Indian Ocean Tuna Commission Working Party on Billfish Working Paper: **IOTC-2010-WPB-03**

Reunion Longline Swordfish Catch Rate Standardization

June 2010

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Summary

This document describes some analyses undertaken to standardize the swordfish CPUE series from the Reunion longline fleet, so that it can be used as a relative abundance index in the 2010 IOTC Working Party on Billfish (WPB). The analysis includes: i) simple descriptive summary of spatial/temporal operations and gear configurations, ii) attempts to identify subsets of the data that represent relatively homogeneous fleets with consistent targeting practices, and iii) Presentation and comparison of annual and quarterly time series of relative abundance derived from GLM models.

The Reunion fleet has operated most consistently in the continental shelf area near La Reunion, but in some years, substantial operations have been undertaken in the Mozambique Channel and northward in the Seychelles. Three different logbook-based datasets were provided to the IOTC secretariat. The data from 1993-2000 were the most useful for CPUE analyses, as they included records at a set by set resolution with many operational details. The data from 2005-8 were also useful, but included fewer fields and were not entirely consistent with the 1993-2000 period. The data from the 2001-2004 period was aggregated at the level of the trip, and did not include location or effort in hooks, and hence was not used at this time.

The data were partitioned in different ways in an attempt to define a consistent core swordfish-targeting fishery for the 1993-2000 period:

- Restricted to a 10x10 degree area near La Reunion only
- Night sets with lightstick use only
- Comparison of data sets with different levels of experience among the Individual Vessels:
    i. All vessels included
    ii. Only vessels that operated for 3+ years included

Linear models were used to predict log(CPUE + C), where C was equal to the lower 10th percentile of the whole CPUE distribution. Explanatory variables included Year, Quarter, 5x5 degree (sub-)Area, Vessel ID, Moon Phase and interaction terms (Year:Area and Year:Quarter). Zero-inflated and delta models were not explored, because zero CPUE observations accounted for only 2% of observations. An iterative model building approach suggested that (in addition to Year) the most useful predictive variables were

the Sub-Area, Quarter and Vessel ID. Moon Phase was consistently identified as highly significant, but explained an inconsequential portion of CPUE variability. Interaction terms (Year:Area and Year:Quarter) were identified as statistically significant, but these terms were rejected, as they explained a trivial amount of the variability for the number of additional parameters required, and the estimated abundance time series were dubious (presumably strongly influenced by a very unbalanced distribution of observations). An automated stepwise model building process using BIC as the selection criterion also supported the removal of interaction terms. Systematic analysis of the plausibility and mechanisms associated with the different predictive terms was not undertaken, because in all cases examined (excluding the models with the interaction terms), the point estimates of the final relative abundance indices from the different standardized series were very similar to each other and the nominal CPUE series. The time series recommended for stock assessment purposes is very similar to that produced by the 2001 WPB (2001).

An initial attempt was made to merge the data from 1993-2000 and 2005-8, to examine the abundance trend observed since the last analysis. Since the 2005-8 data did not include data on set-time, lightstick use, hook type, or other potentially useful operational characteristics, the data that were explored in the merged time series were potentially more heteregenous. Data were restricted to:

- La Reunion area
- Comparison of species-based targeting restrictions:
    - i. All sets included
    - ii. Sets with positive BET catch excluded
    - iii. Sets with positive YFT, BET and ALB catch excluded

Only Year, Area and Quarter effects were estimated. The latter two data sets represented an attempt to identify the sets most likely to be aimed at swordfish targeting. The models from the extended time series suggested that: i) there is very little difference between the nominal and standardized CPUE series, ii) The CPUE in the latter period is substantially lower than the earlier period, and iii) there is no evidence for a trend within the 2005-8 period. Nominal CPUE trends suggest that BET CPUE underwent a dramatic increase between the early and latter periods, while SWO CPUE underwent a dramatic decrease. This is strongly suggestive of a targeting shift. However, removing all sets with positive BET catch, or positive BET, YFT and ALB catch did not have a noticeable impact on estimated relative abundance indices. Given the reported changes in the Reunion targeting between the two periods, and the absence of relevant operational factors from the latter time series (and transition period), it would be questionable to interpret the merged time series as a consistent and informative series at this time. We are not confident that the 1993-2000 and 2005-8 time series are compatible for several reasons: i) anecdotal evidence suggests that the fishery has changed between the two time periods, ii) operational data which might be useful to quantify the targeting shift are not available, and iii) the units of catch differ between the two time series, and it is not clear that the conversion factor from catch in mass to numbers was appropriate.

We conclude that the time series for the period 1994-2000 should be at least as reliable as the Japanese and Taiwanese series in the SW Indian Ocean region, and should be included in the 2010 stock assessment. It is expected that this analysis could be greatly improved if a consistent data series can be recovered to span the whole period from 1993 to the present. We strongly encourage the Reunion fishery to implement logbook and observer programs that will ensure that the appropriate data are collected in the future (e.g. details on set-time, hook-type, bait use, lightsticks, operational details related to set-depth, or any other factors that are believed to affect targeting and catchability).

Introduction

This paper represents an attempt to compile and analyse the historical Reunion swordfish CPUE data in preparation for the WPB in 2010, updating previous work (WPB 2001). Poisson and Rene (1999) describe the development of this fishery. This series is of particular interest this year, as there was agreement to provide a special focus on the South-West (SW) region this year. While swordfish stock structure is poorly understood, it is conceivable that the SW region represents a reasonably distinct sub-population. The WPB has noted that there is evidence that the SW region may be subject to the highest exploitation rates in the Indian Ocean, and thus represents the highest priority from a conservation perspective (WPB 2009).

Stock assessment for most large pelagic fish species requires the interpretation of commercial CPUE as an index of relative abundance. For the Indian Ocean swordfish stock(s), the Japanese and Taiwanese longline fleets have traditionally been used to generate these abundance indices. These fleets have an extensive history, broad spatial coverage, and substantive logbook programmes. However, the operations of these fleets have changed historically, with large shifts in targeting that are poorly quantified. Large discrepancies between the estimated time trends of the two fleets (e.g. Nishida 2008) indicates that at least one series must be substantially biased. This is believed to be related to targeting changes, and there is an ongoing problem that not all of the relevant operational details are available for analysis (e.g. Hooks Per Basket is not available as a proxy for depth prior to the mid-1990s from Taiwan). Conventional fisheries theory (i.e. stationary recruitment dynamics) suggests that the depletion estimated by the Japanese series has been more consistent with the swordfish exploitation history than the Taiwanese series, and this interpretation has generally been given more weight in the assessment and management advice provided by the WPB. However, the WPB also recognized that the Japanese fleet underwent some dramatic changes in the 1990s, that might be exaggerating the estimated level of swordfish depletion at that time, particularly in the SW Indian Ocean region. It was recognized that the swordfish fishery in La Reunion is likely targeting a subset of the same swordfish population as the Japanese and Taiwanese fleets in the SW region and hence might provide an additional useful index.

The primary goal of CPUE standardization is to estimate a time series of (fishery-selected) relative abundance, and this is accomplished, or at least attempted, by identifying and removing the effects of various sources of CPUE variability that are attributable to causes other than changing abundance (e.g. changes in efficiency of the fleet due to improvements in technology or changes in targeting practices). Two tactics were employed in this paper: 1) attempt to identify homogeneous fleets that are likely to have consistent targeting practices, such that only data with core fishing characteristics were included (e.g. core Reunion area, night-sets only, individual boats with a long history, etc.), while other data were discarded, and 2) linear models were used to estimate the effects of independent variables which are expected to influence catchability, such that the effect of these variables can be removed to estimate a time series in which (ideally) the main source of variability is changing swordfish abundance. The first approach can be problematic if too many observations are discarded and the analysis becomes restricted to a very small subset of the fishery (e.g. which may result in a very short time series, or a fishery that does not describe important spatial changes in the population, such as a range contraction). The second approach can be problematic if everything changes at once, or there is a very unbalanced distribution of operations (e.g. changes in abundance and targeting will likely be confounded in the model if all boats face similar economic circumstances and change their operations simultaneously). Of course, neither approach can account for the effects of important variables that are not available to the analysis. The main focus of the analysis was the 1993-2000 period. The potential inclusion of later years is explored and discussed.

Data

Three data sets were provided to the secretariat by IFREMER (La Reunion), with key characteristics summarized in Table 1. The data from 1992-2001 were from the PPR voluntary logbook programme (Poisson and Taquet 2001), which covered the majority of sets during this period, and includes a number of useful operational factors that may be important for the CPUE analysis. There are not enough observations in 1992 and 2001 to be useful (1993 is probably marginal).

The data from 2001-4 do not include location or the conventional unit of longline effort (hooks), so this dataset was not examined. It may be possible to estimate some measure of effort for this period, but this was considered a low priority at this time.

The data from 2005-8 were obtained from a mandatory logbook programme, and it is recognized that there may be more reasons to question the reliability of this data (e.g. unlike the voluntary PPR programme, there were no small swordfish reported in the catches). There are important operational data fields missing that make it only weakly compatible with the 1992-2001 period. CPUE in the analysis was defined in terms of catch in numbers. For the 2005-8 data, the reported catch in mass had to be converted to numbers using the mean annual mass estimates provided by the IOTC secretariat (Miguel Herrera, pers. comm.). These mean size estimates are derived from a mix of fleets that operate in or near the La Reunion area, and may introduce additional sources of bias into the 2005-8 data (e.g. monthly patterns in the size composition is ignored, (e.g. Poisson and Fauvel 2009b). There is additional size data available, that should be incorporated into future analyses.

Spatial and Temporal Distribution of Effort

The historical area of operation of the fleet is shown in Figure 1 for 1992-2001 and Figure 2 for 2005-8. Three distinct sub-regions were defined: the core Reunion fishery (REU), the Mozambique Channel (MZB) and the Seychelles region (SEZ). The spatial patterns are further partitioned by year in Figure 3. Effort distributions in the MZB and SEZ regions are minimal in many years, and only the REU region was considered further. The REU region was further subdivided into four 5x5 degree sub-areas (NW, NE, SW, SE) as a first attempt to see if finer resolution spatial effects are justified.

Monthly CPUE patterns by year suggest a weak seasonal peak around Sep-Oct in the REU region, and again indicate the paucity of observations in the MZB and SEZ region (Figure 4 - Figure 6). To be consistent with some of the assessment requirements, and in recognition of the poor coverage in some months, monthly data was aggregated into quarterly units in subsequent analyses.

The nominal CPUE time series is shown along with the total catch and effort for the REU region in Figure 7 (omitting the period 2001-4), indicating the very limited effort in 1993.

Vessel Consistency

During the period 1992-2001, less than half of the vessels (19 of 41) operated for more than 2 years (Figure 8). If there is high variability in the effectiveness of the vessels, this raises concern about confounding between year and vessel effects. Two approaches were used to (attempt to) account for this problem: i) vessel ID was included as an explanatory variable in some analyses, and ii) some analyses were repeated with all observations of vessels that operated for less than 3 years removed (this corresponds to a removal of 60% of the observations). Vessel effects were only considered in the analysis of the early time series, because the ID code across the different data sets was not consistent (thought should be obtainable in the future).

Note that the vessel is mostly a proxy for other factors. It is probably the skipper of the vessel, and the equipment on board the vessel (e.g. satellite communication of remote sensing data) that is more important than the vessel itself. These factors likely change over time, and this information is probably not available in general.

It is conceivable that other vessel characteristics are important, however, it would take further consideration of mechanisms to decide how to use this data. For example, larger vessels have a greater range and may result in higher catch rates, but presumably the relevant effect on CPUE in this case would be more appropriately described by a spatial effect (higher fish density in more distant regions), rather than the vessel category effect *per se*. Furthermore, if individual vessel ID is included in the model, the vessel category is completely aliased (i.e. if each vessel has its own effect, the vessel category effect is implicitly estimated as part of the individual vessel effect). Licensing arrangements in foreign waters can prohibit access to preferred fishing locations at certain times.

Operational data

The large majority of the operations are night sets with lightstick usage in the 1993-2000 period (Figure 9). As noted in Poisson et al (in press), lightstick usage tends to be a marginally important, but poorly quantified, predictive variable in catch rate analyses (and presumably interacts with set-time). The small number of sets without lightsticks were simply excluded from the modelling analysis of the early period. Unfortunately set-time and lightstick data were not available for the latter time period.

Moon phase was included as a categorical variable in the models for the 1993-2000 period, using the definition as provided in the 1992-2003 data set (4 categories corresponding to lunar days 5-11, 12-19, 20-26, 1-4 + 27-29). Moon phase has been shown to have a significant (and seemingly different) effect on catch rates across a range of swordfish fisheries (e.g. Poisson et al, in press, and references therein). Moon phase was omitted from analyses that include the later data primarily for expedience (but noting that the effect seemed to be trivial in the early data set).

The early dataset includes additional information that could potentially be useful for understanding the fishery along the lines of the analysis of Poisson et al (in press), but was excluded from the analysis at this time. E.g. there is anecdotal evidence and some data to indicate that depredation by marine mammals is non-trivial and increasing over time.

CPUE Standardization models

Traditional linear models with lognormal error assumptions were employed to generate the standardized CPUE series (e.g. Maunder and Punt 2004). Analyses were conducted using R software function lm(), (i.e. equivalent to a Generalized Linear Model of the Gaussian family), and are described in this document using the R modelling notation, e.g.:

Log_e(CPUE+C) ~ IV1*IV2*IV3 + IV4 – IV1:IV2:IV3 – 1,

Where the dependent variable log(CPUE + C) is predicted as a function of (~) four Independent Variables (IV1 to IV4), including all main effects and interaction terms between the variables indicated by *, except for (-) the single 3 way interaction indicated by ':'. In the above model, - 1 indicates that the intercept is not estimated. The errors are assumed to be Gaussian IID. For the Reunion fleet, each observation consists of an individual set, and all of the predictive variables were categorical.

It has been observed that a large number of sets in some fisheries result in 0 swordfish catch, which can cause problems for some statistical standardization models. This could potentially be a problem with the Japanese and Taiwanese swordfish longline series, especially for those fleets that are not targeting swordfish, such that the WPB (2010) recommended exploration of alternative error models (e.g. zero-inflated or delta models). Figure 10 shows that less than 2% (1992-2001) and 5% (2005-8) of sets have positive effort with zero catch in the Reunion fishery. Since the positive CPUE sets appear to roughly follow a lognormal distribution, the traditional lognormal linear model was applied in the standardizations. A small constant (lower 10th percentile of the aggregate CPUE distribution 1993-2000) was added to all observations (to prevent the log(0) error). The subsequent removal of the constant in transforming the annual time series back to linear space resulted in negative indices in some of the highly parameterized models (with interaction terms). Note that for simplicity of interpreting indices, the models were defined and reported in the appendices without the intercept term. However, R^2 is used in interpreting the explanatory power of models, and this term is essentially meaningless in the no-intercept model, so R^2 is reported in Table 2 from the equivalent model in which the intercept is estimated. The final output of interest (i.e. the estimated time series) from the two models is identical.

The analysis was conducted in two phases. First a series of analyses were undertaken using only the detailed data from 1993-2000. Second, an analysis was attempted using the merged data from 1993-2000 and 2005-8. Models discussed in the text are summarized in Table 2, and a standard set of diagnostics and outputs are attached as appendices for some of the models.

Calculation of annual relative abundance indices

The annual abundance index (I_y, for year y) is calculated:

$$I_y = \exp\left(\hat{P}_y^Y + \tfrac{1}{2}\sigma_{\hat{P}}^2\right) - C,$$

Where: $\hat{P}$ represents the parameter estimates from the GLM model, sigma is the SE of the parameter estimate (e.g. Venables and Dichmont 2004), and C is the small constant added to the observations initially. For the few models that involved Year-interaction terms, the annual index included the integration of Year:Area and Year:Quarter effects (assuming that each of the 4 sub-areas in the analysis were equivalent in size).

Confidence bounds on the estimated CPUE series are not reported here. It is usually the case that these bounds are unrealistically narrow and need to be 'realistically' (and somewhat subjectively!) inflated during interpretation in the stock assessment process.

Point estimates for the annual abundance indices from all of the models discussed below are presented on a common relative scale in Figure 12.

EDM0, EDM, EDMM, EDMID - Early Data (1993-2000) Minimal Models

Very simple models were initially fit to see if there were systematic biases in the nominal CPUE series that can be explained by variation in seasonal or spatial effort among years (Table 2). Results are shown in Appendices 0 (EDM0 – includes 1993) and 1 (EDM – excludes 1993), from which we note:

- Residual behaviour is good (approximately normally distributed, with constant variance), except the lower tail of the distribution which is influenced by the addition of the constant.
- All of the factors are statistically significant (though not all of the individual levels of each factor are significant).
- The standardized CPUE time series is almost identical to the nominal CPUE series.
- While it would be desirable to maintain the data from 1993, there were very few observations in this year, which resulted in a very unbalanced design (i.e. interactions could not be estimated). Furthermore, the point estimates were unstable for the 1993 year effect among the models that could be fit, so it was dropped in most analyses.

Two additional predictive terms were added to these simplest of models (not shown, but listed in Table 2). When Moon Phase was added, EDMM, it was found to be statistically significant, but with a negligible effect on the explained variance (R^2 increased from 0.2058 to 0.2091). Moon phase has been observed to have a quantifiable effect on several swordfish fisheries (e.g. Poisson et al in press), and the term was retained in subsequent models using the early data. Presumably there is no reason why the fishers operate differently with respect to moon phase in different years, so it has a minimal effect in the standardization.

In contrast to moon phase, Vessel ID was both statistically significant and explained a lot of the CPUE variation (R^2 increased from 0.21 to 0.30 in EDMID). It is not surprising that different skippers have different levels of skill (or risk aversion, motivation, etc.) that influences catch rates, but it is not obvious how this effect should be included in the model. There may be confounding of effects, e.g. If one skipper always operates in a unique area and has higher catch rates, it may be impossible to conclude whether this is a vessel effect or an area effect.

However, it turns out that neither the moon phase or the vessel ID have much of an influence on the point estimates from the annual standardized time series as discussed under EDBR below.

EDF - Early Data (1994-2000) Full Model

The model EDF was defined to include all of the previously discussed variables, plus Year:Quarter and Year:Area interaction terms. This model (presented in appendix 2) was proposed as an upper limit of what might be optimistically expected to be estimable from the available data. Key points from appendix 2:

- Residual behaviour is good (approximately normally distributed, with constant variance), except the lower tail of the distribution which is influenced by the addition of the constant.
- All of the factors are statistically significant (though not all of the individual levels of each factor are significant).
- The standardized CPUE time series is very erratic, and very different from the nominal series. Furthermore, one year is estimated to have negative abundance (which is nonsensical, but mathematically possible because the constant term is subtracted from the reconstructed annual index after the exponentiation).

This model demonstrates some of the features that might be observed when a CPUE model is over-parameterized. In particular, the erratic time series and negative annual index strongly suggests that something is amiss. Many parameters are estimated to be highly statistically significant in these models, partly because there are a very large number of observations, and the statistical assumptions are probably not adequately met (e.g. sets are not independent, and the statistical design is unbalanced).

Dropping the interaction terms seems like a reasonable starting point to improve the model, and, the following section describes how an automated selection procedure recommended exactly that action. While model EDBR is far simpler than EDF (16 vs: 89 estimated parameters), there is a relatively small difference in the variance explained by the two (R^2 = 0.30 vs 0.33), and there seems to be little justification for retaining the interaction terms.

EDBR - Early Data (1993-2000) Model Reduced using BIC selection criteria

An automated, backward stepwise model selection procedure, R function step(), was employed using BIC as the criterion for rejecting explanatory terms from the full model (EDF above). In general, it would probably be preferable to systematically explore the effects of different explanatory variables in the model, rather than relying on an automated procedure. The selected model is arguably not the best, but the final abundance indices were very robust to the selection of model terms (other than the interactions). The BIC procedure results and final model results are included in appendix 3:

- The BIC selection resulted in retention of the main effects Year, Quarter, Area, Vessel ID, and Moon Phase, while interaction terms were rejected
- Residual behaviour of this model is reasonable (approximately normally distributed, with constant variance)
- There is a trivial difference between the nominal and standardized CPUE series (and the EDM model).

The estimated effects of the Area, Quarter, Vessel ID and Moon Phase from this model are illustrated in Figure 11. The Area, Quarter and Moon Phase effects are relatively small, which presumably explains much of the consistency between the nominal and standardized CPUE series. The vessel effect is potentially large, with the most effective vessels estimated to attain catch rates double that of the least effective.

EDBR-V3 Early Data (1993-2000) Reduced Model, excluding vessels with minimal activity

As shown in Figure 8, there are many vessels that did not operate in the fishery for many years. If the vessels with short histories are either much better worse than the average, this could result in a confounding with the year effect and biasing of the time series. It would be worth generating a time series based on a small subset of boats which operated consistently over the entire time period, but this would result in very few observations. As a compromise, the preceding model was refit using the subset of the early data that excluded vessels that fished for less than 3 years (in the period 1992-2001). Key Points from this model (appendix 4):

- 60% of the data were discarded
- Discarding these observations resulted in very little difference in the time series, such that both the models EDF and EDF-V3 resulted in time series that are very similar to the nominal CPUE.

This approach does not resolve the problem of how to interpret the individual vessel effects, but it does suggest that the time series is robust to the exclusion of the boats with the shortest history.

ADM - Early and Late Data (1993-2000, 2005-8) All observations

The models with the combined early and late data sets (ADM,Table 1) produce results similar to those of the models that use only the early data, in that there is very little difference between the nominal and standardized CPUE series (appendix 5). This model suggests that the relative abundance in 2005-8 is much lower than observed in 2000. However, this analysis cannot be expected to adequately account for the changes in the fishery that are thought to have occurred, unless the changes are manifested primarily through broad seasonal and spatial patterns. Targeting changes from swordfish to tuna might be expected to include changes in set-time, depth, hook type, bait type and/or light-stick usage. There is also a potential change in swordfish size composition (and the assumption of mean sizes used here may be a poor approximation for numbers in the 2005-8 data). None of these effects can be examined with the data available (however, it is noted that some size composition data are available, and additional operational data from 2008-10 are available and could be used in the future).

Changing species composition may provide one measure of targeting that could be informative. However, direct inclusion of species abundance terms in the model can be misleading (e.g. the simplest method of including abundance of other species as an explanatory variable is questionable because the abundance of all species probably changes over time). A comparison of the nominal CPUE series for key species (Figure 12) indicates that bigeye catch rates roughly double between the early and late time periods, while swordfish catch rates roughly half (yellowfin catch rates remain largely unchanged). This could indicate i) a change in targeting, ii) increase in bigeye abundance (which seems unlikely given broader perceptions of the stock, iii) decrease in swordfish abundance, or iv) some combination of the above factors.

As an attempt to discriminate between tuna and swordfish sets, the data were partitioned to remove sets with positive tuna catch, as described in the following two models. This is a more extreme version of the approach used in other fisheries to identify sets with specific characteristics on the basis of species composition. e.g. Chang et al (in prep.) reject sets based on a critical threshold of albacore catch, assuming that this will result in a subset of data which is much more homogeneous in terms of yellowfin targeting. Various problems can be identified with the different means of classifying set types, but these models should at least be useful for quantifying robustness and uncertainty in the CPUE series.

Models ADM-NT and ADM-NT2 - Early and Late Data (1993-2000, 2005-8) excluding tuna sets

The removal of all sets with positive bigeye catch (ADM-NT1) substantially reduces the dataset (to 44% of the original), while removal of sets with bigeye, yellowfin and albacore (ADM-NT2) almost completely destroys the dataset (5% of the original data) (Table 2). Surprisingly, however, as shown in appendix 6 and 7 and Figure 11, the estimated swordfish time series is very robust, even with 95% of the observations systematically removed. Unfortunately, without additional operational detail, we cannot conclude that the absence of the main tuna species from the selected sets is a useful indication of swordfish targeted sets. It may simply indicate a failure to find tuna, or a targeting of some other species (e.g. sharks). This is not an adequate justification for assuming that the early and late time series can be merged into a consistent time series (but nor does it rule out the possibility).

Swordfish time series for stock assessment

The annual swordfish CPUE time series for the models presented in Table 2 are illustrated together in Figure 13. At this time, it appears that the time series is reasonably robust to the assumptions explored, and the results from model EDBR are provisionally recommended to the WPB 2010 for inclusion in the swordfish assessment. These values are included annually and quarterly in Table 3, the quarterly time series is shown in Figure 14.

Conclusions:

1) Despite the high resolution operational level data available for the period 1993-2000, and the statistically significant explanatory variables identified, the linear models used for the catch rate standardization were not able to identify and remove any substantive biases in the nominal time series of annual CPUE. In all of the plausible cases examined, the standardized time series closely resembled the nominal CPUE, even when large numbers of potentially heterogeneous observations were dropped from the analyses. Thus the recommended time series for stock assessment purposes is consistent with that described by the 2001 WPB.

2) The above suggests that the time series is reasonably robust to model selection decisions, and should be useful as an index of abundance in the SW Indian Ocean. One can always speculate that additional factors that were not examined could be important, but the level of detail and apparent homogeneity in this data set seems to be superior to that of many other fleets, and should not be dismissed without good reason.

3) In principle, the comments noted above are also applicable to the extended time series, (1993-2000 and 2005-8), which also appeared to be robust to the systematic removal of large numbers of observations. However the argument is much weaker in this case, because:
   - There is considerable anecdotal evidence to suggest that the relative importance of tuna and swordfish have changed over time in the fishery. However, tuna and swordfish are both valuable and caught in substantial numbers. The distinction in setting practices is probably very subtle and difficult to quantify.
   - There are fewer operational data with which time series biases might be identified in the standardization procedure in the latter period (e.g. notably absent are set-times, hook types and lightstick use). New data collected from the SEALOR project 2008-10 may provide additional useful information.
   - There does seem to be a large increase in bigeye catch rates between the two time periods that is the opposite of the decline in swordfish catch rates. If this is a change in targeting, it could not be quantified from the available data. There is anecdotal evidence to suggest that finer scale spatial/temporal targeting practices are being employed, and these might be explicitly modelled in the future.

4) Until the points noted in 3 can be further clarified, it would not be advisable to assume that the most recent data (2005-8) are consistent with the earlier data. However, it is more likely that the 2005-8 data are internally consistent, and hence it should be more reasonable to accept that there is no substantial trend in swordfish CPUE over this latter period.

5) Efforts should be undertaken to recover the most comprehensive database that is attainable for the Reunion longline fishery, as this could prove to be a very valuable source of localized information to complement the DWF fleets. Additional size composition data, and operational data collected under the SEALOR project 2008-10 should allow the analysis to be improved next

year. We strongly encourage the Reunion fishery to implement logbook and observer programs that will ensure that the appropriate data is collected on a routine basis in the future, including any operational details which conceivably affect targeting and catchability (e.g. set-time, hook-type, bait use, lightsticks, depth or operational proxies for depth, or any other factors that the skippers identify as relevant). It may also be worthwhile attempting to examine the relationship between environmental variability and catch rates.

Acknowledgements

Funding for the PPR programme was supported by the European Union (FEDER), the Conseils Régional, and Général de La Réunion.

References

Chang, S.K., S.Hoyle and H.-I. Liu. In prep. Distant water longline fishery of Taiwan in the WCPO and catch rate standardization for yellowfin tuna (Thunnus albacores) with consideration of target change. XXX

Maunder, M.N. and Punt A.E. 2004. Standardizing catch and effort data, a review of recent approaches. Fish. Res. 70: 141-159.

Nishida, T. 2008. Notes on the standardized swordfish CPUE of tuna longline fisheries (Japan and Taiwan) in WPB6 (1980-2006 and 1992-2006). IOTC-2008-WPB-INF04.

Poisson F., and F. René. 1999. The development of the longline fishery targeting swordfish in Reunion island waters - Processing and marketing. DiNardo G.T., Proceedings of the Second International Pacific Swordfish Symposium, 3 Mar. 1997-6 Mar. 1997, Hawaii, USA, NOAA, NOAA Technical Memorandum NMFS, Honolulu, Hawaii, 1999, 240 p.

Poisson F., and M. Taquet. (Eds), 2001. L'espadon : de la recherche à l'exploitation durable. Programme Palangre Réunionnais, Rapport final, 248.

Poisson, F., and C. Fauvel. 2009 a. Reproductive dynamics of swordf ish (*Xiphias gladius*) in the southwestern Indian Ocean (Réunion Island). Part 2: fecundity and spawning pattern. Aquat.Living Resour. 22:59−68.

Poisson F., and C. Fauvel. 2009 b. Reproductive dynamics of swordfish (*Xiphias gladius*) in the southwestern Indian Ocean (Reunion Island) Part 1: oocyte development, sexual maturity and spawning. Aquat. Living Resour. 22, 45–58.

Poisson, F., J.-C. Gaertner, M. Taquet, J.-P. Durbec, and K. Bigelow. In press. Effects of lunar cycle and fishing operations on longline-caught pelagic fish: fishing performance, capture time, and survival of fish. Fish. Bull. XXX

Venables, W.N., and Dichmont, C.M. 2004. GLMs, GAMs, and GLMMs: an overview of theory for applications in fisheries research. Fish. Res. 70: 319-337.

WPB 2001. Indian Ocean Tuna Commission Report on Billfish 2009. Report of the 2nd Session of the IOTC Working Party on Billfish. St Gilles, La Réunion, November 5-8, 2001.

WPB 2009. Indian Ocean Tuna Commission Report on Billfish 2009. Report of the 7th Session of the IOTC Working Party on Billfish. Seychelles, July 6-10, 2009.

Table 1. Summary of La Reunion longline fishery data sets provided to the secretariat.

Dataset Characteristic	1992-2001	Time Period 2001-4	2005-8
Logbook Programme	Voluntary	?	Mandatory
Date	By set	By trip	By set
Set time	Yes	No	No
Location	By set	No	By set (some records not explained, e.g. 'IRUNE8')
Effort Units	Hooks per set	Sets per trip	Hooks per set
Light sticks reported	Yes	No	No
Vessel ID	Yes	Yes, but code is not compatible with 1992-2001 period	Yes, but code is not compatible with 1992-2001 period
Other species Catch	Yes	Yes	Yes
Catch units	Numbers	?	Estimated mass
Other	Gear configuration, Vessel type, Temperature		
Total number of observations	7970 sets	1773 trips	9943 sets

Table 2. CPUE models discussed in this paper.

Model (details in appendix)	Dependent Variable	Explanatory Variables	Comments
Dataset: 1993-2000, Excluding: lightsticks=0 6376 observations			
EDM0 (app. 0)	log(CPUE+C)	Year + Quarter + Area	Early Data Minimalist model; R^2 = 0.21
Dataset: 1994-2000, Excluding: lightsticks=0 6363 observations			
EDM (app. 1)	log(CPUE+C)	Year + Quarter + Area	Early Data Minimalist model, 1993 omitted; R^2 =0.21
EDMM	log(CPUE+C)	Year + Quarter + Area + MoonPhase	EDM + MoonPhase; R^2 =0.21
EDMID	log(CPUE+C)	Year + Quarter + Area + VesselID	EDM + VesselID; R^2 =0.30
EDF (app. 2)	log(CPUE+C)	Year*Quarter+ Year*Area + MoonPhase + VesselID	Full model (includes interactions); R^2 = 0.33
EDBR (app. 3)	log(CPUE+C)	Year + Quarter + Area + MoonPhase + VesselID	BIC selected model, starting from EDF; R^2 = 0.30
Dataset: 1994-2000, Excluding: lightsticks=0; Vessels with less than 3 years of operation in the period 1992-2001 2531 observations			
EDBR-V3 (app. 4)	log(CPUE+C)	Year + Quarter + Area + VesselID + MoonPhase	BIC selected model, including only vessels with 3+ years of experience; R^2 = 0.28
Dataset: 1993-2000 + 2005-8, 15664 Observations			
ADM (app. 5)	log(CPUE+C)	Year + Quarter + Area	Early and Late Data, R^2 = 0.40
Dataset: 1993-2000 + 2005-8; Excluding sets with positive bigeye catch 6836 Observations			
ADM-NT1 (app. 6)	log(CPUE+C)	Year + Quarter + Area	Early and Late Data, no BET catch R^2 = 0.38
Dataset: 1993-2000 + 2005-8; Excluding sets with positive bigeye, yellowfin or albacore catch 701 Observations			
ADM-NT2 (app. 7)	log(CPUE+C)	Year + Quarter + Area	Early and Late Data, no YFT, BET or ALB catch R^2 = 0.25

Table 3. Recommended time series of swordfish relative abundance for the 2010 stock assessment (from model EDBR) for the La Reunion area.

Annual		Quarterly	
Year	Abundance Index	Year.Quarter	Abundance Index
1994	0.013611503	1994.125	0.013612
1995	0.009249212	1994.375	0.01243
1996	0.006871235	1994.625	0.015103
1997	0.005797507	1994.875	0.014308
1998	0.006428136	1995.125	0.009249
1999	0.006677533	1995.375	0.008372
2000	0.006341657	1995.625	0.010357
		1995.875	0.009767
		1996.125	0.006871
		1996.375	0.00616
		1996.625	0.007769
		1996.875	0.007291
		1997.125	0.005798
		1997.375	0.005161
		1997.625	0.006601
		1997.875	0.006173
		1998.125	0.006428
		1998.375	0.005747
		1998.625	0.007287
		1998.875	0.00683
		1999.125	0.006678
		1999.375	0.005979
		1999.625	0.007559
		1999.875	0.007089
		2000.125	0.006342
		2000.375	0.005667
		2000.625	0.007193
		2000.875	0.00674

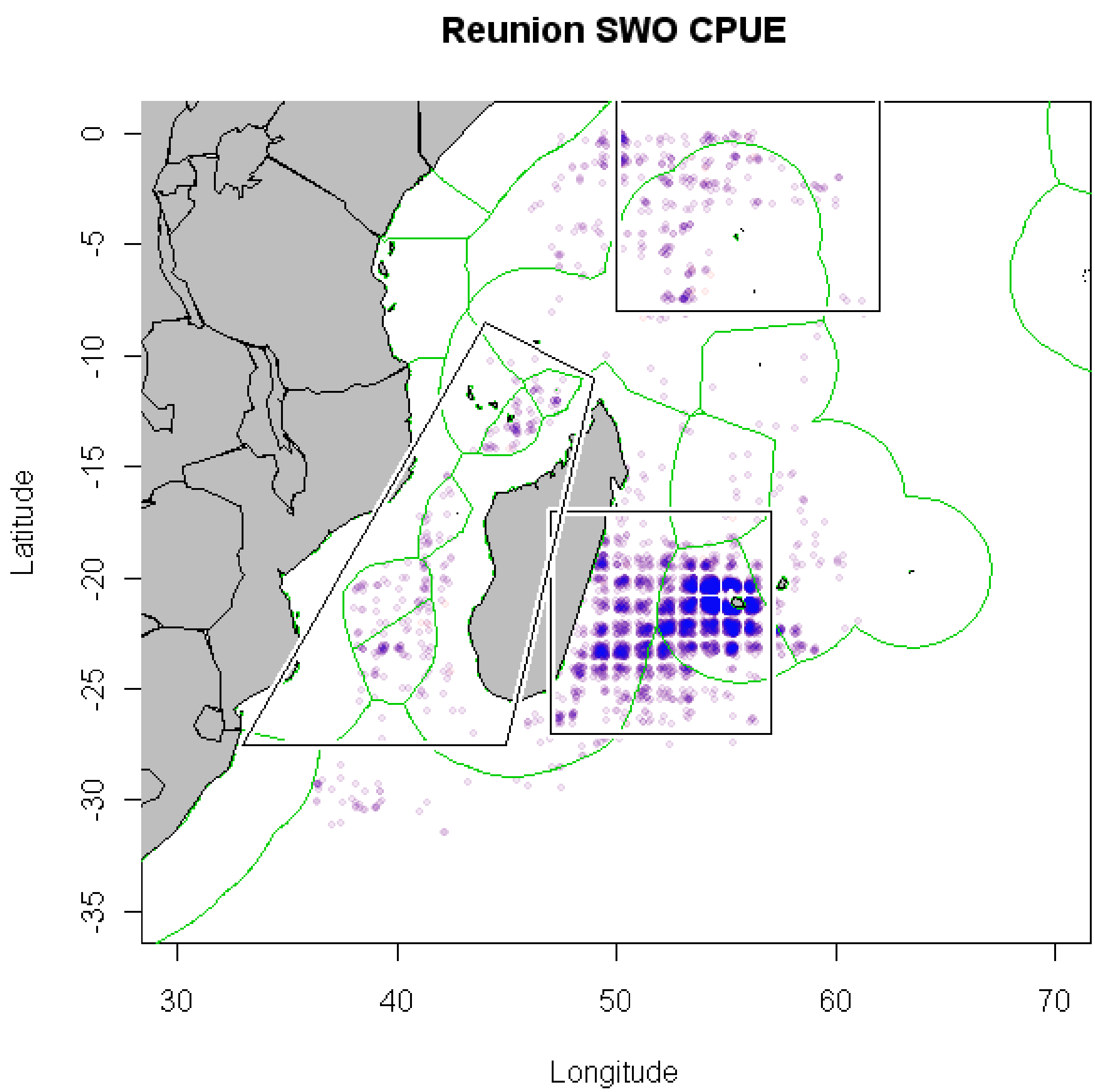


Figure 1. Location of Reunion longline fleet sets 1992-2001. Full colour saturation indicates 20 or more sets. Boxes indicate the 3 regions used for standardization analyses and discussion: Seychelles (SEZ), Mozambique Channel (MZB) and Reunion (REU).

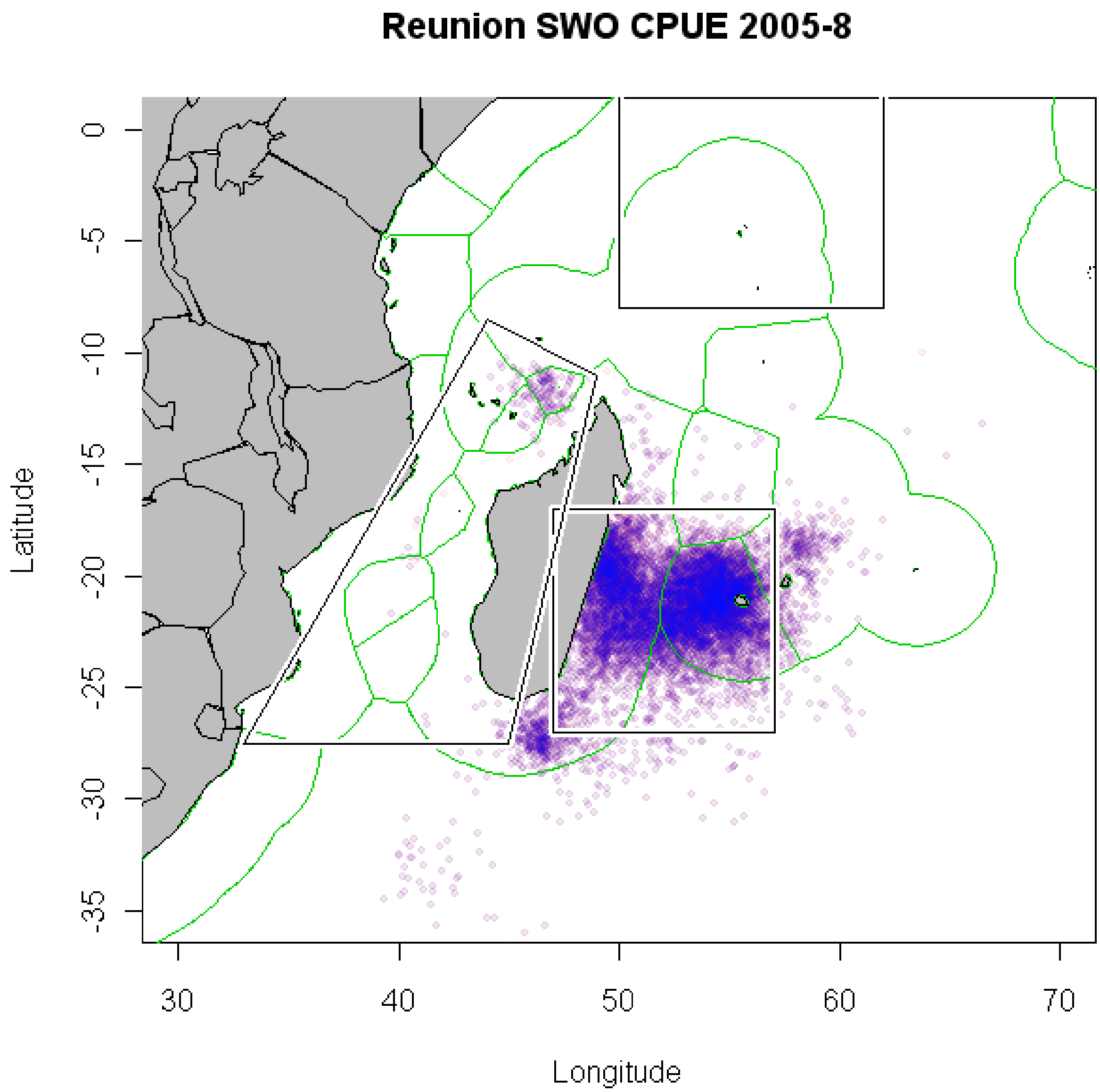


Figure 2. Location of Reunion longline fleet sets 2005-2008. Full colour saturation indicates 20 or more sets (note that locations are jittered (+/- 1 degree to better illustrate repeated observations). Boxes indicate the 3 regions used for standardization analyses and discussion: Seychelles (SEZ), Mozambique Channel (MZB) and Reunion (REU).

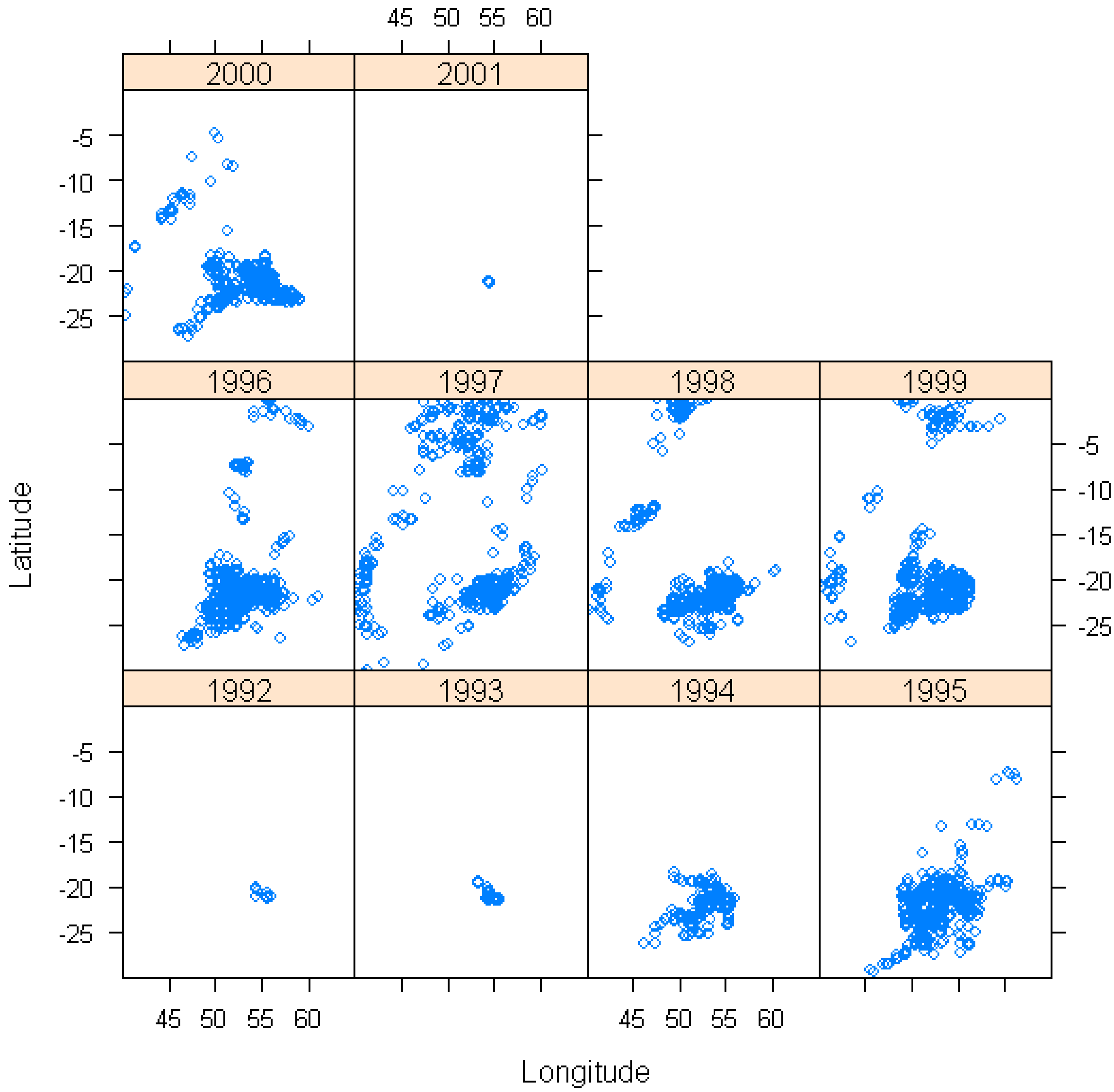


Figure 3. Location of Reunion longline fleet logbook sets by year.

pattern of the La Reunion longline fleet CPUE by year, in the Seychelles region.

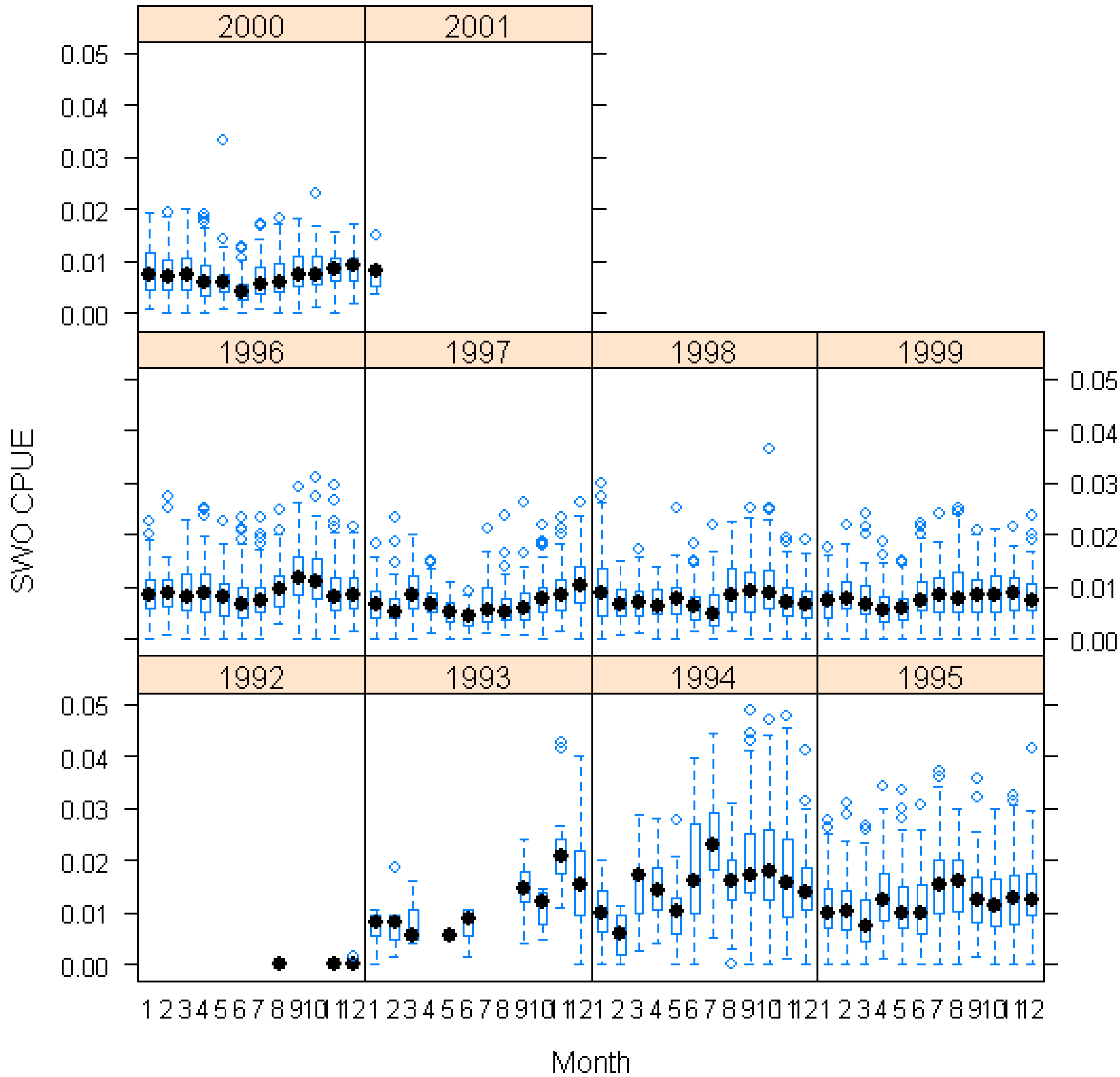


Figure 4. Monthly pattern of the La Reunion longline fleet CPUE by year, in the La Reunion region.

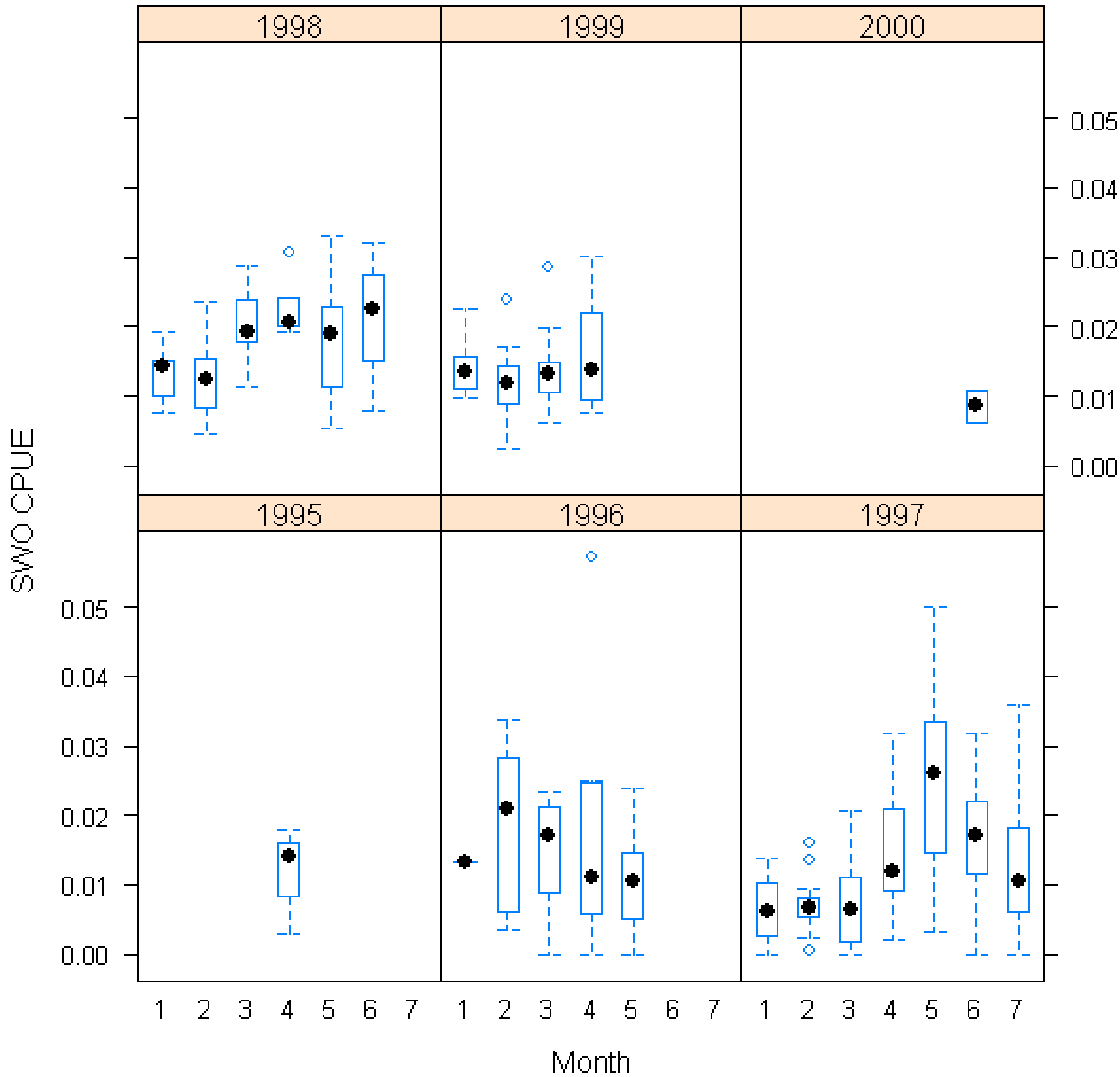


Figure 5. Monthly pattern of the La Reunion longline fleet CPUE by year, in the Seychelles region.

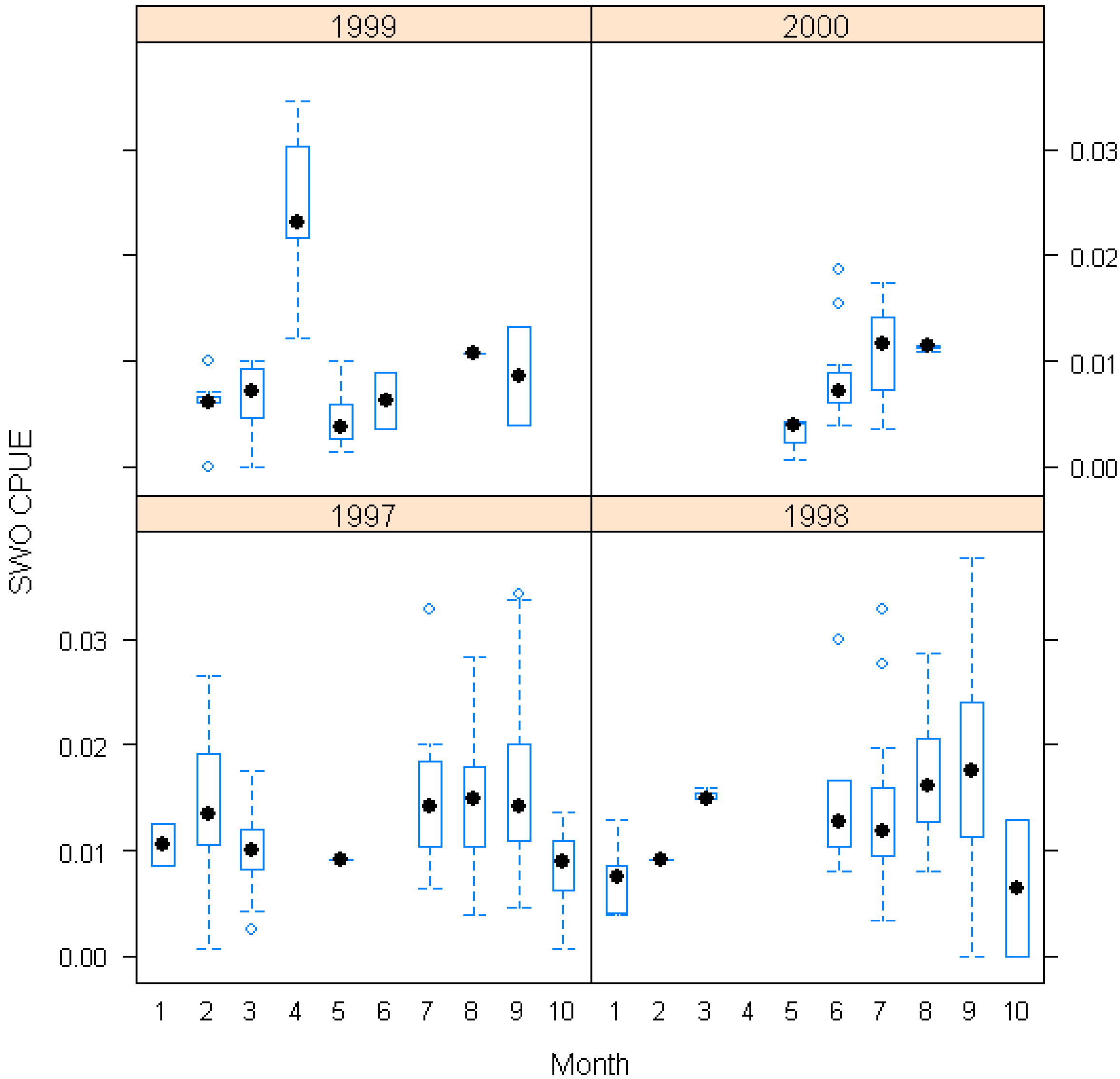


Figure 6. Monthly pattern of the La Reunion longline fleet CPUE by year, in the Mozambique Channel region.

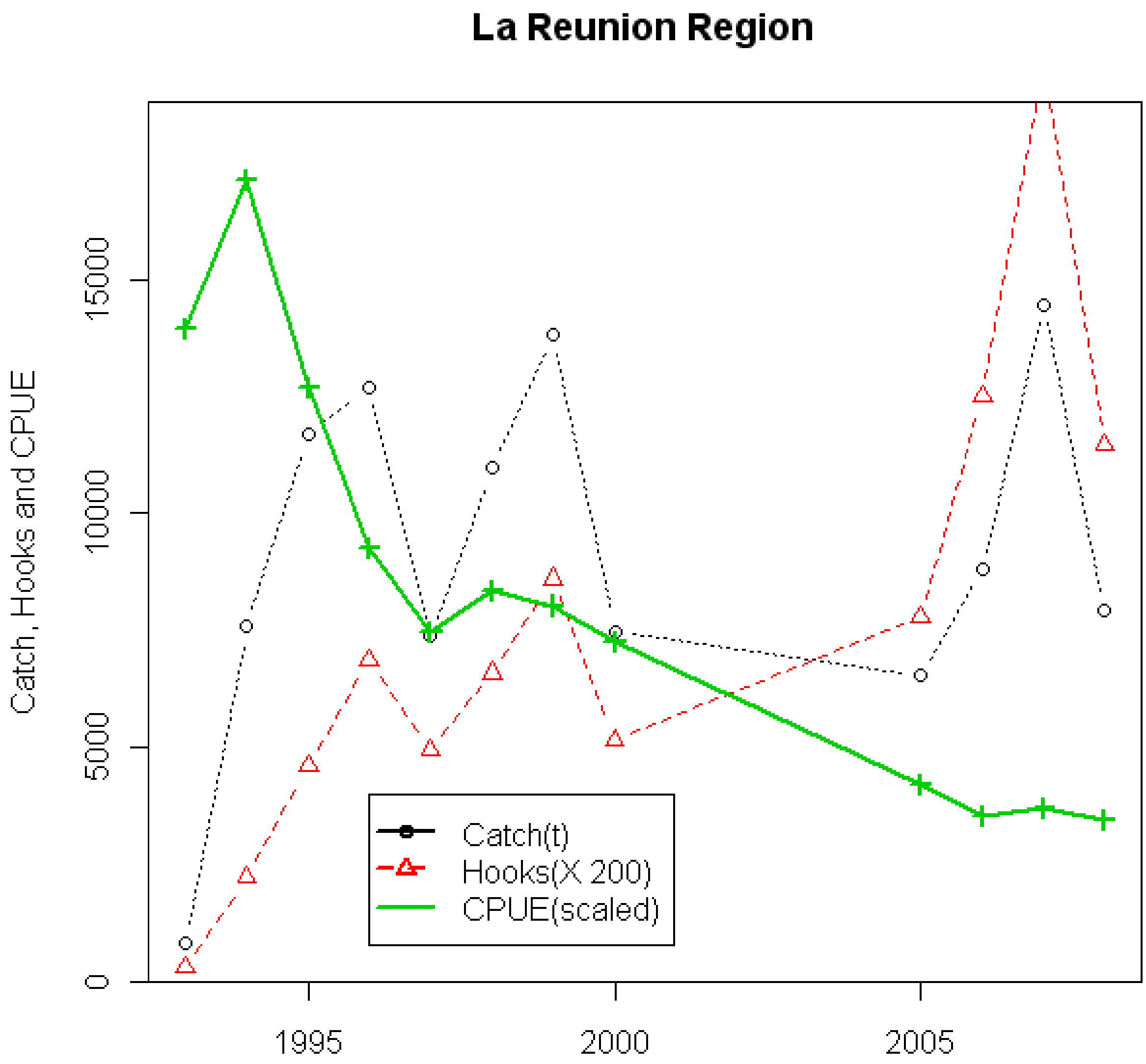


Figure 7. Time series of logbook-reported Total Catch, Total Hooks and nominal CPUE (Total Catch / Total Hooks, scaled to fit on the same axes) for the REU region (1993-2008, with 2001-4 omitted)

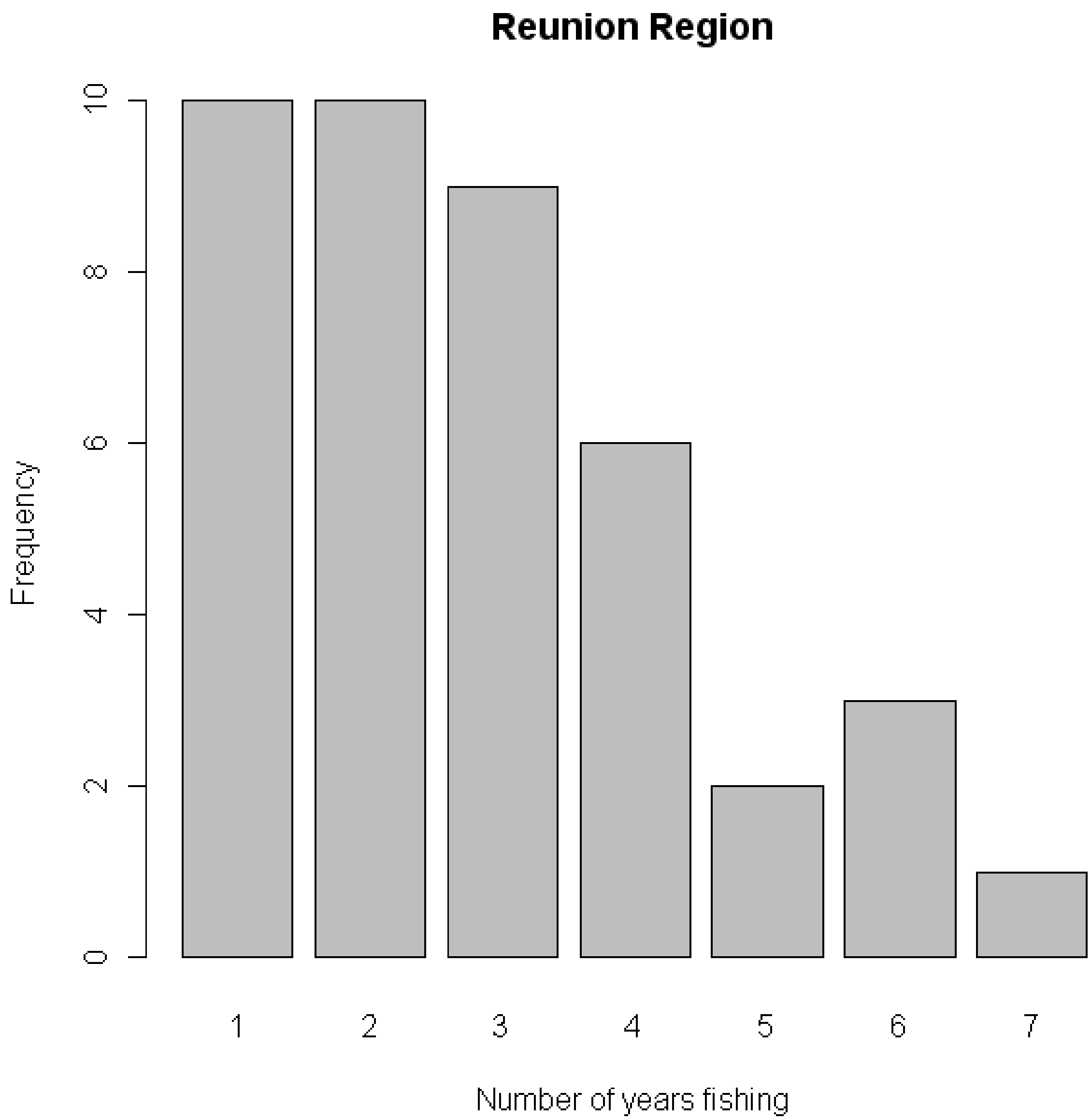


Figure 8. Frequency distribution of the number of years that vessels have fished in the Reunion region (1992-2001).

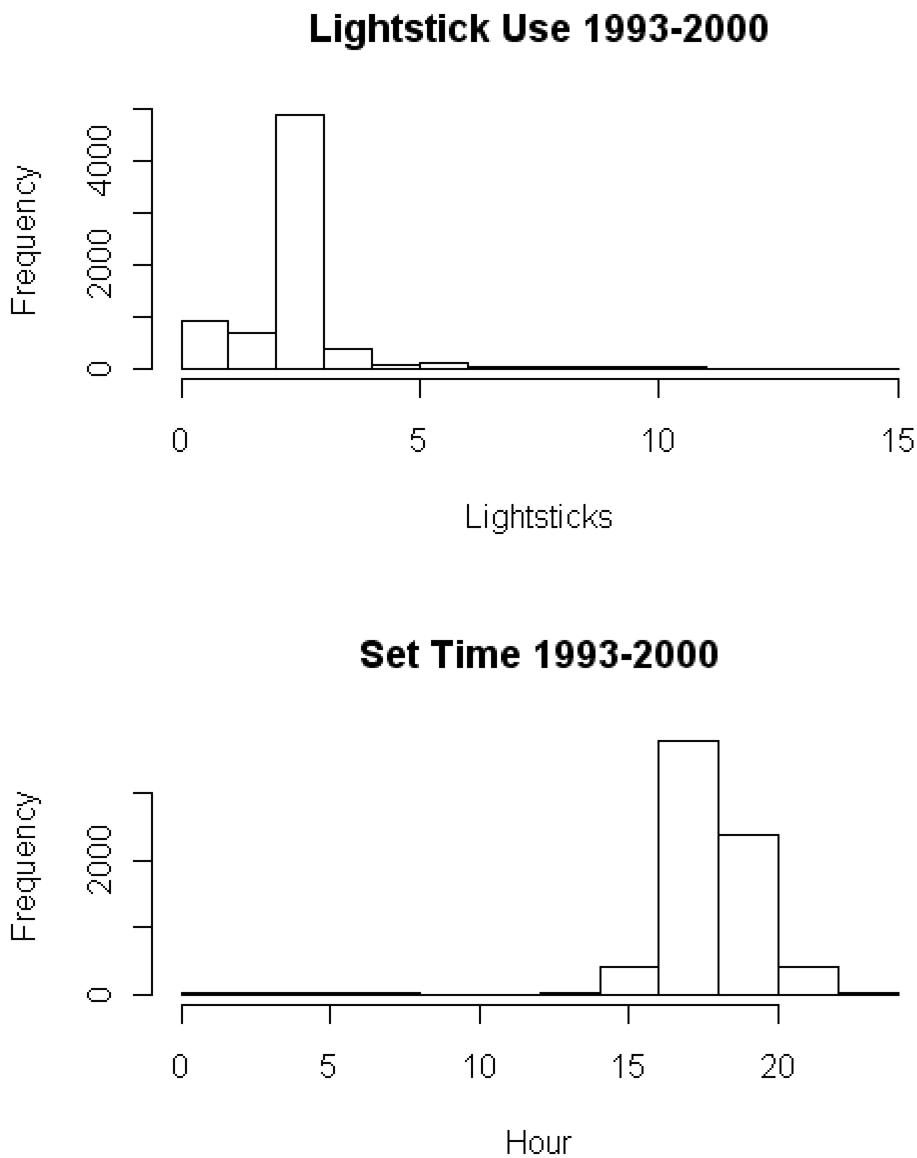


Figure 9. Frequency distribution of lightstick use and set time in the Reunion region (1993-2000).

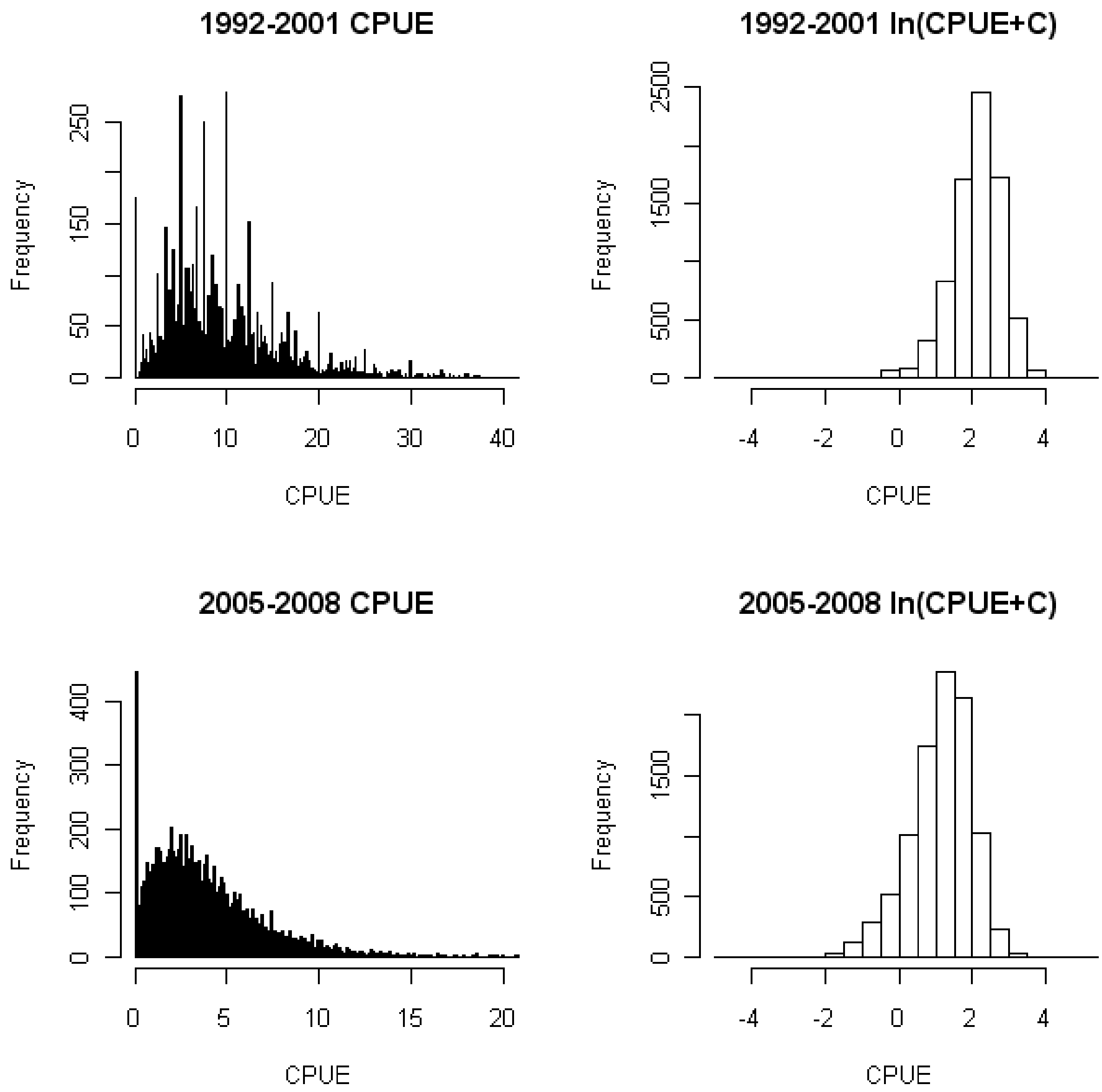


Figure 10. Frequency distribution of Reunion swordfish CPUE by set from the early (<2%) and late (<5%) time periods, illustrating the small number of 0 CPUE sets, and approximate normality of the log(CPUE).

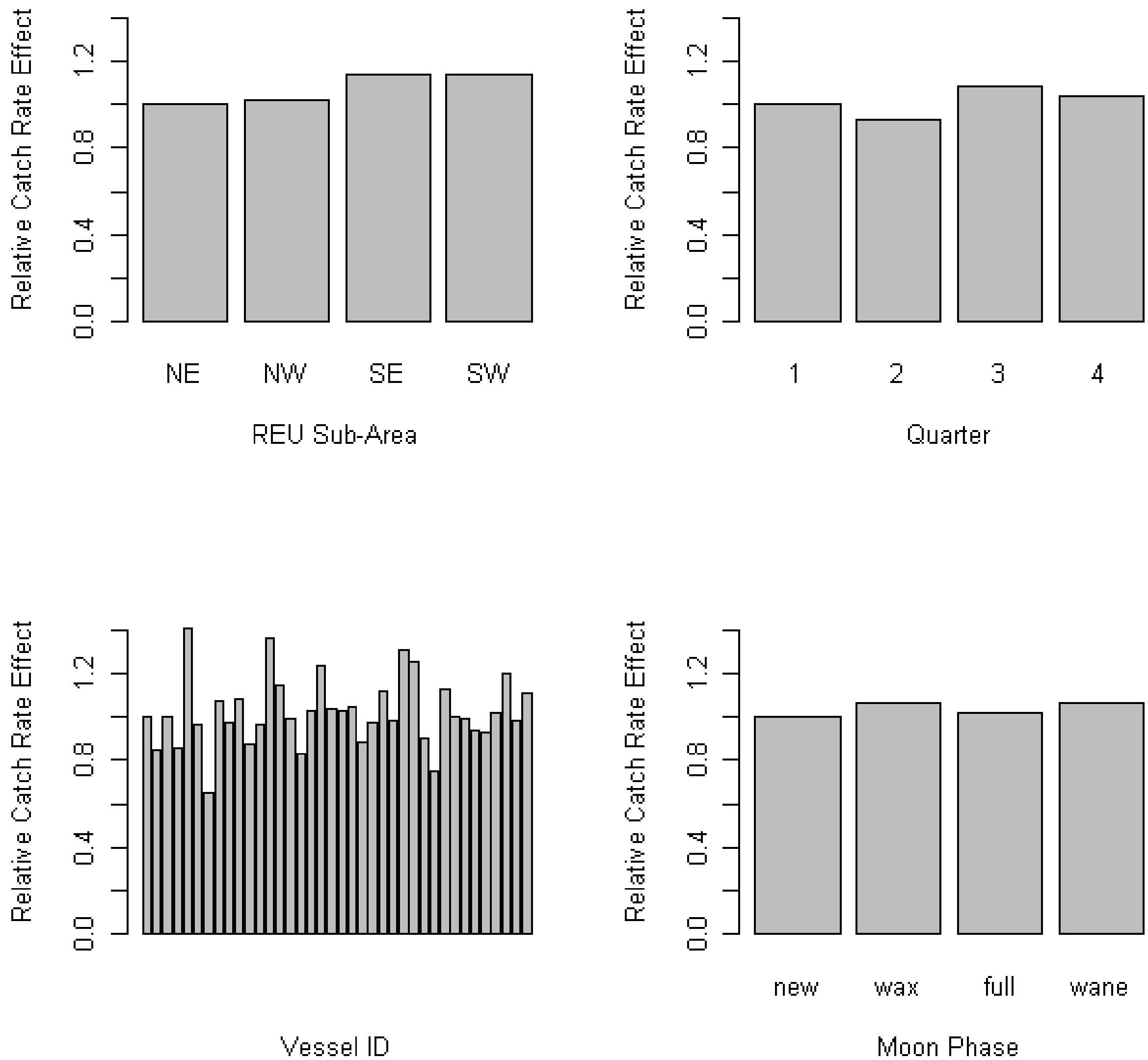


Figure 11. Effects of different explanatory variables on swordfish CPUE variation as estimated by model EDBR.

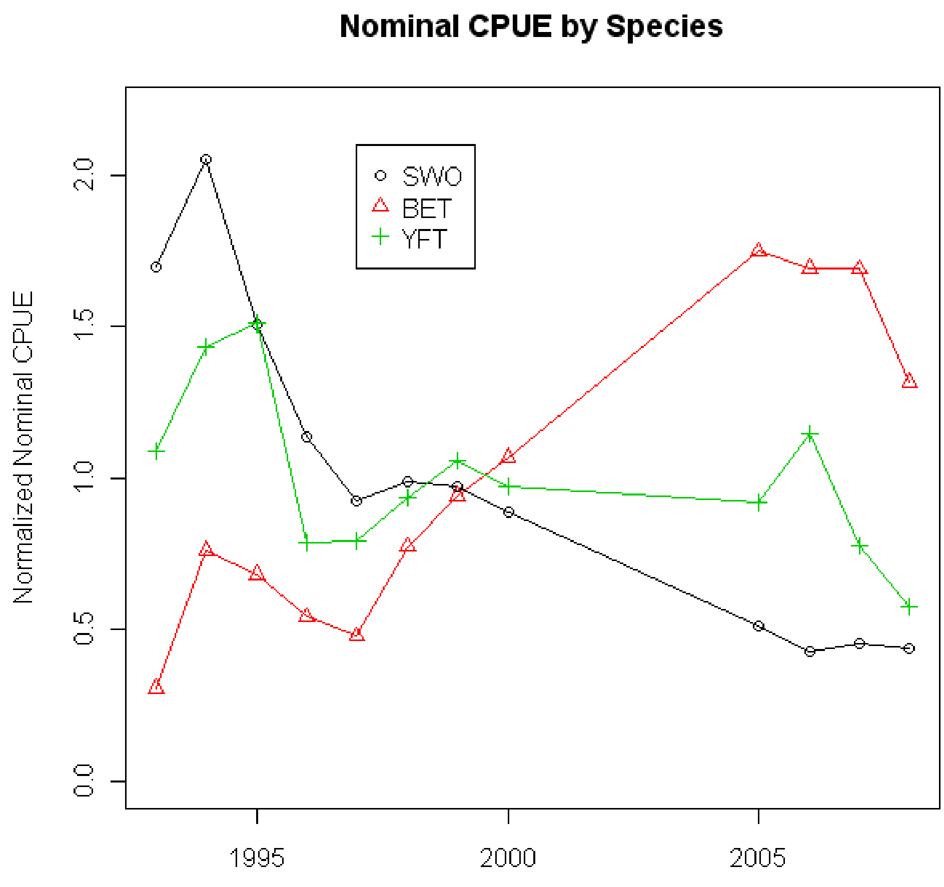


Figure 12. Comparison of nominal CPUE for swordfish, bigeye and yellowfin tuna in the REU region.

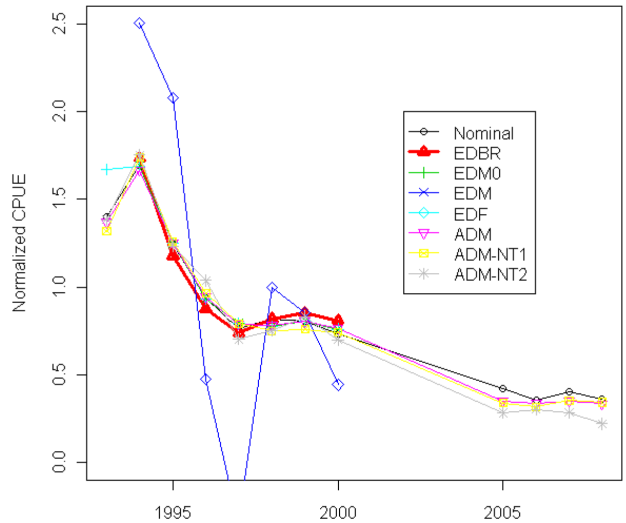


Figure 13. Nominal and standardized CPUE series for the models described in Table 2 (all scaled relative to their respective means over the 1994-2000 period).

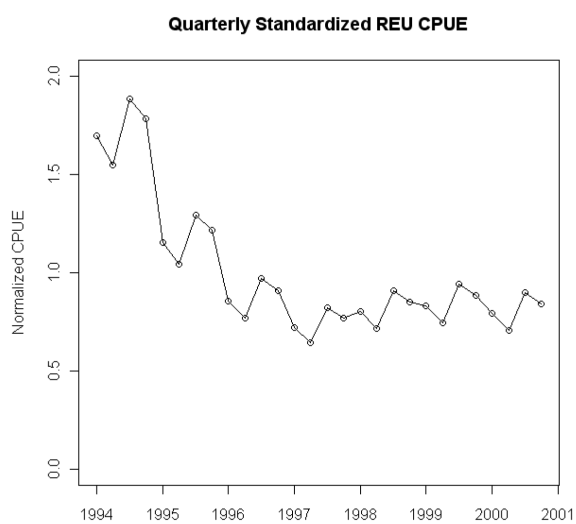
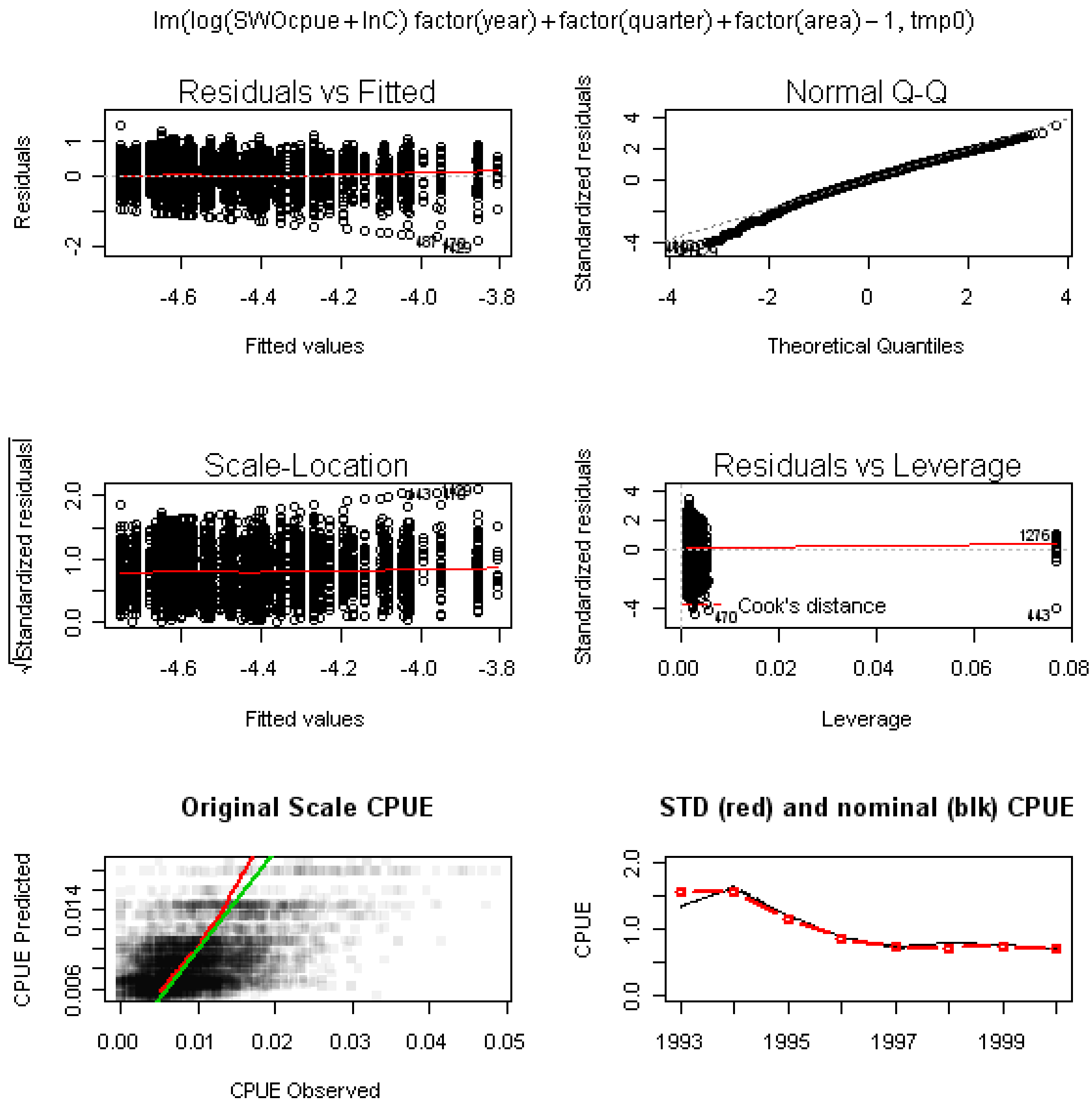


Figure 14. Quarterly CPUE for the REU region from model EDBR.

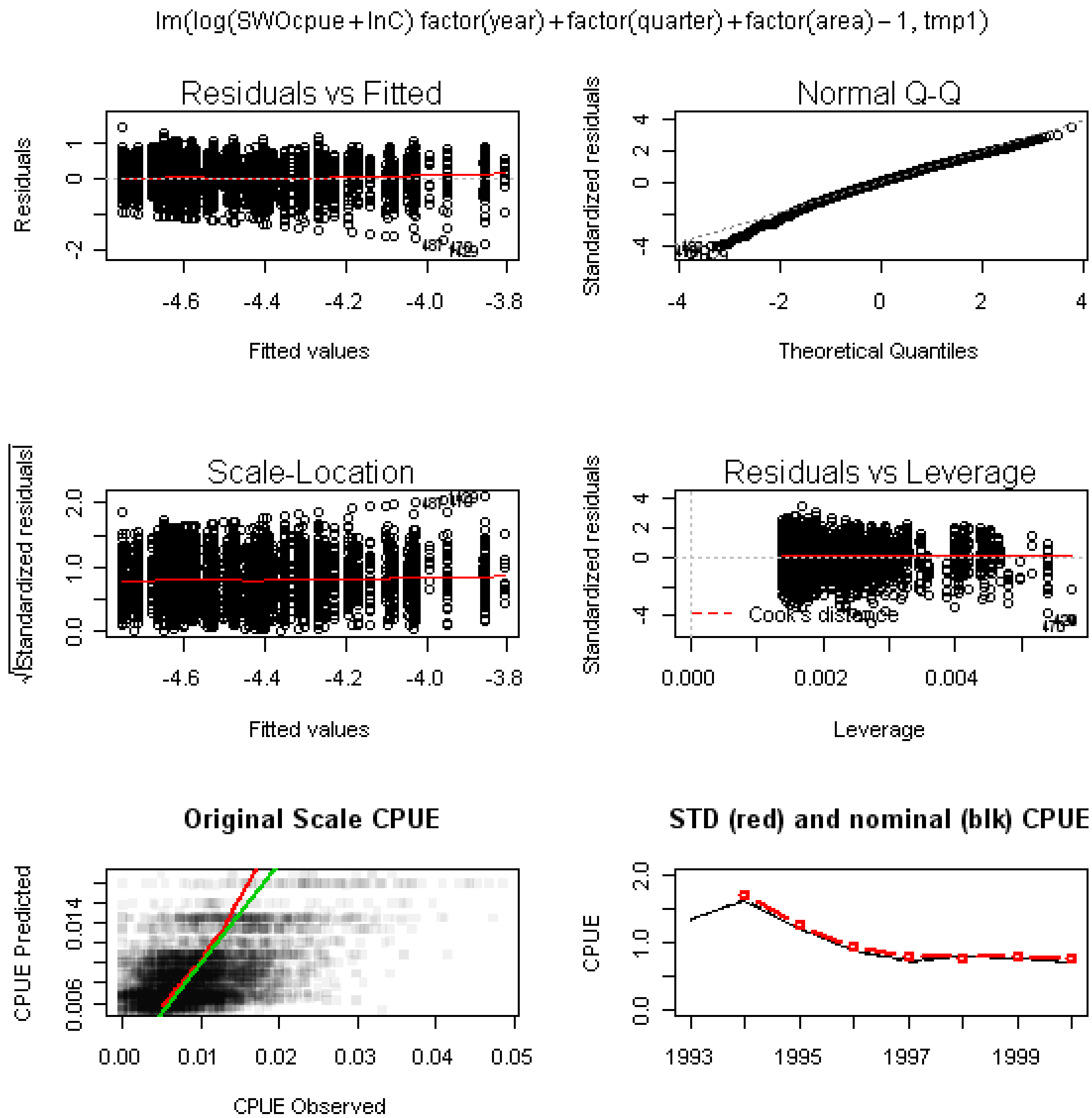
Appendix 0. Key diagnostics and results for model EDM0 (see text Table 1).

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(quarter) +
    factor(area) - 1, data = tmp0)

Residuals:
     Min       1Q   Median       3Q      Max
-1.84991 -0.25386  0.02799  0.28906  1.44721

Coefficients:
                 Estimate Std. Error  t value Pr(>|t|)
factor(year)1993 -4.09586    0.11698  -35.012  < 2e-16 ***
factor(year)1994 -4.08051    0.02153 -189.502  < 2e-16 ***
factor(year)1995 -4.31694    0.01625 -265.675  < 2e-16 ***
factor(year)1996 -4.52710    0.01611 -281.030  < 2e-16 ***
factor(year)1997 -4.63444    0.01814 -255.537  < 2e-16 ***
factor(year)1998 -4.65271    0.01817 -255.995  < 2e-16 ***
factor(year)1999 -4.62603    0.01559 -296.645  < 2e-16 ***
factor(year)2000 -4.66397    0.01593 -292.810  < 2e-16 ***
factor(quarter)2 -0.08922    0.01551   -5.753 9.15e-09 ***
factor(quarter)3  0.05142    0.01619    3.177 0.001495 **
factor(quarter)4  0.05028    0.01511    3.327 0.000882 ***
factor(area)NW    0.07119    0.02491    2.858 0.004281 **
factor(area)SE    0.17535    0.01464   11.980  < 2e-16 ***
factor(area)SW    0.22148    0.01821   12.161  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4183 on 6362 degrees of freedom
Multiple R-squared: 0.9913,     Adjusted R-squared: 0.9913
F-statistic: 5.191e+04 on 14 and 6362 DF,  p-value: < 2.2e-16
```


lm(log(SWOcpue+lnC) factor(year)+factor(quarter)+factor(area)-1, tmp0)
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE

Appendix 1. Key diagnostics and results for model EDM (see text Table 1)

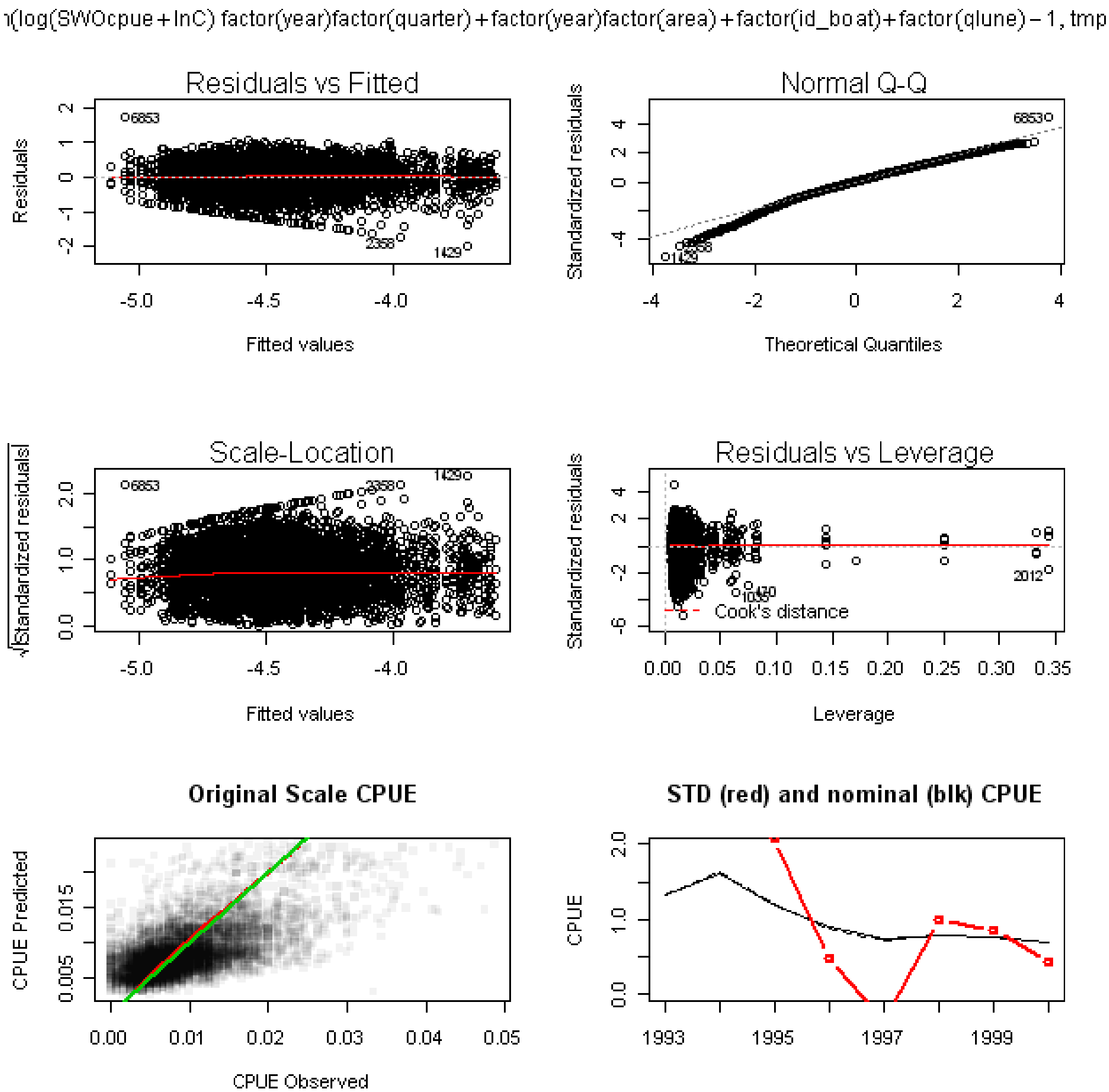
```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(quarter) +
    factor(area) - 1, data = tmp1)

Residuals:
     Min       1Q   Median       3Q      Max
-1.84991 -0.25421  0.02775  0.28851  1.44721

Coefficients:
                 Estimate Std. Error  t value Pr(>|t|)
factor(year)1994 -4.08051    0.02152 -189.634  < 2e-16 ***
factor(year)1995 -4.31694    0.01624 -265.860  < 2e-16 ***
factor(year)1996 -4.52710    0.01610 -281.226  < 2e-16 ***
factor(year)1997 -4.63444    0.01812 -255.715  < 2e-16 ***
factor(year)1998 -4.65271    0.01816 -256.173  < 2e-16 ***
factor(year)1999 -4.62603    0.01558 -296.852  < 2e-16 ***
factor(year)2000 -4.66397    0.01592 -293.014  < 2e-16 ***
factor(quarter)2 -0.08922    0.01550   -5.757 8.94e-09 ***
factor(quarter)3  0.05142    0.01617    3.179 0.001484 **
factor(quarter)4  0.05028    0.01510    3.330 0.000874 ***
factor(area)NW    0.07119    0.02490    2.860 0.004254 **
factor(area)SE    0.17535    0.01463   11.989  < 2e-16 ***
factor(area)SW    0.22148    0.01820   12.169  < 2e-16 ***
```


lm(log(SWOcpue+lnC) factor(year)+factor(quarter)+factor(area)-1, tmp1)
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE

Appendix 2. Key diagnostics and results for model EDF (see text Table 1).

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) * factor(quarter) +
    factor(year) * factor(area) + factor(id_boat) + factor(qlune) -
    1, data = tmp1)

Residuals:
     Min       1Q   Median       3Q      Max
-1.99794 -0.22761  0.02760  0.26294  1.74417

Coefficients:
                                  Estimate Std. Error  t value Pr(>|t|)
factor(year)1994                 -4.278315   0.059524  -71.875  < 2e-16 ***
factor(year)1995                 -4.482199   0.035215 -127.280  < 2e-16 ***
factor(year)1996                 -4.531130   0.035189 -128.764  < 2e-16 ***
factor(year)1997                 -4.657918   0.042494 -109.615  < 2e-16 ***
factor(year)1998                 -4.569110   0.044971 -101.601  < 2e-16 ***
factor(year)1999                 -4.595286   0.040040 -114.768  < 2e-16 ***
factor(year)2000                 -4.608472   0.039250 -117.414  < 2e-16 ***
factor(quarter)2                  0.134501   0.070461    1.909 0.056325 .
factor(quarter)3                  0.245665   0.064466    3.811 0.000140 ***
factor(quarter)4                  0.206426   0.062148    3.322 0.000900 ***
factor(area)NW                   -0.465939   0.104367   -4.464 8.17e-06 ***
factor(area)SE                    0.383715   0.047880    8.014 1.31e-15 ***
factor(area)SW                    0.274674   0.069966    3.926 8.74e-05 ***
factor(id_boat)2                 -0.107938   0.035791   -3.016 0.002574 **
factor(id_boat)3                 -0.011063   0.033603   -0.329 0.742004
factor(id_boat)4                 -0.114517   0.103380   -1.108 0.268019
factor(id_boat)5                  0.324247   0.047457    6.832 9.14e-12 ***
factor(id_boat)6                 -0.015202   0.053802   -0.283 0.777522
factor(id_boat)9                 -0.589114   0.159231   -3.700 0.000218 ***
factor(id_boat)10                -0.031176   0.103646   -0.301 0.763582
factor(id_boat)11                -0.037889   0.030728   -1.233 0.217596
factor(id_boat)12                -0.033833   0.056960   -0.594 0.552553
factor(id_boat)13                -0.104209   0.047473   -2.195 0.028192 *
factor(id_boat)14                -0.036140   0.037007   -0.977 0.328820
factor(id_boat)16                 0.287951   0.034654    8.309  < 2e-16 ***
factor(id_boat)17                 0.146894   0.052443    2.801 0.005110 **
factor(id_boat)18                -0.024252   0.033876   -0.716 0.474069
factor(id_boat)19                -0.200464   0.032649   -6.140 8.75e-10 ***
factor(id_boat)20                -0.008771   0.053013   -0.165 0.868591
factor(id_boat)21                 0.174443   0.053571    3.256 0.001135 **
factor(id_boat)22                 0.091819   0.052503    1.749 0.080370 .
factor(id_boat)23                 0.007220   0.038930    0.185 0.852873
factor(id_boat)24                 0.028629   0.042825    0.669 0.503836
factor(id_boat)31                -0.134784   0.033880   -3.978 7.02e-05 ***
factor(id_boat)32                 0.008536   0.047969    0.178 0.858762
factor(id_boat)33                 0.119011   0.038970    3.054 0.002268 **
factor(id_boat)34                -0.024549   0.061105   -0.402 0.687883
factor(id_boat)36                 0.256994   0.051291    5.011 5.58e-07 ***
factor(id_boat)37                 0.163973   0.199129    0.823 0.410284
factor(id_boat)41                -0.065755   0.047653   -1.380 0.167676
factor(id_boat)43                -0.257594   0.035968   -7.162 8.88e-13 ***
factor(id_boat)44                 0.138355   0.039698    3.485 0.000495 ***
factor(id_boat)45                -0.026707   0.052724   -0.507 0.612485
factor(id_boat)46                -0.001365   0.052136   -0.026 0.979109
factor(id_boat)47                -0.091002   0.043445   -2.095 0.036243 *
factor(id_boat)50                -0.147720   0.090272   -1.636 0.101808
```

```
factor(id_boat)52                   0.034164   0.067338    0.507 0.611926    
factor(id_boat)54                   0.196184   0.048050    4.083 4.50e-05 ***
factor(id_boat)56                   0.025290   0.114444    0.221 0.825113    
factor(id_boat)57                   0.116848   0.064060    1.824 0.068194 .  
factor(qlune)2                      0.059497   0.015138    3.930 8.58e-05 ***
factor(qlune)3                      0.019220   0.014473    1.328 0.184225    
factor(qlune)4                      0.065825   0.015132    4.350 1.38e-05 ***
factor(year)1995:factor(quarter)2 -0.073172   0.078907   -0.927 0.353798    
factor(year)1996:factor(quarter)2 -0.206181   0.078918   -2.613 0.009007 ** 
factor(year)1997:factor(quarter)2 -0.266905   0.082274   -3.244 0.001184 ** 
factor(year)1998:factor(quarter)2 -0.202735   0.086612   -2.341 0.019277 *  
factor(year)1999:factor(quarter)2 -0.247158   0.078458   -3.150 0.001639 ** 
factor(year)2000:factor(quarter)2 -0.318585   0.078317   -4.068 4.80e-05 ***
factor(year)1995:factor(quarter)3  0.007113   0.074938    0.095 0.924385    
factor(year)1996:factor(quarter)3 -0.160681   0.074802   -2.148 0.031746 *  
factor(year)1997:factor(quarter)3 -0.269241   0.081807   -3.291 0.001003 ** 
factor(year)1998:factor(quarter)3 -0.229029   0.080880   -2.832 0.004645 ** 
factor(year)1999:factor(quarter)3 -0.259003   0.075324   -3.439 0.000589 ***
factor(year)2000:factor(quarter)3 -0.241116   0.075822   -3.180 0.001480 ** 
factor(year)1995:factor(quarter)4 -0.066226   0.072324   -0.916 0.359868    
factor(year)1996:factor(quarter)4 -0.185074   0.072046   -2.569 0.010227 *  
factor(year)1997:factor(quarter)4 -0.110089   0.073517   -1.497 0.134324    
factor(year)1998:factor(quarter)4 -0.297357   0.074921   -3.969 7.30e-05 ***
factor(year)1999:factor(quarter)4 -0.184743   0.071906   -2.569 0.010215 *  
factor(year)2000:factor(quarter)4 -0.173322   0.076236   -2.273 0.023031 *  
factor(year)1995:factor(area)NW    0.475053   0.117585    4.040 5.41e-05 ***
factor(year)1996:factor(area)NW    0.426121   0.114991    3.706 0.000213 ***
factor(year)1997:factor(area)NW   -0.234577   0.250836   -0.935 0.349732    
factor(year)1998:factor(area)NW    0.592199   0.249311    2.375 0.017562 *  
factor(year)1999:factor(area)NW    0.560014   0.118110    4.741 2.17e-06 ***
factor(year)2000:factor(area)NW    0.631782   0.115957    5.448 5.28e-08 ***
factor(year)1995:factor(area)SE   -0.226454   0.060162   -3.764 0.000169 ***
factor(year)1996:factor(area)SE   -0.318485   0.057394   -5.549 2.99e-08 ***
factor(year)1997:factor(area)SE   -0.323105   0.063820   -5.063 4.25e-07 ***
factor(year)1998:factor(area)SE   -0.219258   0.060699   -3.612 0.000306 ***
factor(year)1999:factor(area)SE   -0.262962   0.059545   -4.416 1.02e-05 ***
factor(year)2000:factor(area)SE   -0.272270   0.064273   -4.236 2.31e-05 ***
factor(year)1995:factor(area)SW   -0.070046   0.081307   -0.861 0.388998    
factor(year)1996:factor(area)SW   -0.278122   0.079751   -3.487 0.000491 ***
factor(year)1997:factor(area)SW   -0.473571   0.119094   -3.976 7.07e-05 ***
factor(year)1998:factor(area)SW   -0.011373   0.086346   -0.132 0.895215    
factor(year)1999:factor(area)SW   -0.003932   0.080364   -0.049 0.960981    
factor(year)2000:factor(area)SW   -0.301159   0.092887   -3.242 0.001192 ** 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.387 on 6274 degrees of freedom
Multiple R-squared: 0.9927,     Adjusted R-squared: 0.9926 
F-statistic:  9534 on 89 and 6274 DF,  p-value: < 2.2e-16
```

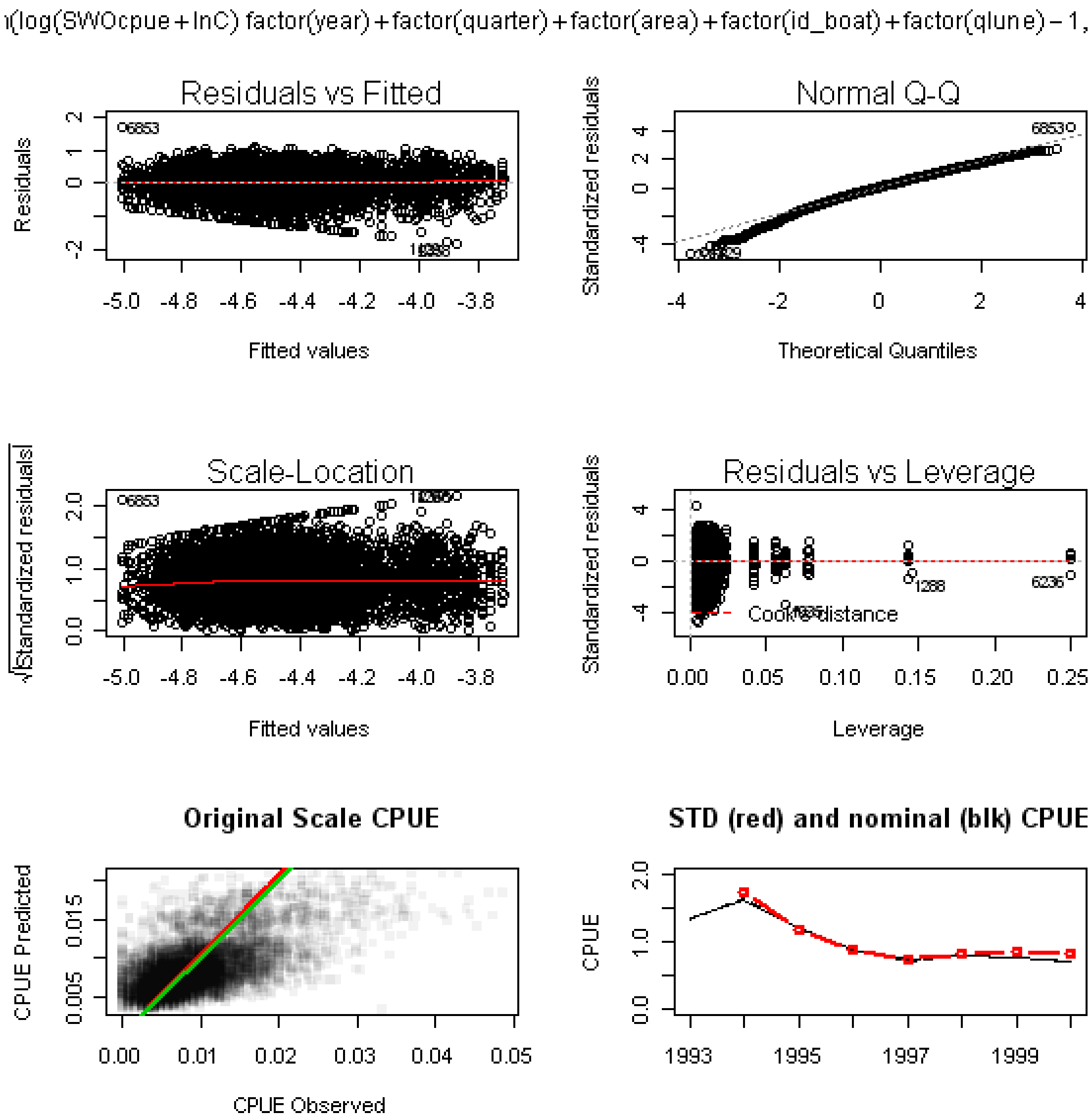

n(log(SWOcpue+lnC) factor(year)factor(quarter)+factor(year)factor(area)+factor(id_boat)+factor(qlune)-1, tmp
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Leverage
Cook's distance
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE

Appendix 3. BIC selection process starting from model EDF, and key results for the final selected model EDBR (see text Table 1).

```
Start:  AIC=-11397.06
log(SWOcpue + lnC) ~ factor(year) * factor(quarter) + factor(year) *
    factor(area) + factor(id_boat) + factor(qlune) - 1

                               Df Sum of Sq     RSS    AIC
- factor(year):factor(quarter) 18    12.309  954.09 -11472
- factor(year):factor(area)    18    20.318  962.10 -11419
<none>                                       941.78 -11397
- factor(qlune)                 3     4.265  946.05 -11394
- factor(id_boat)              38   117.898 1059.68 -10978

Step:  AIC=-11471.95
log(SWOcpue + lnC) ~ factor(year) + factor(quarter) + factor(area) +
    factor(id_boat) + factor(qlune) + factor(year):factor(area) -
    1

                            Df Sum of Sq     RSS    AIC
- factor(year):factor(area) 18    20.703  974.79 -11493
<none>                                    954.09 -11472
- factor(qlune)              3     3.977  958.07 -11472
- factor(quarter)            3    16.216  970.31 -11391
- factor(id_boat)           38   127.777 1081.87 -11004

Step:  AIC=-11492.76
log(SWOcpue + lnC) ~ factor(year) + factor(quarter) + factor(area) +
    factor(id_boat) + factor(qlune) - 1

                  Df Sum of Sq    RSS      AIC
<none>                          974.8 -11492.8
- factor(qlune)    3       4.5  979.3 -11489.6
- factor(area)     3      13.8  988.6 -11429.3
- factor(quarter)  3      17.5  992.3 -11405.6
- factor(id_boat) 38     133.4 1108.2 -11008.1
```

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(quarter) +
    factor(area) + factor(id_boat) + factor(qlune) - 1, data = tmp1)

Residuals:
     Min       1Q   Median       3Q      Max
-1.83221 -0.22868  0.02578  0.26848  1.69638

Coefficients:
                     Estimate Std. Error  t value Pr(>|t|)
factor(year)1994  -4.078508   0.032232 -126.537  < 2e-16 ***
factor(year)1995  -4.376119   0.028604 -152.989  < 2e-16 ***
factor(year)1996  -4.585672   0.029182 -157.138  < 2e-16 ***
factor(year)1997  -4.697022   0.033449 -140.422  < 2e-16 ***
factor(year)1998  -4.630215   0.033485 -138.278  < 2e-16 ***
factor(year)1999  -4.604975   0.033398 -137.882  < 2e-16 ***
factor(year)2000  -4.639143   0.034268 -135.377  < 2e-16 ***
factor(quarter)2  -0.072436   0.015084   -4.802 1.60e-06 ***
factor(quarter)3   0.084253   0.015851    5.315 1.10e-07 ***
factor(quarter)4   0.040206   0.014861    2.705 0.006840 **
factor(area)NW     0.016572   0.025557    0.648 0.516723
factor(area)SE     0.131465   0.015477    8.494  < 2e-16 ***
factor(area)SW     0.126811   0.020311    6.244 4.56e-10 ***
factor(id_boat)2  -0.164229   0.034468   -4.765 1.93e-06 ***
factor(id_boat)3  -0.001465   0.033371   -0.044 0.964988
factor(id_boat)4  -0.150505   0.102463   -1.469 0.141918
factor(id_boat)5   0.344767   0.046016    7.492 7.70e-14 ***
factor(id_boat)6  -0.030967   0.052189   -0.593 0.552960
factor(id_boat)9  -0.422831   0.152416   -2.774 0.005550 **
factor(id_boat)10  0.074423   0.099585    0.747 0.454889
factor(id_boat)11 -0.021363   0.029670   -0.720 0.471543
factor(id_boat)12  0.081813   0.052182    1.568 0.116967
factor(id_boat)13 -0.129707   0.046231   -2.806 0.005037 **
factor(id_boat)14 -0.036190   0.036946   -0.980 0.327355
factor(id_boat)16  0.308224   0.032553    9.468  < 2e-16 ***
factor(id_boat)17  0.135347   0.052464    2.580 0.009908 **
factor(id_boat)18 -0.008711   0.033445   -0.260 0.794509
factor(id_boat)19 -0.185808   0.031526   -5.894 3.97e-09 ***
factor(id_boat)20  0.030023   0.052786    0.569 0.569527
factor(id_boat)21  0.211059   0.051311    4.113 3.95e-05 ***
factor(id_boat)22  0.038312   0.051628    0.742 0.458065
factor(id_boat)23  0.033515   0.038140    0.879 0.379577
factor(id_boat)24  0.042966   0.041680    1.031 0.302655
factor(id_boat)31 -0.125173   0.032492   -3.852 0.000118 ***
factor(id_boat)32 -0.021667   0.045860   -0.472 0.636608
factor(id_boat)33  0.117089   0.038504    3.041 0.002368 **
factor(id_boat)34 -0.012607   0.058213   -0.217 0.828551
factor(id_boat)36  0.269831   0.049947    5.402 6.82e-08 ***
factor(id_boat)37  0.228007   0.198960    1.146 0.251841
factor(id_boat)41 -0.096760   0.045160   -2.143 0.032185 *
factor(id_boat)43 -0.290775   0.034240   -8.492  < 2e-16 ***
factor(id_boat)44  0.118648   0.038700    3.066 0.002180 **
factor(id_boat)45  0.002061   0.051808    0.040 0.968271
factor(id_boat)46 -0.006713   0.051157   -0.131 0.895602
factor(id_boat)47 -0.060319   0.042498   -1.419 0.155849
factor(id_boat)50 -0.074516   0.087856   -0.848 0.396379
factor(id_boat)52  0.016112   0.066082    0.244 0.807378
factor(id_boat)54  0.181713   0.046700    3.891 0.000101 ***
factor(id_boat)56 -0.012367   0.114252   -0.108 0.913805
factor(id_boat)57  0.108154   0.062610    1.727 0.084142 .
factor(qlune)2     0.065202   0.015233    4.280 1.89e-05 ***
```

```
factor(qlune)3     0.020493   0.014570    1.406 0.159631    
factor(qlune)4     0.063855   0.015174    4.208 2.61e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3926 on 6310 degrees of freedom
Multiple R-squared: 0.9924,     Adjusted R-squared: 0.9923 
F-statistic: 1.555e+04 on 53 and 6310 DF,  p-value: < 2.2e-16
```

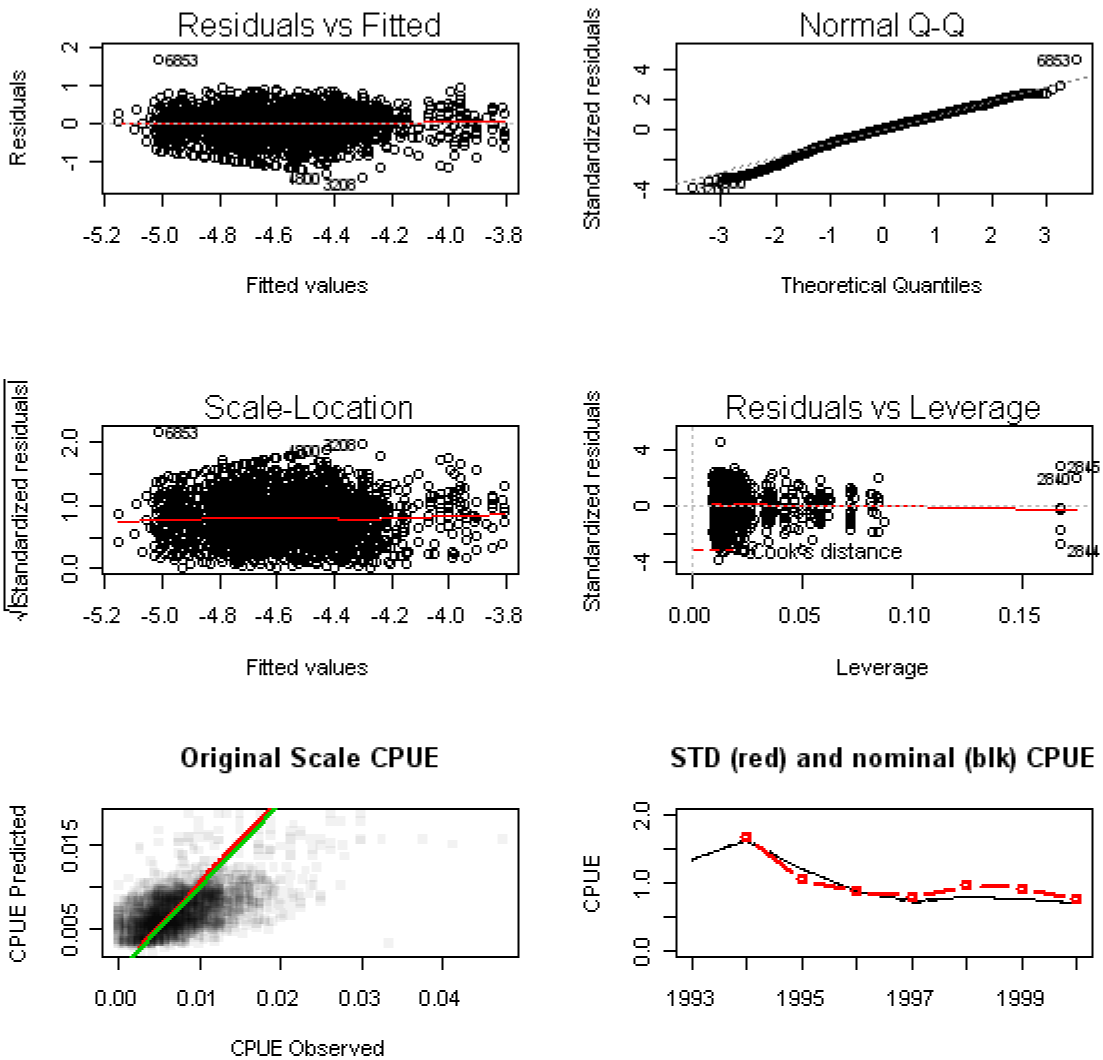

n(log(SWOcpue+lnC) factor(year)+factor(quarter)+factor(area)+factor(id_boat)+factor(qlune)-1, tmp
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE

Appendix 4. Results and diagnostics from model EDBR-V3 (see text Table 2).

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(month) +
    factor(area) + factor(id_boat) + factor(qlune) - 1, data = tmp2)

Residuals:
     Min       1Q   Median       3Q      Max
-1.40412 -0.21854  0.02643  0.24695  1.70408

Coefficients:
                  Estimate Std. Error  t value Pr(>|t|)
factor(year)1994  -4.06690    0.05271  -77.157  < 2e-16 ***
factor(year)1995  -4.41960    0.04274 -103.409  < 2e-16 ***
factor(year)1996  -4.53737    0.04569  -99.298  < 2e-16 ***
factor(year)1997  -4.61237    0.05801  -79.514  < 2e-16 ***
factor(year)1998  -4.48000    0.05780  -77.506  < 2e-16 ***
factor(year)1999  -4.50891    0.05644  -79.887  < 2e-16 ***
factor(year)2000  -4.64457    0.05669  -81.934  < 2e-16 ***
factor(month)2     0.06012    0.03440    1.748 0.080661 .
factor(month)3     0.01764    0.03441    0.513 0.608249
factor(month)4    -0.06392    0.03434   -1.861 0.062793 .
factor(month)5    -0.04882    0.03693   -1.322 0.186347
factor(month)6    -0.08197    0.03850   -2.129 0.033349 *
factor(month)7    -0.02918    0.04021   -0.726 0.468079
factor(month)8     0.08016    0.04021    1.994 0.046310 *
factor(month)9     0.06634    0.03688    1.799 0.072202 .
factor(month)10    0.09838    0.03707    2.654 0.008012 **
factor(month)11    0.04652    0.03912    1.189 0.234505
factor(month)12    0.01542    0.04086    0.377 0.705912
factor(area)NW     0.09170    0.03767    2.434 0.014986 *
factor(area)SE     0.13376    0.02665    5.018 5.58e-07 ***
factor(area)SW     0.17267    0.03237    5.334 1.05e-07 ***
factor(id_boat)2  -0.17754    0.04834   -3.672 0.000245 ***
factor(id_boat)3  -0.14598    0.04783   -3.052 0.002298 **
factor(id_boat)5   0.60734    0.11323    5.364 8.91e-08 ***
factor(id_boat)11 -0.12768    0.04231   -3.017 0.002576 **
factor(id_boat)12 -0.32504    0.11657   -2.788 0.005336 **
factor(id_boat)13 -0.05566    0.08046   -0.692 0.489103
factor(id_boat)14  0.11554    0.07649    1.510 0.131046
factor(id_boat)17 -0.26374    0.16019   -1.646 0.099806 .
factor(id_boat)18 -0.04459    0.05246   -0.850 0.395479
factor(id_boat)19 -0.44287    0.05018   -8.826  < 2e-16 ***
factor(id_boat)23 -0.44729    0.09979   -4.482 7.71e-06 ***
factor(id_boat)24 -0.09932    0.06769   -1.467 0.142399
factor(id_boat)31 -0.29347    0.05382   -5.453 5.45e-08 ***
factor(id_boat)32 -0.26100    0.09292   -2.809 0.005012 **
factor(id_boat)33  0.04998    0.05342    0.935 0.349627
factor(id_boat)41 -0.08642    0.05708   -1.514 0.130161
factor(id_boat)43 -0.31666    0.05677   -5.578 2.70e-08 ***
factor(id_boat)44  0.21378    0.06518    3.280 0.001054 **
factor(id_boat)45  0.05082    0.10213    0.498 0.618776
factor(id_boat)47 -0.11515    0.07017   -1.641 0.100924
factor(qlune)2     0.05800    0.02290    2.533 0.011361 *
factor(qlune)3     0.02031    0.02154    0.943 0.345865
factor(qlune)4     0.06199    0.02245    2.762 0.005789 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3702 on 2487 degrees of freedom
Multiple R-squared: 0.9936,     Adjusted R-squared: 0.9935
```

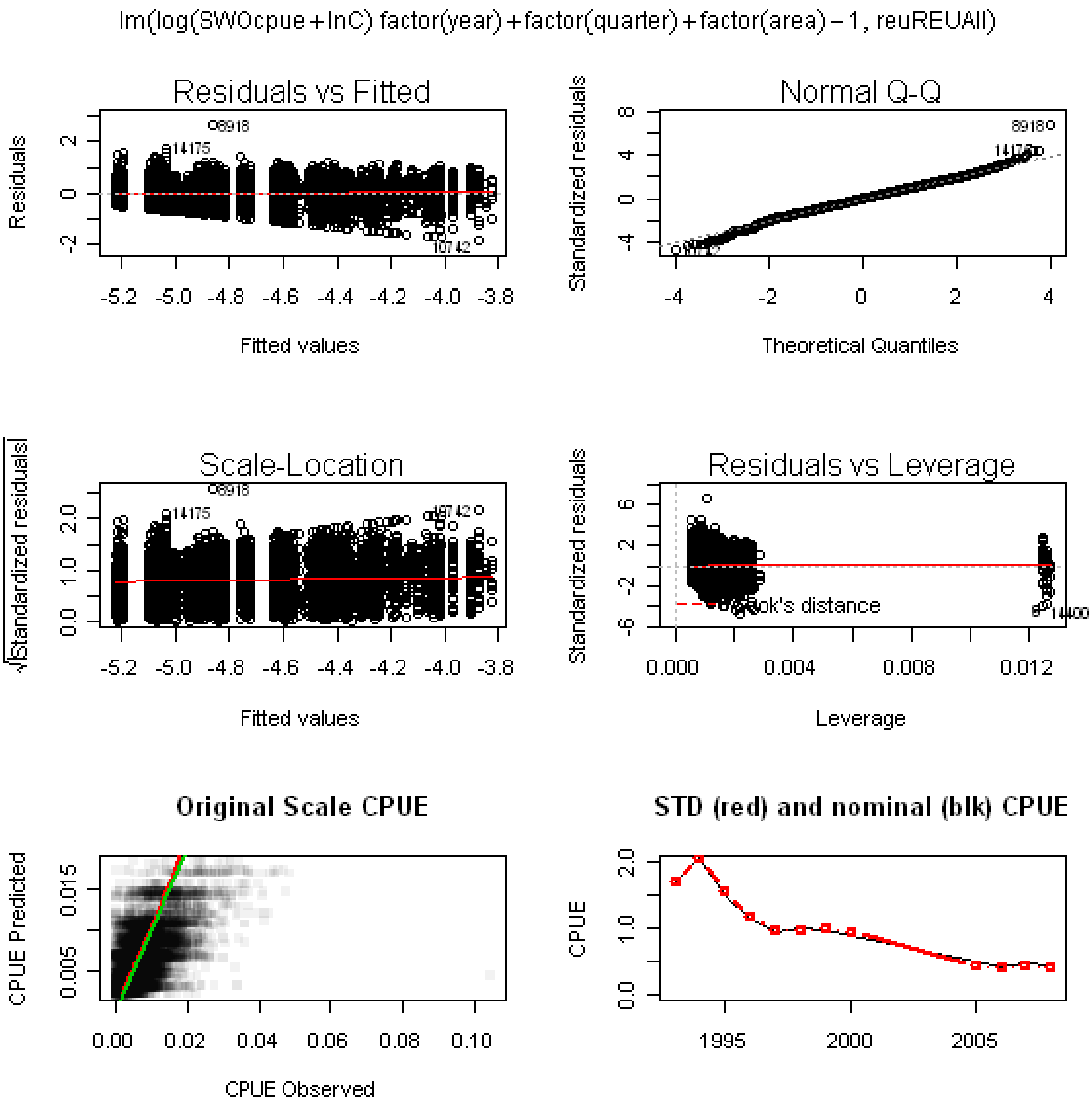
```
F-statistic:  8805 on 44 and 2487 DF,  p-value: < 2.2e-16
```

ı(log(SWOcpue+lnC) factor(year)+factor(month)+factor(area)+factor(id_boat)+factor(qlune)-1, tmp



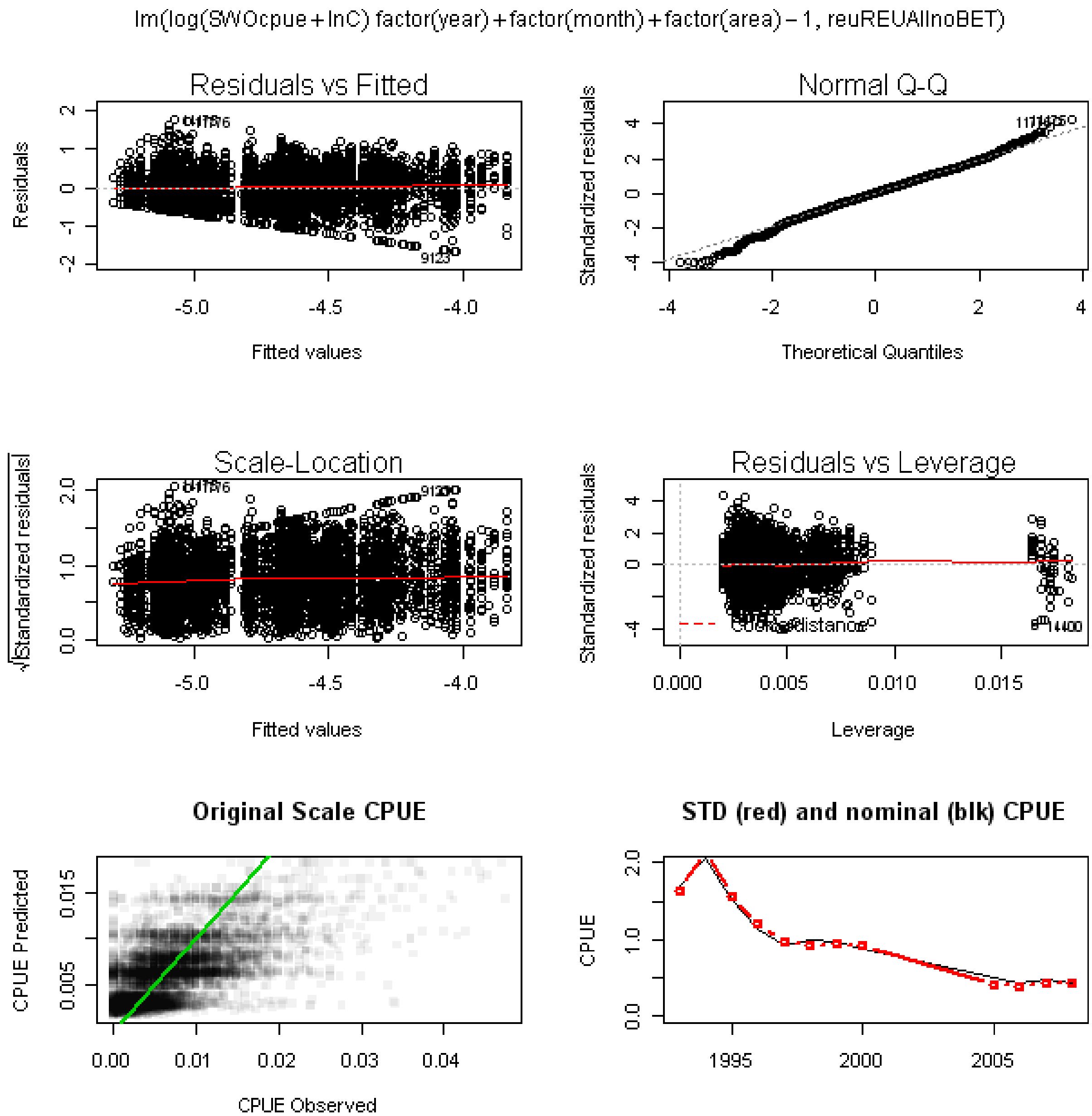
Appendix 5. Summary results and diagnostics from CPUE model ADF (see text Table 2).

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(quarter) + 
    factor(area) - 1, data = reuREUAll)

Residuals:
      Min        1Q    Median        3Q       Max 
-1.826028 -0.261419  0.005242  0.266023  2.637728 

Coefficients:
                  Estimate Std. Error  t value Pr(>|t|)    
factor(year)1993 -4.216797   0.044344  -95.092  < 2e-16 ***
factor(year)1994 -4.061469   0.018568 -218.730  < 2e-16 ***
factor(year)1995 -4.284992   0.013837 -309.675  < 2e-16 ***
factor(year)1996 -4.492794   0.013237 -339.423  < 2e-16 ***
factor(year)1997 -4.615213   0.015606 -295.739  < 2e-16 ***
factor(year)1998 -4.618471   0.014344 -321.978  < 2e-16 ***
factor(year)1999 -4.601261   0.012150 -378.718  < 2e-16 ***
factor(year)2000 -4.634593   0.013903 -333.358  < 2e-16 ***
factor(year)2005 -5.074251   0.013581 -373.632  < 2e-16 ***
factor(year)2006 -5.090645   0.010761 -473.085  < 2e-16 ***
factor(year)2007 -5.076596   0.010106 -502.325  < 2e-16 ***
factor(year)2008 -5.097312   0.011582 -440.118  < 2e-16 ***
factor(quarter)2 -0.124172   0.010276  -12.083  < 2e-16 ***
factor(quarter)3  0.017821   0.009983    1.785   0.0742 .  
factor(quarter)4  0.040812   0.009492    4.300 1.72e-05 ***
factor(area)NW    0.004573   0.009855    0.464   0.6426    
factor(area)SE    0.141902   0.009094   15.604  < 2e-16 ***
factor(area)SW    0.216691   0.010307   21.023  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 0.3953 on 15646 degrees of freedom
Multiple R-squared: 0.9932,     Adjusted R-squared: 0.9932 
F-statistic: 1.277e+05 on 18 and 15646 DF,  p-value: < 2.2e-16
```


lm(log(SWOcpue+lnC) factor(year)+factor(quarter)+factor(area)−1, reuREUAll)
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE

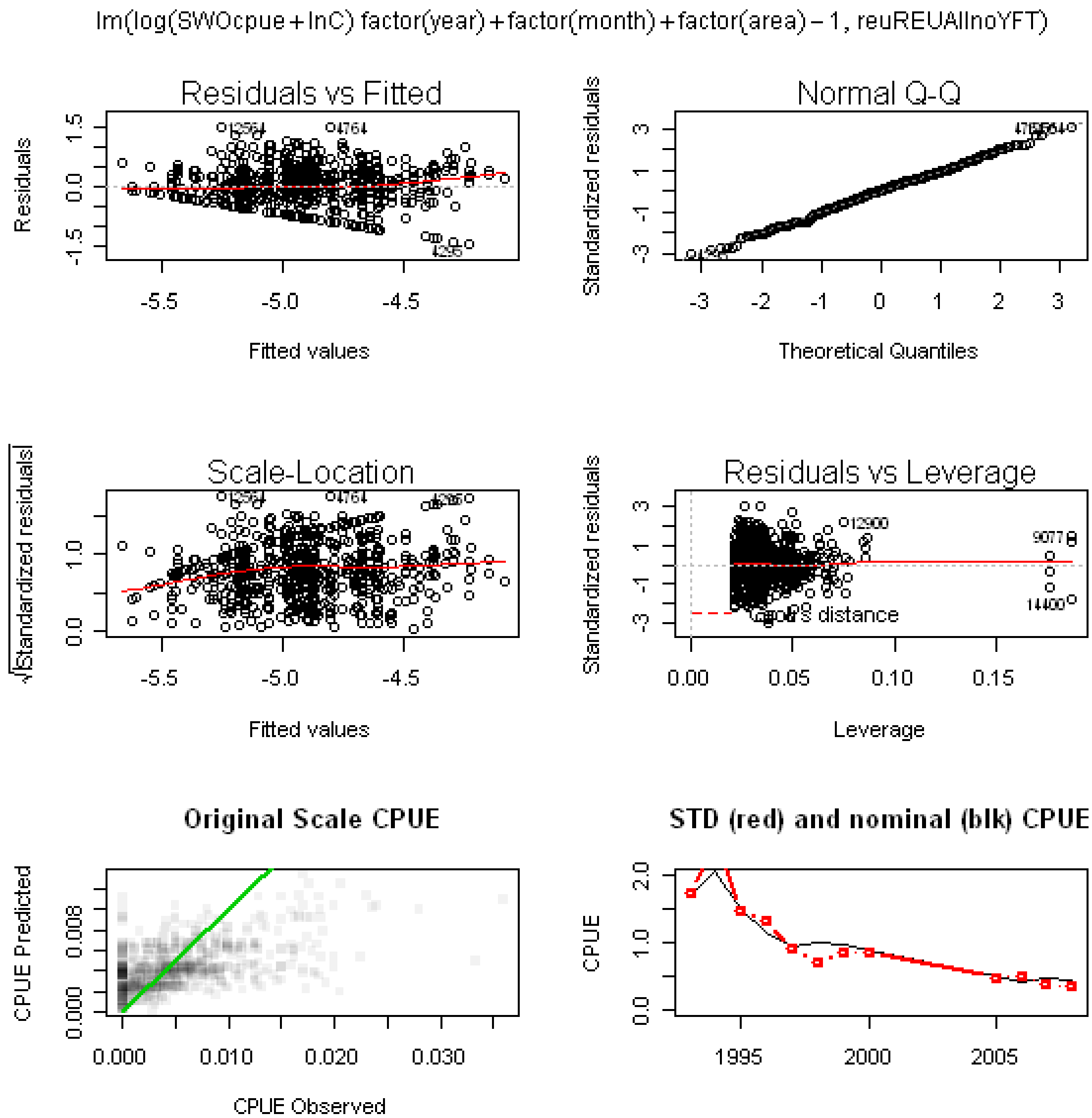
Appendix 6. Summary results and diagnostics from CPUE model ADF-N1 (see text Table 2).

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(month) +
    factor(area) - 1, data = reuREUAllnoBET)

Residuals:
    Min      1Q  Median      3Q     Max
-1.6824 -0.2596  0.0129  0.2741  1.7829

Coefficients:
                   Estimate Std. Error  t value Pr(>|t|)
factor(year)1993 -4.2818180  0.0544478  -78.641  < 2e-16 ***
factor(year)1994 -4.0643408  0.0278823 -145.768  < 2e-16 ***
factor(year)1995 -4.3165062  0.0234099 -184.388  < 2e-16 ***
factor(year)1996 -4.5072788  0.0221117 -203.841  < 2e-16 ***
factor(year)1997 -4.6418269  0.0248316 -186.932  < 2e-16 ***
factor(year)1998 -4.6773480  0.0244134 -191.589  < 2e-16 ***
factor(year)1999 -4.6696031  0.0220220 -212.043  < 2e-16 ***
factor(year)2000 -4.6860789  0.0248212 -188.793  < 2e-16 ***
factor(year)2005 -5.1118109  0.0260672 -196.101  < 2e-16 ***
factor(year)2006 -5.1428913  0.0217349 -236.619  < 2e-16 ***
factor(year)2007 -5.0918859  0.0208545 -244.163  < 2e-16 ***
factor(year)2008 -5.1069168  0.0227952 -224.035  < 2e-16 ***
factor(month)2    0.0333239  0.0245827    1.356 0.175276
factor(month)3    0.0372798  0.0242427    1.538 0.124150
factor(month)4   -0.0536736  0.0258352   -2.078 0.037789 *
factor(month)5   -0.1057085  0.0264917   -3.990 6.67e-05 ***
factor(month)6   -0.1275666  0.0271146   -4.705 2.59e-06 ***
factor(month)7   -0.0008249  0.0284616   -0.029 0.976880
factor(month)8   -0.0024469  0.0268111   -0.091 0.927284
factor(month)9    0.0419535  0.0258179    1.625 0.104214
factor(month)10   0.0894113  0.0226180    3.953 7.79e-05 ***
factor(month)11   0.0228193  0.0211610    1.078 0.280909
factor(month)12   0.0179932  0.0224381    0.802 0.422636
factor(area)NW   -0.0286551  0.0271224   -1.057 0.290774
factor(area)SE    0.1353314  0.0136532    9.912  < 2e-16 ***
factor(area)SW    0.0885734  0.0249406    3.551 0.000386 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4176 on 6810 degrees of freedom
Multiple R-squared: 0.9923,     Adjusted R-squared: 0.9923
F-statistic: 3.384e+04 on 26 and 6810 DF,  p-value: < 2.2e-16
```


lm(log(SWOcpue+lnC) factor(year)+factor(month)+factor(area)-1, reuREUAllnoBET)
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Leverage
Cook's distance
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE

Appendix 7. Summary results and diagnostics from CPUE model ADF-N2 (see text Table 2).

```
Call:
lm(formula = log(SWOcpue + lnC) ~ factor(year) + factor(month) +
    factor(area) - 1, data = reuREUAllnoYFT)

Residuals:
     Min       1Q   Median       3Q      Max
-1.47181 -0.32818  0.02642  0.31689  1.52058

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
factor(year)1993 -4.84194    0.22732 -21.301  < 2e-16 ***
factor(year)1994 -4.60209    0.11338 -40.591  < 2e-16 ***
factor(year)1995 -4.92011    0.10500 -46.859  < 2e-16 ***
factor(year)1996 -4.98052    0.09385 -53.071  < 2e-16 ***
factor(year)1997 -5.15546    0.10778 -47.832  < 2e-16 ***
factor(year)1998 -5.24979    0.10668 -49.211  < 2e-16 ***
factor(year)1999 -5.17778    0.09616 -53.843  < 2e-16 ***
factor(year)2000 -5.17406    0.10346 -50.010  < 2e-16 ***
factor(year)2005 -5.38017    0.13028 -41.297  < 2e-16 ***
factor(year)2006 -5.36918    0.11145 -48.175  < 2e-16 ***
factor(year)2007 -5.43630    0.09834 -55.278  < 2e-16 ***
factor(year)2008 -5.45633    0.10245 -53.257  < 2e-16 ***
factor(month)2    0.23861    0.11385   2.096 0.036467 *
factor(month)3    0.30862    0.10427   2.960 0.003185 **
factor(month)4    0.27798    0.10352   2.685 0.007423 **
factor(month)5    0.36912    0.10172   3.629 0.000306 ***
factor(month)6    0.18831    0.10328   1.823 0.068707 .
factor(month)7    0.27290    0.10280   2.655 0.008124 **
factor(month)8    0.30346    0.10373   2.925 0.003556 **
factor(month)9    0.22453    0.10498   2.139 0.032806 *
factor(month)10   0.20064    0.10378   1.933 0.053605 .
factor(month)11  -0.16684    0.12938  -1.290 0.197664
factor(month)12  -0.07144    0.12182  -0.586 0.557743
factor(area)NW   -0.03869    0.10363  -0.373 0.708992
factor(area)SE    0.14807    0.06217   2.382 0.017517 *
factor(area)SW    0.23927    0.10150   2.357 0.018697 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.5035 on 675 degrees of freedom
Multiple R-squared:  0.99,      Adjusted R-squared: 0.9896
F-statistic:  2577 on 26 and 675 DF,  p-value: < 2.2e-16
```


lm(log(SWOcpue+lnC) factor(year)+factor(month)+factor(area)−1, reuREUAllnoYFT)
Residuals vs Fitted
Residuals
Fitted values
Normal Q-Q
Standardized residuals
Theoretical Quantiles
Scale-Location
√|Standardized residuals|
Fitted values
Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage
Original Scale CPUE
CPUE Predicted
CPUE Observed
STD (red) and nominal (blk) CPUE
CPUE