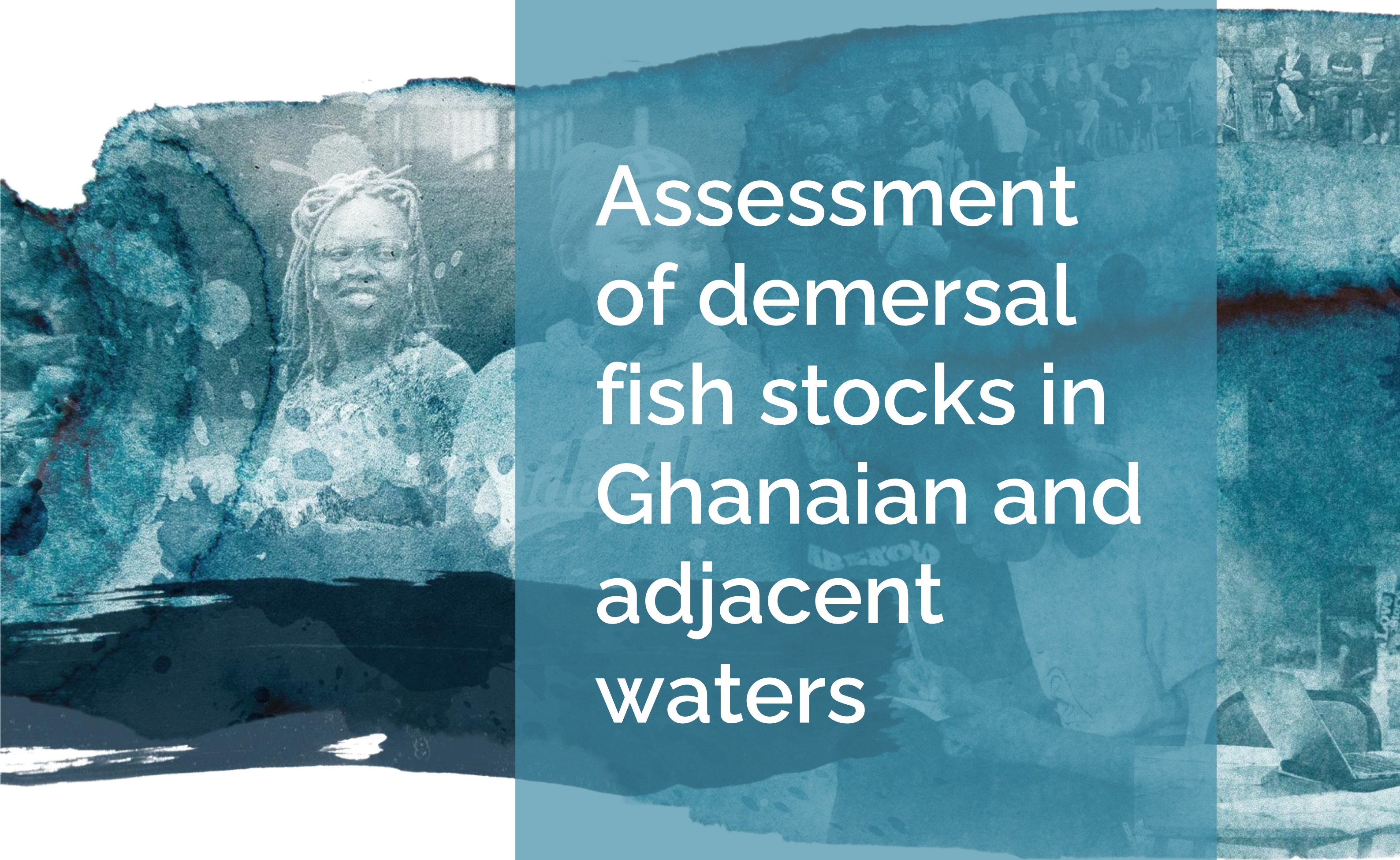

Assessment of demersal fish stocks in Ghanaian and adjacent waters

ONE OCEAN HUB

GCRF Global Challenges Research Fund

UK Research and Innovation

Robin M. Cook[1]
Benjamin K. Nyarko[2]
Joseph Aggrey-Fynn[3]
Emmanuel Acheampong[3]
Godfred Ameyaw Asiedu[3]

[1] MASTS Population modelling group, Department of Mathematics and Statistics, University of Strathclyde, UK.

[2] Department of Geography & Tourism, University of Cape Coast Cape Coast Ghana.

[3] Department of Fisheries and Aquatic Sciences, University of Cape Coast, Ghana.

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Executive summary

a) Five stocks of demersal fish important to Ghana are assessed for the period 1990-2016. 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 bigeye grunt (*Brachydeuterus auritus),* sea breams (*Dentex* spp), threadfin (*Galeoides decadactylus*), red Pandora (*Pagellus bellottii*) and croakers (*Pseudolithus* spp).

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 but do not show a long term trend for three of the five stocks. There is evidence of a recent decline in catches of sea breams and an increase for threadfin.

c) Fishing effort data are available for 17 fleets. Effort trends are highly variable but Ghana industrial trawl shows a marked increase which is also reflected in high catches of some species for this fleet.

d) Catch per unit effort data (cpue) suggest that all stocks have declined from the 1990 level but may have stabilised or increased in recent years. However, the trends may be over-optimistic as the effort data are not corrected for increases in fishing power.

e) A surplus production model is developed to assess the stocks using catch and effort data by fleet. The model also accounts for increasing fishing power over time and missing catch data. Simulation testing of the model shows that it is able to recover the correct parameter values.

f) All five stocks show similar downward trends in stock biomass and increasing fishing mortality. They all 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.

g) In four of the five stocks Ghanaian fleets dominate the fishing mortality with the industrial trawl having a large impact on sea breams and red Pandora. Côte d'Ivoire and Benin make a large contribution to fishing mortality on croakers but otherwise only comprise a small portion of the mortality on other stocks.

h) Estimates of the rate of increase in fishing power vary considerably between fleets and species. Most notable is the above average increase in fishing power by Ghanaian and Benin industrial trawl fleet fishing for seabreams and red Pandora. A smaller increase but similar pattern is also evident in the Ghanaian artisanal hook and line fleet.

i) Equilibrium analyses suggest that all five stocks are at high risk of stock collapse at current (2016) rates of fishing. 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, mixed 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 demersal 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

Demersal fish are exploited by industrial and semi-industrial trawlers, artisanal fishery canoes and taken as bycatch by shrimp trawlers. The artisanal fleet operates in the coastal zone, whereas the trawlers operate at depths of 30 to 70 metres. There has been an increase in the number of active fleets in Côte d’Ivoire, Ghana and Benin. The number of foreign fleets active in the zone is significant in Benin and Côte d’Ivoire. The main demersal species exploited are sea breams (*Pagrus caeruleostictus, Dentex canariensis, Dentex gibbosus, Dentex angolensis), red pandora (Pagellus bellottii), bigeye grunt (Brachydeuterus auritus), croakers (Pseudotolithus senegalensis, Pseudotolithus typus)* and threadfin (*Galeoides decadactylus)*.

1.2.1 Ghana fleets

Current (2016) data suggest that over 12,000 artisanal canoes (Figure 1. 2) and about 144, 000 - 200,000 fishers operate from 334 landing sites in almost 200 fishing villages located along the coast of Ghana (Nunoo et al. 2014; Figure 1. 2). The number of canoes operating on the shelf of Ghana have doubled during the last three decades. About 80% of this fleet is currently motorized compared with only about a half that were motorized in 1990s when there was no government subsidy on fishing fuel (Figure 1. 3). The artisanal fleet is responsible for over 70% of the total annual landings of both pelagic and demersal fish species (Nunoo et al. 2014). Hence they impact significantly on dynamics of the demersal fish stocks.

The main gears employed by the artisanal fishery to capture demersal fish are pursing set, particularly for bigeye grunt, threadfin and other species that are semi-pelagic, and hook and line that is specifically designed to catch demersal fish. In addition, juveniles of some demersal species are captured by beach seines. A total of about 11,500 vessels using these different gears are currently in operation. They have increased by ≈126 per year in the last three decades (Figure 1. 4). In the early-1980s, pursing sets were the most preferred gear and constituted over 50% of all the fishing gears in Ghana. Today, the fishery is dominated by set nets that are more suited for capturing demersal fish, crustaceans and molluscs from deeper waters so it is likely the fishers are switching gears to target these species. Preference for hook and line as a fishing method is however relatively low in Ghana's artisanal fishery. Generally, hook and line are appropriate for catching Sparidae and Ludjanidae. These species occur in rocky and continental slope areas where fishing is difficult. However, very few traditional fishing craft can access fish in those areas hence the low use of hook and line in Ghana's artisanal fishing industry.

Other fleets contributing to the catches of demsersal fish in Ghana are pair-trawlers, particularly from the EU and China (Pauly et al 2013), despite a national ban on pair-trawling in Ghana since 2007 (Nunoo et al, 2014). Data on demersal catches from these fleets are not available. However, estimates by Pauly et al, 2013) suggests an average catch rate of 1252 tonnes per vessel per year between 2002 and 2010.

1.2.2 Other fleets

While Ghana accounts for the majority of the catch in the region, other fleets in neighbouring countries account for some of the catch. Information on these fleets, from FAO (2019), is summarised below.

1.2.2.1 Cote d'Ivoire.

There are approximately 78 industrial trawlers (2016 data) of which half are national and the remainder foreign vessels. The number of vessels has increased from 35 in 2009.

1.2.2.2 Benin

In 2009 Benin had 11 foreign industrial trawlers operating but this has decreased to two in 2016. The artisanal fleet consists of around 728 canoes (2016) which is little changed from 2009.

1.2.2.3 Togo

The artisanal fleet in 2016 comprised around 360 canoes of which the largest component is un-motorised gillnetters (28%) followed by motorised purse seiners (25%) and motorised gillnetters (16%). Other gears are a mixture beach seine and handlines. There has been a decrease in the total number of vessels from 422 in 2010.

1.3 Biology of exploited species

1.3.1 Bigeye grunt

This species can be found at depths of between 10 and 100 metres, in particular between 30 and 80 m. It reaches sexual maturity at a length of around 15cm and grows to about 30cm. It is a semi-pelagic species living near the bottom during the day and moving up the water column to feed at night where it feeds on invertebrates and small fishes.   It is listed as “near threatened” by the IUCN (Carpenter et al, 2015).

1.3.2 Sea breams

Sea breams (Sparidae) are one of the commercially important demersal fish groups that are landed in Ghana. They mostly occur in the continental shelf and slopes, on sandy to rocky substrates at depths below 150 - 200 m. The adults of the sea breams are solitary, whiles the juveniles form aggregations in inshore waters. They can grow to a maximum length of about 72 - 106 cm. Some (e.g. *Dentex gibbosus*) are carnivorous, feeding mainly on molluscs, crustaceans and other invertebrates (Carpenter, 2001; Hamida et al., 2010). Others (e.g. *Pagrus caeruleostictus*) are opportunistic, feeding on prey items from various trophic levels (Carpenter, 2001; Hamida et al., 2010). Sea breams generally reach sexual maturity at the age of 2 years (Carpenter, 2001; Hamida et al., 2010), and are capable of producing 19000 – 1000,000 eggs per individual. Some of the Sparids (e.g. *D. gibbosus*, P. *caeruleostictus*) exhibit hermaphroditism.

The *Dentex* spp. group as defined by the FAO/CECAF Working Group, includes *Dentex canariensis*, *D. gibbosus, D. angolensis* and *Pagrus caeruleostictus* and considered this group as a single stock and is treated as such in this report.

1.3.3 Threadfin

The species is found at depths of up to 50 meters on sandy and muddy bottoms. It is often found in coastal waters. It reaches a maximum length of 50cm and matures sexually at around 12cm. It feeds on benthic invertebrates with shrimps as the preferred prey items. It breeds throughout the year particularly during the lean season. The species is easily accessible to the artisanal fleet. It is also an important bycatch of the coastal shrimp fishery. It is listed as “near threatened” by the IUCN (Carpenter et al, 2015).

1.3.4 Red pandora

This species is generally caught with the *Dentex* spp group. Most of the fish caught are between 12 and 23 cm in length. They occur in schools over hard as well as sandy bottoms, especially in the upper 100 m. They have a predominantly carnivorous diet (including crustaceans, cephalopods, small fish, amphioxus and worms). The species is protogynic hermaphrodite

1.3.5 Croakers

Three species of Pseudotolithus spp. are exploited in the area. These are *Pseudolithus typus, P. senegalensis* and *P. elongatus*. They are not separated in the catch and are therefore treated as a single stock. The distribution and habitat of this group of species are similar to those of threadfin. They are mainly coastal species found in muddy and sandy bottoms. *P. typus* and *P. senegalensis* are larger species growing to 114cm and maturing sexually around 35-50cm. They feed on crustaceans and juveniles of finfish*. P.elongatus* is smaller with a maximum length of 47cm, maturing around 19cm. It has a similar diet to the other species. Most of the croakers caught are between 14 and 34 cm in length.

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 demersal resources in the region (FAO, 2019) which provides catch and effort data from 1990-2016, as well as some length frequency data and swept area biomass estimates from the Nansen surveys. There are numerous studies of 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 27 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 17 different fleets covering the four countries in the region (Table 2. 2). A summary of how data are collected is given in FAO (2019).

As well as considering the raw data a simple model is described and used to extract a common trend from the 17 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. Only the Ghana industrial trawl shows a clear upward trend while the artisanal purse seine fleets of Ghana and Togo both show a long term decline. The Benin industrial trawl effort appears to have a sharp decline in recent years and can be explained by a sharp reduction in the number of vessels since 2012.

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 1990-2016. Here countries are coded by colour with Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue. Clearly the Ghanaian fleets dominate the catches for all stocks though less so for croakers (*Pseudolithus* spp) where both Côte d'Ivoire and Benin make up a significant fraction. Overall Togo makes only a minor contribution to the total catches. In the case of sea breams and red pandora it is noticeable that the Ghana industrial trawl catches have increased in recent years while the same country's hook and line and set net fleet catches have diminished. Catches of sea breams appear to have declined in recent years after rising to a peak around 2005, while those of threadfin have increased overall. Other stocks show no strong trend.

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 three stocks from the Nansen surveys carried out periodically in the region. Data reported in FAO (2019) cover sea breams, croakers and bigeye grunt for some years between 1999 and 2016 and are shown in Figure 2. 3. These show no clear trend though, arguably, for bigeye grunt there is a decline, but this perception is heavily dependent on the large 1999 estimate. In the case if croakers and sea breams these comprise a mixture of species and it is difficult to know whether these correspond to the same species as the fishery exploits.

2.5 Catch per unit effort

The Nansen survey data provide fishery independent estimates of biomass but the observations are sparse and only cover three 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 27-year period is shown in Figure 2. 4 for each stock as a stacked bar chart. If we assume that cpue is a measure of relative abundance, then the height of each bar should be an indication of relative abundance provided the sampling efficiency for each fleet is constant. For bigeye grunt, threadfin and croakers there is some indication of a decline in relative abundance until the most recent years where there is a strong increase. It is driven largely by cpue from Benin industrial trawl for croakers and threadfin. This is the result of low fishing effort and appears to be anomalous, especially given the low total catches from this fleet

(Figure 2. 2). At face value, therefore, it seems that the cpue data for these three stocks are indicating a decline in biomass. It is, however, important to note that data for the earlier years are incomplete and hence the stacked bars for these years may be too low. This would, if anything, suggest a stronger decline. In the case of seabreams and red pandora there is little indication of a trend but with some increase for sea breams.

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 :

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

Here B is the underlying latent trend, q is an offset that scales the trend to cpue and ε_t is 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:

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

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 (blue line) and in all stocks the current cpue is lower than at the start of the series. For bigeye grunt and red pandora there is a long term decline but with some levelling off in the recent period. Both threadfin and croakers show an initial sharp decline but some recovery in more recent years. Sea breams exhibit a sharp decline in recent years following a period of stability. 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.

As is noted above a number of fleets have very low catches and/or missing effort data. In addition, the Benin industrial trawl cpue looks anomalous (Figure 2. 4). A second fit of the model with these fleets excluded (Table 2. 3, fleets with red values) is shown in Figure 2. 5 (red line). The estimated trend shows very little change compared to the full data set suggesting the results are fairly robust even when the very large recent Benin cpue is included.

2.6 Discussion

There is a large amount of catch and effort data covering 27 years and 17 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 is less problematic since it has 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 2012 and 2017 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 Assessment model

3.1 Introduction

A review of the data available shows that the catch and effort data reported in FAO (2019) offer the most promising source to develop a population model that gives a perspective of stock development over time and forms the basis for forward projections that may be used to investigate future management scenarios. In particular, the availability of data by fleet is potentially highly informative in identifying appropriate measures at fine scale to improve fishery performance. As such this points towards a disaggregated stock assessment model that estimates fishing mortality for each fleet. Currently CECAF assessments use only one selected fleet to construct an abundance index and then include only aggregate catches in the assessment. This approach means that much of the effort data is not used and the information on fleet specific contribution to total fishing mortality is lost.

There are two important issues with the data that need to be considered in the development of an appropriate assessment model. Firstly, as can be seen from the data, some components of the feet catches are missing and these need to be accounted for to avoid bias. Secondly, nominal effort data from commercial fisheries are subject to biases of many kinds and their use to derive abundance indices from cpue is subject to this problem. Typically, one might expect technological innovation and changes in fleet behaviour to result in increasing fishing power over time (Englehard, 2008; Palomares and Pauly, 2019). The assessment model, therefore, needs to account for power increases to correct for effective fishing effort.

Here we develop a state-space surplus production model based on that of Cook et al (2021).The model allows for missing data and increases in fishing power over time. Sampling errors in both the catch and effort data are accommodated. The model is then tested on simulated data.

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:

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

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:

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

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:

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

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):

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

3.3 Parameter estimation

Parameters were estimated by fitting the model to the catch and effort data using Bayesian statistical inference with MCMC sampling in the R package "rstan" (Stan Development Team, 2016). In the "reference model" uniform priors were assumed for all parameters and should give similar results to maximum likelihood. However, it is often the case that there is insufficient information in the data to estimate both m and K adequately, especially if the population shows only a declining trend. We therefore investigated alternative weakly informative priors for K that included uniform on either a log or square root scale.

For identifiability it is necessary to constrain the estimates of δ. A simple way to do this is to fix the value of δ for one reference fleet, with the remaining δ values estimated in the model. An alternative is to fix the mean power increment, $\bar{\delta}$, over all n fleets:

$$\frac{\sum_{k=1}^{n}\delta_k}{n} = \bar{\delta} \qquad 3.7$$

We investigated both constraints as described below. The Stan model code in given in Appendix 8.

3.4 Simulation testing

The model was tested using simulated data to check performance and whether the power increment, δ, was estimable. Simulated data were derived from values of K=210000, m =70000 and δ=0.03, 0.07 and 0,05 respectively for three fleets. The process error on biomass was set at σ_B = 0.2. A continuous increase in fishing mortality was assumed for each fleet. Values of F by fleet used to derive simulated data are given in Table 3. 1 along with the error distributions applied (Table 3. 2). A total of 50 sample biomass trajectories and catches were generated using equations 3.1 and 3.2. Fishing effort, uncorrected for fishing power, was derived from the true fishing mortality by solving equation (3.3) for f given values of δ and assuming q=1 for all fleets. For each of the 50 biomass trajectories errors were added to the derived catches and effort to create pseudo observations. The model was then fit to the simulated data under a variety of different assumptions for the prior on K and the values of δ.

In the initial fit of the model to real data from the reference model (uniform priors on m and K), the posterior distribution for K had a very long right hand tail with an indistinct mode. Using the simulated data, we investigated other priors on K to identify weakly informative prior distributions that did not excessively bias the estimates. These were uniform distributions on a square root or log scale that give higher probability to lower values. The model was also run with alternative assumptions on the power increment, δ. For the reference fleet constraint we set δ=0.03 while for the mean power increment constraint we set $\bar{\delta} = 0.03$. Here the value for the power increment is the mid-point of the value estimated by Pauly and Palomares (2019) from a study of 50 fleets worldwide. Model configurations are shown in Table 3.3.

The models were fitted to the 50 data sets and the median value of the estimated values for m, K, B, F and δ saved. We also estimated median values of B/B_{MSY} and F/F_{MSY} for each data set as potentially more robust quantities measuring relative change.

3.5 Simulation test results

Estimates for the main parameters and other quantities of interest for the different model runs using simulated data are summarised in Figure 3. 1. The values of fishing power increment when δ is fixed for a reference fleet, are fairly well estimated for the remaining fleets in all models but with some negative bias. Using the alternative constraint, with mean δ specified, gives estimates closer to the true values. In this model configuration, δ for all fleets is estimated. Here δ for the first fleet (the reference fleet in other models) was estimated to be 0.28, compared to the true value of 0.03.

For the reference model the estimates of K show positive bias and F_{MSY} negative bias. Of the alternative priors on K, the square root uniform performed best in reducing bias on these parameters but with some increased positive bias on fishing mortality. However, there is very little bias in the F ratio. Mis-specification of δ either for the reference fleet or if fixed over all fleets caused substantial bias in the estimates of B and F in the first year, but in the final year this was much lower except when δ=0.03 for all fleets. In all cases the F ratio in the final year was subject to low bias, suggesting that perception of exploitation status in the final year is fairly robust. Two sensitivity runs that fixed the power increment too low, at zero for all fleets or δ_1=0.015, tended to give an overly pessimistic perception of the stock status in the initial year but approached the correct value in the final year. The model correctly recovered the true trends in biomass and fishing mortality both on the absolute and relative scales but with a small amount of bias evident in the biomass estimates (Figure 3. 2).

3.6 Discussion

In the model described here, it appears possible to estimate the increase in effective effort for some fleets within the assessment, or all fleets if the mean power increment can be specified. These estimates are conditioned on having a good estimate of the change in fishing power of at least one reference fleet or an overall mean. Given such an estimate, the results of simulations show that fleet specific estimates of the mean annual increase in fishing power may be made. However, it is clear that mis-specification of the fishing power for the reference fleet can result in substantial bias. The extent of such bias will obviously depend on the magnitude of the mis-specification. In these simulations it does appear that mis-specifying the reference fleet fishing power and estimating the power for the remaining fleets is better than assuming no fishing power increase, or a fixed value for all fleets.

The choice of prior on K had a relatively small effect on its estimated value though the square root-uniform prior appeared to perform well and is adopted as the default prior in the assessments using real data described in the next section.

4 Stock assessments

4.1 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 all stocks is very high and typically above 1.0. Values of natural mortality are also high and similar in magnitude to F. 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 very high values for the stocks analysed here. It is important to note, however, that F calculated in the studies listed in Table 2. 1 is not the same as F in equation 4.2. The latter expresses catch as a constant times the biomass at the start of the year, while F in the studies in Table 2. 1 is the annualised instantaneous rate of fishing mortality. They will be similar when F is small but not when it is large.

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 in the section 3. 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.

4.2 Methods

A "reference model" was configured as the default model for all stocks based on the model and simulation testing in section 3. As there is no information on the fishing power increase for any particular fleet that could be used to quantify δ for a reference fleet, the alternative constraint, 3.7, was used assuming the overall mean power increment over all fleets was 0.03 per year. This value 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 4. 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 Côte d'Ivoire fleet to 0.03 and estimating the remaining fleet values as free parameters but with a lognormal prior (log(0.03),0.09).
3) Re-parameterising the model (equation 3.1) in terms of F_{MSY} and K and placing an informative prior on F_{MSY}

For (3) the model equation is:

$$B_{t+1} = \left[(1 + 2F_{MSY})B_t - \frac{2F_{MSY}B_t^2}{K} - \sum_k Y_{k,t}\right]\varepsilon_t \qquad 4.1$$

Here the purpose of the sensitivity run is to explore the uncertainty in two key model parameters, m, and K. The estimates of these parameters are often highly correlated and hence not well determined. An alternative parameterisation may shed light on the influence of modelling assumptions. The prior on F_{MSY} was assumed to have mean of 0.3 which is an arbitrarily low value to test the robustness of the model. The sensitivity models are specified in Table 4. 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. These were omitted from the analysis but accounted for only a very small portion of the total catch. The fleets included for each assessment are given in Table 4. 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 30,000 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.

4.3 Results

4.3.1 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.

Bigeye grunt: Overall the model fits the data well though for the CI_ind_trl fleet the effort data in the period 2000-2010 appear to be particularly large and are not fitted by the model.

Sea breams: The catch data appear very noisy in relation to the fitted values though in general the model tracks the trends. The G_art_ps and G_cst_trl fleets catch data are not fitted well with systematic positive residuals. However, the G_ind_trl fleet dominates the catches and these data are fitted fairly well. In common with the bigeye grunt, the data for CI_in_trl are not fit in the middle period and there is similar lack of fit with the T_art fleet.

Threadfin: The model tracks the overall trend in the catches in most fleets but not all the variability in the data. There are large positive residuals in the CI_ind_trl and G_art_bs fleets at the end of the time series and the G_art_hl fleet is poorly fitted. As with sea breams there are large outliers in the effort data fits for CI_ind_trl and T_art fleet. Otherwise, the model fits the effort data well.

Red pandora: The trend is the catch data is tracked fairly well for most fleets. However, for the dominant fleet (G_ind_trl) there are systematic negative residuals in the early period followed by positive residuals. The 95% CI for the G_p_trl fleet is extremely large. The effort data are fit well apart from the CI_ind_trl and T_art fleets that show the same residual pattern as the other stocks.

Croakers: The trend is the catch data is tracked fairly well for most fleets but not the annual variability. There are fleets with systematic residual patterns, notably G_art_ps and B_art. The effort data are fit well apart from the CI_ind_trl and T_art fleets that show the same residual pattern as the other stocks. The effort data are fit well apart from the CI_ind_trl and T_art fleets that show the same residual pattern as the other stocks.

Measurement errors associated with the effort data are shown in Figure 4. 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 large in the industrial trawl fleet effort of Côte d’Ivoire and Benin, and the Togo artisanal fleet. Much lower errors are associated with the industrial trawl, artisanal purse seine and set net fleets in Ghana, and the Benin artisanal fleet. These fleets may, therefore, be expected to provide better data for the derivation of cpue abundance estimates.

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 4. 2. Unlike the effort data each stock has a unique catch data series so more heterogeneity is expected within fleets. Typically, the values of κ are small indicating large unexplained variability. There are some exceptions, notably for sea breams in the Togo data where large values can be seen.

4.3.2 Stock trends

The estimated biomass ratio (B/B_{MSY}) and F ratio (F/F_{MSY}) are shown in Figure 4. 3 and Figure 4. 4. The biomass has declined throughout the period of assessment reflecting the continuous increase in fishing mortality. In all cases 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 the stocks are heavily over-exploited relative to MSY.

The model runs with alternative assumptions on F_{MSY} and the fishing power increment show the same trends. For threadfin, while the trends are in the same direction there is greater sensitivity to model configuration. All the sensitivity runs lie within the 95% CI of the reference model.

The fleet contributions to total fishing mortality are shown in Figure 4. 5. It is clear the Ghanaian fleets dominate with the industrial trawl (G_ind_trl) fleet increasing in recent years for sea breams and red pandora. The exploitation of croakers is more diverse with Benin artisanal (B_art) and Cote d'Ivoire industrial trawl (CI_ind_trl) making significant contributions to the mortality.

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

Estimates of F_{MSY} from the reference model and the sensitivity runs are shown in Table 4. 4.The F_{MSY} values are very high and well in excess of 1 when no prior is applied. Using an informative prior with a much lower mean (0.3) results in F_{MSY} values that are around half the unconstrained estimates. The latter are nevertheless more than double the mean of the prior indicating that the data suggest much higher values. Despite the large effect of the prior, it does not appear to have much effect on the B/B_{MSY} and F/F_{MSY} ratios (Table 4. 4) indicating that these ratios provide a robust indicator of relative stock status.

B_{MSY} estimates are also sensitive to the choice of prior on F_{MSY} (Table 4. 4). With a low mean for the prior on F_{MSY}, the B_{MSY} estimate increases illustrating the inverse relationship between the parameter estimates.

The model estimates the depletion from virgin biomass (K) in the first year (1990) of the assessment (Table 4. 4). In all cases the biomass in 1990 is estimated to be below virgin biomass. The range is from around 41% of K for red pandora to 73% for sea beams. The depletion estimates are insensitive to the model configuration.

The model where fishing power increment on the reference fleet was set at δ=0.03 made almost no difference to the estimates of F_{MSY}, B_{MSY} and depletion when compared to the reference model. It appears, therefore that results are insensitive to the constraint on the fishing power increment parameters.

4.3.4 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 4. 6. While there is variability, some fleets show below mean power increments (G_cst_trl, T_art and B_art). Other fleets, such as G_ind_trl and B_ind_trl, show strong increases in power at least for some species (sea breams and red Pandora) and this is reflected in the high fishing mortality for these species by the G_ind_trl 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 4. 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.

4.3.5 Estimated catches

As discussed in the data section, for some fleets reported catches are missing and these need to be taken into account. Provided there is some information on catches and effort for each fleet the model will estimate missing values. The problem is most prevalent in the earlier years as can be seen from the tables in Appendix 1. Figure 4. 7 shows the estimated catches from the model compared to the reported catches. In the early years the estimated catch is higher than the reported catch while in recent years there is closer agreement. By accounting for missing values, the model should provide less biased estimates of stock biomass and fishing mortality for the early period.

4.4 Discussion

The results of the analysis using catch and effort data suggest that all five stocks have been in decline since 1990 and that fishing mortality has continuously increased over the same period. The biomass of all 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}).

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 assumes 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 many 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 effective effort.

The cpue model discussed in Section 2 does not account for changes to fishing power. An extended version of the model is discussed in Appendix 7 which gives very similar results to the reference model when tested on bigeye grunt. This model makes no parametric assumptions about biomass population dynamics suggesting that the main trends emerging from the reference model are insensitive to the Schaefer assumptions of constant m and K.

Estimates of F_{MSY} appear to be very high and greater than 1. This is consistent with estimates of M based on growth rates and temperature Table 2. 1 and implies the stocks are highly productive. However, 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.

5 Stock status and overview

5.1 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 2016) 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.

5.2 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 5. 1 and Figure 5. 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 bigeye grunt and red Pandora, though the uncertainty in the red pandora estimates is particularly large. The threadfin and croaker 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 1990-2016 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.

5.3 Discussion

The studies listed in Table 2. 1 based on length frequency data collected over a short period tend to indicate that most stocks are being fished in excess of F_{MSY}. This is based on the assumption that $F_{MSY} \approx 0.87M$. While there is clearly substantial variability in these estimates even within stocks, there is at least some qualitative agreement that the stocks are over-fished in relation to MSY.

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 4. 5. Only the bigeye grunt assessments in the two studies show any agreement with the CECAF assessment showing the stock fished above F_{MSY} and the biomass below B_{MSY}. CECAF were unable to obtain a satisfactory assessment for sea breams and threadfin. In the case of red pandora the CECAF assessment shows the stock to be fished below F_{MSY} and the biomass to be substantially above B_{MSY}. The result is based on the Côte d'Ivoire industrial trawl cpue as the only index of abundance and is limited to the period 2005-2016 thus missing the early period when much of the stock decline is likely to have occurred. Given the restricted data set used, it is difficult to evaluate the reliability of the assessment.

The CECAF assessment of croakers also uses a single cpue series based on Ghana coastal trawlers. Here the time series is truncated to 1995-2016. The cpue index shows almost no trend over this period and in the absence of any population signal, model parameter estimates will be highly uncertain. In the assessment CECAF found biomass to be above B_{MSY} but also F to be above F_{MSY}. While such a result is possible, it seems unlikely to be realistic.

The assessments reported in this study estimate very high levels of fishing mortality rate. As can be seen from Table 4. 5 that all the F_{MSY} values are above F=1 which means the recent prevailing values of F are well in excess of this value. F in these assessments is estimated as a yield/biomass ratio where the relevant biomass is the value at the start of the year and implies the annual catch is larger than the biomass. If F>1 it means that much of the annual catch results from in year production (i.e. recruitment and growth). Some consideration needs to be given as to whether this is realistic. Sensitivity runs using an informative prior on F_{MSY} with a mean of 0.3 gave similar qualitative results in terms of trends in relative F and relative biomass but with much lower absolute values of F. This points to an indeterminacy in the estimates of the absolute values of F and biomass and requires further investigation.

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 mixed 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 mixed fishery bio-economic model to consider the wider impacts of management scenarios.

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References

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, Samuel Kweku Konney, Ali Abdulhakim, Patrick Kwabena Ofori-Danson and Kofi Ferni Anyan (2017b). Population Dynamics of Bigeye Grunt, Brachydeuterus auritus (Valenciennes, 1831) in Ghana and Management Implications. Fisheries and Aquaculture Journal, 8: 233. doi:10.4172/2150-3508.1000233

Amponsah, Samuel K.K., Patrick K. Ofori Danson and Francis K.E. Nunoo (2016a). Study of the population parameters of the bigeye grunt, Brachydeuterus auritus (Valenciennes, 1831) in Ghanaian coastal waters and its implications for management. International Journal of Fisheries and Aquatic Studies, 4: 413-419.

Amponsah, Samuel K. K., Patrick. K. Ofori-Danson, Francis K.E Nunoo, Godfred A. Ameyaw (2016b). Aspects of population dynamics of Red Pandora, Pagellus bellottii (Steindachner, 1882) from the coastal waters of Ghana. Journal of Scientific and Innovative Research; 5: 215-224.

Asabere-Ameyaw, A., J. Blay, Jr, and K. Yankson (2000). Aspects of the dynamics of the inshore and offshore populations of Brachydeuterus auritus - (Family:Haemulidae) in Ghana. Journal of the Ghana Science Association, 2:113-122.

Bannerman, P.O. and I. Cowx. (2002).Stock assessment of the big-eye grunt (Brachydeuterus auritus Val.) in Ghanaian coastal waters. Fisheries Research, 59:197-207.

Carpenter, K E. (2001). Sparidae. Porgies (seabreams). In Kent E. Carpenter & V. H. Niem (Eds.), FAO species identification guide for fishery purposes. The living marine resources of the Western Central Pacific. Volume 5. Bony fishes part 3 (Menidae to Pomacentridae) (pp. 2990-3003.). Rome: FAO.

Carpenter, K.E., Camara, K., Djiman, R., Lindeman, K., Montiero, V., Nunoo, F., Quartey, R., Sagna, A., Sidibe, A., de Morais, L. & Williams, A.B. 2015. *Galeoides* *decadactylus*. *The IUCN Red List of Threatened Species* 2015: e.T21132319A42691739. https://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T21132319A42691739.en.

Clottey, Michelle Naa Kordei (2020). Population dynamics and reproductive studies of three commercially important sparid species from Ghanaian waters. Ph.D thesis, University of Cape Coast, Ghana, 167pp.

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.*

Engelhard, G.H. 2008. One hundred and twenty years of change in fishing power of English North Sea trawlers, pp 1:25 in Payne, A.I.L., Cotter, J and Potter, T.(eds), Advances in Fisheries Science: 50 Years on From Beverton and Holt. Wiley-Blackwell, Oxford 568 pp

FAO (2019). Report of the FAO/CECAF Working Group on the Assessment of Demersal Resources -Subgroup South, Libreville, Gabon, 6–15 September 2017.

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.

Hamida, N. B. H., Abdallah, O. B. H. H., Ghorbel, M., Jarboui, O., & Missaoui, H. (2010). The Feeding Habits of the Bluespotted Seabream, *Pagrus caeruleostictus* (Valenciennes, 1830), in the Gulf of Gabes (Central Mediterranean). Reviews in Fisheries Science, 18: 65–72. https://doi.org/10.1080/10641260903318230

Konan, Kouadio Justin, Tapé Gnahoré Toussaint Joanny, Soumaïla Sylla, Luaia Lianthuam and K Lohith Kumar (2015). Stock assessment of the bigeye grunt Brachydeuterus auritus (Valenciennes, 1832) in the coastal water of Ivory Coast. International Journal of Agricultural Policy and Research, 3:222-230.

Lazar, N. (2017). Baseline Assessment of Demersal Fish Stocks Of The Western Region Of Ghana. The USAID/Ghana Sustainable Fisheries Management Project (SFMP). Narragansett, RI: Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island. GH2014_ACT092_CRC. 55 pp

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.

Nunoo, F. K. E., Asiedu, B., Amador, K., Belhabib, D., Lam, V., Sumaila, R., & Pauly, D. (2014). Marine Fisheries Catches in Ghana : Historic Reconstruction for 1950 to 2010 and Current Economic Impacts. Reviews in Fisheries Science & Aquaculture, 22: 274–283. https://doi.org/10.1080/23308249.2014.962687

Okyere, Isaac, John Blay (2020). Assessment of the fishery, growth and mortality characteristics of the cassava croaker, Pseudotolithus senegalensis (Sciaenidae) from coastal waters of Ghana. Regional Studies in Marine Science 39:101425. https://doi.org/10.1016/j.rsma.2020.101425.

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.

Pauly D., D. Belhabib, R. Blomeyer, W. W. W. L. Cheung, A. M. Cisneros-Montemayor, D. Copeland, S. Harper, V. W. Y. Lam, Y. Mai, F. Le Manach, H. Osterblom, K. M. Mok, L. van der Meer, A. Sanz, S. Shon, U. R. Sumaila, W. Swartz, R. Watson, Y. Zhai, and D. Zeller (2013). China's distant-water fisheries in the 21st century. Fish and Fisheries, 15:474-488. https://doi.org/10.1111/faf.12032

Pauly, D., Hilborn, R., & Branch, T.A. (2013). Fisheries: Does catch reflect abundance? *Nature*, 494: 303-306.

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

Sossoukpe, Edmond, Rachad Sidi Imorou, Alphonse Adite and Emile Didier Fiogbe (2016). Growth, Mortality and Exploitation of the African Lesser Threadfin Galeoides decadactylus (Pisces, Polynemidae) Fishing by the Gill Net "Soovi" in Benin Nearshore Waters. Journal of FisheriesSciences.com, 10: 31-37.

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. (a) For this method estimates are derived from the mean over the length intervals. FMSY is assumed to be 0.87*M (Zhou et al, 2012).*

Study	Area	Data collected	Method (F/M)	F	M	F/F_{MSY}
Brachydeuterus auritus						
Amponsah et al, 2016a	Ghanaian coastal waters	2014-January 2015	ELEFAN/Pauly	1.48	1.73	0.98
Amponsah et al, 2017a	Ghanaian coastal waters	2014-January 2015	Length cohort analysis/Pauly	2.80(a)	1.07(a)	3.01
Amponsah et al, 2017b	Ghanaian coastal waters	2016-January 2017	ELEFAN/Pauly	1.22	1.44	0.97
Asabere-Ameyaw et al, 2000	Elmina, Ghana	November 1993-October 1995	ELEFAN/Pauly	4.26	2.14	2.29
Bannerman and Cowx, 2002	Ghanaian coastal waters	1990-1991	ELEFAN/Pauly	1.43	1.24	1.33
Konan et al, 2015	Cote d'Ivoire coastal waters	January-December 2009	ELEFAN/Pauly	0.74	1.27	0.67
Lazar, 2017	Ghanaian coastal waters	April 2015-May 2016	ELEFAN/Pauly	1.41	1.41	1.15
Dentex canariensis						
Clottey, 2020	Ghanaian coastal waters	February 2016 to July 2017	ELEFAN/Pauly	1.48	0.47	3.62
Dentex gibbosus						
Clottey, 2020	Ghanaian coastal waters	February 2016 to July 2017	ELEFAN/Pauly	0.50	0.37	1.55
Pagrus caeruleocisticus						
Clottey,2020	Ghanaian coastal waters	February 2016 to July 2017	ELEFAN/Pauly	2.20	0.83	3.05
Galeoides decadactylus						
Lazar, 2017	Ghanaian coastal waters	April 2015-May 2016	ELEFAN/Pauly	1.16	1.16	1.15
Sossoukpe et al 2016	Benin nearshore waters	August 2014 to July 2015	ELEFAN/Pauly	0.24	1.64	0.17
Pagellus bellottii						
Lazar 2017	Ghanaian coastal waters	April 2015-May 2016	ELEFAN/Pauly	3.93	1.19	3.80
Pseudolithus senegalensis						
Okyere and Blay, 2020	Ghanaian coastal waters	July 2012-June 2013	ELEFAN/Pauly	0.26	0.42	0.71
Lazar 2017	Ghanaian coastal waters	April 2015-May 2016	ELEFAN/Pauly	1.55	1.55	1.15

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_trl
Ghana	Trawlers	G_ind_trl
	Pair trawlers	G_p_trl
	Shrimpers	G_shr_trl
	Coastal trawlers	G_cst_trl
	Artisanal-purse-seine	G_art_ps
	Artisanal-beach-seine	G_art_bs
	Artisanal-set-net	G_art_sn
	Artisanal-hook-line	G_art_hl
Togo	Industrial trawlers	T_ind_trl
	Artisanal	T_art
	Artisanal-purse-seine	T_art_ps
	Artisanal-beach-seine	T_art_bs
	Artisanal-set-net	T_art_sn
	Artisanal-hook-line	T_art_hl
Benin	Industrial trawlers	B_ind_trl
	Artisanal	B_art

Table 2. 3. Measurement error associated with each fleet after fitting the factor model to all fleets. Values shown in red were fleets excluded in a second fit of the model where data were missing, had low catches/effort and the Benin industrial fleet. The values are generally very large indicating a high degree of heterogeneity in the fleet cpue trends.

Fleet	Bigeye grunt	Sea breams	Threadfin	Red pandora	Croakers
CI_ind_trl	0.98	1.06	1.10	0.89	0.74
G_ind_trl	0.75	0.64	1.31	0.79	1.58
G_p_trl	3.83	0.84	2.43	1.00	0.92
G_shr_trl	1.34	1.68	1.00	1.29	0.98
G_cst_trl	0.51	1.65	1.40	1.47	0.43
G_art_ps	0.51	2.34	1.40	2.80	1.56
G_art_bs	0.59	2.99	0.96	4.52	0.84
G_art_sn	0.77	1.82	0.35	1.61	0.64
G_art_hl	1.13	0.70	1.42	0.46	0.79
T_ind_trl	1.36	1.87	1.26	2.02	0.67
T_art	0.55	1.18	1.96	0.90	1.30
T_art_ps	1.29	5.10	2.14	5.07	2.27
T_art_bs	1.40	4.79	0.88	5.08	0.83
T_art_sn	1.96	0.88	1.61	2.84	0.49
T_art_hl	0.95	0.45	4.52	0.81	0.74
B_ind_trl	1.16	1.70	0.80	1.79	0.77
B_art	1.09	0.68	0.72	1.36	0.92

Table 3. 1. Fishing mortality by fleet used to generate simulated data.

Year	Fleet 1	Fleet 2	Fleet3
1	0.479	0.033	0.012
2	0.523	0.037	0.012
3	0.510	0.038	0.011
4	0.503	0.043	0.011
5	0.456	0.048	0.011
6	0.506	0.055	0.010
7	0.510	0.061	0.010
8	0.503	0.065	0.009
9	0.501	0.073	0.009
10	0.512	0.083	0.009
11	0.514	0.084	0.009
12	0.545	0.089	0.010
13	0.571	0.094	0.010
14	0.597	0.104	0.010
15	0.681	0.111	0.011
16	0.706	0.121	0.011
17	0.722	0.127	0.012
18	0.700	0.127	0.013
19	0.792	0.122	0.013
20	0.939	0.127	0.013
21	0.978	0.137	0.013
22	1.013	0.149	0.013
23	0.977	0.153	0.014
24	0.960	0.155	0.014
25	0.926	0.159	0.013
26	0.904	0.166	0.013
27	1.008	0.184	0.014
28	1.066	0.192	0.014

Table 3. 2. Error distributions to generate pseudo data in simulation runs.

Parameter	Fleet 1	Fleet 2	Fleet 3
σ_k, standard deviation of lognormal distribution.	0.13	0.3	0.2
κ_k, dispersion parameter of negative binomial distribution	3	11	8

Table 3.3. Model configurations used in simulation runs.

Model acronym	**K prior**	**δ constraint**
K uniform	Uniform	δ_1=0.03
K log uniform	Log uniform	δ_1=0.03
K sqrt uniform	Square root uniform	δ_1=0.03
Mean δ	Square root uniform	Mean δ=0.03
δ=0.015	Square root uniform	δ_1=0.015
δ all =0.03	Square root uniform	All fleets δ =0.03
δ all =0	Square root uniform	All fleet δ =0.03

Table 4. 1. Configuration of the reference model showing the priors in the parameters and constraints used.

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

Table 4. 2. Models used in sensitivity runs. The reference model is given in the first row.

Model label	**Comments**
Mean q=0.03; neg binomial	Reference model
Mean q=0.03; lognormal	As reference but with lognormal errors for catch; prior: σ~uniform(0,10)
δ[1]=0.03	As reference but δ_1=0.03, prior: δ~ Lognormal(-3.51,0.9) on all other values
F_{MSY} prior=0.03	As δ[1]=0.03 but lognormal(-1.2,0.5) prior on F_{MSY}

Table 4. 3. Fleets used in stock assessments. Fleets excluded (x) are those where the catches were small and intermittent.

Country	**Fleet**	**Acronym**	Bigeye grunt	Sea breams	Threadfin	Red pandora	Croakers
Côte d' Ivoire	Industrial trawlers	CI_ind_trl	✓	✓	✓	✓	✓
Ghana	Trawlers	G_ind_trl	✓	✓	✓	✓	✓
	Pair trawlers	G_p_trl	x	x	x	x	x
	Shrimpers	G_shr_trl	✓	✓	x	x	x
	Coastal trawlers	G_cst_trl	✓	✓	✓	✓	✓
	Artisanal-purse-seine	G_art_ps	✓	✓	✓	✓	✓
	Artisanal-beach-seine	G_art_bs	✓	✓	✓	x	✓
	Artisanal-set-net	G_art_sn	✓	✓	✓	✓	✓
	Artisanal-hook-line	G_art_hl	✓	✓	✓	✓	✓
Togo	Industrial trawlers	T_ind_trl	x	x	x	x	x
	Artisanal	T_art	✓	✓	✓	✓	✓
	Artisanal-purse-seine	T_art_ps	✓	x	✓	x	x
	Artisanal-beach-seine	T_art_bs	✓	x	x	x	x
	Artisanal-set-net	T_art_sn	✓	✓	✓	x	✓
	Artisanal-hook-line	T_art_hl	x	✓	x	✓	x
Benin	Industrial trawlers	B_ind_trl	✓	x	x	x	x
	Artisanal	B_art	✓	✓	✓	✓	✓

Table 4. 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 4. 2.

Stock	Reference model	As reference, lognormal errors	F_{MSY} prior=0.3	δ[1]=0.03
		F_{MSY}		
Bigeye grunt	1.03 (0.58-1.64)	1.22 (0.70-1.97)	0.64 (0.47-0.84)	1.08 (0.64-1.74)
Sea breams	1.49 (0.96-2.02)	1.57 (1.06-2.44)	0.70 (0.46-0.89)	1.50 (1.33-2.05)
Threadfin	1.30 (0.59-2.03)	1.34 (0.65-2.13)	0.71 (0.52-0.88)	1.64 (0.88-2.34)
Red pandora	1.88 (0.70-3.67)	1.77 (0.71-3.16)	0.65 (0.44-0.86)	2.24 (0.74-4.08)
Croakers	1.76 (1.07-2.47)	2.04 (1.75-2.96)	0.69 (0.44-0.87)	1.86 (1.10-2.80)
		B_{MSY} **('000t)**		
Bigeye grunt	24.3 (13.9-40.2)	18.0 (10.1-31.7)	34.1 (24.9-50.7)	22.4 (12.8-36.5)
Sea breams	4.7 (3.2-7.2)	3.7 (2.2-5.4)	9.7 (7.0-14.6)	4.7 (3.3-6.9)
Threadfin	3.3 (1.7-8.4)	2.7 (1.3-5.7)	6.2 (3.8-15.0)	2.5 (1.6-5.2)
Red pandora	8.9 (3.8-19.1)	6.9 (2.5-19.2)	19.2 (10.3-43.6)	7.7 (3.6-16.9)
Croakers	1.9 (1.3-3.0)	1.4 (1.2-2.3)	5.0 (3.3-10.3)	1.8 (1.1-2.9)
		Initial depletion, d		
Bigeye grunt	0.69 (0.57-0.77)	0.69 (0.58-0.77)	0.66 (0.51-0.77)	0.66 (0.54-0.77)
Sea breams	0.73 (0.59-0.81)	0.71 (0.67-0.82)	0.76 (0.63-0.84)	0.77 (0.64-0.84)
Threadfin	0.71 (0.43-0.82)	0.66 (0.47-0.79)	0.58 (0.23-0.75)	0.65 (0.37-0.79)
Red pandora	0.41 (0.16-0.64)	0.41 (0.15-0.64)	0.44 (0.15-0.69)	0.42 (0.15-0.68)
Croakers	0.60 (0.46-0.70)	0.54 (0.37-0.67)	0.54 (0.29-0.69)	0.57 (0.39-0.71)

Table 4. 5. Estimates of ratios of F/F_{MSY} and B/B_{MSY} in 2016 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 11 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**
Bigeye grunt	0.34	2.35	0.31	3.56	Ghana industrial trawl
Sea breams	0.26	1.88	NA	NA	Not able to fit to any cpue
Threadfin	0.53	1.76	NA	NA	Not able to fit to any cpue
Red pandora	0.19	2.06	1.50	0.91	Côte d'Ivoire industrial trawl
Croakers	0.43	1.84	1.49	1.24	Ghana coastal trawlers

Figures

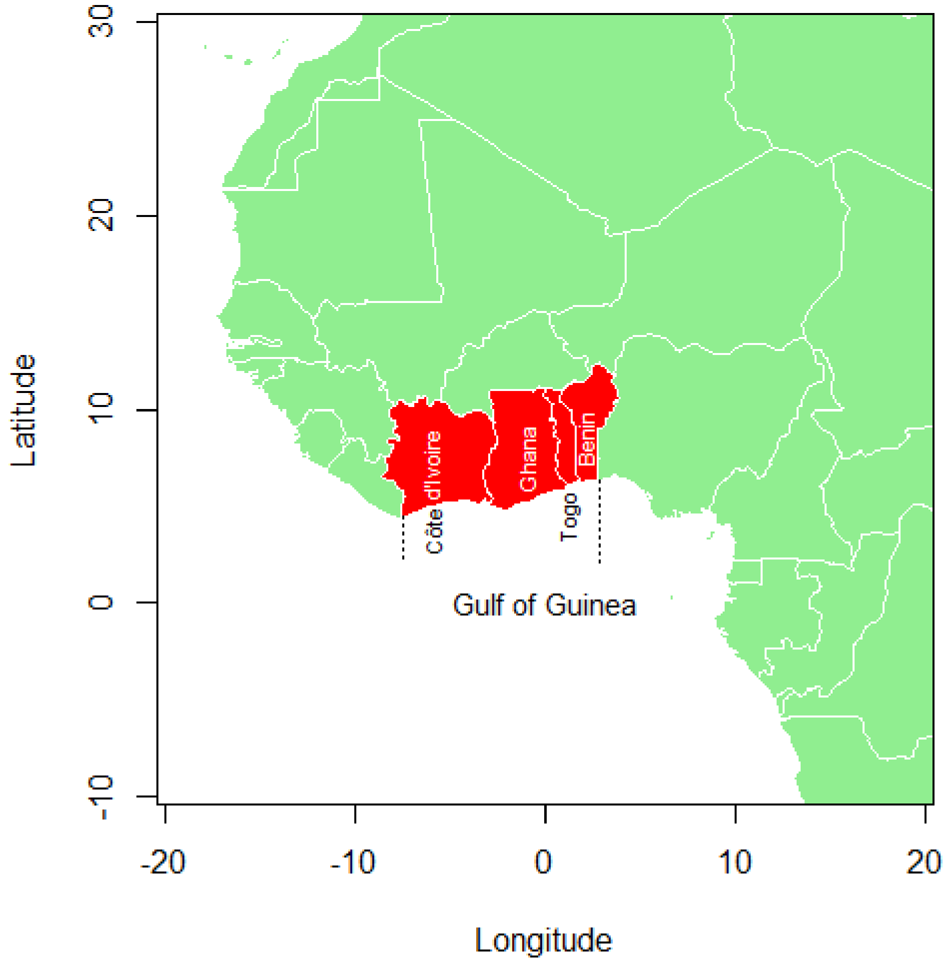

Figure 1. 1. Stock area considered for assessments corresponding to CECAF "western" zone shown as dotted lines. Assessments are based on catches and effort from Côte d'Ivoire, Ghana, Togo and Benin shown in brown.

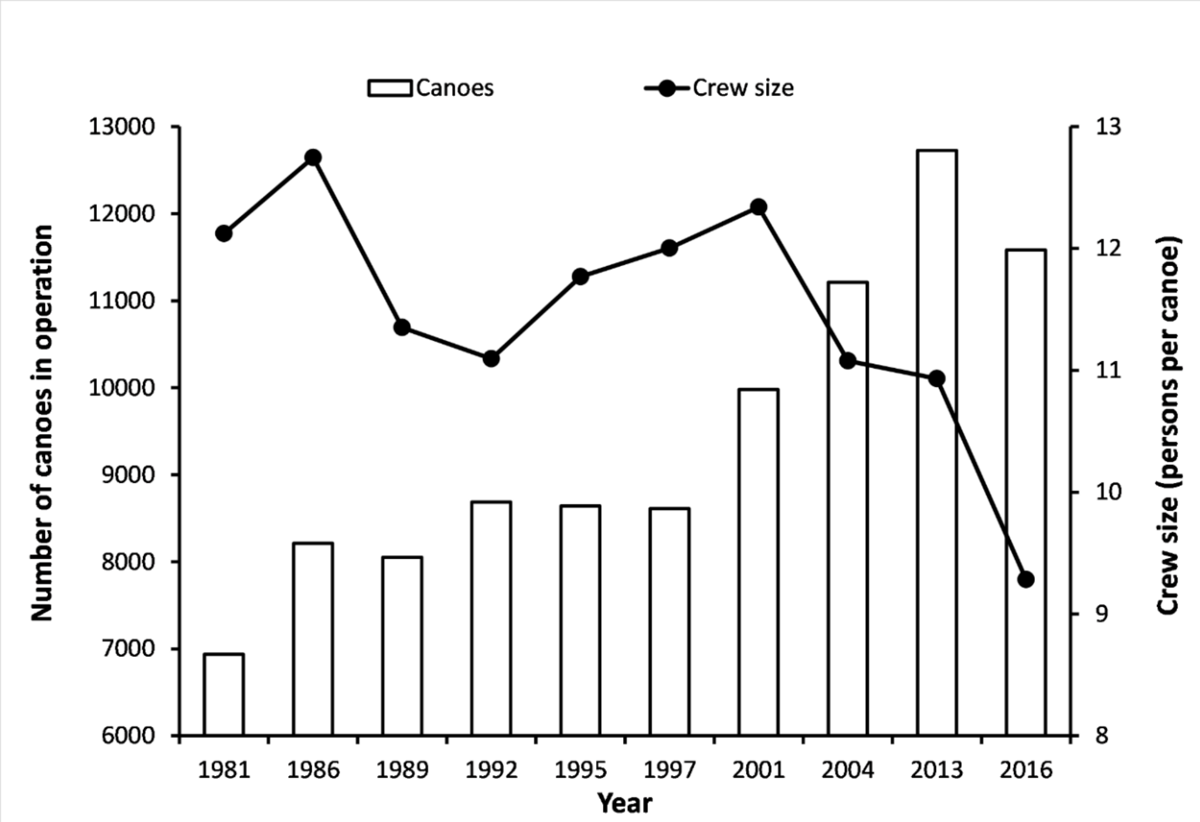

Figure 1. 2. Ghana. Number of canoes (bars) and crew size per canoe (solid line).

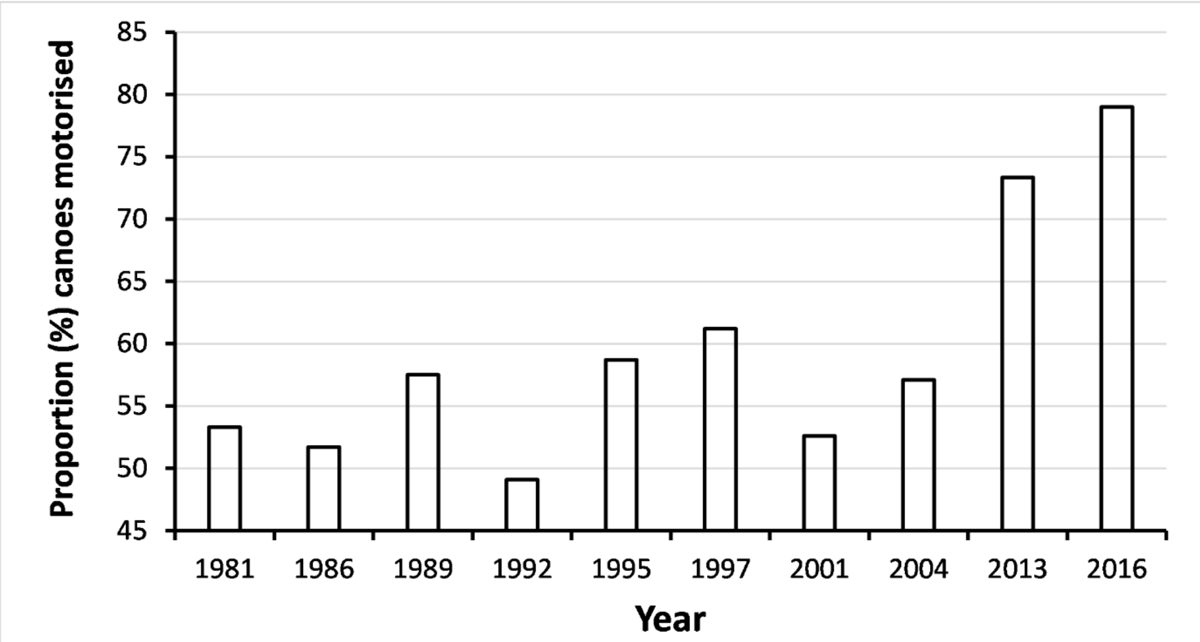

Figure 1. 3. Ghana. Proportion of motorised canoes.

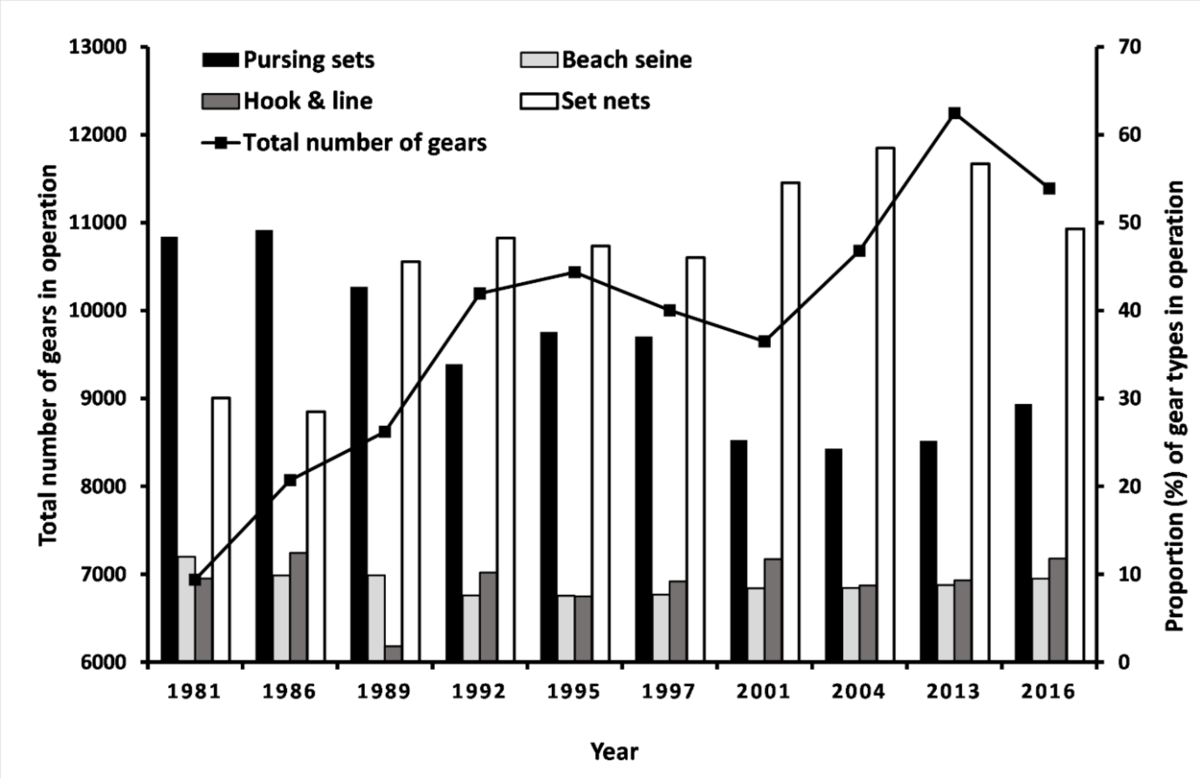

Figure 1. 4. Ghana. Gear types in operation.

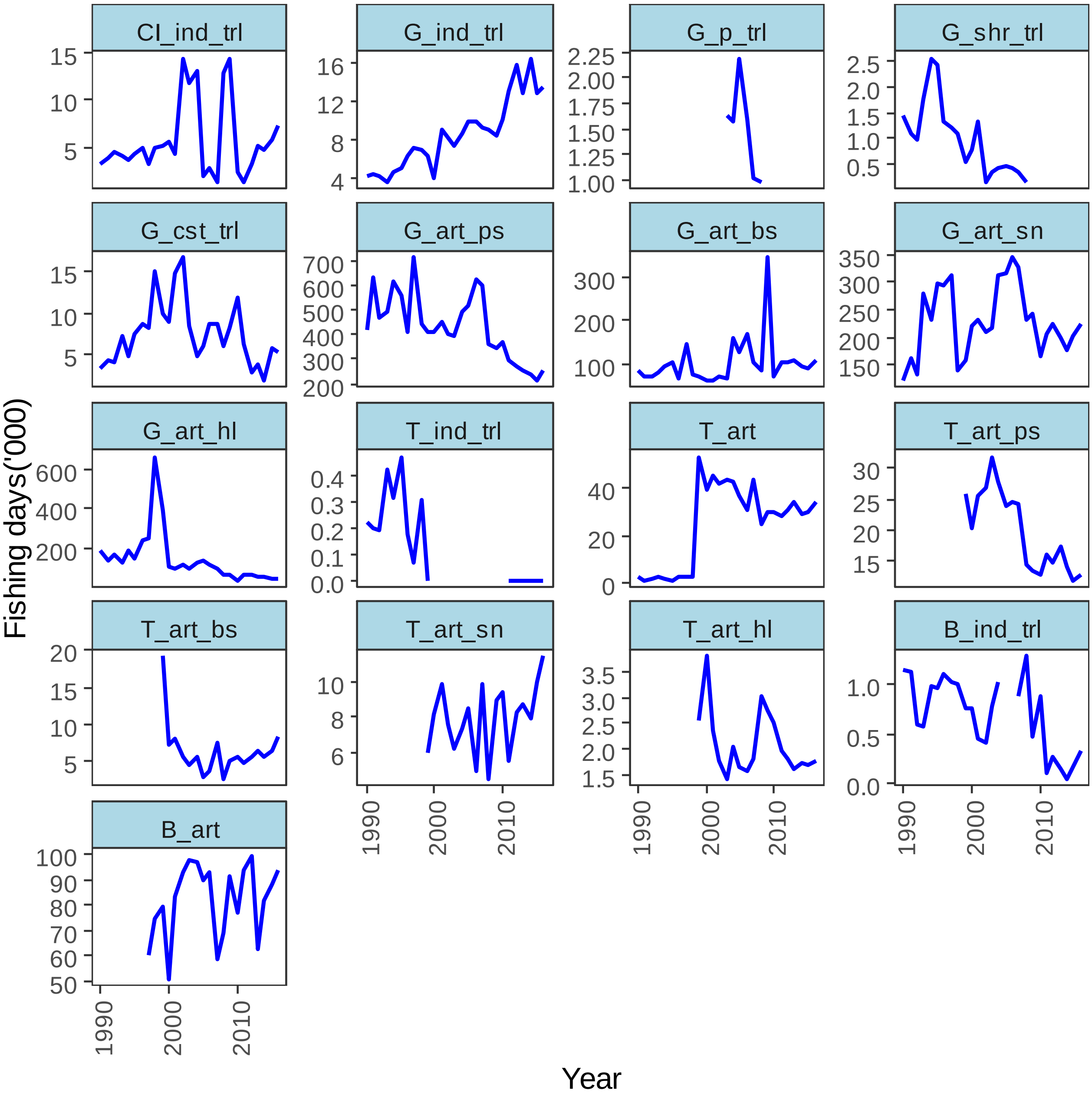

Figure 2. 1. Nominal fishing effort reported as days fishing. Fleet acronyms are identified in Table 2. 2.

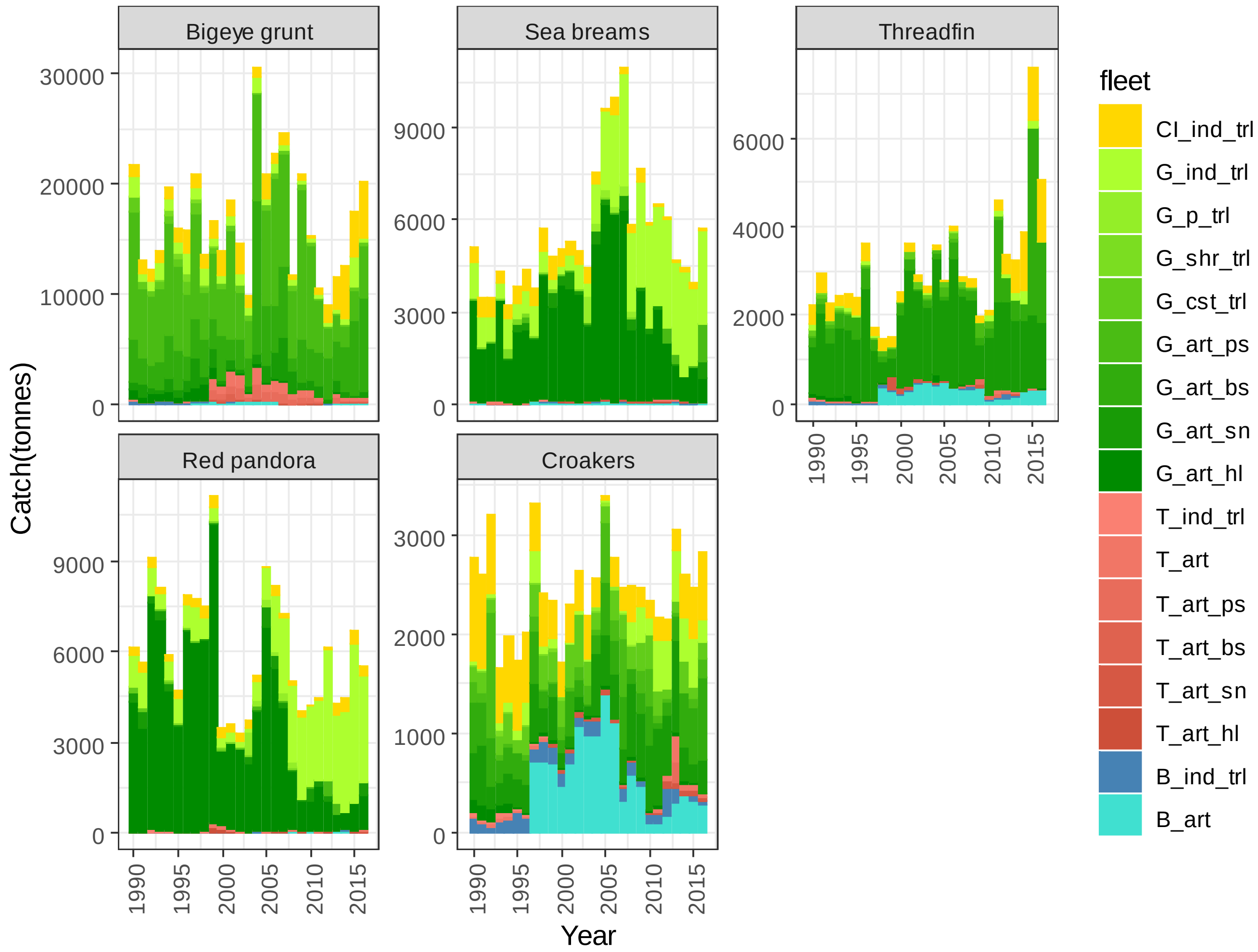

Figure 2. 2. Catches by fleet and country. Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue.

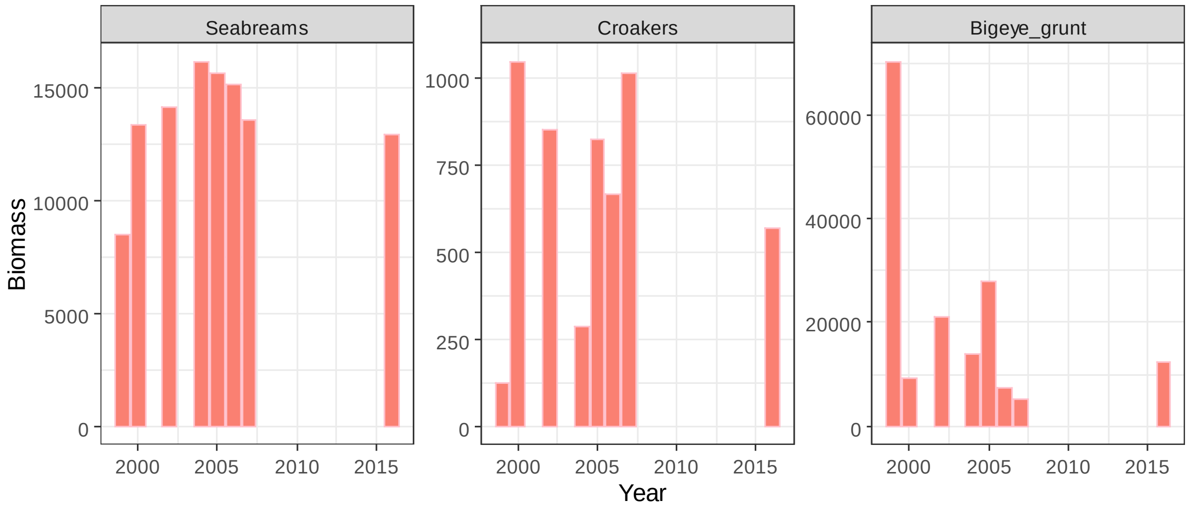

Figure 2. 3. Swept area biomass estimates (tonnes) from the Nansen survey, from FAO(2019).

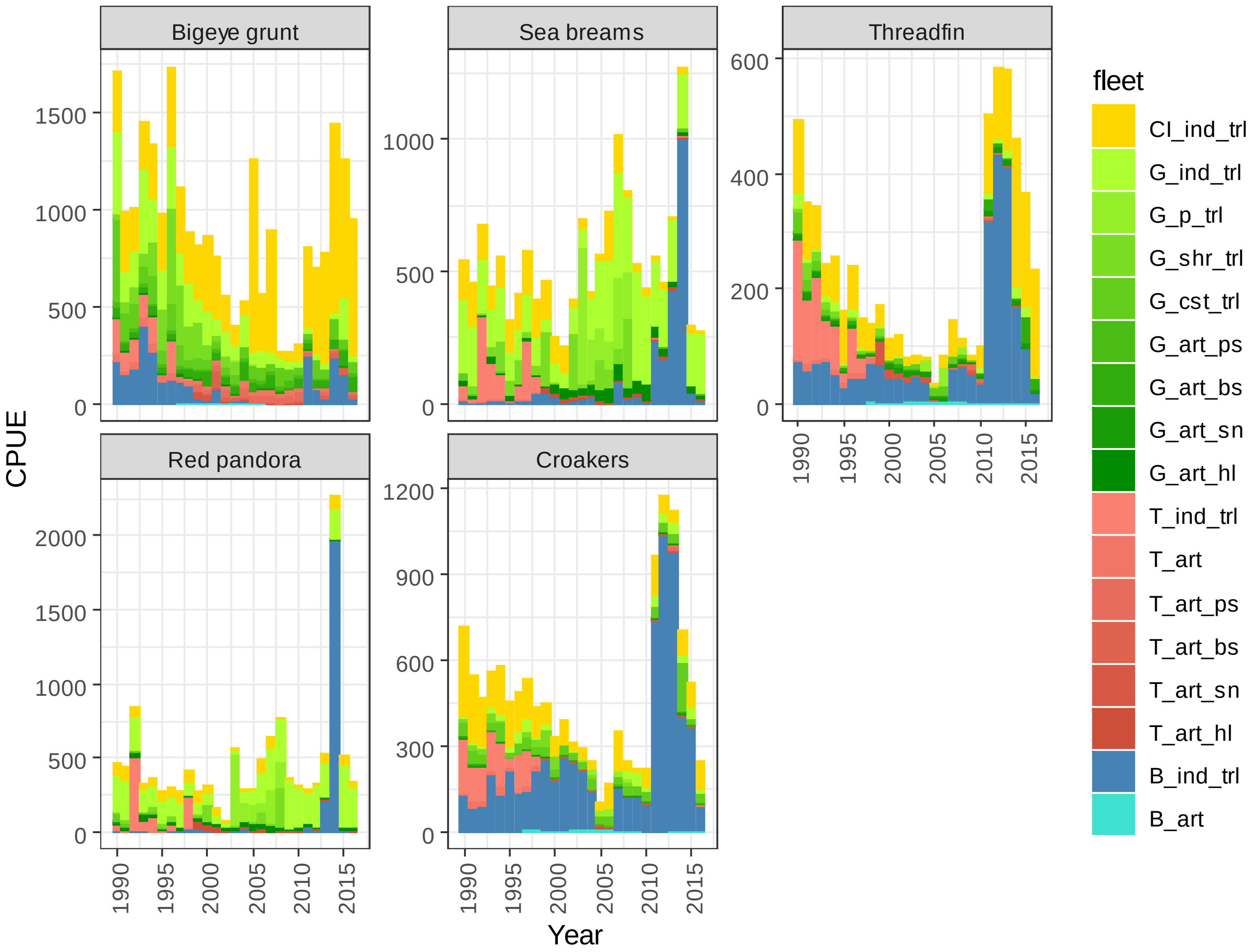

Figure 2. 4. Stacked bar chart of cpue by fleet. The size of each colour block is proportional to the cpue for that fleet. Countries are coded by colour: Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue. Note that in some earlier years data are missing for some fleets and will affect the total height of the bar.

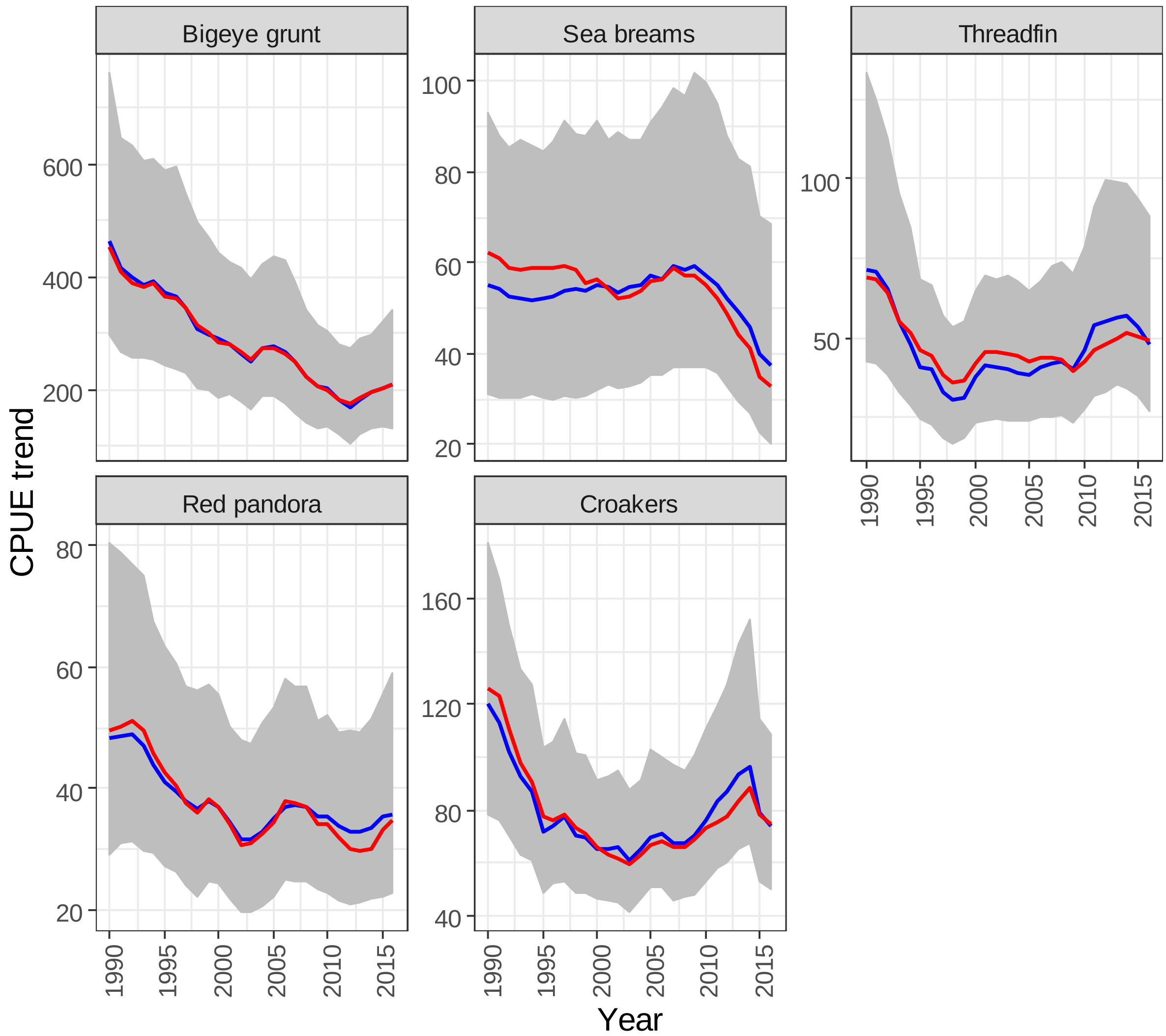

Figure 2. 5. The overall cpue trend estimated from the model for the five stocks. The shaded area shows the 95% CI. The blue line shows the trend with all fleets included. The red line shows the trend when fleets with low catches, missing data and Benin industrial trawl are excluded from the model.

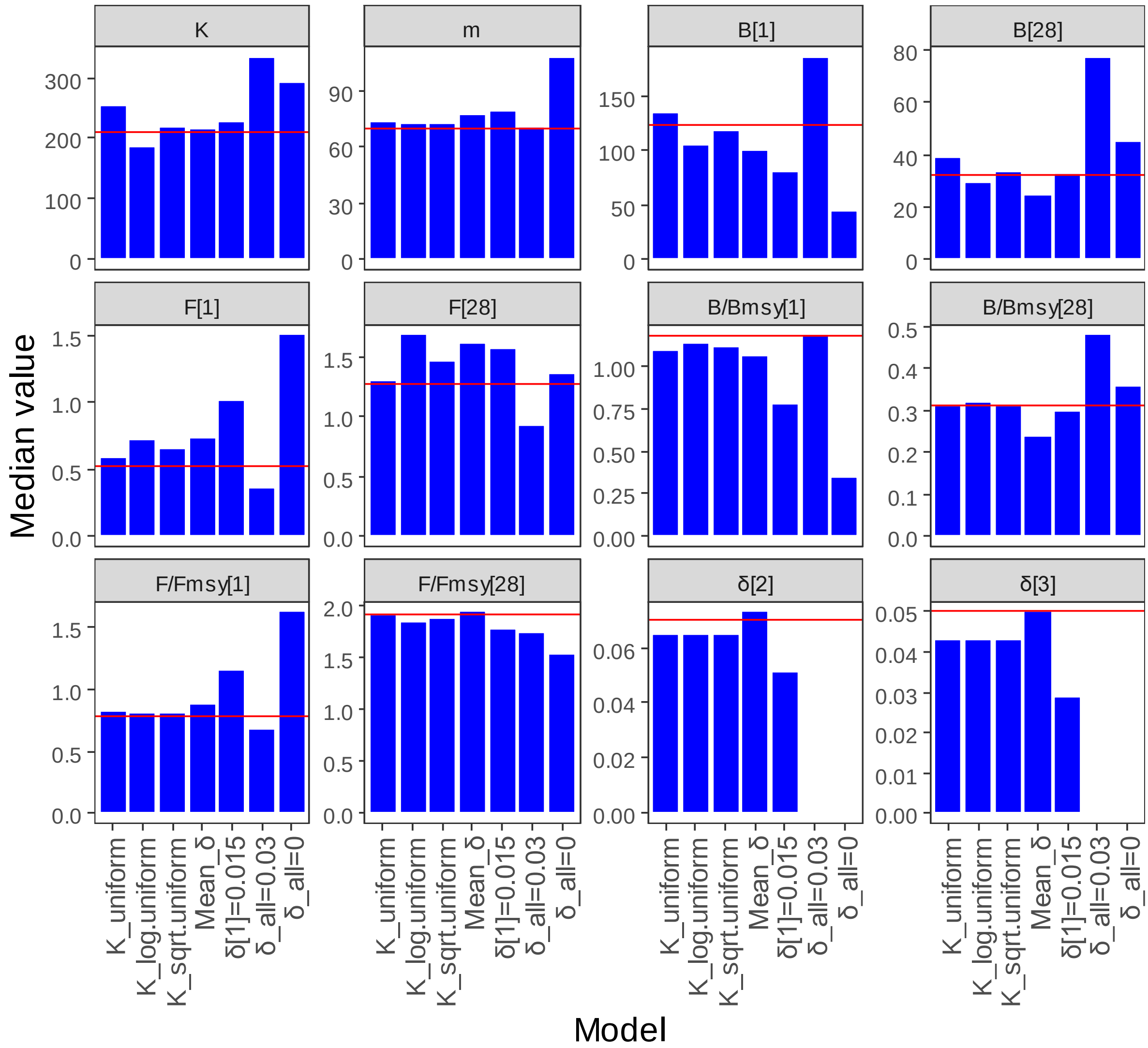

Figure 3. 1. Sensitivity runs on simulated data. The bars show the mean median value of 50 simulations. The solid horizontal line shows the true value. The model configurations labelled K refer to the prior distribution on K. The K_uniform run is the reference model. Models labelled δ refer to the assumption made for fishing power. When δ=0 for all fleets, no correction is made for fishing power. Numbers in square brackets for F and B refer to the first and last year. For δ the brackets refer to the fleet.

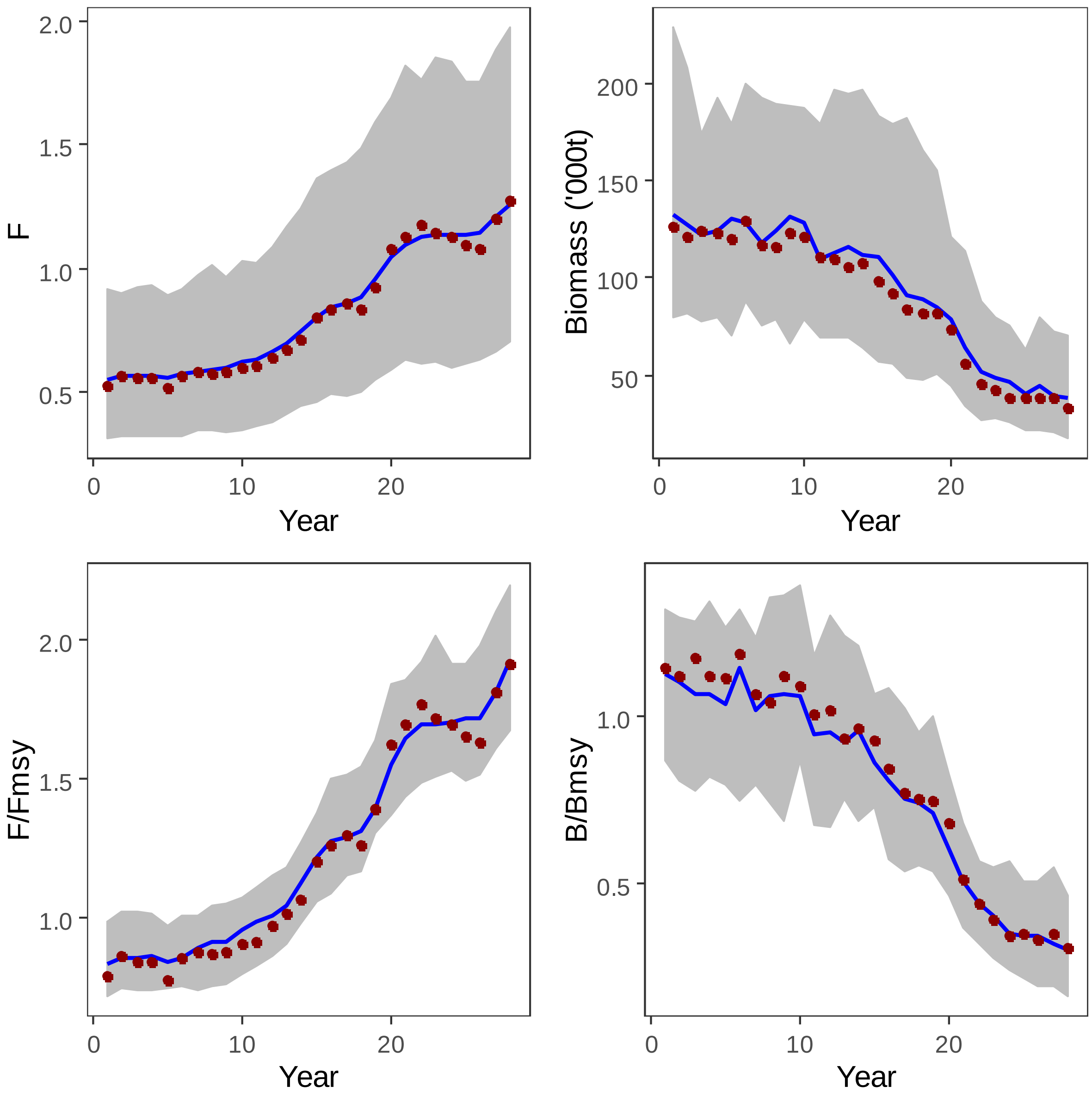

Figure 3. 2. Results from fitting the reference model to 50 simulated data sets. The dots show the true values and the solid line the median value over all data sets. The shaded area encloses the lower 10th and upper 90th percentiles.

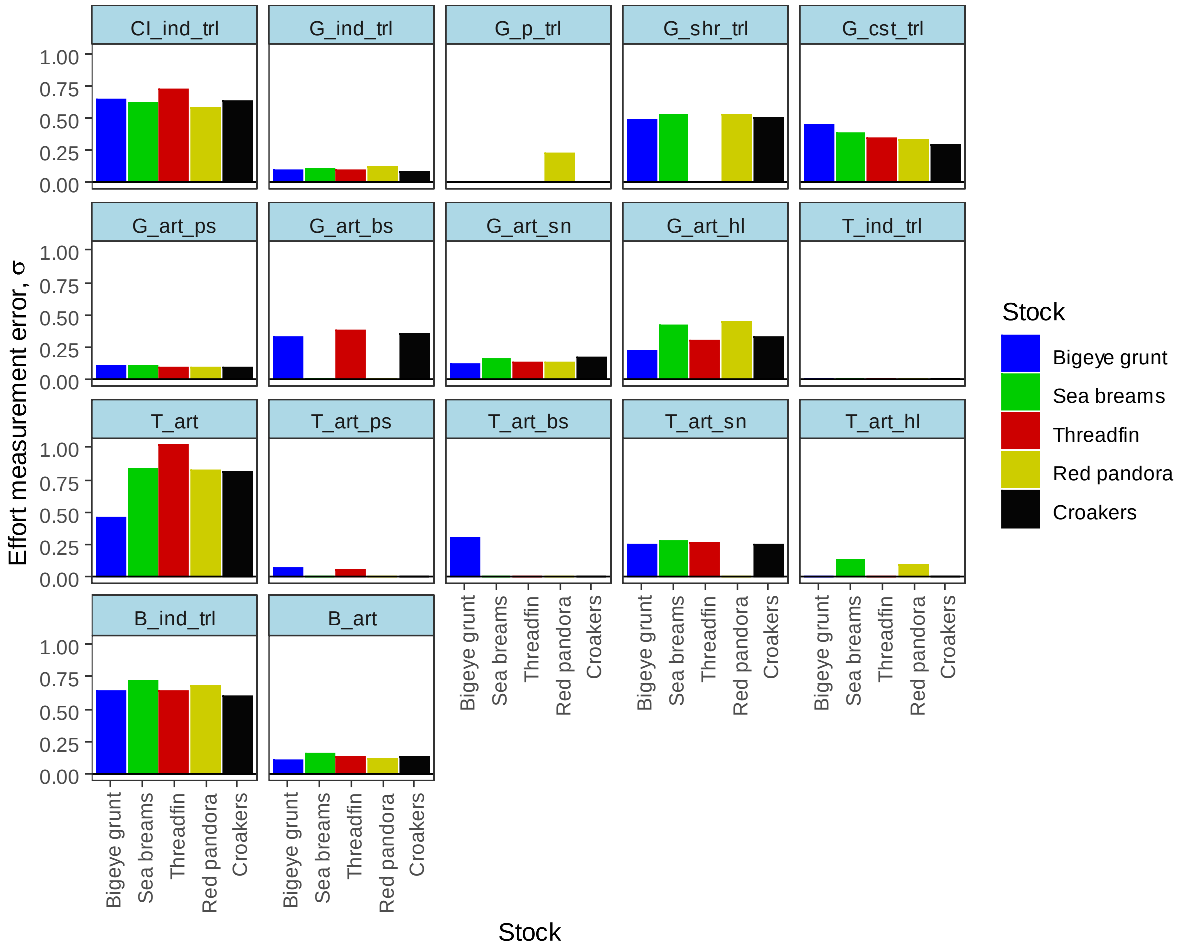

Figure 4. 1. The standard deviation associated with the effort data for each fleet and stock. This is a measure of the measurement error in the effort data assuming it is proportional to fishing mortality. Larger values indicate lower precision.

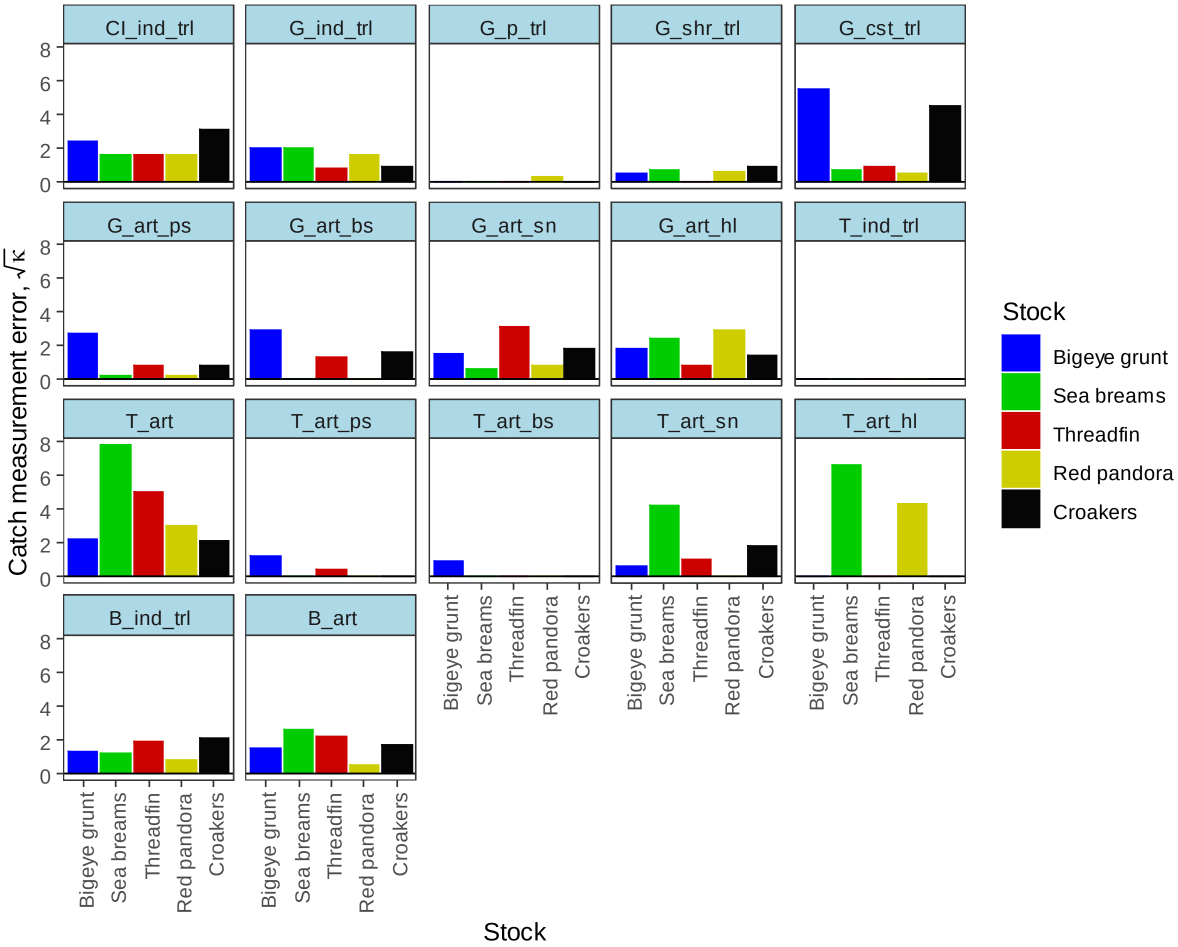

Figure 4. 2. The dispersion parameter, κ, associated with catch data plotted on a square root scale. Large values indicate higher precision.

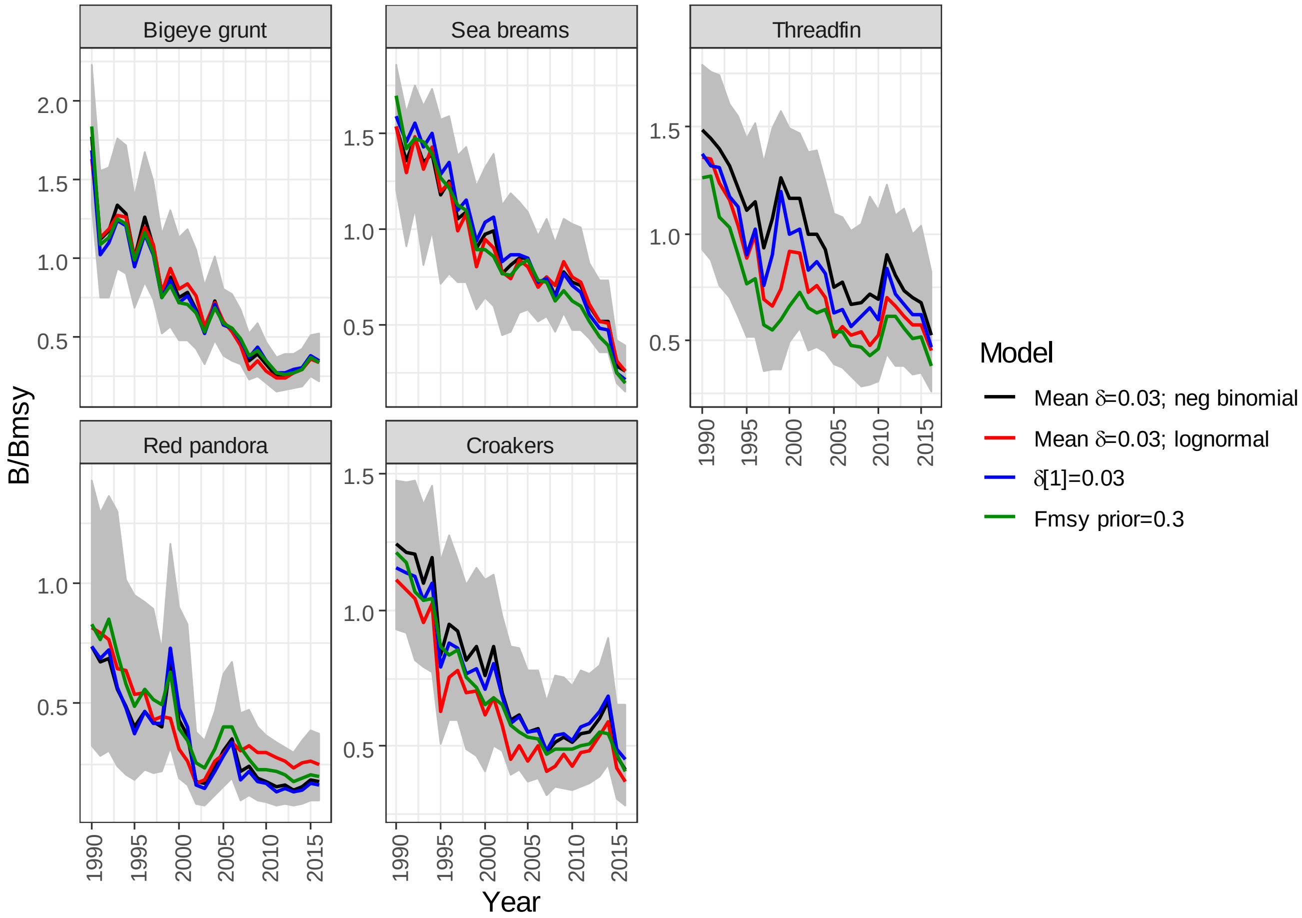

Figure 4. 3. Estimated trends in stock biomass relative to BMSY for the five stocks and four models. The reference model is shown in black. Other colours show results from sensitivity runs. With the exception of threadfin the biomass ratio appears insensitive to model configuration.

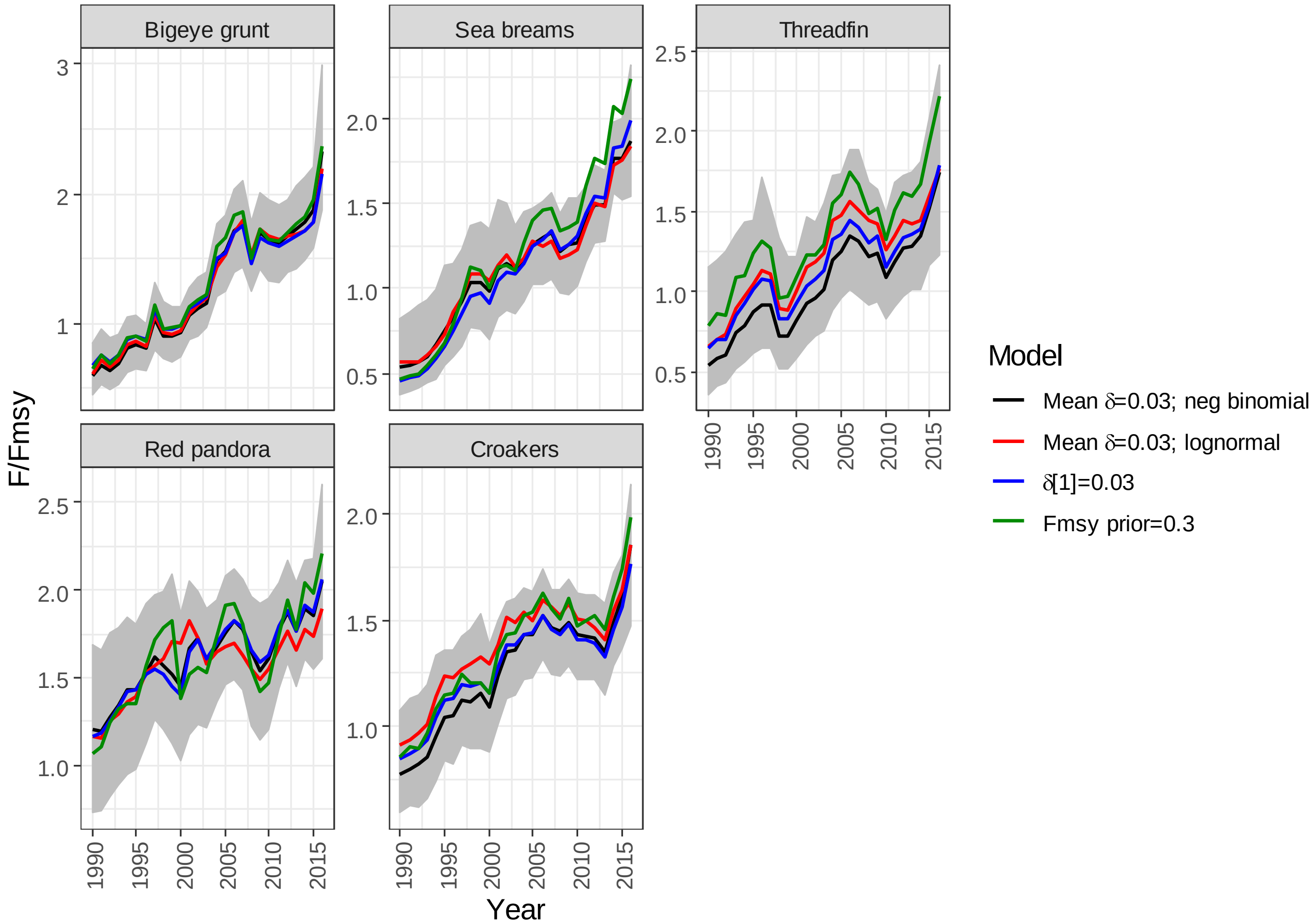

Figure 4. 4. Estimated trends in fishing mortality relative to F_{MSY} for the five stocks and four models. The reference model is shown in black. Other colours show results from sensitivity runs. With the exception of threadfin the F ratio appears insensitive to model configuration.

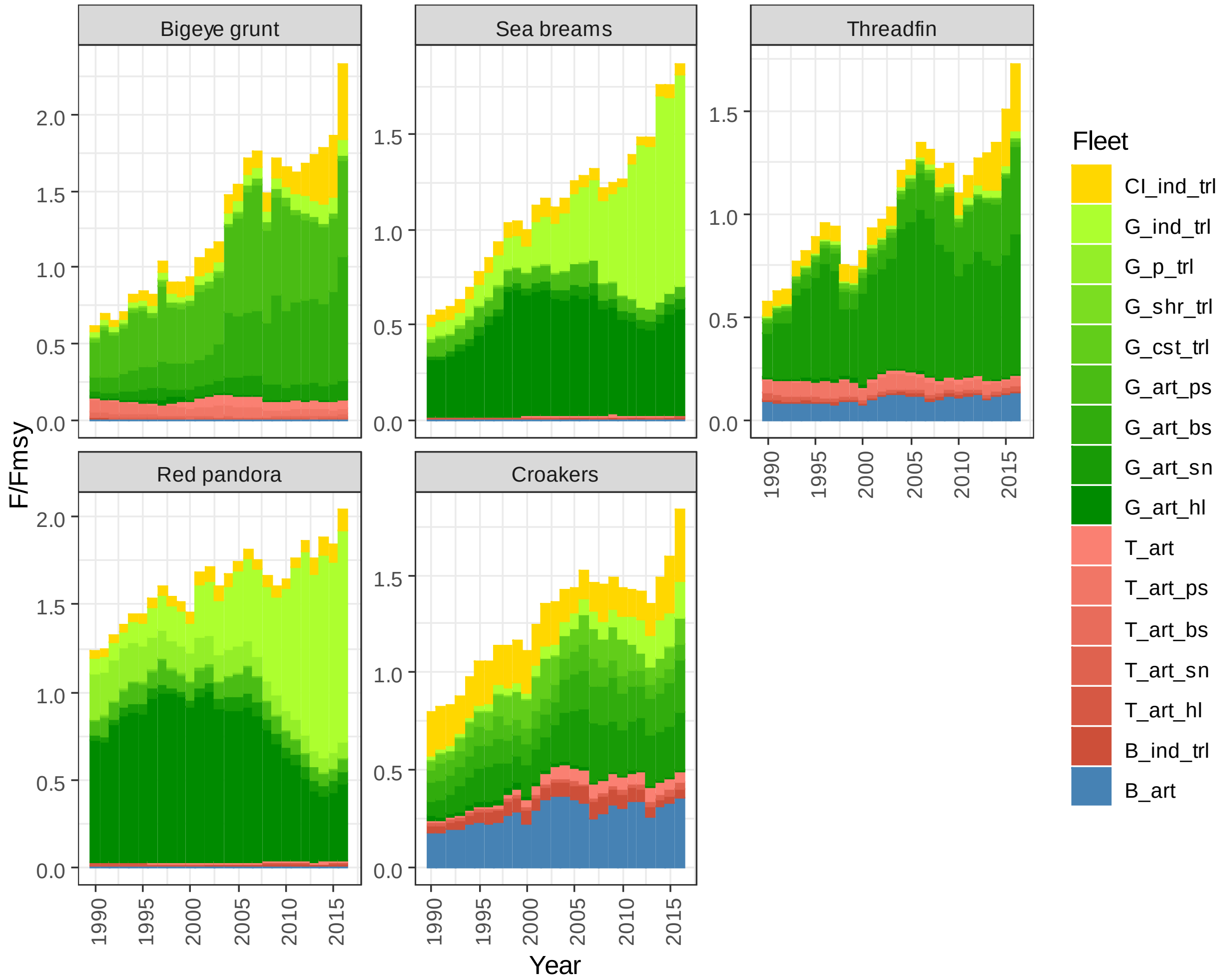

Figure 4. 5. Fishing mortality relative to F_{MSY} by fleet for the five stocks as estimated from the reference model. The total fishing mortality is expressed by the height of the stacked bar while the contribution of each fleet is shown as the width of the relevant colour block. Countries are coded by colour: Côte d'Ivoire=gold, Ghana=green, Togo=pink and Benin=blue. Most stocks are dominated by Ghanaian fleets (green) though for croakers all four countries in the region make a significant contribution to the total mortality.

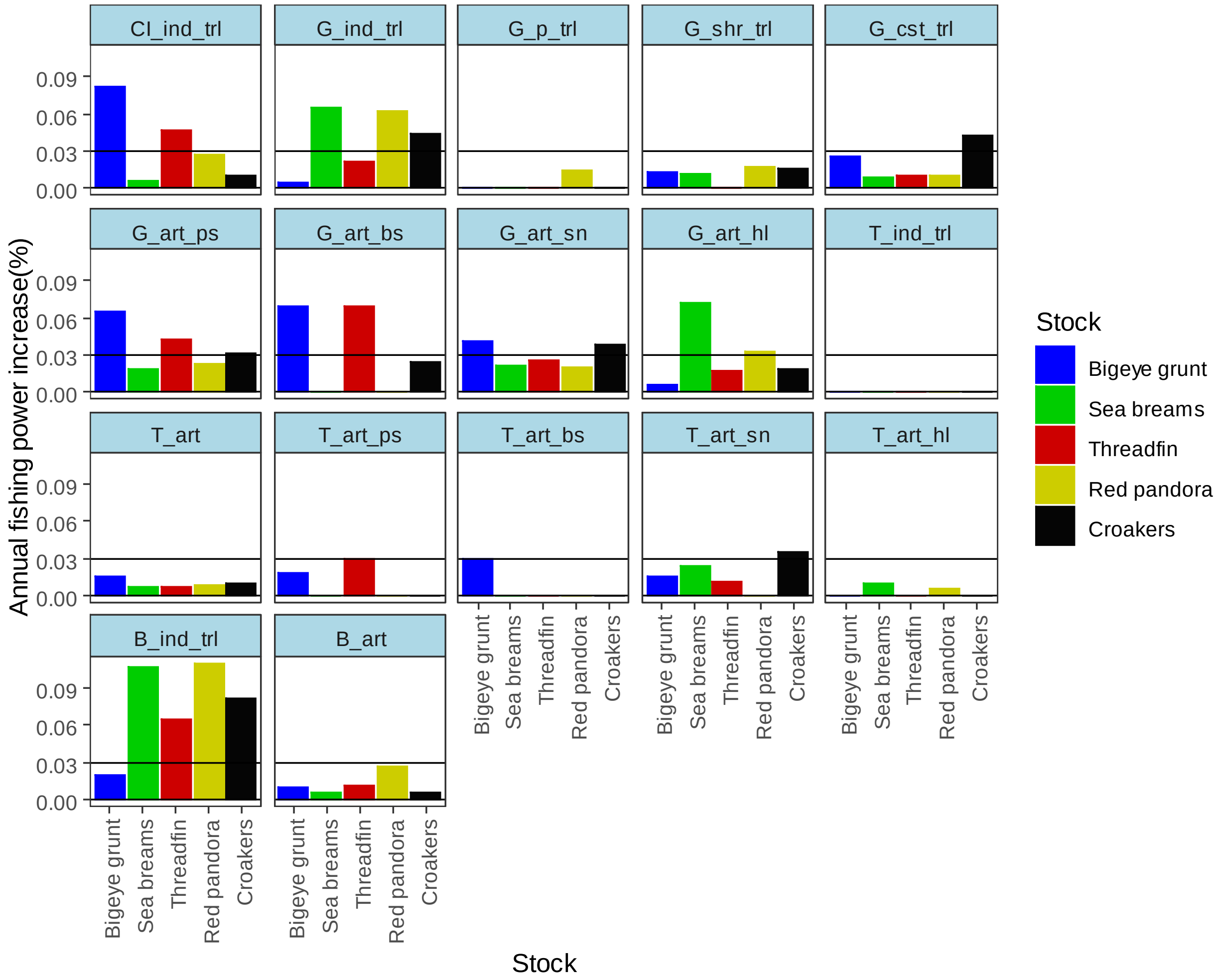

Figure 4. 6. Estimates of fishing power(δ) increase for each fleet by stock from the reference model. The value is fixed at 0.03 for the CI_ind_trl fleet and is not a model estimate. The horizontal line is the mean value of the prior applied to δ (0.03) based on the distribution in Pauly and Palomares (2019).

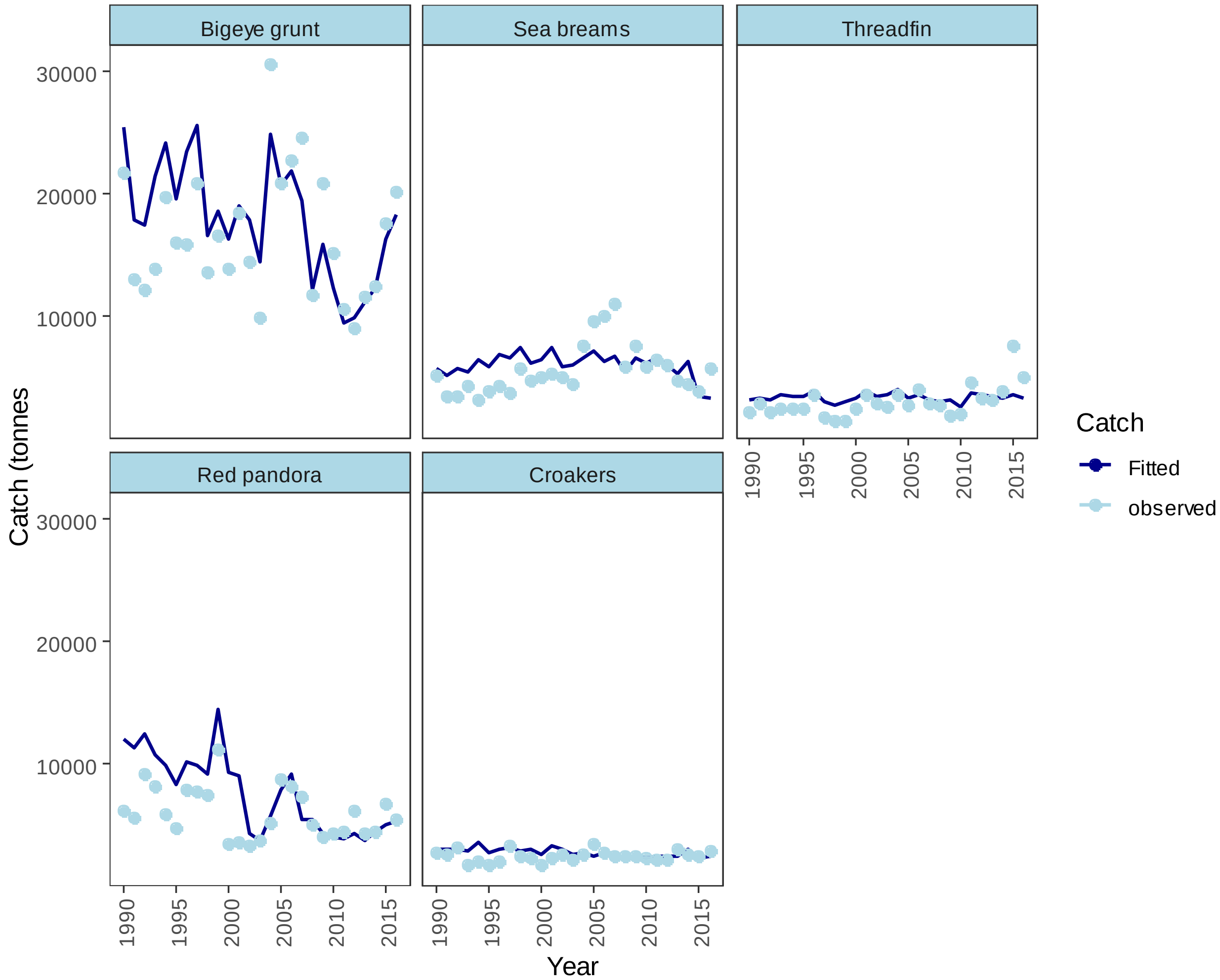

Figure 4. 7. Fitted catches (dark blue line) compared to the aggregate reported catch (pale blue dots). The observed values are affected by missing values from some fleets. As can be seen, the fitted catches are larger in the early years but are closer to the reported catches in the more recent years.

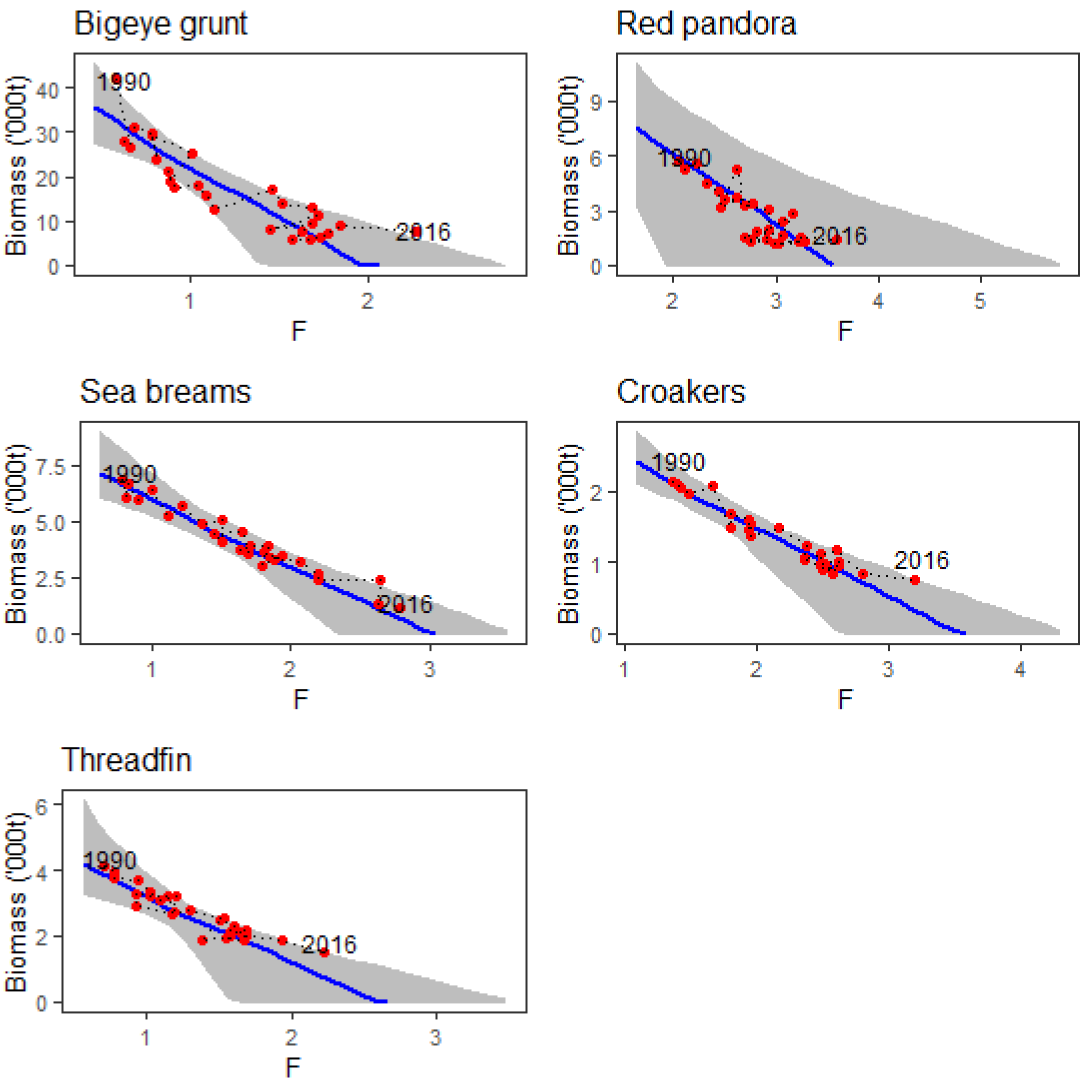

Figure 5. 1. Equilibrium biomass curves for the five stocks based on parameter estimates from the reference model. The blue line shows the median equilibrium value and the shaded area the 95%CI. The red points are the annual values of the biomass estimated from the model plotted as a time series.

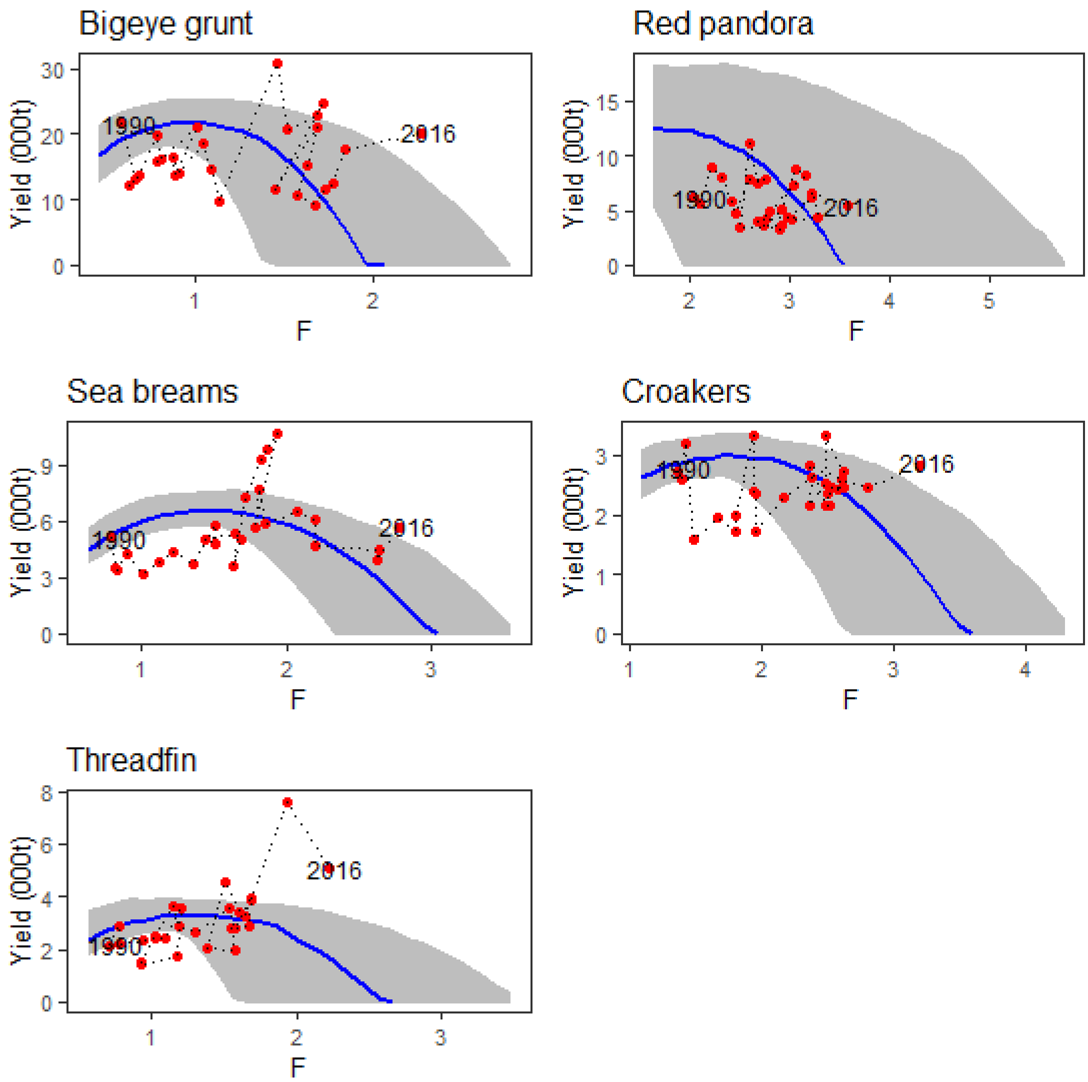

Figure 5. 2. Equilibrium yield curves for the five stocks based on parameter estimates from the reference model. The blue line shows the median equilibrium value and the shaded area the 95%CI. The red points are the annual values of the catch estimated from the model plotted as a time series.

Appendix 1. Catch and effort data used in assessments

Table A1. 1 Fishing effort for 17 fleets expressed as days fishing from FA0(2019). NA indicates no data available.

year	CI_ind_trl	G_ind_trl	G_p_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_ind_trl	T_art	T_art_ps	T_art_bs	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	3339	4162	NA	1431	3373	419130	81538	119449	193618	222	2221	NA	NA	NA	NA	1156	NA
1991	3945	4241	NA	1085	4411	636387	71224	160916	133902	200	668	NA	NA	NA	NA	1121	NA
1992	4659	4088	NA	977	4195	472386	69908	132523	169334	191	1742	NA	NA	NA	NA	583	NA
1993	4303	3505	NA	1772	7266	490855	76527	278138	129914	422	1989	NA	NA	NA	NA	577	NA
1994	3871	4515	NA	2573	4775	623193	92325	230812	184650	315	1169	NA	NA	NA	NA	989	NA
1995	4530	5074	NA	2435	7445	558249	104416	299358	148037	470	868	NA	NA	NA	NA	968	NA
1996	5050	6178	NA	1341	8838	414929	63300	293588	239500	179	2327	NA	NA	NA	NA	1097	NA
1997	3520	7037	NA	1195	8179	718197	145235	312239	250384	71	1917	NA	NA	NA	NA	1015	60049
1998	5014	6897	NA	1090	15003	444723	73859	139585	662322	304	2318	NA	NA	NA	NA	995	74747
1999	5285	6265	NA	529	9993	409129	71457	158068	389068	0	53710	25899	19232	6037	2542	751	79661
2000	5736	3918	NA	774	8964	408645	57923	220686	111757	NA	39532	20184	7390	8160	3798	755	50631
2001	4403	9002	NA	1344	14776	451991	58559	233246	101266	NA	45696	25395	8091	9830	2380	439	83652
2002	14361	8154	NA	138	16746	404260	67463	209819	113026	NA	41938	26905	5668	7597	1768	400	93248
2003	11701	7271	1639	329	8626	395566	63605	217362	93537	NA	44076	31821	4633	6210	1412	786	97890
2004	12932	8579	1575	404	4981	493688	158852	312333	128594	NA	42810	27829	5599	7323	2059	1032	97303
2005	2197	9943	2194	462	6113	515995	126821	316482	142140	NA	36873	23854	2827	8534	1658	NA	89801
2006	3092	9788	1595	408	8838	628833	171287	345576	120364	NA	31070	24642	3867	4978	1574	NA	92898
2007	1576	9279	1029	341	8836	605929	102930	328367	102188	NA	43653	24308	7667	9857	1821	887	58309
2008	12875	9012	985	138	6078	365827	83038	229973	66489	NA	24461	14398	2539	4514	3010	1290	68820
2009	14329	8360	NA	NA	8366	348863	348863	242620	71874	NA	30161	13387	5100	8911	2763	469	91290
2010	2600	10025	NA	NA	11946	367527	71090	164950	37135	NA	30337	12788	5620	9416	2513	880	77415
2011	1553	13029	NA	NA	6240	291871	102715	206380	64710	0	28437	16031	4828	5593	1985	110	93906
2012	3346	15748	NA	NA	3000	267597	100902	225500	63499	0	30517	14714	5664	8326	1813	272	99863
2013	5239	12848	NA	NA	3837	255240	107554	197346	54098	0	34078	17372	6343	8755	1608	151	62884
2014	4932	16494	NA	NA	1856	239834	92788	176793	53351	0	29446	14073	5706	7942	1725	30	81821
2015	5963	12751	NA	NA	5874	208988	88181	203794	45970	0	29992	11887	6428	9971	1706	161	87942
2016	7347	13482	NA	NA	5459	257312	108087	225156	48520	0	34279	12776	8309	11431	1763	320	93800

Table A1. 2 Catch in tonnes of bigeye grunt (Brachydeuterus auritus) by fleet. Data from FAO (2019). NA indicates no data available.

year	CI_ind_trl	G_ind_trl	G_p_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_ind_trl	T_art	T_art_ps	T_art_bs	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	1053	1721	NA	46	1431	11505	4020	598	946	40	92	NA	NA	NA	NA	251	NA
1991	1218	655	NA	62	629	6227	2512	1211	366	19	18	NA	NA	NA	NA	166	NA
1992	1033	755	NA	85	528	6247	2059	478	780	22	65	NA	NA	NA	NA	107	NA
1993	1012	1525	NA	119	655	6648	2536	324	670	49	90	NA	NA	NA	NA	234	NA
1994	1107	1002	NA	440	657	10350	3881	1133	808	44	50	NA	NA	NA	NA	267	NA
1995	1290	1028	NA	510	556	7708	3596	719	466	NA	35	NA	NA	NA	NA	108	NA
1996	2056	1973	NA	656	1212	5574	2137	1079	916	30	73	NA	NA	NA	NA	137	NA
1997	1197	1135	NA	366	900	9621	3511	2776	1082	NA	58	NA	NA	NA	NA	112	206
1998	1286	1531	NA	189	485	4231	3334	769	1440	2	71	NA	NA	NA	NA	90	182
1999	1505	722	NA	95	517	6009	2686	1774	864	NA	1092	775	92	225	0	18	208
2000	2206	656	NA	60	451	4191	4189	345	140	NA	742	435	93	214	0	9	143
2001	1403	751	NA	39	632	9812	1924	771	128	NA	1428	672	649	107	0	33	180
2002	2629	989	NA	8	716	4337	2597	471	168	NA	1148	948	112	88	0	0	325
2003	1122	572	4	22	478	3487	2504	505	149	NA	353	285	60	8	0	11	287
2004	855	1389	0	0	299	9692	13928	880	268	NA	1524	1372	64	88	0	10	304
2005	2169	543	36	0	418	8767	5417	1495	151	0	780	762	18	0	0	NA	313
2006	907	796	0	1	576	11591	4189	2477	99	0	984	984	0	0	0	NA	210
2007	984	514	0	0	381	10174	6489	3891	123	NA	1028	938	36	54	0	NA	22
2008	406	403	0	0	592	6091	1154	2030	46	NA	480	475	3	1	1	NA	13
2009	641	326	0	0	465	13632	3895	642	66	NA	634	622	2	6	4	NA	26
2010	224	239	0	0	453	9334	2903	715	12	NA	678	607	52	14	5	NA	26
2011	645	274	0	0	220	4628	3206	902	17	0	317	295	16	5	1	27	9
2012	1497	342	0	0	311	2622	3719	336	1	0	74	50	19	4	1	19	19
2013	2990	368	0	0	185	2253	3605	1141	6	0	490	376	112	1	1	4	70
2014	4783	440	0	0	195	1795	4218	463	20	0	267	76	189	2	0	7	59
2015	4245	2693	0	0	273	2739	6891	112	49	0	229	4	225	0	0	24	77
2016	5105	410	0	0	313	4757	8506	444	94	0	251	121	130	0	0	9	85

Table A1. 3 Catch in tonnes of sea breams (Dentex spp) by fleet. Data from FAO (2019). NA indicates no data available.

year	CI_ind_trl	G_ind_trl	G_pr_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_ind_trl	T_art	T_art_ps	T_art_bs	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	490	1139	NA	4	101	0	0	1	3298	12	16	NA	NA	NA	NA	11	46
1991	643	973	NA	24	36	0	0	14	1733	3	4	NA	NA	NA	NA	2	45
1992	594	846	NA	6	3	0	0	6	1945	60	11	NA	NA	NA	NA	4	NA
1993	362	494	NA	59	4	0	0	2	3325	59	10	NA	NA	NA	NA	7	NA
1994	431	958	NA	290	20	0	0	44	1404	29	11	NA	NA	NA	NA	9	NA
1995	551	535	NA	136	8	0	0	275	2336	1	9	NA	NA	NA	NA	3	NA
1996	675	723	NA	117	8	201	0	234	2406	9	10	NA	NA	NA	NA	13	NA
1997	574	975	NA	28	13	0	0	91	1983	16	9	NA	NA	NA	NA	11	83
1998	729	706	NA	37	11	0	0	64	4052	18	21	NA	NA	NA	NA	37	74
1999	758	295	NA	109	10	0	0	471	3057	NA	NA	0	0	1	40	32	51
2000	549	271	NA	6	28	0	0	351	3748	NA	NA	0	0	15	49	18	34
2001	434	491	NA	1	13	79	0	538	3689	NA	NA	0	0	11	44	1	20
2002	434	795	NA	29	11	8	0	145	3506	NA	NA	0	0	16	15	5	28
2003	470	467	853	5	7	35	0	86	2445	NA	NA	0	0	29	11	16	27
2004	357	1295	244	7	7	4	0	421	5107	NA	NA	0	0	13	12	25	67
2005	42	2529	263	52	3	0	0	172	6405	0	NA	0	0	12	13	NA	113
2006	573	3002	167	30	1	31	0	36	6145	0	NA	0	0	9	9	NA	22
2007	232	3672	272	20	1	0	0	450	6215	NA	NA	0	0	18	12	74	40
2008	263	2554	176	36	1	0	2	377	2344	NA	NA	0	0	11	19	23	30
2009	377	3439	0	0	1	0	0	134	3604	NA	NA	0	0	20	31	12	31
2010	67	3347	0	0	0	0	0	163	2233	NA	NA	0	0	31	20	3	27
2011	17	3249	0	0	0	0	0	136	2956	0	41	0	0	25	16	26	34
2012	56	3531	0	0	0	493	1	0	1854	0	37	0	0	18	19	46	20
2013	46	2995	0	0	0	338	16	6	1143	0	36	0	0	20	16	65	16
2014	134	3390	0	0	27	19	0	0	769	0	35	0	0	16	19	30	12
2015	174	2530	0	0	1	33	0	0	1179	0	14	0	0	7	7	6	12
2016	56	3040	0	0	0	1227	0	572	770	0	9	0	0	3	6	4	18

Table A1. 4 Catch in tonnes of threadfin (Galeoides decadactylus) by fleet. Data from FAO (2019). NA indicates no data available.

Year	CI_ind_trl	G_ind_trl	G_pr_trl	G_shr_trtl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_ind_trl	T_art	T_art_ps	T_art_bs	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	414	111	NA	11	122	26	241	1062	83	46	13	NA	NA	NA	NA	84	NA
1991	393	26	NA	30	97	110	214	1855	103	22	8	NA	NA	NA	NA	66	NA
1992	352	17	NA	16	62	73	349	1229	76	27	11	NA	NA	NA	NA	42	NA
1993	229	33	NA	25	66	44	306	1589	60	27	15	NA	NA	NA	NA	43	NA
1994	309	68	NA	25	22	39	334	1492	98	24	12	NA	NA	NA	NA	50	NA
1995	400	19	NA	7	14	2	503	1397	26	7	9	NA	NA	NA	NA	28	NA
1996	373	75	NA	5	16	64	467	2512	7	14	17	NA	NA	NA	NA	50	NA
1997	180	28	NA	5	20	38	247	1133	4	2	16	NA	NA	NA	NA	46	NA
1998	238	2	NA	1	25	132	125	467	9	1	25	NA	NA	NA	NA	65	377
1999	186	6	NA	8	31	3	204	445	4	0	NA	2	3	264	0	47	299
2000	219	0	NA	0	23	8	252	1652	5	0	NA	0	0	149	0	30	199
2001	167	11	NA	0	173	9	226	2615	3	0	NA	2	1	95	0	18	302
2002	152	7	NA	0	136	3	79	1973	4	0	NA	0	2	86	0	13	467
2003	144	4	0	0	86	75	161	1642	9	0	NA	0	1	11	0	35	477
2004	56	9	27	0	4	44	153	2606	163	0	NA	0	1	57	0	36	412
2005	9	5	3	0	91	230	99	1809	4	0	NA	0	1	16	0	NA	507
2006	66	6	52	0	131	60	386	2899	1	0	NA	0	1	3	0	Na	375
2007	95	0	1	0	104	44	192	1979	25	NA	NA	45	0	16	0	48	310
2008	168	9	14	0	30	33	214	1909	8	NA	NA	14	1	20	0	76	330
2009	102	4	0	0	15	332	142	782	0	NA	NA	122	7	70	1	22	355
2010	90	93	0	0	10	166	208	1306	4	NA	NA	79	6	18	0	29	79
2011	211	141	0	0	2	51	1882	1967	25	0	83	77	0	6	0	35	112
2012	423	94	0	0	1	0	536	2002	8	0	40	26	0	14	0	118	119
2013	737	142	0	0	4	26	450	1602	15	0	28	10	0	18	0	62	158
2014	1280	294	0	0	0	10	383	1597	0	0	12	0	0	12	0	5	264
2015	1190	188	0	0	3	12	4205	1662	0	0	2	0	0	2	0	15	330
2016	1383	19	0	0	10	0	1816	1471	17	0	6	1	0	5	0	5	325

Table A1. 5 Catch in tonnes of red pandora (Pagellus bellottii) by fleet. Data from FAO (2019). NA indicates no data available.

Year	CI_ind_trl	G_ind_trl	G_pr_trl	G_shr_trtl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_ind_trl	T_art	T_art_ps	T_art_bs	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	245	1038	NA	16	189	0	0	323	4302	8	NA	NA	NA	NA	NA	12	0
1991	322	1160	NA	24	103	0	0	551	3481	1	NA	NA	NA	NA	NA	4	0
1992	297	894	NA	7	30	0	0	226	7532	94	NA	NA	NA	NA	NA	4	NA
1993	181	513	NA	18	30	0	3	314	7037	28	NA	NA	NA	NA	NA	4	NA
1994	216	621	NA	92	53	0	0	245	4652	31	NA	NA	NA	NA	NA	4	NA
1995	275	803	NA	60	26	0	0	22	3538	3	NA	NA	NA	NA	NA	0	NA
1996	338	742	NA	48	22	0	0	84	6643	7	NA	NA	NA	NA	NA	10	NA
1997	287	1106	NA	5	19	0	0	51	6277	0	NA	NA	NA	NA	NA	9	2
1998	364	673	NA	0	13	0	0	64	6270	66	NA	NA	NA	NA	NA	20	0
1999	379	467	NA	10	11	0	0	68	9926	0	145	0	0	0	145	15	0
2000	274	314	NA	82	34	0	0	4	2483	0	120	0	0	0	120	12	0
2001	217	368	NA	4	25	0	0	11	2812	0	75	0	0	0	75	1	0
2002	216	212	NA	0	60	0	0	3	2745	0	17	0	0	0	17	0	1
2003	235	128	785	4	28	0	0	225	2289	0	9	0	0	0	9	5	0
2004	179	604	206	0	3	92	0	88	3930	0	22	0	0	0	22	29	0
2005	7	1048	233	6	6	3	0	672	6761	0	25	0	0	3	22	NA	0
2006	286	1874	112	28	1	3	0	427	5374	0	34	0	0	0	34	NA	0
2007	116	2503	240	6	0	48	0	221	4084	0	7	0	0	1	6	NA	25
2008	131	2554	176	36	0	3	0	93	1912	0	33	0	0	0	33	NA	39
2009	187	2715	0	0	0	0	0	104	954	0	25	0	0	0	25	NA	28
2010	33	2649	0	0	0	78	0	395	1003	0	21	0	0	0	21	NA	33
2011	40	2666	0	0	0	0	0	208	1506	0	9	0	0	0	9	4	12
2012	38	4336	0	0	0	532	0	204	971	0	15	0	0	0	15	3	17
2013	329	2921	0	0	0	361	0	6	553	0	10	0	0	0	10	33	33
2014	448	3323	0	0	0	7	0	26	543	0	8	0	0	0	8	59	34
2015	388	5279	0	0	0	0	0	0	914	0	34	0	0	21	13	1	20
2016	300	3508	0	0	0	0	0	416	1170	0	38	0	0	28	10	1	17

Table A1. 6 Catch in tonnes of croakers (Pseudolithus spp) by fleet. Data from FAO (2019). NA indicates no data available.

fleet	CI_ind_trl	G_ind_trl	G_pr_trl	G_shr_trtl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_ind_trl	T_art	T_art_ps	T_art_bs	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	1036	37	NA	22	149	208	503	469	136	42	18	NA	NA	NA	NA	151	NA
1991	945	30	NA	19	205	93	434	603	143	24	15	NA	NA	NA	NA	97	NA
1992	804	35	NA	20	118	1275	484	229	136	23	34	NA	NA	NA	NA	53	NA
1993	537	82	NA	60	177	63	224	222	78	57	38	NA	NA	NA	NA	115	NA
1994	672	77	NA	27	300	41	263	298	90	48	35	NA	NA	NA	NA	132	NA
1995	709	88	NA	8	120	4	257	294	23	14	15	NA	NA	NA	NA	206	NA
1996	690	241	NA	8	295	51	239	289	18	23	12	NA	NA	NA	NA	152	NA
1997	478	312	NA	25	331	135	544	570	30	9	35	NA	NA	NA	NA	133	723
1998	526	68	NA	31	338	21	167	244	37	11	43	NA	NA	NA	NA	205	720
1999	376	110	NA	34	304	9	145	425	42	0	NA	1	0	25	0	187	688
2000	347	7	NA	36	255	142	121	149	17	0	NA	6	0	30	1	133	477
2001	374	23	NA	NA	428	51	439	125	11	0	NA	8	0	34	1	112	697
2002	388	41	NA	0	524	131	171	144	9	0	NA	0	2	63	1	91	1071
2003	434	5	7	0	235	194	20	88	42	0	NA	0	2	17	0	163	971
2004	279	10	38	5	183	58	185	621	25	0	NA	1	0	36	0	136	989
2005	52	2	52	0	163	605	534	511	24	0	NA	0	1	56	1	NA	1398
2006	272	3	45	0	297	207	338	446	0	0	NA	0	1	34	0	NA	1120
2007	219	24	19	0	241	588	524	345	23	NA	NA	24	0	16	0	134	315
2008	372	226	17	1	215	11	139	745	25	NA	NA	10	0	8	0	148	577
2009	183	353	0	0	293	219	214	634	31	NA	NA	9	0	0	0	56	471
2010	172	174	0	0	335	381	400	656	10	NA	NA	0	0	34	0	86	96
2011	211	517	0	0	241	86	55	775	26	0	35	0	0	35	0	81	99
2012	207	493	0	0	98	39	119	609	9	0	59	0	0	59	0	282	177
2013	214	500	0	0	119	32	241	934	33	0	265	216	0	49	0	147	305
2014	430	433	0	0	316	2	552	341	35	0	56	0	0	56	0	12	367
2015	508	500	0	0	111	81	578	188	5	0	58	0	1	57	0	58	324
2016	683	221	0	0	167	202	817	340	5	0	42	0	0	42	0	28	285

Appendix 2: Model output, bigeye grunt

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	21057	41770	79396	0.339	0.584	1.140
1991	13655	26531	48790	0.383	0.671	1.329
1992	15127	27864	48778	0.352	0.630	1.214
1993	16735	30873	53583	0.394	0.684	1.251
1994	15949	29658	53024	0.466	0.784	1.487
1995	12453	23767	43613	0.485	0.812	1.467
1996	16074	29164	53275	0.459	0.788	1.422
1997	13941	25151	43551	0.613	1.016	1.750
1998	9799	18706	34174	0.534	0.889	1.542
1999	12096	20972	36350	0.525	0.877	1.516
2000	9528	17507	31022	0.546	0.913	1.586
2001	10063	17962	32390	0.626	1.043	1.768
2002	8840	15957	28925	0.643	1.095	1.934
2003	6432	12564	22803	0.678	1.138	1.980
2004	9291	17040	28046	0.891	1.461	2.408
2005	7716	13818	23587	0.926	1.521	2.519
2006	6801	12830	22791	1.054	1.692	2.776
2007	6184	11298	19371	1.068	1.725	2.844
2008	4347	8296	14923	0.875	1.455	2.549
2009	5309	9413	16572	0.970	1.683	2.773
2010	3921	7562	13722	0.914	1.628	2.694
2011	3073	5955	11112	0.931	1.578	2.807
2012	3088	5856	11086	0.968	1.674	2.779
2013	3740	6480	11987	0.992	1.730	2.775
2014	3932	7138	12264	1.055	1.779	2.862
2015	5032	8850	14905	1.131	1.843	3.103
2016	4354	7748	14612	1.370	2.268	3.895

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

	Fleet fishing mortality													
Year	CI_ind_trl	G_ind_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_art	T_art_ps	T_art_bs	T_art_sn	B_ind_trl	B_art
1990	0.038	0.031	0.007	0.029	0.232	0.101	0.026	0.021	0.002	0.087	0.029	0.008	0.006	0.014
1991	0.042	0.030	0.006	0.025	0.319	0.101	0.034	0.017	0.002	0.085	0.028	0.007	0.006	0.013
1992	0.042	0.029	0.007	0.022	0.281	0.103	0.033	0.019	0.002	0.083	0.027	0.007	0.005	0.012
1993	0.044	0.027	0.008	0.024	0.304	0.113	0.057	0.017	0.002	0.078	0.026	0.006	0.005	0.011
1994	0.047	0.033	0.009	0.025	0.389	0.136	0.058	0.020	0.002	0.075	0.026	0.006	0.006	0.010
1995	0.055	0.038	0.009	0.029	0.374	0.148	0.073	0.020	0.002	0.071	0.025	0.006	0.006	0.009
1996	0.063	0.046	0.008	0.038	0.327	0.140	0.077	0.027	0.003	0.068	0.023	0.006	0.005	0.008
1997	0.065	0.052	0.006	0.037	0.499	0.180	0.078	0.033	0.005	0.066	0.022	0.005	0.005	0.008
1998	0.077	0.052	0.005	0.035	0.377	0.176	0.045	0.049	0.009	0.063	0.021	0.005	0.005	0.009
1999	0.090	0.046	0.004	0.032	0.369	0.173	0.051	0.035	0.029	0.061	0.020	0.004	0.004	0.010
2000	0.108	0.034	0.004	0.034	0.391	0.179	0.065	0.017	0.044	0.050	0.014	0.005	0.004	0.007
2001	0.117	0.062	0.003	0.041	0.458	0.171	0.072	0.013	0.059	0.062	0.013	0.005	0.003	0.010
2002	0.147	0.061	0.002	0.047	0.441	0.202	0.071	0.013	0.066	0.067	0.010	0.005	0.003	0.012
2003	0.132	0.057	0.002	0.040	0.446	0.252	0.078	0.012	0.065	0.079	0.008	0.004	0.003	0.013
2004	0.120	0.067	0.002	0.029	0.575	0.432	0.106	0.014	0.069	0.071	0.008	0.005	0.004	0.013
2005	0.110	0.075	0.002	0.034	0.659	0.415	0.117	0.015	0.068	0.063	0.007	0.005	0.004	0.013
2006	0.099	0.075	0.002	0.044	0.801	0.423	0.133	0.013	0.069	0.065	0.007	0.004	0.004	0.012
2007	0.099	0.072	0.001	0.045	0.839	0.434	0.134	0.011	0.072	0.064	0.009	0.005	0.004	0.009
2008	0.117	0.070	0.001	0.059	0.624	0.408	0.108	0.009	0.065	0.041	0.007	0.004	0.004	0.010
2009	0.127	0.067	0.001	0.055	0.656	0.601	0.104	0.008	0.066	0.039	0.009	0.006	0.004	0.012
2010	0.122	0.079	0.001	0.057	0.703	0.508	0.085	0.006	0.066	0.038	0.010	0.006	0.003	0.011
2011	0.146	0.100	0.001	0.044	0.585	0.548	0.101	0.006	0.059	0.046	0.010	0.005	0.003	0.013
2012	0.214	0.117	0.001	0.042	0.538	0.562	0.109	0.006	0.054	0.044	0.012	0.006	0.002	0.014
2013	0.301	0.105	0.001	0.033	0.520	0.565	0.106	0.006	0.058	0.052	0.013	0.006	0.002	0.010
2014	0.371	0.127	0.001	0.029	0.504	0.553	0.101	0.006	0.053	0.043	0.014	0.006	0.001	0.012
2015	0.408	0.113	0.001	0.034	0.491	0.619	0.114	0.006	0.051	0.038	0.016	0.007	0.002	0.013
2016	0.502	0.110	0.001	0.040	0.641	0.825	0.132	0.007	0.052	0.041	0.018	0.008	0.002	0.014

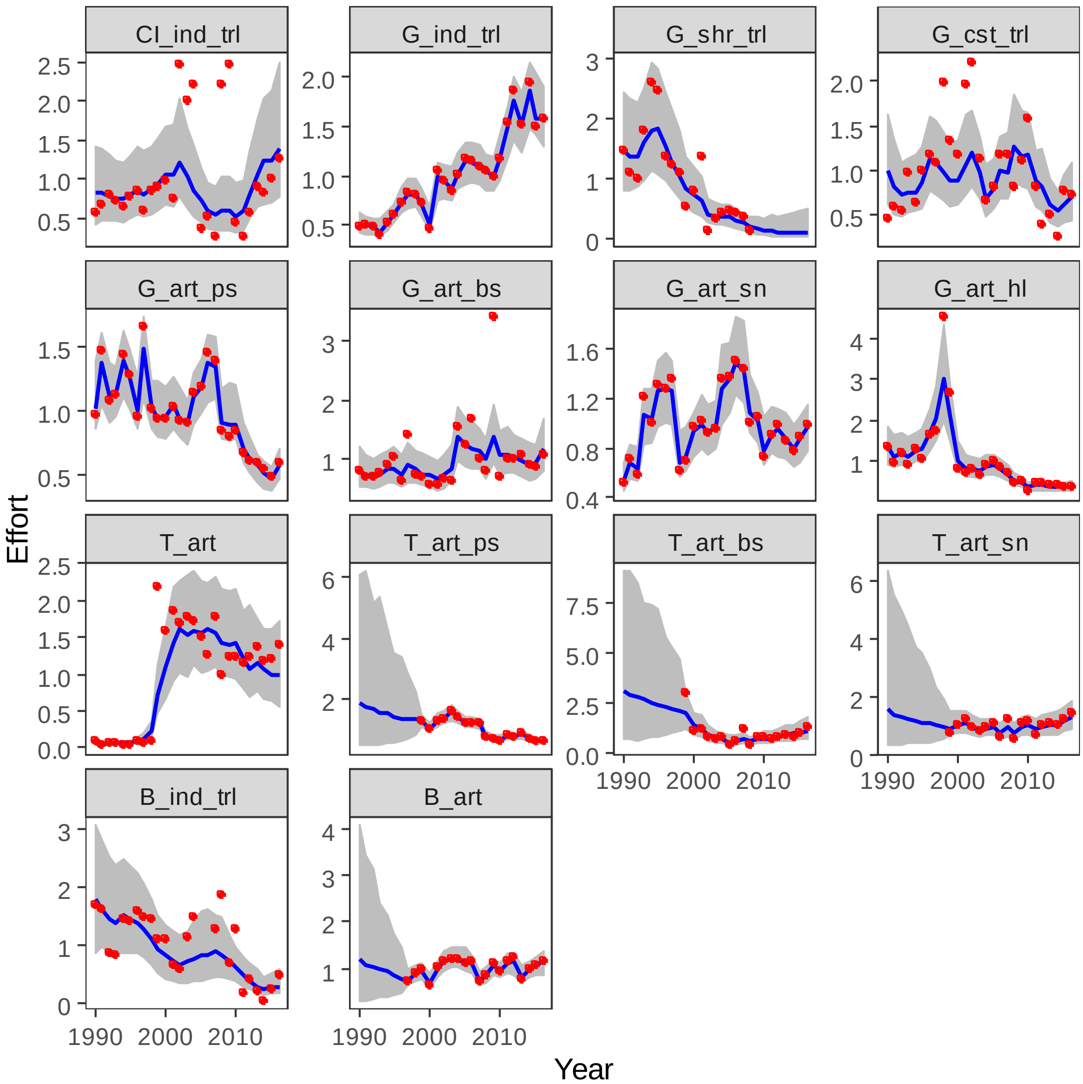

Figure A2. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

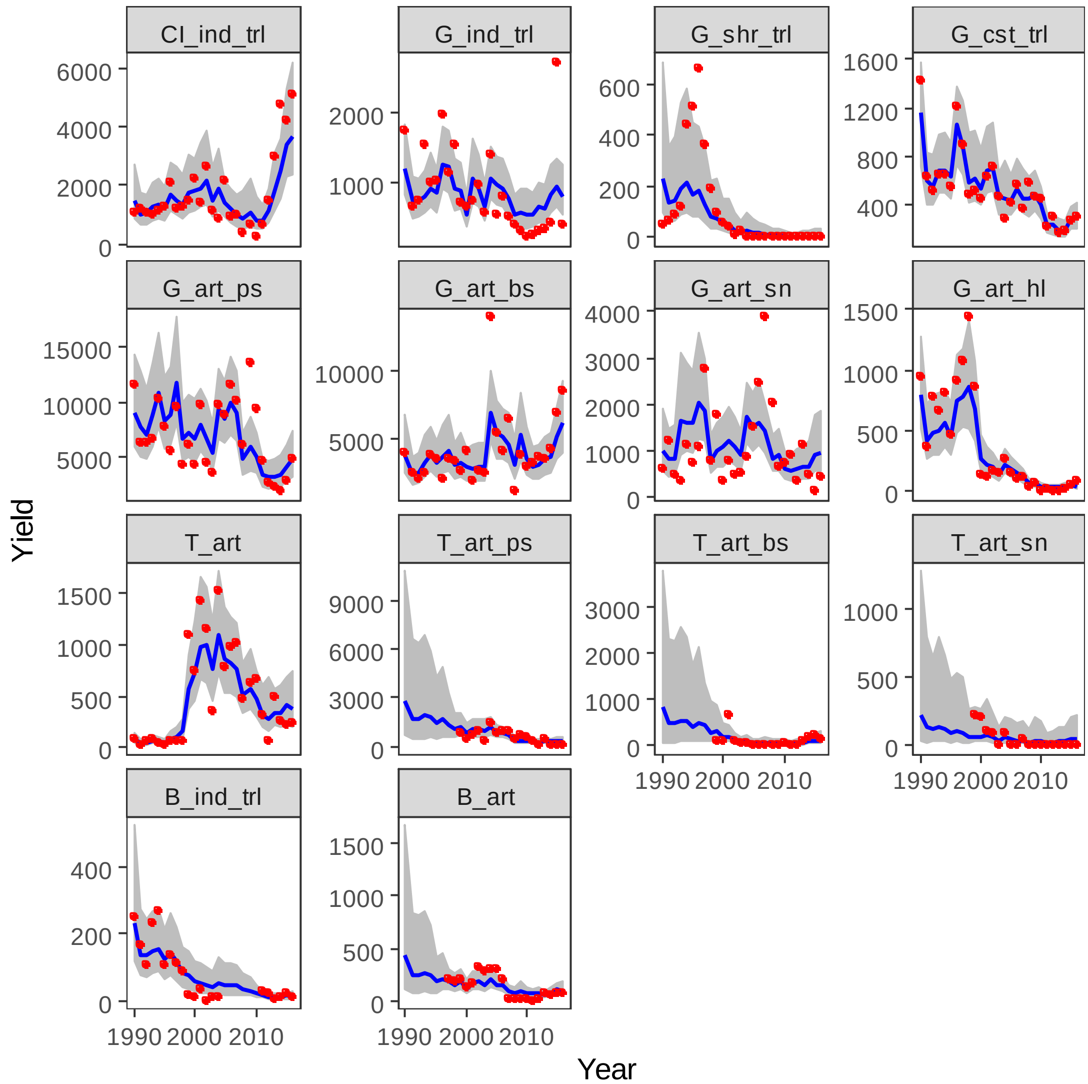

Figure A2. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

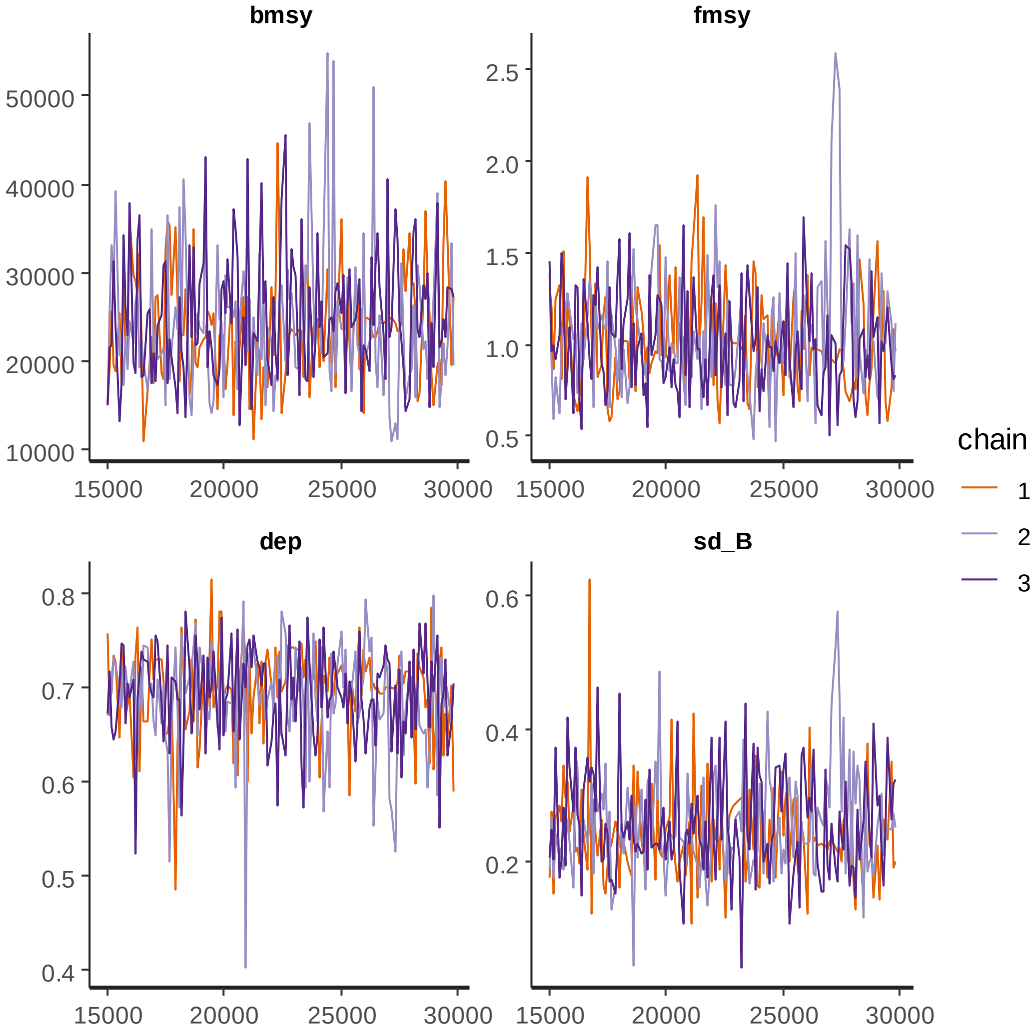

Figure A2. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 3: Model output, sea breams

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	4478	6880	12302	0.460	0.793	1.460
1991	3754	6069	9936	0.457	0.817	1.544
1992	4103	6658	11223	0.472	0.839	1.587
1993	3293	5971	10317	0.536	0.898	1.695
1994	3721	6442	9990	0.590	1.006	1.821
1995	2926	5240	9305	0.635	1.120	1.914
1996	3261	5659	9311	0.748	1.213	2.058
1997	2628	4848	8394	0.841	1.362	2.214
1998	2827	5047	8173	0.940	1.508	2.418
1999	2318	4050	6979	0.936	1.504	2.423
2000	2693	4452	7020	0.841	1.443	2.285
2001	2704	4548	7548	1.003	1.645	2.600
2002	1844	3535	6114	1.064	1.693	2.609
2003	2055	3758	6222	0.997	1.632	2.491
2004	2276	3928	6340	1.074	1.711	2.576
2005	2393	3877	6370	1.215	1.830	2.804
2006	1886	3307	5596	1.248	1.873	2.822
2007	2204	3431	5573	1.275	1.940	2.801
2008	1865	2995	4901	1.121	1.786	2.583
2009	2321	3608	5810	1.143	1.806	2.656
2010	1964	3382	5313	1.162	1.857	2.699
2011	1954	3215	5015	1.334	2.067	2.907
2012	1745	2685	4246	1.444	2.197	3.091
2013	1489	2402	3958	1.467	2.195	3.024
2014	1488	2390	3920	1.748	2.638	3.504
2015	843	1306	2237	1.718	2.626	3.645
2016	709	1148	2006	1.760	2.775	3.941

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

Fleet fishing mortality

Year	CI_ind_trl	G_ind_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_sn	G_art_hl	T_art	T_art_sn	T_art_hl	B_ind_trl	B_art
1990	0.090	0.100	0.017	0.002	0.109	0.029	0.450	0.002	0.005	0.013	0.002	0.009
1991	0.089	0.106	0.016	0.002	0.140	0.034	0.446	0.001	0.004	0.012	0.002	0.009
1992	0.090	0.108	0.016	0.002	0.125	0.035	0.478	0.001	0.004	0.012	0.002	0.009
1993	0.088	0.104	0.018	0.003	0.130	0.052	0.516	0.002	0.004	0.011	0.003	0.009
1994	0.089	0.135	0.019	0.003	0.152	0.055	0.561	0.002	0.004	0.011	0.003	0.009
1995	0.094	0.159	0.019	0.003	0.145	0.065	0.645	0.002	0.004	0.010	0.003	0.010
1996	0.102	0.200	0.016	0.004	0.127	0.065	0.726	0.002	0.004	0.009	0.004	0.010
1997	0.104	0.234	0.014	0.004	0.164	0.063	0.789	0.003	0.004	0.009	0.004	0.010
1998	0.111	0.245	0.012	0.005	0.128	0.044	0.976	0.004	0.003	0.009	0.005	0.010
1999	0.116	0.236	0.010	0.005	0.116	0.045	0.999	0.006	0.003	0.008	0.005	0.010
2000	0.119	0.200	0.009	0.005	0.120	0.054	0.946	0.008	0.004	0.010	0.005	0.008
2001	0.123	0.349	0.008	0.005	0.128	0.061	0.977	0.010	0.004	0.007	0.005	0.010
2002	0.133	0.377	0.006	0.005	0.123	0.061	0.992	0.012	0.004	0.005	0.005	0.012
2003	0.127	0.385	0.006	0.004	0.125	0.065	0.920	0.013	0.005	0.004	0.006	0.013
2004	0.110	0.456	0.006	0.004	0.146	0.081	0.894	0.014	0.004	0.005	0.007	0.014
2005	0.088	0.548	0.005	0.004	0.156	0.087	0.938	0.015	0.004	0.005	0.008	0.014
2006	0.087	0.583	0.005	0.004	0.178	0.093	0.917	0.015	0.004	0.005	0.009	0.012
2007	0.083	0.627	0.004	0.004	0.173	0.090	0.944	0.015	0.005	0.005	0.010	0.010
2008	0.089	0.649	0.004	0.004	0.127	0.075	0.823	0.015	0.005	0.007	0.010	0.010
2009	0.083	0.689	0.004	0.004	0.118	0.071	0.845	0.014	0.006	0.008	0.009	0.012
2010	0.067	0.843	0.003	0.004	0.119	0.061	0.749	0.014	0.006	0.007	0.009	0.012
2011	0.059	1.063	0.003	0.003	0.102	0.067	0.732	0.014	0.006	0.006	0.008	0.013
2012	0.062	1.266	0.003	0.002	0.095	0.071	0.673	0.014	0.006	0.006	0.009	0.013
2013	0.068	1.265	0.003	0.002	0.091	0.069	0.666	0.015	0.007	0.005	0.009	0.010
2014	0.079	1.618	0.003	0.002	0.086	0.067	0.726	0.014	0.007	0.006	0.008	0.011
2015	0.089	1.536	0.003	0.002	0.081	0.074	0.794	0.012	0.007	0.006	0.009	0.013
2016	0.092	1.649	0.003	0.003	0.094	0.083	0.823	0.012	0.007	0.006	0.009	0.014

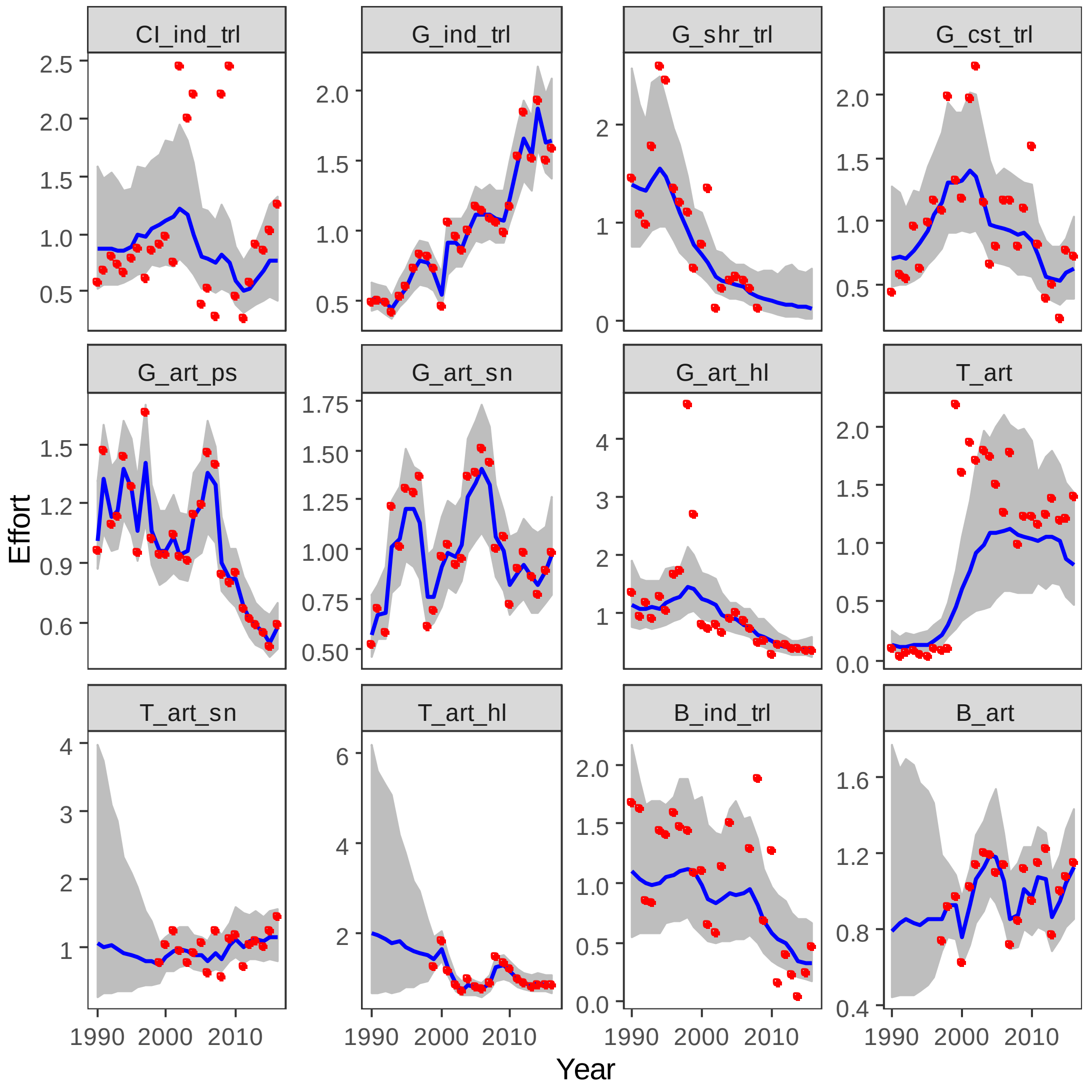

Figure A3. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

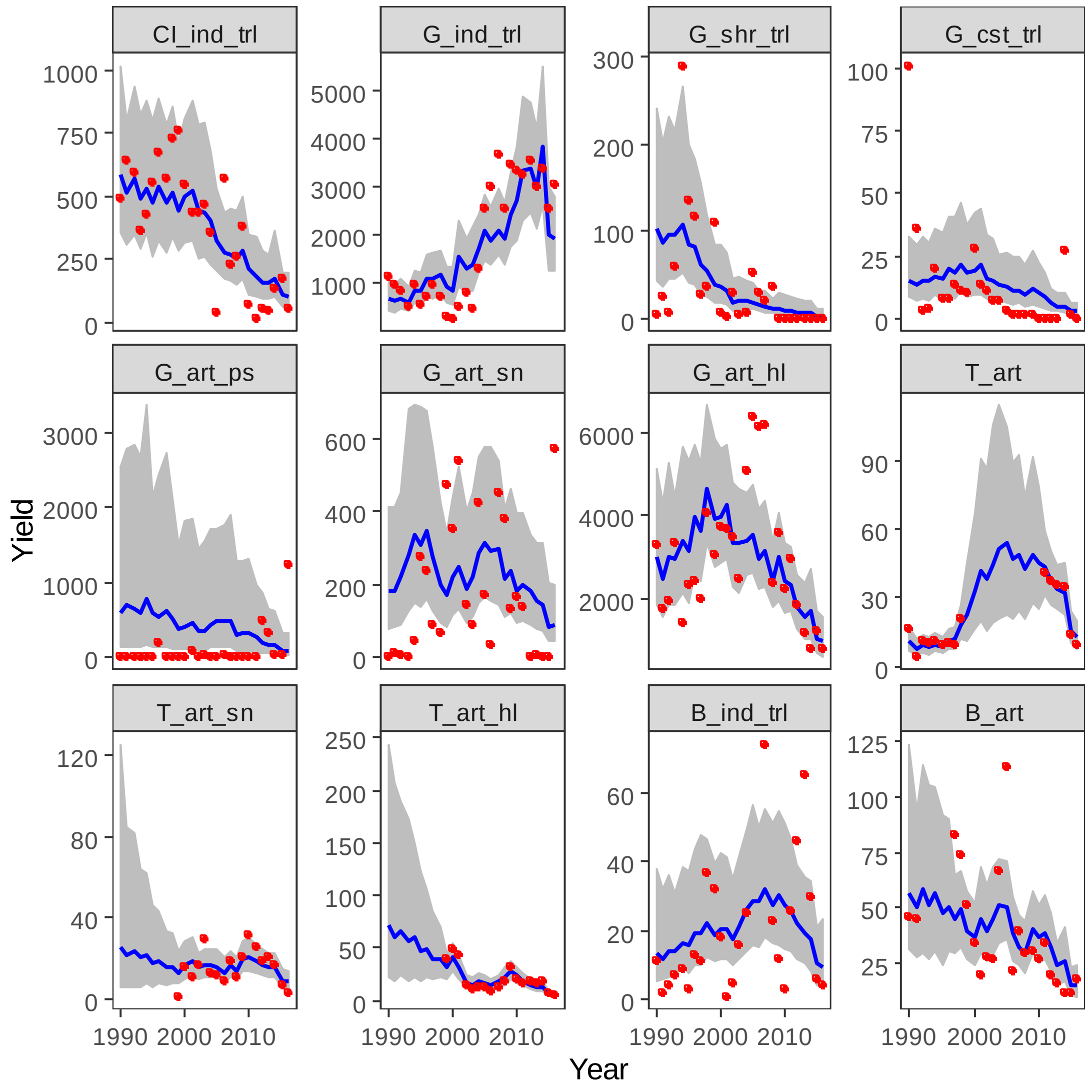

Figure A3. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

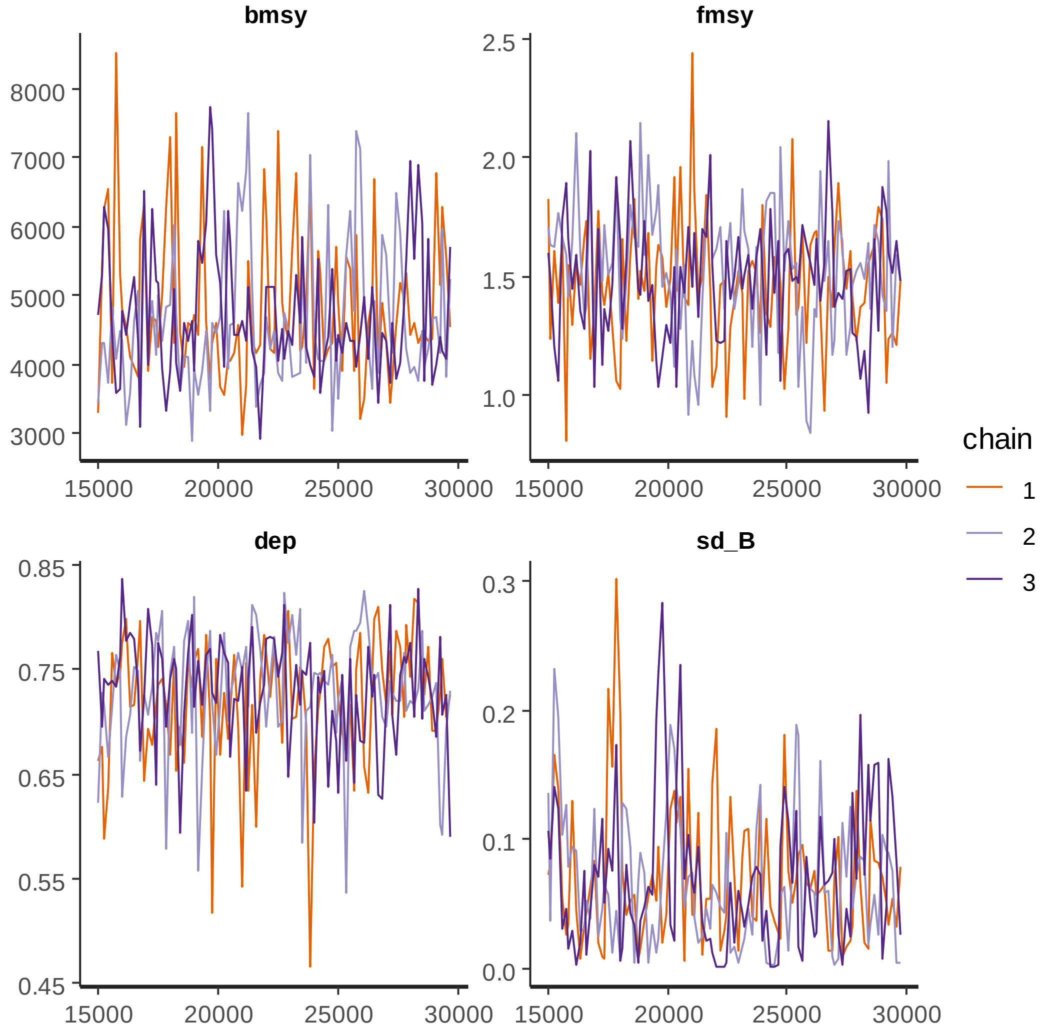

Figure A3. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 4: Model output, threadfin

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	2460	4096	9293	0.345	0.709	1.440
1991	2236	3948	9111	0.383	0.773	1.559
1992	2344	3777	8686	0.371	0.786	1.596
1993	2039	3721	7966	0.487	0.951	1.823
1994	1888	3347	7109	0.503	1.024	1.901
1995	1486	3114	6447	0.540	1.094	2.017
1996	1775	3224	6396	0.610	1.205	2.132
1997	1194	2641	5341	0.566	1.179	2.101
1998	1543	2901	5793	0.443	0.935	1.777
1999	1759	3258	6136	0.471	0.935	1.722
2000	1847	3237	6174	0.496	1.028	1.855
2001	1655	3188	6454	0.601	1.151	2.099
2002	1464	2736	5697	0.598	1.199	2.212
2003	1549	2803	5530	0.633	1.301	2.348
2004	1359	2575	5502	0.747	1.543	2.618
2005	1040	2109	4784	0.793	1.573	2.706
2006	1041	2166	4354	0.910	1.694	2.883
2007	1023	1853	3839	0.849	1.674	2.793
2008	1008	1960	3660	0.744	1.556	2.671
2009	1054	1989	4034	0.768	1.572	2.730
2010	953	1886	4040	0.686	1.384	2.353
2011	1350	2510	4893	0.789	1.515	2.513
2012	1178	2284	4524	0.884	1.608	2.657
2013	1172	2138	4072	0.870	1.642	2.749
2014	1024	1988	3962	0.893	1.691	2.904
2015	1049	1877	3948	0.973	1.933	3.029
2016	691	1490	2992	1.103	2.220	3.776

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

						Fleet fishing mortality						
Year	CI_ind_trl	G_ind_trl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_art	T_art_ps	T_art_sn	B_ind_trl	B_art
1990	0.084	0.008	0.012	0.020	0.067	0.278	0.015	0.003	0.086	0.034	0.016	0.121
1991	0.084	0.008	0.013	0.026	0.067	0.344	0.014	0.003	0.088	0.033	0.015	0.115
1992	0.084	0.008	0.013	0.023	0.074	0.354	0.014	0.003	0.091	0.032	0.014	0.113
1993	0.085	0.008	0.015	0.025	0.080	0.526	0.014	0.003	0.091	0.030	0.014	0.111
1994	0.089	0.009	0.016	0.030	0.092	0.561	0.016	0.003	0.095	0.029	0.015	0.113
1995	0.093	0.011	0.018	0.029	0.100	0.641	0.016	0.004	0.094	0.027	0.016	0.107
1996	0.097	0.013	0.020	0.025	0.105	0.711	0.020	0.005	0.102	0.026	0.017	0.105
1997	0.094	0.015	0.023	0.036	0.116	0.673	0.023	0.006	0.096	0.025	0.018	0.101
1998	0.097	0.015	0.028	0.027	0.105	0.419	0.029	0.008	0.095	0.023	0.018	0.118
1999	0.098	0.014	0.028	0.026	0.102	0.429	0.023	0.011	0.081	0.021	0.017	0.118
2000	0.100	0.011	0.029	0.026	0.102	0.577	0.015	0.014	0.067	0.022	0.015	0.095
2001	0.100	0.020	0.033	0.029	0.104	0.652	0.012	0.016	0.082	0.023	0.014	0.128
2002	0.109	0.020	0.033	0.028	0.120	0.656	0.012	0.019	0.088	0.021	0.015	0.151
2003	0.106	0.019	0.027	0.029	0.139	0.688	0.012	0.021	0.102	0.019	0.017	0.160
2004	0.095	0.022	0.022	0.036	0.180	0.885	0.013	0.022	0.094	0.019	0.019	0.163
2005	0.083	0.025	0.023	0.041	0.208	0.934	0.012	0.023	0.085	0.019	0.021	0.159
2006	0.084	0.026	0.025	0.048	0.237	1.017	0.012	0.024	0.085	0.017	0.024	0.153
2007	0.093	0.026	0.025	0.047	0.244	0.992	0.010	0.025	0.085	0.020	0.025	0.118
2008	0.115	0.026	0.022	0.034	0.274	0.852	0.008	0.025	0.057	0.018	0.026	0.130
2009	0.123	0.025	0.022	0.034	0.352	0.785	0.007	0.025	0.051	0.021	0.023	0.153
2010	0.123	0.031	0.022	0.035	0.303	0.647	0.006	0.025	0.051	0.022	0.021	0.141
2011	0.131	0.040	0.017	0.030	0.327	0.710	0.007	0.024	0.062	0.020	0.019	0.155
2012	0.168	0.047	0.013	0.029	0.330	0.775	0.007	0.019	0.060	0.022	0.019	0.161
2013	0.229	0.043	0.012	0.028	0.361	0.755	0.007	0.016	0.068	0.024	0.016	0.128
2014	0.295	0.052	0.011	0.028	0.388	0.714	0.006	0.012	0.059	0.025	0.011	0.150
2015	0.346	0.045	0.013	0.027	0.478	0.773	0.006	0.010	0.053	0.027	0.012	0.166
2016	0.425	0.046	0.015	0.032	0.548	0.888	0.006	0.010	0.057	0.029	0.013	0.179

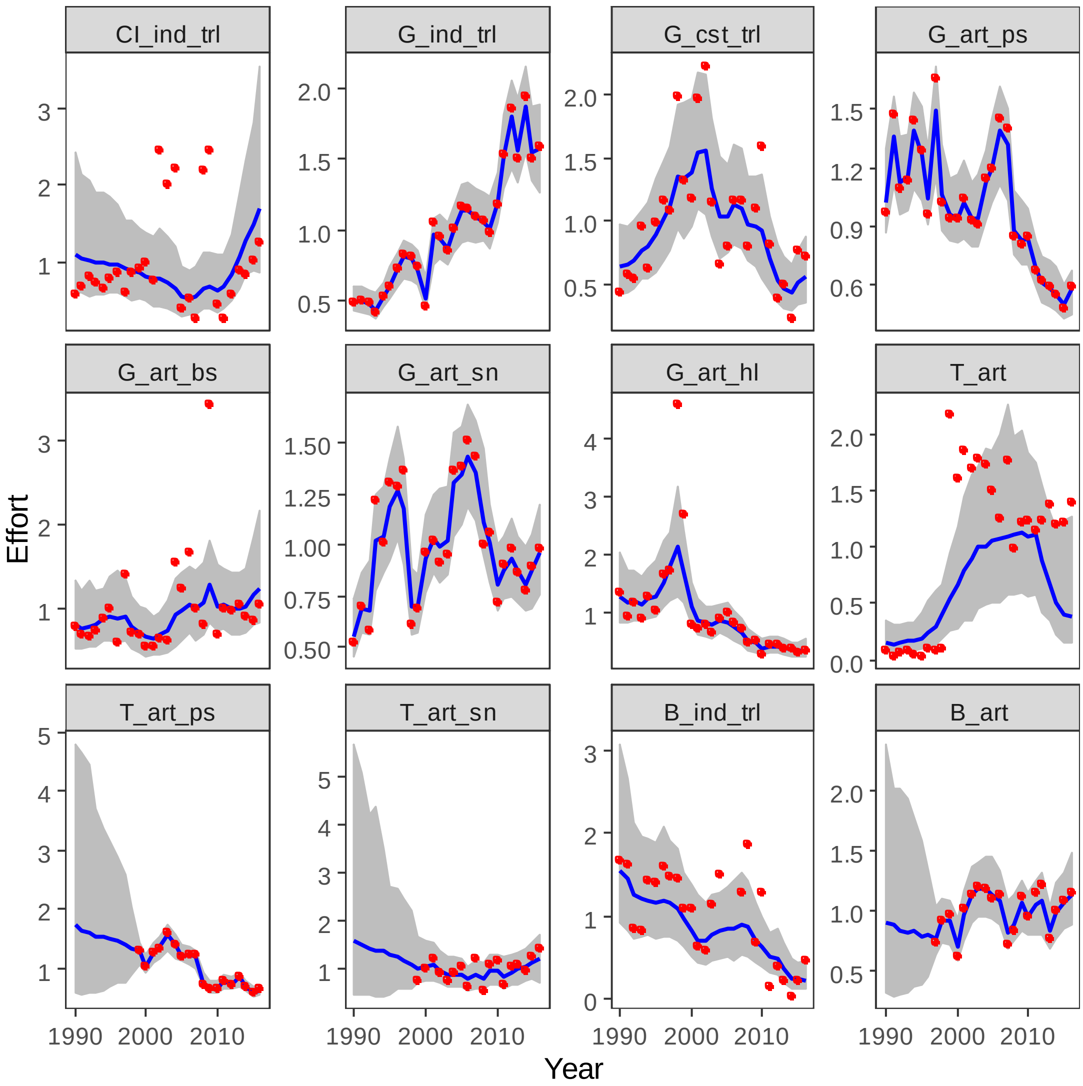

Figure A4. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

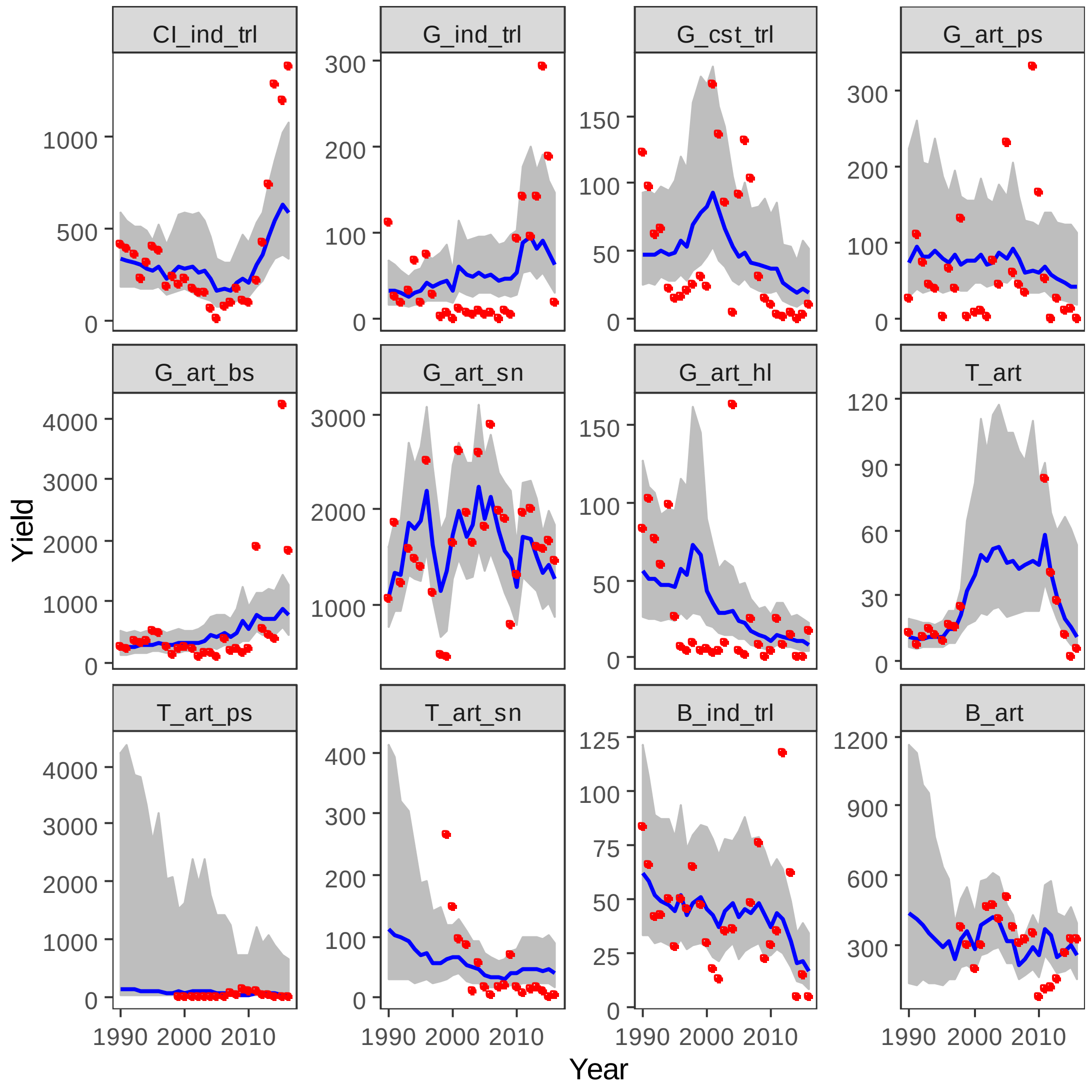

Figure A4. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

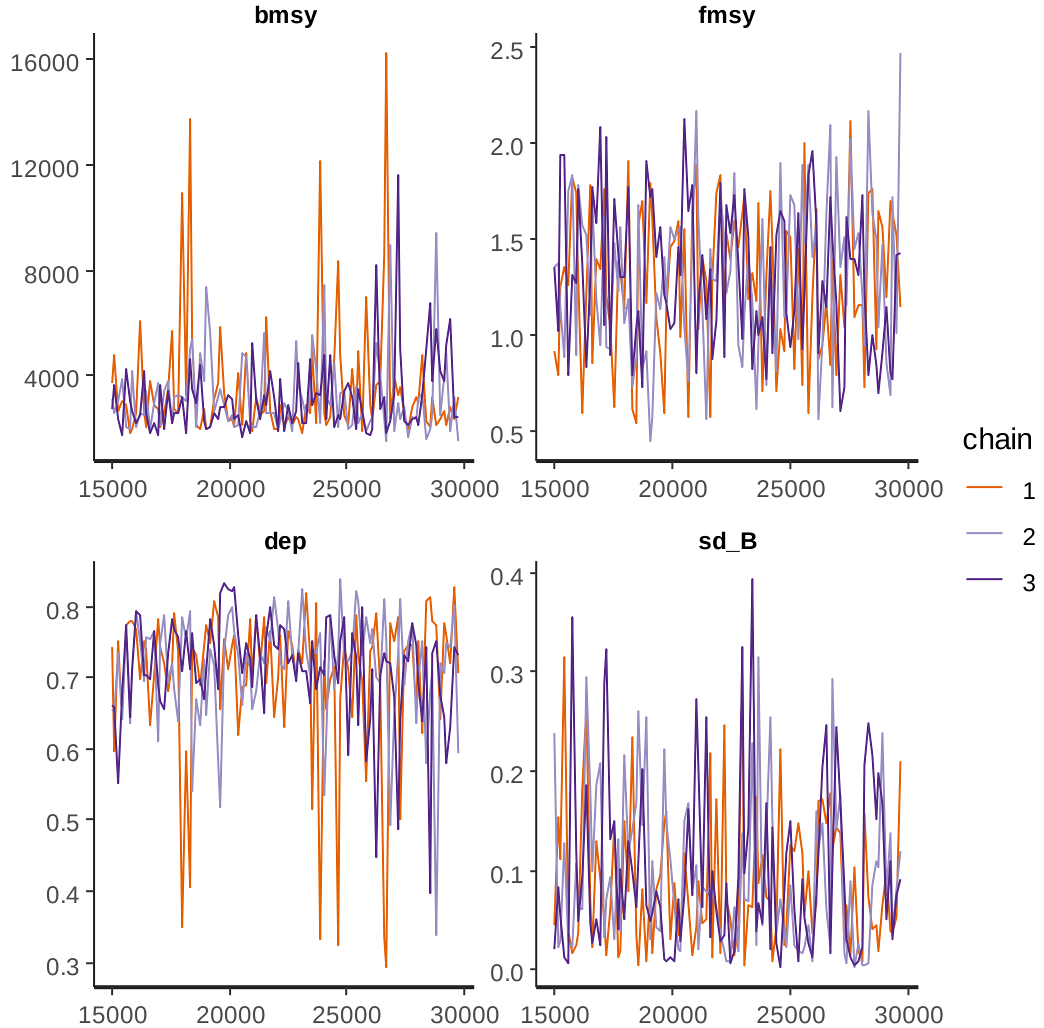

Figure A4. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 5: Model output, red pandora

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	1958	5674	18091	0.559	2.056	5.531
1991	1946	5216	16665	0.648	2.112	5.548
1992	1919	5620	15258	0.709	2.220	5.680
1993	1508	4514	14774	0.766	2.334	5.807
1994	1329	4023	10620	0.824	2.434	5.911
1995	1146	3211	9087	0.866	2.459	5.683
1996	1358	3730	10294	0.967	2.614	5.731
1997	1356	3359	9589	1.130	2.772	6.160
1998	1259	3312	8419	1.193	2.689	5.671
1999	2098	5308	13109	1.217	2.609	5.712
2000	1293	3580	9479	0.886	2.500	5.760
2001	1206	3019	7175	0.927	2.920	6.517
2002	493	1425	4608	0.996	2.904	6.683
2003	458	1341	4234	0.970	2.746	6.360
2004	757	1919	5474	1.125	2.932	6.391
2005	940	2435	7432	1.246	3.066	6.456
2006	1102	2869	7601	1.256	3.166	6.852
2007	607	1690	5700	1.117	3.057	6.606
2008	768	1827	4820	0.982	2.810	6.737
2009	535	1575	4354	0.903	2.688	6.789
2010	532	1411	4308	0.928	2.762	6.681
2011	436	1248	3840	1.169	2.990	6.875
2012	518	1289	3742	1.331	3.227	6.964
2013	446	1176	3206	1.195	3.029	6.739
2014	517	1338	3437	1.390	3.285	6.849
2015	623	1499	3987	1.373	3.233	6.905
2016	548	1417	4047	1.385	3.587	7.794

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

Fleet fishing mortality

Year	CI_ind_trl	G_ind_trl	G_p_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_sn	G_art_hl	T_art	T_art_hl	B_ind_trl	B_art
1990	0.073	0.167	0.475	0.014	0.007	0.159	0.048	1.312	0.003	0.037	0.004	0.013
1991	0.072	0.176	0.452	0.013	0.008	0.212	0.057	1.294	0.003	0.035	0.004	0.012
1992	0.072	0.176	0.440	0.014	0.008	0.179	0.057	1.484	0.003	0.033	0.004	0.012
1993	0.074	0.173	0.432	0.016	0.010	0.187	0.091	1.570	0.003	0.031	0.004	0.012
1994	0.078	0.216	0.410	0.017	0.010	0.225	0.092	1.619	0.003	0.028	0.004	0.012
1995	0.085	0.259	0.370	0.016	0.012	0.211	0.109	1.604	0.004	0.026	0.005	0.011
1996	0.090	0.322	0.331	0.014	0.013	0.177	0.112	1.770	0.005	0.024	0.006	0.010
1997	0.093	0.375	0.302	0.012	0.015	0.251	0.109	1.819	0.006	0.023	0.006	0.010
1998	0.099	0.384	0.281	0.010	0.018	0.184	0.069	1.816	0.009	0.021	0.007	0.011
1999	0.105	0.373	0.282	0.009	0.018	0.171	0.071	1.772	0.015	0.019	0.007	0.012
2000	0.117	0.316	0.304	0.008	0.018	0.174	0.089	1.654	0.020	0.025	0.007	0.010
2001	0.126	0.552	0.328	0.007	0.021	0.189	0.098	1.776	0.021	0.017	0.007	0.014
2002	0.149	0.578	0.309	0.005	0.021	0.179	0.097	1.828	0.020	0.013	0.008	0.016
2003	0.148	0.579	0.282	0.005	0.017	0.180	0.106	1.646	0.018	0.011	0.009	0.017
2004	0.129	0.681	0.270	0.005	0.013	0.216	0.136	1.632	0.018	0.014	0.011	0.017
2005	0.099	0.802	0.294	0.005	0.013	0.235	0.147	1.629	0.018	0.012	0.012	0.017
2006	0.096	0.887	0.256	0.005	0.014	0.280	0.160	1.654	0.017	0.012	0.013	0.017
2007	0.096	0.931	0.210	0.004	0.014	0.271	0.154	1.562	0.017	0.013	0.014	0.013
2008	0.117	1.005	0.203	0.004	0.014	0.189	0.124	1.402	0.018	0.020	0.015	0.014
2009	0.120	1.059	0.207	0.003	0.014	0.180	0.119	1.251	0.018	0.019	0.014	0.018
2010	0.101	1.305	0.207	0.003	0.015	0.183	0.100	1.115	0.018	0.018	0.013	0.017
2011	0.098	1.638	0.194	0.003	0.011	0.155	0.111	1.046	0.018	0.014	0.011	0.020
2012	0.118	1.972	0.184	0.003	0.009	0.143	0.119	0.898	0.018	0.013	0.010	0.021
2013	0.159	1.893	0.170	0.003	0.008	0.138	0.111	0.769	0.018	0.012	0.011	0.016
2014	0.187	2.163	0.163	0.003	0.007	0.134	0.106	0.707	0.019	0.012	0.011	0.019
2015	0.201	2.041	0.165	0.003	0.009	0.124	0.117	0.743	0.022	0.012	0.011	0.021
2016	0.219	2.262	0.173	0.003	0.010	0.145	0.133	0.813	0.025	0.013	0.014	0.023

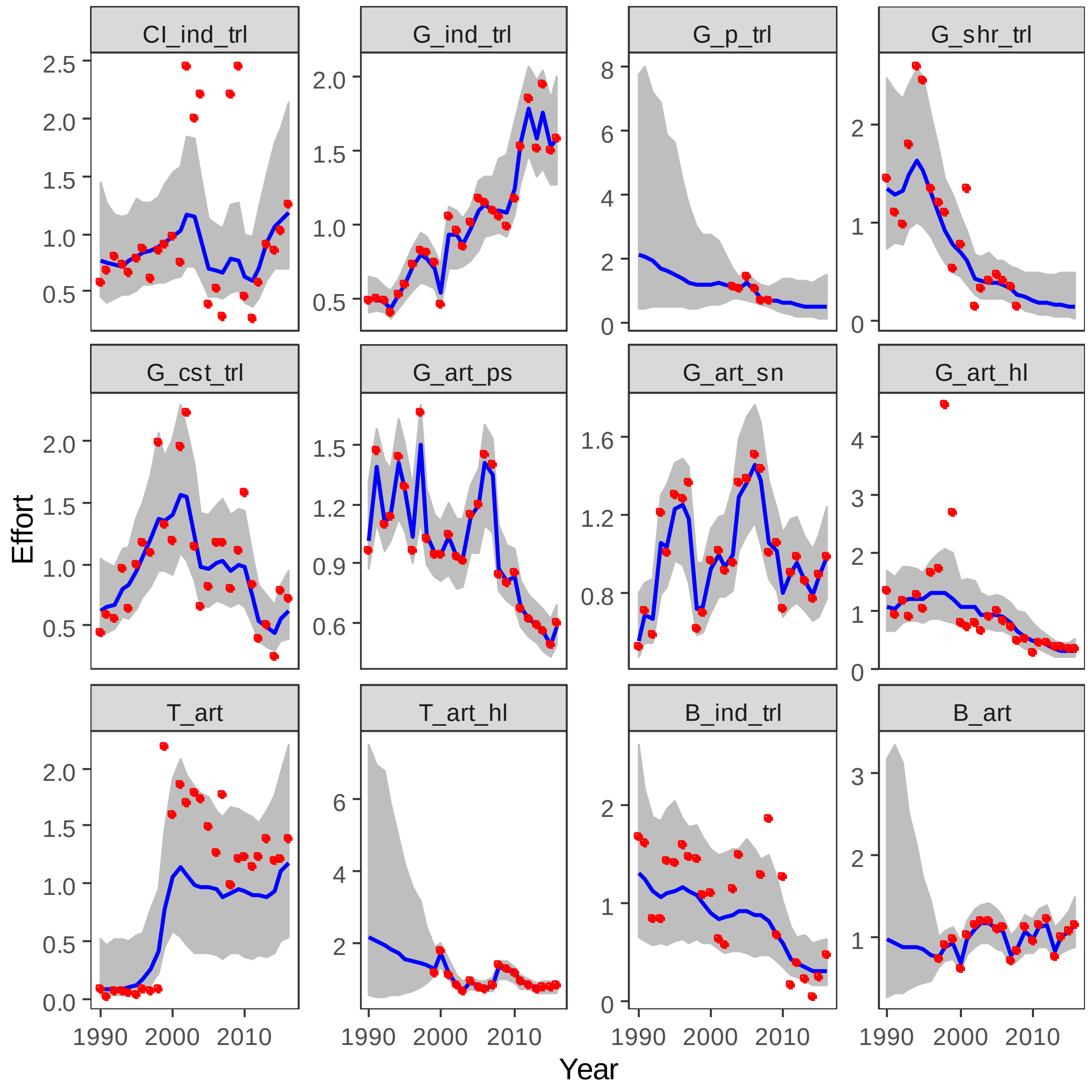

Figure A5. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

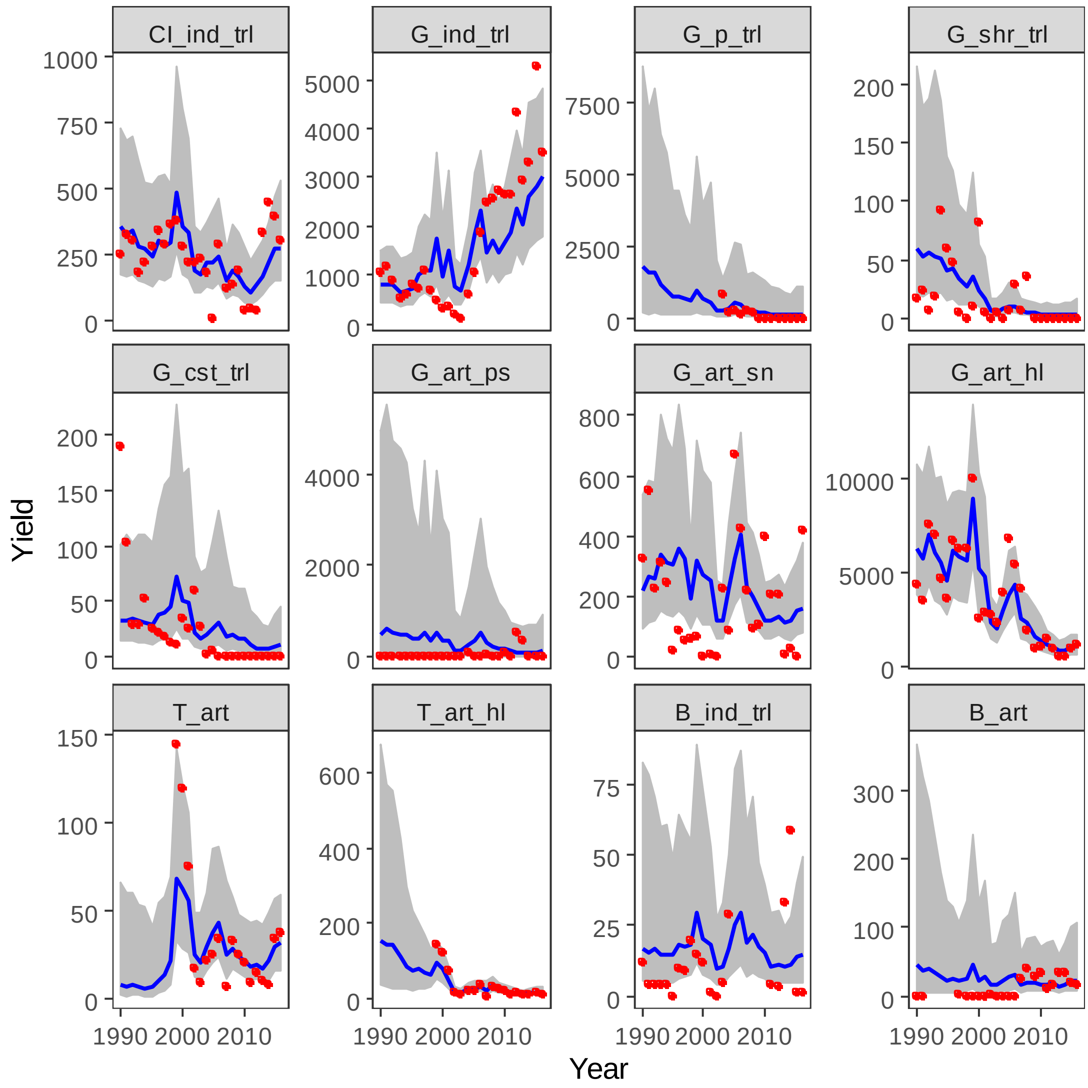

Figure A5. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

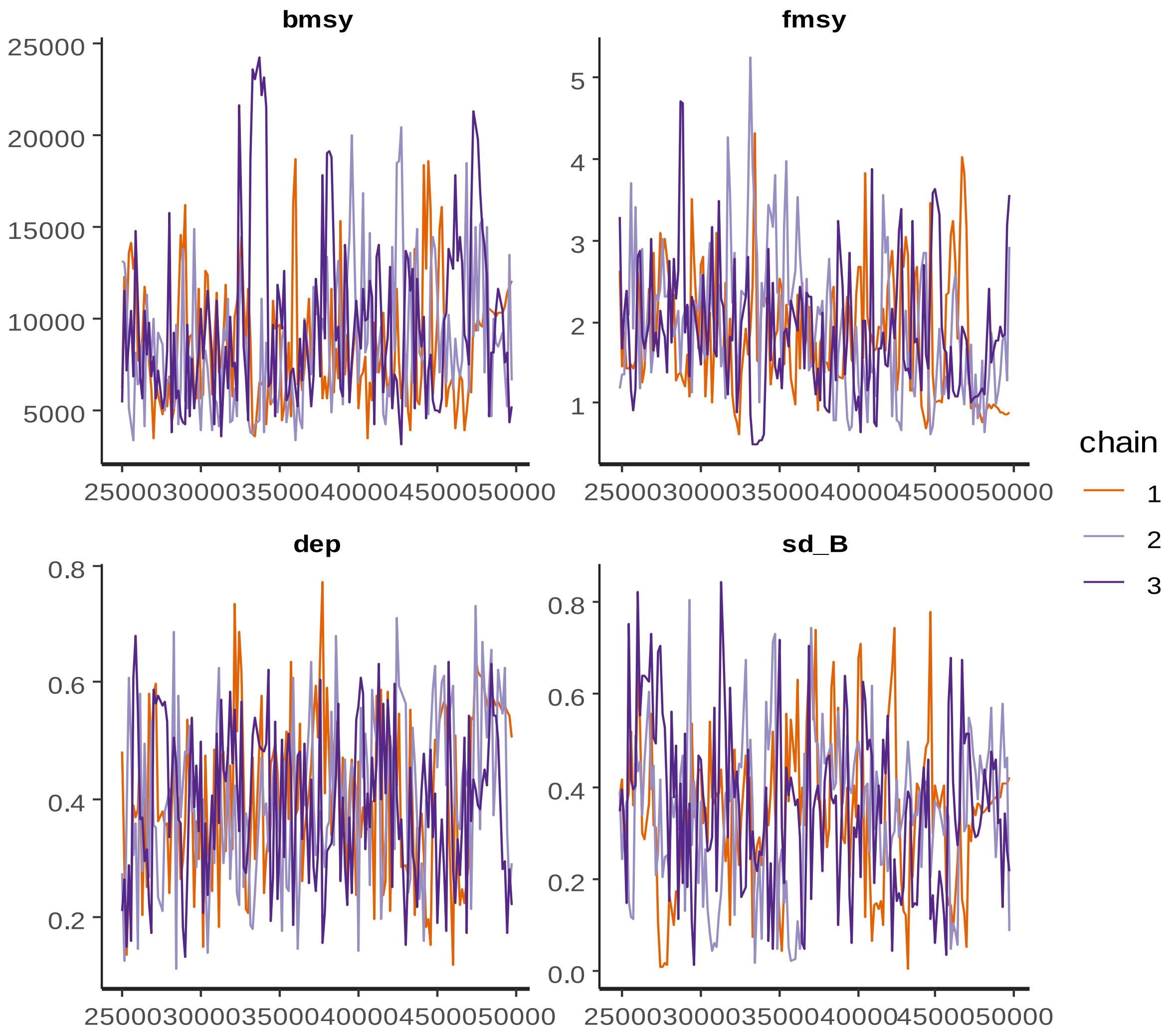

Figure A5. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 6: Model output, croakers

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	1398	2130	3866	0.771	1.364	2.301
1991	1349	2102	3982	0.821	1.396	2.295
1992	1348	2042	3435	0.811	1.417	2.438
1993	1172	1959	3572	0.845	1.479	2.471
1994	1286	2087	3690	0.964	1.661	2.739
1995	789	1482	2747	1.053	1.798	2.897
1996	1038	1691	2854	1.077	1.802	3
1997	990	1604	2895	1.187	1.940	3.190
1998	835	1454	2594	1.136	1.945	3.152
1999	858	1533	2588	1.155	1.956	3.218
2000	660	1373	2347	1.092	1.951	3.186
2001	849	1476	2547	1.307	2.171	3.312
2002	769	1247	2167	1.384	2.377	3.491
2003	641	1077	1956	1.395	2.361	3.542
2004	642	1114	1919	1.493	2.489	3.674
2005	579	987	1781	1.540	2.493	3.708
2006	638	1013	1748	1.611	2.631	3.832
2007	485	851	1563	1.542	2.586	3.740
2008	530	938	1551	1.474	2.534	3.795
2009	557	955	1652	1.529	2.630	3.843
2010	569	910	1548	1.494	2.500	3.725
2011	603	973	1688	1.493	2.512	3.751
2012	574	963	1633	1.509	2.488	3.627
2013	690	1044	1734	1.435	2.368	3.444
2014	772	1173	1852	1.606	2.617	3.757
2015	481	837	1494	1.705	2.807	3.941
2016	441	756	1341	1.995	3.205	4.665

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

	Fleet fishing mortality											
Year	CI_ind_trl	G_ind_trl	G_shr_trl	G_cst_trl	G_art_ps	G_art_bs	G_art_sn	G_art_hl	T_art	T_art_sn	B_ind_trl	B_art
1990	0.397	0.034	0.012	0.070	0.115	0.176	0.133	0.040	0.010	0.034	0.065	0.313
1991	0.371	0.035	0.012	0.082	0.159	0.167	0.157	0.037	0.010	0.032	0.064	0.316
1992	0.371	0.036	0.013	0.081	0.139	0.176	0.162	0.037	0.011	0.032	0.062	0.346
1993	0.332	0.033	0.014	0.104	0.141	0.176	0.240	0.035	0.013	0.031	0.070	0.349
1994	0.362	0.042	0.015	0.122	0.171	0.193	0.256	0.038	0.013	0.031	0.084	0.391
1995	0.398	0.050	0.015	0.132	0.164	0.207	0.310	0.038	0.013	0.029	0.102	0.405
1996	0.383	0.063	0.013	0.172	0.137	0.192	0.317	0.045	0.016	0.028	0.106	0.395
1997	0.354	0.075	0.012	0.202	0.203	0.223	0.324	0.052	0.021	0.026	0.112	0.402
1998	0.372	0.075	0.010	0.248	0.150	0.199	0.224	0.066	0.031	0.026	0.120	0.476
1999	0.380	0.071	0.009	0.251	0.139	0.188	0.241	0.055	0.052	0.025	0.124	0.505
2000	0.375	0.054	0.008	0.258	0.143	0.183	0.282	0.035	0.072	0.028	0.118	0.394
2001	0.357	0.102	0.006	0.307	0.155	0.189	0.294	0.028	0.087	0.031	0.108	0.518
2002	0.388	0.105	0.004	0.354	0.149	0.199	0.307	0.028	0.103	0.031	0.111	0.606
2003	0.380	0.102	0.004	0.255	0.155	0.217	0.341	0.028	0.113	0.028	0.129	0.646
2004	0.299	0.122	0.004	0.201	0.190	0.292	0.449	0.030	0.120	0.030	0.135	0.641
2005	0.218	0.144	0.004	0.201	0.209	0.329	0.483	0.030	0.120	0.033	0.138	0.607
2006	0.246	0.151	0.003	0.254	0.245	0.348	0.522	0.028	0.119	0.029	0.147	0.583
2007	0.261	0.150	0.003	0.272	0.245	0.340	0.527	0.026	0.119	0.033	0.157	0.437
2008	0.323	0.155	0.002	0.261	0.170	0.340	0.486	0.022	0.118	0.028	0.158	0.480
2009	0.289	0.155	0.002	0.300	0.160	0.394	0.451	0.020	0.113	0.034	0.133	0.568
2010	0.251	0.192	0.002	0.329	0.168	0.336	0.408	0.016	0.110	0.039	0.128	0.534
2011	0.240	0.252	0.002	0.241	0.144	0.309	0.447	0.018	0.104	0.037	0.113	0.602
2012	0.248	0.307	0.002	0.155	0.134	0.299	0.462	0.018	0.107	0.044	0.118	0.595
2013	0.287	0.283	0.002	0.153	0.131	0.323	0.460	0.018	0.118	0.048	0.093	0.459
2014	0.379	0.355	0.002	0.174	0.128	0.358	0.437	0.018	0.106	0.050	0.067	0.544
2015	0.501	0.306	0.002	0.197	0.120	0.394	0.456	0.016	0.100	0.058	0.074	0.575
2016	0.647	0.327	0.002	0.230	0.146	0.466	0.520	0.016	0.099	0.067	0.084	0.619

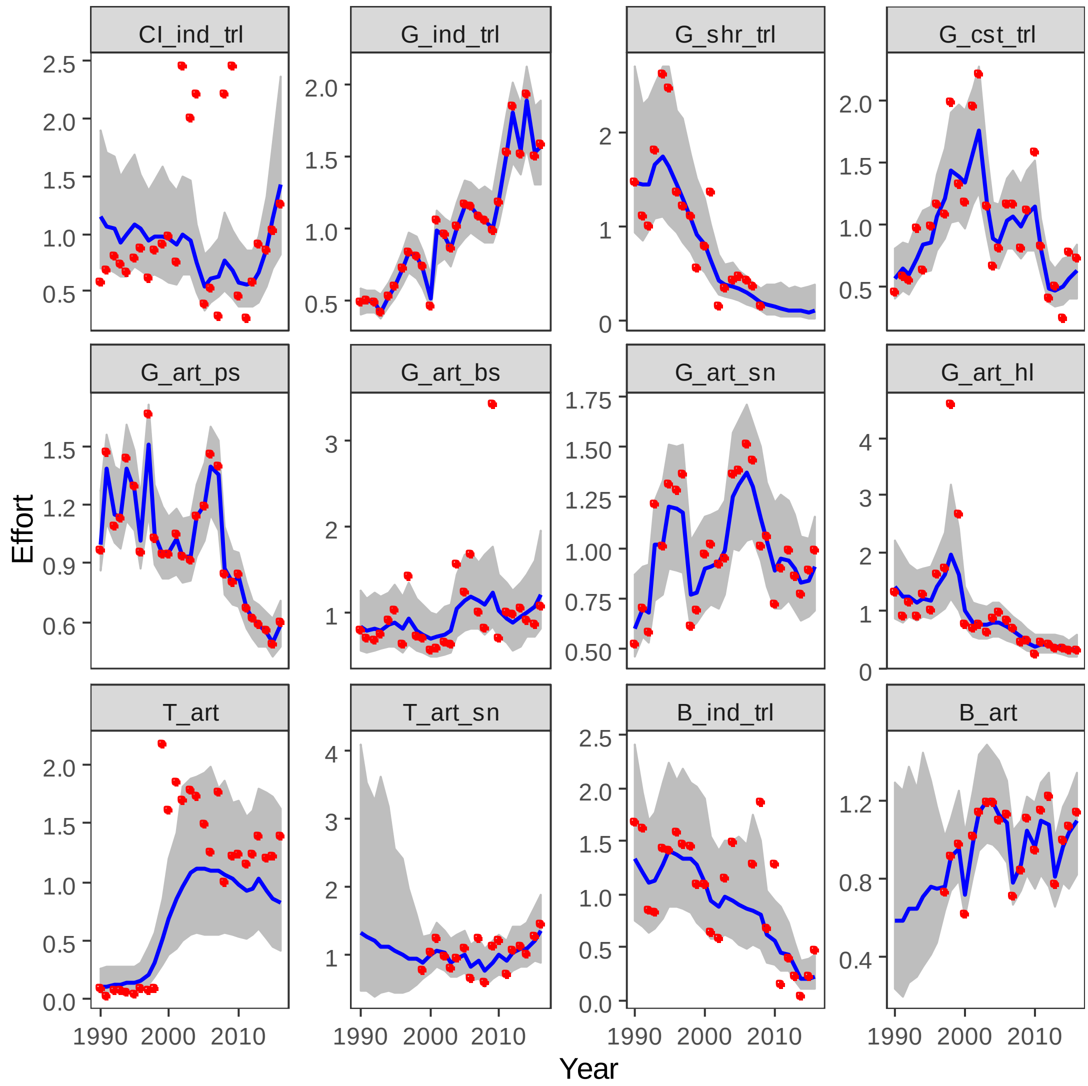

Figure A6. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

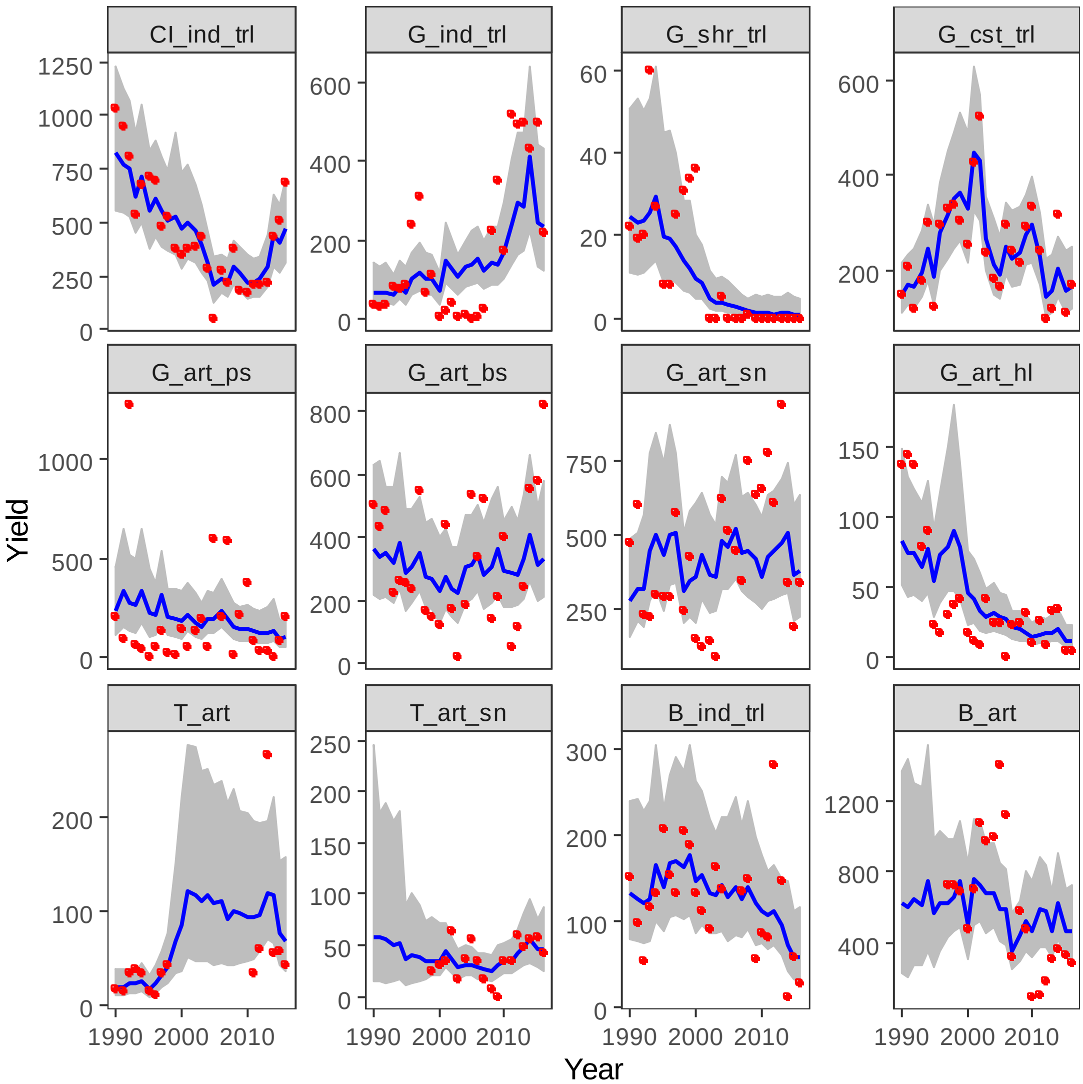

Figure A6. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

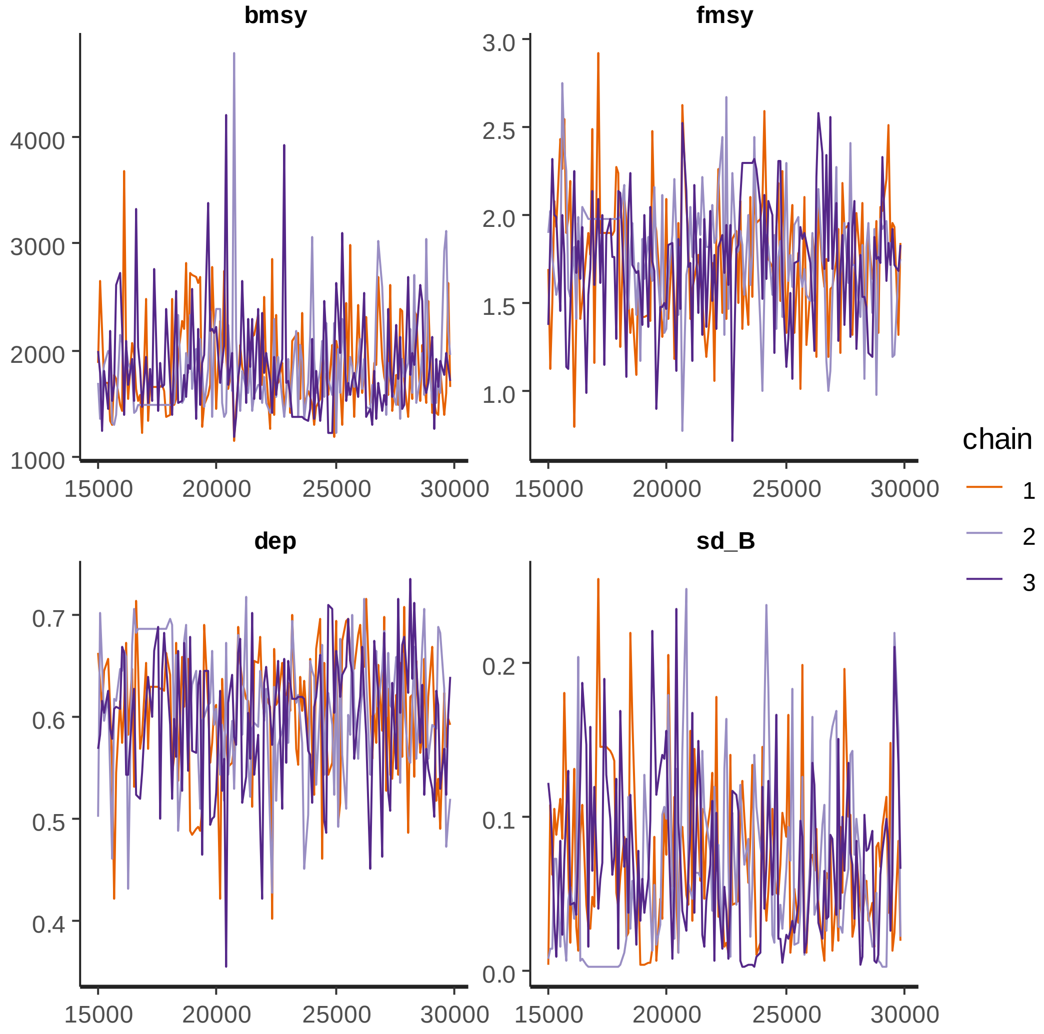

Figure A6. 3. Trace plots of the MCMC chains for key model parameters. Bmsy=B_{MSY}, fmsy=F_{MSY}, dep=initial depletion, d and sd_B=σ_B, the process error on biomass.

Appendix 7. Non-parametric model

Introduction

In the main report a simple catch-per-unit-effort model (cpue) and a Schaefer surplus production model are used to analyse the catch and effort data. The cpue model (section 2) assumes no parametric biomass dynamics and by reducing the catch and effort data to cpue it does not distinguish the errors in the two data types. That model also makes no adjustment for increasing fishing power over time. The Schaefer model (section 3) includes explicit biomass dynamics, accounts for errors in both the catch and effort data separately and allows for increasing fishing power. While it addresses some of the limitations of the cpue model, it might be argued that the assumption of parametric biomass dynamics is overly constraining and perhaps unrealistic. Here we describe an intermediate model that retains the same assumptions as the Schaefer model described in section 3 but where the biomass follows a random walk rather than using a production function. The model is illustrated with application to bigeye grunt.

Model description

Stock biomass, B, follows a random walk and is projected forward from the equation:

$$B_{t+1} = B_t \exp(\varepsilon_t) \qquad \text{A7.1}$$

Where t indexes year, ε_t is a normally distributed random process error with mean and standard deviation (0, σ_B). If we assume that the catch, Y, by fleet, k, is a function of the biomass and the amount of fishing effort, f_k, then:

$$Y_{k,t} = q_{k,t} B_t f_{k,t} \qquad \text{A7.2}$$

Where $q_{k,t}$ is a normalising constant expressing the fishing power, or catchability, of the fleet which may change over time. Here we assume that it increases due technological creep by a mean annual power increment δ. If $q_{k,1}$ is the catchability in the initial year then it needs to be inflated by an amount $(1+\delta)^{(t-1)}$ to account for this annual change, so that:

$$q_{k,t} = q_{k,1}(1+\delta_k)^{(t-1)} \qquad \text{A7.3}$$

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 q=1 for fleet k=1 in year t=1. This will in effect scale the biomass to the fleet for which $q_{1,1}$=1 and hence estimate a trend in biomass, not its absolute scale.

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:

$$'_{k,t} \sim lognormal(\log(f_{k,t}), \sigma_k)$$ A7.4

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 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 :

$$Y'_{k,t} \sim negative\ binomial(Y_{k,t}, \kappa_k)$$ A7.5

Parameter estimation

Parameters were estimated by fitting the model to the catch and effort data using Bayesian statistical inference with MCMC sampling in the R package "rstan". Uniform priors were assumed for all parameters and should give similar results to maximum likelihood. For identifiability it is necessary to constrain the estimates of δ. A simple way to do this is to fix the mean power increment, $\bar{\delta}$, over all n fleets:

$$\frac{\sum_{k=1}^{n} \delta_k}{n} = \bar{\delta}$$ A7.6

We set the mean power increment $\bar{\delta} = 0.03$, the same value used in the assessments described in the main report.

The model does not directly estimate fishing mortality but it is possible to calculate an index of effective effort that accounts for fleet catchability and the increase in fishing power overtime. For each fleet the effective effort, E, can be calculated from:

$$E_{k,t} = q_k f_{k,t}$$ A.7

An overall index of effective effort across fleets, $E_{*,t}$ is therefore:

$$E_{*,t} = \sum_k E_{k,t}$$ A.8

The model was fit to using a minimum of 20,000 iterations with three chains and a thinning rate of 100.

Results

The fit to the fleet catch and effort data are shown in Figure A7. 1 and Figure A7. 2 These show a very similar fit when compared to the Schaefer model (Appendix 2, Figure A2. 1 and Figure A2. 2. The biomass index (Figure A7. 3) also shows the same downward trend as the main assessment reference model (Figure 4. 3) with the index of effective effort showing the same upward trend as fishing mortality (Figure

A7. 4). The mean annual power increment for each fleet is shown in Figure A7. 5 and also shows a similar pattern to the estimates from the reference model.

Conclusion

Clearly the results in terms of stock trends and fishing power changes from this model are very similar to the full Schaefer model with parametric biomass dynamics. This offers some reassurance that the assumptions in the Schaefer model of constant K and m do not unduly determine the estimated trends. Hence in terms of describing biomass and fishing mortality trends there is very little to choose between the models. The principal advantage of the Schaefer model is that estimating parameters that capture the biomass dynamics offers greater potential for predicting future biomass under varying exploitation regimes.

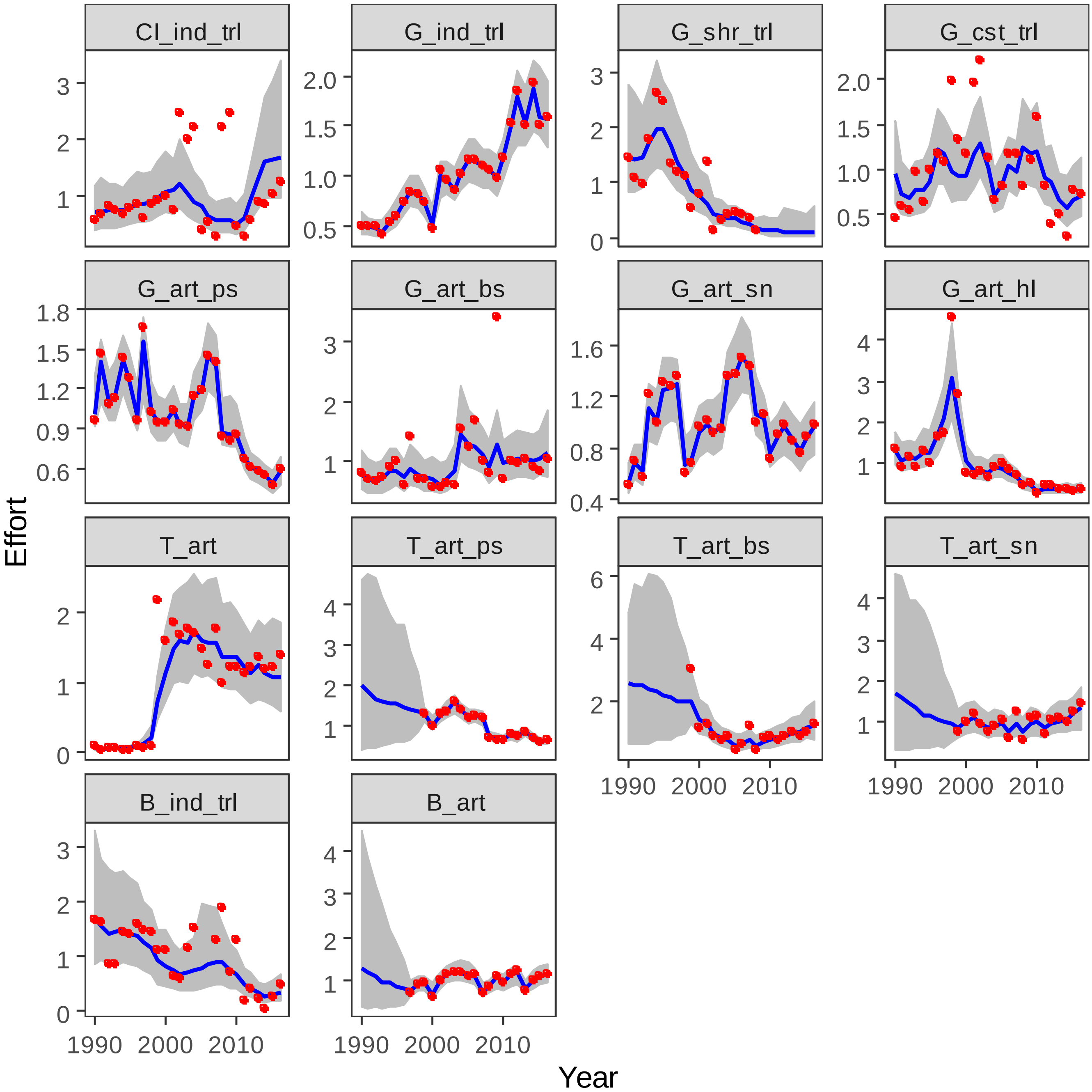

Figure A7. 1. Model fit (blue line) to the effort data (red dots). Grey area is the 95% CI.

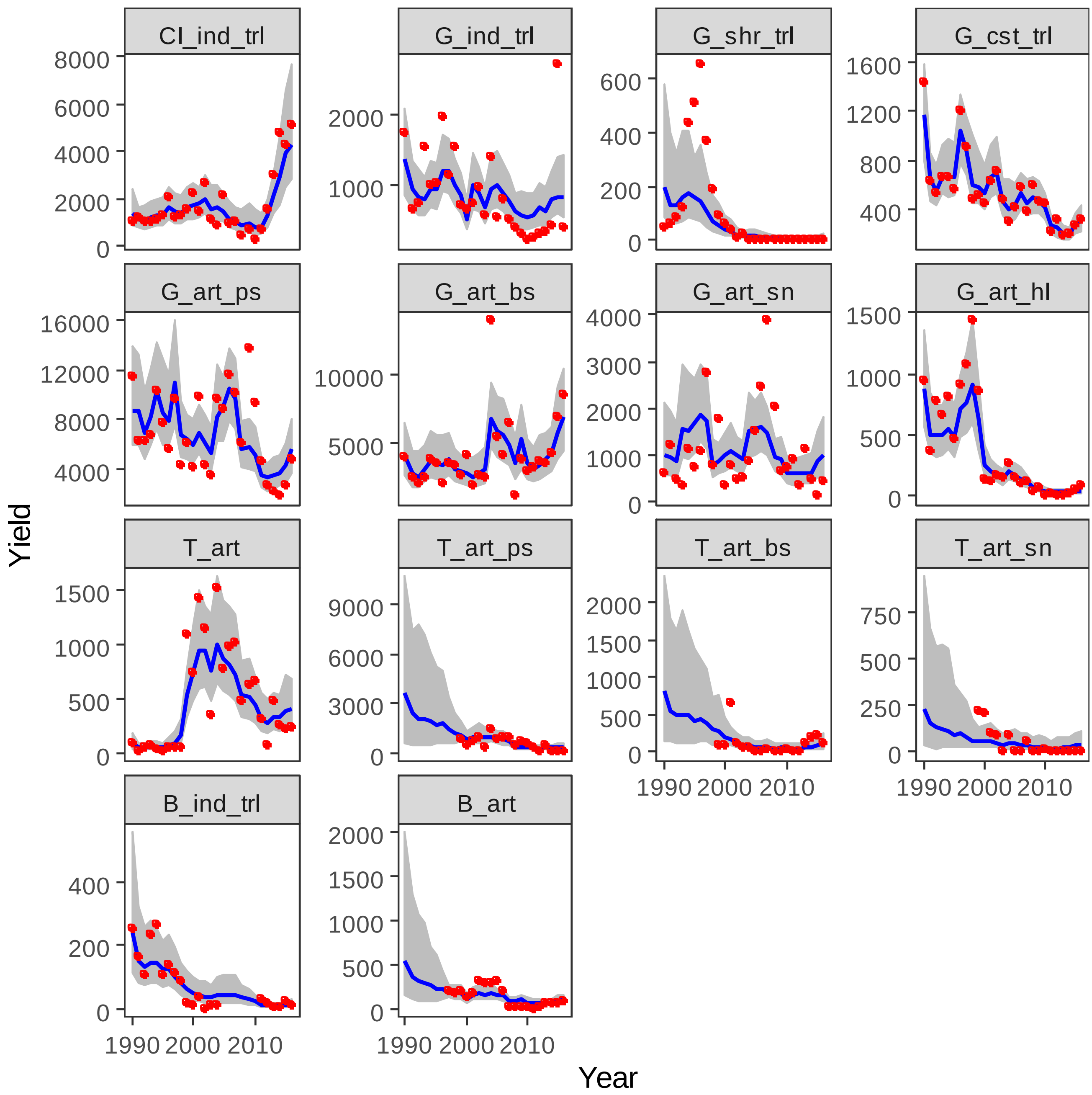

Figure A7. 2. Model fit (blue line) to the catch data (red dots). Grey area is the 95% CI.

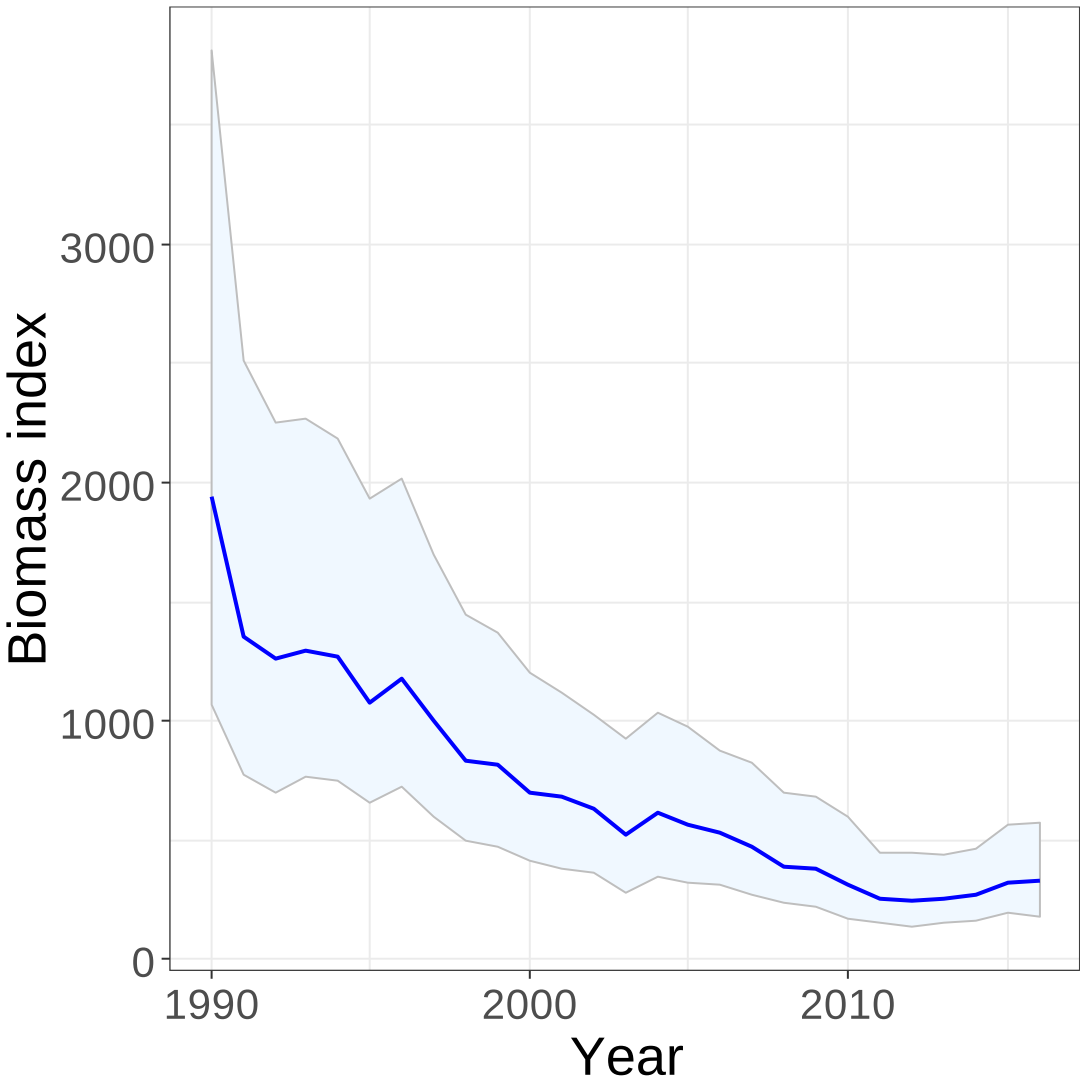

Figure A7. 3. Fitted biomass index with 95% CI (shaded area).

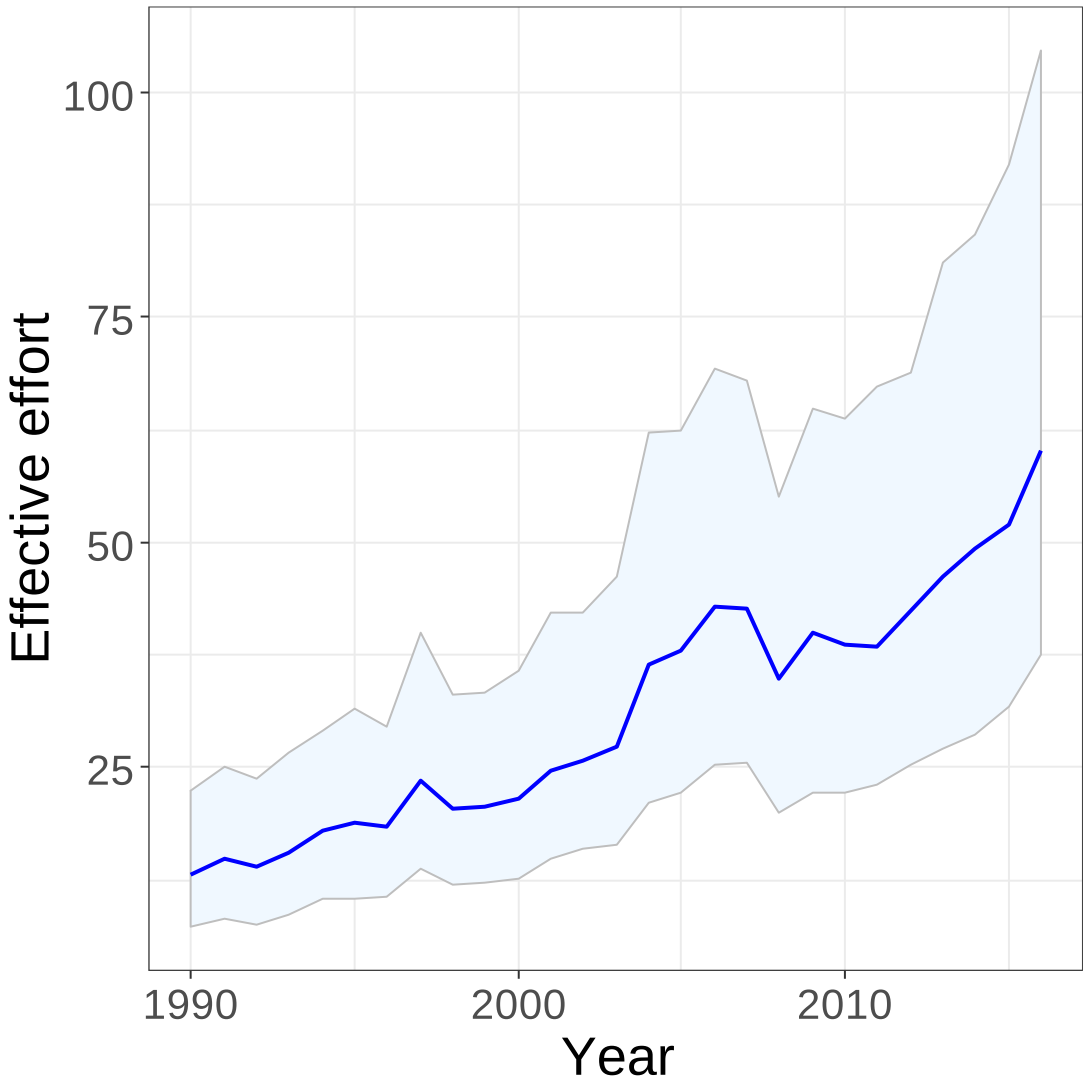

Figure A7. 4. Estimated effective effort from the model with 95% CI (shaded area). If effective effort is proportional to fishing mortality then this trend should reflect the change in fishing mortality over time.

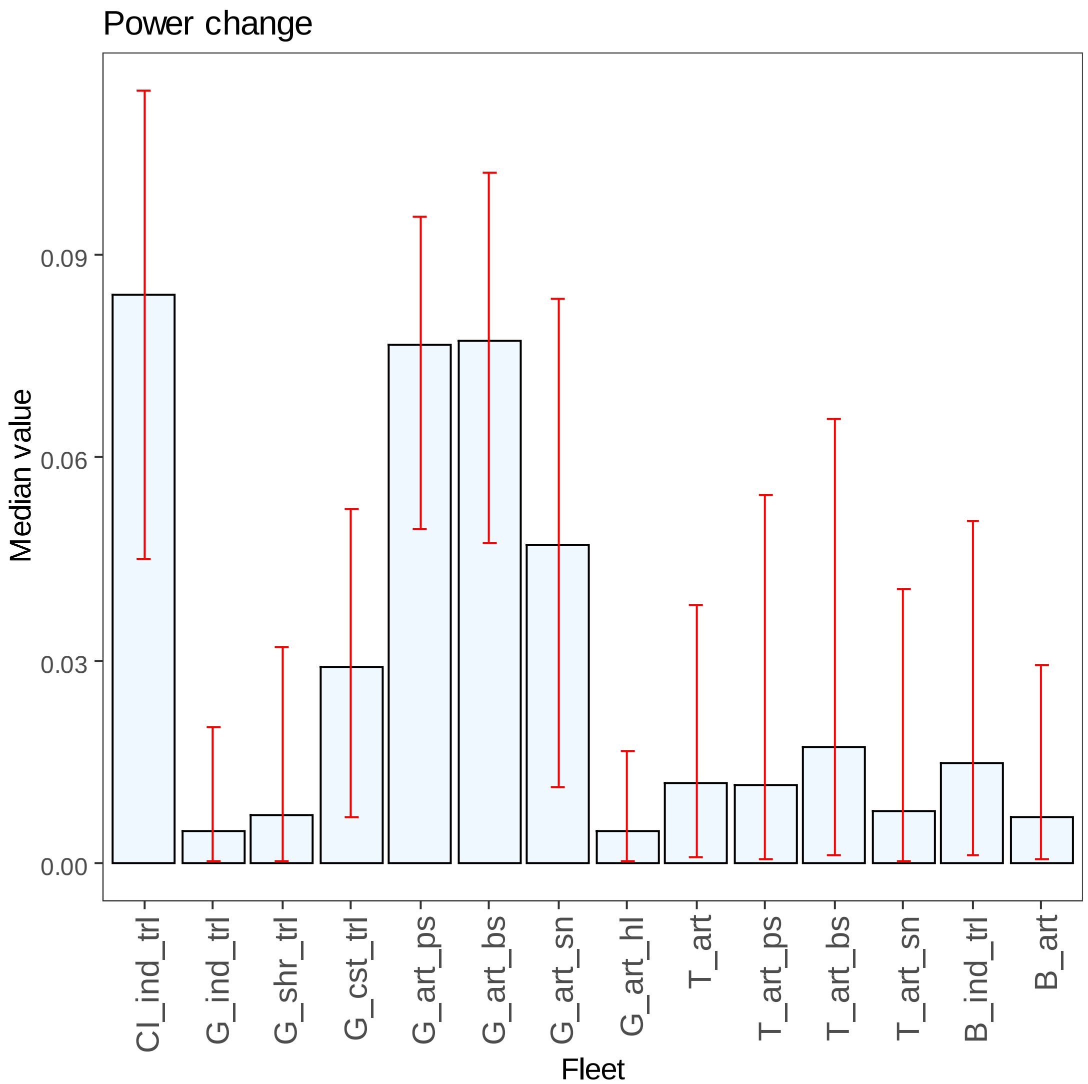

Figure A7. 5. Estimates of the mean annual increase in power for each fleet. Error bars show the 95%CI.

Appendix 8: Reference model code

Stan code for fitting Schaefer model to catch and effort data

```
// model to fit Schaefer model to catch and effort data
// version G2 v3.1.1, 7 April 2021
// includes parameter to account for fishing power increase
// sqrt uniform prior on B0
// uniform prior distribution on msy
// Uses simplex for power increase (qp)
// mean power increase over fleets must be specified (qp1)
// can specify lognormal (dist=1) or negative binomial (dist=0) for
//catch data errors

data{
int yr;     // number of years
int n_eff;  // number of effort series
int ny;     // number of catch series
real bmax;  // upper bound on virgin biomass
real bmin;  // lower bound on virgin biomass
real cmax;  // upper bound for MSY
real d_beta[2]; // parameters for beta distribution for prior on
depletion (dep) parameter
real eff[yr,n_eff]; // effort data
int y_sp[yr,ny]; // catch data
real qmax;  // upper limit on q
real qp1;   // mean annual power increase
real dist;  // indicator for catch error distribution, 0=neg binomial,
1=lognormal
} // end data block

parameters{
real K;     // square root virgin biomass
real dep;   // initial depletion relative to B0
real B_err[yr]; // process errors on biomass
real sd_B;  // SD for process error on biomass
real q[n_eff-1];// fleet catchability
real f[yr,ny];    // fleet Fs (effort)
real sd_f;  // process error on f
real sd_y[ny];    // observation error for catch
real sd_eff[n_eff];// observation error on effort
simplex[n_eff] p; // fishing power increment
real msy;   // msy
} // end parameter block

transformed parameters{
real Q;     // catchability for fleet 1
real B0;    // virgin biomass
real Bt[yr];      // true biomass
real y_obs[yr,ny]; //true catches
real A;     // intermediate derived parameter
real F[yr,ny];    //Partial F
real E[yr];       //total exploitation rate
real sumF;  // sum of F over fleets for starting biomass and fixing Q
calculation
real qp[n_eff];   // power increment
```

```
B0=K*K;          // derive virgin biomass from square root prior
A=4*msy/B0;      // intermediate parameter to simplify model statements

// Estimate initial biomass assuming equilibrium conditions, hence fix
Q for reference fleet
E[1]=A*(1-dep);
for(k in 2:n_eff){
F[1,k]=q[k-1]*f[1,k];
}
if(ny>n_eff) F[1,ny]=f[1,ny];
sumF=sum(F[1,2:ny]);
Q=(E[1]-sumF)/f[1,1];
if(Q<0) Q=0;
F[1,1]=Q*f[1,1];

Bt[1]=B0*dep*exp(B_err[1]);  //initial biomass derived from virgin and
depletion
if(Bt[1]<=0) Bt[1]=.001;     // trap zero or negative biomass

// correct effective effort for fishing power
for(k in 1:n_eff){
qp[k]=p[k]*n_eff*qp1;
}
for(j in 2:yr){
F[j,1]=Q*f[j,1]*(1+qp[1])^(j-1);
for(k in 2:n_eff){
F[j,k]=q[k-1]*f[j,k]*(1+qp[k])^(j-1);
}
if(ny>n_eff) F[j,ny]=f[j,ny];
E[j]=sum(F[j,]);
}

// initial catches in first year
for(k in 1:ny){
y_obs[1,k]=F[1,k]*Bt[1];
}
// project biomass and derive catches
for(j in 2:yr){
Bt[j]=(1+A)*Bt[j-1]-A*Bt[j-1]*Bt[j-1]/B0;
for(k in 1:ny){
Bt[j]=Bt[j]-y_obs[j-1,k];
}
if(Bt[j]<=0) Bt[j]=0.01;
Bt[j]=Bt[j]*exp(B_err[j]);// add process error to biomass
// derive observed catches
for(k in 1:ny){
y_obs[j,k]=F[j,k]*Bt[j];
}
}
}// end transformed parameter block

model{
// priors
msy~uniform(1,cmax);
K~uniform(bmin,bmax);
dep~beta(d_beta[1],d_beta[2]);
sd_B~uniform(0,1);
sd_y~uniform(0.0001,100);
```

```
sd_eff~uniform(0,10);
sd_f~uniform(0,1);
B_err~normal(0,sd_B);
f[1,]~uniform(0.001,10);
q~uniform(0.001,qmax);


// time series of fleet Fs
for(j in 2:yr){
for( i in 1:ny){
f[j,i]~lognormal(log(f[j-1,i]),sd_f);
}
}

// Likelihoods
for(j in 1:yr){
// catch data
for(k in 1:ny){
if(y_sp[j,k]!=-99&&dist==0)
y_sp[j,k]~neg_binomial_2(y_obs[j,k],sd_y[k]);
if(y_sp[j,k]>0&&dist==1) y_sp[j,k]~lognormal(log(y_obs[j,k]),sd_y[k]);
}
// effort data
for(k in 1:n_eff){
if(eff[j,k]>0) eff[j,k]~lognormal(log(f[j,k]+0.001),sd_eff[k]);
}
}
}// end model block

generated quantities{
// get MSY amd BMSY and relative F and biomass
real bmsy;
real fmsy;
real fratio[yr];
real bratio[yr];

bmsy=B0/2;
fmsy=msy/bmsy;

for(j in 1:yr){
fratio[j]=E[j]/fmsy;
bratio[j]=Bt[j]/bmsy;
}
} // end generated quantities block
```