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Catch and CPUE inputs to the South Pacific blue shark stock assessment

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1 Executive summary

This paper presents the rationale, methodology and key results for the three catch data scenarios and the three abundance (CPUE) time-series scenarios that were developed to inform the 2016 South Pacific blue shark stock assessment, including a brief summary of length frequency and tagging data. The catch reconstruction approach relied heavily on observer data given general under-reporting of blue shark catches across fleets.

Observer catch rates allowed the delineation of three broad regions in blue shark catches which were subsequently used to refine fleet definitions within the stock assessment: high catch rates within the tropical swordfish targeting region; very high catch rates in high latitudes in the southern WCPFC-CA, but with a strong seasonal component; and lower catch rates in the middle latitudes/eastern area.

The catch scenarios were designed to rely on different assumptions about the information contained in the observer database. The final reconstructed catch series predict blue shark catches of very different magnitudes over the 1994-2014, with the southwestern Pacific wide CPUE surface catch scenario (#3) predicting the highest catches and the blue shark-to-generic shark catch scenario (#1) predicting the lowest catches for most fleets. Only these two scenarios were used in the final stock assessment for blue shark since they bracket the predictions of the fleet-specific observer catch rates scenario (#2) for the fleets that account for the majority of the catches. Of note, a preliminary comparison of reconstructed catches to trade-based estimates highlighted that the catch estimates used in the assessment might be conservative, even for our highest catch scenario (#3).

Three CPUE scenarios were defined to cover the diversity of the data sources available across the basin-wide distribution for this species: The abundance indices produced under the three scenarios show different trends over time, with the South Pacific observer (#1) increasing slightly, the 'nominal' Chinese Taipei declining (#2) and the New Zealand operational series (#3) increasing after being stable in early years.

Based on this detailed analysis of the available data to support the southwestern Pacific blue shark assessment, our recommendations for future assessments are:

- To overcome challenges in the analysis of observer records collected independently across observer programs within the WCPO, we recommend the provision of expanded metadata to facilitate the merging of variables from different programs into a single harmonized database. This could be assisted by an active collaboration of member countries with SPC during the initial merging operation;
- Emphasis on improving the consistent collection of accurate observer effort during the set is needed, as this variable is essential to the estimation of accurate by-catch rates;
- Noting the importance of operational covariates like hooks-between-floats and set time to interpret CPUE trends, the provision of these data for all fisheries is encouraged;
- The continuation of ongoing efforts to expand observer coverage for longline fleets operating in the WCPO is encouraged, especially given that the collection of length data for bycatch species relies on this effort and these data can be influential in data-poor stock assessments;
- Noting the significant catch of blue sharks and other species of interest associated with the southern bluefin tuna fishery within the WCPFC-CA, increased collaboration with the

concerned parties for the purpose of assessing WCPO stocks should be pursued;

- Noting the increased prevalence of regulations aimed at managing shark mortality across WCPO, future catch reconstruction should prioritize the inclusion of discard mortality scenarios;
- Tagging programs for blue shark are currently restricted to a specific part of the South Pacific blue shark range, limiting their potential to inform movement rates across the assumed range of the stock. Geographical expansion of tagging activities would assist future assessments. In addition, the bulk of the tagging information available to this assessment came from a recreational fishery, but the utility of these data was limited by uncertainty in the length information. The potential to improve these valuable data sources should be examined.
- For the North Pacific, valuable information is available on the location of key mating, parturition and nursery grounds. Gaining comparable information for the South Pacific would be invaluable in the development of targeted data collection programmes, for data analyses and potential management interventions.

Revision 1

- We added a comparison of annual reconstructed catch scenarios with previous WCPO trade-based estimates of catch from fin trade data Clarke (2009), see subsection 3.2, Figure 29 and further discussion around trade-based estimates in the Catch reconstruction and the Results sections;
- The following references were corrected: Clarke (2015); Fowler et al. (2005); Francis et al. (2014);
- The captions in Figure 6 to Figure 19 have been modified to specify a unit of ten thousand hooks for the top-left panel and the y-axis scale on the middle left panel has been corrected to show the full range of reported blue shark catches, when applicable;
- The formatting of Figure 32 was adjusted to follow that of the stock assessment report and match the time-scale for the fitted CPUE series.

2 Introduction

This paper summarizes the methodology and results used to generate the main data inputs for the 2016 southwestern Pacific blue shark *Prionace glauca* stock assessment (Takeuchi et al., 2016). Three types of data inform the stock assessment: catch data, abundance indices from standardized CPUE and length frequency data from on-board observer sampling. Tag release and recapture data are also available for blue shark but have not been included in this assessment (see Takeuchi et al., 2016).

Key challenges in the development of the time-series of data inputs included:

- a lack of historical shark reporting, which was unlikely to reflect an absence of shark catches;
- where shark data were available, there was frequently limited breakdown to the level of shark species, particularly in historical data (though this problem is less acute for blue shark than for other shark species);
- changes in species targeting over the assessment period;
- low observer coverage rates for the longline fishery, in particular for wide-ranging DWFN fleets;
- implementation of shark management regulations which directly impact catch rates[2]. In parallel, regulations that prevent retention and where, therefore, all caught individuals are released, may reduce fishing mortality on caught individuals such that not all catches result in a mortality.

Noting that there is uneven reporting of blue shark catches across fisheries, fleets and time, catches thus had to be reconstructed over the stock assessment period of 1994 to 2014. The reconstructions were undertaken for a range of scenarios identified at the pre-assessment workshop (PAW Pilling and Brouwer, 2016) that attempted to capture the uncertainty in the estimates for fisheries. In one instance, the catch model resulting from each reconstruction was used to generate CPUE abundance time-series. In general, catch reconstruction implies greater predicted catches than those in official records, except when accounting for survival rates after discarding based on regulations where effective catches are reduced (see also section 4).

Given that substantial effort was invested in the reconstruction of catches and that these data constitute one of the key inputs influencing the assessment results, this paper focuses primarily on this component of the analysis and the subsequent generation of CPUE time-series, but also includes a brief summary of the length frequency information and tagging data.

We first review the three strategies used to reconstruct flag-specific time-series of catch for South Pacific blue shark. We then describe the approaches used to develop standardised abundance trends (CPUE), before summarizing spatial and temporal trends in blue shark lengths within the fisheries and briefly describing the available tagging data.

[2]For instance New Zealand recently enacted a fin-retention legislation for sharks (Ministry for Primary Industries, 2015). As a result logbook catches for blue shark have declined sharply while corresponding observer catch rates are high.

3 Catch reconstruction

In general, there are three potential strategies for reconstruction when catch data are missing or unreliable:

1. If an observer program exists, use CPUE derived from on-board observer coverage and reported effort to estimate total catches for the fishery (e.g. Lawson, 2011; Rice, 2012; Rice and Harley, 2013)
2. Use trade data, e.g. from the international trade fin market, to extrapolate shark catches from imports (e.g. Clarke et al., 2006; Clarke, 2015)
3. Use the ratio of catches of blue shark to catches of another species which itself is well reported (e.g. a target species) based on a reliable source of blue shark catches, e.g. vessels that accurately report catches or an observer program

We have used a combination of strategies 1 and 3 here. Strategy 2 was considered, but challenges within this approach in identifying fleet source, fishing grounds and targeting were noted. The decision was taken not to pursue this approach for the current assessment.

Discussions at the Pre-assessment Workshop led to the definition of the assessment period of 1994-2014 (Pilling and Brouwer, 2016). This period was chosen because the starting year both coincides with the period marking the moratorium of drift nets in the high seas in 1992, and the start of on-board observer coverage across a number of fleets.

Catch reconstruction was undertaken for longline fleets operating within the southern WCPFC-CA, as the primary source of blue shark mortality. There is considerable uncertainty associated with the reporting of blue shark catches in longline logsheet data, particularly for earlier years where records may be absent, or shark species catches were amalgamated into a shark 'group' that provided little information on species-level catches. As a result, all approaches taken therein for the reconstruction of catches rely heavily on catch rates determined from observer records. Observers form a reliable alternative source of information for this species as blue shark are easy to identify at the species level and are relatively abundant in the catch (representing the most caught longline species in available observer data)(Rice et al., 2015). However, observer coverage is uneven in space, time and across fleets. To attempt to capture the resulting uncertainty in catch levels, we therefore developed three scenarios to generate reconstructed catch estimates for blue shark utilizing different features of the observer data.

Construction was undertaken for catches of longline vessels from the top 16 fleets (flags) ranked on effort operating in the southern WCPFC-CA. These fleets represent ∼99% of the longline effort (in hooks) recorded within the region. Blue shark catch reconstruction for these fleets relies heavily on the corresponding observer coverage. The information available for different longline fleets is summarised in Table 1, including the availability of observer and logsheet information for that fleet. Note that in consultation with the data management section of the SPC Oceanic Fisheries Programme we grouped the Vanuatu fleet with the Chinese Taipei fleet, as Vanuatu flagged vessels tend to be Chinese Taipei managed.

Table 1: Data availability for each of the main flags in the South Pacific with regards to BSH catch

Fleet	Years LL active	% raised 5×5° effort	Observer program	Years available*	Operational data
American Samoa (AS)	1996-2015	1.05	Yes	2006–2014	Yes
Australia (AU)	1985-2015	0.81	Yes	1994–2014	Yes
China (CN)	1993-2015	8.22	Some***	2003–2014	No
Chinese Taipei (TW)	1964-2015	20.06**	Yes	2007–2014	Partial
Cooks Island (CK)	1994-2015	0.62	Yes	2002–2014	Yes
Fiji (FJ)	1989-2015	4.78	Yes	2002–2014	Yes
French Polynesia (FP)	1992-2015	1.79	Yes	2002–2014	Yes
Japan (JP)	1950-2015	35.08	No***	1994–2014	Few
Korea (KR)	1962-2015	23.41	No***	–	Few
New Caledonia (NC)	1983-2015	0.65	Yes	2001–2014	Yes
New Zealand (NZ)	1989-2015	0.84	Yes	1994–2014	Yes
Papua New Guinea (PNG)	1993-2015	0.63	Yes	1999–2014	Yes
Solomon Islands (SB)	2010-2015	1.59	Yes	1998–2014	Yes
Spain (ES)	2003-2015	0.15	No	–	Full
Tokelau (TO)	1982-2015	0.33	Yes	2004–2015	Yes

* for observer coverage provided by the country
** includes Vanuatu effort
** includes observer records for vessels fishing within EEZs

3.1 Methodology

Catch data inputs
As noted above, only longline fisheries data were used in the analysis. Three types of data were available:

- Operational logsheet data: All set-level (logsheet or operational) records were extracted from SPC holdings for the southern WCPFC-CA. These data report set-specific catches for the main target species (tuna and billfish), as well as catches for key shark species since CMM-2010-07 was enacted. These data are complete for the recent period for SPC-managed fishing records for Pacific islands fleets, but have various degree of temporal and spatial coverage for distant-water fishing nations (DWFNs).
- Raised 5×5 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. Figure 2 shows a map of the average effort from this source for fleets used in the analysis.
- SPC observer data holdings: Collated observer entries from the early SPC/FFA observer programmes, the Regional Observer Program (ROP) along with available data from specific independently managed national observer programs for Australia, China, Chinese Taipei, New Zealand and the United States. Figures 3 and 4 show average observer catch rates for blue sharks at the annual scale and by month, respectively. While no observer data were available from the Japanese observer program for this assessment, observations existed for this fleet through various other national observer programs for waters within EEZs. No observer information was available for the Spanish fleet. When calculating observer effort per set, for some entries, observed effort in hooks was missing but basket observed was present. In those cases we computed the number of hooks observed as the number of basket observed multiplied by the hooks between floats.

Reconstructions were performed for the top 16 flags (see Table 1). The most reliable data source for blue shark catch rates available for each fleet was the observer data, with the exception of the Spanish fleet for which no observer data exists. This fleet has achieved very high blue shark catch rates in the last years, and is known to deploy a combination of fishing strategies targeting swordfish (cf. shallow sets at night) in areas with high blue shark abundance. As noted, there was no observer information available for this longline fleet, and their area of operation (high seas, to the east of the New Zealand EEZ) meant there was no observer coverage from other programs that could be used as a proxy. However, after consultation with Spanish scientists and in combination with the relatively recent initiation of operations (>2000), blue shark catches were considered to be reported accurately for this fleet and did not need to be reconstructed. The exception was for the first year of activity (2003), where no blue shark catches were reported. For this year only the number of blue sharks was estimated based on the swordfish catch, using a ratio of swordfish-to-blue shark catch estimated by month (as for the 2004-2013 period that ratio varies across months but not between years). In all scenarios described below, therefore, this separate approach was used to develop the Spanish fleet time-series.

Catch reconstruction scenario 1: Blue shark-to-generic shark ratio from fleet specific observer programs

The first approach used the total shark catches, and applied a generic fleet-level blue shark/all sharks ratio to calculate the fleet-level blue shark catch time series, using the available data. The assumptions were therefore:

1. Shark numbers reported by the fleet to the Commission are accurate overall, but not by species;
2. The ratio of blue shark to all sharks stays constant within fleets over time and is accurately represented in the observed fishing trips;
3. All blue shark are correctly identified and reported by observers, and suffer 100 % mortality upon being caught.

The fleet-specific blue shark to total shark ratio was estimated from observed sets for the fleet over the assessment period. The ratio was calculated as the aggregated number of individuals identified as blue sharks to the total number of individuals identified as sharks (across reported taxonomic levels). This ratio could be refined by using annual, seasonal and/or spatial trends, but partial observer coverage over some of those dimensions for most fleets implies that additional assumptions would be needed, and that was not pursued further. The ratio by fleet is shown in Table 2.

The total number of raised sharks by fleet was calculated based on the 5×5 raised logsheet longline database by summing across for each flag/year/month/cell combination all catch categories for sharks (including both species-specific and generic shark categories). The reconstructed blue shark catches for that unit was then the product of the blue shark-to-shark ratio and the total shark catches for that unit.

Table 2: Proportion of blue shark to all sharks by observers on vessels by flags

Flag	Proportion
American Samoa	0.531
Australia	0.448
Cooks Islands	0.353
China	0.332
Chinese Taipei	0.101
Spain	—
Fiji	0.477
Japan	0.806
Korea	0.303
New Caledonia	0.637
New Zealand	0.814
French Polynesia	0.476
Papua New Guinea	0.008
Solomon Islands	0.256
Tonga	0.427

Catch reconstruction scenario 2: Fleet-specific observer time-series

Catches can, in theory, be reconstructed from effort and CPUE as: catches = CPUE × effort. This approach has been used in other WCPO shark assessments (e.g. Rice, 2012) and a similar strategy was used here. The second scenario estimates fleet-level catches by year-quarter from smoothed annual catch rates based upon fleet-specific observer information, weighted by observer effort for the year, and applied that to the raised aggregate effort information for the fleet as reported in the 5×5 raised logsheet database (Figure 2). The assumptions were therefore:

1. Fleet-specific temporal trends can apply to effort by that *same fleet in unobserved locations*;
2. Annual catch rates for unobserved years can be interpolated from nearby observed years;
3. Catch rates are constant for the fleet in all fishing grounds for a given year;
4. All blue shark are correctly identified and reported by observers, and suffer 100 % mortality upon being caught.

If the aggregate raised 5×5 data for a year-quarter indicated higher blue shark catches for a fleet than those estimated through this approach, the higher value was taken. The exceptions were:

- Japan, for which observer information was only available for activity within the Australian and New Zealand EEZs. For this fleet, observer-estimated CPUE was only applied to effort within Australian and New Zealand EEZs (approximated by 5×5 cells), and the blue shark catches reported for other areas left as is;
- Korea and China: the overall weighted mean CPUE from the observer program was used within the calculation, as observer coverage was too uneven across years.

The catch rates were modelled using a GAM with a low-flexiblity smooth for years and a categorical quarter effect with the R package mgcv (Wood, 2006). All key variable inputs and model results for this scenario are summarized in Figures 6 to 18.

Catch reconstruction scenario 3: All-observer fleet CPUE surface

Abundance trends used as inputs for stock assessments are traditionally derived from catch-per-unit-effort (CPUE) data. However, multiple factors—fishing technique, season, bait type, etc—can alter the relationship between CPUE and abundance, especially in complex fisheries systems comprising several fleets and spanning large spatial and temporal scales. Nominal catch rates must therefore be standardized to account for changes in these factors over time. In parallel, data emanating from different fleets will often show different abundance signals through time and provide different standardization potential based on the quality of the data and availability of covariates. The final approach was comparable to the second catch reconstruction scenario and is based on the catches = CPUE × effort model, but additional covariates were included to predict catch rates and information was shared across observer fleets. The input observer CPUE was modelled in space and time for use in the generation of blue shark catch estimates, assuming that:

- An overall spatial and temporal trends in observer catch rates can apply to catch rates for unobserved effort in the *same location by different fleets*;
- A single abundance trend is representative of all fishing grounds across the southwestern Pacific;

- All blue shark are correctly identified and reported by observers, and suffer 100 % mortality upon being caught.

Observer CPUE was modelled across all fleets based on covariates either directly present in the 5×5 aggregate data or that could be collated to match the temporal extent and spatial resolution of that dataset (e.g. oceanography variables). Blue shark catch rates were then predicted for each 5×5 degree cell, flag and year given the other covariates. The catch rates was multiplied with the longline effort to give a catch surface for the flag/year/month which was then assigned to a fishery based on either a flag definition or a flag × fishing ground definition. The available covariates were limited based on those available at the 5×5 scale. For instance hooks between floats could not be used, even though it is known to be influential, since this variable was not available for all fleets at this scale. Instead, we attempted to capture this by using as covariates CPUE for species for which targeting is known to require specific operational configurations, here swordfish and southern bluefin tuna.

Details of the approach
We used a delta-lognormal approach to model CPUE as a function of candidate explanatory variables, where the probability of having a set with non-zero catch and the CPUE of the catch when positive are modelled separately using a binomial and a log-normal distribution respectively. The delta-lognormal was chosen as it is easier to derive mean estimator for catch rates than when using zero-inflated or count distributions which can allow for long tails in the data that may not be capturesd in the probability distribution's fitted mean. The binomial GLM uses a binary response variable (y_i ; $1 =\geq 1$ fish caught, or a $0 =$ zero fish caught in set i)

$$y_i \sim \text{Bernoulli}(p_i) \tag{1}$$

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_{yq[i]} + ... \tag{2}$$

where p_i is probability of at least one blue shark individual being caught in set i, the logit link function is used to express this probability in terms of the linear predictor, β_{yq} are the year-quarter coefficients, and '...' are coefficients for the levels of additional factor variables included for set i.

For the lognormal response variable,

$$\log c_i \sim \text{Normal}(\log \mu_i, \sigma^2) \tag{3}$$

$$\log \mu_i = \beta_0 + \beta_{yq[i]} + ... \tag{4}$$

where $\log \mu_i$ is the log-CPUE of the number of blue shark individuals caught in a set, and the parameters in the linear predictor are interpreted as above. The same covariate structure was used for both the lognormal and the binomial component.

We explored the following covariates for the standardization: year-quarter, month, flag, lon-lat cell, sea surface temperature, primary productivity (chlorophyll concentration), bathymetry, and aggregated catch rates for albacore, swordfish and southern bluefin tuna. The retained covariates are described further in Table 3.

The final model structure was: s(yy) + as.factor(flag.id) + s(sst, k=5) + s(chl5d, k=5) + s(SWO.cpue.best,k=4) + s(SBF.cpue.best,k=4). This structure was chosen based on traditional model diagnostics such as the improvement in AIC, residual patterns over space and time, and the contribution of covariates to the final indices. Instead of using lon-lat surfaces, we accounted for the

Table 3: Covariates for the South Pacific observer catch rate surface and rationale

Year	Estimated as continuous spline with no fleet interaction, i.e. the overall abundance trend in time is the same across cells and fleets in the Pacific
Flag	Estimated as categorical effect
Sea surface temperature (SST)	Averaged at the 5 degree cell, 'sst' (Figure 22) and fitted as a low-flexibility smooth to account for seasonal trends in catches (instead of month $\times$ space interaction)
Primary production (chl-a)*	Averaged at the 5 degree cell, 'chl5d' (Figure 23) and fitted as low-flexiblity smooth to account for spatial trends in catches (especially higher catch rates in temperate regions and low catch rates in the middle latitudes)
Swordfish CPUE	Calculated at the 5 degree cell from aggregate data 'SWO.cpue' (Figure 21) and estimated as low-flexibility smooth to account for higher blue shark catch rates in zones of high swordfish CPUE (Figure 20)
Southern bluefin tuna CPUE	Calculated at the 5degree cell from aggregate data 'SBF.cpue' (Figure 21) and estimated as low-flexibility smooth to account for higher blue shark catch rates in zones of high southern bluefin CPUE

*The chl-a was extracted from MODIS and standardized to exclude zones $\leq$ 100m (where very little blue shark catches occur).

spatial component of catch rates by using oceanographic variables averaged by month. Diagnostics are included in Figures 24 to 26, and Figure 27 compares the reconstructed catches by fleet by year-quarter compared to the 5×5 raised logsheet estimates.

3.2 Preliminary validation series from Clarke (2009) trade-based estimates

In an attempt to provide an alternative assessment of the catch reconstruction scenarios developed therein, we did a preliminary comparison of our estimates to those derived by Clarke (2009) based upon shark fin trade data. Clarke (2009) developed three alternative estimates of WCPO blue shark catches of relevance to the longline fishery, using alternative assumptions to allocate global fin trade-based estimates to WCPO-specific quantities. The assumption that resulted in the lowest predicted catches was based on an ocean area scaler and the one that resulted in the highest predictions of catches was based on a longline effort scaler. The reader is referred to that paper for more information. We compared the annual total catch for 1994-2007 for catch scenarios 1 and 3 (i.e., those used in the stock assessment grid) to those two assumptions (Figure 29). Catch scenario 1 predicts lower catches than the lower bound of the ocean-area scaler scenario but a similar trend of catch increases through time. Catch scenario 3 approximately matches the lower bound of the ocean-area scaler scenario but shows a different trend through time.

4 Post-release mortality estimates

An issue raised at the Pre-assessment workshop was the need to consider levels of discard mortality within catch estimates. Investigation of the available observer information on discarding indicated that those fleets that showed high discard rates (Figure 31) accounted for only a small proportion of the estimated blue shark catches (specifically American Samoa, Australia and Cooks Islands, which combined represented less than 1% of the catches in the SP-wide CPUE scenario; see below). It is noted that discard mortality within specific fleets, such as that of Japan, could be influential but observer coverage on that fleet was very low. In turn, the high discard rates seen in the early period of available data could relate to finned individuals. Rates may also change over time, as seen within the New Caledonia fleet, which may be linked to changes in marketing rules that removed the incentive for fishermen to fin, and in French Polynesia where regulations preventing finning and retention of most shark species were introduced. To apply a scenario incorporating post-release mortality would require estimates of hooking mortality and the determination of survival rate for discarded individuals given their condition at release[3]. These would then be applied to the proportion of discarded individuals indexed by fleet and time, given changing regulations. The proportion of individuals estimated to survive hooking and discard would then be removed from the reconstructed catches. Given the level of uncertainty already captured within the blue shark catch estimates, the inclusion of this additional factor was not pursued further for the current assessment.

5 CPUE standardization

Exploratory analyses of the available data for blue shark highlighted the different nature of longline fleets operating in the Pacific, along with their corresponding different levels of shark reporting and observer coverage (see also Table 1). In short, three main types of fleet/data categories were identified:

1. Distant-water fishing nations (DWFNs) with extensive fishing grounds, broad variations in catch rates for blue sharks within those grounds, and sparse or non-existent observer coverage;
2. Domestic fleets from PICTs with narrower fishing grounds, lower blue shark catch rates and relatively low rates of longline observer coverage;
3. Fleets (domestic and DWFNs) with very high catch rates for blue sharks fishing in the South Pacific with 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.

The pre-assessment workshop recommended that, given the development of a single-region assessment model, a set of individual CPUE time series should be developed that would be used individually within assessment runs (Pilling and Brouwer, 2016). Three CPUE scenarios were thus developed to represented the key combinations of fleet and data quality/availability described above:

- South Pacific-wide index including all fleets based on observer data
- an index for a distant water fishing nations based on observer data

[3] For example, hooking mortality estimates for blue shark from an Atlantic longline fisheries ranged from 15% to 35% with discard survival rates varying based on whether the individual was healthy (100% survival) or injured (10 to 19%), noting variable rates of observer reporting of those variables across years (Campana et al., 2009, 2016)

- an index based on high-quality operational data

The rationale and method used for each of the three standardised CPUE series is described in the following sections.

CPUE scenario 1: South Pacific-wide index standardized against all fleet

A standardized CPUE index for South Pacific blue shark was included as part of the key shark species indicator status report presented to the WCPFC Scientific Committee last year (Rice et al., 2015). A similar modelling approach was taken for this first scenario, but included updated observer data for the most recent year as well as new observer programs recently added to SPC holdings (Chinese Taipei and China).

The model structure differs from that used in Rice et al. (2015) and was chosen to minimize AIC while maximizing the number of covariates and drawing on oceanography variables, comparable to CPUE surface catch scenario 3 outlined above. There were, however, two key differences with the CPUE surface model used in the above catch reconstruction:

1. negative binomial error distribution was assumed; and
2. the dispersion parameter from the negative binomial distribution was allowed to change by flag.

This negative binomial with variable dispersion approach consistently results in improved diagnostics than traditional approaches (see section 5 in Rice et al., 2015) but was not practical to generate CPUE estimators to reconstruct catches, so we did not use it in the catch scenario above. However, it is suitable to generate indices of abundance as long as no time covariates are included specifically in the model used to estimate the dispersion coefficients. Year-quarter effects were fitted as categorical variables and extracted directly from model coefficients, with the back-transformed model intercept set to 1.

Additional information on model structure and diagnostics are presented in Figure 32 and the fitted indices are shown in the top panel of Figure 33. For additional information on the methods please refer to Rice et al. (2015).

CPUE scenario 2: Abundance index for a distant water fishing nation

Distant-water fishing nations account for a large portion of the effort but also tend to have low observer coverage given that trips are only anecdotally observed when fishing in EEZs. In parallel, their domestic observer programs often do not extend to the South Pacific and/or are not available to SPC. As of 2016, Chinese Taipei provided access to SPC to its observer data, and additional observations for this fleet are also available through Chinese Taipei vessels flagged under Vanuatu. Chinese Taipei ranks second highest in effort in hooks in the South Pacific and has a wide-ranging fleet targeting a diversity of species across areas with both high and low catch rates for blue shark. It thus represents, arguably, the DWFNs dataset with the most information in the South Pacific. However, observer rates still remain very low compared to the longline effort exerted by the fleet (Figure 19). We therefore used the South-Pacific-wide CPUE surface fitted under the third catch reconstruction scenario (see section 3.1) to generate standardized CPUEs for this fleet by predicting catch rates for Chinese Taipei over the model region for 1994 to 2014. The resulting 'nominal' CPUEs were used as the abundance trend for this fleet, aggregated for each year-quarter. In effect, this allowed the incorporation of the overall Pacific-wide year effect smoother fitted across all observer programs, scaled for each year based on the specific combination of targeting and effort location for the Chinese Taipei fleet. In addition, since the fitted model assumes a different error distribution than that of CPUE scenario 1, and models the year effect as continuous rather than categorical variable, this scenario allows the incorporation of (some) modelling uncertainty in the generation of standardized CPUEs.

The diagnostics for this series are as presented for catch scenario 3 (Figure 26) and the resulting abundance time-series derived from the fitted 'nominal' CPUE are shown in the bottom panel of Figure 32.

CPUE scenario 3: Abundance index from logsheet (operational) data

Logsheet data have the advantage of having full coverage of fishing effort, *vs.* observer data which have sparse coverage rates for longline fleets in the southwestern Pacific. However, full reporting of blue sharks over the assessment period occurs for none of the fleets for which SPC has access to the full extent of logsheet data.

In this regard, fleets operating in New Zealand waters are arguably those with the best coverage, in addition to fishing in a narrow area with uncharacteristically high catch rates for blue shark compared to the rest of the southwestern Pacific. In parallel, they operate close to the Spanish longline fleet which has shown an abrupt increase in nominal blue shark CPUE in recent years but for which no observer coverage exists and information useful for standardization is lacking[4]. This New Zealand dataset was also analysed independently in 2014 (Francis et al., 2014), which serves as a useful benchmark for the current work. This fleet was therefore used to generate the third candidate abundance index for the blue shark stock assessment.

Changes in reporting rates over time and recent legislation (starting October 2014) within the New Zealand EEZ (Ministry for Primary Industries, 2015) impacts the time series of blue shark catches available from this fleet. The New Zealand standardized CPUE series was therefore shortened to remove the years 2013 and 2014. This is because there appears to be drastic changes at that time in the proportion of positive sets coinciding with the shark finning regulation (Figure 34).

The New Zealand blue shark data were standardized by first filtering to included only sets within the New Zealand EEZ, and excluding years 2013 and 2014 (see above). We used a delta-lognormal distribution to model catches. The final model structure included a categorical year-quarter effect, a day time effect and a smooth on hooks-between-floats. The categorical day-time variable included the levels night, dawn, day and dusk, which were computed from the day of the year to account for seasonality in the timing of those events, based on the equations for sunray angles provided NOAA's Global Radiation group[5]. The final covariate structure was selected based on model residuals, AIC scores and to minimize collinearity between covariates. Year-quarters effect were extracted as recommended in Maunder and Punt (2004). The standardized CPUE for this fleet is shown in the middle panel of Figure 32 and the diagnostics for the standardization are shown in Figure 35.

[4] However, the fleet's operational features are said to have remained constant over time (shallow sets in the evenings), such that the abundance trend would remain even if standardized against operational variables.

[5] See www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html

6 Size data

Length frequency data for longline fleets were extracted directly from observer records of longline caught individuals. Only measured lengths categorized as total length or fork length were retained. The conversion used between the two measures was: $FL = 0.838TL\breve{}1.615$, based on sex aggregated estimates from New Zealand individuals (Francis and Duffy, 2005). The minimum length threshold for the free-swimming size was set at 40cm following (Nakano and Stevens, 2008). Figure 36 shows the distribution of lengths by flag over years, Figure 37 shows the average length by 5 degree cell aggregated across flags and Figure 38 compares the length frequency distributions by fleets used in the stock assessment models[6].

7 Tagging

Tagging data play an important role in assessments for tropical tunas in the WCPO (e.g Harley et al., 2014; McKechnie, 2016) and can inform multiple aspects of a stock assessment, notably: population scaling, rates of fishing mortality, movement between regions, and growth curves. However, inference from this type of data relies on good knowledge of tag reporting rates by fleets, tagging releases across the range of the assessed stock, and accurate reporting of release and recapture locations and individual lengths. In the case of South Pacific blue shark, tagging data were available from three different sources: (1) recreational tagging program from the New South Wales Department of Primary Industries Game Fish Tagging Program (Australia); (2) pelagic tagging program of CSIRO (Australia); (3) NIWA billfish and gamefish tagging program (New Zealand). However, the overall number of released tags was low, restricted to a specific area and length at recapture was either missing or of unknown reliability (if collected by recreational fishermen without special training). In addition, given that the chosen assessment structure contained a single model region so that movement between regions did not need to be estimated, the remaining estimable quantities depend on reporting rates which are hard to estimate for recreational fisheries (which comprised the bulk of the returns). We thus elected not to include tagging data in the assessment, but include here a map of the available trajectories of tag releases and returns for further information (Figure 39).

8 Results and Discussion

This paper describes the methodology and results used to generate the three catch data scenarios and the three abundance (CPUE) time-series scenarios for the 2016 southwestern Pacific blue shark *Prionace glauca* stock assessment (Takeuchi et al., 2016). We also included a brief summary of length frequency and tagging data, noting that the latter was not used in the current stock assessment. Our approach relies heavily on observer data as, given general under-reporting of blue shark catches across fleets, it is the one source of reliable information for blue shark catches in the South Pacific.

Analyses of spatial trends in observer catch rates (Figure 3) allowed the delineation three broad regions in blue shark catches which were subsequently used to refine fleet definitions within the stock assessment (Figure 1): high catch rates within the tropical swordfish targeting region, very

[6] Note that these figures include Australian records for recent years which were subsequently shown to be inaccurate. See Takeuchi et al. (2016) for more details.

high catch rates in high latitudes in the South Pacific, but with a strong seasonal component, and lower catch rates in the middle latitudes/eastern area.

The reconstructed catch scenarios predict blue shark catches of very different magnitudes over the 1994-2014 (Figure 30), with the southwestern Pacific wide CPUE surface catch scenario (#3) predicting the highest catches and the blue shark-to-generic shark catch scenario (#1) predicting the lowest catches for most fleets (Figure 28). Only these two scenarios were used in the stock assessment for blue shark since they bracket the predictions of the fleet-specific observer catch rates scenario (#2) for all the fleets that account for the majority of the catches. In addition, scenario #2 relied on strong and probably unmet assumptions for DWFNs, since these fleets often have extensive fishing grounds (Figure 2) but otherwise narrow observer coverage within those grounds, such that the raising of the estimates based on catch rates in observed areas might not be appropriate.

The prediction of low catches by the blue shark to shark ratio scenario is unsurprising since it is based on the assumption that all sharks are reported in aggregated 5×5 catches, whereby basin-wide under-reporting of shark catches is known to have occurred in the Pacific, especially in earlier years (Fowler et al., 2005). Japan is predicted to be the fleet with the highest catches, e.g. under scenario #3, catches for some year-quarters reach $\sim$300,000 individuals. This is driven mostly by predictions of high blue shark catch rates in southern Australia and New Zealand around the fishery targeting southern bluefin tuna, where Japan also happens to have levels of effort. The predicted catch rates were high but still a bit lower than observed estimates (Figure 24), highlighting that those values are not unreasonable. The inclusion of oceanographical variables, especially chlorophyll-a, allowed the spatial variation in catch rates to be reasonably explained, highlighting that optimal models of catch rates have to account for both operational features that promote blue shark by-catch and oceanographic conditions where their abundance is naturally higher.

We performed a preliminary comparison of reconstructed catches to trade-based estimates previously developed by Clarke (2009) (Figure 29). Estimated WCPO blue shark catches based upon trade data increased from the early 1990s, peaked around 2002, and declined slightly to 2006. Dependent upon the assumption used to estimate WCPO-specific quantities, estimates ranged around 1-1.8 million individuals per annum (lower 95% confidence interval for estimates derived based upon WCPO area to global ocean area) to a peak of 4.5-10 million individuals per annum (higher 95% confidence interval for longline effort-based estimates). In comparison, estimates over the period 2000-2006 as reconstructed for this analysis showed similar increasing trends up to 2006 when estimated through the ratio of logbook shark catch against blue shark catch in the observer data. However, the absolute annual estimates from logbook ratio approach lay outside the lower 95% confidence interval developed by Clarke (2009) numbering up to 500,000 individuals in 2006. In addition, the increase in catches from this scenario probably results from the increased reporting of shark catches in fisheries statistics, whereby the increase in Clarke (2009) reflects increased demand for shark fins.

When estimates were developed through the Pacific-wide CPUE approach, a different trend to that from Clarke (2009) was found. Estimates increased to the late 1990s, declining slightly in the early 2000s, then increased again around 2005. Estimates from that approach were more comparable to that of Clarke (2009) (up to 1.5 million individuals) but were again at the lower end of those predictions for the most conservative scenario of WCPO catch allocation. This comparison thus highlights that the catch estimates used in the assessment might be conservative, even for our highest catch scenario, especially since trade-based estimates are themselves expected to be lower than true catches. Development of blue shark catch estimates, particularly from a period lacking in notable observer data, is challenging. The development of alternative time series using approaches such as Clarke (2009) could provide an alternative approach to this end.

The abundance index scenarios from standardized CPUE were chosen to reflect the different combinations of fleet types and data quality available to the assessment. Notably, one of the included series was based on operational data since the rest of the analyses rely on observer data. The abundance indices produced under the three scenarios are included in Figure 32 and show different directional trends over time, with the South Pacific observer (#1) increasing slightly, the 'nominal' Chinese Taipei declining (#2) and the New Zealand operational series increasing after being stable in early years.

Our recommendations based on the analysis of the available data for blue sharks are as follows:

- To overcome challenges in the analysis of observer records collected independently across observer programs within the WCPO, we recommend the provision of expanded metadata to facilitate the merging of variables from different programs into a single harmonized database. This could be assisted by an active collaboration of member countries with SPC during the initial merging operation;
- Emphasis on improving the consistent collection of accurate observer effort during the set is needed, as this variable is essential to the estimation of accurate by-catch rates;
- Noting the importance of operational covariates like hooks-between-floats and set time to interpret CPUE trends, the provision of these data for all fisheries is encouraged;
- The continuation of ongoing efforts to expand observer coverage for longline fleets operating in the WCPO is encouraged, especially given that the collection of length data for bycatch species relies on this effort and these data can be influential in data-poor stock assessments;
- Noting the significant catch of blue sharks and other species of interest associated with the Southern bluefin tuna fishery within the WCPFC-CA, increased collaboration with the concerned parties for the purpose of assessing WCPO stocks should be pursued;
- Noting the increase prevalence of regulations aimed at managing shark mortality across WCPO, future catch reconstruction should prioritize the inclusion of discard mortality scenarios;
- Tagging programs for the blue shark are currently restricted to a specific part of the South Pacific blue shark range, limiting their potential to inform movement rates across the assumed range of the stock. Geographical expansion of tagging activities would assist future assessments. In addition, the bulk of the tagging information available to this assessment came from a recreational fishery, but the utility of these data was limited by uncertainty in the length at capture information. The potential to improve these valuable data sources should be examined.
- For the North Pacific, valuable information is available on the location of key mating, parturition and nursery grounds. Gaining comparable information for the South Pacific would be invaluable in the development of targeted data collection programmes, for data analyses and potential management interventions.

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10 Figures

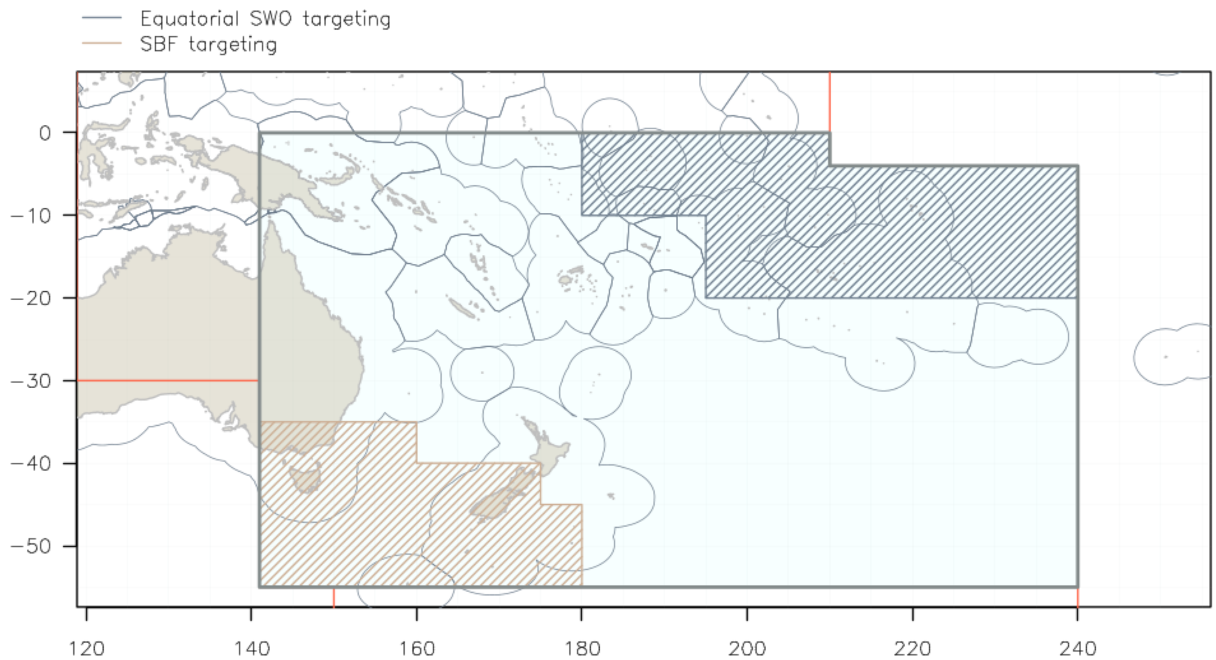

Figure 1: Assessment region map with fishery separation boundaries.

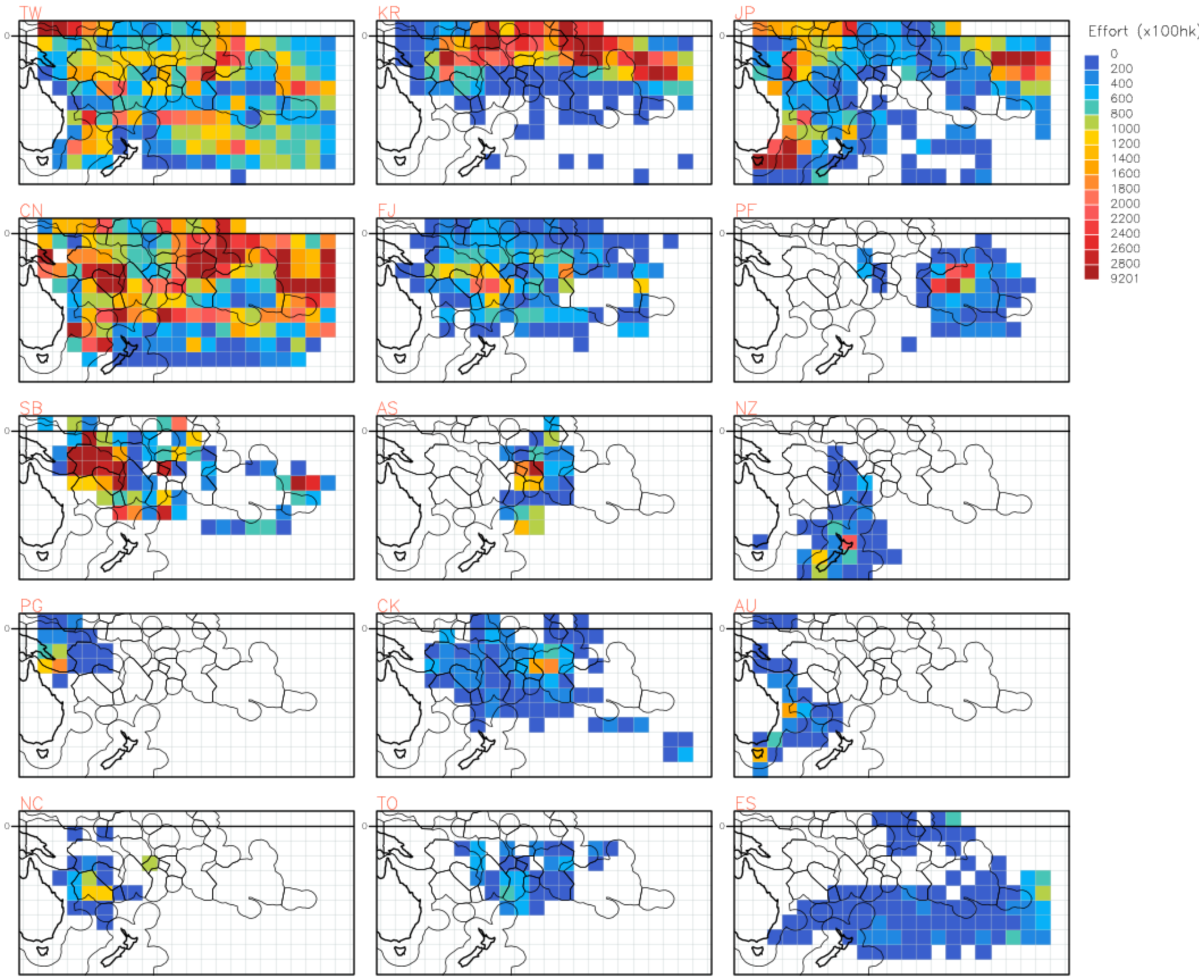

Figure 2: Average longline effort (in hundred hooks) from the 5×5 degree raised logsheet estimates over the 1994-2014 period for all flags used in the assessment, ranked from left to right, top to bottom by the total effort over the time-period.

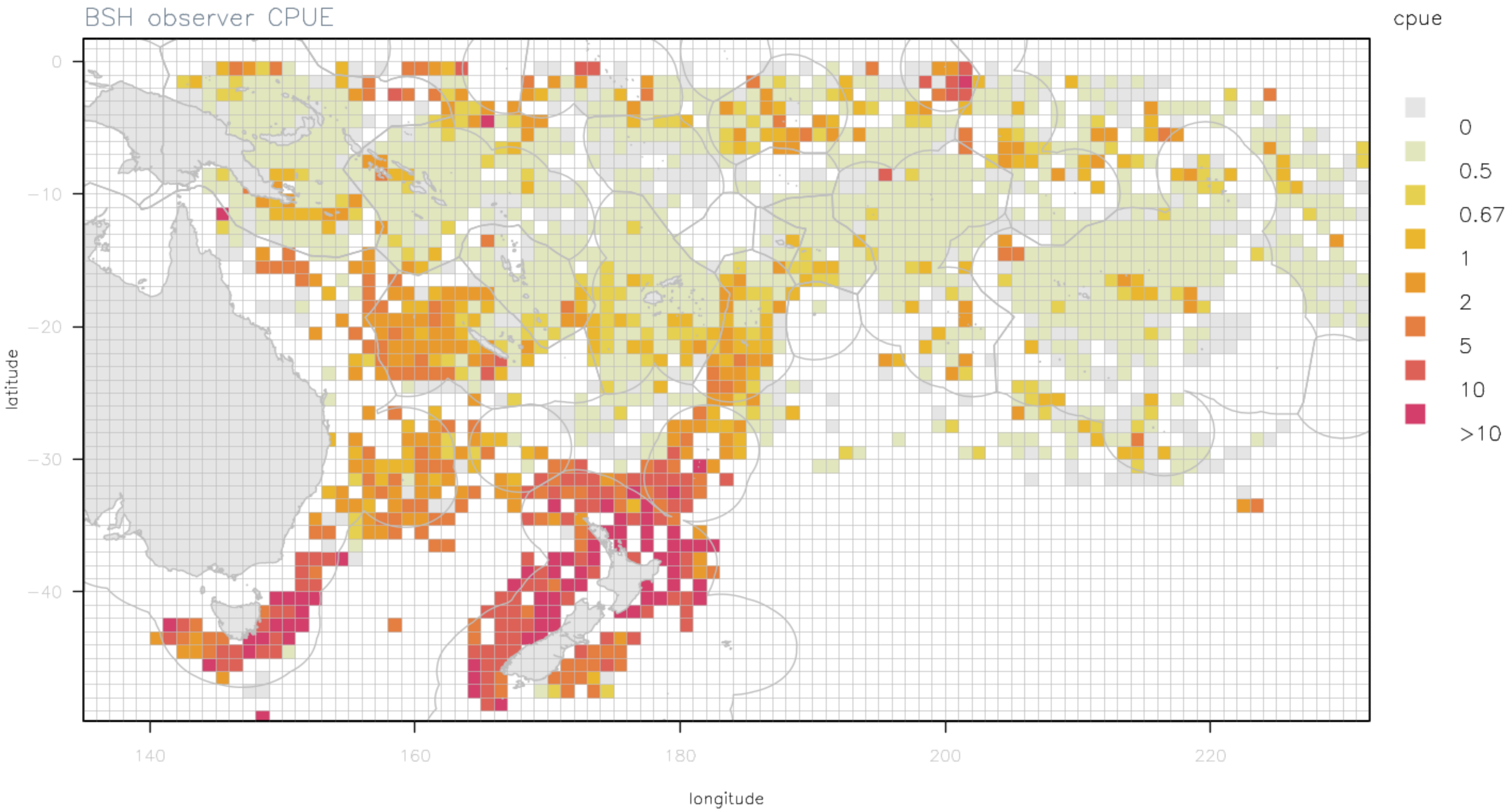

Figure 3: Observed blue shark catch rates by one degree cell aggregated over 1994-2014 for all fleets with observer data.

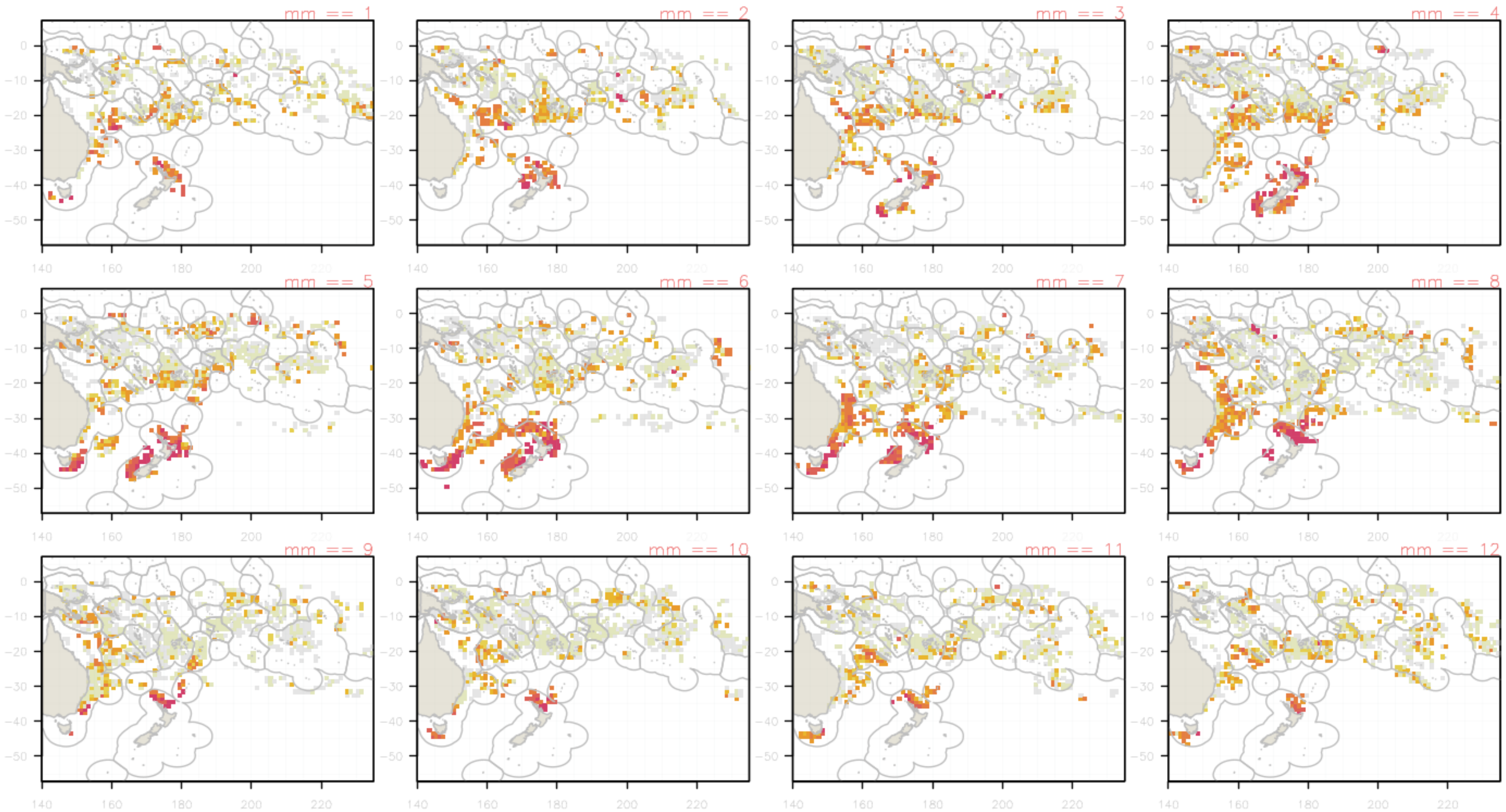

Figure 4: Monthly trend in observed blue shark catch rates aggregated over 1994-2014 at the one degree cell for all fleets with observer records during that month.

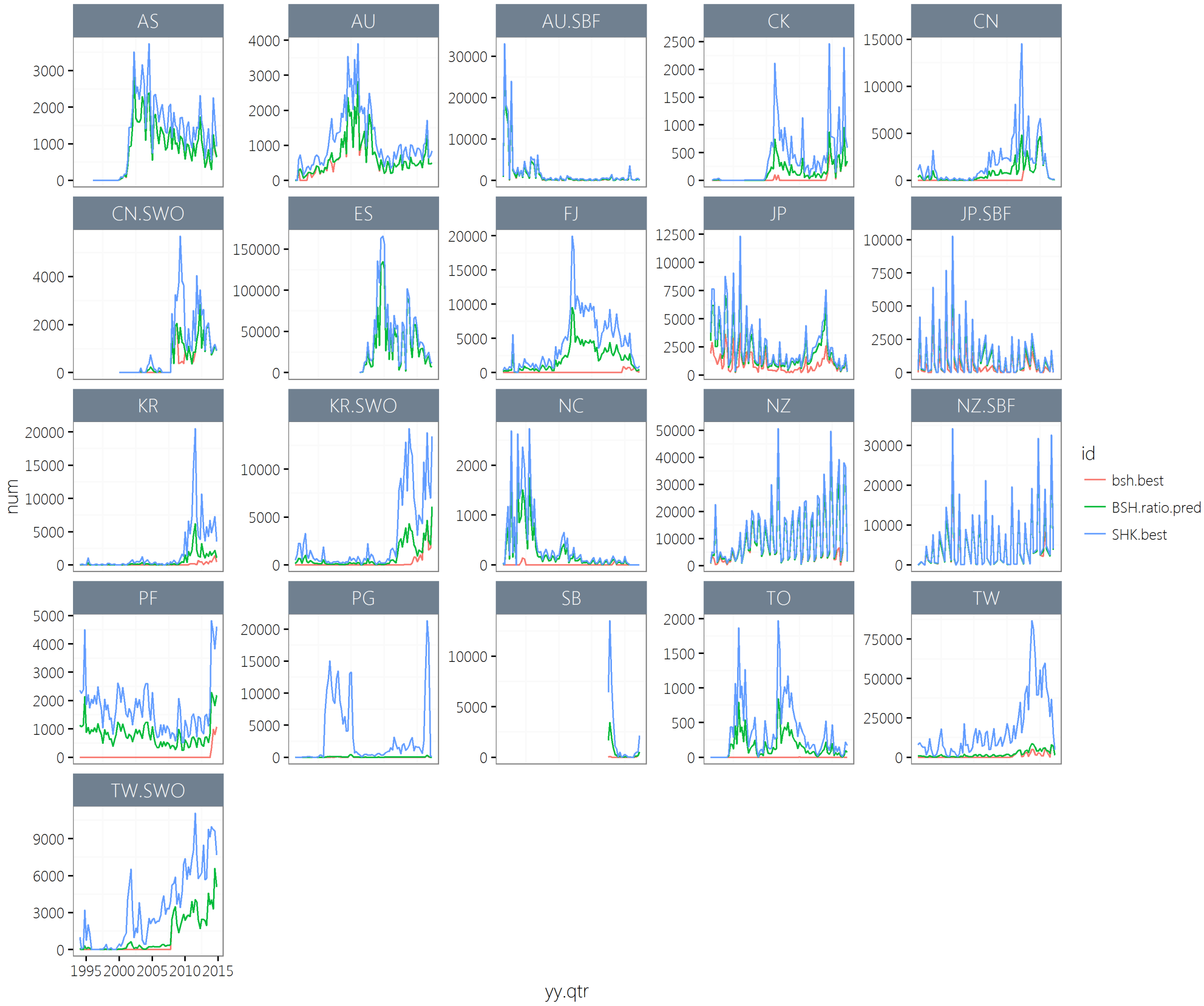

Figure 5: Predicted catches by year-quarter under catch reconstruction scenario 1 (green line). For context the reported generic shark catches and blue shark catches are added in blue and red, respectively.

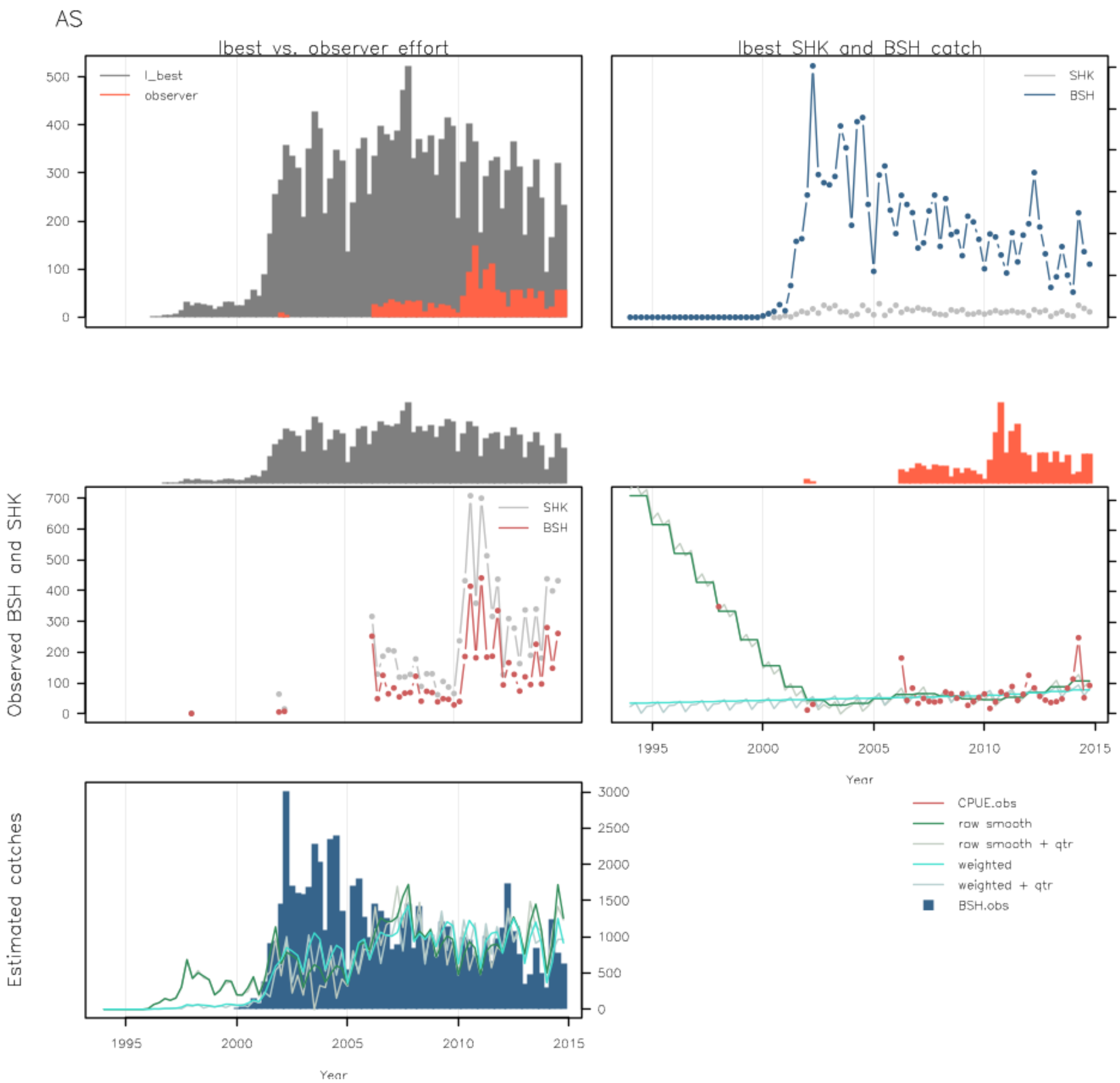

Figure 6: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for American Samoa. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

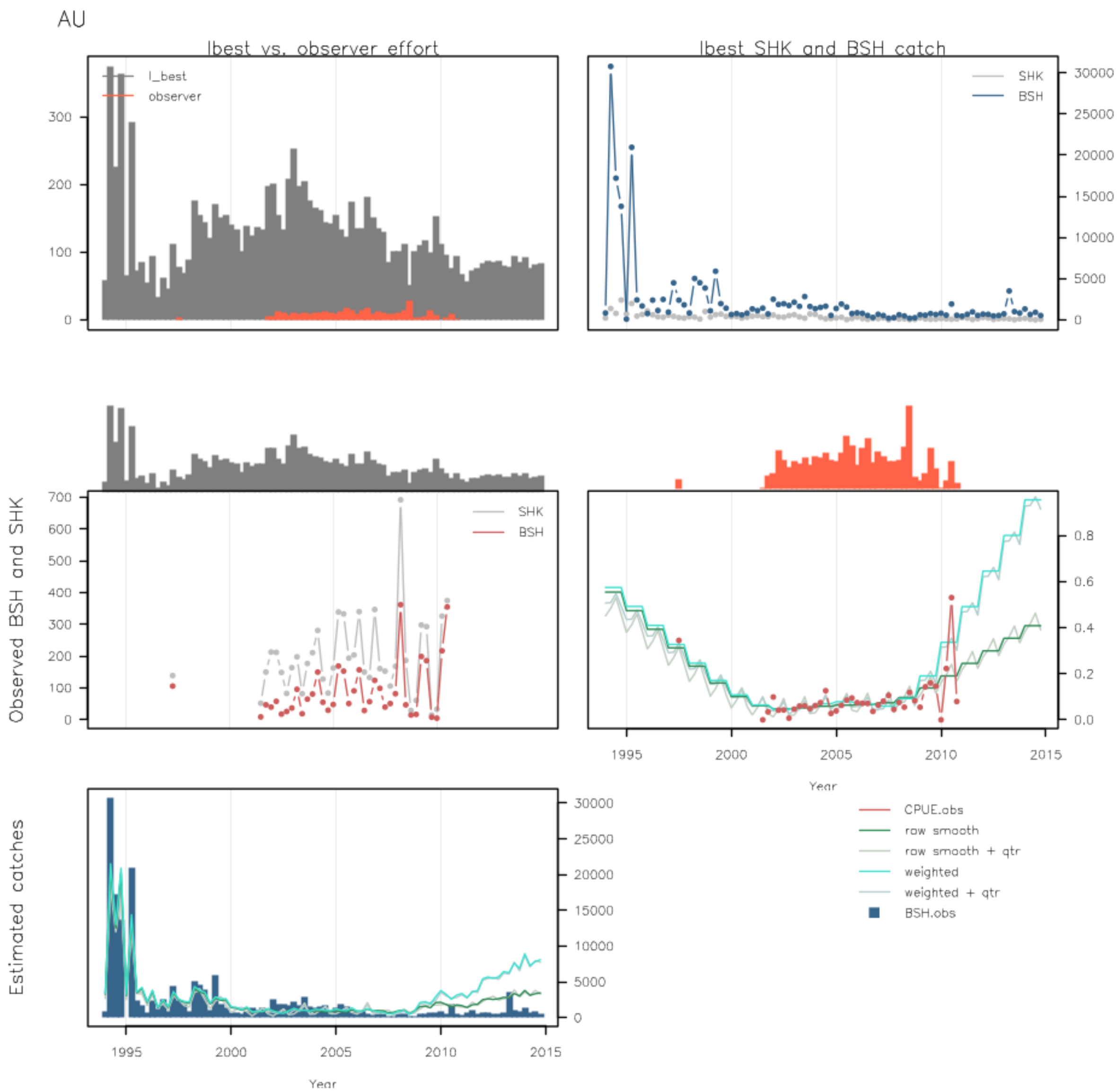

Figure 7: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Australia. Top: 5 × 5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5 × 5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5 × 5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5 × 5 catch database. The final model retained was the weighted spline with the quarter effect.

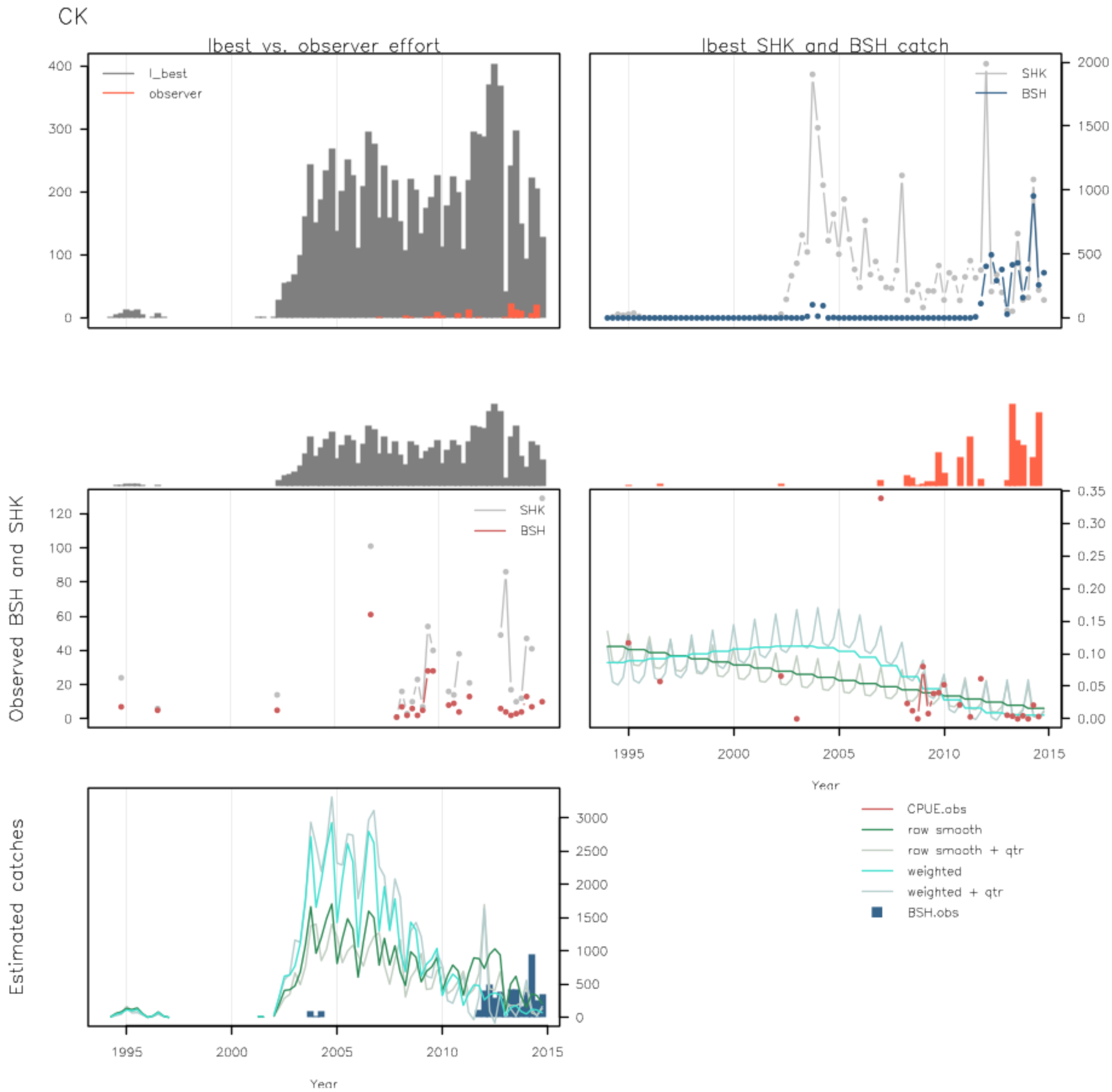

Figure 8: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Cooks Islands. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

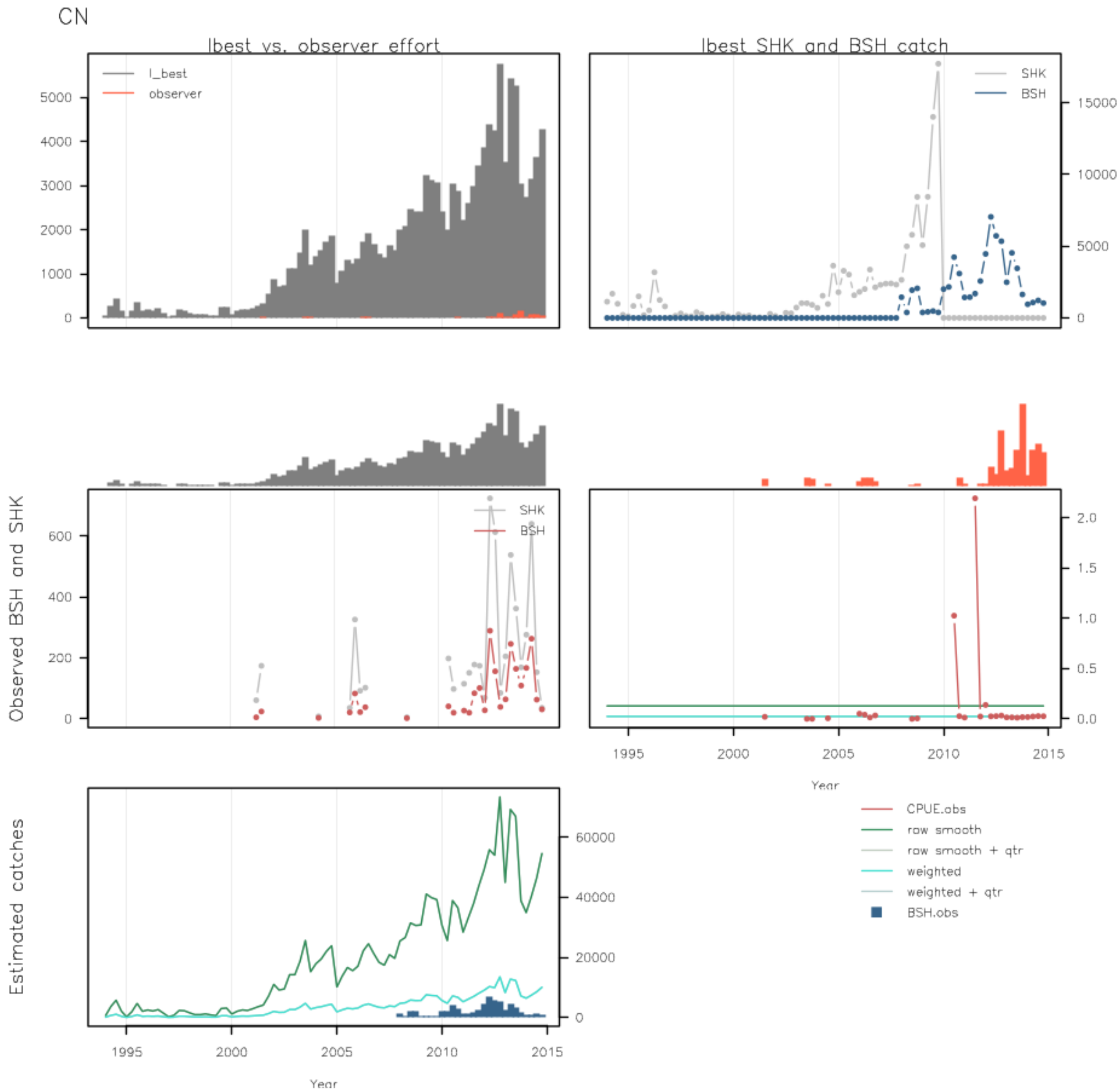

Figure 9: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for China. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

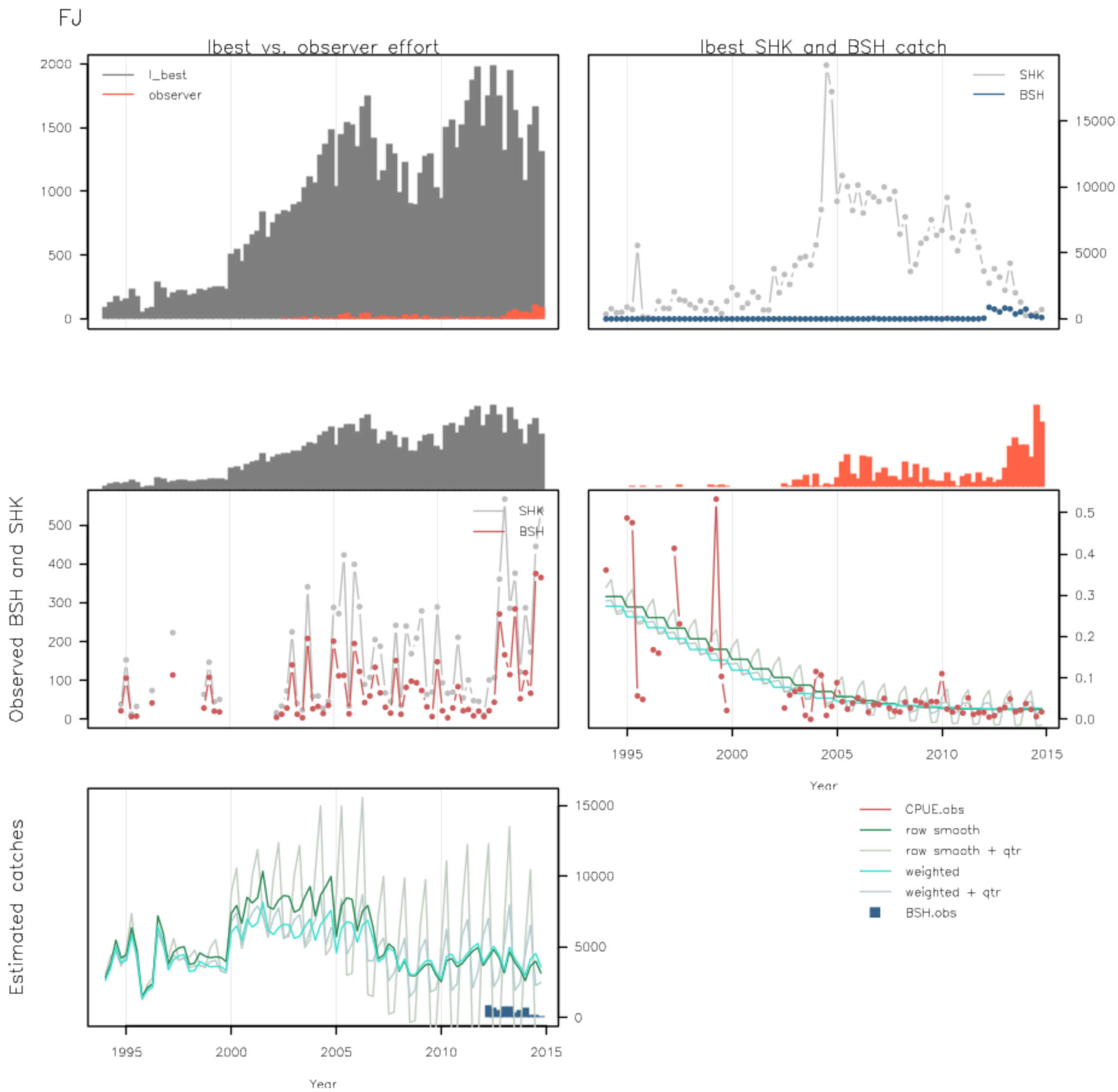

Figure 10: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Fiji. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

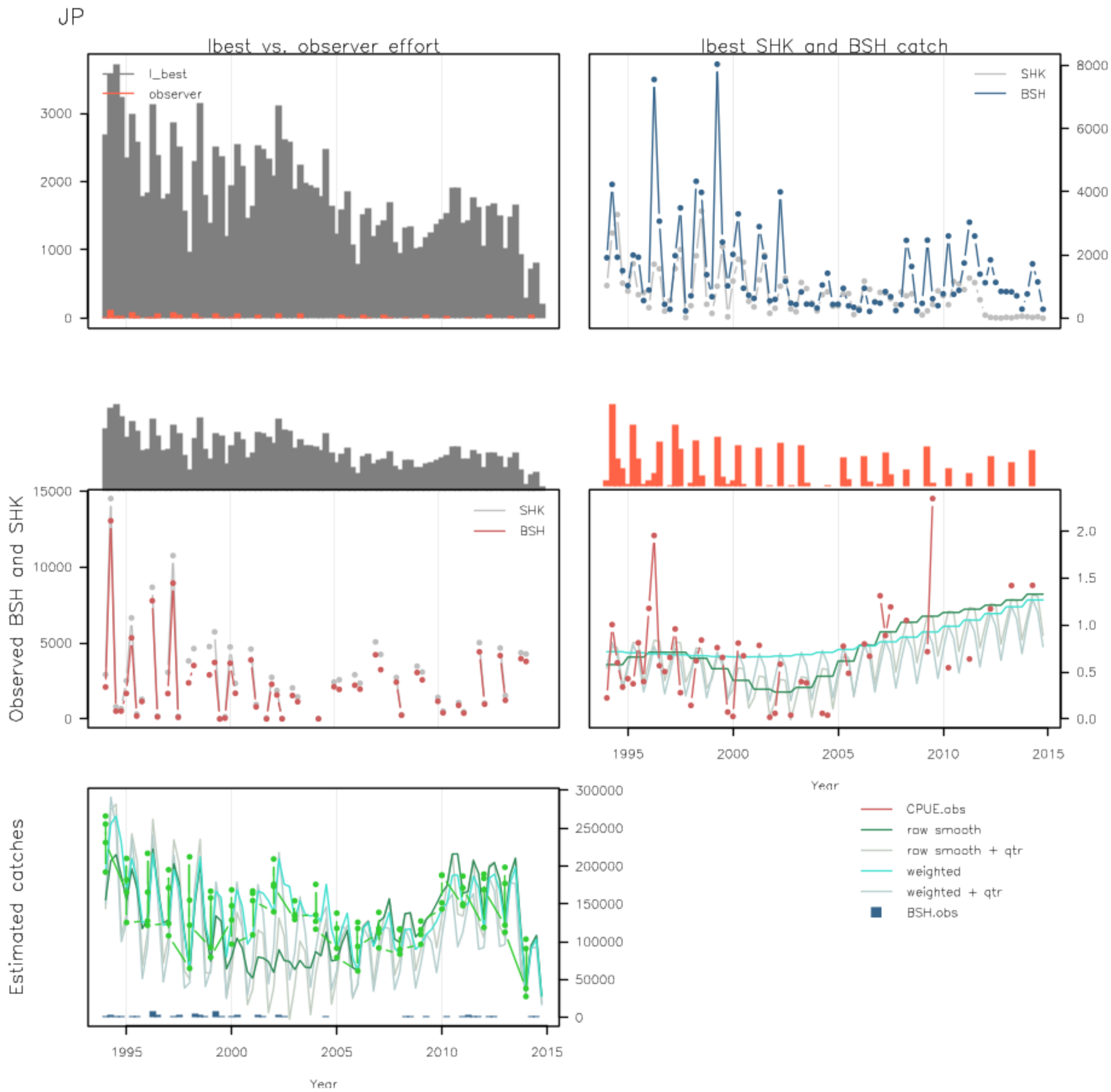

Figure 11: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Japan. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.. The limegreen line shows the predicted catches when the observed catch rate is applied to all Japanase effort and the dark green line shows predicted catches when only the Australian and New Zealand estimates are raised (see Methods).

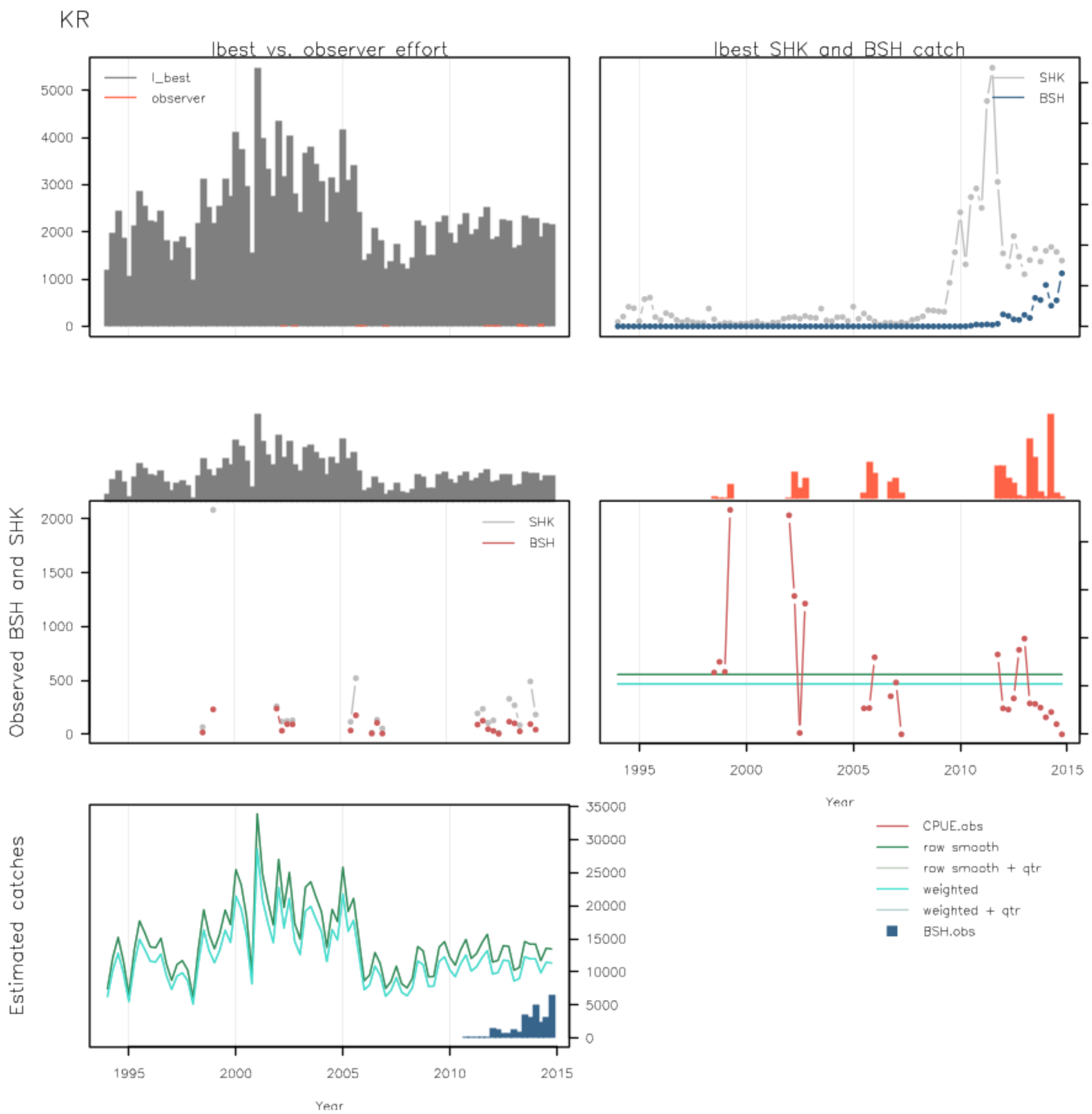

Figure 12: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Korea. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

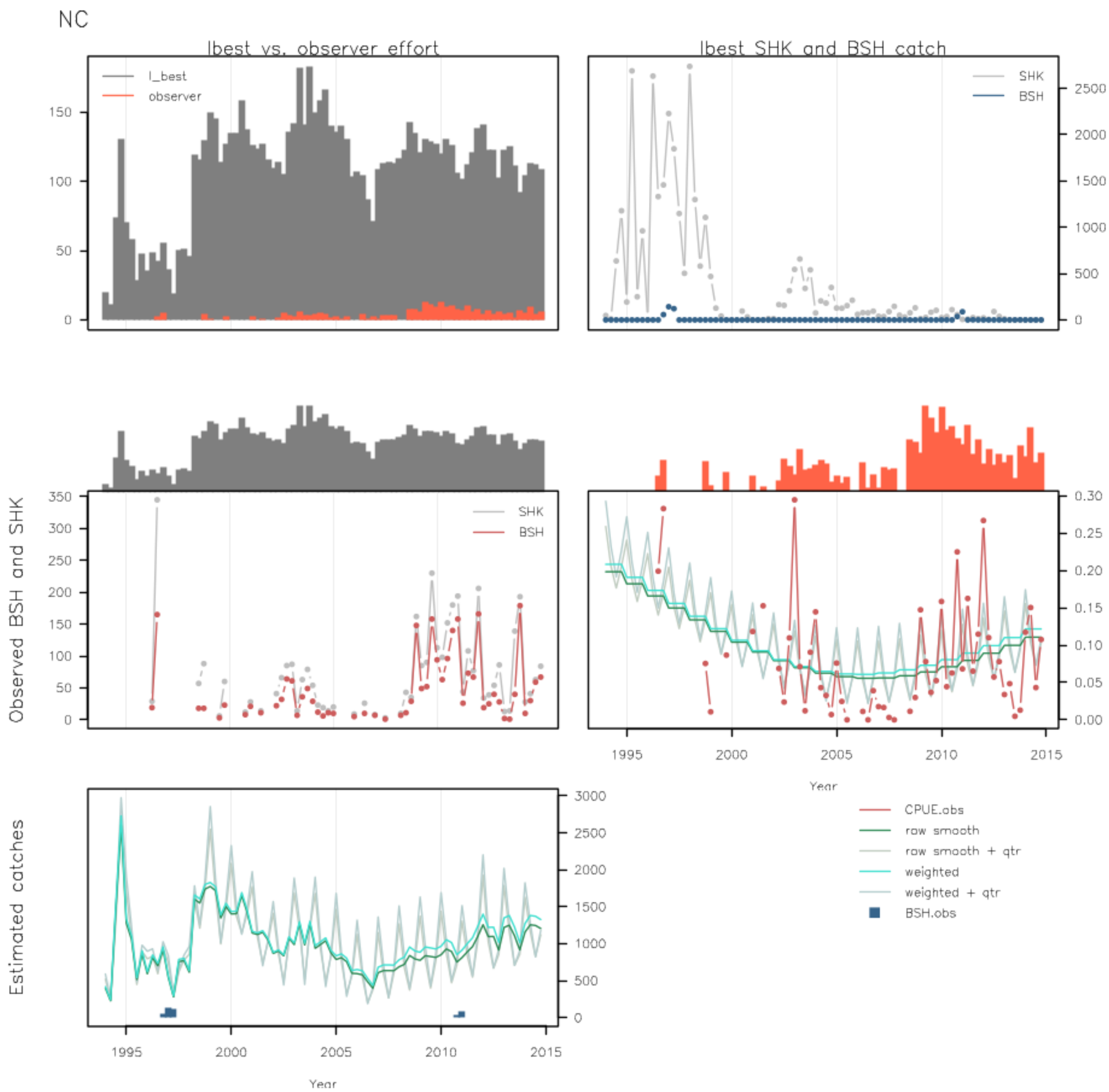

Figure 13: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for New Caledonia. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

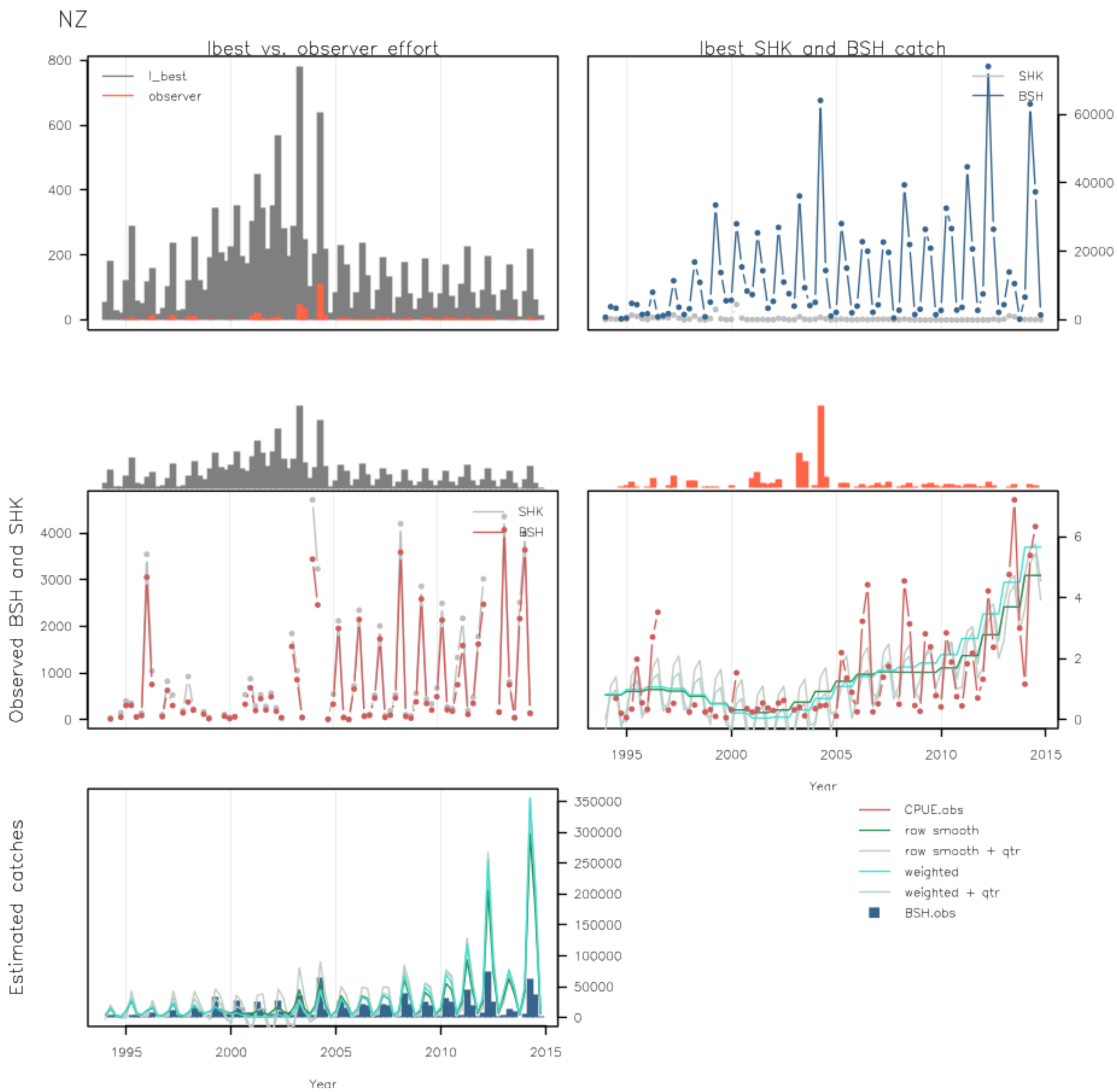

Figure 14: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for New Zealand. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

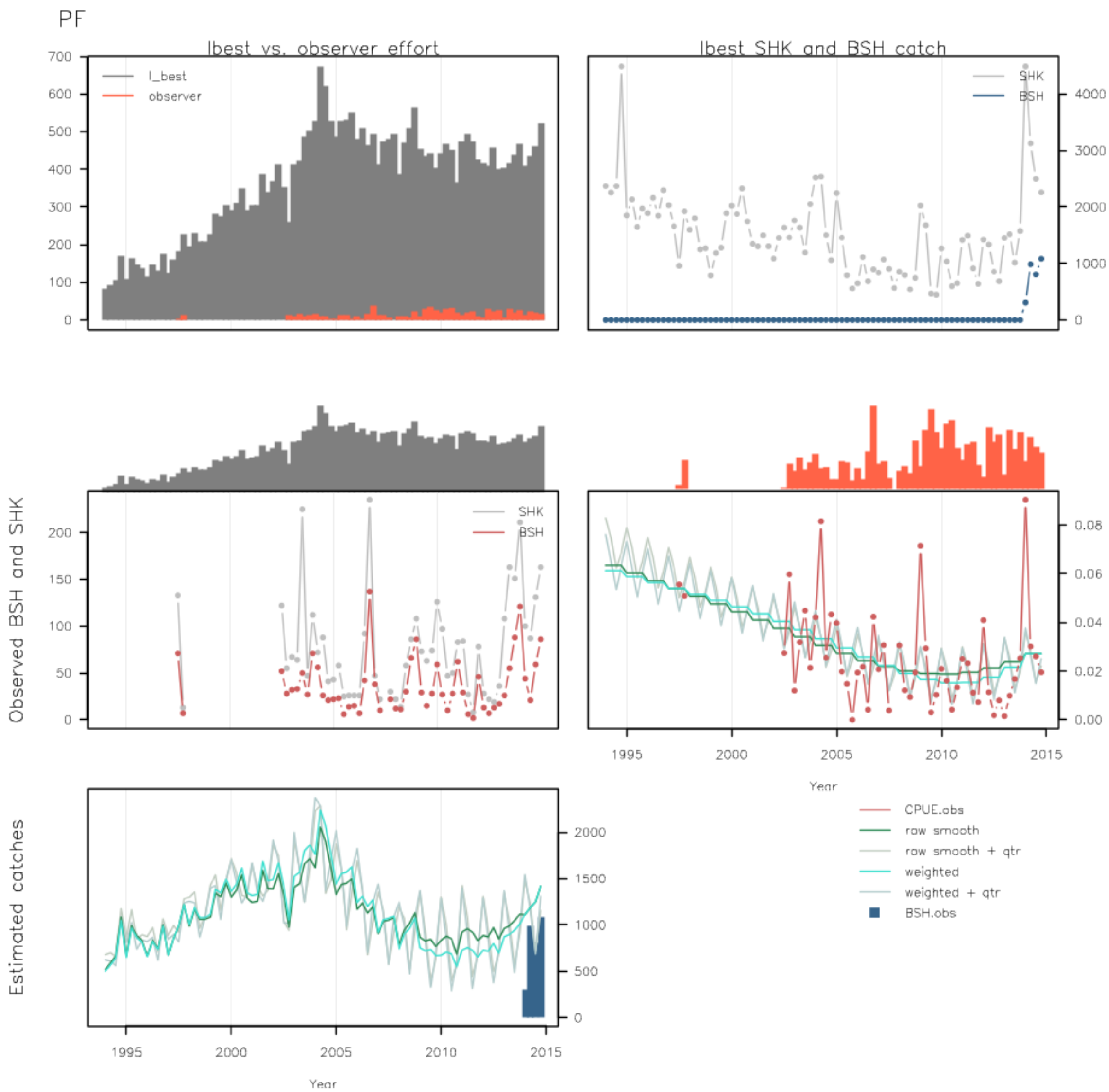

Figure 15: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for French Polynesia. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

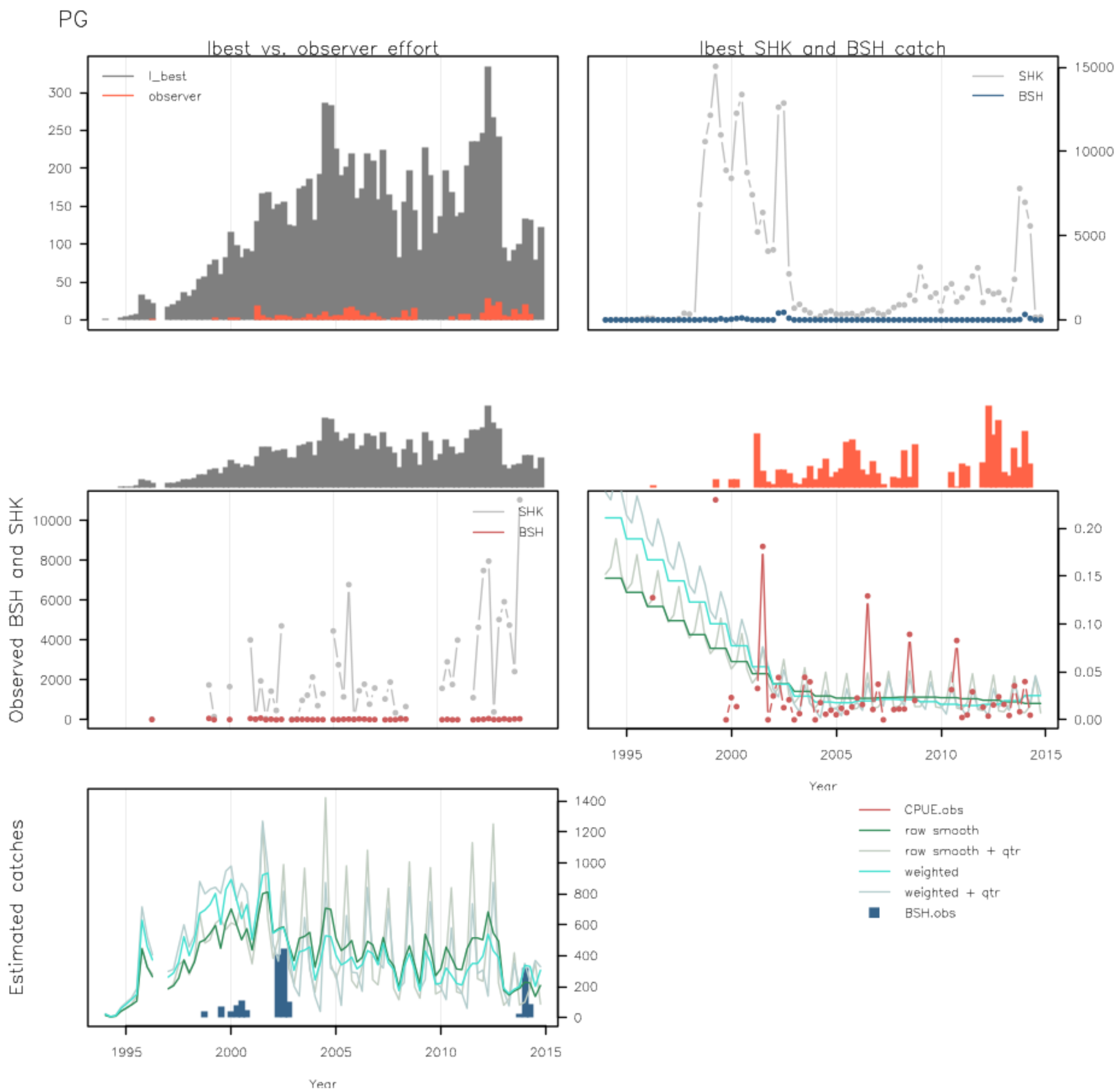

Figure 16: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Papua New Guinea. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

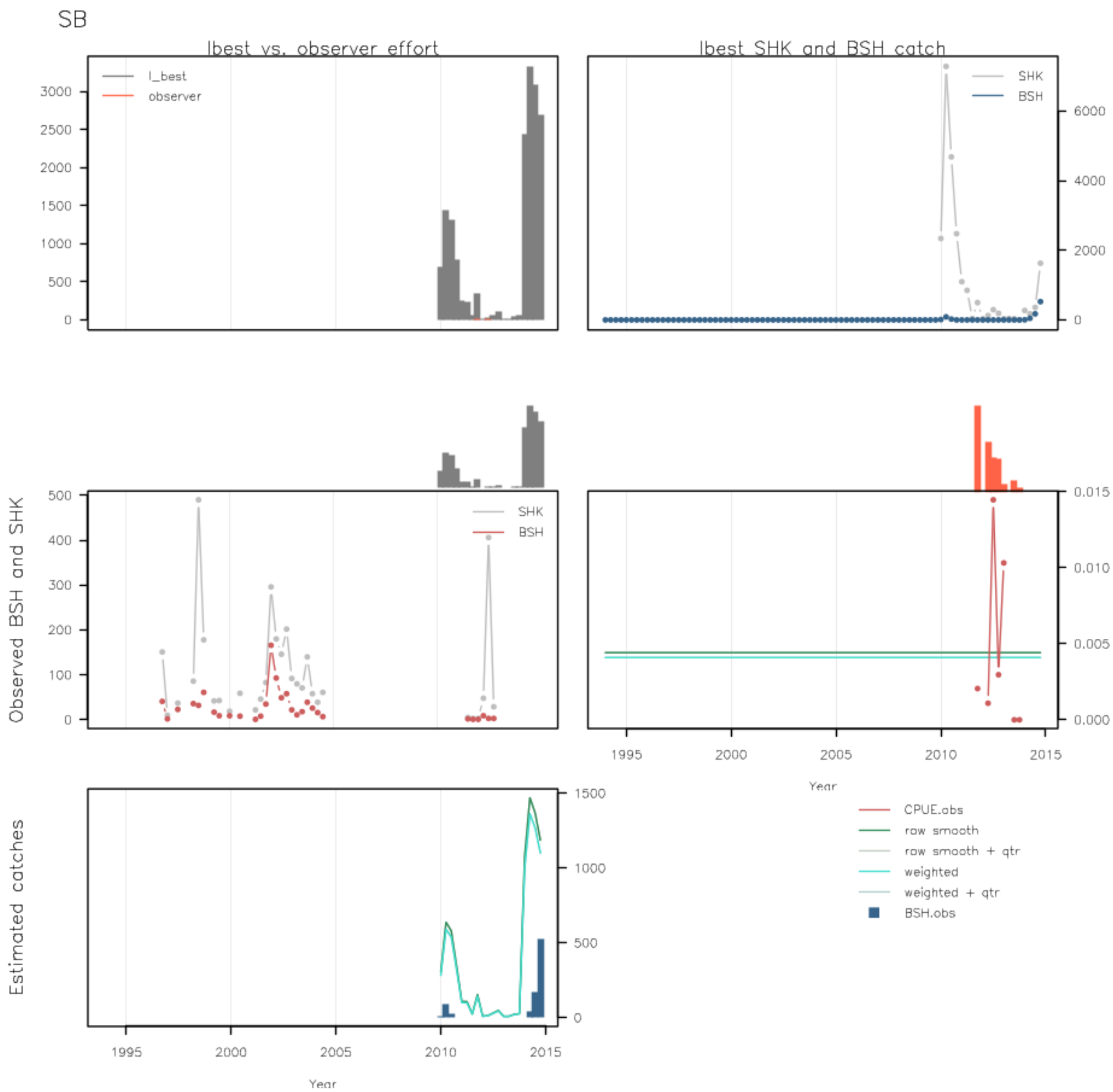

Figure 17: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Solomon Islands. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

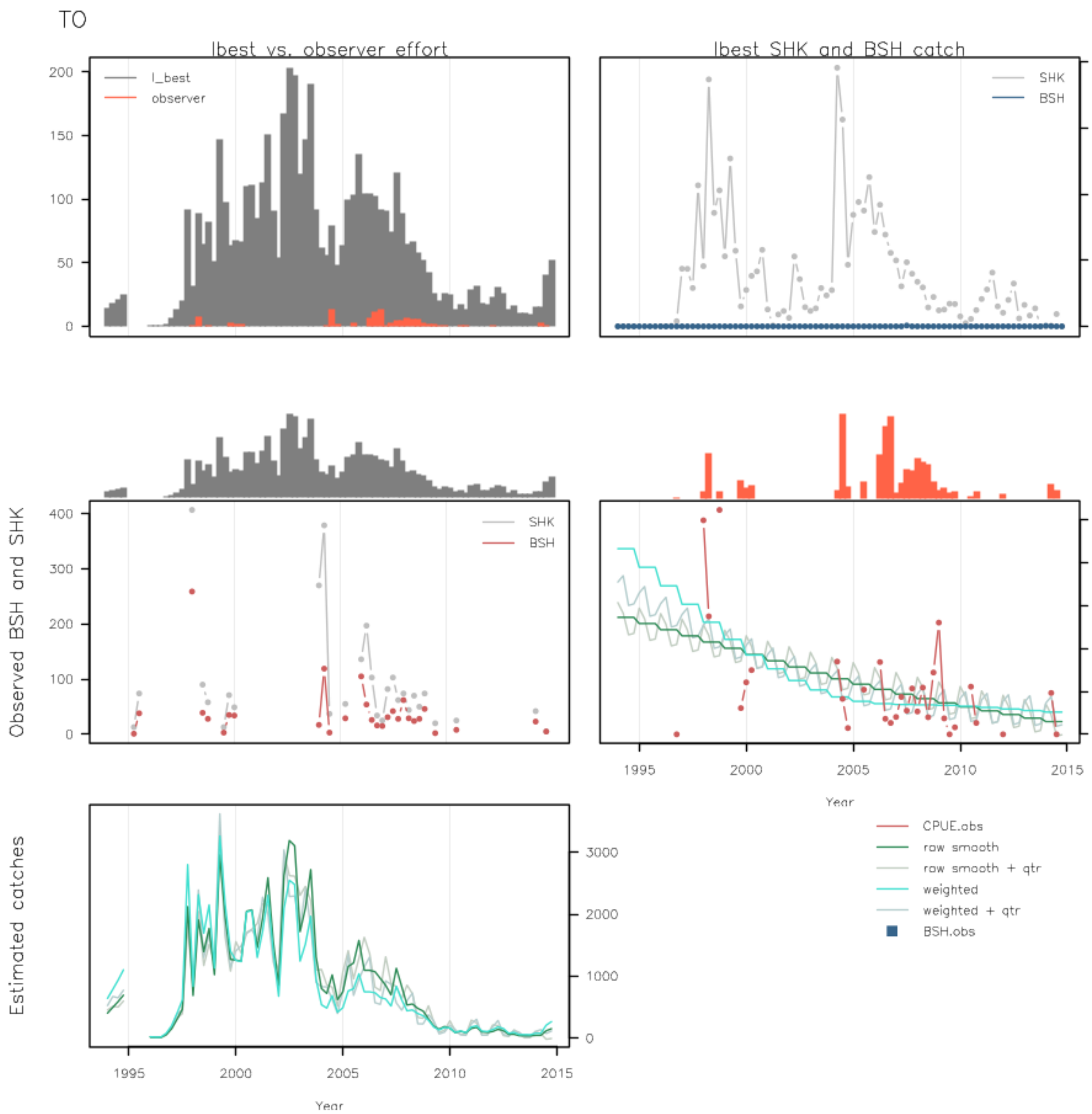

Figure 18: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Tonga. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

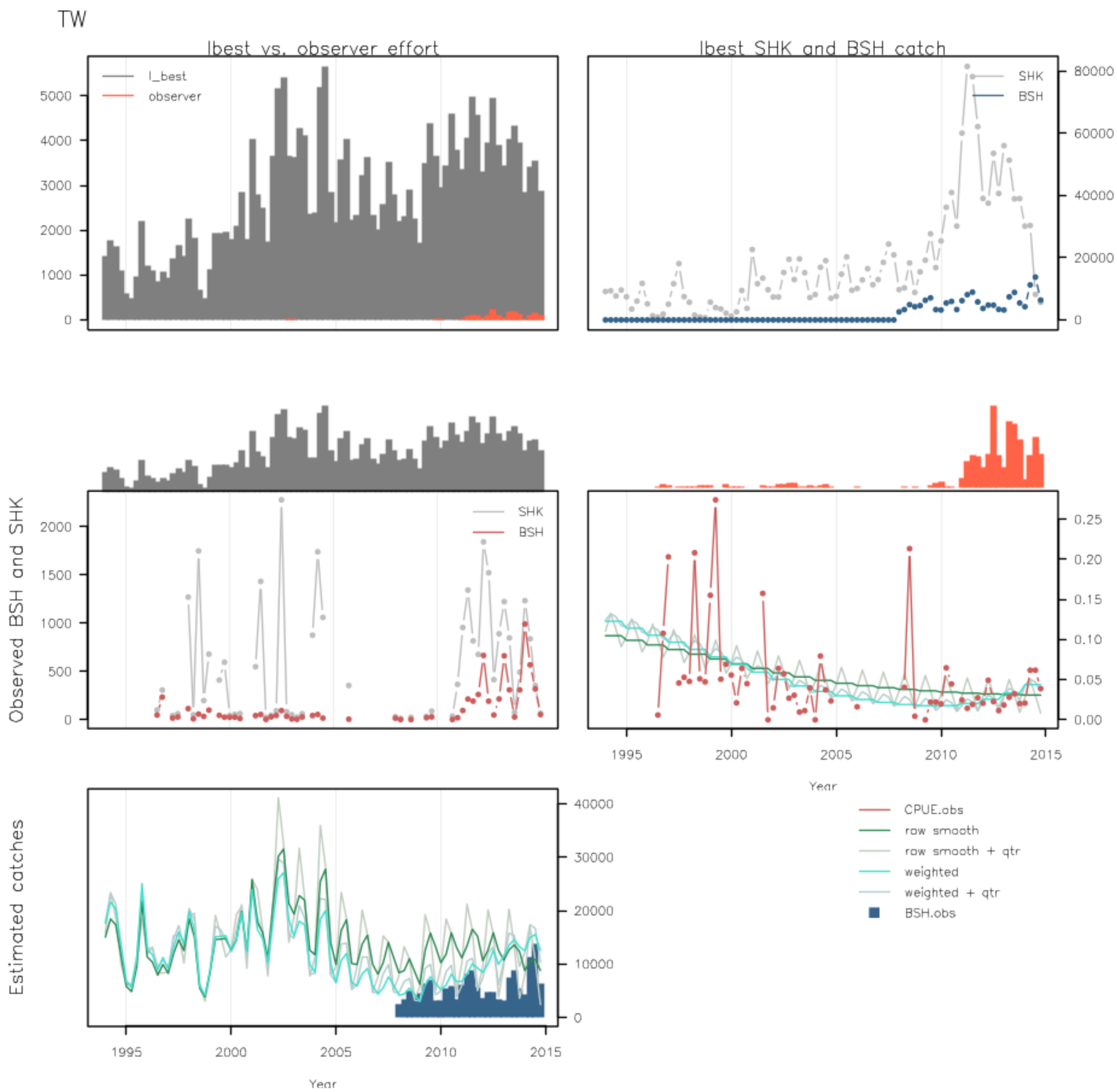

Figure 19: Summary of year-quarter fleet-specific data inputs and results for catch reconstruction scenario 2 for Chinese Taipei. Top: 5×5 raised logsheet effort vs. observer effort in ten thousand hooks (left), 5×5 blue shark and generic catches in individuals (right); Middle: Number of observed blue shark and generic sharks with 5×5 raised logsheet effort in dark grey for scale (left), observed catch rates by year-quarter for the observer program with fitted splined weighted and unweighted by observer effort and with/without the quarter effect, with relative observer effort in red for scale (right); bottom: estimated catches under 4 spline options compared to the observed blue sharks reported in the 5×5 catch database. The final model retained was the weighted spline with the quarter effect.

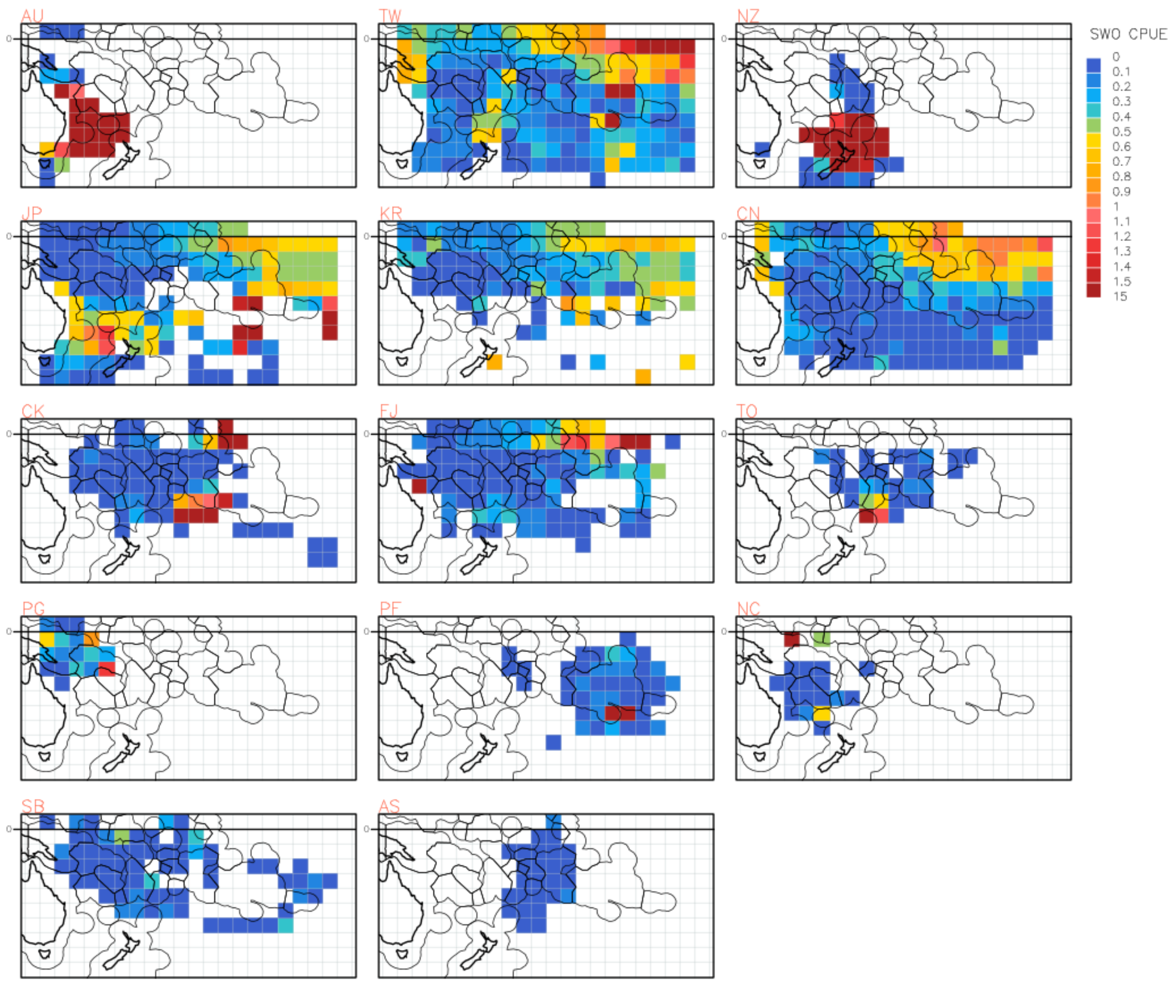

Figure 20: Inputs for catch reconstruction scenario 3, aggregated nominal CPUE, 1994-2014, for swordfish from 5 × 5 degree raised logsheet database, ranked from left to right, top to bottom by total swordfish catches over the time-period.

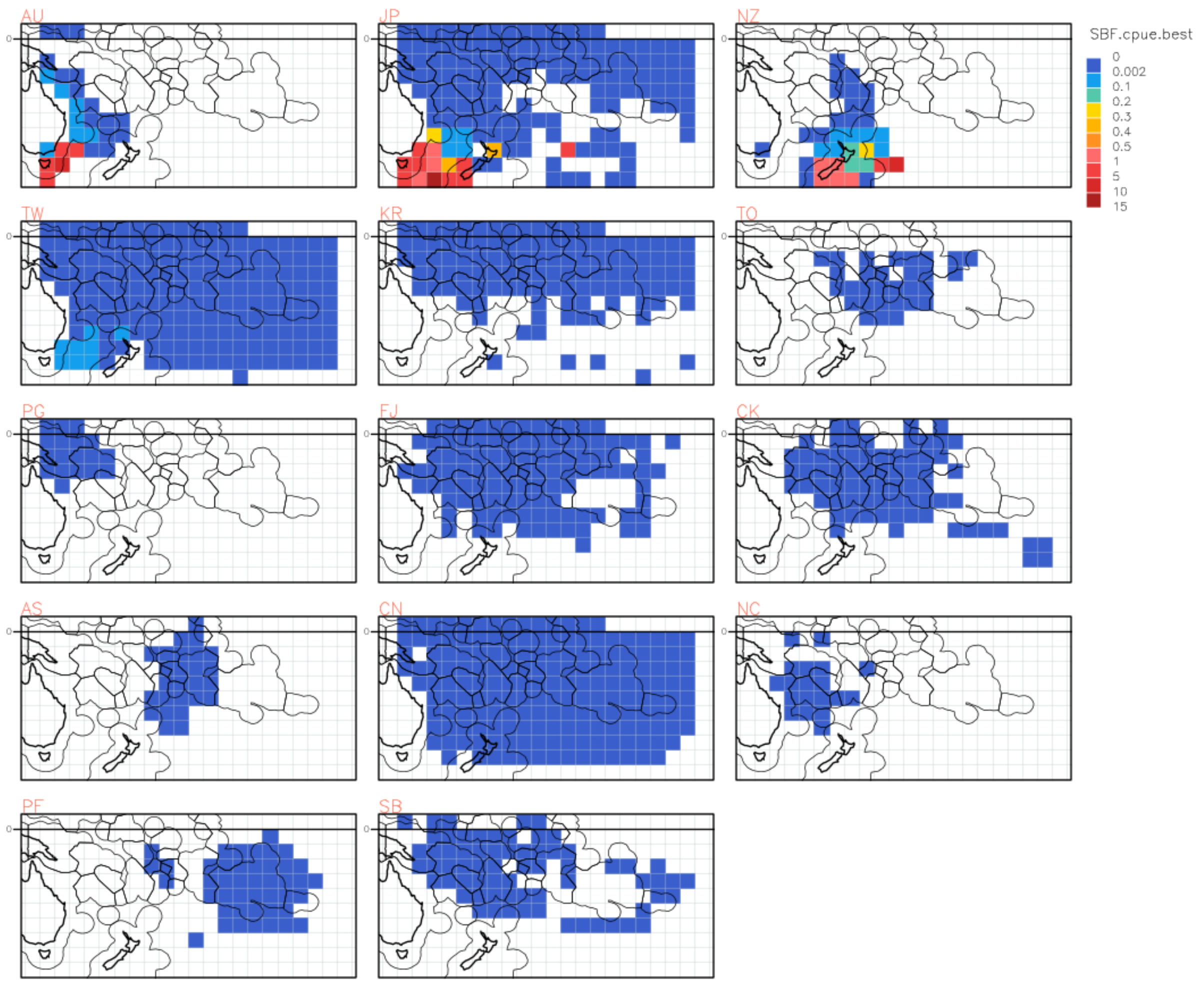

Figure 21: Inputs for catch reconstruction scenario 3, aggregated nominal CPUE, 1994-2014, for southern bluefin tuna from 5×5 degree raised logsheet database, ranked from left to right, top to bottom by total southern bluefin tuna catches over the time-period.

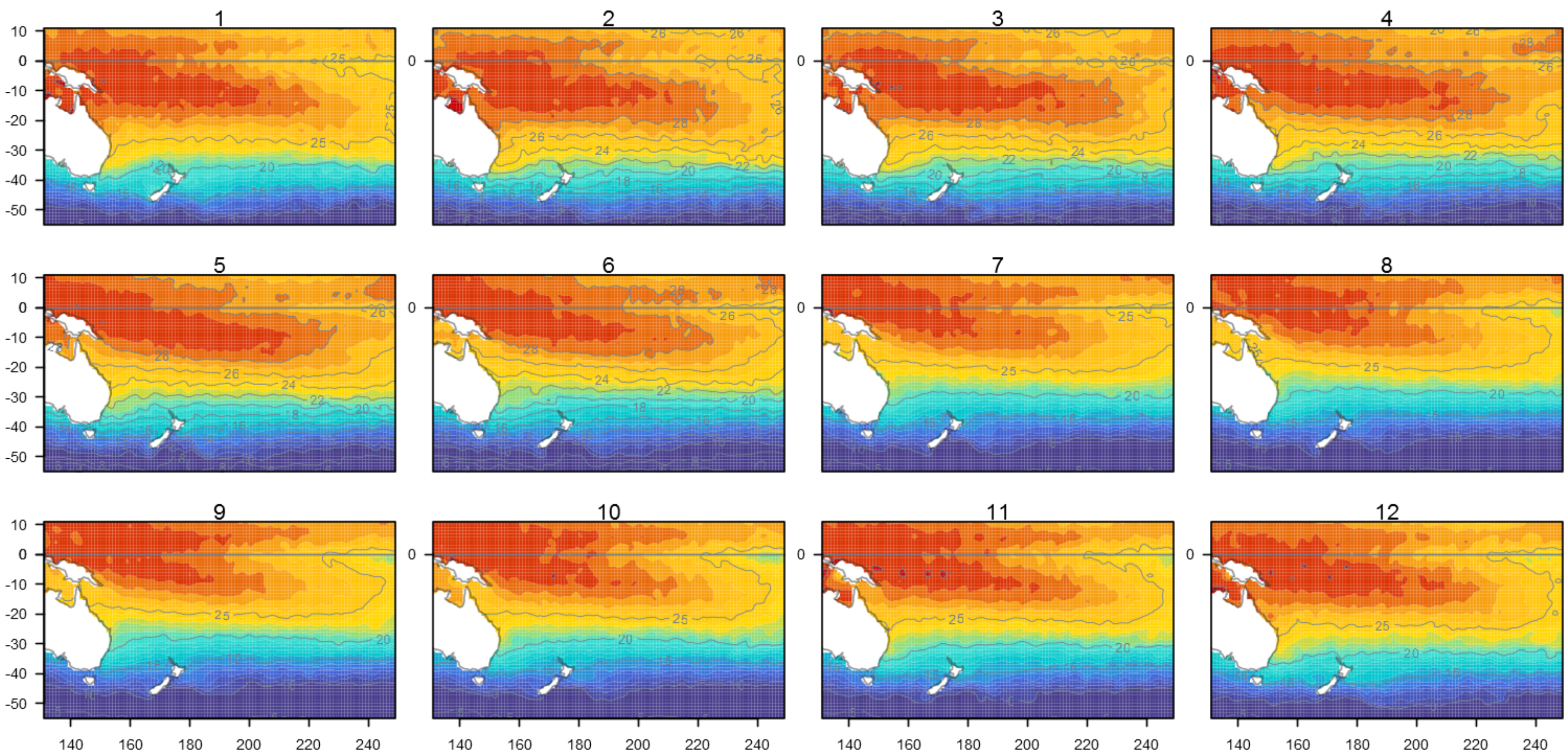

Figure 22: Inputs for catch reconstruction scenario 3, Monthly SST average.

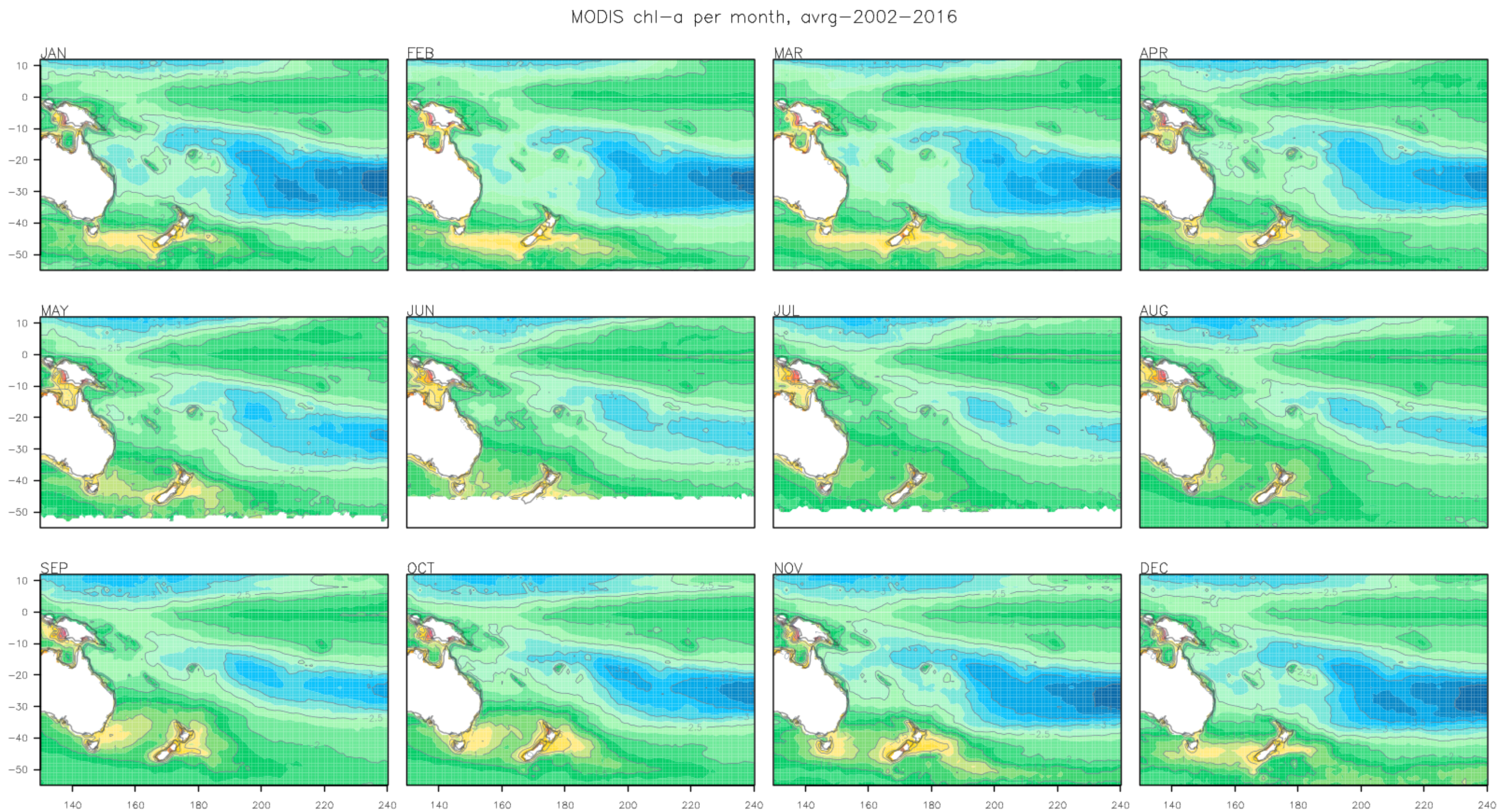

Figure 23: Inputs for catch reconstruction scenario 3, Monthly chlorophyll-a from the MODIS satellite aggregated from 2002-2016.

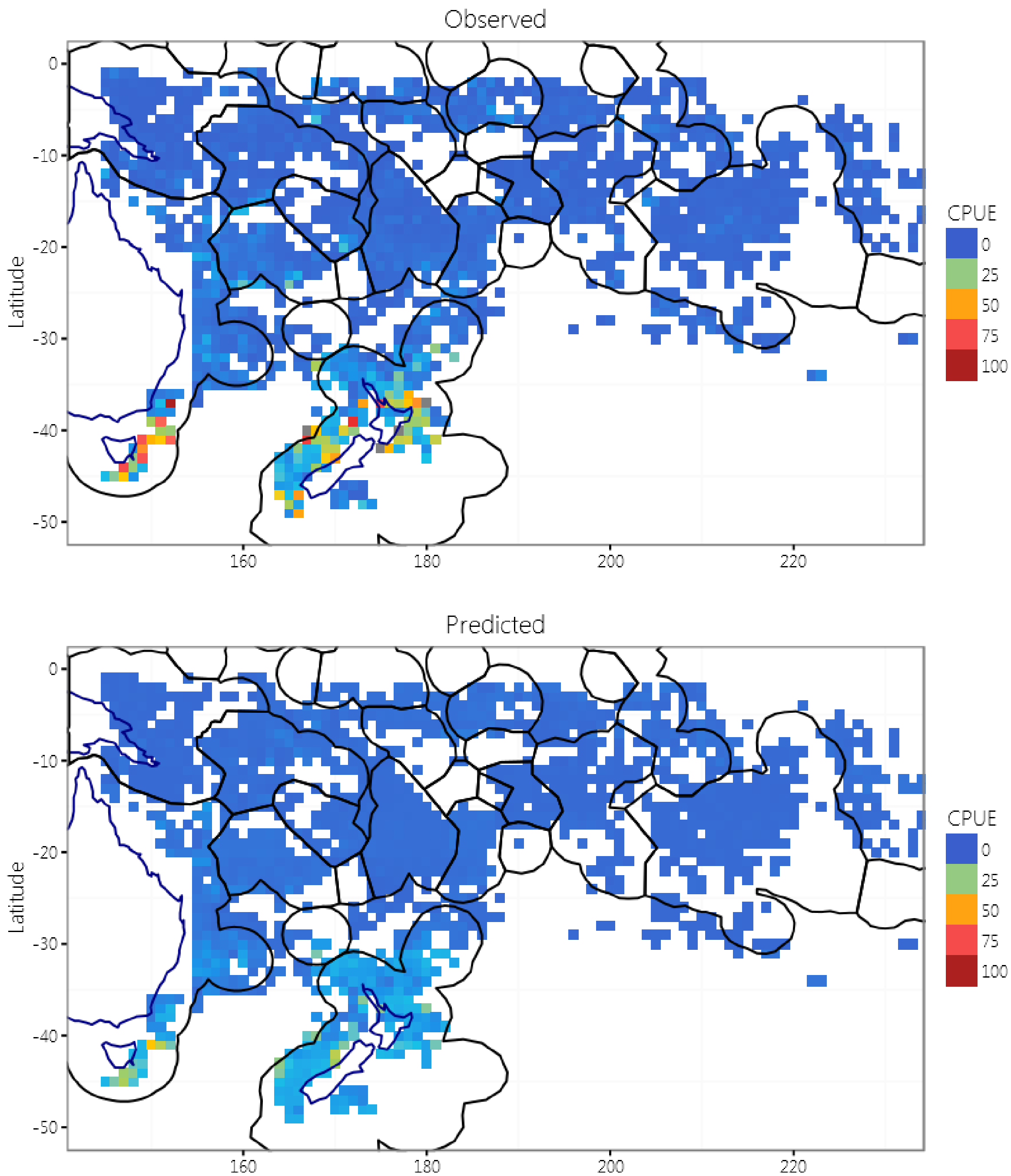

Figure 24: Catch reconstruction scenario 3 diagnostic for the lognormal component, observed vs. predicted blue shark catch rates aggregated by one-degree cells.

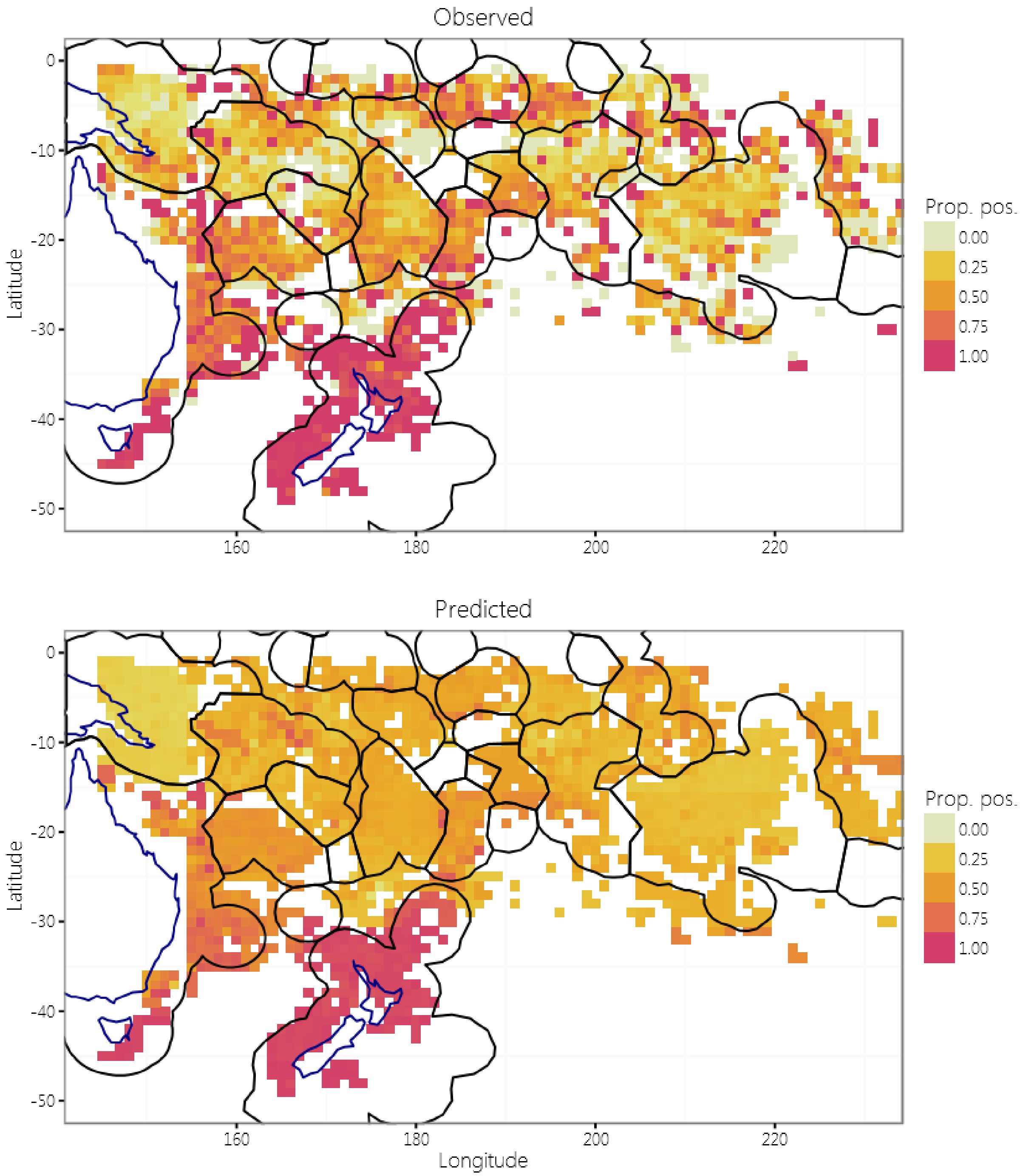

Figure 25: Catch reconstruction scenario 3 diagnostic for the binomial component, observed vs. predicted rates of positive blue shark catch aggregated by one-degree cells.

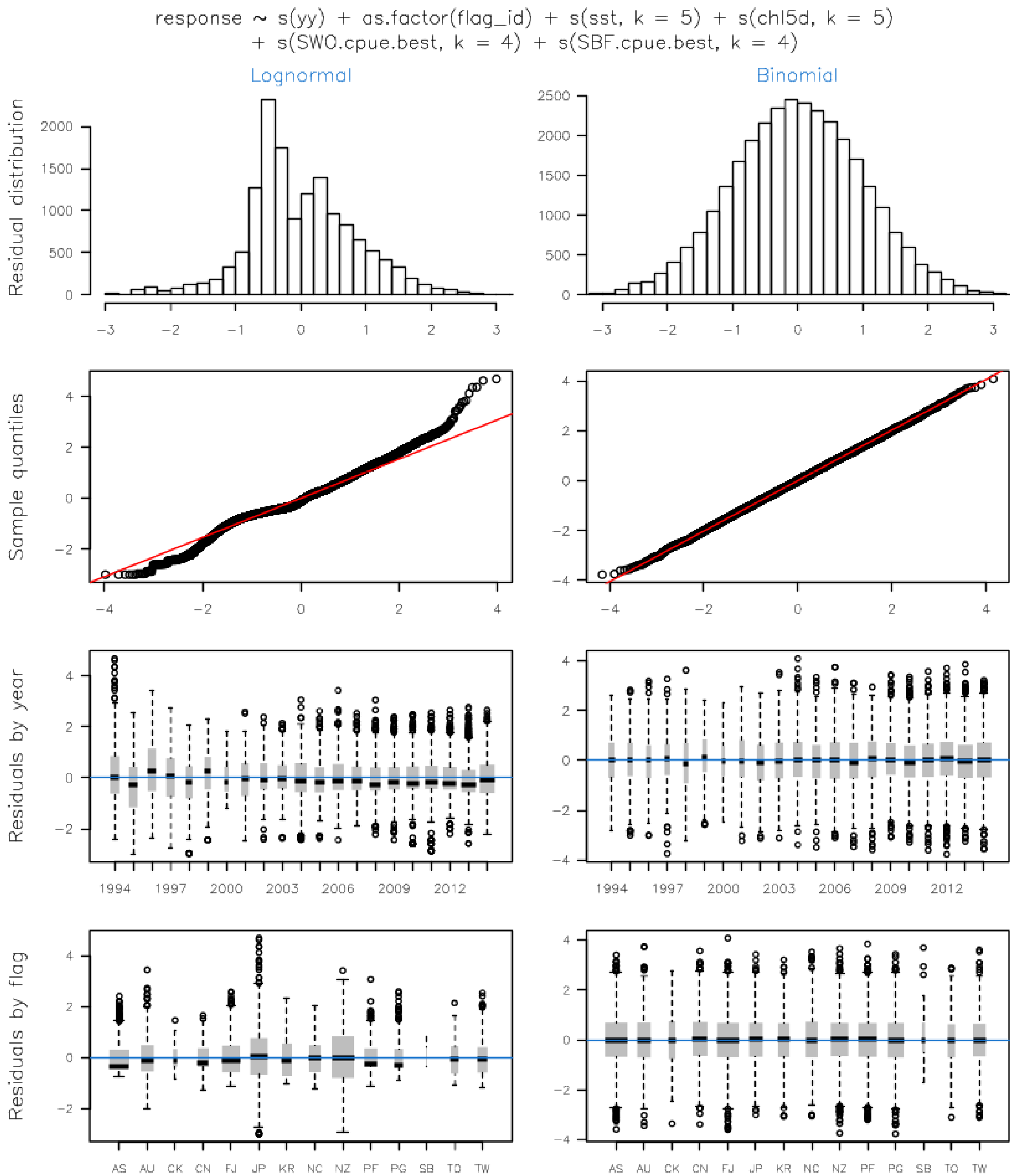

Figure 26: Catch reconstruction scenario 3 diagnostics, key residual diagnostics for the lognormal (left) and binomial component (right), including overall distribution (top), quantile-quantile plot, and distribution by year and flag. Boxplot widths are scaled by the number of records for the levels of the factor.

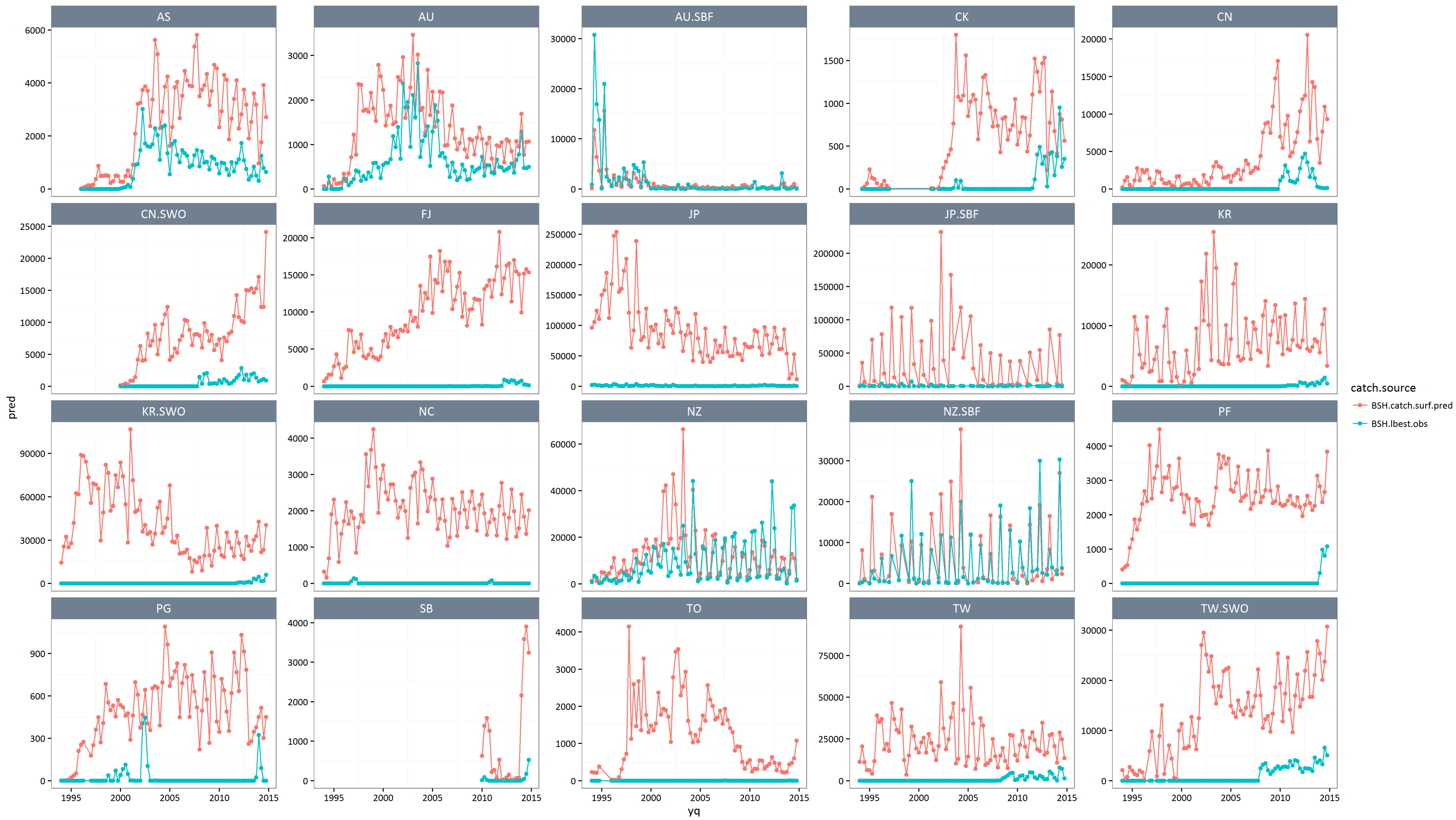

Figure 27: Comparison of predicted catches by fleet and year-quarter for catch reconstruction scenario 3 (red) compared to reported blue shark catches in the 5×5 raised logsheet database (blue).

Figure 28: Comparison of predicted catches by fleet and year-quarter for catch reconstruction scenarios 2 (red) and 3 (green) compared to blue shark catches reported in 5 × 5 raised logsheet estimates.sec:

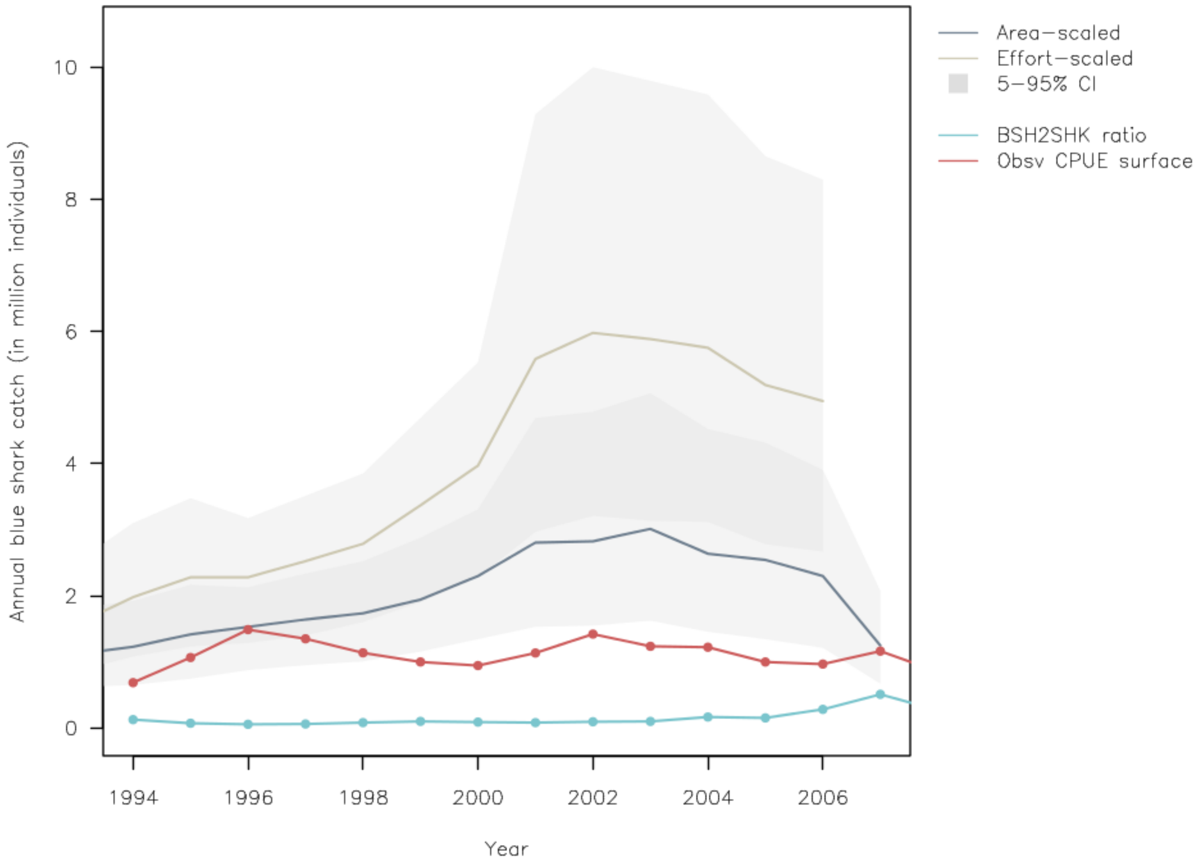

Figure 29: Comparison of predicted trade-based blue shark catches from Clarke (2009) with the two main catch reconstructions developed therein.

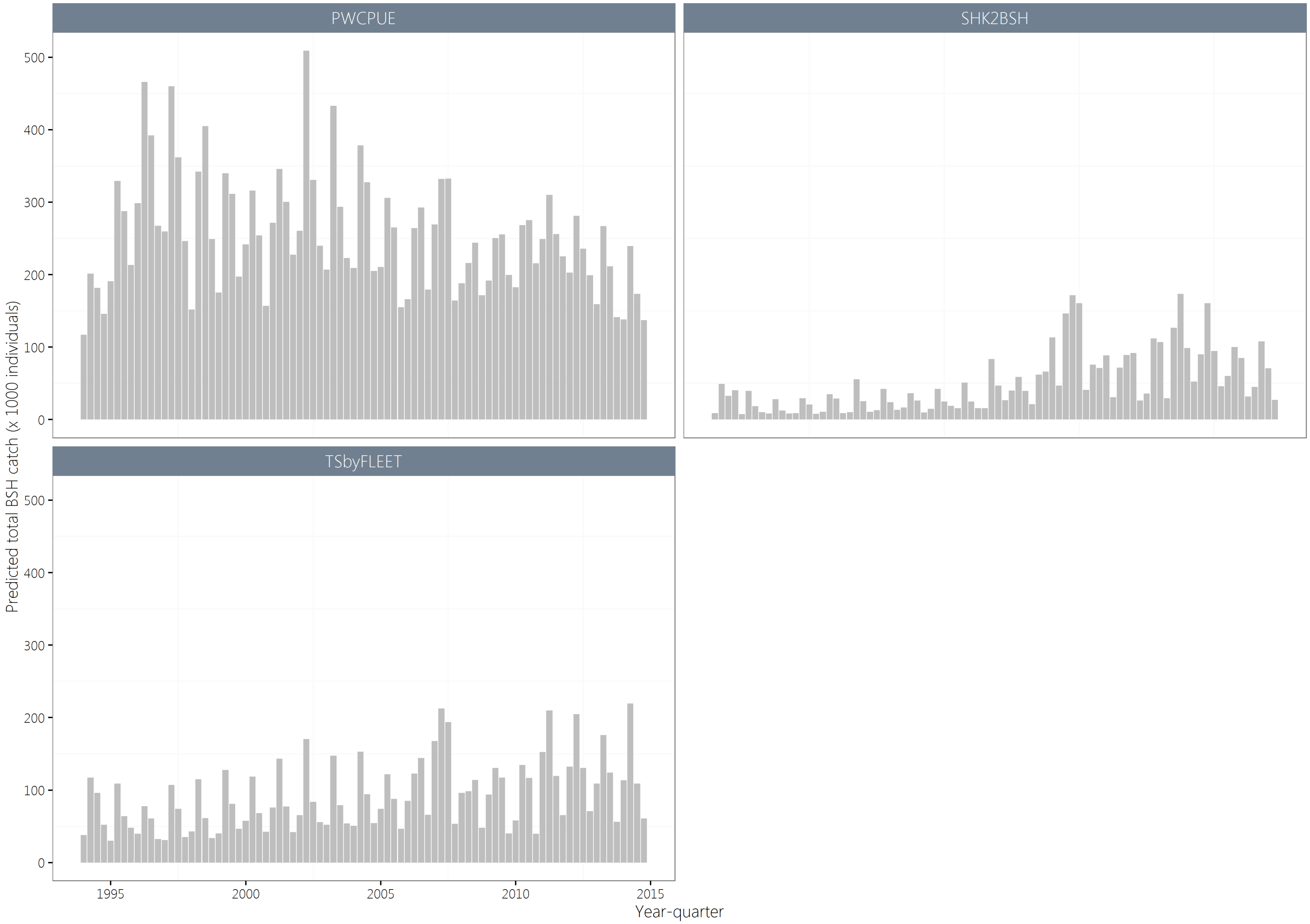

Figure 30: Comparison of predicted total blue shark catches by year-quarter for the three catch reconstruction scenarios, the blue shark to shark ratio (top right), the fleet-specific raised observer time-series estimates (bottom left) and the southwestern Pacific observer CPUE raised catch surface (top left).

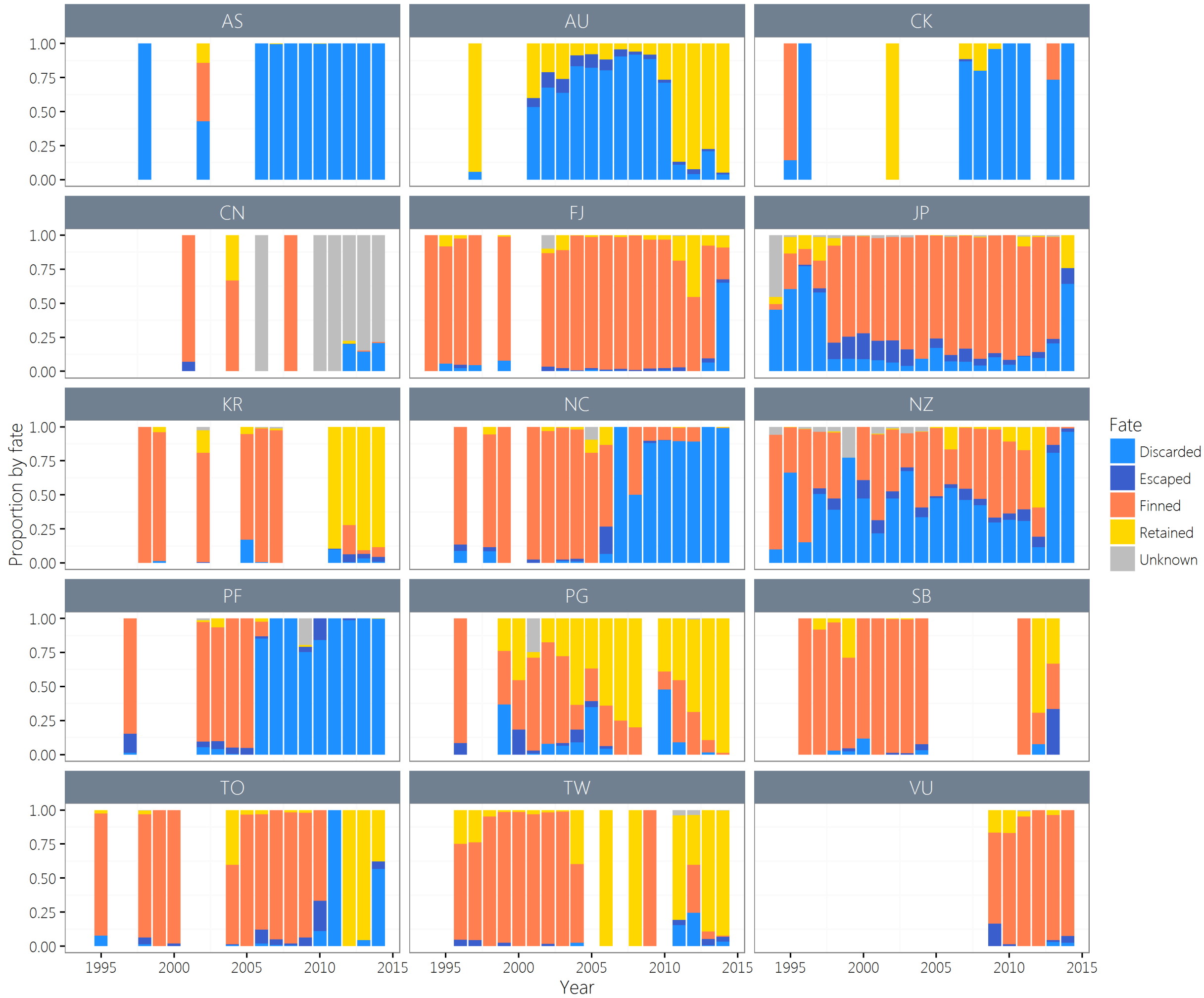

Figure 31: Relative distribution of fates for observed individuals over years for the main flags considered in the assessment.

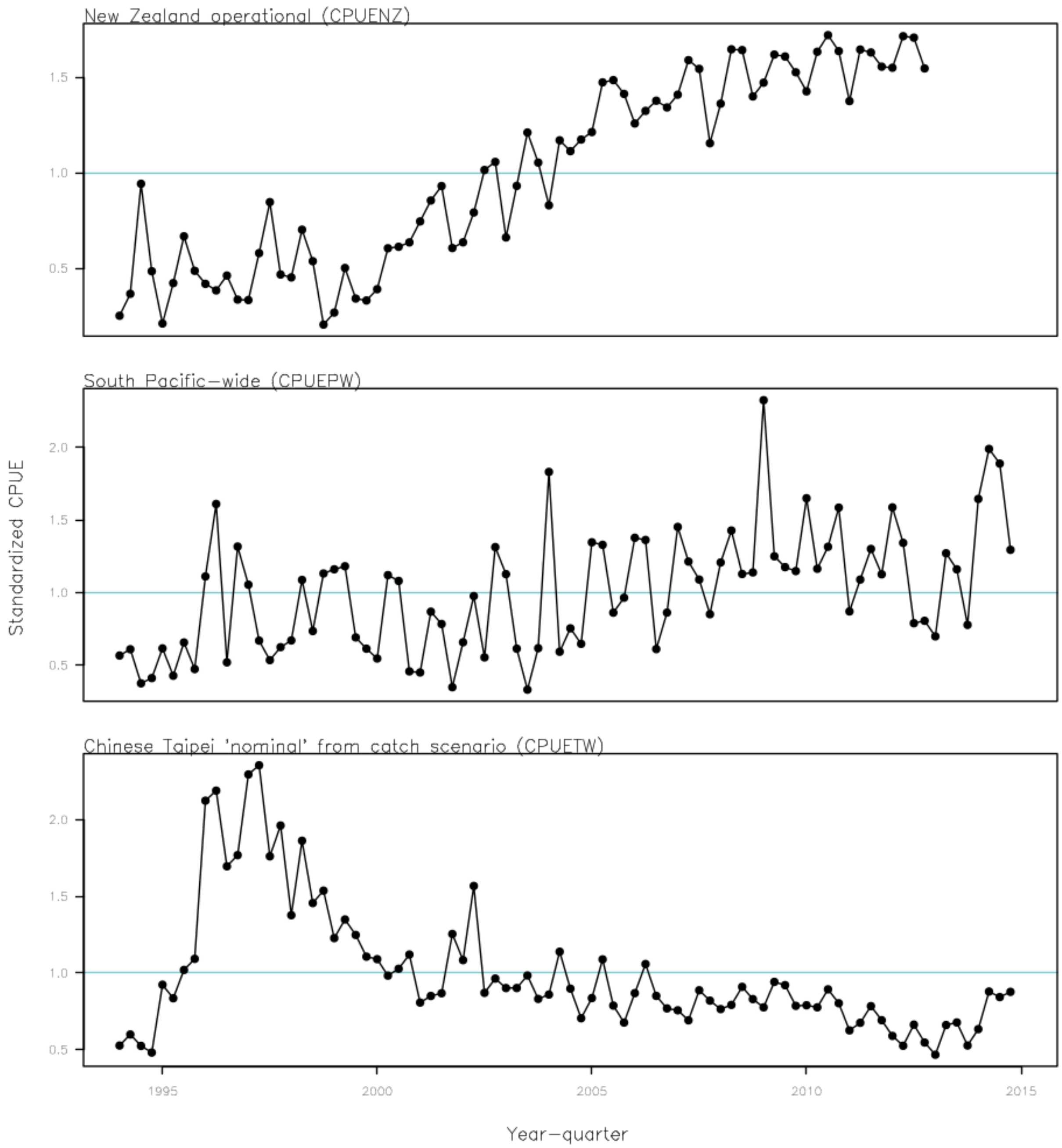

Figure 32: Comparison of abundance trends from the three CPUE standardization scenarios.

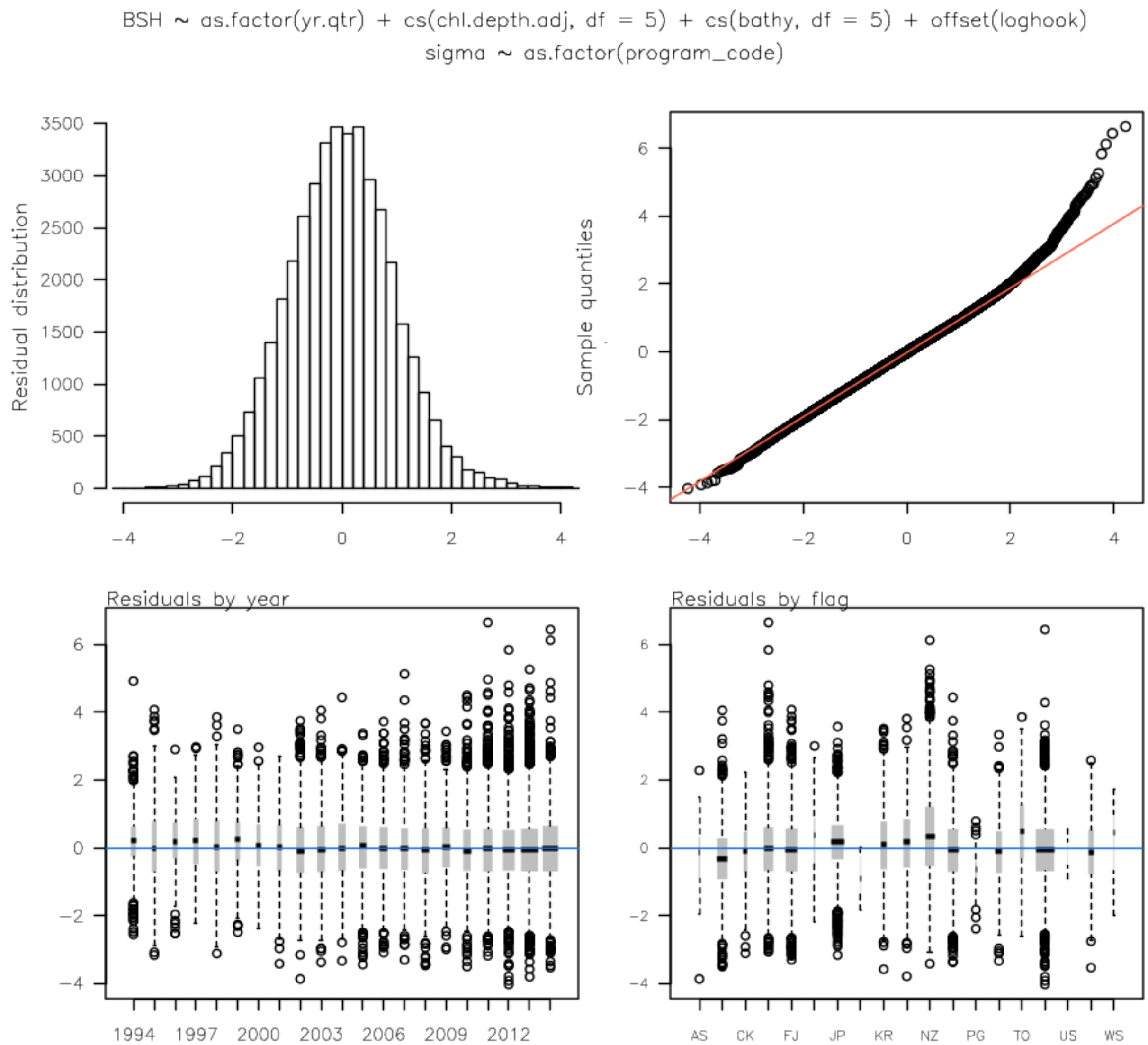

Figure 33: Key diagnostics for the standardization of the South Pacific observer data: residual distribution and quantile-quantile plot, residuals split by year and flag with the width of the box scaled to the number of observation by level.

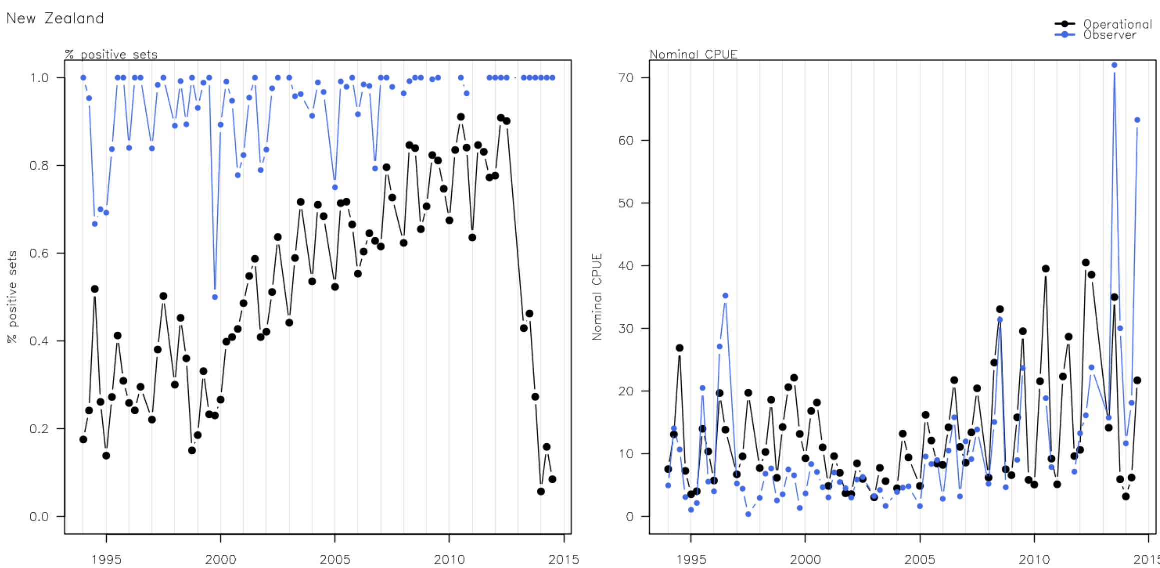

Figure 34: Summary of New Zealand observed (blue) vs. logbook (black) rates of positive blue shark catches (left) and CPUE for positive sets (right).

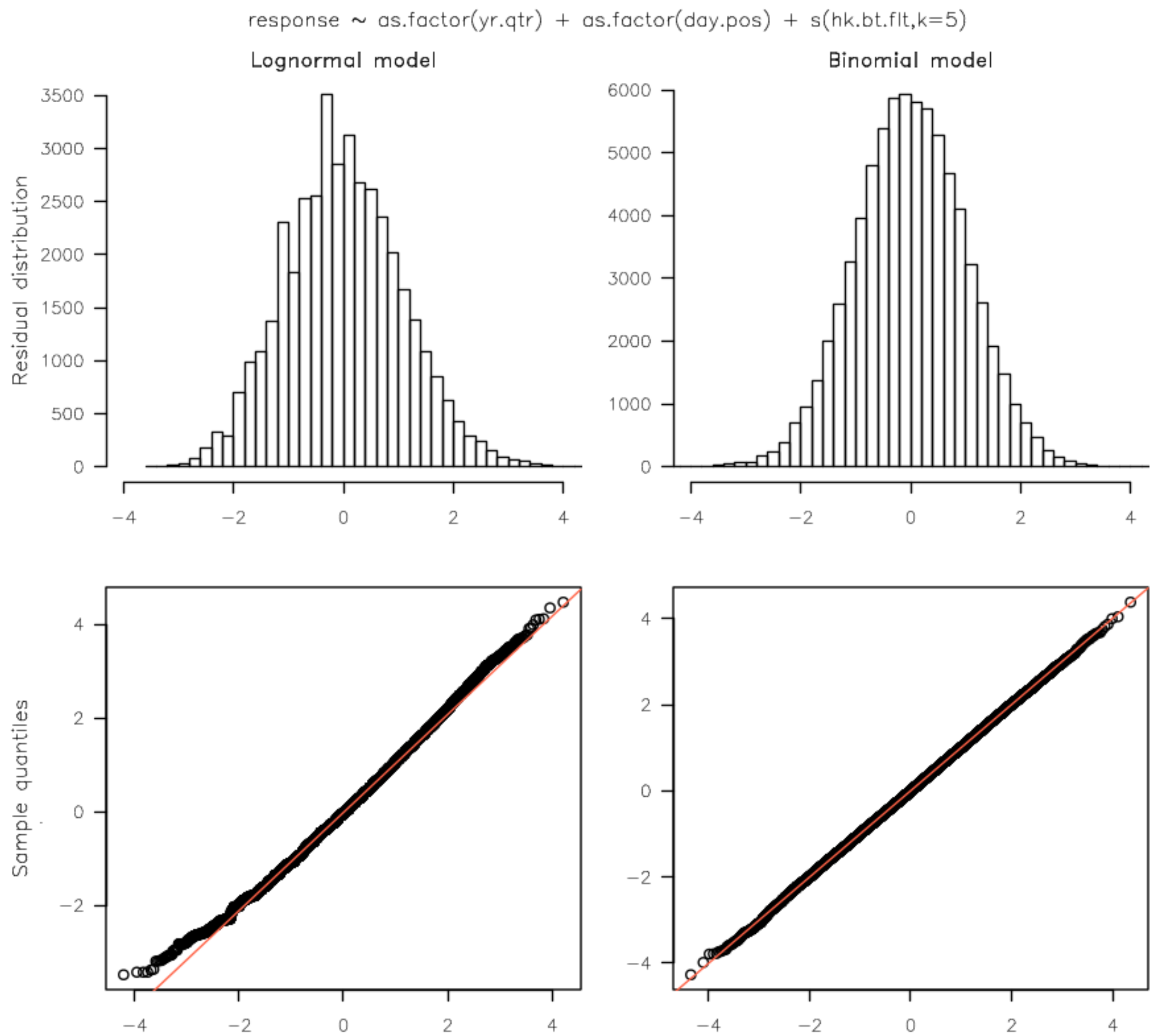

Figure 35: Key diagnostics for the standardization of the New Zealand operational fleet CPUE: residual distribution and quantile-quantile plot for the positive (left) and binomial (right) components of the delta-lognormal model.

Figure 36: Smoothed length-frequency distributions of total length for observed blue sharks over year and by fleet $\times$ observer program for the key fleets with the most records.

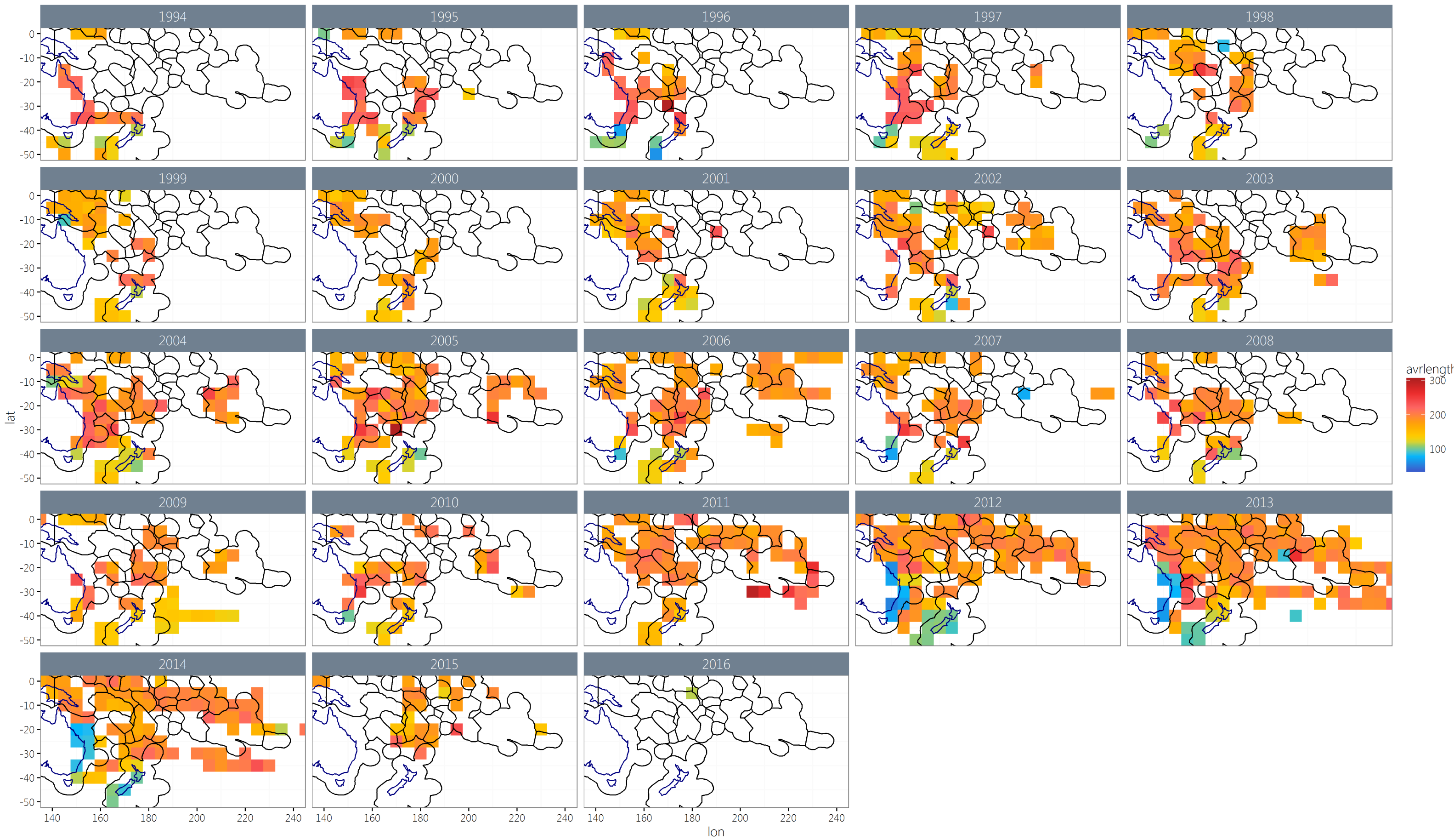

Figure 37: Average observed total length by 5 × 5 degree cells, aggregated over all observer fleets.

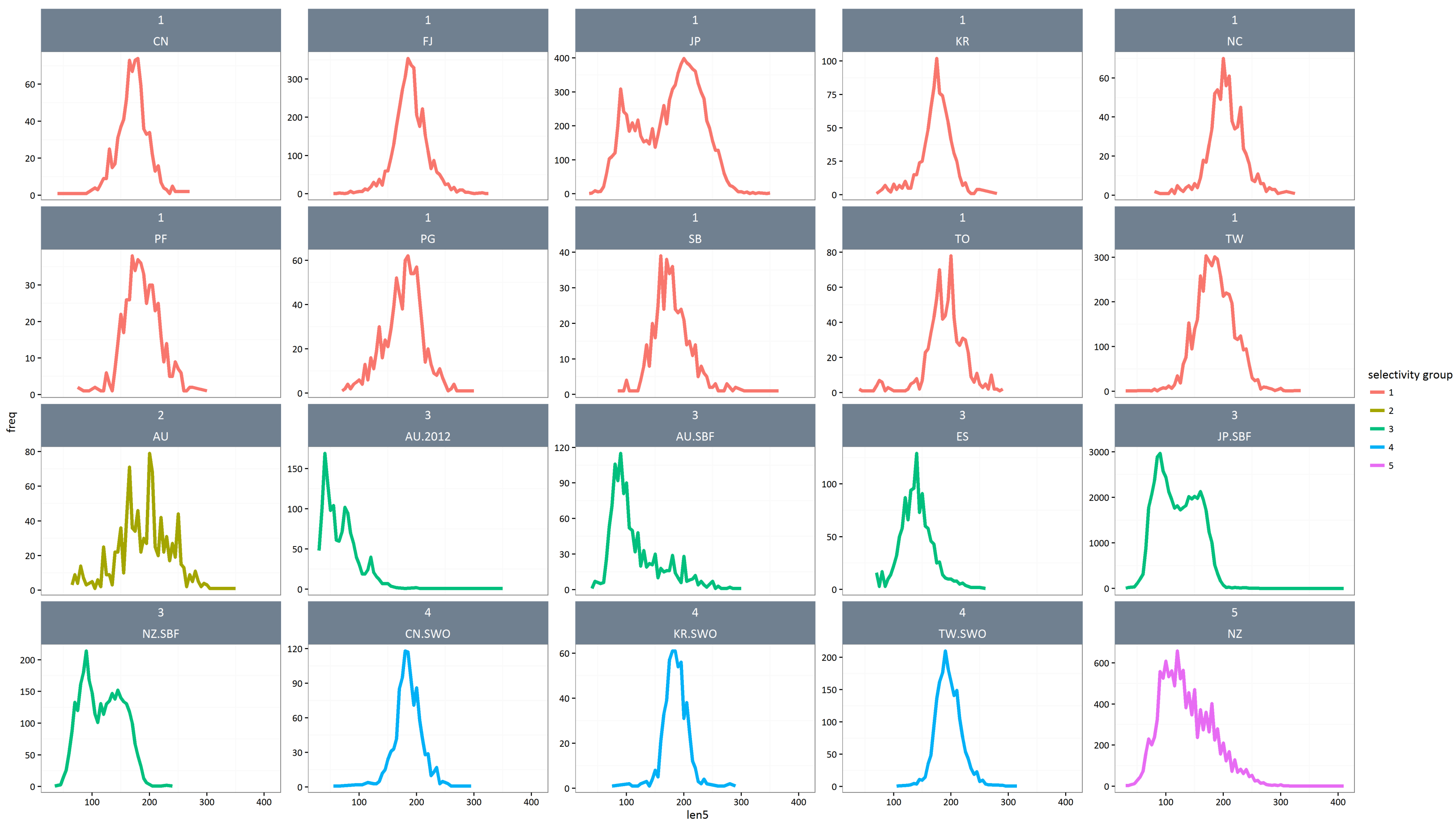

Figure 38: Length-frequency distribution by flag × fleet definitions used in the assessment.

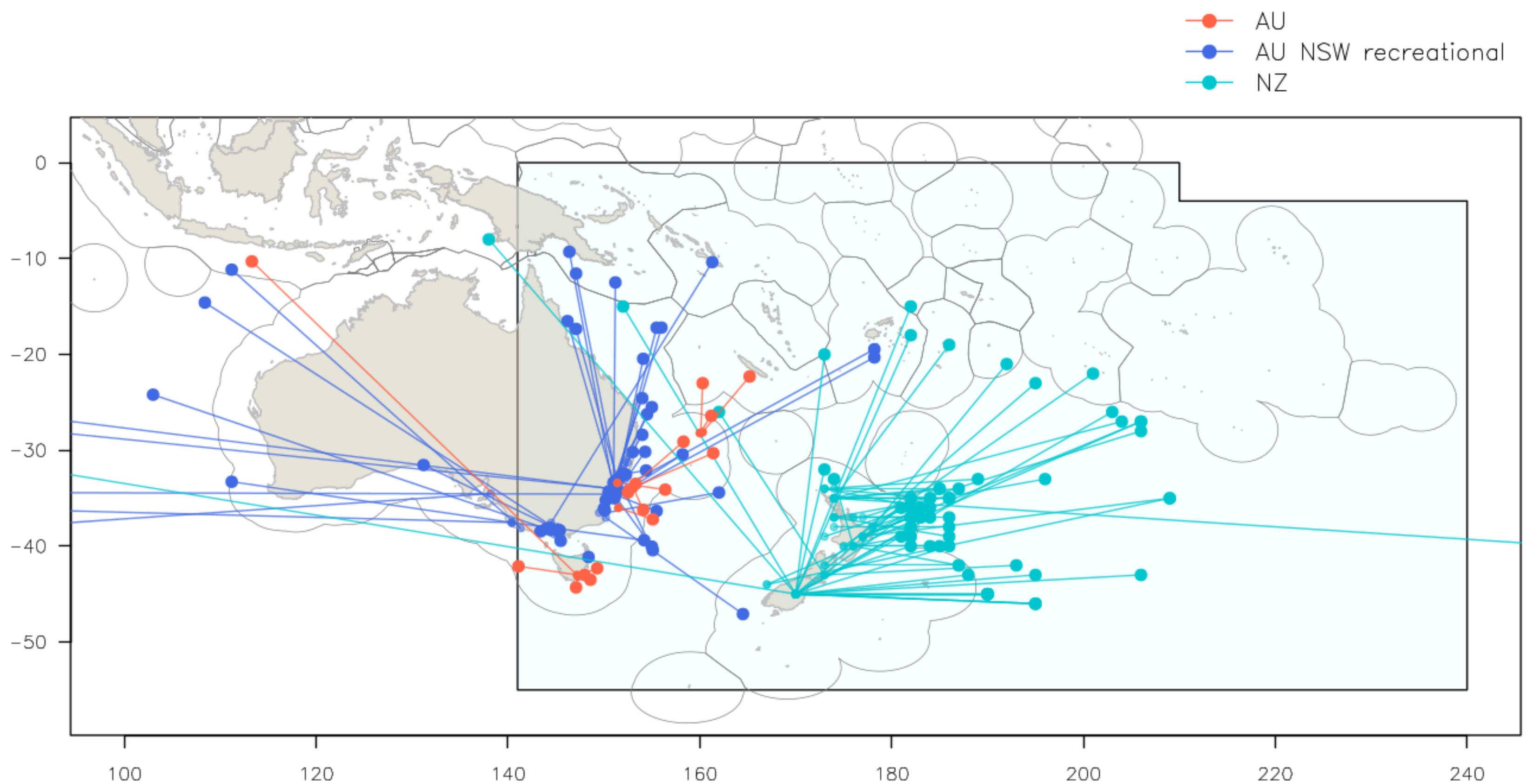

Figure 39: Map of currently available tagging data for blue sharks from the three different sources: Australia CSIRO (red), Australia New South Wales recreational fisheries and New Zealand's NIWA billfish and gamefish tagging programme.