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Estimates of unreported SBT catch by CCSBT non-cooperating non-member states between 2007 and 2020

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EXECUTIVE SUMMARY

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Management of southern bluefin tuna (SBT) requires knowledge of the total catch. Non-cooperating non-members of the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) do not report SBT catches to the Commission, and estimates of this unreported catch are required. This has been achieved in previous iterations of the work (CCSBT-ESC/1609/BGD02/Rev.1; CCSBT-ESC/1909/33; CCSBT-OMMP/2006/04) by fitting a two-part statistical model to the CCSBT catch rate data, and using the estimated catch rate to predict the catch from non-member effort data collected by the other tuna RFMOs (the Indian Ocean Tuna Commission, International Commission for the Conservation of Atlantic Tuna and Western Central Pacific Fisheries Commission). The same approach was applied here, with an update to the estimation model to include an interaction between CCSBT statistical area and calender year. This was necessary to fit recent increases in the CCSBT catch rates, particularly at higher latitudes.

Non-member catches were estimated under an assumed catch rate equal to either the Japanese (JP) or Taiwanese (TW) fleets, representing target and non-target SBT fisheries respectively. Catch estimates under each of these assumptions were taken to represent a range of possible values. Coefficient estimates for these flags were lower in the new model, leading to a reduction in the estimated non-member catch, compared with the previous (2019) iteration of the work. However, non-member effort has simultaneously increased. Using the updated model and data, non-member catch was estimated to be 500 – 1500 tonnes between 2018 and 2020, which overlaps with previous estimates.

Inclusion of a spatio-temporal interaction in the model improved fit to the data, and we suggest that development of this approach would be a productive avenue for future research.

1. INTRODUCTION

The level of unaccounted mortality (UAM) by non-members of the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) is a key input to assessments of stock status for southern bluefin tuna (SBT) and execution of the Management Procedure (MP) that is used to recommend catches. However there is no reliable information available on SBT catch by non-cooperating non-members (NCNMs) of the CCSBT. Analysis of the effort data reported to other regional fisheries management organisations (RFMOs), particularly 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 (e.g. Larcombe 2014, Francis & Hoyle 2019). However, SBT catch is generally not reported to the IOTC, WCPFC or ICCAT (International Committee for the Conservation of Atlantic Tunas), even though these tuna fleets likely take quantities of SBT bycatch in their albacore, bigeye and yellowfin target fisheries. Some catches may also be targeted, and in general, the extent to which non-member SBT catches are due to targeted or bycatch fishing is unknown.

Following work by the Extended Scientific Committee in 2014 (ESC19), two separate papers were presented to ESC20 that provided estimates of non-member catches of SBT from fleets reporting to the IOTC and WCPFC (Chambers & Hoyle 2015, Hoyle & Chambers 2015). Edwards et al. (2016) presented updates (including ICCAT effort data) to ESC21 (CCSBT 2016), and Edwards et al. (2019) included revisions to the data that increased the estimated non-member catches for the Indian and Atlantic Oceans (ESC24; CCSBT 2019). Further work was conducted by Edwards et al. (2020) and presented to the 11th Operating Model and Management Procedure (OMMP) Technical Meeting.

In 2021, the ESC recommended that the non-member effort timeseries be updated to support execution of the MP in 2022 (CCSBT 2021), and this was reported to the 12th OMMP Technical Meeting (Edwards & Hoyle 2022). The CCSBT SBT stock assessment is due to be updated in 2023, and therefore updates to the UAM estimates are required. The current work is intended to fulfill that objective. These UAM updates are based on the methodology described in Edwards et al. (2019) and effort values reported to OMMP12 by Edwards & Hoyle (2022).

2. DATA AND METHODS

2.1. Methodology

The data preparation and analyses follows that described by Edwards et al. (2019) and Edwards et al. (2020) and can be summarized in the following steps:

1. Obtain catch, effort and size data from member and cooperating non-member states reporting to CCSBT by $5^\circ \times 5^\circ$ grid cell, year and month, for the Pacific, Indian and Atlantic oceans.
2. Model length data in order to estimate catch weight in tonnes for CCSBT member fleets that report catches in numbers only (i.e. Japanese fleet).
3. Create adjusted CCSBT effort data for Japan (JP), Korea (KR) and Taiwan (TW) that includes unreported, zero-catch effort recorded in the WCPFC, IOTC and ICCAT data bases.
4. Fit statistical models to catch and adjusted effort data for all CCSBT fleets and estimate spatial and temporal covariates contributing to the catch per unit effort.
5. Use the model results to predict the non-member SBT catch per unit effort for spatio-temporal strata, and based on two alternate assumptions: all non-member effort has the same catchability as estimated for JP, and all non-member effort has the same catchability as

estimated for TW. These fleets represent fisheries in which SBT is largely a target (JP) or a bycatch species (TW).

6. Obtain longline fishing effort reported to the WCPFC, IOTC and ICCAT by non-member, non-cooperating states, and allocate to $5^\circ \times 5^\circ$ grid cell, by year and month.
7. Estimate catch for non-member states by multiplying inferred catch rates by the effort per strata and summing across strata.

2.2. CCSBT catch and effort data

Longline catch and effort data for parties reporting to the CCSBT were obtained directly from the secretariat, up to and including 2020. The CCSBT statistical area definitions are illustrated in Figure 1. Data were aggregated by flag, year, month and $5^\circ \times 5^\circ$ grid cell, with the exception of data from South Africa (ZA) which was reported at a higher spatial resolution. Data from ZA were incomplete for 2019 and 2020 and were therefore excluded. TW data from 2017, 2018 and 2019 were also not present in the data. The effect of these missing data on the final estimates of non-member catch could not be evaluated.

Minor grooming of the data were required, namely the removal of a few exceptionally high catch rate records (greater than 3 kilograms per hook) and sporadic fishing by Korea (KR) in the Pacific. Catches reported to CCSBT prior to 2007 are known to be unreliable (Polacheck 2012). Therefore, we used data from 2007 onwards to parameterise the models and to predict non-member catches.

When preparing the CCSBT data for estimation of the catch rate, estimates of the "adjusted" member effort were created, as described by Edwards et al. (2019). This procedure attempts to account for non-reporting of zero-catch effort by CCSBT members to the CCSBT, which may therefore introduce a bias in the nominal CCSBT catch rates. Calculation of an adjusted effort was conducted by substituting JP, KR and TW effort collected from the other tuna RFMOs (tRFMOs; see below), in cases where this effort was higher than the effort reported to the CCSBT (Edwards et al. 2019). Using the adjusted effort is considered the preferred approach (CCSBT 2016), since an upward bias in the CCSBT catch rates would otherwise translate into an upward bias in the estimated non-member catches. Differences in the Adjusted and Unadjusted effort and catch rates per flag are illustrated in Figure 2, and per statistical area in Figure 3.

The spatial distribution of Adjusted CCSBT catch rates by flag and year are mapped per grid cell in Figures 4 and 5 respectively. There are notable differences in both the amplitude and distribution of catch rates between flags, years and statistical areas. Most important are the differences between catch rates for JP and TW fleets. These are assumed to be targeted (JP) and bycatch (TW) SBT fisheries. Both have a circumpolar distribution. But the TW fleet fishes at lower latitudes, with low catch rates, whilst the JP fleet fishes at higher latitudes at a higher catch rate. There has also been an increase in the Adjusted mean catch rate over time. This change is largely confined to the statistical areas 8 and 9, but also 6 and 7.

Following Hoyle & Chambers (2015), we considered JP catch and effort data to be essential for estimating predicted catch rates, because of the spatial and temporal coverage of the JP fleet, and their relatively consistent fishing methods. However, in contrast to other members, a large proportion of the JP data are reported to the CCSBT in catch numbers, not weight, which makes it necessary to convert the catches in number to catches in weight. This was achieved using methods described in Edwards et al. (2019), including the update by Edwards et al. (2020) that all discarded individuals were assumed to be 18 kilograms.

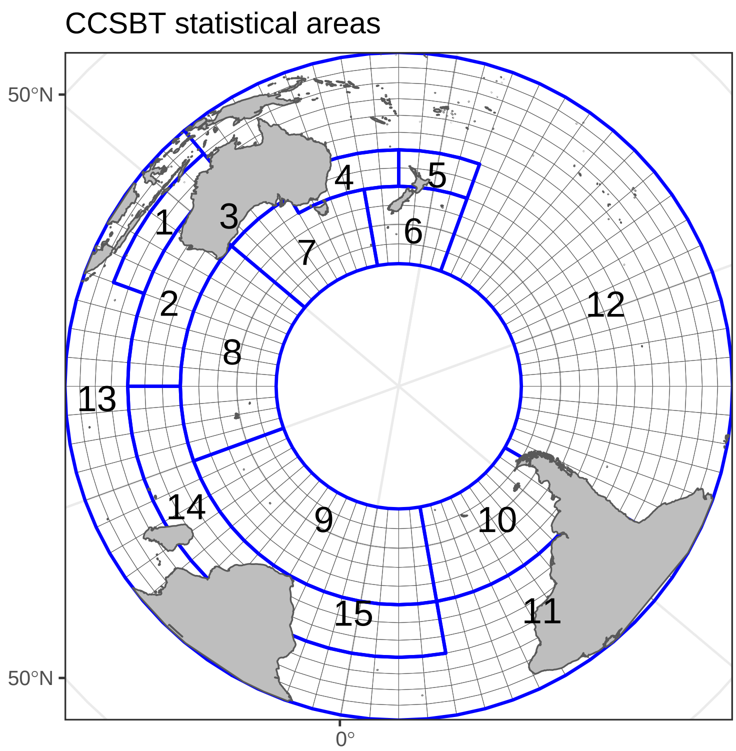


Figure 1: Spatial boundaries for the CCSBT statistical areas. The mapped area is cropped at 0 **and** $60°$**S, which are the CCSBT latitudinal limits.**

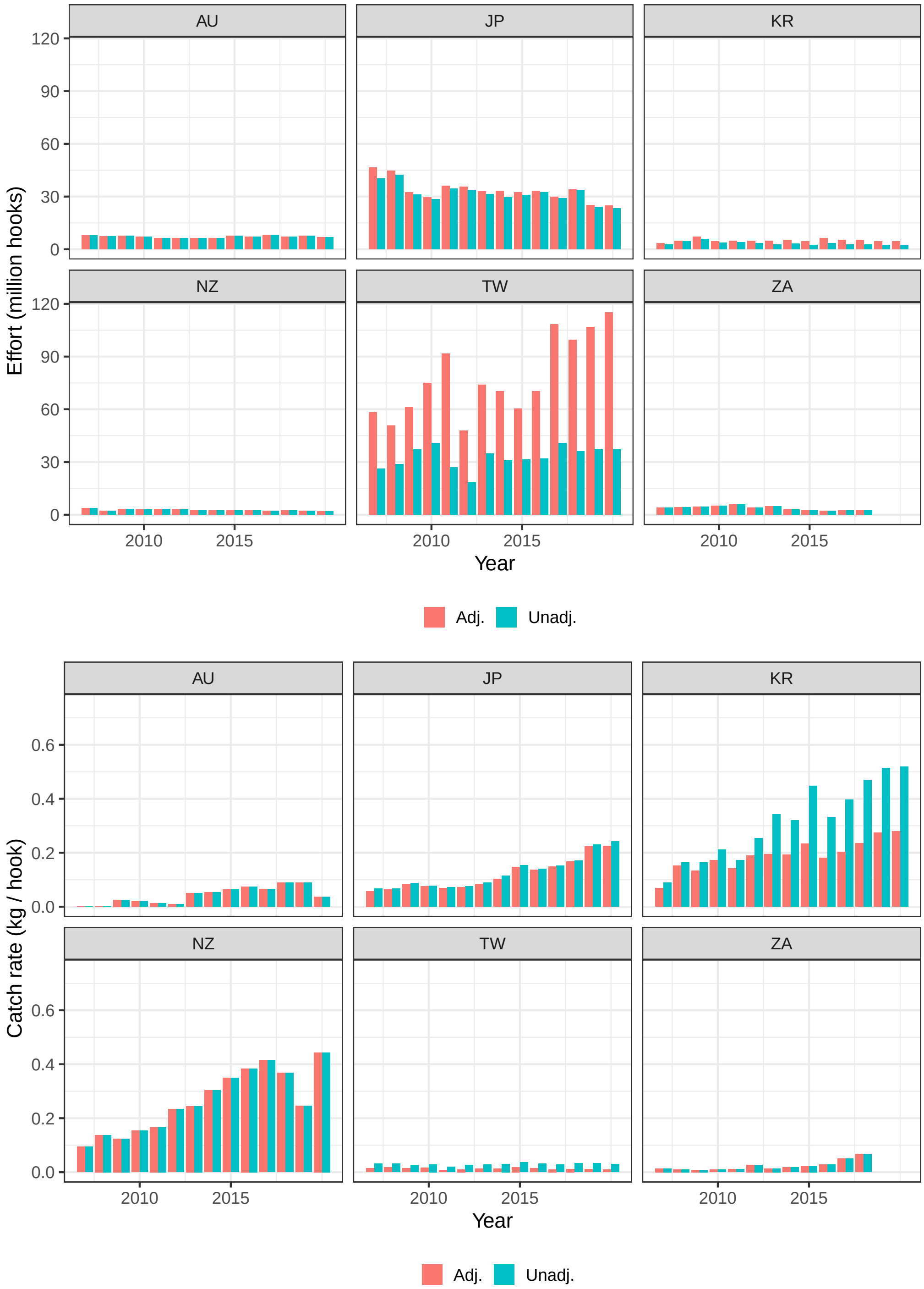


Figure 2: Unadjusted and Adjusted empirical CCSBT effort (top panel) and catch rates (bottom panel), per CCSBT member.

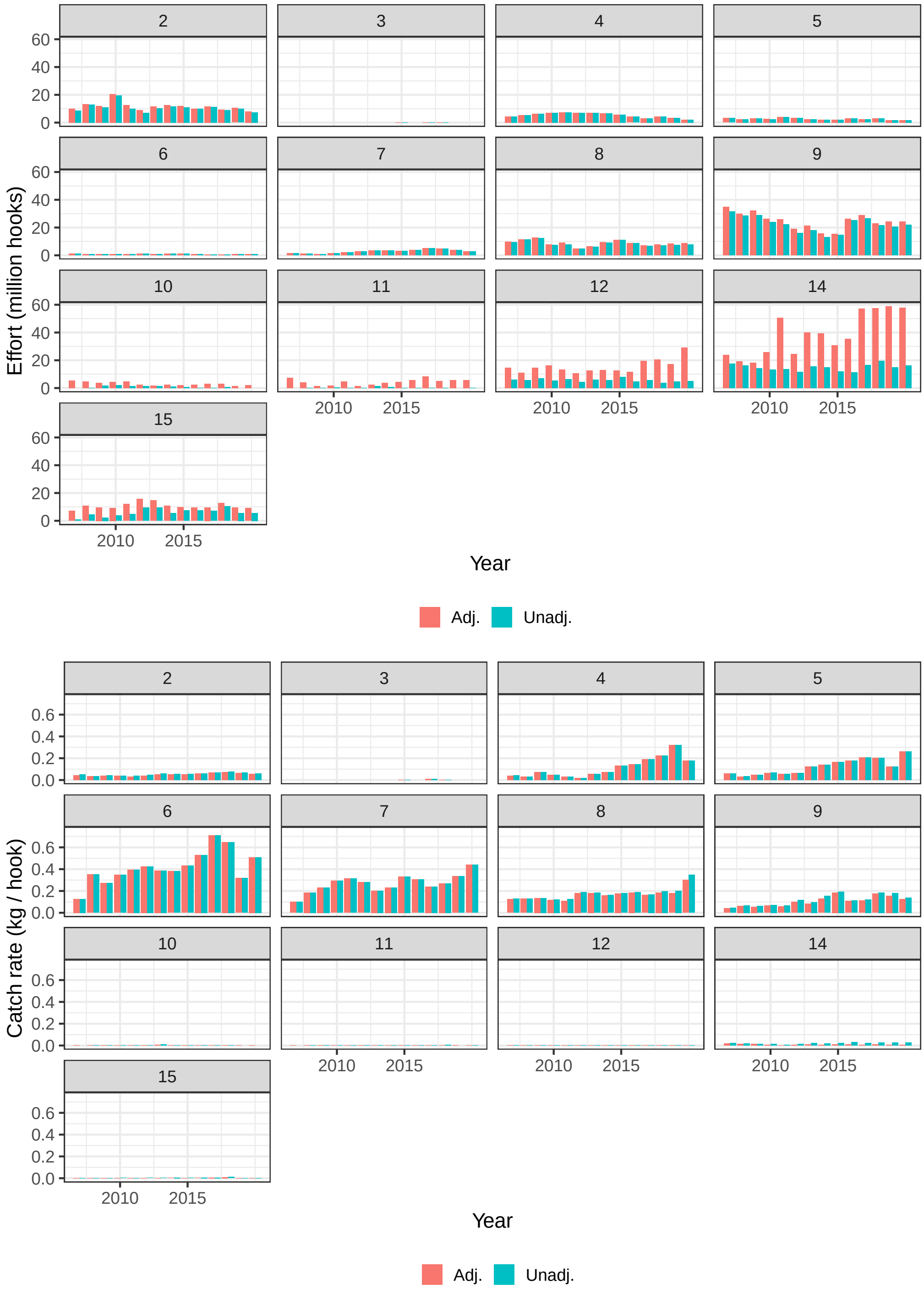


Figure 3: Unadjusted and Adjusted empirical CCSBT effort (top panel) and catch rates (bottom panel), per CCSBT statistical area.

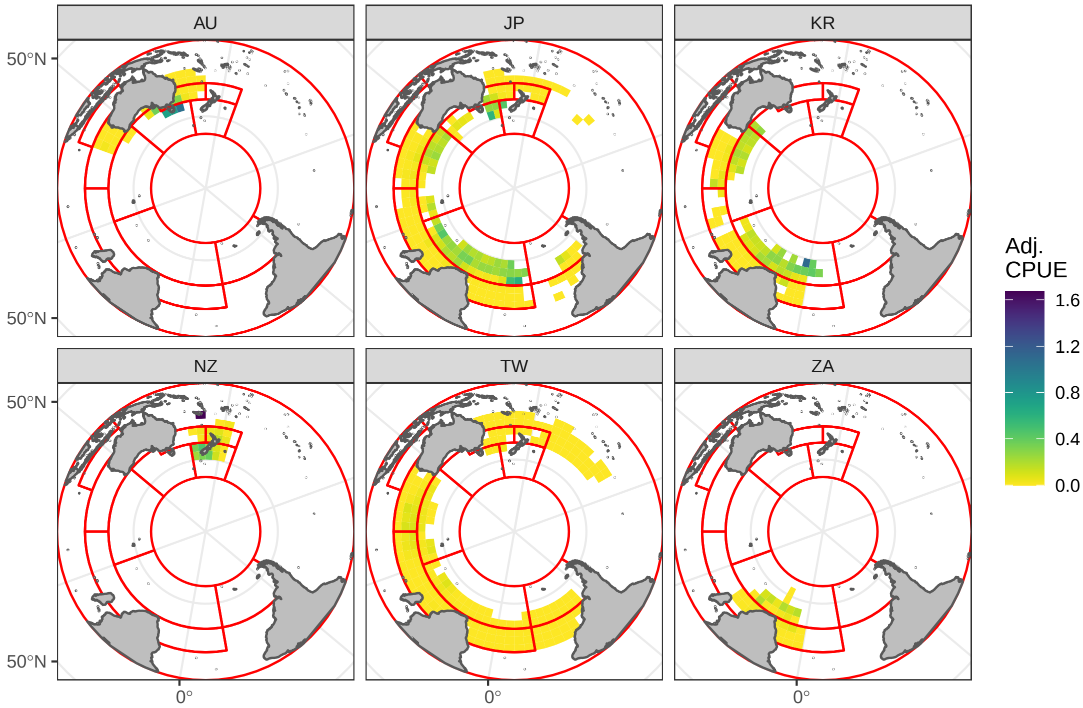


Figure 4: Empirical CCSBT catch rates, assuming an Adjusted catch rate in kg per hook, per CCSBT member flag. Arithmetic mean catch rate values across years are shown.

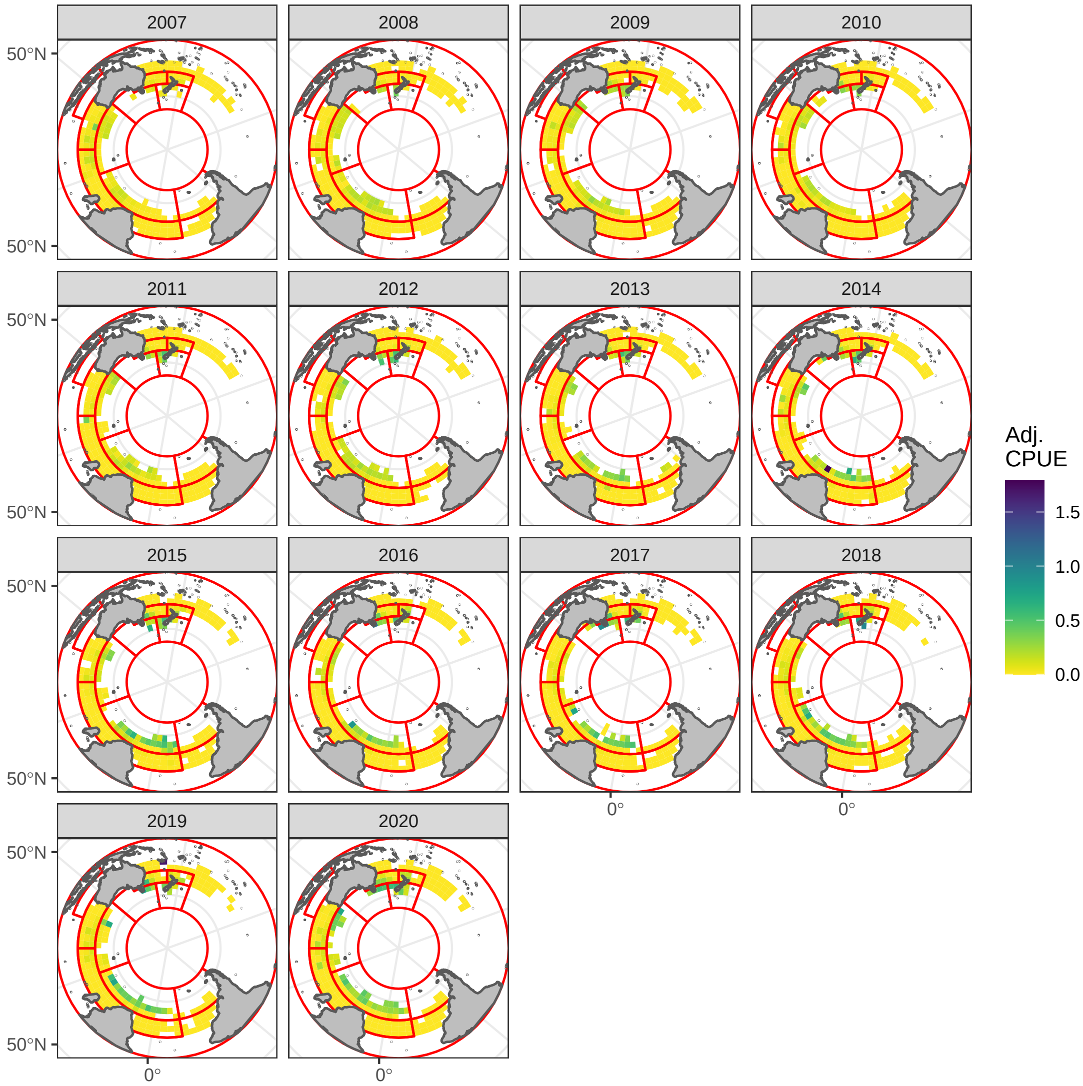


Figure 5: Empirical CCSBT catch rates, assuming an Adjusted catch rate in kg per hook, per year. Arithmetic mean catch rate values across flags are shown.

2.3. Effort data from other tuna RFMOs

Longline effort data from 2007 onwards were collected from the other tRFMOs as detailed by Edwards & Hoyle (2022):

- **IOTC:** Publicly available longline effort data were obtained directly from www.iotc.org.
- **ICCAT:** Task II longline effort data were obtained directly from the databases available at www.iccat.int.
- **WCPFC:** Effort data from the WCPFC is submitted to the CCSBT, and was obtained from the secretariat.

Effort data from the Inter-American Tropical Tuna Commission (IATTC) were not included, due to likely low catches of SBT in that region.

Effort is typically reported by $5° \times 5°$ grid, by month, year and flag. For the IOTC and WCPFC, all the effort data are represented in the database extracts. For ICCAT however, the effort data are incomplete, since only strata containing effort from three or more vessels is released publicly. The amount of effort missing is unknown. In preparing the data, a small amount of effort is reported in days fished rather than hooks. These were converted to hooks using the median number of hooks per day per flag, or else an assumed three thousand hooks per day. The imputed data amount to $< 1\%$ of the effort for each of the other tRFMOs.

All effort data were assigned to the centre point of each grid, to allow data from the other tRFMOs to be aligned. Consistent with previous work, only effort from below the parallel at 20°S was retained. We note that some SBT spawn above 20°S near Indonesia, and this assumption may need to be revised. Catch data from the CCSBT were further used to identify grid cells likely to yield a positive SBT catch from non-member fleets: specifically, only other tRFMO effort within grid cells with corresponding CCSBT effort for that year and quarter, were retained.

The spatial limits of each other tRFMO and the distribution of non-member effort per other tRFMO are illustrated in Figure 6. No spatial overlap was observed in the effort data retained from each of the other tRFMOs. The total non-member effort over time and per CCSBT statistical area is shown in Figure 7. Finally, the total non-member effort per year and other tRFMO is listed in Table 1.

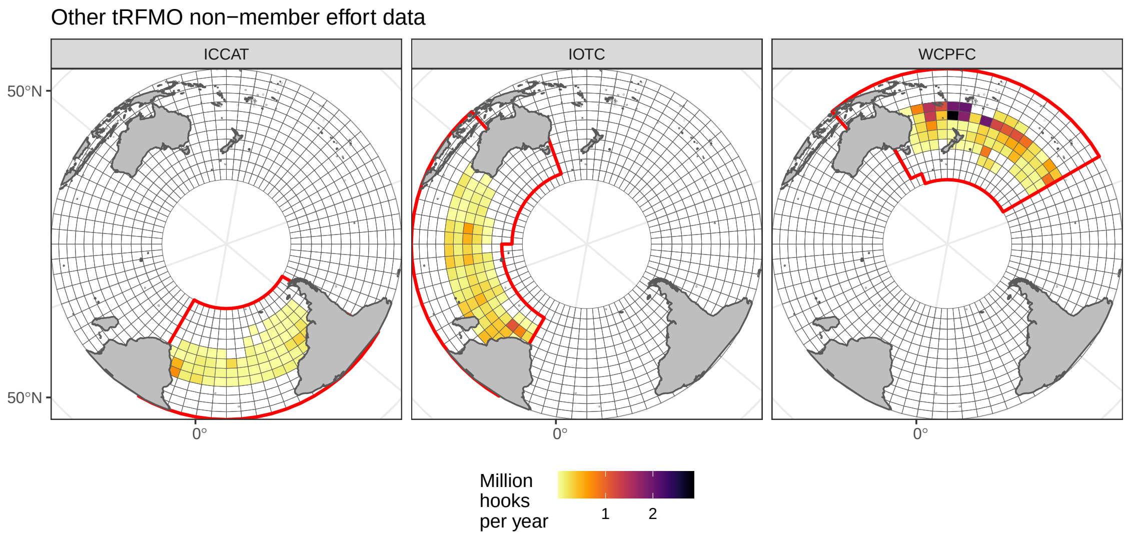


Figure 6: Spatial boundaries for each of the other tRFMOs (excluding IATTC) showing the distribution of non-member fishing effort (million hooks per year).

Figure 7: Total non-member effort (million hooks) per year per CCSBT statistical area.

Table 1: Sum of non-member effort (million hooks) per otRFMO. Effort outside of the spatio-temporal domain of the CCSBT effort data (defined per year, quarter and grid cell) were discarded under the assumption that SBT catch was likely negligible.

Year	ICCAT	IOTC	WCPFC	Total
2007	6.26	4.00	18.72	28.98
2008	4.11	1.83	15.81	21.75
2009	2.90	4.15	17.97	25.02
2010	3.23	8.78	41.36	53.37
2011	2.62	3.43	22.33	28.38
2012	2.76	4.05	29.33	36.14
2013	8.91	5.42	29.54	43.87
2014	3.26	6.54	30.53	40.33
2015	2.62	8.87	36.48	47.97
2016	3.55	13.51	22.41	39.47
2017	3.35	24.70	31.74	59.79
2018	2.96	23.72	31.10	57.78
2019	2.61	24.60	29.88	57.09
2020	2.91	25.28	36.74	64.93

2.4. Predictive model

A two-part (delta) log-normal statistical model was used to fit to the CCSBT catch rates and predict the unreported catches from non-member effort. All fitting and prediction was carried out using native functions in the R statistical package (R Core Team 2021).

The model follows closely that used by Edwards et al. (2019). The binomial model part assumed a logit-link function and contained coefficients for year:quarter, month, grid cell (defined by the Cartesian coordinates), flag and effort:

$$\text{logit}(\text{catch} > 0) = \beta_0 + \beta_{\text{year:quarter}} + \beta_{\text{core}} + \beta_{\text{flag}} + \beta_{\text{lat:lon}} + ns(\text{month}) + ns(\log(\text{hooks}))$$

Interaction terms were constructed using combined factor levels for year:quarter and lat:lon. This restricts estimation to factor combinations with data present and therefore limits the prediction of non-member catches to those strata. A cubic spline ns() with 4 degrees of freedom was used to describe the influence of month, treated as a continuous integer variable. Similarly for log(hooks) with 10 degrees of freedom. The inclusion of effort as a predictor was because the data are aggregated per strata, and the probability of a positive catch record within a strata will be dependent on the effort. We also included a core covariate, to identify whether the effort took place within or outside of the core spatio-temporal strata. Core strata were identified as as months 4 to 9, in statistical areas 4 to 9. We also included the flag, because it has a clear influence on the catch rates.

The model for positive catches was updated from a transformed linear regression to a general linear model with log-link function and effort included as an offset term:

$$\log(\text{catch}) = \beta_0 + \beta_{\text{year:area}} + \beta_{\text{flag}} + \beta_{\text{lat:lon}} + ns(\text{month}) + \log(\text{hooks})$$

In the previous work, a year-flag interaction was included to accommodate increases in the catch rate over time. However this was found to be inadequate given the updated data (see Section 3). To accommodate spatio-temporal changes in the catch rate (Figure 5) we instead included a year:area interaction term as a combination of year and area factor levels, which led to an improved ability of the model to predict the catches. However not all statistical areas supported estimation of this interaction. Specifically, a year:area interaction was estimated for CCSBT statistical areas 4, 6, 7, 8, 9 and 14. For the remaining areas, the area coefficient was assumed to be constant over time. As a consequence of this change, estimated coefficients for JP and TW were reduced, with implications for the prediction of unreported catches by non-members (see Section 3.4).

When updating the model to include a year:area interaction, we further developed a global model to increase the data available for the fit. Previously, model runs had been conducted for Indian/Atlantic and Pacific regions separately. Although we retain these regional definitions in the current work for purposes of model development and validation, we perform final predictions using a single global model.

When predicting catches, the catchability for each non-member fleet is unknown, and we therefore bounded the range of possible values using the JP and TW catchability coefficients estimated from the CCSBT data. These are referred to as "surrogate" flags and represent fisheries in which SBT is assumed to be a target (JP) or a bycatch species (TW).

3. RESULTS

3.1. Application of previous (2019) model to updated CCSBT data

We fitted the previous model from Edwards et al. (2019) to the update CCSBT data extract. For comparison, we also provide model fits to the previous (2019) data. Residual diagnostics for this and subsequent model fits are shown in the Appendix.

Results are shown for the Indian/Atlantic region in Figures 8 and 9, and in in Figures 10 and 11 for the Pacific. In both instances, fit to the catch rate data per flag is reasonable, however prediction of the total catches is poor for the recent period. In the Indian/Atlantic region JP catches are underestimated (Figures 9), and in the Pacific JP catches are overestimated (Figures 11). This result suggests that the model is not suitable for prediction of the catches from non-member effort.

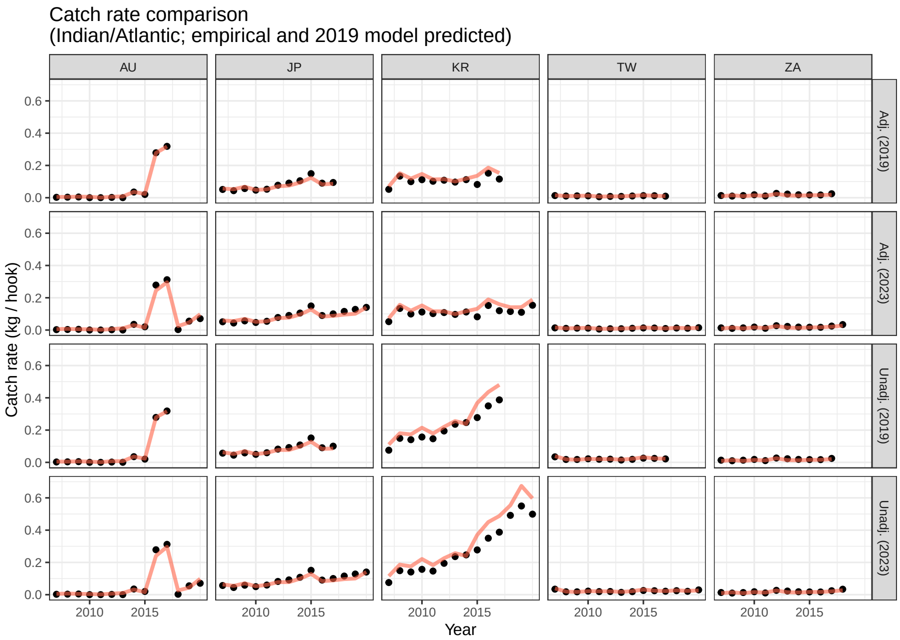


Figure 8: Model fit to empirical CCSBT catch rate data in the Indian/Atlantic region, per CCSBT member flag, using the previous (2019) model. Observed values are shown as points. Model runs assuming an Uadjusted and Adjusted catch rate are shown, for empirical data from the previous (2019) and updated (2023) assessments.

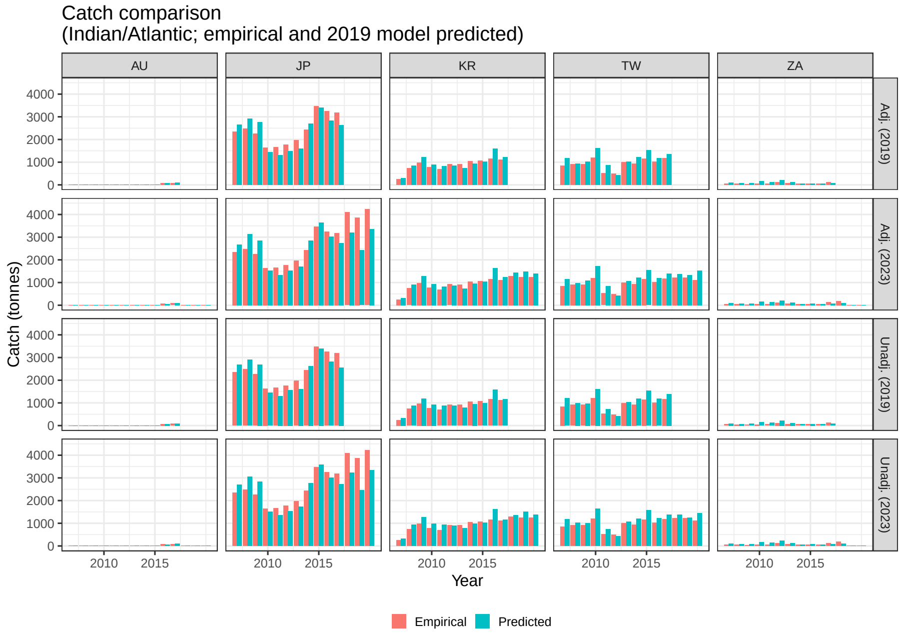


Figure 9: Prediction of empirical CCSBT catch data in the Indian/Atlantic region, per CCSBT member flag, using the previous (2019) model. Model runs assuming an Uadjusted and Adjusted catch rate are shown, for empirical data from the previous (2019) and updated (2023) assessments.

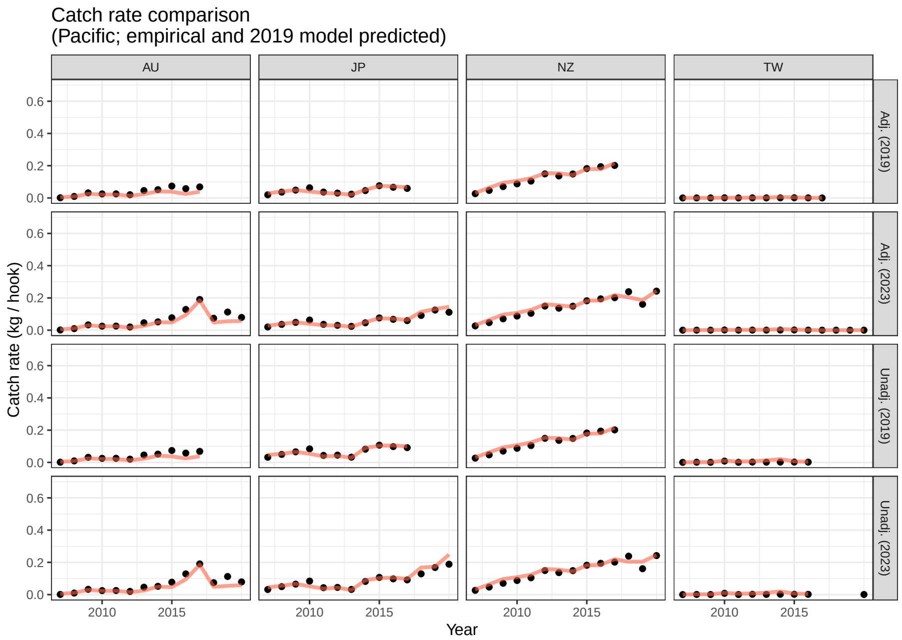


Figure 10: Model fit to empirical CCSBT catch rate data in the Pacific region, per CCSBT member flag, using the previous (2019) model. Observed values are shown as points. Model runs assuming an Uadjusted and Adjusted catch rate are shown, for empirical data from the previous (2019) and updated (2023) assessments. Note that no TW data were reported to the CCSBT in 2017, 2018 and 2019. When adjusting the effort for these TW data, we assume that there have been no catches.

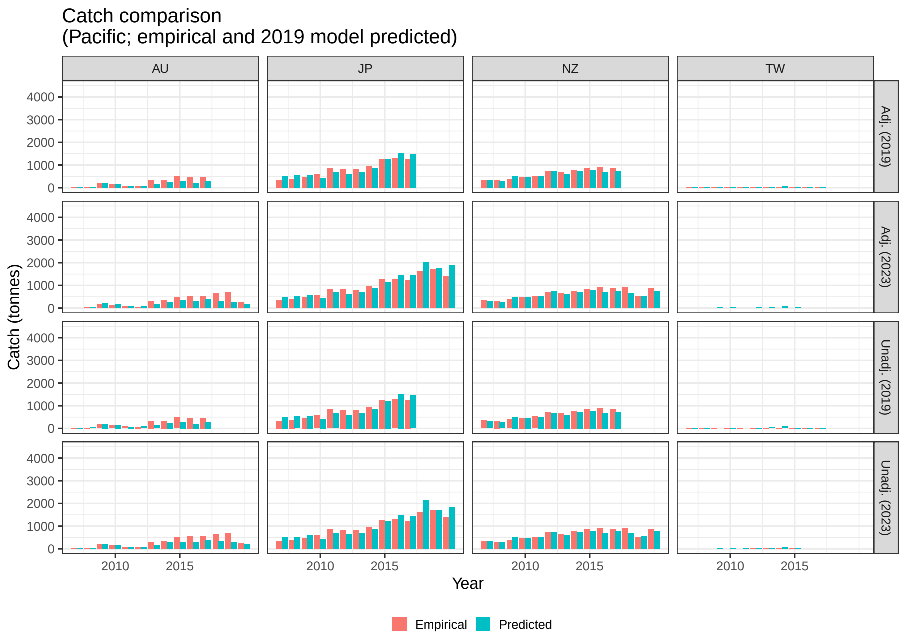


Figure 11: Prediction of empirical CCSBT catch data in the Pacific region, per CCSBT member flag, using the previous (2019) model. Model runs assuming an Uadjusted and Adjusted catch rate are shown, for empirical data from the previous (2019) and updated (2023) assessments.

3.2. Application of updated (2023) model to updated CCSBT data

Given poor performance of the previous (2019) model when applied to the updated CCSBT data, we applied the updated model described in Section 2.4. The previous (2019) model is retained for comparative purposes, replicating the results in the previous section.

In the Indian/Atlantic region the updated (2023) model is able to provide a better fit to the KR catch rate data, at the expense of fitting to the high AU catch rates in 2016 and 2017 (Figure 12). Fit to the catches rates for JP appear similar, but there is a noticeable difference in the predicted catches (Figure 13), with the updated model better able to predict the total catches for JP in recent years. This is more clearly illustrated in Figures 14 and 15, which show the residual differences in the predicted catch rate and catches, respectively. The previous (2019) model is underestimating the recent catch rate and catches for JP. This is similarly reflected in statistical area 8 (Figure 14), which is fished predominantly by JP and KR (Figure 4) and which has seen an increase in the catch rate over time (Figure 5).

In the Pacific, the updated (2023) model again provides a better fit to the JP data (Figures 16 and 17), although the improvement in this instance is smaller. The catch and catch rate residuals illustrated in Figures 18 and 19 indicate that, with the exception of New Zealand (NZ) data, the updated (2023) model yields a better prediction of the catch. This improved prediction of the catches is largely to due statistical areas 4 and 7, which are fished by JP and AU, and which has experienced an increase in the catch rate over time (Figures 4 and 5).

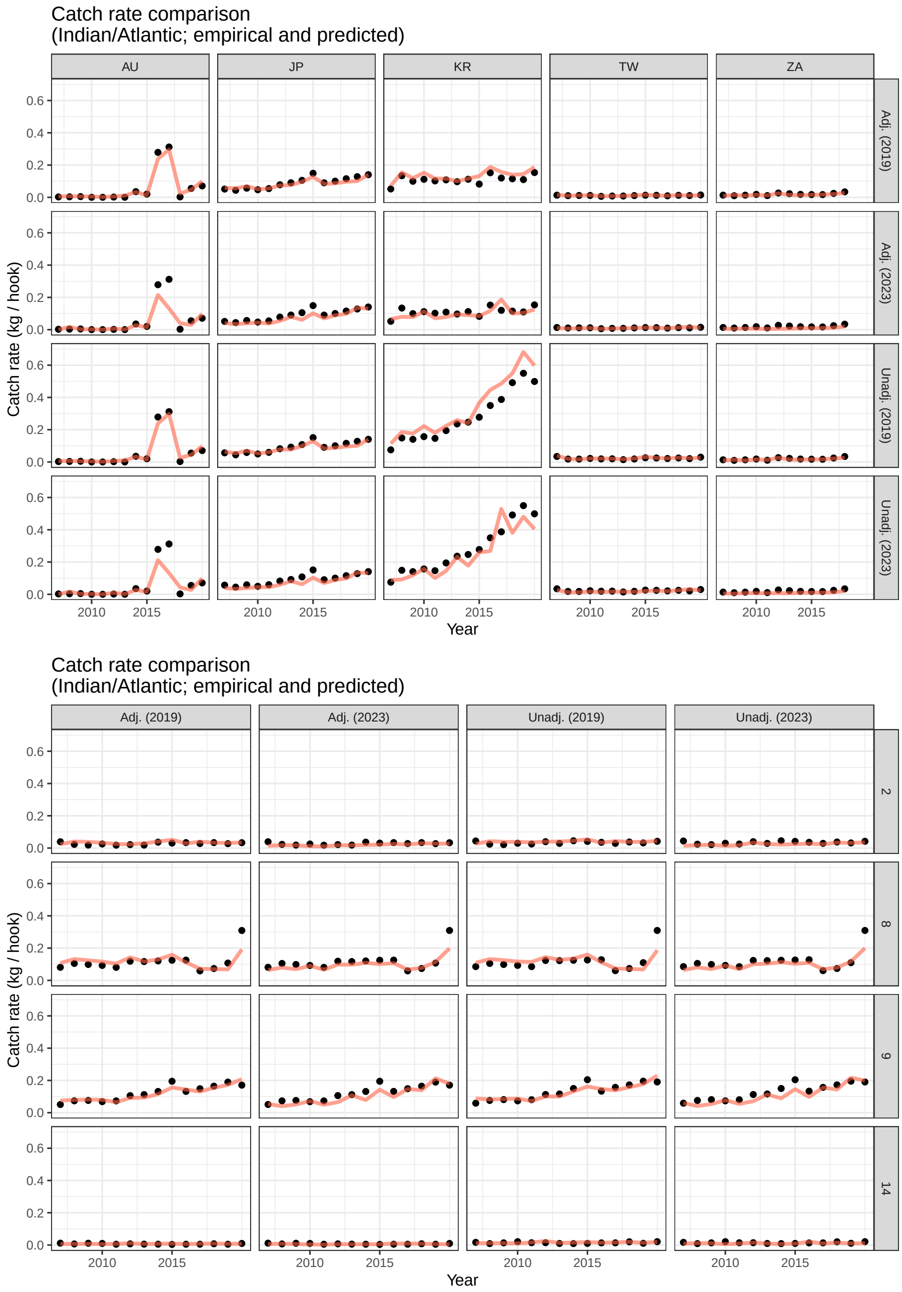


Figure 12: Model fits to updated (2023) empirical CCSBT catch rate data in the Indian/Atlantic region, per CCSBT member flag (top panel) and statistical area (bottom panel). Catch rate is calculated as the mean of the catch over effort. Only a subset of the most important areas, in terms of catch, are shown. Observed values are shown as points. Model runs assume either Uadjusted and Adjusted catch rates, using the previous (2019) and updated (2023) models.

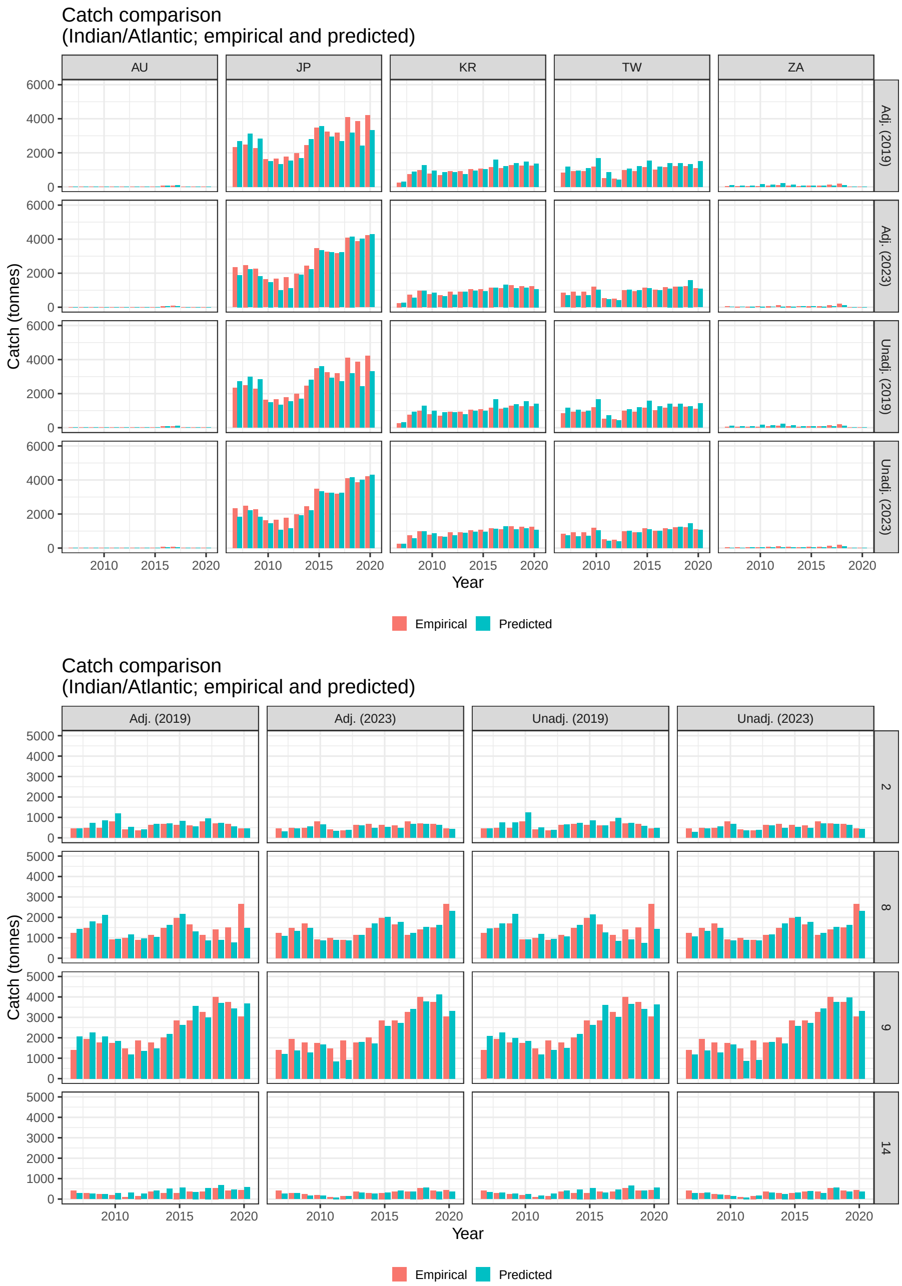
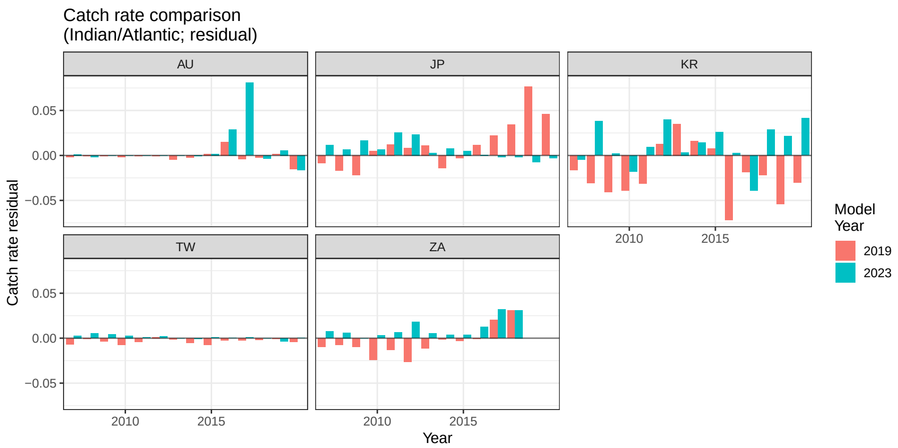


Figure 13: Prediction of empirical CCSBT catch data in the Indian/Atlantic region, per CCSBT member flag (top panel) and statistical area (bottom panel). Only a subset of the most important areas, in terms of catch, are shown. Model runs assume either Uadjusted and Adjusted catch rates, using the previous (2019) and updated (2023) models.



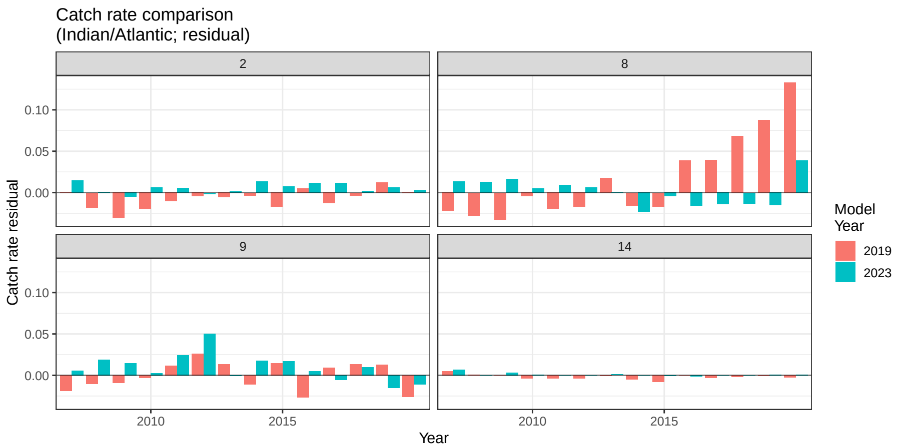
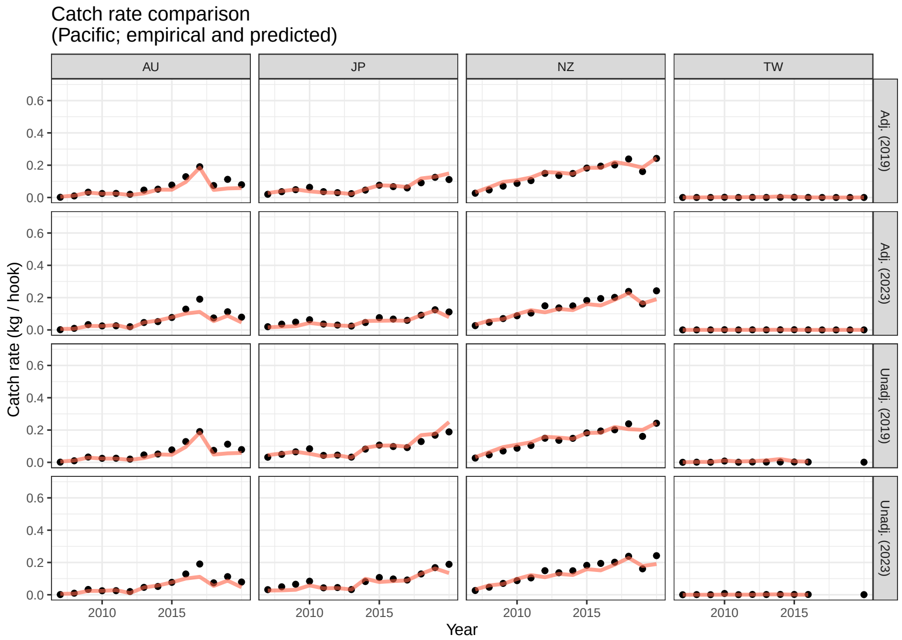


Figure 14: Residuals following prediction of the catch rate by flag (top panel) and statistical area (bottom panel) in the Indian/Atlantic region. Catch rate is calculated as the sum of the catch over the sum of the effort. Positive residuals indicate that the empirical value is greater than the model prediction. Only a subset of the most important areas, in terms of catch, are shown. Model runs assume an Adjusted CCSBT catch rate, using the previous (2019) and updated (2023) models.

Figure 15: Residuals following prediction of the catch by flag (top panel) and statistical area (bottom panel) in the Indian/Atlantic region. Positive residuals indicate that the empirical value is greater than the model prediction. Only a subset of the most important areas, in terms of catch, are shown. Model runs assume an Adjusted CCSBT catch rate, using the previous (2019) and updated (2023) models.



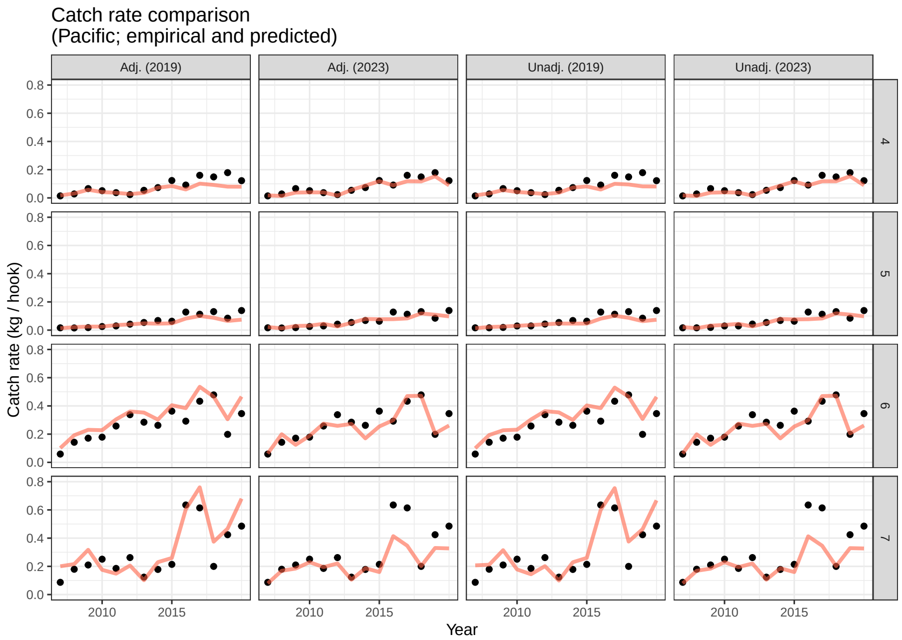


Figure 16: Model fit to updated (2023) empirical CCSBT catch rate data in the Pacific region, per CCSBT member flag (top panel) and statistical area (bottom panel). Catch rate is calculated as the mean of the catch over effort. Only a subset of the most important areas, in terms of catch, are shown. Observed values are shown as points. Model runs assuming an Uadjusted and Adjusted catch rate are shown, using the previous (2019) and updated (2023) models. Note that no TW data were reported to the CCSBT in 2017, 2018 and 2019.

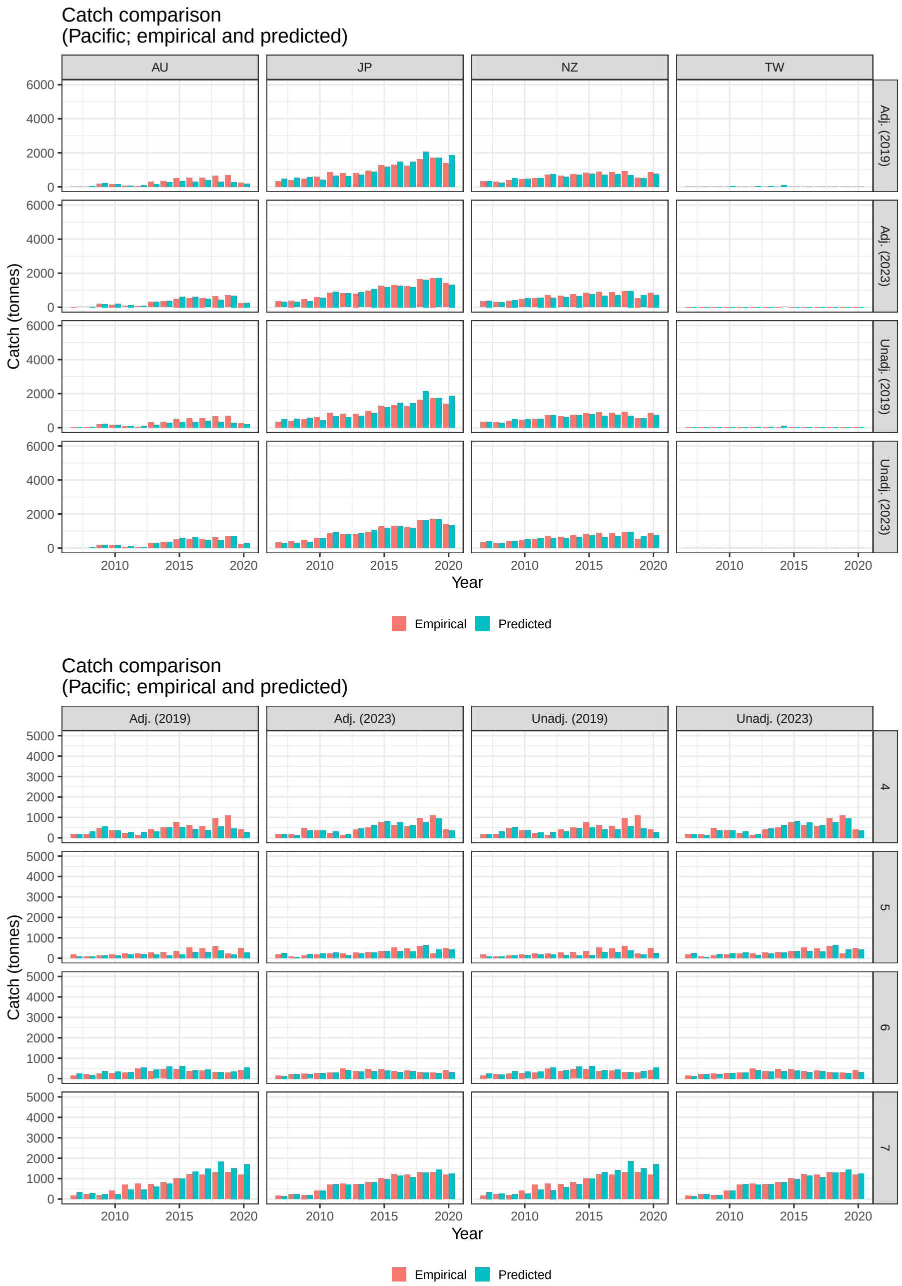


Figure 17: Prediction of empirical CCSBT catch data in the Pacific region, per CCSBT member flag (top panel) and statistical area (bottom panel). Only a subset of the most important areas, in terms of catch, are shown. Model runs assume either Uadjusted and Adjusted catch rates, using the previous (2019) and updated (2023) models.

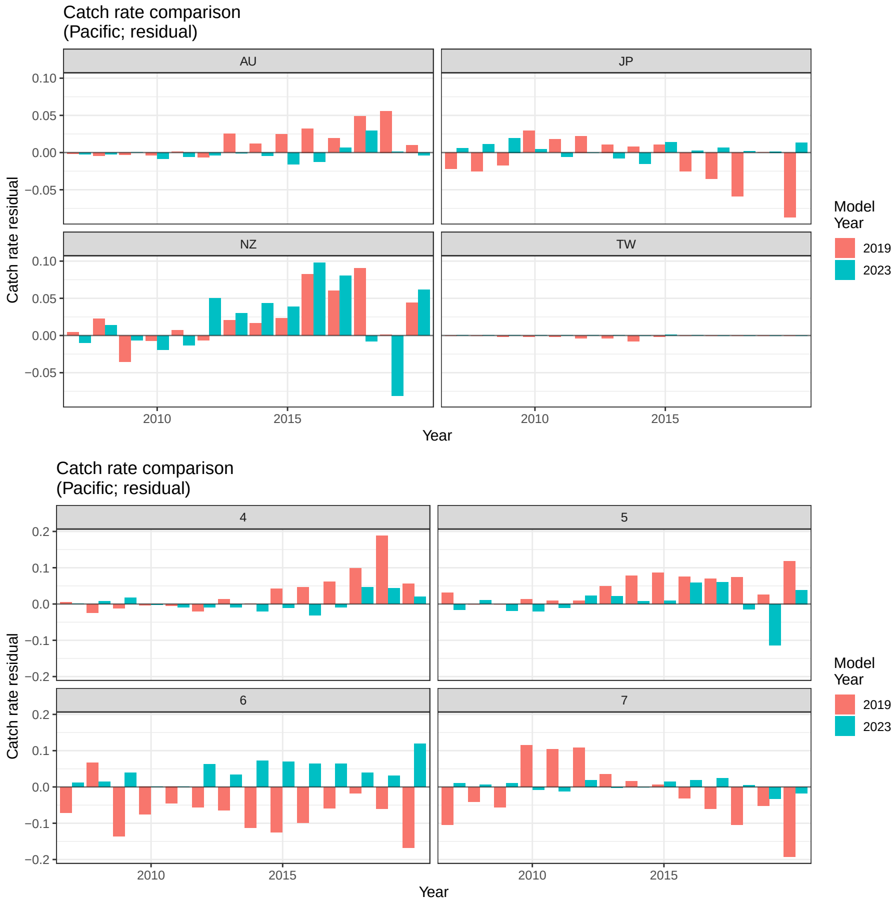


Figure 18: Residuals following prediction of the catch rate by flag (top panel) and statistical area (bottom panel) in the Pacific region. Catch rate is calculated as the sum of the catch over the sum of the effort. Positive residuals indicate that the empirical value is greater than the model prediction. Only a subset of the most important areas, in terms of catch, are shown. Model runs assume an Adjusted CCSBT catch rate, using the previous (2019) and updated (2023) models.

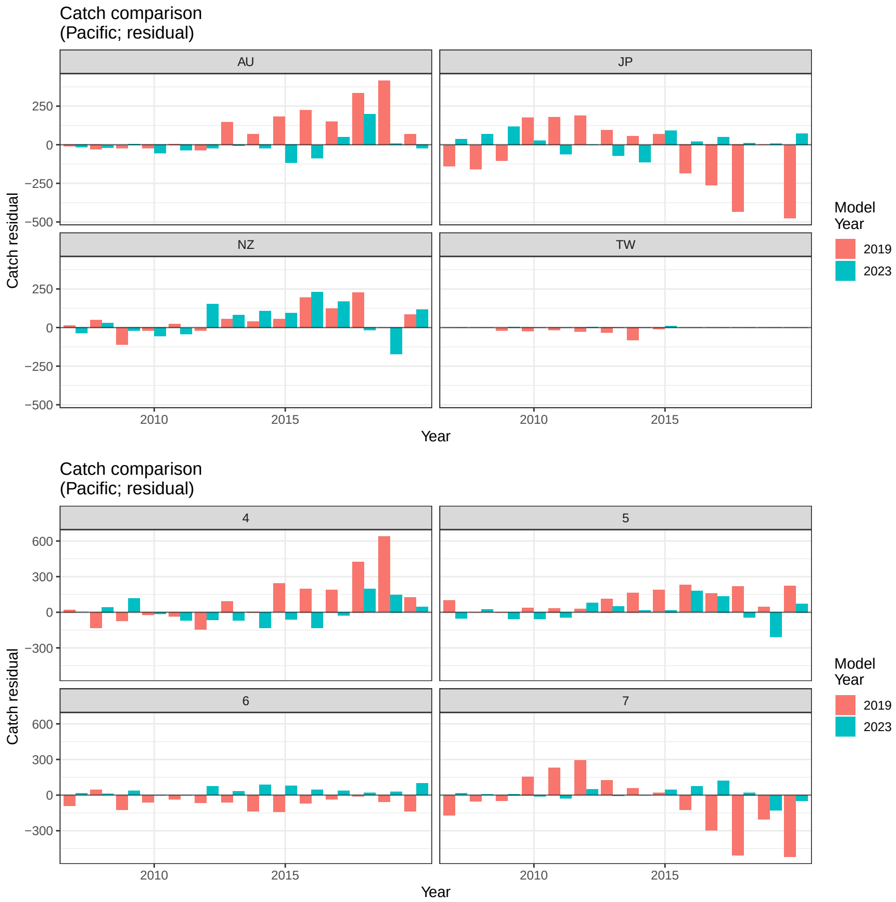


Figure 19: Residuals following prediction of the catch by flag (top panel) and statistical area (bottom panel) in the Pacific region. Positive residuals indicate that the empirical value is greater than the model prediction. Only a subset of the most important areas, in terms of catch, are shown. Model runs assume an Adjusted CCSBT catch rate, using the previous (2019) and updated (2023) models.

3.3. Application of global model to CCSBT data

In the previous section we demonstrated that a year – area interaction was beneficial to the prediction of total catch. However we were unable to estimate a spatio-temporal interaction for all statistical areas. To improve our ability to fit an interaction term for areas 4 and 7 (Figure 1), which in previous assessments have been split between Indian/Atlantic and Pacific regions, we constructed a global model that included all CCSBT catch rate data.

In Figures 20 and 21 it can be seen that the model provides a good fit to the catch rate data by flag, and by statistical area, and is similarly able to predict the catches (Figures 22 and 23). In Figures 24 and 25 we map the observed and model predicted catch rates, and demonstrate good predictive ability of the global model.

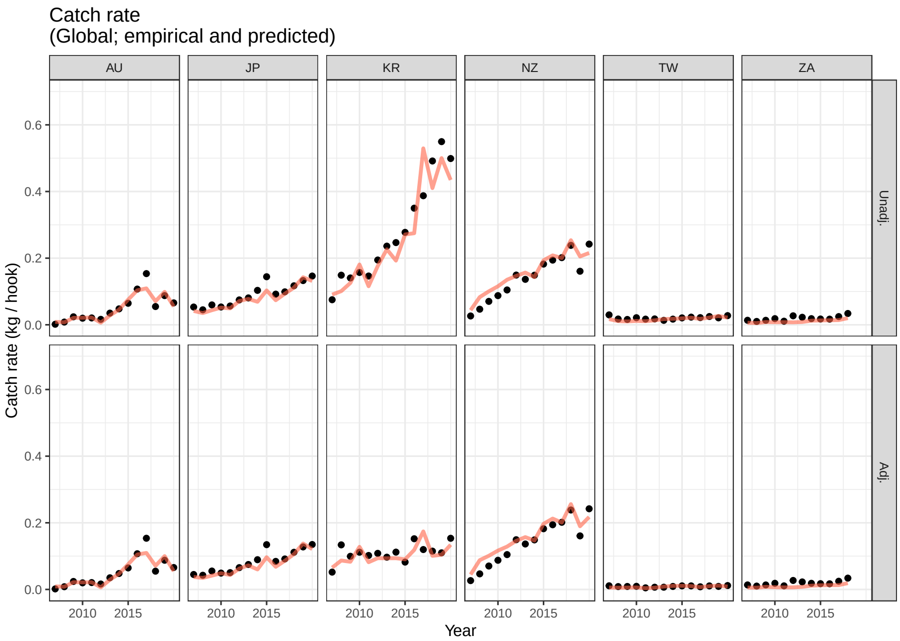


Figure 20: Global model fit to updated (2023) empirical CCSBT catch rate data, per CCSBT member flag. Catch rate is calculated as the mean of the catch over effort. Observed values are shown as points. Model runs assuming an Uadjusted and Adjusted catch rate are shown.

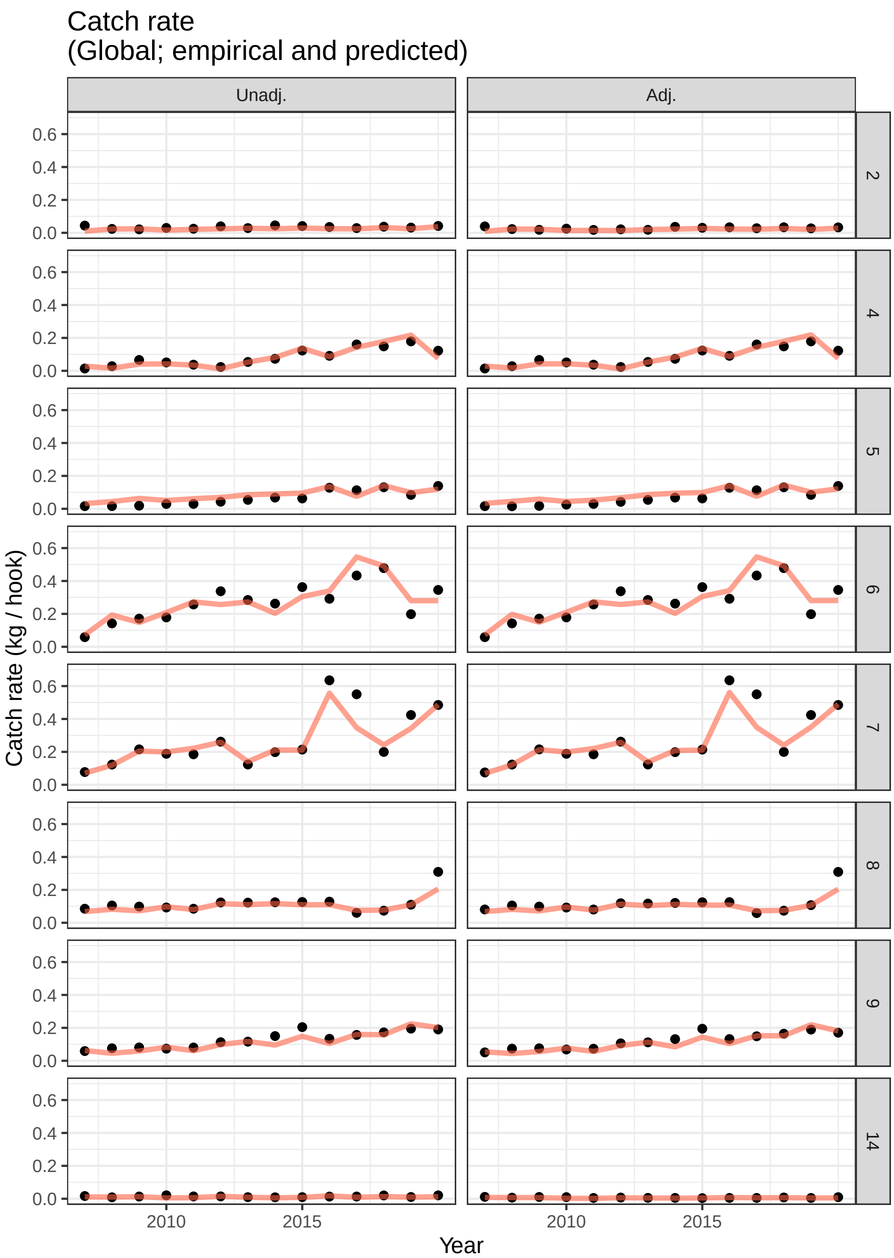


Figure 21: Global model fit to updated (2023) empirical CCSBT catch rate data, per CCSBT statistical area. Catch rate is calculated as the mean of the catch over effort. Observed values are shown as points. Model runs assuming an Uadjusted and Adjusted catch rate are shown.

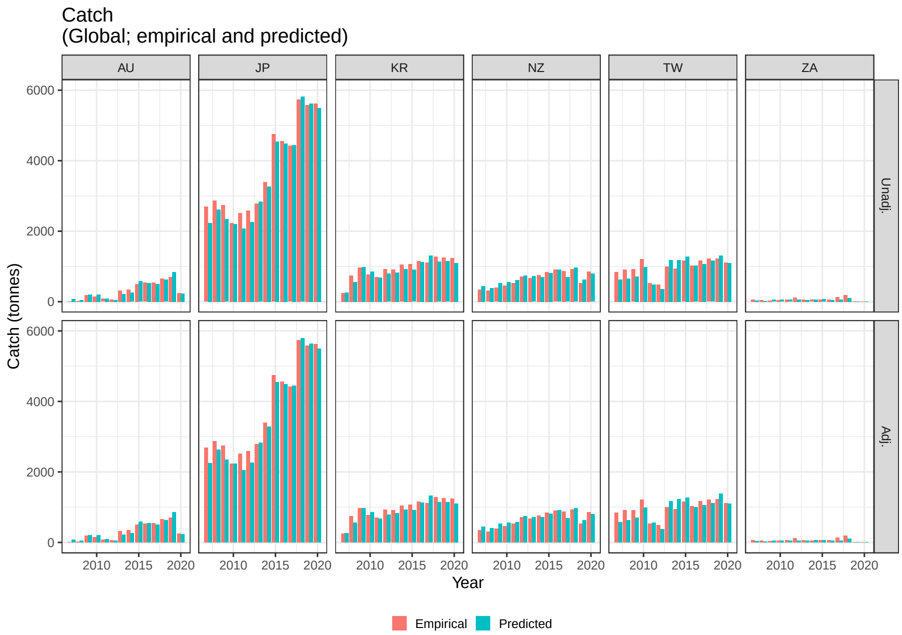


Figure 22: Global prediction of empirical CCSBT catch data, per CCSBT member flag. Model runs assuming an Uadjusted and Adjusted catch rate are shown.

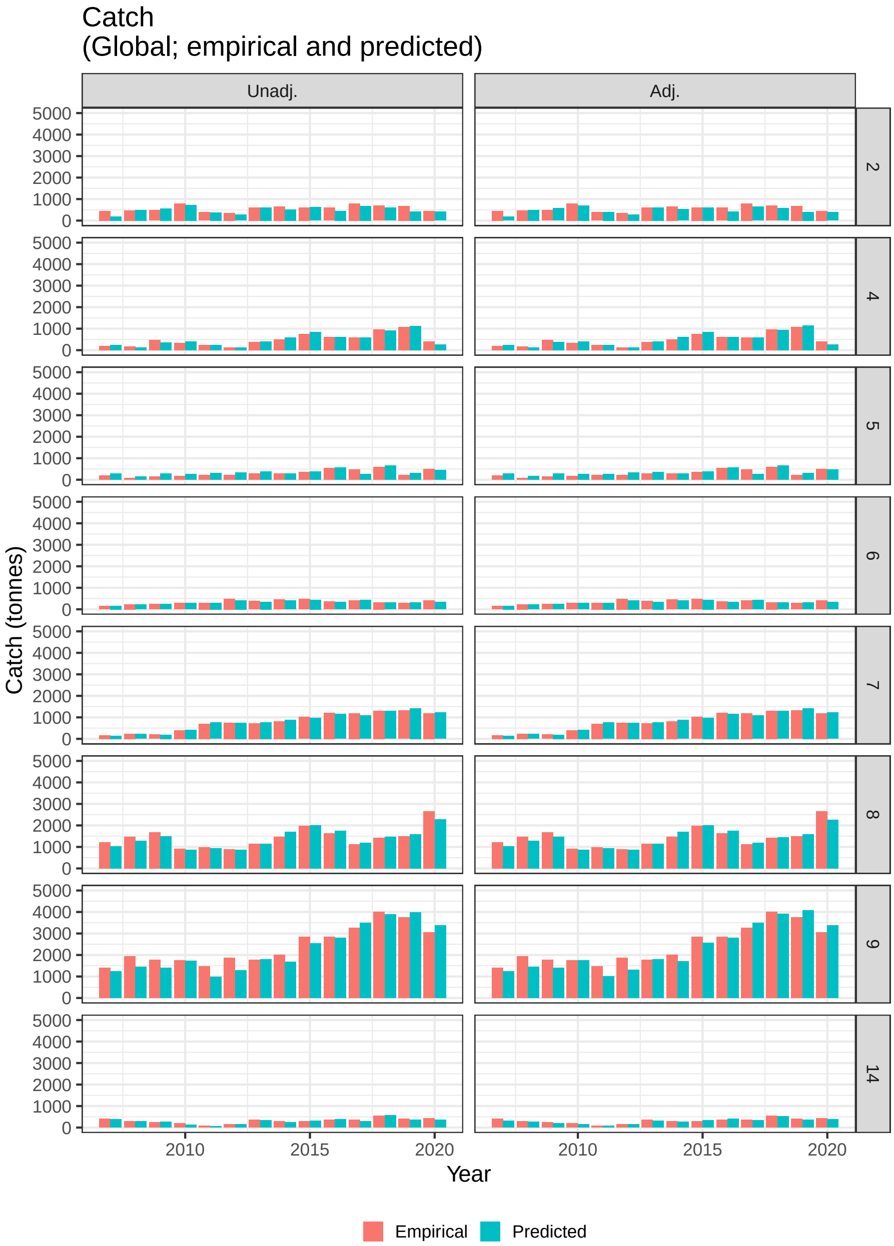


Figure 23: Global prediction of empirical CCSBT catch data, per CCSBT statistical area. Model runs assuming an Uadjusted and Adjusted catch rate are shown.

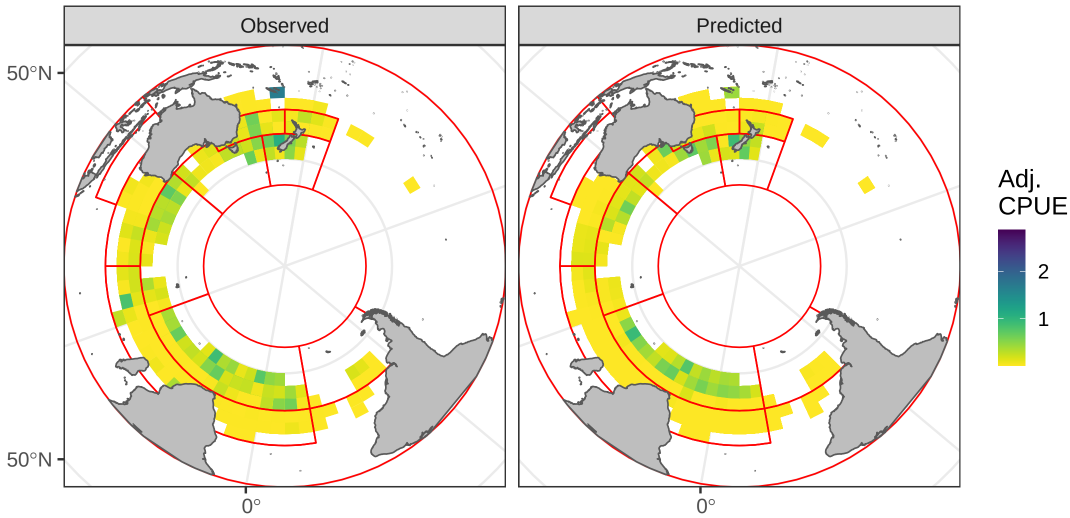


Figure 24: Global prediction of empirical CCSBT catch rate data, assuming an Adjusted catch rate. Catch rate is calculated as the mean of the catch over effort per grid cell

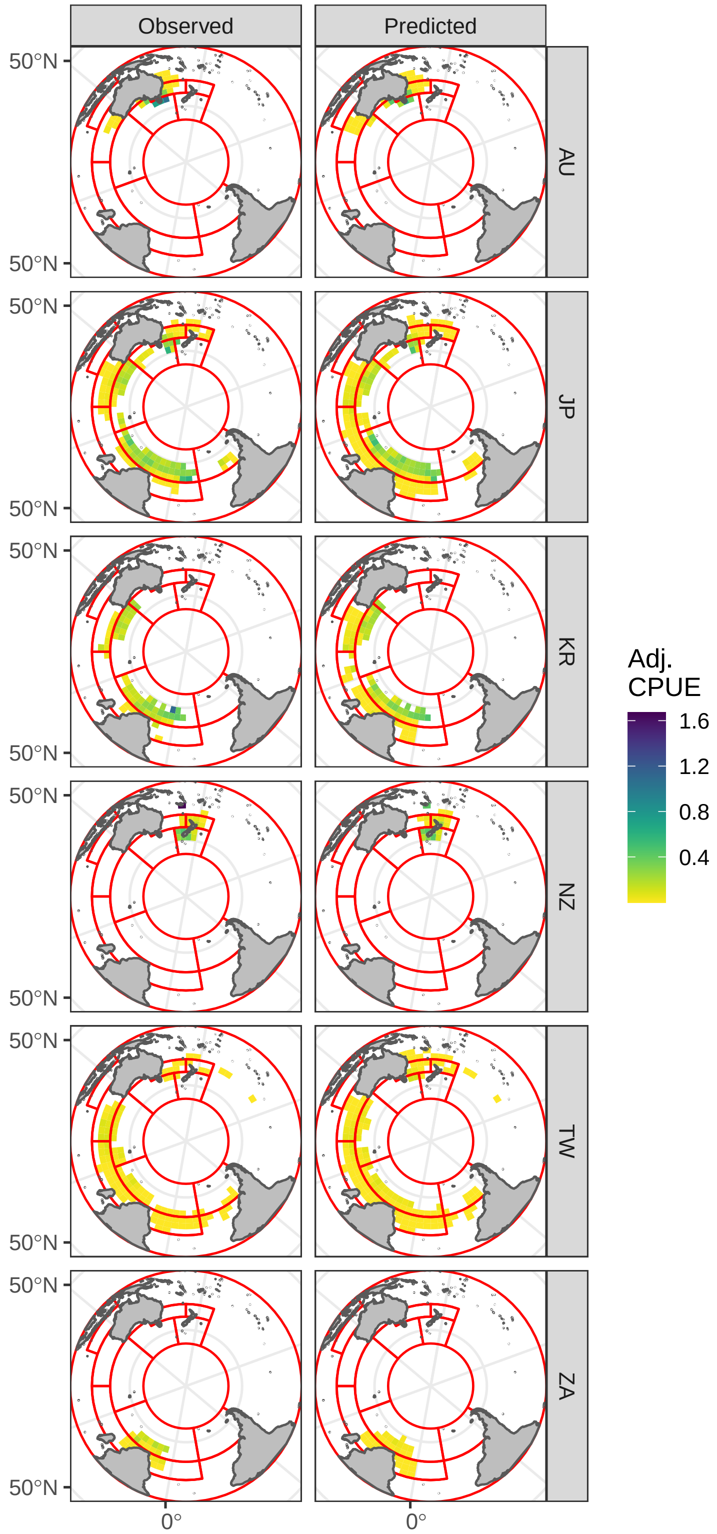


Figure 25: Global prediction of empirical CCSBT catch rate data, assuming an Adjusted catch rate, per CCSBT member flag. Catch rate is calculated as the mean of the catch over effort per grid cell and flag.

3.4. Prediction of non-member catches

We first fitted the previous (2019) model to the updated CCSBT catch rate data and predicted non-member catches using the updated effort from other tRFMOs. Results are illustrated in Figures 26 and 27 for the Indian/Atlantic and Pacific regions respectively. In both cases the updated (2023) model provides a noticeable reduction in the estimated catch, particularly under the assumption of JP catchabilities for the non-member fishing effort.

In the Indian/Atlantic region a reduction in the predicted catches is mostly in statistical areas 9 and 14. In the Pacific region, the reduction in predicted non-member catches is mostly in statistical areas 4 and 5. We can conclude from these results that the estimated catchabilities for JP and TW have been reduced in the updated model. In the previous (2019) model, the JP and TW catchabilities were allowed to change over time to accommodate the increasing SBT catch rates. Although this provided a good fit to the CCSBT data, it may have led to overestimation of the JP and TW catchabilties. In the updated (2023) model, changing catch rates are instead accommodated by the year-area interaction, allowing the data to be fit under an arguably more realistic assumption of constant catchability over time and changing SBT biomass density.

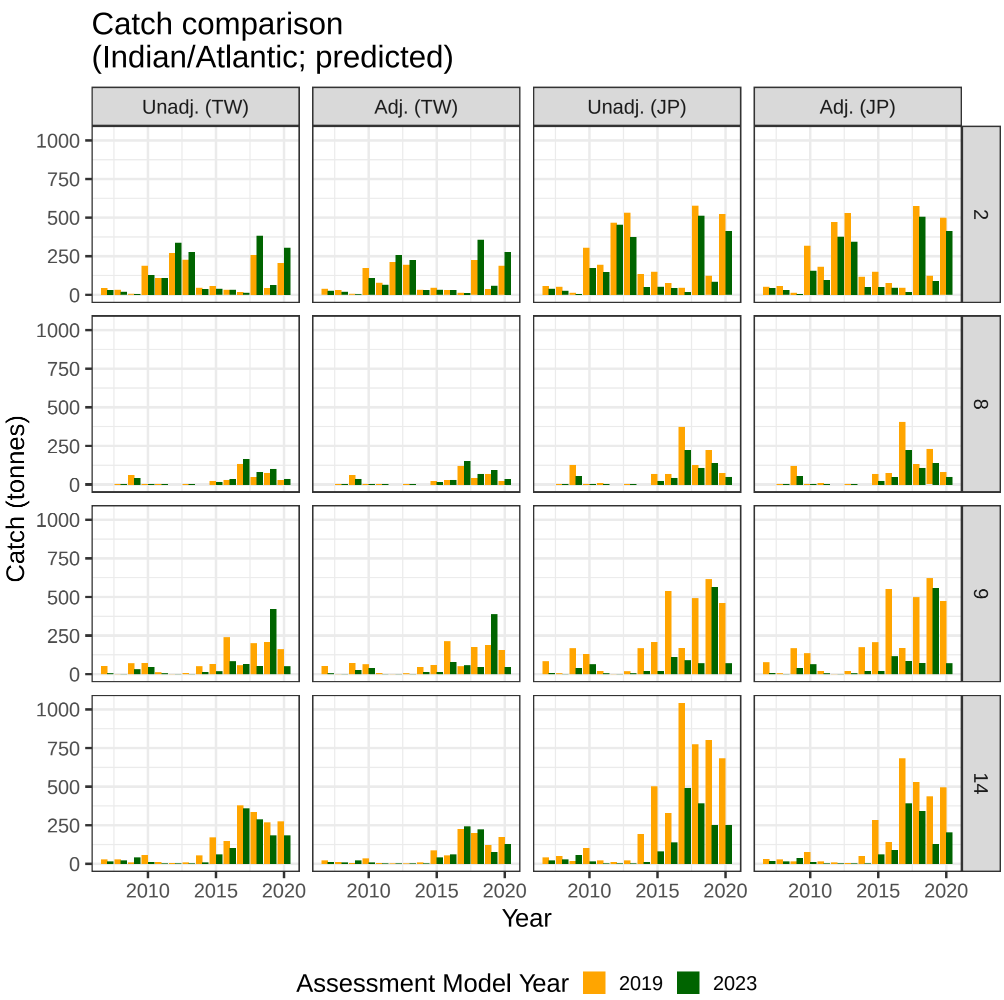


Figure 26: Prediction of non-member catches for the Indian/Atlantic region, assuming Adjusted and Unadjusted CCSBT catch rate data (for estimation of the catch rates) and either TW or JP surrogate flags assumed for the non-member fishing effort.

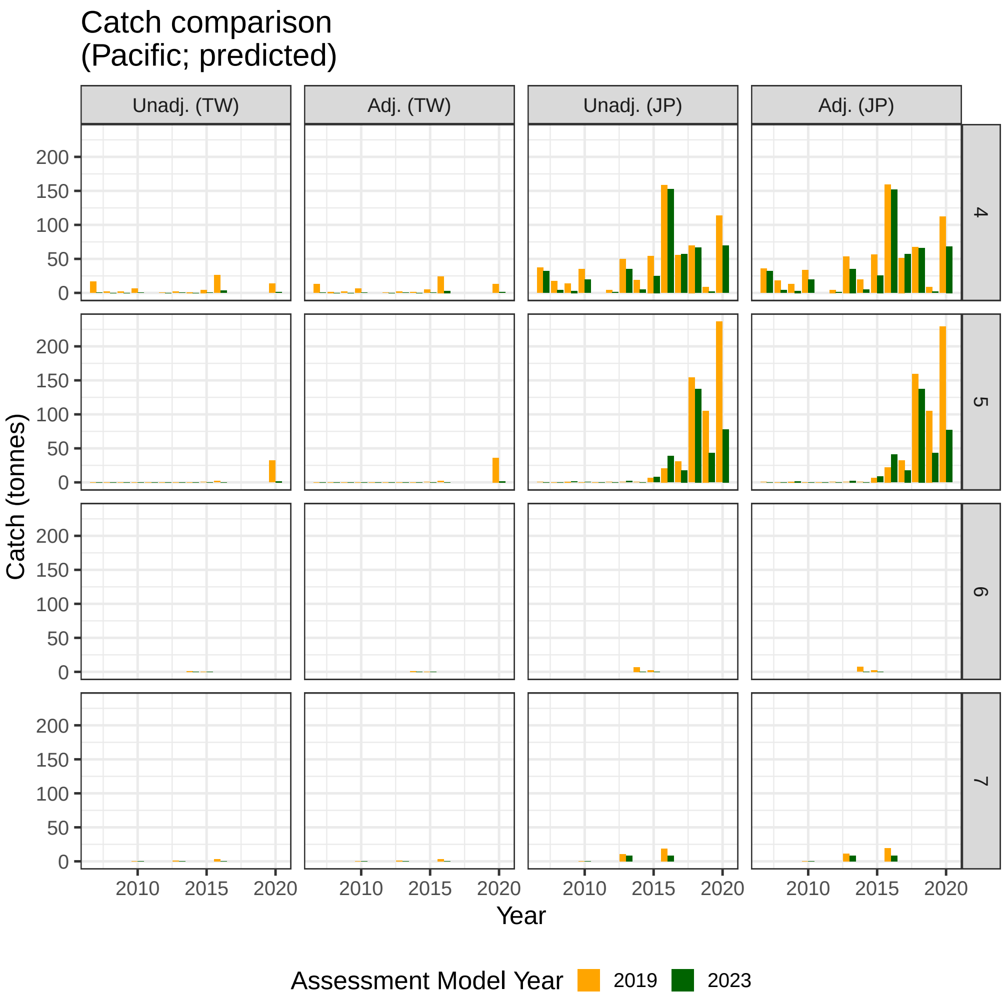


Figure 27: Prediction of non-member catches for the Pacific region, assuming Adjusted and Unadjusted CCSBT catch rate data (for estimation of the catch rates) and either TW or JP surrogate flags assumed for the non-member fishing effort.

Prediction of the non-member catches with the global model generated the results listed in Table 2. For comparison with previous work, which used a regional model, we also generated estimates for the Indian/Atlantic and Pacific regions separately (Table 3). The non-member catches per non-member flag state are listed in Table 4. Finally, the predicted non-member catches are plotted graphically over time in Figure 28, and space in Figure 29.

Table 2: Global estimates of UAM summed across statistical areas and assuming Adjusted and Unadjusted CCSBT catch rates. Either JP or TW surrogate flags are assumed for the non-member effort. The range of values assumes lower and upper limits from the TW and JP catchabilities respectively.

Year	Unadj. (TW)	Adj. (TW)	Unadj. (JP)	Adj. (JP)	Range (Unadj.)	Range (Adj.)
2007	75	51	161	126	75 – 161	51 – 126
2008	53	28	112	72	53 – 112	28 – 72
2009	85	62	181	152	85 – 181	62 – 152
2010	159	111	334	271	159 – 334	111 – 271
2011	113	63	234	151	113 – 234	63 – 151
2012	197	112	409	275	197 – 409	112 – 275
2013	250	167	535	432	250 – 535	167 – 432
2014	83	48	176	121	83 – 176	48 – 121
2015	186	133	398	326	186 – 398	133 – 326
2016	425	318	899	756	425 – 899	318 – 756
2017	532	413	1130	984	532 – 1130	413 – 984
2018	792	645	1668	1511	792 – 1668	645 – 1511
2019	627	488	1334	1155	627 – 1334	488 – 1155
2020	598	482	1275	1160	598 – 1275	482 – 1160

Table 3: Regional estimates of UAM assuming Adjusted or Uadjusted CCSBT catch rates. Either JP or TW surrogate flags are assumed for the non-member effort. The range of values assumes lower and upper limits from the TW and JP catchabilities respectively and represents uncertainty in the fishing behaviour of non-member vessels.

Year	Ocean	Unadj. (TW)	Adj. (TW)	Unadj. (JP)	Adj. (JP)	Range (Unadj.)	Range (Adj.)
2007	Indian/Atlantic	43	35	93	87	43 – 93	35 – 87
2008	Indian/Atlantic	35	26	75	64	35 – 75	26 – 64
2009	Indian/Atlantic	68	59	146	143	68 – 146	59 – 143
2010	Indian/Atlantic	114	97	241	232	114 – 241	97 – 232
2011	Indian/Atlantic	77	58	160	134	77 – 160	58 – 134
2012	Indian/Atlantic	118	100	248	235	118 – 248	100 – 235
2013	Indian/Atlantic	170	136	368	345	170 – 368	136 – 345
2014	Indian/Atlantic	54	43	116	107	54 – 116	43 – 107
2015	Indian/Atlantic	144	115	307	278	144 – 307	115 – 278
2016	Indian/Atlantic	291	237	620	559	291 – 620	237 – 559
2017	Indian/Atlantic	482	385	1025	914	482 – 1025	385 – 914
2018	Indian/Atlantic	676	593	1422	1373	676 – 1422	593 – 1373
2019	Indian/Atlantic	606	483	1290	1141	606 – 1290	483 – 1141
2020	Indian/Atlantic	543	461	1159	1106	543 – 1159	461 – 1106
2007	Pacific	32	16	68	39	32 – 68	16 – 39
2008	Pacific	18	3	37	8	18 – 37	3 – 8
2009	Pacific	17	3	35	8	17 – 35	3 – 8
2010	Pacific	45	14	93	39	45 – 93	14 – 39
2011	Pacific	36	5	74	16	36 – 74	5 – 16
2012	Pacific	79	11	161	39	79 – 161	11 – 39
2013	Pacific	80	31	166	87	80 – 166	31 – 87
2014	Pacific	29	4	60	14	29 – 60	4 – 14
2015	Pacific	43	18	91	48	43 – 91	18 – 48
2016	Pacific	134	81	279	196	134 – 279	81 – 196
2017	Pacific	50	28	104	69	50 – 104	28 – 69
2018	Pacific	117	52	246	139	117 – 246	52 – 139
2019	Pacific	21	4	44	13	21 – 44	4 – 13
2020	Pacific	55	21	116	55	55 – 116	21 – 55

Table 4: Global estimates of UAM per non-member flag state assuming Adjusted CCSBT catch rates. Either JP or TW surrogate flags are assumed for the non-member effort. The range of values assumes lower and upper limits from the TW and JP catchabilities respectively and represents uncertainty in the fishing behaviour of non-member vessels.

Year	CN	SC	NA	UY	FJ	SB	VU	Other
2007	9 – 22	23 – 55	0 – 1	0 – 0	0 – 0	0 – 0	15 – 36	3 – 11
2008	19 – 45	5 – 16	0 – 0	0 – 0	0 – 0	0 – 0	2 – 5	2 – 6
2009	52 – 126	7 – 18	0 – 0	0 – 0	0 – 0	0 – 0	1 – 3	1 – 5
2010	89 – 211	8 – 21	0 – 0	0 – 0	0 – 0	0 – 0	9 – 23	4 – 15
2011	58 – 137	3 – 9	0 – 0	0 – 0	0 – 1	0 – 0	0 – 1	1 – 4
2012	110 – 268	0 – 0	0 – 0	0 – 0	0 – 1	0 – 0	0 – 1	1 – 4
2013	148 – 377	5 – 12	0 – 1	2 – 6	0 – 1	0 – 0	11 – 28	2 – 8
2014	25 – 62	18 – 45	0 – 1	0 – 0	0 – 0	0 – 1	2 – 5	2 – 7
2015	82 – 200	35 – 82	0 – 1	0 – 0	0 – 0	0 – 1	8 – 19	8 – 22
2016	162 – 385	92 – 217	0 – 1	0 – 0	0 – 0	0 – 0	2 – 6	62 – 146
2017	205 – 471	177 – 435	0 – 0	0 – 0	0 – 0	0 – 0	25 – 58	6 – 18
2018	496 – 1130	97 – 245	0 – 0	0 – 0	0 – 0	0 – 0	44 – 112	7 – 24
2019	142 – 344	164 – 408	0 – 1	0 – 0	0 – 0	0 – 0	2 – 6	179 – 396
2020	355 – 836	105 – 265	0 – 0	0 – 0	0 – 1	0 – 2	18 – 44	4 – 12

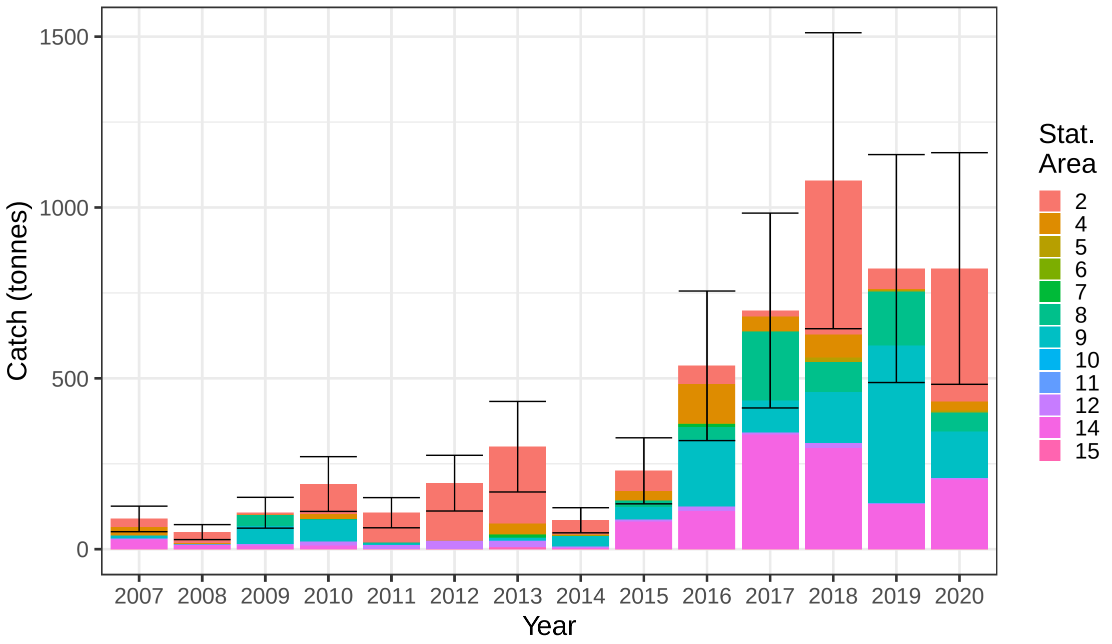


Figure 28: Prediction of total UAM catches by CCSBT non-members assuming Adjusted CCSBT catch rates. Surrogate JP and TW flags provide upper and lower bounds per year. Filled bars represent the mean of JP and TW values per statistical area.

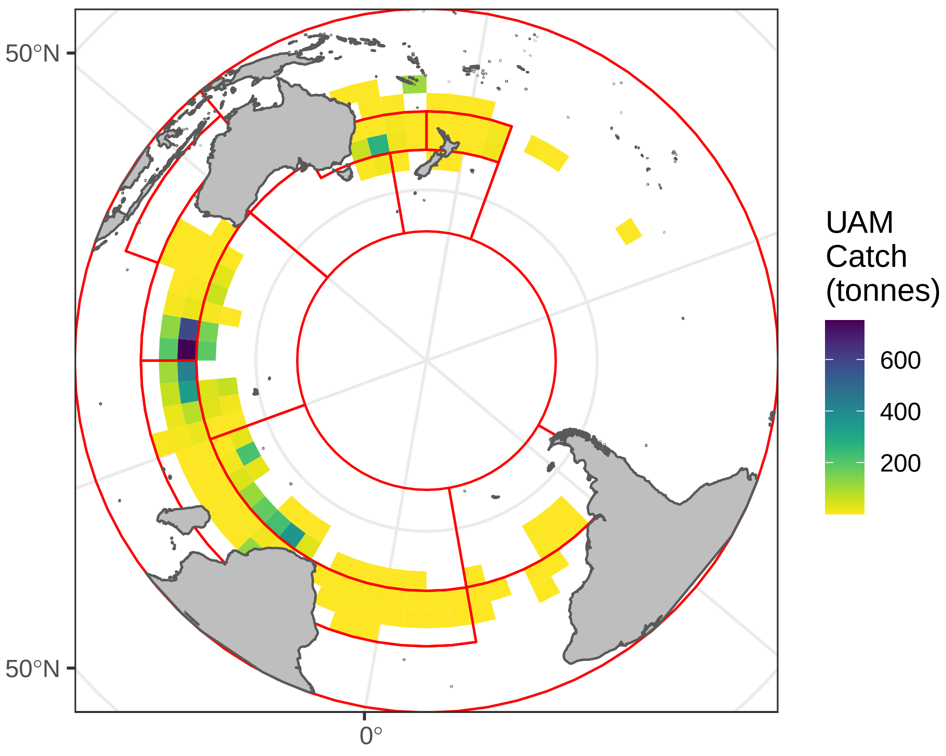


Figure 29: Prediction of average UAM catches per year by CCSBT non-members assuming Adjusted CCSBT catch rates. Surrogate JP and TW flags provide upper and lower bounds per year and figure illustrates the mean of JP and TW values per grid.

4. CONCLUSIONS AND FURTHER WORK

The work in this current report has updated the model for estimation of the SBT catch rates from CCSBT data, which was necessary to improve the fit and predict total catches. The new model includes an interaction term between CCSBT statistical areas and calendar year. In contrast, the previous model contained an interaction between flag and the year, with flag effectively being used as a spatial proxy. However, this may have been inappropriate, since prediction of the catch from non-member data requires the estimated flag coefficients for JP and TW to be applied within other spatial strata; i.e., strata different from the strata that predominate in fitting the model. The updated approach is therefore to be preferred.

Moving to a spatio-temporal model is likely improve realism, since catch rates can be more appropriately represented as a function of the underlying biomass density distribution. However, further development work will be required to improve stability of the model by including spatio-temporal correlation. It is also important to note that adjustment of the CCSBT catch rate data to account for unreported effort by CCSBT members, may also introduce a spatio-temporal change in the catch rates. This is because the effort is only adjusted outside of core spatial strata (statistical areas 4 to 9) and there may be temporal changes in the reporting rate. We suggest that developing a spatio-temporal model should be a priority for future work.

5. ACKNOWLEDGEMENTS

This work was funded by CCSBT and the government of Australia, and overseen by Pamela Mace (Ministry for Primary Industries, New Zealand). Thank you to Colin Millar (CCSBT Secretariat) for providing the CCSBT and WCPFC data.

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7. APPENDIX

Residual diagnostics were generated from the predicted model catches. The residual was calculated as:

$$r = \hat{y} - y$$

where $\hat{y}$ is the catch predicted by the two-part model, and y is the observed value. Residuals were plotted against model fixed effects, with trends across values for each predictor indicative of model mis-specification. Figures A1 to A6 illustrate residual distributions for the different model fits. There are no apparent trends in the residual distributions across covariate factor levels.

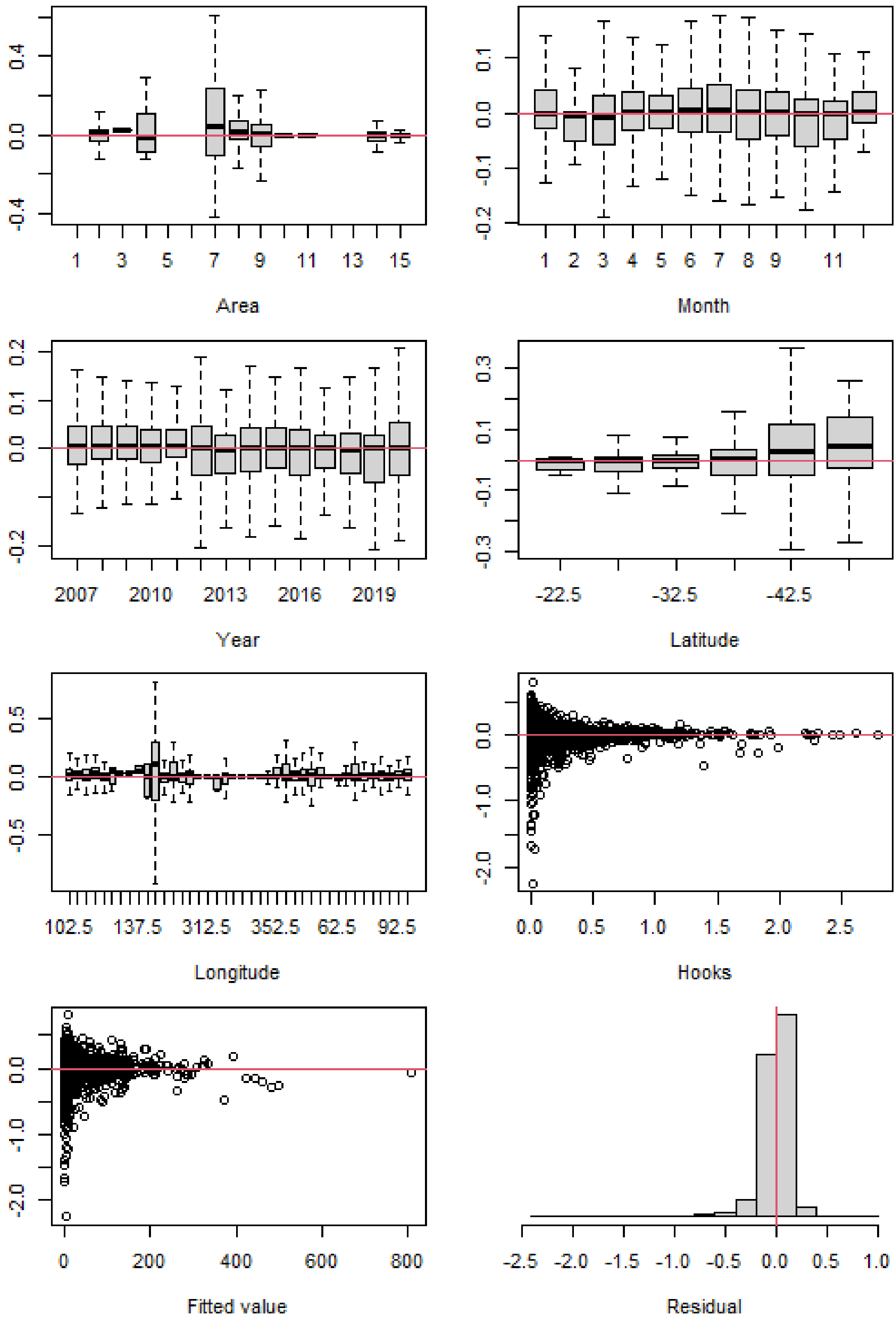

Figure A1: Unstandardised catch rate residual diagnostics for the Indian/Atlantic region, using the previous (2019) model applied to the udpated (2023) CCSBT data. Residuals are calculated using predicted values from the two-part model.

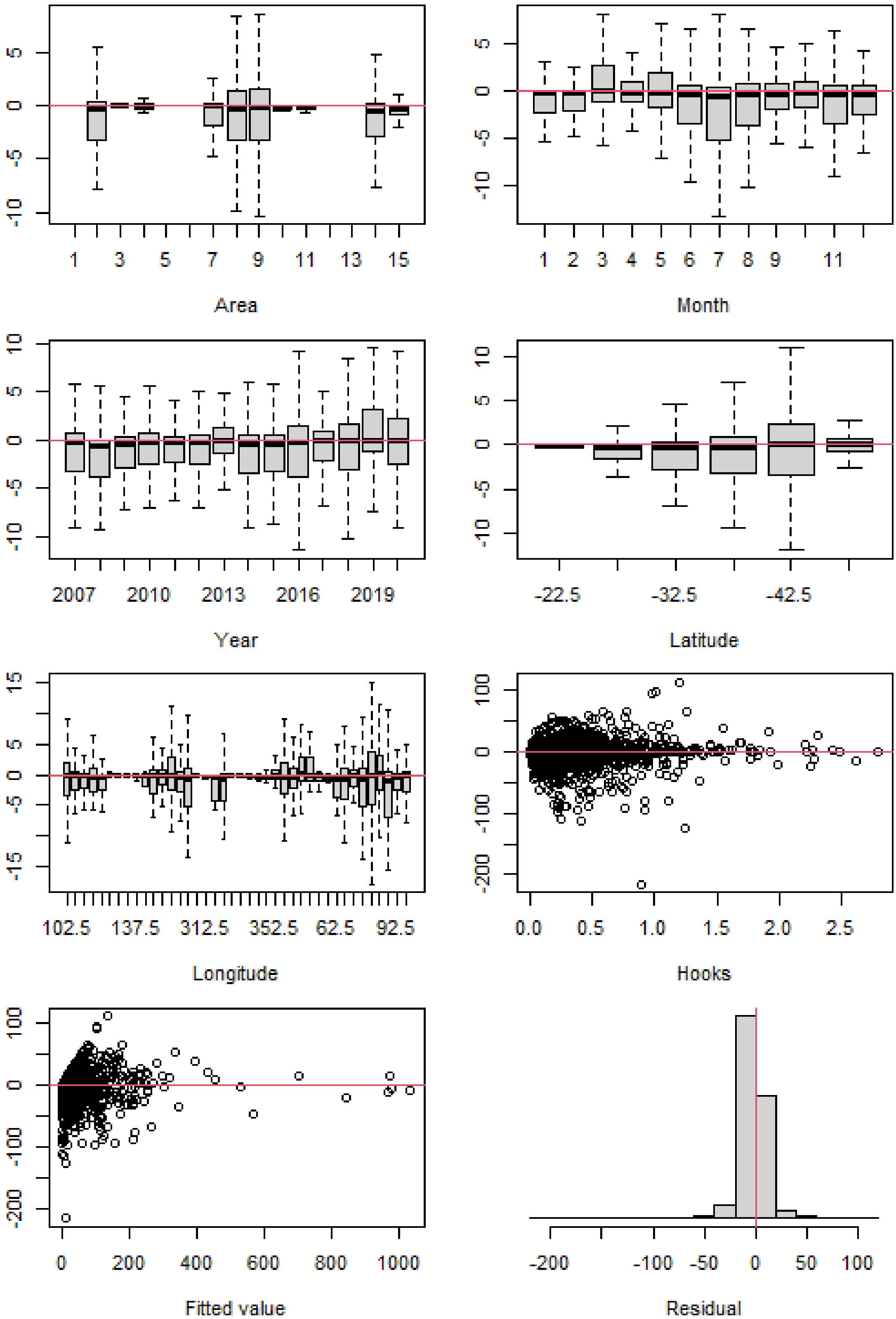

Figure A2: Unstandardised catch residual diagnostics for the Indian/Atlantic region, using the updated (2023) model applied to the udpated (2023) CCSBT data. Residuals are calculated using predicted values from the two-part model.

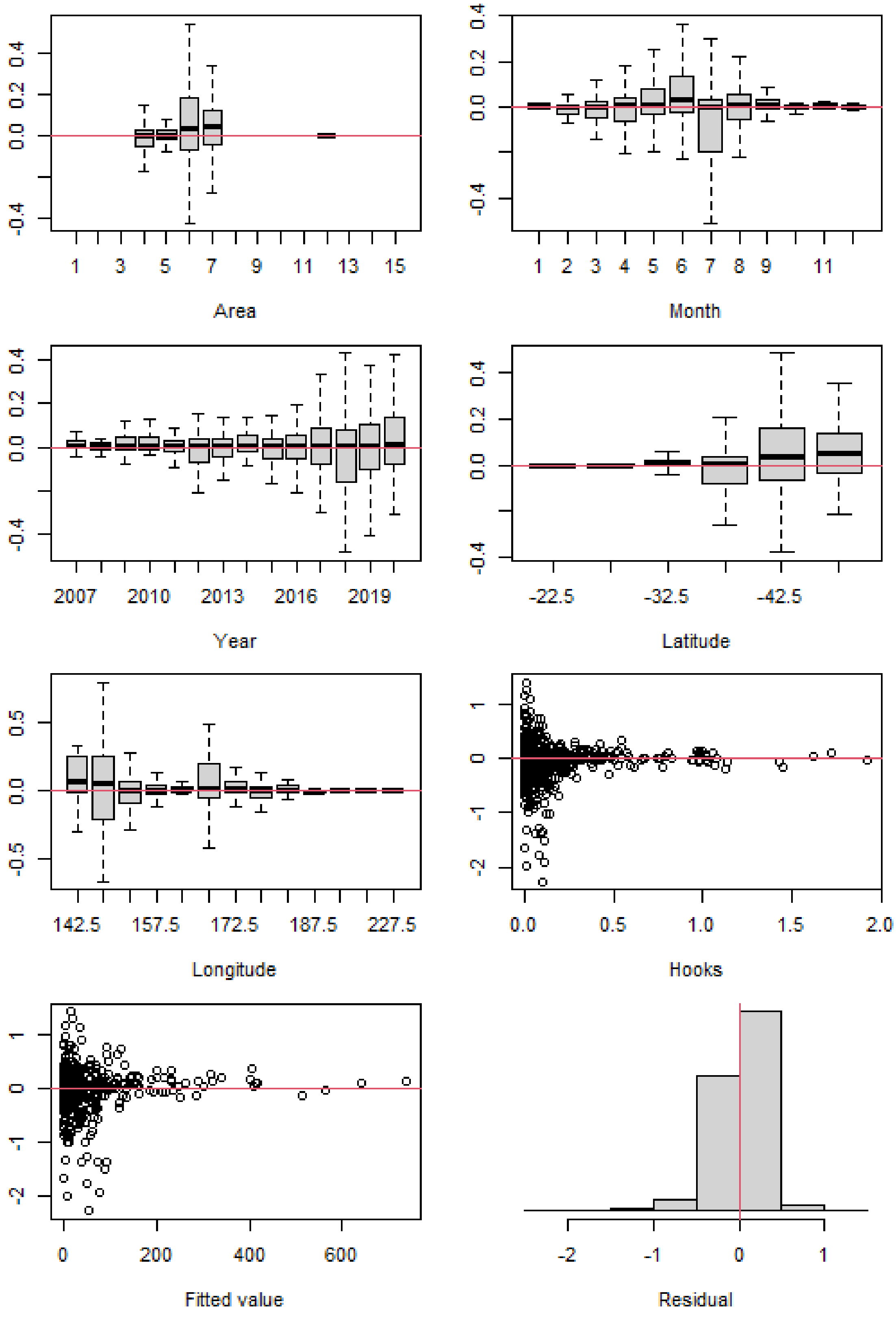

Figure A3: Unstandardised catch rate residual diagnostics for the Pacific region, using the previous (2019) model applied to the udpated (2023) CCSBT data. Residuals are calculated using predicted values from the two-part model.

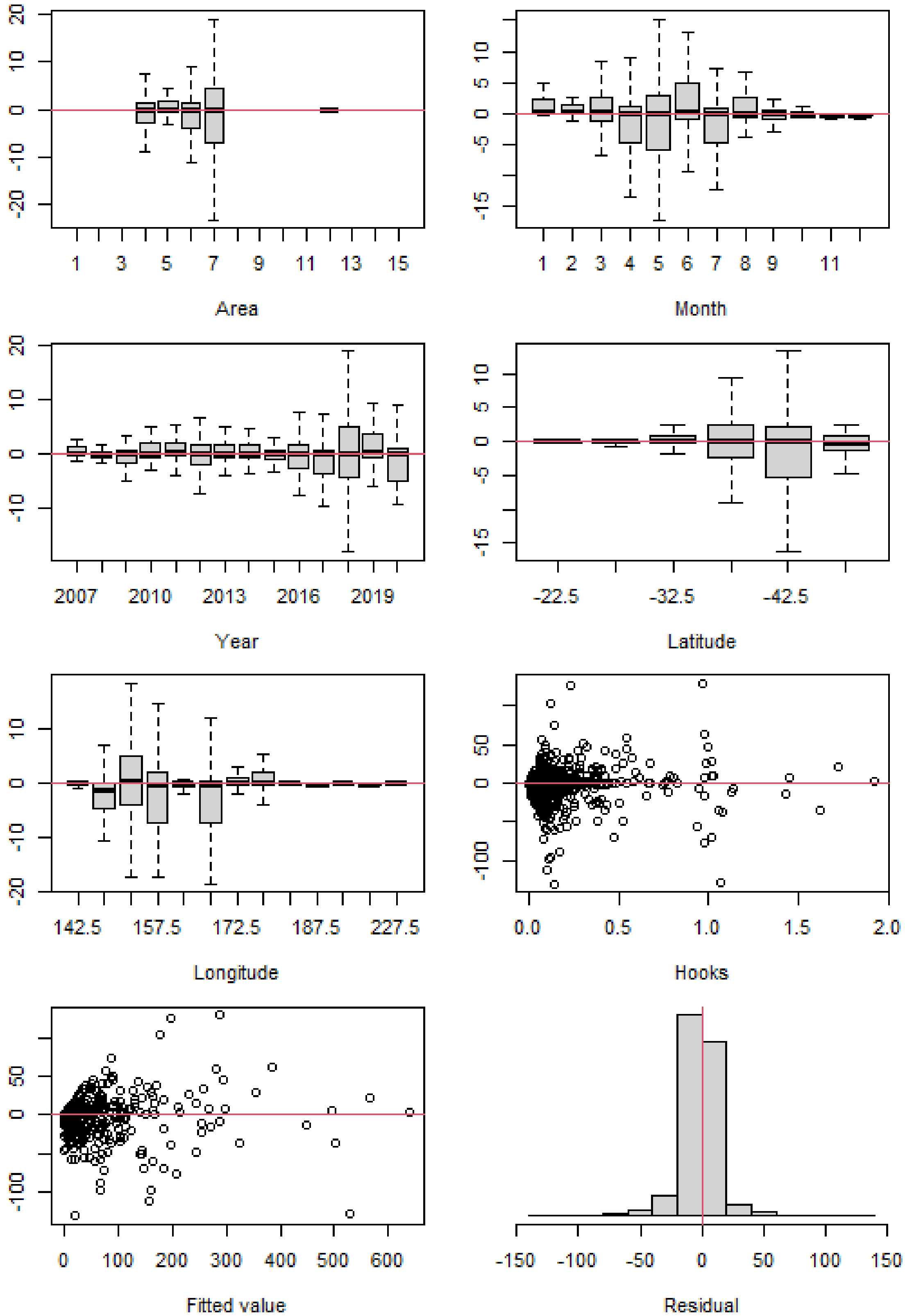

Figure A4: Unstandardised catch residual diagnostics for the Pacific region, using the updated (2023) model applied to the udpated (2023) CCSBT data. Residuals are calculated using predicted values from the two-part model.

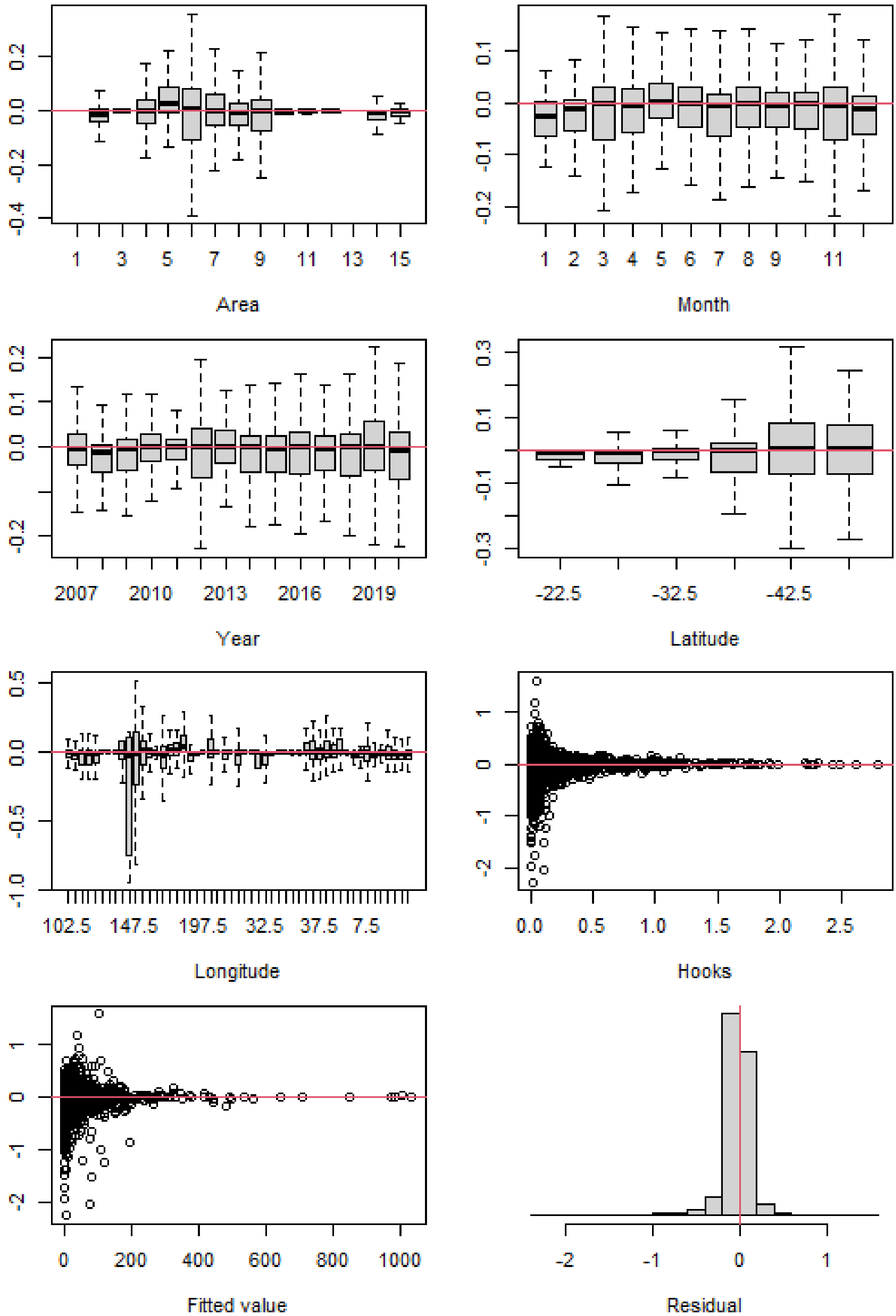

Figure A5: Unstandardised catch rate residual diagnostics for the global model fit, using the updated (2023) model applied to the udpated (2023) CCSBT data. Residuals are calculated using predicted values from the two-part model.

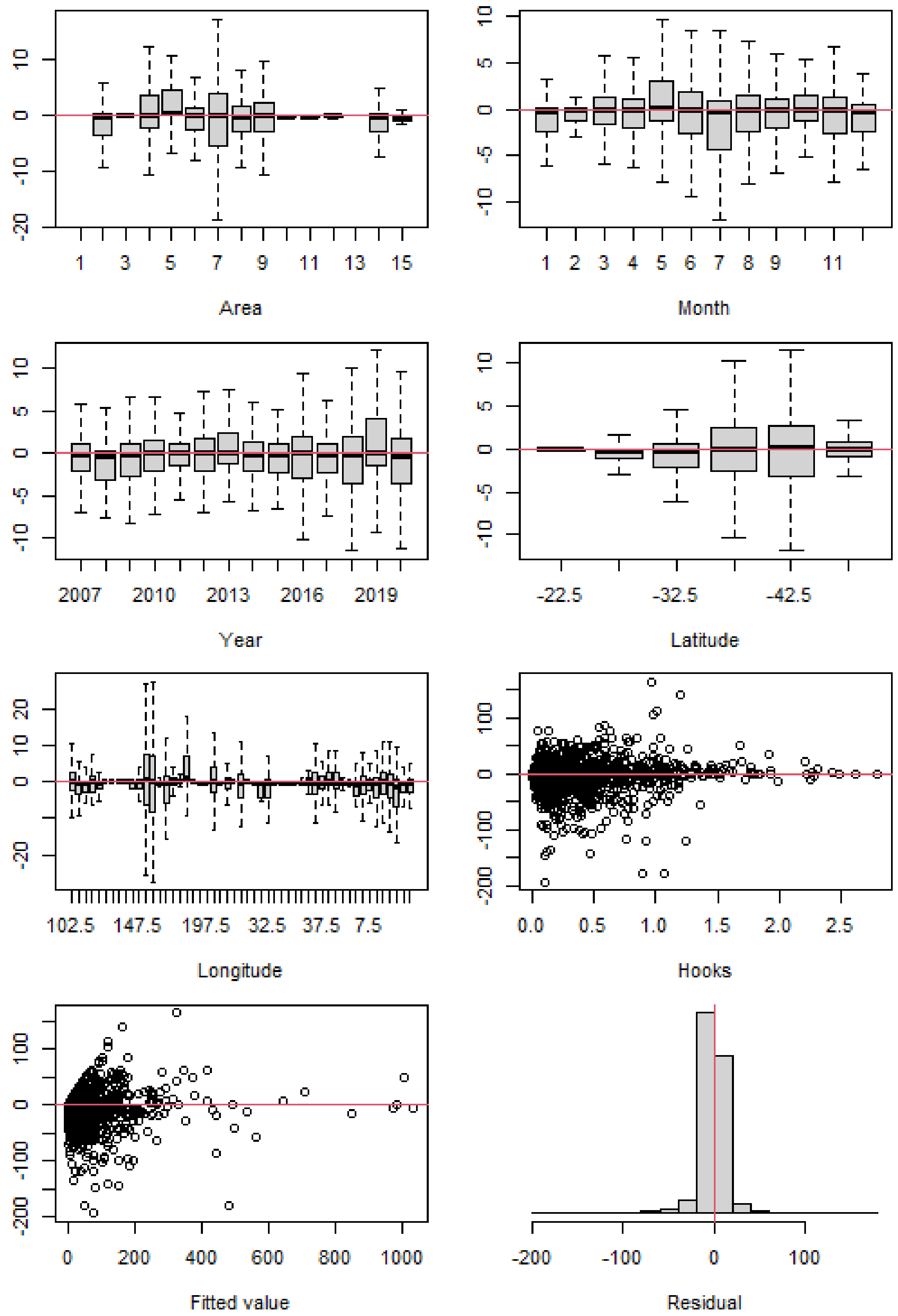

Figure A6: Unstandardised catch residual diagnostics for the global model fit, using the updated (2023) model applied to the udpated (2023) CCSBT data. Residuals are calculated using predicted values from the two-part model.