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Maldives Skipjack Pole and Line Fishery Catch Rate Standardization 2004-2010

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Abstract

A qualitative description and GLM-based standardization of the Maldivian skipjack (*Katsuwona pelamis*, SKJ) pole and line fishery catch rate data are presented for the period 2004-2010. The raw data consist of about 92000 monthly records of catch (numbers) and effort (fishing days) by month, atoll and vessel; vessel characteristics are available from the registry of new vessel. A fairly standard GLM approach was used, estimating log(CPUE) from independent variables Year, Quarter, Atoll, and Length of vessel. There are some irregularities in the data, most notably, a very large number of positive effort, zero SKJ catch records, that do not seem to be consistent with the general perception of how the fishery operates, and with an increasing trend over time. This is thought to represent systematic misreporting of effort or gear type that may bias the CPUE series. We attempted to examine and reduce the influence of the zero CPUE observations by i) using subsets of the data corresponding to larger vessels (which report fewer zeros), ii) using subsets of the data in which SKJ catch is a very high proportion of the total catch (to reduce the influence of non-SKJ targeting trips), and iii) attempting to directly estimate the quarterly probability of not targeting SKJ on the basis of the relationship between the proportion of zero SKJ observations and the number of days spent fishing. All of the models examined resulted in standardized time series that were very similar to each other and the nominal series. Two series are suggested for potential use in stock assessment, however, a number of concerns are noted:

- Further investigation of the fishery operations and data reporting is encouraged, as it would be preferable to understand the cause of the large proportion of zero catches (and other irregularities), rather than trying to compensate through the application of speculative ad hoc analyses.
- There are probably other important factors for which we have no data (e.g. related to the availability of livebait, technological innovations, etc.).
- This fishery is primarily operating around anchored FADs (during this recent time period), such that the relationship between CPUE and abundance might exhibit hyper-stability (i.e. large changes in SKJ abundance may result in large changes to the number and distribution of schools in the region, without strongly affecting the fish density near the FADs).
- The Maldives fishery represents a small portion of the Indian Ocean, such that it may not be indicative of regional abundance, and the short time period does not provide information about abundance changes during the development phase of the industrial fisheries (beginning around 1980).

Introduction

The Indian Ocean skipjack tuna (*Katsuwona pelamis*, SKJ) fishery is one of the largest tuna fisheries in the world, with total catches of 400-600 thousand tonnes over the past decade (Figure 1). There has never been a formal model-based stock assessment for this fishery, in part because there has never been an index of population abundance. The IOTC Working Party on Tropical Tunas (WPTT 2010) recognized that it was worth further effort to attempt to standardize the CPUE of the Maldivian Pole and Line (PL), and this document describes the continuing effort to do so.

Adam (2010) provides a description of the recent Maldives fishery. When nominal effort is defined as a boat day (all fishing vessels assumed to be equally efficient), there appears to be a generally increasing trend in the PL CPUE since the 1970s, with a possible decline in the most recent years (Figure 2). However, there are a number of features in the fishery which have changed over time, and which would be expected to change the nature of the relationship between SKJ abundance and CPUE. Most of the changes are expected to increase the catchability of the average vessel (if effort is defined in terms of a daily fishing trip):

- Over the last 30 years, new vessels have tended to be larger and more powerful, with more fishing poles, higher bait holding capacity, more storage space, longer range and presumably improved electronics.
- A network of anchored FADs was introduced in the 1980s, and most effort has been concentrated near the FADs since then. The number of FADs (~45) and their use, has not changed appreciably during the period of this study.
- Improvements in bait catching techniques. Since around 2000, fishermen began catching bait using lights at night, instead of lift nets during the morning. This has greatly increased the livebait catch and the daily hours available for searching and fishing.
- Use of collector vessels presumably increases the potential range of the vessels from home port.

However, there also appear to be other factors operating in this fishery (or at least in the catch-effort database) which could contribute to an apparent decline in efficiency of the fleet (or change the efficiency in either direction, depending on the trend):

- Limited bait availability is suspected of constraining operations in recent years.
- Fuel subsidies have created incentives to have vessels recognized as fishing vessels, even if that is not their primary purpose. This is thought to have resulted in reporting of fishing effort (and catch) for vessels that were not fishing.
- High fuel costs have likely reduced fishing activity.
- A requirement for license fees to be paid for vessels operating less than 120d per year created an incentive to over-report effort. The fee was abolished in Jan 2009.
- Many vessels can switch between PL and hand line (HL) operations within a fishing trip, and there is reason to think that the correct gear type is not always reported.

Mohamed (2007) proposed a time series of SKJ relative abundance derived from the PL fishery from 1985-2005. That analysis assumed that changes in efficiency over time were adequately explained by, and directly proportional to, mean annual horsepower in the fleet. However, there was no quantitative analysis presented to justify that assumption. Kolody *et al.* (2010) attempted to standardize the PL CPUE series by i) reconstructing the fleet composition from 1958-2007 based on the vessel registry and assumptions about vessel longevity, ii) quantify the relative catchability for different vessel characteristics, based on a partial database of monthly catch and effort by vessel from 2004-7, and iii) estimate time series of relative abundance from aggregate catch and effort by atoll from 1970-2007, combined with (i) and (ii). The trend in the estimated relative abundance time series was found to be very sensitive to the efficiency estimates for small, un-mechanized vessels, that were poorly represented in the 2004-7 data. It was concluded that catch rate standardization could only be meaningfully attempted using the vessel-specific data available since 2004. However, due to inconsistencies in the entry of the vessel identification fields, only ~10% of the observations from 2004-2007 were available at that time.

During 2011, the Maldives Marine Research Centre (MRC) corrected the vessel identification fields, resulting in ~45000 usable vessel-specific PL monthly catch and effort records spanning the period 2004-2010. This paper describes an attempt to standardize the PL CPUE series for use in the 2011 SKJ stock assessment. A number of unresolved issues about these CPUE series are discussed, and some options are presented to illustrate the implications of some sources of uncertainty.

Methods

Data and Pre-processing

Three data sets were used in this analysis, as provided by the Maldives Ministry of Fisheries and Agriculture (MoFA):

i. Monthly catch and effort data from the PL fleet by atoll and vessel 2004-2010.
ii. The registry of new vessels 1958-2010 (which includes many vessel characteristics which should be related to efficiency e.g. length, horsepower).
iii. A subset of daily observations from the logbook programme introduced in 2010.

These data remain confidential. Descriptive and graphical summaries of the data are provided below.

Monthly Catch and Effort Data 2004-2010

The dataset (as provided by MoFA, MRC: "Cleanded_Catch_Effort_2004_2010.csv ", with 2009-2010 superseded by "Catch_Effort_2009.xlsx", "Catach_Effort_2010.xlsx") includes the following fields of relevance to the analysis:

- Year, Month, Atoll
- Vessel Identification Number (VIN), which can be linked to the vessel registry
- Gear type
- Effort in boat days
- Catch in numbers and mass by species

A total of 43638 observations of gear type PL, and skipjack fishery type, were considered to be useful for the analysis. Catch (and CPUE) in numbers were used for all analyses, because mass is calculated as the product of numbers and size category bins, and there were only two size classes historically.

Other measures of effort ('Gear quantity' and 'Total fishermen') were available, but not consistently recorded. Note that aggregated monthly catch and effort data are available dating back to 1970, but catches are not linked with individual vessels prior to 2004 (e.g. Kolody *et al.* 2010).

Traditionally, vessels had operated single day trips (there is no refrigeration, but the boats carry ice). Multiday trips are probably common in recent years, particularly for larger vessels. The catch may be disposed to a collector vessel, land-based collection facility[1] or landed in the home port. Wherever the landing occurred, it was expected that the catch would also be reported at the home port. However, the home port may no longer provide an accurate indication of where the fishing actually occurred. The traditional manner of reporting at the home port has not been followed for vessels participating in the new logbook programme (<10% for 2010).

The annual nominal catch, effort (boat days), and CPUE (effort weighted) from this database are shown in Figure 3. The fishing activity is concentrated on a few atolls, and evenly distributed across months (Figure 4, Figure 5). The nominal CPUE distribution is not consistent across atolls over time (Figure 6). The majority of active vessels fish for ~18-26 days per month, though many months with a single day of effort are recorded (Figure 7).

A number of irregularities were identified (note that number of affected observations are provided only as a rough indication, as a sequential filtering was used):

- The VIN fields were not consistently entered into the database originally[2]. In 2011, MRC staff cleaned up the VIN fields for >90% of records, which should be adequate for purposes of CPUE analyses.
- A number of incomplete records were dropped from the analysis (e.g. missing Effort_Days, vessel identity, etc.).
- This is a database of monthly observations, but there are more than 30000 year, month, vessel, atoll strata with more than one observation. When the total Effort days is summed by month/vessel strata, there are ~1400 records with >31 days (max. 122). This was largely attributed to a partial duplication of records due to port sampling activities (primarily in Malé). As the port sampling records could not be easily identified within the database, only the record with the greatest effort (boat-days) for a particular month/VIN strata was retained for the analysis. This means that legitimate observations of vessels visiting multiple atolls within a month were omitted (but this is not a large number overall).
- The total catch of SKJ was noted to be greater than the total catch of all species (including SKJ) in 2.5% of records (Figure 8). No explanation could be provided for these apparent discrepancies. There did not seem to be anything exceptional about the SKJ catch in these records, but they were discarded since something was evidently wrong.

[1] There are two major collection centres, in the North Felivaru, operated by MIFCO an the other in the South, Kooddoo Fisheries Maldives Pvt, ltd, previously also operated by MIFCO
[2] This is related to the change brought by the Ministry of Transport in the way registry numbers were allocated for vessels / vehicles in the Maldives.

- There are a few observations that indicate extremely large catches would have had to be taken in some months (max. 328013 SKJ in 24 d by one vessel). This may be possible, but would have required exceptional catches on most days in one month. This raises some question of whether collector vessels might be included in this database.
- There are a very large number of positive effort records with zero SKJ catch (23-32% by year, Figure 9), and these observations include months with many days of recorded fishing (Figure 10). Several explanations were proposed:
  - Sometimes SKJ cannot be located during a trip. However, the MoFA/MRC and data section staff considered it unlikely that vessels targeting SKJ would fail to catch any on a regular basis.
  - In some cases, PL vessels were probably targeting neritic tuna (despite reporting the trip as type SKJ).
  - The biggest problem is thought to be misreporting of gear type. Many of the vessels operate as either PL or handline (HL) vessels (targeting large yellowfin tuna or reef fishes).
  - It was thought that misreporting of effort might represent another possibility. Prior to 2009, a license fee was levied for boats that operated for <120 days within a calendar year. This is thought to have resulted in effort being recorded for boats that remained in port. The magnitude of the misreporting problem is not known. However, the number of zero SKJ catch records was actually higher in 2009 and 2010 than 2004-2008 (Figure 9), so this does not seem like an important contributing mechanism.
  - It has been suggested that some fishing vessels might only be reporting landings made at the home port, and excluding fish unloaded at the canneries or transferred to collector vessels.

Specific analyses to try and quantify the implications of alternative interpretations of the zero SKJ catches are discussed below.

Vessel Registry 1958-2010

The Ministry of Transport and Communication maintains the national registry of vessels, including fishing vessels. The vessel registry records key features of new vessels over the period 1958-2010, and includes all of the vessels in the catch and effort database (though not all of the VIN entries were valid). Recorded vessel characteristics include length, breadth, depth, gross tonnage and horsepower, all of which are strongly correlated (Figure 11) and expected to be positively related to fishing efficiency. We note that Mohamed (2007) assumed that total effective effort of the PL fleet was directly proportional to annual average horsepower for the period 1985-2005. However, this seems to be an assumption of convenience that was not the result of any reported analysis.

Vessels around ~12-17m represent the majority of observations, and there is a modest trend toward increased use of larger vessels from 2004-2010 (Figure 12). CPUE increases sharply with increasing vessel size up to ~17m, and then increases slowly to 35+m (Figure 13). Much of the increase in CPUE with vessel size is related the number of zero SKJ catch observations as discussed below.

Logbook Data

A partial database of the 2010 PL logbook programme was obtained (~400 daily records by vessel). These data were used only to help quantify the proportion of true zeros that are likely to be observed in the monthly catch and effort records due to systematic misreporting of gear and/or targeting. Table 1 suggests that it is unusual for a vessel to catch zero SKJ for more than two days in a month, if it is reported as daily SKJ targeting in the logbook. Unfortunately, the logbook sample is small, and there is reason to think that there have been some errors in gear reporting in the early phases of this programme. These daily data would clearly provide a preferable basis for catch rate analyses at some point in the future.

Statistical Analyses

The goal of the catch rate standardization is to estimate a time series of catch rates that would be equivalent to what would be observed if the fishery consisted of a single vessel type, fishing in a consistent manner over time. Ideally this time series can be interpreted as being proportional to fishery-selected abundance in the stock assessment. Two general approaches were explored to achieve this. First, the data were filtered in different ways to identify more reliable and/or homogeneous observations. Second, standard GLM methods were employed (e.g. Maunder and Punt 2004) to estimate the effects of different factors in explaining CPUE variability that is not attributable to abundance, e.g. Using R software function *lm()*:

$$\log\left(CPUE_i\right) = \beta_T X_{T,i} + \beta_1 X_{1,i} \; \dots \beta_n X_{n,i} + e_i$$

where:

log(CPUE) = monthly CPUE observation *i*, transformed in various ways discussed below,

β_T = the temporal effect that we are interested in extracting as the relative abundance time series (quarterly 2004-2010), and $X_{T,i}$ is the time period of observation *i*,

$\beta_1 \dots \beta_n$ = coefficients quantifying the effect of the other continuous or categorical explanatory variables ($X_{x,i}$) for observation *i*, and

e = normally distributed error with variance σ^2.

A range of models were examined (Table 2), with explanations of the dependent and independent variables provided below. The primary intent of the models was to account for variability in vessel catchability, and examine different ways of dealing with the zero SKJ records. The approaches included:

1) Models 4-12 consider only the medium-large vessels (>17m), as the small vessels are prone to reporting a large number of zeros. This is clearly seen when the proportion of zeros over time, and over effort_days per month, is partitioned by length category (Figure 14 and Figure 15).

2) Models 9-10 include only observations in which the monthly catch is predominantly SKJ (>90, >99%). This omits the true zeros, and should reduce the number of months with mixed zeros and positive catches if they are caused by gear misreporting.

3) Models 11-12 attempt to directly estimate and account for the probability that vessels are not targeting SKJ as a function of time (described in the following section). In principle this should also go some way toward accounting for positive effort, zero SKJ catch records that arise as a consequence of not reporting catches that are dropped off at canneries or with collector vessels.

Other error models are often adopted to formally account for zero CPUE observations (e.g. Poisson or delta models), but that does not address the fundamental problem in this case. i.e. Since the data are aggregated by month, we expect that many of the observations with positive catch would actually represent a mix of days spent targeting SKJ and days spent targeting something else.

Model 8 used robust (median-based) regression (R software function rq()) to examine the influence of the exceptionally large (outlier?) catches.

Dependent variable and the interpretation of the zero catches

The dependent variable, monthly CPUE, was treated in different ways to consider alternative interpretations of the troublesome zero catches (Table 3). The relationship between the proportion of monthly zero catch observations and the number of days spent fishing is highly dependent on vessel size (Figure 14, Figure 15). The CPUE data were modelled in three different ways:

1) log(CPUE+C); Models 1-8

This is a fairly standard treatment of positive effort, zero catch data, and following the suggestion of Campbell (2004), C was defined as 10% of the mean CPUE (of all observations included in the specific model). This approach assumes that all of the observations correspond to targeted SKJ fishing. It seems unrealistic given the general perception of fishing success in the fishery (i.e. Figure 10 - it is doubtful that 20% of vessels fishing for 25 days in a given month would catch zero SKJ), but the relationship for the larger vessels might be reasonable.

2) log(CPUE[CPUE>0, SKJ/(Total Catch)>xx%]); Models 9-10

These models assume that any observation with zero SKJ catch represents a vessel that is targeting something other than SKJ. A further constraint was added such that only observations in which SKJ represented >90 or >99% (of all species combined) were included. This should reduce the issue of months with mixed targeting, but the high value / low volume of some of the other target species might undermine this approach.

3) log(CPUE/(1-$P_{0,t}$) + C); Models 11-12

This represents an explicit attempt to estimate the average proportion of effort that is not targeted on SKJ ($P_{0,t}$) for time period t. The CPUE is increased by the factor of 1/(1-$P_{0,t}$) to reflect the fact that there is effectively less effort than the reported value. We assumed that $P_{0,t}$ can represent PL targeting of other species, misreporting of HL gear as PL and failure to report SKJ landings at the home port as a result of offloading elsewhere. We assumed that the proportion of zero catch for a vessel that is truly targeting SKJ is negligible.

A two parameter model for $P_{0,t}$ should be sufficient to describe the relationships shown in Figure 15. We assume that vessels that record effort fall into one of two categories. One set of vessels targets SKJ with a fixed probability every day (a Bernoulli process). The other set of vessels never targets SKJ within the month (but reports effort). In this case the average proportion of effort that is not targeted on SKJ is given by:

$P_{0,t} = (1 - P_{2,t})P_{1,t} + P_{2,t}$,

where:

$P_{1,t}$ = an independent daily probability that a vessel does not target SKJ during time interval *t* for the vessels that occasionally target SKJ.

$P_{2,t}$ = the proportion of vessels that do not target SKJ for the whole month during time interval *t*.

The distribution of monthly zero catches ($P_{E,t}$) as a function of the number of days fished (*E*), is given by:

$P_{E,t} = (1- P_{2,t})(P_{1,t})^E + P_{2,t}$.

$P_{1,t}$ alone (i.e. $P_{2,t}$ = 0) might be sufficient to describe the relationship between the proportion of zeros and fishing days for larger vessels, while $P_{2,t}$>0 seems to be required for the smaller vessels (e.g. Figure 15, ignoring the few observations with >26d fishing per month). Theoretical relationships for this model are shown in Figure 16 for $P_{0,t}$ = 0.6, but with different values of $P_{1,t}$ and $P_{2,t}$. Note that Figure 16 could probably also be derived by assuming that there is a continuum of vessels showing intermediate types of behaviour for those defined in P1 and P2 above, but which lead to the same interpretation of $P_{0,t}$ (e.g. the choice to target SKJ might not be independent among days within a month). Figure 16 emphasizes that important information might be lost when dealing with monthly aggregated data.

Parameter estimation consisted of minimizing the squared deviations between the predicted and observed distributions of zero catch proportions per number of days fished. The parameters were estimated quarterly (model 11) and annually (model 12). Typical fits for the quarterly data are shown in Figure 17. The fits are often poor (though perhaps not as bad as appears in the sense that each proportion represents a different number of observations, and the fitting is weighted by the sample size which is not visible in the plots). The $P_{0,t}$ parameter estimates show considerable variability, with a generally increasing trend over time (Figure 18).

It should be emphasized that this is an *ad hoc* analysis that provides an indication of the implications of a temporal trend in the proportion of zero catches over time if they represent non-SKJ targeting. It seems reasonable for situations with large numbers of observations that conform to the assumptions. However, we do not claim that it is statistically rigorous. And it is highly speculative because we do not understand the processes that are causing the reporting of zero catches.

Independent Variables

The following independent variables were included in some or all models (Table 4):

Y – Year.

Q - Quarter. In most cases Y*Q interactions were included (through a non-repeating quarter factor).

A – atoll, a spatial factor accounting for changes in the spatial distribution of effort. Since this is an indicator of the landing site, it may not always be a very accurate indication of fishing location, particularly now that mechanization allows long distances to be covered, and collector vessels are used.

L, f(L) – vessel length, a general indicator of vessel efficiency, should be correlated with the number of poles, bait capacity, range, hold size, etc.. L was treated as either a categorical variable with levels (<7, 7 - <12, 12 – <17, 17 - <22, 22 - <27, 27 - <32, 32 - <37m), or a continuous variable f(L) (in the latter case, only vessels of >17m were included).

V – Vessel Identity Number (VIN). The information contained in the VIN is confounded with L, and A (to the extent that vessels tend to remain around the same home port). But VIN could potentially be useful for identifying catchability effects from other sources (e.g. skipper skill). However, given the large number of vessels, V requires a large number of degrees of freedom.

We do not have enough information to include other factors which may be important, e.g. use of collector vessels, proportion of time spent FAD fishing, potential bait shortages, number of poles operating, etc.

Standardized CPUE Series

The GLM parameter estimates were converted into an overall relative abundance index using a standard approach (e.g. Campbell 2004):

$$I_t = \exp\left(\beta_t + A \quad + f(L) \quad + \tfrac{1}{2}\sigma^2\right) - C,$$

where:

I is the index for time t,

β_t = the estimated time co-efficient,

A = the estimated co-efficient for the standard atoll (the one with the most observations).

f(L) is the estimated parameter for a standard vessel: length (17-22m) for the categorical case; or 19.5m X the estimated length co-efficient in the continuous case.

σ^2 is the estimated variance (Mean Squared Error), and

C is the small constant (not relevant for all models).

Results and Discussion

Most of the CPUE models examined are not directly comparable on the basis of standard model selection criteria (e.g. AIC, BIC) because they use different data. However, this is not very important in this case because all of the models suggest a very similar time series. The biggest difference among models seems to be the treatment of the zero observations, which is probably not a problem that can be solved with improved statistics unless we can better understand the origins of the zero catches.

In all cases, the Atoll, Length and VIN factors were highly significant predictors of CPUE. The R^2 value for each model, and the linear trend (from a least squares regression fit) is included in Table 2. All models show an overall declining trend over time, and the linear trend provides a simple indication of the relative magnitude of the decline.

Figure 19 compares the standardized time series of the simplest models (1-7). All suggest a similar pattern: increasing CPUE from around 2004-2006, decrease from 2006-2008 and relative stability from 2008-2010. The biggest difference among series relates to the size of the peak in 2006. Using the full dataset (models 1-2) results in the lowest peak, while removing smaller vessels from the analysis results in a higher peak.

The R^2 values from Table 2 indicate that models 1-2 and 7 is much higher than models 3-6. This does not mean that these models provide a better relative abundance time series. In the case of models 1-2 this simply reflects the fact that the small vessels were included in the analysis (they have very different catchability than large vessels, hence there is more CPUE variability to be explained, and it is largely explained by vessel length). At this time we are inclined to prefer models that exclude the smaller vessels, because these vessels are most affected by the large number of unexplained zero catches (e.g. Figure 14, Figure 15). We would expect the inclusion of these vessels to flatten out the standardized series because the observed CPUE in the model is equal to *C*, for >60% of the small vessel observations. In contrast, vessel categories >17m all seem to have similar patterns of zero catch, far fewer zeros than the small vessels, and a fairly linear relationship between CPUE and length (e.g. Figure 13 - Figure 15).

The VIN factor in model 7 clearly explained a lot of the unexplained variance in models 4-6. Undoubtedly individual vessels and skippers have different levels of efficiency that are not explained by the other factors. However, VIN consumes a large number of degrees of freedom, may lead to an unbalanced design, and did not have a large effect on the final time series.

Among the conventional models, 5 and 6 seem the most defensible. In both cases, the residual behaviour seems reasonable (Figure 21 and Figure 22). ANOVA tables and parameter estimates (Table 5, Table 6) indicate that all of the independent variables are highly significant. We tend to favour model 6 on the basis of parsimony (length as a continuous variable), and compare models 8-12 with this one.

The time series for model 8 (median regression) is very similar to model 6, which suggests that the few large SKJ catch observations are not very influential (Figure 20).

Each of models 9-12 were intended to reduce the influence of the zero SKJ catches under the assumption that those observations predominantly represent something other than SKJ targeting. In terms of trend, models 9 and 10 are intermediate between models 6 and 11-12 (Figure 20, Table 2).

Models 11 and 12 are the most optimistic (least CPUE decline), and represent the most thorough attempt to remove the influence of the zero SKJ catches. Overall, we would recommend model 11 over model 12, since it estimates P(0) by quarter. We expect model 11 to be the least biased by the time trend in the unexplained zero catches, but the extra estimation procedure for P(0) presumably inflates the variance. Diagnostic plots for model 11 (Figure 23) suggest that there is no obvious problem with the residual behaviour. The ANOVA and parameter estimates are included in Table 7.

For the purposes of the stock assessment, we recommend the results from model 11 as likely to be the least biased for the purposes of stock assessment. Model 6 might be useful as a sensitivity trial, as it is one of the more defensible options, with one of the steepest declining trends. We think it likely that model 6 does not adequately account for the time trend in the zero catches, but at the end of the day, we are not sure what is causing the zero catches, and there is not a large difference between the two (Figure 24).

The following caveats are noted with respect to the use of this time series in the context of the 2011 stock assessment:

- There are a number of data irregularities that do not seem to be consistent with the general perception of the fishery operations and may be a consequence of systematic reporting errors (e.g. large proportion of positive effort, zero SKJ observations).
- There are operational factors that are suspected of being important, but for which there are no data (e.g. bait availability, technological innovation).
- The analysis lacks contrast, as the relatively short time period covered corresponds only to recent peak catches. Furthermore, anchored FAD fishing is thought to predominate during this period (which can be expected to cause hyper-stability in CPUE indices)
- Even if these CPUE series are reliable indicators of abundance for the Maldives region, there are additional concerns about using them as the primary input for a regional stock assessment, because the Maldives represents a very small part of the Indian Ocean SKJ range, and abundance may not be representative of the whole population.
- Worm and Tittensor (2011) provides evidence suggesting that there may have been a range contraction in the Indian Ocean SKJ population (contraction from the southern periphery toward the core area). There are good reasons to doubt this analysis, but if this is a real effect, it could lead to hyperstability in the CPUE signal derived from the core SKJ region.
- Genetic analyses have suggested that there might be (at least) two SKJ populations in the Indian Ocean (Dammannagoda *et al*. 2011), the relative abundance of the two could differ, and the Maldives fishery would presumably not index both of them accurately.

We encourage further investigation of the existing data irregularities, and expansion of the logbook programme to improve these analyses in the future.

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Table 1. Proportion of zero SKJ catches from the (incomplete) daily 2010 logbook PL data ('TUNA FISHERY', FISHING.GEAR.CODE=1) when aggregated by month and fishing license.

Days Fishing per Month	Number Observations	Proportion of zero SKJ records
1	134	0.5
2	1	1
3-12	11	0

Table 2. Model definitions. Variables defined in Table 3 and Table 4. Note that the R^2 value is calculated from the version of the model with an intercept, while the ANOVA tables represent the no-intercept version (parameter estimates are identical).

Model	Data (N obs)	Dependent Variable	Independent Variables	R^2 and (Linear trend % per Year)	Comments
1-tz.1	Full (43638)	ln(CPUE+C)	Y+Q+A+L	0.45 (-5.9)	Interprets SKJ=0 as low abundance
2-tz.2	Full (43638)		Y*Q+A+L	0.45 (-6.0)	
3-tz.3	12<L<37 m (33653)		Y*Q+A+L	0.33 (-6.4)	
4-tz.4	17<L<32 m (14658)		Y*Q+A+L	0.28 (-7.2)	
5-tz.5	17<L<32 m 12 Atolls (9441)		Y*Q+A+L	0.27 (-6.2)	
6-tz.6	L>17 m 12 Atolls (9578)		Y*Q+A+f(L)	0.28 (-6.7)	
7-tz.7	L>17 m 12 Atolls (9578)		Y*Q+A+f(L)+V	0.46 (-7.3)	
8-tzr.6				(-6.9)	Robust median regression to test influence of high CPUE outliers
9-sp.1	17<L<32 m 12 Atolls SKJ >90% (4792)	ln(CPUE)	Y*Q+A+f(L)	0.19 (-5.9)	Assumes proportion SKJ identifies observations with predominant SKJ targeting
10-sp.2	17<L<32 m 12 Atolls SKJ >99% (3179)		Y*Q+A+f(L)	0.21 (-5.8)	
11-etq.6	17<L<32 m 12 Atolls (9578)	ln(CPE/(1-$P_{0,q}$)+C) (quarterly)	Y*Q+A+f(L)	0.28 (-4.9)	Attempts to adjust effort by time period to remove non-SKJ targeting
12-ety.6	17<L<32 m 12 Atolls (9578)	ln(CPE/(1-$P_{0,a}$)+C) (annual)	Y*Q+A+f(L)	0.27 (-5.0)	

Table 3. Definitions for dependent variables.

CPUE	SKJ numbers / Effort Days in a year/month/atoll/vessel stratum
CPUE/(1-$P_{0,t}$)	CPUE with Effort Days adjusted according to the estimated proportion of vessels not targeting SKJ in a yearly or quarterly period.
C	10% of mean CPUE for the dataset in the specific analysis

Table 4. Definitions for independent variables.

Y	Year
Q	Quarter (Y*Q = Year-quarter interactions)
A	Atoll
L	Vessel Length (5m categories)
f(L)	Vessel Length as a continuous variable (only vessels of L>17m included)
V	VIN – Vessel Identity Number

Table 5. Model 5 ANOVA table and parameter estimates

```
Response: log(cpuen + C)
                    Df Sum Sq Mean Sq  F value    Pr(>F)    
as.factor(yrQtr)    28 332465 11873.7 17792.15 < 2.2e-16 ***
as.factor(Atoll)    10   1647   164.7   246.82 < 2.2e-16 ***
as.factor(lenCat)    2    232   115.8   173.49 < 2.2e-16 ***
Residuals         9401   6274     0.7                       
---
Call:
lm(formula = log(cpuen + C) ~ as.factor(yrQtr) + as.factor(Atoll) + 
    as.factor(lenCat) - 1, data = tmp)

Residuals:
     Min       1Q   Median       3Q      Max 
-2.83102 -0.50156  0.07324  0.54514  3.33578 

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)    
as.factor(yrQtr)2004.125  6.13823    0.05304 115.734  < 2e-16 ***
as.factor(yrQtr)2004.375  5.90609    0.05386 109.663  < 2e-16 ***
as.factor(yrQtr)2004.625  6.09335    0.05295 115.082  < 2e-16 ***
as.factor(yrQtr)2004.875  6.22156    0.05633 110.454  < 2e-16 ***
as.factor(yrQtr)2005.125  6.12441    0.05215 117.429  < 2e-16 ***
as.factor(yrQtr)2005.375  6.19794    0.05238 118.316  < 2e-16 ***
as.factor(yrQtr)2005.625  6.27578    0.05244 119.668  < 2e-16 ***
as.factor(yrQtr)2005.875  6.46408    0.05270 122.666  < 2e-16 ***
as.factor(yrQtr)2006.125  6.46401    0.05288 122.243  < 2e-16 ***
as.factor(yrQtr)2006.375  6.24204    0.05265 118.547  < 2e-16 ***
as.factor(yrQtr)2006.625  6.03499    0.05183 116.445  < 2e-16 ***
as.factor(yrQtr)2006.875  6.20813    0.05122 121.203  < 2e-16 ***
as.factor(yrQtr)2007.125  5.81495    0.05078 114.513  < 2e-16 ***
as.factor(yrQtr)2007.375  5.77664    0.05298 109.026  < 2e-16 ***
as.factor(yrQtr)2007.625  5.81415    0.05128 113.373  < 2e-16 ***
as.factor(yrQtr)2007.875  6.08520    0.04865 125.088  < 2e-16 ***
as.factor(yrQtr)2008.125  5.60102    0.04962 112.884  < 2e-16 ***
as.factor(yrQtr)2008.375  5.79523    0.04938 117.351  < 2e-16 ***
as.factor(yrQtr)2008.625  5.95068    0.04895 121.577  < 2e-16 ***
as.factor(yrQtr)2008.875  6.07270    0.04960 122.441  < 2e-16 ***
as.factor(yrQtr)2009.125  5.70594    0.04589 124.326  < 2e-16 ***
as.factor(yrQtr)2009.375  5.60925    0.04730 118.591  < 2e-16 ***
as.factor(yrQtr)2009.625  5.77935    0.04771 121.147  < 2e-16 ***
as.factor(yrQtr)2009.875  6.04599    0.04822 125.384  < 2e-16 ***
as.factor(yrQtr)2010.125  5.84902    0.05130 114.012  < 2e-16 ***
as.factor(yrQtr)2010.375  5.49290    0.05191 105.820  < 2e-16 ***
as.factor(yrQtr)2010.625  5.79856    0.05292 109.569  < 2e-16 ***
as.factor(yrQtr)2010.875  5.91929    0.05152 114.896  < 2e-16 ***
as.factor(Atoll)HA        0.01946    0.03116   0.624 0.532321    
as.factor(Atoll)HD       -0.42930    0.06019  -7.133 1.06e-12 ***
as.factor(Atoll)KA       -1.20932    0.03502 -34.528  < 2e-16 ***
as.factor(Atoll)LA       -0.34372    0.04089  -8.406  < 2e-16 ***
as.factor(Atoll)LH       -0.02938    0.03928  -0.748 0.454533    
as.factor(Atoll)ME        0.06829    0.04249   1.607 0.108045    
as.factor(Atoll)RA       -0.11780    0.03403  -3.462 0.000539 ***
as.factor(Atoll)SE       -0.01725    0.03380  -0.510 0.609848    
as.factor(Atoll)SH       -0.58514    0.04070 -14.378  < 2e-16 ***
as.factor(Atoll)TH       -0.01531    0.03810  -0.402 0.687881    
as.factor(lenCat)L22      0.24708    0.01991  12.413  < 2e-16 ***
as.factor(lenCat)L27      0.48475    0.02732  17.743  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 0.8169 on 9401 degrees of freedom
Multiple R-squared: 0.9816,     Adjusted R-squared: 0.9815 
F-statistic: 1.252e+04 on 40 and 9401 DF,  p-value: < 2.2e-16
```

Table 6. Model 6 ANOVA table and parameter estimates.

```
Analysis of Variance Table

Response: log(cpuen + C)
                      Df Sum Sq Mean Sq  F value    Pr(>F)    
as.factor(yrQtr)      28 332465 11873.7 17949.94 < 2.2e-16 ***
as.factor(Atoll)      10   1647   164.7   249.01 < 2.2e-16 ***
as.numeric(LengthM)    1    286   286.0   432.42 < 2.2e-16 ***
Residuals           9402   6219     0.7                       
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 
CPUE/MLD/mld2011> summary(tz.6)

Call:
lm(formula = log(cpuen + C) ~ as.factor(yrQtr) + as.factor(Atoll) + 
    as.numeric(LengthM) - 1, data = tmp)

Residuals:
     Min       1Q   Median       3Q      Max 
-2.85612 -0.49377  0.07435  0.53271  3.39196 

Coefficients:
                          Estimate Std. Error t value Pr(>|t|)    
as.factor(yrQtr)2004.125  5.133137   0.075715  67.795  < 2e-16 ***
as.factor(yrQtr)2004.375  4.899601   0.076457  64.083  < 2e-16 ***
as.factor(yrQtr)2004.625  5.083672   0.076218  66.699  < 2e-16 ***
as.factor(yrQtr)2004.875  5.216314   0.078548  66.409  < 2e-16 ***
as.factor(yrQtr)2005.125  5.115920   0.075787  67.504  < 2e-16 ***
as.factor(yrQtr)2005.375  5.191852   0.075857  68.442  < 2e-16 ***
as.factor(yrQtr)2005.625  5.270467   0.076120  69.239  < 2e-16 ***
as.factor(yrQtr)2005.875  5.452236   0.076381  71.382  < 2e-16 ***
as.factor(yrQtr)2006.125  5.455838   0.076494  71.324  < 2e-16 ***
as.factor(yrQtr)2006.375  5.238803   0.076388  68.582  < 2e-16 ***
as.factor(yrQtr)2006.625  5.021022   0.076525  65.613  < 2e-16 ***
as.factor(yrQtr)2006.875  5.192251   0.076684  67.710  < 2e-16 ***
as.factor(yrQtr)2007.125  4.798486   0.076614  62.632  < 2e-16 ***
as.factor(yrQtr)2007.375  4.757147   0.078372  60.699  < 2e-16 ***
as.factor(yrQtr)2007.625  4.787256   0.077859  61.487  < 2e-16 ***
as.factor(yrQtr)2007.875  5.056274   0.076317  66.253  < 2e-16 ***
as.factor(yrQtr)2008.125  4.570069   0.077511  58.960  < 2e-16 ***
as.factor(yrQtr)2008.375  4.757140   0.078263  60.784  < 2e-16 ***
as.factor(yrQtr)2008.625  4.913966   0.077977  63.018  < 2e-16 ***
as.factor(yrQtr)2008.875  5.035656   0.078615  64.054  < 2e-16 ***
as.factor(yrQtr)2009.125  4.668551   0.076361  61.138  < 2e-16 ***
as.factor(yrQtr)2009.375  4.573026   0.077511  58.998  < 2e-16 ***
as.factor(yrQtr)2009.625  4.739126   0.078151  60.640  < 2e-16 ***
as.factor(yrQtr)2009.875  5.008569   0.078243  64.013  < 2e-16 ***
as.factor(yrQtr)2010.125  4.815444   0.080223  60.026  < 2e-16 ***
as.factor(yrQtr)2010.375  4.454925   0.080326  55.461  < 2e-16 ***
as.factor(yrQtr)2010.625  4.754600   0.081537  58.312  < 2e-16 ***
as.factor(yrQtr)2010.875  4.876375   0.080243  60.770  < 2e-16 ***
as.factor(Atoll)HA        0.028308   0.030625   0.924 0.355330    
as.factor(Atoll)HD       -0.476233   0.059443  -8.012 1.27e-15 ***
as.factor(Atoll)KA       -1.185463   0.034918 -33.950  < 2e-16 ***
as.factor(Atoll)LA       -0.353486   0.040540  -8.719  < 2e-16 ***
as.factor(Atoll)LH       -0.010281   0.038957  -0.264 0.791865    
as.factor(Atoll)ME        0.078283   0.042008   1.864 0.062420 .  
as.factor(Atoll)RA       -0.128104   0.033415  -3.834 0.000127 ***
as.factor(Atoll)SE       -0.058418   0.033839  -1.726 0.084314 .  
as.factor(Atoll)SH       -0.557842   0.040609 -13.737  < 2e-16 ***
as.factor(Atoll)TH       -0.032862   0.037924  -0.867 0.386225    
as.numeric(LengthM)       0.052356   0.002518  20.795  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 0.8133 on 9402 degrees of freedom
Multiple R-squared: 0.9817,     Adjusted R-squared: 0.9817 
F-statistic: 1.296e+04 on 39 and 9402 DF,  p-value: < 2.2e-16
```

Table 7. Model 11 ANOVA table and parameter estimates

```
Call:
lm(formula = log(cpuen_adjy + C) ~ as.factor(yrQtr) + as.factor(Atoll) +
   as.numeric(LengthM) - 1, data = tmp)

Residuals:
    Min      1Q  Median      3Q     Max
-2.76816 -0.49255  0.07326  0.53393  3.41106

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
as.factor(yrQtr)2004.125  5.312349   0.074905  70.921  < 2e-16 ***
as.factor(yrQtr)2004.375  5.302692   0.075638  70.107  < 2e-16 ***
as.factor(yrQtr)2004.625  5.317846   0.075384  70.543  < 2e-16 ***
as.factor(yrQtr)2004.875  5.333026   0.077710  68.627  < 2e-16 ***
as.factor(yrQtr)2005.125  5.273728   0.074944  70.369  < 2e-16 ***
as.factor(yrQtr)2005.375  5.714249   0.075014  76.175  < 2e-16 ***
as.factor(yrQtr)2005.625  5.415056   0.075276  71.936  < 2e-16 ***
as.factor(yrQtr)2005.875  5.781178   0.075523  76.549  < 2e-16 ***
as.factor(yrQtr)2006.125  5.550048   0.075634  73.380  < 2e-16 ***
as.factor(yrQtr)2006.375  5.559977   0.075527  73.616  < 2e-16 ***
as.factor(yrQtr)2006.625  5.461799   0.075616  72.231  < 2e-16 ***
as.factor(yrQtr)2006.875  5.307706   0.075753  70.066  < 2e-16 ***
as.factor(yrQtr)2007.125  5.070844   0.075674  67.009  < 2e-16 ***
as.factor(yrQtr)2007.375  5.218006   0.077425  67.395  < 2e-16 ***
as.factor(yrQtr)2007.625  5.142855   0.076910  66.869  < 2e-16 ***
as.factor(yrQtr)2007.875  5.569341   0.075291  73.971  < 2e-16 ***
as.factor(yrQtr)2008.125  4.934037   0.076476  64.517  < 2e-16 ***
as.factor(yrQtr)2008.375  5.008542   0.077186  64.890  < 2e-16 ***
as.factor(yrQtr)2008.625  5.218515   0.076939  67.826  < 2e-16 ***
as.factor(yrQtr)2008.875  5.237642   0.077534  67.553  < 2e-16 ***
as.factor(yrQtr)2009.125  5.054149   0.075311  67.110  < 2e-16 ***
as.factor(yrQtr)2009.375  5.106017   0.076425  66.811  < 2e-16 ***
as.factor(yrQtr)2009.625  5.485979   0.077043  71.207  < 2e-16 ***
as.factor(yrQtr)2009.875  5.223010   0.077154  67.696  < 2e-16 ***
as.factor(yrQtr)2010.125  5.071942   0.079141  64.087  < 2e-16 ***
as.factor(yrQtr)2010.375  4.674503   0.079216  59.009  < 2e-16 ***
as.factor(yrQtr)2010.625  4.974978   0.080385  61.889  < 2e-16 ***
as.factor(yrQtr)2010.875  5.465197   0.079132  69.065  < 2e-16 ***
as.factor(Atoll)HA        0.028090   0.030212   0.930 0.352512
as.factor(Atoll)HD       -0.467553   0.059316  -7.882 3.56e-15 ***
as.factor(Atoll)KA       -1.187953   0.034676 -34.259  < 2e-16 ***
as.factor(Atoll)LA       -0.338444   0.039924  -8.477  < 2e-16 ***
as.factor(Atoll)LH       -0.012419   0.038748  -0.321 0.748587
as.factor(Atoll)ME        0.084638   0.041789   2.025 0.042855 *
as.factor(Atoll)RA       -0.124365   0.032977  -3.771 0.000163 ***
as.factor(Atoll)SE       -0.055320   0.032963  -1.678 0.093333 .
as.factor(Atoll)SH       -0.552821   0.040450 -13.667  < 2e-16 ***
as.factor(Atoll)TH       -0.030818   0.037554  -0.821 0.411873
as.numeric(LengthM)       0.052595   0.002429  21.650  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8138 on 9539 degrees of freedom
Multiple R-squared: 0.9836,     Adjusted R-squared: 0.9836
F-statistic: 1.47e+04 on 39 and 9539 DF,  p-value: < 2.2e-16
```

Table 8. Time series of recommended and sensitivity trial standardized CPUE series for the Maldives PL SKJ fishery.

Year.Quarter	Model 11 (Recommended)	Model 11 Rescaled	Model 6 (Sensitivity)	Model 11 Rescaled
2004.125	622.9957	1.01	525.8544	1.17
2004.375	616.3102	0.99	405.848	0.90
2004.625	626.8297	1.01	498.011	1.11
2004.875	637.5279	1.03	575.8894	1.28
2005.125	596.6433	0.96	516.0612	1.15
2005.375	967.0755	1.55	560.9276	1.25
2005.625	698.2342	1.13	610.944	1.36
2005.875	1039.041	1.67	742.6823	1.65
2006.125	809.6402	1.30	745.4563	1.66
2006.375	818.4432	1.32	590.2934	1.31
2006.625	735.1205	1.18	464.8041	1.03
2006.875	619.7736	1.00	561.2253	1.25
2007.125	473.7538	0.77	362.0645	0.81
2007.375	560.3724	0.91	345.3428	0.77
2007.625	514.5476	0.83	356.764	0.79
2007.875	826.8267	1.33	482.8064	1.07
2008.125	403.8976	0.66	277.8593	0.62
2008.375	440.7544	0.72	343.7549	0.76
2008.625	560.6947	0.91	413.5877	0.92
2008.875	572.9237	0.93	470.9037	1.05
2009.125	464.7085	0.75	310.4845	0.69
2009.375	493.3122	0.80	283.5107	0.63
2009.625	754.8894	1.22	339.1287	0.75
2009.875	563.5477	0.91	459.8703	1.02
2010.125	474.354	0.77	366.0569	0.81
2010.375	294.9778	0.48	246.4216	0.55
2010.625	423.8102	0.69	339.0969	0.75
2010.875	737.87	1.19	393.4573	0.88

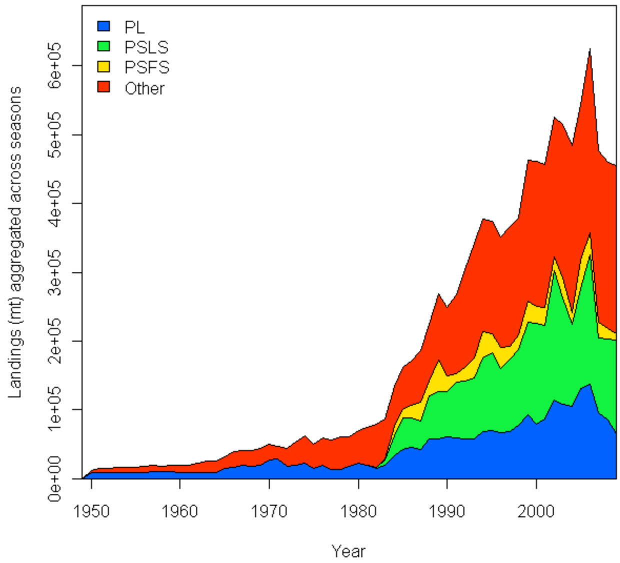


Figure 1. Total Indian Ocean catch over time by fishery (as defined in the 2011 assessment).

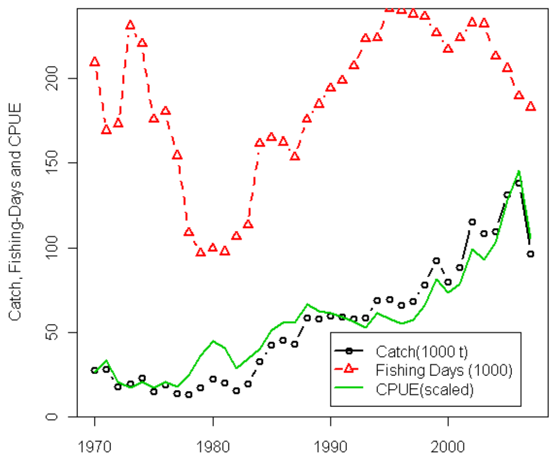


Figure 2. Catch, Effort (boat days) and nominal (effort-weighted) CPUE for the Maldivian Pole and Line fleet (1970-2007, based on the monthly aggregated data that does not contain vessel identity information).

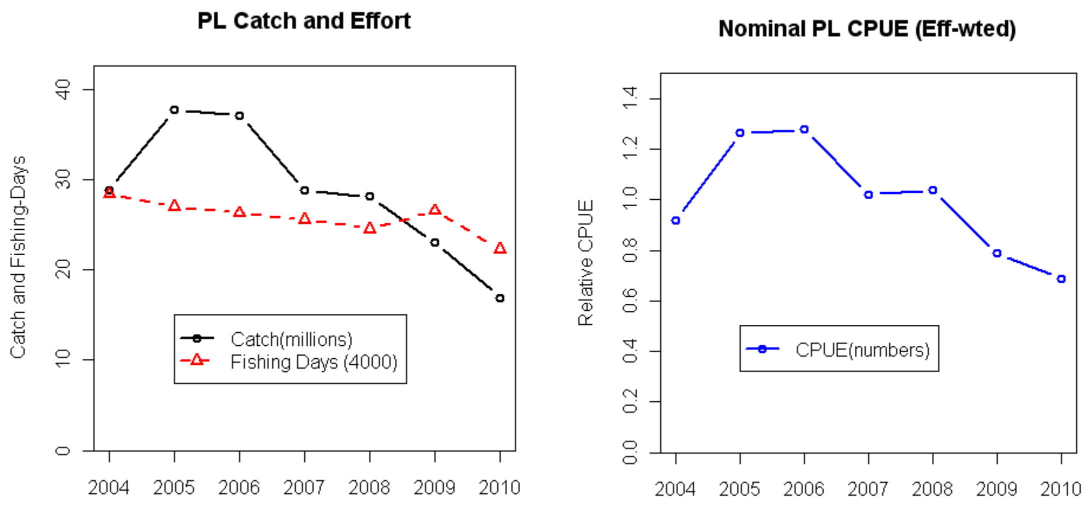


Figure 3. Maldivian skipjack PL fishery catch (numbers), effort (boat fishing days) and nominal CPUE (scaled to a mean of unity), from the monthly catch and effort database (only the records included in the analysis).

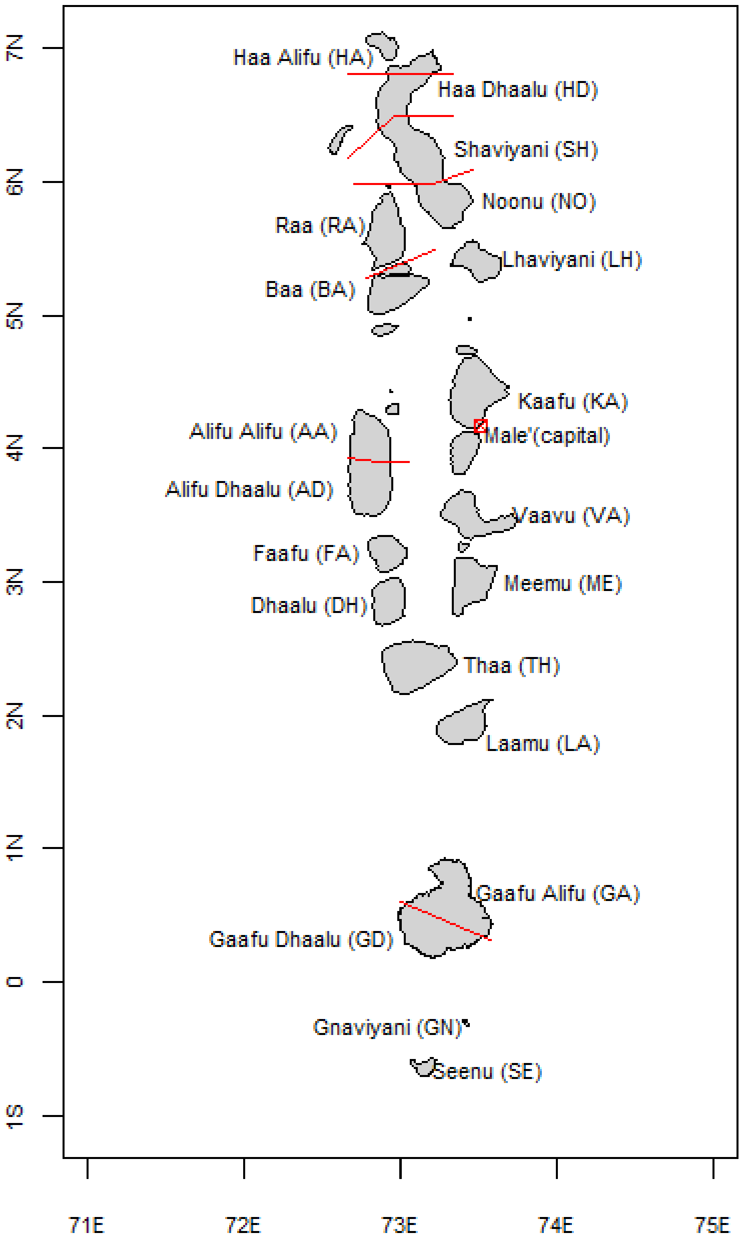
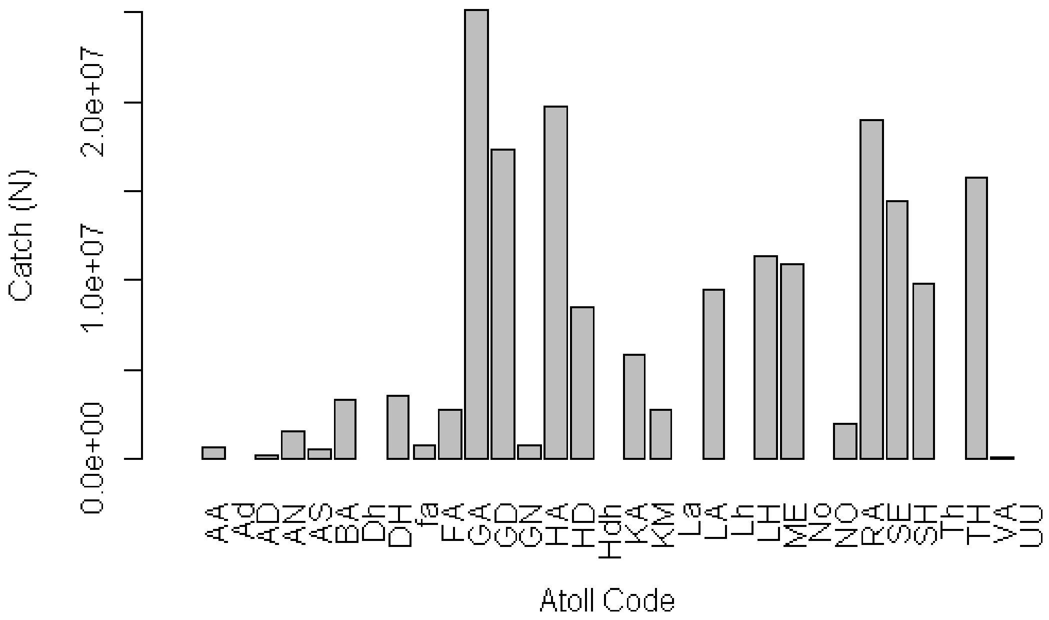


Figure 4. Map of the Maldives.



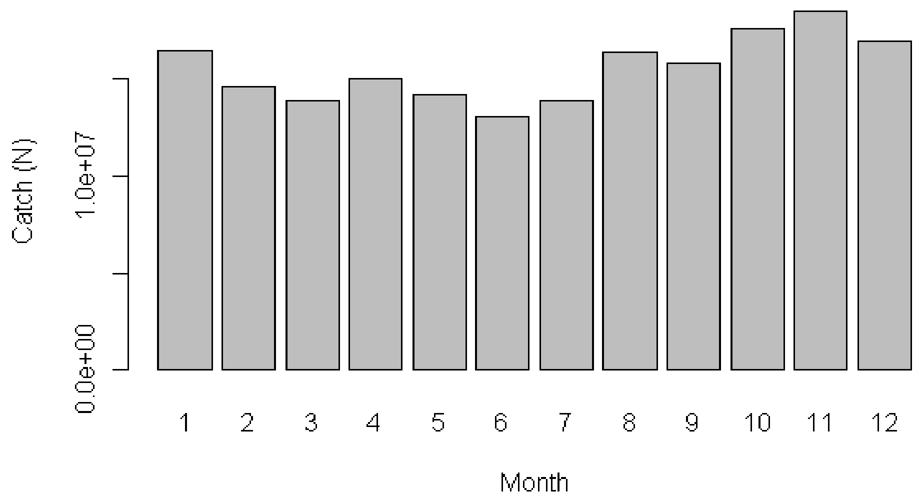


Figure 5. Catch by Atoll and Month for the Maldives PL dataset used in the CPUE analysis.

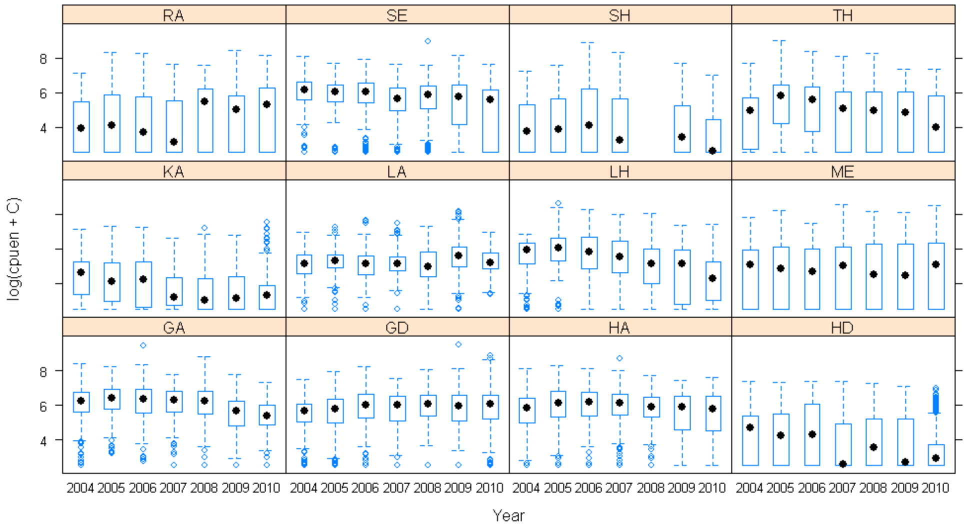


Figure 6. CPUE by Atoll and Year for the 12 most frequently represented Atolls in the database used in the CPUE analysis.

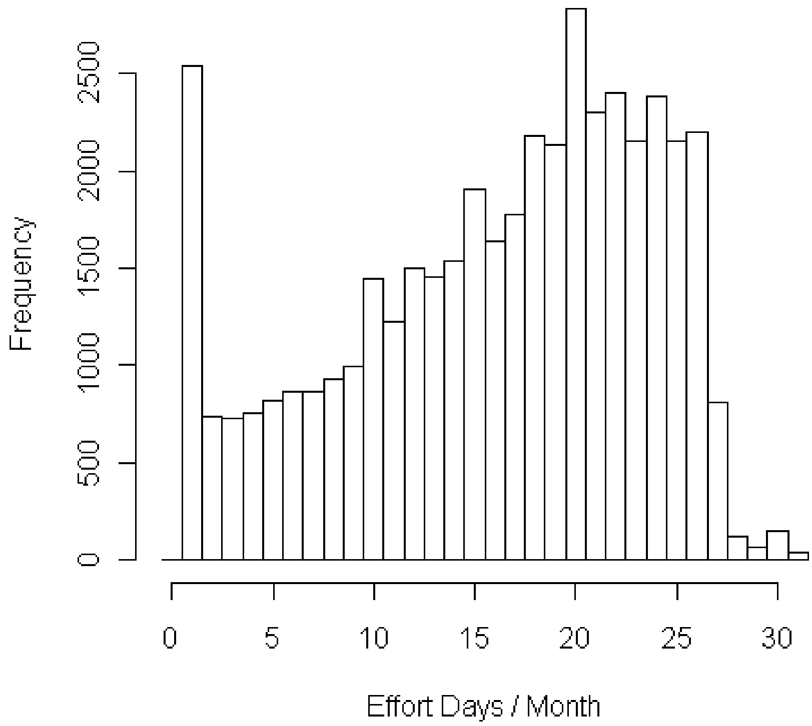


Figure 7. Distribution of fishing days per month in the PL monthly catch effort data (2004-2010).

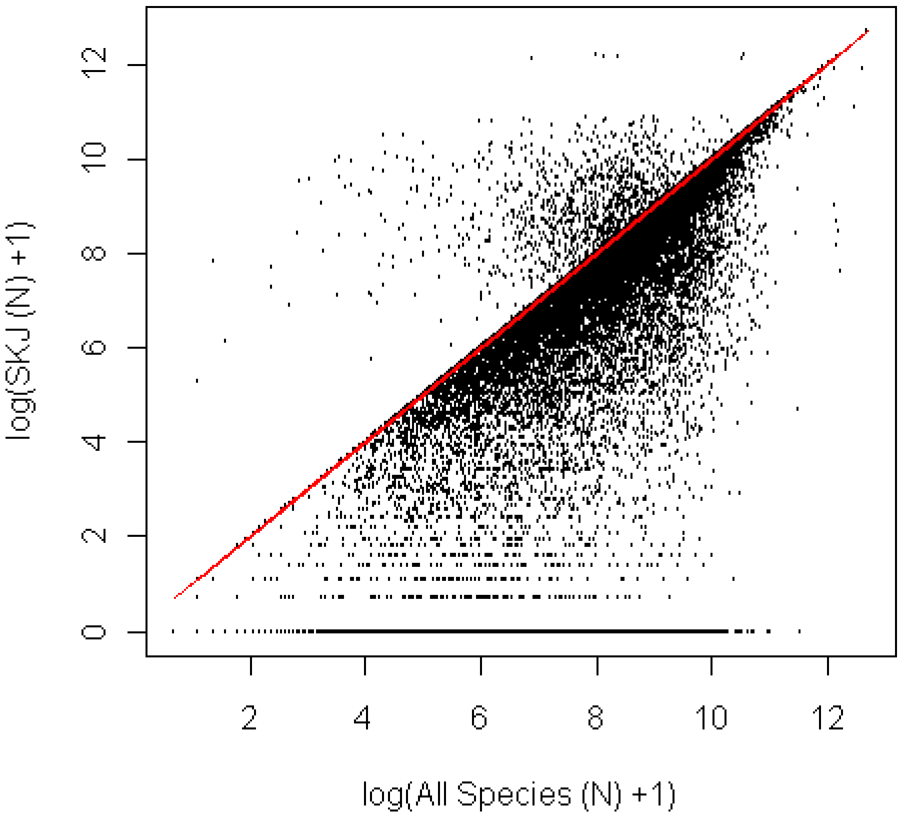


Figure 8. Relationship between catch of SKJ and all species combined (including SKJ) in the monthly catch, effort database for the Maldives PL fishery. Values on (or below) the red line indicate that 100% (or less) of the catch is SKJ. Values above the line suggest that SKJ catches exceed total catches (2.5% of observations).

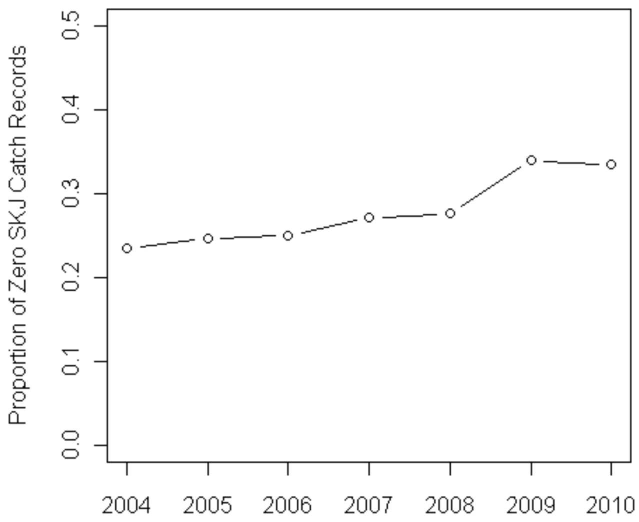


Figure 9. Proportion of monthly PL records with positive effort and zero SKJ catch.

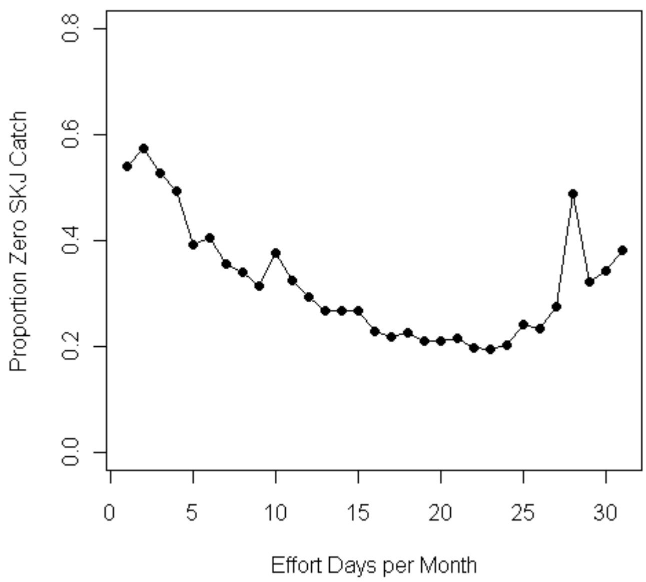


Figure 10. Proportion of observations from the monthly catch and effort database with zero recorded SKJ catch, plotted against the number of days spent fishing.

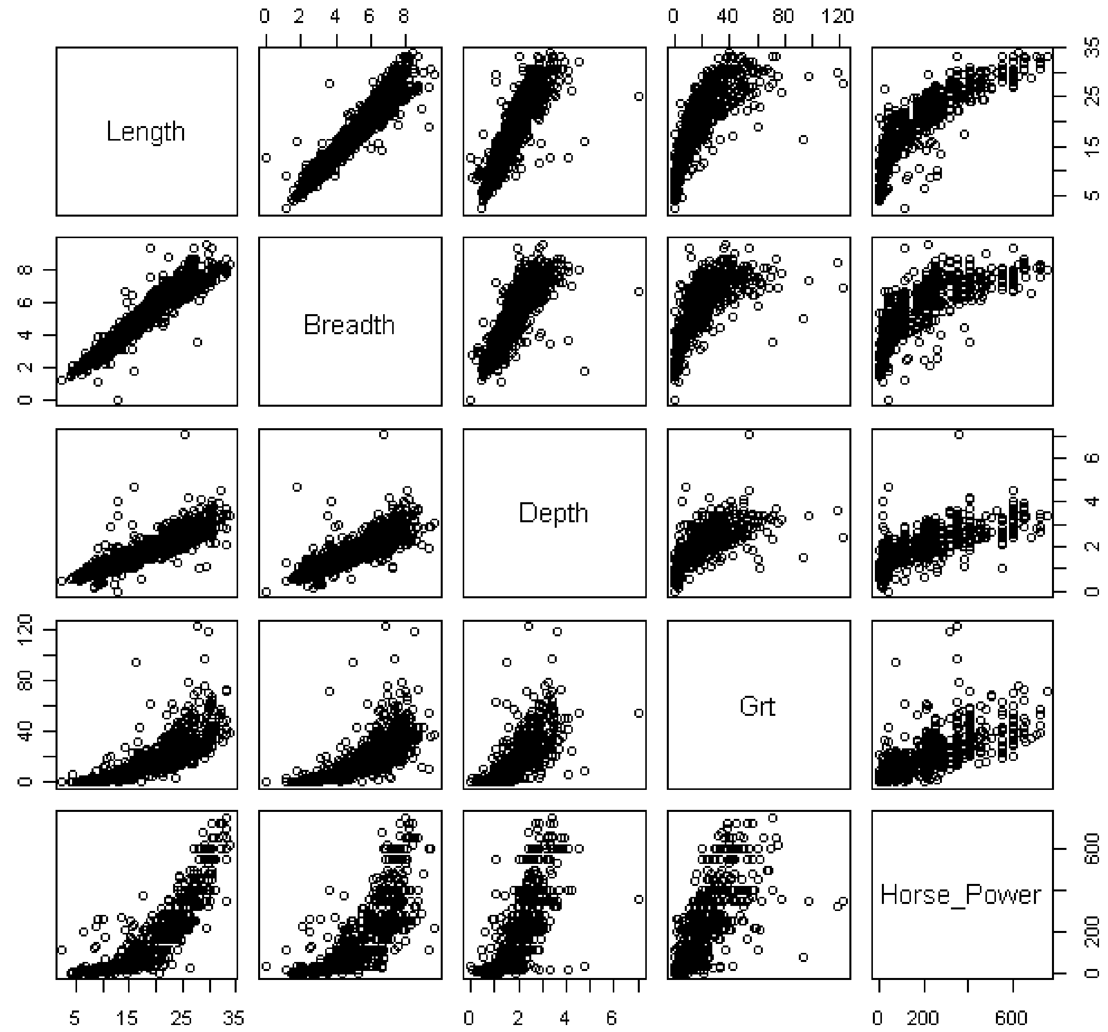


Figure 11. Relationship among vessel characteristics from the Maldives vessel registry (with a few questionable outliers removed).

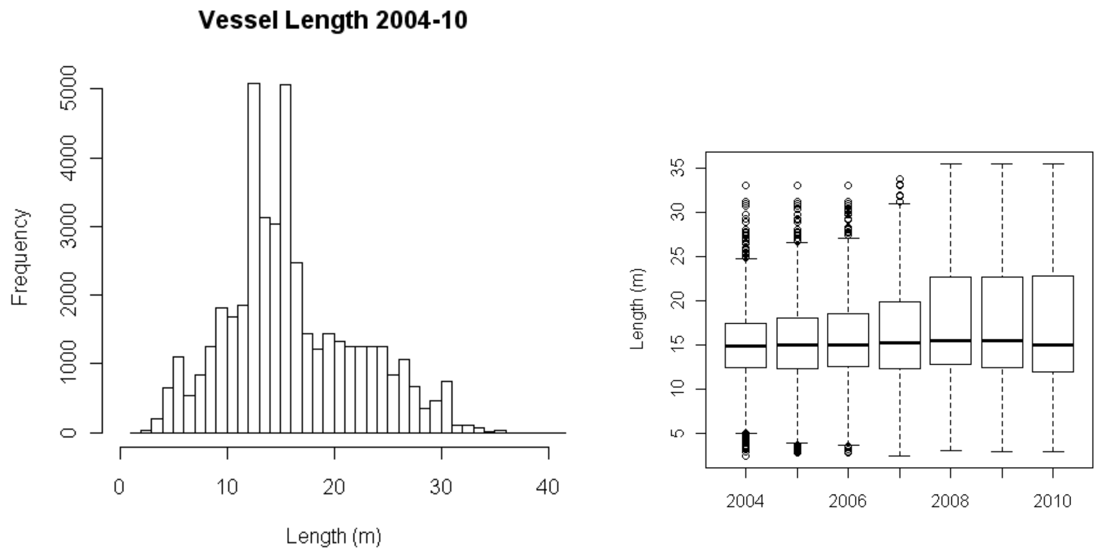


Figure 12. Length distribution of the Maldives PL vessels in the analysis (i.e. with individual boats included multiple times).

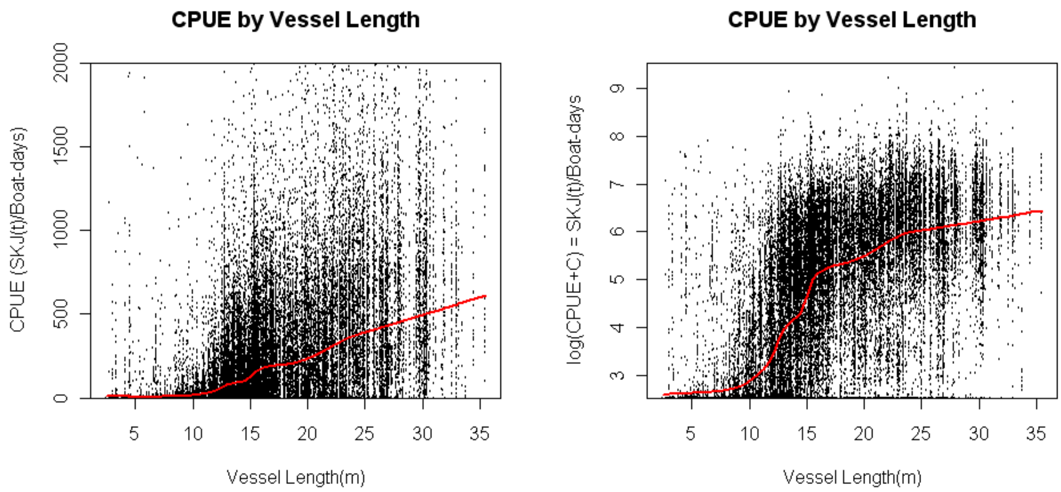


Figure 13. Relationship between SKJ CPUE and vessel length for the Maldives PL vessels in the analysis (red lines are LOWESS smoothers).

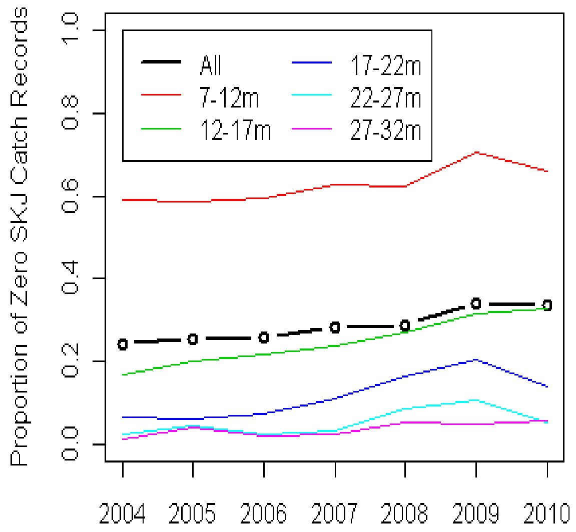


Figure 14. Annual proportion of monthly PL records with positive effort and zero SKJ catch, partitioned by vessel size category.

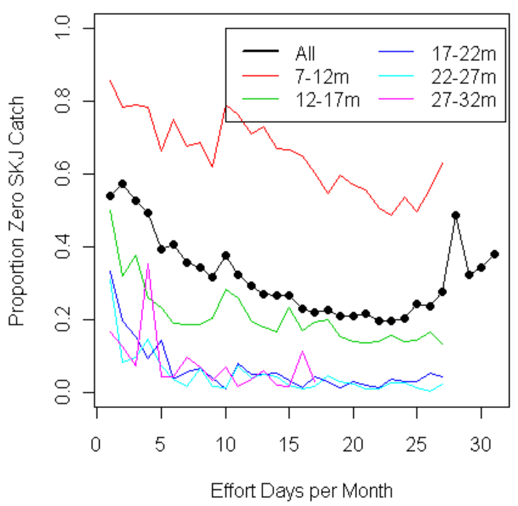


Figure 15. Proportion of observations from the monthly catch and effort database with zero recorded SKJ catch, plotted against the number of days spent fishing, partitioned by vessel size.

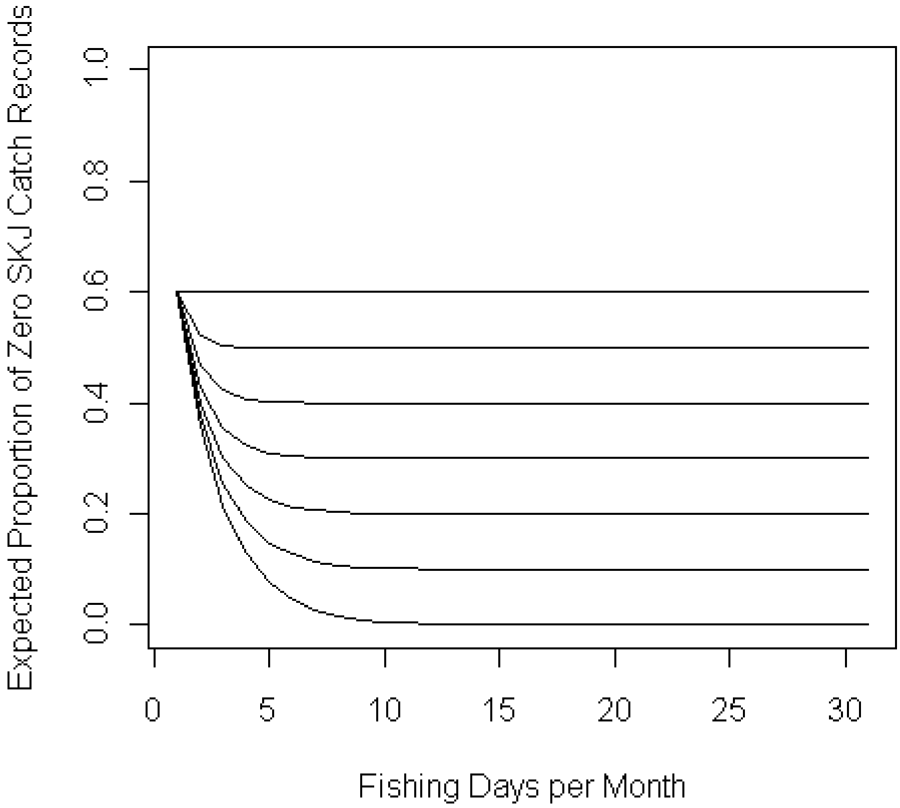


Figure 16. Expected distribution of monthly zero catch observations as a function of number of fishing days, for a range of P1 and P2 values. The total proportion of effort spent not targeting SKJ is identical (0.6) in all cases.

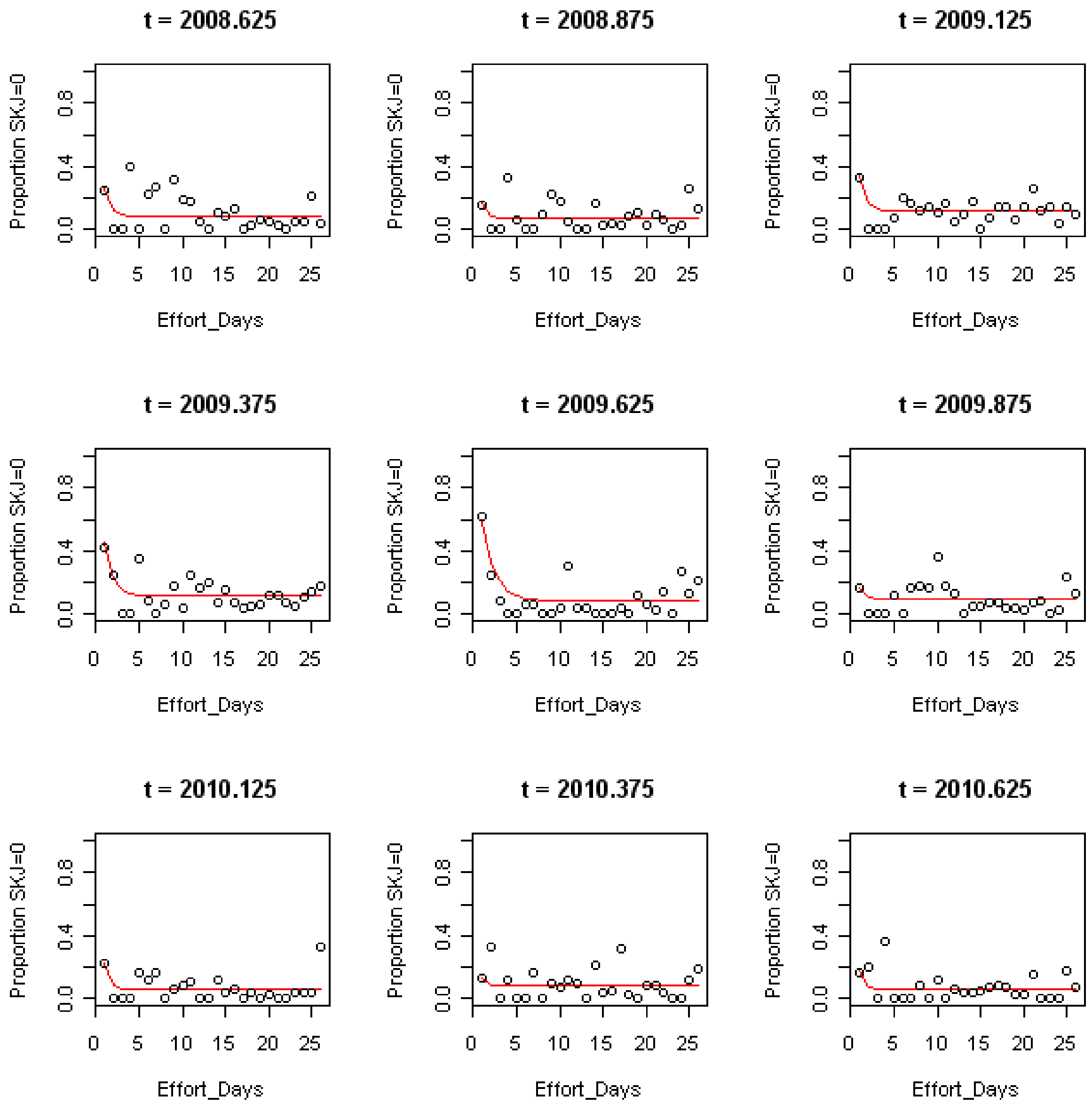


Figure 17. Example of quarterly predicted and observed distribution of the proportion of zero catches as a function of days spent fishing for PL vessels >17m length.

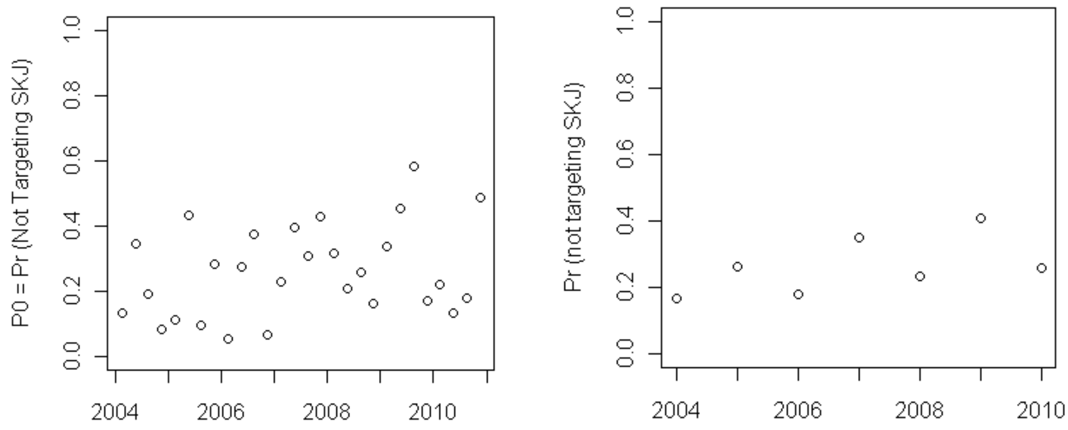


Figure 18. Quarterly (left) and annual (right) estimated proportion of effort that is not targeted on SKJ (vessel length >17m).

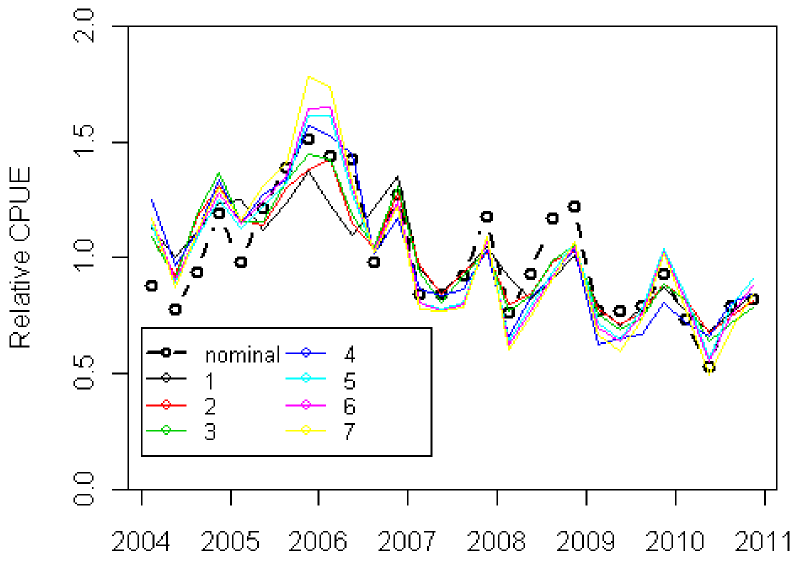


Figure 19. Comparison of standardized time series from models 1-7 (the most 'conventional' models) and the nominal CPUE (rescaled to a mean of unity).

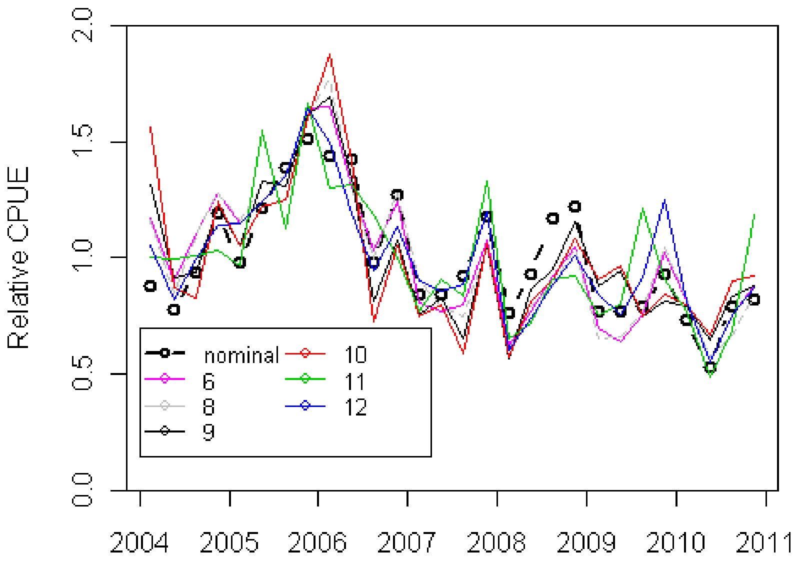


Figure 20. Comparison of the preferred 'conventional' model (6) with a robust model (8), and 4 different attempts to account for the proportion of effort not targeted on SKJ, (9-12) (rescaled to a mean of unity).

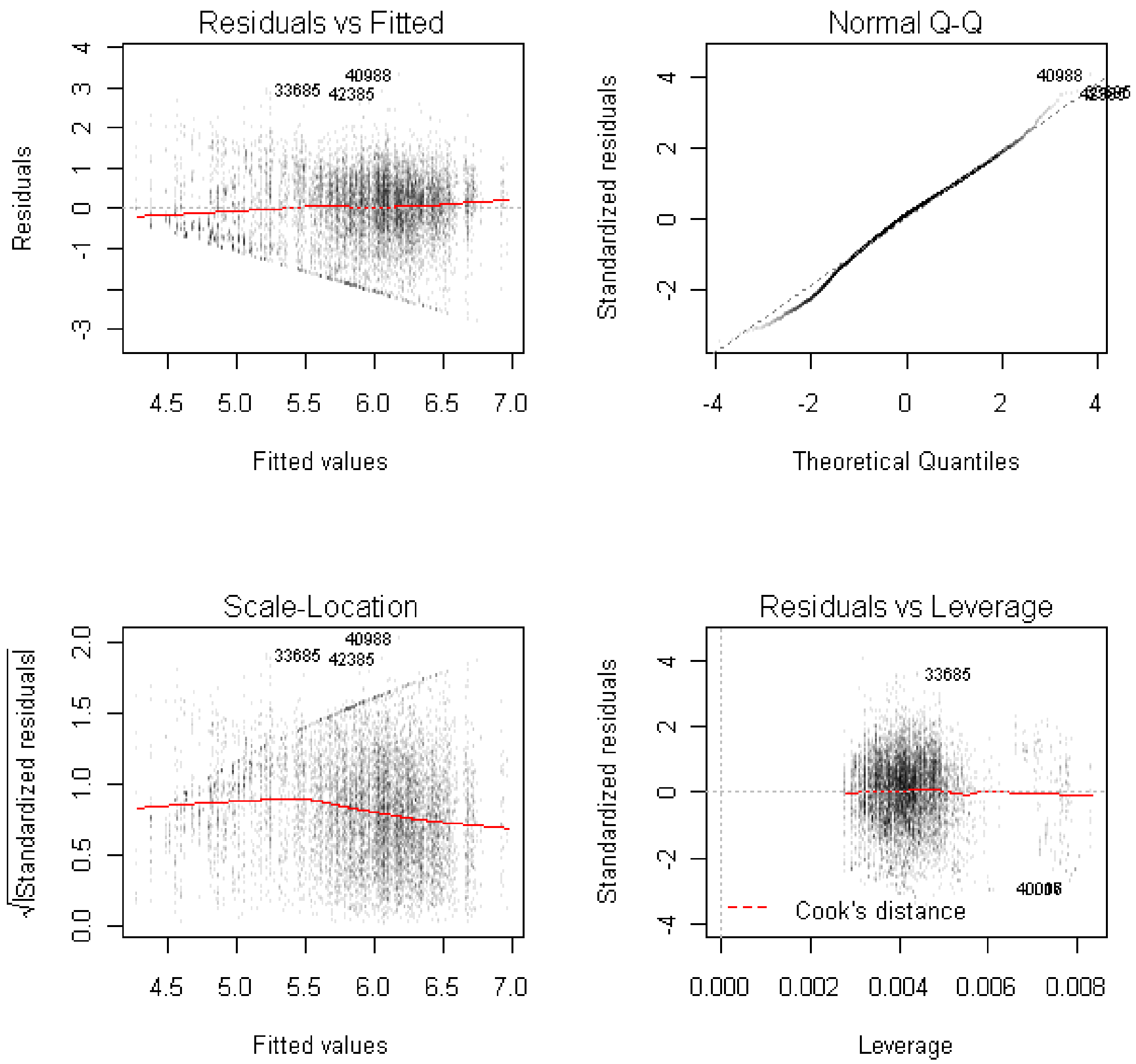


Figure 21. Diagnostic plots for model 5 (tz.5)

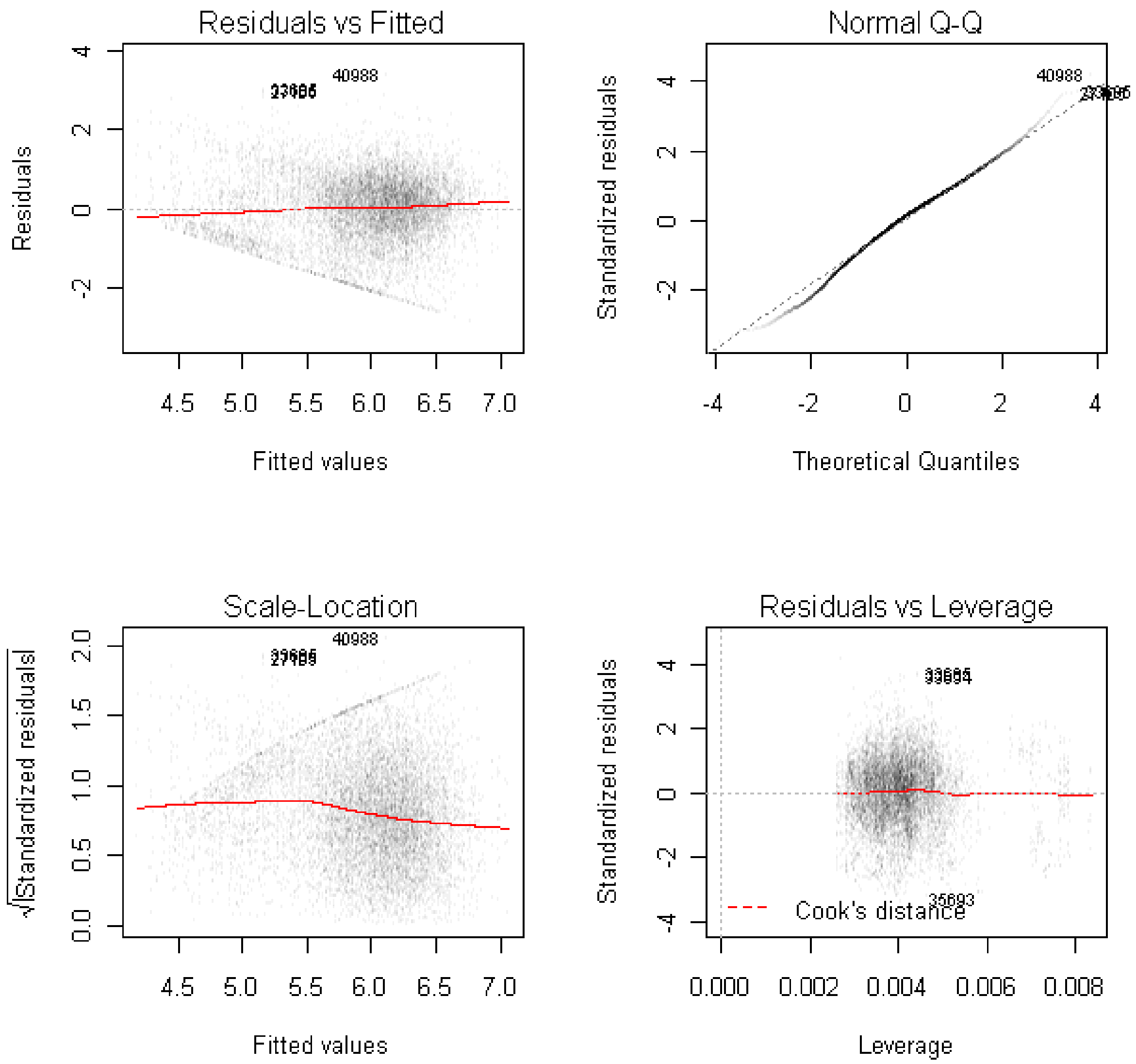


Figure 22. Diagnostic plots for model 6 (tz.6)

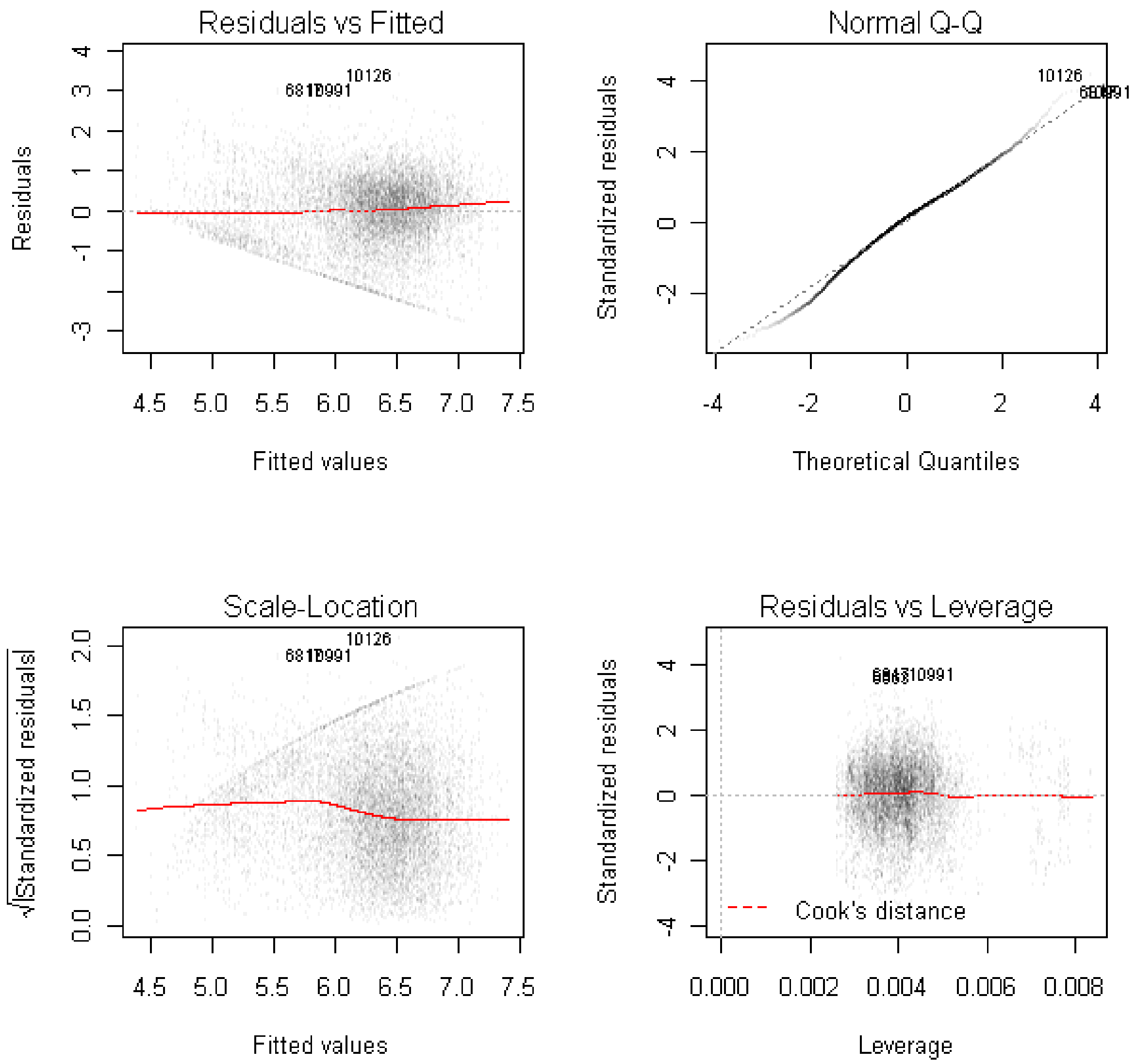


Figure 23. Diagnostic plots for model 11 (etq.6).

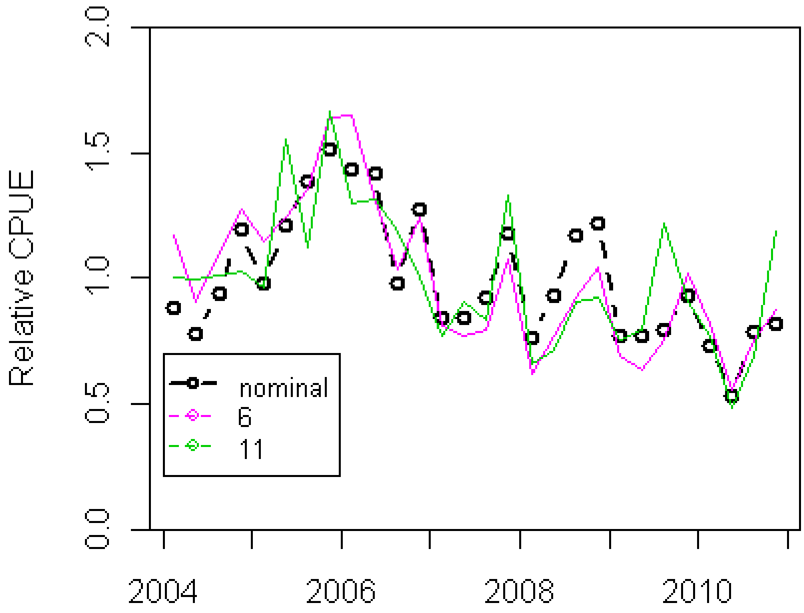


Figure 24. Comparison of the recommended CPUE time series (model 11), with a possible sensitivity series (model 6) and the nominal CPUE series.