Preliminary investigation into the effect of changing spatial fleet dynamics on yellowfin in the Indian Ocean

CHARLES T. T. EDWARDS*

MRAG Ltd.

London, UK

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1 Introduction

In recent years, pirate activity off the coast of Somalia has changed the behaviour of fishing vessels in the Indian Ocean, leading to an altered spatial distribution of effort and establishment of a *de facto* exclusion zone. The minimum extent of this exclusion zone is the Somailan exclusive economic zone, but it can extend up to 600 nm off the coast when seasonal weather patterns permit [1].

This investigation presents a simple model designed to assess the likely consequences for tuna stocks of a spatial change in fishing, focusing here on yellowfin. The population is considered as a single stock, fished in spatially diaggregated zones. Each zone is characterised by an independently estimated selectivity, which represents the size classess available for exploitation. There is no sub-stock structure, so that it does not require estimation of movement parameters. The effects of exploitation in a particular zone are thus propogated instantaneously throughout the population.

The sustainable harvest of fish stocks is known to be dependent on the size distribution of fish caught. Yield-per-recruit models suggest an optimum size class of catch, at which productivity of the population is maximised (e.g. [8]). This represents a balance between the biomass growth of individuals and the population loss through natural mortality. The relationship between size composition of the catch and population productivity has been addressed in the context of fleet interactions within the worlds tuna fisheries, primarily relating to the consequences for bigeye tuna of increased juvenile catches in associate

*e-mail: c.edwards@mrag.co.uk

schools (e.g. [10, 4]). The conclusions have been contradictory [3] possibly as a result of differences in the rates of natural mortality assumed. If the natural mortality in the juvenile component of the population is high, then an increased fishing mortality on this segment of the population is likely to be less than that if natural mortality is low.

An altered spatial distribution is likely to change the size composition of the catch, particularly if it is correlated with a change in the proportion of the catch taken in associated schools, which are known to contain a large number of small yellowfin and bigeye [2]. This investigation is designed to quantify the potential consequences of such a spatial change in fishing pattern for yellowfin stocks in the Indian Ocean.

2 Methods

The model considers a single fish population that is exploited by a number of fishing fleets. Each 'fleet' is defined by both the fishing method and the zone in which it operates. For example, the purse seine fleet fishing on both associated and free-schools in two adjacent zones would be considered as four fleets. The catches made by each fleet affect the population via distinct selectivity ogives, which are estimated during the model fit. The quasi-spatial nature of the model makes it similar in approach to the A-SCALA model developed by the IATTC [9]. However it differs in the paramaterisation. Specifically, the fishing mortality attributed to different fleets does not depend on an assumed relationship with fishing effort, which is difficult to estimate. Instead it allows catches to be allocated to different fleets without reference to the associated effort.

The model makes extensive use of life-history parameters obtained from elsewhere, and is dependent on these assumptions. Furthermore, it only includes a subsection of the catches taken from the yellowfin stock (specifically purse seine and longline only). It should therefore only be considered an exploratory framework in which the relative merits of a changing distribution of catches between fleets can be investigated.

2.1 Population dynamics

2.1.1 Unfished equilibrium

The population age structure at unfished equilibrium is

$$P_a^0 = \begin{cases} 1 & \text{for } a = a^0 \\ P_{(a-1)}^0 e^{-M_{(a-1)}} & \text{for } a^0 < a < a^+ \\ \frac{P_{(a-1)}^0 e^{-M_{(a-1)}}}{1-e^{-M_a}} & \text{for } a = a^+ \end{cases} \tag{1}$$

from which the spawning biomass per recruit is obtained

$$SPR^0 = \sum_{a=1}^{a^+} w_a m_a P_a^0. \tag{2}$$

where M_a is the natural mortality-at-age, a^+ is the plus group age, w_a is the mass at age and m_a is the maturity at age. Age was measured in quarters with $\mathbf{a} = [a^0 = 1, \ldots, a^+ = 28]$. Natural mortality, w_a and m_a were matched to those used in the MULTIFAN-CL assessment [7] (Table 1).

2.1.2 Recruitment

Given the pristine spawning biomass (K), recruitment to the unfished population (R^0) can be estimated from the relationship

$$K = R^0 SPR^0. \tag{3}$$

Pristine recruitment is then used to parameterise the (Beverton-Holt) stock recruitment curve as a function of spawning biomass by time (B_t)

$$R_t = \frac{\alpha B_t}{\beta + B_t} \tag{4}$$

$$\beta = \frac{(1-h)K}{5h-1} \tag{5}$$

$$\alpha = \frac{R^0 4h}{5h-1}. \tag{6}$$

Estimates of K, α, β and h were chosen to equal those used in the MULTIFAN-CL assessment [7] (Table 2). Recruitment fluctuations were not included, as they are unnecessary for the comparative framework considered.

2.1.3 Dynamics

The population was initialiesd at the start of 1999 using the estimated age structure P^S and biomass B^S from the MULTIFAN-CL assessment [7] (Tables 1 and 2). Population dynamics (numbers-at-age N_{ta}) are represented by standard equations for an age-structured fisheries population model:

$$N_{(t+1)a} = \begin{cases} R_{(t+1)} & \text{for } a = 0 \\ N_{t(a-1)} e^{-M_{(a-1)}} - C_{t(a-1)} e^{\frac{-M_{(a-1)}}{2}} & \text{for } 0 < a < a^+ \\ N_{t(a-1)} e^{-M_{(a-1)}} - C_{t(a-1)} e^{\frac{-M_{(a-1)}}{2}} & \\ \quad + N_{ta} e^{-M_a} - C_{ta} e^{\frac{-M_a}{2}} & \text{for } a = a^+ \end{cases} \tag{7}$$

with recruitment given in Equation 4 and spawning biomass

$$B_t = \sum_{a=0}^{a^+} u_a m_a N_{ta} \tag{8}$$

Time is measured in quarterly steps. The catch is restricted to each fleet f, so that catch at age $C_{ta} = \sum_f C_{fta}$, and

$$C_{fta} = k_f N_{ta} e^{\frac{-M_a}{2}} S_{fa} \tilde{H}_{ft} \tag{9}$$

$$\tilde{H}_{ft} = \frac{C_{ft}^B}{k_f B_{ft}^{exp}} \tag{10}$$

$$B_{ft}^{exp} = \sum_{a=0}^{a^+} v_a N_{ta} e^{\frac{-M_a}{2}} S_{fa} \tag{11}$$

where k_f is the proportion of the total population biomass exploited by fleet f. Note that k_f cancels in the above formulation and does not need to be specified.

2.1.4 Selectivity

Each fishing fleet has its own selectivity, a product of both the gear used and the availability of fish in the particular zone being fished. Selectivity is age-based and was estimated for each fleet within a maximum likelihood framework.

For purse seine fleets a cubic spline selectivity pattern was used, with selectivity values estimated at $\mathbf{a} = [1, 2, 3, 4, 6, 8, 10, 12, 16]$. Selectivity for older age classes was assumed equal to that estimated for $a = 16$. For the longline fleet, a double normal selectivity ogive was estimated:

$$S_{fa} = \begin{cases} e^{-\left(\frac{l-\mu_f}{\sigma_f^L}\right)^2} & \text{for } a \leq \mu_f \\ e^{-\left(\frac{l-\mu_f}{\sigma_f^R}\right)^2} & \text{for } a > \mu_f \end{cases} \tag{12}$$

where μ_f, σ_f^L and σ_f^R are estimated parameters.

2.1.5 Parameter estimation

All selectivity parameters were estimated within a maximum likelihood framework, assuming that the observed catches at length follow a multinomial distribution. Thus the likelihood for the observed proportions at length ($\mathbf{p}$), is proportional to

$$L[\mathbf{p}] = \prod_f \prod_t \prod_l (\hat{p}_{ftl})^{\hat{n}_t p_{ftl}}. \tag{13}$$

To estimate predicted proportions-at-length $\hat{p}_l$ from an age-based model we make use of the age-length conversion matrix $\mathbf{A}$, which describes the proportion of fish of age a that are of length l. $\mathbf{A}$ is obtained from an approximate model of the length at age distribution. Owing to differences in the growth rates of individual fish, the length distribution of fish of age a is modelled by a normal distribution, truncated to three standard deviations in either direction (N^*), with the variance increasing with age. Mean and standard deviations of length at age are given in Table 1 [7]. Numerical integration allows the proportion of fish in each length-bin (with $\sum_l A_{al} = 1$) to be estimated from the assumed length distribution at age, thus giving $\mathbf{A}$. It is then possible to estimate $\hat{p}_{fyl} = \sum_a \hat{p}_{fya} A_{al}$. The effective sample size $\hat{n}$ is that which would be expected given a true multinomial distribution of the data. No attempt was made to estimate $\hat{n}$ and it was instead assumed equal to 50 [6].

2.2 Data

Catch and length frequency data for the purse seine and longline fleets were provided by the IOTC Secretariat [5]. For the purse seine fleet data were aggregated according to 5 degree latitutude by 5 degree longitude grids. For the longline fleet, data were only aggregated at a 10 degree latitude by 20 longitude grid resolution. In both cases, these aggregations correspond to the resolution at which length-frequency data were collected. All length frequency data was scaled so that it equalled the total catch per grid by each fleet and school type.

Given time constraints and the lower spatial resolution of the longline data, the spatial dynamics of the purse seine fleet only were considered in this investigation.

2.2.1 Definition of zones

Zones were defined on the basis of the length-frequency distribution of purse seine catches. The mean length for each grid is shown in Figure 1. Further visual inspection of the data suggested the grouping illustrated in Figure 2, which shows grids with similar patterns in the length-frequency data. These groupings were used to define zones (Figure 2), since the quantity of length-frequency data from other grids was negligible. The length-frequency data for each of these zones in shown in Figures 3.

Visual inspection of the distribution of catches by quarter also indicated an intra-annual migration of the purse seine fleet between the defined zones. Combined with the different patterns in the length-frequency data, this suggested they might prove a useful basis for investigating the consequences of a changing spatial distribution of purse seine catches.

2.2.2 Definition of fleets

Purse seine catches were assigned to six different 'fleets' based on the school type: free (FS) and associated (LS) schools; and zone. Longline catches were considered to be from a single fleet.

3 Analysis and Results

Estimated selectivities are shown in Figures 4 and 6, with the associated model fit to the catch-at-length data in Figures 5 and 7. Due to the flexibility of the selectivity parameterisation for the purse seine fleet, model fits were good.

3.1 Catch distribution

This investigation specifically addresses the consequences for the yellowfin stock of a changing distribution of purse seine catches. The catch distribution is described by an allocation to each fleet as defined above, which represent two dimensions, specifically school type and zone. One other dimenension is considered here: the seasonal change in catch between fleets. It is important to note that these three dimensions are assumed to be confounded, so that, for example, a change in the spatial dimension will be associated with a change in the school type fished. The fourth dimension, which is the total annual catch, is not considered.

The distribution of catches by school type, zone and season was adjusted to represent an alternative scenario considered to be representative of fishing prior to the onset of pirate activity. This redistributed catch was then applied to the stock in a retrospective manner using the estimated selectivity curves, to examine whether the current catch distribution is of consequence to the stock, in comparison to the distrubtion that might be expected in the absence of pirate activity.

The distribution of catches by fleet and season is illustrated in Figures 8, 9 and 10. Observed catches are shown in the top row of each figure. These clearly show a seasonal pattern. The first quarter is dominated by free school catches in Zone 2, with minimal catches in the other zones. In the second quarter there is a decrease in catches in Zones 1 and 2 and a slight increase in Zone 3, mostly from associated schools. In the third and fourth quarters catches in Zone 2 remain stable, but there is a large increase in catches from associated schools in Zone 1. Simultaneously, catches in Zone 3 drop to negligible levels.

Prompted by the observed seasonal changes, it was assumed that catches in the third and fourth quarters are representative of the distribution of catches in the absence of pirate activity. Catches were therefore redistributed in the first and second quarter according to that observed in the third and fourth quarter. This was achieved as follows:

1. Estimate the mean proportion of the total annual catch by school type, zone and season.

2. For each school type and zone, estimate the mean proportions from quarters 3 and 4.

3. Apply these mean proportions by school type and zone to quarters 1 and 2, and renormalise to that all proportions sum to one.

4. Multiply the mean proportion by school type, zone and season (observed for quarters 3 and 4, derived for quarters 1 and 2) through by the annual catch for each year.

The Redistributed catch was thus obtained (Figures 8, 9 and 10). It was also necessary to construct a null model for comparison, using the mean proportions from Step 1 multiplied through by the annual catches.

3.2 Retrospective biomass projections

The Null and Redistributed catches were applied in a retrospective manner to the stock, according to the estimated selectivities. The estimated fishing mortalities over time (with $F = -ln(1 - H)$) are shown in Figure 11. It can be seen that the Null model provides a reasonable reproduction of the total fishing mortality obtained from observed catches. However application of the Redistributed catches has a noticeable effect, essentially smoothing the fishing mortality over time. This is because the redistribution nullifies the spike in free school catches in the first quarter, and increases the fishing mortality in the second quarter.

Changing selectivity patterns associated with a modified catch distribution will also affect the fishing mortality-at-age. The mean for each school type and zone is shown in Figure 12 for both the Null and Redistributed models. The Redistributed model is noticeably associated with a decrease in fishing mortality in the older age classes caught in free schools, and an increase in the fishing mortality for younger age classes caught in associated schools.

Estimated spawning biomass from 1999 to 2009 for the Null and Redstribued models is shown in Figure 13. The predicted effect of the catch redistribution is clearly small, and suggests it to be of little consequence for the yellowfin stock.

4 Conclusions and Further work

The population dynamics model described here represents a simple framework for investigating the consequences of a change in the size composistion of the catch, brought about by an altered spatial distribution of fishing. This spatial distribution is assumed to correlate with the school type fished by the purse seine fleet, and the season in which fishing takes place. Spatial redistribution of the longline fleet is not considered. The redistribution of catch by space, school type and season leads to a change in the size composition of the catch, via estimated selectivity curves. However it was shown, in the particular scenario considered, to have little affect on the yellowfin stock.

The utility of the model is clearly dependent on how catches are distributed and redistributed for comparative estimates of the likely consequences. This redistribution of catches was carried out in an elementary and likely inadequate manner. Further work is required to develope a statistical model for the catch distribution, allowing alternative scenarios to be explored in a more rigorous and realistic manner. This should include changes in the total catch [1], which was not addressed here.

The model is also limited in its current implementation by the spatial resolution. Additional work may therefore be conducted to improve this, bearing in mind the associated increase in uncertainty. Uncertainty itself has not been addressed here, and will need to quantified if results are to be taken seriously. Particular attention will need to be paid to the effective sample size ($\hat{n}_t$) and how it is related to the spatial resolution of the model.

5 Acknowlegements

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Table 1: Input biological parameters

Age	M	Length (cm)		Maturity	Weight (kg)	P^S
(Quarters)		Mean	S.D.			
1	0.2000	20.0000	3.8421	0.00	0.161	0.2210
2	0.1760	45.7056	5.2168	0.00	1.841	0.1380
3	0.1520	54.6746	6.7483	0.00	3.161	0.0967
4	0.1280	64.4875	8.3809	0.00	5.209	0.0524
5	0.1040	76.5796	10.0573	0.00	8.764	0.0817
6	0.0800	88.7146	11.7256	0.00	13.690	0.0525
7	0.0800	101.5366	13.3424	0.25	20.621	0.0428
8	0.0800	112.6549	14.8748	0.50	28.278	0.0324
9	0.0800	123.6255	16.3001	0.75	37.511	0.0283
10	0.0800	129.1478	17.6050	1.00	42.871	0.0254
11	0.0840	133.7957	18.7839	1.00	47.778	0.0200
12	0.0957	137.7076	19.8371	1.00	52.207	0.0156
13	0.1060	141.0001	20.7692	1.00	56.163	0.0170
14	0.1140	143.7712	21.5876	1.00	59.671	0.0153
15	0.1188	146.1035	22.3013	1.00	62.767	0.0114
16	0.1197	148.0665	22.9202	1.00	65.490	0.0093
17	0.1168	149.7186	23.4544	1.00	67.887	0.0101
18	0.1111	151.1092	23.9137	1.00	70.000	0.0107
19	0.1038	152.2795	24.3072	1.00	71.871	0.0083
20	0.0967	153.2645	24.6434	1.00	73.542	0.0079
21	0.0907	154.0936	24.9300	1.00	75.049	0.0108
22	0.0863	154.7913	25.1738	1.00	76.428	0.0061
23	0.0834	155.3786	25.3808	1.00	77.711	0.0048
24	0.0818	155.8729	25.5564	1.00	78.929	0.0044
25	0.0808	156.2889	25.7051	1.00	80.111	0.0053
26	0.0804	156.6391	25.8309	1.00	81.284	0.0063
27	0.0802	156.9338	25.9373	1.00	82.477	0.0046
28	0.0801	157.1818	26.0271	1.00	83.717	0.0603

Table 2: Input biological parameters

Parameter	Value
K (tonnes)	6.67E+06
B^S(tonnes)	3.18E+06
α	2.78E+07
β	8.01E+05
h	0.7

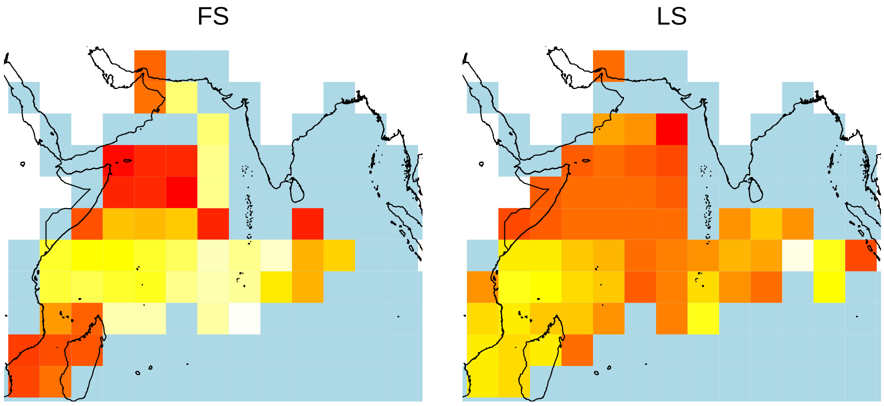

Figure 1: Mean length per grid for free school (FS) and associated school (LS) purse seine catches. Colour range from red (small) to white (large).

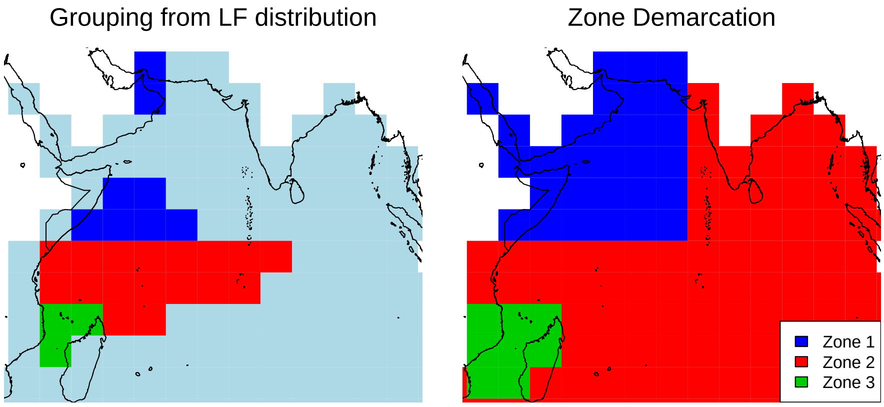

Figure 2: Grouping of grids with similar length-frequency distributions (from visual inspection) and resultant zone demarcations.

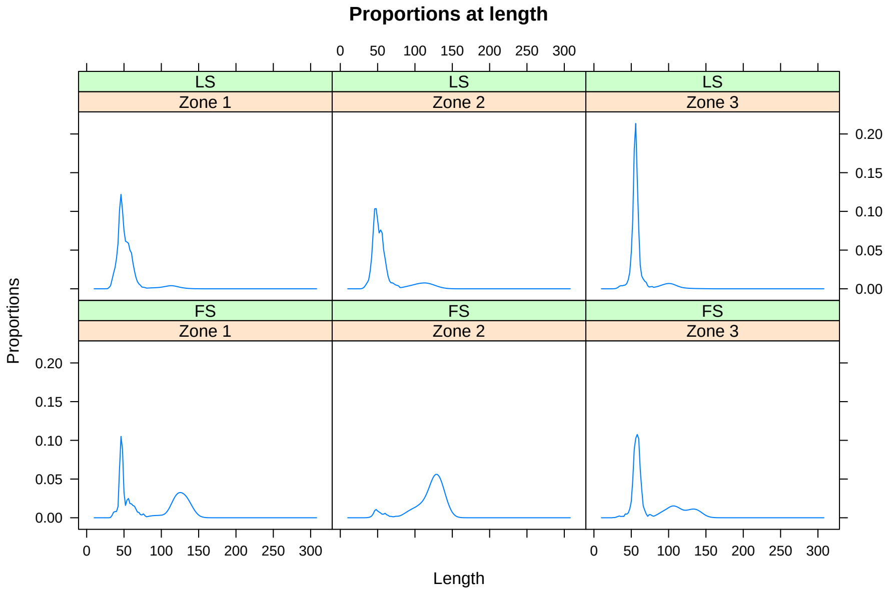

Figure 3: Grouping of grids with similar length-frequency distributions (from visual inspection) and resultant zone demarcations.

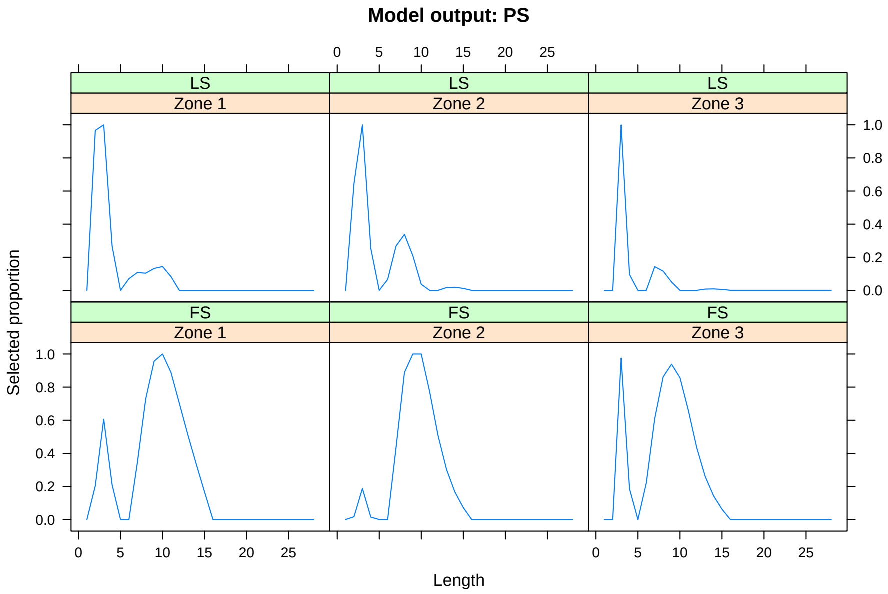

Figure 4: Estimated selectivities for purse seine fleet

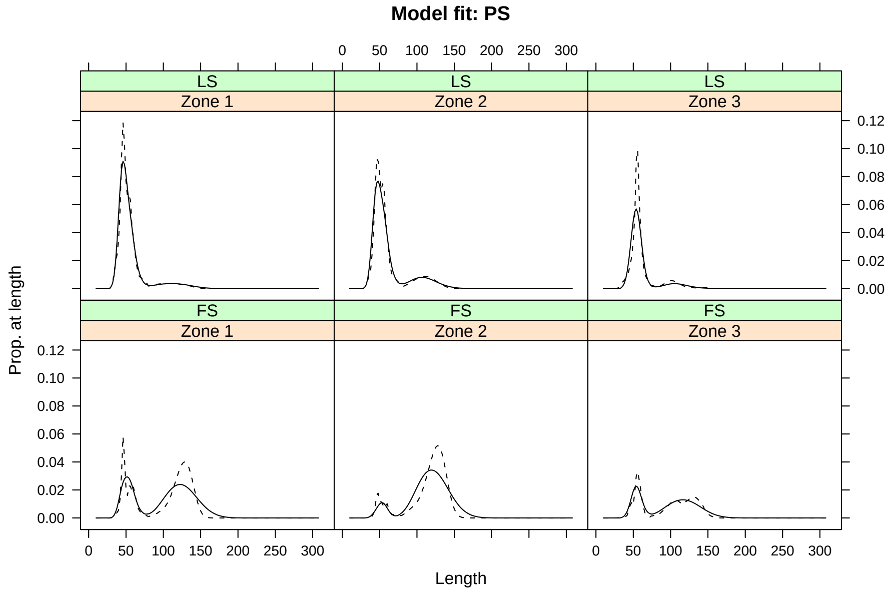

Figure 5: Model fit to catch-at-length data for the purse seine fleet. Solid line: estimated catch-at-length; Dashed line: observed catch-at-length.

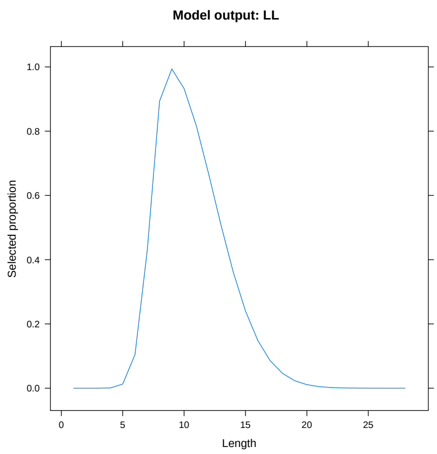

Figure 6: Estimated selectivity for longline fleet

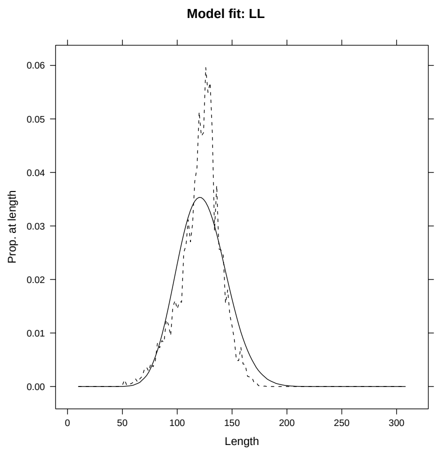

Figure 7: Model fit to catch-at-length data for the longline fleet. Solid line: estimated catch-at-length; Dashed line: observed catch-at-length.

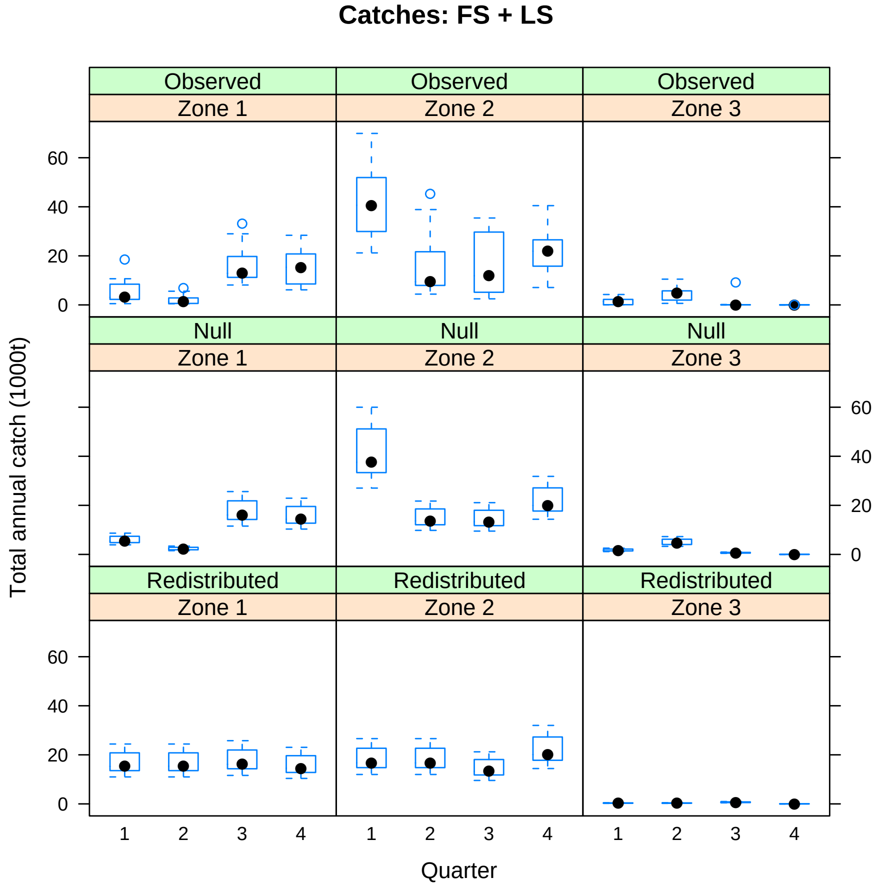

Figure 8: Total catches by quarter and zone for the purse seine fleet. Boxplots represent interannual variation. Observed: raw data; Null: data distributed by season, zone and school type according to the mean annual proportions associated with each; Redistributed: catch for quarters 1 and 2 are obtained from the mean annual proportions by school type and zone for quarters 3 and 4. Catches by school type are given in Figures 9 and 10

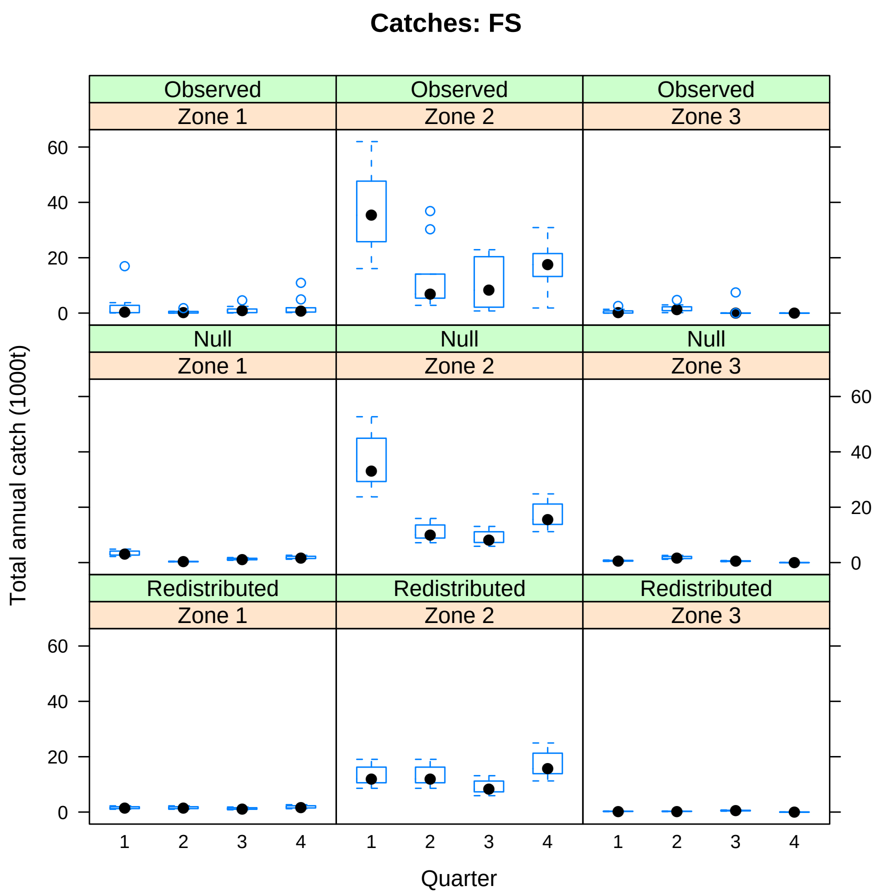

Figure 9: Total free school catches by quarter and zone for the purse seine fleet.

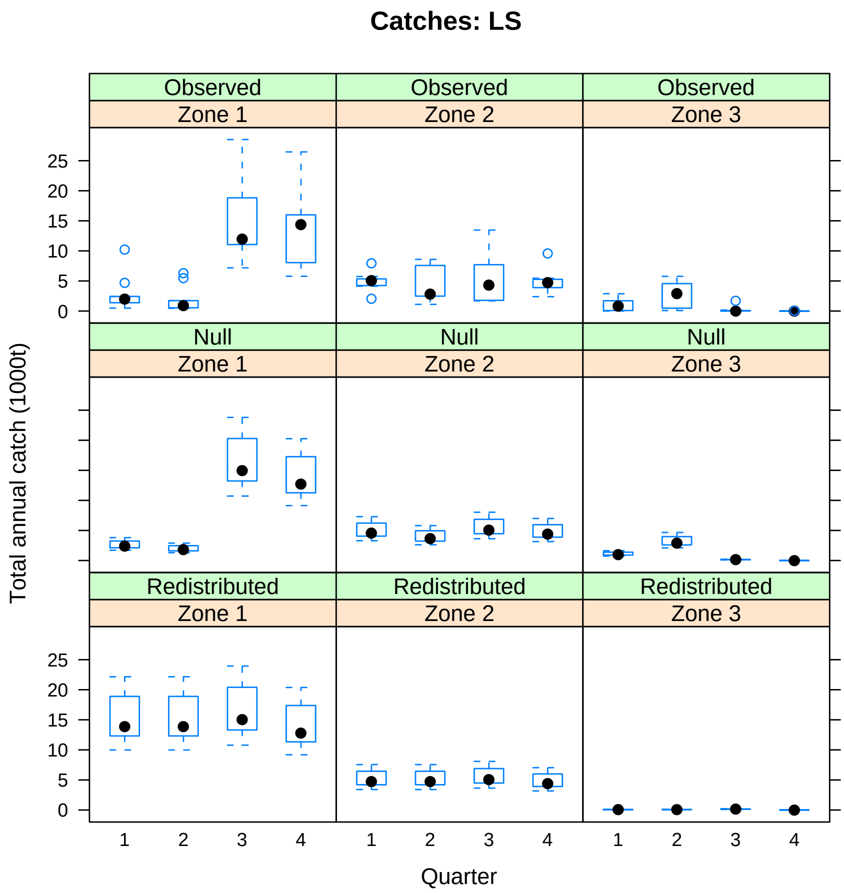

Figure 10: Total associated school catches by quarter and zone for the purse seine fleet.

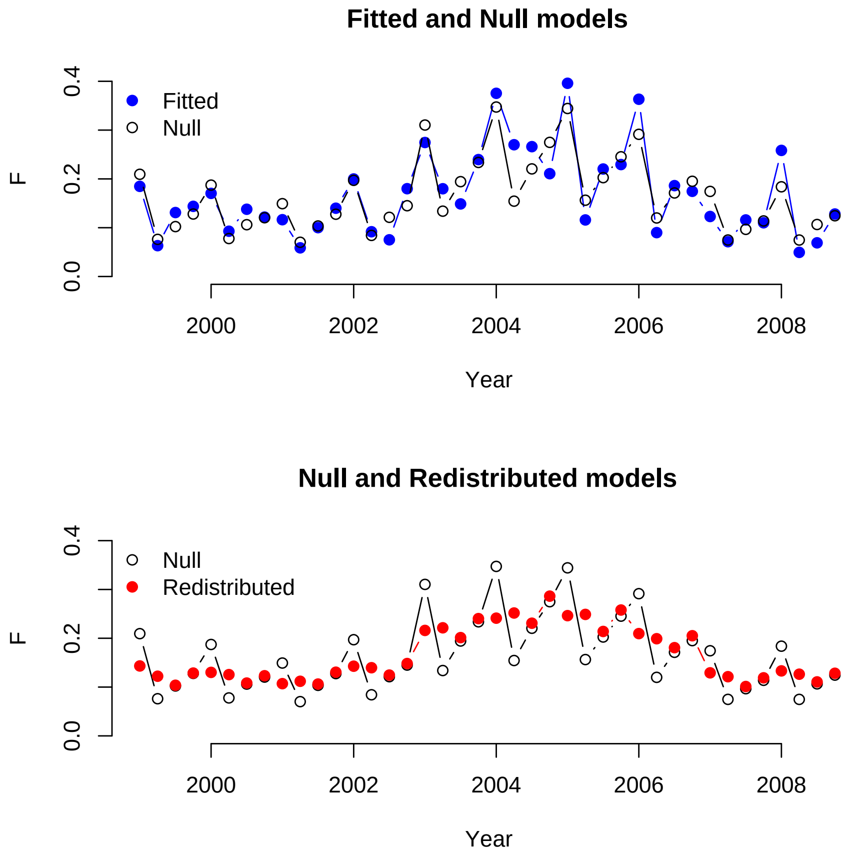

Figure 11: Total fishing mortality over time

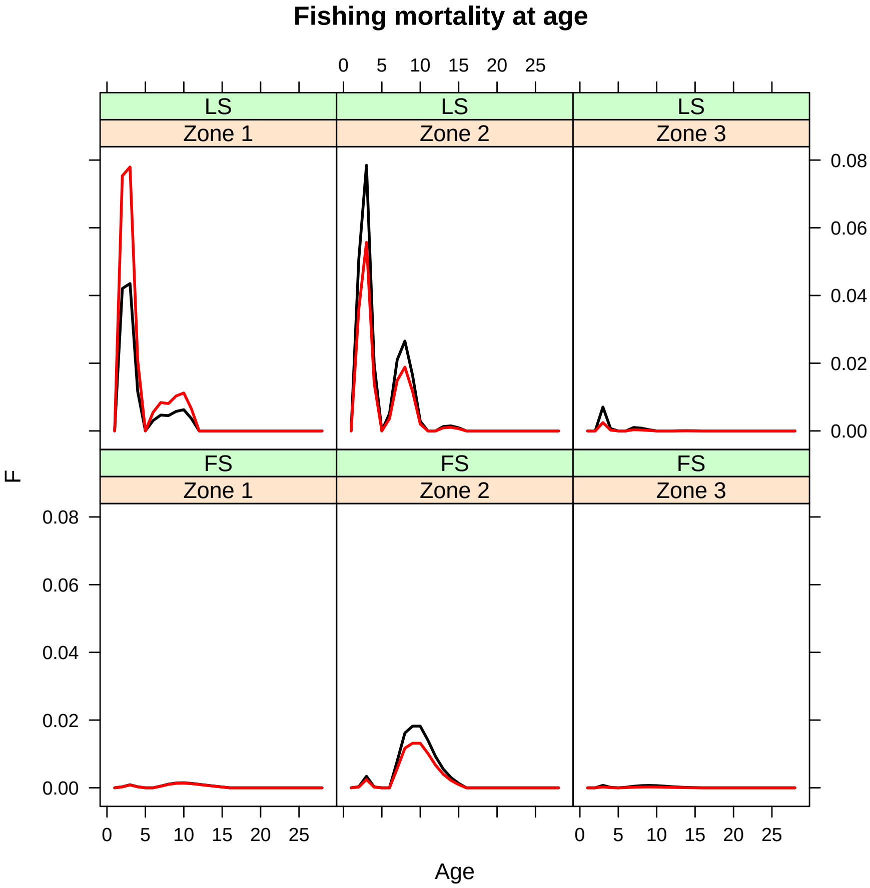

Figure 12: Mean fishing mortality-at-age. Black line: Null model; Red line: Redistributed model.

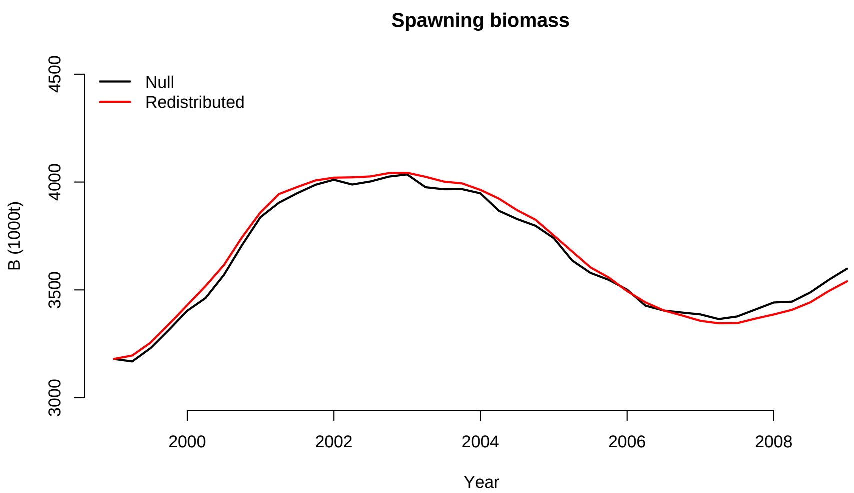

Figure 13: Estimated spawning biomass from 1999 to 2009