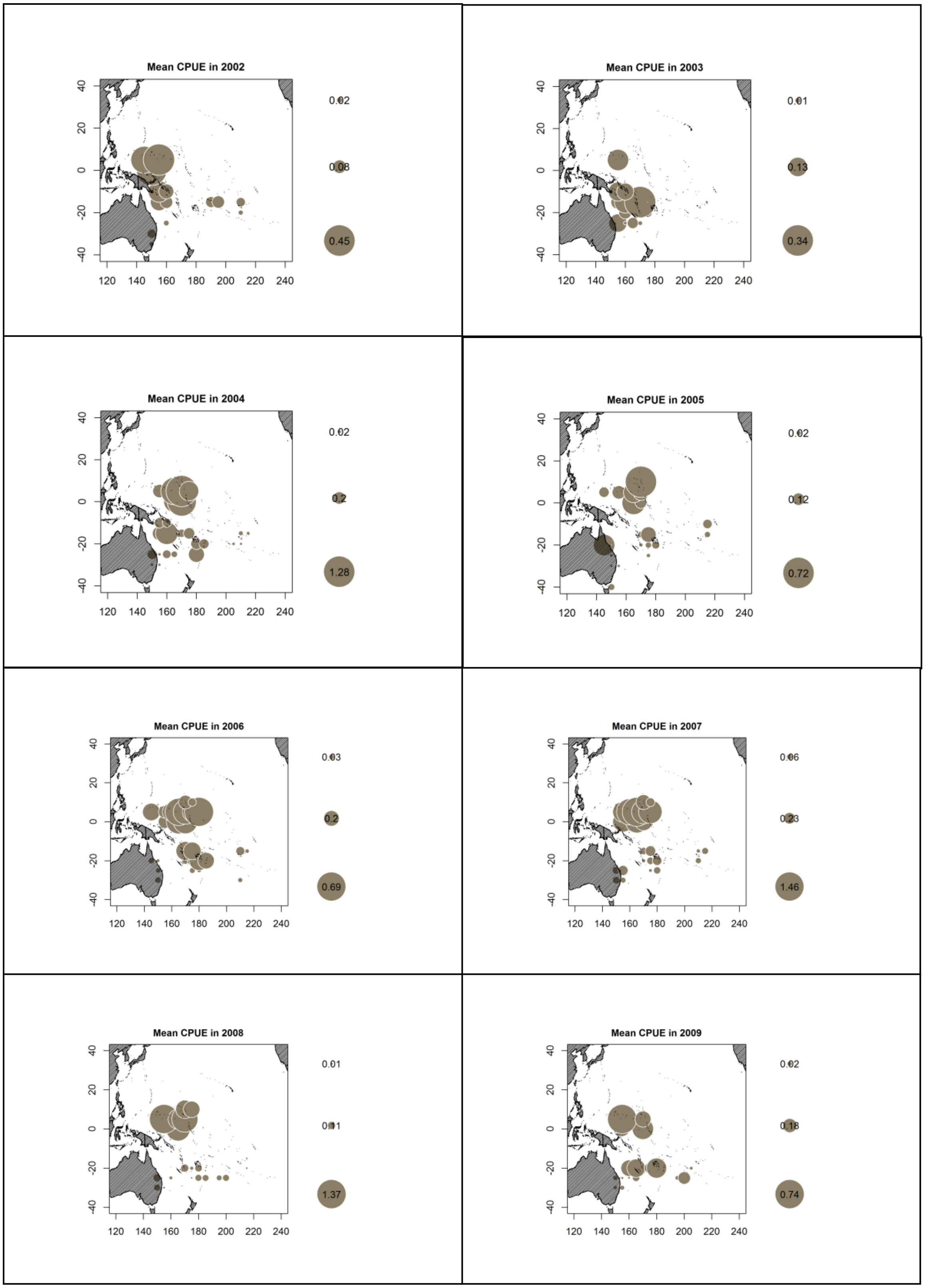


Figure A2a. Annual mean CPUE for silky shark in the SPC LL observer dataset, 2002-2009. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). Actual set locations are rounded southward and westward to the nearest 5ox5o grid point and may be plotted over land as a result.

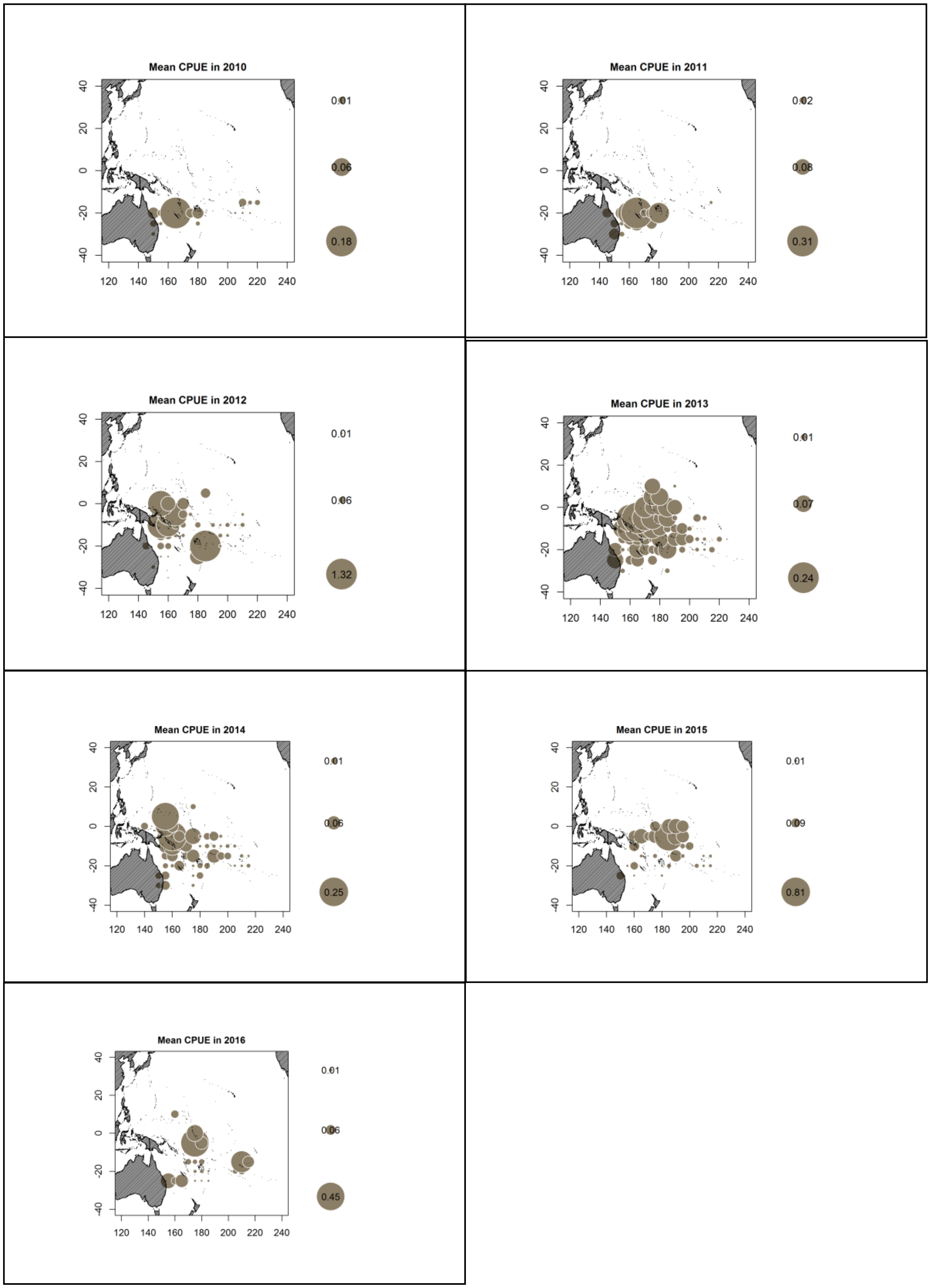


Figure A2b. Annual mean CPUE for silky shark in the SPC LL observer dataset, 2010-2016. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). Actual set locations are rounded southward and westward to the nearest 5°x5° grid point and may be plotted over land as a result.

In order to explore some of the potential explanatory variables that might be useful in standardizing the catch rate data to derive an abundance index, boxplots for latitude, longitude, year, month, hooks between floats and program code were constructed (Figure A3). Of these factors, the spatial, program code and hooks between floats variables appear to be the most promising.

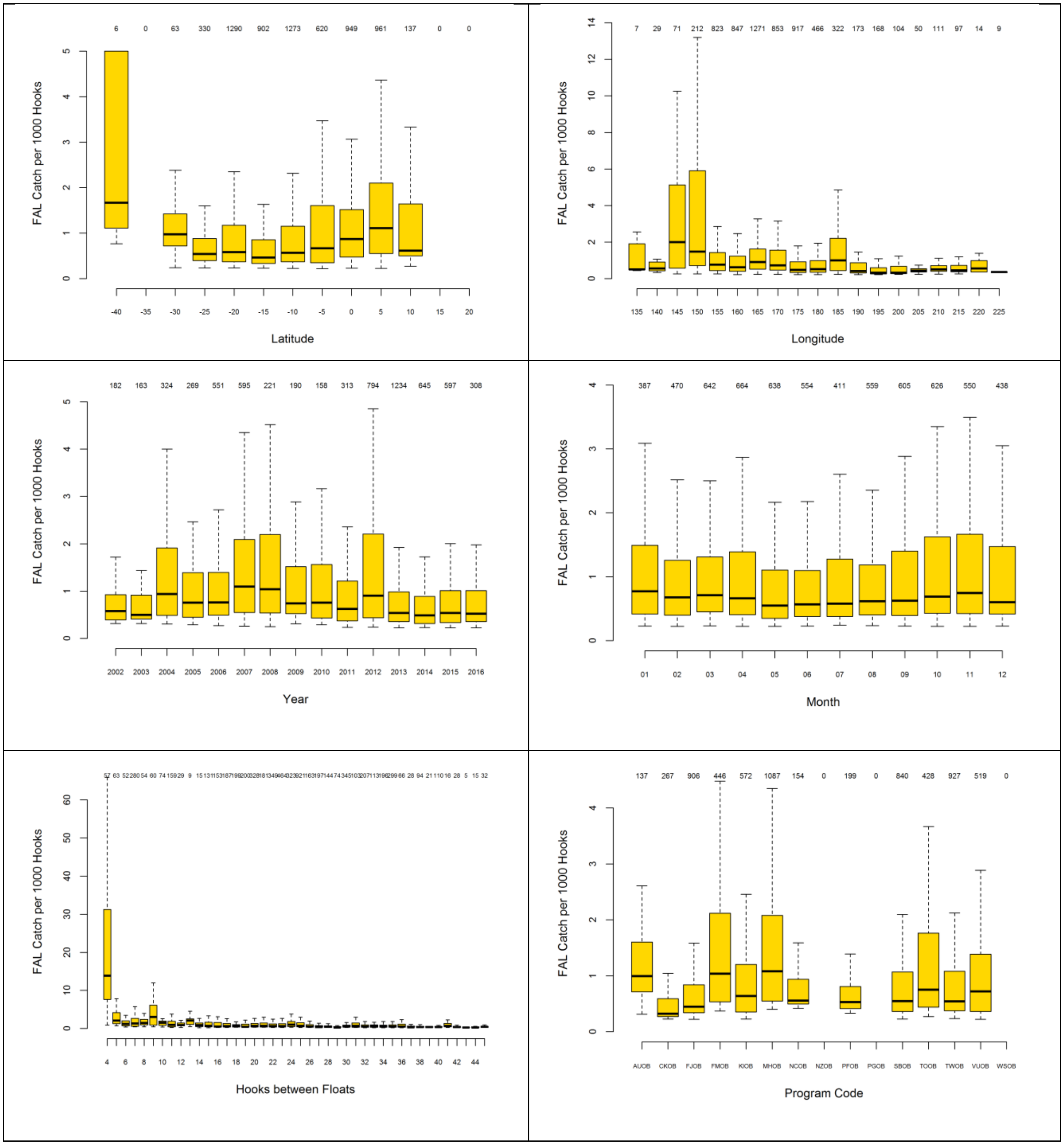


Figure A3. Box and whisker plots of potential explanatory variables in silky shark catch rates for sets with non-zero catch rates in the SPC LL observer dataset. The gold box shows the range between the 25th and 75th percentile (the interquartile range). The black line is the median. The whiskers are plotted at the most extreme data point which is no more than 1.5 times the interquartile range from the box (i.e. extreme outliers are not plotted). The sample size is annotated at the top of each column.

Using the same dataset, nominal CPUE was plotted as the mean of set-by-set catch rates (i.e. catch of FAL divided by hooks fished for each set) by year (Figure A4). It should be noted that this abundance trend will differ from the boxplot by year in Figure A3 as Figure A3 only shows non-zero catches whereas zero and non-zero catches are shown here. There are many reasons why, in general, it should not be expected that the nominal CPUE trend is not an accurate reflection of the true abundance trend of the population (Hoyle et al. 2014). This caveat is particularly important for this dataset as shown by the uneven distribution of observed effort in space and time (Figure A1), in particular, the large increase in observer data from the Chinese Taipei observer programme from 2012 onward (Table A1). The effects of the adoption and implementation of CMM2013-08 prohibiting retention of silky sharks in 2013 and 2014, respectively, also remain to be addressed.

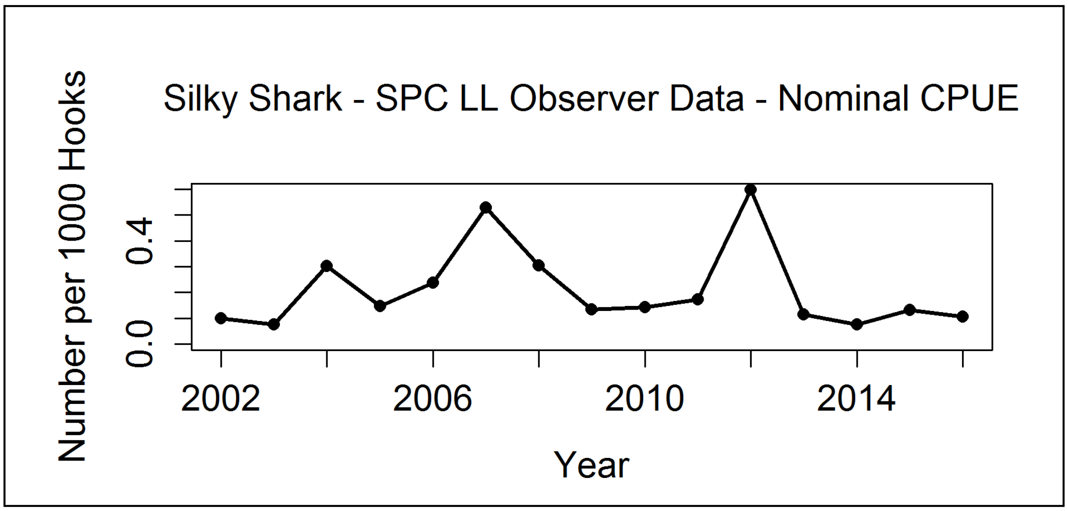


Figure A4. Nominal annual mean CPUE (i.e. mean of individual set catch rates) in the SPC LL observer dataset, 2002-2009.

In addition to compiling catch and effort data, biological data in the form of length frequencies by sex must also be prepared. In the SPC LL observer data available to this study, there are length and sex data available for 8,548 female silky shark and 7,487 male silky sharks between 1995 and 2016. The majority of these (87%) were measured in fork length (FL); the remaining lengths in total length (TL) were converted to fork length using the following equation from Joung et al. 2008 (cited in Clarke et al. 2015): FL=(TL-2.36)/1.21. Lengths were screened to exclude observations below a nominal size at birth of 50 cm FL and a nominal maximum size of 271 cm FL based on the review in Clarke et al. (2015). Spatial representations of length frequencies, shaded on a relative scale, across the WCPO for female and male silky sharks (Figure A5) suggest larger individuals in the southwest for both sexes. Such a pattern may also be present in the southeast but obscured by low or no sampling. There is also a suggestion of large individuals to the east in equatorial waters, although sample sizes in that area are also low.

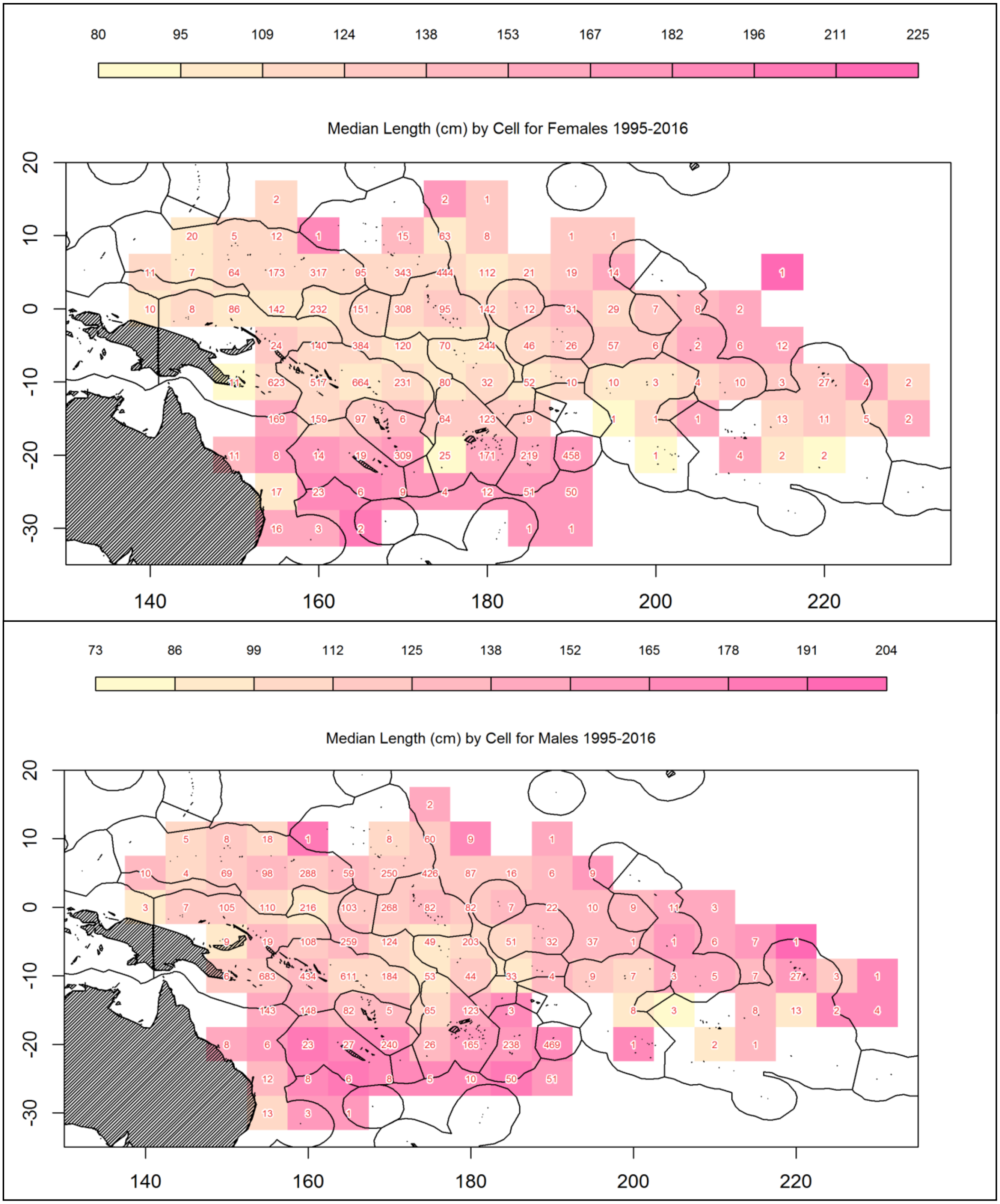


Figure A5. Mapping of median length on a relative scale for female and male silky sharks in the SPC LL observer database, 1995-2016. All lengths shown are in cm fork length (see text for conversion factors). The number annotated in each 5x5 degree cell is the number of measured sharks.

2 United States LL Observer Data

2.1 Data Description

These data were authorized for use by the TCSB in this study by the National Oceanic and Atmospheric Administration's Pacific Islands Fisheries Science Center on 24 February 2017. Unlike the SPC LL observer data, the Hawaii and American Samoa longline observer data files contain set header information for each species-specific catch record and so did not need to be joined. Data for all species recorded by observers were provided. In total the dataset contained 70,331 sets with 7,626 silky sharks (FAL) caught (Table A4).

TableA4. Number of observed sets and number of silky shark catch records in the US Hawaii and American Samoa longline observer data set provided for this study. Year-flag combinations without any observations are shaded in blue.

	Number of Sets		**Number of FAL catch records**	
Year	**Hawaii**	**American Samoa**	**Hawaii**	**American Samoa**
1995	538	0	27	NA
1996	638	0	24	NA
1997	497	0	22	NA
1998	579	0	59	NA
1999	454	0	97	NA
2000	1,396	0	257	NA
2001	2,713	0	638	NA
2002	3,307	0	847	NA
2003	3,081	0	180	NA
2004	3,927	0	329	NA
2005	5,928	0	194	NA
2006	4,162	235	582	90
2007	4,830	327	279	260
2008	5,055	269	171	88
2009	4,746	237	335	72
2010	5,036	890	190	403
2011	4,721	1,017	197	613
2012	4,696	592	251	208
2013	4,447	584	237	291
2014	4,914	515	259	426
Total	**65,665**	**4,666**	**5,175**	**2,451**

The field names in the US longline observer dataset are shown in Table A5. It was assumed that 17 values of longitude which were in the range of 530^{o}-540^{o}E were actually in the range of 230^{o}-240^{o}E and were changed accordingly.

Table A5. Data types extracted for the Hawaii and American Samoa longline observer set and catch datasets. (* indicates that the field was available in the Hawaii longline observer dataset only).

Data Set	**Fields Available**
Hawaiian and American Samoa Longline Observer (set header)	TRIP_NUM, VESSEL_FLAG, PERMIT_NUM, SET_NUM, SET_BEGIN_DATETIME, SET_END_DATETIME, HAUL_BEGIN_DATETIME, SET_BEGIN_LAT, SET_BEGIN_LON, HKS_PER_FLT, NUM_HKS_SET, LITE_DEVICE_TYPE_CODE_VAL, NUM_LITE_DEVICES, NUM_FLTS, NUM_FLTS_OBSRVD*, BAIT_CODE, BAIT_CODE_VAL, LDR_MAT_CODE, LDR_MAT_CODE_VAL, HOOK_TYPE_CODE_VALUE_1, HOOK_TYPE_CODE_VALUE_2, HOOK_TYPE_CODE_VALUE_3, HOOK_TYPE_CODE_VALUE_4, SPECIES_CODE, SPECIES_COMMON_NAME, HK_NUM, CAUGHT_COND_CODE_VAL, KEPT_RETURN_CODE_VAL

From the initial number of records shown in Table A4, the following number of sets (and FAL records) were removed sequentially:

- Removed due to missing lat/long information (9 sets and 2 FAL);
- Removed due to missing hooks fished values (6 sets and no FAL);
- Removed due to missing hooks between floats (22 sets and 7 FAL);
- Removed due to too many or too few hooks per set (280 sets and 4 FAL);
- Removed due to too many or too few hooks between baskets (186 sets and 4 FAL);
- Removed due to being outside the spatial boundaries of the assessment (387 sets and no FAL).

The rationale for applying these filters and for not applying other filters is given in Section 1.1.1 above. In total 890 sets contained 17 FAL were removed from the analysis, leaving 69,441 sets and 7,609 FAL. Over 94% of the sets recorded no catch of silky sharks. All catch and effort data were screened before plotting in accordance with the three-vessel rule (WCPFC 2007).

2.2 Data Exploration

US LL observer coverage is concentrated around Hawaii until 2006 when the American Samoa longline observer programme began (Table A4 and Figure A6). Although the number of observed sets in the US longline observer programme data is similar to that in the SPC longline observer dataset (compare Tables A1 and A4), the US observer coverage is focused on areas which have a relatively low amount of fishing effort compared to other areas in the Pacific (Figure A6). Another important distinction between the US and SPC LL observer datasets is the number of silky shark catch records. Despite the fact that a substantial proportion of the US observed effort lies within areas expected to be core habitat for the silky shark, i.e. 20° north and south of the equator, the number of catch records in the US LL dataset is only one-third of that in the SPC LL dataset. One advantage of the US LL observer dataset is that it appears to be relatively evenly distributed over consistent areas through time. Therefore, while the catch rates of silky shark are relatively low, the dataset may prove easier to standardize to obtain a relative abundance index.

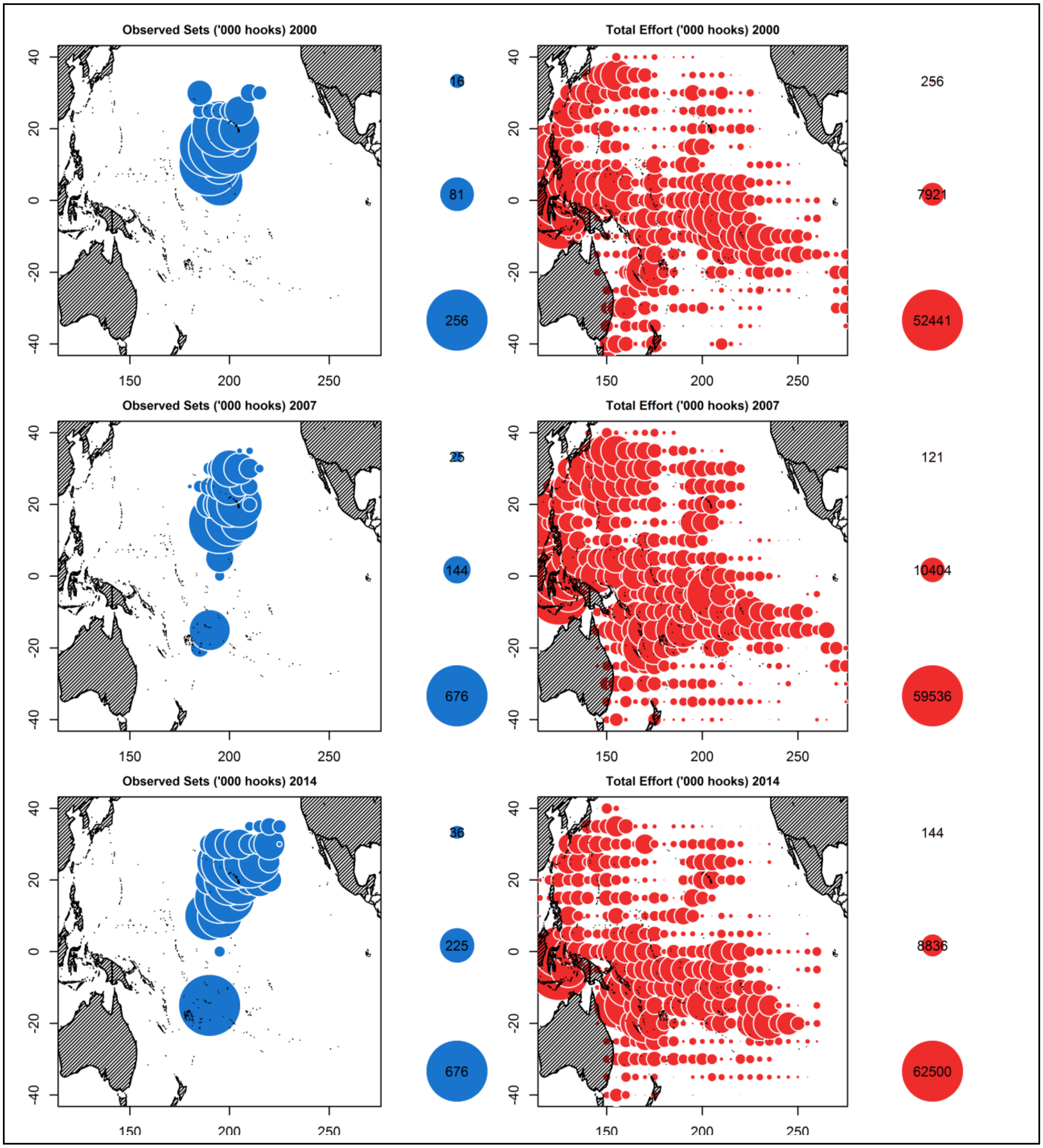


Figure A6. Distribution of observed effort relative to total effort (in thousand hooks) in the Pacific longline fishery (for comparison) for a sample of years (2000, 2007 and 2014) within the extracted US Hawaii and American Samoa LL observer and CES effort datasets. The size of the circles is proportional to the number of hooks fished in each 5°x5° cell (10th, 50th and 90th percentiles given as a legend). Actual set locations are rounded southward and westward to the nearest 5°x5° grid point and may be plotted over land as a result.

Silky shark catch per unit effort (CPUE) within the US Hawaii fishery by year and 5°x5° grid (Figure A7) show the pattern identified in Walsh & Clarke (2011) of the highest catch rates for silky sharks occurring at latitudes within 10° of the equator. Catch rates in the American Samoan fishery are often, but not always, lower than the southerly sets in the Hawaii fishery. Catch rates in the northern region of the Hawaii longline fishery are generally the lowest in this dataset.

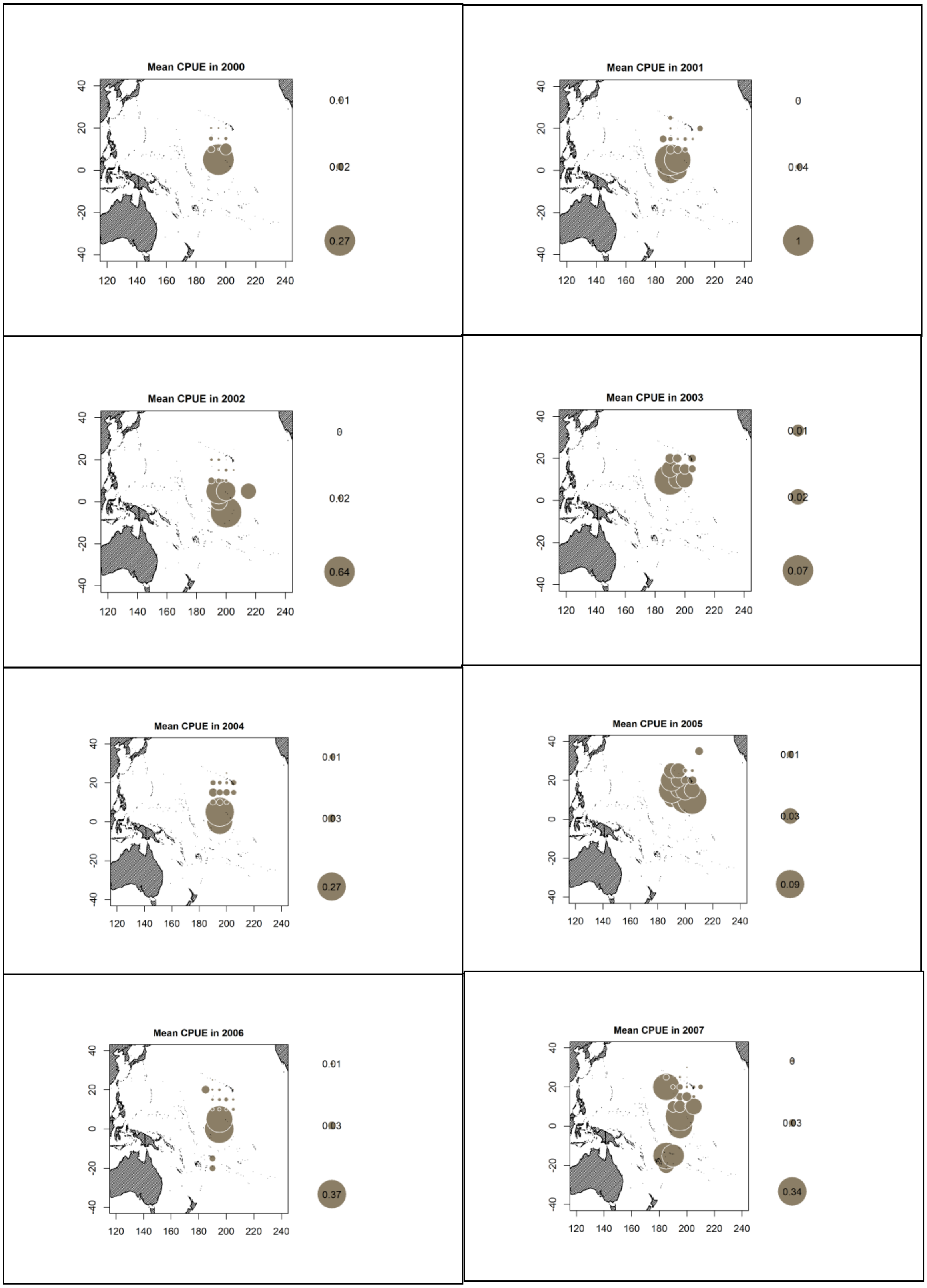


Figure A7a. Annual mean CPUE for silky shark in the US Hawaii and American Samoa LL observer dataset, 2000-2007. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). The legend is rounded to two significant figures.

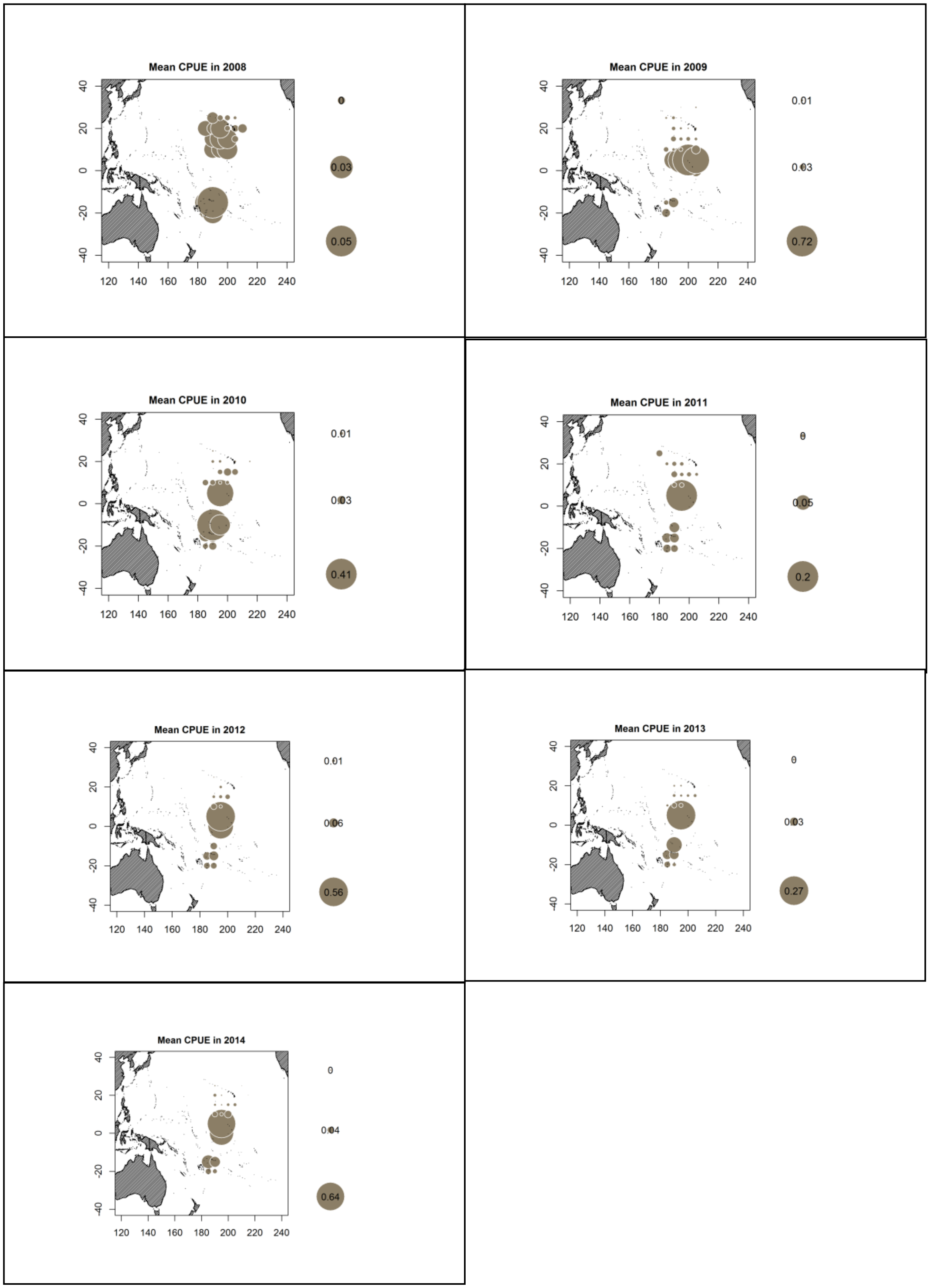


Figure A7b. Annual mean CPUE for silky shark in the US Hawaii and American Samoa longline observer dataset, 2008-2014. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). The legend is rounded to two significant figures.

In order to explore some of the potential explanatory variables that might be useful in standardizing the catch rate data to derive an abundance index, boxplots for latitude, longitude, year, month, hooks between floats and program code were constructed (Figure A8). Catch rates appear higher for shallow sets, the Hawaii fishery and in the latitudinal bands immediately adjacent to the equator.

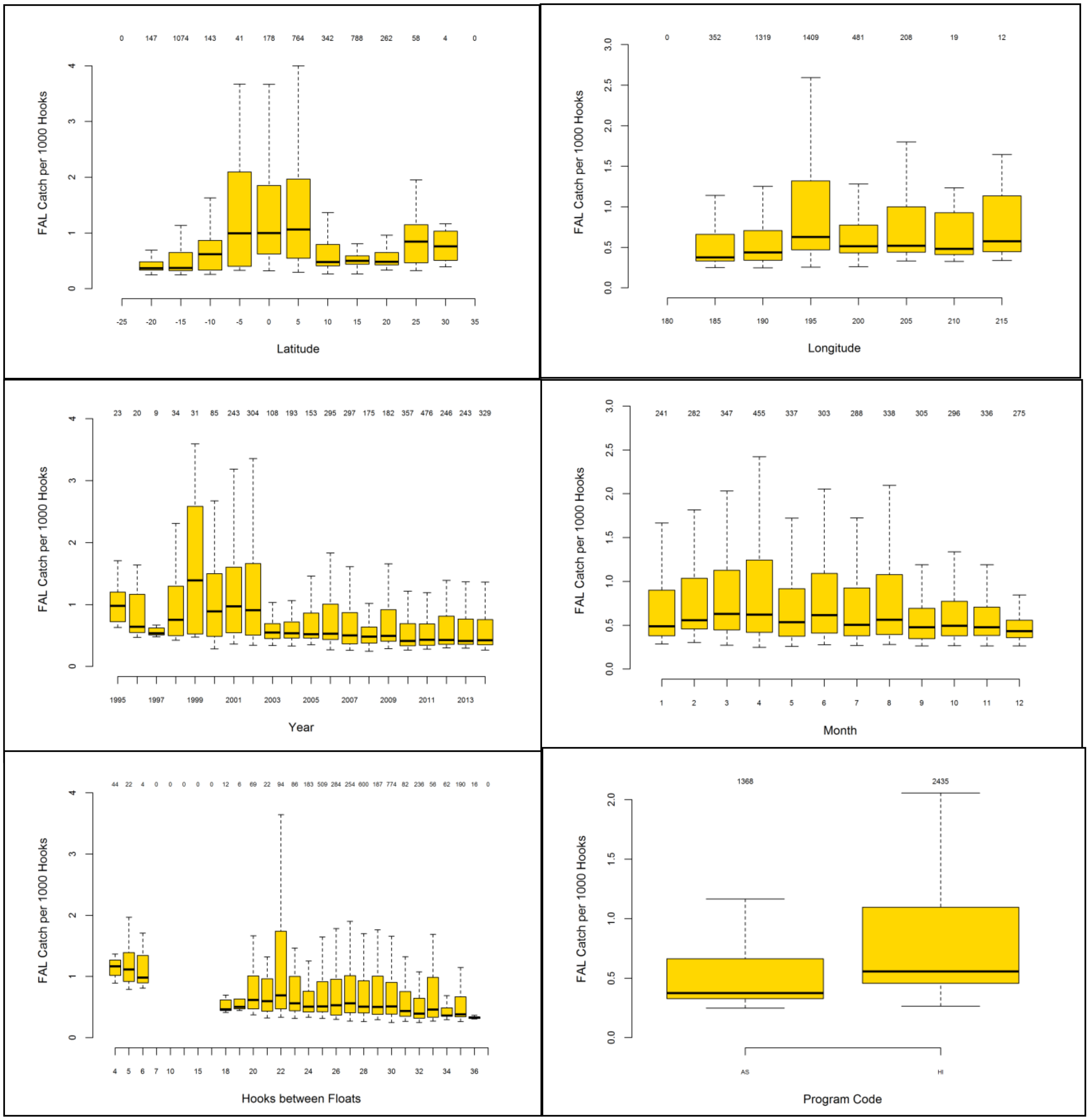


Figure A8. Box and whisker plots of potential explanatory variables in silky shark catch rates for sets with non-zero catch rates in the US LL observer dataset. The gold box shows the range between the 25th and 75th percentile (the interquartile range). The black line is the median. The whiskers are plotted at the most extreme data point which is no more than 1.5 times the interquartile range from the box (i.e. extreme outliers are not plotted). The sample size is annotated at the top of each column.

Nominal CPUE was plotted as the mean of set-by-set catch rates (i.e. catch of FAL divided by hooks fished for each set) by year for the Hawaii and American Samoa fisheries separately (Figure A9). As noted above, as this plot includes all catch records, rather than just the positive catches as shown above, differences between it and the boxplot for year shown in Figure A8 should be expected. The extreme fluctuations in relative abundance observed by Walsh & Clarke (2011) for the US longline fishery through 2010 are not apparent in recent years. Such fluctuations are not uncommon in catch rate indices but nevertheless are biologically improbable given the slow growth and reproductive rates of elasmobranchs. Although the previous study did not find that standardization appreciably changed the nominal index, standardization of the updated nominal times series must be attempted before there can be any confidence in its reliability as an index of abundance.

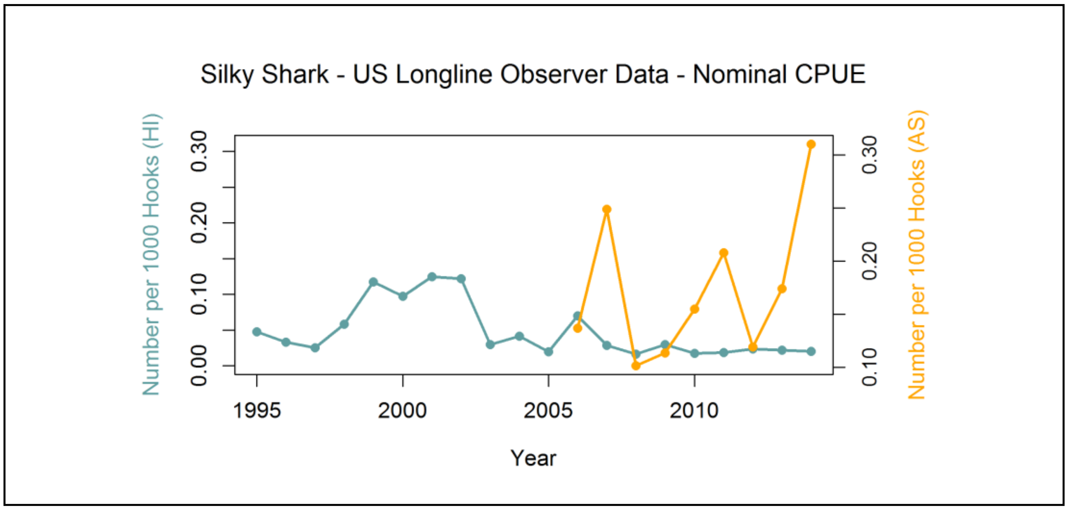


Figure A9. Nominal annual mean CPUE (i.e. mean of individual set catch rates) in the US LL observer dataset, 1995-2014 for Hawaii (HI) and American Samoa (AS) fisheries.

Biological data on silky shark length and sex was requested from the PIFSC in March 2017 and provided in April 2017. A total of 183 length records were provided for 2003-2017 with an average of 13 silky shark lengths measured each year (maximum n=55, minimum n=1). PIFSC staff report that the lengths are estimated to the nearest foot (30.5 cm). The sex of the shark was not recorded (or not provided). Given the low information content of the US longline observer length data for silky shark, no further data exploration was undertaken.

3 Japan Longline Observer Data

3.1 Data Description

Japan agreed to provide data from its Pacific longline observer programme for use in this study on 15 February 2017. Catch data for silky shark only were provided on 16 March 2017 (revised on 21 April 2017) and biological data for silky shark only were provided on 21 April 2017. In comparison to the SPC and US LL observer programmes, the Japan programme has been operating for a much shorter period but it is valuable because it provides coverage of geographic areas not covered by the other two datasets. In total the Japan dataset contained 9,775 sets with 1,579 silky sharks (FAL) caught (Table A6). However, there were 322 sets which did not record any date information, therefore these sets are not shown in the table and were removed from the dataset. They contained 7 silky sharks.

Table A6. Number of observed sets and number of silky shark catch records in the Japan longline observer data set provided for this study (after initial filtering). Years with zero silky sharks recorded are shaded in red.

Year	Sets	Silky Shark Catch
2007	12	0
2008	144	0
2009	93	0
2010	151	12
2011	397	10
2012	975	86
2013	1,804	211
2014	2,297	670
2015	2,999	510
2016	903	80
Total	**9,775**	**1,579**

The field names in the Japan longline observer dataset are shown in Table A7.

TableA7. Data types extracted for the Japan longline observer set and catch dataset.

Key Data Set	Fields Available
Japanese Longline Observer Dataset	CallSign, SetID, SST, SetStart, LatSetStart, LonSetStart, SetEnd, LatEnd, LonEnd, HaulStart, LatHaulStart, LonHaulStart, HaulEnd, LatHaulEnd, LonHaulEnd, hpb, Hooks, ObsHooks, Bait1, Bait2, Bait3, Bait4, Bait5, Target, HookType1, HookType1Ratio, HookType2, HookType2Ratio, MainLineMaterial, BranchLineMaterial, WireLeader, HookswithWireLeader, FAL

From the initial number of records shown in Table A6, the following number of sets (and FAL records) were removed sequentially:

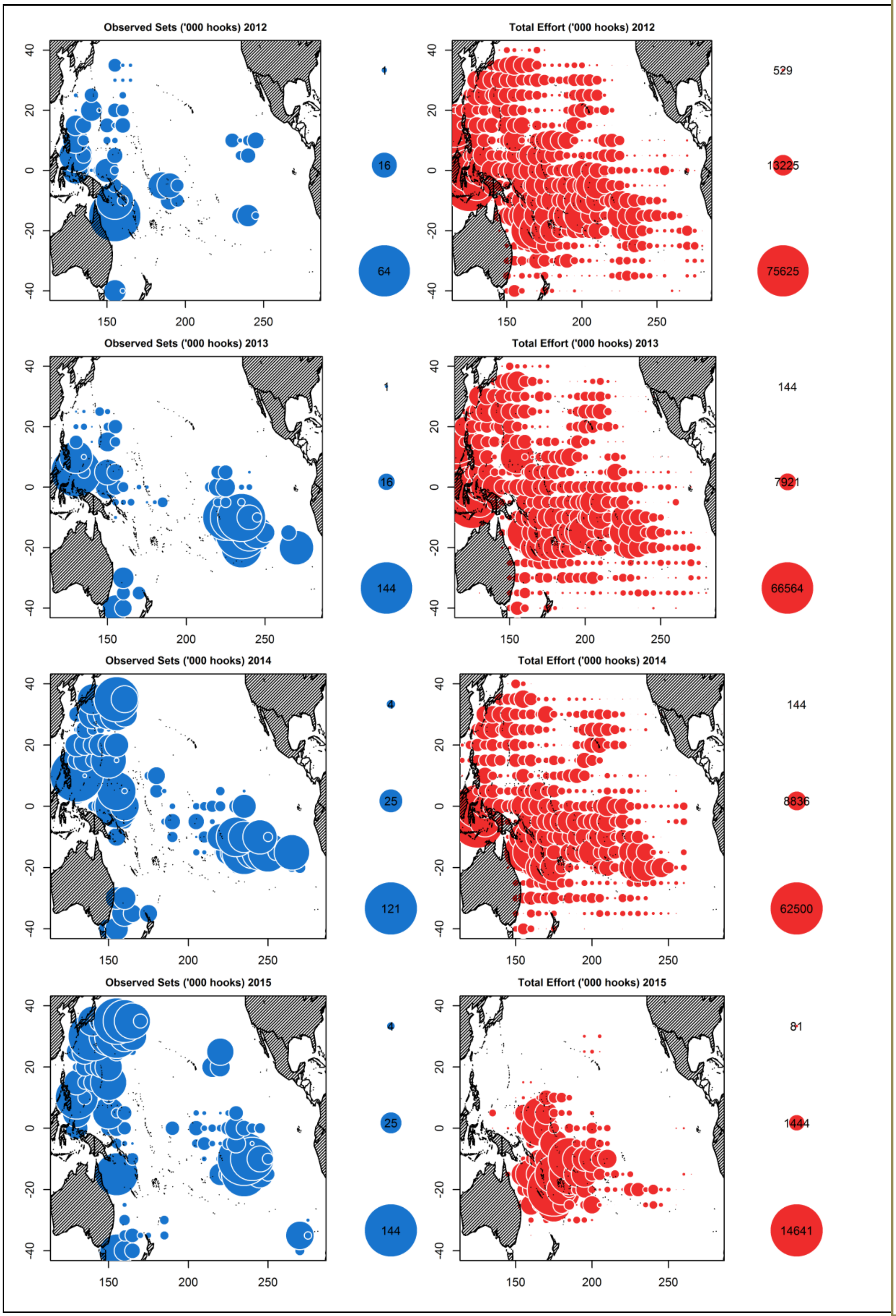
- Removed due to missing lat/long information (1 set and no FAL);
- Removed due to missing hooks fished values (286 sets and 2 FAL);
- Removed due to missing hooks between floats (no sets and no FAL);
- Removed due to too many or too few hooks per set (7 sets and no FAL);
- Removed due to too many or too few hooks between baskets (142 sets and 5 FAL);
- Removed due to being outside the spatial boundaries of the assessment (850 sets and 35 FAL).

The rationale for applying these filters and for not applying other filters is given in Section 1.1.1 above. The spatial filter was relaxed slightly to the east from 230°E to 280°E to account for Japan's longline fishery in the Eastern Pacific Ocean which would likely encounter silky shark. Most of the removed sets were south of 40°S. In total 1,286 sets were removed from the analysis, containing 42 FAL, leaving 8,489 sets and 1,537 FAL. Nearly 93% of the sets recorded no catch of silky sharks.

3.2 Data Exploration

Japan's longline observer data is distributed in three distinct areas: the southern bluefin tuna fishery below 30°S, the Eastern Pacific fishery at or just south of the equator, and the Western Pacific fishery west of 160°E in tropical and subtropical waters (Figure A10). Although it represents only a short time series it provides a useful complement to the SPC LL observer dataset which is concentrated in the southern hemisphere of the Western and Central Pacific, and the Hawaii LL observer dataset in the north Central and Eastern Pacific. It should also be noted that the total number of hooks observed is lower than the other datasets.

Silky shark catch per unit effort (CPUE) for the last five years of the Japan LL observer dataset are plotted by year and 5°x5° grid in Figure A11. Even though these data provide useful 'snapshot' information for the offshore Eastern Pacific, and may thus help link to data being compiled by IATTC, their temporal coverage will not provide a sufficient basis for any indices of abundance. It appears that within the Japan LL observer dataset catch rates are lower in the Eastern and Central Pacific than in the Western Pacific. This pattern is similar to that shown in the SPC longline dataset (compare to Figure A2).



FigureA10. Distribution of observed effort relative to total effort (in thousand hooks) in the Pacific longline fishery (for comparison) for a sample of years (2012-2015) within the Japan longline observer and CES effort datasets (CES effort for 2015 appears to be incomplete and will be updated). The size of the circles is proportional to the number of hooks fished in each 5ox5o cell in thousands of hooks (10th, 50th and 90th percentiles given as a legend). Actual set locations are rounded southward and westward to the nearest 5ºx5º grid point and may be plotted over land as a result.

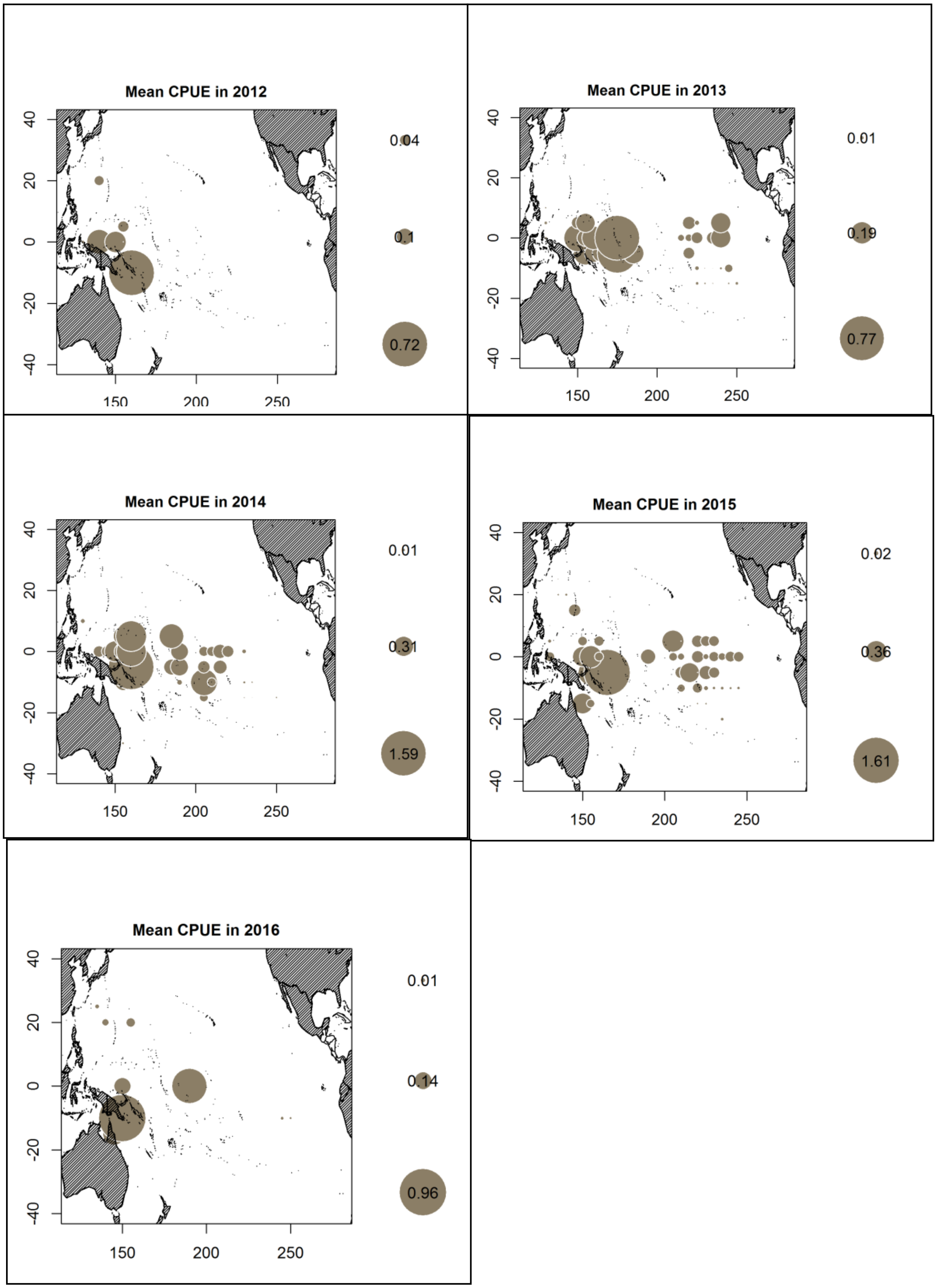


Figure A11. Annual mean CPUE for silky shark in the Japan longline observer dataset, 2012-2016. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). The legend is rounded to two significant figures.

Exploration of the Japan LL observer dataset highlights its small sample size and focus on specific areas (Figure A12). Only a small range of latitudes and longitudes are sampled with reasonable statistical power, and as shown in Figure A11, areas to the west tend to have higher catch rates. Despite the potential information in the dataset, the sample sizes are too small to allow any conclusions to be drawn regarding hooks between floats (almost all > 16) and the use of wire leaders.

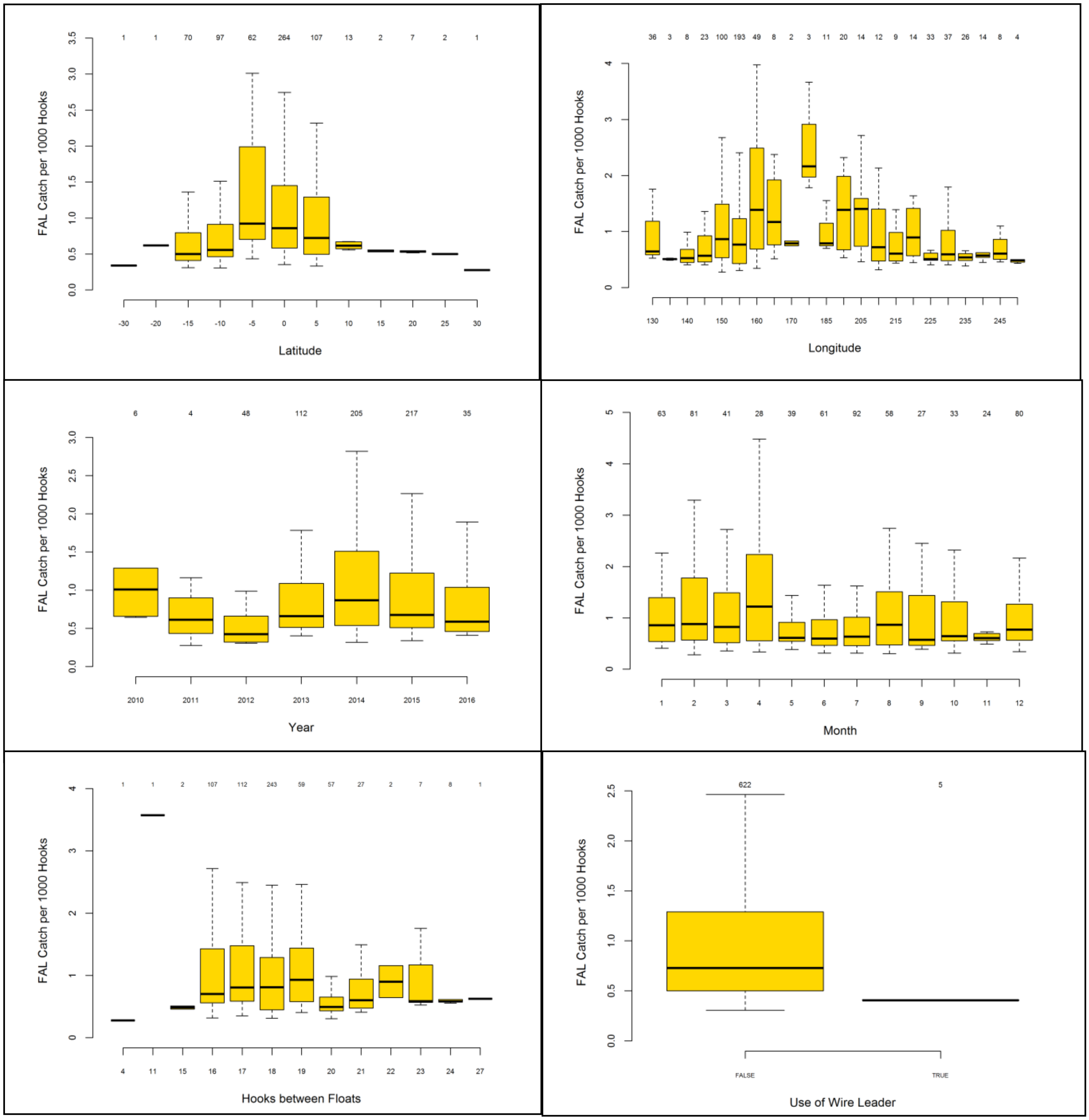


Figure A12. Box and whisker plots of potential explanatory variables in silky shark catch rates for sets with non-zero catch rates in the Japan longline observer dataset. The gold box shows the range between the 25th and 75th percentile (the interquartile range). The black line is the median. The whiskers are plotted at the most extreme data point which is no more than 1.5 times the interquartile range from the box (i.e. extreme outliers are not plotted). The sample size is annotated at the top of each column.

Nominal CPUE for the Japan LL observer dataset is not particularly interesting as the time series is very short and the observations prior to 2012 are very few in number (Figure A13). All of the caveats expressed above regarding unstandardized catch rate indices apply even more strongly to this time series.

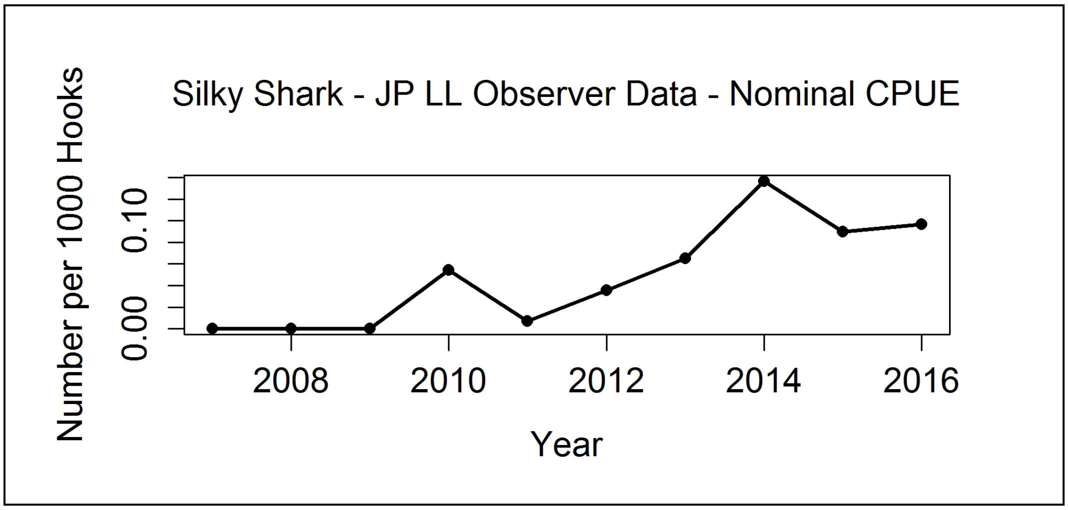


Figure A13. Nominal annual mean CPUE (i.e. mean of individual set catch rates) in the Japan LL observer dataset, 2007-2016.

Biological data on silky shark length and sex was provided in a separate dataset consisting of 1,217 records. Sex was recorded for most records with n=533 females and n=519 males measured; records without sex were removed (n=157). The unit of length was given as either fork length (n=4) or pre-caudal length (n=1022); records without the unit recorded were removed (n=26). To be consistent with the SPC dataset (both longline and purse seine), pre-caudal lengths (PCL) were converted to fork lengths (FL) using the conversion factor equation FL=(PCL*1.09)+1.10 from Joung et al. (2008) as reviewed in Clarke et al. (2015). Sample sizes are small but it is interesting to note larger sizes in the Central and Eastern Pacific as compared to the Western Pacific off Papua New Guinea (Figure A14). This pattern was also noted in the SPC LL observer dataset (compare to Figure A5).

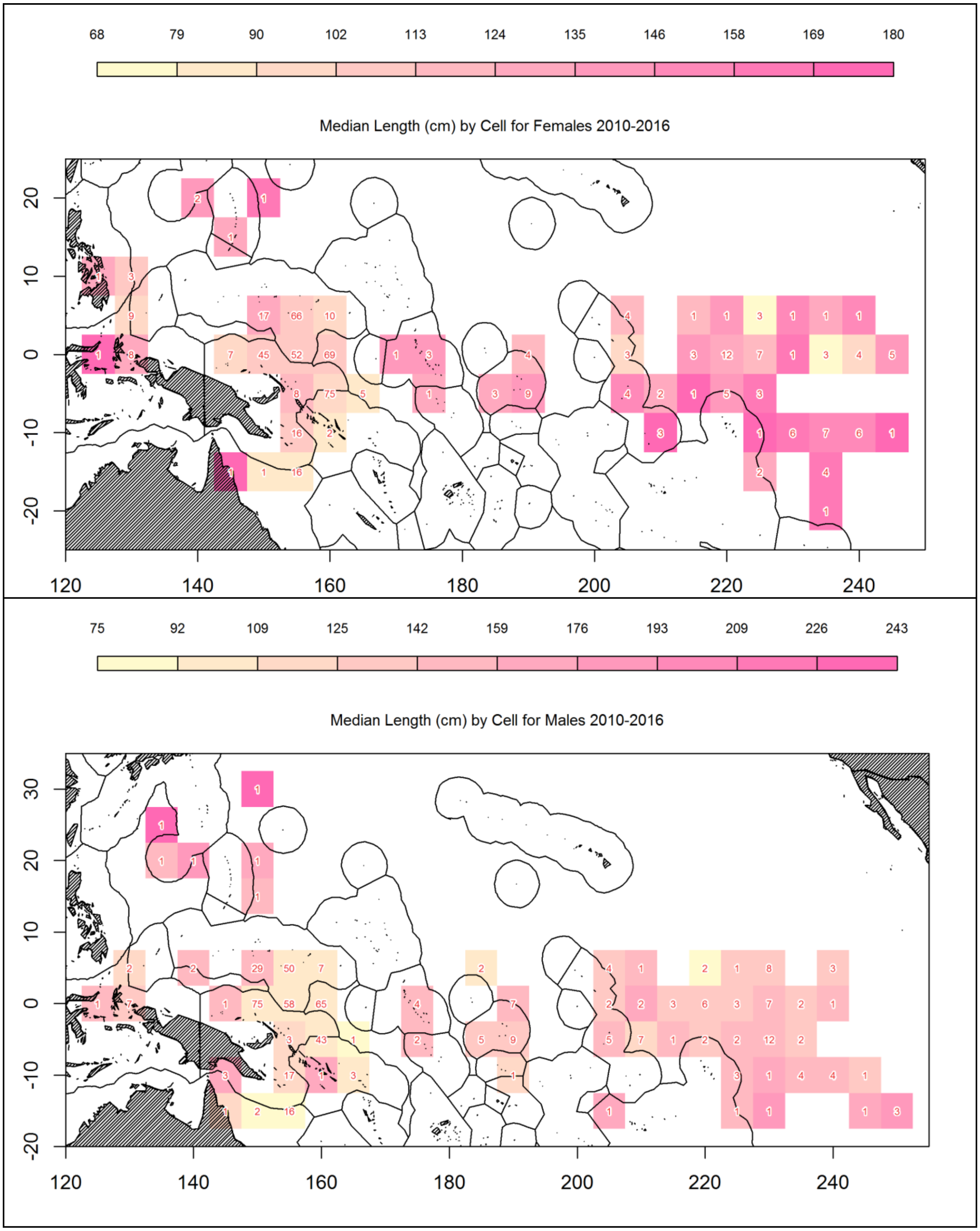


Figure A14. Mapping of median length on a relative scale for female and male silky sharks in the Japan LL observer database, 2010-2016. All lengths shown are in cm fork length (see text for conversion factors). The number annotated in each 5°x5° degree cell is the number of measured sharks.

4 Regional Observer Programme PS Observer Data

4.1 Data Description

The Regional Observer Programme (ROP) purse seine observer data are a WCPFC dataset and thus accessible to the WCPFC Secretariat, however, they are maintained by the Scientific Services Provider and must be extracted from the more comprehensive purse seine observer dataset maintained by SPC. The ROP PS observer data were extracted several times, most recently on 31 March 2017. As for the SPC LL observer data there are two files: one file contains set-level information with one row per set ("Set Header", Table A8) and one file contains catch records for individual fish with one row per fish caught ("Catch", Table A9). The catch dataset contains all species in order to explore potential explanatory variables associated with the catch of target species. Two other datasets on net characteristics and FAD characteristics were obtained and linked to the set header to provide additional potential explanatory variables for catch rate standardization. The field names for the data in each file are shown in Table A10; explanations of the fields and how they are collected can be found in SPC (2017b).

To link each catch record to its set characteristics, a unique identifier was created by combining set identifiers and trip identifiers in the set database. From the joined dataset containing 239,975 sets and 375,706 silky sharks (FAL), the following number of sets (and FAL records) were removed sequentially:

- Removed due to missing lat/long information (7 sets and 1 FAL);
- Removed due to being outside the spatial boundaries of the assessment (38 sets and 43 FAL); and
- Removed due to missing information on the set type (associated or unassociated) (8,539 sets and 16,614 FAL);
- Removed an extreme value of silky shark count in one set (1 set and 14,285 FAL); and
- Removed due to not being within the year range of sufficient observer coverage and reliable species identification (16,589 sets and 17,362 FAL).

Missing and extreme values (latitude, longitude, set type, silky shark counts) were removed due to the potential bias they could impart to catch rate standardizations. The spatial filter was relaxed slightly to the east from 230^{o}E to 280^{o}E to allow for potential cross-endorsed observer trips in recent years and to provide additional biological information for the tropical Eastern Pacific for comparison to other data sets. Data from 2017 were incomplete and thus excluded. The beginning of the year range (2004) was selected on the basis of discussion in Rice (2013) which illustrates that until the early 2000s silky sharks are likely to have been recorded as unidentified sharks. While the trend toward better species identifications was a gradual one, 2004 was selected as a conservative assumption and as a year in which the number of observed sets increased considerably over previous years. In total 25,174 sets, containing 48,305 FAL, were removed from the analysis, leaving 214,801 sets and 327,401 FAL. Over 95% of the unassociated sets recorded no catch of silky sharks; in contrast, only 60% of the associated sets recorded no catch of silky sharks. All catch and effort data were screened before plotting in accordance with the three-vessel rule (WCPFC 2007).

Table A8. Number of observed sets by flag and year extracted for this study (before filtering) from the ROP PS observer dataset. Year-flag combinations without any observations are shaded in blue.

SET	CN	EC	ES	FM	JP	KI	KR	MH	NZ	PG	PH	SB	SV	TV	TW	US	VU	TOTAL
1993	-	-	-	33	152	-	57	-	-	-	-	-	-	-	68	-	-	310
1994	-	-	-	66	99	-	275	-	33	-	-	-	-	-	182	580	-	1,235
1995	-	-	-	46	115	57	30	-	-	71	-	-	-	-	152	743	19	1,233
1996	-	-	-	9	118	35	64	-	45	-	-	-	-	-	-	1,282	-	1,553
1997	-	-	-	-	48	44	80	-	35	82	-	-	-	-	121	1,482	-	1,892
1998	-	-	-	78	57	60	298	-	-	13	-	14	-	-	797	1,006	38	2,361
1999	-	-	-	27	29	19	321	-	-	19	-	86	-	-	305	573	20	1,399
2000	-	-	-	82	117	13	257	-	25	85	-	45	-	-	382	800	-	1,806
2001	-	-	-	72	123	10	138	28	29	60	-	31	-	-	186	1,095	-	1,772
2002	-	-	-	163	94	112	40	78	-	110	-	156	-	-	188	1,138	-	2,079
2003	-	-	-	157	132	72	161	158	17	549	-	116	-	-	65	661	9	2,097
2004	-	-	-	219	139	24	429	256	26	984	-	160	-	-	353	807	138	3,535
2005	-	-	-	183	100	25	358	313	43	751	61	74	-	-	503	528	257	3,196
2006	7	-	-	106	106	75	266	522	26	1,255	-	-	-	-	126	485	29	3,003
2007	-	-	-	87	112	35	270	573	4	1,473	-	67	-	-	300	397	282	3,600
2008	-	-	28	147	98	54	411	450	34	532	-	131	-	-	124	1,503	39	3,551
2009	347	-	4	193	593	140	698	603	77	1,309	510	-	53	25	770	2,894	214	8,430
2010	1,767	372	266	587	3,616	527	4,213	1,211	165	3,419	81	39	145	345	3,989	7,803	662	29,207
2011	1,279	464	137	918	4,284	637	3,735	1,071	189	2,970	493	112	143	228	3,726	5,744	710	26,840
2012	1,152	222	271	807	4,708	1,215	3,554	1,551	343	3,622	422	283	37	271	4,265	7,735	582	31,040
2013	2,667	434	685	115	4,950	1,173	5,009	2,046	215	3,999	755	136	175	205	5,944	7,450	556	36,514
2014	1,882	391	468	736	3,582	1,479	2,881	1,938	165	3,276	823	384	313	92	5,315	8,831	355	32,911
2015	2,121	87	153	1,463	2,209	1,615	1,566	2,085	99	4,591	928	443	83	141	3,890	6,445	166	28,085
2016	936	-	44	1,051	1,941	1,038	337	833	152	2,023	660	122	35	48	1,946	1,029	69	12,264
2017	-	-	-	-	52	-	-	-	-	4	-	-	-	-	2	-	-	58
TOTAL	12,158	1,970	2,056	7,345	27,574	8,459	25,448	13,716	1,722	31,197	4,733	2,399	984	1,355	33,699	61,011	4,145	239,971

Table A9. Number of FAL catch records (each record is one shark) by flag and year extracted for this study (before filtering) from the ROP PS observer dataset. Year-flag combinations without any observations are shaded in blue. Year-flag combinations with zero silky sharks recorded are shaded in red.

CATCH	CN	EC	ES	FM	JP	KI	KR	MH	NZ	PG	PH	SB	SV	TV	TW	US	VU	TOTAL
1993	NA	NA	NA	-	-	NA	-	NA	NA	NA	NA	NA	NA	NA	-	NA	NA	-
1994	NA	NA	NA	-	-	NA	-	NA	-	NA	NA	NA	NA	NA	173	-	NA	173
1995	NA	NA	NA	87	192	-	-	NA	NA	183	NA	NA	NA	NA	3	-	-	465
1996	NA	NA	NA	170	108	-	32	NA	-	NA	NA	NA	NA	NA	NA	-	NA	310
1997	NA	NA	NA	NA	164	-	95	NA	-	11	NA	NA	NA	NA	27	-	NA	297
1998	NA	NA	NA	-	31	30	29	NA	NA	-	NA	-	NA	NA	598	419	-	1,107
1999	NA	NA	NA	-	-	-	63	NA	NA	-	NA	356	NA	NA	360	679	-	1,458
2000	NA	NA	NA	52	150	-	110	NA	-	136	NA	7	NA	NA	59	928	NA	1,442
2001	NA	NA	NA	139	256	7	92	51	-	93	NA	-	NA	NA	519	3,986	NA	5,143
2002	NA	NA	NA	216	339	261	1	18	NA	15	NA	1,043	NA	NA	114	522	NA	2,529
2003	NA	NA	NA	324	113	78	58	312	-	859	NA	847	NA	NA	67	2,485	15	5,158
2004	NA	NA	NA	716	353	58	375	348	5,866	2,169	NA	3,178	NA	NA	750	2,779	220	16,812
2005	NA	NA	NA	1,257	474	-	1,156	324	-	705	956	284	NA	NA	850	1,332	93	7,431
2006	6	NA	NA	124	232	291	381	1,267	107	2,866	NA	NA	NA	NA	173	1,790	41	7,278
2007	NA	NA	NA	343	115	61	535	426	14	2,206	NA	144	NA	NA	429	750	129	5,152
2008	NA	NA	127	225	128	71	166	246	96	313	NA	993	NA	NA	112	1,264	241	3,982
2009	1,219	NA	2	307	2,294	159	127	581	51	2,051	327	NA	762	1	3,183	2,566	70	13,700
2010	777	911	3,824	731	2,690	352	2,562	2,498	959	4,459	101	127	863	155	4,825	13,592	378	39,804
2011	1,860	1,600	394	3,065	15,771	2,333	3,215	17,323	600	5,022	599	211	1,247	60	5,817	33,012	460	92,589
2012	962	203	668	1,451	4,097	2,089	1,478	1,025	113	2,459	201	728	1,680	10	3,288	6,122	214	26,788
2013	2,435	1,002	15,857	66	6,033	1,025	2,867	1,463	114	3,728	466	555	215	10	5,691	6,774	361	48,662
2014	2,086	2,455	2,410	1,567	6,758	1,326	1,156	2,419	136	3,788	860	1,325	856	62	5,375	7,306	418	40,303
2015	1,672	464	981	2,532	1,857	599	3,947	1,760	28	4,215	999	1,048	237	44	6,125	5,590	243	32,341
2016	991	NA	251	2,519	3,527	1,066	570	1,109	9	3,063	1,491	131	12	79	4,719	3,151	49	22,737
2017	NA	NA	NA	NA	45	NA	NA	NA	NA	-	NA	NA	NA	NA	-	NA	NA	45
TOTAL	12,008	6,635	24,514	15,891	45,727	9,806	19,015	31,170	8,093	38,341	6,000	10,977	5,872	421	43,257	95,047	2,932	375,706

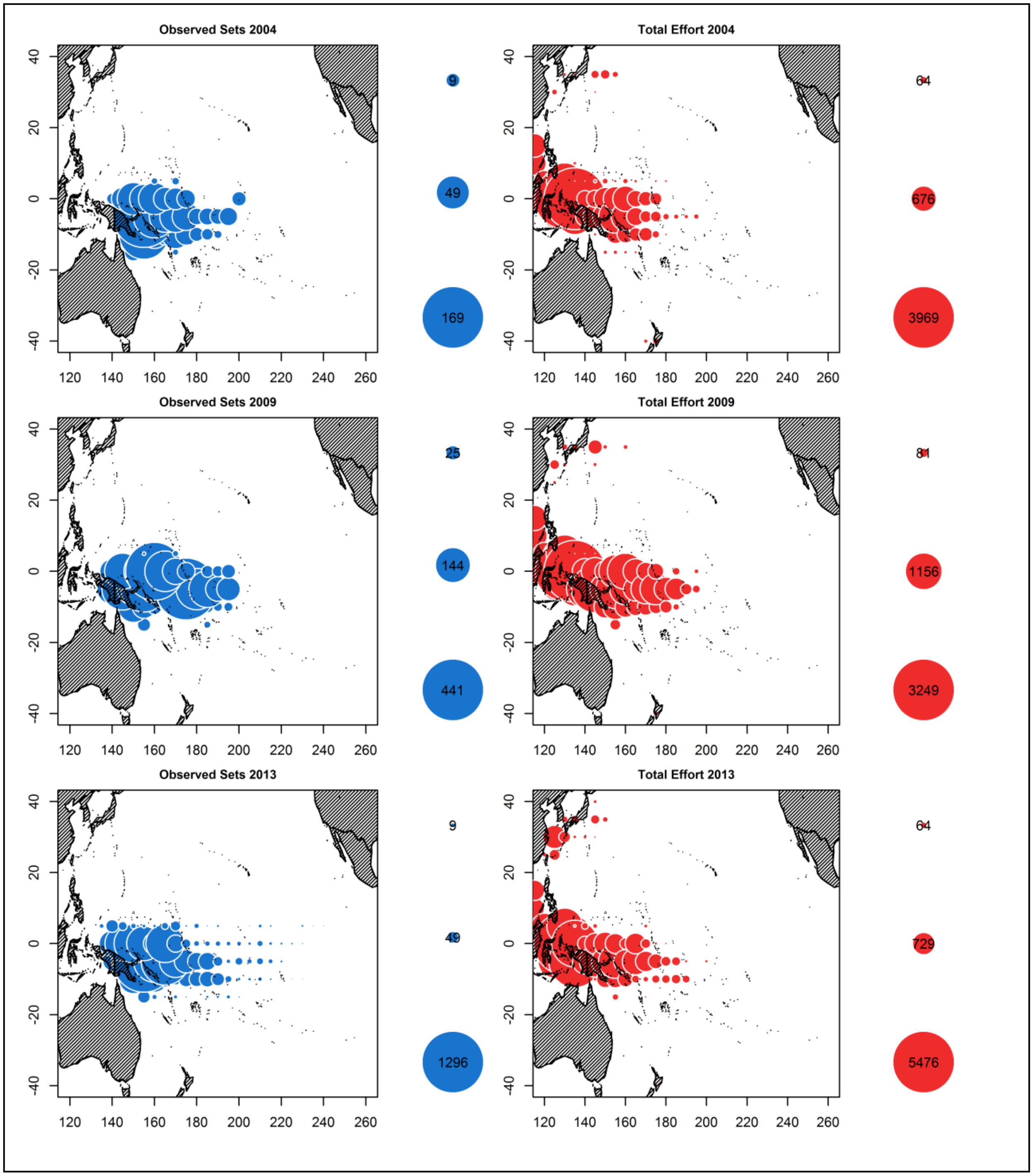
Table A10. Data types extracted for the ROP purse seine observer set and catch datasets.

Data Set	**Fields Available**
Set Header	obstrip_id, obsprg_code, flag, vessel_id, set_id, Set_number, Start_of_set, Skiff_off, Winch_on, Rings_up, Begin_brailing, End_of_brailing, End_of_set, lat, lon, schtype_id, eez_code
Catch Data	obstrip_id, obsprg_code, flag, vessel_id, set_id, act_date, act_time, lat, lon, schtype_id, eez_code, sp_code, fate_code, sp_c_est, sp_n_est, cond_code
Net Characteristics	obstrip_id, tripno, vessel_id, trip_year, net_depth, net_depth_unit, net_depth_m, net_length, net_length_unit, net_length_m, net_strips, net_hang_ratio, mesh_main, mesh_main_unit, mesh_main_cm, brail_size1, brail_size2, brail_type
FAD Characteristics	obstrip_id, tripno, internal_FAD_ID, object_number, origin, date, lat, lon, latd, lond, how_detected, as_found, as_left, max_depth_m, length_m, width_m, comments, main_net_size, attach_net_size, ssi_seen, fad_lifted, material_code, is_attachment

4.2 Data Exploration

Unlike the SPC LL observer dataset, the ROP observer dataset, after cleaning and filtering, overlaps most of the core area of the fishery in the equatorial WCPO (Figure A15). Nevertheless, there is limited or no coverage in other areas, some of which have non-negligible purse seine effort, e.g. primarily the area between Indonesia, the Philippines and Papua New Guinea, but also off Japan and in the East China Sea. While the latter area is not core habitat for silky shark, the former area is likely to encounter this species in substantial numbers and is not accounted for in this, or any other known available, observer dataset. While observer coverage does not appear to have spatially shifted over time, the progression of years in Figure A15 illustrates the increasing percent coverage gained through the implementation of the requirement for 100% observer coverage in the tropical (20°N-20°S) purse seine fishery since January 2010. Some data are available for analysis but are not plotted in the figure due to the three vessel rule, but for the ROP PS observer dataset these filtered data points are very few in number.

Silky shark catch per unit effort (CPUE) by year and 5°x5° grid in the ROP PS observer dataset are shown in Figure A16. In recent years, i.e. when observer coverage rates are higher and the purse seine fishery has expanded to the east due to climatic conditions, catch rates appear to be as high or higher in the Central Pacific than they are in the traditional core area of the fishery off Papua New Guinea. It is important to note that sample sizes in the central Pacific are quite small and may thus be unrepresentative of overall stock conditions. Nevertheless, the presence of high catch rates in the Central Pacific suggests the utility of further exploration of the population connectivity between silky sharks found in western and eastern areas of the Pacific basin.



FigureA15. Distribution of observed effort (in number of sets) relative to total effort (in standardized days fished) in the Western and Central Pacific purse seine fishery (for comparison) for a sample of years (2004, 2009 and 2013) within the extracted ROP PS observer and CES effort datasets. The size of the circles is proportional to the amount of effort in each 5°x5° cell (10th, 50th and 90th percentiles given as a legend). Actual set locations are rounded southward and westward to the nearest 5°x5° grid point and may be plotted over land as a result.

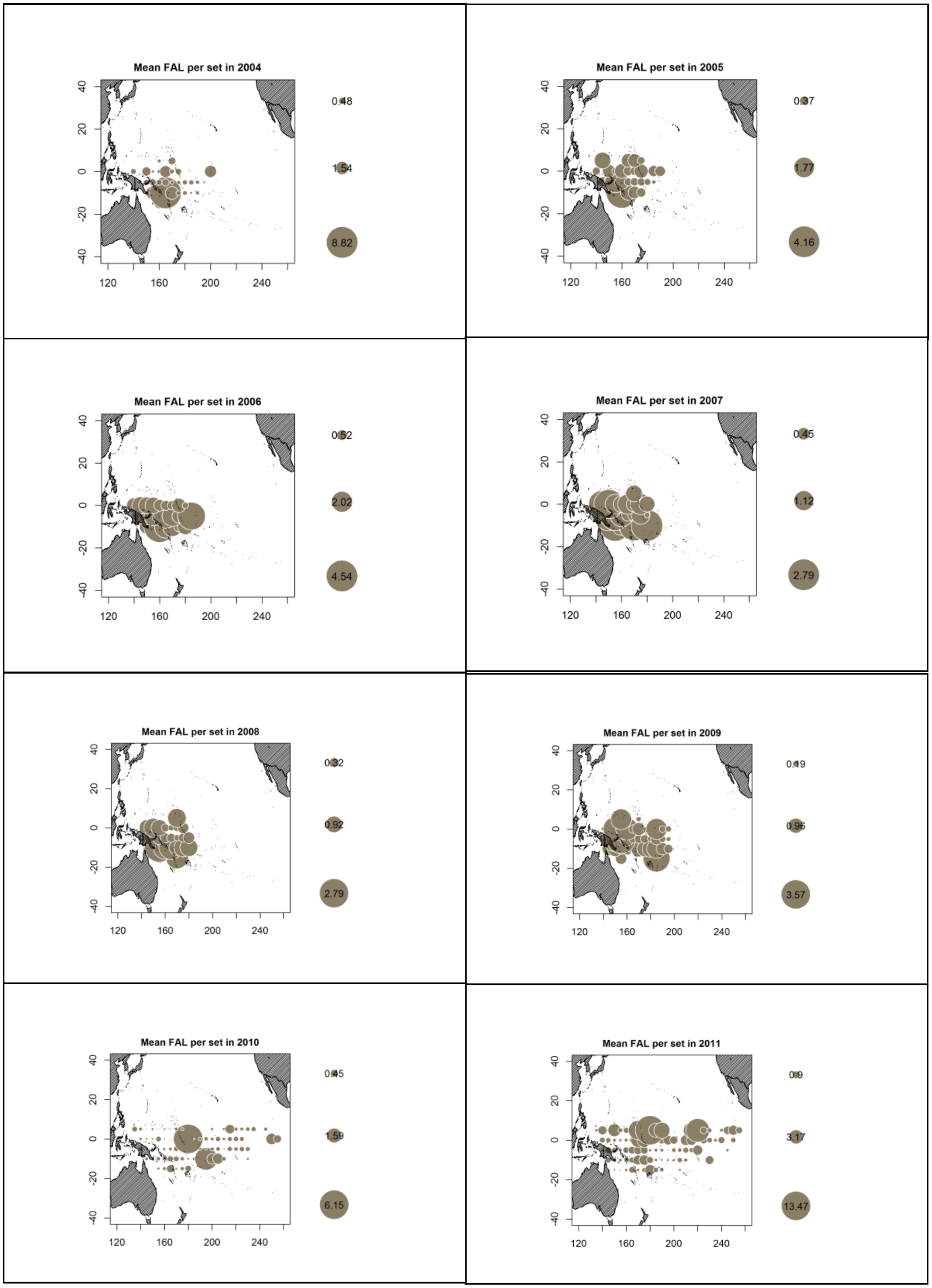


Figure A16a. Annual mean CPUE for silky shark in the ROP PS observer dataset, 2004-2011. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). Actual set locations are rounded southward and westward to the nearest 5°x5° grid point and may be plotted over land as a result.

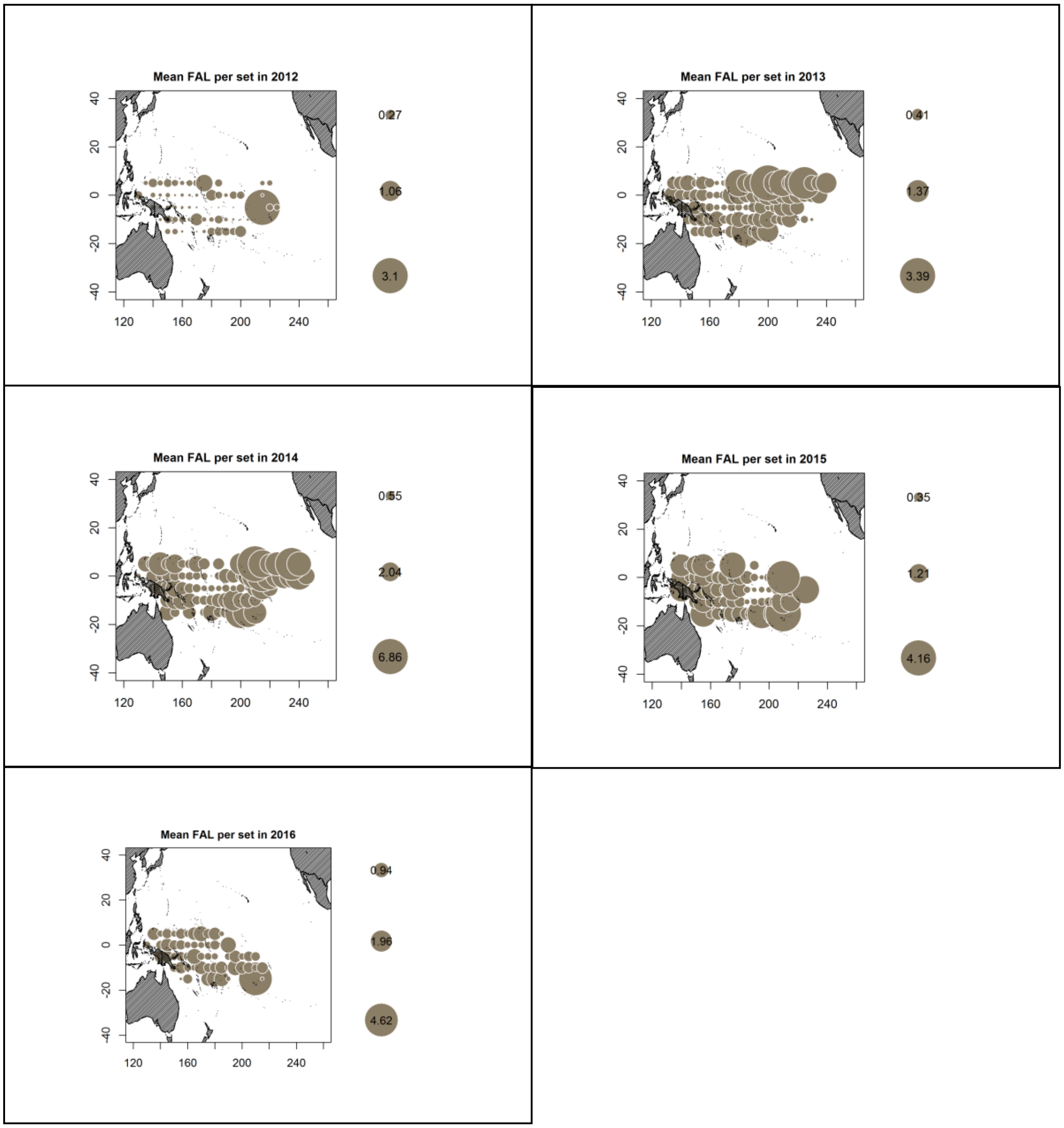


Figure A16b. Annual mean CPUE for silky shark in the ROP PS observer dataset, 2012-2016. The size of the circle is proportional to the CPUE as shown in the legend (10th, 50th and 90th percentiles). Actual set locations are rounded southward and westward to the nearest 5°x5° grid point and may be plotted over land as a result.

A selection of potential explanatory variables for catch rate standardization in purse seine fisheries are presented in Figure A17. The only clear difference in the plots is between the catch rates for associated (ASS) and unassociated (UNA) set types. There are remarkably few visible differences in the temporal or spatial variables, but certain specific areas (250°E longitude and 5°N latitude) demonstrate high catch rates in relatively small samples sizes.

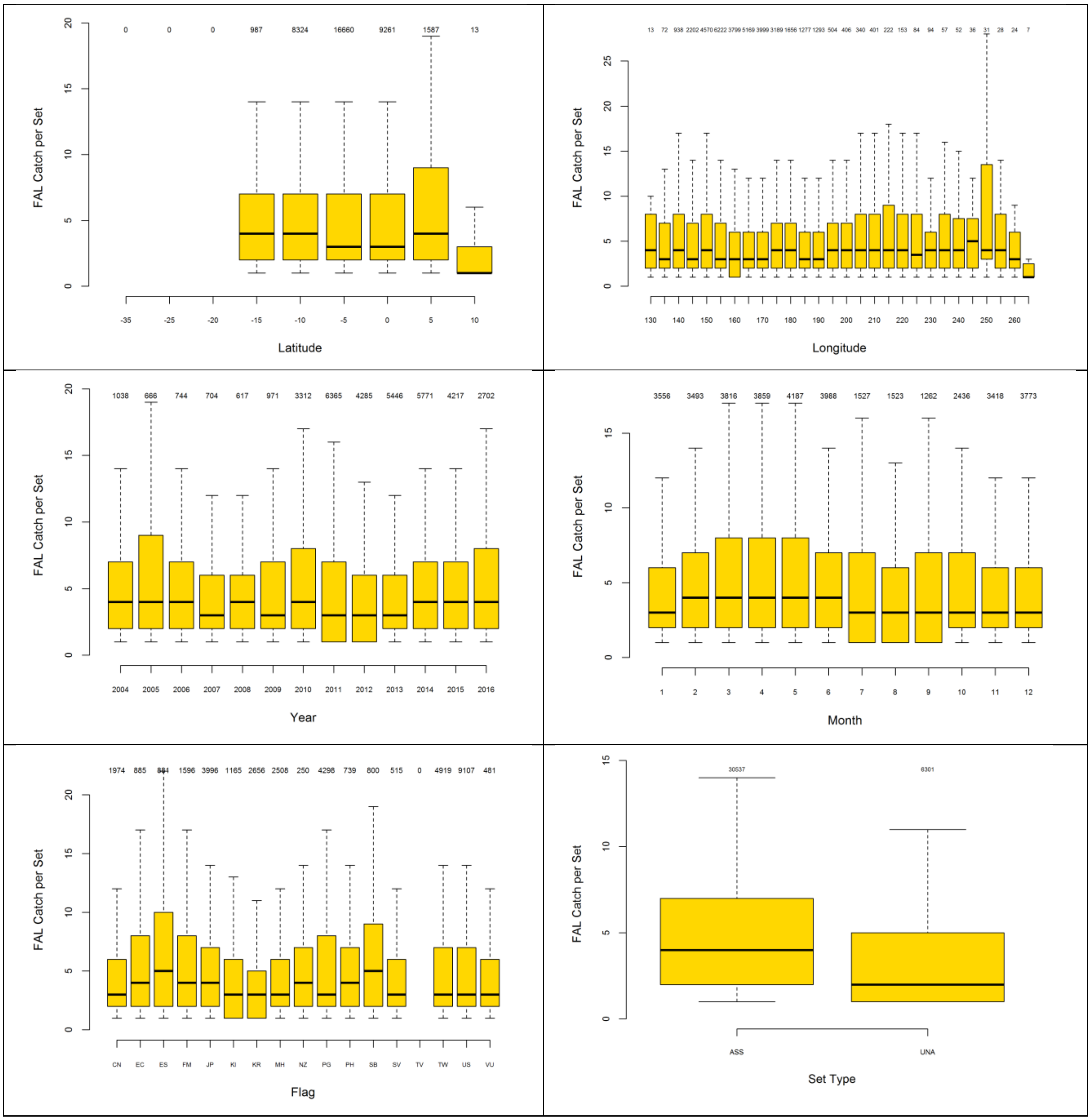


Figure A17. Box and whisker plots of potential explanatory variables in silky shark catch rates for purse seine sets with non-zero catch rates. The gold box shows the range between the 25th and 75th percentile (the interquartile range). The black line is the median. The whiskers are plotted at the most extreme data point which is no more than 1.5 times the interquartile range from the box (i.e. extreme outliers are not plotted). The sample size is annotated at the top of each column.

For purse seine data catch rate per unit effort can simply be taken as catch per set. This catch rate was computed for associated and unassociated sets by year as shown in Figure A18. Again, this abundance trend will differ from the boxplot by year in Figure A17 as Figure A17 only shows non-zero catches whereas zero as well as non-zero catches are shown here. It is interesting to note the SPC LL observer data since 2010 shows a sharp increase in 2012 and relative constant catch rates in other years (Figure A4). A similar trend appears in the ROP PS observer dataset since 2010, although the sharp increase occurs in 2011. This pattern is visible in both associated and unassociated set types except in 2016 (which may be influenced by as yet incomplete data reporting).

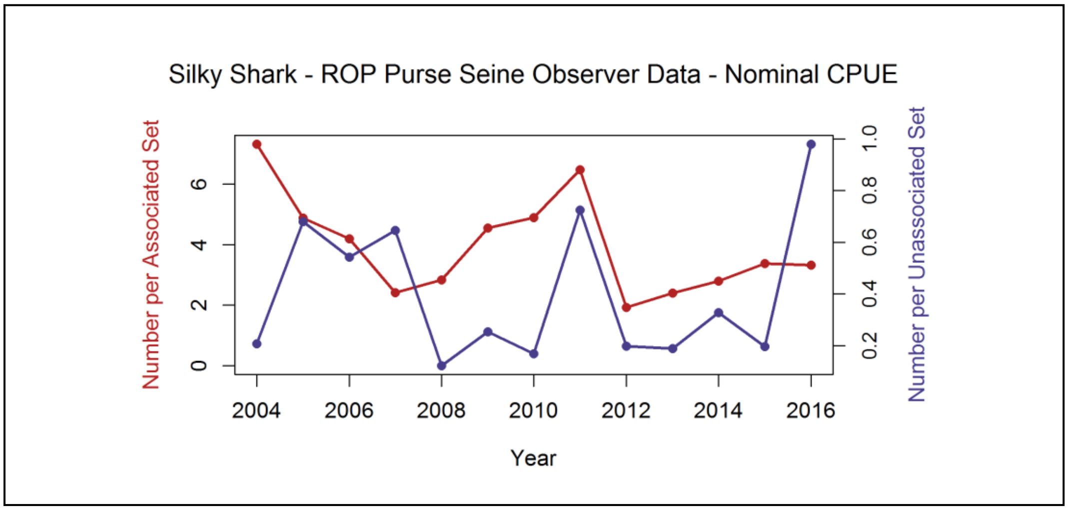
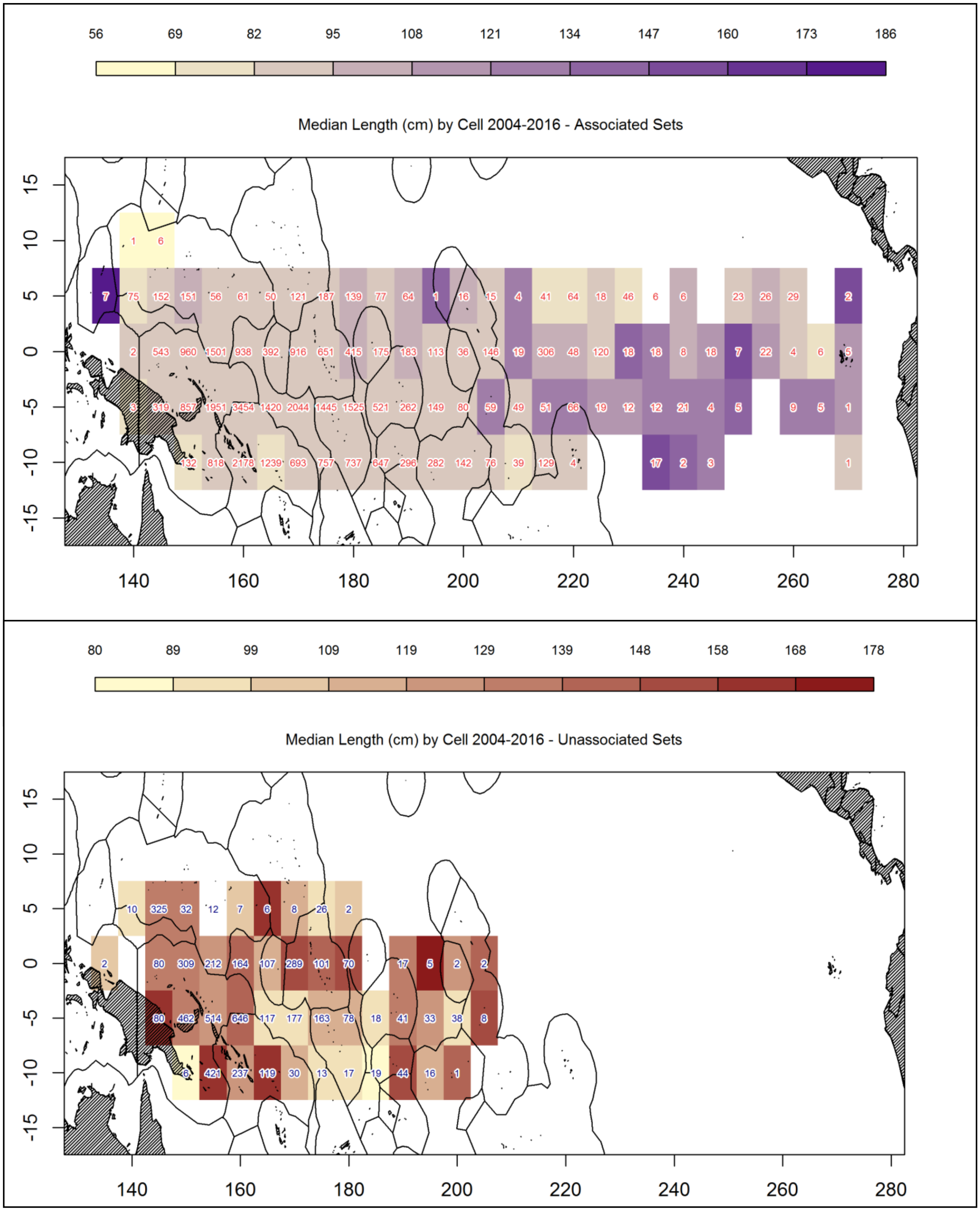


Figure A18. Nominal annual mean CPUE (i.e. mean of individual set catch rates) in the ROP PS observer dataset, 2004-2016.

Length data are available for 30,485 silky sharks caught in the associated set fishery and another 4,339 silky sharks caught in the unassociated set fishery for a total of 34,824 silky sharks measured. However, purse seine observers did not begin collecting information on the sex of measured sharks until 2016 (P. Williams, SPC, pers. comm., 7 March 2017) so fine-scale analysis is somewhat comprised by differences in growth rates between the sexes. All measurements are assumed to be in fork length as that is the convention applied in the ROP LL and PS observer programmes. Lengths were screened to exclude observations below a nominal size at birth of 50 cm FL and a nominal maximum size of 271 cm FL based on the review in Clarke et al. (2015) (n=559 excluded). Only associated sets extend into the Central and Eastern Pacific and sample sizes are low in these areas (Figure A19). Even so, the same pattern of larger individuals to the east is visible in this dataset as in the Japan longline dataset in the Central and Eastern Pacific (Figure A14). There is no strong trend apparent in the purse seine data for larger individuals to be found in the southwest Pacific as in the SPC LL observer data (see Figure A5).



FigureA19. Mapping of median length on a relative scale for silky sharks caught in associated and unassociated sets in the ROP PS observer database, 2004-2016. All lengths shown are in cm fork length (see text for conversion factors). The number annotated in each 5°x5° degree cell is the number of measured sharks. All points were moved southward and eastward to the closest 5°x5° grid point in preparation for merging with the IATTC PS observer dataset.

References

Clarke, S., R. Coelho, M. Francis, M. Kai, S. Kohin, K.M. Liu, C. Simpfendorfer, J. Tovar-Avila, C. Rigby and J. Smart. 2015. Report of the Pacific shark life history expert panel workshop, 28-30 April 2015. WCPFC-SC11-2015/EB-IP-13. Accessed online at https://www.wcpfc.int/system/files/EB-IP-13%20Workshop%20Shark%20Life%20History%20Expert%20Panel%202.pdf

Hoyle, S.D., A.D. Langley and R.A. Campbell. 2014. Recommended approach for standardizing CPUE data from pelagic fisheries. WCPFC-SC-10/SA-IP-10. Accessed online at https://www.wcpfc.int/system/files/SC10-SA-IP-10%20Rec%20methods%20for%20standardizing%20CPUE%20data.pdf

Joung, S.J., C.T. Chen, H.H. Lee and K.M. Liu. 2008. Age, Growth, and Reproduction of Silky Sharks, *Carcharhinus falciformis*, in Northeastern Taiwan Waters. Fisheries Research 90 (1-3): 78–85.

Rice, J. 2013. Catch and catch per unit effort of silky sharks in the Western and Central Pacific Ocean. WCPFC9-SC9-2013/SA-IP-02. Accessed online at https://www.wcpfc.int/system/files/SA-IP-02-Silky-shark-Catch-CPUE.pdf

Walsh, W.A. and S.C. Clarke. 2011. Analyses of Catch Data for Oceanic Whitetip and Silky Sharks reported by Fishery Observers in the Hawaii-based Longline Fishery in 1995–2010. WCPFC-SC7-2011/EB-WP-03. Accessed online at https://www.wcpfc.int/system/files/EB-WP-03%20%5BOceanic%20whitetip%20and%20silky%20sharks%20-%20catch%20data%20analysis%5D.pdf

WCPFC (Western and Central Pacific Fisheries Commission). 2007. Rules and Procedures for the Protection, Access to, and Dissemination of Data Compiled by the Commission. Accessed online at https://www.wcpfc.int/system/files/Rules%20and%20Precedures%20%5BData%5D%20%5Bas%20revised%20at%20WCPFC4%20December%202007%5D.pdf

Annex B. Lennert-Cody, C., S. Clarke, A. Aires-da-Silva, M.N. Maunder and M.H. Román. 2017. Updated stock status indicators for silky sharks in the Eastern Pacific Ocean (1994-2016), with oceanographic considerations. IATTC Document SAC-08-08a(i).

INTER-AMERICAN TROPICAL TUNA COMMISSION

SCIENTIFIC ADVISORY COMMITTEE

EIGHTH MEETING

La Jolla, California (USA)
8-12 May 2017

DOCUMENT SAC-08-08a(i)

UPDATED STOCK STATUS INDICATORS FOR SILKY SHARKS IN THE EASTERN PACIFIC OCEAN (1994-2016), WITH OCEANOGRAPHIC CONSIDERATIONS

Cleridy E. Lennert-Cody, Shelley C. Clarke, Alexandre Aires-da-Silva, Mark N. Maunder, Marlon H. Román

CONTENTS

1. SUMMARY

Indices of relative abundance for the silky shark in the eastern Pacific Ocean (EPO), developed from purse-seine catch-per-set, were updated with data from 2016. The index for all silky sharks north of the equator (north EPO) shows a large decrease in 2016 relative to 2015. In contrast, the index for all silky sharks south of the equator (south EPO) remains at about the 2014-2015 level. Some recent strong increasing trends in the indicators for silky sharks have been identified in previous reports, but they are not biologically plausible. To help further the understanding of potential processes driving the recent trends in the north EPO indices, silky shark indices by sub-region within the north EPO, and by shark size category, were compared to an index of variability in oceanographic conditions, and to a preliminary silky shark index for the Western and Central Pacific Ocean (WCPO) associated-set purse-seine fishery. Based on the preliminary results of these comparisons, it is hypothesized that the recent changes in the silky shark indices for the north EPO, particularly for small silky sharks, may be influenced by changing oceanographic conditions (*e.g.*, El Niño and La Niña events), and thus the north EPO indices are potentially biased. Further analysis will be necessary to evaluate the magnitude of this bias quantitatively and, if the indices for large silky sharks are found to be less susceptible to bias caused by changing oceanographic conditions, they may be used exclusively as stock status indicators in the future. The IATTC staff reiterates its previous recommendation (SAC-07-06b(i), SAC-07-06b(iii)) that improving shark fishery data collection in the EPO is critical. This will facilitate the development of other stock status indicators and/or conventional stock assessments to better inform the management of the silky shark and other co-occuring shark species. Spatio-temporal models that

combine data from multiple gear types to improve spatial coverage should also be explored in the future, to facilitate modeling efforts once data from other sources become available.

2. BACKGROUND

An attempt by the IATTC staff in 2013 to assess the status of the silky shark (*Carcharhinus falciformis*) in the EPO, using conventional stock assessment models, was severely hindered by major uncertainties in the fishery data, primarily total annual catch in the early years for all fisheries that caught silky sharks in the EPO (SAC-05 INF-F). Although the stock assessment attempt produced a substantial amount of new information about the silky shark in the EPO (*e.g.*, absolute and relative magnitude of the catch by different fisheries, and their selectivities), the absolute scale of population trends and the derived management quantities were compromised. Since a conventional stock assessment was not possible, in 2014 the staff proposed a suite of possible stock status indicators (SSIs) that could be considered for managing the silky shark in the EPO (SAC-05-11a), including standardized catch-per-set (CPS) indices from the purse-seine fishery. This document updates the purse-seine CPS indices with data for 2016, hypothesizes possible drivers underlying observed trends, and discusses future research directions with respect to purse-seine indicators for the silky shark.

3. DATA AND METHODS

Data collected by IATTC observers aboard Class-6[1] purse-seine vessels were used to generate CPS-based indices of relative abundance for the silky shark. Observers record bycatches of silky sharks, which occur predominantly in floating-object (OBJ) sets (SAC-07-07b), by size category: small (< 90 cm total length (TL), medium (90-150 cm TL), and large (>150 cm TL)). Annual summaries of spatial data on bycatches (in numbers) of silky sharks in floating-object sets, by size category and for all sizes combined, are shown in Figure 1.

CPS trends for floating-object sets (CPS-OBJ) were estimated using generalized additive models (GAMs). A zero-inflated negative binomial (ZINB) GAM was used to model the bycatch data from OBJ sets because of the presence of many sets with zero bycatch, and also sets with large bycatches. Predictors used in this model were: year (factor); smooth terms for latitude, longitude, time of set, and day of the year (to capture seasonal patterns); and linear terms for depth of the purse-seine net, depth of the floating object, sea-surface temperature, natural logarithm of non-silky bycatch, natural logarithm of tuna catch, and two proxies for local floating-object density. Trends were computed by shark size category and for all sizes combined, using the method of partial dependence, which produces a data-weighted index. Approximate 95% pointwise confidence intervals were computed for the trends for all shark sizes combined by resampling from the multivariate normal distribution of the estimated GAM coefficients, assuming known smoothing and scale parameters. As in previous years, trends were computed for the EPO north and south of the equator, and for four smaller areas within the north EPO:

Area	Latitude	Longitude	No. of OBJ sets
1	North of 8°N	Coast-150°W	2,007
2	0°-8°N	120°W-150°W	6,353
3	0°-8°N	95°W-120°W	17,953
4	0°-8°N	Coast-95°W	7,444

It has been suggested that recent trends in the north EPO silky shark indices integrate immigration and/or recruitment processes with a linkage to the WCPO (SAC-07-06b(i)). To investigate this hypothesis, two exploratory analyses were conducted to develop a better understanding of processes potentially affecting the indices.

[1] Carrying capacity > 363 t

First, through a collaboration with the Western and Central Pacific Fisheries Commission (WCPFC) that was initiated to support a forthcoming ABNJ Tuna Project-funded Pacific-wide assessment for the silky shark[2], it was possible to compute a preliminary standardized trend for the silky shark from observer data collected in associated sets in the purse-seine fishery from 2004-2015 in the WPO between 145°E-180°E and 10°S-5°N. This area was selected because it was fished consistently across the 12-year time period. The trend was estimated using the same ZINB GAM methods used for the EPO, with the following predictors: year (factor), smooth terms for latitude, longitude, time of set and month (month was specified as a cyclic cubic spline), linear terms for the natural logarithm of tuna catch and the natural logarithm of a proxy for local object density, and vessel flag and association type as factors. This preliminary trend was compared to the north EPO CPS-OBJ trends for both small and medium silky sharks, following on a preliminary comparison of the size composition of the sampled catch in the WCPO with that of EPO OBJ sets during 2005-2015 (see Results).

Second, it has been noted previously that silky trends differed spatially within the north EPO (SAC-07-06b(i)). Therefore, a second analysis compared the north EPO silky shark trends, by area, and the WCPO trend, with an indicator of variability in oceanographic conditions, the Indo-Pacific Tripole (TPI) (Henley *et al*. 2015). The TPI is a measure of variability in sea-surface temperature anomalies that captures low and high-frequency links between ocean basins, which influence tropical Pacific oceanographic conditions (Lian *et al*. 2014 and references therein). The TPI shows similarities to the better-known Multivariate El Niño-Southern Oscillation (ENSO) Index (MEI) (Figure 2) (Wolter and Timlin 1993; 1998; 2011;), which is based on sea-level pressure, surface winds, sea-surface temperature, surface air temperature, and cloud cover.

4. RESULTS

4.1. Updated trends in the EPO

For the north EPO, the CPS-OBJ index shows an initial sharp decline during 1994-1998, followed by a period of relative stability at a low level (1999-2009), then a sharp increase from 2009 to 2010, a sharp decrease from 2010 through 2012, a sharp increase from 2012 through 2015 and another sharp decrease in 2016 (Figure 3). As noted in previous documents (*e.g*., SAC-07-06b(i)), the CPS-OBJ trend in the north EPO shows general agreement with standardized presence/absence indices for all silky sharks in the north EPO (obtained using logistic GAMs) for dolphin sets and unassociated sets (Figure 4).

In the north EPO, the trends for the three size categories of silky sharks (Figure 5a) are generally similar to the trend for all silky sharks. However, year-to-year changes in the index for small sharks have not always been the same as those of the indices for medium and large sharks (Figure 5b). This might be expected if the small shark category is a proxy for recruitment (ages 0+ and 1+ years) and the trends in the larger sizes are more reflective of changes in overall stock abundance. Since about 2009, however, the year-to-year changes in the small shark index more closely follow the trends for medium and large sharks (Figure 5b). This suggests that the mechanisms acting on the different size classes may be more complex.

Trends computed by sub-area within the northern EPO suggest that the recent changes in the north EPO index for all silky sharks are most consistent with the trends for the more offshore equatorial regions (Areas 2-3, Figure 6). Updated indices show contrasting trends by sub-area for the most recent year. There was only a small decrease in 2016 in the indices in the far northern area (Area 1, Figure 6) and an increase in 2016 in the indices in the coastal area (Area 4, Figure 6). However, in the more offshore equatorial areas

[2] Led by Dr. Shelley Clarke, Technical Coordinator-Sharks and Bycatch, Western and Central Pacific Fisheries Commission

(Areas 2-3, Figure 6) there was a decrease for all size categories in 2016, with the most pronounced decreases for the indices of small- and medium-sized sharks. Because the EPO indices are data-weighted, the trends are influenced by areas with more sets in the analysis data set. Of the four northern sub-regions, Areas 2 and 3 represent 19% and 53%, respectively, of the sets in the analysis data set for the north EPO (see Data and Methods above).

For the south EPO, the CPS-OBJ indicator for all sharks shows a sharp decline during 1994-2004, followed by a period of stability at much lower levels until 2013, and then a small increase in 2014, with little change through 2016 (Figure 3). In general, the trend for medium sharks is similar to the trend for all sharks, although it does not show as great an increase from 2013 to 2014 as the trend for all sharks. This greater increase in the trend for all silky sharks may be the result of an increased presence of small sharks along the western boundary of the southern EPO in recent years (Figure 1a), and will be investigated further in the future. The trend for large sharks, however, differs from the trend for all sharks in recent years in that it continued to decrease slightly in 2016 (Figure 5b). Trends by sub-area, and for other set types, were not computed for the southern area because of the low levels of silky shark bycatch (Figure 1). In particular, very few small silky sharks are generally caught in the southern area (Figure 1a), which may be due to a lack of recruitment, or possibly a lower selectivity for small sharks by the southern fishery.

4.2. Trends in the WCPO

The size-composition data for silky sharks caught in associated sets in the WCPO between 145°E and180°E from 10°S to 5°N are skewed towards smaller-sized individuals, as are samples from OBJ sets in the north EPO (Figure 7). The modes of the distributions of fork length (FL) from the WCPO, by 5° area, ranged from 67cm to 110cm, with the median at 83 cm, about 10 cm above the upper limit of the EPO 'small' category of 72 cm FL (90 cm TL). For 90% of sharks sampled in the WCPO, fork length was below the upper limit of the EPO 'medium' category of 122cm FL (150cm TL). The range of sampled fork lengths in the WCPO data thus largely overlaps with the 'small' and 'medium' categories of the EPO data, and so the WCPO trend was compared to the trends for both small and medium sharks for OBJ sets for the north EPO, by sub-area, (Areas 1-4 of Figure 6).

The level of agreement between the WCPO and north EPO trends depends on which region within the north EPO is chosen for comparison. In the equatorial region (Areas 2-4, Figure 6), the WCPO trend shows the greatest agreement with the EPO trend for small and medium sharks in the offshore areas (Areas 2-3) and the least agreement with the small shark trend in the coastal area (Area 4) (Figure 8). There is even less agreement between the WCPO trend (Figure 8) and the small shark trend in the region north of 8°N (Area 1 of Figure 6). Thus, the level of agreement between the WCPO trend and the north EPO small and medium trends appears to decrease closer to the coast, as well as north of the equatorial area. To some extent this might be expected, given the difference in oceanographic conditions between the coastal and offshore equatorial areas of the EPO (*e.g.*, Martinez *et al*. 2015). Although the WCPO trend is relatively short (12 years), and comparisons of short time series can be problematic because apparent correlations are more likely to be spurious, the peak in the WCPO trend in 2011 appears to lag one year behind the peak in the EPO trend in 2010 (Figure 8, Areas 2-3). Since the 2009-2010 period included an El Niño event, it may be that this one-year lag is related to the evolution of El Niño conditions across the Pacific.

4.3. Comparison of trends with the TPI

Environmentally-driven population growth (via increased recruitment), movement, and availability to fishing gear are processes that might lead to similar trends in the indices for the WCPO and EPO (Figure 8), and among purse-seine set types within the EPO (Figure 4). However, the increases in the OBJ indices for all sharks in consecutive years, especially in the north EPO, are generally too large to attribute to population growth alone. Specifically, in several years there is no overlap of the upper confidence limit on the estimated finite rate of population increase for a virgin population and the lower confidence limit on the proportional change in the OBJ index from one year to the next (Figure 9).

Although a formal time series analysis will be undertaken in future (see below), the coherence between the OBJ trends for small sharks in the north EPO, the WCPO silky shark trend, and the TPI (Figure 10) suggests that the EPO trend may be biased by changes in oceanographic conditions that influence catchability and/or movement. For the north EPO, the level of agreement of the small shark index and the TPI differs between coastal and offshore areas: in the offshore equatorial area (Area 2) there is considerable agreement between the longer-period fluctuations of the TPI and the small shark index. It is noteworthy that, for both of the strongest El Niño events between 1995 and -2016 (1997-1998 and 2015-2016), the small shark index in Area 2 increased about one year prior to the peak in the TPI. In the coastal equatorial area (Area 4), however, there appears to be less overall agreement between the small shark index and the TPI, and there is about a 1-year lag between the peak in the TPI in 1997-1998 and the peak in the small shark index in about 1998-1999. For the large shark indices, there appears to be less agreement with the TPI, even in the offshore equatorial area (Area 2 of Figure 10). This would be expected if large silky sharks are less sensitive to habitat fluctuations caused by oscillations in the oceanographic environment and/or the abundance of an adult population is inherently less influenced by recent, oceanographically-driven recruitment events.

5. FUTURE WORK

Given the apparent oceanographic influence on the EPO silky shark indices, especially for small sharks in the equatorial north EPO, it is essential that data from other sources be collected to develop additional indicators. Although further analysis may show that the indices for large silky sharks might be better stock status indicators than indices based on all silky sharks, purse-seine fishery indices alone are not sufficient to determine stock status for a species that may be impacted by different oceanographic factors and fisheries in different regions within the EPO. Obtaining reliable catch data for all fisheries catching silky sharks in the EPO, indices of relative abundance for other fisheries (especially longline fisheries, which take the majority of the catch), and composition data, by length/age and sex, is vital. In addition, given the apparent similarities between the WCPO index and the EPO index for small sharks in the western north EPO, Pacific-wide collaborative stock assessment work between WCPFC and IATTC should be pursued to better understand the population dynamics and stock status at the biological stock level, rather than within the confines of RFMO boundaries.

To evaluate the relationship between silky shark indices and environmental forcing quantitatively, future work will focus on using multiple applications of linear autoregressive models to obtain filtered oceanographic indicators (Di Lorenzo and Ohman 2013) on time scales biologically relevant for the silky shark life stages of interest. This filtering process removes variability in an environmental index on scales that are too short to be biologically meaningful for the species and life stages under consideration, while enhancing environmental variability at lower frequencies. The correlation of the filtered environmental indicators with silky shark indices can be computed to quantify the level of agreement between the indices and environmental forcing on specific time scales. Furthermore, changes in the degree of correlation with different amounts of filtering of the environmental indices can be investigated. Indices of oceanographic forcing that will be considered in the analysis include the TPI, the MEI, the North Pacific Gyre Oscillation index, and the Pacific Decadal Oscillation.

ACKNOWLEDGEMENTS

We thank the WCPFC for purse-seine data on silky shark bycatch from the WCPO, Nickolas Vogel for database assistance with the EPO data, and Shane Griffiths for helpful discussions and comments on this document.

REFERENCES

Di Lorenzo, E. and Ohman, M.D. 2013. A double-integration hypothesis to explain ocean ecosystem response to climate forcing. Proceedings of the National Academy of Sciences 110, 2496-2499.

Henley, B.J., Gergis, J., Karoly, D.J., Power, S.B., Kennedy, J., & Folland, C.K. 2015. A Tripole Index for the Interdecadal Pacific Oscillation. Climate Dynamics, 1?14. doi:10.1007/s00382-015-2525-1. See http://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/

Lian, T., Chen, D. Tang, Y. and Jin,B. 2014. A theoretical investigation of the tropical Indo-Pacific tripole mode. Science China: Earth Sciences, 57: 174-188.

Martinez-Ortiz, J., Aires-da-Silva, A., Lennert-Cody, C.E., Maunder, M.N. 2015. The Ecuadorian artisanal fishery for large pelagics: Species composition and spatio-temporal dynamics. PLOS One DOI:10.1371/journal.pone.0135136

Román, M., Sosa-Nishizaki, O., Aires-da-Silva, A., Lennert-Cody, C., Maunder, M., Minte-Vera, C. *In Prep*. Potential Impacts of Fishery Closures on the Demography of the Silky Shark in the Eastern Pacific Ocean.

Wolter, K., and M.S. Timlin, 1993. Monitoring ENSO in COADS with a seasonally adjusted principal component index. Proc. of the 17th Climate Diagnostics Workshop, Norman, OK, NOAA/NMC/CAC, NSSL, Oklahoma Clim. Survey, CIMMS and the School of Meteor., Univ. of Oklahoma, 52-57.

Wolter, K., and M. S. Timlin, 1998. Measuring the strength of ENSO events - how does 1997/98 rank? Weather, 53, 315-324.

Wolter, K., and M. S. Timlin, 2011. El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). Intl. J. Climatology, 31, 14pp., 1074-1087.

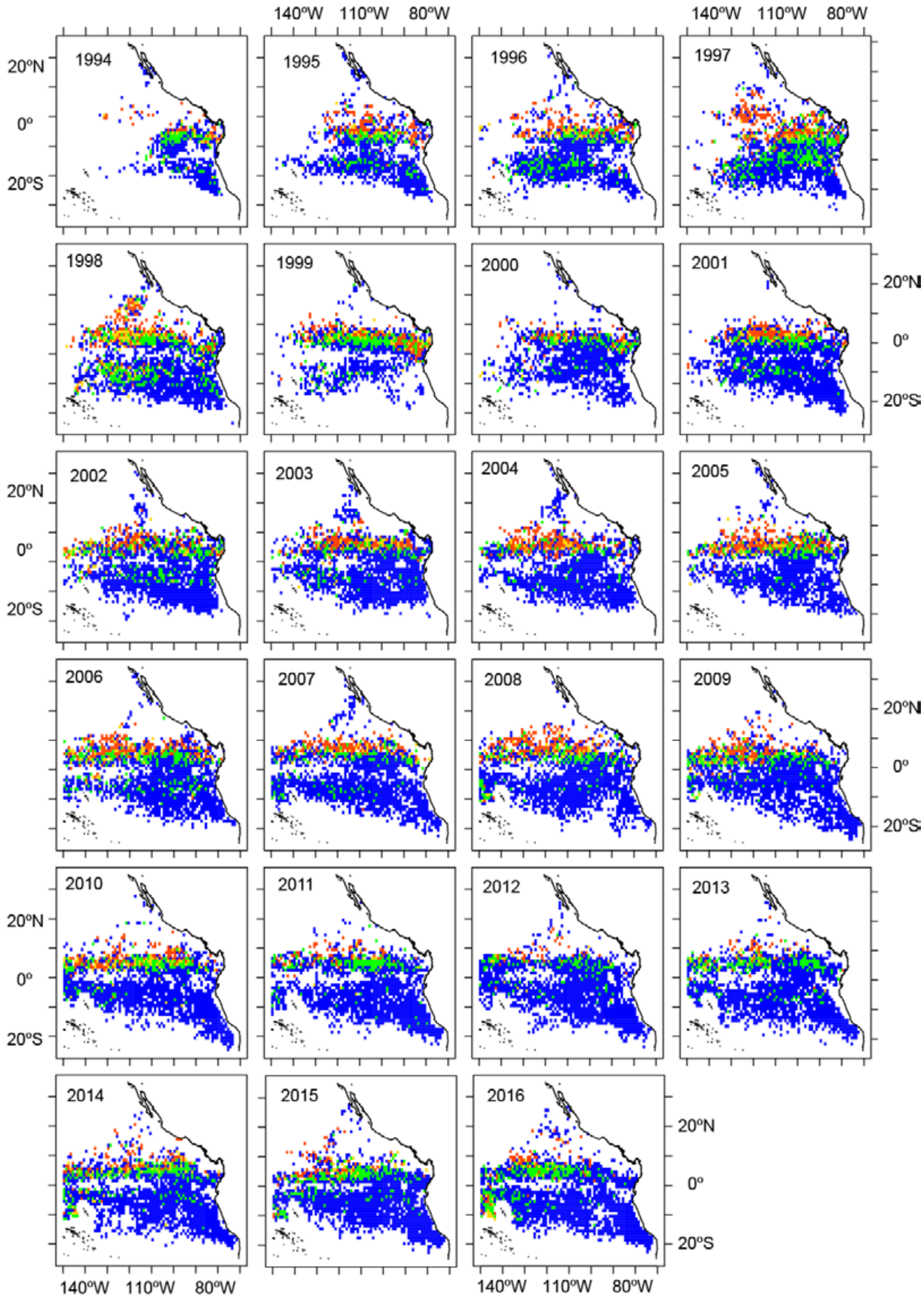


FIGURE 1a. Average bycatch per set in floating-object sets, in numbers, of small (< 90 cm total length) silky sharks, 1994-2016. Blue: 0 sharks per set, green: ≤ 1 shark per set; yellow: 1-2 sharks per set; red: > 2 sharks per set.

FIGURA 1a. Captura incidental media por lance en lances sobre objetos flotantes, en número, de tiburones sedosos pequeños (< 90 cm de talla total), 1994-2016. Azul: 0 tiburones por lance, verde: ≤ 1 tiburones por lance; amarillo: 1-2 tiburones por lance; rojo: > 2 tiburones por lance.

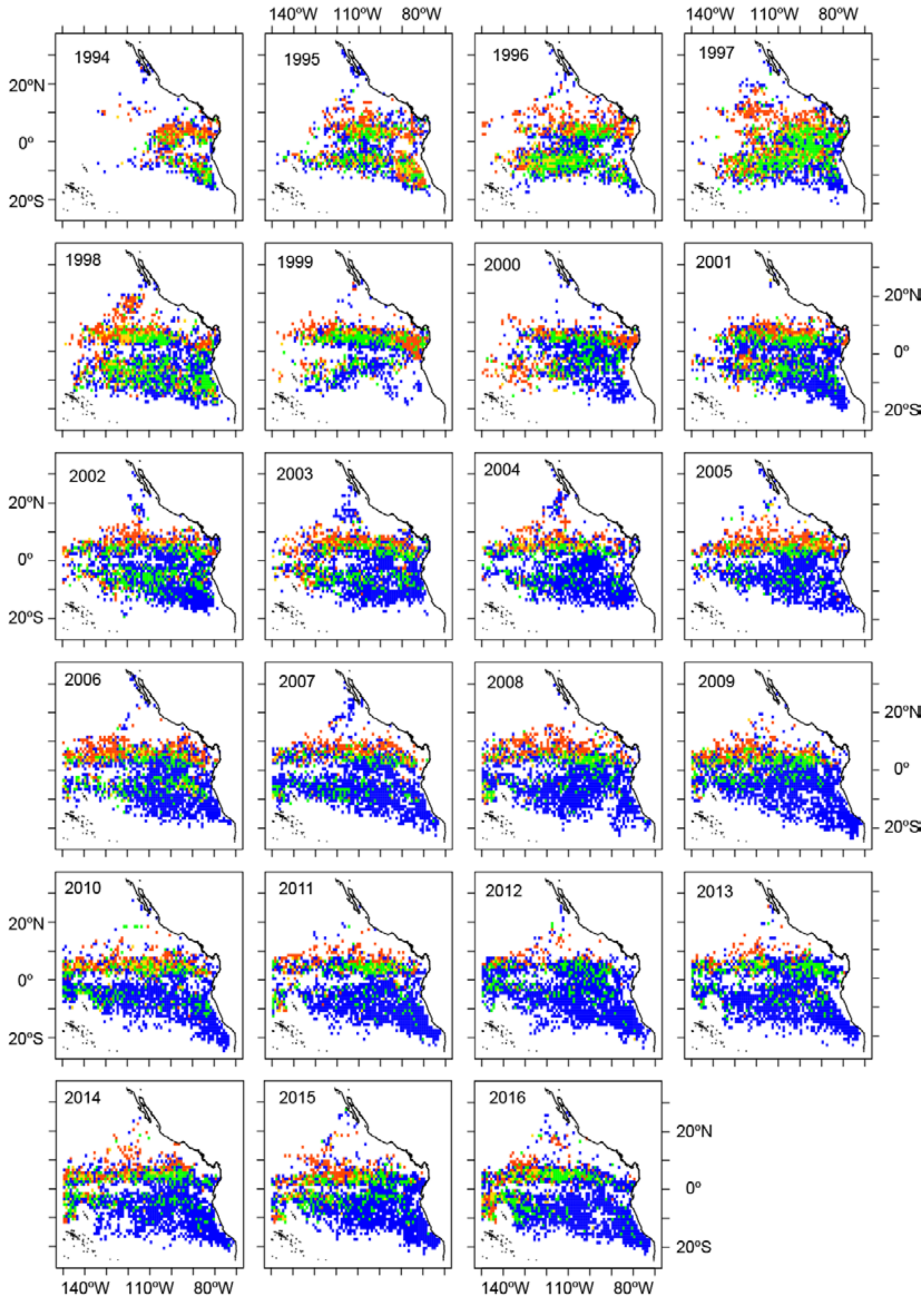


FIGURE 1b. Average bycatch per set in floating-object sets, in numbers, of medium (90-150 cm total length) silky sharks, 1994-2016. Blue: 0 sharks per set, green: ≤ 1 shark per set; yellow: 1-2 sharks per set; red: > 2 sharks per set.

FIGURA 1b. Captura incidental media por lance en lances sobre objetos flotantes, en número, de tiburones sedosos medianos (90-150 cm de talla total), 1994-2016. Azul: 0 tiburones por lance, verde: ≤ 1 tiburones por lance; amarillo: 1-2 tiburones por lance; rojo: > 2 tiburones por lance.

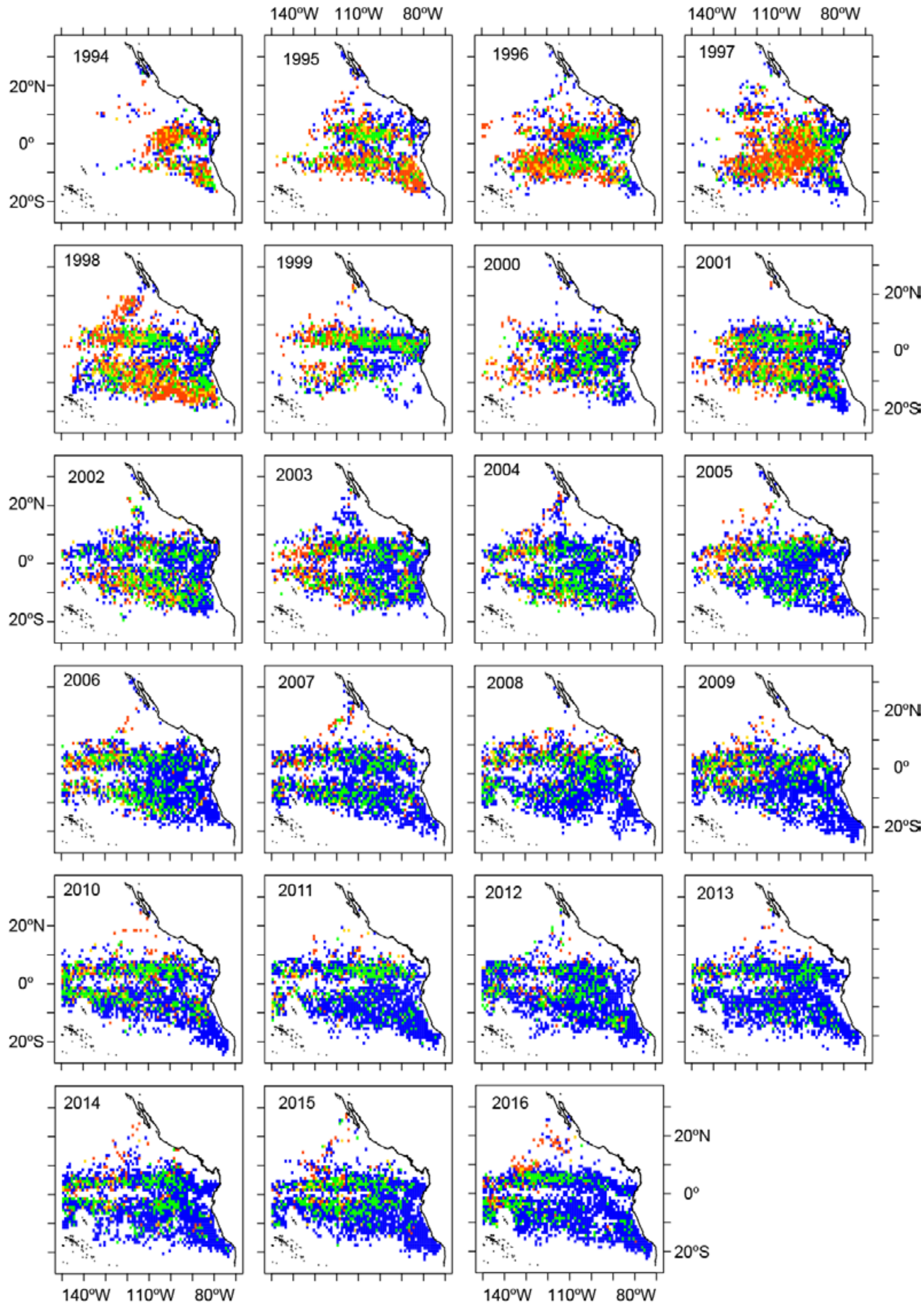


FIGURE 1c. Average bycatch per set in floating-object sets, in numbers, of large (> 150 cm total length) silky sharks, 1994-2016. Blue: 0 sharks per set, green: ≤ 1 shark per set; yellow: 1-2 sharks per set; red: > 2 sharks per set.

FIGURA 1c. Captura incidental media por lance en lances sobre objetos flotantes, en número, de tiburones sedosos grandes (> 150 cm de talla total), 1994-2016. Azul: 0 tiburones por lance, verde: ≤ 1 tiburones por lance; amarillo: 1-2 tiburones por lance; rojo: > 2 tiburones por lance.

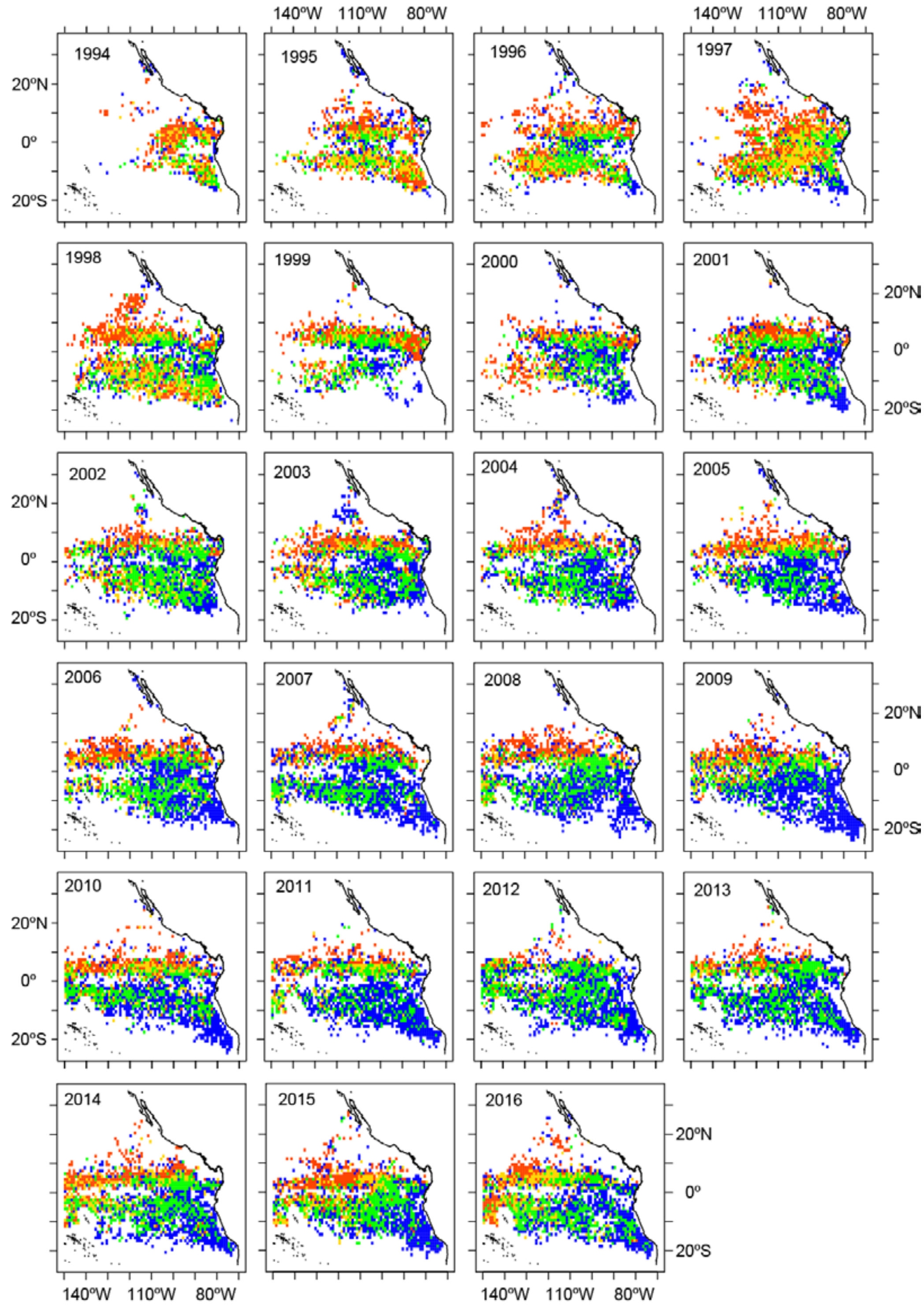


FIGURE 1d. Average bycatch per set in floating-object sets, in numbers, of all silky sharks, 1994-2016. Blue: 0 sharks per set, green: ≤2 shark per set; yellow: 2-5 sharks per set; red: >5 sharks per set.

FIGURA 1d. Captura incidental media por lance en lances sobre objetos flotantes, en número, de todos tiburones sedosos, 1994-2016. Azul: 0 tiburones por lance, verde: ≤ 2 tiburones por lance; amarillo: 2-5 tiburones por lance; rojo: > 5 tiburones por lance.

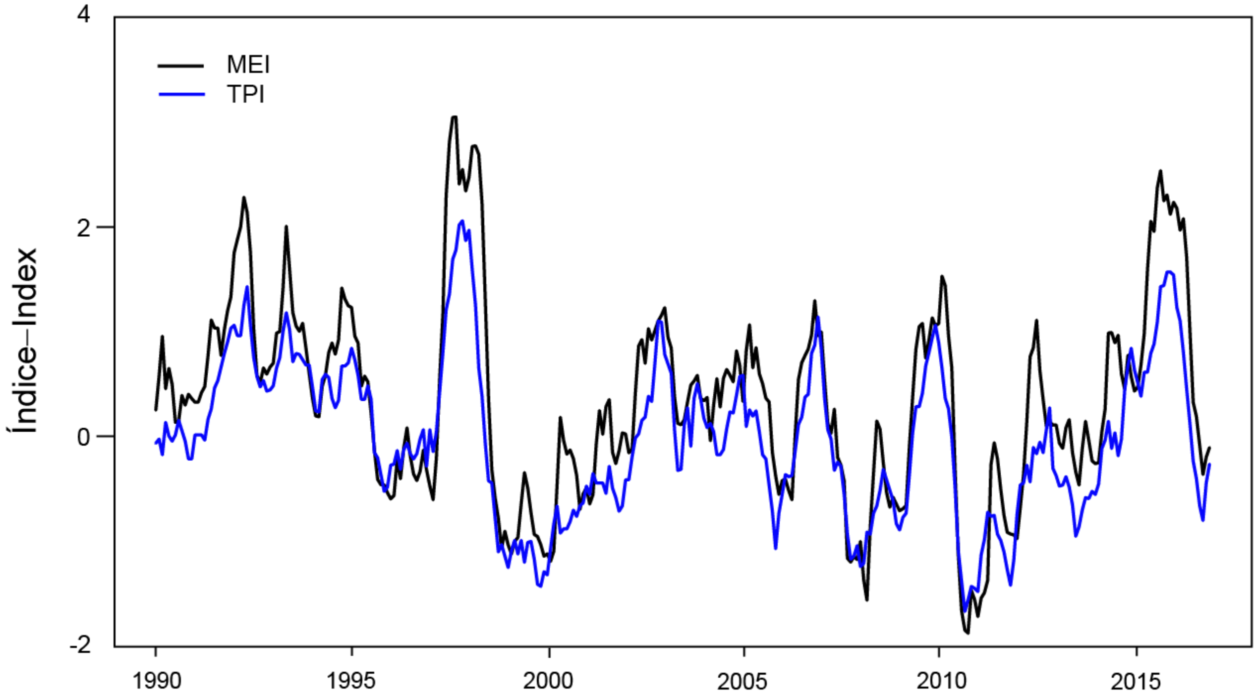


FIGURE 2. Multivariate ENSO Index (MEI; https://www.esrl.noaa.gov/psd/enso/mei/index.html) and Indo-Pacific Tripole Index (TPI; https://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/), 1990-2016.
FIGURA 2. Índice ENOS multivariable (MEI; https://www.esrl.noaa.gov/psd/enso/mei/index.html) e índice tripolar indopacífico (TPI; https://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/), 1990-2016.

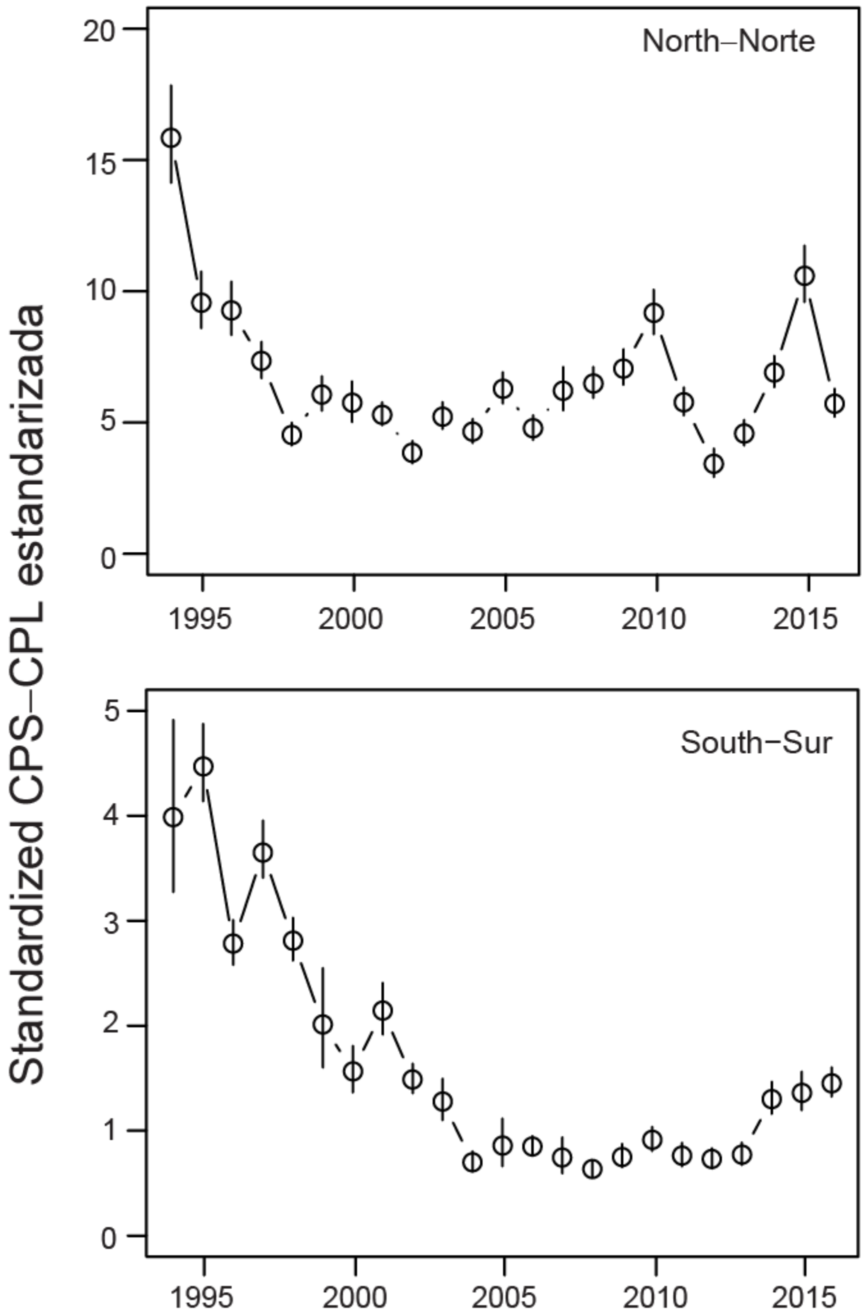


FIGURE 3. Standardized catch-per-set (CPS, in number of sharks per set) of silky sharks (all size classes combined) in floating-object sets in the north (top) and south (bottom) EPO.
FIGURA 3. Captura por lance (CPL, en número de tiburones por lance) estandarizada de todos los tiburones en lances sobre objetos flotantes en el OPO norte (arriba) y sur (abajo).

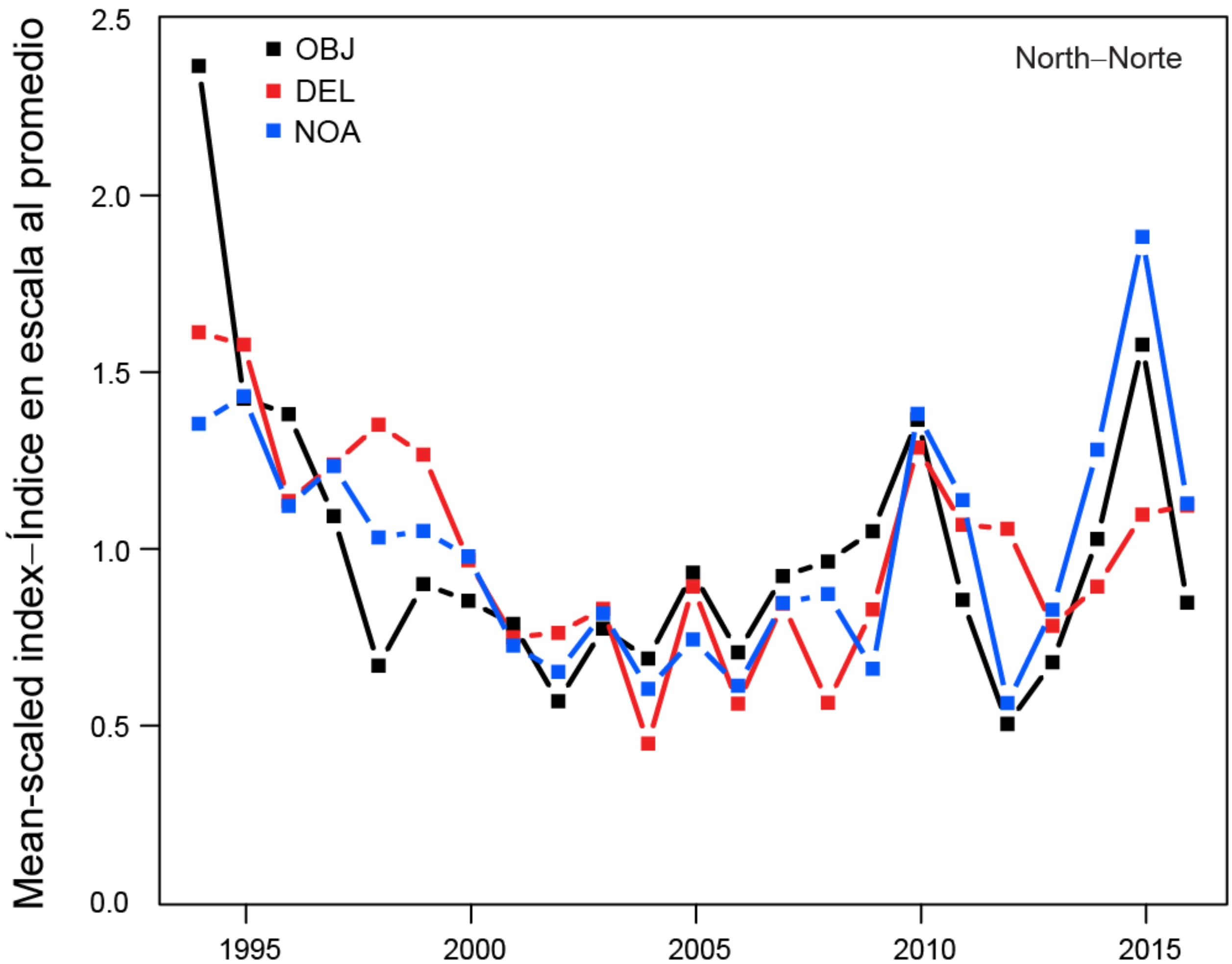


FIGURE 4. Mean-scaled indices for the silky shark in the north EPO for different purse-seine set types (floating-object (OBJ), dolphin (DEL), unassociated (NOA)).

FIGURA 4. Índices en escala al promedio para el tiburón sedoso en el OPO norte en distintos tipos de lance cerquero (objeto flotante (OBJ), delfín (DEL), no asociado (NOA)).

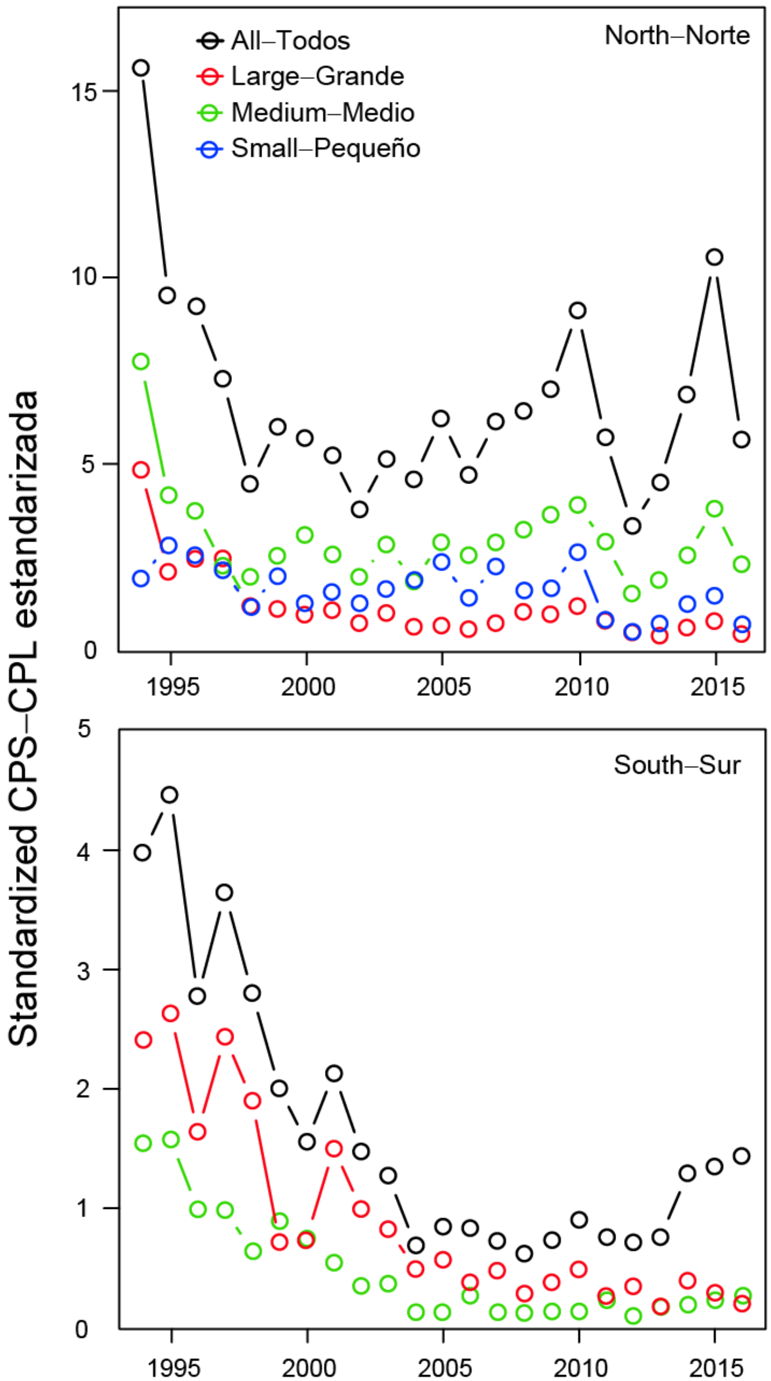


FIGURE 5a. Standardized catch-per-set (CPS; in numbers of sharks per set) in sets on floating objects of silky sharks of three size classes (small, medium, large) and all sizes combined in the north (top) and south (bottom) EPO. No index was computed for small silky sharks in the south EPO due to model instability caused by the low levels of bycatch in recent years; see Figure 1a.

FIGURA 5a. Captura por lance (CPL, en número de tiburones por lance) estandarizada en lances sobre objetos flotantes de tiburones sedosos de tres clases de talla (pequeño, mediano, grande) y todas las tallas combinadas, en el OPO norte (arriba) y sur (abajo). No se calculó un índice para los tiburones sedosos pequeños en el OPO sur debido a la inestabilidad del modelo causada por los bajos niveles de captura incidental en los años recientes (Figura 1a).

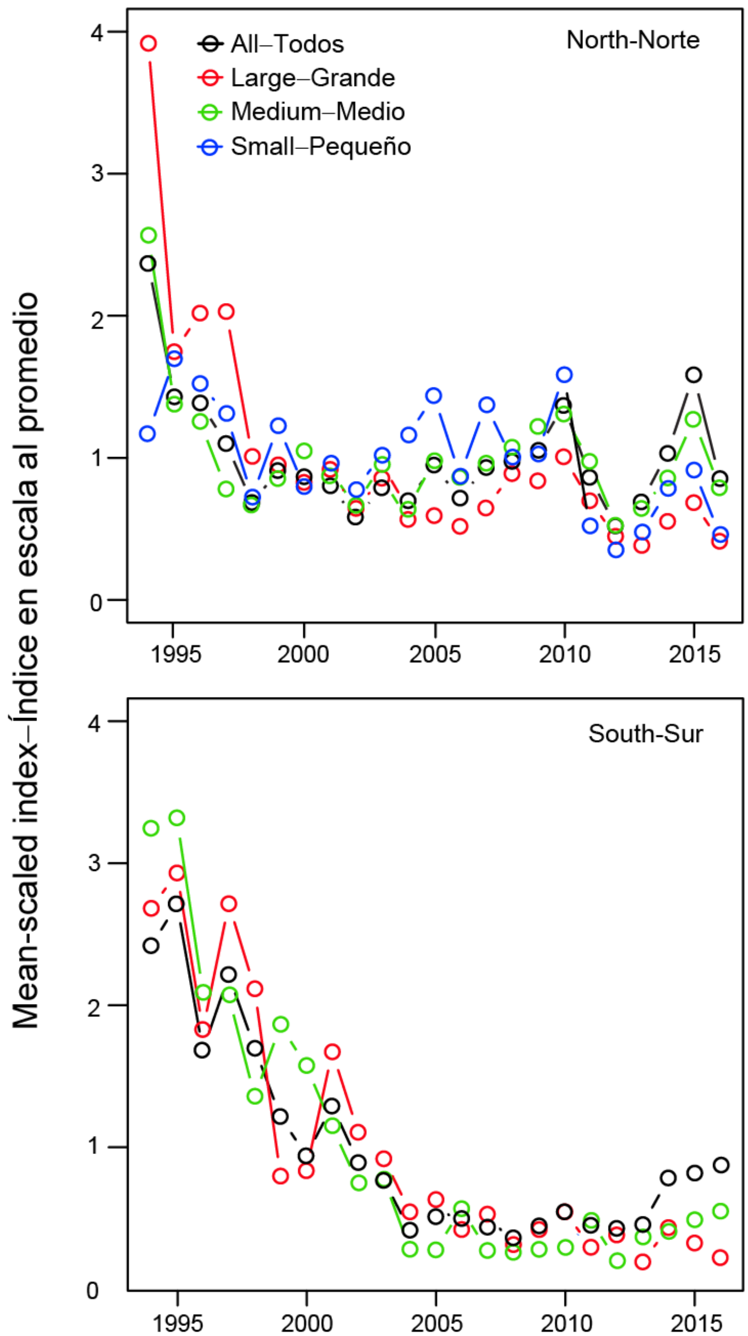


FIGURE 5b. Mean-scaled standardized catch-per-set in floating-object sets (from Figure 3a) for silky sharks of three size classes (small, medium, large) and all sizes combined for the north (top) and south (bottom) EPO. No index was computed for small silky sharks in the south EPO due to model instability caused by the low levels of bycatch in recent years (Figure 1a).

FIGURA 5b. Captura por lance estandarizada en escala as promedio en lances sobre objetos flotantes (de la Figura 3a) de tiburones sedosos de tres clases de talla (pequeño, mediano, grande) y de todas tallas combinadas, en el OPO norte (arriba) y sur (abajo). No se calculó un índice para los tiburones sedosos pequeños en el OPO sur debido a la inestabilidad del modelo causada por los bajos niveles de captura incidental en los años recientes (Figura 1a).

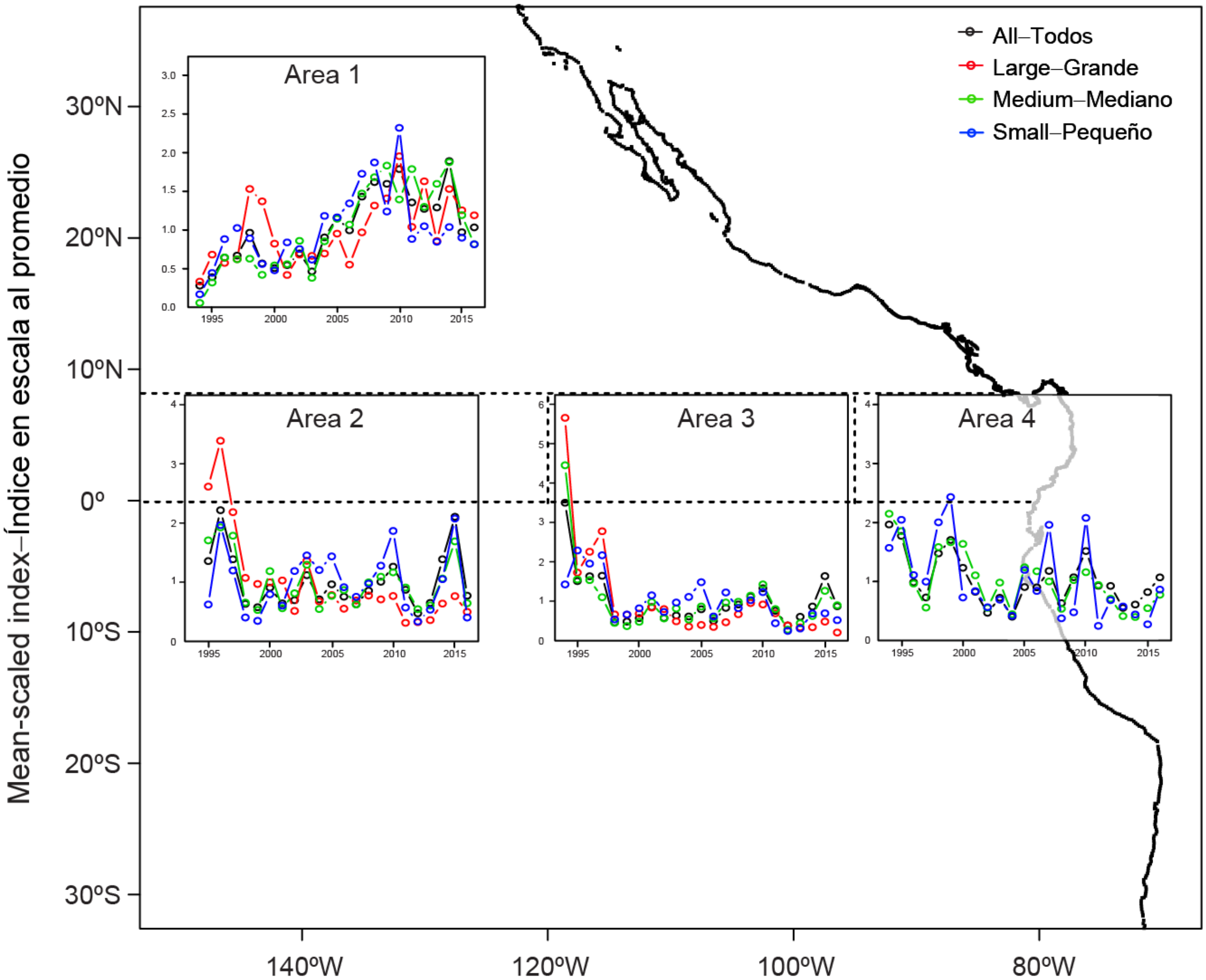


FIGURE 6. Mean-scaled standardized CPS for silky sharks in the north EPO, by sub-area. The black horizontal dashed lines show the locations of the four sub-areas: Area 1 (north of 8°N); Area 2 (0°-8°N and 120°-150°W); Area 3 (0°-8°N and 95°-130°W), and Area 4 (0°-8°N, from the coast to 95°W). No trend was computed for large sharks in Area 4 because of model instability identified in previous analyses.

FIGURA 6. Captura por lance estandarizada en escala al promedio de tiburones sedosos en el OPO norte, por subárea. Las líneas de trazos negras horizontales indican la posición de las cuatro subáreas: Área 1 (al norte de 8°N); Área 2 (0°-8°N y 120°-150°O); Área 3 (0°-8°N 95°-130°O), y Área 4 (0°-8°N, desde la costa hasta 95°O). No se calculó una tendencia para los tiburones grandes en el Área 4 debido a inestabilidad en el modelo identificado en análisis previos.

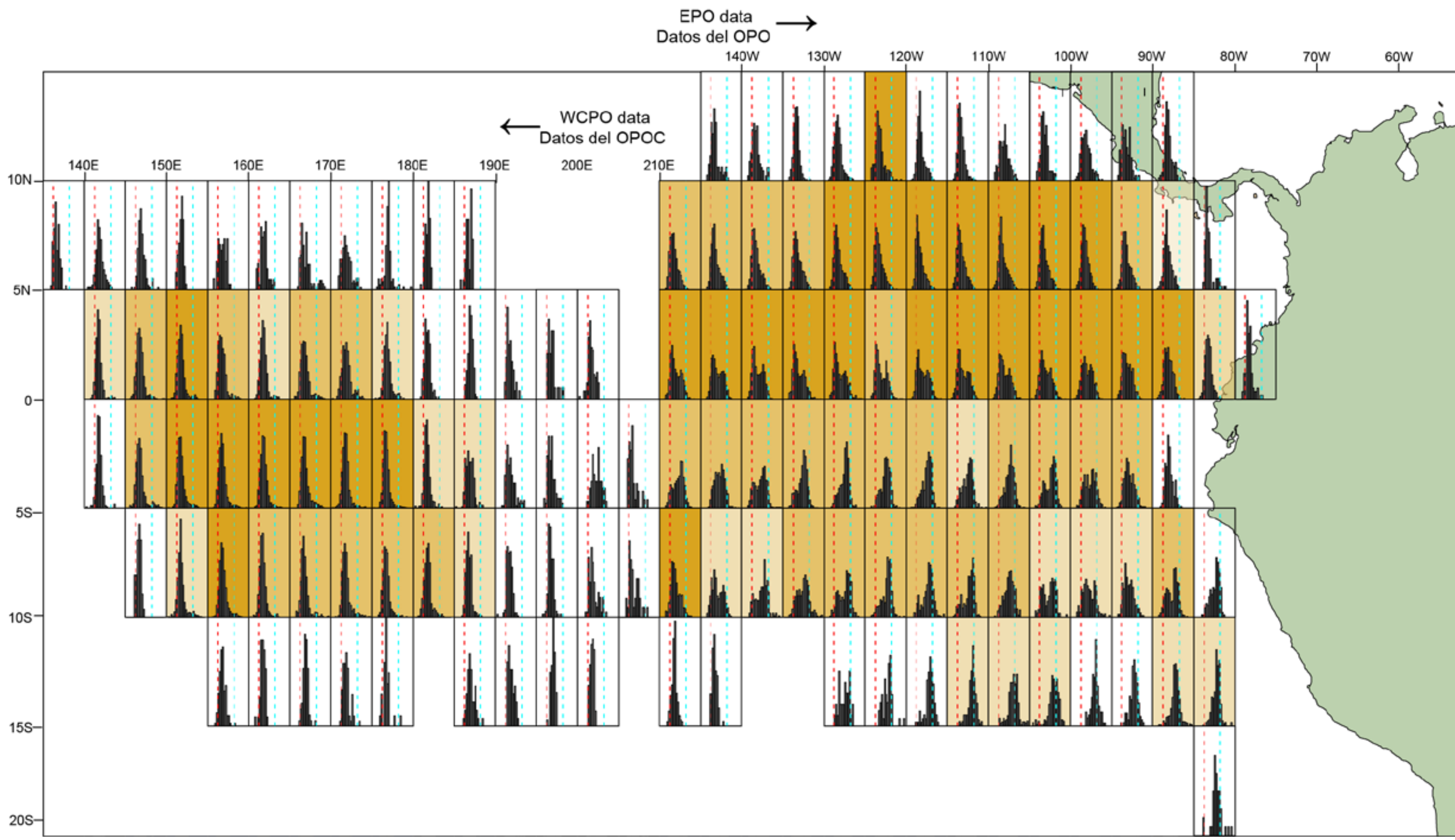


FIGURE 7. Length-frequency histograms (fork length, in cm; FL) for silky sharks sampled from purse-seine sets on floating-objects in the EPO and from associated sets in the WCPO, 2005-2015. The red and blue dashed lines are provided for visual reference and are located at 55cm FL and 165cm FL, respectively. Shading of the histogram panels indicates number of sets in which sharks were measured (white: ≤ 75 sets; light gold: 76-150 sets; gold: 151-300 sets; dark gold: > 300 sets).

FIGURA 7. Histogramas de la frecuencia de talla (talla furcal, en cm; TF) de tiburones sedosos muestreados en lances cerqueros sobre objetos flotantes en el OPO y en lances asociados en el OPOC, 2005-2015. Las líneas de trazos roja y azul representan TF de 55 cm y 165 cm, respectivamente. El color de las casillas indica el número de lances con tiburones medidos (blanco: < 75 lances; amarillo claro: 76-150 lances; amarillo: 151-300 lances; amarillo oscuro: > 300 lances).

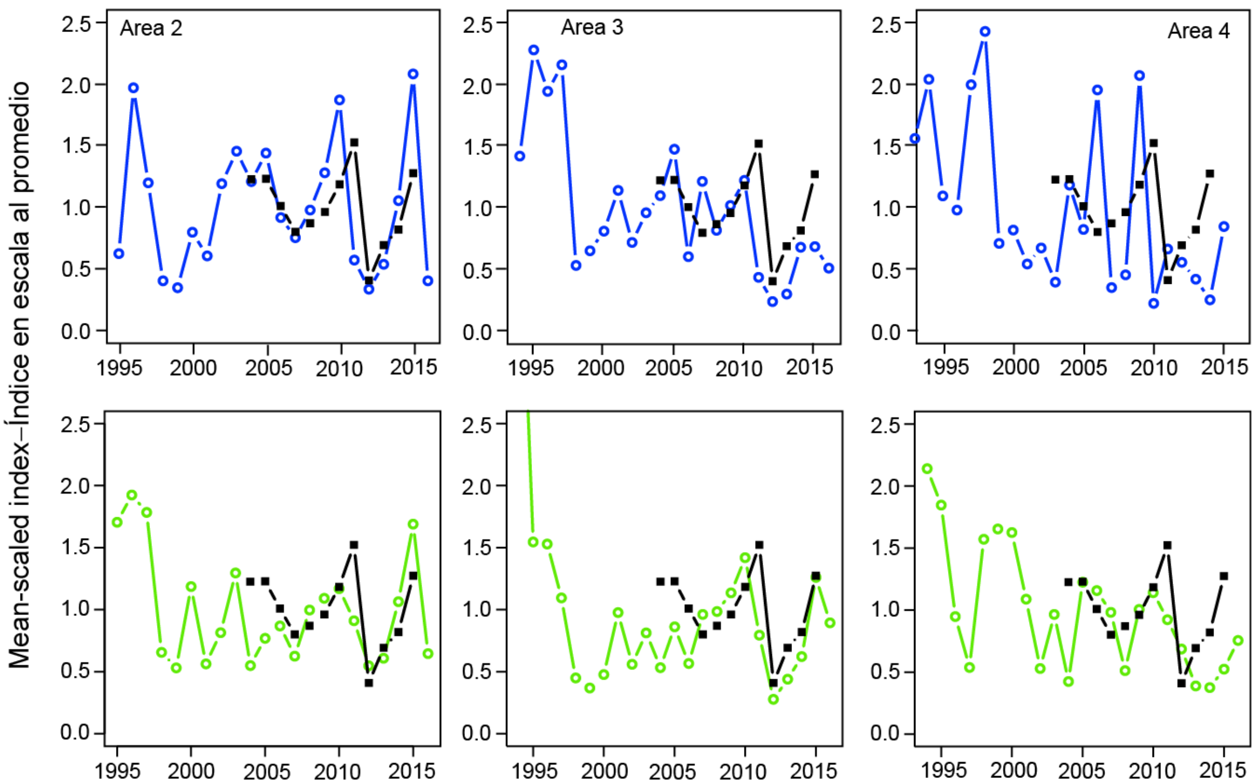


FIGURE 8. Mean-scaled standardized catch-per-set for small (blue) and medium (green) silky sharks in subareas 2-4 in the north EPO (Figure 6) and the preliminary index for the WCPO (black) (145°E-180°E, 10°S-5°N).

FIGURA 8. Captura por lance estandarizada en escala al promedia poro de tiburones sedosos pequeños (azul) y medianos (verde) en las subáreas 2-4 del OPO norte (Figura 6) y el índice preliminar del OPOC (negro) (145°E-180°E, 10°S-5°N).

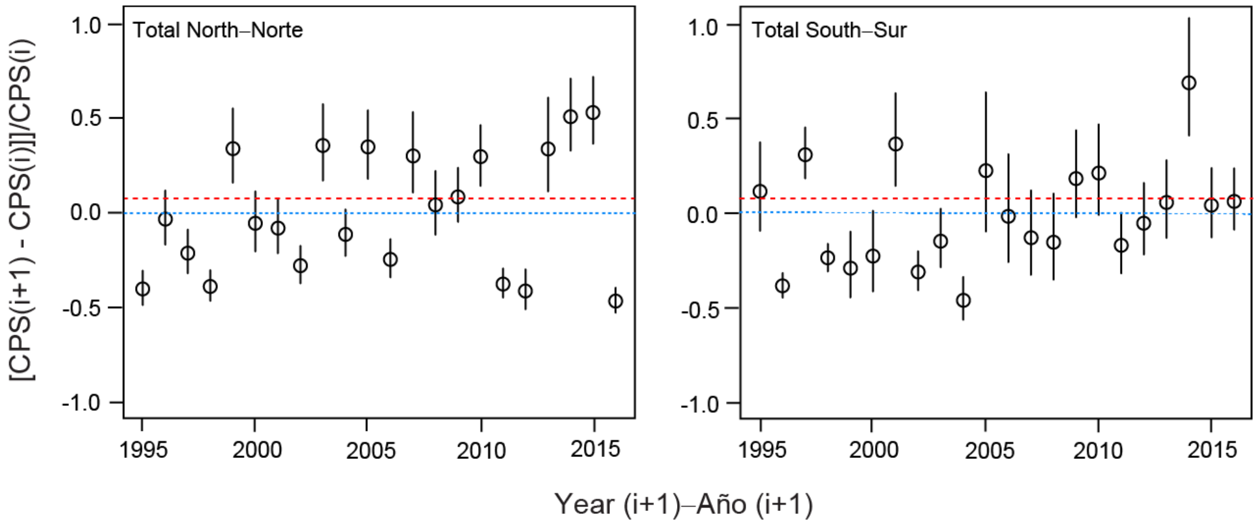


FIGURE 9. Proportional change in the indices for all silky sharks (Figure 2). The proportional change was computed as the difference in CPS from year *i*+1 to year *i*, divided by the CPS in year *i*. The blue dashed line denotes no change. The red dashed line is at the value 0.0745, which is the upper 95% confidence limit on the finite population growth rate for a virgin population, estimated by Román *et al*. (in prep.).

FIGURA 9. Cambio proporcional en los índices de todo tiburón sedoso (Figura 2). Se calculó el cambio proporcional como la diferencia en CPL del año *i* +1 al año *i*, dividido por la CPL en el año *i*. La línea de trazos azul indica ningún cambio. La línea de trazos roja señala el valor de 0.0745, el límite de confianza de 95% superior de la tasa de crecimiento de población finita para una población virgen, estimada por Román *et al*. (en prep.).

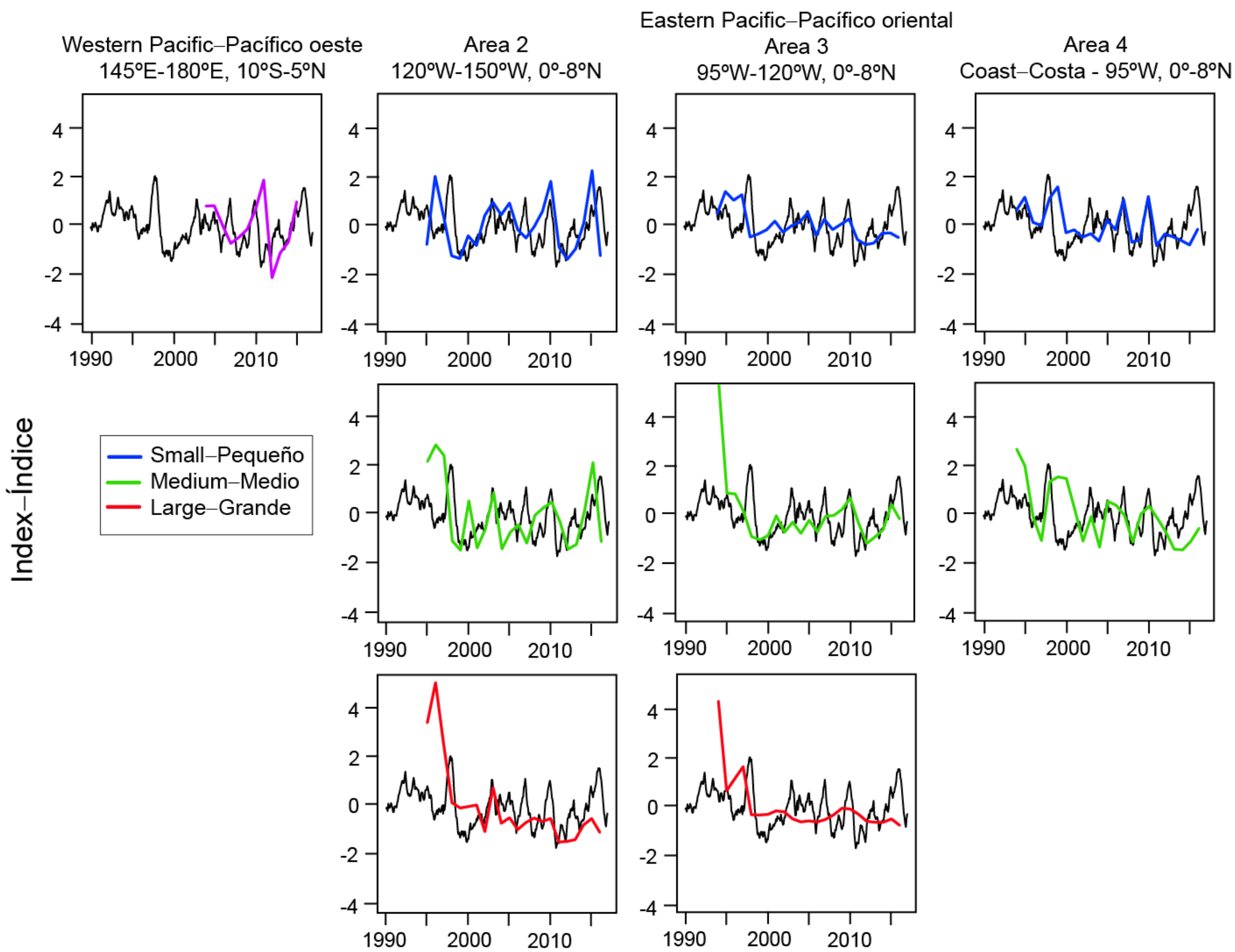


FIGURE 10. Silky shark indices by size for Areas 2-4 of the north EPO (Figure 6) and the WCPO (Figure 8) *versus* the TPI (Figure 2). The black lines correspond to the TPI, the blue, green, and red lines to the EPO indices for small, medium, and large sharks, respectively. And the gray line to the WCPO index. For comparison to the TPI, the shark indices are shown as anomalies (*i.e.*, index – mean(index)).

FIGURA 10. Índices de tiburón sedoso por talla en las áreas 2-4 del OPO norte (Figura 6) y el OPOC (Figura 8) graficados contra el TPI (Figure 2). Las líneas negras corresponden al TPI, las líneas azules, verdes, y rojas a los índices de tiburón sedoso pequeño, mediano, y grande, respectivamente, en el OPO, y la línea gris al índice del OPOC. Para compararlos con el TPI, se ilustran los índices de tiburón sedoso como anomalías (o sea, índice - promedio(índice))

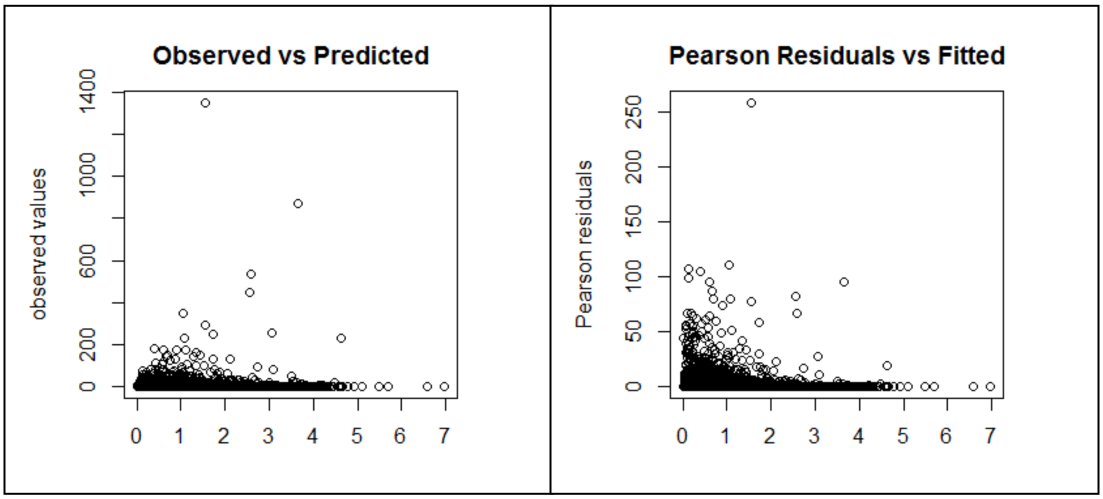
Annex C. Model summary statistics and diagnostics for the WCPO purse seine unassociated fishery, the Hawaii-based longline fishery and the South Pacific longline fishery CPUE standardizations

Summary of ZINB model of WCPO Unassociated Purse Seine Fishery

```
Call:
zeroinfl(formula = FALnumb ~ yearfact + monthfact + s(newlat) + s(newlon) + s
(timeofset) + log.tunakg + flagfact |
    yearfact + monthfact + s(newlat) + s(newlon) + s(timeofset) + log.tunakg
+ flagfact, data = UNAset, dist = "negbin",
    link = "logit")

Pearson residuals:
      Min        1Q    Median        3Q       Max
 -0.25564  -0.18704  -0.16010  -0.12675 139.22681

Count model coefficients (negbin with log link):
                Estimate  Std. Error  z value            Pr(>|z|)
(Intercept)    2.68552778  0.88693046   3.0279           0.0024627 **
yearfact2005   1.86548312  0.46877174   3.9795   0.000069056657164 ***
yearfact2006   0.95188718  0.39419187   2.4148           0.0157447 *
yearfact2007   1.30906429  0.38813492   3.3727           0.0007443 ***
yearfact2008   0.41921710  0.42910624   0.9770           0.3285919
yearfact2009   1.08830286  0.39787540   2.7353           0.0062326 **
yearfact2010   0.40267513  0.31868175   1.2636           0.2063862
yearfact2011   1.03916405  0.31837291   3.2640           0.0010986 **
yearfact2012   0.47514481  0.31977523   1.4859           0.1373132
yearfact2013  -0.07328594  0.31119850  -0.2355           0.8138239
yearfact2014   0.76792466  0.32077026   2.3940           0.0166657 *
yearfact2015   0.21069110  0.32028064   0.6578           0.5106456
monthfact2     0.05002104  0.19182224   0.2608           0.7942717
monthfact3     0.71971171  0.22125712   3.2528           0.0011426 **
monthfact4     0.24597935  0.19762704   1.2447           0.2132551
monthfact5    -0.37776614  0.21923089  -1.7231           0.0848627 .
monthfact6     0.33681706  0.19426478   1.7338           0.0829529 .
monthfact7     0.31592206  0.18140964   1.7415           0.0815987 .
monthfact8     0.41427189  0.18037729   2.2967           0.0216361 *
monthfact9    -0.05921607  0.19260219  -0.3075           0.7584988
monthfact10    0.24443699  0.18055499   1.3538           0.1757973
monthfact11   -0.05786589  0.18700323  -0.3094           0.7569884
monthfact12    0.09444509  0.17551964   0.5381           0.5905160
s(newlat)     -0.03324800  0.01500602  -2.2156           0.0267159 *
s(newlon)     -0.02008626  0.00486474  -4.1289   0.000036443216256 ***
s(timeofset)   0.00080801  0.00819926   0.0985           0.9214986
log.tunakg     0.15087535  0.02174949   6.9370   0.000000000004006 ***
flagfactJP    -0.42070788  0.24356489  -1.7273           0.0841151 .
flagfactKI    -0.91679636  0.29822918  -3.0741           0.0021111 **
flagfactKR    -0.72696066  0.24332648  -2.9876           0.0028118 **
flagfactMH    -0.24380039  0.29157466  -0.8362           0.4030701
flagfactPG    -0.37540199  0.24384418  -1.5395           0.1236784
flagfactSB     0.18805537  0.45739892   0.4111           0.6809693
flagfactTW    -0.51645792  0.24529504  -2.1055           0.0352516 *
```

```
flagfactUS   -0.84732599  0.24856796  -3.4088            0.0006524 ***
flagfactVU   -1.14689660  0.33930822  -3.3801            0.0007246 ***
Log(theta)   -2.58800529  0.07510235 -34.4597 < 0.0000000000000002 ***

Zero-inflation model coefficients (binomial with logit link):
               Estimate Std. Error z value             Pr(>|z|)
(Intercept)  -9.7878836  1.0995943 -8.9014 < 0.0000000000000002 ***
yearfact2005  1.3734335  0.5327339  2.5781            0.0099349 **
yearfact2006  0.0999517  0.5600696  0.1785            0.8583593
yearfact2007  0.8235883  0.5242390  1.5710            0.1161787
yearfact2008  0.9040420  0.5456327  1.6569            0.0975459 .
yearfact2009  1.1395643  0.5131134  2.2209            0.0263590 *
yearfact2010  1.2920703  0.4842035  2.6684            0.0076203 **
yearfact2011  0.4977422  0.4860274  1.0241            0.3057866
yearfact2012  0.8302715  0.4882616  1.7005            0.0890436 .
yearfact2013  0.3595075  0.4821471  0.7456            0.4558857
yearfact2014  0.1022697  0.4868112  0.2101            0.8336046
yearfact2015 -0.5899766  0.4951483 -1.1915            0.2334515
monthfact2   -0.3096263  0.2176116 -1.4228            0.1547828
monthfact3    0.2762535  0.2010505  1.3741            0.1694261
monthfact4    0.2914038  0.1978686  1.4727            0.1408283
monthfact5    0.0672090  0.2246340  0.2992            0.7647924
monthfact6   -0.1306219  0.1919443 -0.6805            0.4961753
monthfact7   -0.4331749  0.1826806 -2.3712            0.0177298 *
monthfact8   -0.5916825  0.1789165 -3.3070            0.0009429 ***
monthfact9   -0.5540694  0.1953596 -2.8362            0.0045661 **
monthfact10  -0.5596729  0.1871905 -2.9899            0.0027911 **
monthfact11  -0.6924908  0.1994159 -3.4726            0.0005155 ***
monthfact12  -0.6463299  0.1940757 -3.3303            0.0008675 ***
s(newlat)     0.0349907  0.0149291  2.3438            0.0190887 *
s(newlon)     0.0613896  0.0052585 11.6743 < 0.0000000000000002 ***
s(timeofset)  0.0299149  0.0090240  3.3150            0.0009163 ***
log.tunakg   -0.0863334  0.0235236 -3.6701            0.0002425 ***
flagfactJP    0.4232314  0.2399111  1.7641            0.0777121 .
flagfactKI   -0.2051602  0.3191017 -0.6429            0.5202692
flagfactKR   -0.2381036  0.2412287 -0.9870            0.3236206
flagfactMH   -0.3380705  0.2745217 -1.2315            0.2181399
flagfactPG   -0.3002702  0.2353046 -1.2761            0.2019233
flagfactSB   -0.6542058  0.5735639 -1.1406            0.2540373
flagfactTW    0.1327911  0.2359008  0.5629            0.5734957
flagfactUS    0.0683387  0.2387198  0.2863            0.7746700
flagfactVU   -0.3034132  0.3393673 -0.8941            0.3712922
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Theta = 0.07517
Number of iterations in BFGS optimization: 90
Log-likelihood: -22003 on 73 Df
```

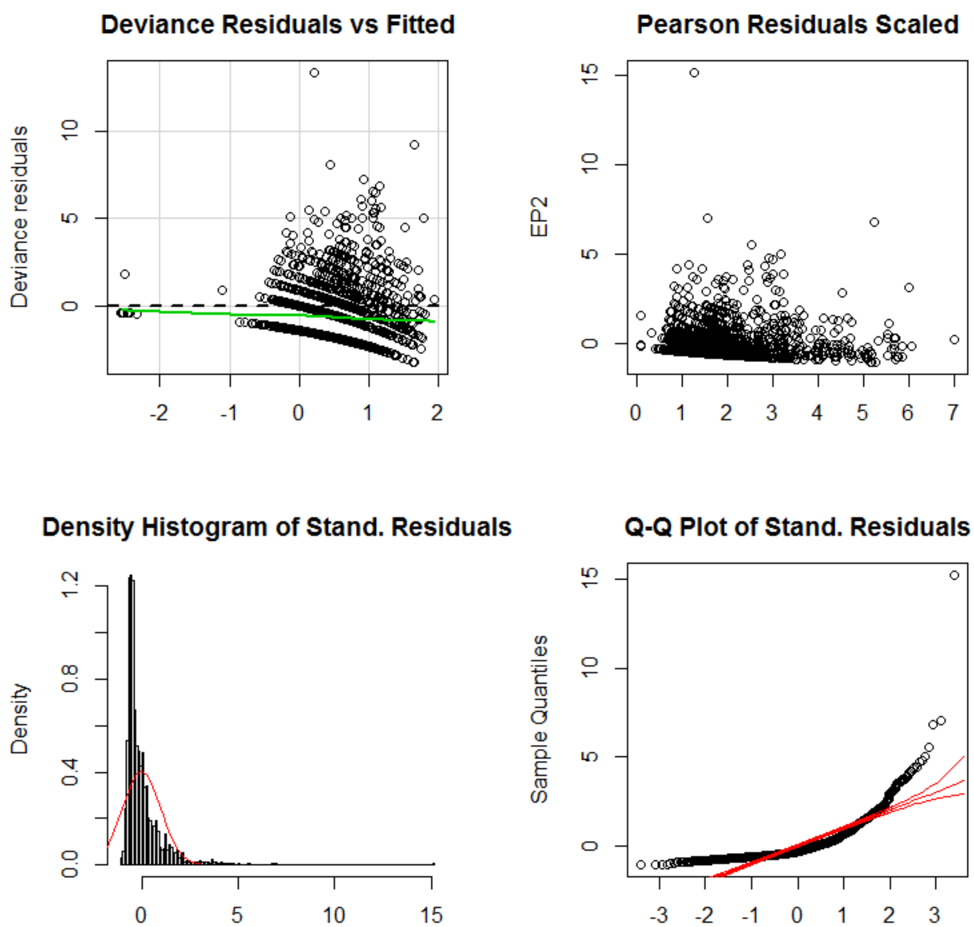
Diagnostics for ZINB model of WCPO Unassociated Purse Seine Fishery



Summary of QP model for Hawaii Longline Deep Set Fishery

```
Call:
glm(formula = FAL ~ yearfact + s(lat1) + s(sst) + offset(loghooks),
    family = quasipoisson, data = Walshdat)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.2420  -1.6857  -0.7914   0.4058  13.3914

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  -9.93421    1.34102  -7.408 2.12e-13 ***
yearfact2001 -0.63730    0.17645  -3.612 0.000314 ***
yearfact2002 -0.85184    0.16783  -5.076 4.34e-07 ***
yearfact2003 -0.89597    0.39542  -2.266 0.023601 *
yearfact2004 -1.44689    0.23817  -6.075 1.57e-09 ***
yearfact2005 -3.00000    2.11409  -1.419 0.156089
yearfact2006 -0.05166    0.18409  -0.281 0.779039
yearfact2007 -1.71387    0.23134  -7.408 2.11e-13 ***
yearfact2008 -0.53166    0.33424  -1.591 0.111892
yearfact2009 -0.79319    0.20168  -3.933 8.77e-05 ***
yearfact2010 -1.36386    0.28738  -4.746 2.27e-06 ***
yearfact2011 -0.80029    0.39777  -2.012 0.044405 *
yearfact2012 -0.72322    0.23167  -3.122 0.001832 **
yearfact2013 -0.32956    0.22216  -1.483 0.138177
yearfact2014 -0.17213    0.25852  -0.666 0.505640
s(lat1)       0.09206    0.03685   2.498 0.012589 *
s(sst)        0.09908    0.04612   2.148 0.031861 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasipoisson family taken to be 4.445363)

    Null deviance: 5370.2  on 1529  degrees of freedom
Residual deviance: 4776.8  on 1513  degrees of freedom
AIC: NA

Number of Fisher Scoring iterations: 6
```

Diagnostics for QP model of Hawaii Deep Set Longline Fishery



Summary of the ZIP model of the South Pacific Longline Fishery

```
Call:
zeroinfl(formula = FAL ~ yearfact + s(hk_bt_flt) + monthfact + s(newlat1d) +
s(newlon1d) + s(AllTuna) + offset(log.hook_est) |
    yearfact + s(hk_bt_flt) + monthfact + s(newlat1d) + s(newlon1d) + s(AllTu
na) + offset(log.hook_est), data = SPCwork,
    dist = "poisson", link = "logit")

Pearson residuals:
     Min       1Q   Median       3Q      Max
-1.49378 -0.30494 -0.24489 -0.18798 24.15693

Count model coefficients (poisson with log link):
               Estimate Std. Error z value             Pr(>|z|)
(Intercept)  -2.7768785  0.6833384 -4.0637     0.000048302053583 ***
yearfact2003  0.1143046  0.5067438  0.2256              0.821538
yearfact2004  0.4157346  0.4708317  0.8830              0.377247
yearfact2005  0.3103873  0.4619732  0.6719              0.501665
yearfact2006  0.4852225  0.4635136  1.0468              0.295175
yearfact2007  0.2396161  0.4650033  0.5153              0.606343
yearfact2008  0.1730797  0.4673669  0.3703              0.711137
yearfact2009  1.2042387  0.4597852  2.6191              0.008815 **
yearfact2010  0.2329535  0.4820340  0.4833              0.628903
yearfact2011 -0.0442409  0.4723097 -0.0937              0.925372
yearfact2012  0.5641032  0.4650597  1.2130              0.225142
yearfact2013 -0.3968655  0.4624704 -0.8581              0.390814
yearfact2014 -0.5035538  0.4698085 -1.0718              0.283797
yearfact2015 -0.2830251  0.4648578 -0.6088              0.542629
yearfact2016  0.6490979  0.4604675  1.4096              0.158643
s(hk_bt_flt) -0.0347939  0.0050383 -6.9060     0.000000000004987 ***
monthfact02   0.0508099  0.1975309  0.2572              0.797005
monthfact03  -0.1367351  0.1911790 -0.7152              0.474473
monthfact04  -0.4960779  0.1929254 -2.5713              0.010130 *
monthfact05  -0.0733184  0.1866596 -0.3928              0.694473
monthfact06  -0.2490295  0.1914505 -1.3008              0.193343
monthfact07  -0.3143870  0.1967154 -1.5982              0.110002
monthfact08  -0.4074905  0.1967536 -2.0711              0.038352 *
monthfact09  -0.0812565  0.1903597 -0.4269              0.669483
monthfact10  -0.6348655  0.2135157 -2.9734              0.002945 **
monthfact11  -0.2227343  0.2131357 -1.0450              0.296007
monthfact12   0.3802578  0.1972675  1.9276              0.053902 .
s(newlat1d)   0.1146647  0.0084385 13.5882 < 0.00000000000000022 ***
s(newlon1d)  -0.0120045  0.0027536 -4.3596     0.000013031682503 ***
s(AllTuna)    0.0078570  0.0011028  7.1243     0.000000000001046 ***

Zero-inflation model coefficients (binomial with logit link):
               Estimate Std. Error  z value              Pr(>|z|)
(Intercept)  -9.0248065  0.8874618 -10.1692 < 0.00000000000000022 ***
yearfact2003  0.3132428  0.6045479   0.5181             0.6043578
yearfact2004 -0.2429564  0.5708908  -0.4256             0.6704182
yearfact2005  0.0062446  0.5610291   0.0111             0.9911193
yearfact2006 -0.5279522  0.5610783  -0.9410             0.3467253
yearfact2007 -0.7765633  0.5656418  -1.3729             0.1697869
yearfact2008 -0.6468497  0.5675334  -1.1398             0.2543879
yearfact2009  0.2774208  0.5578254   0.4973             0.6189595
yearfact2010 -0.3838493  0.5819006  -0.6596             0.5094800
yearfact2011 -0.8401439  0.5796977  -1.4493             0.1472596
yearfact2012  0.6472538  0.5770715   1.1216             0.2620249
yearfact2013 -0.5820628  0.5617602  -1.0361             0.3001363
yearfact2014 -0.3735477  0.5694291  -0.6560             0.5118216
yearfact2015 -0.0393463  0.5597728  -0.0703             0.9439630
yearfact2016  0.2535404  0.5549252   0.4569             0.6477492
s(hk_bt_flt) -0.0170466  0.0061538  -2.7701             0.0056037 **
```

```
monthfact02  -0.2564002  0.2372856  -1.0806              0.2798950
monthfact03  -0.5107879  0.2283065  -2.2373              0.0252674 *
monthfact04  -0.6190216  0.2305128  -2.6854              0.0072441 **
monthfact05  -0.3973276  0.2207109  -1.8002              0.0718263 .
monthfact06  -0.5241174  0.2311159  -2.2678              0.0233433 *
monthfact07  -0.3761998  0.2403156  -1.5654              0.1174797
monthfact08  -0.5466782  0.2387071  -2.2902              0.0220118 *
monthfact09  -0.3711910  0.2285167  -1.6243              0.1043012
monthfact10  -0.2761340  0.2604124  -1.0604              0.2889754
monthfact11  -0.2884863  0.2535869  -1.1376              0.2552779
monthfact12  -0.1694501  0.2348810  -0.7214              0.4706451
s(newlat1d)  -0.0995524  0.0122755  -8.1098 0.0000000000000005068 ***
s(newlon1d)   0.0127137  0.0034598   3.6747              0.0002381 ***
s(AllTuna)   -0.0113759  0.0018572  -6.1252 0.0000000009057270495 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Number of iterations in BFGS optimization: 68
Log-likelihood: -6369.1 on 60 Df
```

Diagnostics for ZIP model of South Pacific Longline Fishery