Collaborative study of tropical tuna CPUE from multiple Indian Ocean longline fleets in 2017

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Executive Summary

In June and July 2017 a collaborative study was conducted between national scientists with expertise in Japanese, Korean, Seychelles, and Taiwanese longline fleets, an independent scientist, and an IOTC scientist. The meetings addressed Terms of Reference covering several important issues related to bigeye and yellowfin tuna CPUE indices in the Indian Ocean. The study was funded by the Indian Ocean Tuna Commission (IOTC).

Terms of Reference

- Provide indices of abundance for bigeye and yellowfin tunas and draft working papers to be presented at the WPM09 (13-15 October 2017) and WPTT19 (17-22 October 2017).
- Provide support and training to national scientists in their analyses of catch and effort data.
- The analyses will consider data to be provided by Japanese, Taiwanese, Korean, and Seychelles research agencies.
- Analyses will be carried out in a series of meetings in March and April. After preliminary meetings between the consultant and some of the participating data providers to prepare each dataset and develop methods, there will be a joint meeting between all participating countries and the consultant.

Tasks will include the following, to the extent possible in the available time:

- Work with the Stock Assessment Officer to coordinate a series of meetings between data holders and the consultant.
- Prepare and test computer hardware and software that will facilitate the fast and efficient running of large numbers of computer-intensive analyses.
- Load, prepare, and check each dataset, given that data formats and pre-processing often change between years and data extracts, and important changes to fleets and reporting sometimes occur in new data. The Seychelles data have not previously been included in the analyses and will require additional preparation.
- Conduct the following analyses to improve CPUE methods:
    - Apply cluster analyses and bigeye and yellowfin CPUE standardization using reliable data from each CPC. Prepare separate indices for each fleet, and joint indices. Thoroughly check all code and results in order to validate indices.
    - Develop a simulator to test methods for standardizing CPUE, and to allow the development and testing of new code during periods when the joint data are unavailable.
    - Explore alternative modelling and data transformation methods in order to normalise residuals and to accommodate strata with no zero catches.
    - Explore spatial and temporal patterns in residuals by fleet and cluster, in order to better understand the factors driving CPUE changes, to explore potential confounding effects and possible seasonal catchability changes.
    - Identify appropriate subareas for modelling time-area interactions within regions, by region and species. Explore adding subarea-time interactions in the standardization models, to address differences in trends among areas.
    - Explore residual patterns spatially and among clusters, fleets and vessels through time, and change models where necessary to address any problems identified.
    - Investigate the 1976-80 discontinuity in the tropical CPUE of bigeye and (to a lesser extent) yellowfin.
    - Explore options for extending the Japanese time series of vessel effects into the pre-1979 period.

- Increase understanding of the fisheries that provide the CPUE by a) exploring the size data associated with each fleet, if possible with size data at the vessel set level (including using standardizing method to identify spatial and temporal patterns); and b) exploring vessel movement patterns through time. This task involves using data held by the IOTC Secretariat.
- Develop standard methods for estimating relative regional weights so as to apportion relative abundance among regions.

Unlike previous years, this document covers only the joint indices of abundance, describing their development for bigeye and yellowfin tunas. New developments covered in this paper include addition of data from the Seychelles, splitting the western tropical areas into northern and southern subregions for both species, and testing the inclusion of time-area interactions in the model.

Other issues are covered in related papers (refs, once titles and numbers are posted) that describe the data preparation, cluster analyses, and individual indices for each fleet; investigate the 1976-1980 discontinuity in longline CPUE; explore the size data associated with the Japanese longline fleet; develop standard methods for estimating relative regional weight so as to apportion abundance among regions; and develop a simulator for testing CPUE analysis methods.

Data for the four fleets were standardized for each region to estimate indices of abundance. Indices were estimated using two approaches, delta lognormal and lognormal + constant, but the main approach was the delta lognormal. All models included the explanatory variables year-quarter and 5° cell as categorical variables, and a cubic spline on hooks as a covariate. Models for tropical regions included a cubic spline fitted to hooks between floats, while models for temperate areas included a categorical variable for cluster. Some models included vessel identity as a categorical variable. Models were run for the period 1952-1979 without vessel identity, for the later period 1979-2015 with vessel identity, and for the whole period 1952-2015 both with and without vessel identity.

Figures and tables are provided for each set of indices, including both quarterly and annual indices. Diagnostic plots are also presented.

Introduction

In June and July 2017 a collaborative study of longline data and CPUE standardization for bigeye and yellowfin tuna was conducted between scientists with expertise in Japanese, Taiwanese, Korean, and Seychelles fleets, an independent scientist, and an IOTC scientist. The study was funded by the Indian Ocean Tuna Commission (IOTC). The study addressed the Terms of Reference outlined below, which cover the most important issues that had previously been highlighted by different working parties. Work was carried out, for those factors relevant to them, for the following:

- Area: Indian Ocean
- Fleets: Japanese longline; Taiwanese longline, Korean longline, Seychelles longline
- Stocks: Bigeye tuna, yellowfin tuna.

Terms of Reference

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- Provide support and training to national scientists in their analyses of catch and effort data.
- The analyses will consider data to be provided by Japanese, Taiwanese, Korean, and Seychelles research agencies.
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- Explore residual patterns spatially and among clusters, fleets and vessels through time, and change models where necessary to address any problems identified.
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- Explore options for extending the Japanese time series of vessel effects into the pre-1979 period.
- Increase understanding of the fisheries that provide the CPUE by a) exploring the size data associated with each fleet, if possible with size data at the vessel set level (including using standardizing method to identify spatial and temporal patterns); and b) exploring vessel movement patterns through time. This task involves using data held by the IOTC Secretariat.
- Develop standard methods for estimating relative regional weights so as to apportion relative abundance among regions.

- All work is subject to the agreement of the respective fisheries agencies to make the data available.
- To document the analyses in accordance with the IOTC "Guidelines for the presentation of CPUE standardisations and stock assessment models", adopted by the IOTC Scientific Committee in 2014; and to provide draft reports to the IOTC Secretariat no later than 60 days prior to the meeting of the WPTT19, i.e. 17 August 2017, and the final report no later than 15 days prior to the meeting of the WPTT19, i.e. 2 October 2017.
- To undertake any additional analyses deemed relevant by the WPTT19 or the IOTC Secretariat up to 60 days after the start date of the contract.

Methods

Data cleaning and preparation

The four datasets had many similarities but also significant differences. The variables differed somewhat among datasets, as did other aspects such as the sample sizes, the data coverage and the natures of the fleets.

Data preparation and analyses were carried out by each participant, using a standard set of scripts developed for this purpose in R version 3.3.0 (R Core Team 2016). The approaches used are described by Hoyle et al. (2015b) and Hoyle et al. (2016). The datasets and the analyses are described in working papers by each participant and will not be further reported here. The Japanese data for 2016 are preliminary.

For more detail about the Japanese, Korean, and Taiwanese fleets, see the descriptive figures in the following WPTT information papers (Hoyle et al. 2015a, Hoyle and Okamoto 2015, Hoyle et al. 2015c). For detail about the Seychelles fleet, see the WPTT working paper provided by the Seychelles (ref).

Plotting and data selection

We pooled data from multiple fleets into a single analysis for years 1952-2016. The pooled dataset included all data from the Japanese (1952-2016) and Korean (1971-2016) fleets. For the Taiwanese fleet data from 2005-2016 were included. For the Seychelles fleet all data (2000-2016) were included, except in analyses that included hooks between floats.

Joint analyses included prepared and clustered data from each of the fleets. In some analyses clusters that caught very few of the species of interest were omitted, because they provide little relevant information and may cause analysis problems due to large numbers of zeroes, and memory problems due to large sample sizes. Cluster selection was based on review and discussion of the plots of covariates and species compositions by cluster.

For standardization of each region, data were selected for vessels that had fished for at least N1 quarters in that region. The standard level of N1 was 8 quarters in the equatorial regions and 2 quarters in the southern regions. Subsequently, vessels, 5° cells, and year-quarters were included if they had at least 100 sets. Each of these criteria was varied where needed to estimate more year-quarter effects. For example, for analyses of the 1952-1979 period the 100 sets criteria were reduced to 50 sets to increase the size of the dataset. For datasets with more than 60,000 sets the number of sets in each stratum (5° square * year-quarter) was limited by randomly selecting 60 sets without replacement from strata with more than this number of sets. Testing suggested that this approach did not cause bias, and the effects on trends of random variation were reduced to very low levels at 30 sets per stratum (Hoyle and Okamoto 2011), suggesting that 60 sets was more than adequate.

CPUE standardization

CPUE standardization methods generally followed the approaches used by Hoyle and Okamoto (2011) with some modifications. The operational data were standardized using generalized linear models in R. Indices were prepared for each species and region using several approaches, summarised in Table 1 and further described below.

Table 1: Species, regions, distributions and variables used in CPUE analyses.

Species	**Regions**	**Fleets**	**Target variable**	**Vessel ID**	**Period**	**Distribution**
BET	1, 2, 3, 4, 1n, 1s	All	Cluster	Y, N	1952-2016	logC, bin, logN
				N	1952-1979	
				Y	1979-2016	
		All except SY	HBF	Y, N	1952-2016	
				N	1952-1979	
				Y	1979-2016	
YFT	2, 3, 4, 5, 2n, 2s	All	Cluster	Y, N	1952-2016	
				N	1952-1979	
				Y	1979-2016	
		All except SY	HBF	Y, N	1952-2016	
				N	1952-1979	
				Y	1979-2016	

Distributions

Lognormal constant analyses were carried out using generalized linear models that assumed a lognormal distribution. In this approach the response variable $\log(CPUE + k)$ was used, and a Normal distribution assumed. The constant *k*, added to allow for modelling sets with zero catches of the species of interest, was 10% of the mean CPUE across all sets.

Delta lognormal analyses (Lo et al. 1992, Maunder and Punt 2004) used a binomial distribution for the probability *w* of catch rate being zero and a probability distribution *f(y)* , where y was log(catch/hooks set), for non-zero (positive) catch rates. The index estimated for each year-quarter was the product of the year effects for the two model components, $(1 - w).E(y|y \neq 0)$.

$$\Pr(Y = y) = \begin{cases} w, & y = 0 \\ (1 - w)f(y) & otherwise \end{cases}$$

$\mathrm{g}(w) = (CPUE = 0) \sim covariates + \epsilon$, where *g* is the logistic function.

$\mathrm{f}(y) = CPUE \sim covariates + \epsilon$

In each case the covariates included year-quarter (*yrqtr*), and 5° cell (*latlong5*) fitted as categorical variables, and a cubic spline function *h* with 10 degrees of freedom applied to the continuous variable *hooks*. Analyses including the vessel identifier (*vessid*) fitted it as a categorical variable. Analyses including hooks between floats (*hbf*) fitted it as a continuous variable using a cubic spline φ, while those including cluster (*cl*) fitted it as a categorical variable.

Data in all models except the binomial model were 'area-weighted', with the weights of the sets adjusted so that the total weight per year-quarter in each 5° square would sum to 1. This method was based on the approach identified using simulation by Punsly (1987) and Campbell (2004), that for set *j* in area *i* and year-quarter *t*, the weighting function that gave the least average bias was: $w_{ijt} = \frac{log(h_{ijt}+1)}{\sum_{j=1}^{n} \log(h_{ijt}+1)}$. Given the relatively low variation in number of hooks between sets in a stratum, we simplified this to $w_{ijt} = \frac{h_{ijt}}{\sum_{j=1}^{n} h_{ijt}}$.

For the lognormal constant and positive lognormal GLMs, model fits were examined by plotting the residual densities and using Q-Q plots.

Data periods

Vessel identity information for Japan was only available from 1979, and most of the data before 1979 was Japanese. The Korean dataset started in 1971 and had vessel ids throughout, but covered a limited area with relatively low effort, so its influence was small in some analyses. The full Taiwanese dataset started in 1979, and in any case Taiwanese data before 2005 were omitted.

Overlap between vessels with the same id across years is required to avoid confounding between year effects and vessel ids. Thus we could not apply a consistent approach across all years when including vessel ids in the model.

The discontinuity in vessel 1979 could be addressed in several different ways. We therefore analysed the data in several ways so as to provide the assessment scientists with appropriate data.

First, we standardized the full dataset from 1952 to the present without including vessel effects.

Then we standardized the full dataset with vessel effects, assigning an identical dummy vessel ID to all sets that lacked vessel identity information. However, using a dummy value introduces several problems. First, most Japanese vessels begin to report their callsign in 1979, but a few do not, and these are presumably self-selected and not randomly selected from the vessel population. We therefore omitted all sets without vessels ids starting in 1979.

There is overlap in some cases due to Korean vessel ids, which start in 1971. However may be limited in scope by restricting the overlap between dummy and real vessel IDs to one year – 1979 – and removing sets with missing vessel IDs after this time. It may also be adjusted the time period 1952-1978 so that the relative averages in 1978 and 1979 were the same as in the analysis for the full time series without vessel effects. A second problem is that residuals may be more variable before 1979, without a true vessel ID in the model, which can introduce bias into the standardization.

A more general solution was to estimate two time series: 1952-1979 without vessel effects, and a second time series 1979-2015 with vessel effects (omitting all sets without vessel IDs). Subsequently the analyst may use the two time series as desired, either as separate indices in the assessment, or concatenating them after adjusting the averages so that the estimates for 1979 are the same.

Covariate effects

The effects of covariates were examined by plotting the predicted effects, with 95% confidence limits, of each parameter at observed values of the explanatory variables. Spatial effects with 95% confidence intervals were plotted by latitude. The cumulative vessel effects through time were examined by plotting each vessel's effect at every time that vessel made a set. An average vessel effect over time was examined by calculating the mean of the vessel effects for all sets made by the fleet during each time period, and this was also plotted. There is insufficient space to include all plots in the report, but these are available on request.

Changes in catchability through time were investigated by fitting to the operational data both with and without a term for individual vessel. The two models were designated respectively the 'base model' and the 'vessel-effects model'. Abundance indices were calculated for each model, and normalized to average 1.

For all model comparisons, the indices estimated for each year-quarter were compared by dividing the base model by the vessel effects model, plotting the time series of ratios, and fitting a log-linear regression. The slope of the regression represented the average annual compounding rate of change in fishing power attributable to changes in the vessel identities; i.e. the introduction of new vessels and retirement of old vessels. Gradients are shown on the figures, together with confidence intervals.

Indices of abundance

Indices of abundance were obtained by applying the R function predict.glm to model objects. The datasets used for prediction included all year-quarter values, with all other variables fixed at either the median for continuous variables, or the mode for categorical variables. Binomial time effects were obtained by a) generating logit time effects from the glm, and b) adding a constant to these logit time effects so that the mean of the back-transformed proportions was equal to the proportion of positive sets across the whole dataset. The main aim with this approach is to obtain a CPUE that varies appropriately, since variability for a binomial is greater when the mean is at 0.5 than at 0.02 or 0.98, and the multiplicative effect of the variability is greater when the mean is lower. The outcomes were normalised and reported as relative CPUE with mean of 1.

Uncertainty estimates were provided by applying the R function predict.glm with type = ”terms” and se.fit=TRUE, and taking the standard error of the year-quarter effect. For the delta lognormal models we used only the uncertainty in the positive component. Uncertainty estimates from standardizing commercial logbook data are in general biased low and often ignored by assessment scientists, since they assume independence and ignore autocorrelation associated with (for example) consecutive sets by the same vessels in the same areas. There may be a very large mismatch between the observation error in CPUE indices and the process error in the indices that is estimated in the assessment. This is particularly true for distant water longline CPUE, where very large sample sizes generate small observation errors.

Residual distributions and Q-Q plots were produced for all but the binomial analyses. For the lognormal positive analyses that included cluster in the model, median residuals were plotted by cluster. For all lognormal positive analyses, residuals by year-quarter were plotted by flag; median residuals by year-quarter were plotted by flag; and median residuals by 5° cell were mapped onto a contour plot for each flag.

Time-area interactions

We explored the potential to improve indices by including time-area interactions in the models. These models take considerably longer to fit and use much more RAM than the standard models without time-area interactions, and considerable testing was required. We ran a representative subset of models, with runs for each species and the four larger regions. We ran both types of targeting model, with cluster and hooks between floats, and all four time periods. However we omitted the delta lognormal models and ran only the lognormal constant models.

Time-area interactions were included in the model by adding interactions between latitude and year, and latitude and quarter. These were fitted as categorical variables, with latitudes grouped by 5° (*lat5*).

Models with time-area interactions can have more missing values than those without interactions. We ran the equivalent time + area model in parallel with each time x area model.

Expected catch rates were then predicted for each combination (stratum) of year-quarter and 5° cell, with all other variables fixed at the median (continuous variables) or the mode (categorical variables). Expected catch rates were predicted for a) the time x area model, b) the time + area model, and c) the time x area model but with missing values replaced by the equivalent predictions from the time + area model.

We multiplied each predicted catch rate by the cell area, to give each cell the appropriate weight. We then summed across cells by year-quarter to generate the time series of indices.

Results

We estimated delta lognormal indices for all regions of bigeye regional structure B2 (Figures 2 - 7) and for the split region 1 (regional structure B3, Figures 4 and 5); and for all regions of yellowfin regional structure Y (Figures 8 - 9) and for the split north-western region 2 (regional structure Y2, Figures 10 and 11). Diagnostics for the lognormal positive distribution indicated some negative skewness in the distributions of residuals (Figures 14 - 17).

We estimated a number of other indices, but here present figures for only the indices likely to be used in assessments, so as to conserve space. In tropical areas (bigeye regions 1 and 2, and yellowfin regions 2 and 5) we selected figures from the analysis that omits low-target clusters from the dataset, and includes HBF but not cluster in the model. In temperate areas (bigeye and yellowfin regions 3 and 4) we selected figures from the analysis that omits low-target clusters from the dataset, and conversely includes cluster but not HBF in the model. This is because in southern regions there are well known differences in fishing behaviour among vessels targeting different species, and these differences are reflected in the species composition, making it appropriate to use cluster in the standardization model. For example, the Japanese southern bluefin tuna fishery takes largely SBT, with some catch of albacore. The Taiwanese oilfish fishery is also a clear example, with a very high representation of species 'other'.

In tropical areas however, although there have been changes in targeting through time, vessels are believed to target bigeye and yellowfin at the same time and using similar methods, but to different extents by area and season, and with changes through time. In this complex situation clustering may be useful to remove data from clearly separate fisheries (such as the southern bluefin tuna fishery that occurred in eastern areas near Indonesia in the 1960s and 70s). However including cluster in the model may be problematic due to the confounding of clusters with abundance change. We have therefore used hooks between floats in the models for tropical areas, as was done in previous years' analyses. However, unlike previous analyses, we excluded clusters with minimal catch of the species of interest for reasons described above.

In reporting results we focus mainly on the two shorter sets of indices in the lower half of each set of figures. These cover the 1952 – 1979 period without vessel effects, and the 1979 – 2016 period with vessel effects.

For bigeye tuna the tropical indices in regions 1 (Figure 2) and 2 (Figure 3) show a moderate decline followed by a sharp spike upwards in the late 1970s. In the western area the declining trends subsequently resume and continue until the early 2000s, followed by a period of stable CPUE until about 2010 when a positive spike occurs. This is followed by a sharp decline so that CPUE is estimated to be currently at its lowest observed level. In the eastern tropical region 2 there is also a general decline in CPUE after 1980, with an increase in CPUE after 2010 that is much smaller than in the west. CPUE in the eastern tropical region 2 is currently also at or close to the lowest level observed.

The two split sections of western tropical bigeye region 1 show different patterns from one another and from the full region 1. In the period 1952 – 1979, the southern subregion 1s (Figure 4) shows slightly less decline until 1976 than the full region 1 while the northern subregion 1n declines more (Figure 5). All show similar spikes in the late 1970s. The decline from 1979 to the early 2000s is slightly less in the southern subregion than in the full region 1, but steeper in the northern subregion. The short-lived increase after 2010 is very large in the northern subregion, but smaller in the southern subregion.

For bigeye in western temperate region 3 (Figure 6), data are more sparse and less reliable than the tropical indices in the period before 1990, due to low sample sizes in the original data and omission of sets with very low bigeye species composition. Standardized CPUE increases during the 1960s to a peak in the early 1970s, then a few years of lower catch rates and sparse data. For the period since 1990 the indices are somewhat similar to the northern indices, with declining CPUE overall, but a suggestion of some increase since 2010. In eastern temperate region 4 (Figure 7) the pattern is quite similar. Standardized CPUE increases during the 1960s to a peak in the early 1970s, after which it drops for a few years and then increases again. In the 1990s the CPUE drops, increases until 2000, then declines again and becomes sparse and variable.

For yellowfin tuna, indices in the tropical areas were characterized by very steep declines in standardized CPUE prior to 1975. From 1980-1989 the western tropical region 2 CPUE (Figure 8) increased during the 1980s, then declined until 1995, increased again until 2005, and then decreased again. After that time it remained close to the lowest level observed. The eastern tropical region 5 followed a similar pattern until 1990 but then declined steadily, and by 2016 was also close to the lowest level in the time series (Figure 9).

The western tropical region was split into two subregions in the regY2 structure. The south-western tropical region 2s (Figure 10) and the north-western tropical region 2n (Figure 11) followed similar trends before 1979, declining steeply. Estimated catch rates were highly variable, partly due to sparse data. After 1980 CPUE increased in both subregions and then declined with medium-term variability until 2010. Catch rates increased somewhat in both subregions after 2010.

Yellowfin in western temperate region 3 followed a similar pattern to the western tropical indices, with a decline until the mid-1970s followed by an increase until the late 1980s, and subsequently a slow decline with significant variability (Figure 12). In eastern temperate region 4 the pattern was similar to the western temperate area before 1979 (Figure 13). After 1979 catch rates increased until the mid-2000's, but then declined rapidly and reached their lowest observed levels by 2016.

Residuals for these analyses were reasonably normally distributed (Figures 14 to 17), with the residuals for the tropical indices tending to be more left skewed, particularly in the case of bigeye tuna.

Median residuals were also reported by year-quarter (Figures 18 to 23) and by 5° cell (Figures 24 to 29), with additional grouping by flag in the tropical areas, where the selected models did not include cluster variables, and by cluster in the temperate areas.

Patterns by year are affected by the introduction of different fleets and changes in the number of vessels, which affect the variability of the medians by fleet and by cluster. Changes in the trends of the medians, however, may indicate problems in the modelling such as changes in fishing power by part of the fleet that are not explained by the available data.

In the bigeye north-western tropical dataset (Figure 18) before 1979 the Japanese residuals become more positively skewed through time. In the south-western tropical dataset before 1979 the Japanese residuals become more positively skewed after the arrival of Korean vessels in 1975. In all analyses there is a tendency for the median residuals to be above zero, and the southwestern tropical Korean median residuals before 1979 are all above 0.

There are no clear spatial residual patterns in the split north-western regions for bigeye tuna, apart from a tendency for less positive residuals in the south for Japan, and more positive further south for Korea in the southwestern tropical subregion before 1979. In the eastern tropical region the Taiwanese residuals are negative in the north after 1979. Further south the variation is stronger due to sparser data, but no clear patterns emerge.

CPUE trends for the area x time and area + time models were surprisingly similar. The largest divergence in the tropical areas occurred for bigeye after 2010, which may be associated with effort being reintroduced to the piracy area. There was more variation in the southern areas where data are sparser.

Discussion

The CPUE indices presented in this paper are derived from joint analysis of Japanese, Korean, Seychelles, and Taiwanese data. In 2015 and 2016 this joint paper included analyses of data from individual fleets, but this year the methods and results for the individual fleets, including cluster analyses, are provided in separate papers (refs).

The general approach was to run separate models for different areas, so that parameter estimates and uncertainty distributions could differ among areas (Chang et al. 2011). The models used 5° cell area effects, as recommended by the 2013 IOTC CPUE workshop (Anon 2013) to account for changes in effort distribution, and adjusted statistical weights to allow for changing effort concentration (Punsly 1987, Campbell 2004). The models included vessel effects where available, to account for some effects of changing fishing power and targeting within the fleet (Hoyle and Okamoto 2011). They also used cluster analysis based on species composition in order to identify target change, and to separate out effort using different fishing strategies (He et al. 1997). Cluster was used as a variable in the standardization models in temperate areas, but not in tropical areas due to concerns about confounding with abundance changes in the species of interest.

Another change from 2016 was the inclusion of data from the Seychelles. These data were first made available this year and at this stage were only included in the indices that used clustering. Most of the Seychelles time series does not report the hooks between floats variable, which is required for the tropical indices. This was unfortunate because most of the Seychelles effort is in the western tropical area. In future this dataset should be included in tropical indices, but we will need to find a way to address the lack of HBF, perhaps using a proxy variable based on understanding of how HBF and other setting methods are used for targeting.

A further change was the split of the western tropical area into northern and southern subregions. This was done to accommodate a change in the 2016 stock assessments to improve tag mixing (Langley 2016). Trends appeared to differ between the subregions.

Another new development was to test the use of time-area interactions. The time + area approach assumes uniform population trends within regions, although full independence is permitted between regions. This independence is appropriate given the potential for differing error distributions and covariate relationships, but such effects may also be important within regions. The time + area approach allows for spatial variation in catch rates at the 5° cell level, but assumes that differences among areas do not vary through time. Areas without data are assumed to follow the same trends as areas with data. This approach would be reasonable for a well-mixed population, or for a population in which areas without data were fished by fleets not included in the dataset. These factors may be true to some extent for Indian Ocean tuna, but mixing at large scales is probably limited (Kolody and Hoyle 2014), and reduced fishing pressure in defined areas (e.g. due to piracy in the area near Somalia) may lead to spatial variation in population density.

When including time-area interaction terms in the model, we modelled the spatial component of the interactions as 5° of latitude. This was only one of many possible spatial configurations. The R code is reasonably flexible and can be changed to apply time-area interactions to different spatial structures. Given the limitations on data access, there was insufficient time to explore more than one configuration option, but other options should be explored in future, particularly given the effort changes in the north-western tropical area due to piracy.

Time area interactions at 5 degrees latitude made surprisingly little difference to the observed trends. The largest differences occurred in the temperate areas with low sample sizes, suggesting that much of the difference may have been due to increased uncertainty. There was limited time for testing, and we recommend further work to refine the approach and test alternative spatial configurations.

The joint data were only available for one week, and much of this time was also occupied by training, presentations, and discussions during the joint CPUE workshop. This very limited data access was a constraint on testing and development.

CPUE indices are very influential components of stock assessment models, and further work to improve and validate indices is a high priority. We suggest the following priorities for further work:

1) Explore options for extending the Japanese time series of vessel effects into the pre-1979 period.
2) Increase understanding of the fisheries that provide the CPUE by a) further exploring the size data associated with each fleet, if possible with size data at the vessel set level; and b) exploring vessel movement patterns through time.
3) Explore alternative modelling and data transformation methods in order to normalise residuals and to accommodate strata with no zero catches.
4) Explore alternative subarea-time interactions to the standardization models, to address differences in trends among areas. Continue to explore residual patterns spatially and among clusters, fleets and vessels through time, and change models where necessary to address any problems identified. Develop additional residual and exploratory plots to explore possible confounding effects, such as maps of residuals by season to explore seasonal catchability changes.
5) Test alternative methods for identifying and accounting for targeting.

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Figures

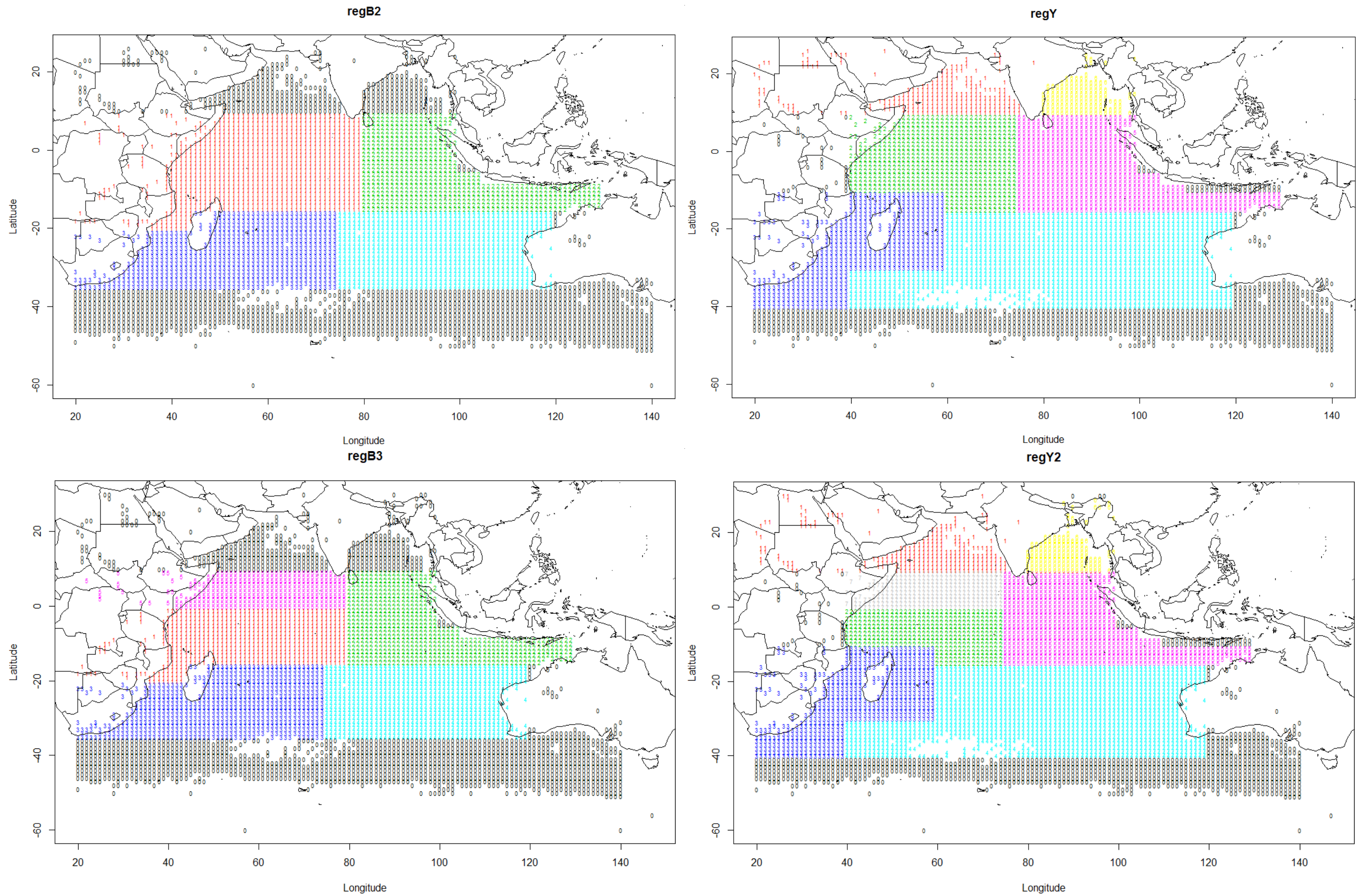

Figure 1: Maps of the regional structures used to estimate bigeye (left), and yellowfin (right) CPUE indices in both the four-region (above) and five-region (below) versions. The four region models are labelled regB2 and regY, and the five region models are regB3 and regY2.

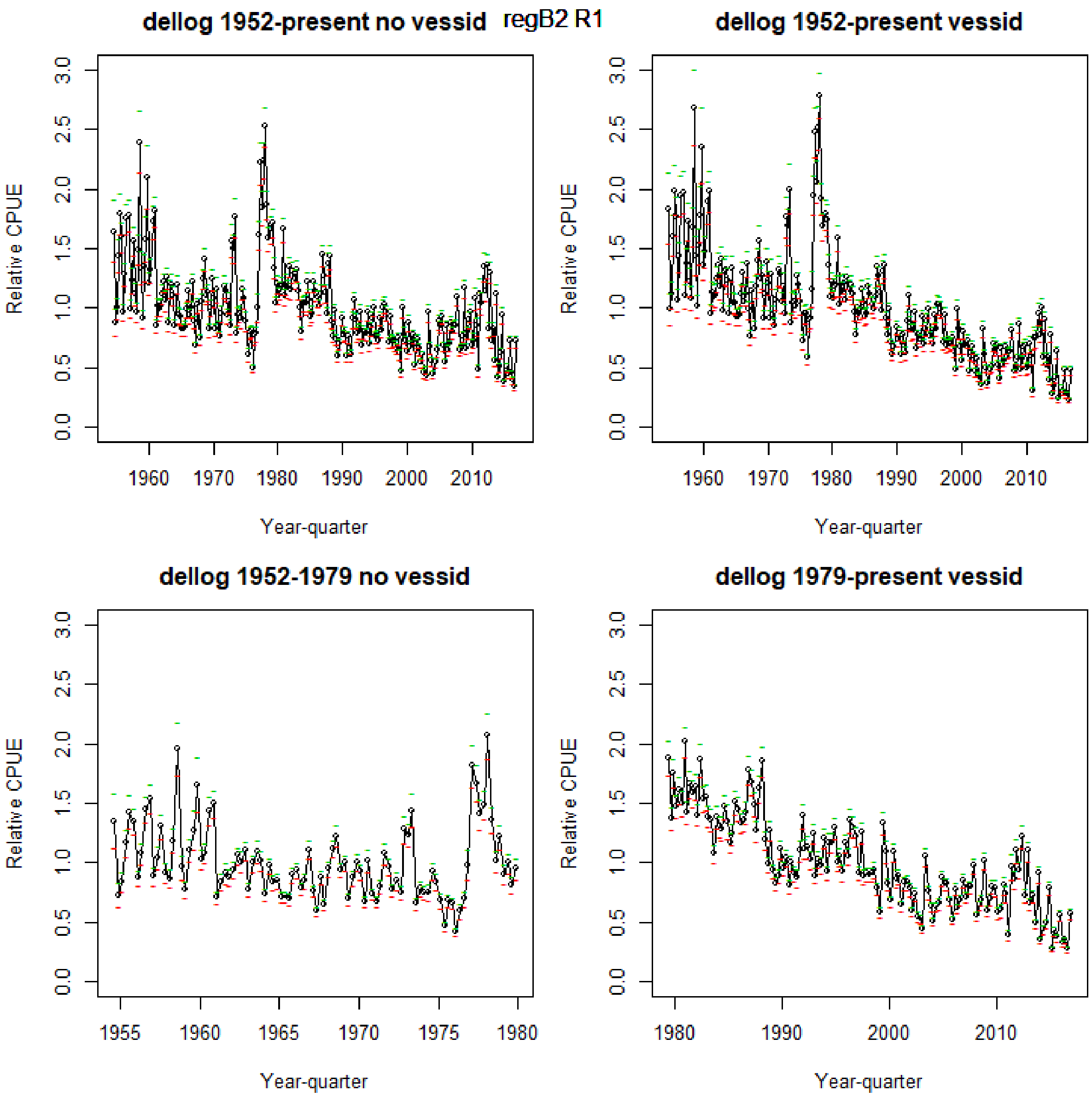

Figure 2: Estimated CPUE series for bigeye region 1 (western tropical), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

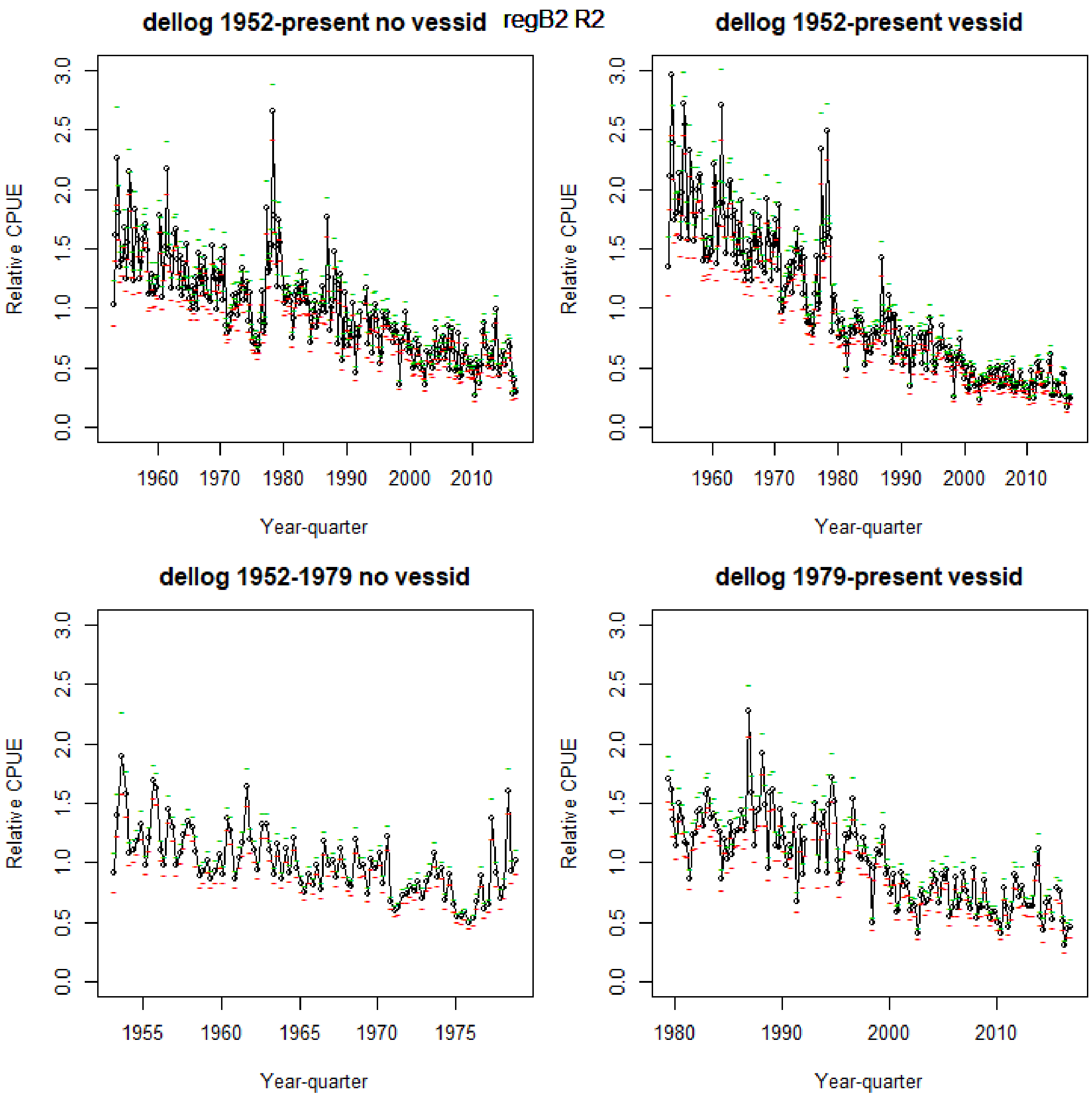

Figure 3: Estimated CPUE series for bigeye region 2 (eastern tropical), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

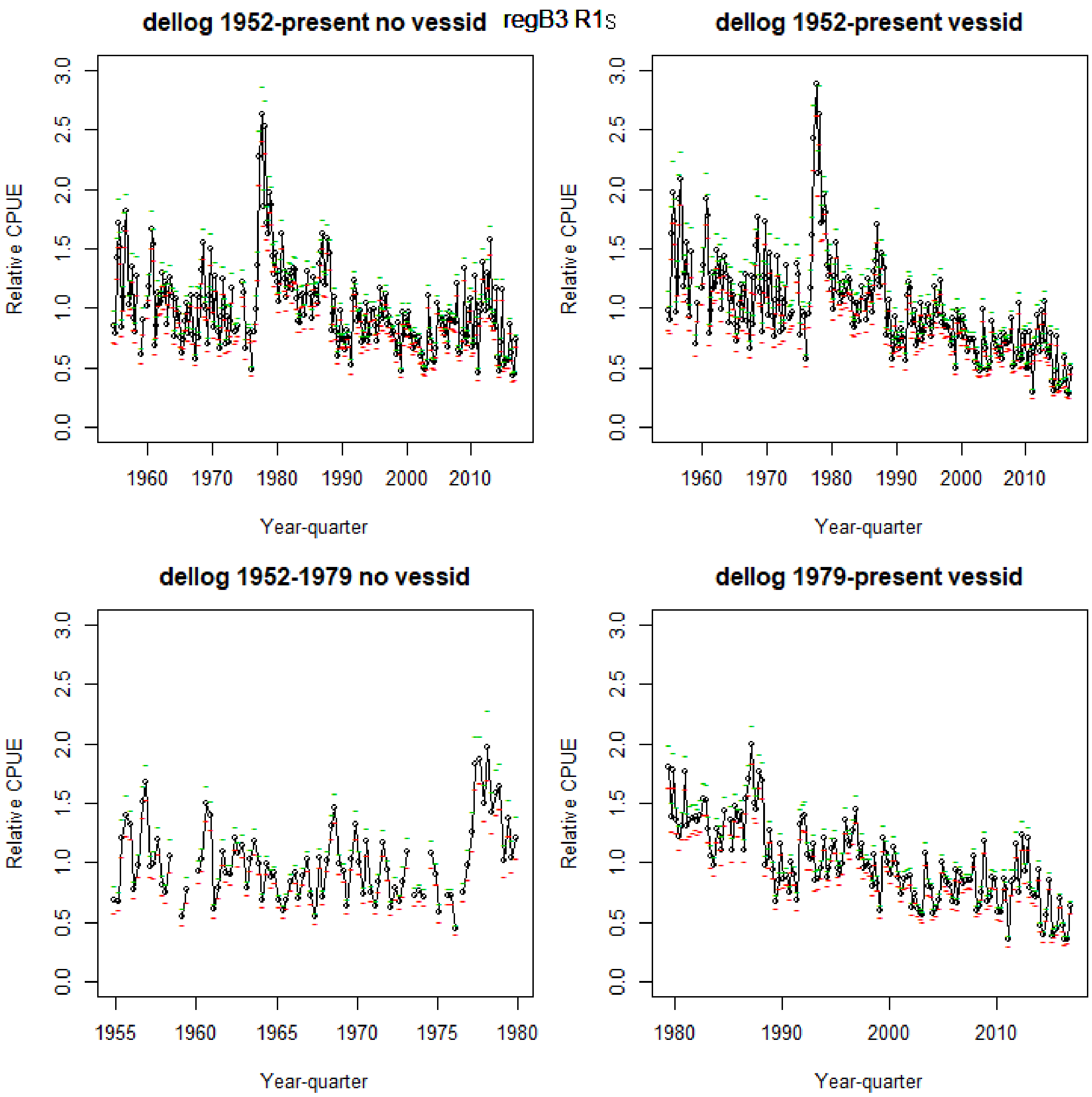

Figure 4: Estimated CPUE series for bigeye region 1s (south-western tropical) in regional structure B3, which is the southern part of the western tropical region. The plots include time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

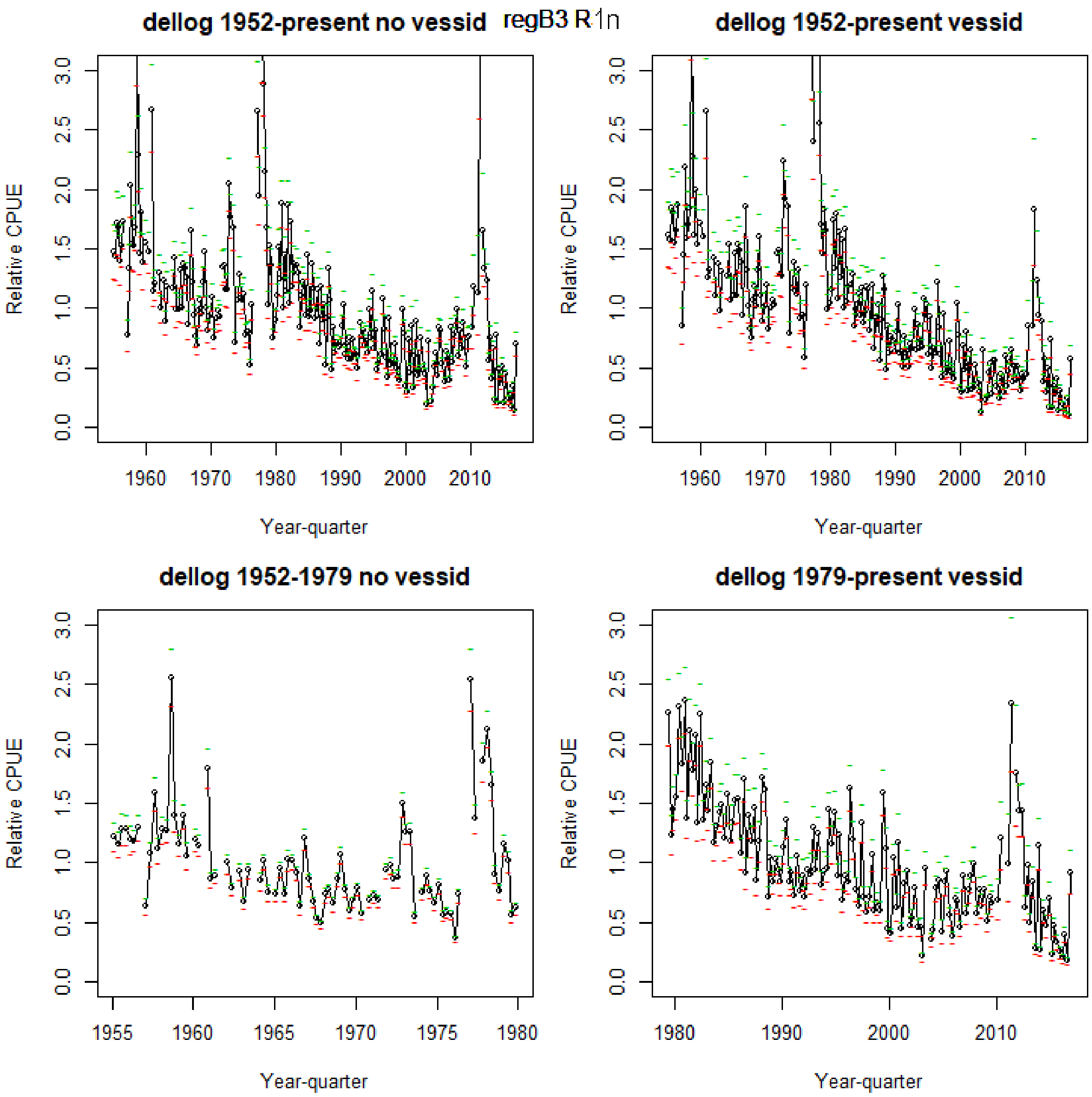

Figure 5: Estimated CPUE series for bigeye region 1n (south-western tropical) in regional structure B3, which is the northern part of the western tropical region. The plots include time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

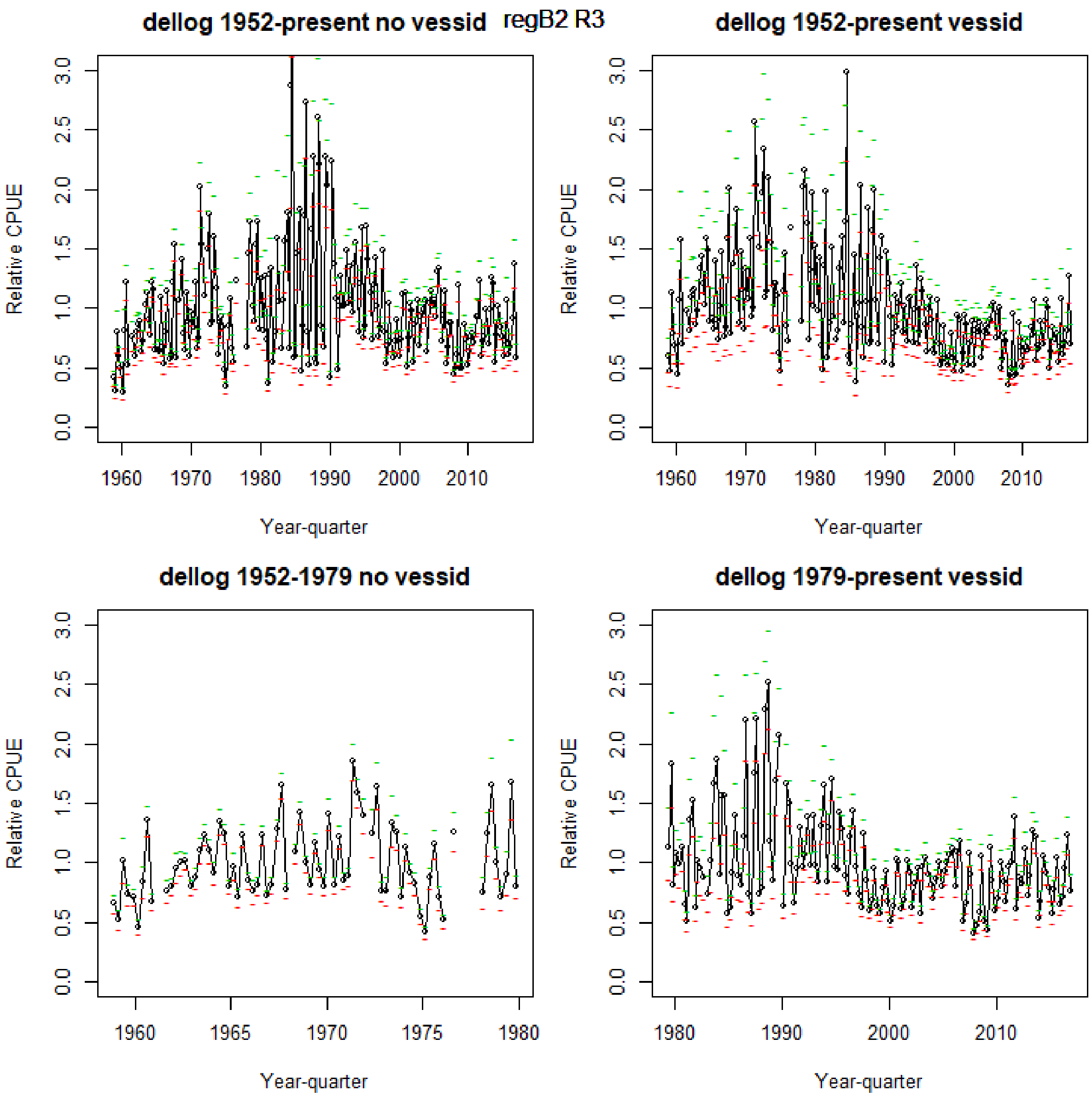

Figure 6: Estimated CPUE series for bigeye region 3 (western temperate), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

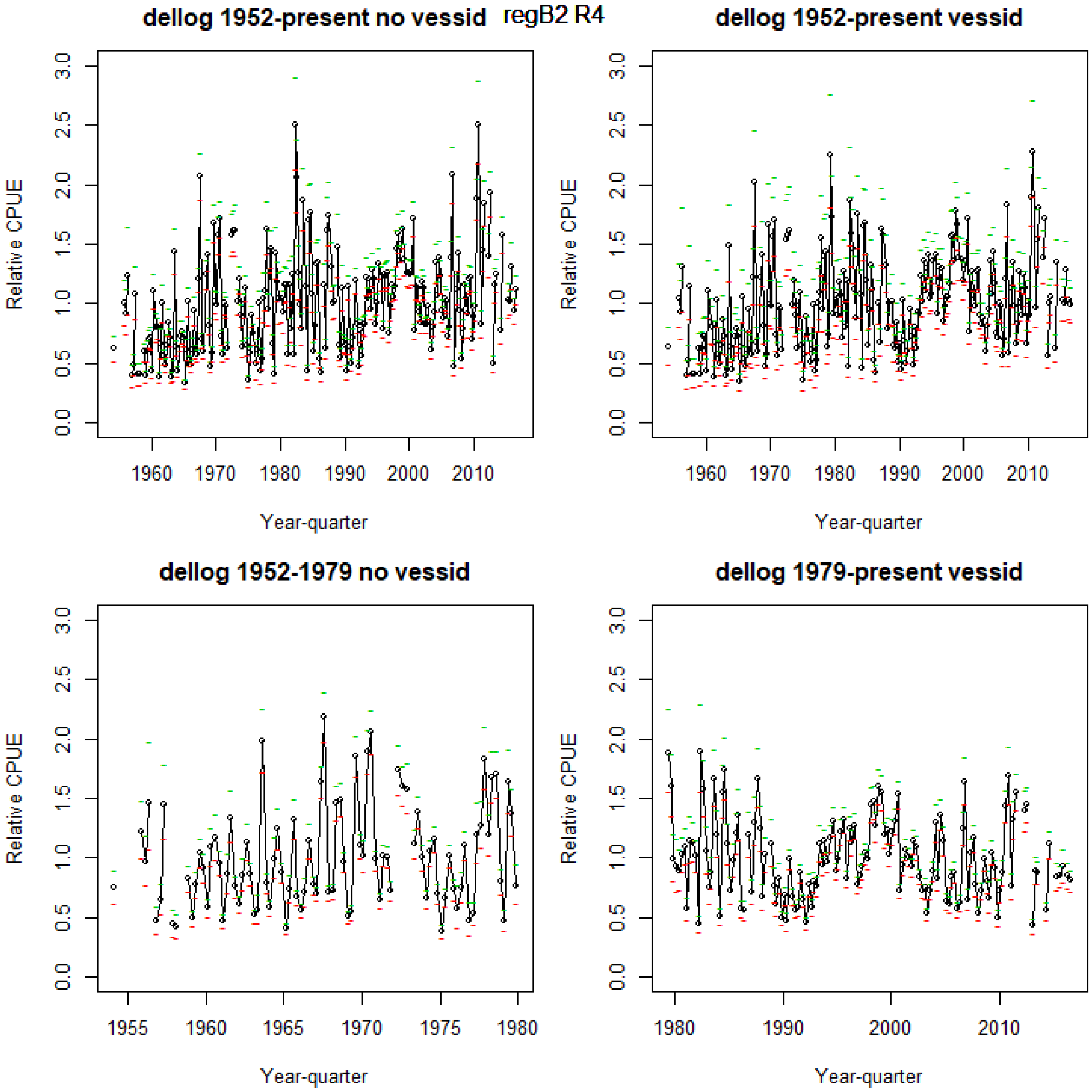

Figure 7: Estimated CPUE series for bigeye region 4 (eastern temperate), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

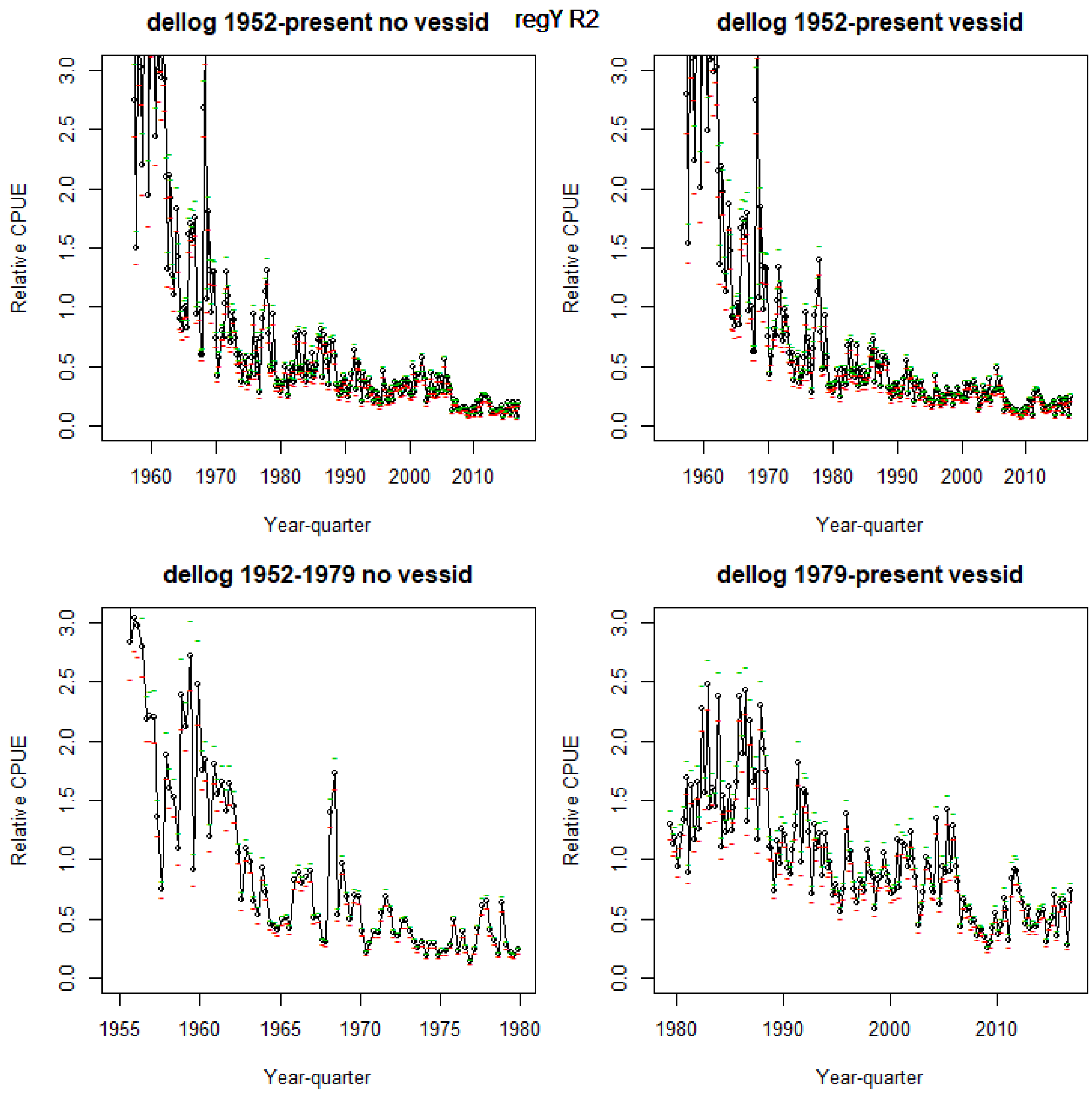

Figure 8: Estimated CPUE series for yellowfin region 2 (western tropical), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

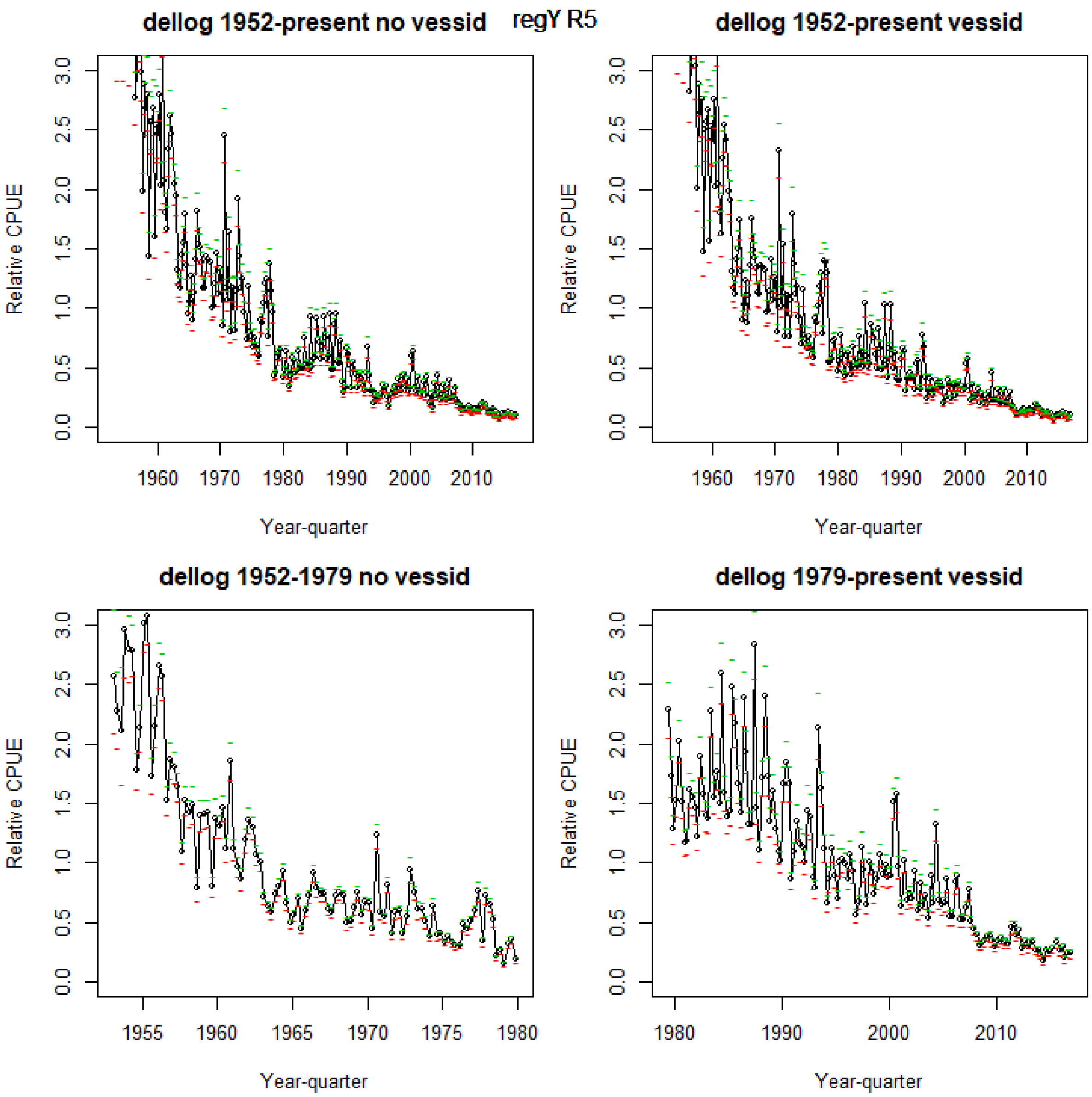

Figure 9: Estimated CPUE series for yellowfin region 5 (eastern tropical), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

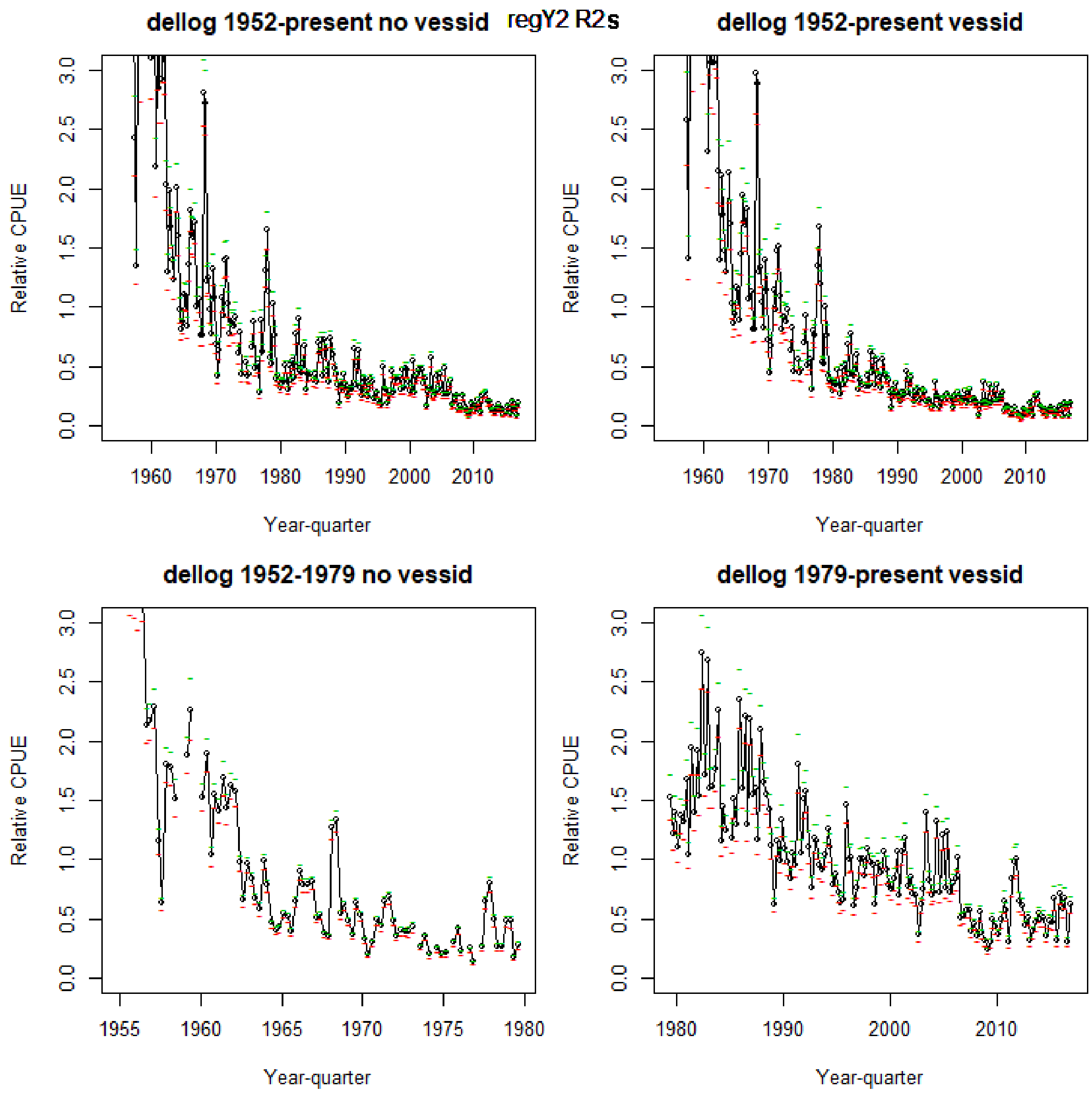

Figure 10: Estimated CPUE series for yellowfin region 2s (south-western tropical) in regional structure Y2, which is the southern part of the western tropical region. The plots include time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

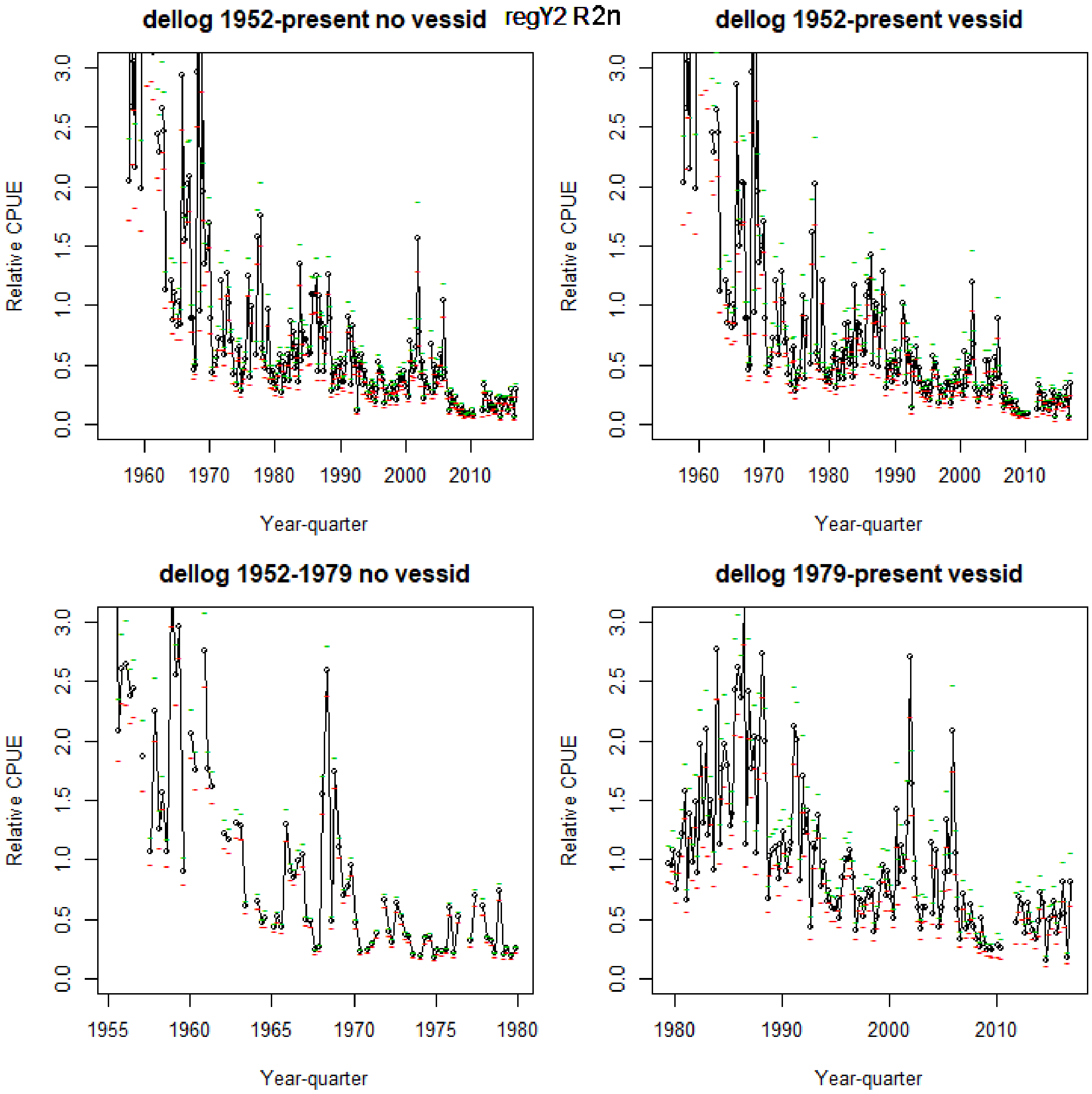

Figure 11: Estimated CPUE series for yellowfin region 2n (north-western tropical) in regional structure Y2, which is the northern part of the western tropical region. The plots include time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

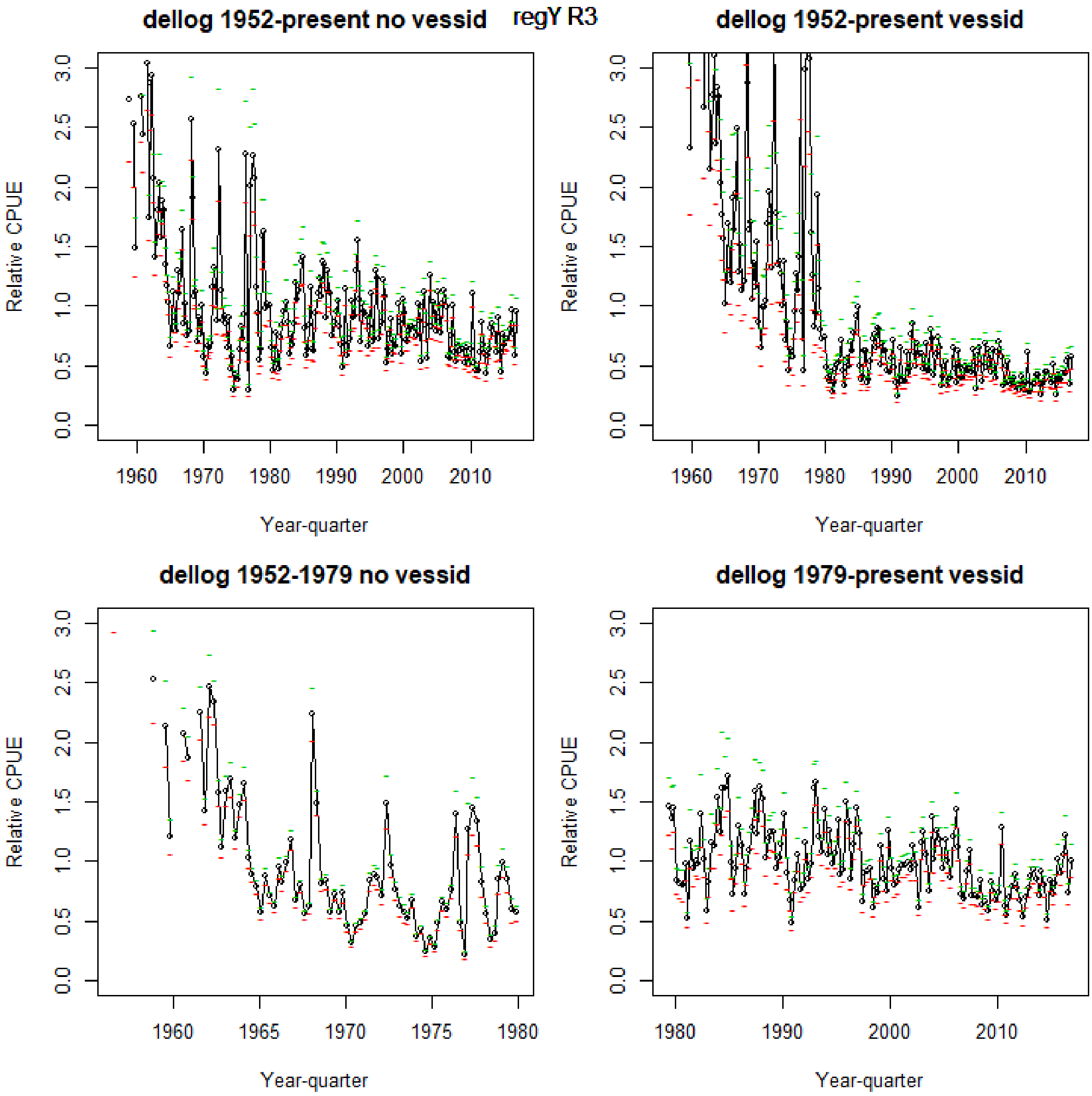

Figure 12: Estimated CPUE series for yellowfin region 3 (western temperate), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

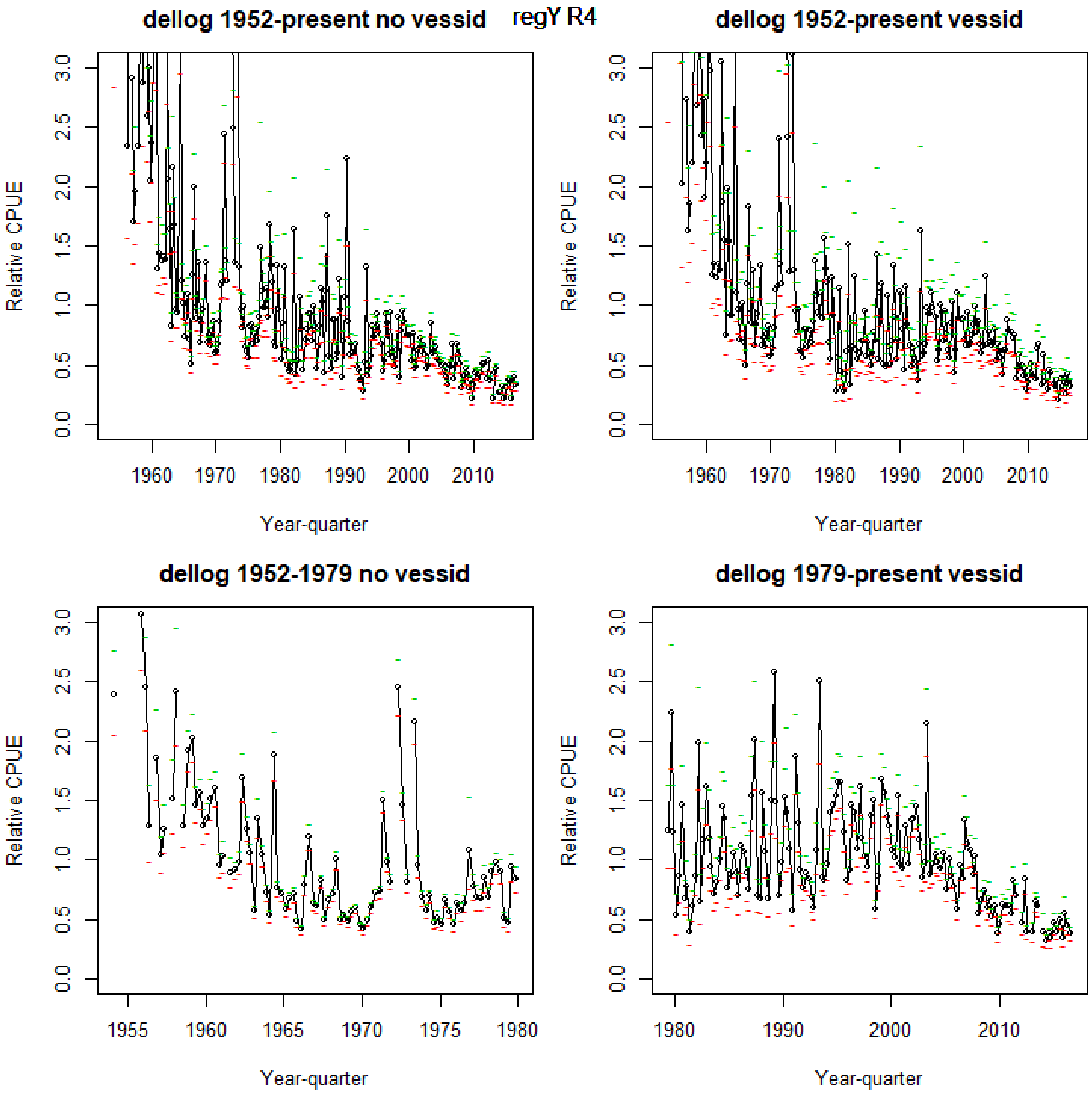

Figure 13: Estimated CPUE series for yellowfin region 4 (eastern temperate), including time series for all years (top) both with (right) and without (left) vessel effects, and time series for 1952-79 without vessel effects, and 1979-2015 with vessel effects.

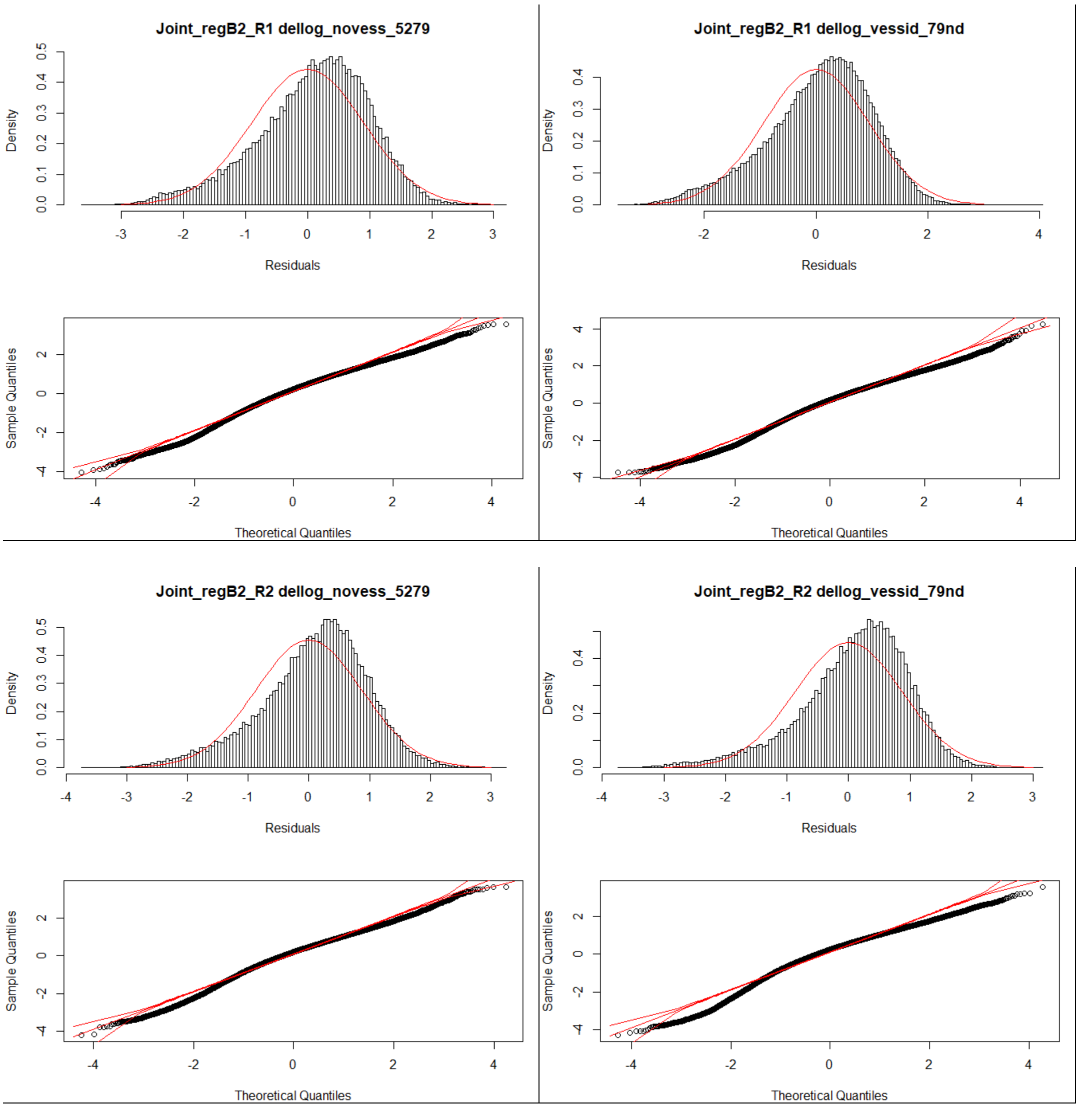

Figure 14: Diagnostics plots for bigeye lognormal positive models in tropical regions 1 and 2, for 1952-79 without vessel effects (left) and for 1979-2015 with vessel effects (right).

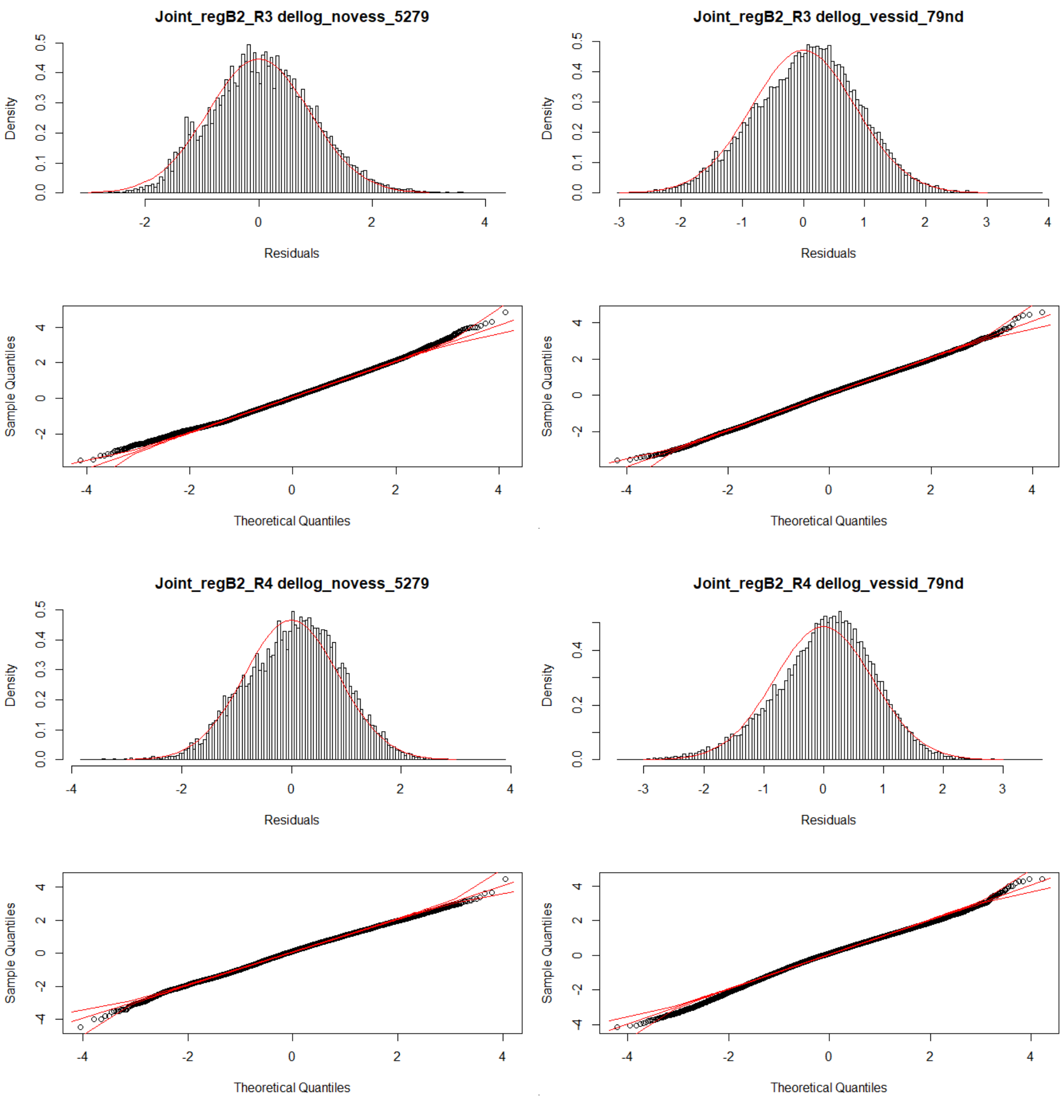

Figure 15: Diagnostics plots for bigeye lognormal positive models in temperate regions 3 and 4, for1952-79 without vessel effects (left) and for 1979-2015 with vessel effects (right).

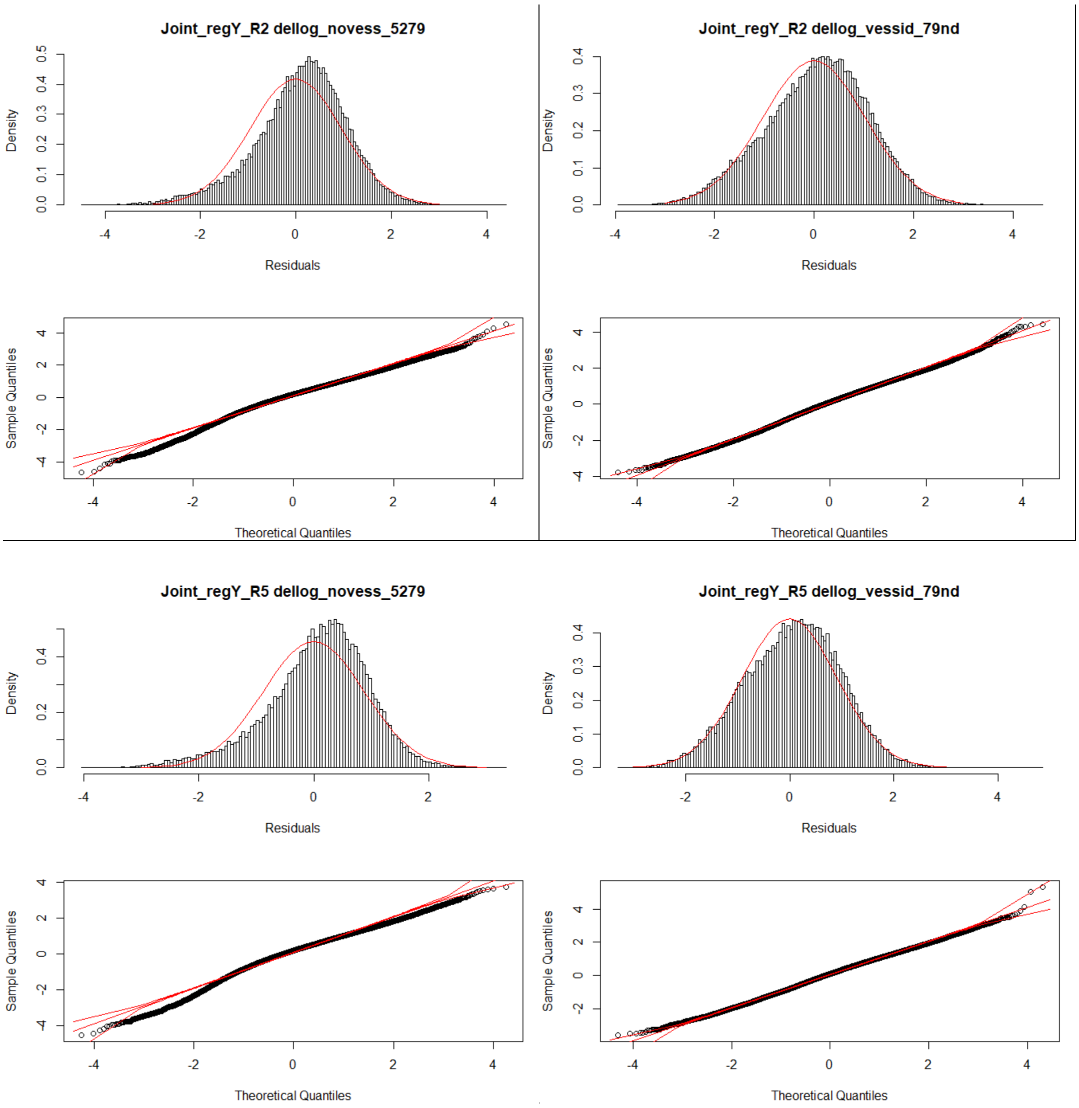

Figure 16: Diagnostics plots for yellowfin lognormal positive models in tropical regions 2 and 5, for 1952-79 without vessel effects (left) and for 1979-2015 with vessel effects (right).

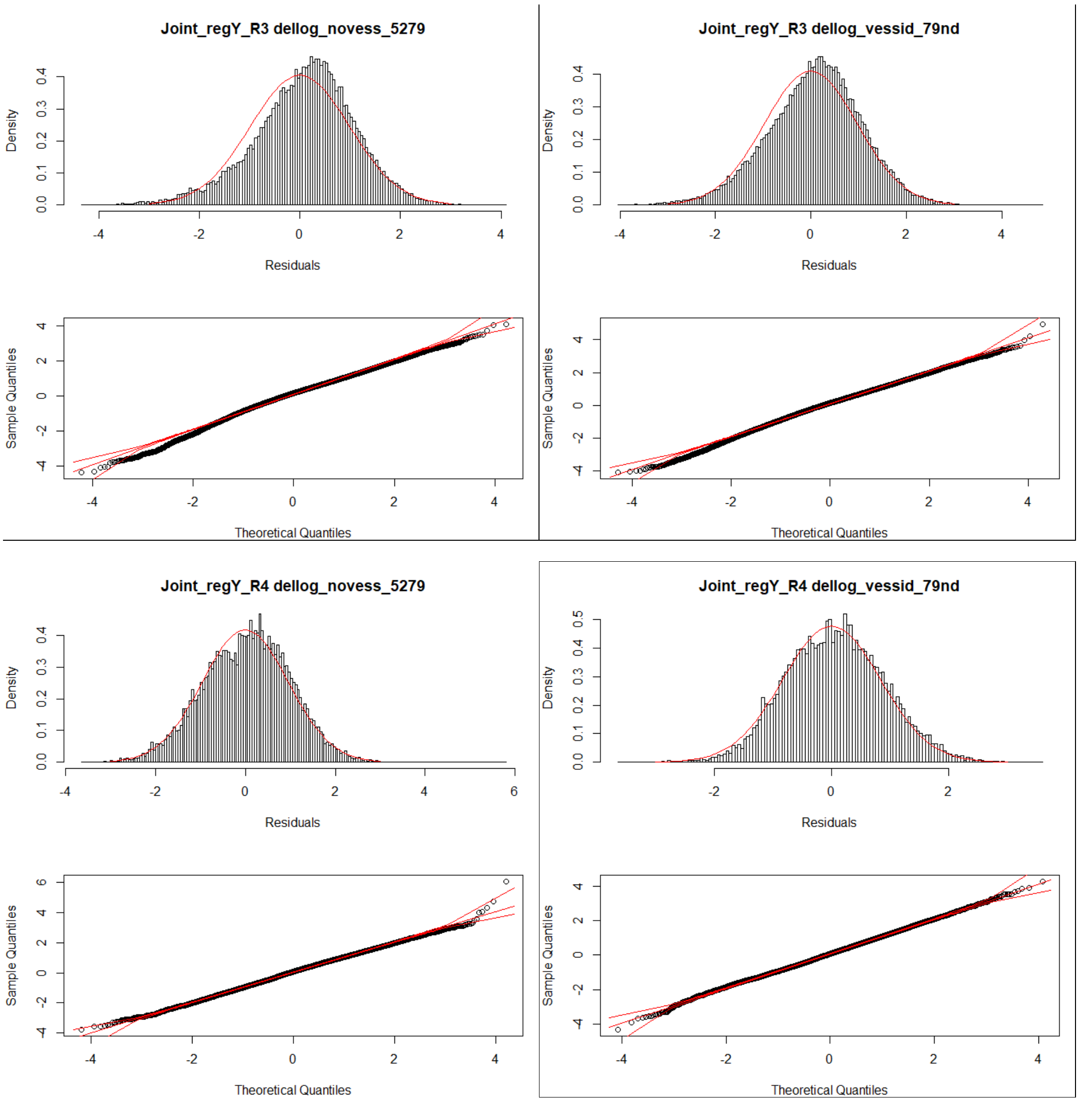

Figure 17: Diagnostics plots for yellowfin lognormal positive models in temperate regions 3 and 4, for1952-79 without vessel effects (left) and for 1979-2015 with vessel effects (right).

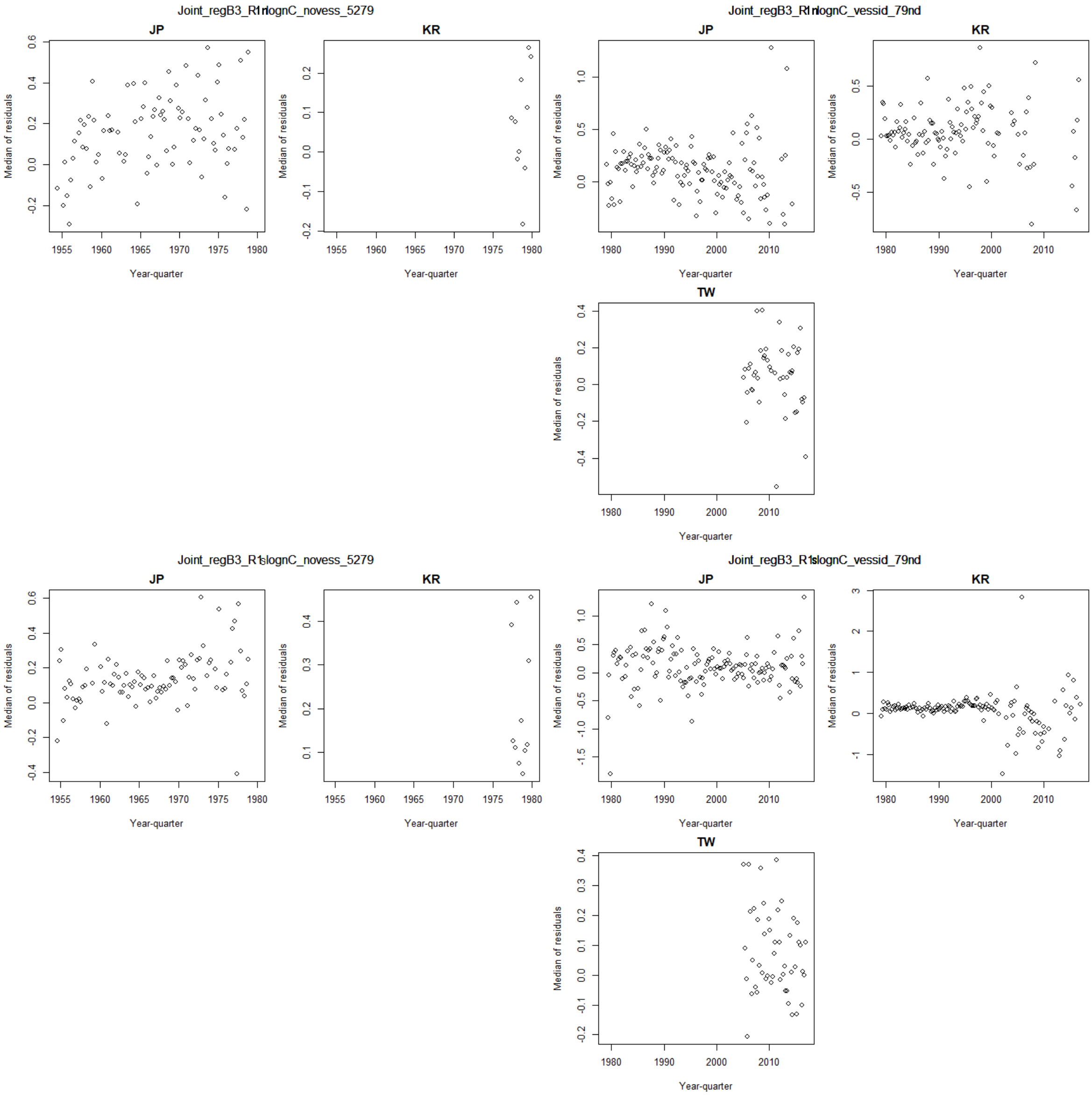

Figure 18: Median residuals from the lognormal constant model per year-quarter (x-axis), by flag (subplots), for bigeye in region 1n (north-western tropics) above, and region 1s (southwestern tropics) below. Residuals are shown for 2 models: 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

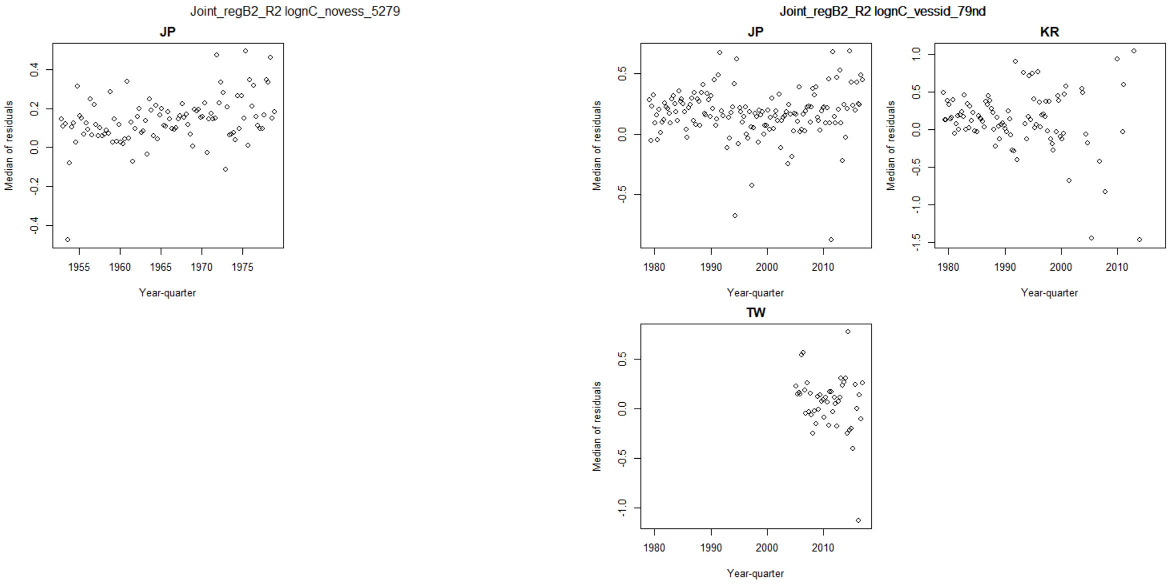

Figure 19: Median residuals from the lognormal constant model per year-quarter (x-axis), by flag (subplots), for bigeye in region 2 (eastern tropics). Residuals are shown for 2 models: 1952-1979 without vessel effects (above), and 1979-2015 with vessel effects (below).

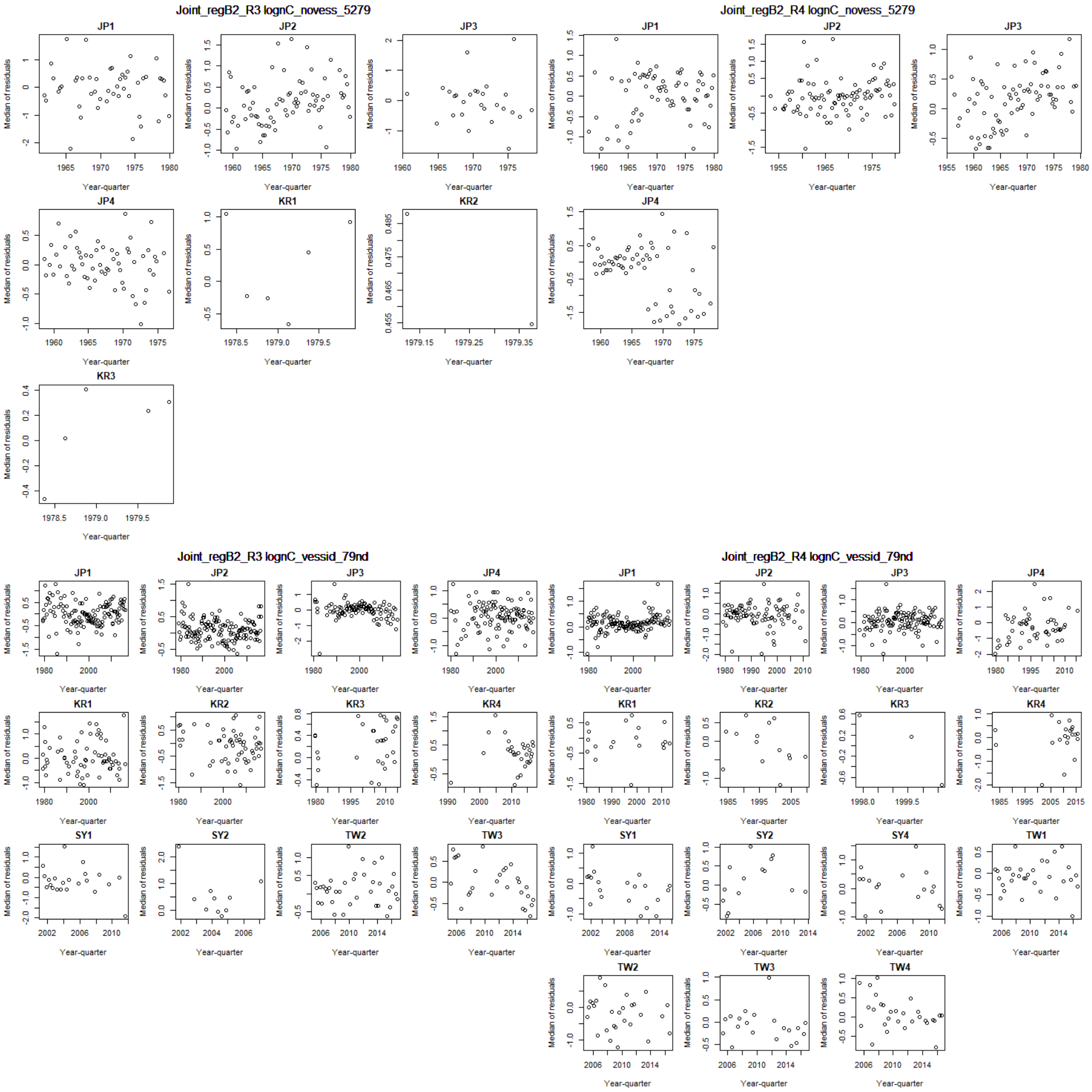

Figure 20: Median residuals from the lognormal constant model per year-quarter (x-axis), by cluster (subplots), for bigeye in region 3 (western temperate, left) and region 4 (eastern temperate, right). Residuals are shown for 2 models: 1952-1979 without vessel effects (above), and 1979-2015 with vessel effects (below).

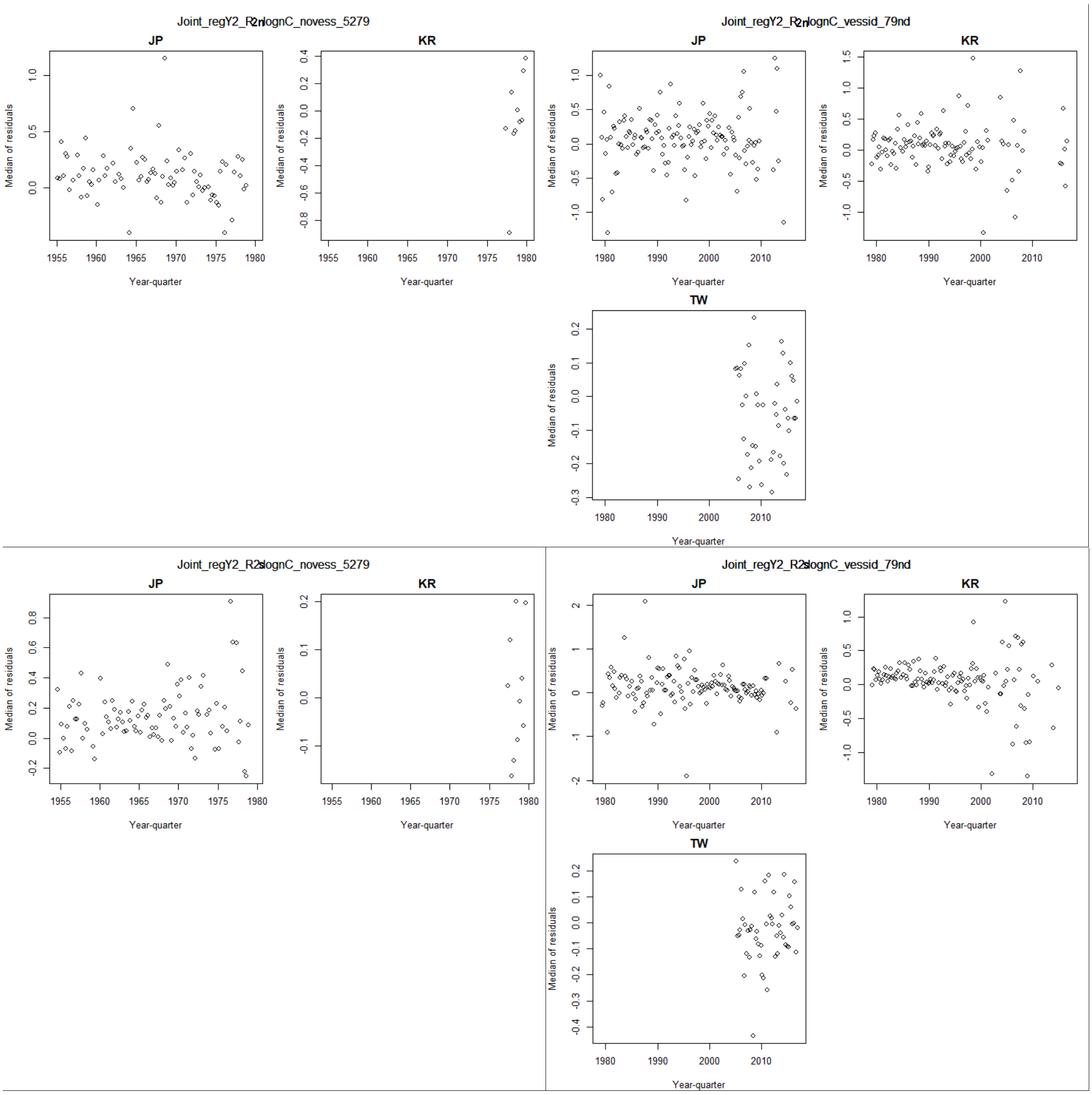

Figure 21: Median residuals from the lognormal constant model per year-quarter (x-axis), by flag (subplots), for yellowfin in region 2n (north-western tropics, above), and 2s (south-western tropics, below). Residuals are shown for 2 models: 1952-2015 without vessel effects (left), and 1979-2015 with vessel effects (right).

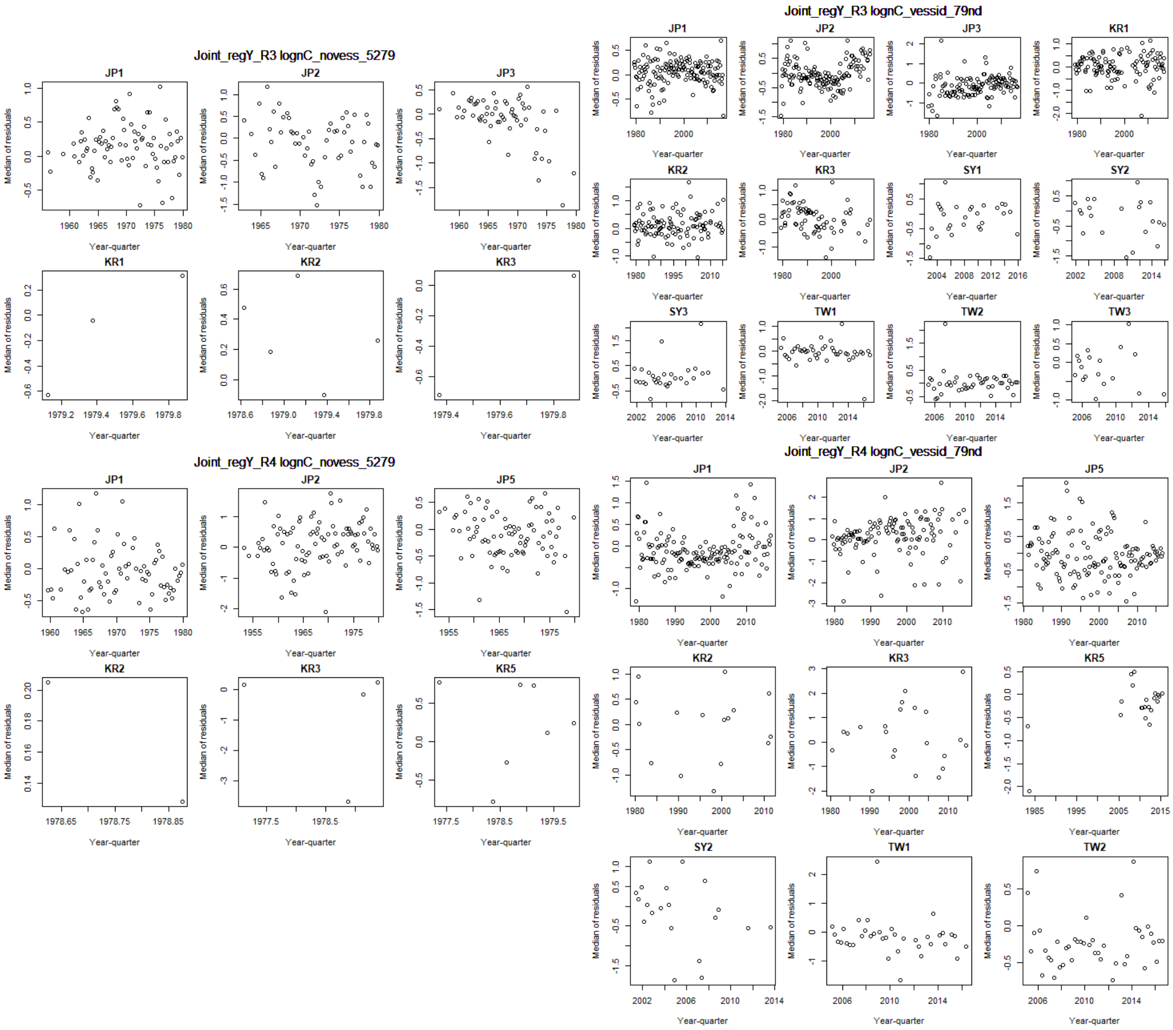

Figure 22: Median residuals from the lognormal constant model per year-quarter (x-axis), by cluster (subplots), for yellowfin in regions 3 (western temperate, above) and 4 (eastern temperate, below). Residuals are shown for 2 models: 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

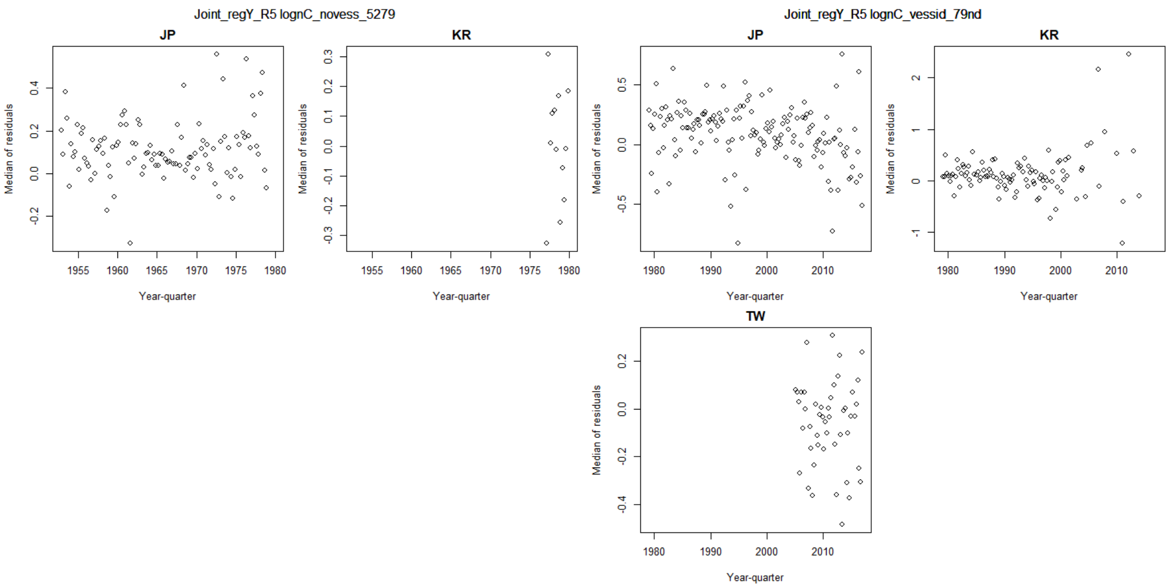

Figure 23: Median residuals from the lognormal constant model per year-quarter (x-axis), by flag (subplots), for yellowfin in region 5 (eastern tropics). Residuals are shown for 2 models: 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

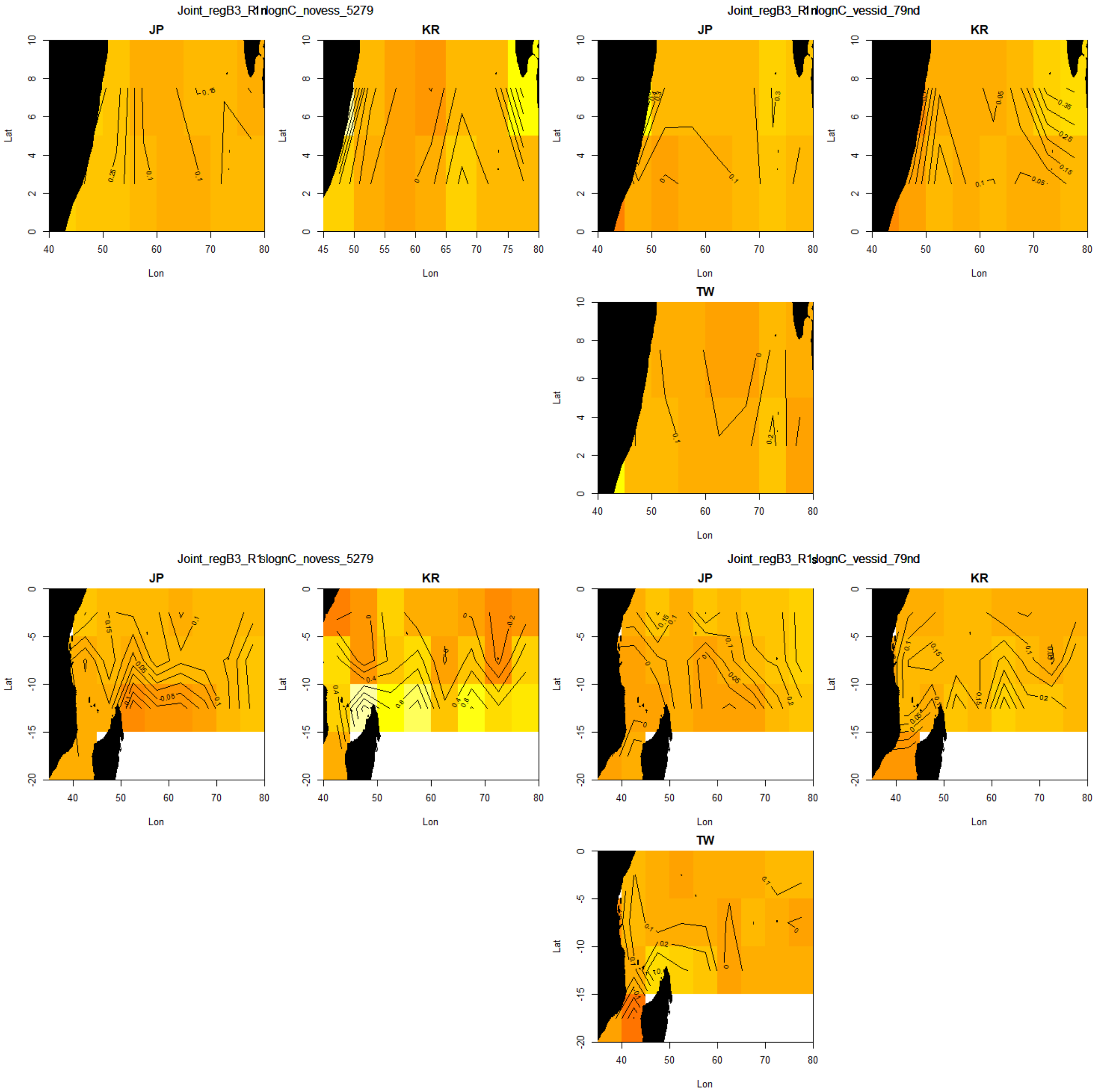

Figure 24: Bigeye residuals for western tropical regions 1n (above) and 1s (below), by flag. Median residuals are mapped by 5° cell for the periods 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

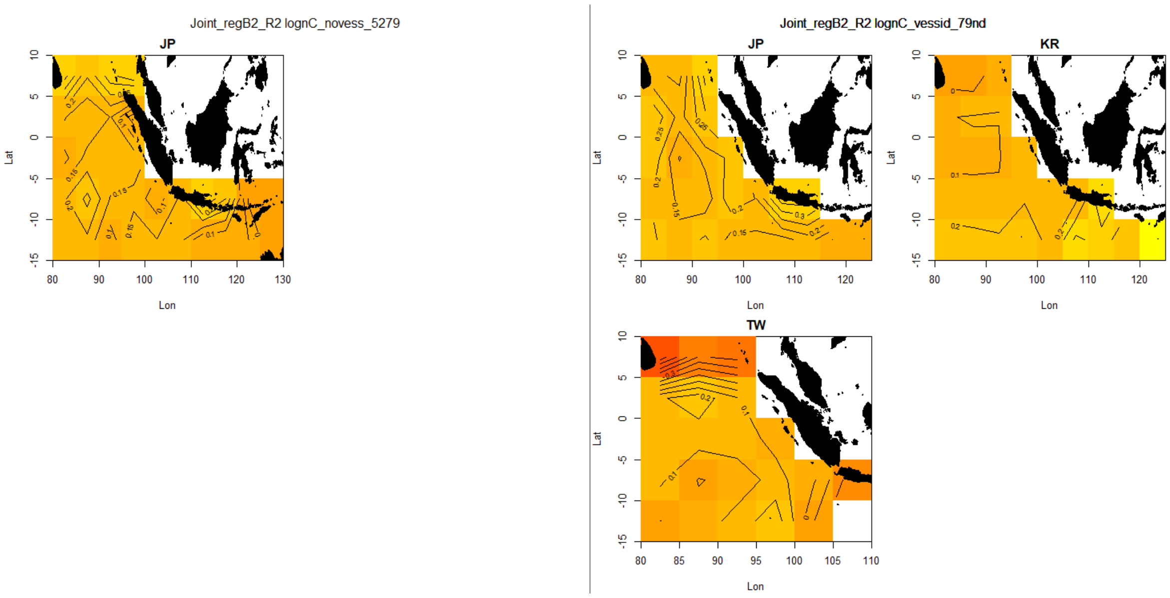

Figure 25: Bigeye residuals for eastern tropical region 2, by flag. Median residuals are mapped by 5° cell for the periods 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

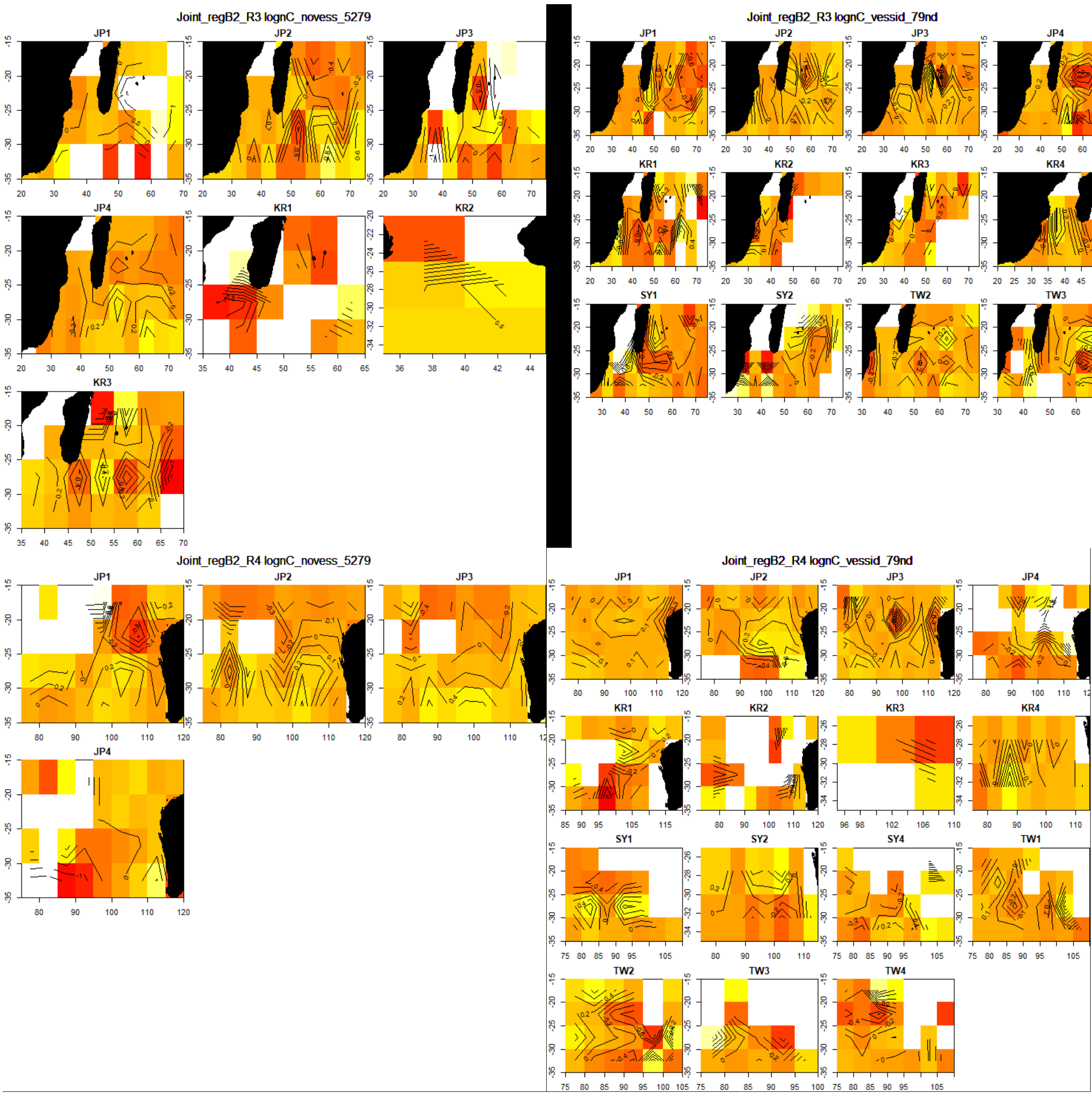

Figure 26: Bigeye residuals for temperate regions 3 (above) and 4 (below), by cluster. Median residuals are mapped by 5° cell for the periods 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

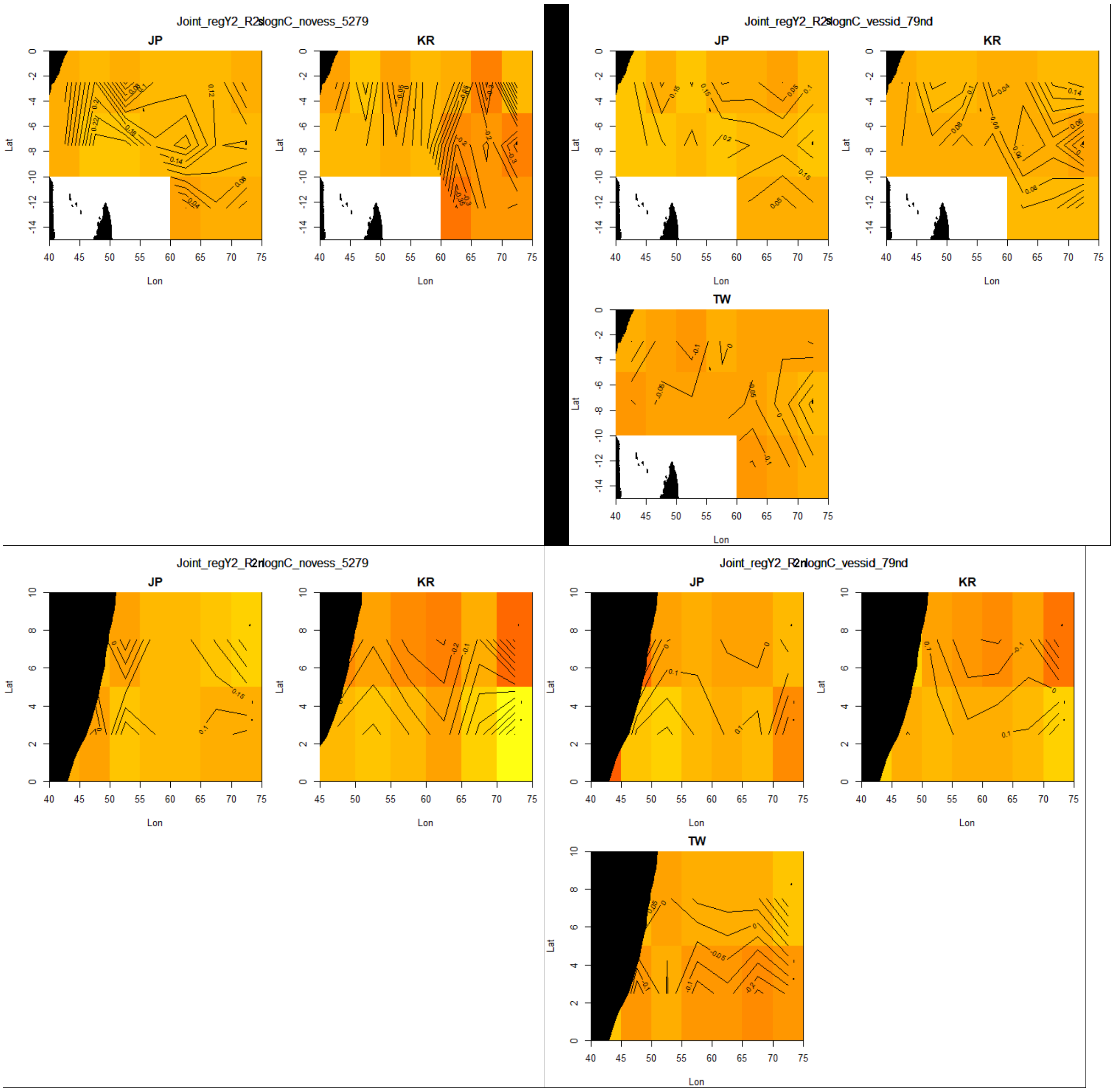

Figure 27: Yellowfin residuals for western tropical regions 2n (above) and 2s (below), by flag. Median residuals are mapped by 5° cell for the periods 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

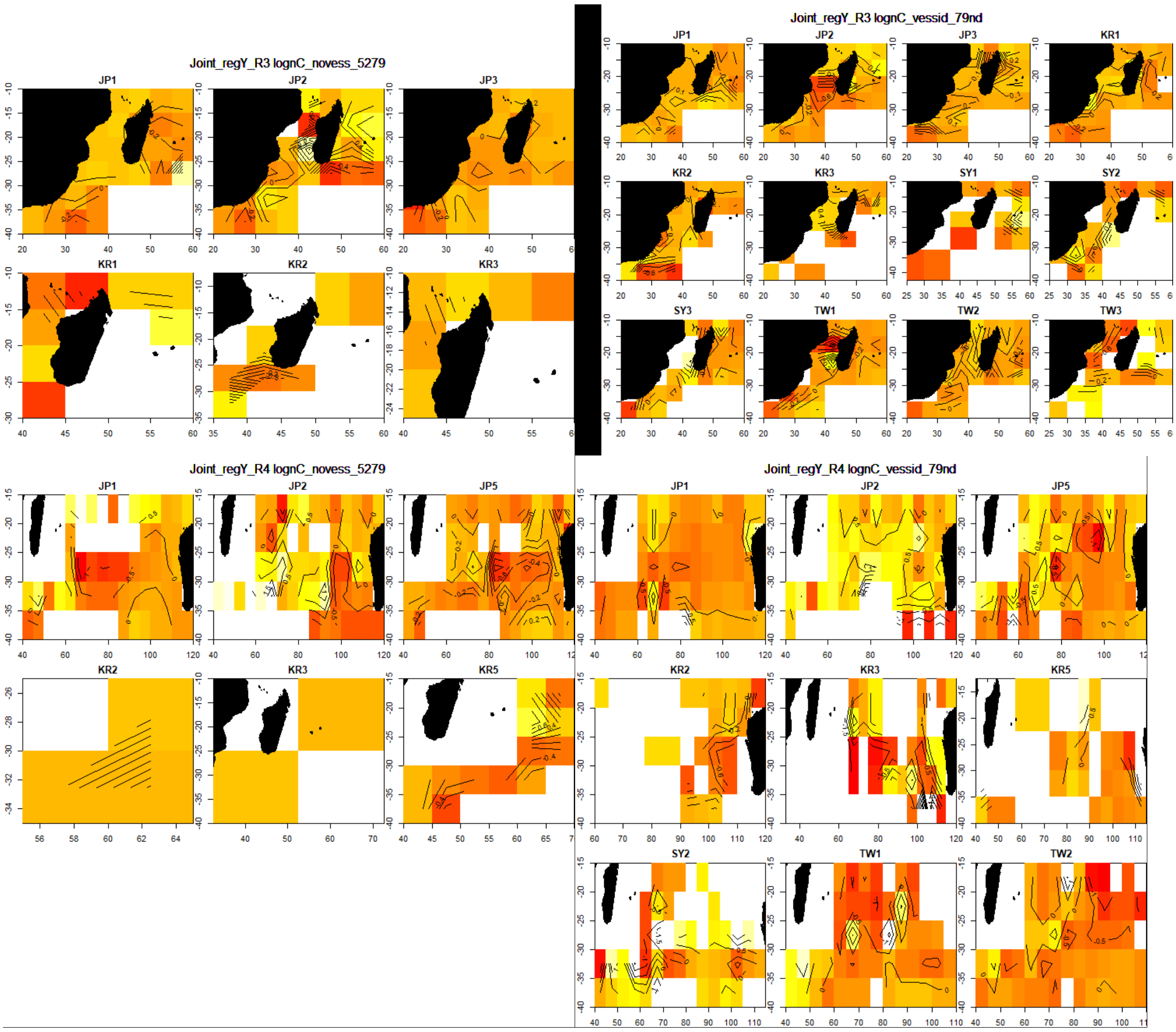

Figure 28: Yellowfin residuals for temperate regions 3 (above) and 4 (below), by cluster. Median residuals are mapped by 5° cell for the periods 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

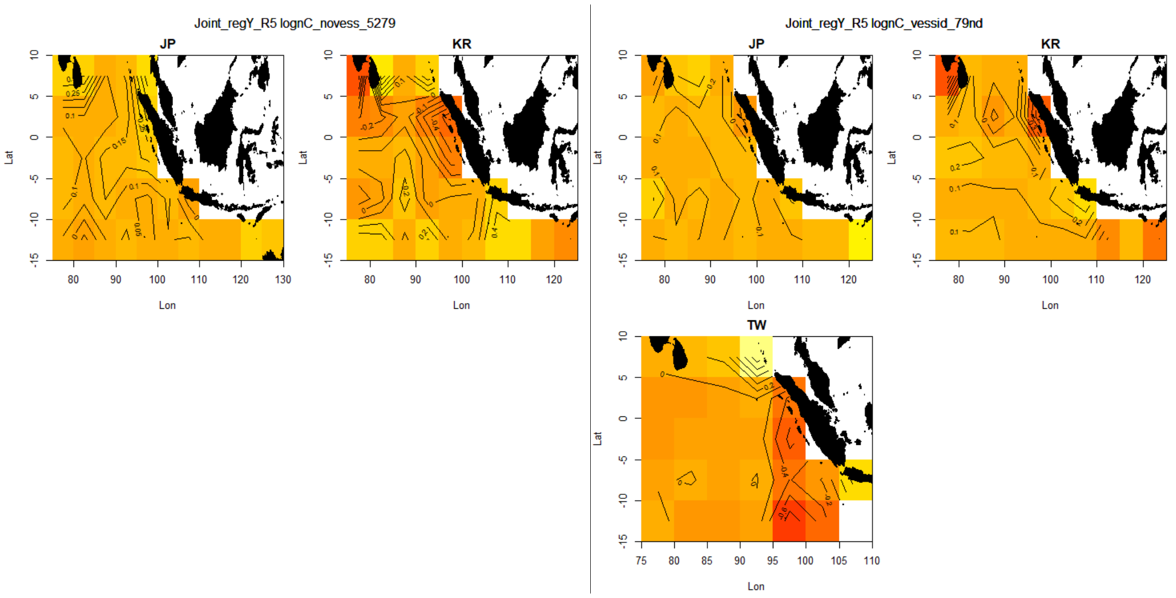

Figure 29: Yellowfin residuals for tropical region 5, by flag. Median residuals are mapped by 5° cell for the periods 1952-1979 without vessel effects (left), and 1979-2015 with vessel effects (right).

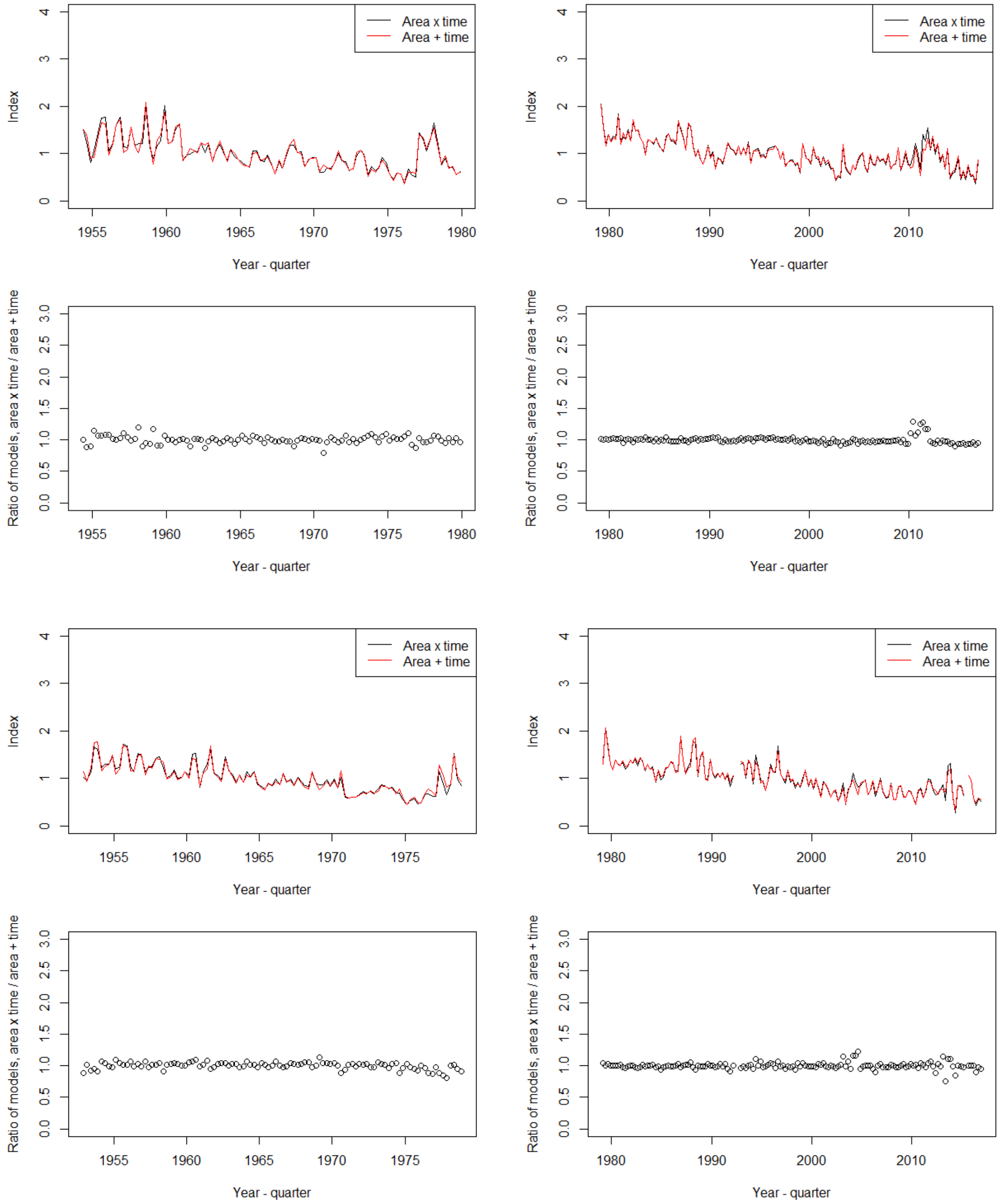

Figure 30: For bigeye in regions 1 (western tropical, above) and 2 (eastern tropical, below), index comparisons between time x area (black) and time + area (red) models. Results are provided for 1952-1979 (left) and 1979-2016 (right). Ratios between time x area and time + area models are in the lower panels.

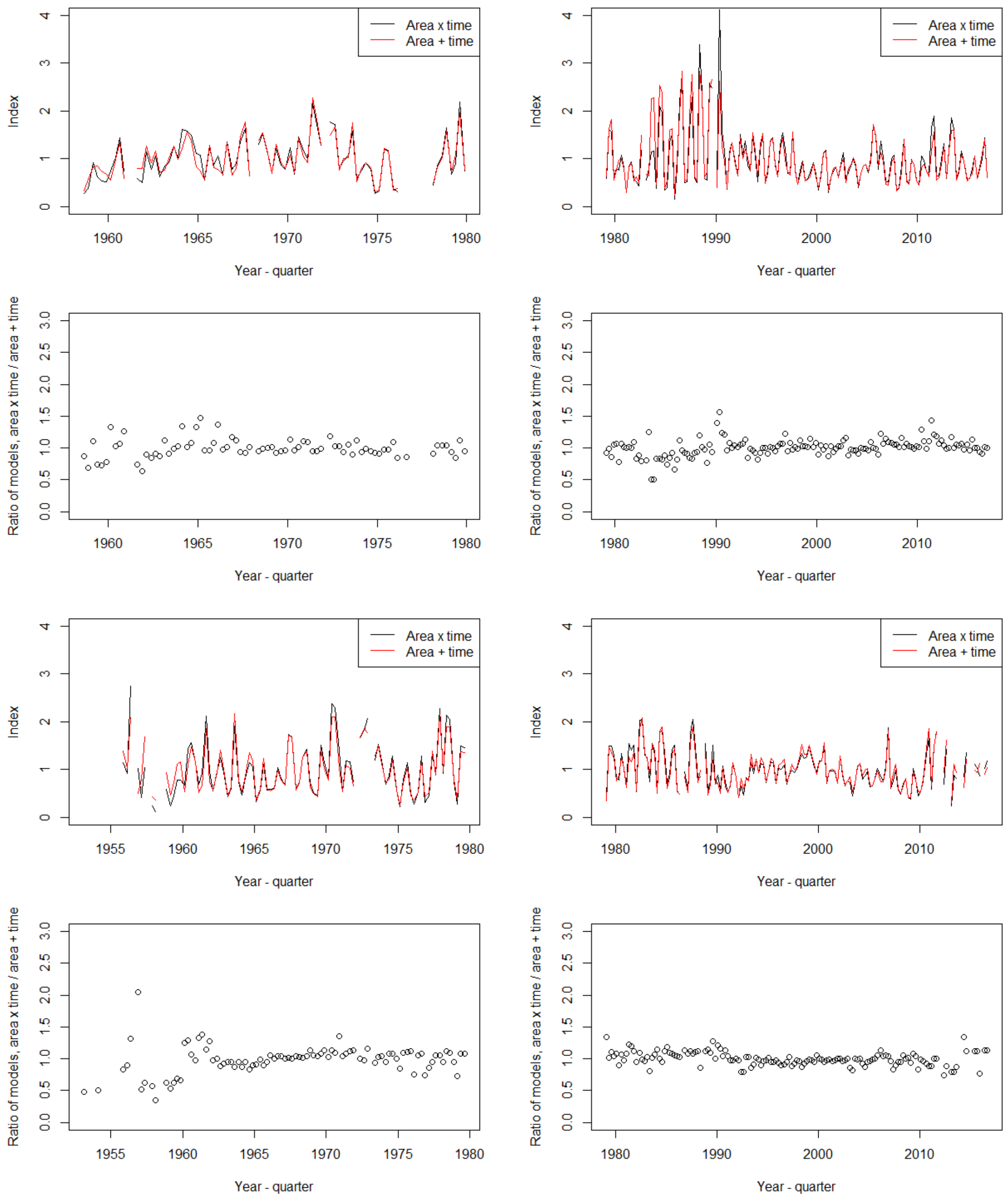

Figure 31: For bigeye in regions 3 (western temperate, above) and 4 (eastern temperate, below), index comparisons between time x area (black) and time + area (red) models. Results are provided for 1952-1979 (left) and 1979-2016 (right). Ratios between time x area and time + area models are in the lower panels.

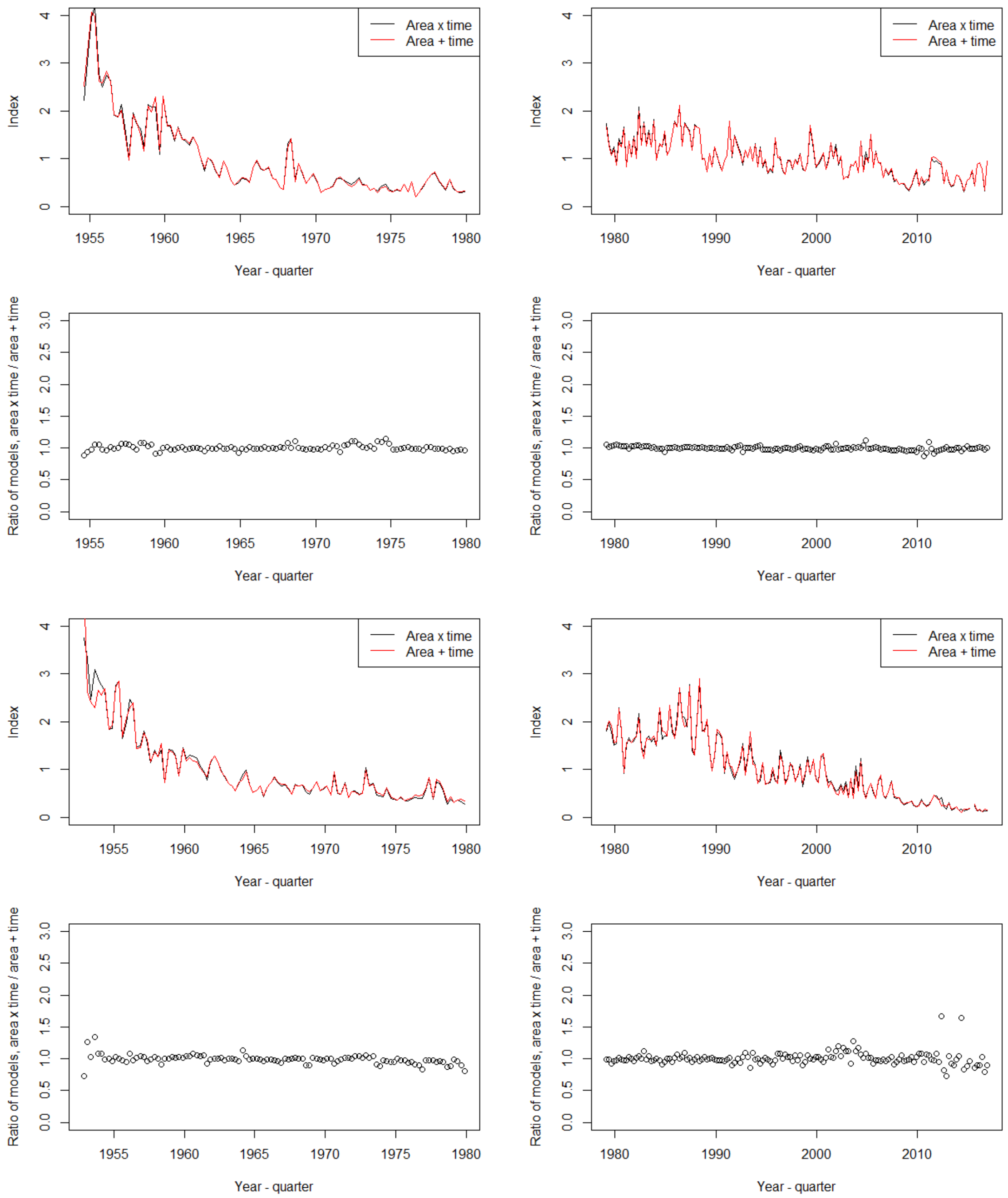

Figure 32: For yellowfin in regions 2 (western tropical, above) and 5 (eastern tropical, below), index comparisons between time x area (black) and time + area (red) models. Results are provided for 1952-1979 (left) and 1979-2016 (right). Ratios between time x area and time + area models are in the lower panels.

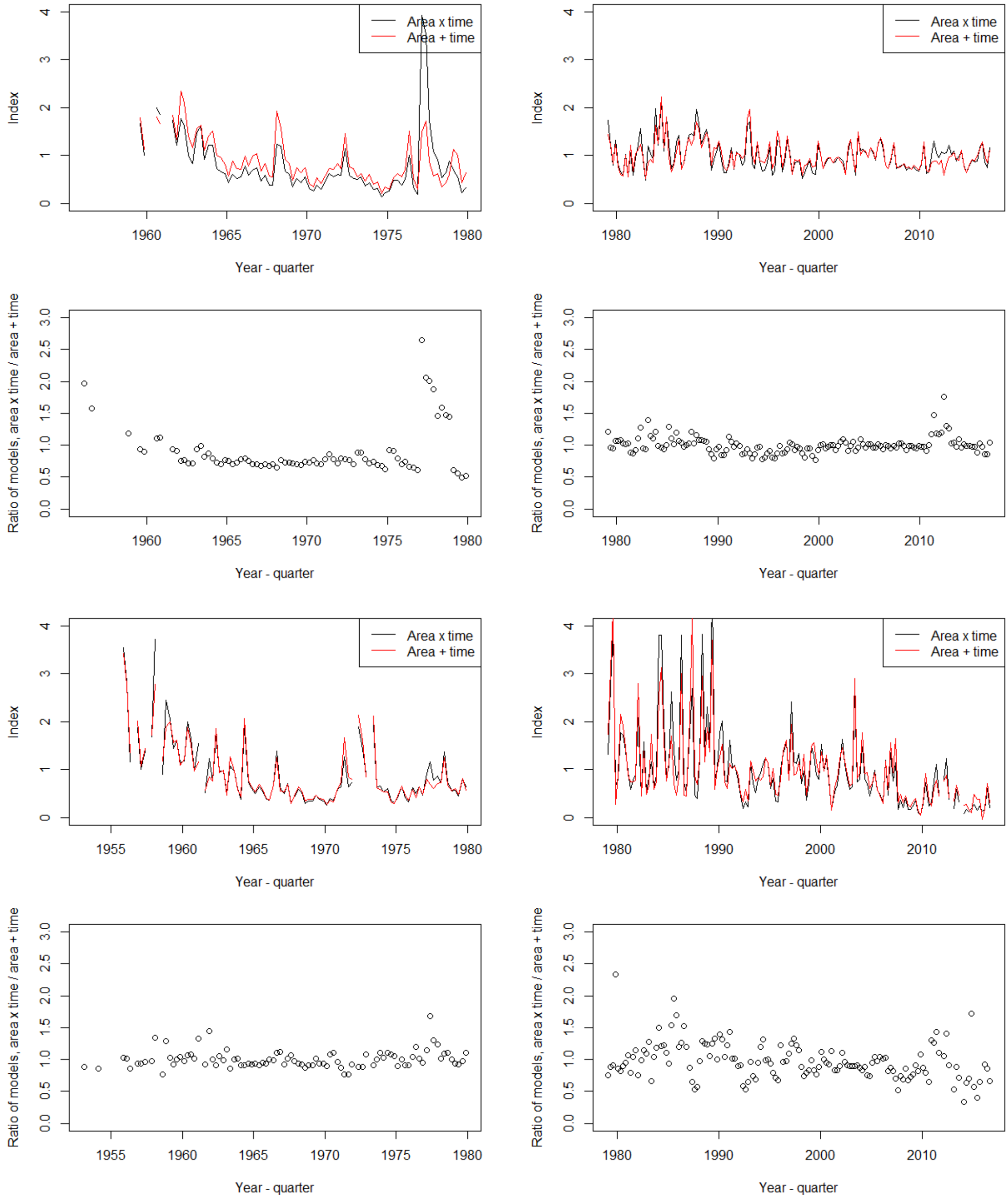

Figure 33: For yellowfin in regions 3 (western temperate, above) and 4 (eastern temperate, below), index comparisons between time x area (black) and time + area (red) models. Results are provided for 1952-1979 (left) and 1979-2016 (right). Ratios between time x area and time + area models are in the lower panels.