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Estimating Southern Bluefin Tuna Catches by Non-Members of CCSBT

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ESTIMATING SOUTHERN BLUEFIN TUNA CATCHES BY NON-MEMBERS OF CCSBT.

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Executive summary

This paper contributes to determining the probable catch of SBT in other tuna fisheries by parties not reporting catch to the CCSBT, about which there is currently no reliable information. Information on longline fishing effort in the Indian Ocean and the Western Pacific were obtained from the Indian Ocean Tuna Commission and Western and Central Pacific Fisheries Commission. Effort within CCSBT statistical areas reported by cooperating parties (members and cooperating non-members) vs non-cooperating parties was compared between the regional fishery datasets and the CCSBT catch and effort dataset.

In order to obtain a sufficiently large dataset of CCSBT catch and effort data, we converted Japanese catches in number to catches in weight, by modelling fish size patterns in space and time. We then modelled catch rates (in weight per hook) in the CCSBT data in order to estimate expected catch rates by year, month, flag, and 5 degree square. These expected catch rates were combined with reported non-member fishing effort by year, month, and 5 degree square, in order to predict expected catches. The catchabilities of the Japanese and Taiwanese fleets were used with the non-member effort as alternative assumptions.

Introduction

The Extended Commission of CCSBT discussed the issue of “Unaccounted mortality of southern bluefin tuna” in 2013 and requested the Scientific Committee to give advice on the impact of these catches on the rebuild of SBT.

The sources of mortality include:

- Unreported or uncertainty in retained catch by Members, for example:
  - surface fisheries,
  - artisanal catch,
  - non-compliance with existing measures (e.g. catch over-run);
- Mortality from releases and/or discards;
- Recreational fisheries;
- Catches by non-Members;
- Research Mortality Allowance; and
- Any other sources of mortality that the Extended Scientific Committee is able to provide advice on (including depredation).

The objective of this paper is to contribute to determining the probable catch of SBT by non-members of CCSBT in other tuna fisheries that do not report catch to CCSBT. Cooperating non-members do report catch to CCSBT, and in this paper we have grouped them with members in all analyses. To distinguish them in this paper, those reporting catch are referred to as ‘parties’, and those not reporting are referred to as ‘non-parties’. The methods and results in this paper may be compared with those in Chambers and Hoyle (2015), which uses random forest methods to address the same objective.

There is no reliable information available on SBT catch by non-cooperating parties. Information from a number of sources has indicated that a market for SBT exists in China. Although a small amount of catch in this market is supplied by catch from members and cooperating non-members, it may also be supplied with SBT that is not reported to CCSBT, since in 2013 exports were reported to be larger than imports (CCSBT Secretariat 2014).

Analysis of the effort data reported to the IOTC (Indian Ocean Tuna Commission) and WCPFC (Western and Central Pacific Fisheries Commission) shows a large degree of overlap with SBT fishing grounds for these tuna fisheries (Larcombe 2014, and unpublished data). However, SBT catch by non-parties of CCSBT is not reported to WCPFC although these tuna fleets likely take quantities of SBT bycatch in the albacore, bigeye and yellowfin target fisheries. Observer reports presented at the 2014 Scientific Committee of WCPFC showed SBT catch on some trips in the other tuna target fisheries, but only a very small proportion is reported. There may also be bycatch of SBT in pelagic longline fisheries in the south Atlantic.

Methods

Overview of methods

a) Obtain effort by each country targeted at all tuna species for time (months) and area strata (latitude or 5 degree squares).
b) Model size data in order to estimate bycatch in tonnes for member fleets that report catches in numbers only.
c) Fit GLM to aggregated catch and effort data for all fleets, and estimate spatial and temporal covariates contributing to CPUE. Use the results to predict relative CPUE of targeted effort by stratum.
d) Predict total catch based on two alternate assumptions: all non-member effort has the same catchability as estimated for Japan, and all effort has the same catchability as estimated for Taiwan. These fleets represent fisheries in which SBT may largely a target (Japan) or a bycatch species (Taiwan). Estimate potential catch of non-parties by multiplying effort by assumed bycatch rates per stratum, and summing across strata.

Data acquisition and preparation

Non-member catch and effort data for the Pacific Ocean were obtained via the public domain data held by the WCPFC. These data were obtained in 2 formats, which we have labelled PD_agg and PD_flag. 1) PD_agg, downloaded from https://www.wcpfc.int/node/4648, was aggregated across all fleets and flags, and reported by year, month, and 5 degree square. 2) PD_flag, obtained via a data request to WCPFC, was stratified in time and space in the same way as PD_agg, and also grouped by flag. Both public domain datasets omit strata that include fewer than three vessels in order to avoid potential identification (WCPFC 2007), which meant that more data were omitted from the less aggregated dataset PD_flag.

Indian Ocean non-member catch and effort data were obtained from http://www.iotc.org/documents/ce-longline. For IOTC data, in cases when an individual vessel can be identified, the data are aggregated prior to release by time, area or flag to preclude such identification. Thus no catch and effort are omitted from the IOTC dataset in order to avoid potential identification. A small amount of IOTC effort was reported in days rather than hooks, and these were omitted.

The WCPFC western boundary runs from the Australian coast to 55S along the 140E line, then from 55S to its southern limit at 60S along the 150E line (http://www.fao.org/fishery/rfb/wcpfc/en#Org-GeoCoverage). The boundary between WCPFC data and IOTC data includes an area of overlap between 140E and 150E, since the IOTC eastern boundary runs from the Australian coast to its southern limit at

55S along the 150E line (http://www.iotc.org/about-iotc/competence). The IOTC southern boundary is at 45S from 20E to 80E, and at 55S from 80E to 150E.

For these analyses, we used IOTC data for the region of overlap between 140E and 150E, except for statistical area 4 for which we used WCPFC data.

Catch and effort data for parties reported to CCSBT were obtained from the file 'Catch_Effort_2014_July.txt' in the 2014 CCSBT data compilation CD: (SEC_CCSBTDataCD_Interim Update_2014_Revision_2.zip). Data were prepared by extracting all records with gear code longline ('LL'), and removing records with missing values for year or effort.

The Japanese longline size sampling data held by CCSBT were obtained from http://www.ccsbt.org/site/sbt_data.php. Data were prepared by extracting only the records with gear code 'LL', and by removing records with class precision > 2 cm. The average length in each length class was assumed to be the middle value, i.e. 107.5 cm for a fish in the length class 108 with class precision of 1 cm, since the label indicates the upper end of the length class. Analyses that included size frequencies used the adjusted frequencies.

In CCSBT data, the latitude and longitude numbers indicate the north-western corner of a grid square, while in the WCPFC data they indicate the south-western corner. For IOTC data, they indicate the corner closest to 0 latitude and 0 longitude. In this paper all spatial data are managed at the 5 degree square level, and all latitudes and longitudes have been converted to indicate the centre of the grid square.

Length-weight relationships for southern bluefin tuna were based on the length to processed weight conversion factors agreed at the 1994 SBT Trilateral Workshop on Age and Growth, 17 Jan - 4 Feb, 1994, with the formula $Processed\ weight = A \times Len^B$ (Table 1). Weights were converted from processed to whole weight by adding 15%, as agreed at the 1994 workshop. Juveniles were defined as less than 130 cm, adults as greater than or equal to 130 cm.

Analyses

We loaded the CCSBT data and plotted the spatial distributions of reported effort and SBT catch by parties, in order to identify areas in which significant catch might be taken by non-parties. We also loaded the regional (WCPO and IO) catch and effort data.

We compared the reported effort by parties between the CCSBT and the regional datasets, by dividing regional (PD_flag and IO) effort by CCSBT effort for each year since 1990, for each CCSBT statistical area. Statistical areas 4 and 7 cross the boundary at 150E so appear in both the IOTC and WCPFC data, but only the appropriate CCBST locations were compared for each statistical area. Comparisons were also made after further grouping by flag.

In order to estimate the amount of data lost in the WCPO due to the three-vessel rule, we compared the effort in the PD_agg and PD_flag datasets by year since 2000. We divided total catch per year in PD_flag by the equivalent total in PD_agg, first for sets in the WCPO south of 30S and west of 170W so as to be inside the CCSBT statistical areas 4-7, and secondly for sets in the WCPO south of 30S and east of 170W, so as to be within CCSBT statistical area 12, but south of 30S where catch rates may be appreciable.

In order to determine the distribution of potential unaccounted mortality, the spatial distribution of the effort was mapped separately for parties and non-parties of CCSBT for the areas of interest, which was south of 30S in the Pacific Ocean, and south of 25S in the Indian Ocean. We summed the total effort in thousands of hooks by 5 degree square for the years 2001-2012, and plotted the average annual effort. We also examined both the proportion and the sum of effort reported by non-parties through time by statistical area.

The objective was to predict non-member catches in weight by multiplying non-member effort (in hooks) by expected catch rates (in weight per hook). These expected catch rates would be estimated from the catch and effort data provided by parties. We considered Japanese catch and effort data to be essential for determining expected catch rates, because of the spatial and temporal coverage of the Japanese fleet, and their relatively consistent fishing methods. However most of the Japanese data report catch numbers but not weight, which made it necessary to convert the catches in number to catches in weight. To estimate catch weights we multiplied catch in number by the expected size distributions, which we determined from the Japanese length frequency sampling data held by CCSBT.

Testing the relationship of catch with mean weight

This approach assumes that mean weight and catch size are independent, and so we tested the assumption. There was no information with the Japanese size sampling data to indicate the size of the catch, but both catch weight and catch number are available for many catch and effort data records (Australia (AU) 20%, Japan (JP) 0.4%, Korea (KR) 99%, New Zealand (NZ) 39%, Taiwan (TW) 27%, South Africa (ZA) 99%). We calculated mean weight as equal to weight_retained/number_retained in the CCSBT catch and effort. We applied a generalized additive model using package mgcv (Wood 2011) implemented in R 3.2.1 (R Core Team 2014), to model mean weight as a function of year, month, statistical area, flag, and number retained, using the CCSBT catch and effort dataset for the Indian Ocean (Equation 1). We transformed mean weight by taking the square root, to normalize residuals.

$$mean\ weight^{0.5} \sim year + month\_area + flag + s(\log(number\ retained)) \qquad (1)$$

Year, month-area, and flag were modelled as factors, with month-area formed as the combination of month and statistical area. Number_retained was modelled using a smoother. To observe the potential relationship between number_retained in a stratum and mean size, we plotted the predicted mean weight for Japanese catches in statistical area 2 across all months.

Estimating mean weight per stratum

The next step was to estimate mean sizes for all spatio-temporal strata, in order to convert catch numbers into catch weights for the Japanese data. For these analyses we used the CCSBT size data from Japan, and ran the analyses separately for the Indian Ocean and the Pacific Ocean. Before estimation, the length frequency data were converted to weight frequency based on the length-weight relationship, as described earlier.

We separated the CCSBT data into Indian Ocean and Pacific Ocean components, and modelled each dataset separately. We stratified the converted weight frequency data in each dataset by year, month, and statistical area. Mean weights were estimated for all strata in two stages: first, strata with total adjusted frequency of at least 100 were assigned the observed mean weight. Second, strata with adjusted frequency of fewer than 100 fish were assigned an expected mean weight, based on modelling.

The original size data format had one row per stratum x length, with a field to indicate frequencies. Before modelling, the format of the weight frequency data was changed to facilitate the generation of diagnostics, with one row per individual frequency. The frequencies were reduced by a factor of 10 for the Indian Ocean data and 4 for the Pacific Ocean data, to permit analysis within the available computer memory.

Fish weight was modelled as a function of year, month, and statistical area (Equation 2) with a generalized linear model implemented in R 3.2.1 (R Core Team 2014). All available Japanese weight frequency data were included in the model.

$$Weight \sim Year + month\_area \qquad (2)$$

The month and the statistical area were combined into a categorical variable 'month-area' to avoid problems with interaction terms, since there were different amounts of data across months in different statistical areas. The model assumed that inter-annual variation was consistent for area-month combinations. There were statistically significant interactions between year and month-area effects, but these were ignored so as to be able to predict sizes for sufficient strata. Applying a square root transformation to the weights normalized the residuals.

The fitted model was used to predict mean transformed weights for each stratum. Due to the distribution of the data and the square root transformation, back-transformed nominal mean weights tended to be lower than the true mean. We removed this bias by, for each stratum, sampling 2000 residuals with replacement and adding them to the predicted mean to generate 2000 parametric bootstrap samples, back-transforming by squaring the samples, and taking the mean of the back-transformed samples as the predicted weight for the stratum. Estimates were unavailable for several month-by-area combinations that lacked size sampling data, and were copied from other months for the same statistical areas.

For all CCSBT effort that reported SBT catch in retained number but not weight, expected retained weights were calculated by multiplying retained numbers by expected mean weights for the appropriate stratum.

In order to examine the results of the estimation process, we used the same approach to predict retained weights for CCSBT effort that reported catch in both numbers and weight. We plotted these results by flag, with observed weight plotted against predicted weight.

CPUE standardization and catch prediction

Catches were predicted by estimating expected catch rates per stratum from the CCSBT member data, and multiplying by non-member effort. As with the weight analyses, these analyses were conducted separately for Indian Ocean and Pacific Ocean data.

CPUE analyses indicated that there was variation associated with location, fleet, year, and season. However, catch rates could not be estimated for all areas where SBT catch has been taken in the past, due to low member effort in some locations. Reported effort by CCSBT parties declined rapidly to the east of New Zealand (Figure 2). Subsequent analysis of the spatial patterns of catch rate using generalised linear models (see below) did not suggest that catch rates to the east of New Zealand are substantially lower than further east, but catch from these areas was assumed to be negligible.

Catch rates for parties in CCSBT data were analysed separately for the Pacific and Indian Ocean. For the purposes of these analyses the Indian Ocean was defined as CCSBT statistical areas 1, 2, 3, 7, 8, 9, 13, and 14, and the Pacific was defined as CCSBT statistical areas 4, 5, 6, 7, and 12, with statistical area 7 to the west of 150E included in Indian Ocean analyses, and to the east of 150E included in Pacific analyses.

Catch rates were estimated using generalised linear models fitted to year-quarter, month, flag, 5 degree square, and a cubic spline f() fitted to the number of hooks. We applied two approaches. The first (Model 1) included all data and fitted the CPUE with a lognormal distribution, after adding a constant *K* to avoid errors when catches were zero.

$$\log\left(\frac{wt_{retained}}{hooks} + K\right) \sim yq + ns(mm, df = 4) + flag + latlong \qquad \text{Model 1}$$

The model was fitted to categorical variables year-quarter (*yq*), flag, and 5 degree square ('latlong'), and with a cubic spline ns() with 4 degrees of freedom fitted to the continuous variable month (*mm*). The constant *K* was defined as 10% of the mean CPUE, where CPUE was retained weight / hooks.

Secondly, we applied a modified delta lognormal approach (Models 2a and 2b). This approach involved first modelling the probability of nonzero catch with a binomial glm, and then modelling the distribution of CPUE for nonzero catches with a lognormal model (Lo *et al.* 1992).

$$\mathrm{wt}_{\mathrm{retained}} > 0 \sim yq + ns(mm, df = 4) + flag + latlong + ns(hooks, df = 4) \qquad \text{Model 2a}$$

$$log\left(\frac{\mathrm{wt}_{\mathrm{retained}}}{hooks} + K\right) \sim yq + ns(mm, df = 4) + flag + latlong \qquad \text{Model 2b}$$

In this approach hooks was included as a predictor for the delta model, fitted as a cubic spline with 4 degrees of freedom, because strata with more effort were expected to be more likely to include non-zero catch. However it was not appropriate to use the number of hooks set as a predictor for the positive model when working with aggregated data. In order to normalize residuals in the positive glm, we modified the usual lognormal approach by adding a constant *K* to the response variable. *K* was calculated as 10% of the mean of positive catches.

To estimate non-member catches we predicted CPUE based on the equivalent variables in the data from IOTC and WCPFC, by using the 'predict.glm' function in R. We back-transformed the predictions from Model 1 and Model 2b to the nominal scale by exponentiating and subtracting *K*. Given the lognormal distribution of the response variables, we added a bias correction factor of ½ the estimated variance to the predicted CPUE from Model 1 and Model 2b. CPUE for the delta lognormal models was predicted by multiplying the predicted probability of positive catch from Model 2a by the predicted catch rate from Model 2b. Catches were predicted by multiplying predicted catch rate by observed effort.

We checked the estimates by predicting catches for member fleets using the CCSBT input data, and comparing them with reported catches. We also plotted average catch rates.

Results and Discussion

Reported effort by CCSBT parties declined rapidly east of New Zealand (Figure 2). In the WCPO, the majority of SBT catch was taken south of 30S, within the CCSBT statistical areas 4-7 (Figure 3). Significant member effort was reported throughout the Indian Ocean, but the majority of the catch again occurred south of 30S. However there was also significant catch between 25S and 30S.

Reported effort for parties was similar but not identical for most statistical areas in the WCPO and the CSSBT datasets (Figure 4). WCPFC effort was consistently lower than CCSBT effort in statistical areas 4 and 7, but more similar in statistical areas 5 and 6. Much more effort was reported to the WCPFC than to the CCSBT for statistical area 12, which was outside the CCSBT core area. In the Indian Ocean, more effort was reported to the CCSBT than the IOTC in most years in the southern statistical areas 7, 8, and 9, while more effort was reported to the IOTC in the more northern statistical areas 2, 13, and 14.

Disaggregating these ratios by flag indicated that consistency between the datasets varied among flags, and by statistical areas within flag (Figure 5 and **Error! Reference source not found.**).

In order to estimate how much WCPO data may have been lost due to the three-vessel rule, we compared the effort in the PD_agg and PD_flag datasets for each year since 2000. Within statistical areas 4-7 the proportion of effort included in the PD_flag dataset has declined since 1990 and in 2012 was approximately 80% of PD_agg (Figure 6). The remaining 20% has been removed due to the three vessel rule, which dictates that data can only be reported for strata that include effort from at least three vessels. However, non-member effort is higher in areas where member effort is low (Figure 7). The proportion of effort reported east of 170W has declined by more than 20%, and in 2012 was about 55% of the effort in the aggregated dataset (Figure 6). Due to the three-vessel rule, the aggregated dataset will also be underreporting the actual level of effort, and the level of underreporting is unknown. The results of these analyses have been affected by the difficulty of obtaining reliable WCPFC data.

In the Indian Ocean the spatial distributions of IOTC-reported effort by parties and non-parties were relatively similar (Figure 7), although there was no reported non-member effort to the south of Australia during the period examined (2001-2012). In the WCPO however a high proportion of the non-member effort was concentrated outside and to the east of the CCSBT area.

The proportions of effort in each statistical area attributed to non-parties have varied through time and between areas (Figure 8). In the Indian Ocean non-member effort reaches at least 10% of total effort in statistical areas 1, 2, 13, and 14, and is insignificant elsewhere. Reported effort is very low in statistical area 1 (Figure 9) but statistical areas 2 and 14 each contain significant effort, as does statistical area 13 which is outside the CCSBT core. In the WCPO, non-member effort is substantial in statistical area 12 which is outside the CSBT core, but elsewhere is low. Uncertainty (due to the three vessel rule) about how much of the member and non-member effort is included in the PD_flag dataset may substantially affect the WCPO estimates.

Size analyses

The relationship between mean weight and the covariates year, month-area, flag, and number_retained was modelled using generalized additive models. All variables explained significant variation ($p << 0.01$). Residuals from the transformed data were sufficiently close to normally distributed to be used for inference. The relationship between log(number_retained) and mean weight was fitted with a smoothing function with 3.9 effective degrees of freedom, and showed a clear decline in mean weight with increasing number retained (Figure 10). Similar relationships were observed in separate analyses for individual flags.

This relationship between number_retained and mean weight suggests that estimates of catch weight for Japanese effort will be somewhat biased, but the effect is relatively small compared to other uncertainties in the modelling. Moreover, some uncertainty about the reliability of the relationship is introduced by the fact that mean weight is estimated by dividing weight_retained by number_retained, which means that any uncoupling between the two would tend to produce a decline in mean weight as number_retained increases.

Subsequently we analysed the sampled Japanese size data. In the Pacific, sufficient data were available to calculate observed mean weights for 1051 strata (year by month by statistical area), and mean weights were predicted for the remaining 2808. In the Indian Ocean, observed weights were calculated for 4749 strata, and weights predicted for 9473.

Residuals from the generalized linear models were relatively normally distributed after transformation, and there was only limited variation in variance among statistical areas (Figures 11-14).

Estimates of mean weight were obtained for the majority of statistical area-month combinations, and inferred for the remainder (Figures 15-16). Mean weights were also predicted for year by month by statistical area strata (Figures **Error! Reference source not found.** and **Error! Reference source not found.**).

The relationship between predicted and observed retained weight varied between flags, with predicted weights very close to observed weights for Japan in both the Indian Ocean (Figure 19) and Pacific Ocean (Figure 20). In the Indian Ocean the predicted weights were on average similar to reported weights for Korea, higher than reported for Taiwan, slightly higher for Australia, and lower for South Africa. For the Pacific Ocean the predicted weights were similar to reported for Korea, slightly higher than reported for Australia, and lower than reported for New Zealand and Taiwan.

These differences between predicted and reported effort may reflect differences in average fishing locations and fishing behaviour between fleets. The predictive model takes into account year, month and statistical area, but there are also consistent differences in mean size within statistical areas that the model does not take into account. Including latitude in the model may improve predictions.

The predictions of catch weight for Japanese effort appear to be sufficiently reliable to use in CPUE analyses, with the proviso that observed weights were only available in the Japanese data for comparison for a single year.

Catch predictions

Standardizations for both Pacific and Indian Ocean CCSBT data fitted the data relatively well, but with positively biased residuals for small numbers of hooks, particularly in the Indian Ocean (Figures 22 - 24). The spatial effects showed the expected patterns of higher catch rates further south. Surprisingly, alternative models with interaction terms between quarter and statistical area did not substantially improve the model fit, or give significantly better catch predictions for the CCSBT data.

Catch predictions with CCSBT data gave total catch estimates that were close to the observed estimates and without significant bias (Figure 27 and Figure 28), apart from overestimating Japanese catch in the Pacific Ocean between 1995 and 2005. This result suggests that the model is acceptable for predicting non-member catch.

Non-member catch was estimated for the Pacific and Indian Oceans, by year and by statistical area (Tables 2- 5). Estimates for the Pacific Ocean for 2000-2012 were low with a highest estimate of 48 tonnes in 2010, if catchability for non-parties was assumed to be the same as Japan. Estimates of non-member catch for the Indian Ocean were also affected by the assumed catchability. The low-catchability estimates varied between 7 tonnes in 2002 and 98 tonnes in 2012, while the high-catchability estimates varied between 18 tonnes in 2002 and 228 tonnes in 2012.

Acknowledgments
The analyses described in this report are based on publicly available data from the Indian Ocean Tuna Commission (IOTC), provided by its contracting parties (members) and cooperating non-contracting parties, and from the Western and Central Pacific Fisheries Commission (WCPFC), provided by its members, participating territories and cooperating non-members. The analyses also use the CCSBT data provided by members and cooperating non-members. Thanks to Colin Millar of the CCSBT Secretariat for helping to obtain the WCPFC catch and effort data. Thanks also to Kevin Sullivan of the New Zealand Ministry for Primary Industries for suggesting aspects of the approach used. This work was funded by the Ministry for Primary Industries (New Zealand), and the Fisheries Resources Research Fund and Australian Bureau of Agricultural and Resource Economics and Sciences (Australia).

Figures

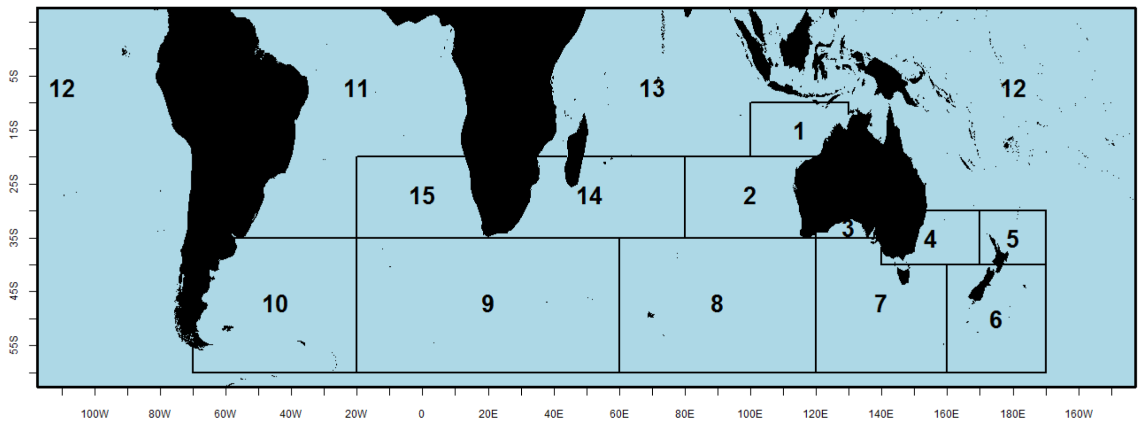

Figure 1: Map showing the CCSBT statistical areas

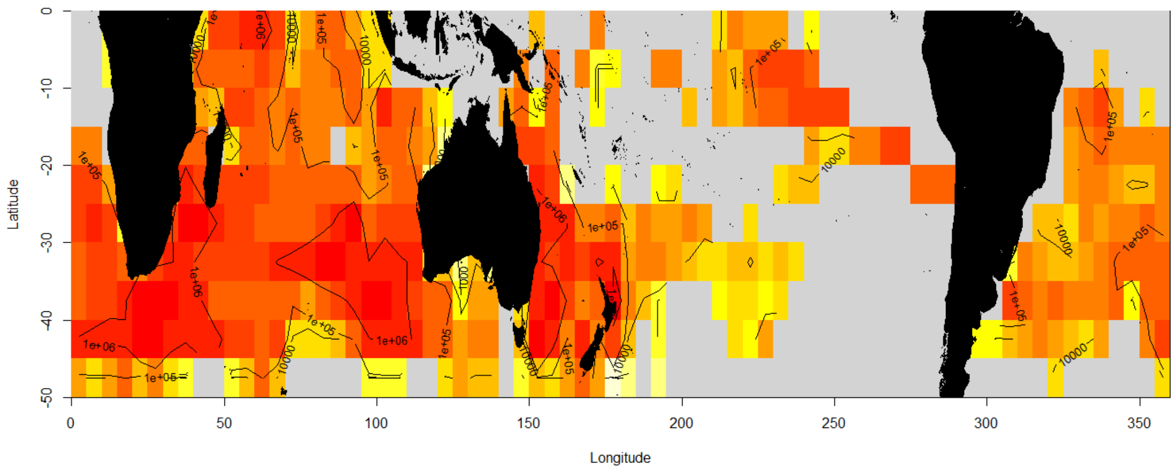

Figure 2: Average annual effort reported to CCSBT by parties since 2001 by 5 degree square. Red shading indicates higher effort than yellow, and areas with no reported effort are grey.

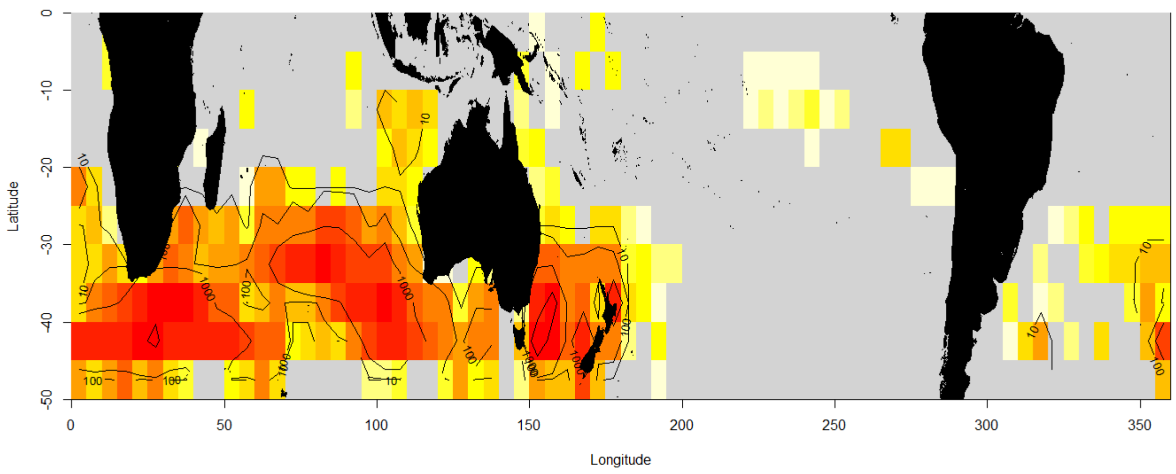

Figure 3: Average annual SBT catch in tonnes reported to CCSBT by parties since 2001 by 5 degree square. Red shading indicates higher catch than yellow, and areas with no reported catch are grey.

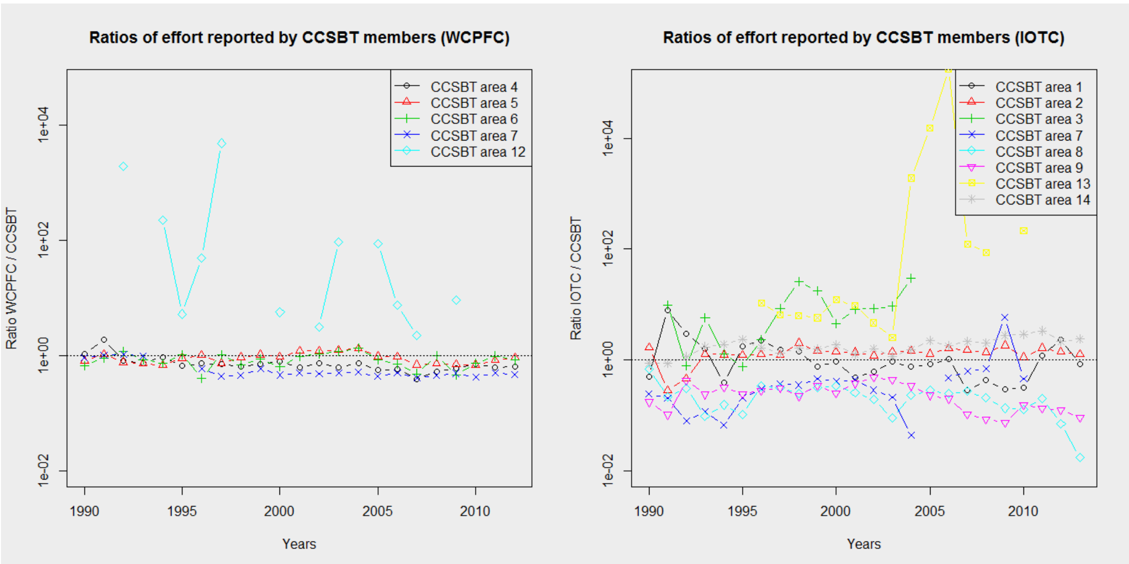

Figure 4: Ratios of CCSBT parties' effort reported in regional datasets to effort reported to the CCBST, by statistical area and year. Strata without effort in one of the datasets are excluded.

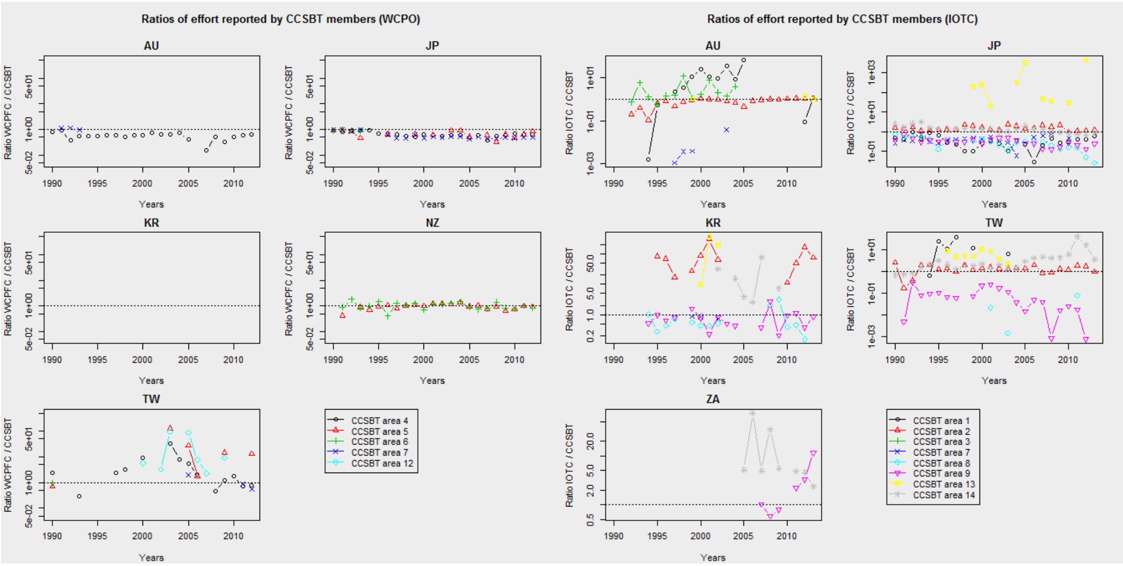

Figure 5: Ratios of CCSBT members' and cooperating parties' effort reported in the IOTC dataset vs effort reported to the CCBST, by flag, statistical area, and year. Strata without effort in one of the datasets are excluded. Flags are Australia (AU), Japan (JP), Republic of Korea (KR), New Zealand (NZ), Taiwan (TW), and South Africa (ZA).

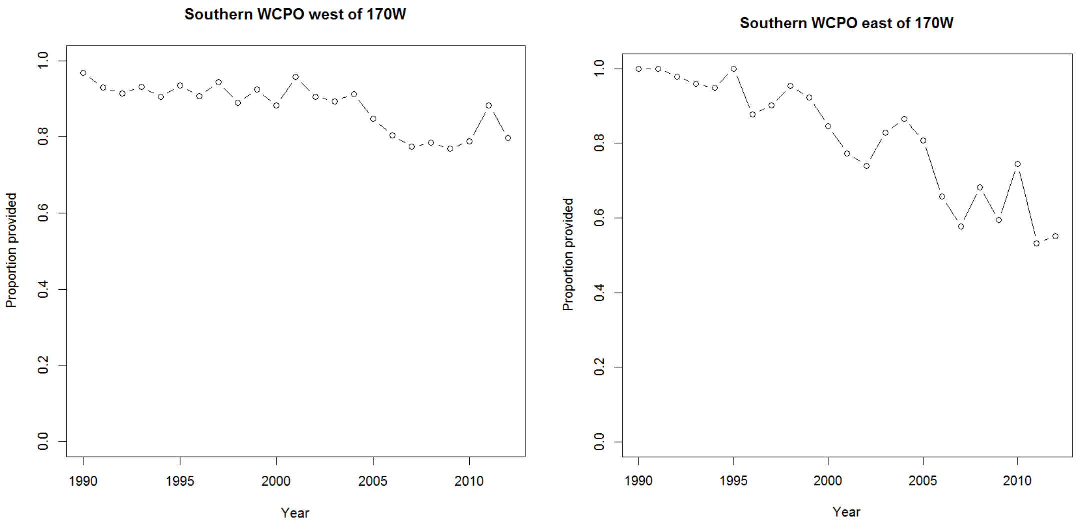

Figure 6: Ratio of effort in the PD_flag and PD_agg datasets, by year, for sets south of 30S and west of 170W (left) and for sets south of 30S and east of 170W (right).

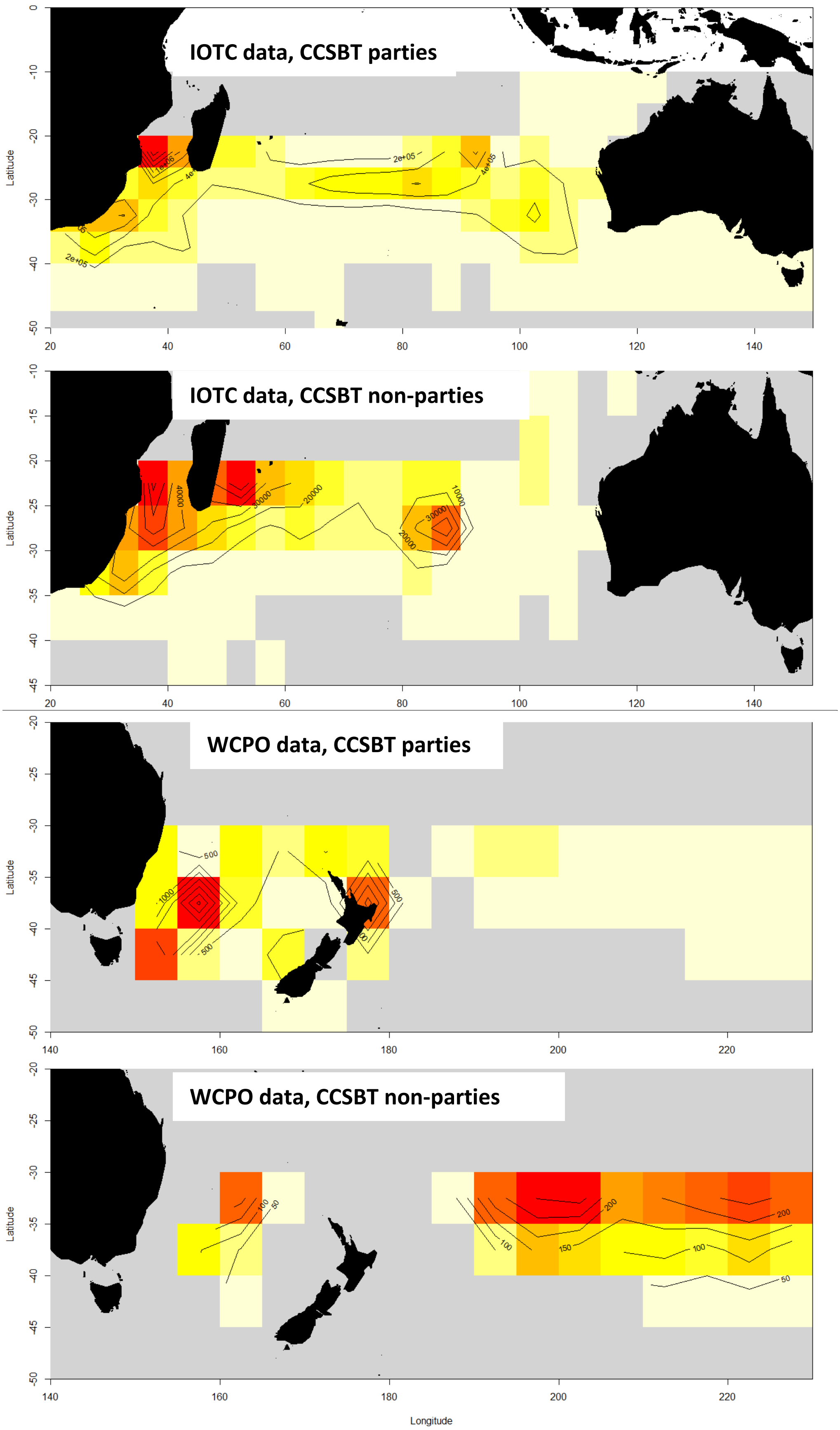

Figure 7: Spatial distribution of mean annual effort reported to IOTC and WCPFC 2001-2012 (thousands of hooks) by CCSBT parties (members and cooperating parties) and non-parties. Higher levels of effort are red, and grey indicates no reported effort.

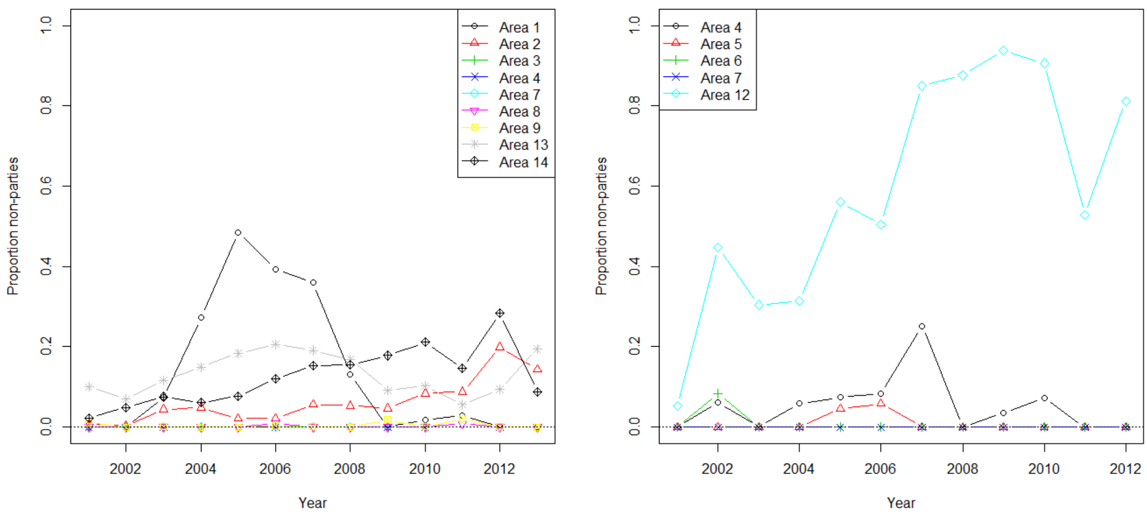

Figure 8: Proportion of effort in the IOTC dataset (left) and in the WCPFC dataset PD_flag south of 30S (right) reported by flags that are not parties of CCSBT, by statistical area and year.

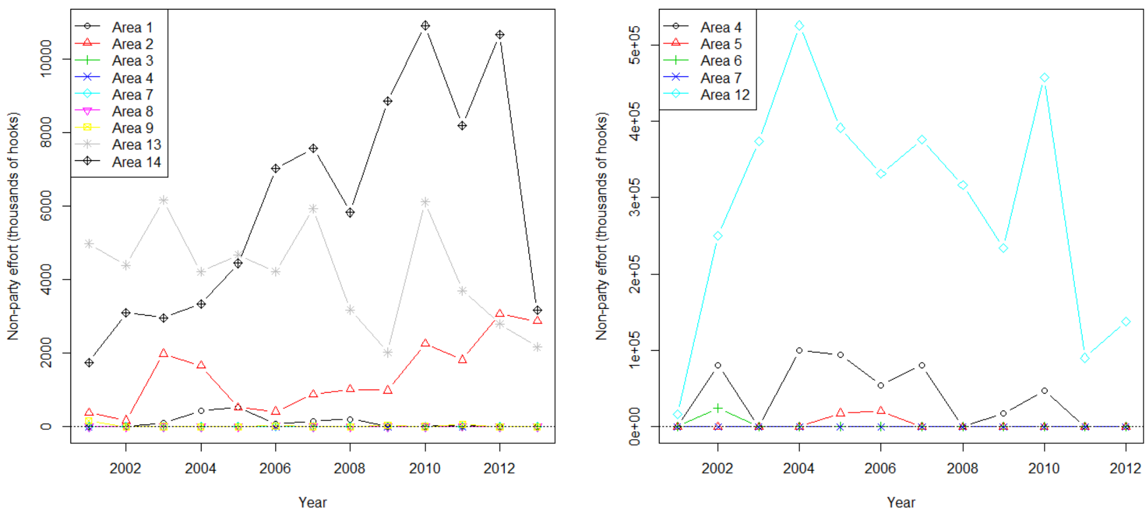

Figure 9: Effort (thousands of hooks) in the IOTC dataset south of 10S (left) and in the WCPFC dataset PD_flag south of 30S (right) reported by flags that are not parties of CCSBT, by statistical area and year.

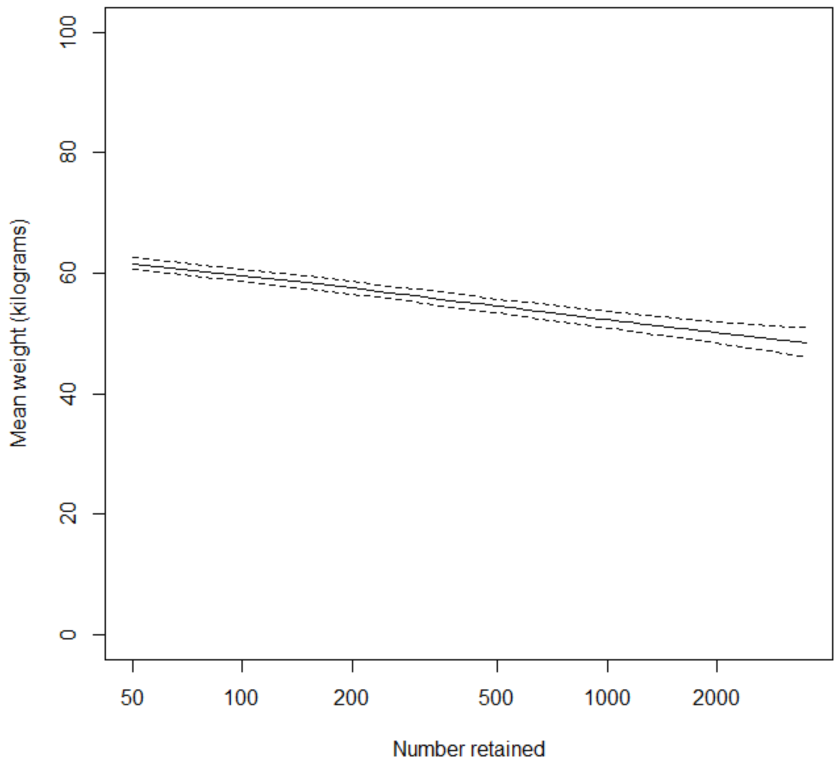

Figure 10: Number_retained versus predicted mean weight for Japanese effort in statistical area 2, with 95% confidence intervals around the predicted effect of number_retained.

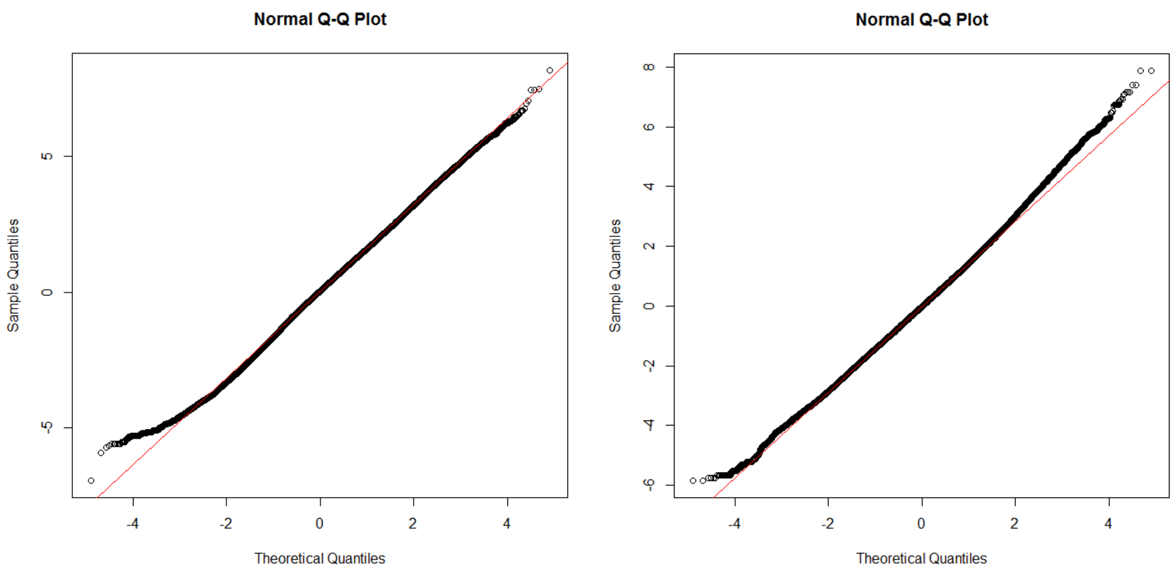

Figure 11: Diagnostic Q-Q plots for the generalized linear models of weight frequency data for the Indian Ocean (left) and Pacific Ocean (right).

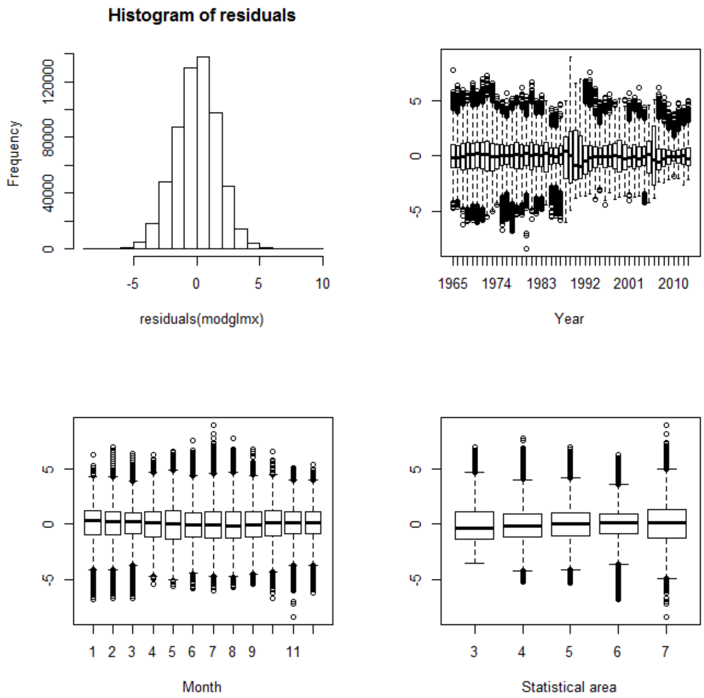

Figure 12: Histogram and boxplots of residuals from the analysis of size data for the Pacific Ocean.

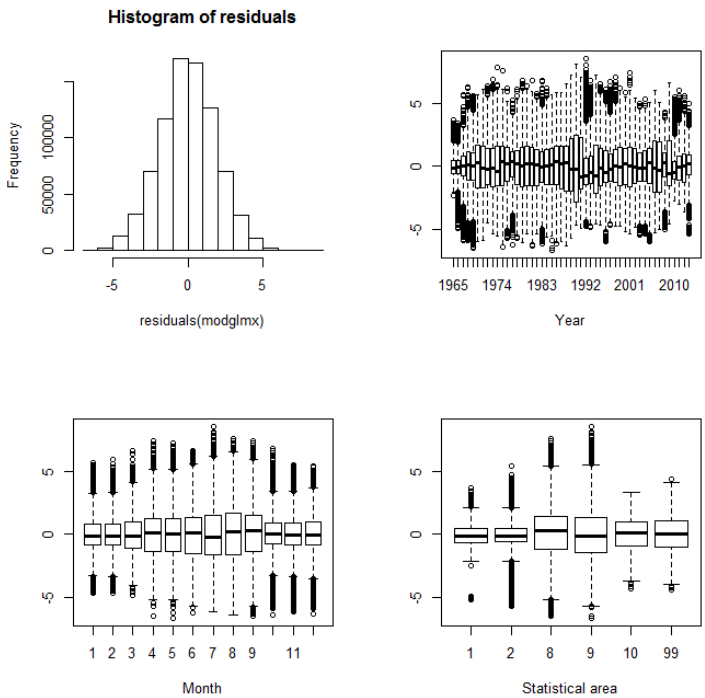

Figure 13: Histogram and boxplots of residuals from the generalized linear models of weight frequency data for the Indian Ocean.

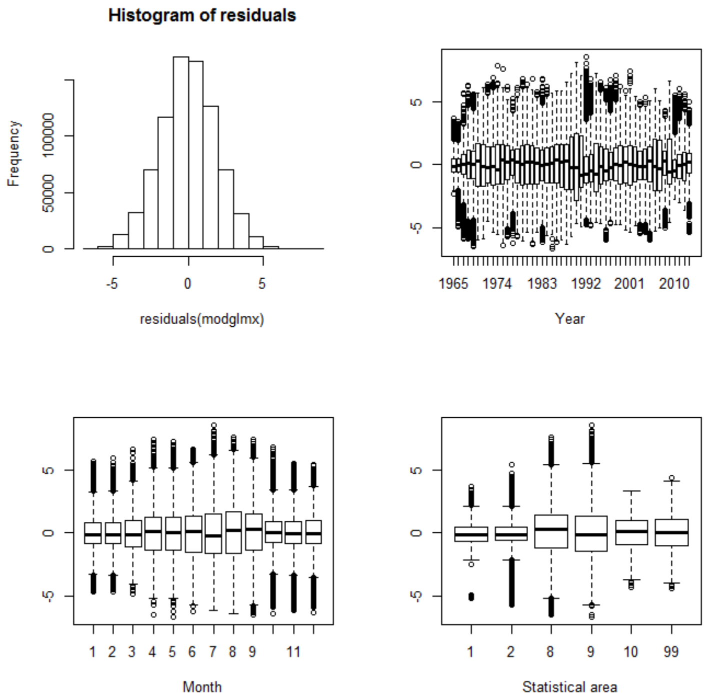

Figure 14: Histogram and boxplots of residuals from the generalized linear models of weight frequency data for the Indian Ocean.

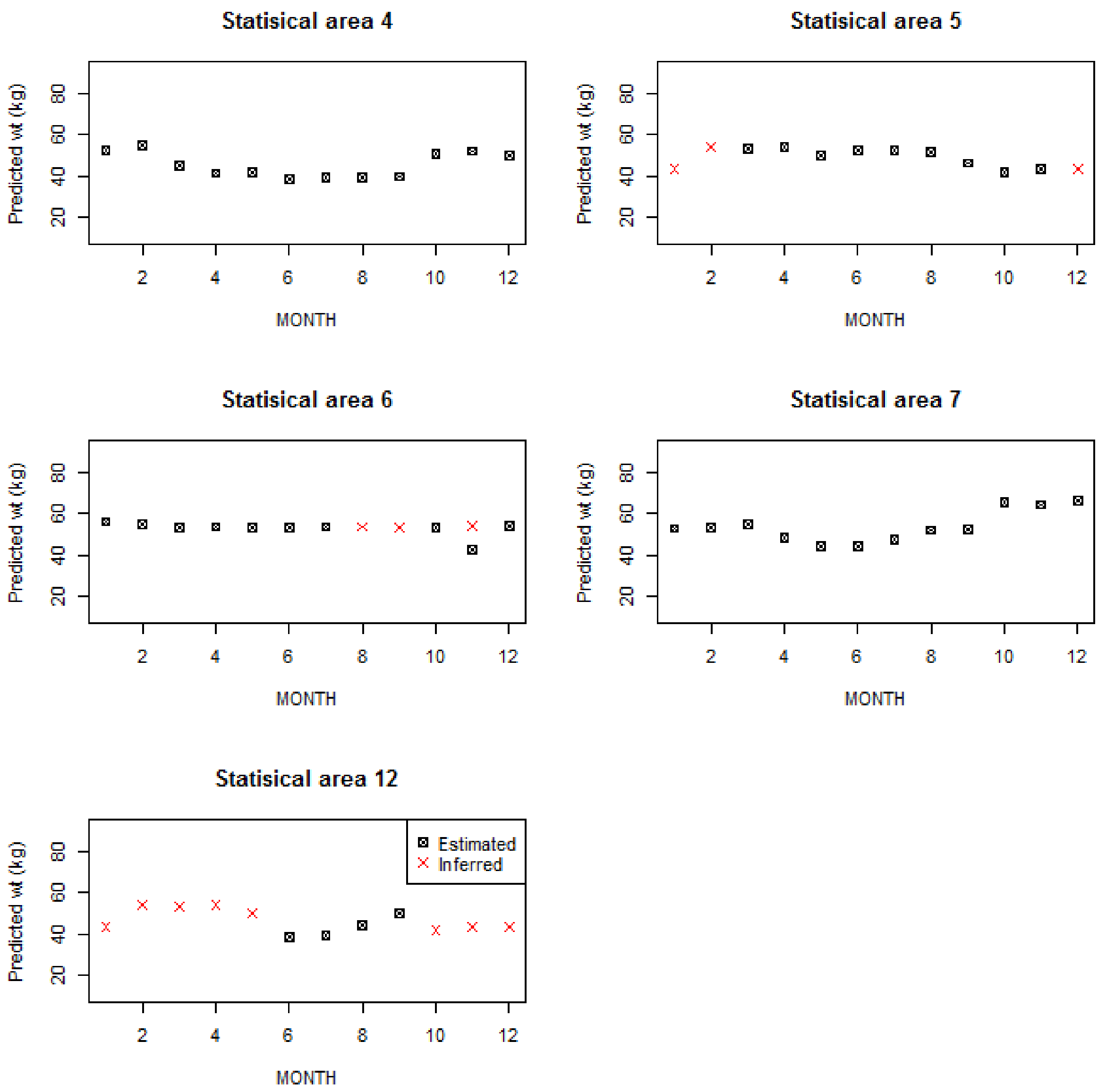

Figure 15: Predicted mean weights by month and statistical area for the Pacific Ocean. Estimated weights are plotted with black square, and inferred weights with red X's. In the month where both estimated and inferred values are plotted, the estimated value was considered unreliable and replaced with inferred values

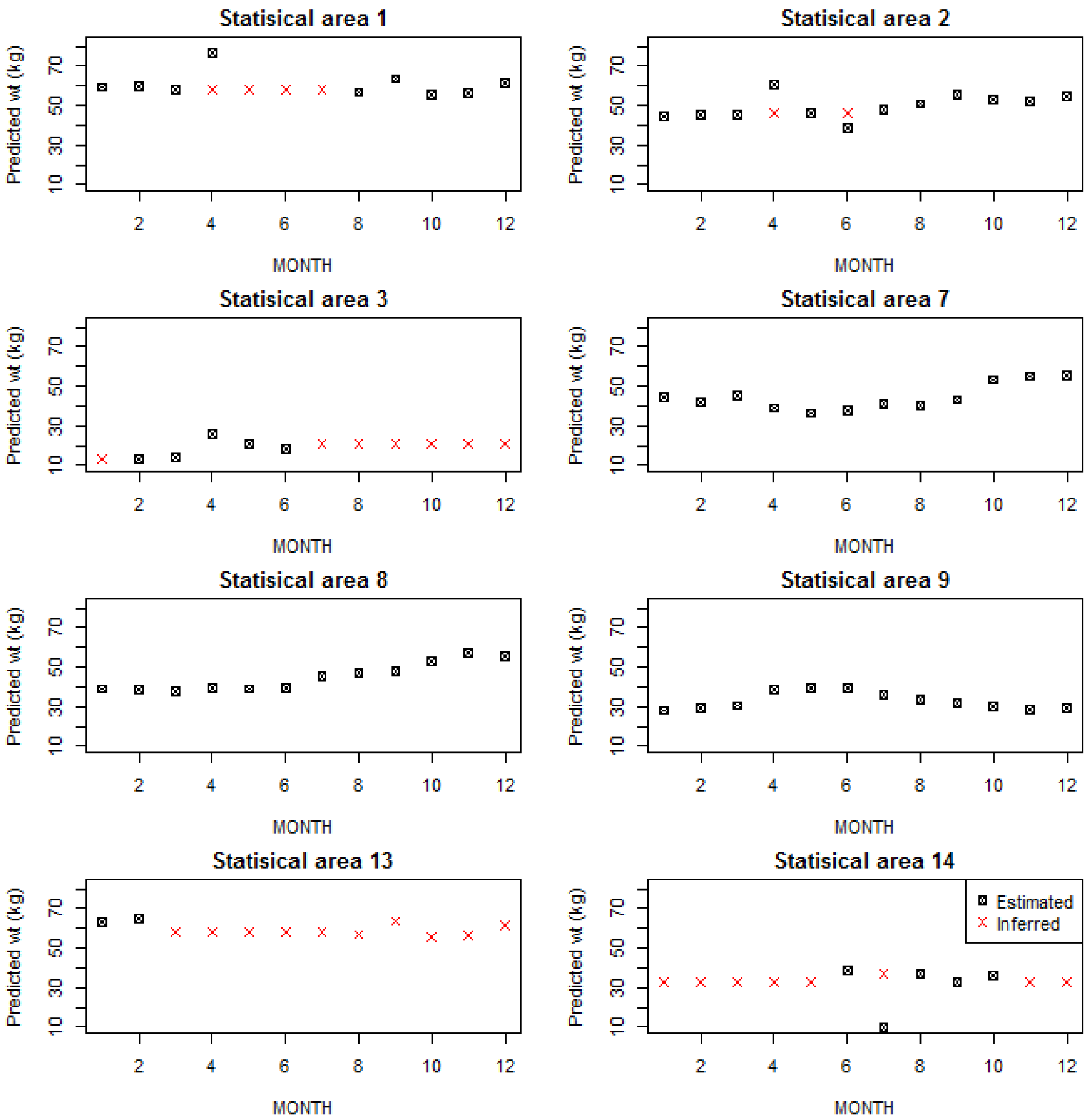

Figure 16: Predicted mean weights by month and statistical area for the Indian Ocean. Estimated weights are plotted with black square, and inferred weights with red X's. In the few months where both estimated and inferred values are plotted, the estimated values were considered unreliable and replaced with inferred values.

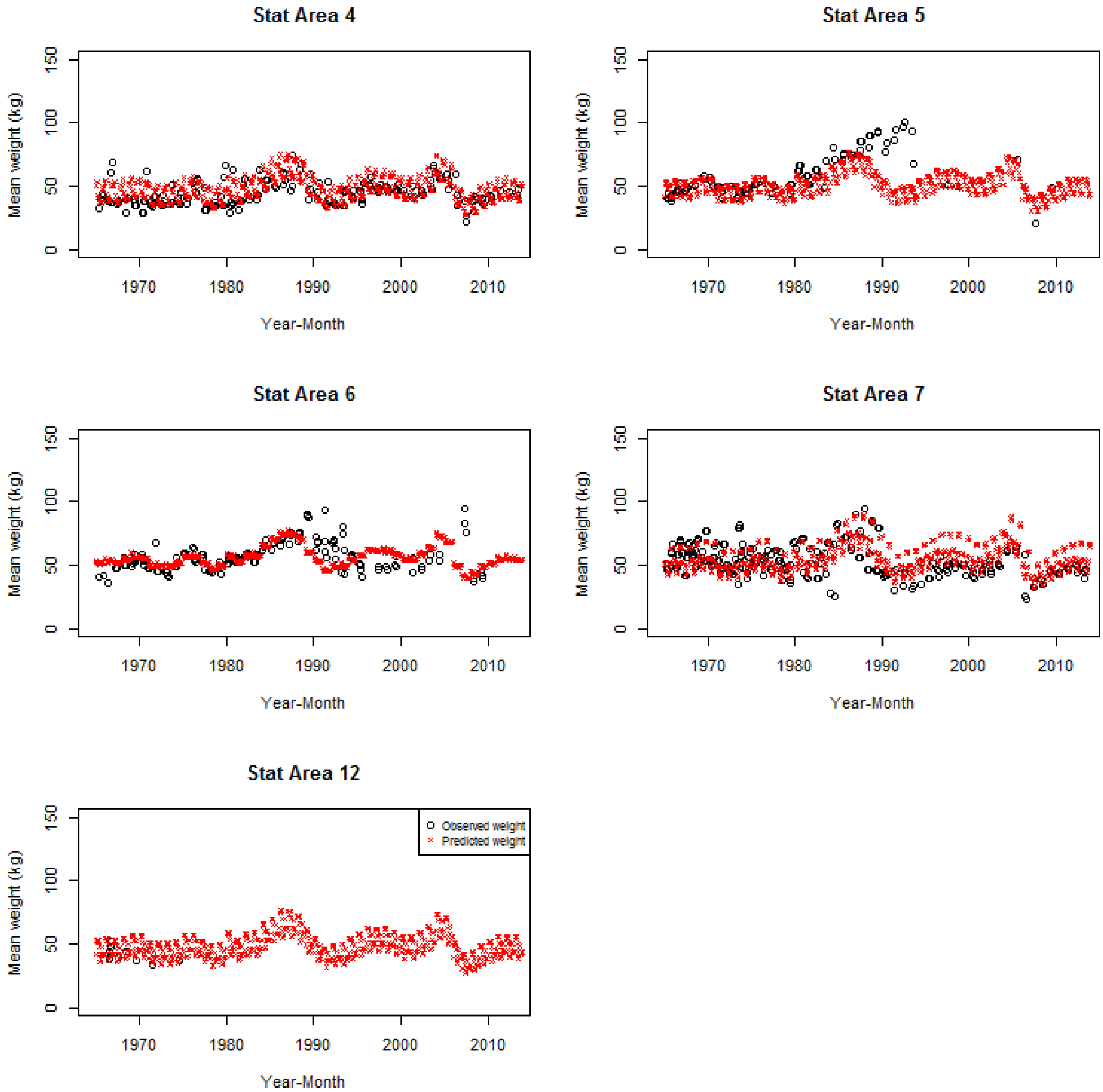

Figure 17: Observed (black circles) and predicted (red crosses) mean weights for Japanese sets in the Pacific Ocean.

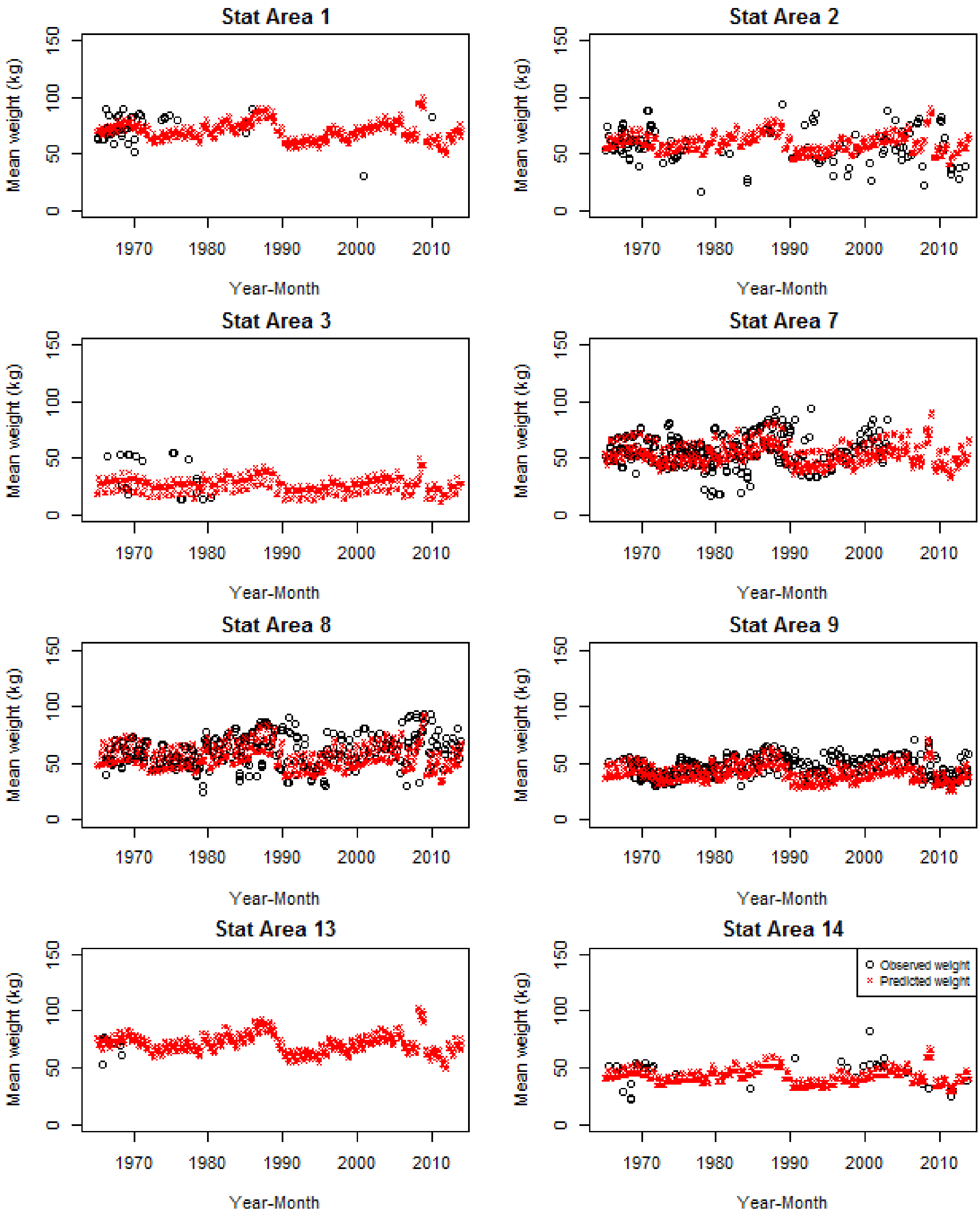

Figure 18: Observed (black circles) and predicted (red crosses) mean weights for Japanese sets in the Indian Ocean.

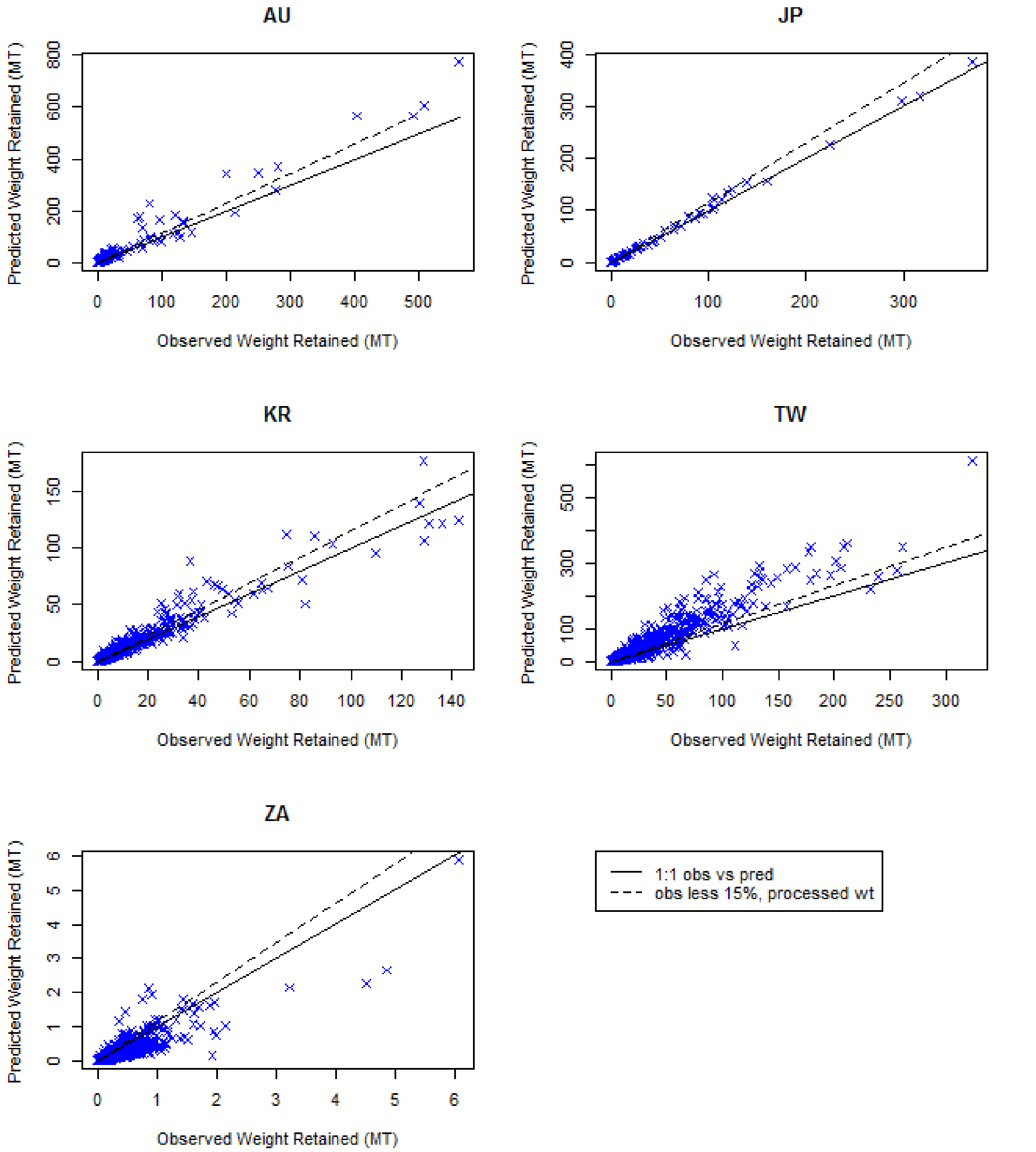

Figure 19: Comparisons of observed and predicted catches in metric tonnes (MT) by flag in the Indian Ocean, with predictions based on multiplying numbers caught by mean observed or predicted weights in the Japanese catch for each stratum (year-month-statistical area). Flags are Australia (AU), Japan (JP), Republic of Korea (KR), Taiwan (TW), and South Africa (ZA).

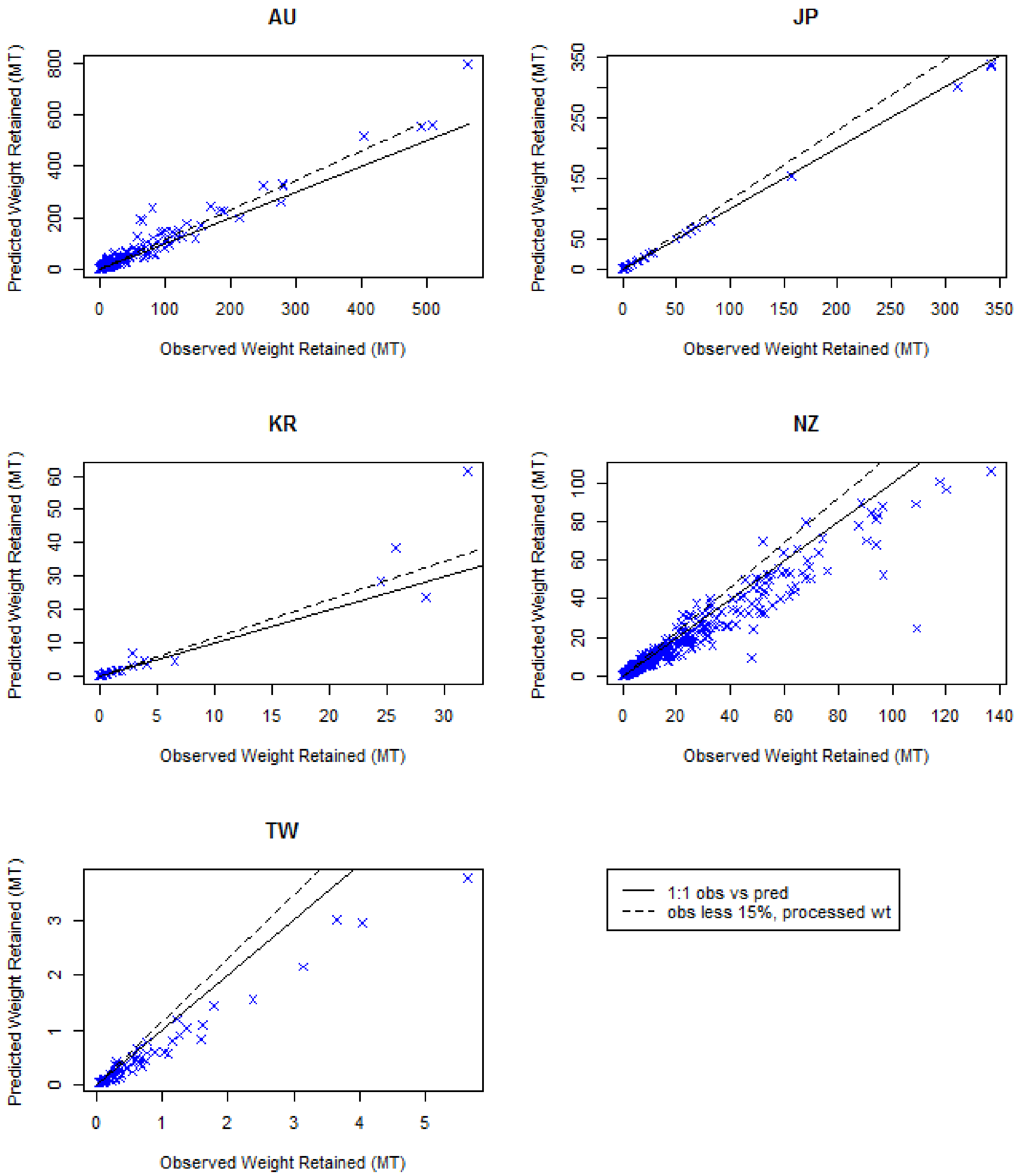

Figure 20: Comparisons of observed and predicted catches in metric tonnes (MT) by flag in the Pacific Ocean, with predictions based on multiplying numbers caught by mean observed or predicted weights in the Japanese catch for each stratum (year-month-statistical area). Flags are Australia (AU), Japan (JP), Republic of Korea (KR), New Zealand (NZ), and Taiwan (TW).

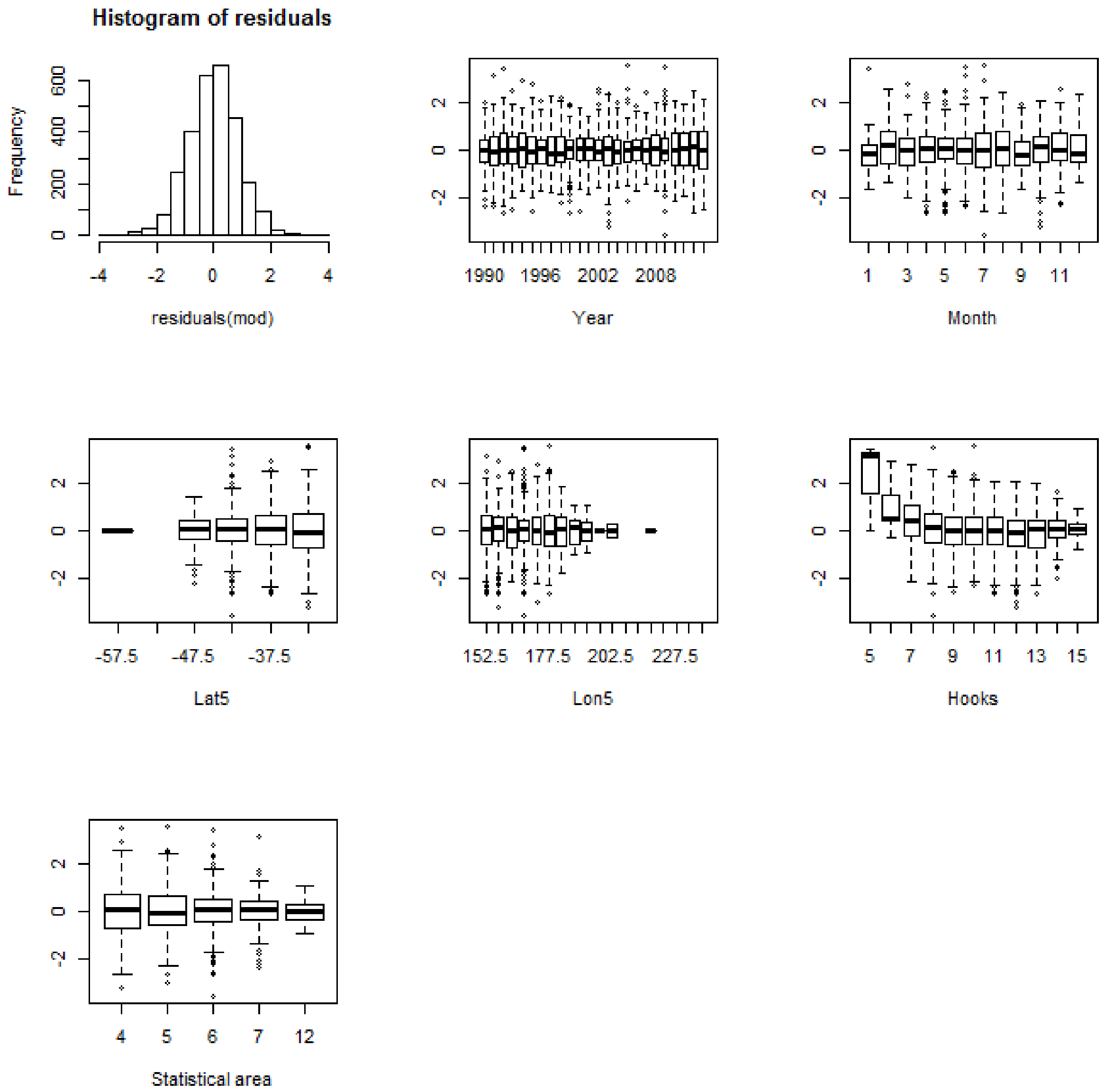

Figure 21: Histograms of residuals and boxplots of residuals versus covariates for the Pacific Ocean positive GLM. Lat5 and Lon5 represent the latitude and longitude in 5 degree categories. Hooks have been categorized by taking the natural logarithm and grouping by unit on the log scale.

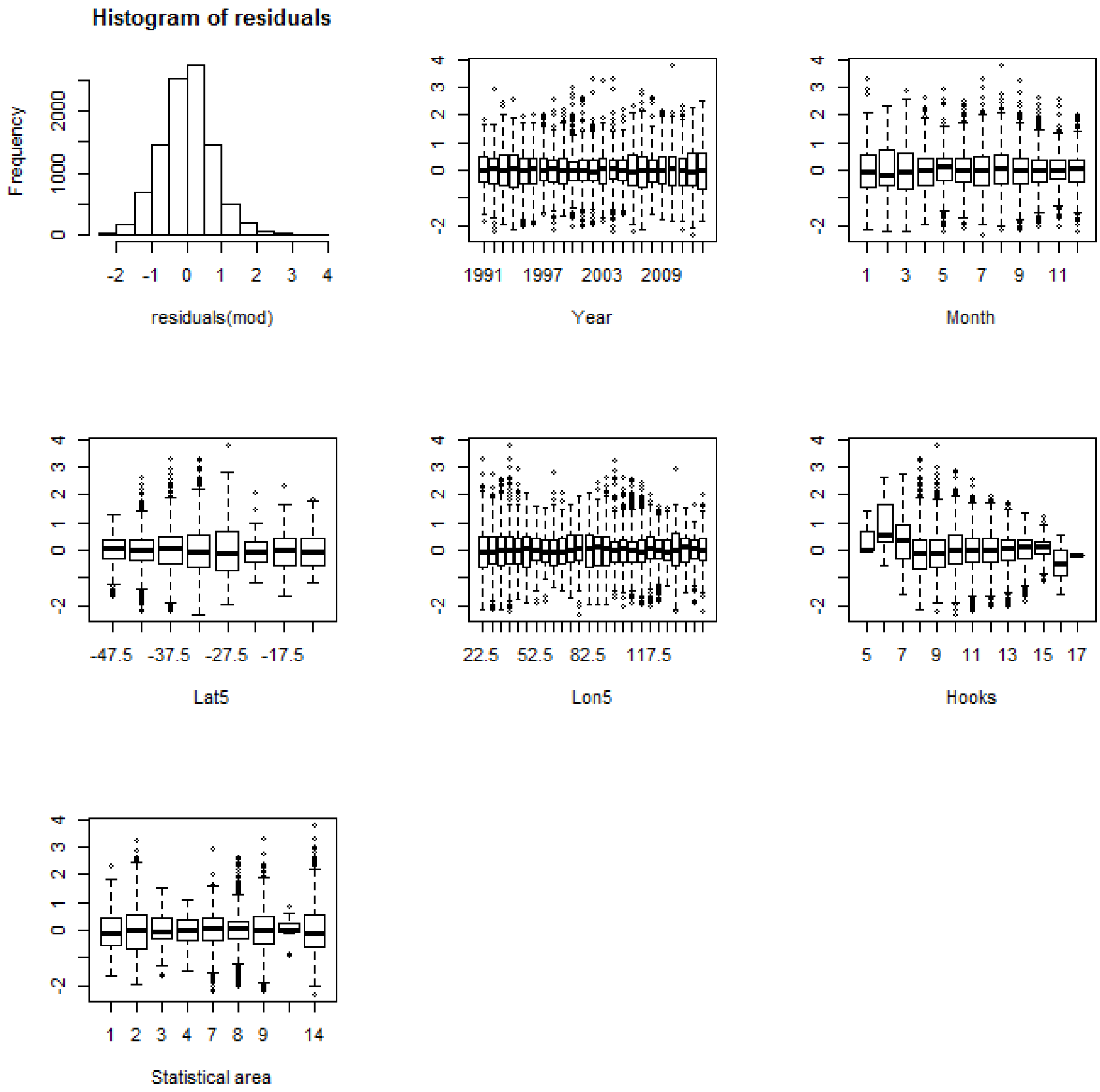

Figure 22: Histograms of residuals and boxplots of residuals versus covariates for the Indian Ocean positive GLM. Lat5 and Lon5 represent the latitude and longitude in 5 degree categories. Hooks have been categorized by taking the natural logarithm and grouping by unit on the log scale.

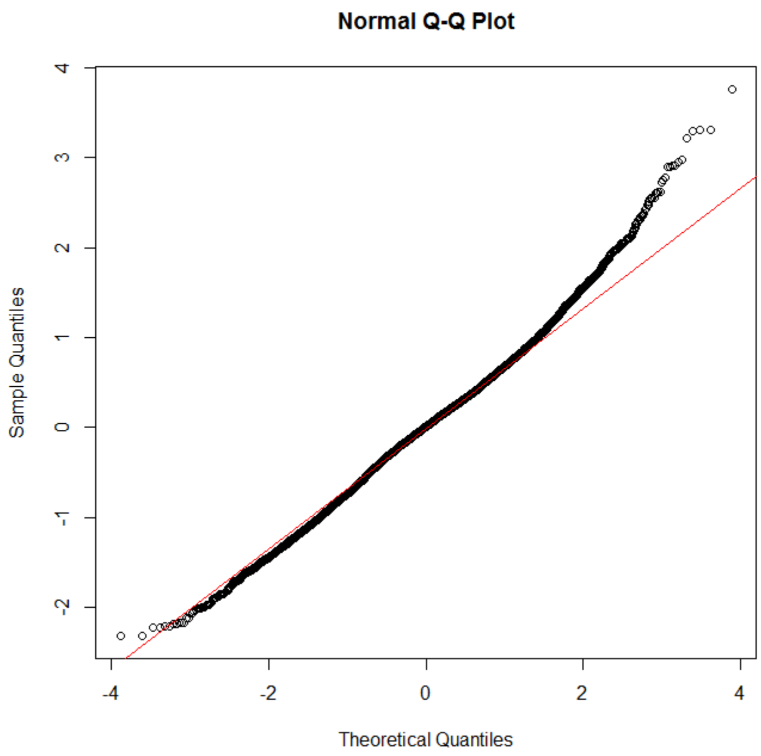

Figure 23: Diagnostic Q-Q plot for the CPUE standardization of Indian Ocean positive catches.

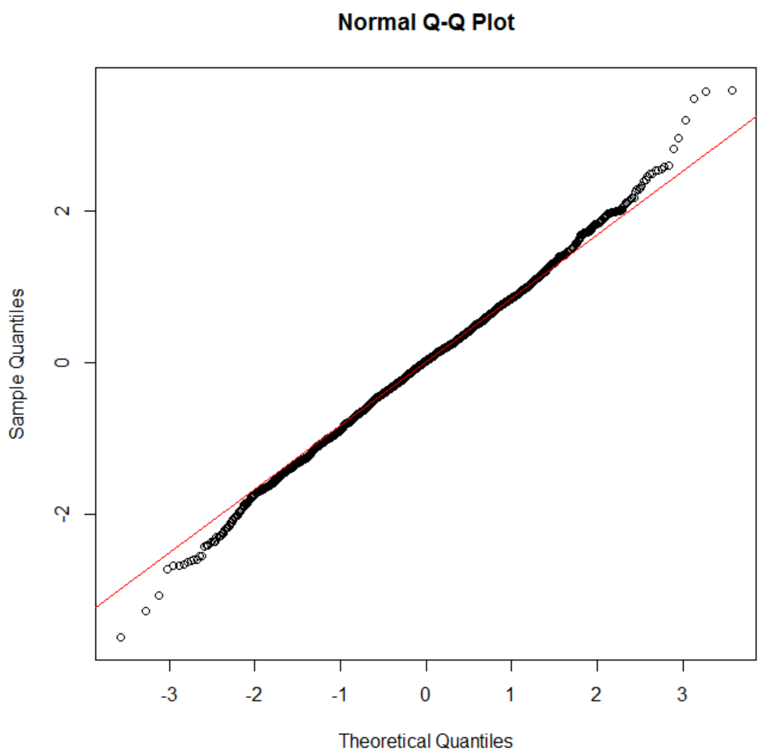

Figure 24: Diagnostic Q-Q plot for the CPUE standardization of Pacific Ocean positive catches.

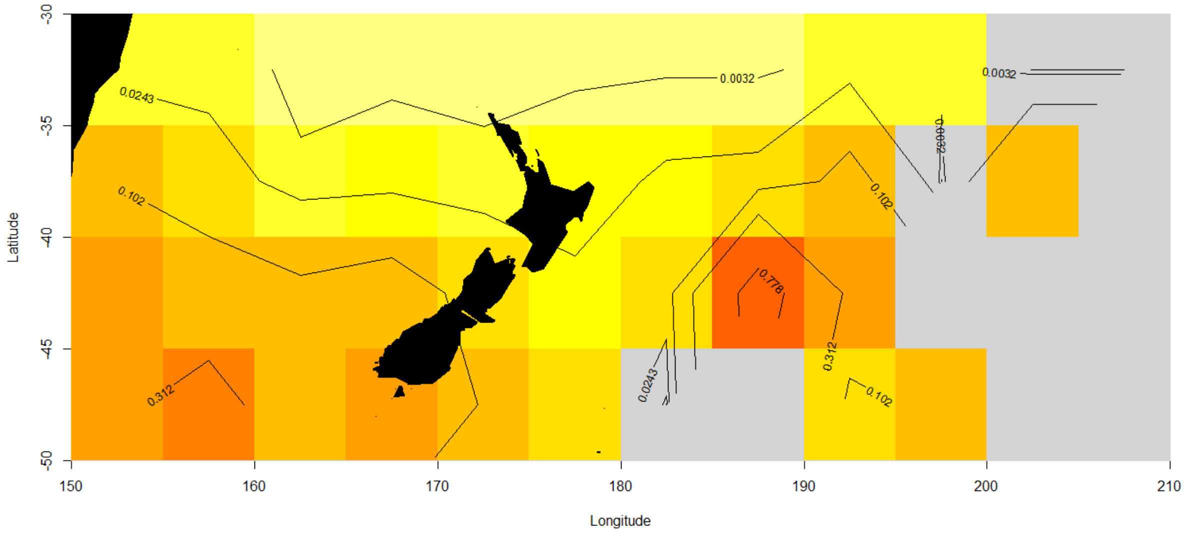

Figure 25: Relative catch rates of southern bluefin tuna by 5 degree square in the Pacific, predicted for May 2001. Red colour indicates higher catch rates and yellow lower catch rates.

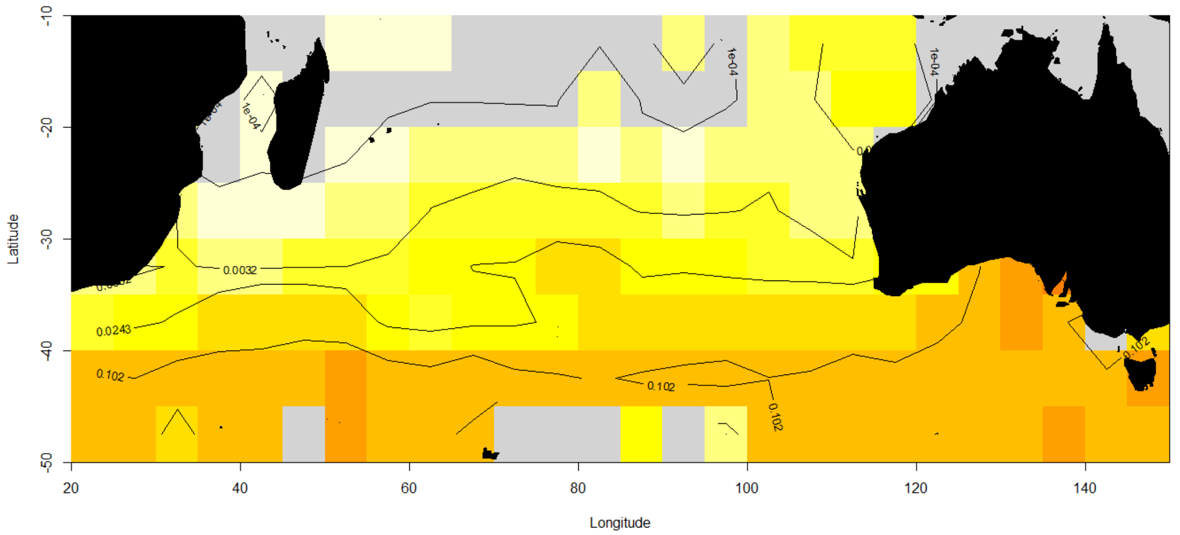

Figure 26: Relative catch rates of southern bluefin tuna by 5 degree square in the Indian Ocean, predicted for May 2001. Red colour indicates higher catch rates and yellow lower catch rates.

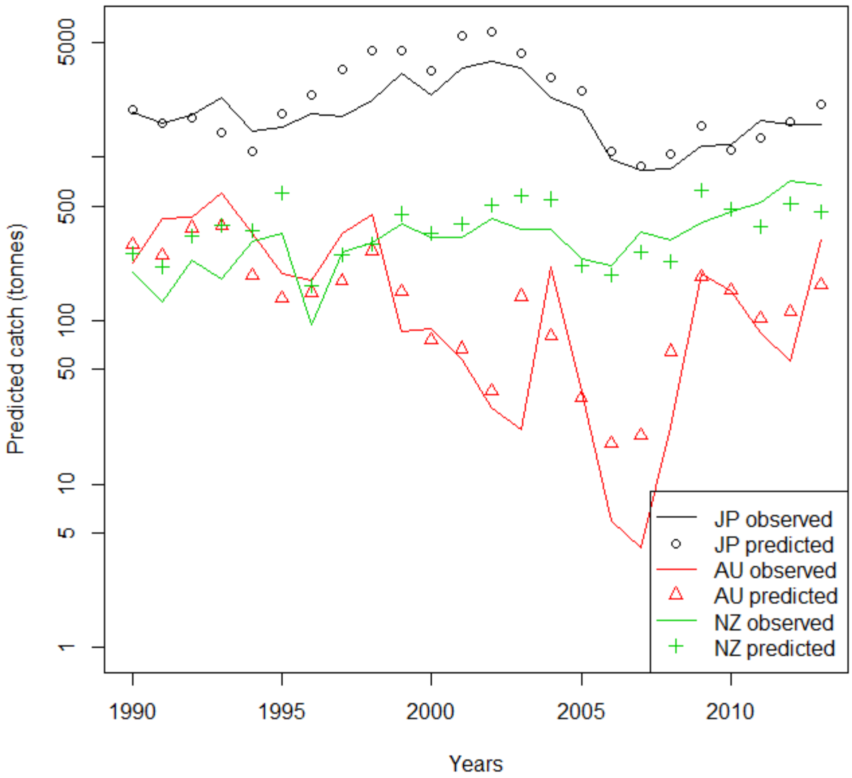

Figure 27: Comparison of observed and predicted catches in the Pacific Ocean for Japan (JP), Australia (AU) and New Zealand (NZ), based on multiplying predicted CPUE by effort in the CCSBT data.

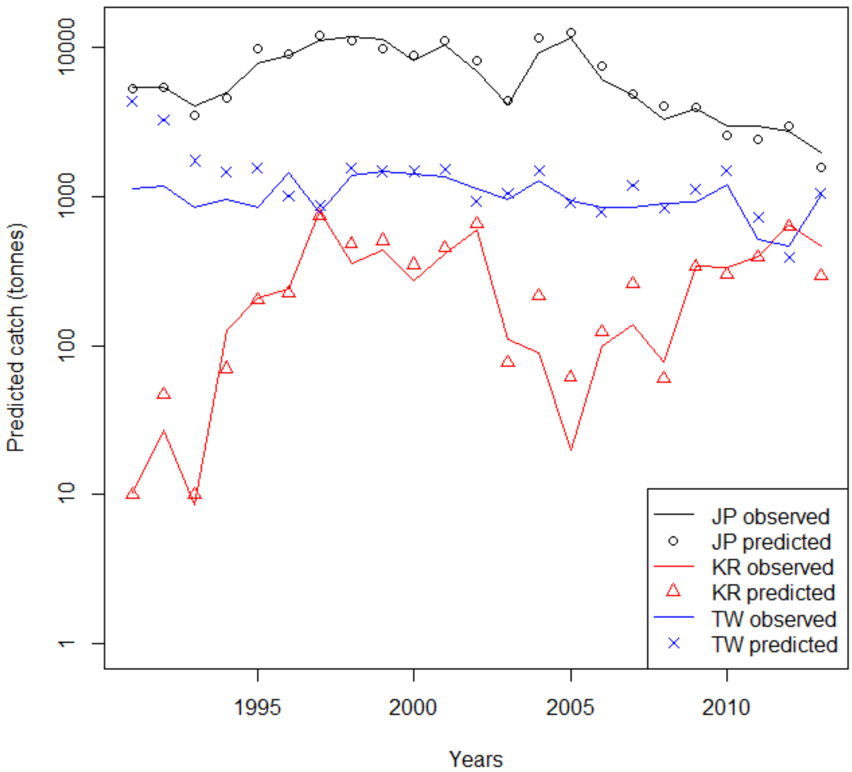

Figure 28 Comparison of observed and predicted catches in the Indian Ocean for Japan (JP), Korea (KR) and Taiwan (TW), based on multiplying predicted CPUE by effort in the CCSBT data.

Tables

Table 1: Length to processed weight conversion factors agreed at the 1994 SBT Trilateral Workshop on Age and Growth, 17 Jan - 4 Feb, 1994. The parameters are used in the equation $Weight = A.Length^B$, with *A* and *B* defined separately for adults and juveniles.

Statistical area	Quarter	A_JUV	B_JUV	A_ADULT	B_ADULT
1	1	1.3545E-05	3.0214	7.3465E-06	3.157
2	1	1.3545E-05	3.0214	7.3465E-06	3.157
3	1	1.3545E-05	3.0214	5.5706E-06	3.2164
4	1	1.3545E-05	3.0214	5.5706E-06	3.2164
5	1	1.3545E-05	3.0214	8.3688E-06	3.1429
6	1	1.3545E-05	3.0214	8.3688E-06	3.1429
7	1	1.3545E-05	3.0214	5.5706E-06	3.2164
8	1	1.3545E-05	3.0214	3.9080E-07	3.7529
9	1	1.3545E-05	3.0214	5.1065E-06	3.2393
10	1	1.3545E-05	3.0214	5.1065E-06	3.2393
1	2	8.9030E-06	3.1225	1.8240E-07	3.9056
2	2	8.9030E-06	3.1225	1.8240E-07	3.9056
3	2	8.9030E-06	3.1225	5.5706E-06	3.2164
4	2	8.9030E-06	3.1225	5.5706E-06	3.2164
5	2	8.9030E-06	3.1225	2.9786E-06	3.3411
6	2	8.9030E-06	3.1225	7.3465E-06	3.157
7	2	8.9030E-06	3.1225	5.5706E-06	3.2164
8	2	8.9030E-06	3.1225	1.8240E-07	3.9056
9	2	8.9030E-06	3.1225	5.1065E-06	3.2393
10	2	8.9030E-06	3.1225	5.1065E-06	3.2393
1	3	1.5216E-05	3.0009	1.8240E-07	3.9056
2	3	1.5216E-05	3.0009	1.8240E-07	3.9056
3	3	1.5216E-05	3.0009	1.5380E-06	3.4754
4	3	1.5216E-05	3.0009	1.5380E-06	3.4754
5	3	1.5216E-05	3.0009	3.9490E-06	3.2886
6	3	1.5216E-05	3.0009	3.9490E-06	3.2886
7	3	1.5216E-05	3.0009	1.5380E-06	3.4754
8	3	1.5216E-05	3.0009	1.8240E-07	3.9056
9	3	1.5216E-05	3.0009	4.7780E-07	3.7032
10	3	1.5216E-05	3.0009	4.7780E-07	3.7032
1	4	1.3545E-05	3.0214	7.3465E-06	3.157
2	4	1.3545E-05	3.0214	7.3465E-06	3.157
3	4	1.3545E-05	3.0214	1.5380E-06	3.4754
4	4	1.3545E-05	3.0214	1.5380E-06	3.4754
5	4	1.3545E-05	3.0214	3.9490E-06	3.2886
6	4	1.3545E-05	3.0214	8.3688E-06	3.1429
7	4	1.3545E-05	3.0214	1.5380E-06	3.4754
8	4	1.3545E-05	3.0214	3.9080E-07	3.7529
9	4	1.3545E-05	3.0214	4.7780E-07	3.7032
10	4	1.3545E-05	3.0214	4.7780E-07	3.7032

Table 2: Predicted catches for the Pacific, based on alternative assumptions that non-member catchabilities match those of Taiwan or Japan.

Year	Assume TW		Assume JP	
	Sarea 4	Sarea 6	Sarea 4	Sarea 6
2002	-0.1	2.9	3.5	21.4
2004	1.7	0	25.3	0
2005	0.9	0	18.2	0
2006	1.5	0	15.2	0
2007	4.3	0	35.3	0
2009	0.1	0	2.1	0
2010	5.8	0	48.3	0

Table 3: Estimated Indian Ocean catch by year and statistical area, assuming all fleets have the same catchability as JP (Japan) vessels

q=JP	Statistical Area					
	1	2	8	9	13	14
2000	0	0	0	0.3	0.4	107.2
2001	0	25	0	24.6	0.1	11.3
2002	0	0.2	0	0	0.1	17.2
2003	0.5	18.7	0	0.4	4.5	9.8
2004	4	23.2	0	0	9.2	37
2005	7.2	13.2	0	0	0.2	63.6
2006	0.7	9.6	6.1	2.2	1.3	90.7
2007	0.5	20.2	0	0.2	1	94.2
2008	1	12.8	0	0	0.4	61.5
2009	0	89.8	0	1.5	0.1	63.5
2010	0	84.7	0	0.3	24.9	105.1
2011	0.1	86.8	0.2	1.5	0.8	63.2
2012	0	148.3	0	0.3	12.7	67.1
2013	0	114.8	0	0	0	7.8

Table 4: Estimated Indian Ocean catch by year and statistical area, assuming all fleets have the same catchability as TW vessels

q=TW	Statistical Area					
	1	2	8	9	13	14
2000	0	0	0	0.1	0.1	45.8
2001	0	11.4	0	11.9	0	4.7
2002	0	0	0	0	0	6.6
2003	0.1	7.2	0	0.2	1.9	3.8
2004	1.2	9	0	0	3.8	15.4
2005	2.5	5.8	0	0	0	28.4
2006	0.2	4.1	2.9	1	0.3	36.2
2007	0.1	8.2	0	0.1	0.2	37.9
2008	0.3	5.2	0	0	0	25.4
2009	0	43.6	0	0.6	0.1	24.6
2010	0	36.5	0	0.2	10.5	42.1
2011	0	38.4	0.1	0.6	0.1	25.1
2012	0	64.8	0	0.1	5.7	27.3
2013	0	50.2	0	0	0	3

Table 5: Estimated Indian Ocean catch by year, assuming all fleets have the same catchability as either JP (Japan) or TW (Taiwan) vessels.

	q=TW	q=JP
2000	46	107.9
2001	28	61
2002	6.7	17.5
2003	13.2	33.9
2004	29.5	73.4
2005	36.7	84.3
2006	44.7	110.6
2007	46.5	116.1
2008	30.9	75.6
2009	69	154.9
2010	89.2	215
2011	64.4	152.6
2012	97.9	228.3
2013	53.2	122.6

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