Catch Rate Standardization for the Maldivian Skipjack Pole and Line Fishery 1970-2007

Oct 2010

Dale Kolody (dale.kolody@iotc.org)
M. Shiham Adam (msadam@mrc.gov.mv)
Charles Anderson (anderson@dhivehinet.net.mv)

Summary

This paper describes an attempt to estimate a relative abundance index from the Maldivian skipjack tuna (*Katsuwonus pelamis*) pole and line (PL) fishery catch and effort data for use in stock assessment. This fleet has operated for hundreds of years, and has evolved rapidly over the last couple decades from an artisanal fleet into a substantial industrial operation. There are detailed records about many elements of the fishery which may be useful for quantifying changes in efficiency over time, however not all of these records are currently available in electronic format. We attempted to quantify seasonal, spatial and vessel characteristic effects on the efficiency of the fleet over time. Vessel-specific data are only available from a small number of observations in the period 2004-2007. To estimate historical efficiency, a fleet composition model was employed in which the vessel registry provides the year of entry of different vessels into the fleet, and each vessel was assumed to remain active for a fixed number of years. The vessel effects estimated from 2004-7 were then applied to the historical fleet composition to estimate effective effort from the aggregate catch and effort data series from 1970-2007. The nominal CPUE (and GLM standardized series that excluded vessel effects) shows a strong increasing trend that parallels the fleet trend toward larger boats over the past two decades. The CPUE series that are standardized for changing fleet composition are either stable or decreasing over time. The most pessimistic model examined suggests that the standardized catch rates may have declined to about one third of the levels observed in the 1970s. Encouragingly however, no consistent decline was observed over the last 10 years (in which catches have been the highest on record) for any of the time series (but note that there is a drop between 2006 and 2007, and that years 2008-9 were not included in the analysis). Main problems with the analysis include:

- There are few observations from the smallest vessels in the 2004-2007 period (with limited contrast in some important factors), and the historical time series is sensitive to the efficiency estimates for these vessels. There are additional important changes in vessel characteristics that cannot be examined from these data (e.g. the transition to mechanized operations)
- It is possible to estimate some of the core features of the historical fleet characteristics from the vessel registry, but producing relative abundance indices requires several speculative assumptions. e.g. i) vessel type (the registry does not distinguish between PL and other types of fishing vessels), ii) the registry only indicates the year that the vessel enters the fishery, not the year of exit from the fishery or the number of days spent fishing in any specific year, and iii) the registry is incomplete (at least prior to the 1980s).
- Given the increasing frequency of trans-shipping, it is not clear whether the spatial information is meaningful in recent years.

This analysis suggests that the skipjack catch rates standardized for vessel effects might be stable or could have declined substantially since the 1970s (e.g. due to the local or broader Indian Ocean fishery), however, we do not have a lot of confidence in specific relative abundance estimates at this time. If possible, efforts should be made to recover the detailed information from the individual atolls (or a reasonable subset of them), and link these data to the vessel registry details in the manner of what was done for 2004-2007. If this detailed time series can be extended to include the most recent years, this may prove to be highly informative even without the historical extrapolation (i.e. by the next WPTT, there could be a consistent time series from 2004-10 that accounts for individual vessel characteristics). However, efforts should be made to recover the historical data as well. Assuming that catch rates can be standardized to account for vessel efficiency, there remains a difficult question of how these catch rates relate to abundance in the local fishery, and the broader Indian Ocean.

Introduction

The Indian Ocean skipjack tuna (*Katsuwona pelamis*, SKJ) fishery is one of the largest tuna fisheries in the world, with recent annual catches exceeding 400000 t (Figure 1). While some bioeconomic modelling was undertaken a few years ago (Mohamed 2007), there has never been a formal model-based stock assessment presented to the Indian Ocean Tuna Commission (IOTC). The Working Party on Tropical Tuna (WPTT) has historically concluded that the stock is probably not over-exploited, but recognizes that the steady increase in SKJ catches over the last three decades represents a mounting concern (WPTT 2009). Accordingly, SKJ was identified as a priority for stock assessment in 2010. Two sources of data are now available which are thought to make this feasible: i) the recovery phase of the Indian Ocean Regional Tuna Tagging Programme (RTTP) is largely complete, and ii) detailed catch and effort data from the Maldives SKJ pole and line fishery has been compiled in electronic format since 2004, which will hopefully allow the development of an informative relative abundance index.

This paper describes a preliminary examination of the catch and effort data from the Maldivian pole and line skipjack fishery, undertaken to evaluate the potential usefulness of this time series as a relative abundance index for stock assessment. A range of descriptive summaries and model results are presented, limitations of the current approach are discussed, and proposals for future improvement are identified.

Methods

Data

Three data sets were used in this analysis, as provided by the government of the Maldives: i) operational catch and effort data from the pole and line fleet 2004-2007 (includes observations disaggregated by vessel), ii) aggregate catch and effort data 1970-2007, and iii) the registry of new vessels 1958-2010 (which includes some vessel characteristics, but does not distinguish among types of fishing vessels). These data remain confidential. Further description and graphical summaries of the data are presented in the Results and Discussion.

Catch Rate Standardization

Simple GLM-based standardization analyses were combined with speculative models of vessel recruitment and attrition, in an attempt to come up with indices of SKJ relative abundance. Analyses were conducted in 3 phases:

1. The operational data 2004-2007 were used to examine the effects of time-area and vessel characteristic effects on pole and line catchability over this relatively short time period.
2. Standardization was attempted on the aggregate data (1970-2007) including time-area effects, but not vessel characteristics.
3. A fleet composition model was employed to generate estimates of historical fleet characteristics from the vessel registry. The vessel characteristic effects (from 1) were combined with the fleet composition estimates to adjust the total effort (from 2) into an estimate of effective effort from which relative abundance indices could be calculated from 1970-2007. A small number of alternative assumptions were tested to demonstrate the sensitivity of the relative abundance indices.

Model details are provided in the results and discussion. The GLM notation is adopted from the statistics package R.

Results and Discussion

Operational Catch and Effort 2004-2007

This dataset consists of 3486 observations of SKJ catch by vessel, month and atoll. As these data are aggregated by month, they are not really 'operational' level (i.e. the fishing of an individual school), however, the term is adopted to distinguish this dataset from the more extensive dataset that is aggregated across vessels (described in the next section). Fields include:

- SKJ catch (metric tonnes)
- Atoll – this is the place of landing, and in recent years does not always provide a good indication of the location of catch due to the increasing use of carrier vessels.
- Individual vessel identification (459 unique vessels)
- Effort (boat-days)
- Gear Quantity (pole-days) and Total Fishermen – these are potentially useful auxiliary measures of effort, but the fields are incomplete (i.e. large number of zero observations, especially for the latter)
- Vessel length

Additional vessel characteristics (e.g. hull type, horsepower, etc.) should be obtainable by linking with the vessel registry. Equivalent data should also be available for 2008-2009. However, due to conflicting format problems for vessel identification fields, these additional data could not be obtained for the analysis this year.

The time series from 2004-2007 is expected to be too short to provide a useful index of abundance. For the purpose of this paper, the main value of these data are to quantify the effects of operational factors that are not recorded in the aggregate 1970-2007 dataset.

Annual time series of catch, effort (boat-days), and nominal CPUE (sum(C)/sum(E)) are shown in Figure 2. These data cover only 8% of the catch (39 000 t) that is reported in the aggregated dataset over the same period (475 000 t). Furthermore, most of the observations (>90%) are from 2004-2005.

Figure 3 indicates that there is considerable variability in the CPUE observations, but a potentially important relationship between vessel length and CPUE is evident. Presumably, a number of factors are responsible. Relative to the smaller vessels, larger vessels have a larger bait capacity, larger hold, longer range, more fishermen operating more poles, and may be less constrained by weather.

Figure 4 illustrates that smaller boats may spend fewer days fishing each month, but the effect is only evident for the relatively few observations of vessels less than 10m.

Different models were employed to estimate the vessel length effect on the observed CPUE, but only three representative models are described here:

Model A) log(CPUE) ~ lengthCategory + Year + Month + Atoll

Model B) log(CPUE) ~ lengthCategory + Year

In models A and B, length was fit as a categorical variable (*lengthCategory*) with 5 levels (0-10, 11-15, 16-20, 21-25, >25 m). Very few observations were recorded for vessels of length <5m or >30m. All of the factors were highly significant for both models (Table 1, Table 2). Standard diagnostics indicate that the residual behaviour is less than ideal for both models (Figure 5, Figure 6).

Figure 7 illustrates the estimated effect of vessel length on CPUE for models A and B. The two models are qualitatively very similar, suggesting that there is a reasonably linear increase in CPUE with vessel size up to ~ 20m, at which point the relationship reaches a plateau. The largest vessels are estimated to be roughly 20 X (model A) and 100 X (model B) as effective as the vessels <10m in length. We might expect model A to provide the better estimates of the vessel length effect because it attempts to account for seasonal and atoll effects. However, model A may also be over-parameterized, and there are concerns about the assignment of catch to atoll.

Figure 8 shows the result of a third model, in which log(CPUE) was estimated as a continuous function of vessel length. The function adopted was equivalent to a von Bertalanffy growth curve, which can essentially have a linear increase with length at one extreme, CPUE independent of length at the other extreme, or a saturating, asymptotic function somewhere in between. There is no theoretical justification for this function, other than it seems to resemble the data. This approach estimates a 25m boat to be approximately 10X as effective as a 10m boat. Qualitatively, the relationship does not appear to fit very well for vessels smaller than 10m. (When extrapolated to account for effective effort across the full time series in section 3, this model yielded results similar to model B, and is not discussed further).

We do not claim that these models are the best, or even particularly good, estimators for the relationship between vessel characteristics and catchability. i.e. There may be better measures of efficiency derived from horsepower, or number of poles per vessel; GAMs may provide a more appropriate continuous function. However, these models are sufficient to demonstrate some important points:

- Observed catch rates clearly vary with vessel length in a manner that is qualitatively consistent with expectations. Somehow the vessel characteristics need to be accounted for when interpreting the historical CPUE series.
- Due to the lack of contrast in this short time series, it will probably be difficult to accurately quantify the relative efficiency of vessels of different sizes. This is particularly true for the smaller vessel sizes, and it is these vessels which are more important further back in the historical record. Furthermore, there are no observations of other potentially important vessel characteristics (e.g. powered vs: unpowered).
- Since additional vessel-specific data exist, it should be a higher priority at this time to recover these data, rather than tinkering with the statistical subtleties in these models.

Note that the short relative abundance time series estimated by models A and B are compared with the other models that attempt to account for vessel effects in Figure 21.

Aggregate Catch and Effort 1970-2007

This dataset consists of 8988 observations of monthly SKJ catch and effort in boat-days, disaggregated by atoll. As noted previously, an obvious problem with these data are the absence of information with which to quantify what a boat-day means for vessels with very different characteristics.

Figure 9 illustrates the time series of annual catch, effort and nominal CPUE: sum(C)/sum(E). Nominal effort in boat-days is fairly constant over the time series (except for a 6 year period of diminished effort around 1980). Catch and CPUE trends are very similar, consistently increasing, with around a 5 X increase across the whole time series.

The CPUE distributions are shown in Figure 10, indicating a high degree of variability, and very few observations with 0 Catch (<0.5%). Monthly CPUE by year is shown in Figure 11, which suggests that there is not much seasonality in the catch rates.

Figure 12 compares the catch rates by atoll for the first and last 5 years of the time series. Catch rates appear to be reasonably consistent across atolls in the early years, but vary considerably in later years. This could reflect changes in the distribution of the stock (e.g. in relation to a declining population size), or it may reflect a concentration of industrial operations.

A simple GLM was fit to attempt to quantify the effects of seasonal and spatial variability on CPUE:

Model C) log(CPUE>0) ~ Year + Month + Atoll

The three factors were highly significant (Table 3). Standard graphical diagnostics are provided in Figure 13 (in which it is evident that there are problems in the residual behaviour. A similar model that also estimated with Year: Atoll interactions, but the design was poorly balanced and probably over-parameterized (not shown).

The standardized CPUE trend from model C was largely unchanged from the nominal CPUE (Figure 17). If this increasing CPUE trend reflects skipjack abundance, then it suggests that there is probably non-stationary recruitment dynamics or a shifting spatial distribution of the population. Either way, the index might not be very useful as the main abundance index with which to quantify the impact of the skipjack fishery on the Indian Ocean population. However, it is clear from the preceding section that we cannot calculate a meaningful relative abundance index without accounting for the vessel effects.

A historical fleet composition model: accounting for increasing efficiency in the nominal effort series

The Maldives registry of marine vessels provides a record of how the composition of the fleet has changed since 1958. While many characteristics of individual vessels are recorded in the registry, there are no direct links between the registry and the extended catch and effort time series 1970-2007. At this time, the best we can do is explore some speculative scenarios about fleet composition over time, and see what sort of effect this has on the relative abundance indices given the estimated vessel effects estimated from the operational data.

Figure 14 illustrates the time series of fishing vessels entering the registry since 1958. Other sources (e.g. Jauharee et al 2009) suggest that there have consistently been around 1500-2000 pole and line throughout the history of the fishery (since 1970). Perhaps some vessels are very durable and date back decades prior to 1958, but it is more likely the registry is very incomplete (at least prior to the 1980s).

Figure 15 illustrates the time series of individual fishing vessel length in the registry over time, and by atoll. There is clearly an increasing trend in new vessel size over time which justifies concerns about the definition of effort in the aggregated 1970-2007 data series. However there is no obvious tendency for the larger vessels to register on particular atolls (i.e. does not explain the pattern from Figure 10).

Mohamed (1985) used vessel horsepower as a proxy for vessel efficiency, though the derivation of the specific relationship was not described. Figure 16 illustrates the relationship between fishing vessel length and horsepower from the registry. Horsepower appears to increase as an exponential function of length for the majority of vessels. However this plot indicates a couple other points of concern about the vessel registry:

- The registry does not distinguish among types of fishing vessels, so we are treating all vessels as PL vessels.
- Vessels longer than 35m are probably not PL vessels (or represent errors in the registry).
- There are a substantial number of sizeable vessels with 0 horsepower. At this time we do not have any data with which to comment on the effect of mechanization on catch rates. Note that Jauharee et al (2009) document that almost all PL vessels were unmechanized prior to 1975, and almost all vessels were mechanized after 1985.

While the registry provides a general indication of the trends in the fleet over time, a number of strong assumptions are required to produce an explicit time series of effective effort in the fishery. To generate a relative abundance index from the aggregated time series of PL CPUE 1970-2007, we used the following assumptions, individual vessels (or aggregations of identical vessels) are indexed i, years y, nominal annual effort in boat-days is $E_y = \Sigma E_{y,i}$,vessel-specific catchability is defined by q_i and C is catch:

1) Each vessel is active for an identical number of years, A, starting with the year it registers.
2) In each year, the fleet is composed of I_y vessels, the sum of active vessels from the registry. As the registry is incomplete, the true number of vessels is often much greater than I_y, however, as long as the vessel registry is representative of the vessel characteristics entering the fleet, this will not affect the total effective effort calculation. i.e. The nominal annual effort from the aggregated data series (1970-2007) is split among vessel types according to the distribution of active vessels. If there are only two types of vessel, the effective effort will be the same regardless if there are 2 vessels of each type, or 200 vessels of each type.
3) Within a year, each of the active vessel spends the same number of days fishing $E_{i,y}$=E_y / I_y (the observed total annual boat-days divided by the number of active vessels). Again, this will not be a realistic value for an individual vessel for years when the registry is incomplete.

4) Each vessel has an efficiency, q_i (estimated from length using the 2004-7 operational data) and the effective effort for that vessel is $q_i\, E_{y,i}$ (the product of efficiency and nominal effort in boat-days apportioned to that vessel or aggregation of identical vessels).
5) The overall effective effort of the fleet in year y is $\Sigma_i\, q_i E_{y,i}$ (the sum of the effective effort of the individual vessels active in that year).
6) The final time series of relative abundance is estimated C_y / $\Sigma_i\, q_i E_{y,i}$ (the total annual catch divided by the total annual efficiency-adjusted effort).

At this time, additional catchability effects caused by variation in the seasonal and spatial distribution of effort were ignored (i.e. we are not sure what the spatial data means and the two effects together make very little difference to the overall time series as shown in Figure 17).

Four time series were generated with the fleet composition model:

Model D5) Length-based catchability is adopted from GLM model A, and each vessel remains active for 5 years (A=5)

Model D15) Length-based catchability is adopted from GLM model A, A=15

Model E5) Length-based catchability is adopted from GLM model B, A=5

Model E15) Length-based catchability is adopted from GLM model B, A=15

Figure 18 illustrates the time series of the number of vessels in the fleet that would be expected with the models above, if the registry accounted for all vessels. The model clearly does not predict the number of vessels believed to have operated in the early part of the fishery. With an assumed 5 year period of active service, the number of vessels reaches a plateau of around 1000 vessels in recent years. If the registry is complete since the 1980s, this indicates that an active service period longer than 5 years is likely. In contrast, assuming 15 years of active service results in a time series with greater than 2500 vessels in recent years, and the number of vessels is still increasing. This suggests that the two options probably span reality, and the true mean vessel lifespan is probably somewhere between 5 and 15 years.

Figure 19 illustrates the mean vessel length over time estimated by the fleet composition models. As would be expected given the increasing trend in vessel size in the registry, the shorter vessel lifespan assumption estimates larger mean sizes in most years, but the difference between A=5 and A=15 is less than 1m in mean length for most years. Note that the mean lengths are only a graphical summary, and that effective effort calculation is based on the integration of effective effort across all active vessels.

Figure 18 compares the effective effort from the 4 fleet composition models. The models are clearly more sensitive to the estimation of the vessel-length-efficiency relationship than the vessel lifespan assumption. The divergence in the series is largely driven by the influence of the smaller vessels which are numerically dominant in the early part of the time series.

Figure 21 compares relative abundance indices derived from the 4 fleet composition models. The trends are very different to those derived without consideration of the vessel efficiency effects on nominal effort (Figure 17). Models D5 and D15 suggested that SKJ abundance has been relatively stable throughout the historical time series. In contrast, models E5 and E15 suggest that CPUE may currently be half to a third of the values observed in the 1970s. The timing of the model E CPUE decline roughly corresponds to the increased catches observed in the 1980s-1990s (Figure 1). However, it is worth noting that none of the models show a consistent decline over the most recent 10 year period, during which the catches have been at historically high levels. This recent period is also the period in which the vessel registry is the most complete, and from which the length-efficiency relationships were derived. Note that the preceding comment relates to general model behaviour. From the perspective of recent stock status indicators, it would be relevant to note that all models estimate a drop in CPUE between 2006-7, and 2008-9 are not examined here.

Figure 21 also shows the very short (2004-7) standardized time series from models A and B. The trends are remarkably similar given that models A and B are derived from only 8% of the catch and effort data used in models D and E. This suggests that it may be possible to derive a representative CPUE index from a relatively small subset of the operational data.

While this has been a useful exercise for exploring PL catch rate standardization, we are not confident that any of these series accurately reflect historical skipjack abundance. It is clear that vessel effects are important, but more work is required to quantify these effects. Efforts should be made to acquire more of these data from the most recent years, and historically, to improve the estimation procedure. Provided that effort can be standardized to account for vessel effects, two important questions still need to be considered for this fishery in the context of stock assessment: i) What is the relationship between standardized CPUE and abundance (i.e. would we not expect hyperstability in this relationship since the fish concentrate in schools, and there seems to be gear saturation when schools are located?), and ii) How does skipjack abundance in the Maldives relate to abundance across the broader Indian Ocean (this can be addressed by analyzing the IO RTTP data)?

Conclusions

1) This analysis attempted to standardize the Maldives SKJ pole and line fishery catch and effort data to produce a relative abundance index that can be used for stock assessment.

2) The available data were sufficient to demonstrate that there have been important developments in vessel characteristics over time and these characteristics affect catchability, such that nominal effort in boat-days is probably not a meaningful index of effort.

3) The relationship between vessel length and catchability was estimated and found to be more influential on catch rates than seasonal and spatial effects. Unfortunately, the operational data with which to quantify vessel effects is limited to a short time period with limited observational contrast (i.e. few small vessels, no mechanization data).

4) We used a model of historical fleet composition (derived from the vessel registry and vessel lifespan assumptions) combined with aggregate catch and effort data, to estimate time series of effective effort and relative abundance from 1970-2007. Unlike the nominal CPUE series (which indicates a continuous upward trend), these standardized series suggest that

CPUE has been stable or declined substantially over the 1980s-1990s. All of the series examined were relatively stable over the last 10 years.

5) We are not confident in the specific time series estimated from the current analysis because i) the vessel-efficiency relationship is derived from a small number of observations with limited contrast, ii) the standardized relative abundance indices are sensitive to the estimated relationship between vessel length and catchability, iii) the vessel registry is a very crude indicator of fleet composition (i.e. it does not distinguish between PL and other fishing vessel types, nor does it provide any direct information about vessel longevity in years or annual effort in days), and iv) other potentially important factors were not considered in detail (e.g. spatial effects unclear, smaller boats may spend fewer days fishing due to weather constraints, etc.).

6) The highest priority for improving this analysis should be the acquisition of the high quality catch and effort data by vessel that is known to exist on the individual atolls. By next year, if all of this data could be acquired since 2004, this might provide an informative time series (2004-10) that lessens the need to reconstruct the historical fleet activity. However, if the historical catch and effort data exist by vessel as well, efforts should be made to acquire these data (or at least a representative sample).

References

Jauharee, A.R., S. Fujiwara, M.S. Adam, K. Itoh, T. Nishida, and R.C. Anderson. 2009. Atlas of tuna fisheries and resources in Maldives. OFCF tuna atlas project in the IOTC waters: tuna atlas series – No. 3 Maldives. 125 pp.

Mohamed, S. 2007. A bioeconomic analysis of Maldivian skipjack tuna fishery. M.Sc. thesis, University of Tromso. 39 pp.

Table 1. Analysis of Variance Table for model A.

```
Response: log(cpeDays)
                       Df Sum Sq Mean Sq  F value    Pr(>F)    
as.factor(lenCat)       5 5952.3 1190.46 662.6814 < 2.2e-16 ***
as.factor(Year)         3   29.6    9.86   5.4890   0.00093 ***
as.factor(Month)       11  101.0    9.18   5.1092 5.738e-08 ***
as.factor(Atol_Code)   21 1147.8   54.66  30.4267 < 2.2e-16 ***
Residuals            2676 4807.3    1.80                       
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 2. Analysis of variance table for model B.

```
Response: log(cpeDays)
                    Df Sum Sq Mean Sq  F value    Pr(>F)    
as.factor(lenCat)    5 5952.3 1190.46 532.3214 < 2.2e-16 ***
as.factor(Year)      3   29.6    9.86   4.4092  0.004228 ** 
Residuals         2708 6056.1    2.24                       
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 3. Analysis of Variance Table for model C.

```
Response: log(cpue)
                   Df Sum Sq Mean Sq  F value    Pr(>F)    
as.factor(Year)    38 220043  5790.6 5684.356 < 2.2e-16 ***
as.factor(Month)   11     66     6.0    5.909 1.178e-09 ***
as.factor(Atoll)   22   5128   233.1  228.809 < 2.2e-16 ***
Residuals        8877   9043     1.0                       
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Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
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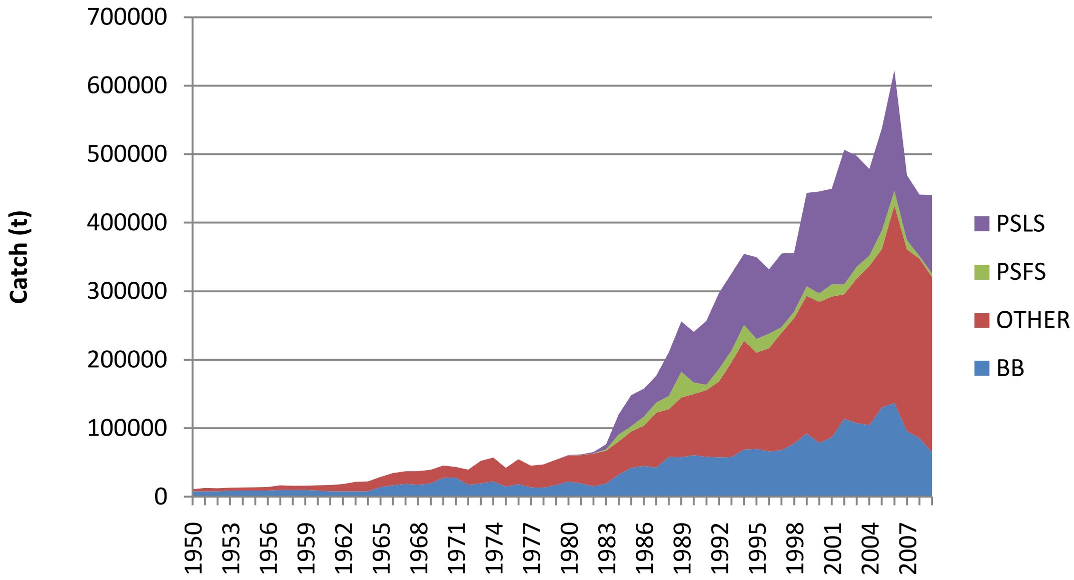


Figure 1. Total Indian Ocean skipjack tuna catches in the Indian Ocean disaggregated by fleet. 'BB' refers to the Maldivian pole and line fleet.

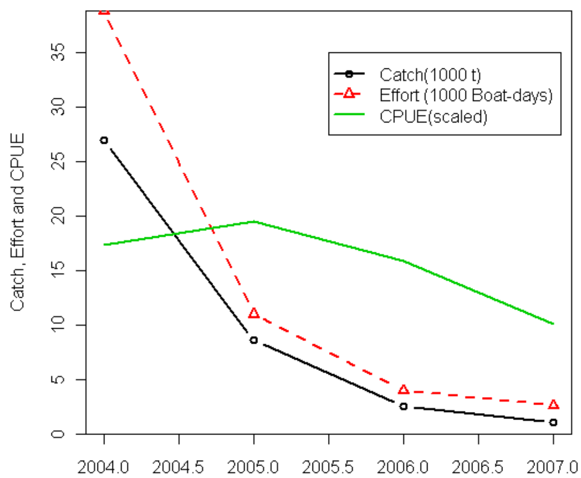


Figure 2. Catch, effort and nominal SKJ CPUE (sum(Catch)/sum(Effort)) for the 4 years with operational data.

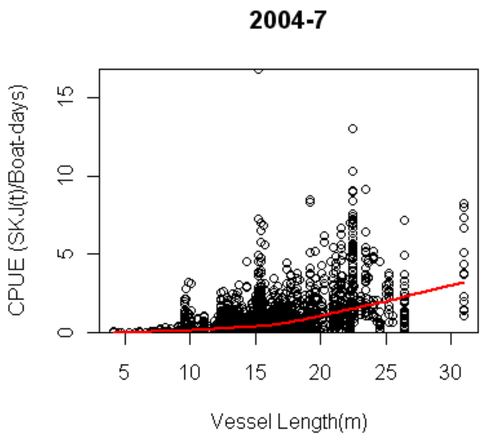


Figure 3. Relationship between vessel length and CPUE during the 2004-7 period. Circles correspond to monthly averages for individual vessels, the red line is a LOWESS smoother.

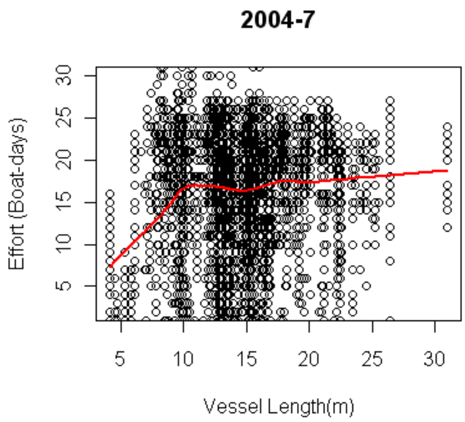


Figure 4. Relationship between vessel length and effort in boat-days during the 2004-7 period. Circles correspond to monthly averages for individual vessels, the red line is a LOWESS smoother.

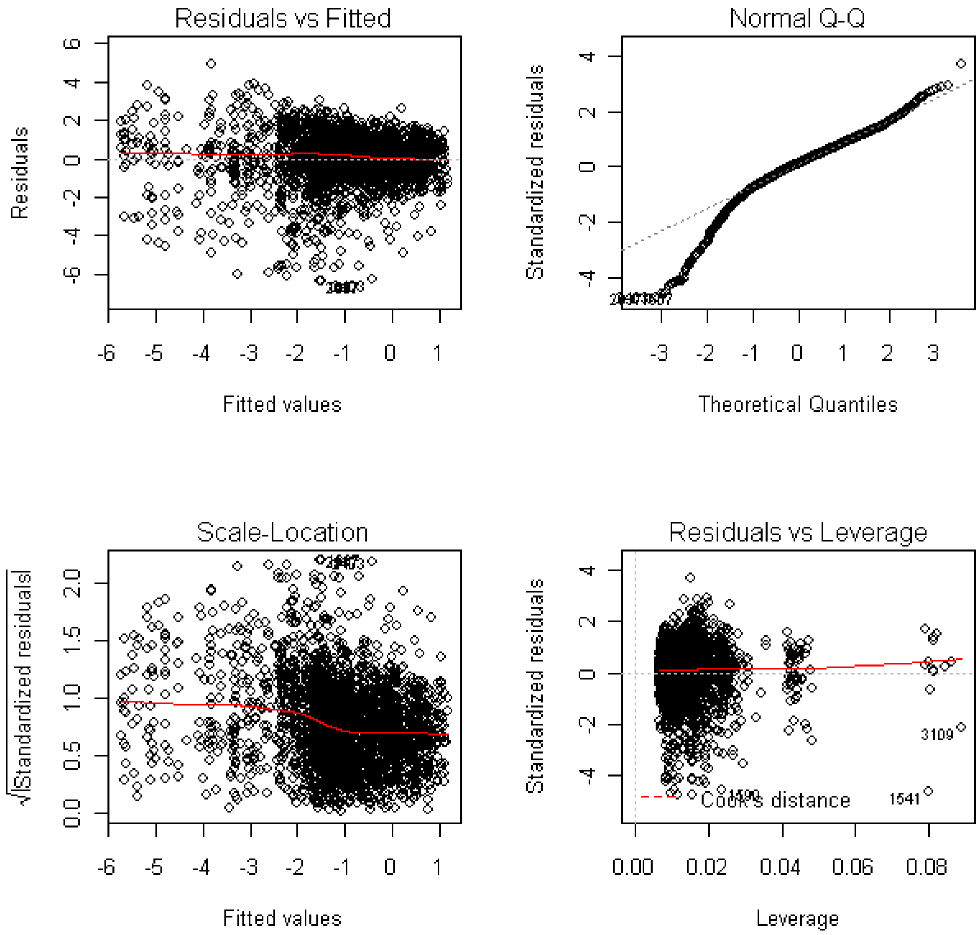


Figure 5. Standard GLM diagnostic plots for model A.

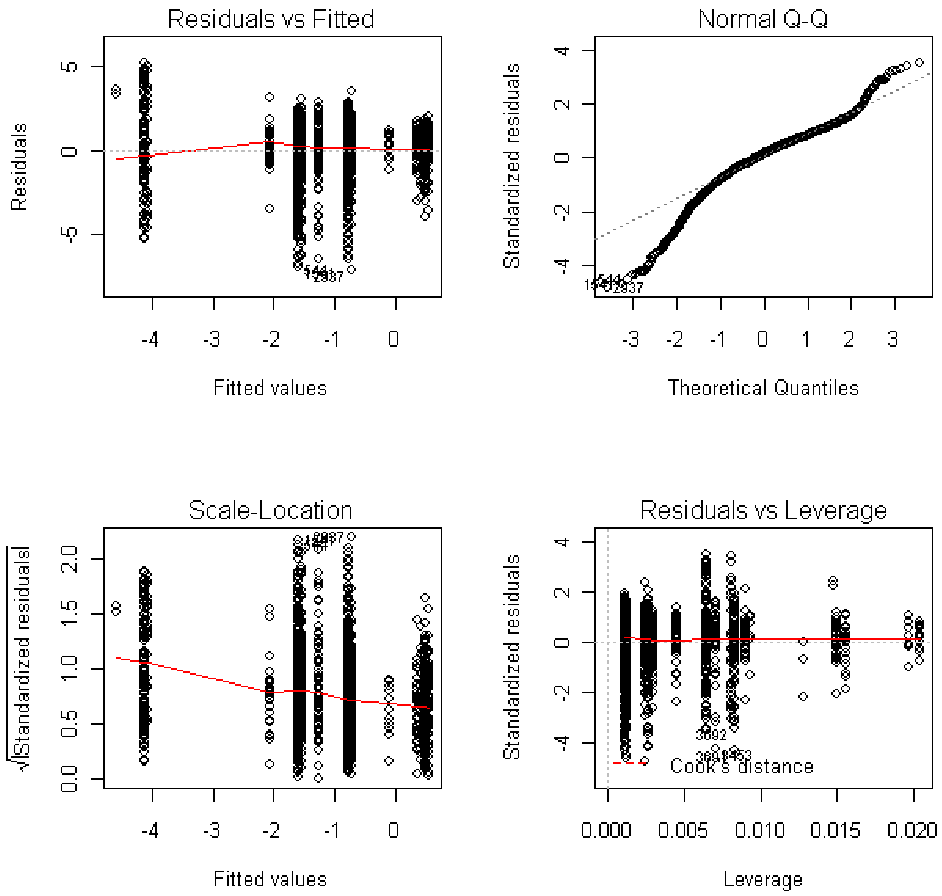


Figure 6. Standard GLM diagnostic plots for model B.

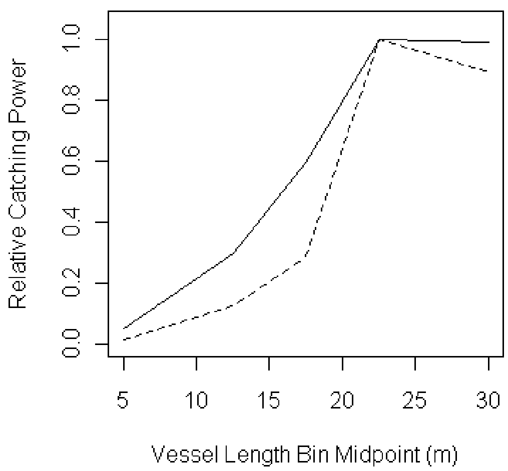


Figure 7. Effect of vessel length on catchability estimated by GLM models A and B.

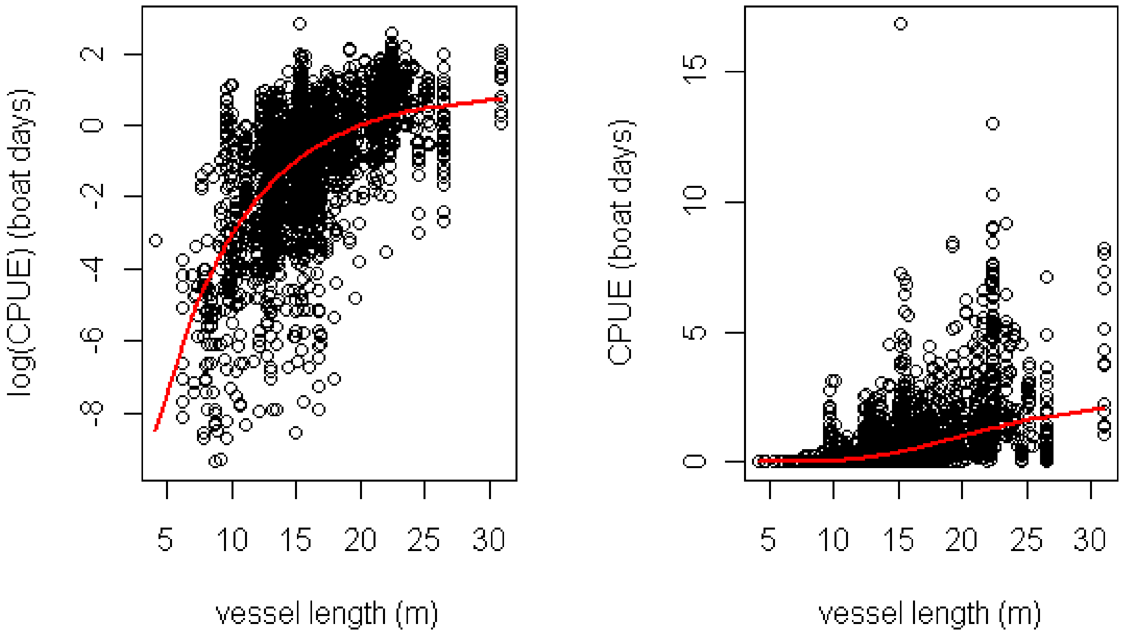


Figure 8. Estimated relationship between vessel length and CPUE (effort in boat days), including a least squares model of saturating effective effort (i.e. a von Bertalanffy growth equation fit to the log(CPUE)).

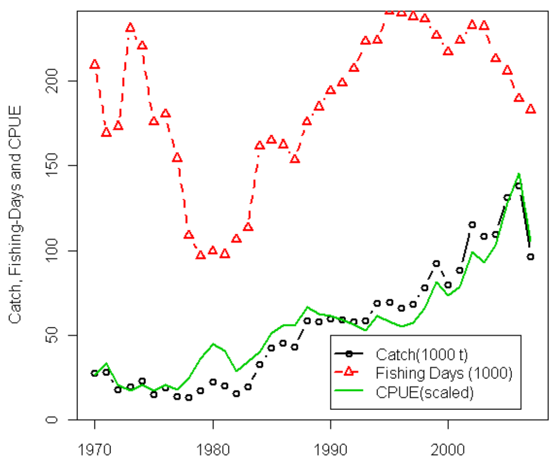


Figure 9. Catch, Effort (boat days) and nominal CPUE for the Maldivian Pole and Line fleet aggregated data set.

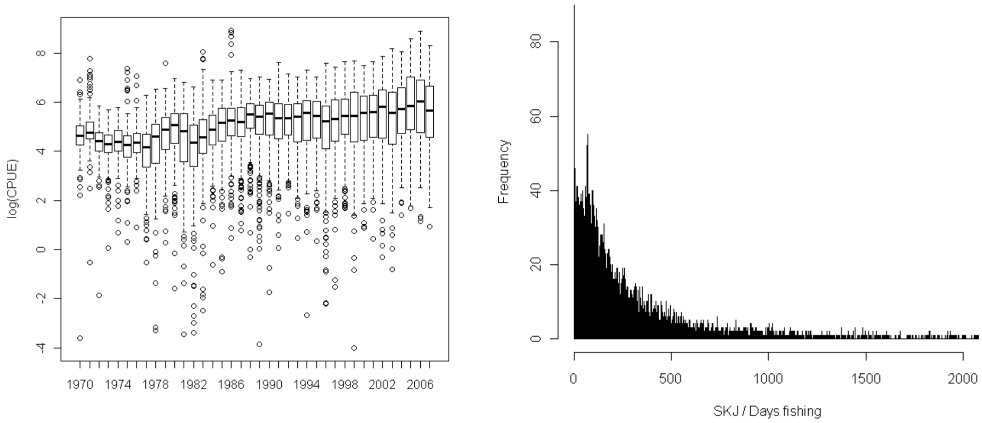


Figure 10. Boxplots showing the distribution of log(CPUE) over time (left), and aggregated over all years (right). 40 of 8988 of observations have positive effort and zero catch (<0.5%).

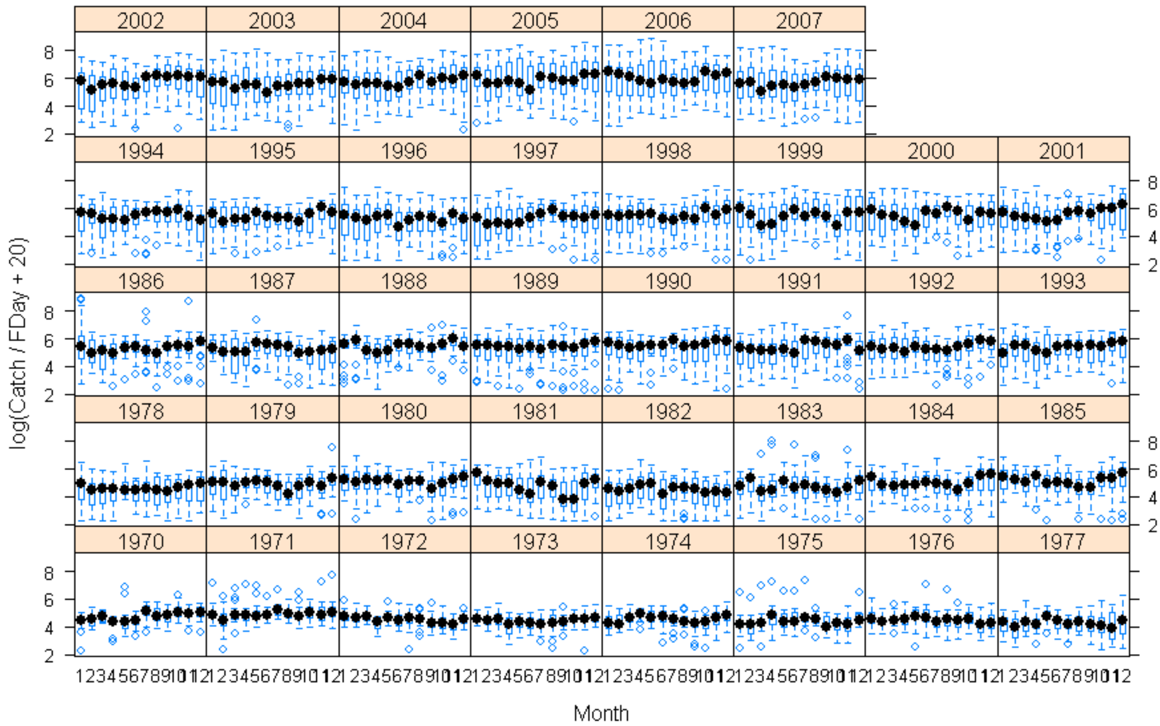
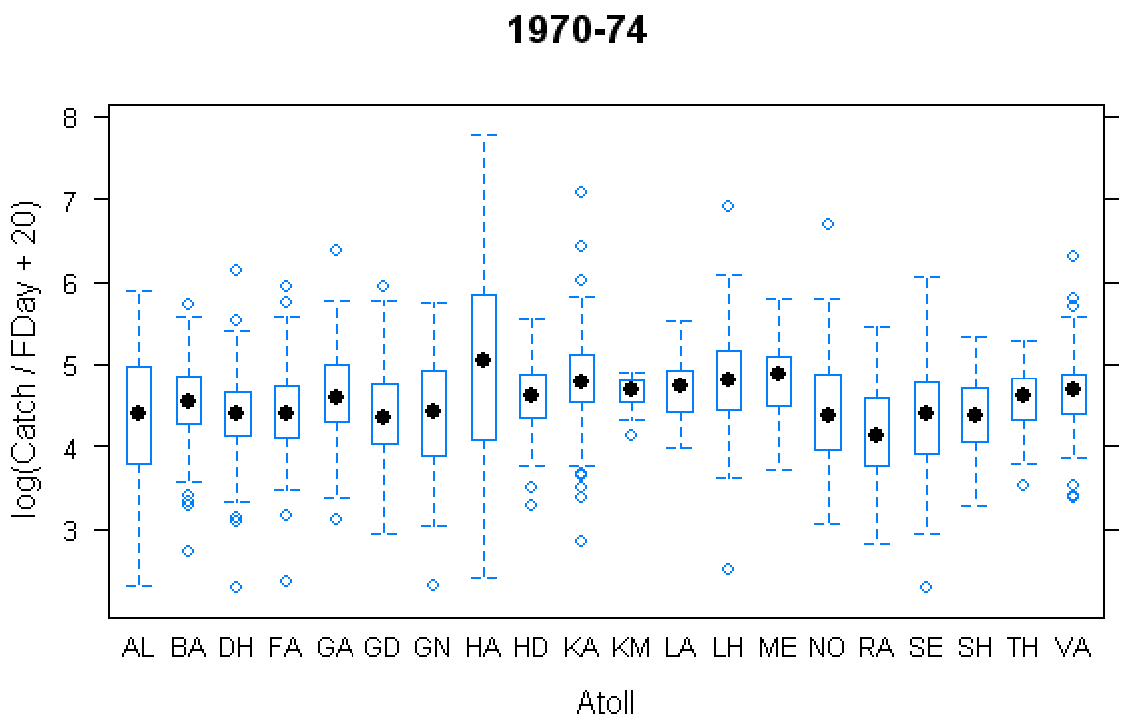


Figure 11. Monthly CPUE by year.



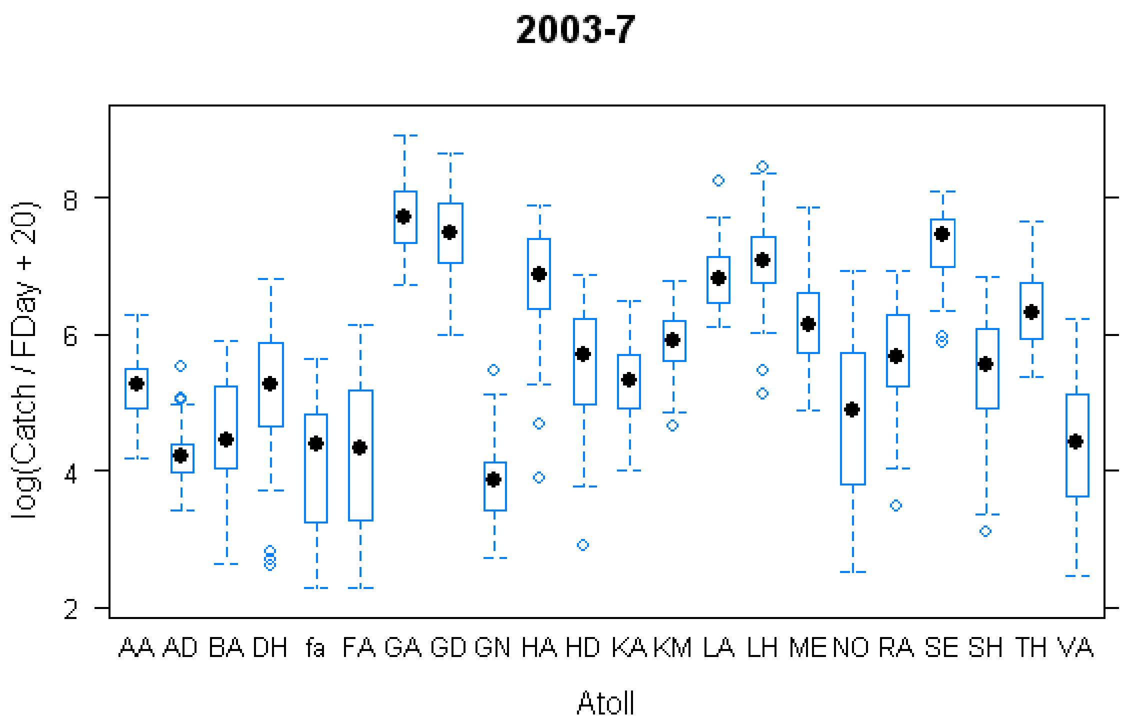


Figure 12. Catch rates by Atoll during the first (top panel) and last (bottom panel) 5 years of the time series

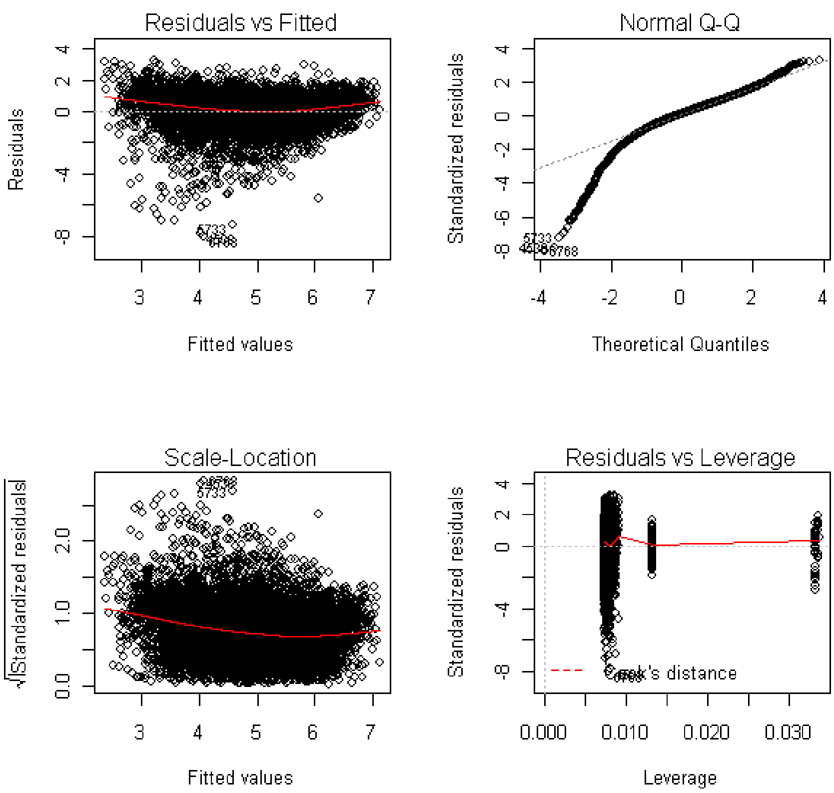


Figure 13. Standard GLM diagnostic plots for model C.

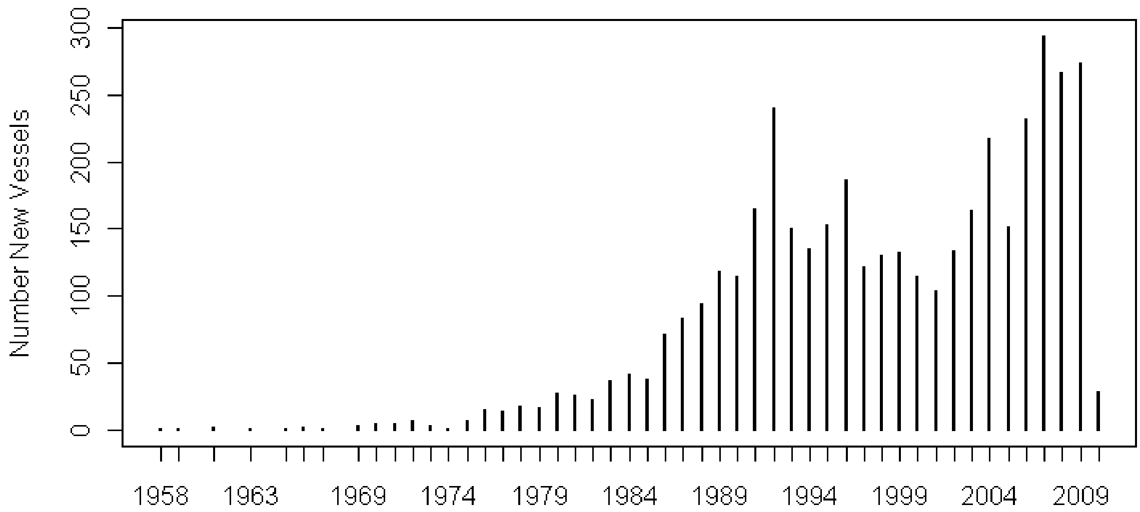


Figure 14. Number of new vessels registered by year.

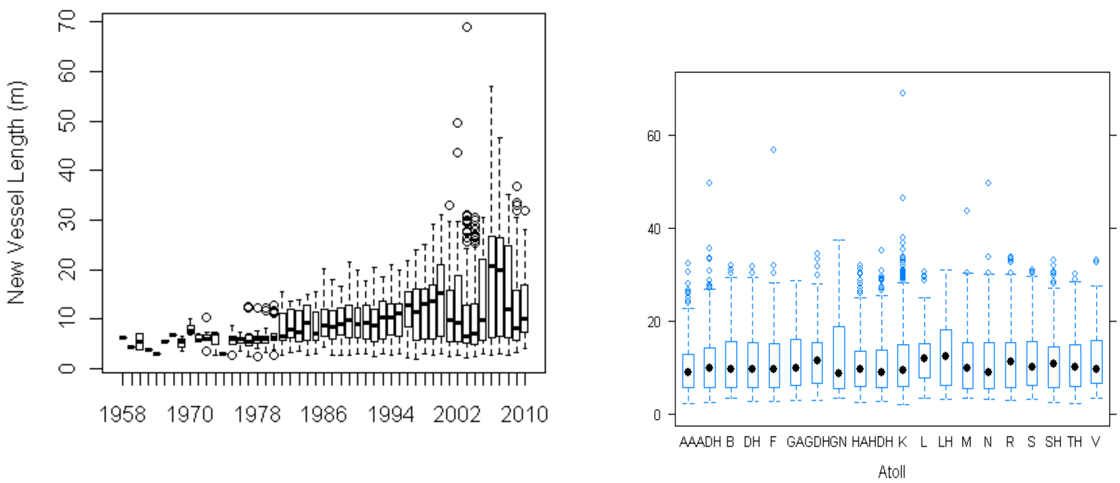


Figure 15. Length of newly registered vessels by year (left panel) and Atoll (right panel).

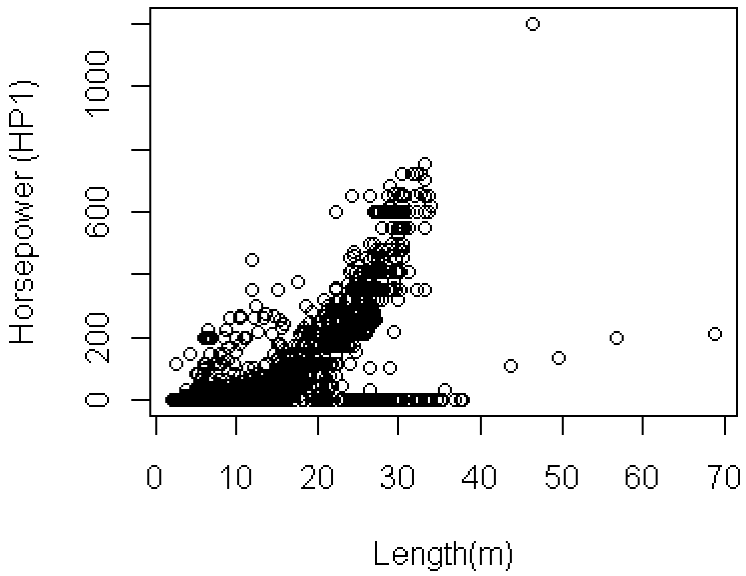


Figure 16. Relationship between fishing vessel length and horsepower in the registry. Note that no PL vessels over 31 m are observed in the operational data from 2004-7.

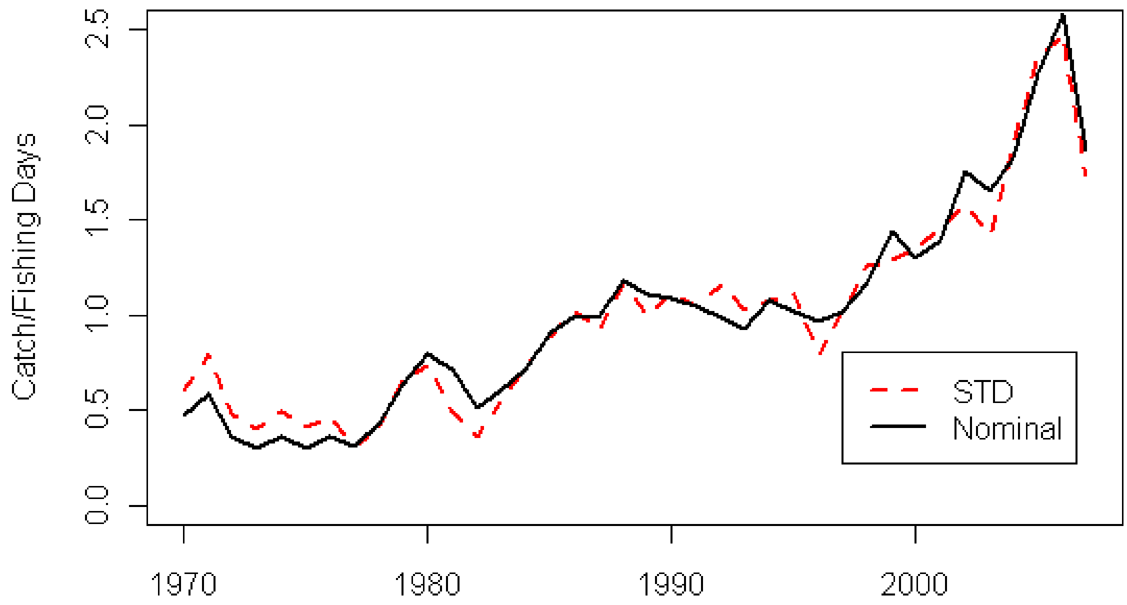


Figure 17. Comparison of nominal and standardized (model C) CPUE series, scaled relative to their respective means.

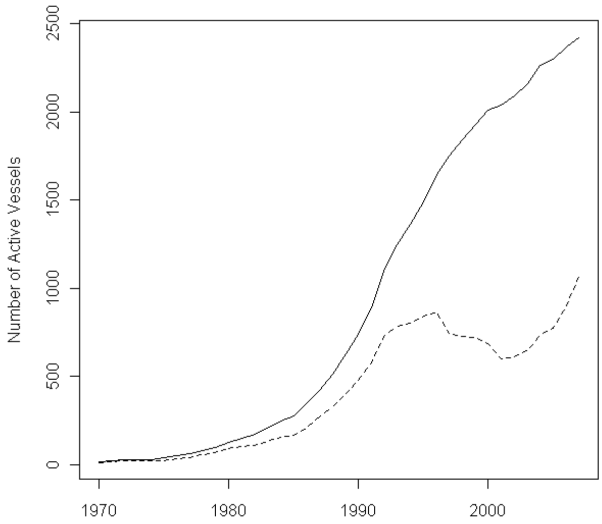


Figure 18. Comparison of the number of active fishing vessels in the fleet model assuming a 5 year (broken line) and 15 year (solid line) active lifespan for each vessel.

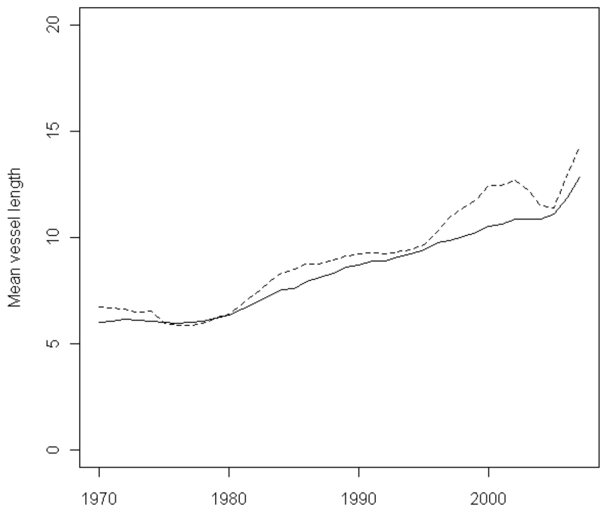


Figure 19. Comparison of the mean length of the fleet over time according to the fleet model assuming a 5 year (broken line) and 15 year (solid line) active lifespan for each vessel.

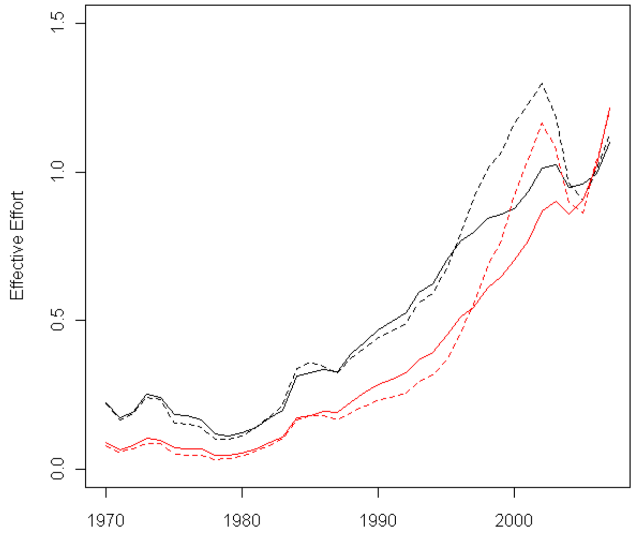


Figure 20. Comparison of the total effective effort series estimated historically from the fleet attrition and GLM-based vessel efficiency models. Black lines indicate the length-efficiency relationship derived from model A (which includes additional terms for month and atoll), red lines model B. Solid lines indicate a vessel lifespan of 15 years, broken lines a vessel lifespan of 5 years. Each series is scaled to have a mean of 1 over the last 4 years.

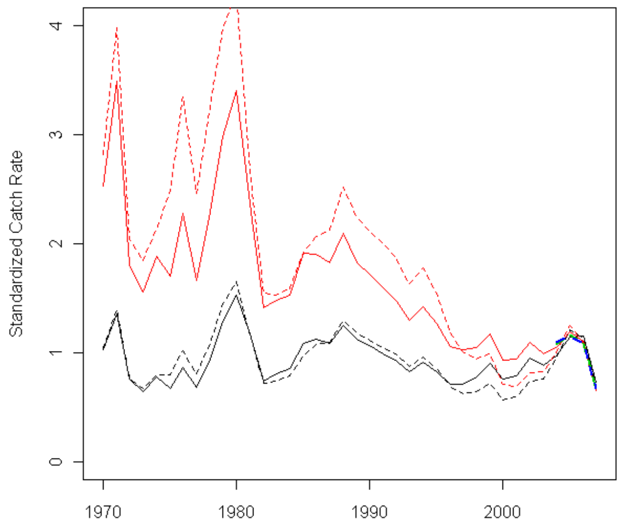


Figure 21. Comparison of the final relative abundance indices estimated by combining the fleet composition model with GLM-based vessel efficiency models. Black lines indicate the length-efficiency relationship derived from model A (which includes additional terms for month and atoll), red lines model B. Solid lines indicate a vessel lifespan of 15 years, broken lines a vessel lifespan of 5 years. Each series is scaled to have a mean of 1 over the last 4 years. The standardized CPUE series from models A (green) and B (blue) 2004-7 are also shown (largely overlapping with the other series).