Ghana fisheries projection model (GFPM)

Introduction

The Ghana fisheries projection model (GFPM) is a tool for exploring how various fish stocks respond to changes in fleet fishing effort in the future. All the projections are based on stock assessments that use data from 1990-2021 and are described in Appendix 1 which also lists the stocks and fleets.

A Schaefer surplus production model defines the core population dynamics of the stocks used in GFPM. It will return forecast changes in biomass, catch and revenues (value of catch) for any chosen scenario. The results can be summarised by stock and fleet. It will also provide estimates of saiko catches.

The most recent data driving GFPM is for the year 2021 and forms the base year for all projections. The tool can be used for any number of years into the future but projections beyond 10 years are subject to considerable uncertainty and need to be interpreted with care.

GFPM is a stochastic model that considers uncertainty in the initial conditions (e.g. biomass and fishing mortality in 2021) as well as process error (i.e. random effects in the annual biomass and fishing mortality). Forecasts are based on simulations that produce a distribution for the quantities of interest rather than simple deterministic values. The width of these distributions provides an estimate of the uncertainty and will typically be larger as time increases from the base year. While projections are made from the base year of 2021, the historical values of biomass etc are shown for comparison. It is important to note that the estimates of revenues are all based on price information provided by the user for current conditions. GFPM does not account for historical prices, changes in value or inflation.

Scenario model

The population dynamics are described by a Schaefer model in terms of the carrying capacity, B_0, and fishing mortality at maximum sustainable yield, F_{MSY}. The biomass, B, at time t is projected forward from the equation:

$$B_{t+1} = \left[B_t\left(1 + 2F_{MSY}\left(1 - \frac{B_t}{B_0}\right)\right) - \sum_j Y_{j,t}\right]\exp(\varepsilon_t)\,, \qquad \varepsilon_{j,t} \sim normal(0, \sigma_B) \tag{1}$$

Where $Y_{j,t}$ is the unobserved true catch by fleet j in year t and $\varepsilon_{j,t}$ is a random process error with a zero mean and standard deviation σ_B. The catch by fleet, $Y_{j,t}$, is a function of the biomass that depends on an annual fishing mortality, $F_{j,t}$, such that:

$$Y_{j,t} = B_t F_{j,t} \tag{2}$$

F is assumed to be proportional to fishing effort, f, with constant catchability, q, so that $F=qf$. Saiko is taken only by one fleet (industrial trawl, referenced with subscript I) and the catch by this fleet can be split into a recorded catch $Y_{I,r,t}$ and a saiko catch, $Y_{I,s,t}$, so that:

$$Y_{I,r,t} = B_t F_{I,r,t} \text{ and } Y_{I,s,t} = B_t F_{I,s,t} \tag{3}$$

The fishing mortality due to saiko is a fixed proportion of the industrial fleet fishing mortality:

$$F_{I,r,t} = \alpha F_{I,t} \text{ and } F_{I,s,t} = (1 - \alpha) F_{I,t} \tag{4}$$

Where α represents the proportion of the fishing mortality associated with the recorded catch.

Results from the assessments provide estimates of biomass for each stock in 2021 forming the base year (denoted by *) for forward projections under differing fishing scenarios. The assessments also provide estimates of fishing mortality by fleet, *j* on stock, *i*, in 2021 i.e. $F_{j,i,*}$. Any variation in fleet effort affects the fishing mortality by that fleet on all stocks equally, so that for a future year, *t*, the fishing mortality is given by:

$$F_{j,i,t} = h_{j,t} F_{j,i,*} \tag{5}$$

Where *h* represents a multiplier that rescales *F* reflecting a change in fleet effort. The stock biomass and associated catches can now be projected forward for given values of *h* using equations (1) and (2).

Equation (5) assumes that fleets fish in the same way regardless of the level of effort. In the case of saiko, it is of interest to know how a change in fleet behaviour, even if effort is unchanged, affects fishing mortality. In this case, if the saiko *F* is reduced by a multiplier, β_t, then the revised fishing mortality is given by:

$$F_{I,i,t} = h_{I,t} F_{I,i,*}\left(\alpha_{i,*} + \beta_{i,t} - \alpha_{i,*}\beta_{i,t}\right) \tag{6}$$

Where the subscript I references the industrial trawl fleet. The revised annual value of α is now given by:

$$\alpha_{i,t} = \frac{1}{\left(1 - \beta_{i,t} + \frac{\beta_{i,t}}{\alpha_{i,*}}\right)} \tag{7}$$

Here β represents a change in fleet behaviour because it alters the fishing mortality related to saiko affected stocks while the mortality on other stocks taken by the same fleet remains unchanged. By implication it assumes that measures can be taken to limit the saiko catches without affecting overall nominal fleet effort, such as days fishing.

Fishery projections are made by drawing a vector of parameters from each of the samples saved from the MCMC chains in the stock assessments (see Appendix 1) and running the biomass forward for a specified number of years. In each run process error is modelled as random effects on the biomass (equation (1)) and on the fishing mortality where for each year the realised fishing mortality $F'_{j,i,t}$ is derived from a lognormal distribution:

$$F'_{j,i,t} \sim lognormal\left(\log\left(F_{i,j,t}\right), \sigma_f\right) \tag{8}$$

Where σ_f is the standard deviation expressing the process error on F and is taken from the stock assessment model output.

The projections are repeated for all 500 samples derived from the stock assessments. The estimated ratio B/B_{MSY} from each run is saved and summarised by the median and 95% interval for each year. Revenues are calculated as a simple multiple of the catch multiplied by the unit price for each stock. Saiko catches are excluded from the revenue calculations.

Guidance for users

Running the model requires the user to specify effort multipliers for each fleet. The model assumes the effort in the base year=100%. This means all subsequent years are scaled to that value. Hence a 10% reduction in effort would correspond to effort of 90% while a 10% increase would take a value of 110%. Removing a fleet from the fishery is simulated by setting the effort multiplier to zero. Large changes in the effort multiplier between consecutive years, such as a change from 100% to 50% (halving the effort in a single year) will be very disruptive to the operation of the fishery and it is generally more realistic to consider smaller annual changes of 5-20% per year. However, very small changes of just a few percent are likely to be ineffective in practice due to resistance by the fishery in implementation.

Simulating changes to saiko catches is achieved in a similar way to the fleet effort changes. The model takes the base year as 100% and any reduction is modelled by setting a multiplier between 0-100. However, this multiplier only applies to stocks taken as saiko by the industrial trawl fleet. It does not affect non-saiko stocks fished by the industrial trawlers. Changing the saiko multiplier assumes that the industrial fleet can adjust its behaviour to avoid certain stocks (such as fishing in different areas to avoid saiko) without changing the amount of effort (days fishing).

In its current form GFPM calculates revenues based on price data input by the user. These are single values for each stock and are applied throughout the historical and projection period. This is not a true economic model and therefore does not take into account changes in price resulting from supply and demand, inflation etc.

The base year of 2021 for projections is constrained by the data currently available for stock assessment. Over time conditions in 2021 will be superseded by real events in the fishery that may alter the trajectory of the stocks. As 2021 slips further into the past, it will make projections from the current model less relevant unless the underlying data are updated. This will require an update to the stock assessments and should be done annually if possible. In any event an update every five years would be desirable as a minimum.

Appendix. Assessment model description

Data

Table 1 lists the catch and effort data for 11 stocks exploited by 10 fleets in Ghanaian waters. For the period 2000-2021 data were provided by the Ghana Fisheries Scientific Survey Division (FSSD). Data from 1990-1999 were taken from the relevant FAO reports (FAO 2019a and b). Data in the FAO reports include the period 2000-2016/7 and overlap with the FSSD data. There were small discrepancies between the two data sets in the overlap period. We chose the FSSD values in preference to FAO data as they were cross checked with FSSD. In the case of the industrial trawl effort data, the FSSD values were substantially higher than the corresponding FAO data leading to a scale mismatch between the periods 1990-1999 and 2000-2021. However, in the overlap period the two effort series were correlated so we rescaled the FAO effort data for 1990-1999 to the FSSD units using a calibration regression.

In the case of the pelagic species, FAO catch data are aggregated into a single "artisanal" fleet comprising the four artisanal fleets APW, set net, beach seine and hook and line. Catches for 1990-1999 were therefore split down to fleet using the mean ratio of the catches by fleet from the overlap period 2000-2016 in the FSSD data in order to provide a consistent time series.

The EJF (2020) report provides an estimate of the overall magnitude of the saiko catch from which catch by species can be calculated. The estimate of 100,000t is for one year only, 2017. The EJF estimated the species composition for the period September 2018- September 2019 to be 11% round sardinella, 6% flat sardinella, 6% bigeye grunt and 3% red Pandora. The data appear to have been collected systematically from two principal ports, Elmina and Tema. These percentage compositions were applied to the 2017 overall saiko catch figure to obtain estimates of the species catch for that year.

Assessment model including saiko

The stock assessment model in Cook et al (2021) was adapted to allow the inclusion of saiko catch and applied it to all stocks listed in Table 1.

The population dynamics are described by a Schaefer model in terms of the carrying capacity, B_0, and fishing mortality at maximum sustainable yield, F_{MSY}. The biomass, B, at time t is projected forward from the equation:

$$B_{t+1} = \left[B_t\left(1 + 2F_{MSY}\left(1 - \frac{B_t}{B_0}\right)\right) - \sum_j Y_{j,t}\right]\exp(\varepsilon_t)\,, \qquad \varepsilon_{j,t} \sim normal(0, \sigma_B) \tag{2}$$

Where $Y_{j,t}$ is the unobserved true catch by fleet j in year t and $\varepsilon_{j,t}$ is a random process error with a zero mean and standard deviation σ_B. The catch by fleet, $Y_{j,t}$, is a function of the biomass that depends on an annual fishing mortality, $F_{j,t}$, such that:

$$Y_{j,t} = B_t F_{j,t} \tag{3}$$

We assume 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:

$$F_{j,t} = q_j f_{j,t}(1 + \delta_j)^{(t-1)} \tag{4}$$

For identifiability it is necessary to constrain the estimates of δ. We set the mean power increment, $\bar{\delta}$, over all m fleets to 0.03 corresponding to the median power increase from a study of 50 fleets (Palomares and Pauly, 2019):

$$\bar{\delta} = \frac{\sum_{j=1}^{m} \delta_j}{m} = 0.03 \tag{5}$$

In order to reduce the number of effective parameters to be estimated we assume that fishing effort follows a random walk,

$$f_t \sim lognormal\left(\log(f_{t-1}), \sigma_f\right) \tag{6}$$

The model is easily adapted to include saiko catches subject to certain assumptions. If saiko is taken only by one fleet (industrial trawl, referenced with subscript I) then the catch by this fleet can be split into a recorded catch $Y_{I,r,t}$ and a saiko catch, $Y_{I,s,t}$, so that:

$$Y_{I,r,t} = B_t F_{I,r,t} \text{ and } Y_{I,s,t} = B_t F_{I,s,t} \tag{7}$$

We now make a similar assumption as in equation (1) that the fishing mortality due to saiko is a fixed proportion of the industrial fleet fishing mortality:

$$F_{I,r,t} = \alpha F_{I,t} \text{ and } F_{I,s,t} = (1-\alpha) F_{I,t} \tag{8}$$

Where α represents the proportion of the fishing mortality associated with the recorded catch. With this assumption it is possible to estimate α given at least one observed value of saiko. Catches of saiko for all years can then be estimated since these values are now a simple function of the model parameters (equations 7 and 8). The estimates will be less prone to observation error since they are calculated from fitted values rather than the observed reported catch in equation (1).

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:

$$f'_{j,t} \sim lognormal(\log(f_{j,t}), \sigma_j) \tag{9}$$

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 there are a number of zero observations and 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 et al, 2021):

$$Y'_{j,t} \sim negative\ binomial(Y_{j,t}, \kappa_j) \tag{10}$$

Equation (9) is applicable for all non-saiko fleets where the reported catch represents all the catch. For the industrial fleet the observed catch is partitioned between the recorded catch and saiko. For the recorded component equation (10) similarly applies:

$$Y'_{r,t} \sim negative\ binomial(Y_{r,t}, \kappa_r) \tag{11}$$

Given multiple observations of $Y'_{r,t}$ the dispersion parameter κ_r is estimable. However, for the single saiko observation the dispersion parameter cannot be estimated so we assume it takes the same value as κ_r so that:

$$Y'_{s,t} \sim negative\ binomial(Y_{s,t}, \kappa_r) \tag{12}$$

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). As far as possible uniform priors were applied to the model parameters (Table 2). However, a square root uniform prior was applied to the carrying capacity B_0. A beta prior with a mean of 0.3 which approximates to the midpoint of a meta-analysis of F_{MSY} values calculated by Sparholt et al (2021) was applied to F_{MSY}. In the model, the biomass in the first year is a parameter to be estimated. For convenience a depletion parameter, *d*, was estimated representing the proportion of virgin biomass, B_0, present in the initial biomass, i.e $B_1=dB_0$, and set a uniform prior (0,1) on *d*. Three MCMC chains for 50000 iterations were run with a thinning rate of 150 and a burn-in of 25000. This gave 500 samples for each model fit which were saved for use in the scenario model.

For some stocks the catches for a given fleet were very small, often with many zero values. We aggregated fleets where the mean fleet catch represented less than 5% of the total mean catch into an "Other" category. These catches were included in the model fit but without associated effort data since aggregating non-standardised effort across diverse fleets is not appropriate. Table 1 shows the fleets used for each stock.

The model was fitted to all stocks setting α=1 for those stocks for which there is no saiko catch.

References

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 (2021) *106048.*

EJF 2020. The "people's" fishery on the brink of collapse. Small pelagics in landings of Ghana's industrial trawl fleet. Environmental Justice Foundation, 1 Amwell Street, London, EC1R 1UL, United Kingdom. https://ejfoundation.org/resources/downloads/EJF-report-small-pelagics-2020-final.pdf

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

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

Sparholt, Henrik, Bjarte Bogstad, Villy Christensen, Jeremy Collie, Rob van Gemert, Ray Hilborn, Jan Horbowy, Daniel Howell, Michael C Melnychuk, Søren Anker Pedersen, Claus Reedtz Sparrevohn, Gunnar Stefansson, Petur Steingrund (2021). Estimating Fmsy from an ensemble of data sources to account for density dependence in Northeast Atlantic fish stocks. *ICES Journal of Marine Science*, 78, 55–69, https://doi.org/10.1093/icesjms/fsaa175.

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

Table 1.. Stocks and fleets used in the analysis. The APW fleet represents the "ali","poli" and "watsa" purse seine gears. Solid dots identify fleet effort and catches used in each stock assessment. Open circles identify fleet catches that were aggregated into an "other" category and used in the assessment but without corresponding aggregate effort data.

Stock	Fleet									
	Industrial trawl	Pair trawl	Coastal trawl	Shrimp trawl	APW	Beach seine	Set net	Hook and line	Inshore purse seine	Drifting gill net
Anchovy *Engraulis enrasicolus*					●	●	○	○	○	
Bonga *Ethmalosa fimbriata*					●	●	●		○	●
Round sardinella *Sardinella aurita*	●				●	●	●	○	●	○
Flat sardinella *Sardinella maderensis*	●				●	●	●	○	●	○
Chub mackerel *Scomber colias*	●				●	○	○	●	●	○
Cunene mackerel *Trachurus trecea*	○				●	●	●	○	●	○
Bigeye grunt *Brachydeuterus auritus*	●	○	●	○	●	●	●	●		
Croakers *Pseudotolithus spp*	●	○	●	○	●	●	●	●		
Red Pandora *Pagellus bellottii*	●	●	○	○	○	○	●	●		
Sea breams *Dentex spp*	●	●	○	○	●	○	●	●		
Threadfin *Galeoides decadactylus*	●	●	○	○	●	●	●	●		

Table 2. Priors used on model parameters for the stock assessment model.

Parameter	Prior distribution
F_{MSY}	Beta(2,5)
$\sqrt{B_0}$	Uniform(1,$\sqrt{10 * \max(catch)}$)
d	Uniform(0,1)
$f_{1,j}$	Uniform(0.01,10)
q_j	Uniform(0.001,100)
σ_B	Uniform(0,1)
σ_f	Uniform(0,1)
σ_j	Uniform(0,10)
κ_j	Uniform(0.001,100)
κ_r	Uniform(0.001,100)
α	Uniform(0,1)