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Decomposing purse seine CPUEs to estimate an abundance index for yellowfin free-swimming schools in the Indian Ocean during 1981– 2011

E Chassot[a,*], L. Dubroca[a], A. Delgado de Molina[b], C. Assan[c], M. Soto[b], L. Floch[a], Fonteneau A.[a]

[a] *Institut de Recherche pour le Développement, UMR 212 EME (IRD/Ifremer/Université de Montpellier 2)*
Avenue Jean Monnet, BP 171, 34 203 Sète Cedex, FRANCE
[b] *Instituto Español de Oceanografia, PO Box 1373, S/C Tenerife, SPAIN*
[c] *Seychelles Fishing Authority, BP 570, Victoria, SEYCHELLES*

Abstract

The current stock assessment of yellowfin tuna in the Indian Ocean does not include any abundance index derived from purse seine fishing. The overall objective of the analysis was to assess whether temporal changes in yellowfin population abundance in the Indian Ocean could be related to changes in the number or/and the size of tuna schools. Three indices of catch per unit effort (CPUE) were considered for the European purse seine fleet fishing on free-swimming schools during 1981-2011 so as to decompose tuna abundance and vessel fishing power. First, the number of sets per searching day was considered to model the number of schools and the ability to detect tuna schools. Second, the proportion of successful sets was used to model the ability to succeed in the set. Third, the yellowfin catch per positive set was used as a proxy of the size of the schools and the ability to maximise the catch from the school. GLM analyses were performed to standardize the annual time series of CPUE by considering a vessel effect and a spatio-temporal effect. Model results suggested a significant decrease in the number of free-swimming schools of yellowfin since the early 1980s. Meanwhile, the size of the schools did not show any temporal pattern. More recent vessels appeared to favour school detection while the purse seiner length resulted in better ability to catch larger schools. Model diagnostics indicate strong departure from underlying assumptions and call for changes in the model error structures to improve fitting and predictions.

Keywords: free-swimming school, purse seine fishing, *Thunnus albacares*

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[*] Corresponding author
Email address: `Emmanuel.Chassot@ird.fr` (E Chassot)

1. Introduction

Most assessment models of tropical tunas only include information on the changes in stock abundance through time series of commercial catch per unit of effort (CPUE) collected from longline fishing. The main reasons that impair the use of abundance indices derived from purse seine (PS) fishing are threefold. First, purse seiners are characterized by constant and non-linear changes in fishing technology over time that is aimed at improving school detection (e.g. satellite imagery, bird radars, helicopters), fish accessibility (e.g. increased vessel size and speed, deeper and faster nets), and catchability (e.g. FADs) (Gaertner & Pallarés 2002, ISSF 2012). Second, purse seiner CPUEs tend to poorly represent local abundance due to their high mobility that allow them to quickly reallocate effort to productive areas (Walters 2003, Carruthers et al. 2011). Local aggregations of purse seiners in productive fishing grounds generate high catches associated with high levels of effort, but only moderate CPUE values, yielding a weak link between abundance and CPUE values. Third, PS fisheries target multispecies schools characterized by a size-dependent associative behaviour and a high spatio-temporal patchiness which seem to be related to both environmental conditions (Fiedler et al. 1987, Fonteneau et al. 2008) and ethological processes (Fréon & Dagorn 2000) but remain poorly understood.

Moreover, PS fishing strategies have been substantially modified by the increasing use of artificial drifting fish aggregating devices (FADs) worldwide over the last two decades (Fonteneau et al. 2000, Dagorn et al. 2012). FAD-fishing effort has been mainly dedicated to the construction and deployment of FADs and the improvement in their geo-location as well as to the recent development of satellite-tracked echo-sounder fish finder units attached to the floating objects. Consequently, the traditional PS nominal effort based on fishing time or searching time (i.e. time devoted to the searching of tuna concentrations and schools) appears not consistent to measure an overall PS fishing effort that is expected to be proportional to the fishing mortality exerted on tuna populations.

The European PS fishing fleet of the Indian Ocean (IO) has been targeting yellowfin tuna since the early 1980s through two major fishing modes which result in different species and size compositions of the catch (Floch et al. 2012). Purse seine fishing currently contributes to 40% of the total catch of yellowfin tuna in the IO which exceeded 520,000 t in 2004 and have been estimated at an annual mean of 375,000 t over the last decade. Regarding the complexity of PS fishing effort, current assessment models for the IO stock of yellowfin only include abundance indices derived from Asian longline fisheries (Langley et al. 2011). The inclusion of information from PS appears however essential with regards to the differences in catchability and fishing patterns between longline and PS and the contraction of longline fisheries in recent years.

Here, we focus on the European PS fishery targeting free-swimming schools (FSC) of tropical tunas which has contributed to 60% of the total PS catch of yellowfin during 1981-2011 and represents the large majority of the large yellowfin caught (i.e. >80 cm) (Floch et al. 2012).

The FSC fishery is active all over the year with 2 major seasons (Nov-Feb and Jun-Jul) that correspond to the periods of aggregations of yellowfin for spawning (Stéquert et al. 2001, Zudaire et al. 2010). Tuna abundance results from both the combination of the number of schools and the size of the schools and improvements in fishing technology have generally concerned either one or the other of these 2 components. The objective of the present analysis was to use the comprehensive datasets that have been collected since the beginning of the PS fishery to investigate for changes in the abundance of yellowfin during the last 3 decades. The originality of our modelling approach lies in the decomposition of the fishing power into 3 components described through different CPUE time series: (i) the ability to detect tuna schools through the number of sets per searching day ($CPUE_1$), (ii) the ability to succeed in catching the fish through the proportion of positive sets ($CPUE_2$), and (iii) the ability to catch a large amount of fish through the biomass caught per positive set ($CPUE_3$). While $CPUE_1$ would give insights into the number of yellowfin schools, $CPUE_3$ is expected to provide information on the spatio-temporal variability in the yellowfin school size. In addition, another objective of the analysis was to explain the relative vessel-specific fishing power with their technical attributes to describe the changes in the overall power of the fleet.

2. Materials & Methods

2.1. Fisheries data

The European (and associated flags) purse seine fishing activities have been monitored by the Institut de Recherche pour le Développement (IRD), the Instituto Español de Oceanografia (IEO) and the Seychelles Fishing Authority (SFA) in the Indian Ocean during 1981-2011 through the collection of logbook, well maps, and records of unloading and transhipment (Armas et al. 1998, Pianet et al. 1999). Data processing has been done in a consistent way since 1981 and mainly consists of: (i) correcting for the species composition of the catch for the 3 principal market tunas through size-species samples collected at unloading and (ii) adjusting total catch declared in the logbooks to the commercial landings on a trip basis (Pallarés & Hallier 1997). The influence of the data processing on the estimation of landings for large yellowfin caught on free-swimming schools is expected to be low as the correction in species composition mainly concerns juveniles of tunas caught on FAD-associated schools (Pallarés & Hallier 1997). As opposed to the Atlantic Ocean, the information on the fishing mode (i.e. log/FAD-associated vs. free-swimming school) has been collected from the logbooks since the beginning of the fishery.

2.2. CPUE indices

Searching time (days) was computed by subtracting the time spent setting the gear from the fishing time. The time spent setting the gear was estimated by regressions linking duration and size of sets, from at-sea measurements made by scientific observers. Searching time can not be distinguished between fishing on FAD-associated schools and free-swimming schools. Although it might overestimate the nominal effort, all searching time was assumed here to be devoted to free-swimming schools since purse seiners always search for such schools, even during the season predominated by FAD-fishing. Purse seiners that spent at least 5 years in the Indian Ocean during 1981-2011 with a minimum of 100 d y^{-1} every year were selected for consistency reasons, e.g. to reduce variability due to inexperienced skippers. The core areas of fishing on free-swimming schools were considered in the analysis: South Somali, Northwest Seychelles, Southeast Seychelles, and Maldives-Chagos (Pallarés & Hallier 1997; Fig. 1). The Mozambique Channel is also characterized by major fishing activities on free-swimming schools but skipjack is preponderant in the catch. The selection process resulted in the removal of about 40 purse seiners from the analysis but the remaining vessels represented most of the fishing activities and catch of the whole purse seine fleet (Table 1). The number of sets per searching day (CPUE_1) was used as a proxy of the number of tuna schools (i.e. school abundance/density) and the ability to detect them. The proportion of successful sets, i.e. the ratio of the number of sets that resulted in fish catch over the total number of sets (CPUE_2) was used to quantify the ability of the vessels to capture the school. Particuliar environmental conditions or fish behaviour could favor fish vulnerability in some strata. Finally, the amount of yellowfin catch (t) per positive set (CPUE_3) was used as a proxy of the size of the school and the ability to maximise the catch from the school.

2.3. Vessel attributes

The TURBOBAT database has been maintained by the IRD, IEO, and SFA since 1981 and describes technical attributes of the European purse seiners of the Indian Ocean since 1981. Here, we used the initial year of service (YOS) of the vessels, their length overall (LOA), and fish carrying capacity (CC) to investigate for relationships with the relative vessel-specific fishing power assumed constant over time and estimated from CPUE analyses (see Section 2.4).

2.4. Modelling approach

Generalized linear modelling (McCullagh and Nelder 1989) approaches were used to model observed CPUEs as a function of vessel, i.e. individual fishing power assumed constant over time, and spatio-temporal strata, i.e. factors combining year, month, and area of fishing. Replacing individual fishing powers by a function of vessel attributes that appear pertinent (e.g. carrying capacity) is appealing and can be useful for reducing the number of parameters to estimate. However, this approach results in most cases in a poor predictive capacity of the individual vessel power based on its known characteristics. Although the relationships between fishing power and attributes can be useful for input-based management measures or for understanding the overall trends in effort and capacity, the estimation of variations in apparent abundance is largely improved when using direct estimates of individual vessel fishing power (Robson 1966, Laurec 1977). Interactions between spatial, annual, and monthly factors were included in the model through the 'stratum' effect since the spatial distribution of yellowfin abundance in the Indian Ocean has been shown for some time to be non stationary over seasons and years (Floch et al. 2012).

The model for CPUE_1 was built assuming a delta distribution for the number of sets per searching day. A binomial distribution with logit link for the presence of tuna schools was coupled with a lognormal distribution for school density when schools were present. The abundance index was obtained as the product of the annual effect of the 'LSMeans' of the lognormal and binomial models (Stefanson 1996). Variance of the indices were calculated using the Delta method assuming that both estimators are independent (Casella and Berger 2002). A bias correction was applied to the lognormal estimates (Laurent 1963). CPUE_2 data giving the probability of set success were assumed to follow a binomial distribution. CPUE_3 observations of yellowfin catch per positive set were assumed to follow a lognormal distribution. Parameter inference was conducted using maximum likelihood estimation and models evaluations and diagnoses were carried out through residual analysis (McCullagh and Nelder 1989). All statistical analyses were performed using freeware and open-source R software (R Development Core Team 2012).

3. Results

3.1. Spatio-temporal patterns in effort and catch

The main fishing areas for yellowfin caught on free-swimming schools are the Northwest and Southeast Seychelles between the equator and 10°S (Figs. 1 and 3). The nominal fishing effort in searching days has increased over time in the South Somali area but it resulted in small catches of yellowfin since this area is mainly characterized by FAD-fishing (Fig. 2; Floch et al. 2012). The effort has also increased in the northwest of the Seychelles over time until 2007 and strongly decreased since then. Meanwhile, the effort has steadily decreased in the area southeast of the Seychelles since the mid-1980s to a minimum of about 1,300 searching days in 2010-2011. The effort in the Maldives-Chagos area has remained low during 1981-2011 with small catches of yellowfin (Fig. 2-3). The abnormally high catches observed at 0.3°N and 56°E were not made on free-swimming schools but correspond to tuna schools assiocated with the Travin Bank seamount (Fig. 1).

3.2. School abundance

The 4 areas were described by strong differences in the presence and density of tuna schools (Figs. 4-5). The bimonial component of the CPUE_1, i.e. the proportion of searching days with fishing sets which indicated the presence of tuna schools, showed that the probability of finding tuna schools per day was higher in the southeast of the Seychelles and in the areas of the Maldives-Chagos (proportion > 0.8) than in South Somali and northwest Seychelles. The proportion of days with school detection showed an apparent decrease in the South Somali area and in the southeast of the Seychelles over time (Fig. 4). Meanwhile, the northwest of the Seychelles was characterized by a relative stability during 1984-2011 with a decrease during 1999-2000 and an increase during 2003-2005 (Fig. 5). The probability of detecting schools in the Chagos area was high but described by high interannual variability. The lognormal component of CPUE_1 showed that the number of schools detected per searching day was on average higher in the southeast than in the northwest of the Seychelles (Fig. 5). It showed a decrease in South Somali during 1986-2002 and was quite high (> 0.8 set d^{-1}) during 2005-2008. It was highly variable in the Chagos area during 1981-2011.

Whatever the fishing area and period, no major difference was found between purse seiners in their ability to detect the presence of tuna schools per searching day. The first component of the model for CPUE_1 was mainly explained by the 'stratum' effect while the 'vessel' effect only contributed to 2% of the total deviance explained (Table 2). The effect of the vessels, i.e. power of detection, was more pronounced with regards to the density of schools detected per searching day and represented about 5% of the total deviance explained. Model predictions showed a decrease in the CPUE_1 in the 2 principal areas of fishing on free-swimming schools around the Seychelles (Fig. 7). Overall yearly predictions of CPUE_1 indicated a significant decrease in the abundance of yellowfin free-swimming schools during 1981-2011 (adjusted's r = 0.71, slope = -1.7%; p-value < 0.001; Fig. 8).

3.3. School size

Observed levels of CPUE_3, i.e. catch of yellowfin per positive set, were quite similar between the 4 areas of interest, with smaller values in South Somali. The annual time series of CPUE_3 were shown to be stable over time in South Somali and the northwest of Seychelles (Fig. 11). It showed an apparent slow increase in the southeast of the Seychelles and more variability in the Maldives-Chagos area. The vessel and stratum effects were found to significantly explain the observed CPUE_3 (Table 2). When accounting for differences in vessels and monthly and spatial variaitons, the annual mean values of CPUE_3 predicted by the model were found to be very stable over 1981-2011 with high uncertainty for predictions for the upper confidence interval (Fig. 12). Model residuals showed strong patterns in the variance which indicated that the assumption of homoscedasticity was violated.

3.4. Fishing power

3.4.1. Power of detection

No significant difference was found between the Spanish and the French purse seiners in the ability to detect tuna schools. The purse seiner power of detection steadily increased with the age of the vessels. The individual power derived from the analysis of CPUE_1 was found to be significantly positively related with the initial year of service of the purse seiners (slope = +0.8% y^{-1}, p-value < 0.001) (Fig. 13). The power of detection was related to the length of the vessels. The minimum power of detection did not vary with LOA, i.e. large vessels could have poor ability in detecting the tuna schools. By contrast, the maximum power of detection of the vessels was found to increase with LOA, indicating that the maximum power of detection was observed for the largest vessels (Fig. 14).

3.4.2. Power of set success

The probability of succeeding in a set was shown to significantly vary between vessels and strata (Table 2). No significant difference was found between French and Spanish vessels in this fishing power component. The minimum level of relative power, approximated by the 10% quantile regression model, was found to increase with vessel length(Fig. 15). This suggests that increasing vessel length would decrease the probability of missing a fishing set, likely through the vessel speed which enables to reduce the time required to close the net.

3.4.3. Power of capture

No difference was found between the French and Spanish components of the European purse seine fleet in the power to capture the school. No relation was found between the vessel-specific relative power and the age of the vessels. The power was shown to be characterized by a high variability with length. The minimum levels of yellowfin catch per positive set, approximated by the 10% quantile regression model, were however shown to significantly increase with vessel length (slope = 0.054, p-value < 0.05) (Fig. 16).

4. Discussion

4.1. Major points

Our results show that the decomposition of purse seine CPUEs into 3 components appears useful to provide information on the changes in apparent tuna abundance and fishing power. While the modelling of the number of sets per day aims to describe the spatio-temporal changes in the apparent abundance of the number of schools, the catch of yellowfin per positive set provides information on the size of free-swimming schools. Accounting for differences in vessel-specific fishing power and spatio-seasonal variations, our findings suggest that the number of schools has decreased during 1981-2011 while the mean size of the schools has remained stable over time. This indicates that the annual time series of standardised CPUE_1 might provide a useful index of tuna abundance for the assessment of yellowfin with regards to the contraction of longline fisheries in the recent years and the non availability of CPUEs for 2011 in the 2012 assessment. Current results are still preliminary and call for improvements in the statistical modelling approach as well as for sensitivity analyses to some modelling choices (see section 4.3).

4.2. Changes in fishing power

Our modelling approach enables to estimate the different components of the fishing power of the vessels, i.e. detection, success, and catch. Our results show that the European purse seiners have exhibited a significant increase in their ability to detect tuna schools over time. This corresponds to an average increase of 8% per decade despite the fact that old vessels are constantly updated with devices to remain efficient. Vessel length appears to increase the fishing power of detection by increasing the maximum number of schools encountered on a daily basis. This might be linked to the the vessel speed which is highly correlated with vessel size. Vessel length also appears to have an impact on the rates of success of fishing on free-swimming schools, likely again due to the vessel speed. Finally, while the power in catching the school highly varies between purse seiners, larger vessels appear to be able to have higher minimum levels of catch per set than small oners.

4.3. Perspectives

The diagnostics conducted for the statistical models applied to observed CPUEs indicate strong departure from underlying assumptions which calls for model improvements through changes in the error structures (i.e. quasi-Poisson distribution for CPUE_1). In addition, removing the Maldives-Chagos area might improve predictions since this area has shown high interannual variability in the effort and catch over time which might be related to yellowfin migrations and environmental conditions. Similarly, the South Somali area has been a major area for FAD-fishing and searching time might then not fully represent the nominal effort devoted to free-swimming schools. Including a co-variate such as the proportion of FAD sets could enable to account for searching time devoted to FAD-fishing, particularly in the recent years where the strategy of purse seiners seem to have changed (Floch et al. 2012). A sensitivity analysis to the criteria used for vessel selection (i.e. 100 days and 5 years) would also be useful to assess the robustness of the results.

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5. Tables

Table 1: Representativeness of selected data. Cumulated number of vessels, fishing effort (searching days), number of sets and positive sets (i.e. with catch), and yellowfin catch (t) on free-swimming schools for the whole European purse seine fleet of the Indian Ocean during 1981-2011 and for the fleet subset selected in the analysis

	Vessels	Effort	Sets	Positive sets	Catch
All data	118	266,265	139,077	74,312	1,800,000
Selected data	79	247,336	128,985	69,153	1,700,000
Representativeness	67%	93%	93%	93%	95%

Table 2: Deviance tables for CPUEs. Degrees of freedom (df), percentage of deviance explained, and *p*-values for the 3 CPUE models. The delta-model for CPUE_1 combines (i) a binomial distribution with logit link for the presence of tuna schools (i.e. proportion of days with sets) and (ii) a lognormal distribution for school density (i.e. number of sets per day) when schools were present. Error structures for CPUE_2 and CPUE_3 are binomial and lognormal, respectively

Factor	Df	% Dev.	*p*-value
CPUE_1			
Comp. 1: Prop. d with sets			
Vessel	78	2%	< 0.001
Stratum	1,192	98%	< 0.001
Comp. 2: Number sets d^{-1}			
Vessel	78	5.1%	< 0.001
Stratum	1,192	94.9%	< 0.001
CPUE_2			
Vessel	78	16.3%	< 0.001
Stratum	974	83.7%	< 0.001
CPUE_3			
Vessel	78	6.8%	< 0.001
Stratum	894	93.2%	< 0.001

6. Figures

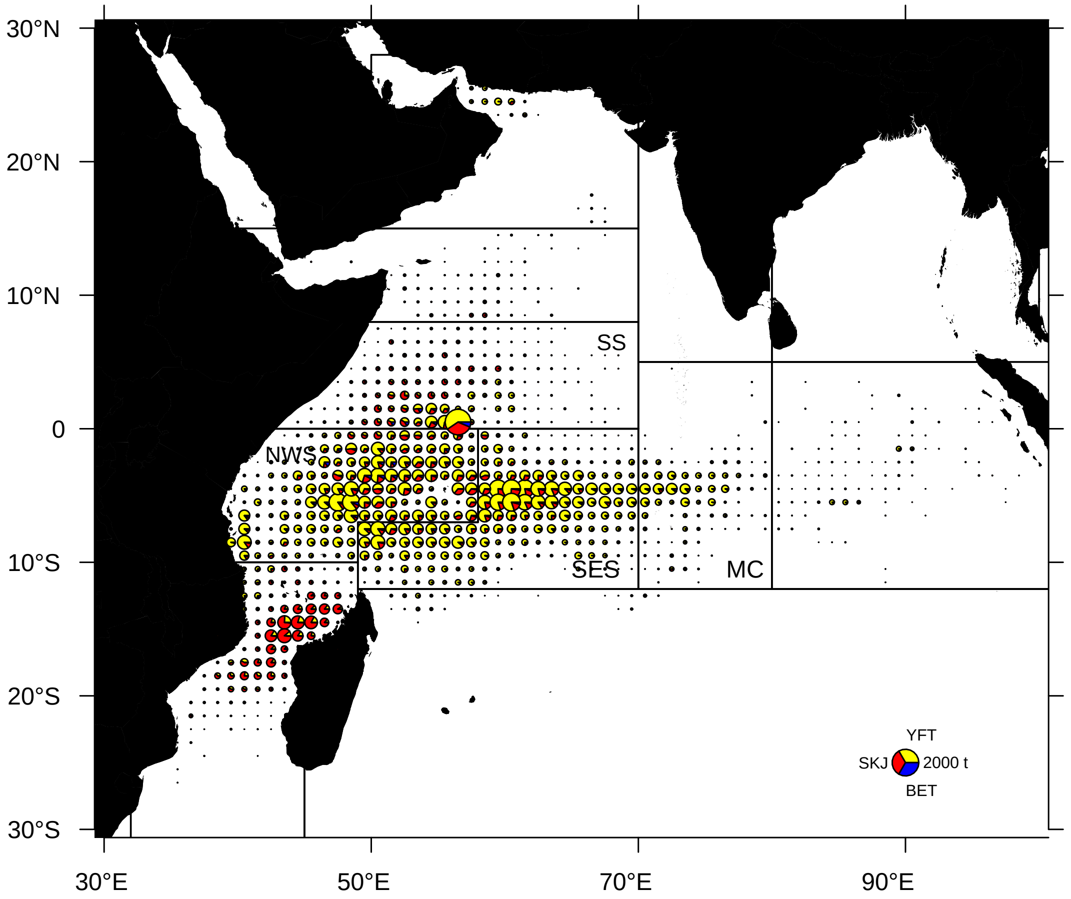

Figure 1: **Distribution of the fishery catches**. Mean annual catch by species on free-swimming schools by the European purse seine fishing fleet during 1981-2011. YFT = yellowfin; SKJ = skipjack; BET = bigeye tuna. SS = South Somali; NWS = Northwest Seychelles; SES = Southeast Seychelles; MC = Maldives-Chagos

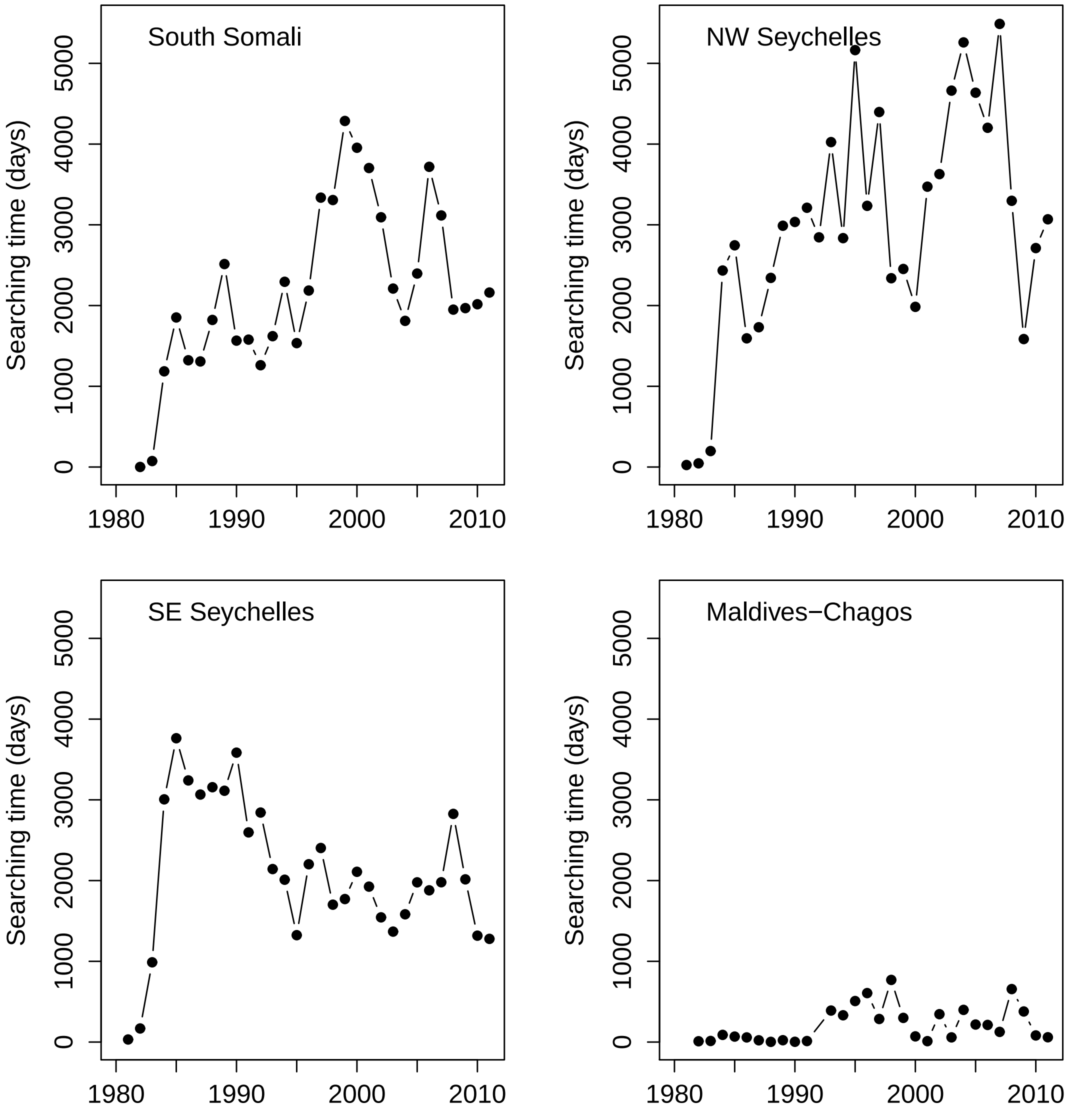

Figure 2: **Purse seine fishery nominal effort**. Annual fishing effort (searching days) for the European purse seine fishing fleet in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011

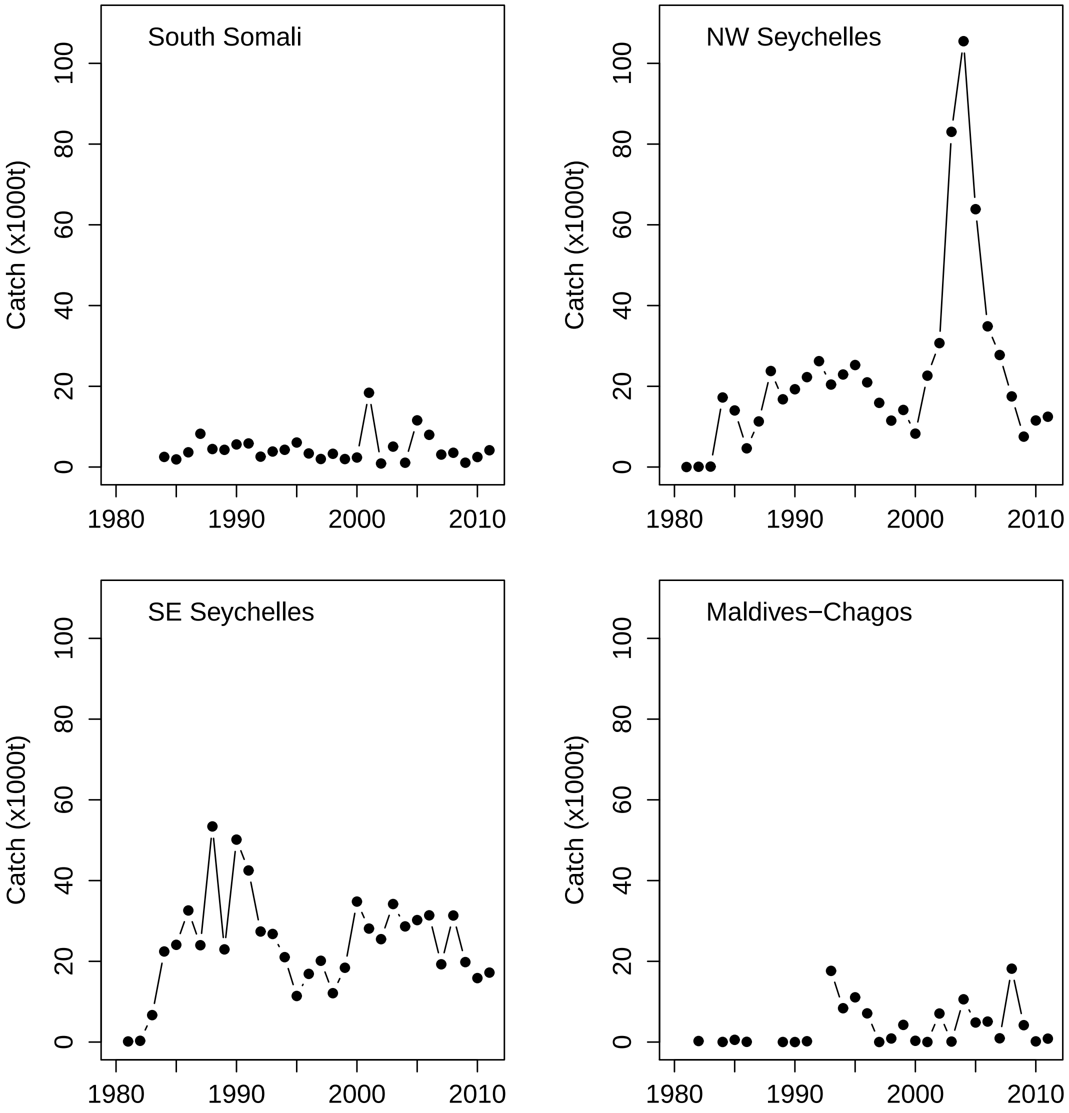

Figure 3: **Purse seine fishery catches**. Annual catch (metric tonnes) of yellowfin for the European purse seine fishing fleet in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011

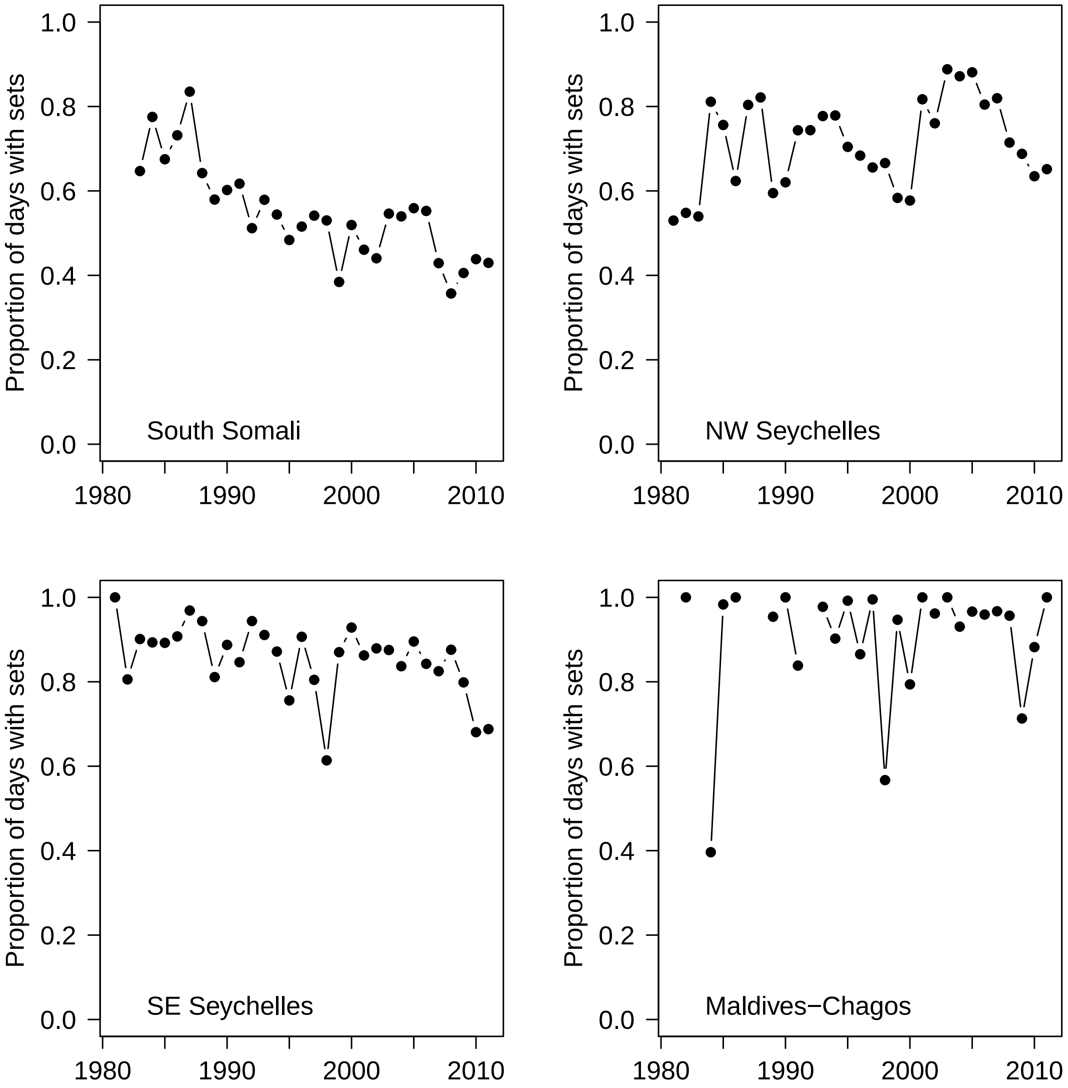

Figure 4: **CPUE$_1$ observations for the binomial component**. Mean annual proportion of searching days with fishing sets per vessel for the subset of selected vessels in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011 (see text for details)

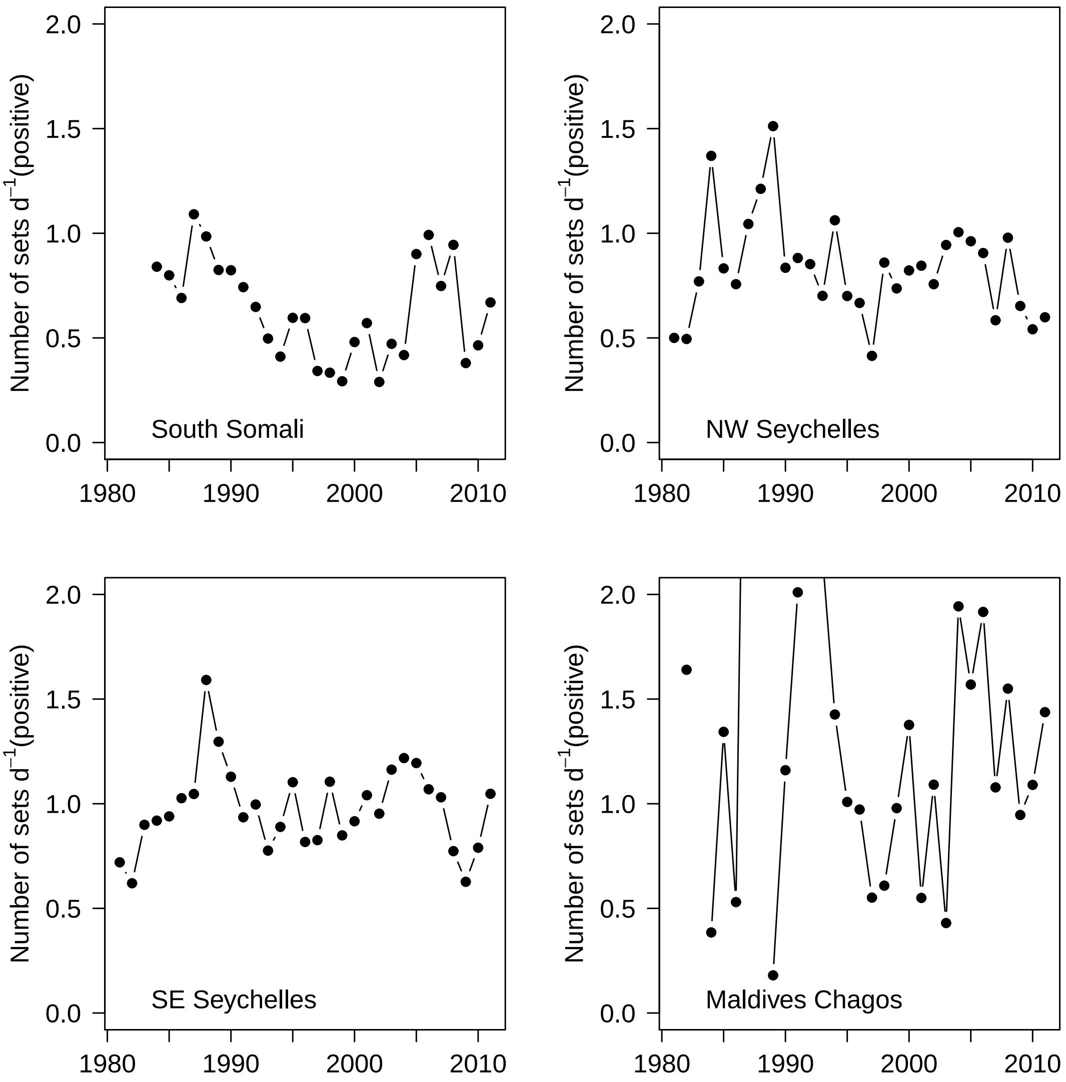

Figure 5: **CPUE$_1$ observations for the lognormal component**. Mean annual number of sets per searching day with detection of schools per vessel for the subset of selected vessels in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011 (see text for details)

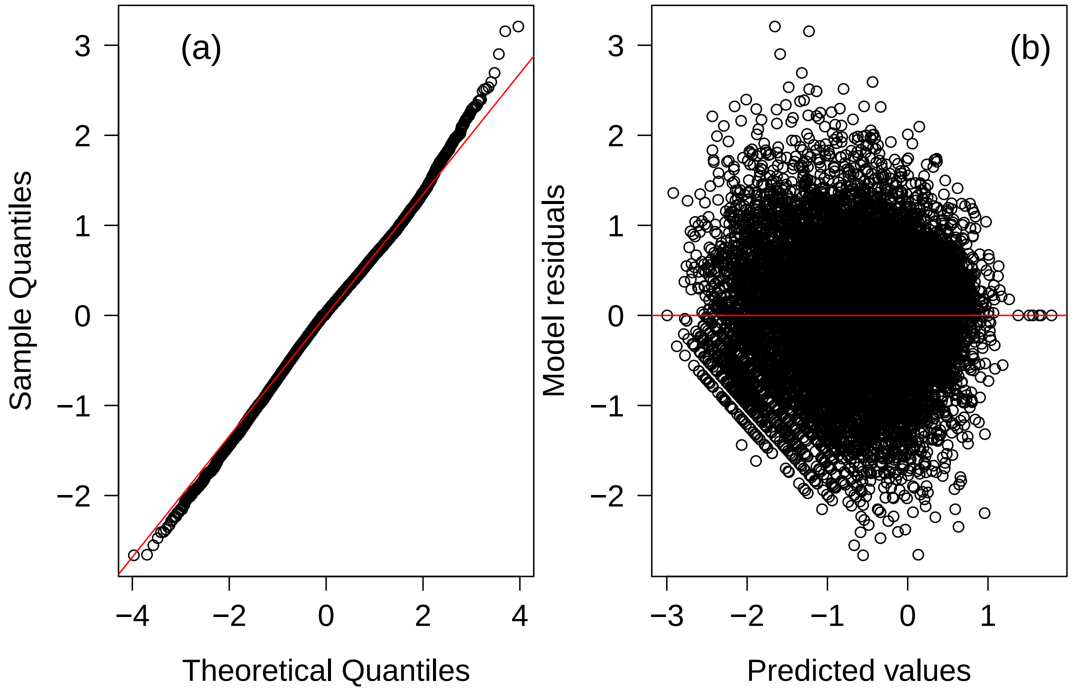

Figure 6: **Model diagnostic plot for CPUE$_1$.** (a) Quantile-quantile plot for the lognormal component of CPUE$_1$, (b) Model residuals as a function of predicted values

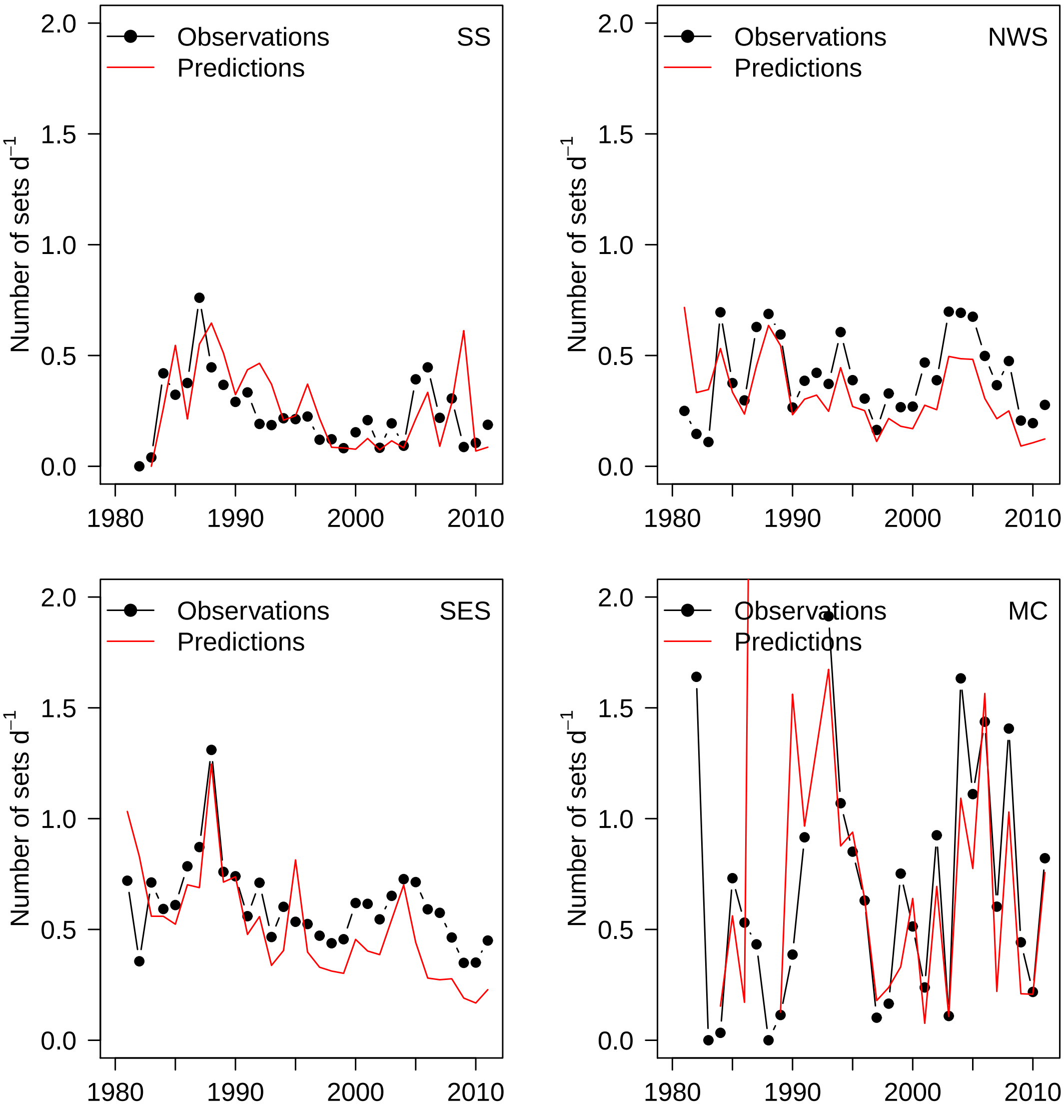

Figure 7: **$\mathbf{CPUE_1}$ predictions**. Mean annual number of sets per searching day per vessel observed (black dotted line) and predicted (red solid line) for the subset of selected vessels in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011

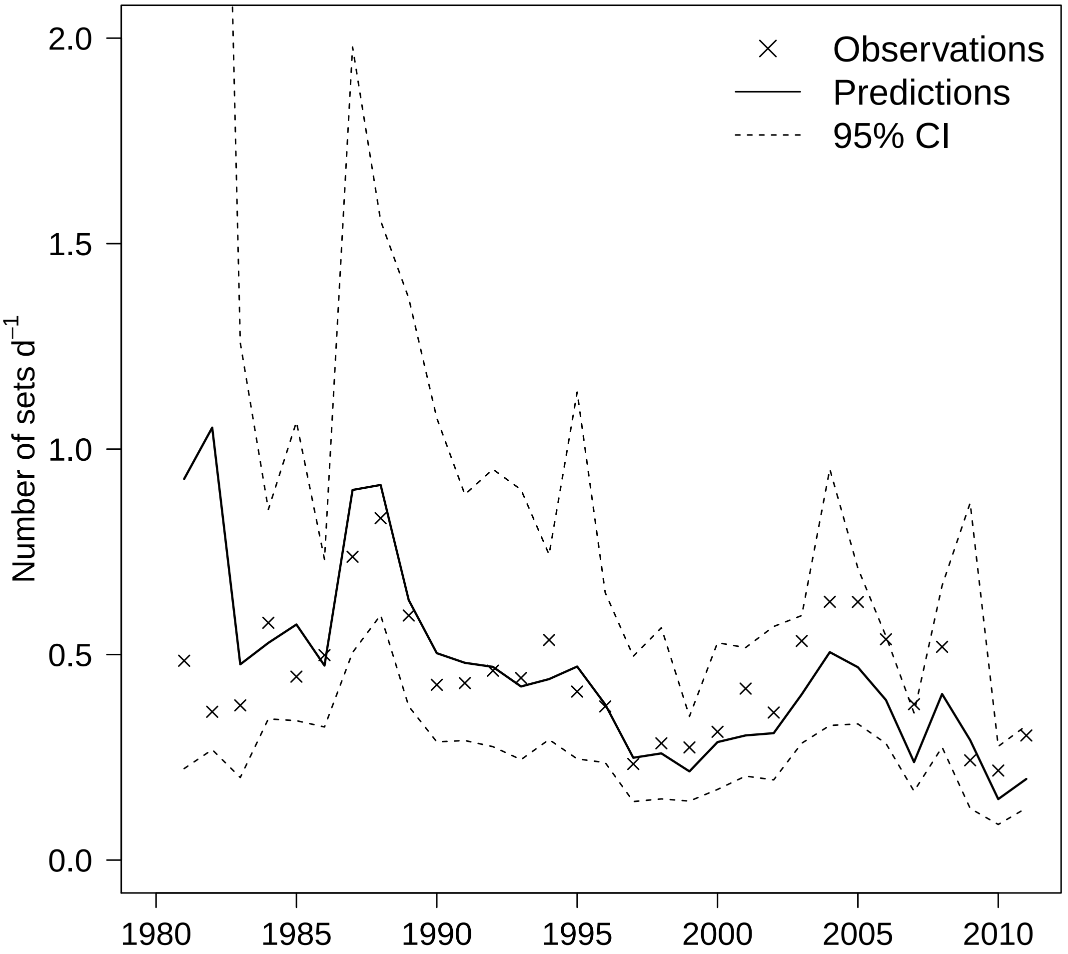

Figure 8: **Standardised annual time series for CPUE$_1$**. Predictions for the number of sets per searching day based on the delta-GLM for CPUE$_1$ for the purse seine fleet fishing on free-swimming schools during 1981-2011

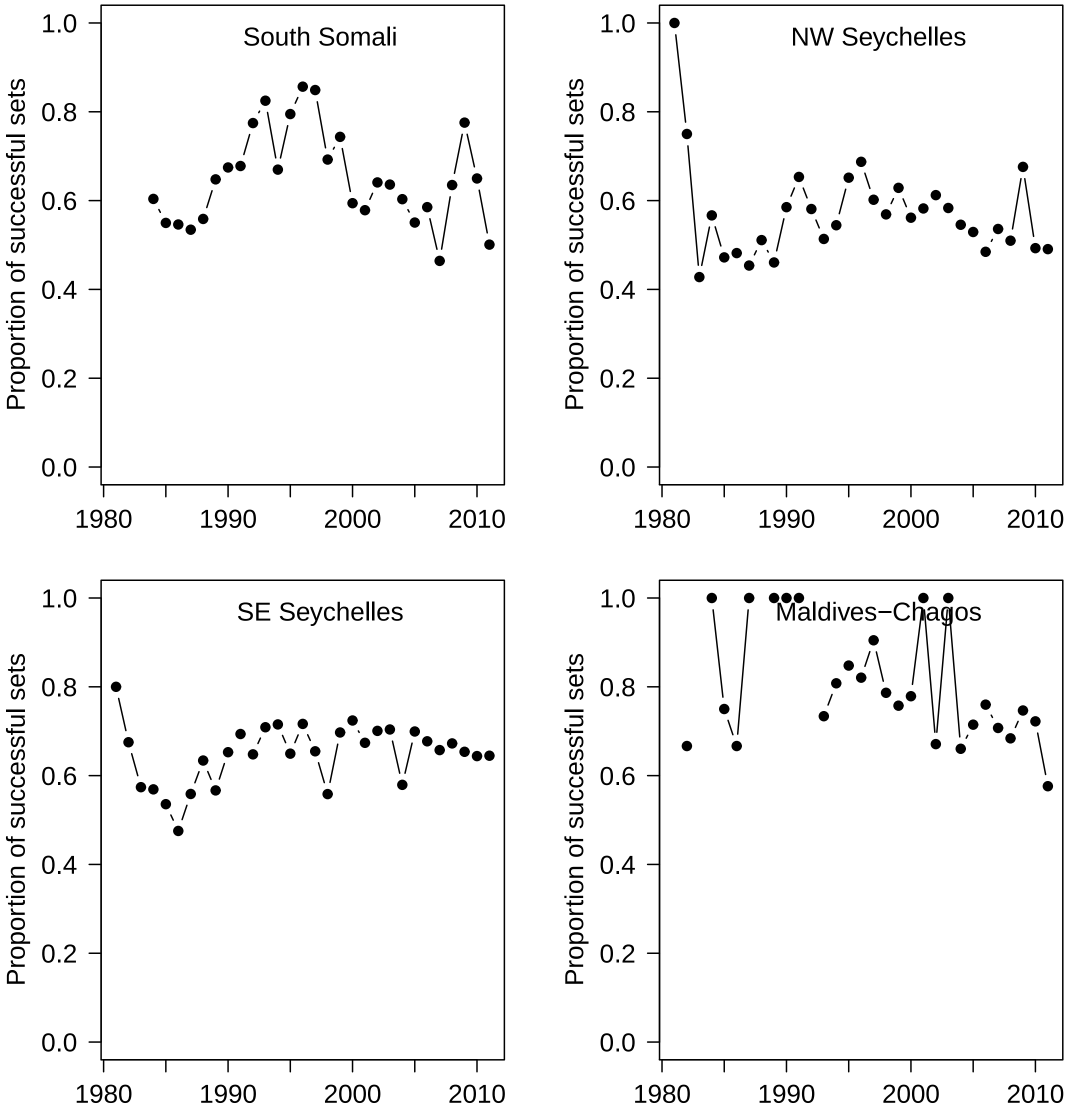

Figure 9: **$\mathbf{CPUE_2}$ observations**. Mean annual proportion of successful sets per vessel for the subset of selected vessels in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011

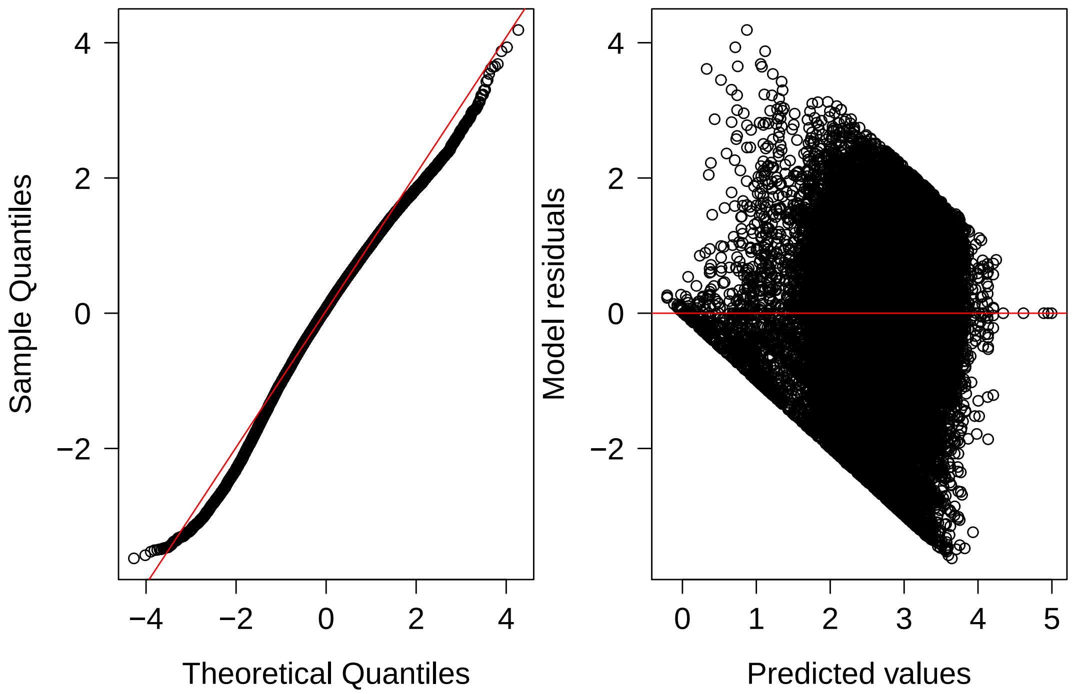

Figure 10: **Model diagnostic plot for CPUE$_3$**. (a) Quantile-quantile plot for CPUE$_3$, (b) Model residuals as a function of predicted values

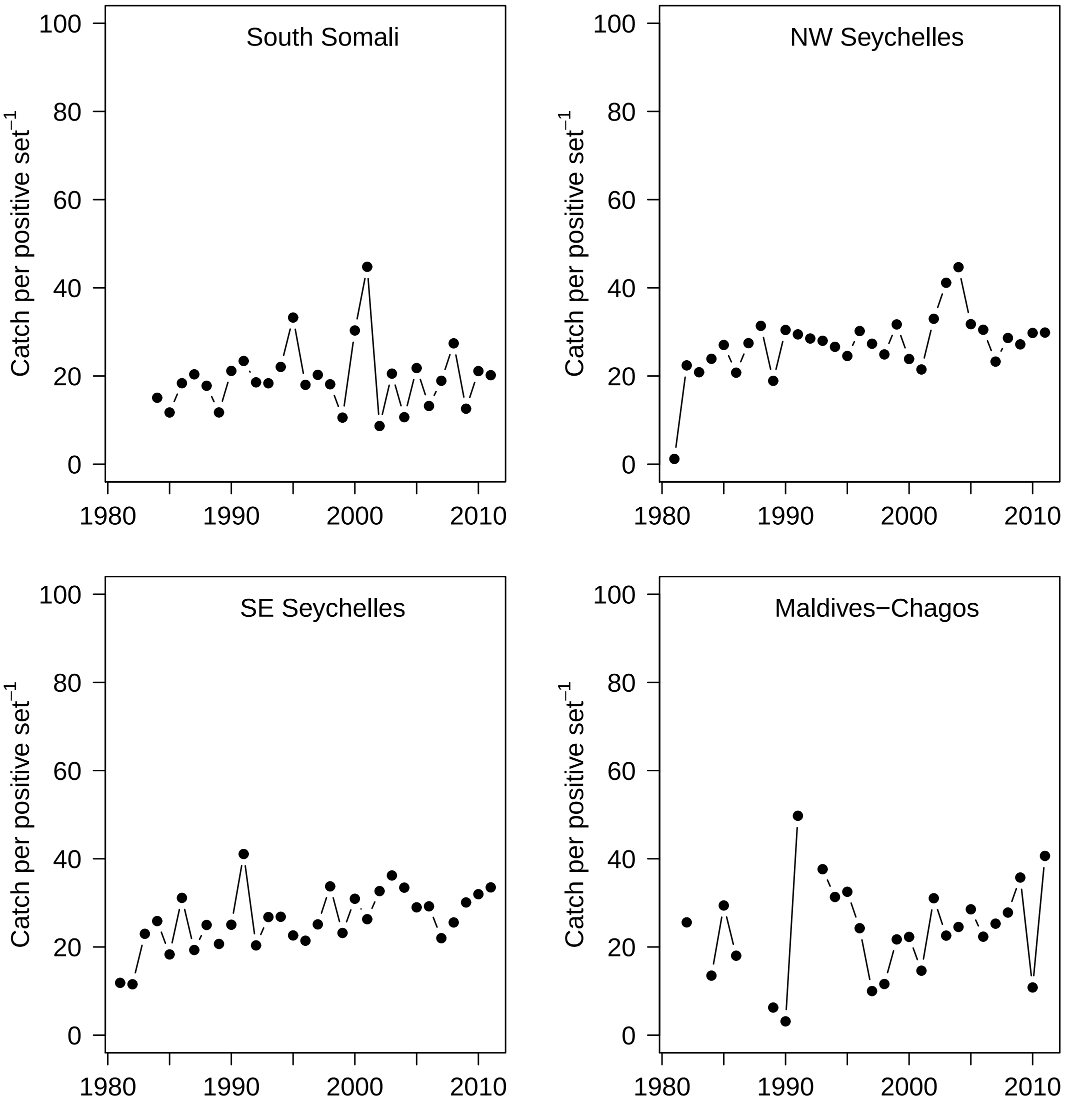

Figure 11: **CPUE$_3$ observations**. Mean annual catch of yellowfin per positive set for the subset of selected vessels in the 4 major areas of purse seine fishing on free-swimming schools during 1981-2011

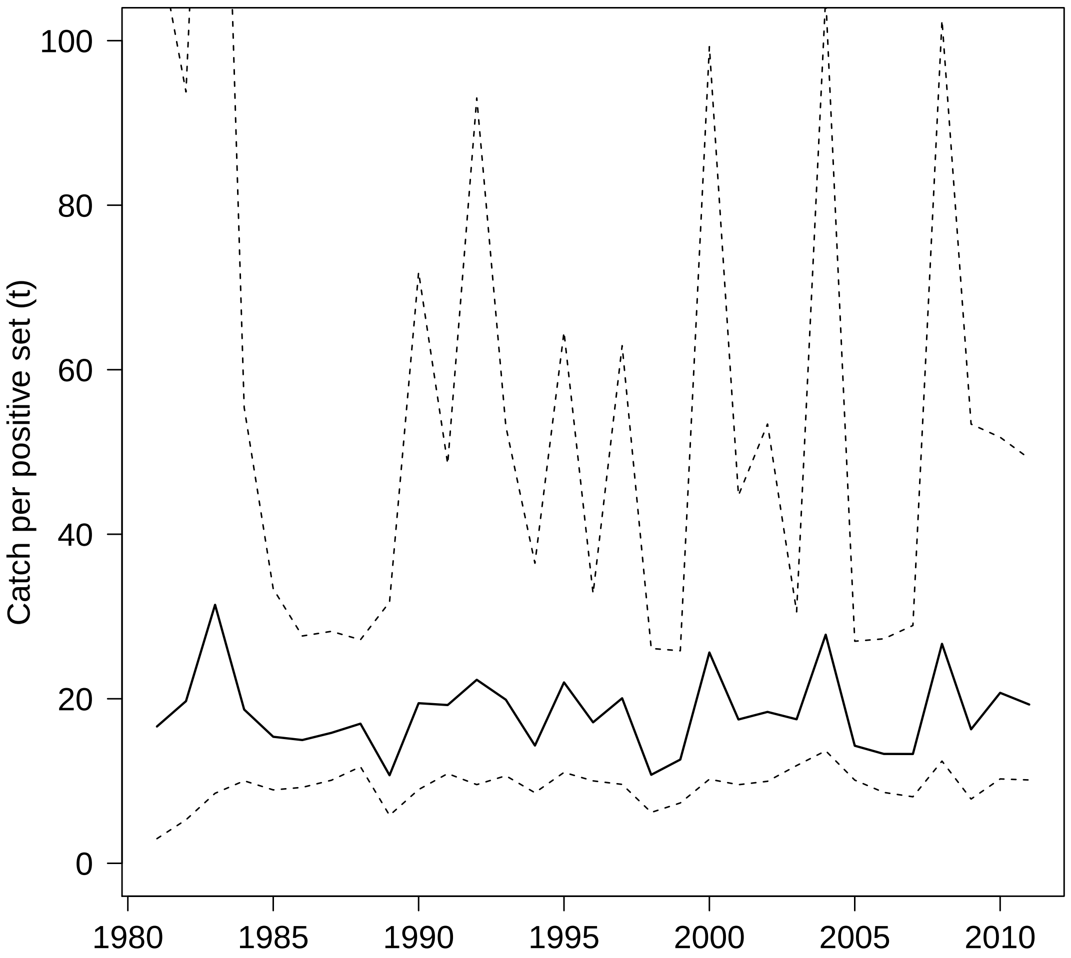

Figure 12: **Standardised annual time series for CPUE$_3$**. Predictions for the catch of yellowfin per positive set based on the GLM for CPUE$_3$ for the purse seine fleet fishing on free-swimming schools during 1981-2011

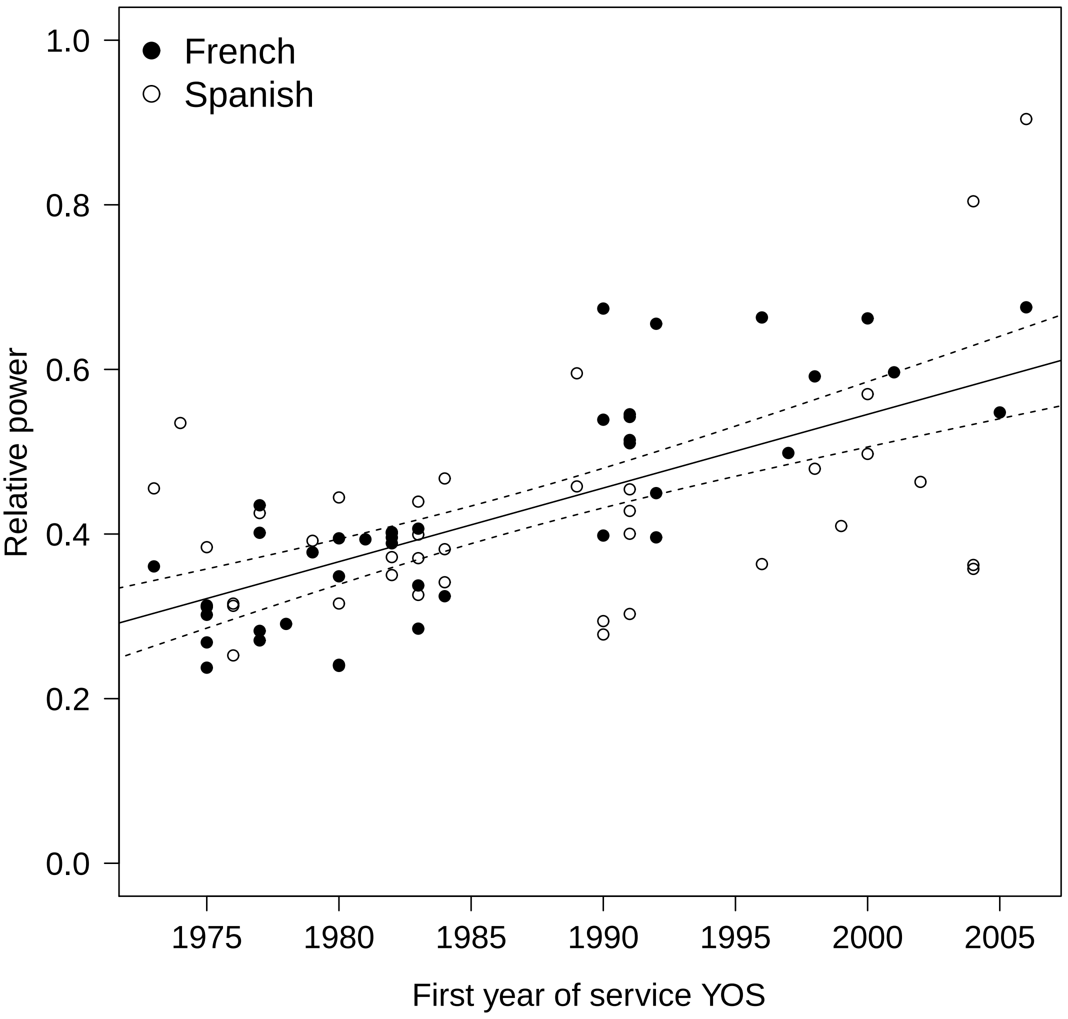

Figure 13: **Detection power as a function of vessel age**. Relationship between individual fishing power of detection derived from the modelling of observed $CPUE_1$ and the initial year of service of the purse seiners. Solid line indicates mean linear regression. Dashed lines indicate 95% confidence interval

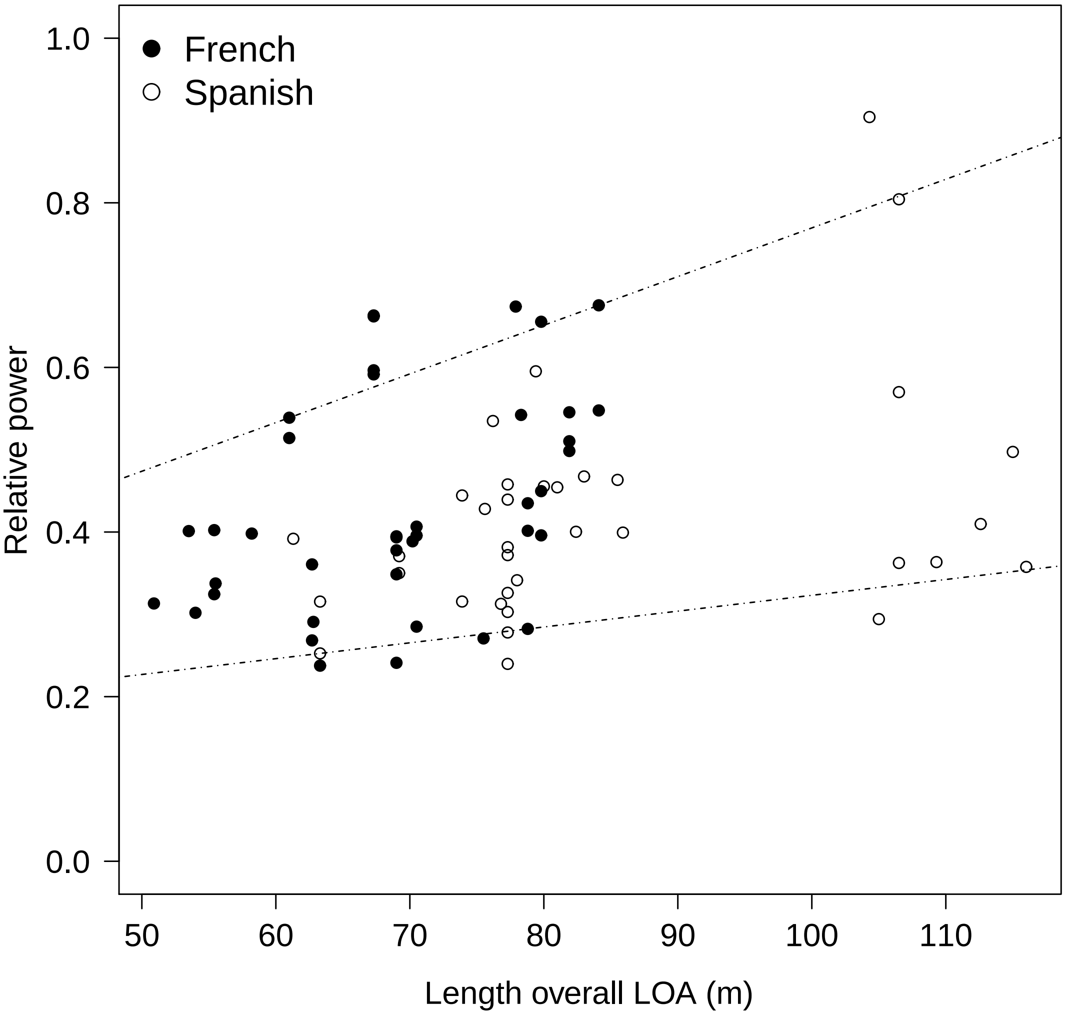

Figure 14: **Detection power as a function of vessel length**. Relationship between individual fishing power of detection derived from the modelling of observed CPUE_1 and the length overall (LOA) of the purse seiners. Dashed lines indicate regression models for 10% and 90% quantiles of the vessel effect used as indicators of minimum and maximum fishing power, respectively

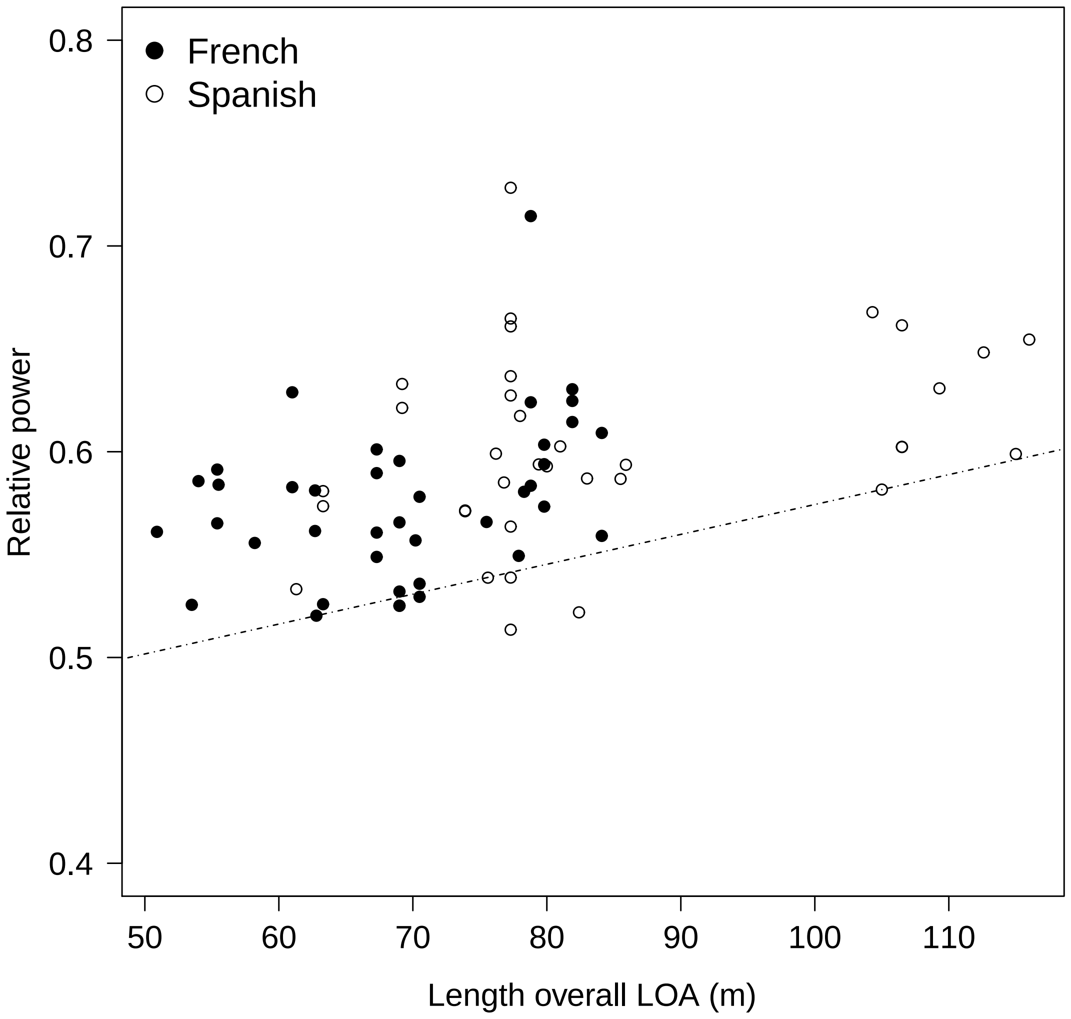

Figure 15: **Success power as a function of vessel length**. Relationship between individual fishing power in succeeding in the set derived from the modelling of observed $CPUE_2$ and the length overall (LOA) of the purse seiners. Dashed line indicates regression model for 10% quantile of the vessel effect used as an indicator of minimum fishing power

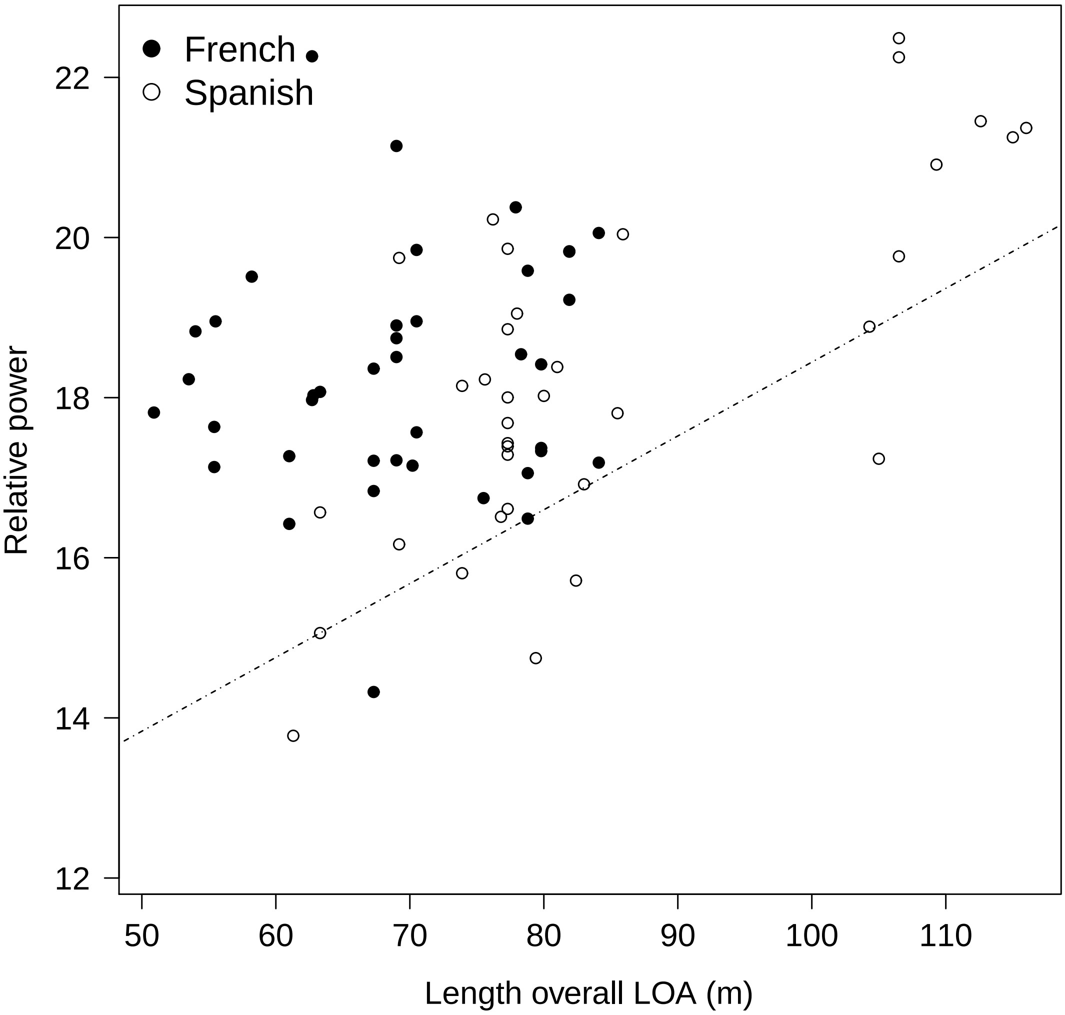

Figure 16: **Capture power as a function of vessel length**. Relationship between individual fishing power in catching the school derived from the modelling of observed $CPUE_3$ and the length overall (LOA) of the purse seiners. Dashed line indicates regression model for 10% quantile of the vessel effect used as an indicator of minimum fishing power