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Assessment of blue shark in the southwestern Pacific

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1 Executive Summary

This paper presents the 2016 stock assessment of blue shark (*Prionace glauca*) covering the southern hemisphere component of the Western and Central Pacific Fisheries Commission Convention Area (WCPFC-CA) and fisheries for the period 1994–2014. This represents the first attempt to assess this stock, noting that the species has previously been assessed within the North Pacific (Kleiber et al., 2009; ISC, 2014; Rice et al., 2014). This assessment relies on the stock assessment software MULTIFAN-CL (Fournier et al., 1998; Hampton and Fournier, 2001; Kleiber et al., 2014), which fits size-based, age- and spatially-structured population models to data from multiple sources.

A number of challenges were experienced in the development of this assessment. While the stock of blue shark within the southern WCPFC-CA may be considered ‘data rich’ for a shark species, it is considered data poor in comparison to assessments performed for tuna and most billfish. Catch data are generally of poor quality and have to be reconstructed (see Tremblay-Boyer and Takeuchi, 2016), such that both catch inputs and the resulting CPUE time-series are uncertain. A major objective of this assessment is therefore to establish and examine key areas of uncertainty, and the impacts on estimates of stock status.

An initial grid of 36 model runs across four different axes of structural uncertainty was examined. These used two assumed catch time series, three CPUE time series, three assumptions of the stock recruitment relationship steepness parameter, and two alternative penalties for deviations from the stock recruitment relationship. Comparison of the objective function indicated that uncertainty in the catch time series estimates was influential for the results. There was also a weak tendency for support of higher steepness.

Stock assessments conducted using MULTIFAN-CL and other similar methods usually report stock status relative to the spawning biomass and fishing mortality at maximum sustainable yield (MSY) and spawning biomass relative to unfished levels (so-called depletion estimates). In both cases, predictions of equilibrium recruitment are required from an assumed or estimated stock recruitment relationship (SRR). Early attempts to estimate the SRR, even when the steepness parameter was specified, resulted in very large estimates of unexploited equilibrium recruitment and spawning biomass that were considered to be unrealistic. Therefore, we do not present any results in this assessment that were dependent on SRR estimates. Instead, we computed estimates of unexploited spawning biomass and depletion based on the estimated recruitments without adjustment for the SRR. No estimates of MSY-related quantities were possible under these circumstances.

For model runs conditioned on the Pacific-wide CPUE-based catch estimation, biomass declines moderately over the period of the assessment; however, for the runs conditioned on the observer-based blue shark/general shark ratio catch estimation, biomass is stable in the first half of the time series and tends to increase thereafter. For all of the runs, spawning biomass depletion is estimated to be 0.08 to 0.10, inferring very strong impacts of fishing from unexploited conditions. However, these impacts have been fairly stable over the period of the assessment. Recruitment is

variable from year to year for the Pacific-wide CPUE-based catch estimation runs, but is higher in the second half of the time series for the observer-based ratio catch estimation runs.

Given the encountered issues with available data, generally poor fits to CPUE time series by the model, and uncertainty in the estimated stock recruitment relationship, we view this assessment as a work-in-progress. We do not recommend that the derived stock status estimates be used as the basis for management advice at this time. Based on the uncertainties in data inputs, recommendations for future work and assessments are as follows:

- an investigation into catch, effort and length data prior to 1994 should be undertaken, particularly for the high seas driftnet fishery that was active in the South Pacific until the early 1990s;
- future catch reconstructions should utilise data sources additional to observer data, such as trade data;
- SC should develop a strategy to ensure observer deployments are spatially and temporally representative of fishing effort; to inform this strategy, it is recommended that spatial and temporal observer coverage for each fleet is reported and evaluated in an annual observer data gaps paper;
- pending availability of resources, SPC should undertake a systematic, fleet-specific evaluation of the nature and extent of these data quality issues as a specific project and report the findings to SC13;
- pending availability of resources, SPC should undertake an analysis of the statistical power of WCPO observer coverage configurations to detect changes in spatio-temporal abundance of bycatch species;
- the use of Electronic Monitoring and Electronic Reporting approaches should be pursued to supplement observer coverage;
- approaches to ensure the full enumeration of key shark catches in logsheets (both retained and discarded) should be pursued;
- an investigation should occur into whether there is a size bias in the individual lengths recorded by the observers;
- observers should report the sex of sharks for all fish handled;
- the project “Develop proposed target and limit reference points for elasmobranchs” specified as part of the 2015 Shark Research Plan should continue to be prioritized so that planned stock assessments for sharks in the WCPO be effectively translated into management advice;
- further work focused on growth, mortality, reproduction and movement for South Pacific blue shark should be prioritised to overcome the paucity of biological data for this stock;

- further work on stock structure should be undertaken for blue shark in the WCPO south of the equator to confirm the assumption of independent North and South Pacific blue shark stocks;
- an investigation of the potential for modern genetic techniques, such as gene tagging and close-kin genetic analysis, to provide fishery independent indicators of population size should be undertaken;
- a careful consideration of the availability and quality of additional sources of data existing east of the WCPFC-CA should be performed before future stock assessments for South Pacific blue shark occur;
- active collaborations between interested CCMs should be pursued for future South Pacific blue shark assessments, e.g., through expert workshops.

Lower priority recommendations are included in Section 8.2.

Revision 1: 26 July 2016 We have clarified some of the issues experienced within this assessment and have noted in the Executive Summary that we view this as a work-in-progress. To reduce the implications of the poorly estimated stock recruitment relationship (SRR) on the estimates of depletion, we have used an alternative approach where unexploited spawning biomass and hence depletion estimates, were calculated using the estimated recruitments rather than those adjusted using the SRR. The method to calculate initial population size was also revised to use the average age-specific fishing mortality over the first five years of the assessment period. This change reduced the number of runs in the structural uncertainty grid because it was no longer necessary to make explicit assumptions about the initial population age structure. However, we stress that this assessment remains a work in progress and that we do not recommend that the derived stock status estimates be used as the basis for management advice at this time.

2 Introduction

This paper presents the 2016 stock assessment of blue shark (*Prionace glauca*) covering the southern hemisphere component of the Western and Central Pacific Fisheries Commission (WCPFC) Convention Area and fisheries for the period 1994–2014. This represents the first attempt to assess this stock, noting that the species has previously been assessed within the north Pacific (Kleiber et al., 2009; ISC, 2014; Rice et al., 2014).

The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, which indicate the stock status and fishing impacts. We attempt to summarize the stock status in terms of reference points adopted or under consideration by the WCPFC. However, we note that reference points for shark species remain an area of discussion and hence the use of specific benchmarks within the presentation of stock status in this report should be interpreted in the context of those discussions.

This assessment relies on the stock assessment software MULTIFAN-CL (Fournier et al., 1998; Hampton and Fournier, 2001; Kleiber et al., 2014), which implements size-based, age- and spatially-structured population models. Model parameters are estimated by maximizing an objective function, consisting of both likelihood derived from data and prior information components.

The current assessment is supported by an analysis of observer data to construct both CPUE time series, catch estimates, and size frequencies (Tremblay-Boyer and Takeuchi, 2016). It is also informed by the results of an expert workshop on the life history parameters of shark species (Clarke et al., 2015).

A number of challenges were experienced in the development of the assessment. While the stock of blue shark within the southern WCPFC-CA may be considered ‘data rich’ for a shark species, it is data poor compared to assessments for tuna and billfish in the WCPO. Catch data are generally of poor quality and have to be reconstructed, such that both catch inputs and the resulting CPUE time-series are uncertain. A major objective of this assessment is therefore to establish and examine key areas of uncertainty, and the impacts on estimates of stock status.

3 Background

3.1 Biology and ecology

Blue sharks are large, highly migratory pelagic carcharhinids. They are a relatively productive shark species found in tropical and temperate waters from around 50^oN to 50^oS around the world (Nakano and Stevens, 2008). No genetic evidence of distinct population structure within the Pacific has been found (Taguchi and Yokawa, 2013). However, while blue shark have been caught near the equator, they are most frequently found in cold, temperate waters, leading to a general spatial separation within the WCPO. No tagged individuals have crossed the equator yet (Stevens et al., 2010; Sippel et al., 2011). As a result, the assumption is that two stocks exist in the Pacific, one in the north and one in the south.

Life history parameter information specific for the South Pacific stock is limited. Available information on the biological parameters for this shark is summarized in the report of the Pacific shark life history expert panel workshop held in April 2015 (Clarke et al., 2015). This section summarizes the information presented in that report and readers are referred to that document for more details.

Sex-specific growth profiles have been identified, with male blue shark reaching a larger asymptotic length than females (295-369 cm TL for males *vs.* 242-304 cm TL for females). Age and growth estimates are available from specific locations, based for example on counts of opaque growth zones in sectioned vertebrae, although validation of the periodicity of those zones has not been confirmed (Manning and Francis, 2005). Studies to further evaluate the growth of blue shark in the Pacific are underway (Malcom Francis, *pers. comm.*) but results are not yet available. Divergence of male and female growth may occur around 8 years of age, which is approximately the age at maturity; age at 50% maturity has been estimated to be 8 years for males and 7-9 years for females. Studies in New Zealand waters have shown that male blue shark become sexually mature around 190-195 cm fork length (FL), while female blue shark mature at slightly smaller sizes of 170-190 cm FL.

The report of the Expert Workshop (Clarke et al., 2015) considered that the reproductive pattern and cycle of the Pacific blue shark was relatively uncertain. Japanese data suggest mating may occur year-round, while Chinese Taipei data suggest strong seasonality. Gestation in females may last between 9-12 months, and Australian data suggest young are often born in spring or summer. The litter size of blue shark ranges from 13-68, with a mean of 35 pups. This makes them a relatively fecund shark species. Size-at-birth information is uncertain, although information from New Zealand suggests full-term pup sizes of 54cm in February. Sex ratio of embryos is 1:1. The workshop recommended that resolving uncertainty in the reproductive parameters should be considered a priority for future studies of this species.

The conversion factors for length-weight of this shark are also uncertain. For blue shark in the North Pacific, the ISC plans to undertake a comparison of conversion factors and meta analysis of them, if possible. Similar work might be necessary to improve future stock assessments of blue shark in the South Pacific.

Estimates of blue shark natural mortality rate are uncertain, and available estimates rely on commonly used equations based upon growth parameter estimates. For example, Manning and Francis (2005) estimated rates of 0.19 to 0.21 for fish in New Zealand waters using Hoenig's approach (Hoenig, 1983).

3.1.1 Fisheries

Within the Western and Central Pacific Ocean (WCPO), blue shark is the most common and frequently reported shark species in longline catches, averaging 60-90% of shark bycatch recorded by observers in the region of the WCPFC-CA south of 10°S (e.g. Rice et al., 2015). There are substantial regional and depth variations in their occurrence within longline fisheries. The distant-water longline fleets of Japan, Korea, Chinese Taipei, European Union and China, and the domestic longline fleets of a number of Pacific Island Countries and Territories (PICTs) catch blue shark over a large proportion of their geographic range (for the spatial distribution of officially reported catches for the last 5 years, see Figure 1).

While not generally sought after for their meat (but see Dent and Clarke, 2015), blue shark are a major part of the international fin trade (Clarke et al., 2006) and therefore represent a potentially valuable 'bycatch' species. These fleets for which the shark represents a bycatch may target very different species dependent upon their latitude. In turn, specific longline fleets actively target blue shark. For example, the EU longline fleet is known to target both swordfish and blue shark in the southern WCPFC-CA at different times of the year (Poseidon et al., 2013).

Historically, a driftnet fishery operated within the South Pacific in the late 1980s until a United Nations moratorium on industrial-scale drift-netting in 1992 (Murray, 1994). Based upon available information from other driftnet fisheries within the Pacific, this fishery is likely to have caught important quantities of blue shark. This issue is discussed in more detail below.

3.2 Previous assessments

Blue sharks in the North Pacific have been subject to stock assessments as a stock unit (Kleiber et al., 2009; ISC, 2014; Rice et al., 2014). This report represents the first attempt to assess the stock within the southern WCPFC-CA. Unlike other shark stock assessments recently presented to the WCPFC Scientific Committee (ISC, 2014; Rice and Harley, 2012, 2013b; Rice et al., 2014), MULTIFAN-CL (Davies et al., 2015) was used as the stock assessment platform. It had previously been utilised for the North Pacific blue shark assessment of Kleiber and Takeuchi (2001).

The WCPFC Scientific Committee has previously reviewed analyses of stock status and related indicators for key shark species within the WCPO (e.g. Clarke et al., 2011b; Rice et al., 2015), which have included analyses of data for South Pacific blue shark. Those indicator analyses examined trends in nominal and standardised catch rates, and in the size structure of catches. Reported trends in nominal longline catch rates from observers within the southern hemisphere showed a decline over time (e.g. Clarke et al., 2011b). The number of observed longline sets in which blue shark were reported, and the number of spatial cells in which high CPUE (defined as more than 1 shark per 1000 hooks) were also found to decline between the late 1990s and the end of the data series in 2014 by Rice et al. (2015).

Standardisation of catch rates through modelling approaches can provide better understanding of potential CPUE trends. Two analyses of blue shark CPUE have been undertaken on observer-collected longline data in recent years. Clarke et al. (2011b) found that catch rates in the southern hemisphere showed a fluctuating trend over the period 1996-2010 with a decline to 2003, a peak in 2008 and a return to lower catch rates in 2009-10. Rice et al. (2015) also identified declines in the initial 1995-2003 period, relatively stable CPUE between 2004-2009, and a subsequent decline during 2010-2015. However, challenges in the interpretation of the trends in CPUE were noted in both reports, including:

1. Potential longline species/stock targeting effects;
2. Changes in regulations over time;
3. Changes in data availability.

A further uncertainty is that region-wide analyses may integrate across local trends. For example, Francis et al. (2014) standardised catch rate information available from the New Zealand observer programme, and found a notable increase in the standardised CPUE achieved over the period 2006 to 2013.

In order to understand trends in indicators, and to quantify shark status in relation to management reference points, regional stock assessments are required. WCPFC SC8 requested an assessment of South Pacific blue shark be conducted for 2013. The preliminary analyses to support that assessment were presented to the SPC pre-assessment workshop in April 2013. The workshop recommended that efforts should focus solely on the determination of plausible catch and CPUE series for presentation to WCPFC SC9 to allow that body to determine the feasibility of conducting an assessment (SPC-OFP, 2013). The resulting paper Rice and Harley (2013a) noted that while in general data existed to support a stock assessment, all data sets (observer, logsheet, aggregate) shared the same characteristics of poor coverage with respect to space, time, or species identification.

This process reflected the basis of the design of the WCPFC's Shark Research Plan (Clarke and Harley, 2010; Clarke et al., 2011a; Harley et al., 2013), being that initial indicator analyses such as those described above would be used for an initial assessment of shark species, and where those studies indicated further analysis was needed for certain stocks, a stock assessment would be attempted. The results of the shark indicator analyses of Rice et al. (2015), in particular the declining trend in some CPUE time series, continued to raise concerns over the status of South Pacific blue shark. Based upon those results, Rice et al. (2015) noted that an assessment of blue shark in the South Pacific should be the highest priority of the shark stocks examined. With the adoption of the Shark Research Plan and associated Stock Assessment Schedule (WCPFC, 2015, Attachment H) endorsed by WCPFC12 (WCPFC12 report, para 429), a stock assessment for southwest Pacific blue shark was scheduled for 2016.

4 Data compilation

Data used in this assessment consist of fishery-specific catch, effort and length-frequency (size) data. Details of these data and their stratification are described below. While there is clear indication of sexual dimorphism in growth of blue sharks (Clarke et al., 2015), the available data were insufficiently disaggregated by sex to allow a sex-structured model to be developed. Improvement in the sex-separation of data to support the development of sex-structured models in the future, and greater observer coverage of longline fleets to support this activity, is strongly recommended.

4.1 Spatial stratification

The area encompassed by this assessment is the southern western and central Pacific Fisheries Commission Convention Area (WCPFC-CA), starting at the eastern boundary for Southern Australia of 141°E and including the overlap area with the Inter-American Tropical Tuna Commission (Figure 2).

A previous survey of the available data for South Pacific blue shark suggested 5 regions be considered within assessment models (Rice and Harley, 2013a). For the current iteration, we elected to keep a single model region due to considerable issues with data quality and the limited ability of the available blue shark tagging information (see section 7 in Tremblay-Boyer and Takeuchi, 2016) to support separate model regions and allow the estimation of movement among them.

4.2 Temporal stratification

Following considerable discussion about the uncertainty in data for both longline and driftnet fisheries before 1990 at the SPC Pre-assessment workshop (PAW; Pilling and Brouwer, 2016), and based upon the experience of attendees, the assessment period was extended back to 1994 only. The driftnet fishery operating within the south Pacific in the late 1980s potentially caught important quantities of blue shark, but no data were available on blue shark catches from this fishery, except for anecdotal reports from early observer trips within SPC (e.g. Sharples et al., 1991). Given the limited ability to estimate reasonable catch levels for this historical fishery, the starting year of 1994 was chosen to coincide with the period where driftnet fishing was banned and observer programmes were started in the region. The assessment period thus represents a trade-off between maximising the length of the time-series of available and/or reliable catch data and minimising the impacts of increasing uncertainty in the catch reporting of blue shark as the time period extends further into the past. The end of the assessment period was set to 2014 since the catch inputs are heavily reliant on observer data which have longer updating delays.

Over the 1994-2014 period, population dynamics were updated at annual intervals, given a single recruitment event per year, but fishery inputs were incorporated at the quarterly scale to allow for seasonal variation in catchability. The selection of 1994 as the start year minimized one aspect of the uncertainty arising from blue shark catches within the historical South Pacific driftnet fishery, but meant that the initial population status was below unfished levels, which had to be accounted for in the model parameterization (see Section 5.1.2).

4.3 Definition of fisheries

MULTIFAN-CL requires all catch and effort and length-frequencies, to be allocated to "fisheries". For pelagic assessments, fisheries are typically defined based on gear type, fishing method and region. Ideally, these fisheries are defined to have selectivity and catchability characteristics that do not vary greatly over time.

Only longline fleets were retained for the southern WCPFC-CA blue shark assessment. Longliners are the main gear impacting the stock for the period 1994-2014 and they are the only gear for which it was plausible to reconstruct time series of blue shark data based primarily on the observer coverage spanning the southern WCPFC-CA (see Figure 3 in Tremblay-Boyer and Takeuchi, 2016). The longline fleets operating in the South Pacific can be broadly assigned to three categories in the context of the blue shark assessment:

1. distant-water fishing nations (DWFNs) with extensive fishing grounds, broad variations in catch rates for blue sharks within those grounds, and sparse or absent observer coverage;
2. domestic fleets from PICTs with more restricted fishing grounds, lower blue shark catch rates and relatively low rates of longline observer coverage; and
3. fleets (domestic and DWFNs) with very high catch rates for blue sharks fishing in the South Pacific, varying levels of observer coverage (none for Spain, some for Japan, more for Australia and New Zealand) and partial to full sets of logsheet fleet data available to the SPC.

We defined an initial set of 15 fisheries based on the longline effort within the South Pacific from $5 \times 5°$ raised logsheet effort estimates of SPC holdings. These fleets are described in Table 1 of Tremblay-Boyer and Takeuchi (2016), and account for about 99% of longline effort within the WCPFC-CA in the South Pacific. Some of these fleets were further divided based on their fishing grounds and their targeting of specific species. More specifically, spatial trends in observer catch rates highlighted that: (1) catch rates for blue sharks were extremely high at high latitudes in the South Pacific during winter. These regions tended to be associated with swordfish targeting (in the northern region) or southern bluefin tuna targeting (in the south), mainly by the fleets of Spain, Australia, New Zealand and Japanese vessels operating within Australian/New Zealand waters; and (2) catch rates for blue shark in tropical waters tended to be low on average, unless associated with swordfish targeting in the equatorial region (primarily by the DWFNs fleets of China, Chinese Taipei and Korea). The outline for the resulting three fishery subregions (related to swordfish targeting in the northeast, the tropical waters subregion, and southern bluefin tuna targeting in the southwest) are shown in Figure 2. The boundary for the equatorial swordfish targeting subregion was informed by the 2013 assessment for this species (Davies et al., 2013) and refined based on patterns in observed swordfish catch rates (Figure 20 in Tremblay-Boyer and Takeuchi, 2016). Fleets that operated in one or more of these subregions were split to reflect this, that is, the Australian, Japanese and New Zealand fleets were divided into 'core' and southern bluefin tuna targeting fisheries based on their fishing grounds, and, similarly, the Chinese, Korean and Chinese Taipei fisheries were divided into 'core' and swordfish targeting fisheries.

Finally, the main Australia fleet was split into pre- and post-2012 fisheries to account for a marked shift towards smaller individuals in the length frequency of blue shark individuals observed from this fishery. It was subsequently found that this was due to a database conversion error within the Australia databases, but was not accounted for in the assessment due to the late discovery of this issue. The impacts of this on assessment results will be examined.

The final fleet count for this stock assessment was thus 22, based on flags and fishing grounds as defined above. Fisheries definitions and groupings are summarized in Table 1.

4.4 Catch and effort data

The designation of blue shark as a 'key shark species' in 2008 and subsequent incorporation of shark species-specific reporting within logsheets (WCPFC, 2010) has improved catch information considerably in recent years. However, as discussed further in sections 2 and 3 of Tremblay-Boyer and Takeuchi (2016), there are multiple issues with data reporting, including under-reporting of catches and the grouping of catches of all shark species into a generic 'shark' category. These imply that for most fleets catches cannot be used as reported and must be 'reconstructed'. There are three types of catch data available for the southern WCPFC-CA:

1. Operational logsheet data: All set-level (logsheet or operational) records were extracted from SPC-held databases. These data report set-specific catches for main target species (tuna and billfish), as well as catches for key shark species since CMM 2008-06 and CMM 2010-07 were enacted. These data are complete for SPC-managed fishing records for Pacific Island fleets but have various degrees of coverage rates in space and time for distant-water fishing nations.

2. Raised $5 \times 5°$ logsheet data: Best estimates of longline effort and catches at the five degree scale as computed by the Oceanic Fisheries Data Management section of SPC. These data have better temporal and spatial coverage than the operational logsheet data as not all countries provide the latter. This dataset constitutes the most accurate estimate of longline fishing effort in the Pacific but catch estimates for non-target species, including blue shark, are not felt to be reliable.

3. SPC observer data holdings: Collated observer entries for PICT observer programmes, along with available data from specific independently managed national observer programs for

Australia, China, Chinese Taipei, New Zealand and the United States. There was no observer data available from the Japanese observer program but there were observations on Japanese vessels from various other national programs for waters within Exclusive Economic Zones (EEZs). There was no observer information available for the Spanish fleet.

Catch reconstruction for all fleets defined in Section 4.3 were performed under three scenarios based on observer and raised 5 × 5 logsheet data. Three scenarios for abundance trends via CPUE standardizations were performed based on the operational logsheet and observer data. The approach is briefly described in the following sections, but see Tremblay-Boyer and Takeuchi (2016) for more information.

All catch data inputs to the model were in numbers of fish while effort was in hooks fished. Effort was standardized as described below for the fleets for which an index of abundance was included, and otherwise was extracted directly from the raised 5 × 5° logsheet estimates for the southern WCPFC-CA, aggregated over all 5 degree cells for which a record existed for the fleet in a given year-quarter.

4.4.1 Catch scenarios

Reconstruction of historical catches was performed for the main 15 fleets under three scenarios:

- Catch reconstruction scenario 1: Blue shark-to-all sharks ratio from fleet specific observer programmes
- Catch reconstruction scenario 2: Fleet-specific observer time-series
- Catch reconstruction scenario 3: All-observer fleet CPUE surface

Only scenarios 1 and 3 were retained in the final grid as they bracket the predicted catches from scenario 2 and are presumed to represent plausible lower and upper ranges of blue shark catch (but see discussion in Tremblay-Boyer and Takeuchi, 2016). In addition, scenario 2 was only performed on the initial definition of 15 fleets since it relies on fleet-specific observer coverage which were not always available for the flags after the split into swordfish or southern bluefin tuna targeting fleets. Quaterly predictions of catches for scenarios 1 and 3 are shown per fishery in Figure 3 and aggregated per MFCL fishery grouping in Figure 4. In addition, the geographic distribution of total reconstructed catches for the assessment period are presented in Figures 5 and 6, with the split by flag shown in Figure 7 (for context, see also the spatial distribution of official catches by flag, Figure 1). Details of the flags, and their respective catches within each longline fishery are provided in Tremblay-Boyer and Takeuchi (2016).

Note that no discard mortality scenario was used since the fleets for which this would be relevant (mainly, American Samoa, New Caledonia, French Polynesia) made up a small proportion of total catches and the difference was small compared to the difference between predicted catches under catch scenarios 1 and 3.

4.4.2 Standardized CPUEs

Examination of the available datasets failed to identify an 'ideal' CPUE time-series from which to assume an abundance trend (Tremblay-Boyer and Takeuchi, 2016). Instead, we defined three CPUE scenarios that represent the key combination of fleet and data quality/availability as described in section 4.3:

- CPUE scenario 1: a South Pacific-wide index including all fleets based on observer data, using a negative binomial error distribution (CPUEPW);
- CPUE scenario 2: an index for a distant water fishing nation, the Chinese Taipei/Vanuatu fleet, based on observer data and using Pacific-wide fitted 'nominal' CPUEs from the all-observer fleet CPUE surface (CPUETW);
- CPUE scenario 3: an index based on high-quality operational data, the New Zealand operational fleet, using a delta-lognormal distribution (CPUENZ).

The methods to generate these indices are described in Tremblay-Boyer and Takeuchi (2016) and the final series used as inputs to the assessment are shown in Figure 8. At the pre-assessment workshop, it was agreed that only one abundance time-series should be used at a time to inform the stock-assessment model (Pilling and Brouwer, 2016). In their respective scenarios within the grid, the South Pacific index was applied to the Japanese fleet as it constituted the bulk of the estimated catch. The Chinese Taipei index was applied to the 'core' of the Chinese Taipei fleet (i.e. not to the swordfish component of that fleet: TW.SWO) and the New Zealand index was applied to the main New Zealand fleet. The indices were used to generate standardized effort as the ratio of catch to standardized CPUE following the usual MFCL approach. The CVs of effort penalty of the fisheries with standardized effort were set to 0.22, while 0.71 was used for fisheries without standardized effort.

4.5 Size data

The length-frequency data available for South Pacific blue sharks were obtained from observer records from the SPC observer holdings. Total lengths were converted into fork lengths (upper jaw to fork in tail) given the sex-aggregated conversion provided in Francis and Duffy (2005)(see Tremblay-Boyer and Takeuchi, 2016, for more details). Observed lengths were compiled into 5 cm intervals from 40 to 335 cm, for a total of 61 bins. Length-frequency sample sizes and distributions by fishery grouping are shown in Table 2 and Figure 9, respectively.

5 Model description

In this assessment blue shark in the southern WCPFC-CA is assumed to be a single closed population (stock).

5.1 Population dynamics

The model used a single spatial region and 20 annual age classes. The oldest age class comprised a "plus group" in which mortality and other parameters are assumed to be constant. The population is updated at annual time steps over the period 1994-2014. Since a single spatial region is used, movement dynamics were not considered. Although the first year of the stock assessment was chosen to be 1994, it is highly likely blue sharks in the South Pacific have been extensively exploited historically by both the longline fisheries and the driftnet fishery active during the 1980s to early 1990s. The choice of initial year was primarily driven by the availability of fishery catch-and-effort data for blue shark and agreed upon at the Pre-Assessment workshop (Pilling and Brouwer, 2016).

5.1.1 Recruitment

In MULTIFAN-CL, recruitment is defined as the appearance of age class 1 fish in the population. As noted, little is known about the reproductive cycle of blue shark in the South Pacific. In this stock assessment assumptions were made to simplify the modelling process. Namely, recruitment was assumed to occur once a year on January 1st. The choice of annual recruitment rather than continuous recruitment is based on the notion that as blue shark is exclusively exploited by longline gear, the level of juvenile blue shark catches is likely to be small, and largely independent of the true recruitment cycle (e.g. if they are actually spawning year around or have a significant spawning peak). A one year time lag from spawning to recruitment was used as an approximation of the 8-9 month gestation period reported in the Atlantic (Hazin and Lessa, 2005).

Unlike other stock assessments using MULTIFAN-CL, this stock assessment assumed a higher penalty (i.e., lower variance) than assumed for tuna species on model estimated recruitments compared to those calculated from the stock recruitment function. This is based on the logic that shark have a small number of pups compared with number of eggs produced by tuna, implying there should be less variation from the deterministic stock recruitment relationship. A conventional Beverton-Holt stock recruitment function was used for the stock recruitment relationship. In the recent stock assessment of blue shark in the North Pacific, a more complicated three parameter stock recruitment function (LFSR, Taylor et al., 2013) was used (ISC, 2014; Rice et al., 2014). However it was not considered completely successful, with the note that the resulting model could fit data equally well, but lead to a very optimistic or very pessimistic stock status when fitting to the same data (Rice et al., 2014).

Given the one year time lag from spawning to recruitment, twenty years of data were in theory available to estimate the SRR. However, the final two years and the initial two years were excluded from the estimation, the former being set equal to the arithmetic mean of estimated recruitments over the period, the latter due to the need to allow the population to adjust from the assumed 'initial population' state (see below). Sixteen years of estimates (1996-2011 for adult biomass, 1997-2012 for recruitment) were therefore used within the stock-recruitment estimation.

5.1.2 Initial population

At the start of stock assessment period (1994) blue shark are likely to have already been exploited for more than 30 years, and an unfished equilibrium condition at that time is highly unlikely. However, it was not known to what extent blue shark was exploited in 1994. We have assumed an initial equilibrium age distribution based on the average, age-specific, total mortality over the first 5 years of the assessment period.

5.1.3 Growth

As described in the previous section blue shark has different growth curve parameters by sex. Although the most recent version of MULTIFAN-CL is capable of incorporating sex structure into the model, the current stock assessment was run as a sex aggregated model due to the limited sex-specific data available. Combined sex growth curve parameters for south Pacific blue shark are not available. We therefore obtained sex combined growth curve by averaging the growth curve of each sex estimated by Hsu et al. (2011)(Figure 14).

5.1.4 Natural mortality

Little is known about the natural mortality of this shark. Kleiber and Takeuchi (2001) used an age constant natural mortality of 0.2 in their stock assessment of North Pacific blue shark. Recent north Pacific blue stock assessments (Rice et al., 2014; ISC, 2014) used sex differential age specific natural mortality for blue shark in the South Pacific. Manning and Francis (2005) estimated 0.21 for male and 0.19 for female through life history based method of Hoenig (1983). This stock assessment applied 0.2 for all ages (Figure 11). It may be worthwhile to consider alternative natural mortality values, or age-specific functions, as was done for the North Pacific blue shark stock assessment, but in order to reduce the dimension of uncertainty grids to tractable levels we only used a single assumed value.

5.1.5 Maturity

Clarke et al. (2015) suggest that 50% maturity is 8 and 7-9 years for males and females, respectively. Within this stock assessment an age at 50% maturity of 8 years is assumed (Figure 12).

5.2 Fishery dynamics

5.2.1 Selectivity

Selectivity is fishery-specific, and assumed to be length-based to the extent that ages with similar lengths must have similar selectivities at age. Although the most recent version of MULTIFAN-CL allows selectivities to vary between different time periods for the same fishery, within this stock assessment each fishery in the model was designed to have time invariant selectivity (see Table 1).

Not all fisheries within the model had sufficient size composition data to estimate stand-alone selectivities. Based on preliminary trial MULTIFAN-CL runs which are not shown in this document, groups of fisheries that appeared to share common selectivities were designated. Based on this process the selectivity groupings were:

1. distant water and PICT tropical longline group;
2. Australian longline before 2012, as since that time the observed size declined notably;
3. Japanese, Chinese-Taipei, Australian and New Zealand longline operating in the southern bluefin fishing area within the Australian EEZ around Tasmania, the New Zealand EEZ and southern high seas area. This group catches relatively smaller blue shark compared with the other groups, with the exception of the Australian longline after 2012 which caught the smallest size of blue shark;
4. the northeastern region ‘swordfish’ fisheries.

5.2.2 Catchability

Catchability was assumed to be constant over time for the longline fishery assigned the standardised CPUE time series, with quarterly variation. For the remaining fisheries with nominal effort (CPUE) their catchability was allowed to vary over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken annually, and deviations were constrained by a prior distribution of mean zero and a variance equivalent to a coefficient of variation (CV) of $\sim$0.7.

5.2.3 Effort deviates

Effort deviation penalties were implemented using the same approach as for other MULTIFAN-CL stock assessments, being constrained by prior distributions having a mean of zero and a specified variance. Time invariant penalties were applied to the effort deviations. For fisheries assigned the standardized CPUE (effort), a higher penalty (10), corresponding to a CV of 0.22, was used. A lower penalty (1) corresponding to a CV of about 0.70 was used for the remaining fisheries with nominal effort.

5.2.4 Size Composition Sample Size

The size frequency data were modelled using a robust normal distribution and, as is usual in integrated stock assessment models, were assigned an effective sample sizes lower than the number of fish sampled. The sample size was divided by 20 such that the maximum effective sample size applied to the size composition likelihood was 50 for each fishery and quarter.

5.3 Components of the objective function

MULTIFAN-CL has several different likelihood components and penalty functions to allow estimation of many model parameters, often numbering in the several thousands. Components of the total objective function for this stock assessment comprise the following:

- catch likelihood
- size composition likelihood (for method of weighting of size composition data, see section 5.2.4)
- penalties for effort deviations and catchability deviations
- penalties for stock recruitment
- penalties for selectivity

The number of model parameters to be estimated is more than 2000. More than half of these parameters are effort deviations.

5.4 Parameter estimates and uncertainties

The model parameters were estimated by minimizing the sum of the negative log likelihood components listed above. Minimization to convergence was performed with an efficient optimisation routine using exact derivatives with respect to the model parameters (auto-differentiation; Fournier et al., 2012), based on sequential application of the chain rule to calculate derivatives. They are written in C++ (Stroustrup, 2013). The core part of the code is common to ADMB (Fournier et al., 2012). The use of automatic differentiation allows models with many parameters to be fitted efficiently. Convergence of the minimization was judged by absolute value of the gradient of the negative log likelihood function. If all of the absolute values of the gradients were less than 0.001, the model was considered to have converged.

In this stock assessment, the uncertainty in the results was evaluated through a grid approach aimed at assessing the impacts of structural uncertainty in model parameters and fishery data. More specifically, the large uncertainty in fishery data inputs prevent an informative estimation of statistical uncertainty by the conventional approach of variance-covariance matrices. This will have to be addressed in future stock assessments when improved fisheries data become available.

5.5 Stock assessment interpretation methods

Stock assessments conducted using MULTIFAN-CL and other similar methods usually report stock status relative to the spawning biomass and fishing mortality at maximum sustainable yield (MSY) and spawning biomass relative to unfished levels (so-called depletion estimates). In both cases, predictions of equilibrium recruitment are required from an assumed or estimated stock recruitment relationship (SRR). Early attempts to estimate the SRR, even when the steepness parameter was specified, resulted in very large estimates of unexploited equilibrium recruitment and spawning biomass that were considered to be unrealistic. Therefore, we do not present any results in this assessment that were dependent on SRR estimates. Instead, we computed estimates of unexploited spawning biomass and depletion based on the estimated recruitments without adjustment for the SRR. No estimates of MSY-related quantities were possible under these circumstances.

6 Model runs

Given the uncertainty over the key input information and the life history characteristics of blue shark in the South Pacific, this stock assessment examined four different axes of structural uncertainty (Table 3). These included two sets of fisheries data (catch scenarios and CPUE time series) and two model parameters. In total, 36 combinations of structural uncertainties were considered. Details of each dimension of the grid are described below.

6.1 Fishery data

Figure 13 summarizes the availability of fishery data (catch, effort and length composition) in each year by fishery. To capture uncertainty in these inputs, the two time series estimates of historical blue shark catch in the southern WCPFC-CA (SC12-SA-WP-09 Figure 4) and three standardized CPUE time series (Figure 8) were evaluated within the model. The two catch estimates aimed to bracket the range of potential catch levels, representing a lower possible bound of catch (CATCHSHK) and an upper bound of catch (CATCHPW). Three CPUE time series are used which represent moderately increasing (CPUENZ), relatively stable after initial decline (CPUETW) and slowly declining (CPUEPW) stock trends.

6.2 Steepness

Three different fixed values of steepness were examined. These were based on the assumption that blue shark is one of the more productive species among sharks, but still less productive than tropical tuna stocks like bigeye. This resulted in three values of 0.4, 0.6 and 0.8. A value of 0.4 closely corresponds with the mid-value used in the oceanic whitetip and silky shark stock assessments (Rice and Harley, 2012, 2013b), while 0.8 corresponds to the value used in the reference case of the bigeye stock assessment (Harley et al., 2014).

6.3 Penalty on recruitment variability

The parameter σ_R is the standard deviation of the recruitment penalty. In order to keep stock dynamics close to the assumed stock recruitment relationship previous shark stock assessments (Rice and Harley, 2012; Rice et al., 2014; Rice and Harley, 2013b; ISC, 2014) assumed smaller σ_R values (0.1 and 0.31). This stock assessment took the same approach, but considered two different values (0.1, 0.31) of σ_R within the grid.

7 Results

7.1 An examination of results from the initial grid

Among 36 runs from the grid, 34 runs were considered to have converged successfully. For those models, the model fit to the data was examined through the negative of the objective function (Figure 15). Strictly speaking, it is not possible to directly compare models using different data in this way. Nevertheless the comparison of objective function between catch scenarios (Top left Figure 15) clearly suggests that the uncertainty in the catch time series estimates dominates the results of this stock assessment.

7.2 Summary of results from six runs to describe general tendency

This section summarizes the results of six model runs, chosen from combinations of the two catch time series estimates and three standardized CPUEs. Within these runs, steepness was fixed at 0.6, and σ_R at 0.31 (Table 4).

Figure 16 shows estimated trends of catchability and effort deviations, and time series plots of observed and predicted CPUE are shown in Figure 17. These are calculated through division of observed or predicted catch by normalized observed or predicted effort respectively, for the run using the Pacific-wide CPUE scenario. Figure 17 highlights the generally poor model fit to CPUE scenarios that predict increasing abundances with the exception of New Zealand CPUE with observer-based blue shark/general shark ratio catch scenario. The fit to the Chinese Taipei CPUE scenario which indicated gradual decline after 2000 is relatively good with the Pacific-wide CPUE based catch, especially post-2000.

Figure 18 presents estimated selectivities by age. All the fishery groups were estimated to have asymptotic selectivity with the exception of fishery group 3 where New Zealand CPUE and observer-based blue shark/general shark ratio catch scenario was applied. Nevertheless, of the fishery groups assumed to have asymptotic selectivity, the New Zealand fishery (fishery 14) selectivity starts to increase from younger ages compared to other groups with asymptotic selectivity. This together with the steep decline of aggregated length composition at older ages of this fishery (Figure 19) might be an indication that the New Zealand fishery (fishery 14) may have dome-shaped selectivity.

Figure 19 shows overall fit to length composition by fishery for one of the six selected runs -the fits for the other runs are essentially identical and are not shown. For most fisheries, MULTIFAN-CL was able to fit the available length composition data reasonably well. Exceptions were the Australian southern bluefin fishery (fishery 3) and the Australian longline after 2012 (fishery 22)[2]. For some fisheries, the older animals were overestimated. This might indicate that those fisheries in reality have dome shaped selectivity.

Figure 20 compares estimated total biomass, spawning stock size and spawning stock size relative to expected spawning stock size without fishing and recruits. Depending on the catch time series used, total biomass has fluctuated without trend (observer-based blue shark/general shark ratio) or gradually declined over time (Pacific-wide CPUE based catch). Overall, spawning stock size is estimated to have been slowly declining (Pacific wide CPUE based catch scenanrio) or stable (observer-based blue shark/general shark ratio catch scenario with Pacific wide CPUE or Chinese-Taipei CPUE) or increasing in the recent decade (observer-based blue shark/general shark ratio catch scenario with New Zealand CPUE). Trends of spawning stock size relative to expected spawning stock size without fishing has shown similar trends compared with those shown in the spawning stock size itself. This similarity may be due to relatively stable recruitment in this period and hence relatively stable expected spawning stock size without fishing.

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[2] On July 13, 2016, OFP was informed that observer data submitted by Australia for the period 2010-2014 that were the source of blue shark size composition data of the Australian fisheries (fisheries 2, 3, 22) contained an error. Lack of fit to fisheries 3 and 22 may be an artifact arising from this issue

7.3 Stock status and biological reference points

To date for shark species WCPFC has not yet determined biological reference points. Stock status for shark assessments previously presented to the Scientific Committee was assessed relative to MSY-based quantities and reference points. As noted earlier, in this assessment, it was not possible to obtain realistic estimates of equilibrium unexploited recruitment and spawning biomass using the SRR; therefore, estimates of MSY-based quantities could not be obtained.

Estimates of total biomass, spawning biomass, spawning biomass depletion and recruitment are shown for the six representative runs in Figure 20. For runs conditioned on the Pacific-wide CPUE-based catch estimates, biomass declines moderately over the period of the assessment; however, for the runs conditioned on the observer-based blue shark/general shark ratio catch estimates, biomass is stable in the first half of the time series and tends to increase thereafter. For all of the runs, spawning biomass depletion is estimated to be 0.08 to 0.10, inferring very strong impacts of fishing from unexploited conditions. However, these impacts have been fairly stable over the period of the assessment. Recruitment is variable from year to year for the Pacific-wide CPUE runs, but is higher in the second half of the time series for the observer-based ratio catch estimation runs.

8 Discussion and conclusions

8.1 Sources of uncertainties

This stock assessment represents the first attempt to assess the stock status of blue shark in the southern WCPFC-CA. The results of this stock assessment highlight the difficulty in determining stock status relative to MSY-based reference points from currently available catch and effort data for blue shark, and based upon necessary assumptions of blue shark biological characteristics. We view this assessment as a work-in-progress. We do not recommend that the derived stock status estimates be used as the basis for management advice at this time.

There were substantial differences, in unexploited stock size for runs based on different historical catch estimates, that are symptomatic of the difficulties faced when performing the assessment. Compared with the longevity of blue shark of 20 years or more, 21 years of data within the stock assessment period is insufficient when combined with limited available size composition data and an uncertain index of abundance. In order to reduce uncertainty in the stock assessment, it will be necessary to improve the historical data and continue to collect catch, effort and size data to extend the time series for future assessments. Recovery of historical fishery data on blue shark from key fisheries is also potentially beneficial to reduce uncertainties. The lack of biological parameters specific to blue shark in the South Pacific Ocean is of concern, since they are vital to conduct a stock assessment by modern quantitative fish stock assessment tools such as MULTIFAN-CL.

In the coming years, the requirement of WCPFC CMM 2010-07 to submit specific shark catch data will improve the quality of logsheet catch time-series. However, observer coverage will continue to be required to ensure that catch (including discards) is reported accurately. Observer-derived data fills multiple roles in the assessment of bycatch species:

1. it can be used as a basis to derive the time series of catch estimates and indices of abundance used within the assessment;
2. it can provide length-frequency data;
3. it allows the identification of operational drivers of high catch rates used to standardised CPUE time series, including from fleets for which logsheet data may not otherwise be available;
4. it improves our understanding of the fate of individuals once caught.

Furthermore, this assessment underscores the importance of promoting high quality and representative observer coverage across the fisheries in the WCPFC for scientific purposes.

Although survival rates following discarding were not included within the current catch scenarios, as CCMs are increasingly implementing legislation aiming at reducing shark mortality and/or increasing utilization, it will become a priority to account for hooking and discard mortality in reconstructed catches. Observer data will also be critical for this purpose.

8.2 Recommendations for future work

Noting the areas of uncertainty specified within the previous section, several areas of future work are highlighted. We classify these areas into those directed at improving data; those related to improving information on species life history; and those focused on improving modelling approaches.

Data improvements

Given the relatively short time series of data relative to blue shark longevity, recommendations focus upon the continued collection of accurate catch, effort and length composition data of blue shark in the South Pacific, as well as attempts to rebuild the time series of historical catches.

1. **It is recommended that an investigation into catch, effort and length data prior to 1994 be undertaken, particularly for the high seas driftnet fishery that was active in the South Pacific until the early 1990s**;
2. **It is recommended that future catch reconstructions utilise data sources additional to observer data, such as trade data**;
3. Noting that the annual reporting of observer data focuses solely on whether fleets meet mandated 5% coverage levels, **it is recommended that SC develop a strategy to**

ensure that observer deployments are spatially and temporally representative of fishing effort; to inform this strategy, it is further recommended that spatial and temporal observer coverage for each fleet is reported and evaluated in an SC observer data gaps review paper;

4. Despite improvements, significant issues in logsheet reporting of blue shark and other key shark species still remain (Williams, 2016) and could impact future analyses of shark status. **We recommend that, pending availability of resources, SPC undertake a systematic, fleet-specific evaluation of the nature and extent of these data quality issues as a specific project and report the findings to SC13**.
5. More formal monitoring of the quality of current observer coverage should be performed annually, including the ability to accurately represent seasonal and spatial trends. **We recommend that, pending availability of resources, an analysis of the statistical power of WCPO observer coverage configurations to detect changes in spatio-temporal abundance of bycatch species be undertaken**;
6. Noting the practical difficulties of increased observer coverage on longline vessels, **it is recommended that the use of Electronic Monitoring approaches be pursued to supplement observer coverage**;
7. Noting the implications of recent fishery discarding regulations for catch reporting and hence CPUE time-series, **it is recommended that approaches to ensure the full enumeration of key shark catches in logsheets (both retained and discarded) are pursued**;
8. The majority (>60%) of blue shark records for the South Pacific in the SPC observer data holdings lack a length measurement. Given that larger individuals may not always be brought on-board, **we recommend an investigation into whether there is a size bias in recording length.** Again, electronic monitoring would help to clarify this;
9. Sex-specific modelling in blue shark could not be pursued within this assessment due to the lack of sex-specific information. **We recommend that observers report sex of sharks for all fish handled;**
10. **It is recommended that the project "Develop proposed target and limit reference points for elasmobranchs" specified as part of the Shark Research Plan (Brouwer and Harley, 2015) continues to be prioritized so that planned stock assessments for sharks in the WCPO be effectively translated into management advice**.

Recommendations for biological studies

1. Noting the paucity of biological data for this assessment, **we recommend further work focused on growth, mortality, reproduction and movement for South Pacific blue**

shark;

2. This assessment assumed that blue shark in the southern WCPFC-CA comprised a single stock, distinct from that in the northern hemisphere. **We recommend that further work on stock structure be undertaken for blue shark in the WCPO south of the equator to confirm this assumption.**
3. The estimation of absolute population size of blue shark is one of the major areas of uncertainty in the assessment. **It is recommended that an investigation of the potential for modern genetic techniques, such as gene tagging and close-kin genetic analysis, to provide fishery independent indicators of population size be undertaken**;

Future assessments

1. Given that the main challenges in the current assessment were data related, **a careful consideration of the availability and quality of additional sources of data existing east of the WCPFC-CA should be performed before future stock assessments for South Pacific blue shark occur**;
2. There are ongoing long-term data consolidation and review activities across stakeholders for blue shark in the North Pacific (e.g. Kleiber and Takeuchi, 2001) which have allowed a number of data problems to be identified and solved. **We recommend that a similar active collaboration between interested CCMs for any South Pacific blue shark assessment occur, e.g., through expert workshops.**

Model oriented recommendations

Noting that an assessment output is based upon the quality of information available, the recommendations above are felt to be of higher priority to those made in the current section.

1. **We recommend that alternative formulations of the stock recruitment function within Multifan-CL be considered for future assessments, including the potential to incorporate shark specific information of reproductive biology (e.g. litter size)**;
2. **We recommend that the potential to place a prior on the unexploited stock size be examined**.

References

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

Clarke, S., Coelho, R., Francis, M., Kai, M., Kohin, S., Liu, K., Simpfendorfer, C., Tovar-Avila, J., Rigby, C., and Smart, J. (2015). Report of the pacific shark life history expert panel workshop, 28-30 april 2015. WCPFC-SC11-2015/EB-IP-13.

Clarke, S., Harley, S., L., P., and Williams, P. (2011a). A progress report on the shark research plan. WCPFC-SC7-2011/EB-IP-01, Pohnpei, Federated States of Micronesia, 9–17 August 2011.

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

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

Clarke, S., McAllister, M., Milner-Gulland, E., Kirkwood, G., Michielsens, C., Agnew, D., Pikitch, E., Nakano, H., and Shivji, M. (2006). Global estimates of shark catches using trade records from commercial markets. *Ecology Letters*, 9(10):1115–1126.

Davies, N., Fournier, D. A., Hampton, J., and Bouye, F. (2015). Recent developments and future plans for MULTIFAN-CL. WCPFC-SC11-2015/SA-IP-01, Pohnpei, Federated States of Micronesia, 5–13 August 2015.

Davies, N., Pilling, G., Harley, S., and Hampton, J. (2013). Stock assessment of swordfish (*Xiphiasiphias gladius*) in the in the southwest Pacific Ocean. WCPFC-SC9-2013/SW-WP-05, Pohnpei, Federated States of Micronesia, 6–14 August 2013.

Dent, F. and Clarke, S. (2015). State of the global market for shark products. FAO Fisheries and Aquaculture Technical Paper No. 590, Rome, FAO, 187 pp.

Fournier, D., Hampton, J., and Sibert, J. (1998). MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Canadian Journal of Fisheries and Aquatic Sciences*, 55:2105–2116.

Fournier, D. A., Skaug, H. J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M. N., Nielson, A., and Sibert, J. (2012). AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optimization Methods and Software*, 27(2):233–249.

Francis, M. and Duffy, C. (2005). Length at maturity in three pelagic sharks (*Lamna nasus*, *Isurus oxyrinchus*, and *Prionace glauca*) from New Zealand. *Fishery*, 103(3):489–500.

Francis, M. P., Clarke, S. C., Griggs, L., and Hoyle (2014). Indicator based analysis of the status of new zealand blue, mako and porbeagle sharks. New Zealand Fisheries Assessment Report 2014/69, 109 p, Ministry for Primary Industries.

Hampton, J. and Fournier, D. (2001). A spatially-disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean. *Marine and Freshwater Research*, 52:937–963.

Harley, S., Rice, J., and Williams, P. (2013). A progress report on the shark research plan. WCPFC-SC9-2013/EB-WP-06, Pohnpei, Federated States of Micronesia, 6–14 August 2013.

Harley, S. J., Davies, N., Hampton, J., and McKechnie, S. (2014). Stock assessment of bigeye tuna in the Western and Central Pacific Ocean. WCPFC-SC10-2014/SA-WP-01, Majuro, Republic of the Marshall Islands, 6–14 August 2014.

Hazin, F. and Lessa, R. (2005). Synopsis of biological information available on blue shark, (*Prionace glauca*), from the southwestern Atlantic ocean. Collective Volume of ICCAT 58 no.3 (2005):1179-1187.

Hoenig (1983). Empirical use of longevity data to estimate mortality rates. *Fisheries Bulletin*, 82(1):898–903.

Hsu, H.-H., Guann-Tyng, L., Shoou-Jeng, J., and ., L. K.-M. (2011). Age and Growth of the Blue Shark, Prionace glauca, in the Central and South Pacific. ISC/12/SHARKWG-1, International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean.

ISC (2014). ISC shark working group: Stock assessment and future projections of blue shark in the North Pacific. ISC14/SHARKWG Annex 13, Taipei, Chinese Taipei, July 16–21 2014.

Kleiber, P., Clarke, S., Bigelow, K., Nakano, H., McAllister, M., and Takeuchi, Y. (2009). North Pacific blue shark stock assessment. NOAA Technical Memo NMFS-PIFSC-17, Pacific Islands Fisheries Science Center, Honolulu, Hawaii.

Kleiber, P., Hampton, J., Davies, N., Hoyle, S. D., and Fournier, D. (2014). *MULTIFAN-CL User's Guide*. Accessible online at: `http://www.multifan-cl.org/`.

Kleiber, P. and Takeuchi, Y.and Nakano, H. (2001). Calculation of plausible maximum sustainable yield (MSY) for blue sharks (*Prionace glauca*) in the North Pacific. Southwest Fish. Sci. Cent. Admin. Rep. H-01-02, 10pp, Honolulu Lab., Southwest Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Honolulu, Hawaii.

Manning, M. and Francis, M. P. (2005). Age and growth of blue shark (*Prionace glauca*) from the New Zealand Exclusive Economic Zone. New Zealand Fisheries Assessment Report 2005/26, 52p.

Murray, T. (1994). A review of the biology and fisheries for albacore, *Thunnus alalunga*, in the South Pacific Ocean. In Shomura, R. S., Majkowski, J., and Langi, S., editors, *Interactions of Pacific tuna fisheries*, FAO Fisheries Technical Papers, pages 188–206.

Nakano, H. and Stevens, J. (2008). The biology and ecology of the blue shark, *Prionace glauca*, in Sharks of the Open Ocean: Biology, Fisheries and Conservation (eds M. D. Camhi, E. K. Pikitch and E. A. Babcock). Blackwell Publishing Ltd., Oxford, UK.

Pilling, G. and Brouwer, S. (2016). Report from the SPC pre-assessment workshop, Noumea, April 2016. Technical Report WCPFC-SC12-2016/SA-IP-01, Bali, Indonesia, 3–11 August 2016.

Poseidon, MRAG, COFREPECHE, and NFDS (2013). Review of tuna fisheries in the Pacific Ocean. Framework contract MARE/2011/01–Lot 3, specific contract 6, Brussels, 118p.

Rice, J., Harley, S., and Kai, M. (2014). Stock assessment of blue shark in the North Pacific Ocean using Stock Synthesis. WCPFC-SC10-2014/SA-WP-08, Majuro, Marshall Islands, 6–14 August 2014.

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

Rice, J. and Harley, S. J. (2013a). Potential catch and CPUE series to support a stock assessment of blue shark in the south Pacific Ocean. WCPFC-SC9-2013/SA-WP-04, Pohnpei, Federated States of Micronesia, 6–14 August 2013.

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

Rice, J., Tremblay-Boyer, L., Scott, R., Hare, S. R., and Tidd, A. (2015). Analysis of stock status and related indicators for key shark species of the Western Central Pacific Fisheries Commission Rev 1 (29 July 2015). WCPFC-SC-11/EB-WP-04, Pohnpei, Federated States of Micronesia, 5–13 August 2016.

Sharples, P., Bailey, K., Williams, P., and Allan, A. (1991). Report of observer activity on board JAMARC driftinet vessel R.V. *Shinhoyo Maru* fishing for albacore in the South Pacific Ocean. Technical Report Tuna and Billfish Assessment Programme no. 24, South Pacific Commisson, Noumea, New Caledonia.

Sippel, T., Wraith, J., Kohin, S., Taylor, V., Holdworth, J., Taguchi, M., Matsunaga, H., and Yokawa, K. (2011). A summary of blue shark *(Prionace glauca)* and shorfin mako shark *(Isurus oxyrincus)* tagging data avilable from the North and Southwest Pacific ocean. ISC/11/SHARKWG-2/04, La Jolla, US, 28 November–6 December.

SPC-OFP (2013). Report from the SPC pre-assessment workshop. WCPFC-SC9/SC-IP-01, Noumea, New Caledonia.

Stevens, J., Bradford, R., and West, G. (2010). Satellite tagging of the blue sharks *(Prionace glauca)* and other pelagic sharks off eastern Australian : depth behaviour, temperature experience and movements. *Marine Biology*, 157:575–591.

Stroustrup, B. (2013). *The C++ Programming Language*. Addison-Wesley, 4th edition edition.

Taguchi, M. and Yokawa, K. (2013). Genetic population structure of blue sharks (*Prionace glauca*) in the Pacific Ocean inferred from the microsatellite DNA marker. ISC/13/SHARKWG-1/08, La Jolla, US, 7–14 January.

Taylor, I., Gertseva, V., D., M. R., and N., M. M. (2013). A stock recruitment relationship based on per-recruit survival, illustrated with application to spiny dogfish shark. *Fisheries Research*, 142:15–21.

Tremblay-Boyer, L. and Takeuchi, Y. (2016). Catch and CPUE inputs to the South Pacific blue shark stock assessment. WCPFC-SC12-2016/SA-WP-09, Bali, Indonesia, 3–11 August 2016.

WCPFC (2010). Conservation and management measure for sharks. Conservation and Management Measure 2010–07, Seventh Regular Session of the WCPF Commission, Honolulu, USA, 6–10 December 2010.

WCPFC (2015). Report of the Scientific Committee Eleventh Regular Session. , Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean., Bali, Indonesia, 3–8 December 2015.

Williams, P. (2016). Scientific data available to the Western and Central Pacific Fisheries Commission. WCPFC-SC-12/ST-WP-1, Bali, Indonesia, 3–11 August 2016.

Table 1: Definition of fisheries and selectivity groupings

	Fishery name	Grouping	Shape of selectivity	CPUE
FL1	American Samoa	1	Asymptotic	
FL2	Australia	2	Asymptotic	
FL3	Australia SBT	3	Dome shape	
FL4	Cook Islands	1	Asymptotic	
FL5	China	1	Asymptotic	
FL6	China SWO	4	Asymptotic	
FL7	EU Spain	3	Dome shape	
FL8	Fiji	1	Asymptotic	
FL9	Japan	1	Asymptotic	PW
FL10	Japan SBT	1	Asymptotic	
FL11	Korea	1	Asymptotic	
FL12	Korea SWO	4	Asymptotic	
FL13	New Caledonia	1	Asymptotic	
FL14	New Zealand	5	Asymptotic	NZ
FL15	New Zealand SBT	3	Asymptotic	
FL16	French Polynesia	1	Asymptotic	
FL17	PNG	1	Asymptotic	
FL18	Solomon Islands	1	Asymptotic	
FL19	Tonga	1	Asymptotic	
FL20	Chinese Taipei	1	Asymptotic	TW
FL21	Chinese Taipei SWO	4	Asymptotic	
FL22	Australia after 2012	3	Dome shape	

Table 2: Number of individual length samples for each fleet

fish.flag	# individuals
American Samoa	2
Australia	637
Australia SBT	1953
Cooks Islands	18
China	717
China SWO	1122
Spain	1206
Fiji	3814
Japan	8390
Japan SBT	48972
Korea	685
Korea SWO	740
New Caledonia	755
New Zealand	11797
New Zealand SBT	3270
French Polynesia	519
Papua New Guinea	843
Solomon Islands	464
Tonga	770
Chinese Taipei	4435
Chinese Taipei SWO	2091
Australia after 2012	453

Table 3: Description of the structural sensitivity grid used to characterise uncertainty in the assessment.

Axis	Levels	Options	Description
Catch scenarios	2	Pacific-wide CPUE based, observer-based blue shark/general shark ratio	Catch scenario
CPUE	3	CPUEPW, CPUENZ, CPUETW	CPUE scenario
steepness	3	0.4, 0.6, 0.8	Steepness of Beverton-Holt stock recruit relationship
σ_R	2	0.1, 0.31	Standard deviation of log deviates of recruitment from deterministic recruitment

Table 4: Summary of model settings of six selected runs shown as an illustrative purpose

Run code	Catch scenario	CPUE	steepness	σ_R
PW-NZ-06-01-15	Pacific-wide CPUE based	NZ	0.6	0.31
PW-PW-06-03-15	Pacific-wide CPUE based	PW	0.6	0.31
PW-TW-06-03-15	Pacific-wide CPUE based	CT	0.6	0.31
SB-NZ-06-03-15	observer-based blue shark/general shark ratio	NZ	0.6	0.31
SB-PW-06-03-15	observer-based blue shark/general shark ratio	PW	0.6	0.31
SB-CT-06-03-15	observer-based blue shark/general shark ratio	CT	0.6	0.31

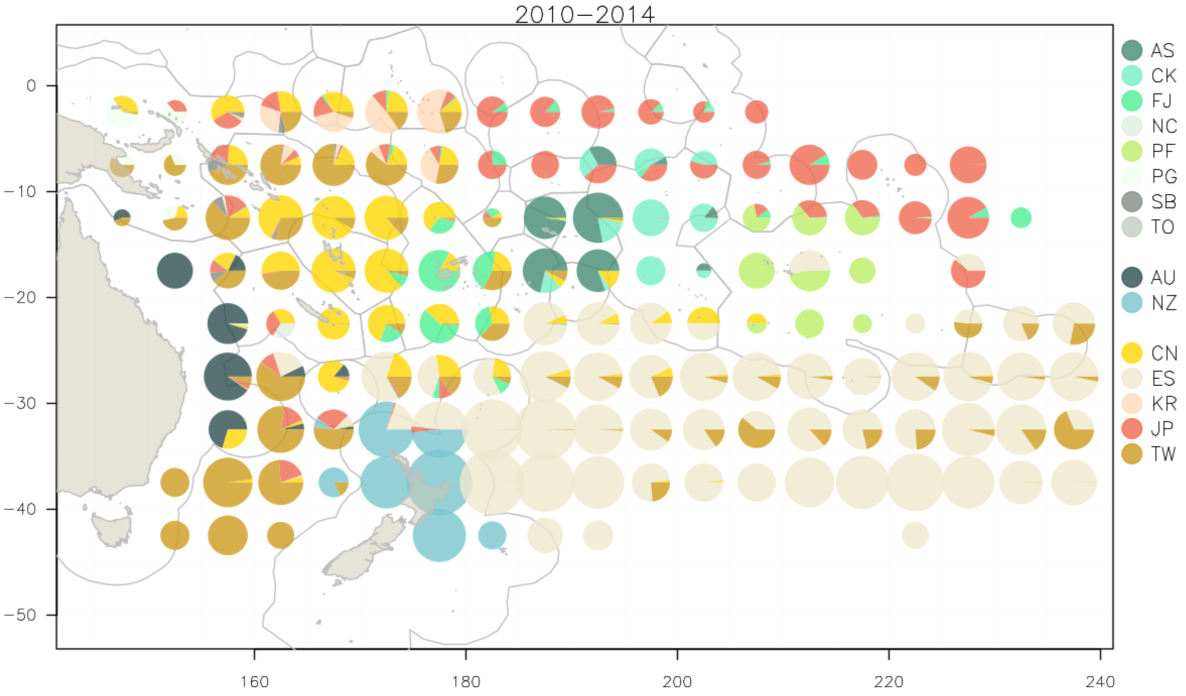

Figure 1: Reported blue shark catches in the WCPFC-CA by flag for 2010-2014. The size of the bubble is proportional to total catch in the cell. Note in the legend the separation of fleets into PICTs, South Pacific coastal states and DWFNs.

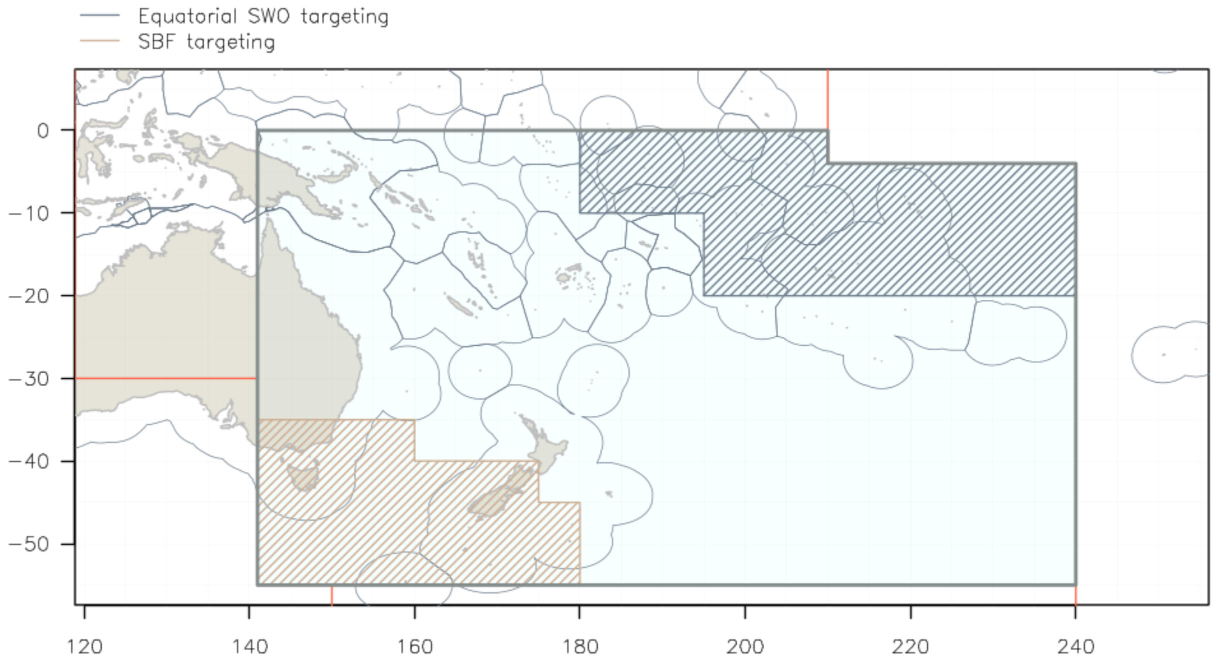

Figure 2: Map of the stock assessment region boundary with the southern WCPFC-CA drawn in grey and the boundaries used to define swordfish (north-east) and southern bluefin tuna (south-west) targeting fleets highlighted in cross-hatch.

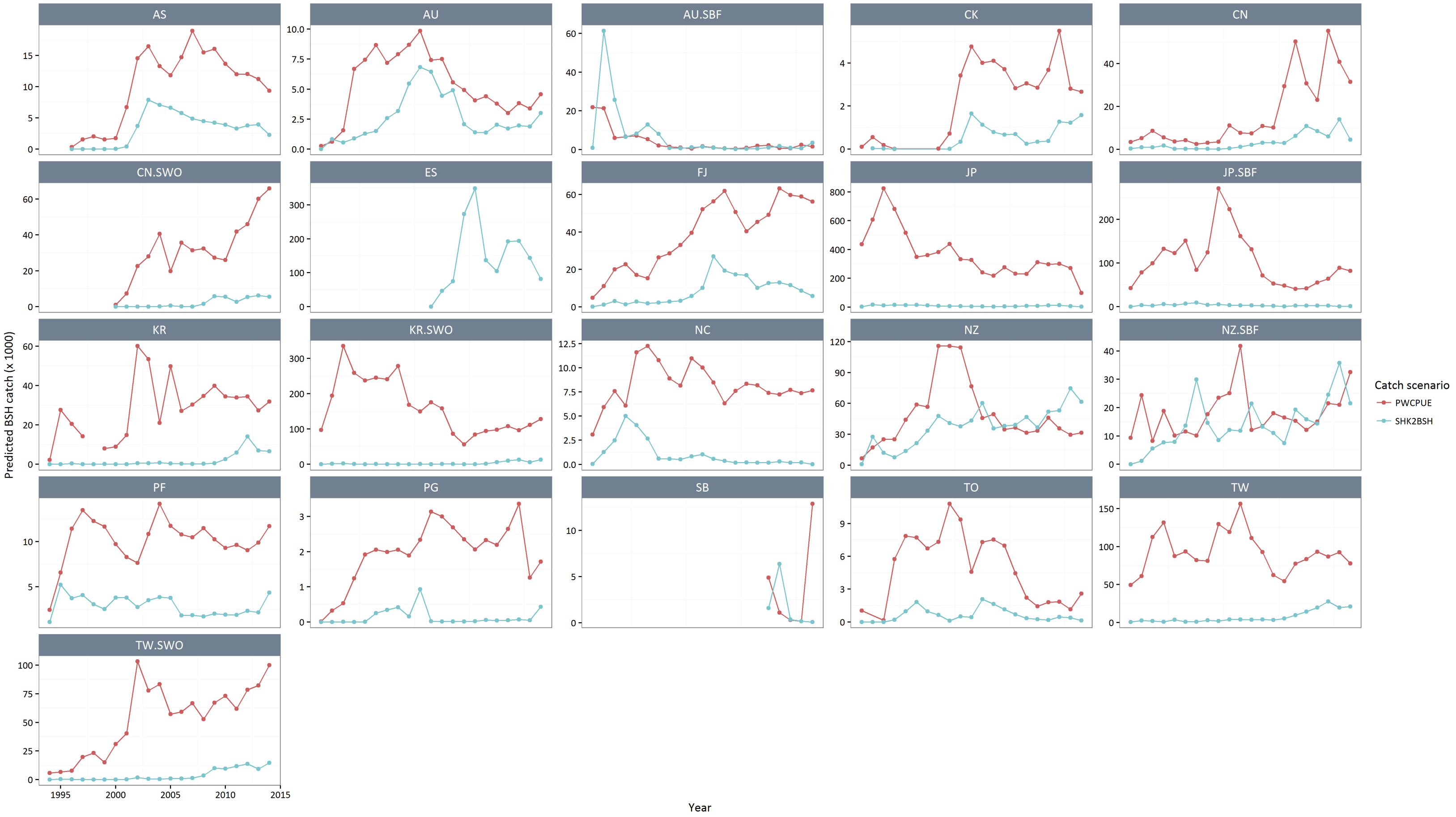

Figure 3: Time-series of annual reconstructed catches by key fleets for the two catch scenarios retained in the grid where PWCPUE is the Pacific-wide CPUE based scenario and observer-based blue shark/general shark ratio is the blue shark-to-all shark ratio catch scenario.

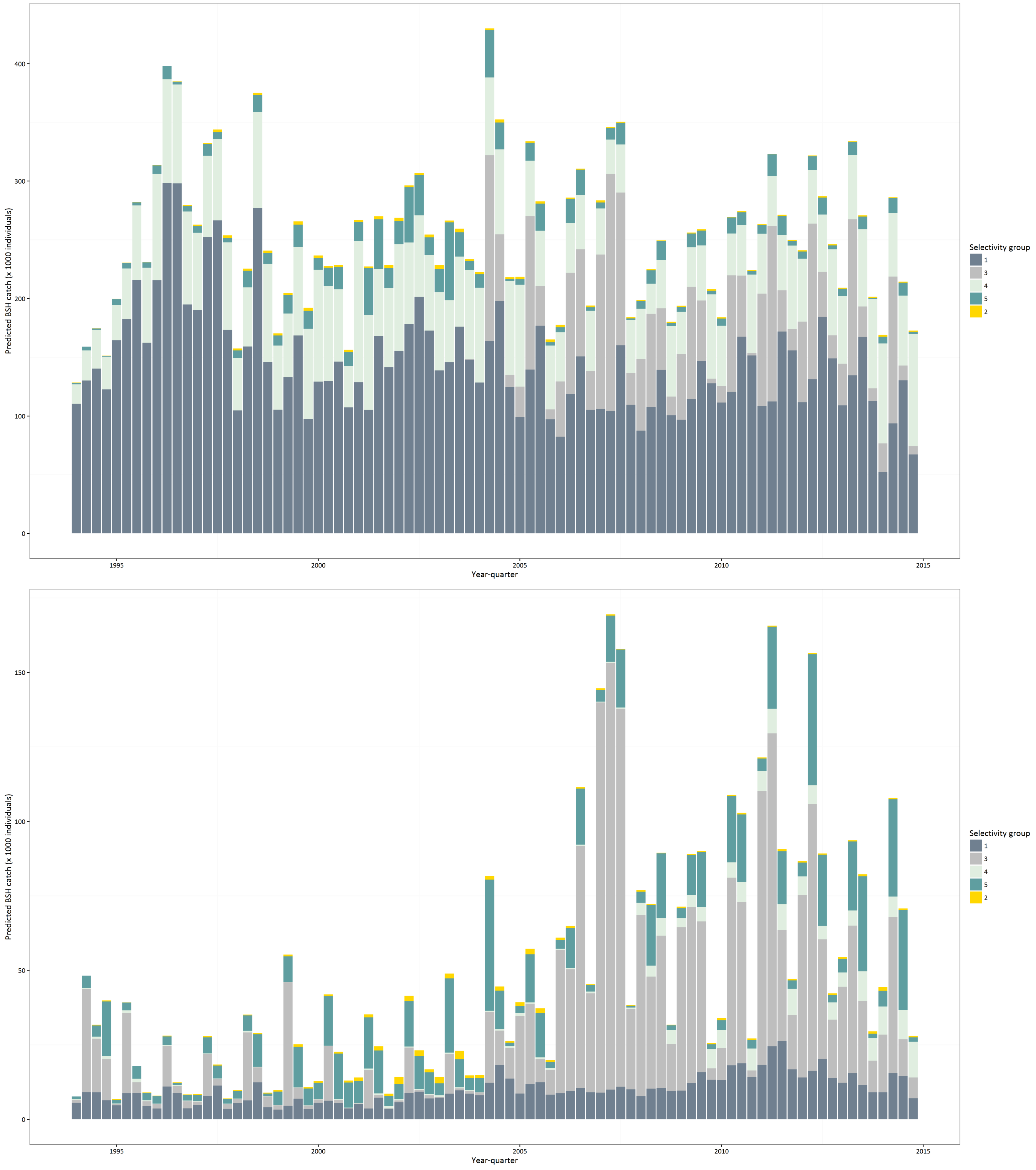

Figure 4: Total catch (1000s individuals) by year-quarter for the five fleet groups (see Table 1) assumed to have common selectivities. Top figure is Pacific-wide CPUE based catch estimates, the bottom figure is the estimate from the ratio of all shark catch against blue shark catch in the observer data.

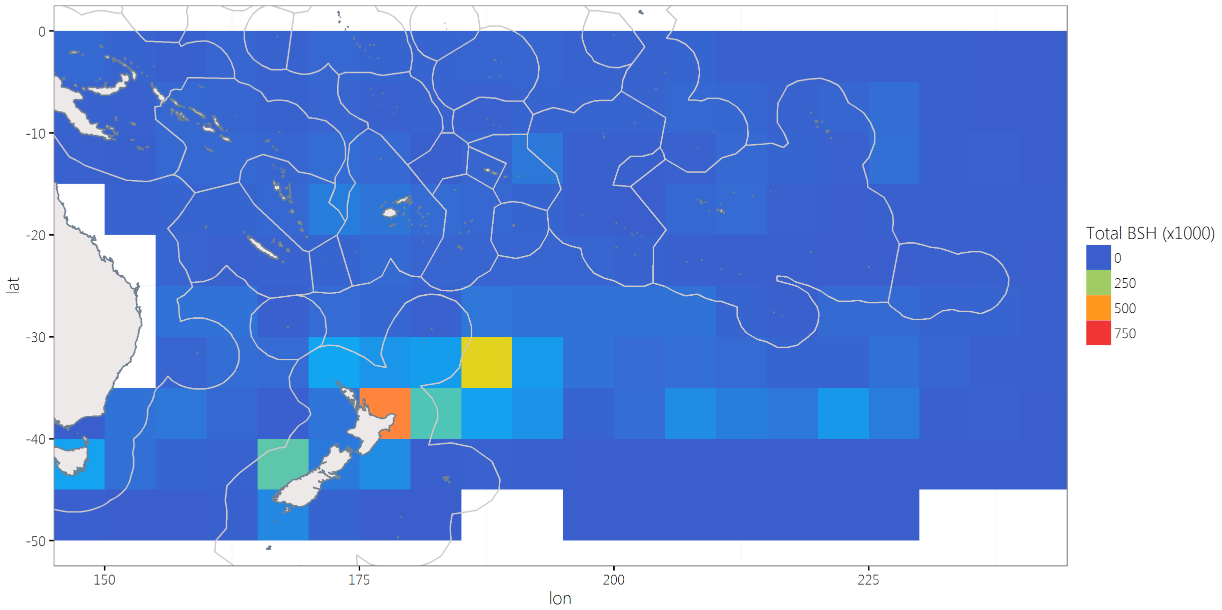

Figure 5: Predictions of total blue shark catches (in 1000 individuals) by 5×5 degree cell over the period 1994-2014 for the blue shark-to-all-shark catch scenario.

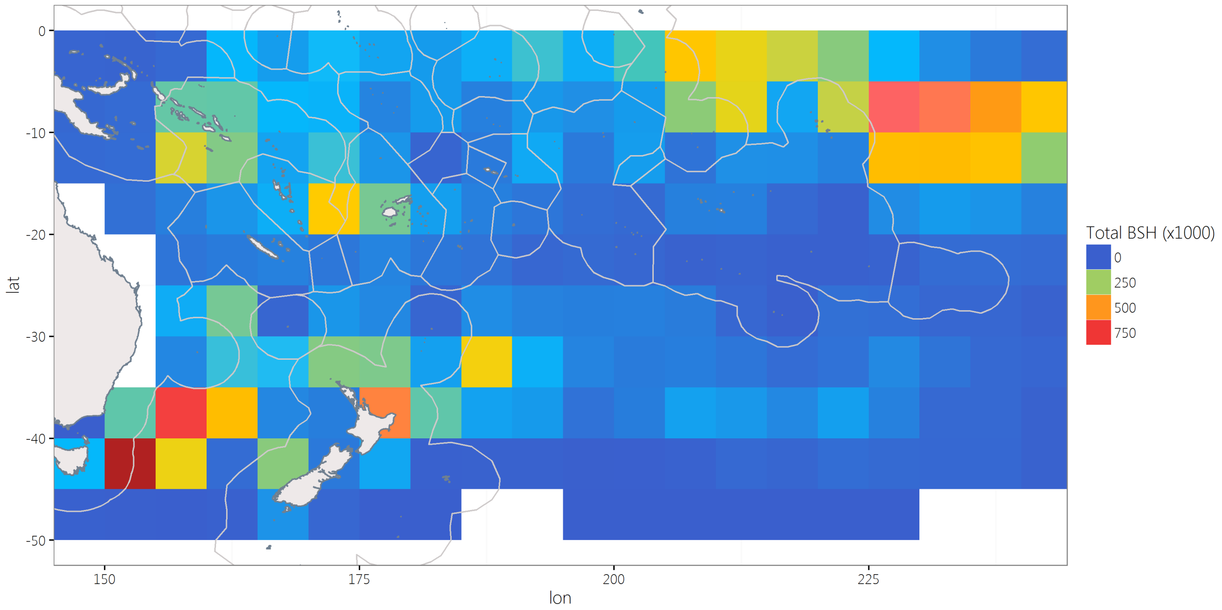

Figure 6: Predictions of total blue shark catches (in 1000 individuals) by 5×5 degree cell over the period 1994-2014 for the South Pacific-wide all-observer CPUE surface catch scenario.

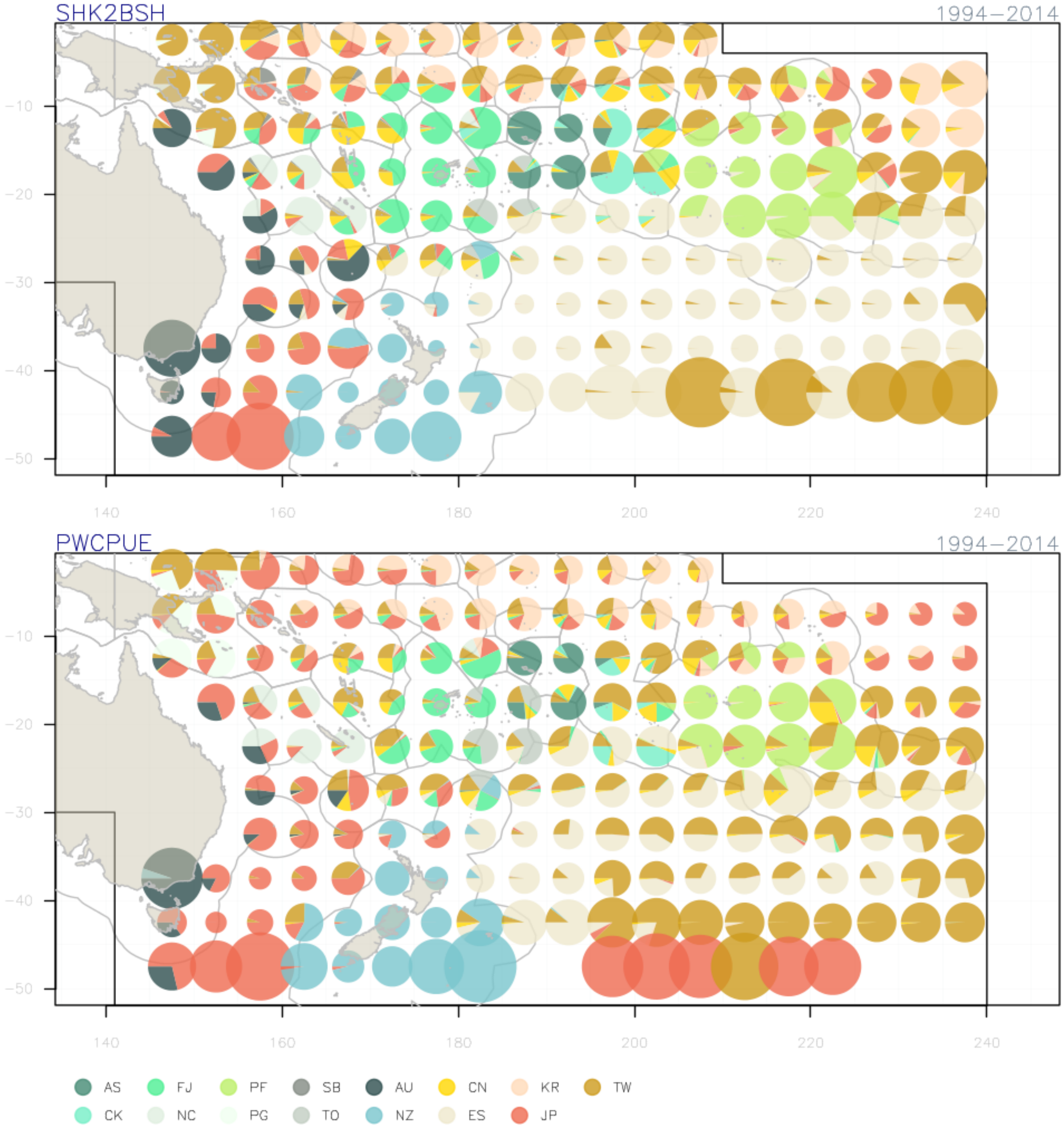

Figure 7: Reconstructed blue shark catches in the WCPFC-CA by flag for the assessment period 1994-2014 for the two main scenarios: blue shark-to-all shark fleet-specific ratio (top) and South Pacific-wide all-observer surface (bottom). Within each panel, the size of the bubble is proportional to total catch in the cell. Note in the legend the separation of fleets into PICTs, South Pacific coastal states and DWFNs.

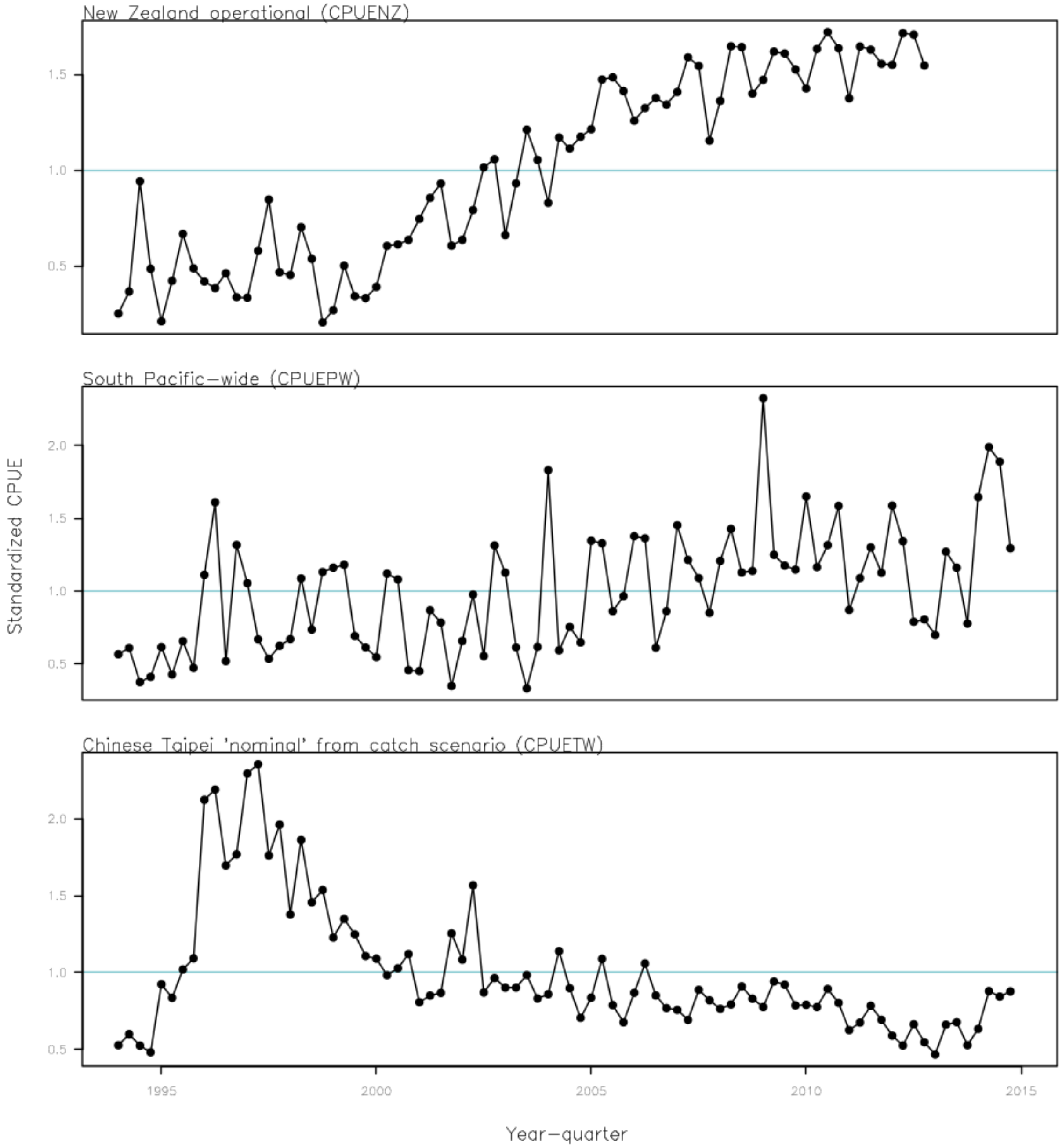

Figure 8: Abundance time-series for the three CPUE scenarios.

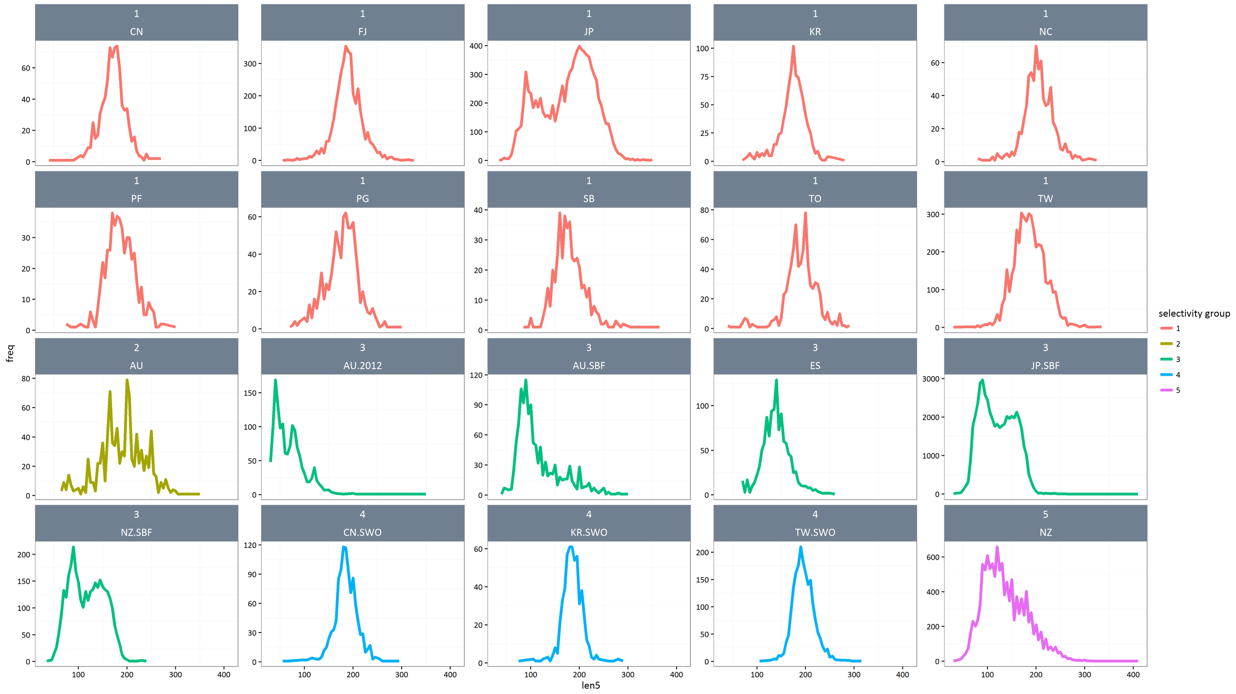

Figure 9: Length frequency distributions by fishery and grouping

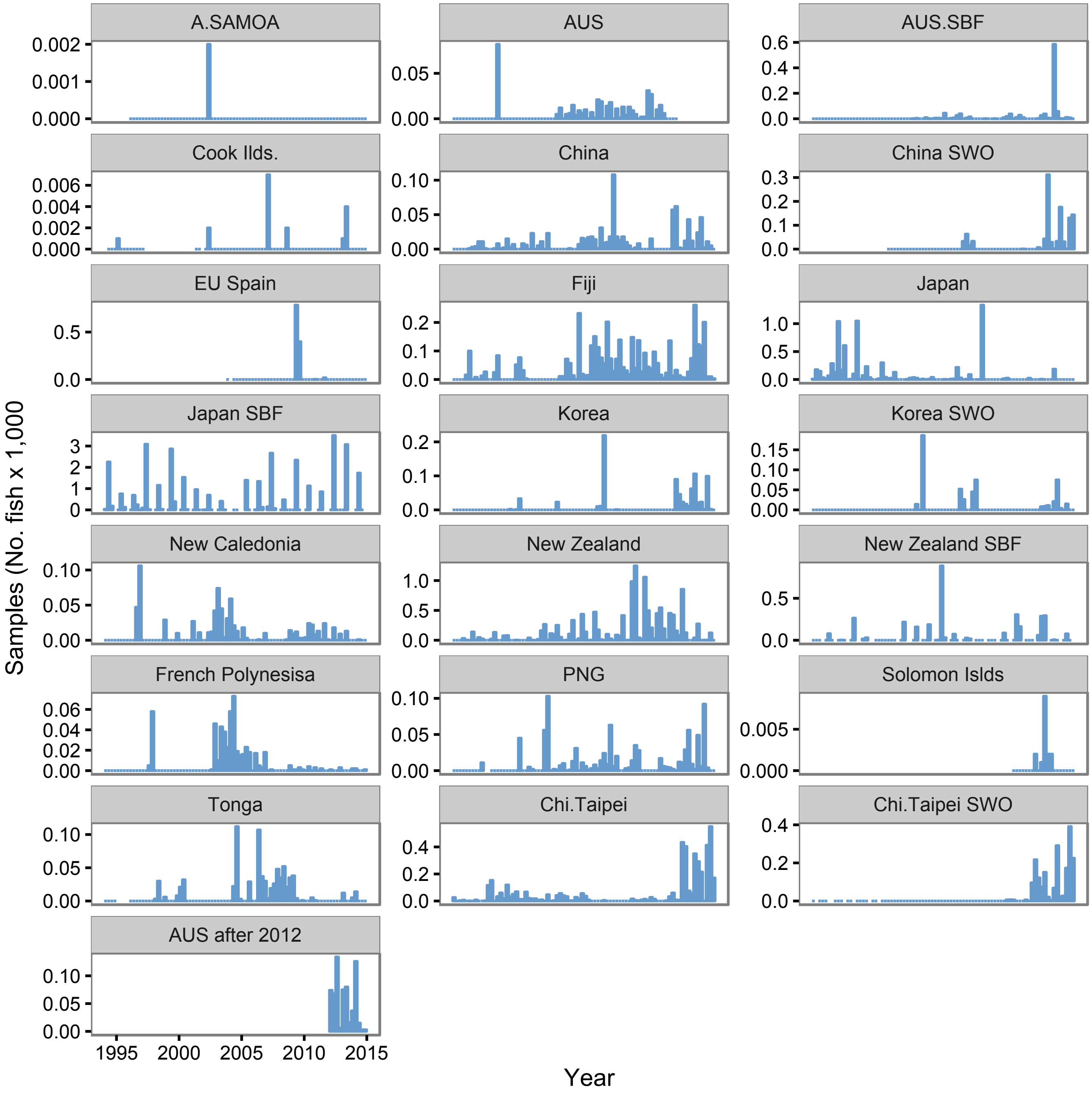

Figure 10: Distribution of length frequency samples by fishery for this stock assessment.

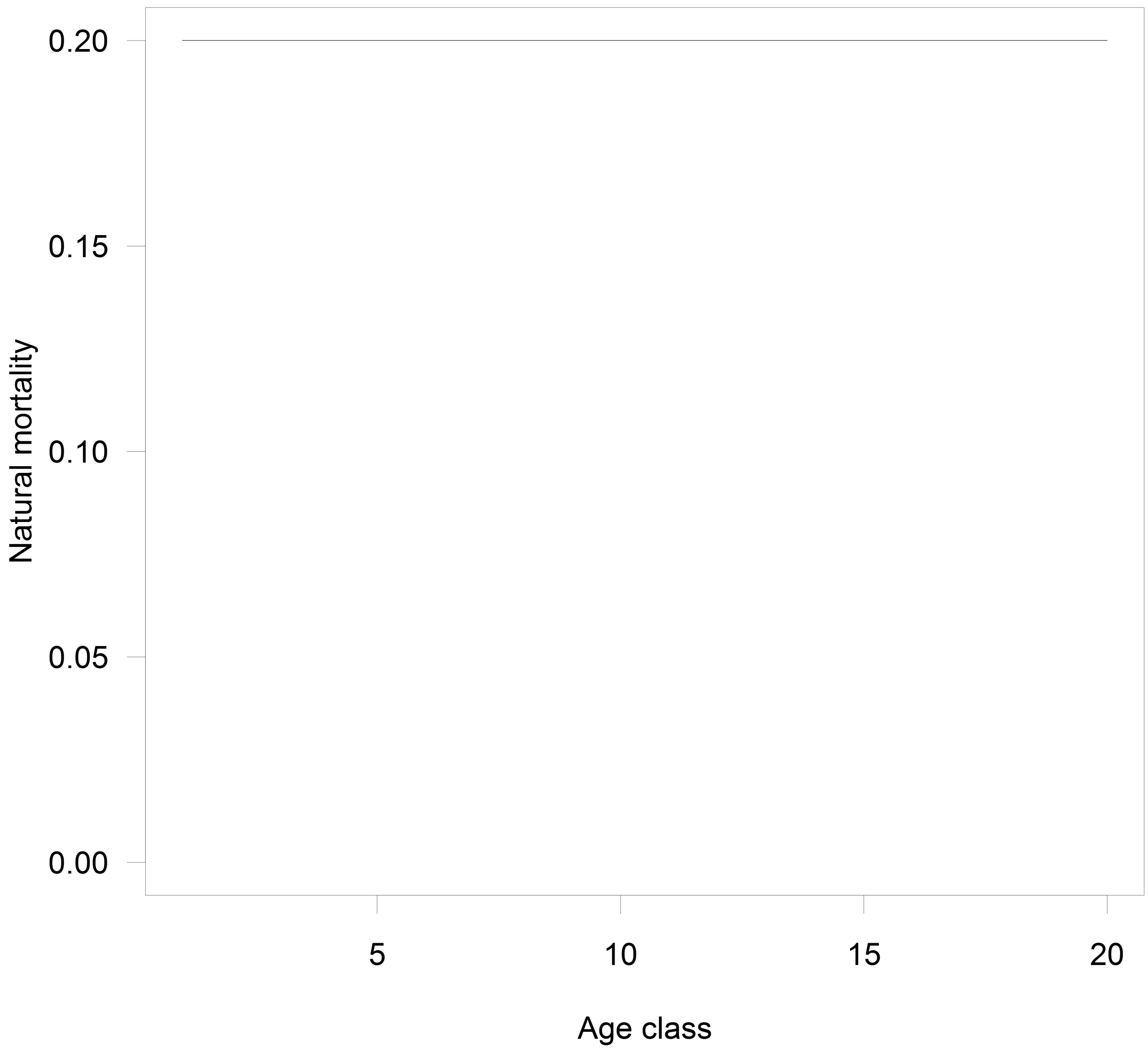

Figure 11: Natural mortality-at-age as assumed in this stock assessment.

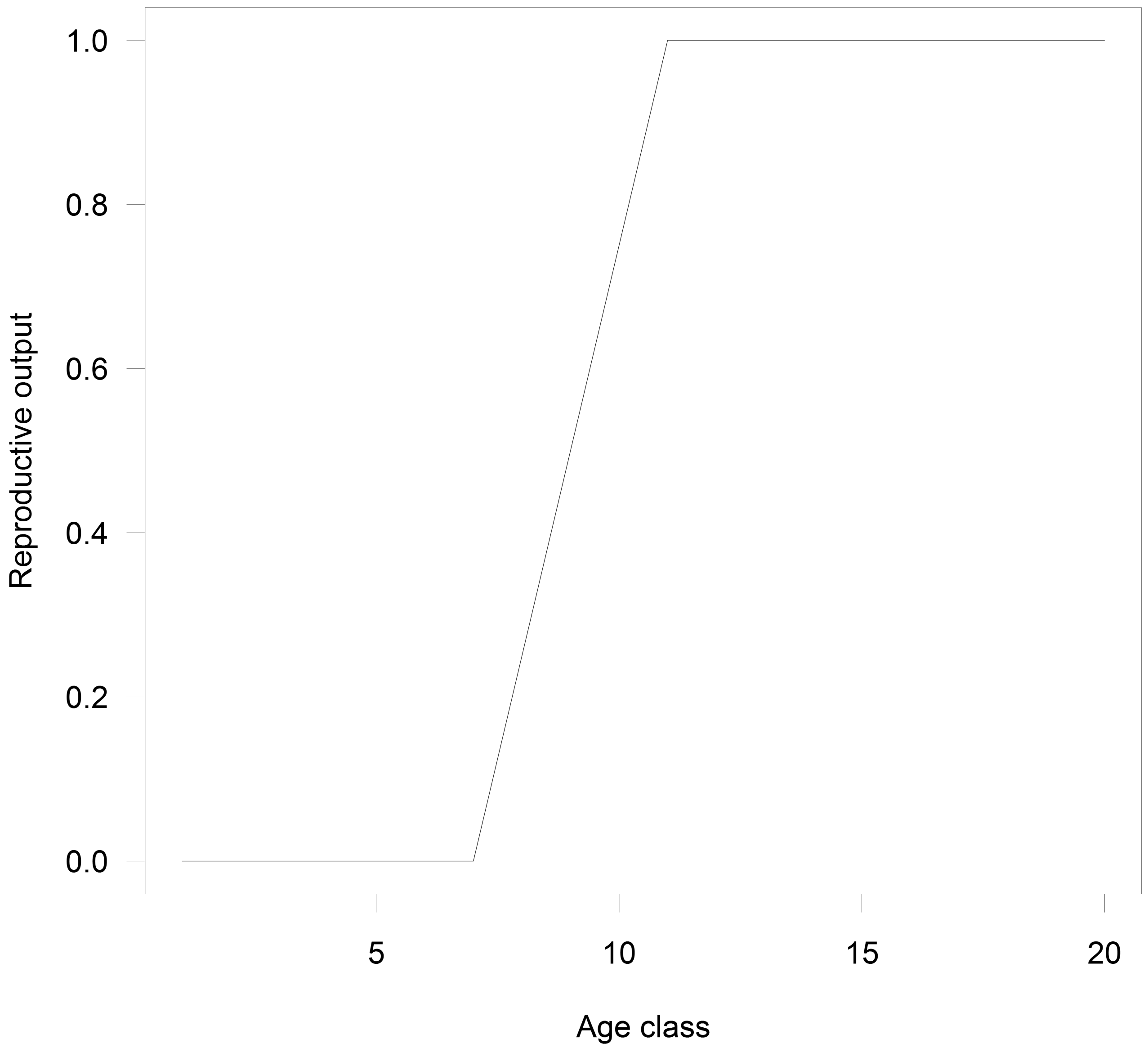

Figure 12: Maturity-at-age as assumed in this stock assessment.

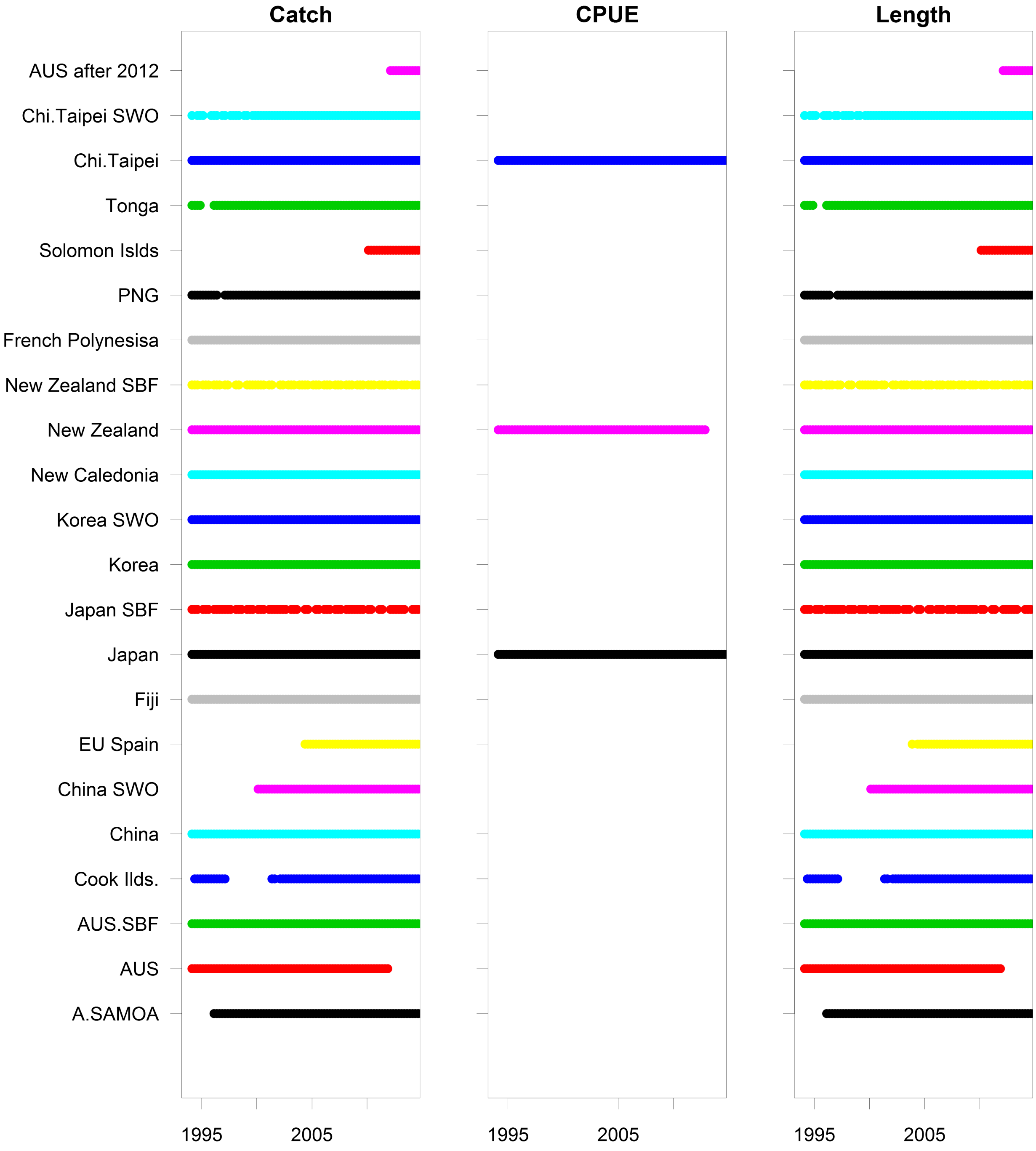

Figure 13: Presence of catch, CPUE and length frequency data by year and fishery for this stock assessment. For Japan (fishery 9) line indicating availability of CPUE is because Pacific wide CPUE is applied to fishery 9 .

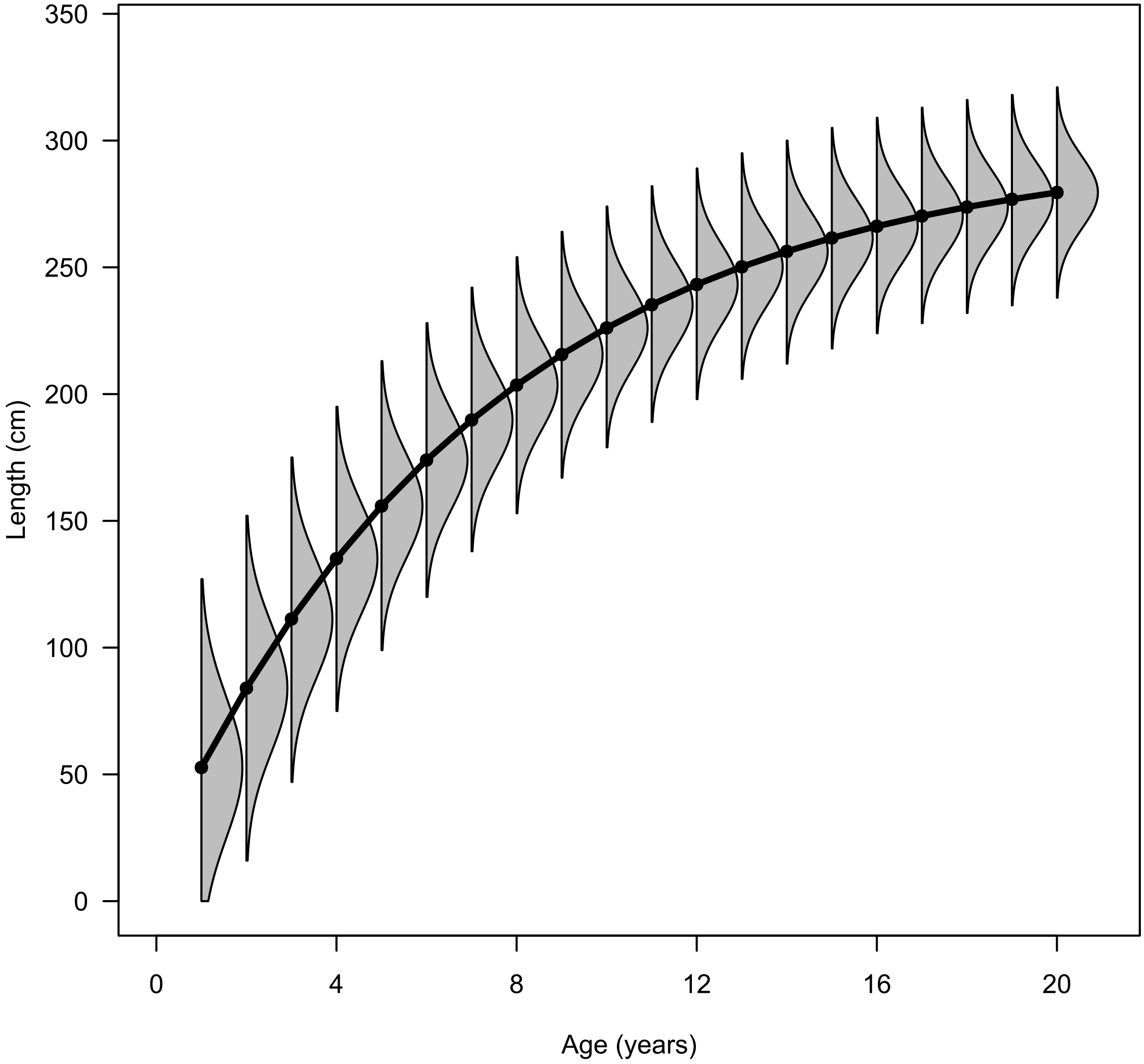

Figure 14: Length-at-age (in years) as assumed in this stock assessment.

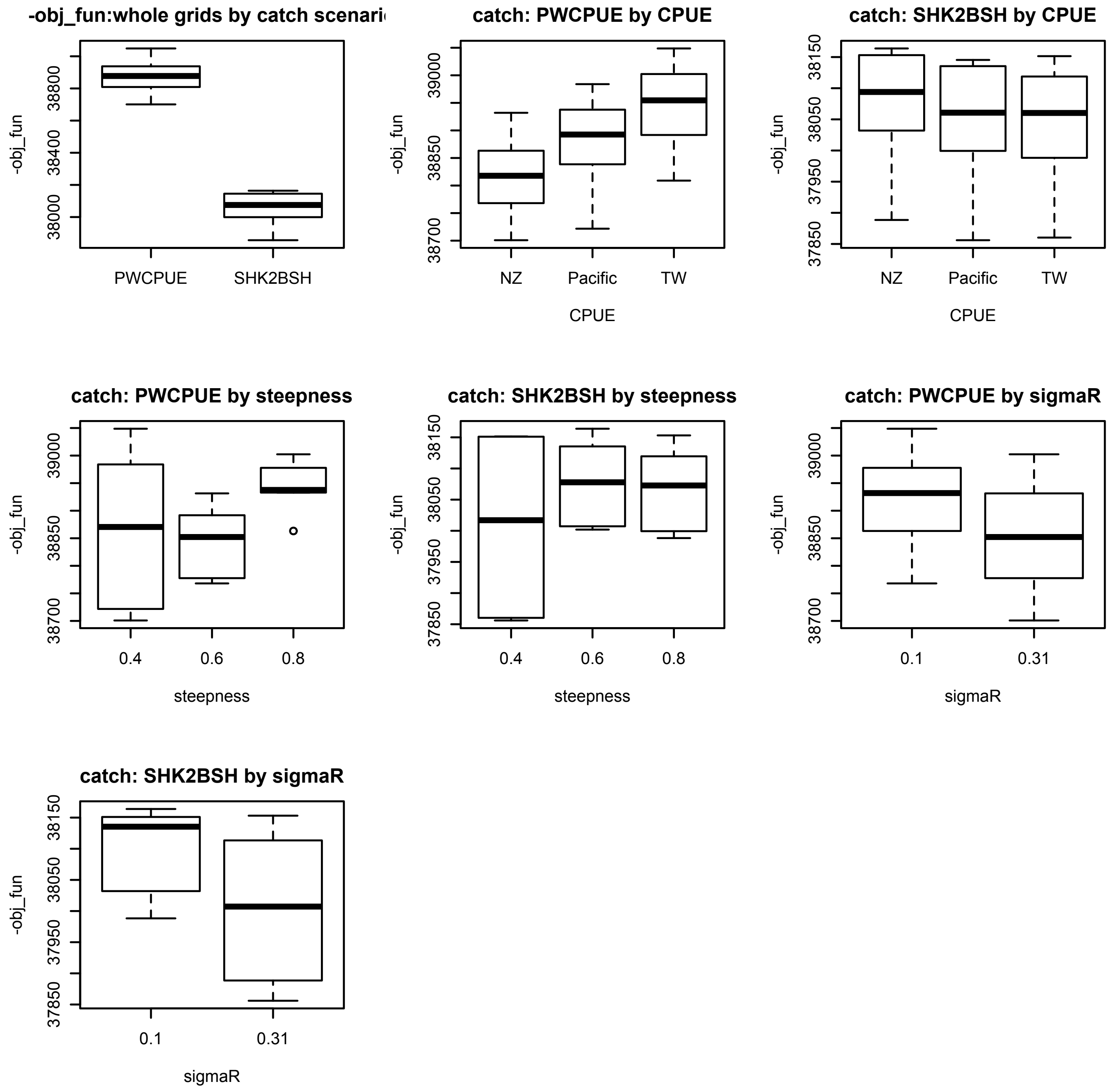

Figure 15: Box plots of negative of the objective function values. Larger values indicate the model fits the data better. From the left top negative of objective function value by catch scenario, by CPUE (top center and right), by steepness within catch scenario (middle left and center), by σ_R (SD of SRR) within catch scenario (middle right and bottom left).

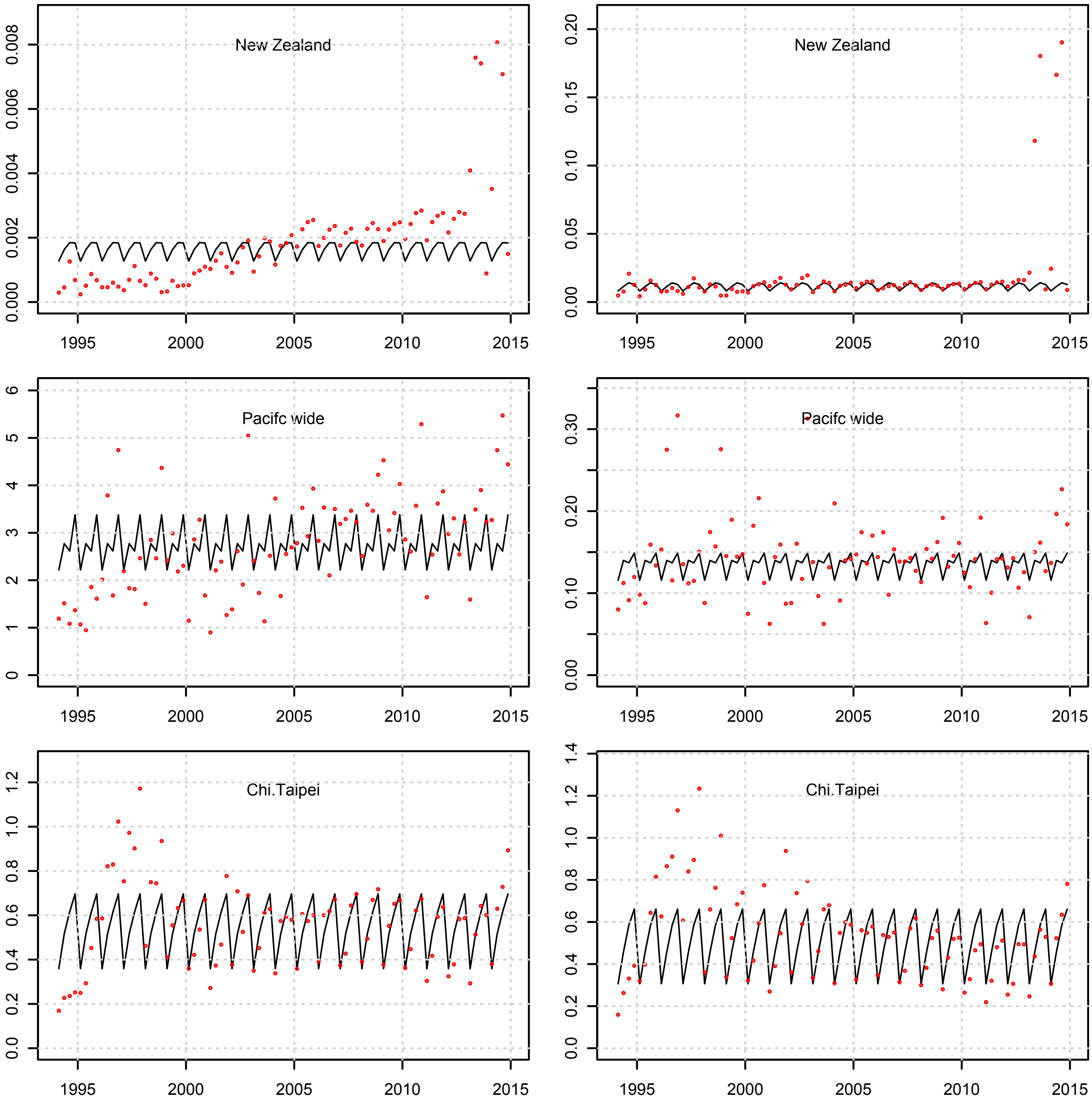

Figure 16: Estimated catchability (line) and associated effort deviations (red dot) for each run. The left panel presents runs using Pacific wide CPUE based catch estimates. The right panel presents runs using ratio catch blue shark against shark.

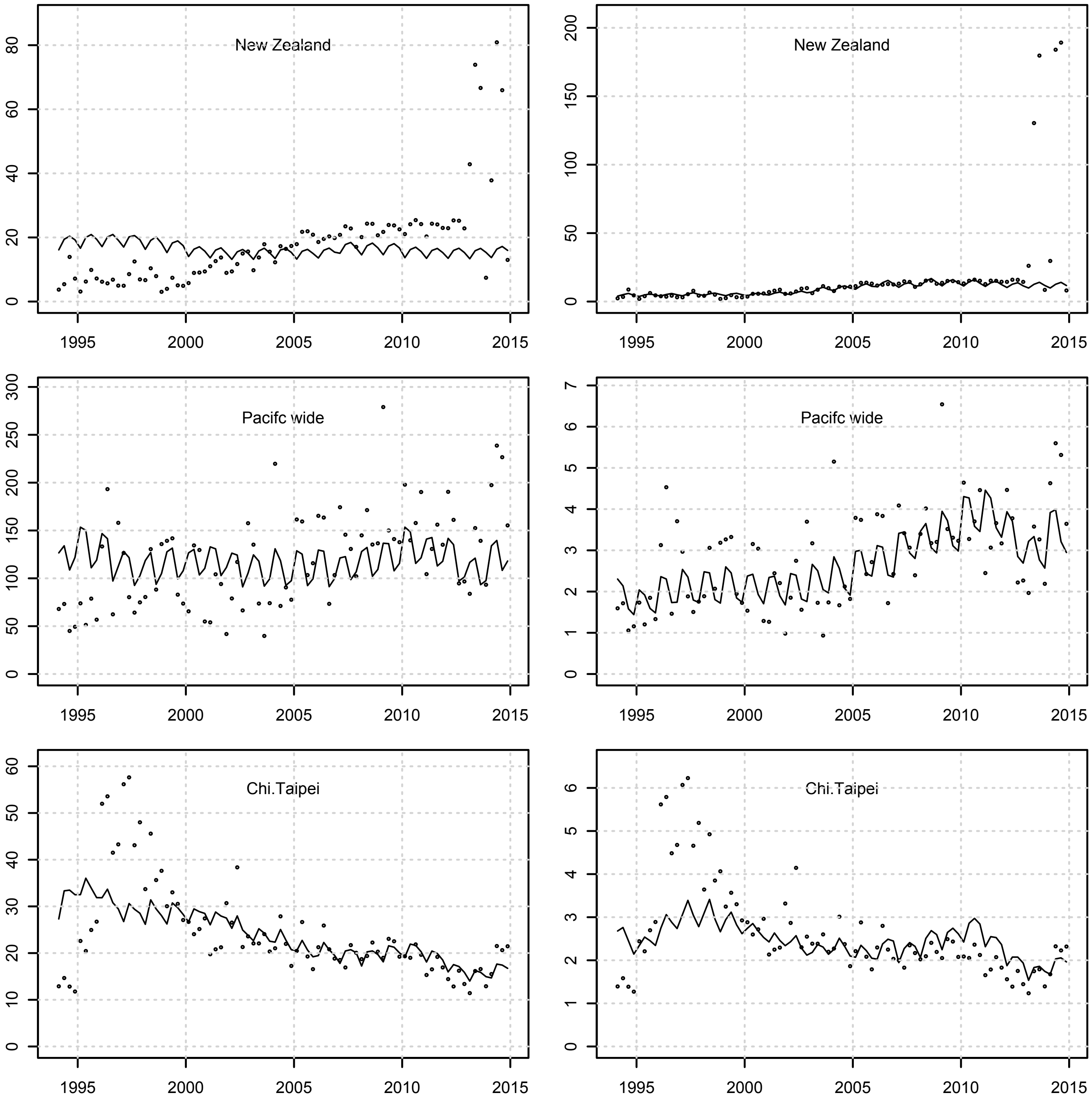

Figure 17: Observed (black dot) and predicted (line) CPUE to standardized CPUE used for each run. Left panel presents runs using Pacific wide CPUE based catch estimates. Right panel presents runs using ratio catch blue shark against shark.

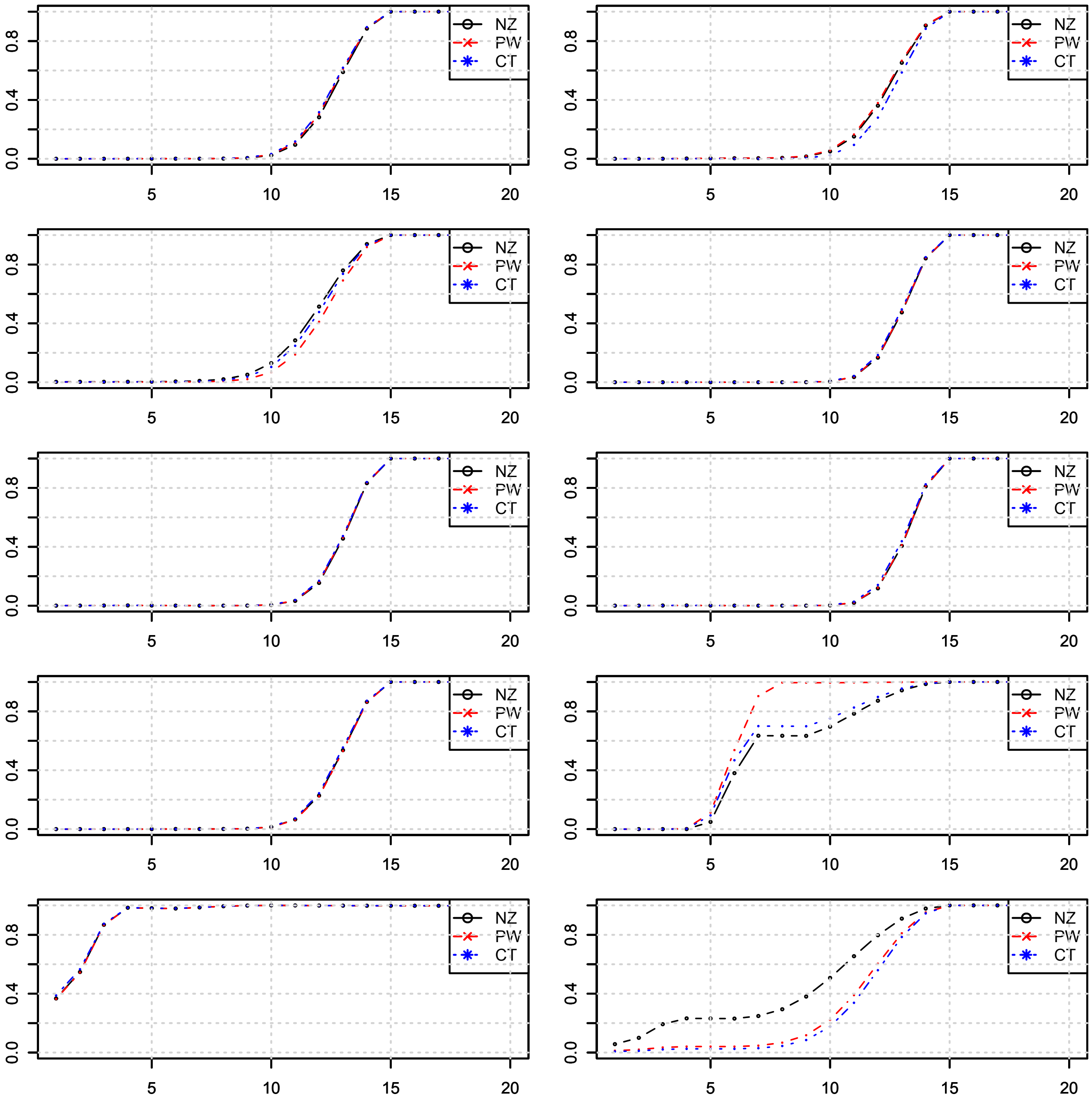

Figure 18: Estimated selectivity by age by group of fishery with common selectivity (selectivity groups 1 to 5, down rows, see Table 1). Left panel overlay selectivity estimates of runs using Pacific wide CPUE based catch estimate. Right panel overlay those from runs using catch estimates based on ratio of shark catch composition.

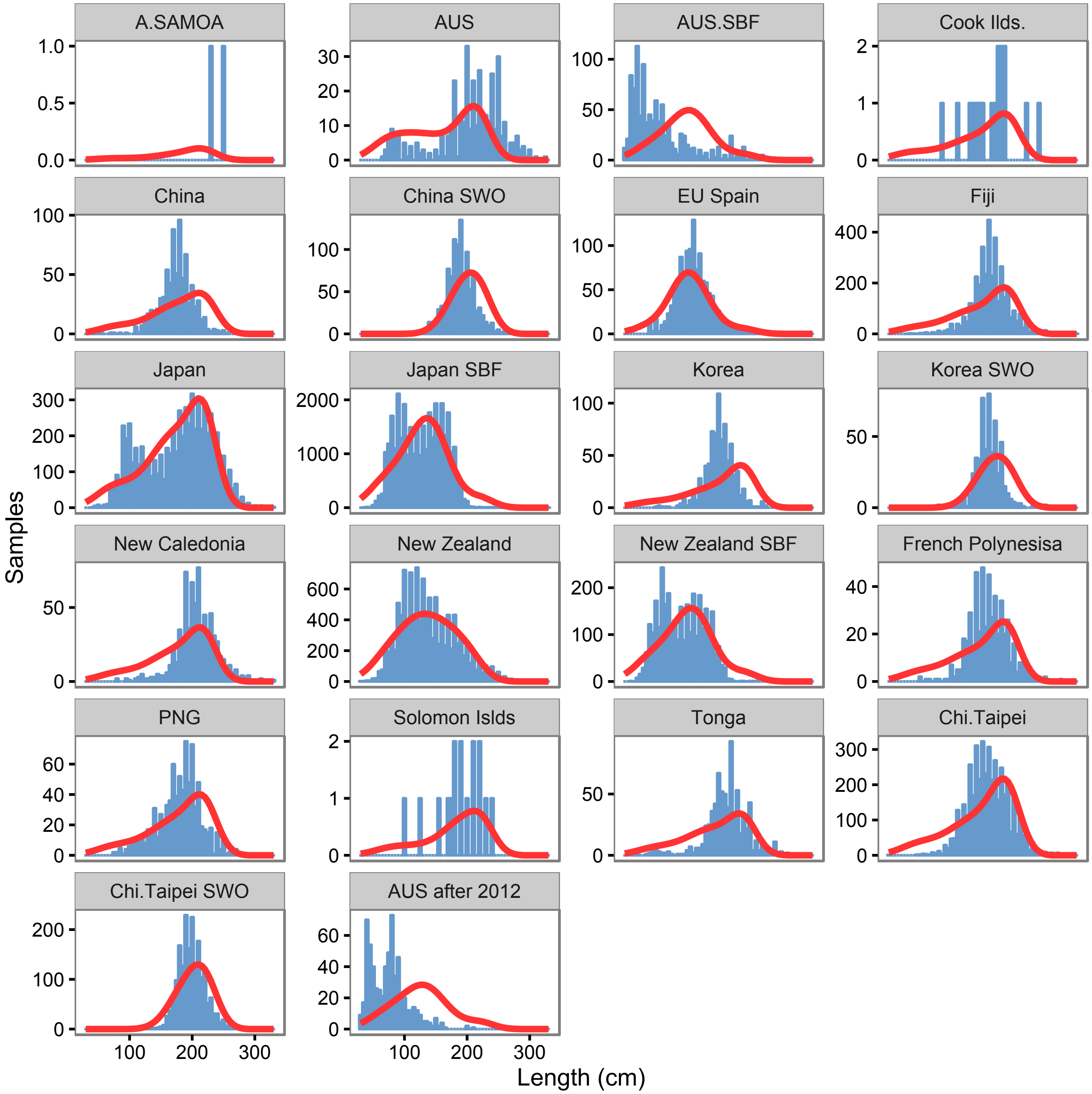

Figure 19: Composite (all time periods combined) observed (blue histograms) and predicted (red line) catch at length for all fisheries from the run with standardized CPUE from New Zealand Observer data (CPUENZ).

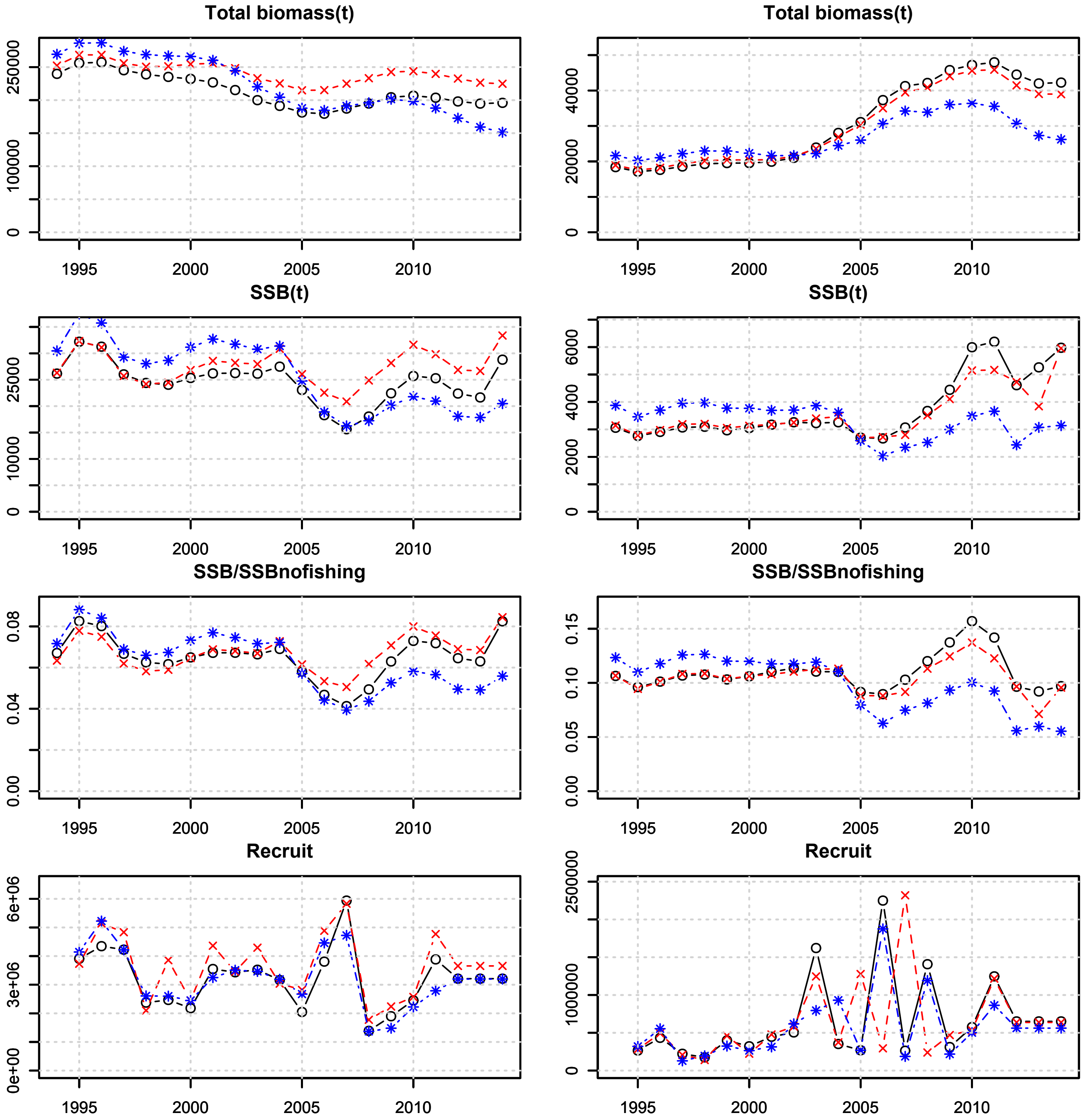

Figure 20: Comparisons of estimated total biomass(t), spawning biomass(t), ratio of spawning biomass against expected spawning biomass without fishing and recruitment among six selected runs listed in Table 4. Lines with circle, X and asterisk represents runs using New Zealand CPUE, Pacific wide CPUE and Chinese-Taipei CPUE respectively. The left side shows the results from runs using Pacific wide CPUE based catch scenario. The right side shows results from runs using catch estimate using the ratio of observer blue shark catch aginst general shark catch in logbook data. All runs assumed steepness=0.6 and $\sigma_R = 0.31$.