Assessment of small pelagic fish stocks in Ghanaian and adjacent waters

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Executive summary

a) Five stocks of small pelagic fish important to Ghana are assessed for the period 1990-2017. These are based on the stock area as used by FAO that also includes catches from Côte d'Ivoire, Togo and Benin. The stocks assessed include anchovy (*Engraulis encrasicolus*), round sardinella (*Sardinella aurita*), flat sardinella (*Sardinella maderensis*), bonga shad (*Ethmalosa fimbriata*) and Cunene horse mackerel (*Trachurus trecea*).
b) Ghana accounts for the largest proportion of the total catches for all stocks from the four countries in the assessment unit. Total catches are variable and show some long term decline for four of the five stocks. Catches of horse mackerel have increased.
c) Fishing effort data are available for 6 fleets. Effort trends are highly variable but Ghanaian fleets, that account for most of the catch show a marked increase.
d) Catch per unit effort data (cpue) suggest that all stocks, except horse mackerel have declined from the 1990 level but may have stabilised or increased slightly in recent years. However, the trends may be over-optimistic as the effort data are not corrected for increases in fishing power. Horse mackerel cpue shows no long term trend.
e) A surplus production model is used to assess the stocks using catch and effort data by fleet. The model also accounts for increasing fishing power over time, missing catch data as well as observation errors in the catch and effort data.
f) Four of the five stocks show similar downward trends in stock biomass and increasing fishing mortality. They appear to be fished above F_{MSY} and the current biomass is below B_{MSY}. The estimates of F_{MSY} are uncertain but the estimated stock status relative to MSY is robust to different modelling assumptions. The horse mackerel stock shows no clear trend in biomass and while is appears to be fished above F_{MSY}, the stock status is highly uncertain.
g) In all five stocks Ghanaian fleets dominate the fishing mortality with the artisanal fleet having a large impact. Côte d'Ivoire makes a large contribution to fishing mortality on sardinella and horse mackerel. Togo makes a significant contribution to anchovy mortality
h) Estimates of the rate of increase in fishing power vary between fleets and species. Most notable is the above average increase in fishing power by the Togo artisanal fleet for anchovy and round sardinella, and the Benin artisanal fleet for most stocks.
i) Equilibrium analyses suggest that all five stocks are at high risk of stock collapse at current (2017) rates of fishing, though there is large uncertainty in the case of horse mackerel. Much of the catch appears to be dependent on in year production (recruitment and growth).
j) Despite uncertainty in the estimates of B_{MSY} and F_{MSY}, the model described in the analysis provides the basis for a multi-fleet, fishery model that can be used to investigate management scenarios and economic impacts.

Contents

1 Introduction

1.1 Background

This report forms part of work package RP3 - Integrated Evidence for Ocean Management – as part of the Ghana Workplan. It contributes to deliverable 3.03 "Part I Fisheries data collation" and "Part II Inshore fish stock assessment". The work is based primarily on data collated by the Fishery Committee for the Eastern Central Atlantic (CECAF) and reported in FAO (2019) on pelagic fish exploited by four countries, including Ghana, in the Gulf of Guinea (Figure 1. 1). While RP3 is focused on Ghana, the regional stock assessments supported by FAO define the stock area as the "western" zone and include catches by Côte d'Ivoire, Togo and Benin. The assessments performed in this report therefore include data from this wider area. However, within this assessment unit, Ghanaian catches dominate, and because data are available by country and fleet it is possible to partition out the Ghanaian component of the fishery. As is common in many stock assessment units throughout the world, the boundaries of the assessment are somewhat arbitrary and may not correspond to true biological units. As there is no biological data to define stock identity the assessment unit as used by FAO is adopted here.

1.2 Fisheries

The fleet descriptions set out below are drawn from the CECAF working group (FAO,2019).

1.2.1 Ghana fleets

Artisanal purse seine and beach seines are the main fishing gear used in exploiting the small pelagic resources. There are two types of artisanal purse seine gear differing in mesh size; the "watsa" with a 25 mm mesh and the "poli" with a 10 mm mesh. The beach seine has a mesh size of 10 mm and is operated mainly along estuaries. The artisanal gear is operated from dugout canoes, and as of 2016 there are 3 346 artisanal purse seine canoes and 1 084 beach seine canoes operating along the entire coast of Ghana. The canoes vary between 12 and 18 m in length and are powered by outboard motors of 40 hp.

The inshore fleets are locally built wooden vessels fitted with inboard engines of up to 400 hp and have lengths ranging between 8 and 37 metres. These vessels are multipurpose and are used for both purse seining and bottom trawling. They operate as purse seiners during the upwelling periods and switch to bottom trawling for the rest of the year. The purse seiners target the sardinellas, chub mackerel and other Carangidae species. They fish in the same coastal waters as the artisanal fleet during the upwelling seasons. There are about 230 inshore vessels operating from 7 landing centres (these are sites with a port or semi-harbour facility).

1.2.2 Other fleets

1.2.2.1 Cote d'Ivoire.

From 2013 to 2017, the number of industrial vessels increased to 46 which is twice the number in 2012 (20 vessels). These vessels use surface trawls and, recently, encircling surface gillnets. They operate along the entire coast at more than 4 nm from the coast. Since 2008, the industrial fleet targeting small pelagic fish has been dominated by Chinese sardine boats (FAO 2019).

1.2.2.2 Benin

The artisanal fleet consists of more than 100 canoes mainly fishing with purse seines, sovi bottom set gillnets, sardinella gillnets, dagbadja gillnets, beach seine and ali watcha gillnets. Because the current practice of packaging the fish aboard the trawlers, it is difficult to separate the pelagic species clearly. The small pelagic fish are mixed in 20 kg sacks with other species and frozen on board before they are landed and sold. However, about a dozen tonnes of small pelagic species are landed per year by several trawlers.

1.2.2.3 Togo

Seven types of fishing gear are used in the artisanal fishery: ring purse seine, beach seine, surface gillnet, bottom set gillnet, floating gillnet, shark gillnet, and line. The different gear types are used all year round. The purse seine is used to catch all small pelagics. Among the most fished species are Caranx spp., Trachurus spp., round sardinella, flat sardinella and anchovy. The period of greatest abundance for the species targeted by the Togolese fisheries is from July to October, corresponding to the high season. The beach seine is also used to catch small pelagic fish. The surface gillnet is mainly used to fish for round sardinella and flat sardinella. The industrial fishery is not very developed, and its production has been insignificant since 1999.

1.3 Biology of exploited species

The summarised biology of the five species described here is taken from FishBase.

1.3.1 Anchovy

Mainly a coastal marine species, forming large schools that enters lagoons, estuaries and lakes, especially during spawning. Tends to move further north and into surface waters in summer, retreating and descending in winter. Feeds on planktonic organisms. Anchovy is a pelagic, spring-summer multiple spawning species.

1.3.2 Round sardinella

A coastal, pelagic, species preferring clear saline waters. It is a schooling species that is strongly migratory, often rising to surface at night and dispersing. It is a cold water species, preferring temperatures between 18-25°C It shoals near the surface in the period of upwelling, but retreating below the thermocline in the hot season, down to depths of 200 to 300m. It feeds mainly on zooplankton, especially copepods and larvae of mysids, but also some phytoplankton, especially by juveniles. The breeding pattern is extremely complex, with two principal spawning periods in some areas (linked with upwelling regimes off west Africa).

1.3.3 Flat sardinella

A coastal, pelagic species, but tolerant of low salinities sometimes in estuaries and lagoons. It forms schools, preferring waters of 24°C, at surface or down to 50m and is strongly migratory. It feeds on a variety of small planktonic invertebrates, also fish larvae and phytoplankton. It breeds only once in the year, during the warm season between July and September, in coastal waters; juveniles and adults show clear north-south migrations in the Gabon-Congo-Angola sector and the Sierra Leone-Mauritania sector of the Atlantic Ocean, each area having nurseries; these movements are correlated with the seasonal upwelling.

1.3.4 Bonga shad

Bonga shad is found in fairly shallow coastal waters, lagoons and estuaries, and sometimes also in lower courses of coastal rivers, but as much as 300 km up rivers. It feeds principally on phytoplankton, chiefly diatoms, filtered by the very fine gillraker sieve. It breeds throughout the year in estuaries and in rivers.

1.3.5 Horse mackerel

Adults are sometimes found near the surface. They form schools. Commercial fishing trawlers catch this species at depths up to 650 m. Adults feed mainly on crustaceans. Eggs are pelagic.

2 Data used in assessments

2.1 Introduction

Data used in the assessments reported here are taken from the most recently available CECAF report on small pelagic resources in the region (FAO, 2019) which provides catch and effort data from 1990-2017, as well as some length frequency data and swept area biomass estimates from the Nansen surveys. There are a number of studies using length frequency data reported in the literature that provide estimates of fishing and natural mortality as well as growth parameters. These are based on length samples taken over a short time period, usually 12-18 months, and often in a limited geographical area (Table 2. 1). They provide a snapshot of the stock at a point in time in a localised area and, while important, the data are not used directly in the assessments discussed later in this report which cover a larger geographical area over 28 years.

The regional stock assessments undertaken by CECAF are based primarily on commercial catch and effort data. These provide the principal inputs used in assessments and form the main focus for discussion in this section. The data are available for 6 different fleets covering the four countries in the region (

Table 2. 2).

As well as considering the raw data a simple model is described and used to extract a common trend from the fleets for the main species, based on commercial catch per unit effort (cpue) data. The model assumes that the cpue data are proportional to stock abundance so that any estimated trend should provide an indication of biomass development over time.

2.2 Effort data

Fishing effort is estimated using survey methodology based on samples taken at points of landing. Since the landings are widely distributed this will inevitably lead to measurement error that will depend on the sample size and the methods used to raise samples to total fleet size. It will vary by country and fleet.

Table 2. 2 lists the fleets where effort data are reported and the acronyms used in this report. Figure 2. 1 shows the effort by fleet. In some years, effort data are missing leading to breaks in the time series. Clearly recorded effort is highly variable and there is no consistent trend across fleets. The Ghanaian, Benin and Cote d'Ivoire fleets show a clear upward trend while the Togo artisanal shows a long term decline.

2.3 Catch data

As with effort, the catch data are estimates derived from surveys and will therefore be subject to measurement error. Figure 2. 2 shows the estimated catches for the five stocks considered in this report plotted as a stacked bar chart. This shows catch by fleet over the period 1990-2017. Here countries are coded by colour with Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue. Clearly the Ghanaian artisanal fleet dominates the catches for all stocks though less so for sardinella where Côte d'Ivoire makes up a significant fraction in recent years. Overall Togo makes only a minor contribution to the total catches.

It should be noted that there are gaps in the reported catches for some fleets, especially in the earlier years and this will mean that the height of the bars in Figure 2. 2 will tend to under-estimate the total catch for some years. This problem has a bearing on the stock assessments since it will cause bias in abundance and mortality estimates unless a correction is made for these missing data.

2.4 Biomass estimates

Some estimates of biomass are available for anchovy and sardinella spp from the Nansen surveys carried out periodically in the region and reported in FAO (2019). Data for anchovy are shown in Figure 2. 3.These show no clear trend. The FAO report does not present full acoustic survey data for sardinella but notes a large decrease in abundance from 119000t in 2006 to 4750t in 2017.

2.5 Catch per unit effort

The Nansen survey data provide fishery independent estimates of biomass but the observations are sparse and only cover two of the species that are routinely assessed by CECAF. Commercial cpue data offer one of the few data sources that might provide estimates of relative abundance over time. They form the principal source of abundance information used by CECAF to fit assessment models and hence estimate population parameters. Commercial cpue data are well known to be subject to bias for a wide variety of reasons and need to be interpreted with appropriate care. Here, we simply show trends in the raw cpue data in an attempt to identify any obvious trends.

Fleet cpue over the 28-year period is shown in Figure 2. 4 for each stock. Here the time series are standardised to the series mean to aid comparison of trends on a similar scale. There is considerable variability in the trends though the Ghanaian fleets (shown in green) tend to show a decline for all species except horse mackerel. By contrast the Togo fleets (pink) show an increase in cpue for anchovy and round sardinella. Thus while the fleets that dominate the fishery show declining cpue, there is no overall consistency in the trends.

With the high degree of variability in the cpue data it is difficult to identify any clear trend in abundance from inspection of the raw data. In order to try to extract a common trend from the data we fitted a simple single factor model to the data of the type described by Conn (2010). This assumes that for each fleet, k, in year t, $cpue_{t,k}$ is a measure of the underlying stock biomass, B_t, but is subject to a fleet dependent sampling error, $\varepsilon_{t,k}$. Thus we might write :

$$\log(cpue_{t,k}) = q_k + \log(B_t) + \varepsilon_{t,k} \qquad 2.1$$

Here B is the underlying latent trend, q is an offset that scales the trend to cpue and ε_t is a lognormally distributed error. The parameters can be estimated from the data provided one of the q values is specified. For convenience we fixed q=0 for one fleet which scales B to that cpue series and is therefore a measure of relative, not absolute, biomass. In addition, we apply a time series smoother to account for the correlation between the successive biomass values so that:

$$\log (B_t) \sim normal(\log (B_{t-1}), s) \qquad 2.2$$

Where s is the standard deviation of the process error in biomass. The advantage of such a model is that it should correctly weight the data according to how well each time series follows the underlying trend. It is also able to account for missing values in the time series and hence reduces this potential source of bias.

The estimated overall trend is shown in Figure 2. 5 and in all stocks except horse mackerel the current cpue is lower than at the start of the series. For anchovy and round sardinella there is a long term decline but with some levelling off in the recent period. Bonga shad shows an initial sharp decline but some recovery in more recent years. The measurement error associated with each fleet is given in Table 2. 3. These values represent the “uniqueness” for each time series which characterises how different the individual fleet trends are from the underlying common trend. The values are large indicating that the time series are not highly correlated with the common trend. Fleets with higher uniqueness will contribute less to the estimated common trend.

2.6 Discussion

There is a large amount of catch and effort data covering 28 years and 6 fleets that exploit five stocks. In principle such data provide appropriate inputs for stock assessment modelling that could estimate stock trends and fishing mortality by fleet. There are, however, a number of data related issues that need to be considered in any assessment modelling. Firstly, because both the catch and effort data are derived from surveys they are subject to sampling error that needs to be considered in the model. Secondly, for some fleets catch records are missing and these also need to be accounted for to avoid bias.

Missing values in the effort series are less problematic since thy have no bearing on the estimates of total removals by the fishery. The main issue with the effort data is whether it is appropriate to use it to derive cpue data as input to a stock assessment model. Given that there are sampling errors in both the catch and effort data, cpue estimates are likely to be subject to large errors that increase noise in the time series. It would be preferable to use the data separately in their original form in an assessment model to avoid this problem. It would also overcome the problem of observations where there is catch but no effort information to calculate cpue.

An important issue not addressed in this section is the question of fishing power. The cpue trends shown in Figure 2. 5 imply that fishing power has remained constant over the full time period and this is unlikely (Palomares and Pauly, 2019). Hence the cpue trend seen in Figure 2. 5 may overestimate relative biomass at least in the more recent period. The problem of increasing fishing power needs to be taken into account in any assessment model where nominal effort data are used.

A number of studies using length frequency data, mainly collected between 2014 and 2019 have been used to estimate fishing and natural mortality (Table 2. 1). These data provide estimates at one point in time and make assumptions about annual data reflecting equilibrium conditions. The data could be included in an integrated assessment model such as Stock Synthesis (Methot and Wetzel, 2013) but their limited number of years and geographical coverage means that they are unlikely to provide much additional information for a full population dynamics model. These data are therefore not considered further but the results from the relevant studies are discussed in relation to the assessments described later in this report.

3 Stock assessments

3.1 Introduction

Assessments of the five stocks have been undertaken in a number of studies using length frequency data usually collected over a period of approximately one year (Table 2. 1). These studies estimate fishing mortality (F) and natural mortality (M). The latter is based on the well-known method of Pauly (1980) that makes use of growth parameters and sea surface temperature while F is typically derived from ELEFAN (Pauly, 1987). As only one year of data is used, these methods essentially assume that the observed data correspond to an approximate equilibrium since they use the descending limb of the length frequency as a measure of Z (total mortality) and this will change if fishing mortality changes through time.

Results from the studies listed in Table 2. 1 suggest that fishing mortality on most stocks is very high. Values of natural mortality are also high. Natural mortality is often considered a predictor of F_{MSY}. Zhou et al (2012), for example, propose the relationship $F_{MSY}=0.87M$ which would suggest high values for the stocks analysed here. Using this measure, most studies suggest the stocks are being fished below F_{MSY} except for anchovy and flat sardinella in two of the case studies.

The five stocks considered here are routinely assessed by CECAF using catch and effort data (FAO, 2019). These assessments make use of a version of the Schaefer surplus production model described by Haddon (2011). As implemented by CECAF, the approach has a number of limitations:

1. A single cpue series is used as an abundance index, but it is unclear how the selection of the chosen series is made. It is likely that using cpue series from different fleets may lead to quite different perceptions of stock trends and levels of exploitation.
2. The model assumes that the reported catch data are free of sampling error and this is likely to result in unwanted noise in the biomass estimates. The assessments also make no correction for missing catch data which may cause bias.
3. Commercial fishing effort is likely to be affected by increasing fishing power over time and unless accounted for will tend to cause positive bias in abundance estimates in more recent years leading to an over-optimistic perception of stock biomass.

To overcome some of these problems the assessments reported here use the model described by Cook et al (2021) outlined below. The model is fit directly to the catch and effort series without transforming them to cpue and thus allows for errors on both types of data. Fishing power increase is estimated in the model and hence should reduce bias in abundance estimates. As the model is framed in state-space, missing catches can be estimated, and this too should reduce bias.

3.2 Model description

The assessment model is derived from the familiar form of the Schaefer model due to Fletcher (1978) parameterised in terms of the carrying capacity, K, and maximum sustainable yield, m. The biomass, B, at time t is projected forward from the equation:

$$B_{t+1} = \left[\left(1 + \frac{4m}{K}\right) B_t - \frac{4mB_t^2}{K^2} - \sum_k Y_{k,t}\right] \varepsilon_t \qquad 3.1$$

Where $Y_{k,t}$ is the catch by fleet k and ε_t is a log-normally distributed random process error with mean and standard deviation (0, σ_B). If we assume that the catch is proportional to the biomass with a fishing mortality, F, then:

$$Y_{k,t} = B_t F_{k,t} \qquad 3.2$$

It might be supposed that F is approximately proportional to fishing effort, f, with constant catchability, q, so that F=qf. However if effective fishing effort increases over time due technological creep by an annual power increment δ, then f (or q) must be inflated by an amount $(1+\delta)^{(t-1)}$ so that:

$$F_{k,t} = q_k f_{k,t} (1 + \delta_k)^{(t-1)} \qquad 3.3$$

In order to reduce the number of effective parameters to be estimated we assume that fishing effort follows a random walk, $f_t \sim lognormal(\log(f_{t-1}), \sigma_f)$, and that the initial biomass, B_1, is at equilibrium. For n fleets, the equilibrium assumption allows one of the catchability constants, q, to be determined. Writing B_1=dK, where d is the depletion from virgin biomass (K), then q for fleet 1 is given by:

$$q_1 = \frac{\left(2F_{MSY}(1 - d) - \sum_2^n q_k f_{k,1}\right)}{f_{1,1}} \qquad 3.4$$

Clearly the catches, Y, and effort, f, are observed with error. For fishing effort, we assume lognormal errors so that observed effort f ', is given by:

$$f'_{k,t} \sim lognormal(\log(f_{k,t}), \sigma_k) \qquad 3.5$$

The catches for the stocks of interest here are derived from surveying a sample of vessels which is then scaled to fleet level. The associated observation errors may therefore be large. It is commonplace to assume lognormal errors (e.g. Nielsen and Berg 2014) but since it is likely the observations are over-dispersed we assume that the observed catch, Y', is subject to negative binomial errors with dispersion parameter, κ, (Cook, 2019):

$$Y'_{k,t} \sim negative\ binomial(Y_{k,t}, \kappa_k) \tag{3.6}$$

3.3 Methods

A “reference model” was configured as the default model for all stocks based on the analysis described in Cook et al (2021). The fishing power increase, δ, for the Ghanaian artisanal fleet was set=0.015 based on the analysis in Lazar et al (2018). The remaining fleet δ values were estimated as free parameters but with a lognormal prior (log(0.03),0.09). This prior is based on the study by Pauly and Palomares (2019) of 50 fleets and is the mid-point of the range of their estimates. Apart from this constraint, an informative square root prior for carrying capacity, K, was applied, while all other priors on the parameters were uniform. The model configuration is shown in Table 3. 1.

In addition to the reference model, sensitivity runs were performed to explore different modelling assumptions. These were:

1) Assuming lognormal errors for the catch data rather than negative binomial
2) Replacing the constraint on δ in the reference model by setting δ on the Ghanaian fleet to 0.03.

The sensitivity models are specified in Table 3. 2.

The data used are listed in Appendix 1 and are taken from FAO (2019). In some fleets the reported catches were very small and/or intermittently reported. The fleets included for each assessment are given in Table 3. 3. Before model fitting, each fleet effort data series was divided by its mean so that the catchability parameters are estimated on a similar scale.

The model was fit to the five stocks using the Bayesian package “rstan” (Stan Development Team, 2016). A minimum of 20,000 iterations were performed with three chains and a thinning rate of 100. If the Rhat statistic indicated poor chain mixing, the number of iterations was doubled until Rhat=1.

3.4 Results

3.4.1 Model fit

The reference mode fits to the catch and effort data for each stock are shown in Appendices 2-6 with additional model output. In many cases the model fits both the catch and effort data reasonably well but there are clearly systematic residual patterns in some data sets.

Anchovy: Overall the model tracks the trend in the catch and effort well though there is considerable scatter around the fitted line.

Bonga shad: The data for both the effort and catch data are fitted well. However, in 2016 there is a large outlier for the catch for the Cote d'Ivoire fleet leading to some lack of fit in recent years.

Round sardinella: There is good fit to the effort data. The model tracks the overall trend in the catches in most fleets but less well for the Ghana industrial and inshore fleets.

Flat sardinella: There is generally a good fit to the effort data. The model fits the catch data for the artisanal fleets of Ghana, Togo and Benin well but there is poor fit to the remaining three fleets.

Horse mackerel: There is good fit to the effort data for three of the four fleets. The trend in the effort data for Togo is tracked well but not the annual variability. The fit to the catch data is generally poor with systematic patterns in the residuals.

Measurement errors associated with the effort data are shown in Figure 3. 1. Here, the same effort data are used for each stock so some similarity in the stock specific values might be expected. The errors are lowest in the Ghana artisanal fleet.

The errors in the catch data are characterised by the dispersion parameter, κ, which scales the variance in the negative binomial distribution. Here large values of κ indicate higher precision and for plotting convenience are shown on a square root scale in Figure 3. 2. Unlike the effort data each stock has a unique catch data series so more heterogeneity is expected within fleets. The values of κ are largest in the Ghana and Benin artisanal fleets indicating higher precision.

3.4.2 Stock trends

The estimated biomass ratio (B/B_{MSY}) and F ratio (F/F_{MSY}) are shown in Figure 3. 3 and Figure 3. 4. The biomass has declined throughout the period of assessment reflecting the continuous increase in fishing mortality. In all cases, except horse mackerel, the biomass is now below B_{MSY} (ratios <1) and F is above F_{MSY} (ratios>1). Furthermore, the upper bound of the 95% CI is below 1 for B_{MSY}, while the lower bound for F_{MSY} is well above 1 indicating the there is a high degree of confidence that these stocks are heavily over-exploited relative to MSY. For horse mackerel although the median estimates of B/B_{MSY} and F/F_{MSY} indicate the stock is over-exploited, there is large uncertainty in the status of the stock.

Sensitivity runs with alternative model assumptions on the error distribution and the fishing power increment show the same trends and all the median estimates lie within the 95% CI of the reference model (Figure 3. 3 and Figure 3. 4). The greatest differences are evident in anchovy for the early years and in horse mackerel where there are differences in scale. However, none of the sensitivity runs suggest alternative stock status.

The fleet contributions to total fishing mortality are shown in Figure 3. 5. It is clear the Ghanaian fleets dominate with the artisanal (g_art) fleet increasing in recent years. The Togo artisanal fleet is important for anchovy while the Côte d'Ivoire fleet is important for sardinella and horse mackerel.

3.4.3 F_{MSY}, B_{MSY} and initial depletion

Estimates of F_{MSY} from the reference model and the sensitivity runs are shown in Table 3. 4.The F_{MSY} values are high and in excess of 1 for sardinella but lowest for bonga shad (0.26). Horse mackerel values are close to 1. For these stocks the values are fairly insensitive to alternative model configurations. However, for anchovy F_{MSY} is sensitive to the assumed fishing power increment for the Ghana fleet and ranges from 0.7 in the reference model to 0.4 when $\delta=0.03$. Despite the large effect of the δ assumption, it does not appear to have much effect on the F/F_{MSY} ratios (Figure 3. 4) indicating that these ratios provide a robust indicator of relative stock status.

The sensitivity of B_{MSY} estimates differs across stocks (Table 3. 4). Bonga shad and flat sardinella values are insensitive to model assumptions. For anchovy the choice of δ for the reference fleet has the largest effect. In the case of round sardinella and horse mackerel, the greatest sensitivity is to the error distribution assumption on the catch data.

The model estimates the depletion from virgin biomass (K) in the first year (1990) of the assessment (Table 3. 4). In all cases the biomass in 1990 is estimated to be below virgin biomass. The range is from around 41% of K for bonga shad to 60% for horse mackerel. The depletion estimates are largely insensitive to the model configuration.

3.4.4 Fishing power

An important feature of the model is the inclusion of fishing power increment (δ) as a parameter to be estimated. The estimates from the reference model are shown in Figure 3. 6. The largest power increment is seen in the Togo fleet especially for anchovy and round sardinella. The Benin fleet also shows higher values compared to the reference fleet.

The effect of positive increases in fishing power is to decrease the estimates of relative abundance of the stock biomass in recent years. This can be seen by comparing the biomass trends in Figure 3. 3 to the raw cpue values in Figure 2. 5. In the cpue trend the biomass appears to stabilise or increase for most stocks in recent years. However, when fishing power is taken into account the biomass trend does not stabilise but continues to decline.

3.5 Discussion

The results of the analysis using catch and effort data suggest that, with the exception of horse mackerel, all stocks have been in decline since 1990 and that fishing mortality has continuously increased over the same period. The biomass of the stocks appears to have been fished to below B_{MSY} and they are still being fished above F_{MSY}. While it is difficult to estimate F_{MSY} with any certainty, the relative rate of fishing (F/F_{MSY}) appears to be robust to model configurations, as does the biomass ratio (B/B_{MSY}). While the horse mackerel assessment is very uncertain the downward trend in biomass and upward trend in fishing mortality is still apparent.

There is some similarity between the assessment model results and the trend in cpue, but with the assessment model giving a more pessimistic perception of recent biomass. This is because the model estimates that fishing power has increased over the period of the assessment. It is important to note that an informative prior was applied to δ based on a meta-analysis and this will contribute substantially to the estimates of fishing power. Lazar et al (2018) provide empirical evidence for increases in fishing power for the fleets exploiting small pelagic stocks in Ghana and it seems likely that similar increases occur on other fleets. The estimates of δ for some fleets differ from the mean value in the prior (0.03) suggesting that the data do contain some information on this parameter, and given that fishing power is likely to have increased, the trends emerging from assessment model are likely to be more realistic than models assuming no increase in fishing power.

The values of F_{MSY} are very uncertain because the data only contain information during stock decline. This means that the stock trajectory can be explained either as a productive stock with a low virgin biomass or a less productive stock with a higher virgin biomass. Clearly, with this uncertainty it is more challenging to estimate how the stocks would respond to a reduction in fishing mortality. Nonetheless, the apparently poor state of all these stocks does suggest some urgency is required to reduce exploitation rates.

4 Stock status and overview

4.1 Introduction

The assessments of all five stocks indicate that the biomass is declining and that fishing mortality is increasing. Furthermore, there is evidence that the biomass is below B_{MSY} and that F is above F_{MSY}. Fishing above F_{MSY}, though sub-optimal in terms of potential catch, does not necessarily mean that fishing is unsustainable in the long run, and it may simply indicate the there is a loss of yield with an acceptable risk to the biomass. Here we consider the current fishing mortality (at least the estimate for 2017) and the equilibrium biomass expected at this level of exploitation to identify possible risks to the stocks. We also compare the estimates obtained from our analysis with other assessments for the same stocks in order to see whether there is any consistency in the results.

4.2 Equilibrium analysis

The surplus production model used in our assessments (equation 3.1) has two parameters, m and K that describe the population dynamics of the stocks. Given estimates of these parameters it is possible to calculate the equilibrium biomass at any value of F simply by setting $B_{t+1}=B_t$ and solving for the biomass. Also from equation (3.2) the equilibrium yield can be found once equilibrium biomass is known. Using estimates of m and K from the reference model we constructed the equilibrium biomass and equilibrium yield curves for the five stocks. These are shown in Figure 4. 1 and Figure 4. 2 with the annual values from the model plotted as a time series. In both figures the annual values track the expected equilibrium with the catches declining beyond MSY as fishing mortality increases. A similar picture can be seen for biomass but what is important is that for most stocks the current fishing mortality is associated with a high probability that the biomass is zero and implies there is a substantial risk of stock collapse. In effect the current rate of exploitation is not sustainable. The problem seems to be worst for sardinella and bonga shad. The anchovy and horse mackerel biomass and exploitation appear to be in a slightly better state but, given the uncertainty the risk of stock collapse is real since the current F is within the zero biomass 95%CI.

Over the period 1990-2017 fishery catches have tended to be maintained at an apparently high level for most stocks. This has occurred by increasing the fishing mortality to compensate for a declining stock. In the short term such a process of maintaining catches by increasing fishing to compensate for declining biomass is possible. However, the equilibrium analysis suggests this cannot continue indefinitely and that there is a real risk that catches will eventually collapse.

4.3 Discussion

The studies listed in Table 2. 1 based on length frequency data collected over a short period give a mixed picture of stock status in relation to F_{MSY}. There is clearly substantial variability in these estimates even within stocks making it difficult to draw any conclusions on stock status.

The international assessments of these stocks undertaken by CECAF should in principle be similar to those presented here since they use a similar population dynamics model and make use of essentially the same data. Where CECAF were able to obtain an assessment these can be compared to the current study in Table 3. 5. The sardinella assessments performed in this study show close agreement with the CECAF assessment indicating the stocks being fished above F_{MSY} and the biomass below B_{MSY}. CECAF were unable to obtain a satisfactory assessment for bonga shad and horse mackerel. In the case of anchovy the CECAF assessment shows the stock to be fished below F_{MSY} and the biomass to be above B_{MSY}. The result is based on the Togo artisanal cpue which has an increasing trend over time. However, it appears that the fishing power of this fleet has increased significantly and when this is taken into account a very different trend in biomass emerges. For this stock the inclusion of Ghanaian and Benin cpue supports the declining trend in biomass.

The assessments reported in this study estimate very high levels of fishing mortality rate. As can be seen from Table 3. 5 all the F/F_{MSY} values are above 1 which means the recent prevailing values of F are unlikely to support a sustainable fishery.

As far as possible the assessments made use of all the available fleet catch and effort data. This may not be the best use of the data if some time series are of poor quality or simply unrepresentative. It is possible that the very high Fs estimated in the assessments are the result of data that do not adequately reflect abundance. Further investigation of the appropriate data to include is necessary, but is a potentially substantial amount of work.

Although there is uncertainty in the estimates of B_{MSY} and F_{MSY} the analyses described here provide the basis for a fleet disaggregated fishery model to be developed that would enable the investigation of potential management scenarios. It is possible with the parameter values obtained to consider the impact of changes in fleet behaviour on catches and biomass of all five species and the interaction between species. This could also facilitate the development of a multi-fleet fishery bio-economic model to consider the wider impacts of management scenarios.

Acknowledgement

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References

Amponsah, S. K.K. , Ofori-Danson, P.K. and Nunoo, F.K.E. 2016. Population dynamics of Engraulis encrasicolus (Linnaeus, 1758) within Ghana's coastal waters. International Journal of Fisheries and Aquatic Studies, 4:258-263.

Amponsah, Samuel K.K., Patrick K. Ofori-Danson, Francis K.E. Nunoo and Godfred Ameyaw. (2017a) Virtual population analysis and estimates of maximum sustainable yield of some commercially important fish species in the coastal waters of Ghana and management implications. International Journal of Fisheries and Aquatic Research, 2:1-7.

Amponsah S.K.K., Ofori-Danson P.K., Nunoo F.K.E. and Ameyaw G.A. 2017b. Population dynamics of Sardinella aurita (Val., 1847) within Ghana's coastal waters. Research in Agriculture Livestock and Fisheries, 4: 237-248.

Amponsah S.K.K., Ofori-Danson P.K., Nunoo F.K.E. and Ameyaw G.A. 2019. Estimates of Population parameters for Sardinella maderensis (Lowe, 1838) in the coastal waters of Ghana. Greener Journal of Agricultural Sciences, 9:23-31.

Amponsah, Samuel K.K., Selasi Yao Avornyo, Patrick Ofori-Danson, Samuel Henneh and Nana Ama B. Afranewaa. 2021. Assessing the population characteristics of Carangids in the Coast of Ghana, West Africa. Research in Marine Sciences,6:965 – 976.

Conn, P.B. (2010). Hierarchical analysis of multiple noisy abundance indices. Canadian Journal of Fisheries and Aquatic Science. 67: 108–120.

Cook, R. M. 2019. Inclusion of discards in stock assessment models. Fish and Fisheries, 20: 1232-1245. https://doi.org/10.1111/faf.12408.

Cook, R., Acheampong, E., Aggrey-Fynn, J, and Heath, M. (2021). A fleet based surplus production model that accounts for increases in fishing power with application to two West African pelagic stocks. Fisheries Research, 243, *in press.*

FAO. 2019. Report of the FAO/CECAF Working Group on the Assessment of Small Pelagic Fish – Subgroup South. Elmina, Ghana, 12-20 September 2018.. CECAF/ECAF Series / COPACE/PACE Séries No. 19/81. Rome.

Fletcher, R.I. 1978. Time-dependent solutions and efficient parameters for stock production models. U.S. Fisheries Bulletin. 76:377-388.

Haddon, M. 2011. Modelling and quantitative methods in fisheries, 2nd Edition. CRC press, Boca Raton FL.

Lazar, N., Yankson K., Blay, J., Ofori-Danson, P., Markwei, P., Agbogah, K., Bannerman, P., Sotor, M., Yamoah, K. K., Bilisini, W. B. (2018). Status of the small pelagic stocks in Ghana and recommendations to achieve sustainable fishing 2017. Scientific and Technical Working Group. USAID/Ghana Sustainable Fisheries Management Project (SFMP). Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island. GH2014_SCI042_CRC 22 pp.

Methot Jr., R. D. and Wetzel, C.R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research, 142: 86-99.

Nielsen, A. and Berg, C. W. (2014). Estimation of time-varying selectivity in stock assessments using state-space models, Fisheries Research, 158, 96–101.

Palomares, M. L. D., and Pauly, D. 2019. On the creeping increase of vessels' fishing power. Ecology and Society 24(3):31. https://doi.org/10.5751/ES-11136-240331

Pauly, Daniel (1980). On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks, *ICES Journal of Marine Science*, 39, 175–192, https://doi.org/10.1093/icesjms/39.2.175

Pauly,D. (1987). A review of the ELEFAN system for analysis of length-frequency data in fish and aquatic invertebrates. p. 7-34. In: Pauly, D. ; Morgan, G.R. (eds.) Length-based methods in fisheries research. ICLARM conference proceedings 13, 468 p. ICLARM, Manila, Philippines, and Kuwait Institute for Scientific Research, Safat, Kuwait.

Stan Development Team 2016. Stan Modeling Language: User's Guide and Reference Manual. Version 2.14.0. http://mc-stan.org/.

Sossoukpe, E., G Djidohokpin, E D Fiogbe 2016. Demographic parameters and exploitation rate of Sardinella maderensis (Pisces: Lowe 1838) in the nearshore waters of Benin (West Africa) and their implication for management and conservation. International Journal of Fisheries and Aquatic Studies, 4: 165-171

Zhou, S., Shaowu Yin, James T. Thorson, Anthony D.M. Smith, and Michael Fuller. (2012). Linking fishing mortality reference points to life history traits: an empirical study. Canadian Journal of Fisheries and Aquatic Science 69: 1292–1301.

Tables

*Table 2. 1 Stock assessments conducted on length frequency data covering approximately one year. The assessment method refers to the estimate of fishing mortality (F) or natural mortality (M). Note that F as estimated from these assessments is not the same as F described in the Schaefer surplus production model. FMSY is assumed to be 0.87*M (Zhou et al, 2012).*

Study	**Area**	**Data collected**	**Method (F/M)**	**F**	**M**	**F/F$_{MSY}$**
		Engraulis encrasicolus				
Amponsah et al, 2016	Ghanaian coastal waters	July 2014-January 2015	ELEFAN/Pauly	1.81	1.59	1.31
Amponsah et al, 2017a	Ghanaian coastal waters	June 2014-January 2015	VPA	0.56(a)	1.59	0.40
		Sardinella aurita				
Amponsah et al, 2017b	Ghanaian coastal waters	June 2014-January 2015	ELEFAN/Pauly	0.76	3.17	0.28
		Sardinella maderensis				
Amponsah et al, 2019	Ghanaian coastal waters	June 2014-January 2015	ELEFAN/Pauly	1.63	1.30	1.44
Sossoukpe, et al, 2016	Benin coastal waters	August 2012-July 2013	ELEFAN/Pauly	1.30	2.62	0.57
		Trachurus trecea				
Amponsah et al, 2021	Ghanaian coastal waters	July 2018-June 2019	ELEFAN/Pauly	1.14	3.60	0.36

(a) For this method estimates are derived from the mean over the length intervals.

Table 2. 2. Fleets for which catch and effort data are reported in FAO (2019).

Country	**Fleet**	**Acronym**
Côte d' Ivoire	Industrial trawlers	ci_ind
Ghana	Industrial trawlers	g_ind
	Artisanal	g_art
	Inshore	g_ins
Togo	Artisanal	t_art
Benin	Artisanal	b_art

Table 2. 3. Measurement error associated with each fleet after fitting the factor model to all fleets. The values are generally very large indicating a high degree of heterogeneity in the fleet cpue trends.

Fleet	Anchovy	Bonga shad	Round sardinella	Flat sardinella	Horse mackerel
ci_ind	NA	1.97	NA	NA	2.11
g_ind	NA	NA	0.85	1.27	NA
g_art	0.74	0.63	0.63	0.32	2.18
g_ins	NA	NA	0.57	1.30	1.38
t_art	0.63	NA	1.21	1.19	1.72
b_art	0.32	0.24	0.57	0.59	NA

Table 3. 1. Configuration of the reference model showing the priors in the parameters and constraints used.

Parameter	Description	Prior
m	Maximum sustainable yield	Uniform(1,2*max(catch))
σ_k	Standard deviation of effort observation error on each fleet	Uniform(0,1)
κ_k	Negative binomial dispersion parameter for catch observations for each fleet	Uniform(0.0001,100)
$f_{k,1}$	Effort in year one for each fleet	Uniform(0.001,10)
K	Virgin biomass	Square root uniform
d	Initial depletion	Uniform(0,1)
δ_k, $k \neq 1$	Fleet fishing power increment	Lognormal(log(0.03),0.9)

Table 3. 2 Models used in sensitivity runs. The reference model is given in the first row.

Model label	Comments
$\delta[1]=0.015$; neg binomial	Reference model
$\delta[1]=0.15$; lognormal	As reference but with lognormal errors for catch; prior: σ~uniform(0,10)
$\delta[1]=0.03$; neg binomial	As reference but $\delta_1=0.03$
$\delta[1]=0.03$; lognormal	As reference but $\delta[1]=0.03$ and lognormal errors for catch; prior: σ~uniform(0,10)

Table 3. 3 Fleets used in stock assessments. Fleets excluded are those where the catches or effort were absent.

Fleet	Anchovy	Bonga shad	Round sardinella	Flat sardinella	Horse mackerel
ci_ind		✓			✓
g_ind			✓	✓	
g_art	✓	✓	✓	✓	✓
g_ins			✓	✓	✓
t_art	✓		✓	✓	✓
b_art	✓	✓	✓	✓	

Table 3. 4 Estimates of key parameters for the five stocks from four model configurations. Numbers in brackets are the 95% CI. Model definitions are given in Table 3. 2.

Stock	**Reference model**	**As reference, lognormal errors**	**δ[1]=0.03, negative binomial errors**	**δ[1]=0.03, lognormal errors**
F_{MSY}				
Anchovy	0.70(0.15-1.83)	0.62(0.17-1.71)	0.43(0.13-1.2)	0.40(0.13-1.10)
Bonga shad	0.26(0.11-0.53)	0.25(0.17-0.53)	0.23(0.10-0.45)	0.22(0.10-0.46)
Round sardinella	1.10(0.40-1.98)	1.36(0.51-2.27)	0.86(0.26-1.81)	1.16(0.86-1.85)
Flat sardinella	1.32(0.60-2.16)	1.19(0.29-2.05)	1.31(0.61-1.91)	1.28(0.31-2.09)
Horse mackerel	1.0(0.22-1.95)	1.27(0.25-2.25)	0.96(0.14-1.96)	1.08(0.11-2.10)
B_{MSY} ('000t)				
Anchovy	165(126-488)	175(32-495)	241(132-508)	232(54-497)
Bonga shad	6.9(2.5-10.7)	6.4(1.8-10.8)	7.1(2.5-10.7)	6.6(2.3-10.9)
Round sardinella	100(43-260)	67(34-166)	141(46-422)	79(37-214)
Flat sardinella	17(10-32)	21(9.6-69)	18(12-34)	18(9.6-53)
Horse mackerel	18(3.6-84)	5.1(1.0-34)	16(3.9-79)	7.8(1.2-73)
Initial depletion, d				
Anchovy	0.47(0.10-0.67)	0.44(0.23-0.67)	0.57(0.39-0.71)	0.55(0.36-0.72)
Bonga shad	0.41(0.19-0.65)	0.42(0.19-0.67)	0.51(0.29-0.70)	0.52(0.26-0.77)
Round sardinella	0.53(0.35-0.64)	0.53(0.38-0.65)	0.60(0.41-0.72)	0.62(0.45-0.71)
Flat sardinella	0.56(0.37-0.69)	0.49(0.30-0.63)	0.64(0.46-0.75)	0.61(0.46-0.72)
Horse mackerel	0.60(0.23-0.82)	0.55(0.19-0.78)	0.71(0.36-0.89)	0.71(0.26-0.94)

Table 3. 5 Estimates of ratios of F/F_{MSY} and B/B_{MSY} in 2017 for all five stocks form the current study and the CECAF assessments in FAO (2019). In the CECAF assessments a single cpue series is used. In this study at least 3 time series of catch and effort data are used. Both studies use a Schaefer surplus production model.

	This study		**FAO (2019)**		
Stock	**B/B_{MSY}**	**F/F_{MSY}**	**B/B_{MSY}**	**F/F_{MSY}**	**cpue series used**
Anchovy	0.40	1.84	1.51	0.44	Togo artisanal
Bonga shad	0.20	2.25	NA	NA	Not able to fit data
Round sardinella	0.28	2.04	0.21	5.08	Ghana artisanal
Flat sardinella	0.14	2.19	0.10	7.08	Ghana artisanal
Horse mackerel	0.61	1.57	NA	NA	Not able to fit data

Figures

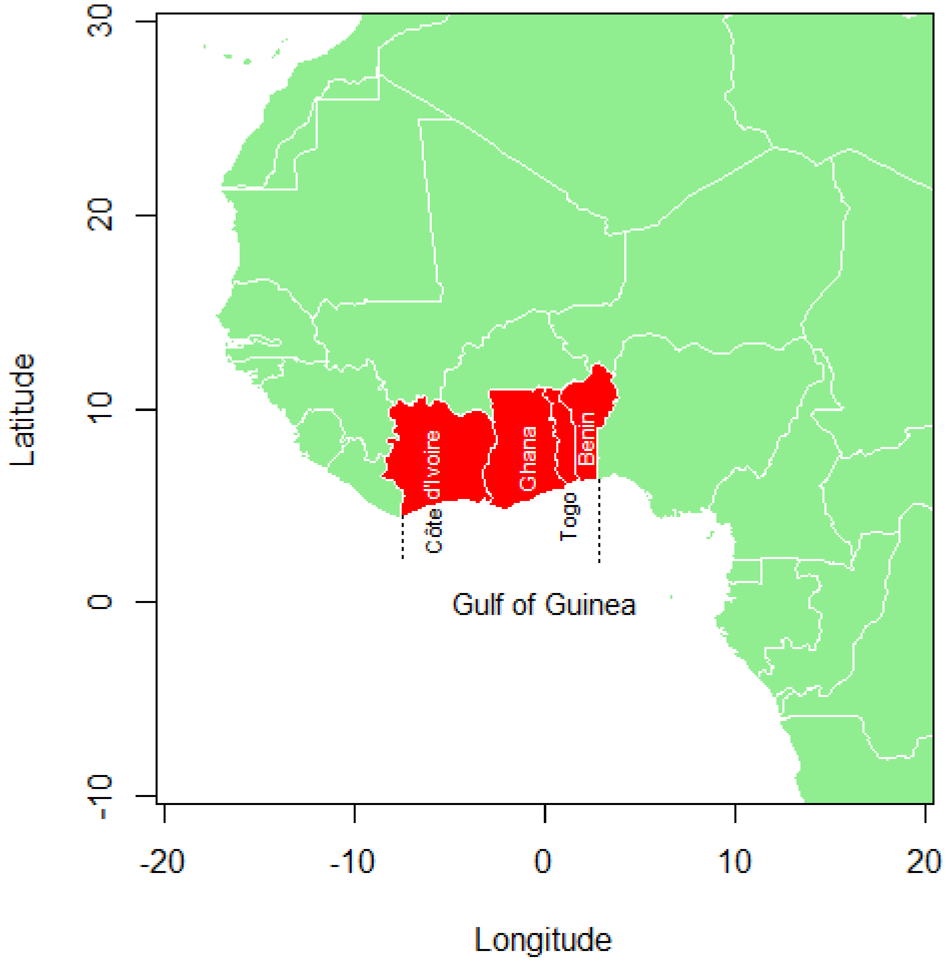

Figure 1. 1 Stock area considered for assessments corresponding to CECAF "western" zone shown as dotted lines. Assessments are based on catches and effort from Côte d'Ivoire, Ghana, Togo and Benin shown in brown.

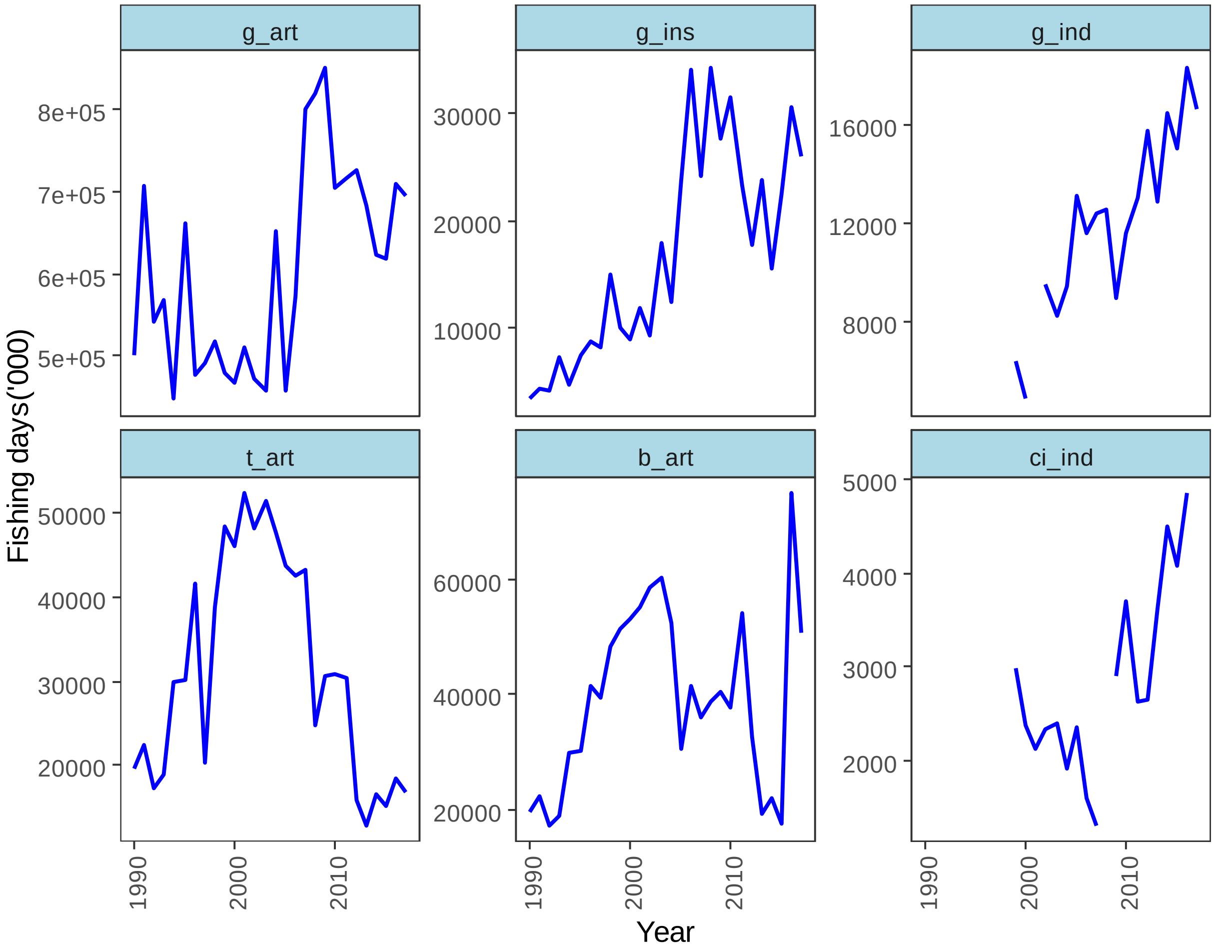

Figure 2. 1 Nominal fishing effort reported as days fishing. Fleet acronyms are identified in Table 2. 2

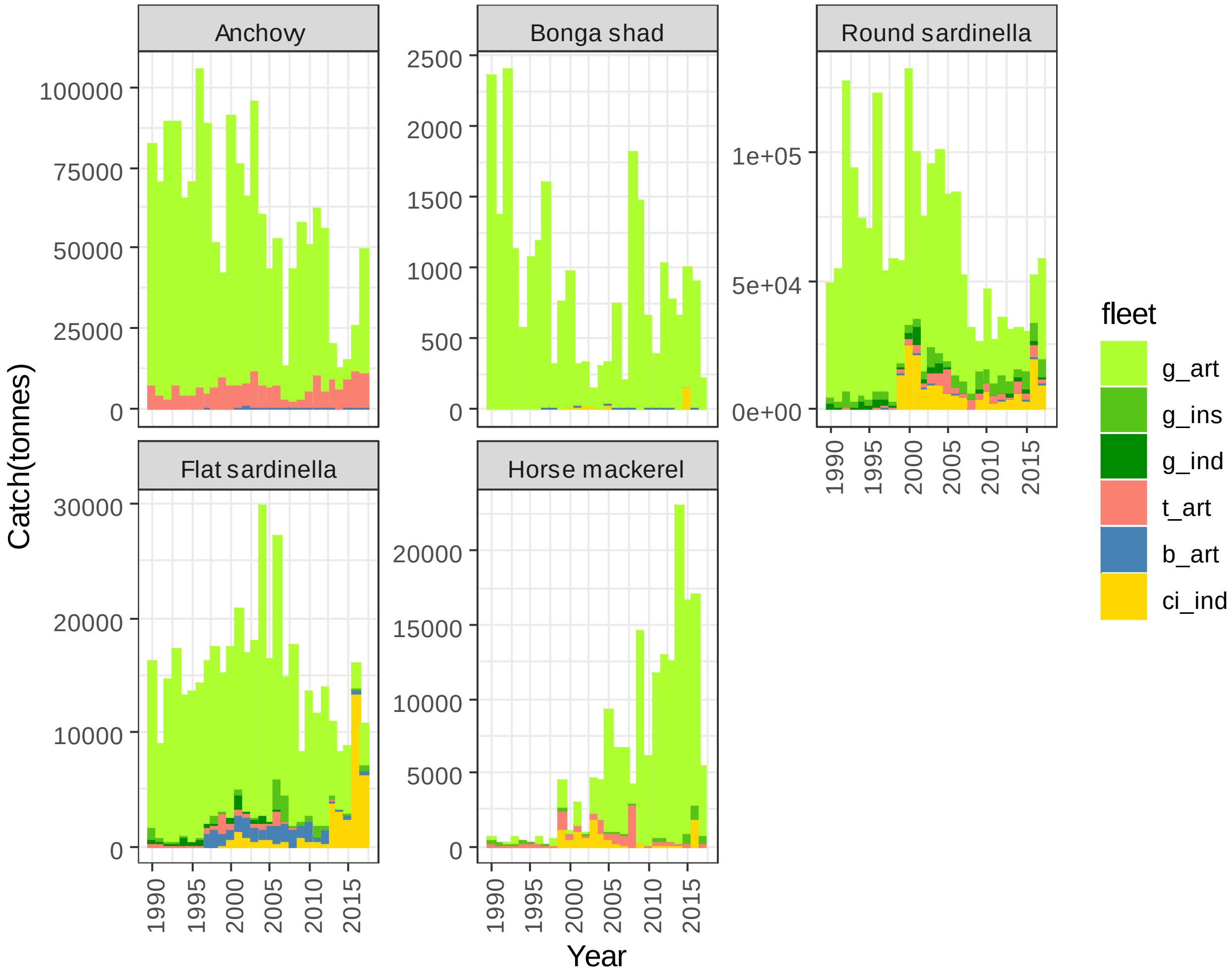

Figure 2. 2 Catches by fleet and country. Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue

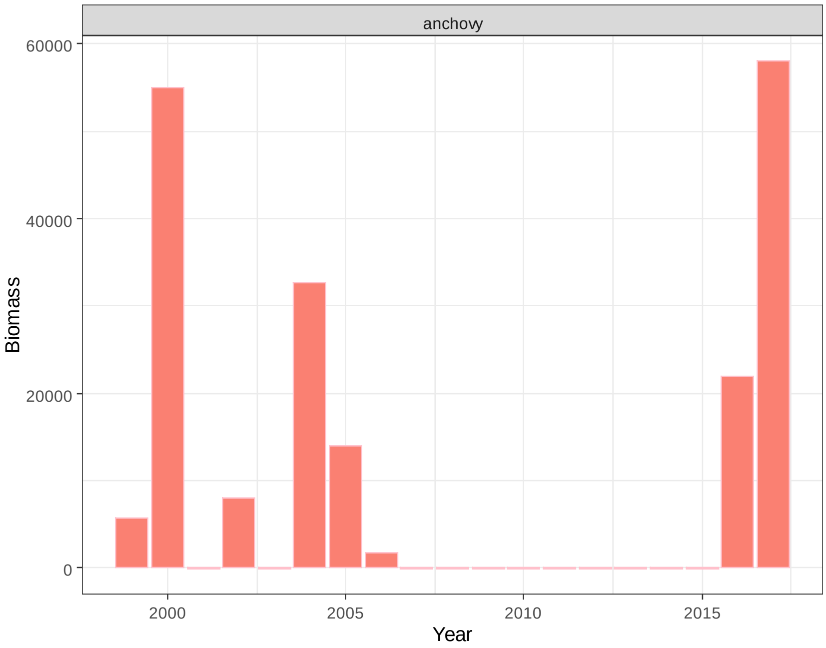

Figure 2. 3 Swept area biomass estimates (tonnes) of anchovy from the Nansen survey, from FAO(2019).

Figure 2. 4 Time series of cpue by fleet. Each cpue series is standardised to its mean. Countries are coded by colour: Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue.

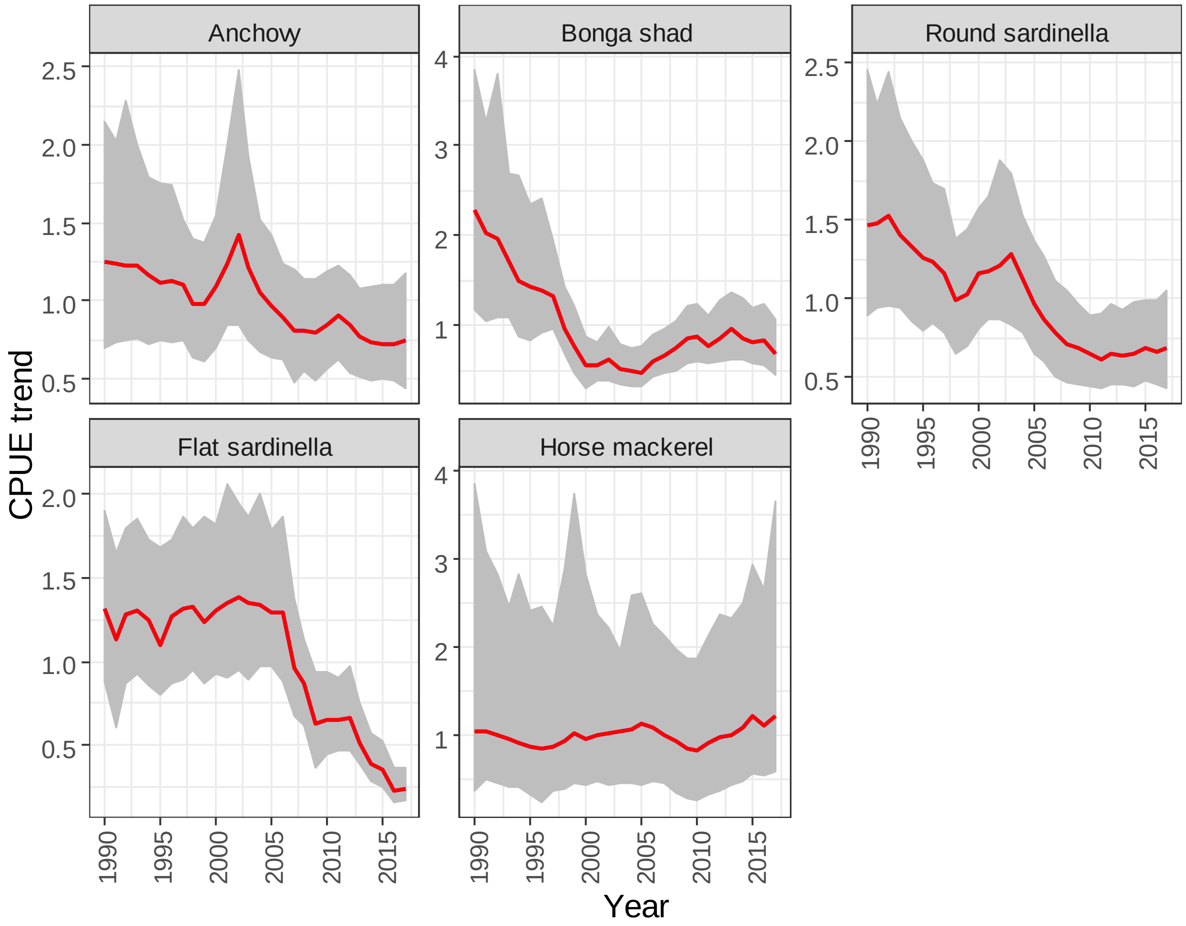

Figure 2. 5 The overall cpue trend estimated from the factor model for the five stocks. The shaded area shows the 95% CI.

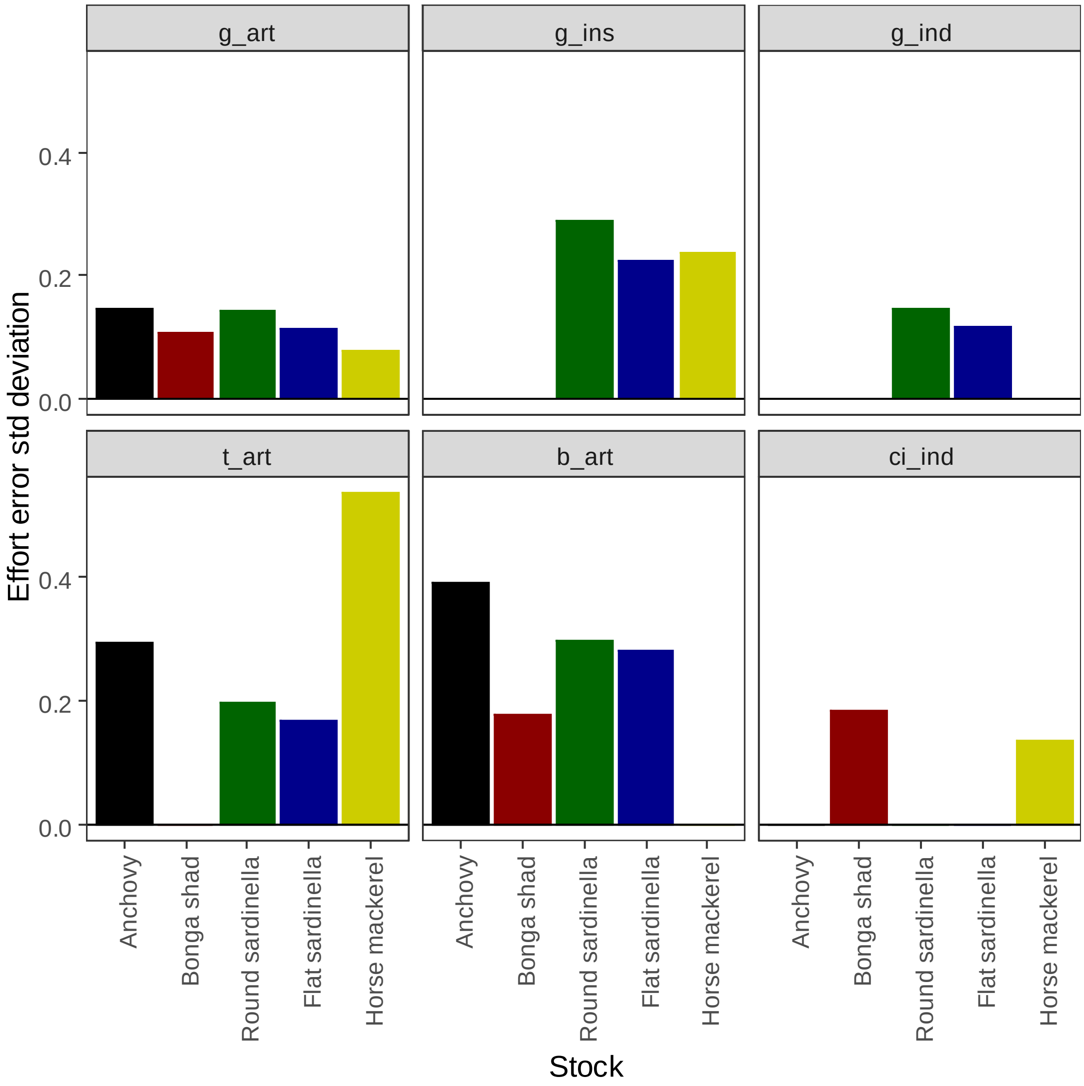

Figure 3. 1 The standard deviation associated with the effort data for each fleet and stock. This is an estimate of the measurement error in the effort data. Larger values indicate lower precision.

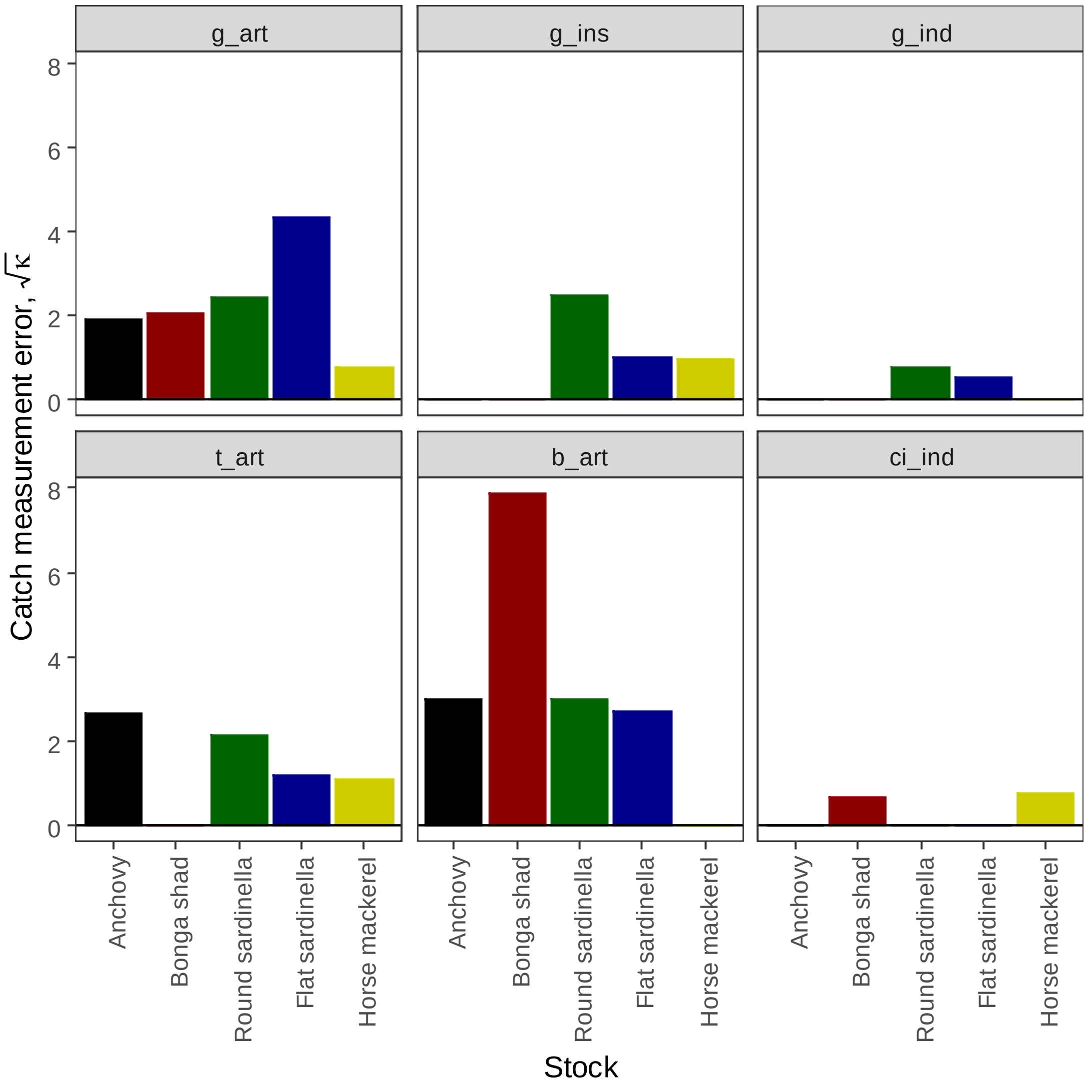

Figure 3. 2 The dispersion parameter, κ, associated with catch data plotted on a square root scale. Large values indicate higher precision.

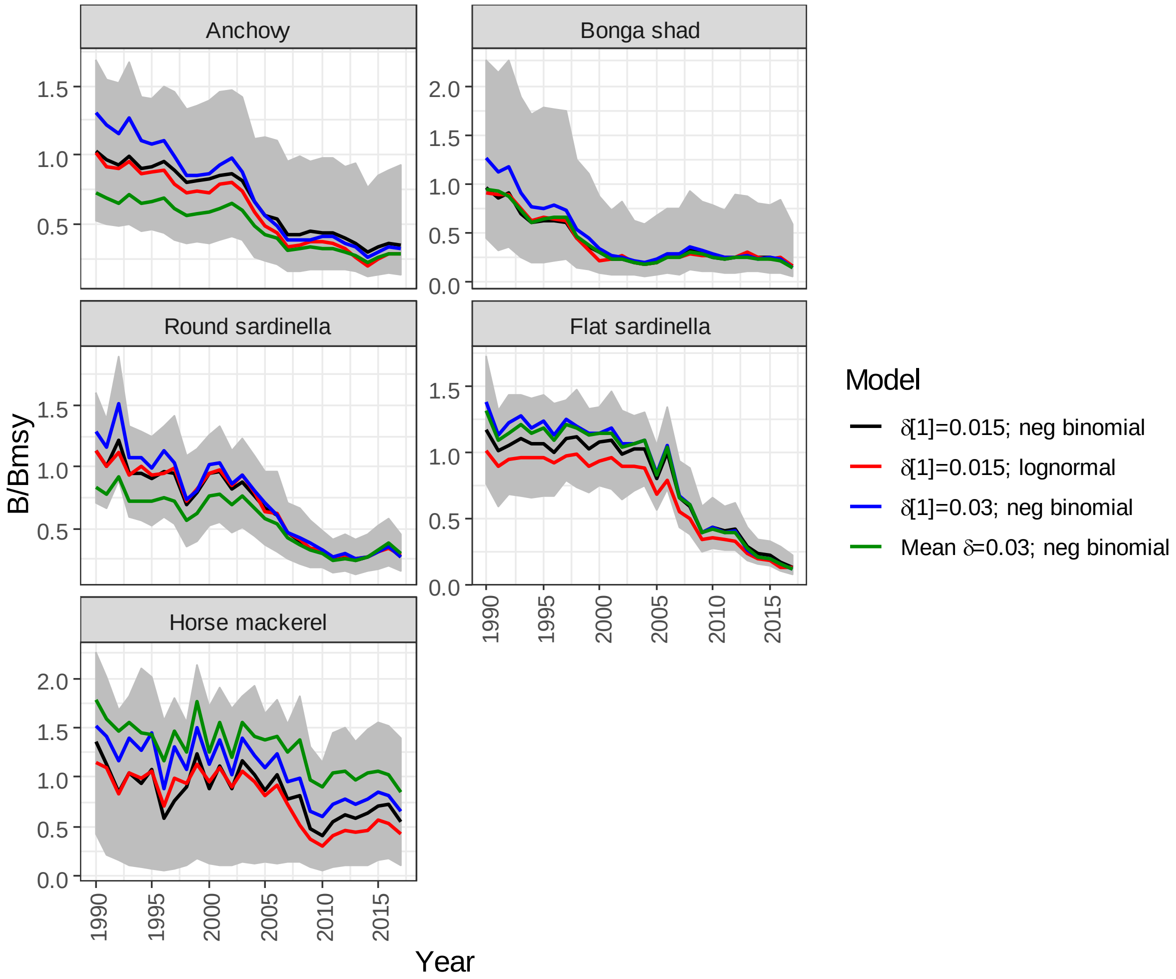

Figure 3. 3 Estimated trends in stock biomass relative to B_{MSY} for the five stocks and four models. The reference model is shown in black. Other colours show results from sensitivity runs.

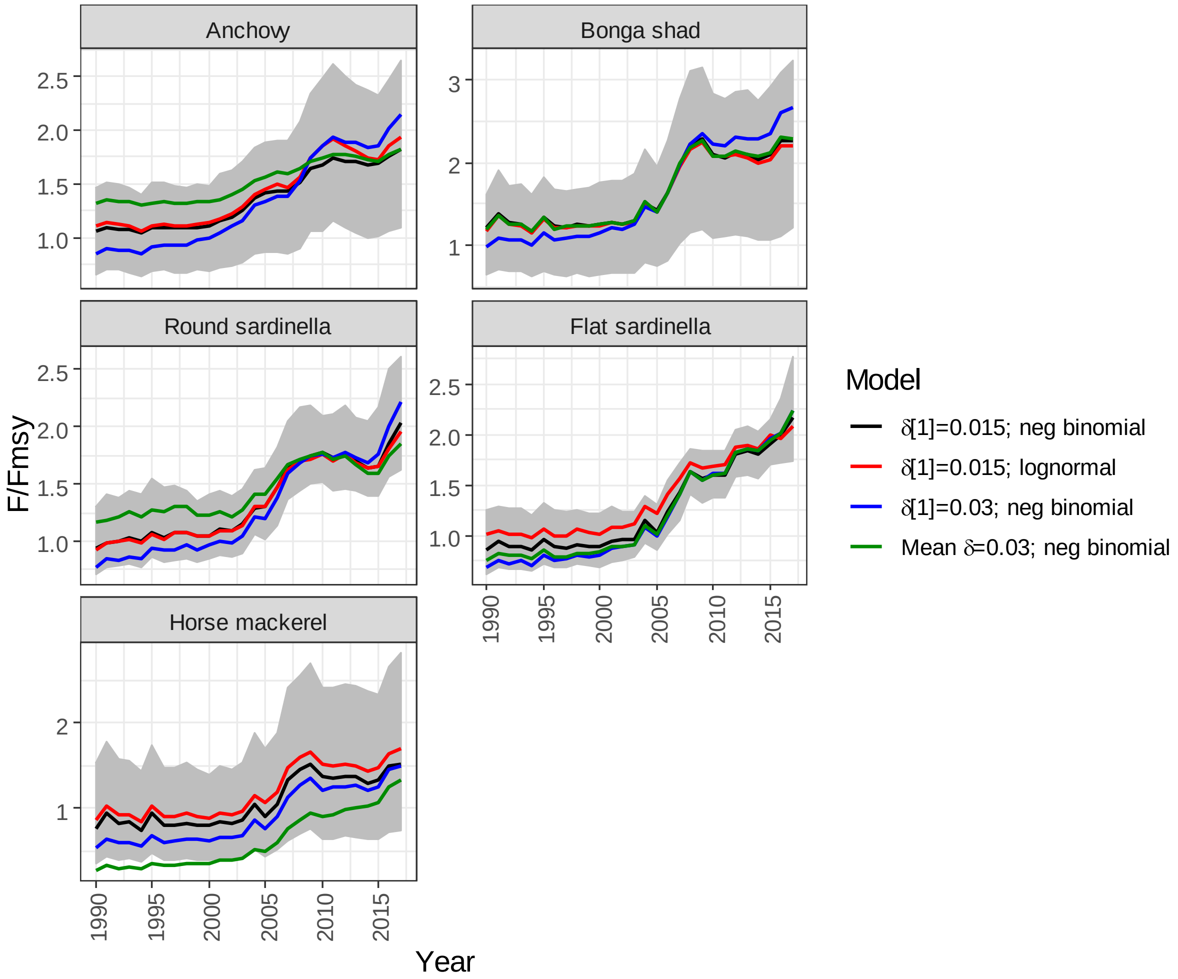

Figure 3. 4 Estimated trends in fishing mortality relative to F_{MSY} for the five stocks and four models. The reference model is shown in black. Other colours show results from sensitivity runs.

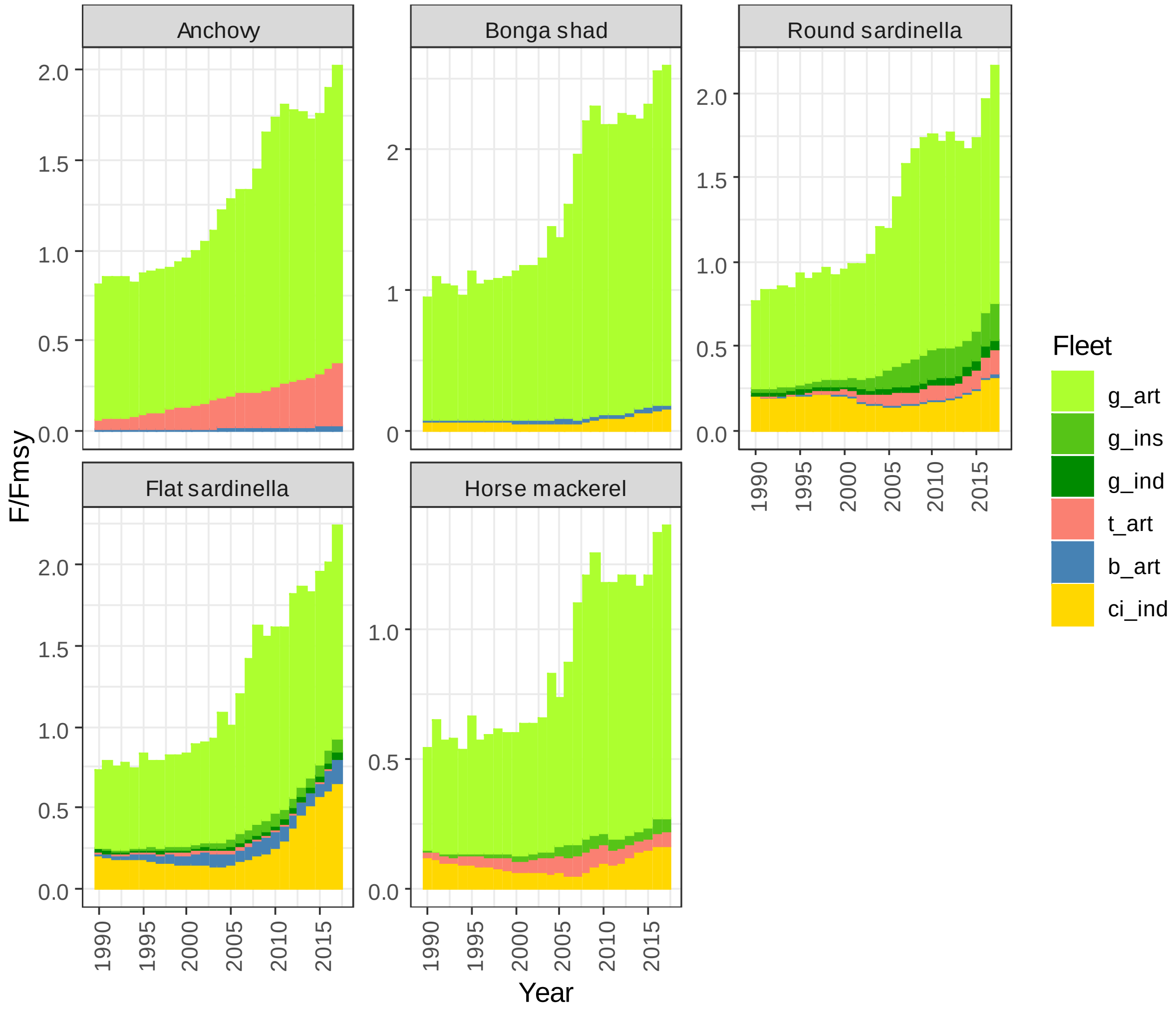

Figure 3. 5 Fishing mortality relative to F_{MSY} by fleet for the five stocks as estimated from the reference model. The total fishing mortality is expressed by the height of the stacked bar while the contribution of each fleet is shown as the height of the relevant colour block. Countries are coded by colour: Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue. Most stocks are dominated by Ghanaian fleets (green).

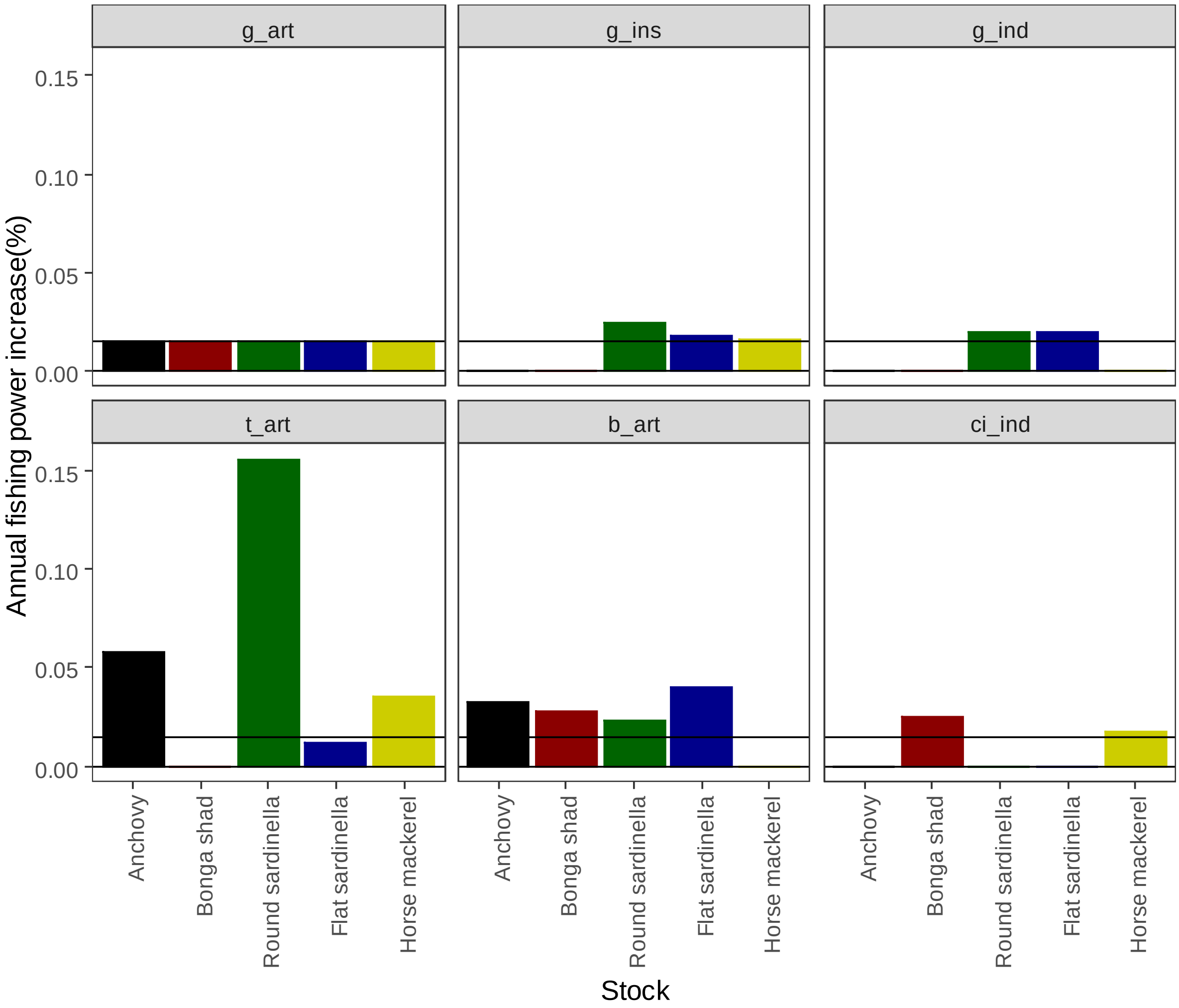

Figure 3. 6 Estimates of mean annual fishing power (δ) increase for each fleet by stock from the reference model. The value is fixed at 0.015 for the g_artl fleet and is not a model estimate. The horizontal line shown is the δ value for the g_art fleet.

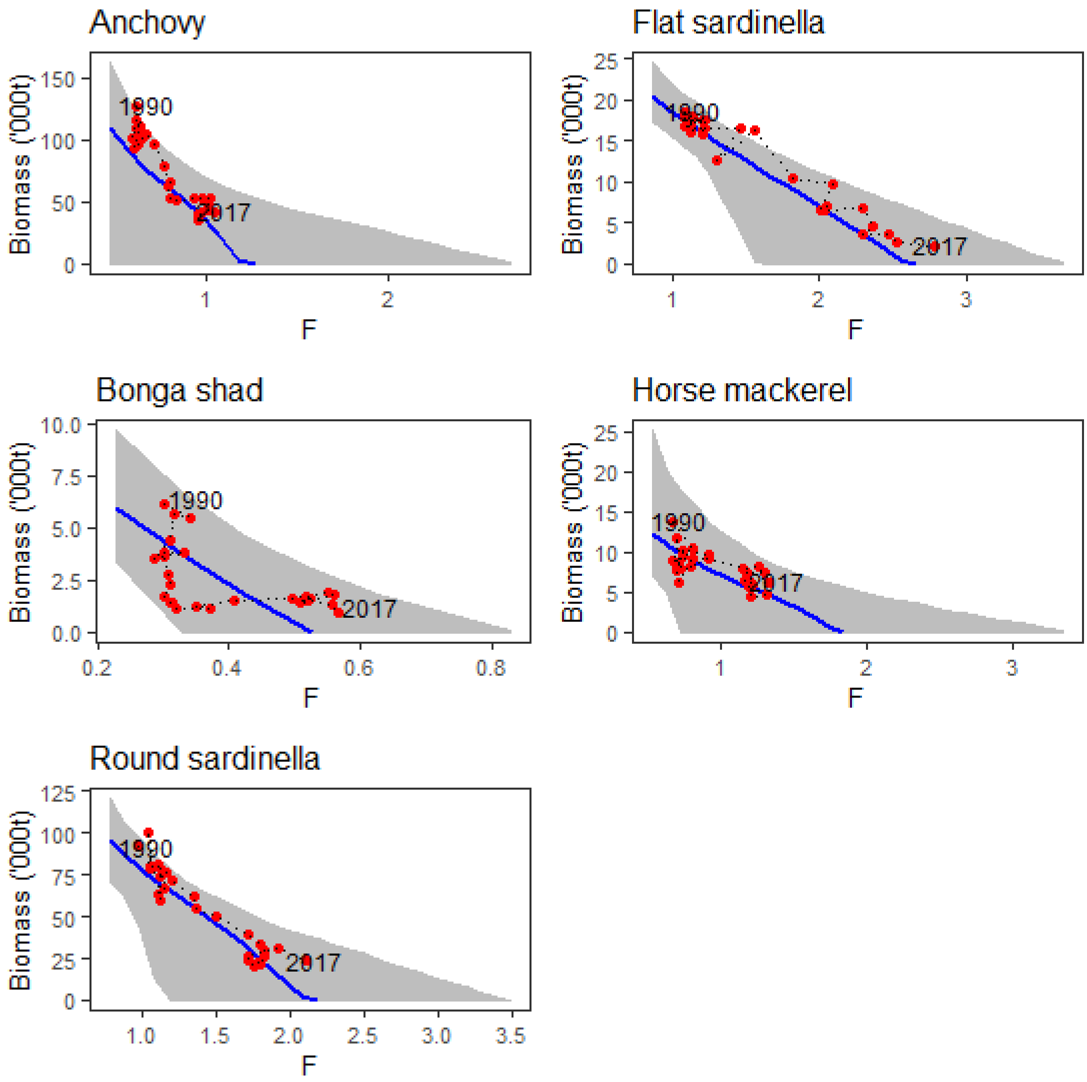

Figure 4.1 Equilibrium biomass curves for the five stocks based on parameter estimates from the reference model. The blue line shows the median equilibrium value and the shaded area the 95%CI. The red points are the annual values of the biomass estimated from the model plotted as a time series.

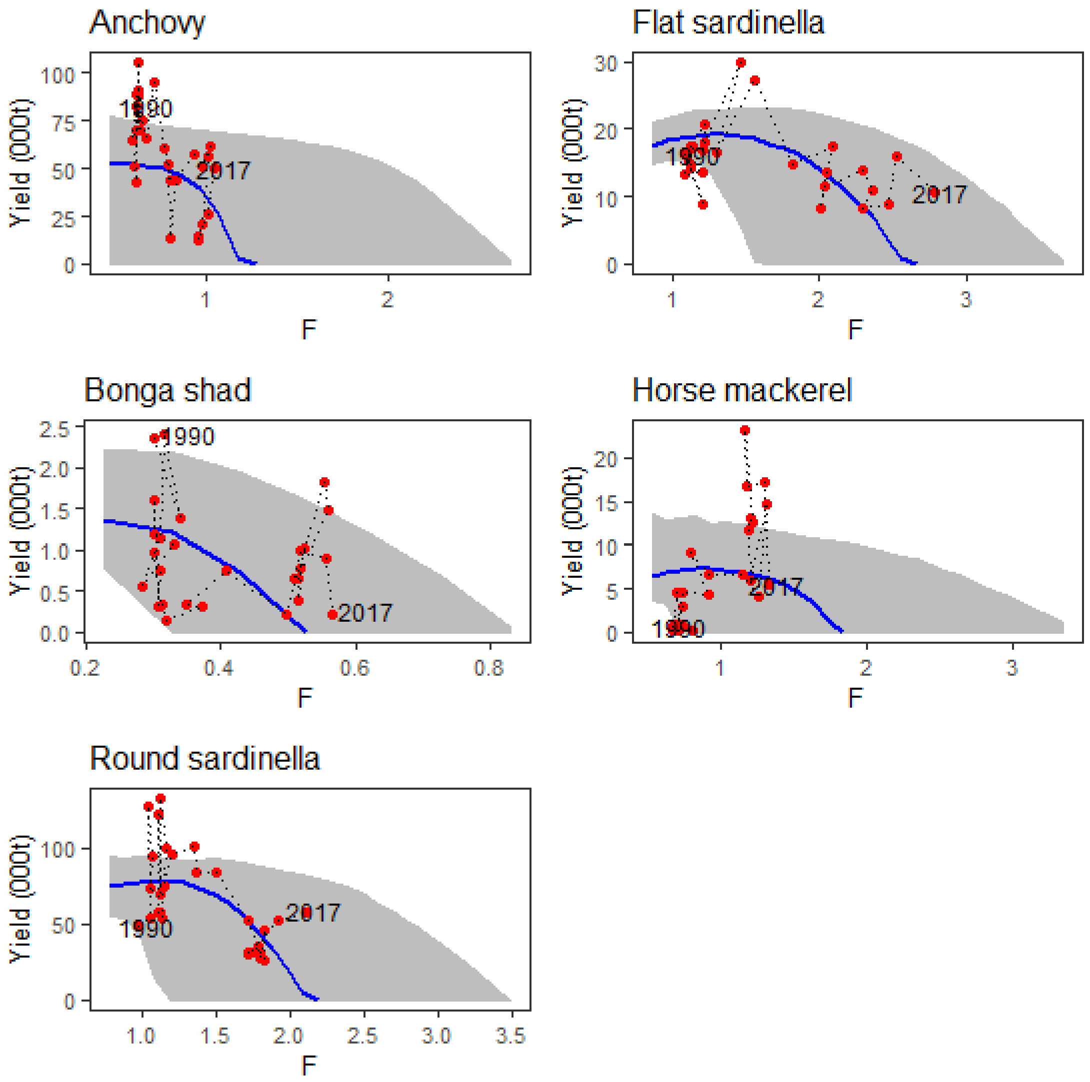

Figure 4. 2 Equilibrium yield curves for the five stocks based on parameter estimates from the reference model. The blue line shows the median equilibrium value and the shaded area the 95%CI. The red points are the annual values of the catch estimated from the model plotted as a time series.

Appendix 1. Catch and effort data used in assessments

Table A1. 1 Fishing effort for 6 fleets expressed as days fishing from FAO(2019). NA indicates no data available.

Year	g_art	g_ins	g_ind	t_art	b_art	ci_ind
1990	500664	3373	NA	19526	19526	NA
1991	707611	4411	NA	22466	22466	NA
1992	542294	4195	NA	17318	17318	NA
1993	567382	7266	NA	18959	18959	NA
1994	447742	4775	NA	29890	29890	NA
1995	662665	7445	NA	30245	30245	NA
1996	478229	8838	NA	41689	41689	NA
1997	491688	8179	9825	20310	39507	NA
1998	518582	15003	NA	38798	48313	NA
1999	480589	9993	6337	48514	51489	2988
2000	466568	8964	4797	46206	53328	2370
2001	510550	11793	NA	52416	55166	2131
2002	471723	9308	9526	48315	58632	2329
2003	459171	17949	8183	51445	60468	2403
2004	652550	12512	9385	47677	52635	1914
2005	459199	23790	13136	43849	30658	2358
2006	573912	34150	11580	42569	41647	1603
2007	800682	24158	12425	43229	36152	1311
2008	819527	34290	12592	24835	38899	NA
2009	850793	27655	8933	30541	40563	2893
2010	704710	31489	11572	30937	37855	3699
2011	715510	23185	13029	30266	54321	2630
2012	725823	17817	15748	15748	32448	2648
2013	683912	23799	12848	12848	19350	3616
2014	622244	15556	16494	16494	21855	4501
2015	618940	22525	15030	15030	17675	4084
2016	709314	30609	18372	18372	75124	4849
2017	694588	26016	16632	16632	50795	NA

Table A1. 2 Catch in tonnes of anchovy (Engraulus encrasicolus) by fleet. Data from FAO (2019). NA indicates no data available.

Year	g_art	t_art	b_art
1990	74668	7552	NA
1991	65490	4713	NA
1992	85384	3551	NA
1993	81350	7831	NA
1994	60519	4573	NA
1995	65497	4779	NA
1996	98341	7072	NA
1997	82724	4759	681
1998	44644	6325	464
1999	32107	9796	478
2000	83501	7164	417
2001	68175	6660	852
2002	57639	6932	1472
2003	82930	11479	806
2004	52629	6940	533
2005	36400	6479	591
2006	44854	6981	680
2007	10081	2691	635
2008	40612	2197	658
2009	54409	2714	675
2010	45051	5098	746
2011	51171	10310	547
2012	50210	5181	673
2013	11157	8553	798
2014	6125	6597	138
2015	5368	8901	664
2016	13230	11667	700
2017	38409	10691	613

Table A1. 3 Catch in tonnes of bonga shad (Ethmalosa fimbriata) by fleet. Data from FAO (2019). NA indicates no data available.

Year	g_art	b_art	ci_ind
1990	2366	NA	NA
1991	1378	NA	NA
1992	2408	NA	NA
1993	1137	NA	NA
1994	570	NA	NA
1995	1073	NA	NA
1996	1196	NA	NA
1997	1593	17	NA
1998	300	14	NA
1999	749	NA	9
2000	948	5	19
2001	282	8	22
2002	295	12	27
2003	128	9	14
2004	303	7	1
2005	287	10	32
2006	723	16	9
2007	198	13	NA
2008	1805	14	NA
2009	1468	10	0.4
2010	643	12	1
2011	378	11	4
2012	1016	8	4
2013	757	14	2
2014	656	10	0
2015	834	9	156
2016	888	12	0
2017	219	7	NA

Table A1. 4 Catch in tonnes of round sardinella (Sardinella aurita) by fleet. Data from FAO (2019). NA indicates no data available.

Year	g_art	g_ins	g_ind	t_art	b_art	ci_ind
1990	43167	2396	2377	561	NA	NA
1991	50447	2265	993	365	NA	NA
1992	119515	6268	581	734	NA	NA
1993	90600	2134	613	342	NA	NA
1994	67566	2327	3386	360	NA	NA
1995	65598	2143	1750	331	NA	NA
1996	115070	3331	3067	739	NA	NA
1997	46387	3010	1998	1300	731	NA
1998	54596	1369	541	1045	297	NA
1999	39124	1256	800	1986	644	13640
2000	98865	3178	2479	1912	494	25041
2001	64104	3209	7093	3123	860	21142
2002	59400	3449	1320	1807	1058	7824
2003	70314	8323	2396	4018	767	9354
2004	78454	3594	3608	4700	598	9326
2005	64389	2600	378	9394	522	6251
2006	70672	4326	354	2499	675	5453
2007	40759	4712	377	1173	598	4612
2008	24904	2889	0	3198	637	NA
2009	11198	7291	990	2376	543	3900
2010	30195	5824	0	2652	265	7235
2011	16749	4263	493	2777	190	2413
2012	22166	6560	0	2845	236	3732
2013	19402	5252	1250	685	129	4175
2014	15879	3403	1229	4689	76	6431
2015	14861	6535	2039	2285	418	3610
2016	18530	6749	1577	5116	257	20069
2017	38519	6518	1310	1512	285	10037

Table A1. 5 Catch in tonnes of flat sardinella (Sardinella maderensis) by fleet. Data from FAO (2019). NA indicates no data available.

Year	G_art	G_ins	G_ind	T_art	B_art	CI_ind
1990	14549	940	419	258	NA	NA
1991	8207	242	175	327	NA	NA
1992	14240	165	102	160	NA	NA
1993	16797	185	108	150	NA	NA
1994	12310	156	597	162	NA	NA
1995	13092	119	309	86	NA	NA
1996	13501	118	541	166	NA	NA
1997	14070	113	353	432	1218	NA
1998	14770	698	95	408	1495	NA
1999	12056	49	141	1622	1073	154
2000	14935	35	438	638	824	658
2001	15853	530	1252	445	1434	1372
2002	13693	81	233	358	1765	756
2003	15419	158	423	208	1279	489
2004	27052	50	637	542	996	560
2005	14241	72	67	204	1305	565
2006	21384	2644	62	1316	1687	186
2007	10218	2320	66	188	1496	535
2008	15772	128	0	65	1591	NA
2009	5994	274	0	20	1168	752
2010	10745	566	NA	3	1751	512
2011	9643	1076	0	64	376	411
2012	11958	385	NA	37	1264	211
2013	6506	351	0	49	331	3736
2014	4876	20	0	63	200	3025
2015	5830	201	0	7	299	2403
2016	2104	151	0	3	459	13315
2017	3531	614	0	5	319	6248

Table A1. 6 Catch in tonnes of horse mackerel (Tracurus trecae) by fleet. Data from FAO (2019). NA indicates no data available.

Year	G_art	G_ins	T_art	CI_ind
1990	76	403	148	NA
1991	NA	90	135	NA
1992	33	67	92	NA
1993	364	116	107	NA
1994	NA	62	224	NA
1995	NA	6	149	NA
1996	482	12	163	NA
1997	NA	24	107	NA
1998	357	71	72	NA
1999	1777	360	1207	1134
2000	31	30	449	458
2001	1517	23	501	965
2002	35	44	154	660
2003	2255	NA	475	1840
2004	2529	33	916	949
2005	8195	74	451	487
2006	5615	134	716	201
2007	5750	130	719	99
2008	1255	32	2869	NA
2009	14314	26	58	151
2010	5973	62	7	2
2011	11118	200	354	19
2012	12347	279	268	117
2013	12162	21	222	76
2014	22817	20	174	46
2015	15796	599	236	0
2016	14305	944	2	1866
2017	4699	423	279	NA

Appendix 2: Model output, Anchovy

Table A2. 1. Estimates of biomass, B, and fishing mortality, F, from the reference model. Low and Hi refer to the 95% CI with Med giving the median value.

Year	B_Low	B_Med	B_Hi	F_Low	F_Med	F_Hi
1990	38272	127983	445503	0.157	0.622	1.825
1991	33406	111645	447673	0.171	0.642	1.854
1992	31920	110223	462703	0.154	0.623	1.958
1993	35289	116844	505732	0.150	0.618	1.952
1994	31362	102073	456230	0.138	0.591	1.914
1995	33324	109418	375929	0.149	0.619	1.895
1996	33217	112495	440951	0.155	0.626	2.016
1997	33246	106821	400256	0.155	0.628	2.019
1998	30156	93282	348939	0.158	0.607	1.993
1999	31466	96998	337016	0.155	0.620	1.975
2000	30378	97138	354954	0.157	0.628	1.986
2001	31131	102233	360716	0.156	0.651	1.988
2002	32974	105474	394966	0.166	0.672	2.066
2003	30133	96003	347238	0.168	0.712	2.182
2004	25017	79175	265604	0.189	0.768	2.410
2005	22403	66311	247548	0.201	0.802	2.495
2006	21941	63324	229454	0.194	0.796	2.596
2007	16872	52929	196866	0.194	0.799	2.609
2008	16845	51141	203833	0.217	0.839	2.691
2009	17838	53475	222337	0.250	0.935	2.760
2010	16618	53706	209940	0.269	0.975	2.807
2011	15744	53581	198228	0.278	1.027	2.752
2012	14943	47466	197325	0.254	1.014	2.970
2013	13604	42022	177066	0.251	0.976	3.007
2014	10862	35297	160697	0.244	0.961	2.916
2015	12718	39842	169896	0.259	0.958	2.852
2016	14005	44014	174346	0.263	1.017	2.870
2017	12755	42440	199403	0.267	1.050	3.060

Table A2. 2. Estimates of fishing mortality by fleet. Fleet definitions are given in

Table 2. 2.

Fleet fishing mortality

Year	g_art	t_art	b_art
1990	0.669	0.049	0.007
1991	0.689	0.051	0.007
1992	0.681	0.054	0.007
1993	0.679	0.059	0.008
1994	0.651	0.064	0.008
1995	0.670	0.069	0.008
1996	0.673	0.076	0.008
1997	0.666	0.080	0.008
1998	0.660	0.087	0.008
1999	0.661	0.096	0.009
2000	0.661	0.099	0.009
2001	0.679	0.105	0.010
2002	0.699	0.111	0.010
2003	0.732	0.120	0.010
2004	0.791	0.127	0.011
2005	0.815	0.136	0.012
2006	0.834	0.141	0.012
2007	0.826	0.144	0.013
2008	0.874	0.145	0.014
2009	0.950	0.151	0.014
2010	0.978	0.157	0.015
2011	1.002	0.166	0.015
2012	0.980	0.173	0.016
2013	0.970	0.179	0.016
2014	0.936	0.185	0.016
2015	0.923	0.193	0.017
2016	0.958	0.208	0.018
2017	0.997	0.221	0.019

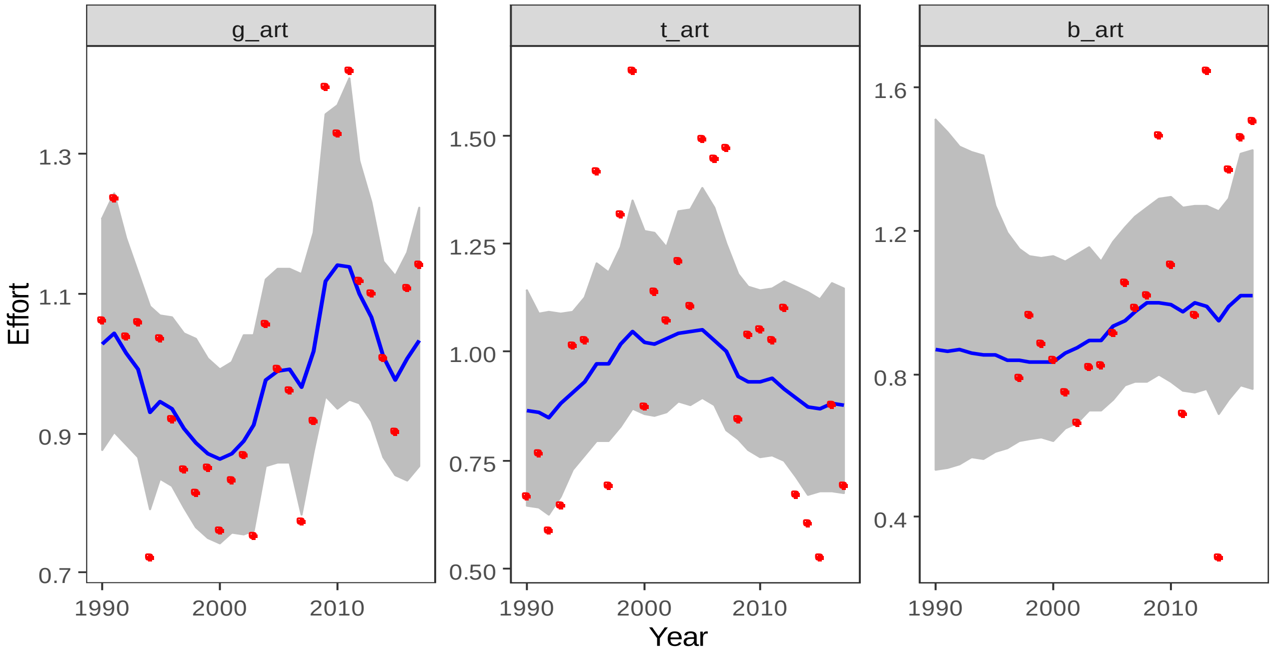

Figure A2. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

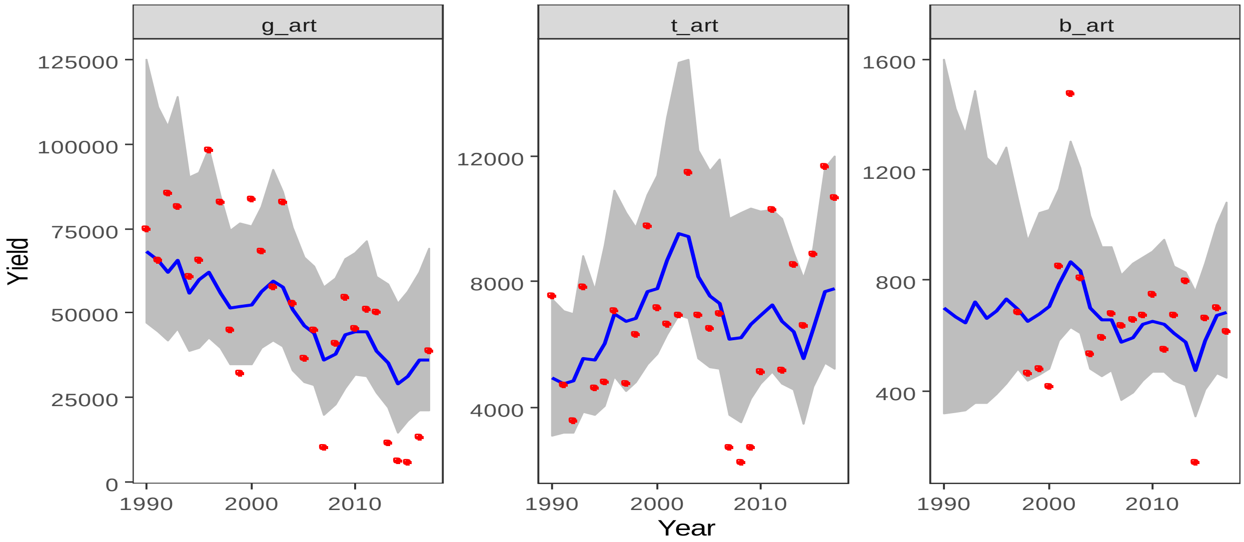

Figure A2. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

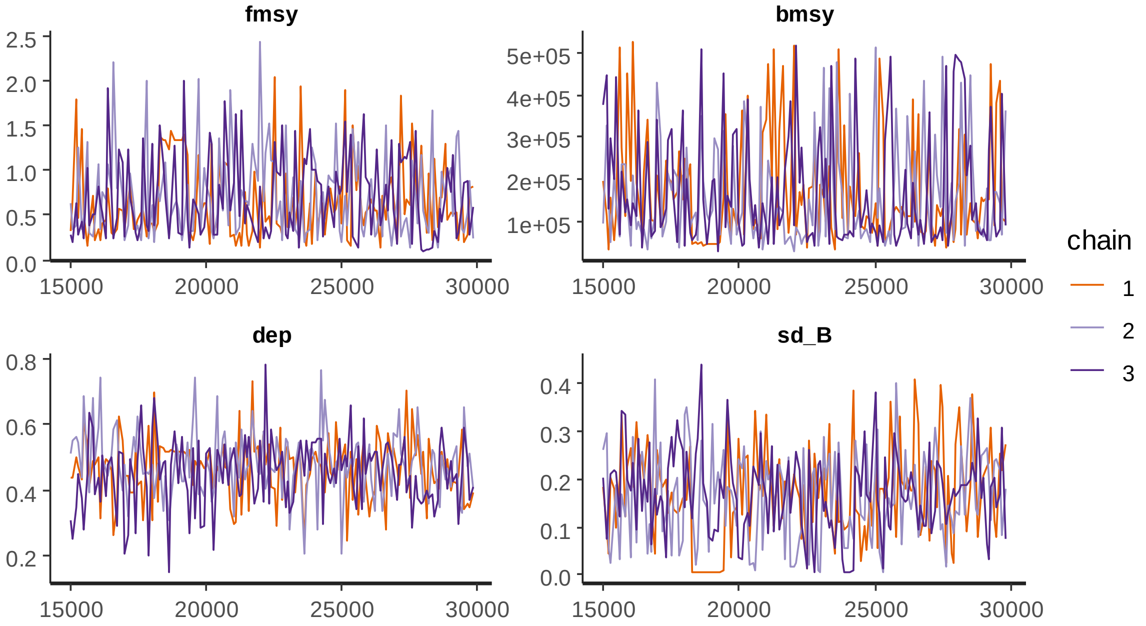

Figure A2. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 3: Model output, bonga shad

Table A3. 1. Estimates of biomass, B, and fishing mortality, F, from the reference model. Low and Hi refer to the 95% CI with Med giving the median value.

Year	B_Low	B_Med	B_Hi	F_Low	F_Med	F_Hi
1990	2576	6116	13738	0.111	0.301	0.614
1991	1968	5492	13874	0.135	0.341	0.671
1992	2080	5681	13055	0.124	0.318	0.643
1993	1649	4409	11045	0.124	0.310	0.644
1994	1240	3522	10485	0.110	0.285	0.628
1995	1328	3872	10929	0.133	0.332	0.656
1996	1519	3873	10283	0.109	0.301	0.639
1997	1547	3610	10292	0.115	0.302	0.624
1998	1016	2742	7115	0.116	0.309	0.623
1999	892	2282	6999	0.114	0.310	0.663
2000	752	1742	5338	0.120	0.301	0.690
2001	534	1442	4595	0.122	0.311	0.640
2002	560	1413	4515	0.120	0.313	0.651
2003	404	1172	3844	0.122	0.320	0.699
2004	439	1104	3525	0.148	0.372	0.756
2005	504	1235	3895	0.128	0.350	0.741
2006	673	1562	4202	0.158	0.408	0.844
2007	649	1627	4284	0.196	0.496	1.012
2008	935	1924	5056	0.214	0.552	1.196
2009	807	1856	5195	0.222	0.559	1.146
2010	695	1572	5105	0.198	0.515	1.122
2011	581	1518	4353	0.194	0.514	1.087
2012	640	1603	4667	0.209	0.525	1.084
2013	739	1688	5309	0.202	0.517	1.068
2014	635	1459	4989	0.187	0.508	1.040
2015	654	1532	4849	0.195	0.520	1.072
2016	541	1315	4239	0.223	0.556	1.162
2017	291	962	3600	0.225	0.567	1.151

Table A3. 2. Estimates of fishing mortality by fleet. Fleet definitions are given in

Table 2. 2.

Fleet fishing mortality

Year	q_art	b_art	c_ind
1990	0.292	0.005	0.018
1991	0.337	0.005	0.018
1992	0.315	0.005	0.018
1993	0.309	0.005	0.018
1994	0.284	0.005	0.018
1995	0.328	0.005	0.018
1996	0.301	0.005	0.018
1997	0.302	0.005	0.018
1998	0.305	0.005	0.018
1999	0.306	0.006	0.018
2000	0.311	0.006	0.017
2001	0.314	0.007	0.016
2002	0.310	0.007	0.017
2003	0.320	0.007	0.017
2004	0.376	0.008	0.016
2005	0.349	0.009	0.016
2006	0.408	0.010	0.015
2007	0.497	0.009	0.015
2008	0.553	0.008	0.018
2009	0.569	0.007	0.022
2010	0.524	0.007	0.026
2011	0.516	0.007	0.026
2012	0.526	0.007	0.028
2013	0.511	0.007	0.033
2014	0.489	0.007	0.038
2015	0.504	0.007	0.040
2016	0.545	0.008	0.044
2017	0.549	0.008	0.045

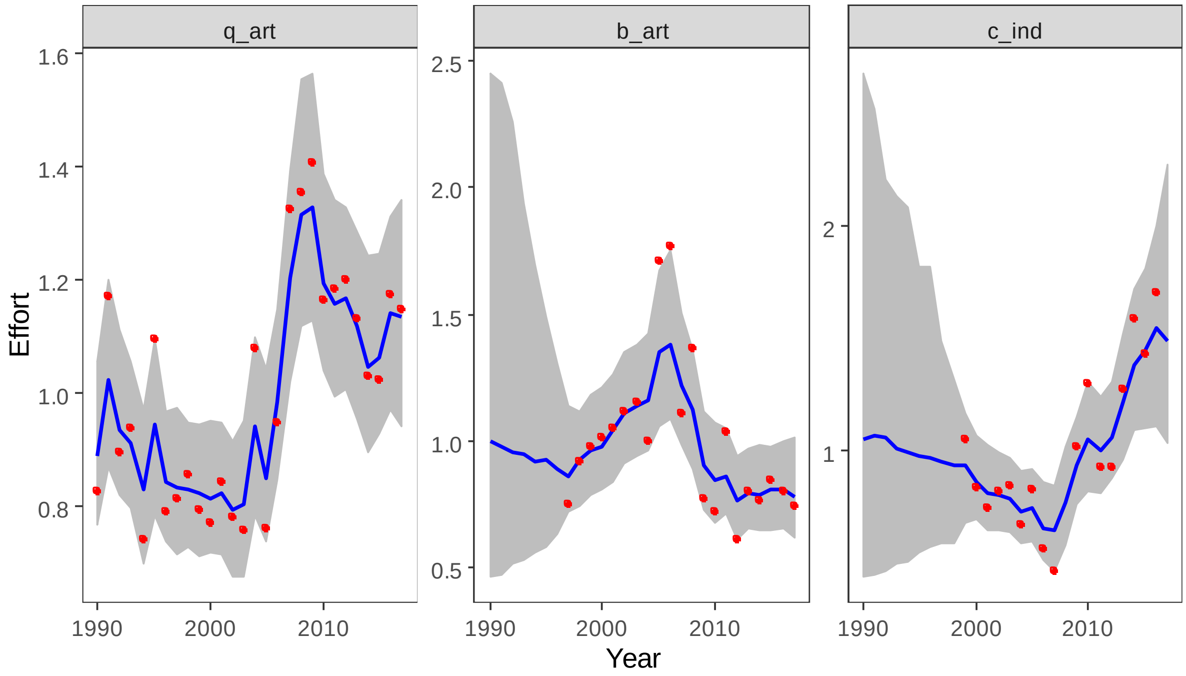

Figure A3. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

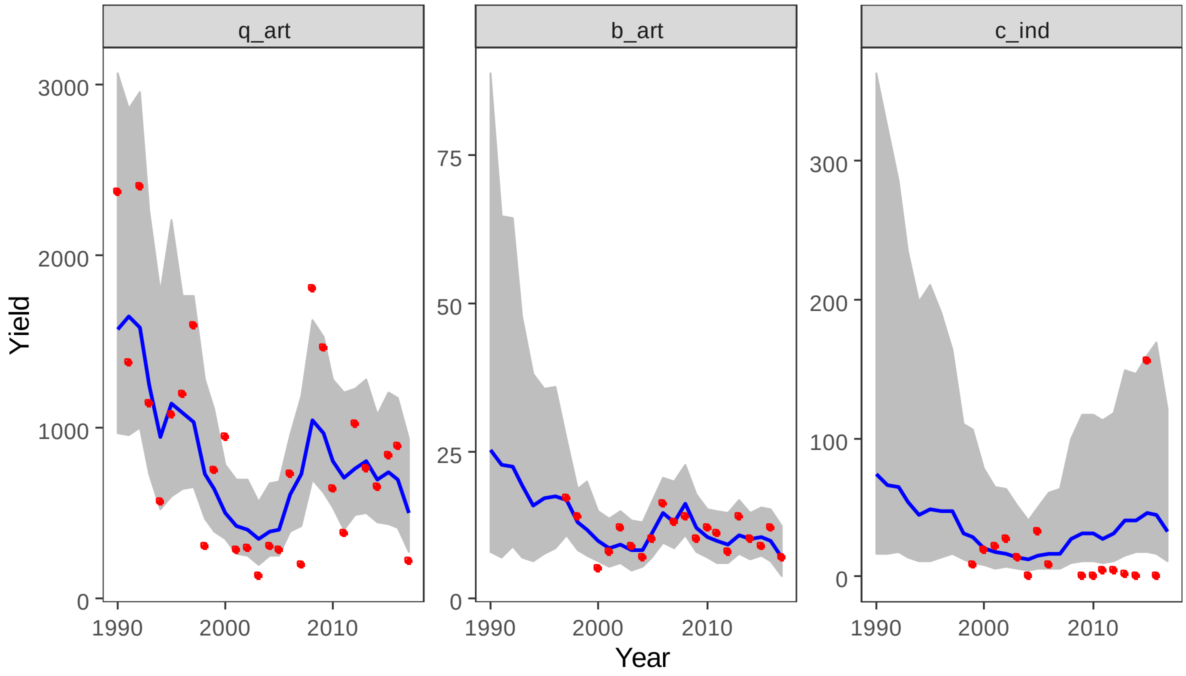

Figure A3. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

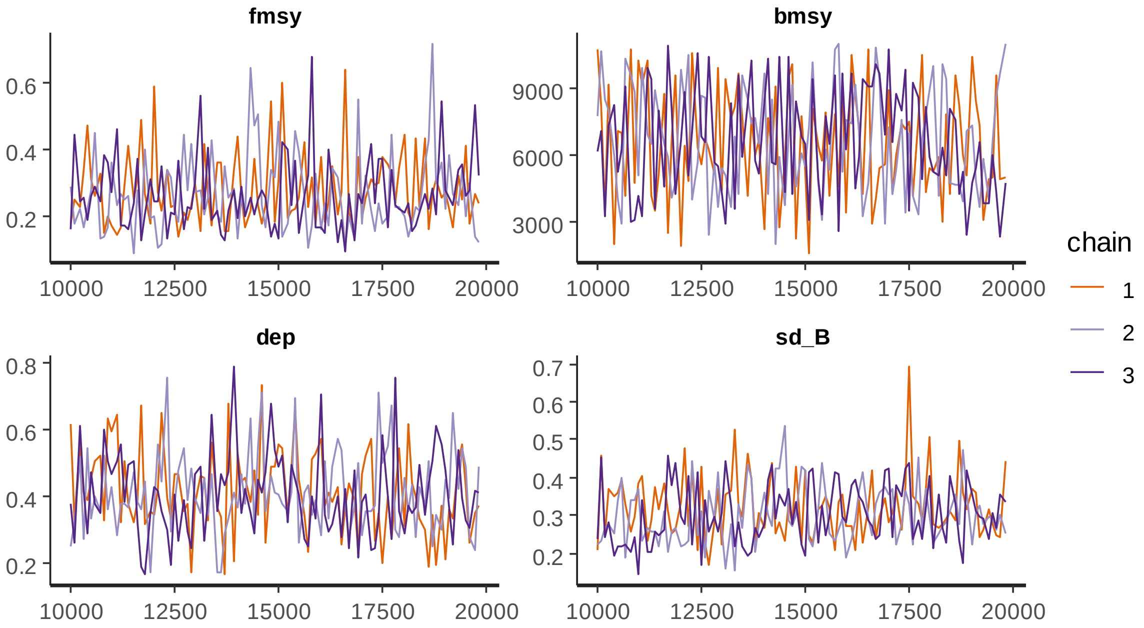

Figure A3. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 4: Model output, round sardinella

Table A4. 1. Estimates of biomass, B, and fishing mortality, F, from the reference model. Low and Hi refer to the 95% CI with Med giving the median value.

Year	B_Low	B_Med	B_Hi	F_Low	F_Med	F_Hi
1990	45647	91586	271382	0.399	0.974	2.018
1991	39450	80273	265510	0.410	1.048	2.016
1992	44435	100747	327844	0.400	1.037	2.147
1993	35762	79085	248052	0.413	1.064	2.194
1994	39387	78590	198464	0.408	1.044	2.223
1995	33859	74299	229435	0.449	1.115	2.262
1996	36358	81222	223823	0.448	1.098	2.192
1997	39849	77118	198378	0.434	1.132	2.320
1998	23478	60103	149677	0.429	1.114	2.309
1999	32629	63373	159692	0.408	1.108	2.174
2000	37710	74519	206525	0.442	1.122	2.160
2001	38333	76401	206168	0.466	1.160	2.262
2002	32863	66897	175442	0.446	1.143	2.297
2003	36282	72172	183382	0.489	1.202	2.365
2004	29791	62503	164139	0.558	1.342	2.629
2005	26786	54715	140178	0.527	1.363	2.767
2006	24270	50085	124718	0.617	1.502	3.001
2007	16767	39468	98163	0.730	1.716	3.160
2008	15182	33785	84833	0.740	1.794	3.316
2009	14216	29254	72254	0.765	1.814	3.496
2010	12707	26180	66737	0.738	1.824	3.633
2011	9521	21568	52994	0.738	1.787	3.490
2012	10599	22832	56722	0.742	1.775	3.549
2013	9040	20551	50032	0.742	1.754	3.471
2014	10780	23570	52421	0.749	1.712	3.226
2015	13572	26142	64431	0.776	1.718	3.226
2016	15545	30409	74296	0.874	1.921	3.560
2017	11528	23803	55440	0.899	2.109	3.916

Table A4. 2. Estimates of fishing mortality by fleet. Fleet definitions are given in

Table 2. 2.

Fleet fishing mortality

Year	G_art	G_ins	G_ind	T_art	B_art
1990	0.744	0.024	0.027	0.005	0.004
1991	0.230	0.809	0.027	0.027	0.005
1992	0.005	0.220	0.806	0.030	0.026
1993	0.006	0.005	0.227	0.826	0.032
1994	0.026	0.007	0.005	0.239	0.790
1995	0.033	0.027	0.009	0.006	0.245
1996	0.860	0.038	0.027	0.012	0.007
1997	0.246	0.809	0.044	0.027	0.015
1998	0.008	0.251	0.835	0.048	0.027
1999	0.017	0.009	0.259	0.847	0.053
2000	0.023	0.023	0.009	0.252	0.795
2001	0.054	0.021	0.031	0.011	0.245
2002	0.809	0.058	0.019	0.038	0.011
2003	0.237	0.851	0.065	0.024	0.047
2004	0.012	0.226	0.843	0.073	0.028
2005	0.054	0.013	0.199	0.884	0.091
2006	0.029	0.063	0.013	0.188	1.026
2007	0.100	0.033	0.072	0.012	0.179
2008	1.011	0.125	0.040	0.081	0.012
2009	0.170	1.165	0.151	0.041	0.084
2010	0.012	0.168	1.316	0.166	0.042
2011	0.087	0.013	0.170	1.358	0.187
2012	0.042	0.085	0.014	0.182	1.379
2013	0.200	0.039	0.094	0.013	0.192
2014	1.370	0.211	0.044	0.103	0.012
2015	0.210	1.314	0.199	0.050	0.107
2016	0.012	0.211	1.361	0.198	0.056
2017	0.094	0.010	0.224	1.268	0.198

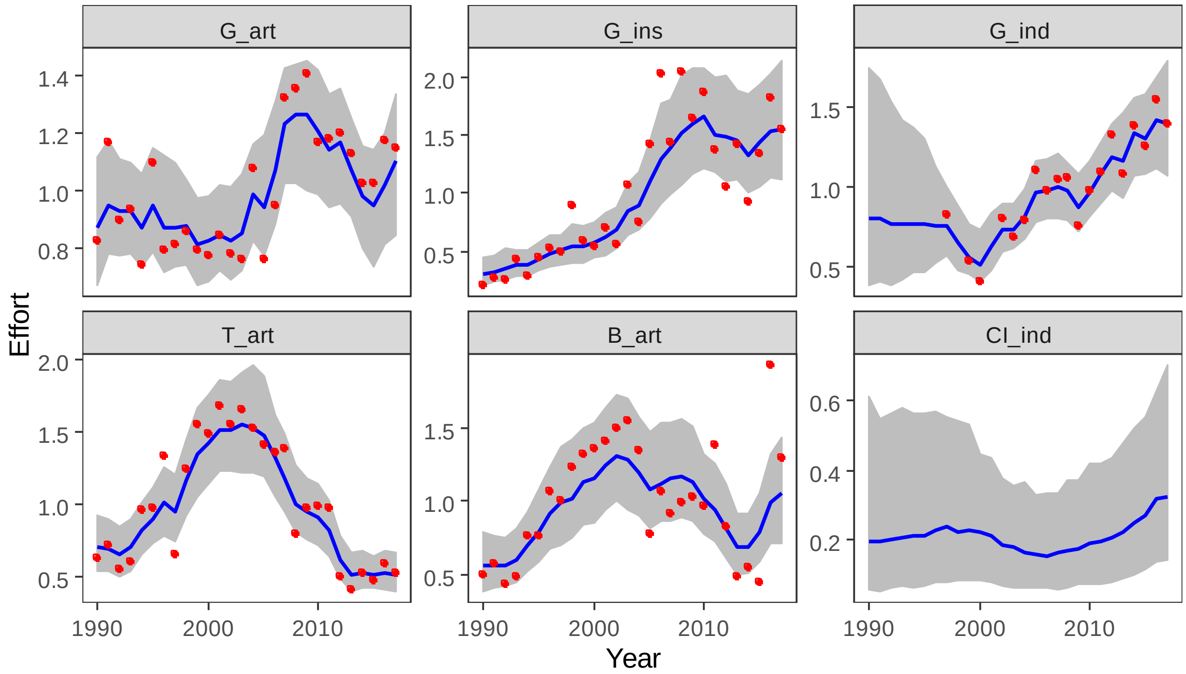

Figure A4. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI. There are no effort data for the CI_ind fleet.

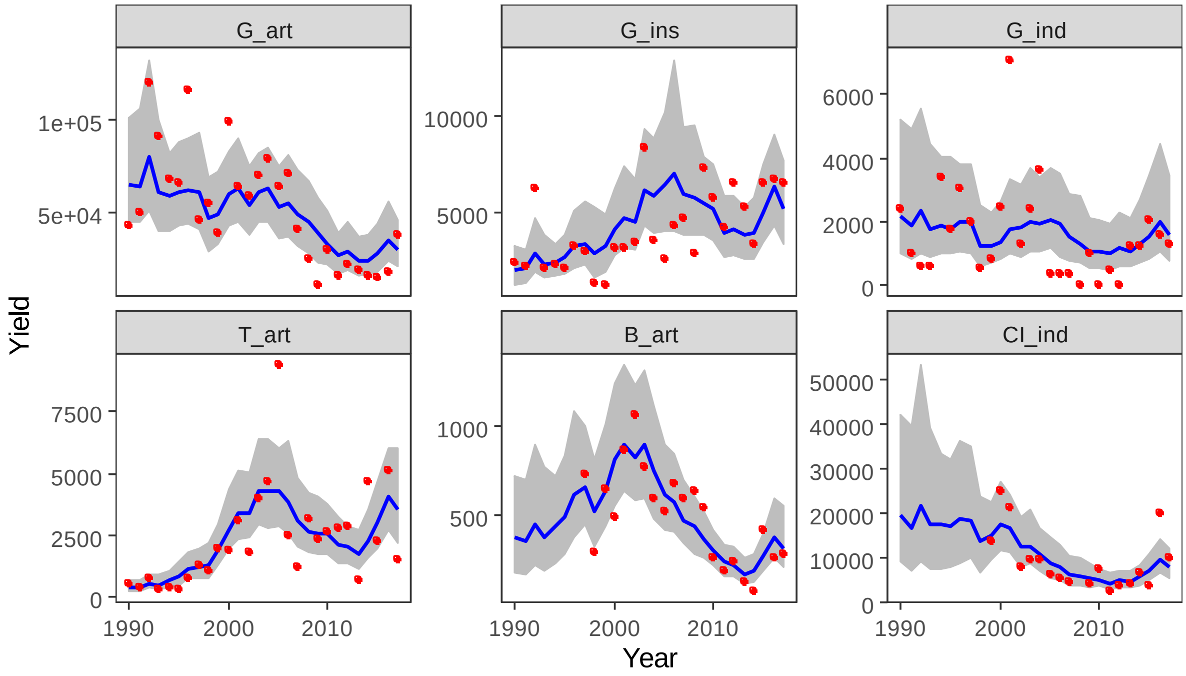

Figure A4. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

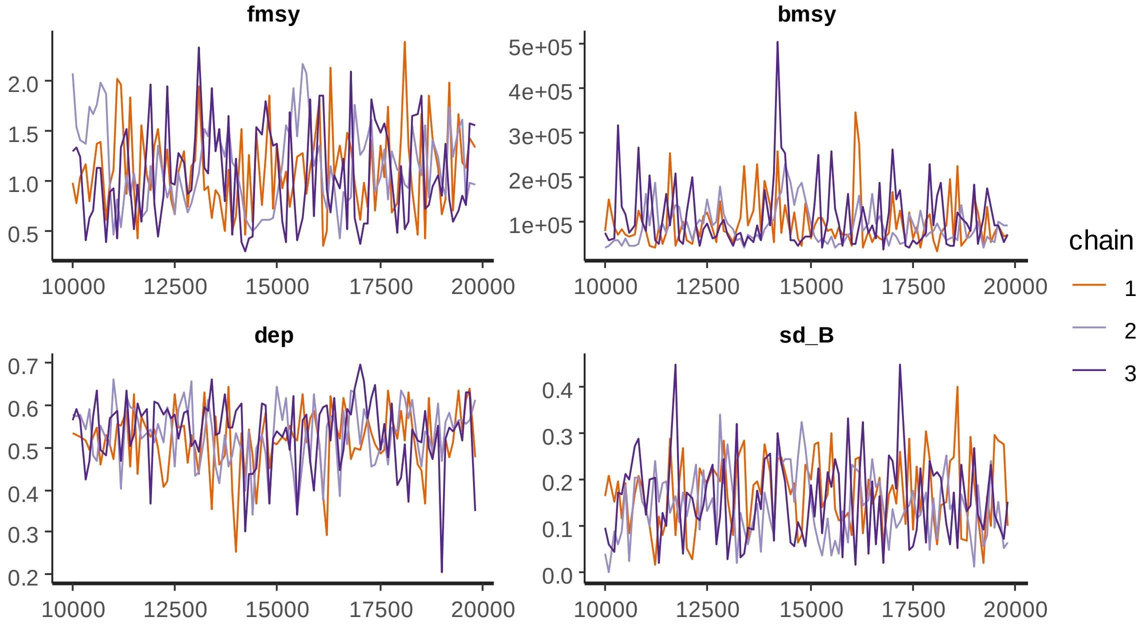

Figure A4. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 5: Model output, flat sardinella

Table A5. 1. Estimates of biomass, B, and fishing mortality, F, from the reference model. Low and Hi refer to the 95% CI with Med giving the median value.

Year	B_Low	B_Med	B_Hi	F_Low	F_Med	F_Hi
1990	10693	18482	39055	0.471	1.081	2.339
1991	7091	16221	36085	0.544	1.200	2.419
1992	9143	16469	32522	0.489	1.126	2.401
1993	9786	17708	35006	0.522	1.129	2.447
1994	8715	16859	34580	0.474	1.073	2.404
1995	9090	17549	36313	0.576	1.198	2.486
1996	8391	16110	34231	0.503	1.122	2.398
1997	10211	17663	36905	0.494	1.083	2.259
1998	9496	18033	36602	0.540	1.138	2.409
1999	9112	16449	33901	0.536	1.104	2.456
2000	9606	17234	35354	0.518	1.117	2.339
2001	9645	17428	35341	0.562	1.212	2.337
2002	8141	15817	33611	0.560	1.201	2.313
2003	9060	16568	31287	0.587	1.214	2.379
2004	9207	16471	34233	0.713	1.457	2.596
2005	7113	12730	27905	0.603	1.304	2.475
2006	10035	16191	31351	0.737	1.563	2.724
2007	5149	10466	25140	0.929	1.819	3.129
2008	5225	9675	19906	0.978	2.093	3.541
2009	3108	6585	16179	0.970	2.004	3.375
2010	3889	6944	15557	0.972	2.051	3.511
2011	3465	6572	13370	1.004	2.035	3.323
2012	3823	6712	12776	1.133	2.298	3.810
2013	2459	4598	9974	1.167	2.361	3.907
2014	2026	3656	7702	1.184	2.292	3.916
2015	1963	3569	7208	1.187	2.466	4.123
2016	1387	2761	6422	1.318	2.525	4.061
2017	1178	2208	4804	1.335	2.782	4.620

Table A5. 2. Estimates of fishing mortality by fleet. Fleet definitions are given in

Table 2. 2.

Fleet fishing mortality

Year	G_art	G_ins	G_ind	T_art	B_art
1990	0.820	0.011	0.027	0.011	0.033
1991	0.271	0.937	0.012	0.026	0.012
1992	0.034	0.258	0.876	0.013	0.026
1993	0.011	0.035	0.249	0.895	0.015
1994	0.025	0.012	0.039	0.239	0.820
1995	0.016	0.024	0.015	0.048	0.246
1996	0.952	0.019	0.024	0.017	0.057
1997	0.230	0.837	0.023	0.023	0.019
1998	0.069	0.221	0.833	0.025	0.022
1999	0.016	0.076	0.206	0.868	0.032
2000	0.019	0.022	0.087	0.199	0.846
2001	0.030	0.016	0.027	0.093	0.191
2002	0.848	0.030	0.014	0.028	0.098
2003	0.179	0.912	0.034	0.019	0.030
2004	0.106	0.171	0.898	0.035	0.023
2005	0.029	0.116	0.167	0.910	0.046
2006	0.023	0.030	0.112	0.160	1.132
2007	0.051	0.027	0.029	0.107	0.161
2008	0.972	0.068	0.034	0.027	0.101
2009	0.168	1.172	0.089	0.033	0.027
2010	0.110	0.184	1.407	0.092	0.036
2011	0.025	0.119	0.204	1.621	0.099
2012	0.036	0.019	0.127	0.236	1.505
2013	0.096	0.031	0.019	0.136	0.262
2014	1.491	0.098	0.036	0.019	0.141
2015	0.311	1.448	0.088	0.041	0.017
2016	0.128	0.378	1.610	0.080	0.048
2017	0.012	0.119	0.485	1.546	0.083

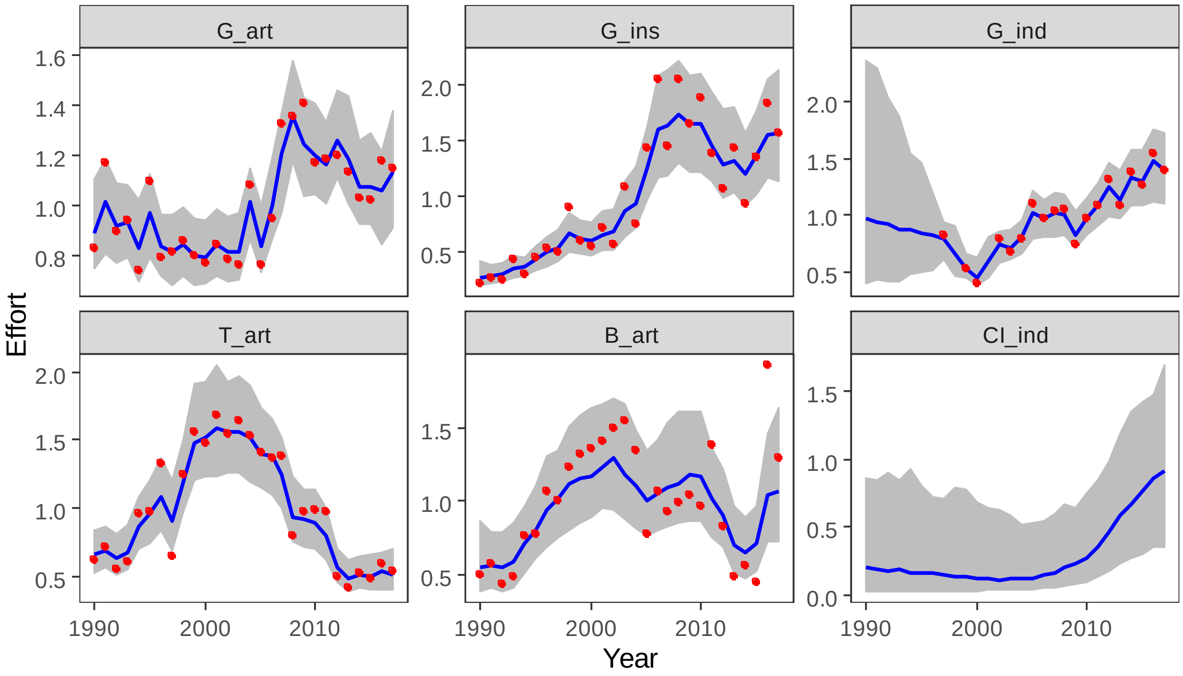

Figure A5. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

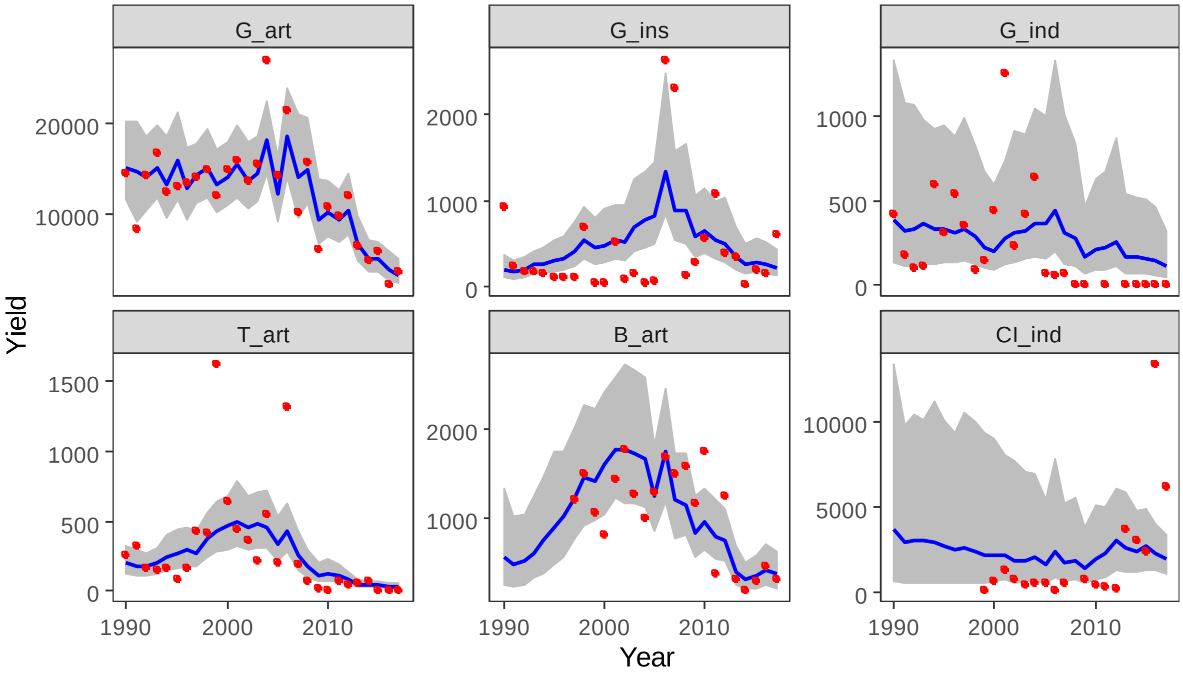

Figure A5. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

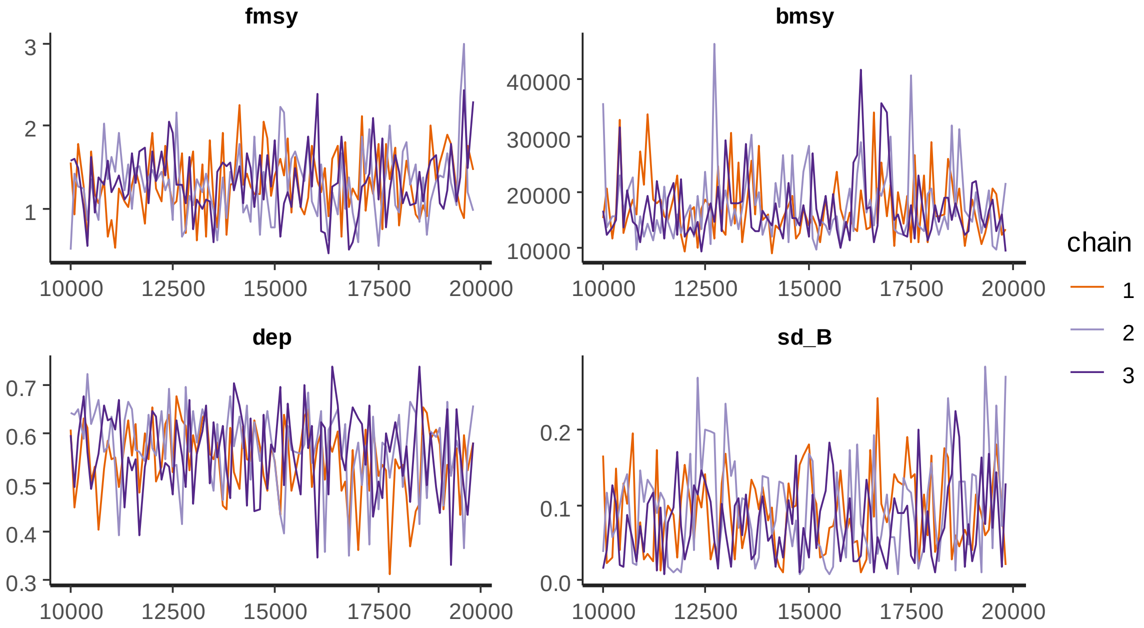

Figure A5. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 6: Model output, horse mackerel

Table A6. 1. Estimates of biomass, B, and fishing mortality, F, from the reference model. Low and Hi refer to the 95% CI with Med giving the median value.

Year	B_Low	B_Med	B_Hi	F_Low	F_Med	F_Hi
1990	4890	13678	79604	0.181	0.667	1.649
1991	3404	10509	57077	0.222	0.811	1.969
1992	2556	8562	37334	0.192	0.718	1.715
1993	3167	9556	32692	0.204	0.736	1.732
1994	2631	8837	34482	0.183	0.674	1.655
1995	1791	9184	30128	0.236	0.811	1.959
1996	842	6182	23094	0.200	0.711	1.684
1997	1409	7729	25490	0.205	0.707	1.640
1998	2708	7909	30176	0.209	0.732	1.707
1999	4495	11720	43541	0.201	0.705	1.604
2000	2449	8589	32661	0.201	0.693	1.604
2001	3666	9884	35187	0.215	0.744	1.678
2002	2171	8577	32831	0.209	0.709	1.648
2003	4097	10166	36657	0.210	0.738	1.708
2004	3178	9787	35746	0.253	0.917	2.154
2005	2901	8174	28049	0.231	0.799	1.852
2006	3431	9176	38641	0.263	0.920	2.180
2007	2168	8013	32827	0.337	1.157	2.661
2008	2451	8303	43451	0.365	1.256	2.992
2009	1143	4838	23446	0.383	1.315	3.077
2010	1175	4374	17588	0.358	1.209	2.677
2011	1548	5595	22322	0.343	1.194	2.722
2012	1837	6265	29309	0.339	1.210	2.753
2013	1791	5887	28355	0.334	1.221	2.739
2014	1908	6448	30732	0.320	1.165	2.633
2015	2221	7465	36054	0.337	1.176	2.621
2016	2252	7555	33394	0.376	1.297	2.956
2017	1672	6132	31135	0.376	1.334	3.122

Table A6. 2. Estimates of fishing mortality by fleet. Fleet definitions are given in

Table 2. 2.

Fleet fishing mortality

Year	G_art	G_ins	T_art	CI_ind
1990	0.591	0.007	0.031	0.120
1991	0.758	0.007	0.031	0.118
1992	0.652	0.008	0.032	0.115
1993	0.662	0.009	0.034	0.112
1994	0.580	0.009	0.038	0.109
1995	0.751	0.011	0.042	0.109
1996	0.618	0.013	0.046	0.102
1997	0.627	0.015	0.047	0.098
1998	0.649	0.018	0.050	0.091
1999	0.626	0.018	0.053	0.086
2000	0.621	0.018	0.054	0.075
2001	0.673	0.019	0.058	0.071
2002	0.643	0.021	0.060	0.073
2003	0.656	0.027	0.065	0.074
2004	0.843	0.029	0.072	0.068
2005	0.699	0.039	0.078	0.072
2006	0.848	0.047	0.086	0.059
2007	1.098	0.049	0.088	0.055
2008	1.199	0.055	0.089	0.074
2009	1.249	0.054	0.082	0.098
2010	1.094	0.054	0.076	0.117
2011	1.108	0.048	0.071	0.103
2012	1.135	0.044	0.064	0.108
2013	1.093	0.045	0.057	0.134
2014	1.025	0.043	0.050	0.161
2015	1.030	0.051	0.050	0.164
2016	1.147	0.059	0.059	0.185
2017	1.169	0.060	0.064	0.189

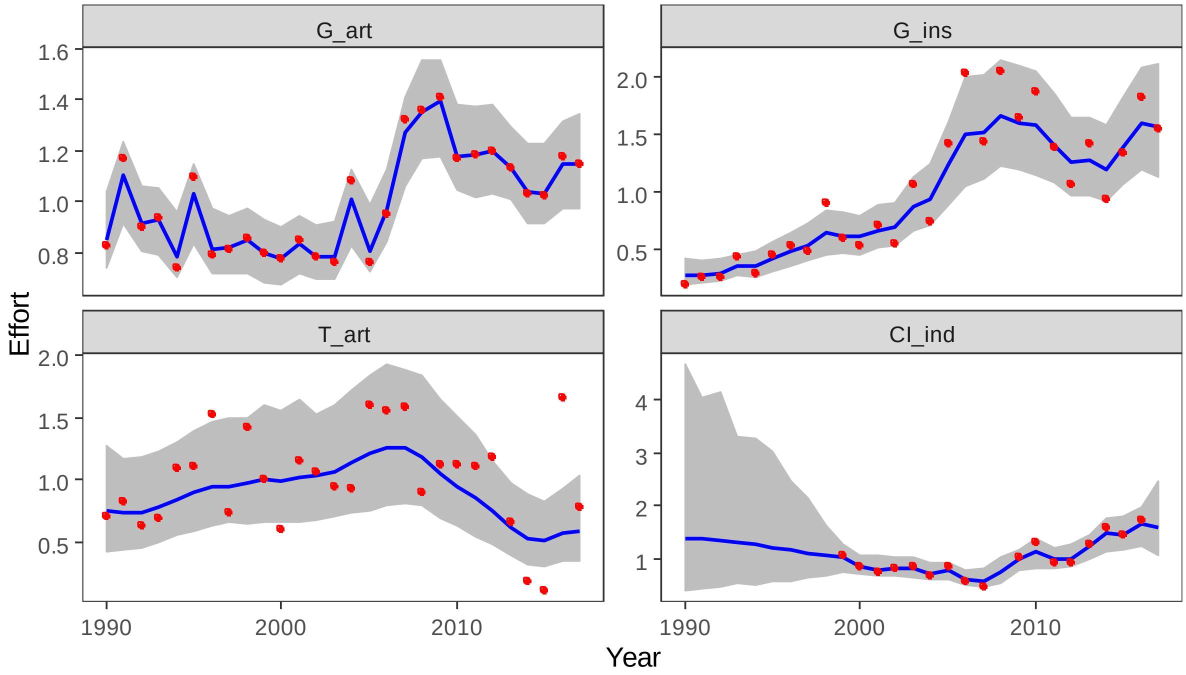

Figure A6. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

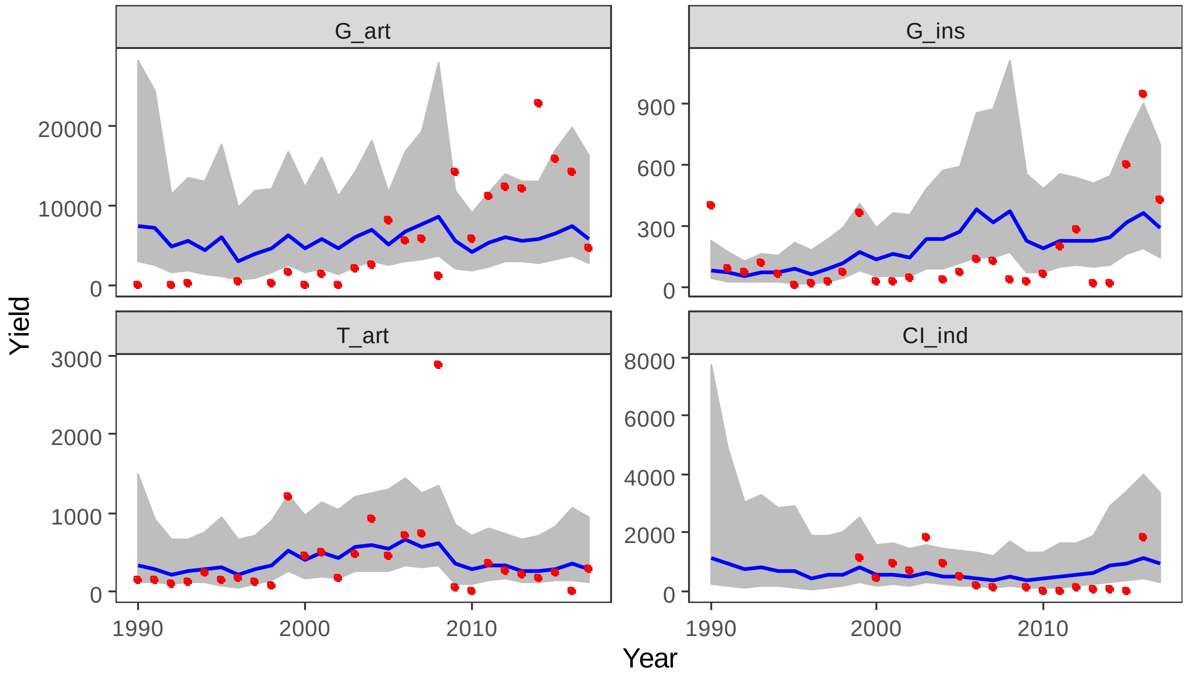

Figure A6. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

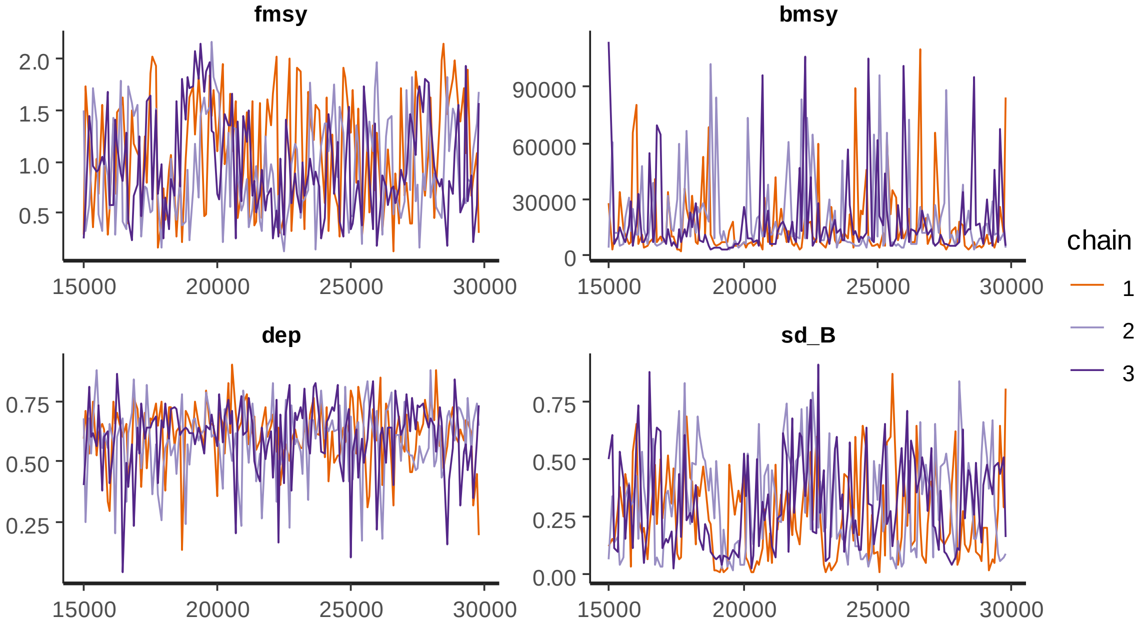

Figure A6. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.