Assessing a data-limited horse mackerel stock using the Gadget modelling framework

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Marine Resource Management

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Abstract

Over the past years, fisheries stock assessment in Angola has been done using cohort analysis in a yield-per recruit, and schaefer surplus production model. Lack of biological data such as sex, size and age-based differences in these models limits a holistic view of the dynamics of the fish stock population. Therefore, the Gadget modelling framework was used to build a stock assessment model to analyse the horse mackerel stock along the Angolan coast.

A time-series survey data collected onboard of R/V DR. FRIDTJOF NANSEN and commercial catch data consisting of sex, maturity, gear, and length distribution was used to assess the stock. As the model is size and age structured it is able to integrate various disparate data sets and thus is able to provide insights into the population dynamics.

The main objective of the project was to investigate the feasibility of assessing the horse mackerel stock using the age-length Gadget modelling framework in order to:

1. Provide an estimate of the absolute biomass and thus improve advice on exploitation;
2. Define short- and long-term projections from the model;
3. Set biological and management reference points.

The model showed a bad fit due to inconsistent data. This highlights the need for further data exploration. However, it seems to capture some of the trends in the larger length groups. Overall, the Gadget modelling framework proved to be a feasible tool to assess the stock dynamics of horse mackerel data.

Úrdráttur

Á liðnum árum hefur úttekt á veiðiþoli fiskistofna við Angóla verið framkvæmd með greiningu á afrakstri á nýliða og árgangastyrk í afraksturslíkani. Lífmælingar, ss kyn, kynþroski, stærð og aldur, hafa ekki verið nýttar í fyrrnefndum líkönum og takmarkar það möguleikann á heildrænni úttekt á stofninum. Hér er því heildrænt mat á viðgangi brynstirtlu undan ströndum Angóla sett fram byggt á stofnmatslíkan byggt á Gadget umhverfinu.

Tímaraðir lífmælingagagna (þ.m.t kyn, kynþroski og lengd) söfnuðum í leiðangri R/V DR. FRIDTJOF NANSEN annars vegar og úr veiðum hinsvegar voru nýttar til þess að meta líkan af viðgangi brynstirtlustofnsins. Þar sem líkanið er aldurs- og stærðarháð getur það samþætt upplýsingar af margvíslegum toga og veitt þannig innsýn inn í viðgang stofnsins.

Markmið verkefnisins voru að kanna hvort hægt væri að meta stofnstærð brynstirtlu með aldur-lengdarháðu líkani smíðuðu í Gadget umhverfinu með það að markmiði að:

1. Meta heildar lífmassa stofnins og bæta þannig ráðgjöf um nýtingu
2. Herma viðgang stofnsins til lengri og skemmri tíma
3. Meta viðmiðunarpunkta og mögulegar aflareglur sem taka tillit til hámarksafraksturs- og varúðarsjónarmiða

Niðurstöðurnar sýna að líkanið á erfitt með að fylgja ósamstæðum gögnum. Líkaninu tekst hinsvegar að fylgja leitni í vísitölum stærri fiska. Á heildina litið reyndist Gadget líkanaumhverfið vel til þess að meta viðgang brynstirtlustofnsins.

Dedicated to my late Father who was an advocate of knowledge seeking

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Abbreviations

CPUE – Catch Per Unit Effort
EEZ – Exclusive Economic Zone
EU – European Union
FAO – Food and Agriculture Organization
ICES – International Council of Exploration of the Sea
INIPM – Instituto Nacional de Investigação Pesqueira e Marinha
LOSC – Law of the Sea Council
MFDB – Mareframe Database
MSY – Maximum Sustainable Yield
TAC – Total Allowable Catch
UN – United Nations

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I want to thank first and foremost my faculty coordinator Prof. Gunnar Stefánsson for suggesting as main advisor Dr. Bjarki Þ. Elvarsson who has been tremendously helpful and given imperative support. Both have provided important guidance, ideas, inspiration and helped me in numerous sessions where we have discussed and progressed with the main ideas. Secondly, I would like to thank GRÓ Fisheries Training Programme for their generous funding of my Master's program. It has allowed me to stay more focused on my work and spend more time on it, for which I am ever grateful. I want to especially thank Dr. Tumi Tómasson.

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1 Introduction

1.1 Background

In order to increase the accuracy of available stock biomass estimates there is a need to employ assessment models that can use diverse information of the stock for the results to be as close to reality as possible. Such assessments improve the management measures through the advice given on allocation of TAC of certain fish stocks (Carruthers, et al., 2014), particularly those that are of great commercial importance which is the case for the Cunene horse mackerel (*Trachurus trecae*) in Angola. Management measures aim to maintain or restore the population level of fish stock to achieve maximum sustainable yield (MSY) (Hilborn, et al., 2020), which is towards fulfillment of the SDG 14.4. This in a way, coincides with the World Summit on Sustainable Development of 2002 which recommends the exploitation of fish stocks sustainably by setting harvest control rules employing precautionary approach and MSY when allocating TAC (UN, 2002). It also fulfils one of the duties of coastal states under UNLOS article 62 “Adopting conservation and management measures to ensure that fish stocks in its EEZ are not endangered by over-exploitation, taking into account the best scientific evidence available” (UN, 1982). However, for a stock to be assessed and advised based on MSY requires robust data sets consisting of among others age-structured data, abundance indices from surveys or commercial fleets (NOAA FISHERIES, 2012).
Many stock assessment models require for instance growth, natural mortality and recruitment, as well as selectivity data and information to be able to interpret the assessment (Maunder & Piner, 2014). In the absence of or limited analytical stock assessment and catch-at-age composition data, assumptions have to be made which can either be implicit or explicit depending on the method used (Bonfil, 2012). However, the use of assumptions increases bias and error in the assessment and increases the uncertainty of the results and management advice (Maunder & Piner, 2014). A data set is classified as data limited when it lacks content that permits a clear assessment, resulting in quantitative prediction (ICES, 2012).

Various exploited stocks around the world lack age information. One main reason can be the complexity involved in reading the otolith and scale rings which reflects the years (Longhurst & Pauly, 1987; Green, *et al*., 2009). Cunene horse mackerel is no exception to that deficiency, actually it presents worse challenges for the fact of it being a tropical species. The low cyclic interruptions to growth (Longhurst & Pauly, 1987), and a weak seasonality which is necessary to generate time-dependent banding in calcified structures needed to derive age and age-based life-history affects otolith reading of tropical species (Pitcher & Hart, 1982; Longhurst & Pauly, 1987). However, in recent years, more attention has been dedicated in studying ways of how to improve the reading of the tropical species otolith (Green, *et al*., 2009), but due to high investment needed such methods have not been applied yet for Cunene horse mackerel.

The exclusion of biological data such as sex, size, and age-based differences in the surplus production models that treat stock as identical biomass, implicates significantly on our ability to accurately model the dynamics of the fish population (Haddon, 2011).
It is, therefore, necessary to look at the uncertainty in parameter estimates whenever models are fitted to data, and for the sake of comparison and validation it is always prudent to run different models with the same data set so that there is less error in scientific recommendations and thus improving management advice (Bonfil, 2012). In light of looking for assessment models that would address the aforementioned limitations as well the errors, a Gadget model will be used. This model integrates various steps of analysis into a single stock assessment model, and by using other size-structured biological information it provides understanding into the stock dynamics (Begley, 2017; Elvarsson, *et al*., 2018).

1.2 Angolan fisheries

1.2.1 Horse mackerel fishery in Angola

Horse mackerel is a straddling stock shared between Angola and Namibia in the south, considered to be the most important species in Angola for it constitutes 24% of total annual catches and is the most consumed species by the population (INIPM, 2017; Agostinho & Ólafsdóttir, 2018). There are two horse mackerel species (*Trachurus* spp), that is, Cunene horse mackerel (*Trachurus trecae*) and Cape horse mackerel (*Trachurus capensis*) which are managed as one stock. The fishery began in the late 1940s and has been managed using total allowable catch (TAC) since 1995. The TAC is established by scientific stock assessment conducted by the National Fisheries Research Institute (INIPM). The fishery averages 55 000 tons per year caught predominantly by semi-industrial and industrial fleets, that use purse seine and trawl as the gears for fishing.

Horse mackerel fishery is one of the main fisheries in Angola with its importance on the economy and human diet as a source of animal proteins with national consumption of 19 kg per person yearly (Chilamba, 2016; Agostinho & Ólafsdóttir, 2018). The fishery operates in three provinces located adjacent to the major horse mackerel distribution areas: Namibe, Benguela and Luanda (Figure1).

Figure 1. Horse mackerel fishery in red circles. Source: Chilamba, 2016.

The fluctuation in catches reported amongst other, is a result of changes in population size, fleet composition and fishing effort (ITC Executive Forum, 2003).

In 1995, TAC was implemented as fisheries management tool to regulate the catches. The TAC is set based on scientific advices (INIPM, 2016). A TAC limits have fluctuated with an average of 60 thousand tones (INIPM, 2016; INIPM, 2018), (Figure 2).

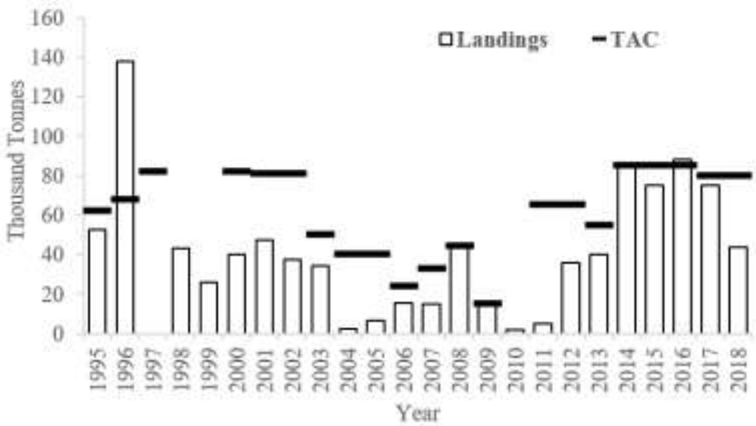

Figure 2. Horse mackerel catches and recommended total allowable catches in Angolan EEZ from 1985 to 2018 (source: INIPM, 2018).

Over the years, INIPM has relied on Schaefer surplus production and yield per recruit models to assess the Cunene horse mackerel stock, relying on catch data and abundance indices from surveys conducted during the winter season since 1985 (MinPescas, 2019). However, inconsistencies in the catch data and lately in the implementation of surveys has led to a need for alternative models that assess the population size with less bias and uncertainty using the available data. Age-Structured models as described by Haddon (2011) and other VPA-based methods (Maunder & Piner, 2014), depend on data that have age information and consistency over a period of years, and cannot be used to assess the stock. This is due to limited age data, which is a fundamental component needed among others to assess the dynamics of the stock (Bonfil, 2012).

Due to the high value and importance of the species, it is of paramount interest for scientists and managers to increase knowledge on the population dynamics of horse mackerel. The development of an analytical modelling assessment may help predict horse mackerel population dynamics in depth and with an increased level of precision.

1.3 Objective

The main objective of this project was to investigate the feasibility of assessing horse mackerel stock size in Angola's waters by using the length Gadget modelling framework. The results of from using this modelling framework, will serve to fill the gap present in the stock production model.

1.3.1 Specific objectives

a) Provide an estimate of the absolute biomass which depends the advice on management;
b) Define short- and long-term projections from the model;
c) Set biological and management reference points.

1.4 Structure of thesis

This thesis comprises five main chapters summarized as follows. Chapter one gives an overview of the horse mackerel fishery in Angola and assessment, and objectives of the study. In chapter two, a review of the concept of stock assessment, its application in fisheries management, and a brief review of using the Gadget model in the study is given. In chapter three, a detailed account of the methodological aspects of the study is given, including methods of data collection and, the empirical model used. In chapter four, the study results are given and starts by providing the population estimate, likelihood scores and the biomass estimate. The last chapter gives the discussion of the results, study limitations, recommendations and study conclusions are highlighted.

2 Literature review

2.1 Fisheries management

Management of natural resources is an ever-challenging task and fishery is no exception (Jentoft & Chuenpagdee, 2009). It is rare to find a thriving management policy implemented in a fishery around the world despite the advanced efforts of adapting policies to new realities by engaging as much as possible the three main pillars of sustainability composed of the environmental, economic and social dimensions in policy frameworks (Song & Chuenpagdee, 2010).

Fisheries management has no clear definition nor a generally accepted one, however, it encompasses a range of complex attributes that jointly implemented can achieve the main goal which is sustainable fisheries resource utilization (Cochrane, 2002). It is a broad field that applies various measures or approaches with the sole purpose of sustainably managing a particular fishery. Some managers use seasonal closures during periods of recruitment as a management approach, while others prefer TAC system that depends on stock assessment (Melnychuk, *et al*., 2017). Implementation of MPAs has been widely advocated as appropriate for managing multiple fish species (Hilborn, et al., 2020). However, the efficacy is highly dependent on the enforcement as well as compliance from the resource users (de Beer, 2014). Because of different stressors that impact marine ecosystems it is important that fisheries management strategies are not static i.e., they should be adaptable in line to changes that are occurring in the system (de Beer, 2014). The dynamics and complexities are so intrinsic in fisheries and coastal systems that sometimes, governors are confronted with challenging and complicated tasks with no apparent solution. The uncertainties are always present without regards to the available tools in use. The list is so long that such problems deserve being termed as "wicked" (Jentoft & Chuenpagdee, 2009).

Undeniably, fisheries management consists of diverse challenges that more often than not leads to poor results (Jentoft & Chuenpagdee, 2009). These results, revamps the game of scape goat that governments know best to play while scientists are trying to understand the system and why the proposed solutions do not work out, and the policy makers will be re-strategizing their policies to give quick solutions which many times are not consistent (Jentoft & Chuenpagdee, 2009).

2.2 Stock assessment methods

Scientific assessment is one of the keys to sustainable fisheries management. However, the vast majority of the world's fisheries lack scientific assessments or management guidance, resulting in high risk of decline and collapse (Hilborn & Peterman, 1995).

Stock assessment is one key component in the fisheries management cycle. It incorporates various steps including collection of data, data analyses, and information and result sharing so that there is awareness or understanding of abundance changes in stocks due to fishing pressure. Stock assessment helps in improving the prediction of how stocks will change with time (NOAA FISHERIES, 2012). It serves mainly to develop mathematical models among other methods with gathered fishery data that can be used to identify sustainable management practices through models' interpretation and predictions. The models also provide reference points like MSY, harvest rates that fishery managers can use as a basis in assessing as well as. defining current and future possible condition of a particular fishery (Lorenzen, *et al*., 2016).

Various quantitative models have been used in stock assessment of different fish species. Under a scenario where data of a given stock is limited, length-based methods tend to be instrumental to determine and quantify future catch as well as outlining limitations and applicability of such models. Length Based Spawning Potential Ratio (LBSPR), Length Based Thompson and Bell (TB) i.e. yield per recruit model, the Schaefer model and other, surplus production models, are some of the models used (Chong, et al., 2020).

There is a need for alternative models that would provide better assessment using more information in order to more accurately reflect the reality of the dynamics of the stock. However, the lack of age, and CPUE data makes it challenging to come up with such assessments.

Gadget (Globally applicable Area Disaggregated General Ecosystem Toolbox) model is a multispecies ecosystem model with a robust and flexible framework (Begley & Howell, 2004). Gadget can take many features of the ecosystem into account: One or more species, multiple areas, size at maturity, reproduction and recruitment, multiple commercial and survey fleets (Stefánsson, 2003). A suitable integration of various components of a model is possible to apply likelihood components. Gadget's suitability can further be supported by the integration of species interaction and the impact of fishing pressure on that species (Taylor, *et al*., 2007). It is possible to integrate sets of data into the same model with incomplete time series data at different aggregation levels and scales (Bartolino, *et al*., 2011). Thus, the Gadget modelling framework is flexible, and can cope with little data. Gadget is freely available and has been widely applied in stock assessment especially in the EU, Iceland and Norway because of its flexibility and its ability to run on little data, and to integrate various features. For instance, it been used for assessment of ling (*Molva molva*) and tusk (*Brosme brosme*) in Icelandic waters using size- and age-structured data (Elvarsson, *et al*., 2018).

2.3 Horse mackerel biology

Two horse mackerel species are found in Angolan waters, Cunene horse mackerel (*Trachurus trecae*) and Cape horse mackerel (*Trachurus capensis*). However, for this study only the focus is on the Cunene horse mackerel. It is a benthopelagic species that occurs in coastal waters at depths between 0-50 m and in deeper shelf waters at depths up to 500 m (Vaz-Velho, *et al*., 2006). The species is found from southern Angola extending to the northern border of Guinea-Bissau (latitude from 35°N to 19°S) (FAO, 2017). Juveniles occupy the southern part of the distribution range in colder and more nutrient rich waters compared to the north (INIPM, 2017). Adults are more abundant in the northern part with the highest abundance recorded off the central part of Angola (latitude from 9°S-13°S) at depths from 20 m to 100 m. Cunene horse mackerel is usually located in temperatures ranging from 15°C to 22°C (FAO, 2017). Limited information is available on seasonal migrations of the species, spawning location, and spawning season. It is believed that *T. trecae* like other *Trachurus* species, spawn throughout the year with peaks from May to August which coincides with the closed fishing season (Ndjaula, *et al*., 2013; INIP, 2014). Cunene horse mackerel recruits to the fisheries at the age of 2 which corresponds to 21 cm fish (Vaz-Velho, *et* al, 2006; INIPM, 2016), maximum age reported is 10 years (FAO, 2017).

3 Methodology

The research followed the methodology described by Elvarsson et *al.* (2018), which specifies data challenges in stock assessment using Gadget, using the available data on the population of horse mackerel. The assessment model is further extended by setting up a projection model by which precautionary biomass reference points were derived. The projection model was then used as the operating model on which a management strategy evaluation was based, and application of simple harvest control rule simulated.

The data used is of Cunene horse mackerel, that occurs extensively in the entire Exclusive Economic Zone (EEZ) of Angola, between the Congo river (6°S) and the Cunene river mouth (17.15°S), mostly caught at night when they aggregate into surface shoals. They have a diel vertical migration (INIPM, 2014). Abundance indices from annual scientific surveys, catch data as well as sex, maturation, type of gear used and, age-length distribution constitute the data that will be used to assess the stock in the age-length Gadget modelling framework.

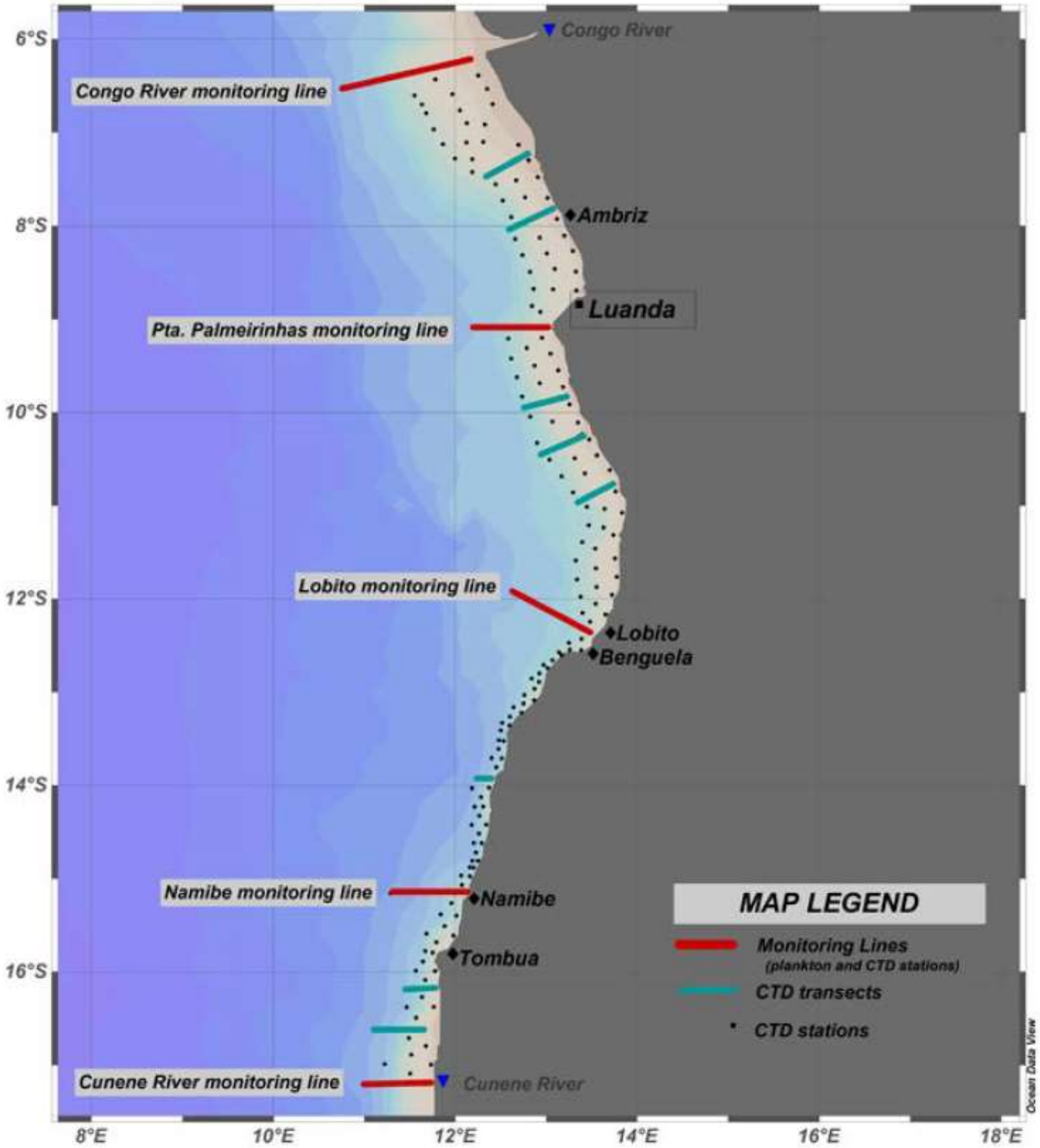

Figure 3. The study area in Angola's EEZ where independent survey and commercial catch data was collected. Dotted lines represent the stations within the survey transects and the light blue and red lines are the environmental parameter points. Source: (Michelson, *et al*., 2015)

3.1 Data collection

The data was collected from, the commercial fishery and from independent surveys conducted from 1985 during winter and summer covering the entire area of distribution within the Angolan EEZ (Agostinho & Ólafsdóttir, 2018). The surveys are randomly stratified in transects were both bottom and pelagic trawls are used to confirm the acoustic responses and collect specimen for biological sampling. Due to the inconsistency in the summer surveys, this study only uses the winter survey data.

The commercial fishery consists of two fleets, the industrial fleet mainly dominated by bottom trawl gear and semi-industrial fleet that is dominated by purse seine gear. These two fleets supply landing data and specimens to INIPM for biological sampling consequently incorporated into stock assessment models.

3.2 Setup of a Gadget run and model operation

Initially the data was imported and processed into a database system interfaced with MFDB (Lentin & Elvarsson, 2020), and final analysis was conducted using Rgadget (Elvarsson & Lentin, 2020), the two being special R packages (Elvarsson et *al*., 2018). The latter R package allows rapid and reproducible model building and analysis within the Gadget framework (Elvarsson, et *al*., 2018).

An in-depth description is given on various aspects involved in operating the model. Steps taken in this model followed the instructions from the Gadget User Guide (MFRI, 2017) as well as the updates from a course offered by Elvarsson & Woods (2020).

Various aspects constitute the model, ranging from model components, likelihood and observation (figure 6).

3.2.1 General Gadget model framework

The general composition of the present Gadget model framework is of an age-length based nature, consisting of several equations and initial parameters.

A total of seven R codes were created to make the model functional. This was set by creation of an R code that uploads and runs the fleet data constituted by two commercial fleets, bottom trawl and purse seine, and a survey fleet. The catch distribution data, the survey indices, defined likelihood for the model, the model setup and lastly the main setup were. The model setup consists of population dynamics parameters from body growth, maturation, and recruitment. These are described by fixed values from length-weight relationship constant, natural mortality (M=0.3), and l_{50} of maturity (mat2=20). Estimated processes such as growth according to a von Bertalanffy growth equation, growth dispersion, recruitment length, fishing selectivity, maturity ogive, initial abundances and survey catchability were set. The setting up of the immature and mature portions of the stock component (age range from 1 to 10 years, and 4 length bins 4-20, 20-30, 30-40 and 40-60) with its various parameters ranging from stock to predator. The proceeding step within this code is definition of timeseries range (1995 to 2018) each year divided into 4 steps composed of three months, structuring the area set to 1 and finally the last chunks of the code linking to the first five codes that enable the model to run. The codes all followed the structure from the ling assessment model by Elvarsson *et al*., (2018), (Github, 2020)

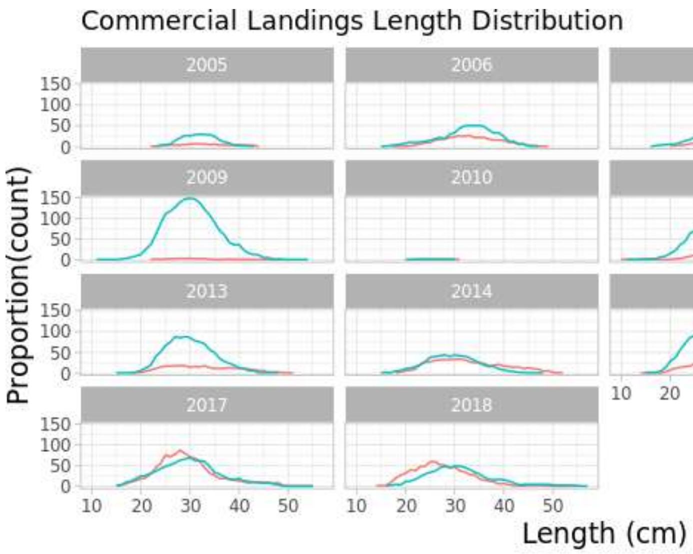

Figure 4. Length distribution proportions of horse mackerel in the commercial landings data over the years. Green and red colours denote the purse seine and bottom trawl gear respectively.

The numbers of fish predicted (Ny,t,r,l) at the most disaggregated level are numbers at year y, time step t, area r, and length l.

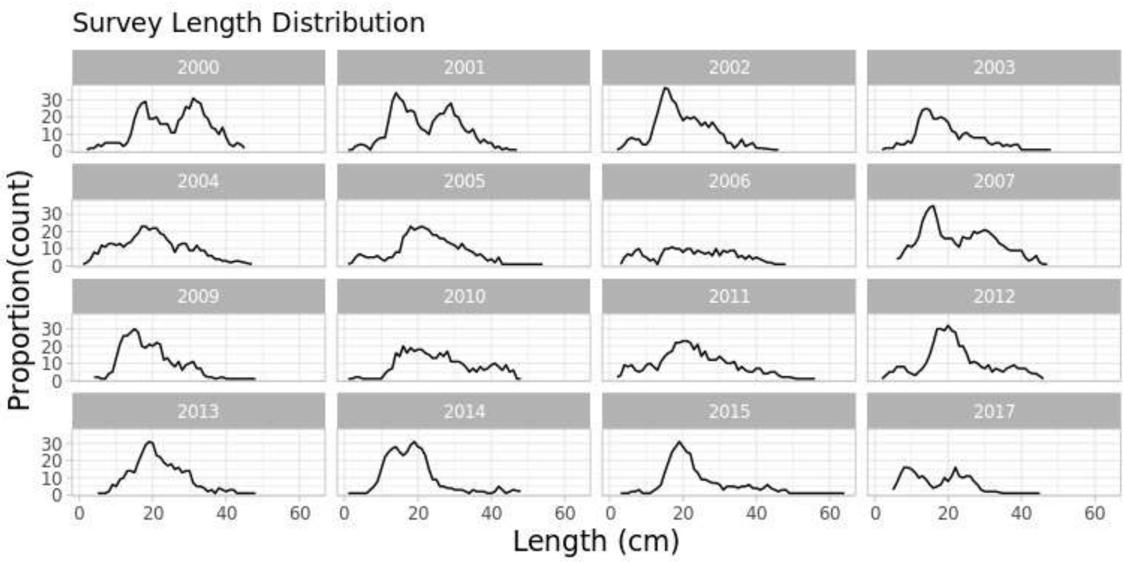

Figure 5. Length distribution proportions of horse mackerel in the independent survey data over the years.

The preceding length distribution represents a mere plotting of the observed data without any adjustments nor extrapolation whereas the length distribution figures in the result chapter is from the model, thus is the best combination of the observed data with the estimated proportions using the Gadget model.

A fishing process on both the mature and immature fish is described by a selectivity curve (see equation at 3.4.5) estimated by fleet and the total catches. The predicted length-, and maturity compositions are projected based on the input parameters and the likelihood fit according to the estimated selectivity curve and population composition predicted by the model at the time of the fishing event. By aggregating the various calculated levels facilitates in comparing the data by growth, length distribution as well as the description of population dynamics and its effects due to fishing such as total biomass levels, fishing mortality and recruitment. Finally, biomass is calculated using a length weight relationship formula ($w = a*L^{\wedge b}$).

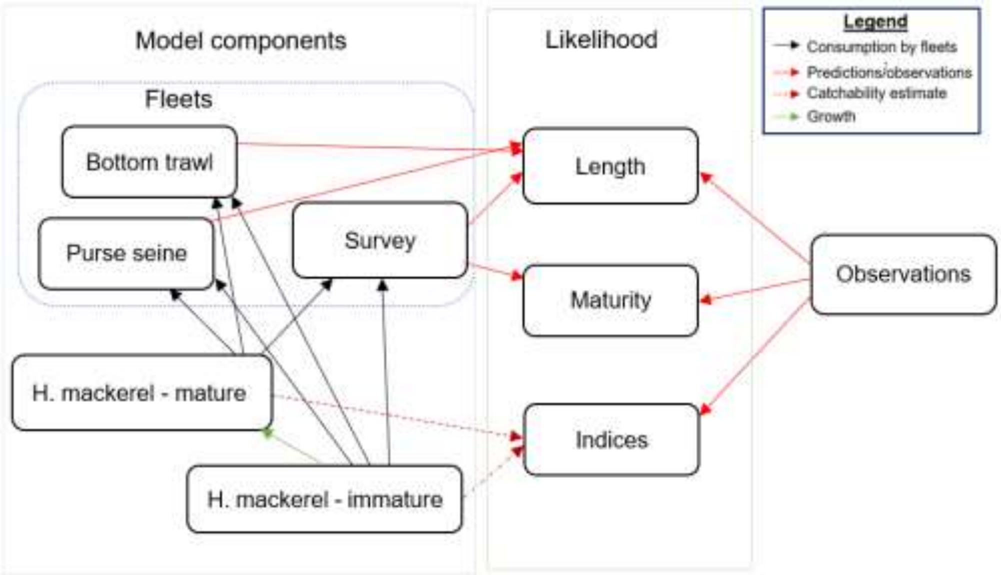

Figure 6. Schematic description of the Gadget model for Cunene horse mackerel. Lines indicate flow from one model component to the other. Black lines indicate consumption by predators (fleets), red lines the modelled predictions/observations sent to the likelihood and green line movement between immature and mature stock component. Dashed red lines indicate that predictions of survey indices were not adjusted by survey selectivity; instead, catchability was estimated. Source: adapted from Elversson, *et al*., 2018.

The model output is compared to data using a weighted likelihood function. The weights were estimated using an iterative reweighting heuristic, first applied by Taylor *et al*. (2007) and implemented in Rgadget. This heuristic, attempts to estimate the weights as the inverse of the model residual variance for each dataset. To prevent optimization issues a minimum CV was applied to the survey indices.

3.2.2 Specifications of the horse mackerel model

The horse mackerel model has a time range from 1995 to 2018 split into quarterly time-steps, covering a single area of the Angolan EEZ. The population of the horse mackerel stock was simulated in this model, splitting the stock into two portions, immature stock which was simulated with ages from 0 to 4. The length range considered is 4–20 cm. The mature fish was simulated from age 1 to age 10. The length range considered is 20 –52 cm. Two fishing fleets (purse seine and bottom trawl) were simulated in the model, along with one survey fleet.

3.2.3 Growth

Growth was based on a two-staged process whereby length and density were taken into consideration. It began by modelling size-dependent features through the application of a simplified Von Bertanlanffy function which is a parametric growth function adopted in this study:

$$\Delta l = (l_{\infty} - l)(1 - e^{-k\Delta t})$$

where l_{∞} is the maximum asymptotic length, t is time, and k is the annual growth rate. Lastly, the modelling of dispersion around the growth increment ($G_{l'}^{l}$) according to a beta–binomial density as described by Stefánsson (2005):

$$G_{l'}^{l} = B(\alpha, \beta, n)$$

with a mean αβ=Δl and $\alpha = \frac{\beta\, \Delta l}{n - \Delta l}$

where n is fixed as the highest length group steps by which a fish can grow in a particular timestep, and β estimated.

The weight at length-group l, $W_{s,l}$, was calculated as follows:

$$W_{s,l} = \mu_s\, l^{\omega s}$$

3.2.4 Natural mortality

Stock assessment models frequently adopt a constant natural mortality value. Therefore, the same assumption was used in this assessment, whereby based on previous assessment of horse mackerel stock M = 0.3 (INIPM, 2018) was chosen for the model.

3.2.5 Fleets

To cater for fishing selectivity in the model, a particular fleet function was modelled to display the different selectivity with respect to the type of gear used for fishing. An exponential l_{50} suitability function was used to estimate the length-based selectivity of the various portions of the stock as follows:

$$S_f(l) = \frac{1}{1 + e^{(-b_f\left(l - l_{50,f}\right))}}$$

where $S_f(l)$ is the selectivity of fishing fleet f on length l, and b_f and $l_{50,f}$ are fleet-specific parameters describing the logistic selectivity curve.

3.2.6 Maturation

Following Elvarsson, *et al*., (2018) maturation was modelled from the immature (s=0) to the mature (s=1) stock component, as shown in the equation below:

$$A_{a,l',l,s,y,t} = \begin{cases} N_{a,l',s'} = 0, y, t * m_l^{l'} \; if \; s = 1 \; and \; t > 1 \\ -N_{a,l',s'} = 0, y, t * m_l^{l'} \; if \; s = 0 \; and \; t > 1 \end{cases}$$

Where $m_l^{l'}$ is the proportion of immatures being matured after growing from length l′ to l, which is defined by:

$$m_l^{l'} = \begin{cases} \frac{\lambda(l-l')}{1+e^{-\lambda(l-l_{50})}} \; if \; a < a_{maxmat} \\ m_l^{l'} = 1 \; if \; a = a_{maxmat} \end{cases}$$

where l_{50} is the length at which 50% maturity and estimated along with a λ, with a_{maxmat} representing upper boundary of the maturity ogive after which all fish are mature.

3.2.7 Recruitment

The number of recruits each year (R_y) is estimated from a fixed effect entering in the population within the model as demonstrated in the equation below:

$$N_{a_{min},l,s} = o, y, t' = R_y p_l$$

Where *N* is the number of recruits entering the population, *t'* denotes the time-step of recruitment, *s* = 0 represents the immature, *l* denotes the length group, and p_l the recruited proportion in length-group *l*. The proportion p_l is calculated by a normal density, in which mean length set to the initial length (l_0).

3.2.8 Likelihoods

Length distributions modelled for both surveys and commercial fishery components will be compared to the likelihood data through the sum of squares function as follows:

$$l_f = \sum_y \sum_t \sum_l (\pi_{f,l,y,t} - \pi'_{f,l,y,t})^2$$

Where l_f is the fish number at a particular length, *f* the fleet, *y* the year, *t* the time-step, and *l* denoting the length. The proportions were calculated as below:

$$\pi_{f,l,y,t} = \frac{\sum_{a'} \sum_{s'} O_{f,a',l,s',y,t}}{\sum_l{}' \sum_{a'} \sum_{s'} O_{f,a',l',s',y,t}}$$

and

$$\pi'_{f,l,y,t} = \frac{\sum_{a'} \sum_{s'} C_{f,a',l,s',y,t}}{\sum_l{}' \sum_{a'} \sum_{s'} C_{f,a',l',s',y,t}}$$

Where $\pi_{f,l,y,t}$ is the proportion of the total fish observed belonging to a certain fleet/ length/year/time-step combination (*f, l, y, t*), and $\pi_{f,l,y,t'}$ is the corresponding proportion in the modelled population. Sum of squares is used to contrast data proportions to predicted maturity proportions.

The minimum CV value for the Survey index was set at 0.4 for each length range which was compared to the modelled abundance at a given year and time-step. Thus the survey index likelihood calculation, and a sum of squares of a log linear regression was used to test the fitness between the modelled data ($N'_{g,y,t}$) and the observed index ($I_{g,y}$) in the likelihood components, using Bartolino, *et al*., (2011) and Elvarsson, *et al.*, (2018):

$$l_g^{SI} = \sum_y \sum_t \left(logI_{g,y} - \left(logq_g + b_g logN'_{g,y,t} \right) \right)^2$$

Where

$$N'_{g,y,t} = \sum_{l \in g} \sum_a \sum_s N_{a,l,s,y,t}$$

$I_{g,y}$ denotes the summed survey index within an indicated length range, $N'_{g,y,t}$ the modelled index within the length range, q_g is the catchability, b_g is the control to the shape of the power function which relates the abundance index. Here b_g is set to be 1.

Table 1. Length aggregation of survey indices used in tuning the model

Name	Min	Max
si.4 – 20	4	20
si.20 – 30	20	30
si.30 – 40	30	40
si.40 – 60	40	60

The data used in the present model is comprised of commercial fleet landing data and the independent survey data. The former data source provides landing values in tons from 1995 to 2018, while the biological and catch distribution ranges from 2005 to 2018. The latter data source provides abundance indices and its respective biological data from 2005 to 2017.

Natural mortality at 0.3, growth function, selectivity, estimate of maturity ogive, length-weight relationship, initial abundances, variances for length at recruit and of initial mean lengths, survey catchability, and scalars were parameters used in the operating model.

3.2.9 Optimization

To achieve flexibility in the model, Gadget was allowed to estimate most of the parameters, using optimizing iterative weighing algorithm. In this procedure, the individual likelihood components were combined into a weighted likelihood function (Stefansson, 2003; Taylor, *et al.*, 2007; Bartolino, *et al*., 2011). The length-group survey indices and, likelihood components were grouped and weighted together to avoid overfitting, consequently guarantying different survey index yearly in a weighted group (Elvarsson, *et al.*, 2018).

3.2.10 Retrospective analysis

The probable historical reconstruction of changes that might have occurred over the period from 1995 to 2017, based on the length frequency, landings and abundance estimates from survey data. This data with output from simulation of the model provides inference of the changes between the referred period.

3.2.11 Biological reference points

The biological reference points were divided into two in accordance to the priorities and objectives. The precautionary approach (pa) reference points and the maximum sustainable yield (MSY) reference points. By following ICES technical guidelines (ICES, 2017) derivation of reference points was done based on the fishing mortality (F). A spawning stock biomass (SSB) vs recruitment plot was used to examine the stock assessment estimates and draw assumptions of what type best represents the stock based on the ICES technical guidelines under steps 2 and 3.

4 Results

Results shown here begin by presenting the population indices divided into four length class bins, the optimization of length distribution with gear selectivity, and the stock proportion with the age composition from von Bertalanffy equation. Furthermore, it presents the model results from the stock assessment that illustrates the population dynamics, recruitment, fishing mortality as well as the biomass estimate, and it ends with projection of the possible management recommendation parameters.

4.1 Population indices

The population indices derived from the survey data set show length groups, whose fit to the abundance indices was not uniform (Figure 7). With the exception of length group with survey index 30-40 other groups present a relatively poor fitting. In the length groups less than 30 cm, the model fit initially seemed to predict slightly above then below the observed surveyed data, whereas for the length group above 40 cm the model fit tended to predict slightly lower in relation to the observed data without catching the peak in 2010.

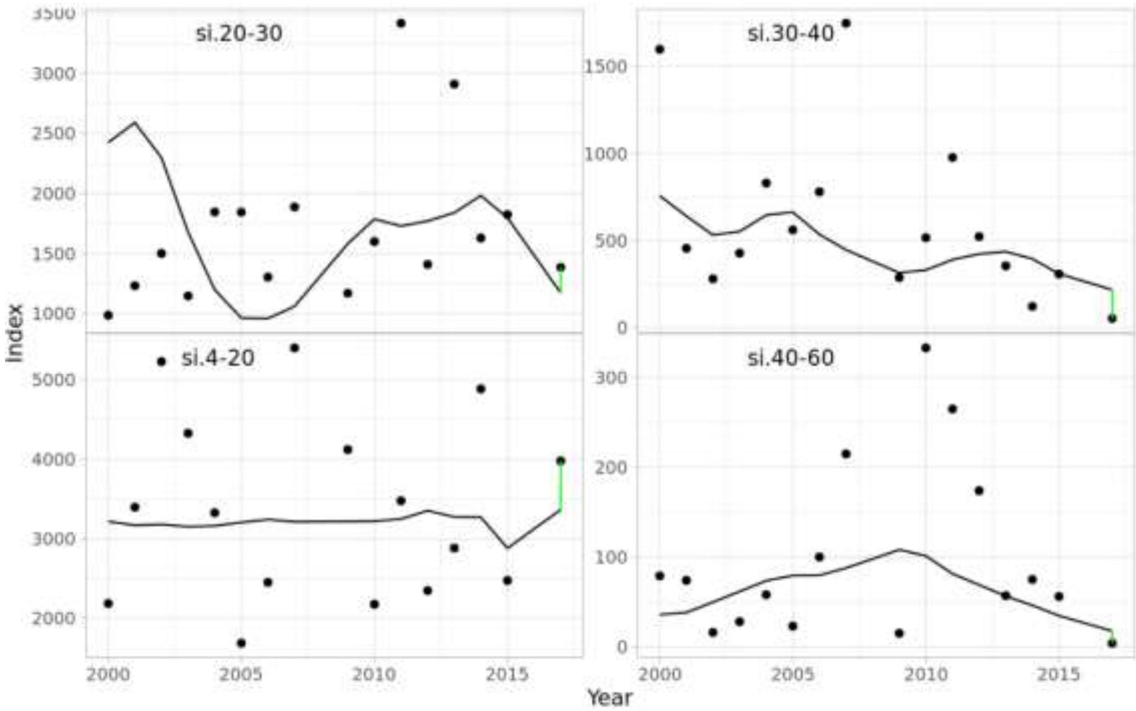

Figure 7. Population abundance indice estimates divided into four different length groups in bins of 16, 10 and 20 cm. Whereby the dots denote the observed data and the solid line represent the simulation of the model.

4.2 Length distribution

The estimated length distribution in general, fitted better with observed data from the purse seine fishing gear samples in comparison to bottom trawl and survey samples. The three fishing gears presented a relatively bigger contrast between the observed data and the estimate that presented relatively smaller values.

Bottom trawl prediction did not fit well to the observed data, with the exceptions of 2011,2nd quarter, 2014,4th quarter, 2014,1st quarter, 2016,1st quarter, and 2018,4th quarter. Larger length proportions were predicted in the observed data with the exception of 2018,3 that presented a rather larger length proportion for the estimated data (Figure 8). It possible that the length distribution is poorly sampled, as it seems to be dominated by one or two samples per quarter. The fit in later years does not seem to be as poor as the earlier ones.

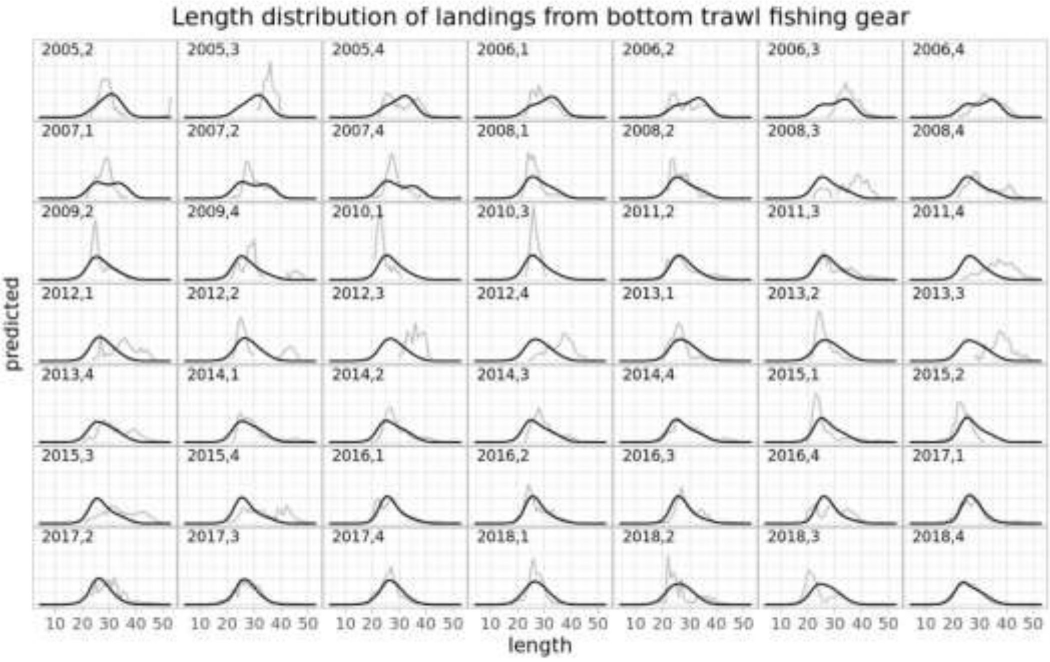

Figure 8. Length distribution from landings of bottom trawl fishing gear. Dark line shows the prediction by the base model and the grey line denotes the observed values. Numbers after the commas in years refers to the quarter of the fishing period.

The purse seine sample data presented a good fit in comparison to bottom trawl and survey data. However, the observed predictions are rather higher in comparison to the estimated data in many of the year steps with some exceptions such as the case of 2006,1st quarter, 2007, 4th quarter, 2008, 4th quarter, 2009, 4th quarter, 2016,1st quarter, 2017, 2nd quarter that showed lower predictions. In general, there is a consonance in the length distribution for the observed and estimated data despite 2007, 1st quarter and 2016,4th quarter that present smaller length for the observed data and larger length for the observed data respectively (Figure 9).

The survey data presented non fitting predictions between the estimated and the observed data (Figure 10). The length distribution showed smaller length for the observed data save 2012, 2nd quarter where the observed lengths are bigger than the estimated. Therefore, it can be noted that the survey length distribution showed inconsistencies between years, like the high proportion in 15 cm in 2002 that disappears in 2003.

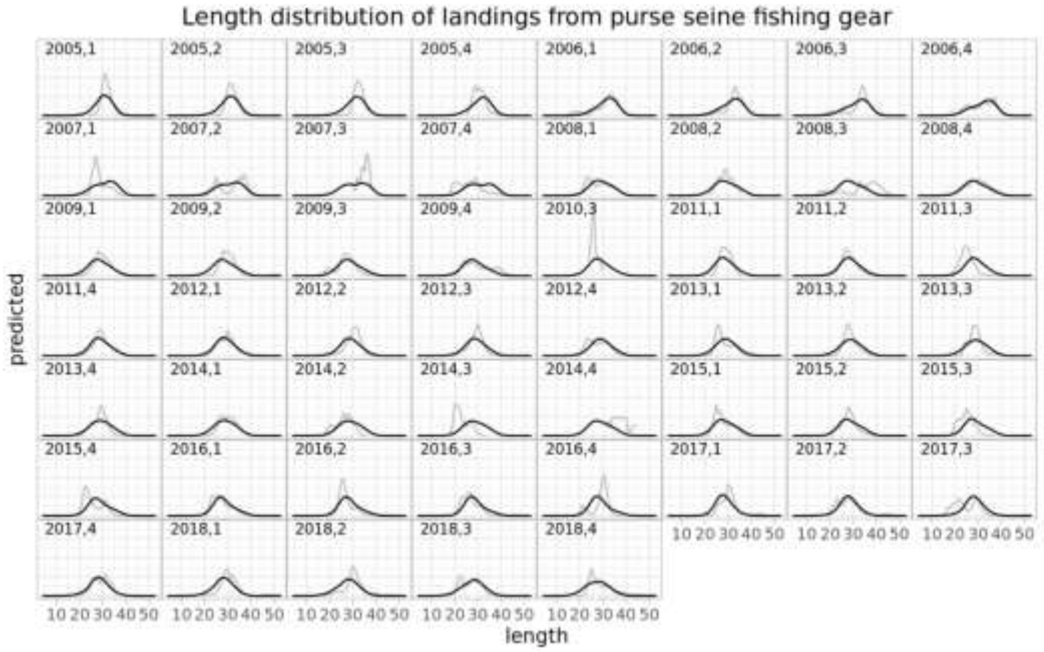

Figure 9. Length distribution from landings of purse seine fishing gear. Dark line shows the prediction by the base model and the grey line denotes the observed values. Numbers after the commas in years refers to the quarter of the fishing period.

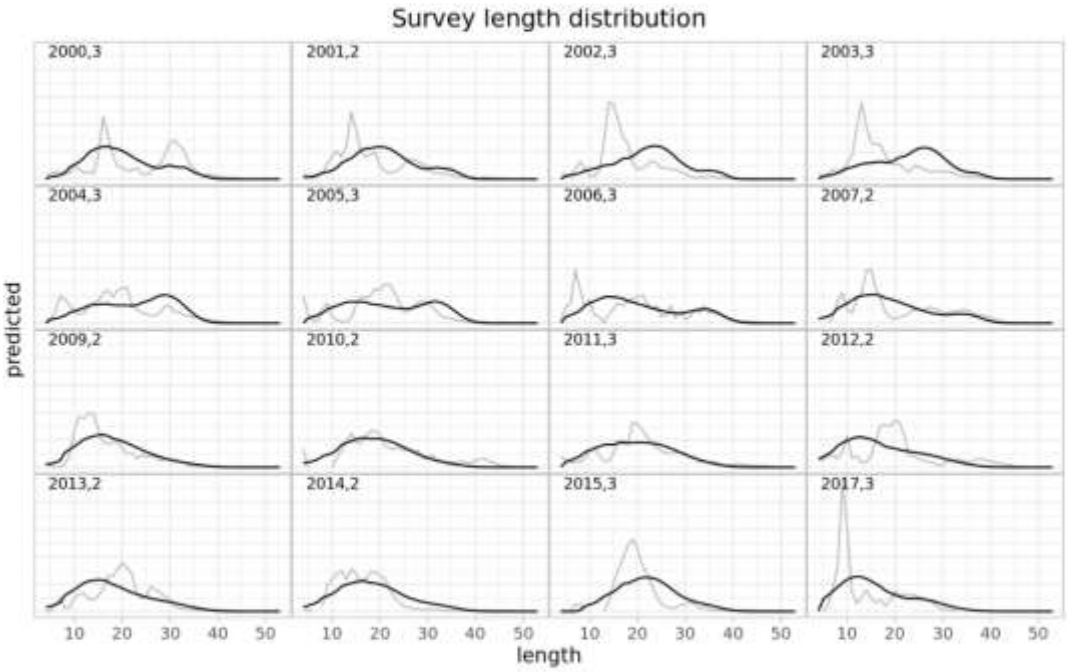

Figure 10. Length distribution from survey. Dark line shows the prediction by the base model and the grey line denotes the observed values. Numbers after the commas in years refers to the quarter of the fishing period.

4.3 Proportion mature

The length at which about half of the population is matured is in all cases except for 2012,2nd quarter 15 cm (Figure 11) and above this length the proportion of mature fish increases rapidly reaching 100% maturity at about 28 cm.

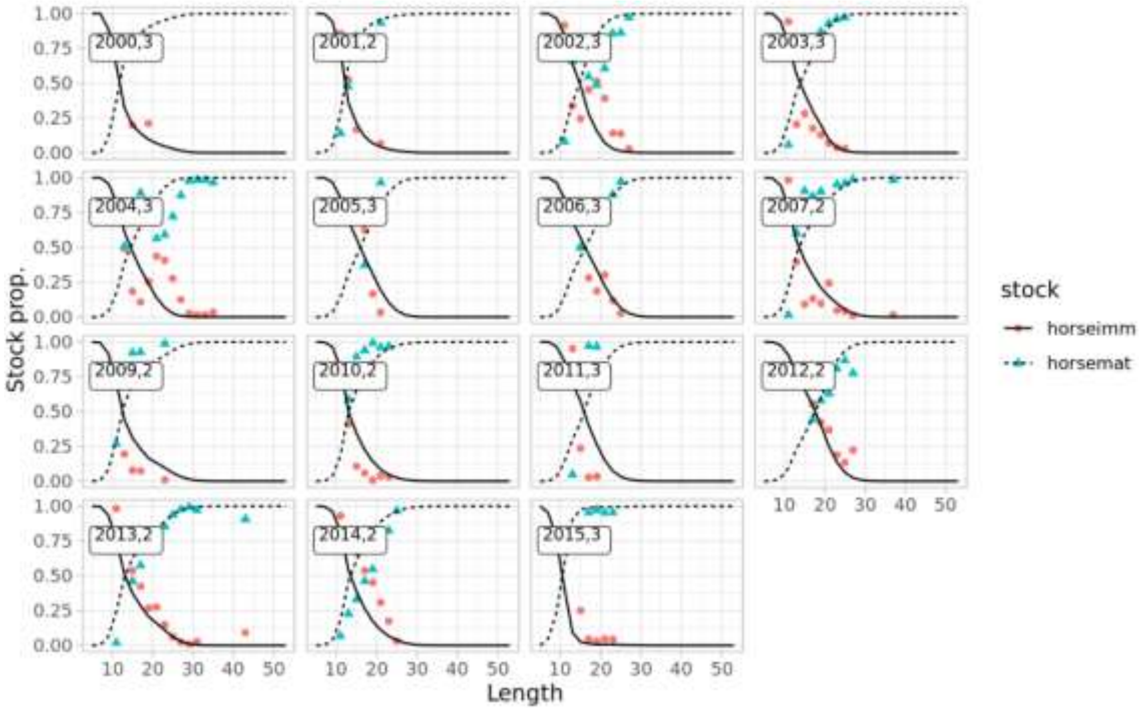

Figure 11. Proportion immature and mature horse mackerel at different length and times. Horseimm denotes the immature population of horse mackerel and horsemat the mature horse mackerel population. Dots representing the data.

4.4 Age composition

Although there was no age data in the data input, the application of a von Bertalanffy equation enabled to estimate the age composition based on length.

The number of fish within an age group tends to decrease with age throughout the timeseries. However, from 2005 to 2015 the inverse is observed, younger ages represented a smaller quantity of fish while the older fish registered a higher number of fish (Figure 12). Age 10 was registered throughout the timeseries and constituted considerable proportion of the total biomass.

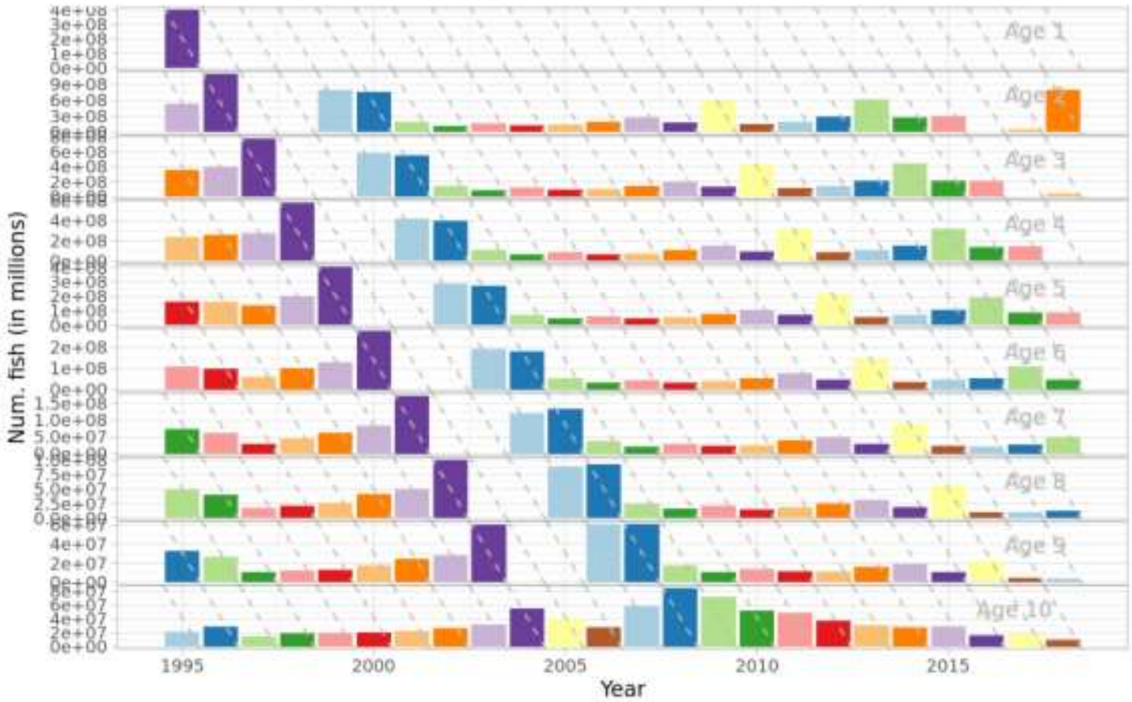

Figure 12. Age composition of horse mackerel, whereby each sloping line consisting of a same coloured histogram resembles an age of a horse mackerel population.

In general, the six model runs show the same pattern/behaviour with respect to the mean length per age. A rapid growth is noticeable until approximately length of 20 cm then a rather slower growth onwards (Figure 13).

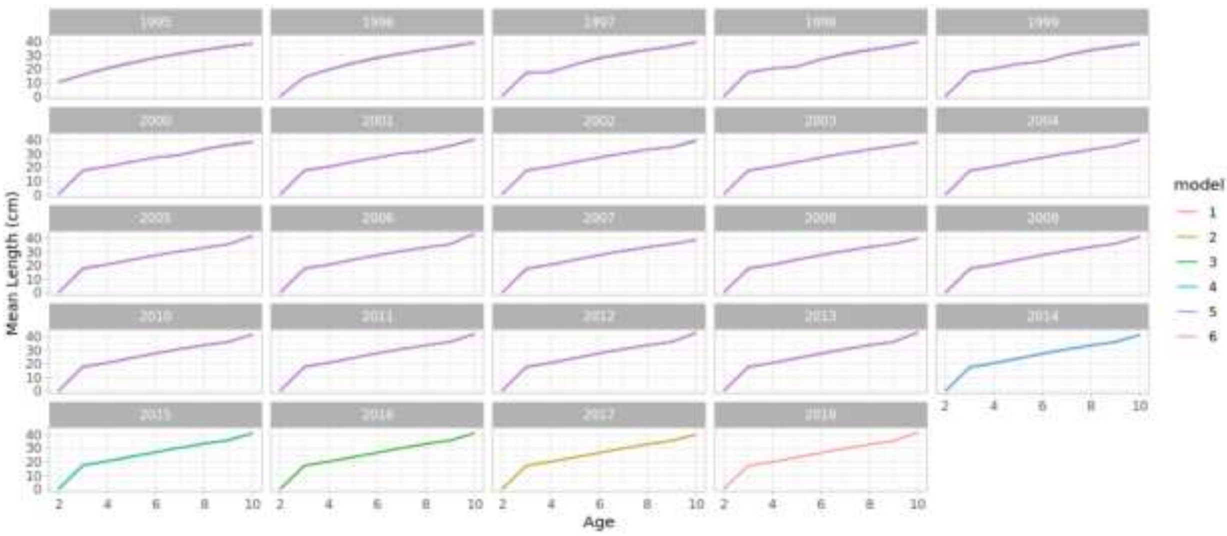

Figure 13. Growth estimate of the horse mackerel fish population at a mean length.

4.5 Stock assessment overview

In general, the model predicted a continuous decline in total biomass from 2014. However, while the mature part of the stock declined biomass of immature fish increased. Fishing mortality has been increasing from 2010 while up until then fishing mortality had been at or below 0.25 with the exception of 1996 (Figure 12). The lowest landing was registered in 2010 below 10 thousand tons. There have been large fluctuations in recruitment, 2015 was one of the years that registered an almost no recruitment, onwards a sharp increase in recruitment, with no two good years in 2017 and 2018 (Figure 14). From the model the fishery appears to mainly target the mature population.

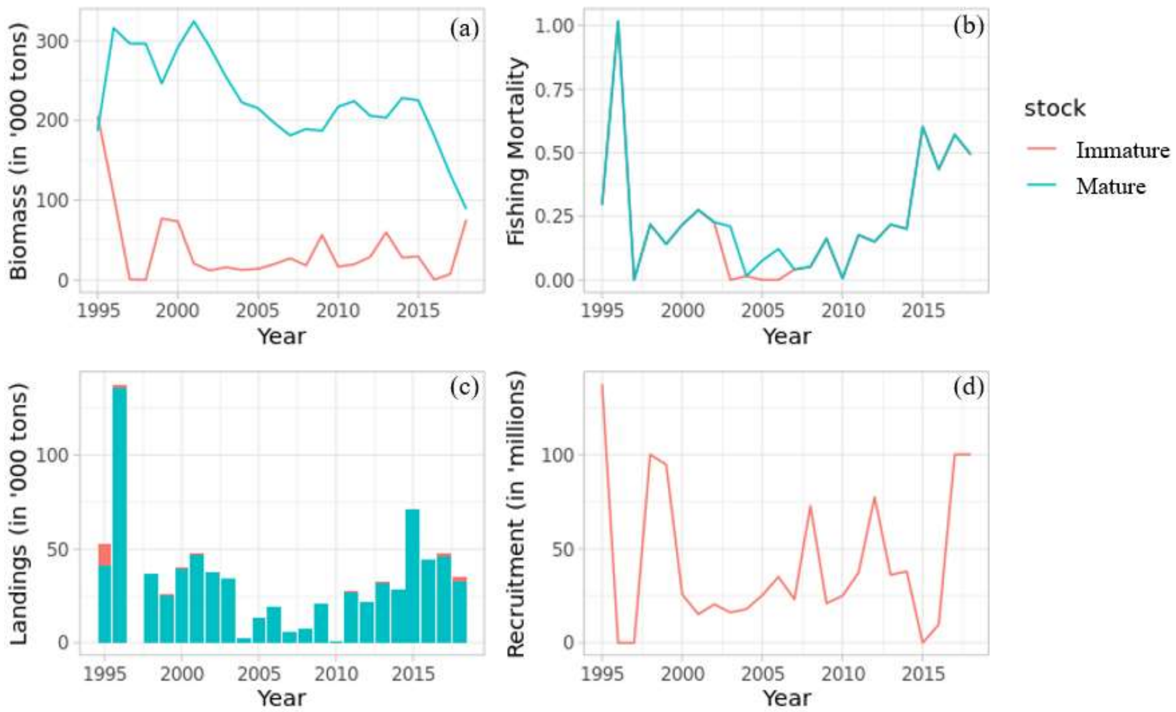

Figure 14. Total biomass estimates (a), fishing mortality (b), landings (c), recruitment (d).

4.6 Retrospective analysis

Retrospective analysis shows an initial unstable overall level in biomass of mature fish (SSB) from 1995 to 2000, then a downward trend in 2006 to 2012. The last model trial did have a huge margin from the baseline model (Figure 15). Recruitment estimates fluctuate throughout the period of study while F has been steadily increasing since 2004.

The historical assessment estimates present an uneven state in the stock projection, which can explain the uncertainty effect due to lack of age data. A weak correlation of the present stock status estimate that maybe considered to be related to the previous years' assessments.

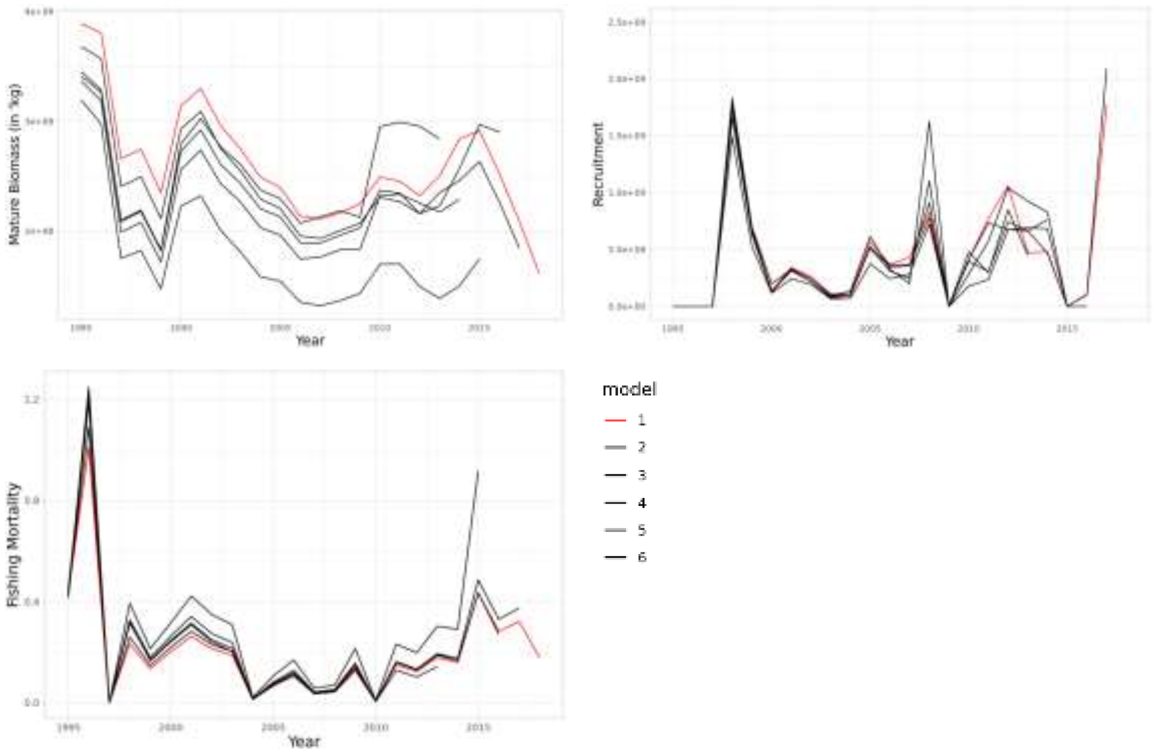

Figure 15. Five year analytical retrospective analysis of the base run assessment (red line) of horse mackerel. The various black lines indicate the retrospective model estimates.

4.7 Biological reference points & projections

A plot SSB vs recruitment was generated to estimate points that would serve as reference for management (Figure 16).

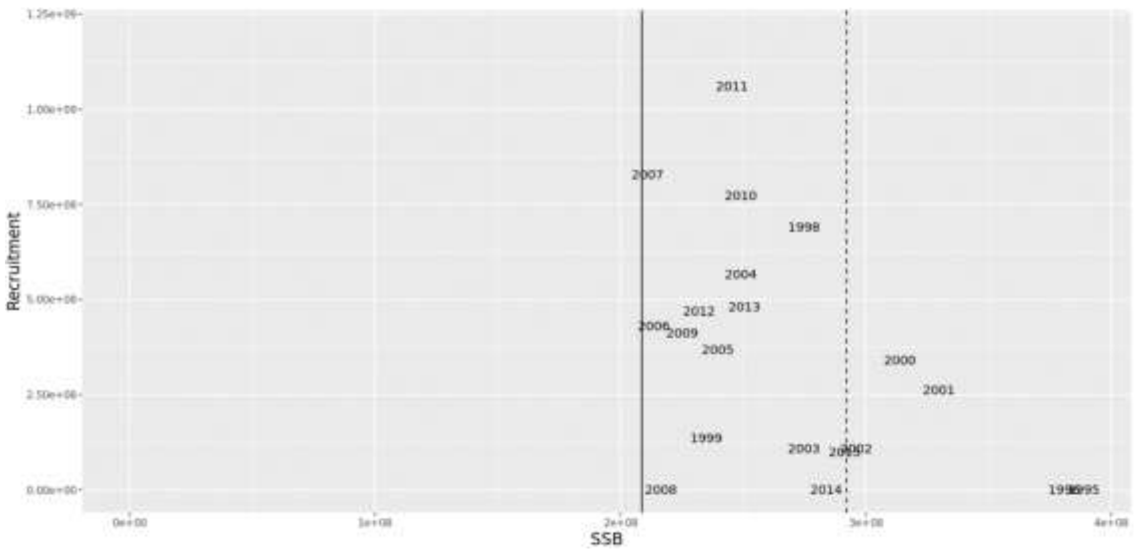

Figure 16. Spawning stock biomass recruitment relationship for the horse mackerel showing a narrow range in SSB and a relatively stable recruitment. Vertical line denotes de B_{lim} and the dashed vertical line denotes the B_{pa} point.

For the timeseries recorded horse mackerel has a rather wide dynamic range of SSB and an inverse relationship to recruitment. Thus, following the ICES technical guidelines (ICES, 2017), when SSB – R has an inverse or no relationship there is no way of estimating limit reference points. Therefore, a B_{loss} is used as a value for B_{pa}, F_{lim} and F_{pa} are calculated with standard factor e $^{1.645 * \sigma}$. Whereby for F_{pa} calculations the standard factor carries a minus sign before 1.645. σ is the standard deviation of ln(SSB) and ln(F) respectively and both carrying an equivalent value of σ = 0.20, which is the default ICES value for assessment error.

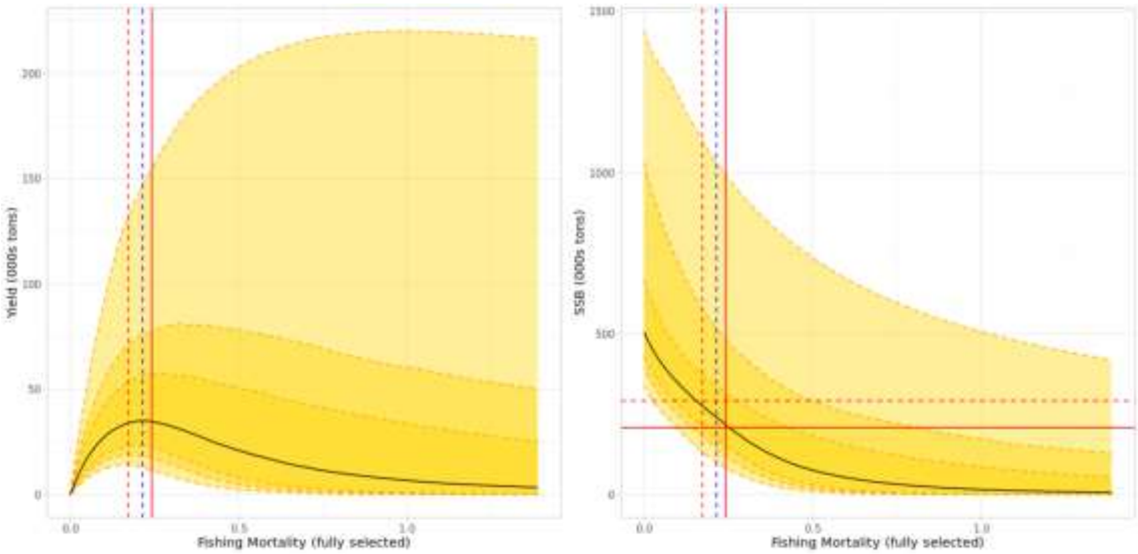

Figure 17. Biological reference points for distributional densities for the yield (left) and SSB (right) plots as a function of harvest rate targets which in this case are equivalent to fishing mortality. The black solid curves with yellow shaded area denotes the median and 5 to 95% interquantile ranges, respectively. The red lines indicate F_{pa} (vertical dashed), F_{lim} (vertical solid) and B_{pa} (horizontal dashed), B_{lim} (horizontal solid). Black dashed vertical lines indicates F_{msy}(dashed).

The reference points broadly fall into two categories, those to achieve precautionary approach (pa) goals and those for the maximum sustainable yield goals. Two components biomass (B) and fishing mortality (F) are further described into absolute(limit) and precautionary (pa). B_{lim} refers to the biomass at which if reduced below this level limit the reproductive capacity of the stock will be impaired. When the biomass is low the SSB will consequently also be low, leading to reduced recruitment. When the exploitation rate is at F_{lim} (mortality limit), median SSB in projections is lead to equate to B_{lim}. There is half a chance that SSB will either be above or below B_{lim} since stock equilibrium for F is reached at median SSB (ICES, 2017). B_{pa} is the biomass level above which the stock maintains its reproductive capacity despite the uncertainties. There is less than 5% chance that SSB estimates are below B_{lim} thus, giving a 95% chance of SSB being equal to B_{lim}. A fishery will be considered as sustainable if the fishing mortality is below F_{pa} taking into account the uncertainties. This carries its basis from the assumption that an F rate is found to guarantee 5% chance of being above F_{lim}. Finally, the F_{msy} point is supposed to lead the fishery to maximum sustainable yield in the long run. This is based on two assumptions: 1) F = F_{msy} when SSB is greater or equal to MSY $B_{trigger}$ and 2) F = F_{msy} *SSB/MSY $B_{trigger}$ if SSB is less than MSY $B_{trigger}$.

Table 2. Table of the reference points estimated from the horse mackerel

Framework	Reference point	Value
MSY approach	MSY $B_{trigger}$ H_{msy} F_{msy}	292 thousand tons 0.25 0.277
Precautionary approach	B_{lim} B_{pa} F_{lim} F_{pa}	208 thousand tons 292 thousand tons 0.28 0.21

5 Discussion

Overall, the objectives set out for this study were addressed. The stock assessment overview provided a glimpse of how the stock has been behaving given to fishing mortality and the recruitment that is also affected by environmental changes with emphasis to increase in temperature. The biomass estimates proportions showed an increasing trend of immature fish and a decrease in the mature fish, thus, showing that recruitment was successful in the last years of the timeseries. The historical analysis of the data showed that the uncertainty increases as years are removed from the timeseries data. This if looked better shows the quality of data and its consistency that increase the value of uncertainty. Hence, the adoption of the retrospective analyses estimate for management advice would either minimize or increases.

Issues with data

Although commercial fisheries data was incorporated in the study there is still an enormous concern with uncertainty in just understanding the dynamics of the stock (Maunder & Piner, 2014). Therefore, the need for reliable and relevant data that would improve the assessment of the status of the stock. Sampling strategy on surveys and commercial landings to be able to increase the number of otolith samples per length group that would increase the likelihood of achieving an age key for horse mackerel stock. Improving communication among the players involved in the industry to be able to create awareness about the importance of providing realistic and accurate data to scientists. Another mechanism that would be adopted, is the integration of trained observers on board to facilitate in collecting data that is useful for research or evaluation.

Model estimates

The model estimates are very uncertain. This is because of inconsistent data mentioned in the previous section. Therefore, to improve the assessment, the data collection needs to be more consistent. In addition, the inclusion of age data could potentially improve the model performance, particularly if sample routinely.

The challenges encountered at obtaining age data is due to difficulties experienced in reading otolith of horse mackerel which are very clear making it hard to read the rings. Although, effort has been put into reading the otoliths, to date, there is still no age key for horse mackerel age data. Therefore, there is still a need to invest more in this field so that future assessments can carry age data and possibly with that minimize the uncertainties in the model estimates.

The present model addressed selectivity, population indices, age proportion based on length data, recruitment, spawning stock biomass, mortality and landings. Looking at these components that the model presented plus the retrospective analysis that sheds light into how the model behaves in absence of certain years data, enables one to have in-depth information about the dynamics of the stock. This model also provided a projection of how the stock and the fishery will behave in the future, presenting as well the reference points that would be useful in formulating advices for management purposes of the horse mackerel fishery. The present management advices are based on outputs of the surplus production model which does not give a more exhaustive analysis of the stock, thus, the Gadget modelling framework proved to be a model that would provide information with property to infer managerial recommendations. Not only does it provide projection of future stock but most importantly it provides precautionary approach reference points that would be very useful to follow for a sustainable or to recuperate the horse mackerel stock.

5.1 Feasibility of Gadget in analysing horse mackerel population dynamics

To improve the understanding of stock dynamics it is of paramount importance to incorporate age data inclusion in assessment. Not only does the inclusion of age data give a fuller dynamic of the stock but also it minimises uncertainties of the assessment if reliable aging is available (Bonfil, 2012). Therefore, age data is required in order to improve model accuracy of most if not all assessments. However, age data is difficult to obtain for some fish species particularly pelagic species close to the tropics (Pitcher & Hart, 1982; Longhurst, 1987) which is the case for the Angolan horse mackerel.

In the absence of age data, the Gadget framework because of its flexibility in running models for data limited stocks (Elvarsson *et al*, 2018), was adopted to study its feasibility in assessing the Angolan horse mackerel. The model showed overall, general trends of the Angolan horse mackerel data provided. Albeit the less than perfect accuracy of the projections, it is important to note that the model fitted badly to the observed data.

5.2 Population dynamics of the Angolan horse mackerel

The results proved to be relevant towards the description of the stock in its immature and mature stage proportions in the total biomass, recruitment, fishing mortality and on the total landings. The index plots for the first four length group showed a normal pattern to the overall biomass estimates over the years. However, for lengths beyond 50 cm a distorted pattern was observed, and this can be associated to the small samples size for that represent such length group.

The first and last sections of the length and landing timeseries affected substantially the behaviour of the recruitment. High noise levels experienced at both ends of the model projection is primarily due to the absence of age data as well limited data.

SSB-recruitment plot revealed, no relationship in recruitment. No B_{lim} estimate could be made. Instead, a B_{pa} is estimated based on historical F levels.

A relationship was observed between landings and fishing mortality. F from 2000 to 2015 landings were below 25,000 tonnes and F levels were below 0.25 while when F levels went above 0.25 in the following years the landings increased. As fishing mortality increased, the biomass reduced from 200,000 tonnes to 100,000 tonnes for the mature part of the population, while the biomass of immature horse mackerel increased from less than 25,000 to slightly above 50,000 tonnes in 2018. A review in the management policy of horse mackerel fishery is needed to curb the continuous depletion of the stock and reduce fishing mortality.

The absence of age data and the inconsistent quality of data over the 10 years of assessment has a large impact on the biomass estimates consequently the recruitment estimates.

Pelagic species are sensitive to environmental changes which manifests itself in changes in population parameters of horse mackerel. Thus, the inclusion of environmental parameters in the Gadget modelling framework would improve the assessment of the horse mackerel species in the Angolan waters, in particular when it comes to recruitment and natural mortality.

5.3 Applicability to developing fisheries research in Angola

The Gadget model provides an alternative way to assess the stock which could provide improved management recommendation based on reference points and a precautionary approach. In the absence of age data, an integrated size-structured model was the best alternative to other age-based methods that would have required age data from survey and the two commercial fleets. In other words, the simplicity and flexibility of Gadget model in assessing limited data stocks, can be useful in filling the gaps of stock assessment work in Angola.

Although the Gadget modelling framework showed to be feasible to assess horse mackerel stock, the model estimates do not present level of confidence yet to be used for management purposes. Therefore, at present if this assessment model would be adopted with emphasis on the retrospective pattern, it would provide misleading recommendations on the state of the stock. This is a result of the high uncertainty and inconsistency experienced in the retrospective analysis of the present model.

Reproducibility of this assessment would be practical in future studies or stock assessment. Because of the software used and the codes generated that would be applied and this would be of great contribution in research and assessment not only for horse mackerel but even for other species in Angola. This work therefore, serves as a basis for further research that would culminate in improving the assessment and consequently management advices.

6 Conclusions

The Gadget model framework serves well to assess horse mackerel, a data limited stock. Further studies are recommended prior using the reference points for management purposes.

Although there is high uncertainty in the modelling, the fishing mortality is high and this shows the need to reduce the fishing pressure to below the F_{msy} in order to increase the reproductive capacity of the stock and make the fisheries sustainable. The evaluation was based on the best scientific information and knowledge available at the time. Therefore, associated uncertainties in the simulation of the reference points are bound to be evident, hence the need of a continuous timely review of the management performance rules.

Age data is of paramount importance to improving the model thus providing a better assessment. Environmental data can improve the recruitment and projection models. Thus, the importance of including environmental data in future studies.

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