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Maldives Skipjack Pole and Line Fishery Catch Rate Standardization 2004-2011: Reconstructing Historic CPUE till 1985

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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 2004-2011. The raw data consists of around 124000 records of catch (numbers) and effort (fishing days) by month, atoll and vessel; vessel characteristics were added to the CPUE dataset based on information from the registry of vessels. A subset of 56,698 records were extracted from the dataset, identified as records of fishing activity targeting skipjack. In the process, the paper discusses several data quality issues with the CPUE dataset, notably records with zero skipjack catch with a directed PL fishery and which were eventually discounted from the final analysis. FAD data was also incorporated into the analysis using the number of active FADS associated with the nearest atoll that the landing data is collected from. In order to do this, the distribution of FADs was split into three regions incorporating the North Atolls, Middle Atoll and South Atolls. Vessel specific data including hull-type effects, length of the boat (as a vessel size class) and horse power was also used in the analysis. GLM based models using a log response on CPUE were examined. The final model presented estimated log(CPUE) from independent variables Year, Month, Area (N, S, or M), number of FADs used in the area, and Length of vessel, and interaction effects between the last 3 categories. The data was analysed at a monthly resolution before being was collapsed into quarterly signals for 2004-2011. Finally, using vessel length as a continuous covariate, the CPUE data was estimated for historic periods till 1985.

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 (**Error! Reference source not found.**). The Maldives standardized CPUE is one of the only reliable sources of information for CPUE for the stock assessment of Skipjack and hence further efforts have been made to use this data, and reconstruct historic series as well. The IOTC Working Party on Tropical Tunas (WPTT 2012) recognized that it was worth further effort to extend the CPUE series of the Maldivian Pole and Line (PL) fishery, and this document describes the continuing effort to do so.

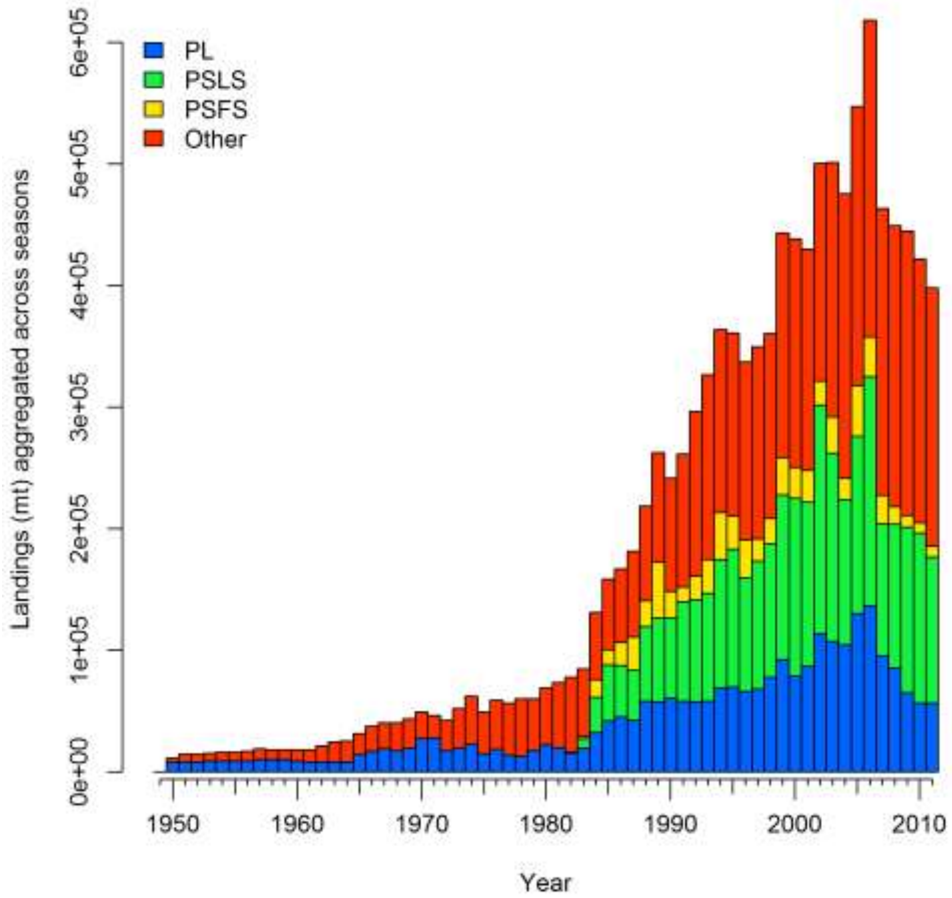

Figure 1. Aggregate Indian Ocean SKJ catch in mass over time disaggregated by the fleets defined for the assessment.

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 (**Error! Reference source not found.**). 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.

In Adam (2012) we realize the difficulty of standardization due to fleet efficiency, inconsistencies between information held in different databases and using different data collection methodologies, and the issue of using anchored FADs to improve catch rates from the mid 1980's.

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. FAD deployment began in the early 1980's and increased from very few FADs to a number of active FADs (~ 45 by the early 2000's). Since 2006, the number of active FADs has increased dramatically, almost doubling in number to around 85.
- An attempt to use these FADs to standardize the signal by area is attempted here for the first time.
- 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 live bait 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. The total number of fishing days (per month) has fallen from around 8000 in 2004 to around 5000 in 2011. But the number of vessels has also decreased, so actual fishing days per vessel have actually increased (from around 12 days per month in 2004 to 16 days per month in 2011).
- 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. Ultimately, it is possible by focussing on PL, we are missing the true number of boats targeting Skipjack, though is highly unlikely.

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). However, that attempt was not very successful and was eventually abandoned. Kolody et. al. (2011) used a standardized GLM based method to account for the probability of zero catches (we now know that these records were incorrectly coded at MRC), and catch rate as a function of year, quarter, atoll and vessel-length.

The attempt made here extends Kolody *et. al.* (2011) analysis by adding the effects of FAD, and also estimates historic CPUE catch rates using vessel length as a covariate (being related to HP and larger boast with higher efficiency, i.e., catchability) to estimate rates to the mid 1980's. Prior to that, the fleet was primarily non-mechanized and the authors felt extending the series beyond the 1980s raised concerns on the reliability of the CPUE estimates.

Methods

Data and Pre-processing

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

i. Monthly catch and effort data 2004-2011, by atoll and vessel.
ii. The registry of vessels 1958-2011, containing vessel dimensions including length and horsepower.
iii. Anchored FAD database from 1981-2012, including the FAD location, nearest atoll, date of deployment and date the FAD was either lost or recovered.

These data remain confidential, however descriptive and graphical summaries of the data are provided below.

Monthly Catch and Effort Data 2004-2011

The CPUE dataset provided by MoFA/MRC[1] consists of monthly observations of catch and effort (days per month) by vessel, for 2004 to 2011, and includes information taken from log-books for 2010 and 2011. The dataset includes the following fields of relevance to the analysis:

- Year, Month, Atoll of fishing activity
- Vessel Identification Number (VIN) (which can be linked to the vessel registry)
- Fishery type (e.g., skipjack, lobster, resort/sport fishing)
- Gear type
- Effort in boat days
- Catch in numbers and mass (Mt), by species
- Hull Type, Vessel length, Vessel Category, and Horsepower

[1] Data provided in Excel format by MoFA, MRC: 'newdatasetFADS.csv ', with 2011 superseded by 'Catch_Effort_2009.xlsx', 'Catch_Effort_2011.xlsx'.

A sub-set of records were extracted for the analysis identified as fishing activity targeting skipjack. In the process, a number of issues related to missing information or the quality of the data led to a number of records being omitted from the final analysis.

The data were initially filtered on gear ('pole and line') and fishery type ('skipjack'), however it was noted around 50% of selected records reported zero skipjack catch (but positive effort) consistently over a number of months. While not uncommon that skipjack cannot be located during single trips, it is unlikely vessels targeting skipjack would fail to catch any on a regular basis; nor is there evidence of strong enough seasonality in the nominal catch series to suggest long periods of no catch should be expected. Several alternative explanations were proposed:

- <u>Recorded gear and fishery type</u>
  The biggest problem is thought to be misreporting of gear and/or fishery type. Many of the vessels operating as pole and line or handline vessels are actually targeting large yellowfin or neritic tuna (despite reporting the trip as skipjack fishery type.

- <u>Partial landings</u>
  Some fishing vessels might only be reporting landings made at the home port, and exclude catch unloaded at the canneries, land-based collection facility[2], or transferred to collector vessels. In theory – irrespective of wherever the landing occurred – it is expected that the catch would also be reported at the home port; however this can no longer be guaranteed, particularly as the traditional manner of reporting at the home port has not been followed for vessels participating in the new logbook programme (covering <10% of vessels in 2010). As such, there is the possibility that observed changes (i.e., decline) in the nominal catch may be an artefact of partial unloading in collector vessels or changes to the reporting system.

- <u>Deliberate misreporting of effort</u>
  Prior to 2009, a license fee was levied for boats that operated for less than 120 days within a calendar year. This is thought to have resulted in effort being recorded for boats that remained in port (and consequently) reporting no catch. The magnitude of the misreporting problem is not known; however, the proportion of zero SKJ catch records was actually higher in 2009 and 2010 than 2004-2008, so this does not seem like an important contributing mechanism.

A number of other issues with the CPUE data were noted by the authors, but not corrected, either because (i.) they concern a small number of records and were considered to have a negligible impact on the final results, or (ii.) it was unclear how the records should be dealt with. Specifically:

- <u>Missing vessel ID and/or dimensions</u>
  13,500 records (11% of the total dataset) were missing either vessel identification numbers (VIN), or length and horsepower dimensions, required for modelling the relationship between CPUE and vessel efficiency in calculating the CPUE back-series to the 1970s.

[2] 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

- Invalid monthly effort
  A small number of records (45 in total) reported effort greater than 30 days in a month – which is highly unlikely – including 8 records which reported effort greater than 31 days. The discrepancies were largely attributed to a partial duplication of records due to port sampling activities (primarily in Malé).

- Reliability of atoll reported for fishing activity/landing
  The atoll assigned to each record is assumed to relate to area of fishing activity and landing site. Over two thirds of vessels report activity in only one atoll – in many cases over the course of many months, and even years, which is perhaps surprising. This raises questions on the accuracy of the atoll recorded by each vessel, but also the extent to which the fishing activity takes place in the same atoll as the landing place. The issue may confound analysis of the CPUE that attempts to model area effects based on variation between individual atolls or similarly low spatial resolutions; aggregating the data into larger geographic units (such as atoll region) may be the appropriate scale in studying the extent that variations in the CPUE are related to location.

- Effort of 1 day per month
  Traditionally, vessels have operated single day trips (as there is generally no refrigeration, but the boats may carry ice); multiday trips are more common in recent years, particularly for larger vessels. Around 40-50% of vessels targeting skipjack fish for 15 days or more (cumulatively) per month. However – up to 2009 – a further third of vessels reported only a single day of effort per month, which seems highly unusual; after 2009 the proportion of drops to around 4% (Figure 1, Appendix 1). One suggestion is that these vessels are actually multi-purpose, and report the minimum effort (of 1 day) each month in order to claim financial subsidies available to fishing vessels.

Taking all of these issues into consideration, the authors followed the recommendation of MoFA/MRC in applying the following conditions in selecting records as representing vessel activity targeting skipjack:

- Vessels operating Pole and line.
- Effort (in days) greater than zero.
- Total skipjack catch (per month) greater than zero[3].
- Records containing valid vessel identification (VIN) number.

Applying the criteria, a subset of 56,998 observations (around 46% from the total 123,792 CPUE records) were identified as targeting skipjack and used in the final analysis. The nominal catch (and CPUE) in numbers were used for all analyses detailed below, as mass is calculated as the product of numbers reported in each size category (consisting of 'large' and 'small' skipjack only). Effort used in

[3] While the criterion excludes a small number of CPUE records that genuinely report actual zero skipjack catch for a given month, the sub-set of CPUE records were still considered representative of skipjack catch and effort enough to be used in the statistical analysis.

the calculation of CPUE was taken as the number of days fishing; other measures of effort ('Gear quantity' and 'Total fishermen') were available, but not consistently reported for each vessel record.

A second CPUE dataset from 1970 was provided by MoFA, reporting monthly catch and effort for from 1970 but at an aggregated level (i.e., total catch and effort for all vessels in each month). Information on the vessel size or power, taken from the vessel registry, could not be linked directly to the dataset; therefore the data was not used directly in the analysis below, other than as a historical CPUE series to be compared to the estimated CPUE (see figure 2).

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 vessels over the period 1958-2010, and includes all of the vessels in the catch and effort database (although 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 and expected to be positively related to fishing efficiency. We note that previous studies by Mohamed (2007) assumed that total effective effort of the pole and line fleet was directly proportional to annual average horsepower for the period 1985-2005 but, as previously stated, the relationship was not formally defined. One of the purposes of this paper was to empirically test the assumption of vessel efficiency on CPUE by including vessel length as a covariate to backward forecast the CPUE index series to the mid-1980s.

Vessels around ~12-17m represent the majority of observations in the CPUE dataset, although there is a modest trend in increased use of larger vessels from 2004 to 2011. For vessels identified as targeting skipjack (based on the criteria discussed above), the average size of vessels increased from 16.9m in 2004 to 20.2m by 2011.

Anchored FADs 1981-2012

A database containing records of anchored FADs was also provided by MoFA/MRC, containing details of the date the FAD was deployed, date of recovery or that the FAD was lost, longitude/latitude, and nearest atoll.

Based on the date of deployment and recovery for each FAD, a list of active FADs was calculated for each month, for each atoll area and region (north, middle, and south), and added to the CPUE dataset by joining on the atoll recorded for each vessel activity.

Overview of main trends in skipjack nominal catch and CPUE

- The nominal for skipjack catch reported by Maldives has declined dramatically over the last decade. Between 2004 Q4 and 2011 Q4, total skipjack catch decreased by 50% from 28,600Mt to 14,500Mt, while effort decreased by 35% from 23,000 to 15,000 fishing days (Figure 2, Appendix 1).
- In addition to the overall decline in catch, there are large fluctuations in the nominal catch series, which suggest some seasonality effect (with most peaks around calendar quarters 1 and 4 each year) although the cycles do not strictly follow a regular pattern.
- The majority of the nominal skipjack catch – and effort to a lesser extent – tends to be concentrated among a small number of atolls (albeit noting the issues regarding the reliability to which atoll is reported for each activity and landing, discussed above). Of the 26 atolls in total, between 50-60% of the skipjack catch each year is concentrated in six atolls (Gaafu Alifu (GA),

Gnaviyani (GN), and Sennu (SE) in the south, and Kaafu (KA) and Laamu (LA) in the mid atoll area, and Haa Alifu (HA) in the north) (Figure 3, Appendix 1).

- Likewise, the pattern of CPUE closely follows that of the nominal catch, showing a fluctuating, but decreasing trend from a peak of over 1.8 in mid-2006.
- CPUE increases sharply with vessel size. In 2011, a CPUE of 0.31 is reported for vessels 12-17m in length (the common vessel type), 0.84 for vessels 17-22m, 1.25 for vessels 22-27m, and 1.79 for vessels over 27m.

Statistical Analysis

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. First, the data were filtered in different ways to identify more reliable and/or homogeneous observations (using positive catches, positive efforts, identifiable VINS, and Pole and Line gear). Once this was done, 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 g*lm()*:

$$\log(CPUE_i) = \beta_T X_{T,i} + \beta_1 X_{1,i} \ldots \beta_n X_{n,i} + e_i \qquad (1)$$

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*,

$\beta_1 \ldots \beta_n$ = 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 (**Error! Reference source not found.**), with explanations of the dependent and independent variables provided below.

Independent Variables

The following independent variables were included in some or all models (**Error! Reference source not found.**):

Y – Year.

M - Month.

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 (<7m, 7 - <12m, 12 – <17m, 17 - <22m, 22 - <27m, 27 - <32m, 32 - <37m, note there was also one value of 58m in the filtered dataset), 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. Nonetheless, we did look at a model that accounts for this and have included it as one of our sets for discussion.

Four final set of models are presented:

Model 1: Main effects model (Year and month interaction model)
Model 2: Interaction effects model using Vessel length as a covariate with Atoll area interactions.
Model 3: Vessel and Atoll effect model (Using main effects, Atoll Area effects, and VIN Numbers with VIN: Atoll interaction).
Model 4: FAD effect model: Accounting for FAD effects at an aggregated spatial resolution (not Atoll but 3 areas, N, Mid, and S areas).

Standardized CPUE Series

The final model recommended was Model 4 as it incorporated vessel effects and FAD effects at an aggregated spatial resolution. This resolution maybe appropriate as vessels no longer operate in one Atoll, but multiple areas and land at various Atolls. Hence, the atoll effect detected while significant, maybe entirely spurious.

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

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

where:

I is the index for time t,

β_t = the estimated time co-efficient,

A = the estimated co-efficient for the standard Area (mid area was chosen as it had the most records)

FAD= the number of active FADs in any given region (average number was used 21.24 across all regions and records)

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, to account for 0 CPUE's, but in our case we discarded these values due to data collection errors (mis-specified gear and fishery).

Reconstructing Historic Time Series using Vessel Length

Vessel length is highly correlated with Horse power (Persons r=0.79, Spearmans r=0.87). Hence we chose only vessel length (as a continuous measure) to estimate the historic CPUE to the mid 1980's. Prior to that the vessels were mostly non-mechanized, and the fleet structure was quite different (Anderson 1987), and using the relationship beyond that time maybe spurious.

Model 1 estimated the following (note the CPUE series chosen was the Vessel area FAD, model 4 described above):

$$CPUE_i = \alpha + \beta \overline{Vlen}_i + \varepsilon \quad (3)$$

Using estimated α and β, and average vessel length (Vlen) at time i, we estimated CPUE from January, 1985 to December, 2003. We then standardized the entire series from January, 1985 to December, 2011, averaging the entire series to 1.

Results and Discussion

Generalized Linear Models

The covariate factors used in model 1 are as follows:

$$\ln(CPUE_{i.m}) = \alpha_i Y_i + \sum_{x=1}^{12} \beta_x M_x + \sum_{y=1}^{n} \gamma_y A_y + \sum_{z=1}^{m} \theta_z V_z + \sum_{y=1}^{n} \sum_{z=1}^{m} \phi_{yz} A_y V_z + \varepsilon \quad (4)$$

Where Y is the year effect, M the month effect, A an Atoll effect, V a length category effect for vessel size, and A*V is the Atoll and Vessel Length category interaction.

When looking at an index we only used the Year and Month effects in the standardization.

The second and third index series examined was using the same model with all effects, averaged out for average vessel category and Northern Atoll used (Shaviyanai, SH) and also computed for southern atoll (Laamu, LA).

Since, there are no continuous measures used in the standardization, the indices when standardized to 1 are all equivalent.

The second model examined was:

$$\ln(CPUE_{i.m}) = \alpha_i Y_i + \sum_{x=1}^{12} \beta_x M_x + \sum_{y=1}^{n} \gamma_y A_y + \sum_{z=1}^{m} \theta_z VIN_z + \sum_{y=1}^{n} \sum_{z=1}^{m} \phi_{yz} A_y VIN_z + \varepsilon \quad (5)$$

Where all variables are identical to equation 4 except instead of a length category, we now use a VIN as a vessel effect, and due to large number of VINS lose a lot of degrees of freedom. This model had to deal with memory issues in R, and thus was abandoned as the VINs had too many degrees of freedom.

The 5th model examined was incorporating FAD's (FAD variable is the number of active FADs) at a coarser scale than the atoll levels (Figure yy). We now have three areas (LA), (North (N), South(S), and Middle (M)). The model examined was:

$$\ln(CPUE_{i.m}) = \alpha_i Y_i + \sum_{x=1}^{12} \beta_x M_x + \sum_{y=1}^{n} \gamma_y LA_y + \sum_{z=1}^{m} \theta_z V_z + \lambda FAD + \sum_{y=1}^{n} \sum_{z=1}^{m} \phi_{yz} LA_y V_z + \sum_{y=1}^{n} \kappa_y LA_y + \varepsilon \quad (6)$$

Diagnostics of each of the 3 main model with ANOVAS (eq 4, 5 and 6) are in Appendix 1, 2 and 3 with the parameters as well.

Table 1 shows the results of the actual index and standardized index for the main effect model, the VIN model and the FAD based models.

Table 1: Results of the CPUE standardization (all models) and standardized (2models)

Year	Quarter	Model 1 (Year and Month Interaction)	Model 1 (Vessel:North)	Model 1 (Vessell:South)	Model 3: FAD effects model		Stdized Vessel:Atoll	Standardized FAD	PL - preferred	PL - Dale Sensitivity
2004	1	3.49	0.46	0.80	0.82		1.02	1.22	1.01	1.17
2004	2	3.28	0.43	0.75	0.73		0.96	1.09	0.99	0.9
2004	3	3.58	0.47	0.82	0.81		1.04	1.20	1.01	1.11
2004	4	4.24	0.56	0.98	0.95		1.24	1.41	1.03	1.28
2005	1	4.35	0.58	1.00	0.97		1.27	1.44	0.96	1.15
2005	2	4.09	0.54	0.94	0.86		1.19	1.28	1.55	1.25
2005	3	4.46	0.59	1.03	0.95		1.30	1.41	1.13	1.36
2005	4	5.29	0.70	1.22	1.12		1.54	1.66	1.67	1.65
2006	1	4.26	0.56	0.98	0.94		1.24	1.40	1.3	1.66
2006	2	4.00	0.53	0.92	0.84		1.17	1.24	1.32	1.31
2006	3	4.37	0.58	1.00	0.93		1.27	1.38	1.18	1.03
2006	4	5.17	0.69	1.19	1.09		1.51	1.62	1	1.25
2007	1	3.16	0.42	0.73	0.67		0.92	1.00	0.77	0.81
2007	2	2.97	0.39	0.68	0.59		0.87	0.88	0.91	0.77
2007	3	3.24	0.43	0.75	0.66		0.95	0.98	0.83	0.79
2007	4	3.84	0.51	0.88	0.77		1.12	1.15	1.33	1.07
2008	1	3.15	0.42	0.72	0.62		0.92	0.92	0.66	0.62
2008	2	2.96	0.39	0.68	0.55		0.86	0.81	0.72	0.76
2008	3	3.23	0.43	0.74	0.61		0.94	0.90	0.91	0.92
2008	4	3.82	0.51	0.88	0.71		1.12	1.06	0.93	1.05
2009	1	3.03	0.40	0.70	0.56		0.88	0.83	0.75	0.69
2009	2	2.84	0.38	0.65	0.49		0.83	0.73	0.8	0.63
2009	3	3.10	0.41	0.71	0.55		0.91	0.81	1.22	0.75
2009	4	3.68	0.49	0.85	0.64		1.07	0.95	0.91	1.02
2010	1	2.65	0.35	0.61	0.44		0.77	0.66	0.77	0.81
2010	2	2.49	0.33	0.57	0.39		0.73	0.58	0.48	0.55
2010	3	2.72	0.36	0.63	0.43		0.79	0.64	0.69	0.75
2010	4	3.22	0.43	0.74	0.51		0.94	0.76	1.19	0.88
2011	1	2.15	0.29	0.50	0.33		0.63	0.49		
2011	2	2.02	0.27	0.47	0.30		0.59	0.44		
2011	3	2.21	0.29	0.51	0.33		0.64	0.49		
2011	4	2.61	0.35	0.60	0.38		0.76	0.57		

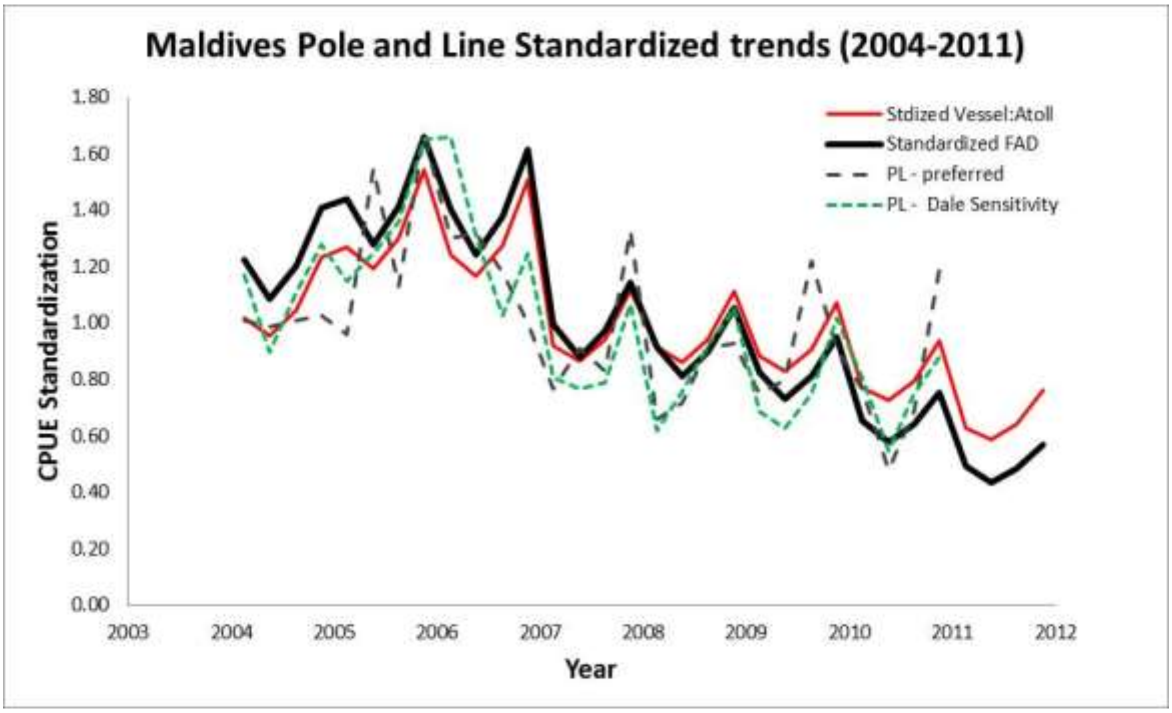

Figure 1: Standardized Index of the new models with comparison to Kolody and Adam (2011) models.

Reconstructing the Historic Series using the FAD based series.

Table 2: Coefficients of the regression with ANOVA on the series.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.54	3.54	198.19	0.0
Residual	94	1.68	0.02		
Total	95	5.22			

Parameters

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.16	0.18	17.84	0.00	2.80	3.51
Avg.Size	-0.13	0.01	-14.08	0.00	-0.15	-0.12

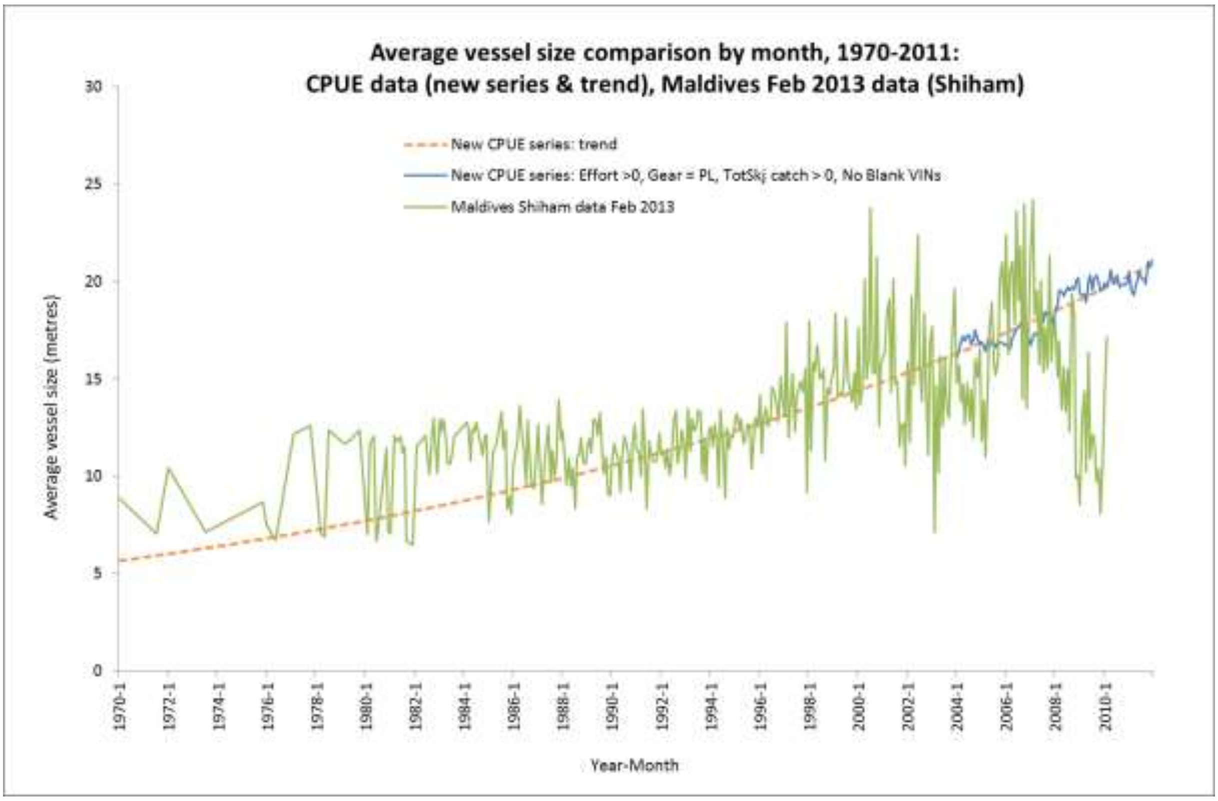

Figure 2: The relationship between average vessel size over time

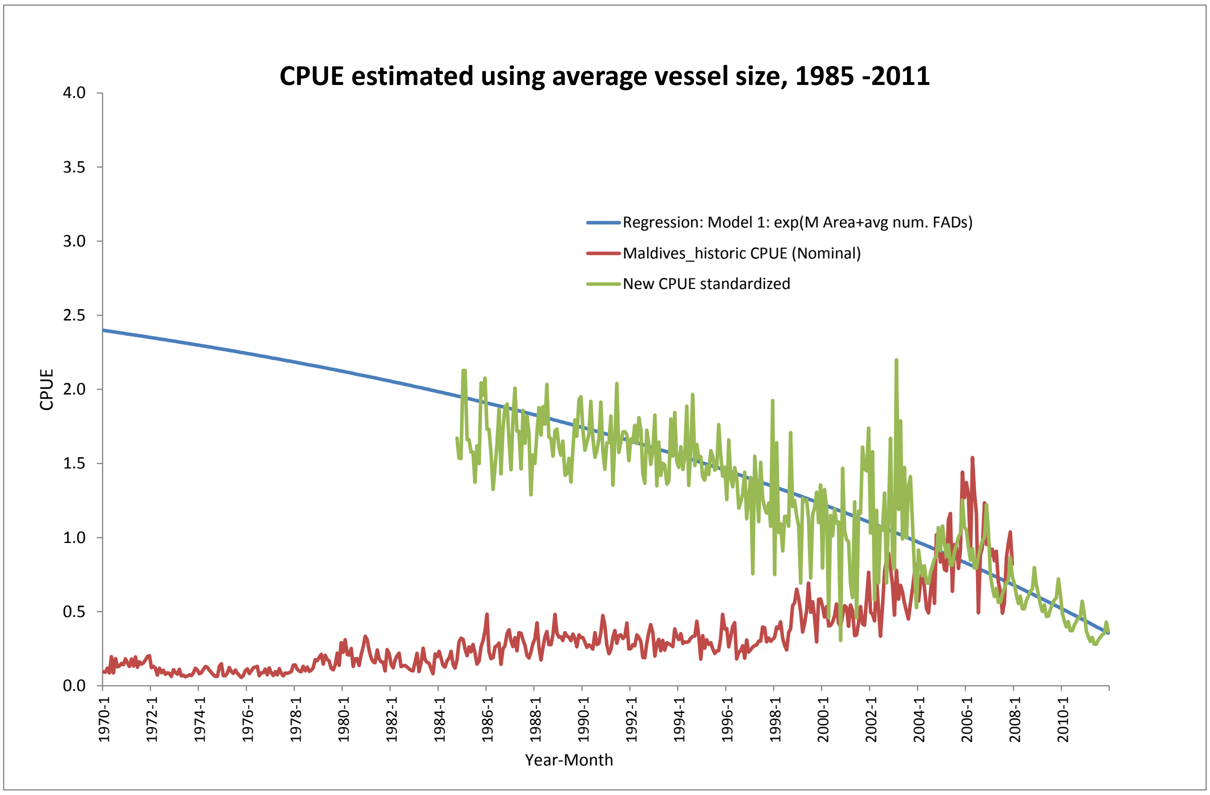

Figure 3: The historic series (CPUE standardized from 1985-2011).

Table 3: Values of the standardized CPUE for Maldives PL fisheries from 1985-2011 by quarter.

Year	Quarter	CPUE-STD		Year	Quarter	CPUE-STD		Year	Quarter	CPUE-STD
1985	1	1.62		**1996**	1	1.18		**2007**	1	0.55
1985	2	1.32		**1996**	2	1.16		**2007**	2	0.49
1985	3	1.23		**1996**	3	1.02		**2007**	3	0.54
1985	4	1.67		**1996**	4	1.05		**2007**	4	0.63
1986	1	1.38		**1997**	1	1.02		**2008**	1	0.51
1986	2	1.22		**1997**	2	1.09		**2008**	2	0.45
1986	3	1.38		**1997**	3	1.00		**2008**	3	0.50
1986	4	1.49		**1997**	4	1.16		**2008**	4	0.58
1987	1	1.44		**1998**	1	0.94		**2009**	1	0.46
1987	2	1.34		**1998**	2	0.86		**2009**	2	0.41
1987	3	1.46		**1998**	3	1.08		**2009**	3	0.45
1987	4	1.25		**1998**	4	0.99		**2009**	4	0.53
1988	1	1.40		**1999**	1	0.83		**2010**	1	0.36
1988	2	1.46		**1999**	2	1.00		**2010**	2	0.32
1988	3	1.47		**1999**	3	0.85		**2010**	3	0.36
1988	4	1.37		**1999**	4	1.03		**2010**	4	0.42
1989	1	1.32		**2000**	1	0.91		**2011**	1	0.27
1989	2	1.20		**2000**	2	0.72		**2011**	2	0.24
1989	3	1.31		**2000**	3	0.93		**2011**	3	0.27
1989	4	1.53		**2000**	4	0.77		**2011**	4	0.32
1990	1	1.36		**2001**	1	0.73				
1990	2	1.45		**2001**	2	0.63				
1990	3	1.31		**2001**	3	1.08				
1990	4	1.36		**2001**	4	1.28				
1991	1	1.40		**2002**	1	0.87				
1991	2	1.38		**2002**	2	0.81				
1991	3	1.35		**2002**	3	0.83				
1991	4	1.35		**2002**	4	1.02				
1992	1	1.39		**2003**	1	1.14				
1992	2	1.42		**2003**	2	1.17				
1992	3	1.24		**2003**	3	1.03				
1992	4	1.29		**2003**	4	0.65				
1993	1	1.32		**2004**	1	0.68				
1993	2	1.21		**2004**	2	0.60				
1993	3	1.24		**2004**	3	0.67				
1993	4	1.34		**2004**	4	0.78				
1994	1	1.25		**2005**	1	0.80				
1994	2	1.31		**2005**	2	0.71				
1994	3	1.38		**2005**	3	0.78				
1994	4	1.29		**2005**	4	0.92				
1995	1	1.17		**2006**	1	0.78				
1995	2	1.25		**2006**	2	0.69				
1995	3	1.28		**2006**	3	0.76				
1995	4	1.22		**2006**	4	0.90				

Final Conclusions and Recommendations

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

- Several issues remain regarding the quality of CPUE dataset; in many cases invalidating a number of records that could otherwise be useful as data inputs in the stock assessment. Specifically:

  i. large proportions of zero skipjack catch recorded as skipjack fishery – should they all be automatically discounted from the analysis?
  ii. completion missing vessel identification numbers or vessel dimensions from the CPUE dataset;
  iii. accuracy of the atoll recorded for fishing activity and landing – to what extent is it reasonable to associate the fishing activity and landing to the same atoll?
  iv. clarification of the status of vessels reporting effort of 1 day per month (over a third of vessels up to 2009) – how should these be treated in the analysis?
  v. improvements in the selection criteria for identifying skipjack targeted records; should a broader gear definition be used in selection criteria to reflect changes in skipjack targeted vessels (e.g., recent changes from pole and line to handline)?
  vi. There are also operational factors that are suspected of being important, but for which there are no data (e.g. bait availability, technological innovation).
  vii. An attempt is made to compare th effect of AFADs to the catch ate by comparing a larger spatial scale. However, 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). The analysis does not account for this effect.
  viii. 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.
  ix. 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.

Acknowledgements

The authors are grateful to Ms. Aishat, Ms. Shafana and Ms. Fahmeeda Islam, for their diligent work cleaning up the vessel identity fields, and adding it to the overall database, as well as checking the data from 2010 and 2011. The MOFA is also thanked for sharing their data with us.

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Appendix 1: Nominal catch and CPUE

Figure 1. Distribution of fishing days per month, for skipjack targeted vessels 2004-2011.

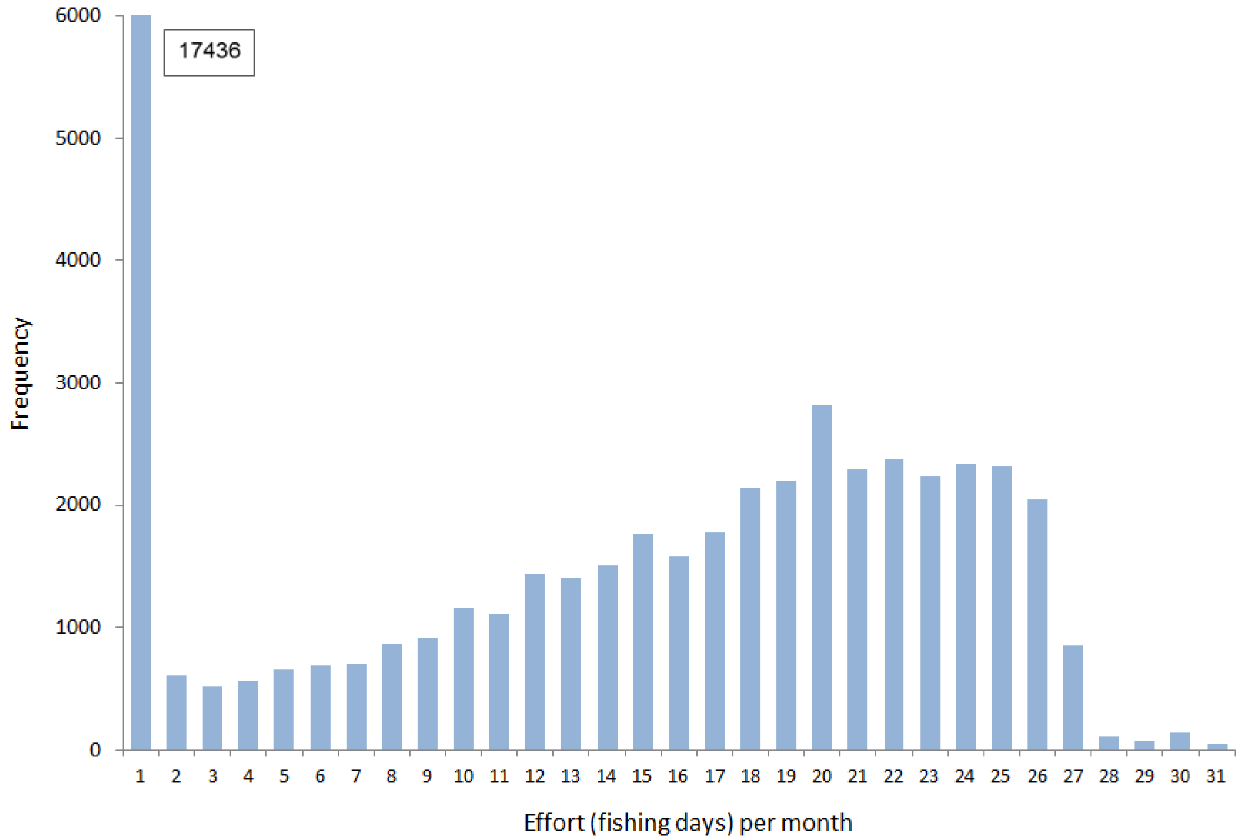


Figure 2. Proportion of records reporting effort of 1 day per month, for skipjack targeted vessels 2004-2011.

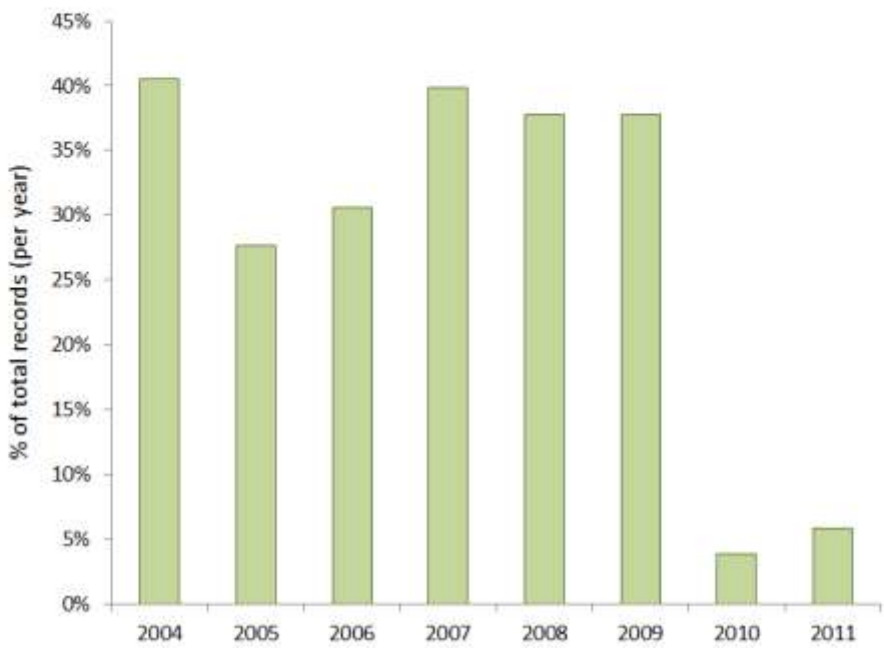
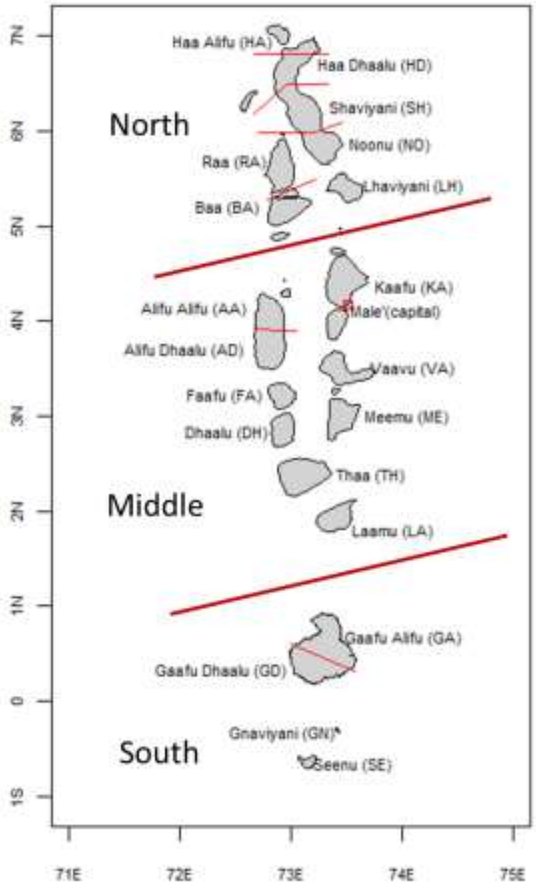


Figure 3. Map of Atolls, and number of active FADs 2001-2013



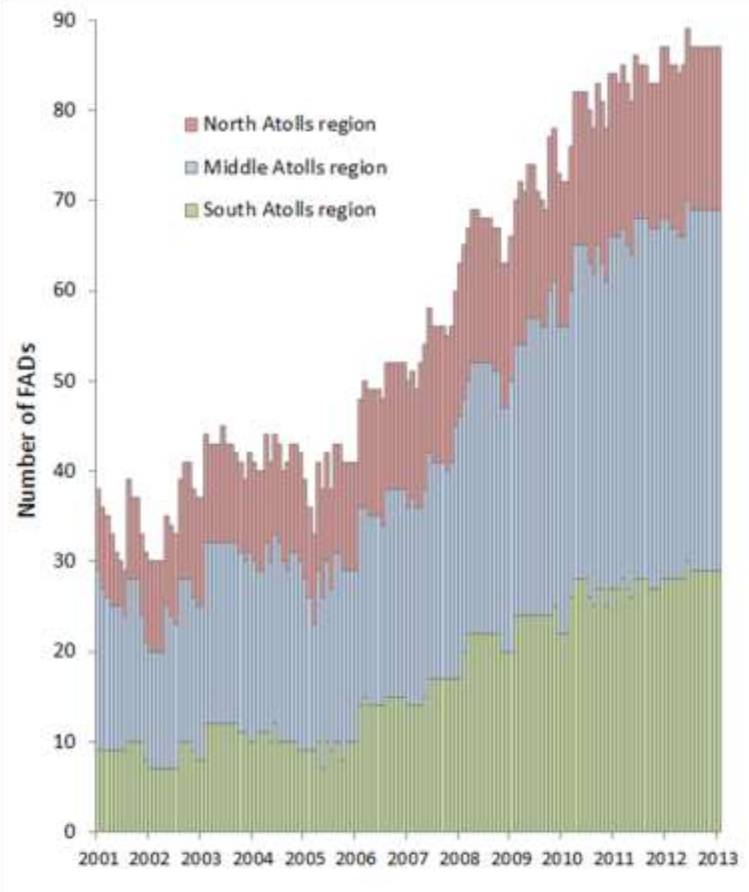


Figure 4: Nominal catch and effort, and CPUE 2004-2011.

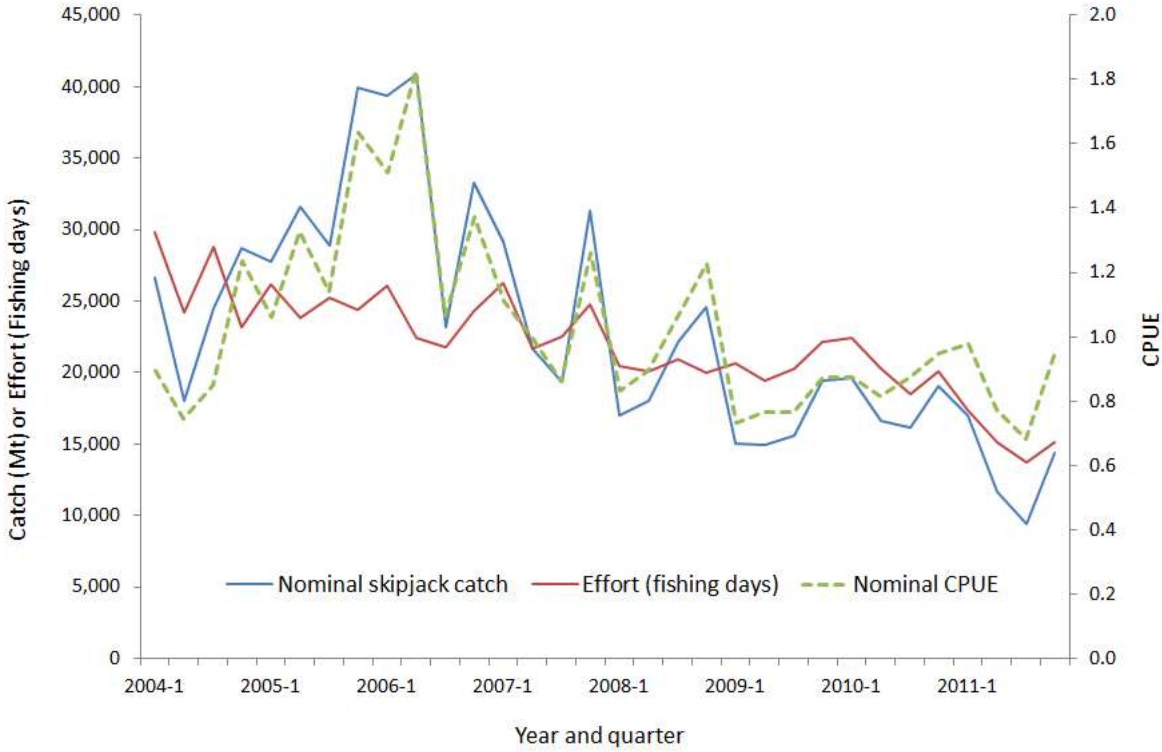
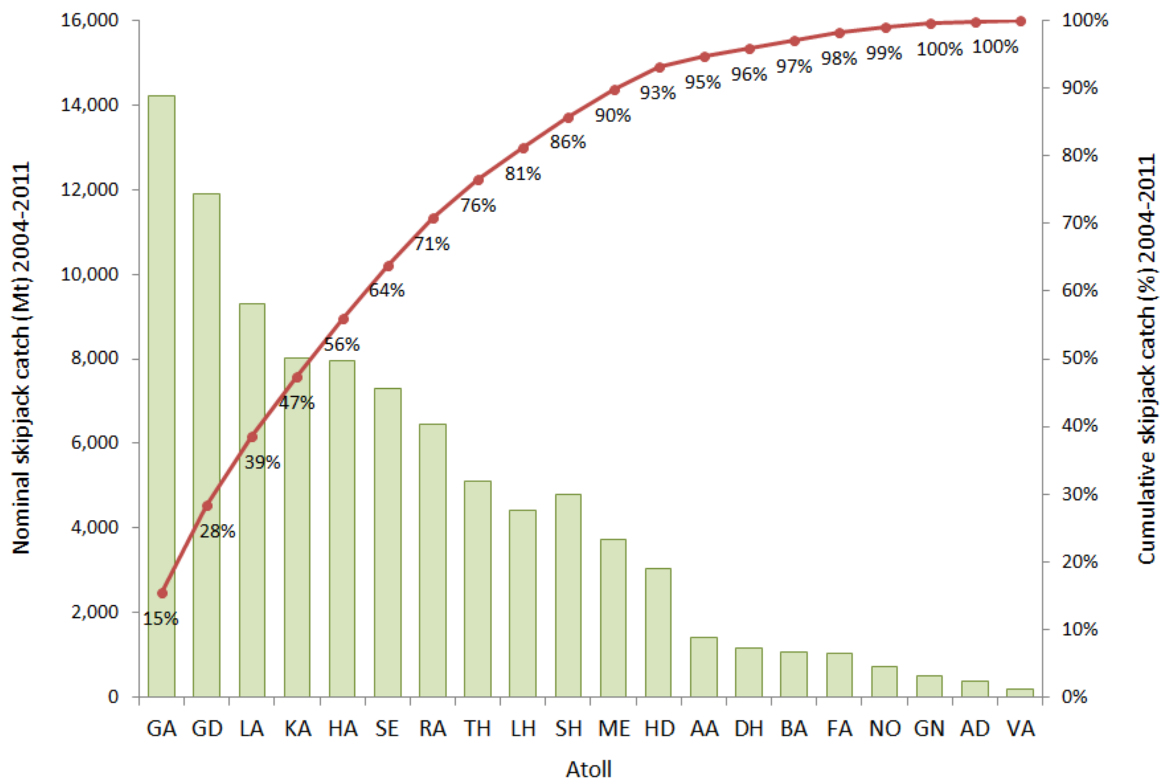


Figure 5. Distribution of nominal skipjack catch by Atoll, 2004-2011.



Appendix 2: Model 1 Results

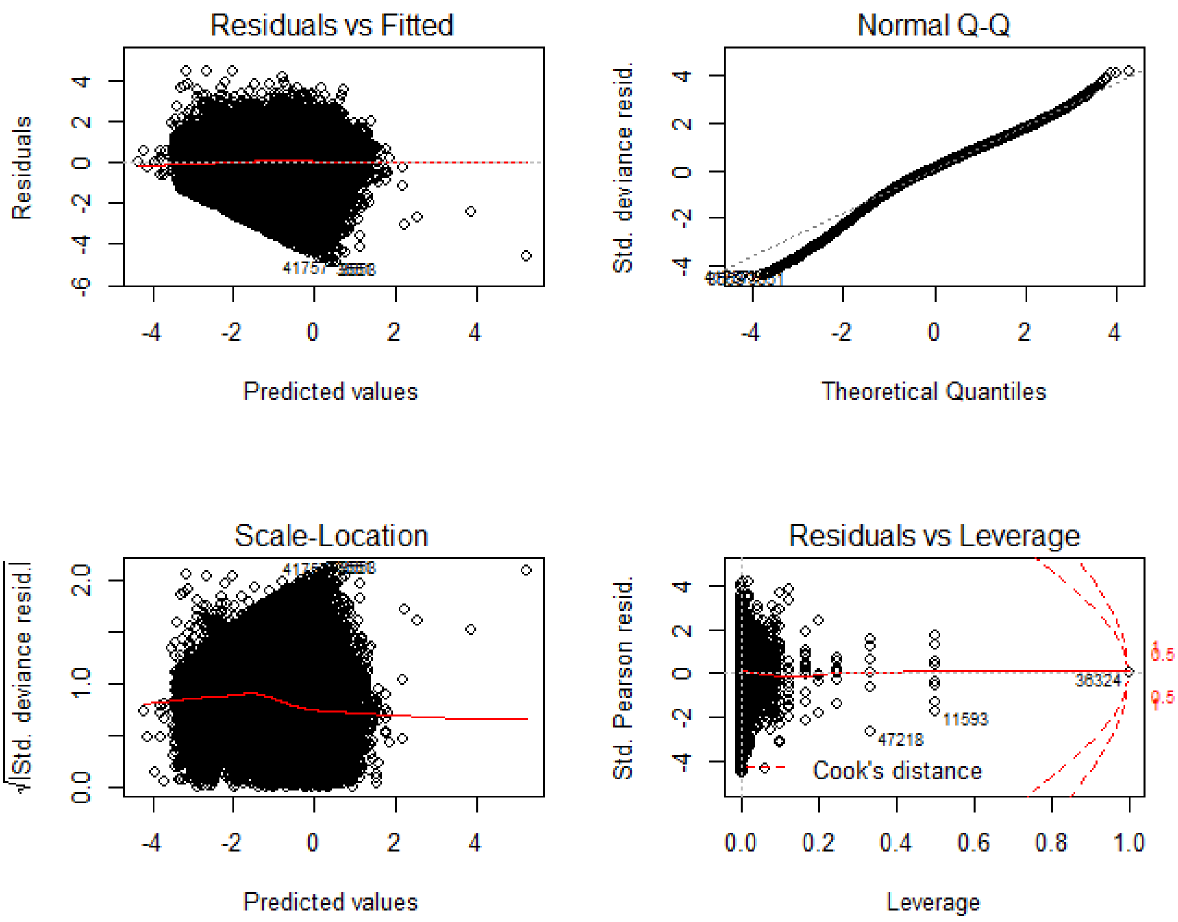


Figure 1: Residual diagnostics of the model using Year, Month, Atoll, Vessel length Category, and Vessel length category (Atoll) Interaction.

Table 1: ANOVA for the Model in equation (1)
Response: log(CPUE)

Terms added sequentially (first to last)

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)	
NULL			54591	104301			
factor(Year)	7	1775.3	54584	102525	211.544	< 2.2e-16	***
factor(Month)	11	896.8	54573	101629	68.006	< 2.2e-16	***
factor(Atoll)	26	26658.5	54547	74970	855.251	< 2.2e-16	***
factor(Vessel.Cat)	6	6489.2	54541	68481	902.130	< 2.2e-16	***
factor(Atoll):factor(Vessel.Cat)	126	3244.8	54415	65236	21.481	< 2.2e-16	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
Table 2: Summary Results for Model 1

Call:
glm(formula = log(CPUE) ~ factor(Year) + factor(Month) + factor(Atoll) +
    factor(Vessel.Cat) + factor(Atoll):factor(Vessel.Cat))

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-5.1820  -0.6136   0.0877   0.7301   4.5842

Coefficients: (30 not defined because of singularities)
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                          1.3491204  1.1091220   1.216 0.223843
factor(Year)2005                     0.2209247  0.0169799  13.011  < 2e-16 ***
factor(Year)2006                     0.1986567  0.0167356  11.870  < 2e-16 ***
factor(Year)2007                    -0.0996603  0.0173760  -5.736 9.77e-09 ***
factor(Year)2008                    -0.1032244  0.0178052  -5.797 6.77e-09 ***
factor(Year)2009                    -0.1426546  0.0178807  -7.978 1.51e-15 ***
factor(Year)2010                    -0.2740999  0.0206602 -13.267  < 2e-16 ***
factor(Year)2011                    -0.4831716  0.0236115 -20.463  < 2e-16 ***
factor(Month)2                      -0.1020975  0.0216096  -4.725 2.31e-06 ***
factor(Month)3                      -0.2056878  0.0217954  -9.437  < 2e-16 ***
factor(Month)4                      -0.0720142  0.0229204  -3.142 0.001679 **
factor(Month)5                      -0.2032384  0.0233207  -8.715  < 2e-16 ***
factor(Month)6                      -0.2173934  0.0230228  -9.443  < 2e-16 ***
factor(Month)7                      -0.1465509  0.0223600  -6.554 5.65e-11 ***
factor(Month)8                      -0.0658097  0.0221022  -2.978 0.002907 **
factor(Month)9                      -0.0135153  0.0222329  -0.608 0.543260
factor(Month)10                      0.0236789  0.0222437   1.065 0.287096
factor(Month)11                      0.2027230  0.0221848   9.138  < 2e-16 ***
factor(Month)12                      0.0495697  0.0221190   2.241 0.025027 *
factor(Atoll)AA                     -2.2479267  1.1151836  -2.016 0.043831 *
factor(Atoll)AD                     -3.8290138  1.1228180  -3.410 0.000650 ***
factor(Atoll)AN                     -2.3958169  1.1055948  -2.167 0.030240 *
factor(Atoll)AS                     -2.5465079  1.1956841  -2.130 0.033197 *
factor(Atoll)BA                     -2.1676340  1.3524898  -1.603 0.109007
factor(Atoll)Dh                     -1.3407357  1.2307285  -1.089 0.275990
factor(Atoll)DH                     -1.8659392  1.1153934  -1.673 0.094353 .
factor(Atoll)fa                     -1.3761434  1.2282518  -1.120 0.262545
factor(Atoll)FA                     -2.9509873  1.1229502  -2.628 0.008594 **
factor(Atoll)GA                     -0.4104776  1.2367107  -0.332 0.739958
factor(Atoll)GD                     -1.6154789  1.1214431  -1.441 0.149722
factor(Atoll)GN                     -4.3185772  1.1127634  -3.881 0.000104 ***
factor(Atoll)HA                     -1.7076492  1.2122423  -1.409 0.158939
factor(Atoll)HD                     -3.6626791  1.1531002  -3.176 0.001492 **
factor(Atoll)KA                     -2.6439174  1.1956623  -2.211 0.027022 *
factor(Atoll)KM                     -1.2785626  1.1114474  -1.150 0.250001
factor(Atoll)LA                     -2.1192332  1.1206416  -1.891 0.058618 .
factor(Atoll)LH                     -2.7918404  1.1466077  -2.435 0.014900 *
factor(Atoll)ME                     -5.6142828  1.5585842  -3.602 0.000316 ***
factor(Atoll)NO                     -2.3764783  1.2764626  -1.862 0.062641 .
factor(Atoll)RA                     -2.8628775  1.1468017  -2.496 0.012549 *
factor(Atoll)SE                     -5.1083910  1.1617188  -4.397 1.10e-05 ***
factor(Atoll)SH                     -3.3779767  1.1206268  -3.014 0.002576 **
factor(Atoll)Th                     -3.4918665  1.3411959  -2.604 0.009229 **
factor(Atoll)TH                     -2.4216302  1.0976001  -2.206 0.027367 *
factor(Atoll)VA                     -0.1063203  1.1208517  -0.095 0.924429
factor(Vessel.Cat)2                 -2.2923180  1.7563875  -1.305 0.191853
factor(Vessel.Cat)3                 -2.8840936  1.5879376  -1.816 0.069337 .
factor(Vessel.Cat)4                 -1.6386944  1.5582412  -1.052 0.292974
factor(Vessel.Cat)5                  1.2087645  0.1715447   7.046 1.86e-12 ***
factor(Vessel.Cat)6                  1.4138254  0.1743360   8.110 5.18e-16 ***
factor(Vessel.Cat)7                 -0.1239643  0.1873179  -0.662 0.508111
factor(Atoll)AA:factor(Vessel.Cat)2  0.4445990  1.8163328   0.245 0.806629
factor(Atoll)AD:factor(Vessel.Cat)2  2.6044408  1.7722652   1.470 0.141688
factor(Atoll)AN:factor(Vessel.Cat)2  0.2379075  1.7612531   0.135 0.892550
factor(Atoll)AS:factor(Vessel.Cat)2  0.6846002  1.8161345   0.377 0.706209
factor(Atoll)BA:factor(Vessel.Cat)2  0.8649579  1.9215172   0.450 0.652609
factor(Atoll)Dh:factor(Vessel.Cat)2         NA         NA      NA       NA
factor(Atoll)DH:factor(Vessel.Cat)2  0.6824671  1.7710987   0.385 0.699990
factor(Atoll)fa:factor(Vessel.Cat)2         NA         NA      NA       NA
factor(Atoll)FA:factor(Vessel.Cat)2  2.1595970  1.7958760   1.203 0.229163
factor(Atoll)GA:factor(Vessel.Cat)2  1.5531191  1.8646773   0.833 0.404896
factor(Atoll)GD:factor(Vessel.Cat)2 -0.8213443  1.8122389  -0.453 0.650392
factor(Atoll)GN:factor(Vessel.Cat)2  2.3906330  1.7597815   1.358 0.174316
factor(Atoll)HA:factor(Vessel.Cat)2  1.0389324  1.8560355   0.560 0.575646
factor(Atoll)HD:factor(Vessel.Cat)2  2.8651990  1.7857084   1.605 0.108606
```

factor(Atoll)KA:factor(Vessel.Cat)2	0.8072419	1.8139293	0.445	0.656304	
factor(Atoll)KM:factor(Vessel.Cat)2	1.8415843	1.7595836	1.047	0.295288	
factor(Atoll)LA:factor(Vessel.Cat)2	2.5082140	1.7807312	1.409	0.158980	
factor(Atoll)LH:factor(Vessel.Cat)2	2.5835773	1.7900461	1.443	0.148941	
factor(Atoll)ME:factor(Vessel.Cat)2	4.1997940	2.0849668	2.014	0.043981	*
factor(Atoll)NO:factor(Vessel.Cat)2	1.4797830	1.8719368	0.791	0.429234	
factor(Atoll)RA:factor(Vessel.Cat)2	1.2212049	1.7827699	0.685	0.493344	
factor(Atoll)SE:factor(Vessel.Cat)2	3.5417178	1.7944126	1.974	0.048415	*
factor(Atoll)SH:factor(Vessel.Cat)2	2.6293490	1.7645933	1.490	0.136214	
factor(Atoll)Th:factor(Vessel.Cat)2	NA	NA	NA	NA	
factor(Atoll)TH:factor(Vessel.Cat)2	1.1548217	1.7520982	0.659	0.509829	
factor(Atoll)VA:factor(Vessel.Cat)2	NA	NA	NA	NA	
factor(Atoll)AA:factor(Vessel.Cat)3	3.8754733	1.6005096	2.421	0.015464	*
factor(Atoll)AD:factor(Vessel.Cat)3	3.4053090	1.6019691	2.126	0.033533	*
factor(Atoll)AN:factor(Vessel.Cat)3	2.6405678	1.5889178	1.662	0.096545	.
factor(Atoll)AS:factor(Vessel.Cat)3	3.1533974	1.6527574	1.908	0.056401	.
factor(Atoll)BA:factor(Vessel.Cat)3	2.5510860	1.7670701	1.444	0.148834	
factor(Atoll)Dh:factor(Vessel.Cat)3	3.1175602	1.7074694	1.826	0.067880	.
factor(Atoll)DH:factor(Vessel.Cat)3	2.4718098	1.5949117	1.550	0.121193	
factor(Atoll)fa:factor(Vessel.Cat)3	1.1560924	1.7437012	0.663	0.507327	
factor(Atoll)FA:factor(Vessel.Cat)3	3.4103343	1.5996809	2.132	0.033021	*
factor(Atoll)GA:factor(Vessel.Cat)3	1.6557636	1.6810164	0.985	0.324639	
factor(Atoll)GD:factor(Vessel.Cat)3	2.8352217	1.5973265	1.775	0.075907	.
factor(Atoll)GN:factor(Vessel.Cat)3	3.2518267	1.5912250	2.044	0.040998	*
factor(Atoll)HA:factor(Vessel.Cat)3	2.7215765	1.6624470	1.637	0.101617	
factor(Atoll)HD:factor(Vessel.Cat)3	4.1077080	1.6193405	2.537	0.011194	*
factor(Atoll)KA:factor(Vessel.Cat)3	2.4926595	1.6500915	1.511	0.130891	
factor(Atoll)KM:factor(Vessel.Cat)3	2.5448306	1.5897613	1.601	0.109435	
factor(Atoll)LA:factor(Vessel.Cat)3	2.9877305	1.5962737	1.872	0.061255	.
factor(Atoll)LH:factor(Vessel.Cat)3	3.4475871	1.6152117	2.134	0.032810	*
factor(Atoll)ME:factor(Vessel.Cat)3	6.5449384	1.9294443	3.392	0.000694	***
factor(Atoll)NO:factor(Vessel.Cat)3	2.3405638	1.7098009	1.369	0.171033	
factor(Atoll)RA:factor(Vessel.Cat)3	3.4125608	1.6150212	2.113	0.034604	*
factor(Atoll)SE:factor(Vessel.Cat)3	6.3767947	1.6261250	3.921	8.81e-05	***
factor(Atoll)SH:factor(Vessel.Cat)3	3.6904533	1.5963507	2.312	0.020792	*
factor(Atoll)Th:factor(Vessel.Cat)3	NA	NA	NA	NA	
factor(Atoll)TH:factor(Vessel.Cat)3	3.2796939	1.5803507	2.075	0.037964	*
factor(Atoll)VA:factor(Vessel.Cat)3	NA	NA	NA	NA	
factor(Atoll)AA:factor(Vessel.Cat)4	3.0239321	1.5779993	1.916	0.055331	.
factor(Atoll)AD:factor(Vessel.Cat)4	2.8508104	1.5753144	1.810	0.070351	.
factor(Atoll)AN:factor(Vessel.Cat)4	1.8231478	1.5571751	1.171	0.241682	
factor(Atoll)AS:factor(Vessel.Cat)4	1.1171316	1.6333698	0.684	0.494014	
factor(Atoll)BA:factor(Vessel.Cat)4	1.7095304	1.7419129	0.981	0.326395	
factor(Atoll)Dh:factor(Vessel.Cat)4	-0.3927927	1.7067107	-0.230	0.817979	
factor(Atoll)DH:factor(Vessel.Cat)4	2.0276119	1.5642668	1.296	0.194910	
factor(Atoll)fa:factor(Vessel.Cat)4	1.7487202	1.7167008	1.019	0.308373	
factor(Atoll)FA:factor(Vessel.Cat)4	2.7794557	1.5701398	1.770	0.076700	.
factor(Atoll)GA:factor(Vessel.Cat)4	0.6667825	1.6521868	0.404	0.686526	
factor(Atoll)GD:factor(Vessel.Cat)4	2.1658662	1.5678373	1.381	0.167151	
factor(Atoll)GN:factor(Vessel.Cat)4	4.6520091	1.6843376	2.762	0.005748	**
factor(Atoll)HA:factor(Vessel.Cat)4	2.0849916	1.6342427	1.276	0.202026	
factor(Atoll)HD:factor(Vessel.Cat)4	3.1027912	1.5916051	1.949	0.051244	.
factor(Atoll)KA:factor(Vessel.Cat)4	1.3212045	1.6217937	0.815	0.415273	
factor(Atoll)KM:factor(Vessel.Cat)4	1.6196830	1.5601004	1.038	0.299186	
factor(Atoll)LA:factor(Vessel.Cat)4	2.2888655	1.5671520	1.461	0.144151	
factor(Atoll)LH:factor(Vessel.Cat)4	2.9082865	1.5862952	1.833	0.066751	.
factor(Atoll)ME:factor(Vessel.Cat)4	5.3082237	1.9053783	2.786	0.005340	**
factor(Atoll)NO:factor(Vessel.Cat)4	1.3350823	1.6858072	0.792	0.428391	
factor(Atoll)RA:factor(Vessel.Cat)4	2.8172278	1.5865513	1.776	0.075789	.
factor(Atoll)SE:factor(Vessel.Cat)4	5.7052313	1.5974416	3.571	0.000355	***
factor(Atoll)SH:factor(Vessel.Cat)4	2.9969001	1.5672339	1.912	0.055853	.
factor(Atoll)Th:factor(Vessel.Cat)4	2.7080284	1.7740242	1.526	0.126894	
factor(Atoll)TH:factor(Vessel.Cat)4	2.5764766	1.5515558	1.661	0.096804	.
factor(Atoll)VA:factor(Vessel.Cat)4	NA	NA	NA	NA	
factor(Atoll)AA:factor(Vessel.Cat)5	0.2216919	0.2788322	0.795	0.426575	
factor(Atoll)AD:factor(Vessel.Cat)5	-0.5259806	0.2926818	-1.797	0.072324	.
factor(Atoll)AN:factor(Vessel.Cat)5	-0.6443735	0.1966923	-3.276	0.001053	**
factor(Atoll)AS:factor(Vessel.Cat)5	-1.1854362	0.6551019	-1.810	0.070372	.
factor(Atoll)BA:factor(Vessel.Cat)5	-1.6572816	0.8300817	-1.997	0.045881	*
factor(Atoll)Dh:factor(Vessel.Cat)5	-2.2874471	0.7836290	-2.919	0.003513	**
factor(Atoll)DH:factor(Vessel.Cat)5	-2.6348702	0.2702312	-9.750	< 2e-16	***
factor(Atoll)fa:factor(Vessel.Cat)5	NA	NA	NA	NA	
factor(Atoll)FA:factor(Vessel.Cat)5	1.2063139	0.2797934	4.311	1.62e-05	***
factor(Atoll)GA:factor(Vessel.Cat)5	-1.6241312	0.5744875	-2.827	0.004699	**
factor(Atoll)GD:factor(Vessel.Cat)5	-0.3267524	0.2442915	-1.338	0.181048	
factor(Atoll)GN:factor(Vessel.Cat)5	2.0405740	0.3007344	6.785	1.17e-11	***
factor(Atoll)HA:factor(Vessel.Cat)5	-0.5072211	0.5202375	-0.975	0.329575	

```
factor(Atoll)HD:factor(Vessel.Cat)5 -1.4104716  0.4388580  -3.214 0.001310 **
factor(Atoll)KA:factor(Vessel.Cat)5 -2.2486043  0.4833813  -4.652 3.30e-06 ***
factor(Atoll)KM:factor(Vessel.Cat)5 -0.7838537  0.1885006  -4.158 3.21e-05 ***
factor(Atoll)LA:factor(Vessel.Cat)5 -0.2696322  0.2477101  -1.088 0.276380
factor(Atoll)LH:factor(Vessel.Cat)5  0.6055847  0.3439809   1.761 0.078326 .
factor(Atoll)ME:factor(Vessel.Cat)5  3.7379594  1.1099980   3.368 0.000759 ***
factor(Atoll)NO:factor(Vessel.Cat)5 -0.8859386  0.7500574  -1.181 0.237544
factor(Atoll)RA:factor(Vessel.Cat)5  0.1715610  0.3417955   0.502 0.615711
factor(Atoll)SE:factor(Vessel.Cat)5  3.1451138  0.3902106   8.060 7.78e-16 ***
factor(Atoll)SH:factor(Vessel.Cat)5  0.0107035  0.2516525   0.043 0.966074
factor(Atoll)Th:factor(Vessel.Cat)5  0.4033595  0.8120079   0.497 0.619372
factor(Atoll)TH:factor(Vessel.Cat)5         NA         NA      NA       NA
factor(Atoll)VA:factor(Vessel.Cat)5         NA         NA      NA       NA
factor(Atoll)AA:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)AD:factor(Vessel.Cat)6  1.4010726  1.1228208   1.248 0.212104
factor(Atoll)AN:factor(Vessel.Cat)6 -1.8775891  0.2392505  -7.848 4.31e-15 ***
factor(Atoll)AS:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)BA:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)Dh:factor(Vessel.Cat)6 -1.7111644  0.9564385  -1.789 0.073604 .
factor(Atoll)DH:factor(Vessel.Cat)6 -2.1519813  0.3014269  -7.139 9.50e-13 ***
factor(Atoll)fa:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)FA:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)GA:factor(Vessel.Cat)6 -1.8548436  0.5758202  -3.221 0.001277 **
factor(Atoll)GD:factor(Vessel.Cat)6 -0.0483206  0.2467937  -0.196 0.844773
factor(Atoll)GN:factor(Vessel.Cat)6  1.4199099  0.2565602   5.534 3.14e-08 ***
factor(Atoll)HA:factor(Vessel.Cat)6 -0.7999735  0.5262807  -1.520 0.128504
factor(Atoll)HD:factor(Vessel.Cat)6 -2.7563138  1.1531034  -2.390 0.016836 *
factor(Atoll)KA:factor(Vessel.Cat)6 -0.9893469  0.5009686  -1.975 0.048288 *
factor(Atoll)KM:factor(Vessel.Cat)6 -0.7301943  0.1932434  -3.779 0.000158 ***
factor(Atoll)LA:factor(Vessel.Cat)6 -0.3749812  0.2431781  -1.542 0.123079
factor(Atoll)LH:factor(Vessel.Cat)6 -0.0972519  0.3998058  -0.243 0.807814
factor(Atoll)ME:factor(Vessel.Cat)6  3.9839280  1.2122286   3.286 0.001015 **
factor(Atoll)NO:factor(Vessel.Cat)6  0.7933032  0.7109352   1.116 0.264488
factor(Atoll)RA:factor(Vessel.Cat)6  0.4505676  0.3537843   1.274 0.202823
factor(Atoll)SE:factor(Vessel.Cat)6  2.8975975  0.3906810   7.417 1.22e-13 ***
factor(Atoll)SH:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)Th:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)TH:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)VA:factor(Vessel.Cat)6         NA         NA      NA       NA
factor(Atoll)AA:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)AD:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)AN:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)AS:factor(Vessel.Cat)7 -0.9189260  0.5662019  -1.623 0.104603
factor(Atoll)BA:factor(Vessel.Cat)7 -0.4193023  0.8011403  -0.523 0.600711
factor(Atoll)Dh:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)DH:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)fa:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)FA:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)GA:factor(Vessel.Cat)7 -0.2250592  0.5835539  -0.386 0.699743
factor(Atoll)GD:factor(Vessel.Cat)7  0.8505481  0.2580186   3.296 0.000980 ***
factor(Atoll)GN:factor(Vessel.Cat)7  0.3499595  0.2873079   1.218 0.223205
factor(Atoll)HA:factor(Vessel.Cat)7  0.0007039  0.5292018   0.001 0.998939
factor(Atoll)HD:factor(Vessel.Cat)7  1.0641789  0.3801063   2.800 0.005117 **
factor(Atoll)KA:factor(Vessel.Cat)7 -0.2223093  0.4902613  -0.453 0.650226
factor(Atoll)KM:factor(Vessel.Cat)7  0.1555319  0.2032755   0.765 0.444198
factor(Atoll)LA:factor(Vessel.Cat)7  0.4164987  0.2578848   1.615 0.106304
factor(Atoll)LH:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)ME:factor(Vessel.Cat)7  3.6925625  1.1147852   3.312 0.000926 ***
factor(Atoll)NO:factor(Vessel.Cat)7 -0.0202020  0.6723314  -0.030 0.976029
factor(Atoll)RA:factor(Vessel.Cat)7  0.3689138  0.3560161   1.036 0.300100
factor(Atoll)SE:factor(Vessel.Cat)7  4.0975132  0.4049218  10.119  < 2e-16 ***
factor(Atoll)SH:factor(Vessel.Cat)7  0.9276368  0.2589260   3.583 0.000340 ***
factor(Atoll)Th:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)TH:factor(Vessel.Cat)7         NA         NA      NA       NA
factor(Atoll)VA:factor(Vessel.Cat)7         NA         NA      NA       NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for gaussian family taken to be 1.198861)

    Null deviance: 104301  on 54591  degrees of freedom
Residual deviance:  65236  on 54415  degrees of freedom
AIC: 165006

Number of Fisher Scoring iterations: 2
```

Appendix 3: Model 3 Results (FAD Effects)

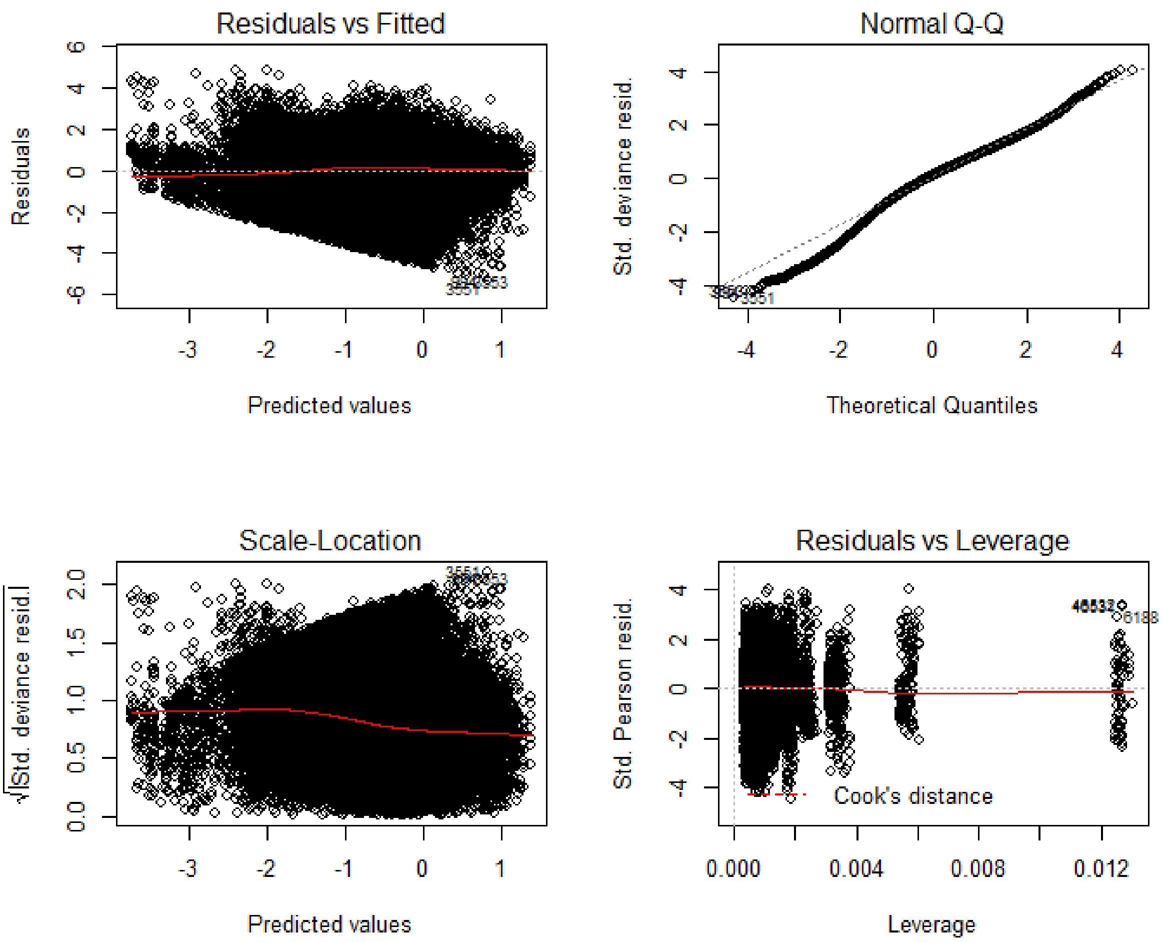


Figure 2: Residual Diagnostics of the FAD effects model on broader spatial resolution

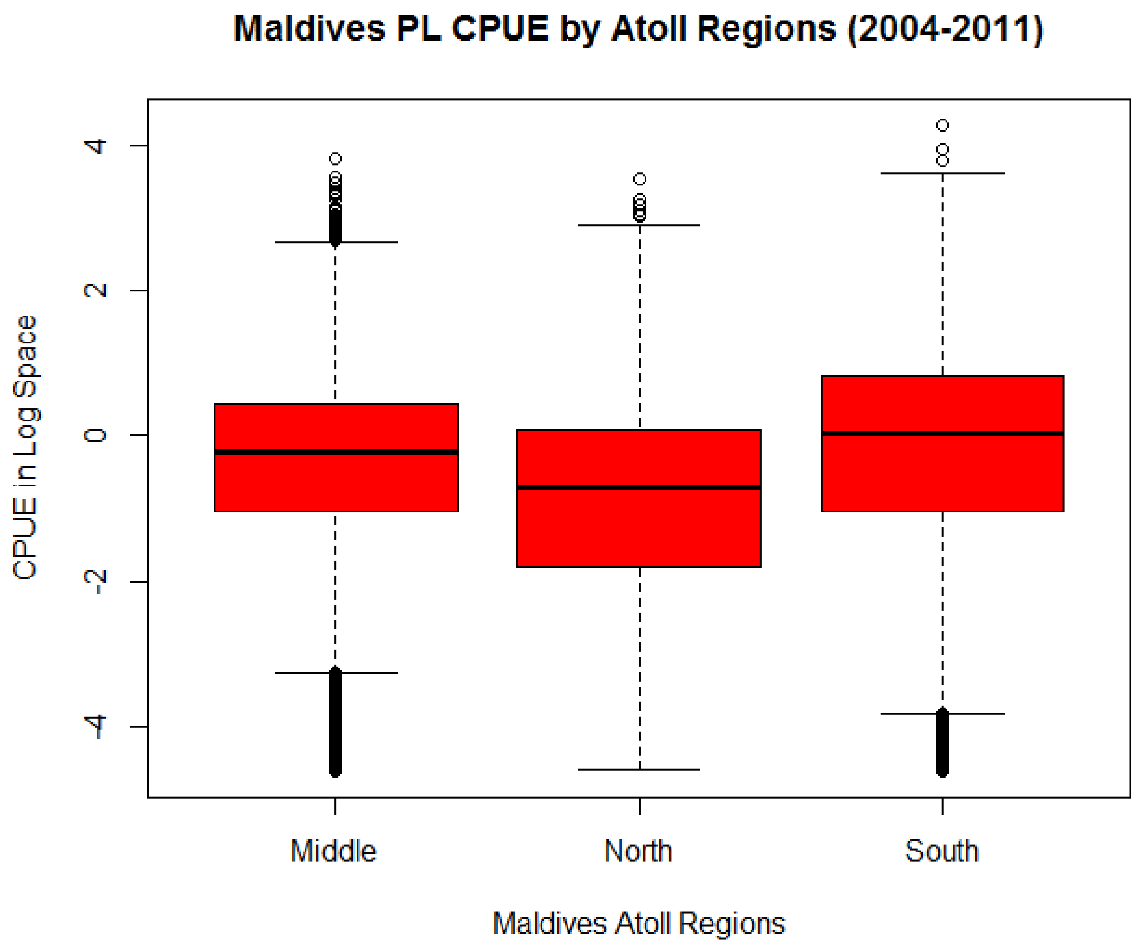


Figure 3: Log CPUE rates by different regions

Table 3: ANOVA on the model with FAD and broader spatial Area effects

Response: log(CPUE)
Terms added sequentially (first to last)

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)	
NULL			54591	104301			
factor(Year)	7	1775.3	54584	102525	176.461	< 2.2e-16	***
factor(Month)	11	896.8	54573	101629	56.728	< 2.2e-16	***
factor(Vessel.Cat)	6	18666.6	54567	82962	2164.678	< 2.2e-16	***
factor(FADREG2)	2	1456.9	54565	81505	506.857	< 2.2e-16	***
Region_FAD	1	122.3	54564	81383	85.065	< 2.2e-16	***
factor(Vessel.Cat):factor(FADREG2)	12	2553.7	54552	78829	148.069	< 2.2e-16	***
factor(FADREG2):Region_FAD	2	429.2	54550	78400	149.320	< 2.2e-16	***

Table 4: Summary of Model Parameter values

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-0.745629	0.087126	-8.558	< 2e-16	***
factor(Year)2005	0.162523	0.018654	8.713	< 2e-16	***
factor(Year)2006	0.135893	0.020022	6.787	1.16e-11	***
factor(Year)2007	-0.207825	0.023984	-8.665	< 2e-16	***
factor(Year)2008	-0.290225	0.033341	-8.705	< 2e-16	***
factor(Year)2009	-0.391580	0.039231	-9.981	< 2e-16	***
factor(Year)2010	-0.624690	0.047456	-13.164	< 2e-16	***
factor(Year)2011	-0.907488	0.055081	-16.476	< 2e-16	***

```
factor(Month)2                       -0.114017   0.023651  -4.821 1.43e-06 ***
factor(Month)3                       -0.212601   0.023877  -8.904  < 2e-16 ***
factor(Month)4                       -0.124305   0.025441  -4.886 1.03e-06 ***
factor(Month)5                       -0.279477   0.025833 -10.818  < 2e-16 ***
factor(Month)6                       -0.279000   0.025902 -10.771  < 2e-16 ***
factor(Month)7                       -0.181333   0.024713  -7.338 2.21e-13 ***
factor(Month)8                       -0.122415   0.024507  -4.995 5.90e-07 ***
factor(Month)9                       -0.070128   0.024704  -2.839  0.00453 **
factor(Month)10                      -0.047885   0.025174  -1.902  0.05716 .
factor(Month)11                       0.152057   0.024763   6.140 8.29e-10 ***
factor(Month)12                      -0.006228   0.025049  -0.249  0.80365
factor(Vessel.Cat)2                  -1.690007   0.078910 -21.417  < 2e-16 ***
factor(Vessel.Cat)3                  -0.292900   0.067860  -4.316 1.59e-05 ***
factor(Vessel.Cat)4                   0.096971   0.068215   1.422  0.15516
factor(Vessel.Cat)5                   0.431497   0.069954   6.168 6.95e-10 ***
factor(Vessel.Cat)6                   0.650161   0.073662   8.826  < 2e-16 ***
factor(Vessel.Cat)7                  -0.024128   0.070569  -0.342  0.73242
factor(FADREG2)N                     -0.649589   0.165893  -3.916 9.02e-05 ***
factor(FADREG2)S                     -0.986563   0.121749  -8.103 5.46e-16 ***
Region_FAD                            0.026258   0.002817   9.322  < 2e-16 ***
factor(Vessel.Cat)2:factor(FADREG2)N  1.551536   0.158207   9.807  < 2e-16 ***
factor(Vessel.Cat)3:factor(FADREG2)N  0.967186   0.149527   6.468 1.00e-10 ***
factor(Vessel.Cat)4:factor(FADREG2)N  1.250361   0.151095   8.275  < 2e-16 ***
factor(Vessel.Cat)5:factor(FADREG2)N  1.488228   0.152029   9.789  < 2e-16 ***
factor(Vessel.Cat)6:factor(FADREG2)N  1.591257   0.164573   9.669  < 2e-16 ***
factor(Vessel.Cat)7:factor(FADREG2)N  0.663635   0.154775   4.288 1.81e-05 ***
factor(Vessel.Cat)2:factor(FADREG2)S  1.191119   0.128061   9.301  < 2e-16 ***
factor(Vessel.Cat)3:factor(FADREG2)S  1.245017   0.113331  10.986  < 2e-16 ***
factor(Vessel.Cat)4:factor(FADREG2)S  2.142810   0.114773  18.670  < 2e-16 ***
factor(Vessel.Cat)5:factor(FADREG2)S  2.259765   0.114092  19.807  < 2e-16 ***
factor(Vessel.Cat)6:factor(FADREG2)S  2.256857   0.116871  19.311  < 2e-16 ***
factor(Vessel.Cat)7:factor(FADREG2)S  2.527398   0.120297  21.010  < 2e-16 ***
factor(FADREG2)N:Region_FAD          -0.040987   0.006124  -6.693 2.21e-11 ***
factor(FADREG2)S:Region_FAD          -0.037490   0.002231 -16.808  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for gaussian family taken to be 1.437212)

    Null deviance: 104301  on 54591  degrees of freedom
Residual deviance:  78400  on 54550  degrees of freedom
AIC: 174770

Number of Fisher Scoring iterations: 2
```