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A SURPLUS PRODUCTION ANALYSIS OF THE CAPE HORSE MACKEREL (*TRACHURUS CAPENSIS*) MIDWATER TRAWL FISHERY IN NAMIBIA

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ABSTRACT

This paper examines the optimal yield and stock development of the Cape horse mackerel (*Trachurus capensis*) fisheries. Surplus production analysis based on the Gordon-Schaefer (1954) bioeconomic model was applied to the Cape horse mackerel midwater trawl fishery in Namibia, using empirical yearly data from 2009-2020. Cost of capital was observed to be relatively low and was adjusted to the long-term average capital cost of the Icelandic pelagic industry. Effort was measured as trawling duration and CPUE as catch per hour trawled. The findings support model theories and concepts that the maximum economic yield (Y_{MEY}) is estimated to be 327,091Mt, lower than maximum sustainable yield, $Y_{MSY,}$ at 342,115Mt. The respective corresponding efforts were estimated to be 23,455 and 29,673 hours of trawling. There is a small margin between the two static reference points and therefore, overfishing could cause a sudden decline in profits. The results suggest that effort exerted in 2020 was sufficient to achieve maximum sustainable yield, however that was not obtained due to an unresponsive fishing allocation. The use of bioeconomic modelling can inform fisheries management to determine optimal fleet sizes and fishing effort, giving Namibia an advantage to maximise the potential benefits from the Cape horse mackerel fishery. However, bioeconomic analysis is fundamentally driven by effort parameters and therefore, further research may be required to develop a consensus on an accurate effort measure and other dynamic factors that affect the Cape horse mackerel fishery.

Keywords: Bioeconomic analysis, Cape horse mackerel, effort, sustainable management, optimal yield, maximum sustainable yield, maximum economic yield, Namibia

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1 INTRODUCTION

The fisheries sector represents an important source of economic growth, employment, food security and foreign exchange in Namibia. In 2020, over 610 million USD of fish was traded and the contribution of fisheries to the nation's Gross Domestic Product (GDP) was 3.9% (NSA, 2020). Fish and fisheries products ranks 4th in export trade values with an 11.4% share (NSA, 2020). There are seven main targets in Namibia's industrial fishery: Hake (Merlucciidae), Cape horse mackerel (*Trachurus capensis*), Monkfish (*Lophius spp*.), rock lobster (Palinuridae**)**, crab, line fish and large pelagics. Total catches, including both targeted and untargeted species, are in the range of half a million metric tonnes per year (Figure 1).

Namibia boasts one of the most productive fishing grounds in the world that is largely supported by an upwelling system, the Benguela Current, one of four major eastern boundary upwelling systems of the world. The upwelling brings nutrient rich deep cold waters to the surface of the ocean, which simulates primary production of small microorganisms that support zooplankton and thus pelagic fish stocks (FAO, 1999).

The Namibia fisheries sector is structured on the principal objective to rebuild the stocks to a level at which it can sustain catches at maximum sustainable yield (MSY), thereby providing the maximum social and economic benefits to the country. When the country gained independence in 1990, Namibia's marine resources were mainly exploited by foreign fleets and a few privileged Namibians, and many species were over-exploited due to an open access policy (Blessing & Teweldmedhin, 2016). This has driven the development of the mandate for Namibia to sustainably manage living aquatic resources and the aquaculture sector.

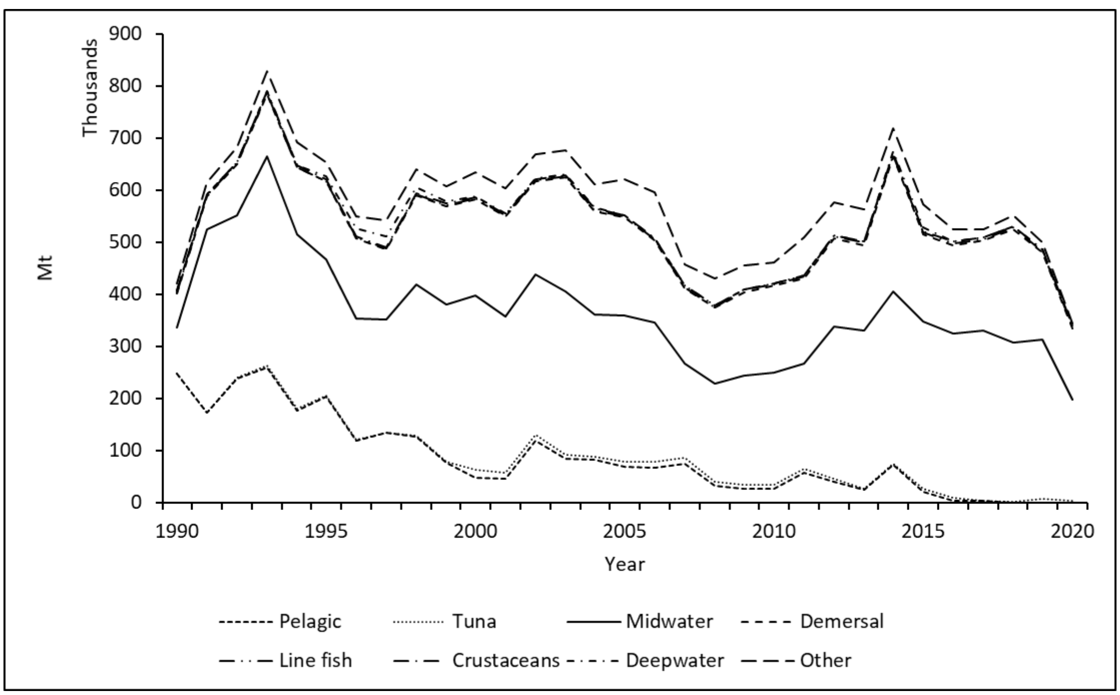

Figure 1. Total Catches in Namibia EEZ.

Cape Horse Mackerel is the dominant species in terms of biomass in Namibian waters, however it generates less revenue than hake which is exported to higher value markets such as the European Union (EU) (Ruppel & Ruppel-Schlichting, 2016). According to the MFMR statistics, over 68% of 2019 total catches were made up of Cape Horse Mackerel.

The fisheries sector is crucial for food security and over 97% of the population is aware of its importance for human consumption (Erasmus, Kadhila, Thyberg, Kamara, & Bauleth-D'Almeida, 2021). Local fish consumption stands at 16 kg per capita (NFCPT, 2020). Over 90% of total fish sold locally is Cape Horse Mackerel as it is affordable to the majority of the population, has high edible yield, and is readily accessible countrywide through local fish shops and retail shops, a government driven initiative. Total employment in the fisheries sector is estimated around 17000, of which are based on Cape Horse Mackerel business operations (MFMR, 2020).

This paper describes the Namibian fisheries management system, the biological status of the Cape Horse Mackerel stock and integrates economics data to apply a surplus production analysis and estimate optimal management options using maximum economic yield (MEY) and maximum sustainable yield (MSY) as reference points.

1.1 Problem Statement

Namibia has been applauded for its fisheries management system which has eliminated problems of open access. However, like any other management system, it has its flaws that require further development to increase its role in building up the national economy. Natural fish capital – the wealth of fish – has been in decline in Namibia from 1990 to 2007 (Akawa & Nashima, 2013). In addition, analysis from an unpublished report produced in 2020 on the value of Namibia’s marine fishery resources shows a declining trend in fishery contribution to state revenues. A decline in revenues could be attributed to a decrease in either fish prices or catch volume or both. The cause for the decline remains unclear and there is a need to conduct a separate study into the causes of the decline.

In many parts of the world, natural resources constitute a significant share in accumulation of total wealth, and fish is the foremost natural resource in Namibia. Wealth accumulation is achieved through preservation measures for long term use and optimal utilisation of the resources that maximises economic yields. In theory, sustainable resource management is achieved through a balance of three elements: environment, economics, and social. However, this has been difficult to implement for most fisheries management systems around the world.

In the case of Namibia, management places considerable weight on socioeconomics in the decision-making processes (MFMR, 2013). This could result in an ineffective management system and therefore, pose a risk to the sustainability of the resource which can lead to loss of livelihood and ultimately, loss of income/profits. Perspectives on fisheries differ between countries; however, it is important to consider all the economic, social, and environmental aspects of fisheries so that no issue or sub-issue is omitted (FAO, 2003).

Fisheries management in Namibia has promoted investments, employment creation, and local empowerment in fisheries since the country's independence in 1990. This has meant more user rights to fishing Cape Horse Mackerel, regardless of TAC remaining at a similar level over this period. In 2012, a total of 55 additional user rights were granted to fish Cape Horse Mackerel fishers, which led to a short run of chartering additional vessels and increasing fishing effort (Figure 2). Increasing access to fishing when the stock is not increasing puts more pressure on the resource and reduces per capita share as more players are targeting the same limited resource.

Gross registered tonnage (GRT) can be used as a measure of fishing effort and the build-up capacity is linearly proportional to exploitation levels of fish stock (Anticamara, Watson, Gelchu, & Pauly, 2011). From 2012, a trend of GRT accumulation is reflected as additional trawlers enter the Cape Horse Mackerel fishing fleet, which is greatly associated with the granting of new user rights (Figure 2).

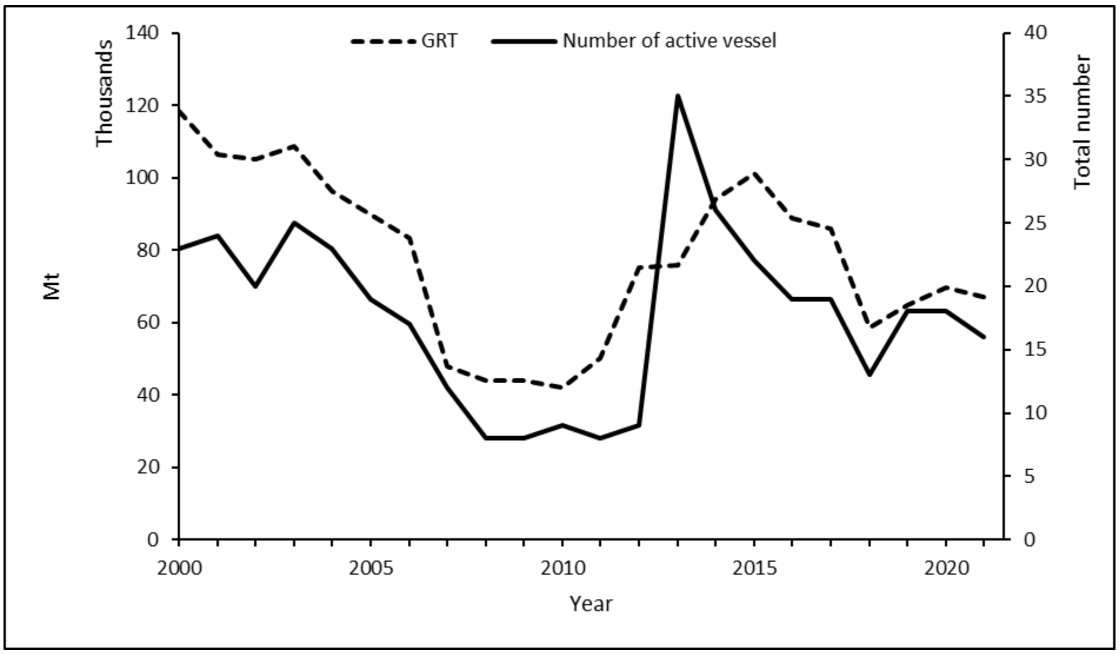

Figure 2. Fleet size and Gross Registered Tonnage - GRT

In 2021, the total number of user right holders stood at 127 of which 115 were grouped into joint ventures and 12 were individual right holders. Quotas are allocated free of charge; however, the majority of user right holders do not own fishing vessels, which brings about inefficiency in the fishery as they are not involved in fish production. User right holders who lack capacity to harvest their portion of quota enter joint partnerships, often with foreigners, to catch fish on their behalf in exchange for a quota usage fee. A lack of fishing capacity by most user right holders gradually results in overall inefficiency.

Catches of Cape Horse Mackerel have mostly been lower than the recommended TAC (Figure 3). The fisheries industry has raised concerns regarding poor catches both in terms of availability and sizes of fish. Therefore, there is a need to conduct more studies on the Cape Horse Mackerel to avoid reduction in fish stock and ultimately, improve catches, income, employment, and foreign earnings. Part of this study will describe the optimal level of effort for harvesting Cape Horse Mackerel that will maximise economic benefits.

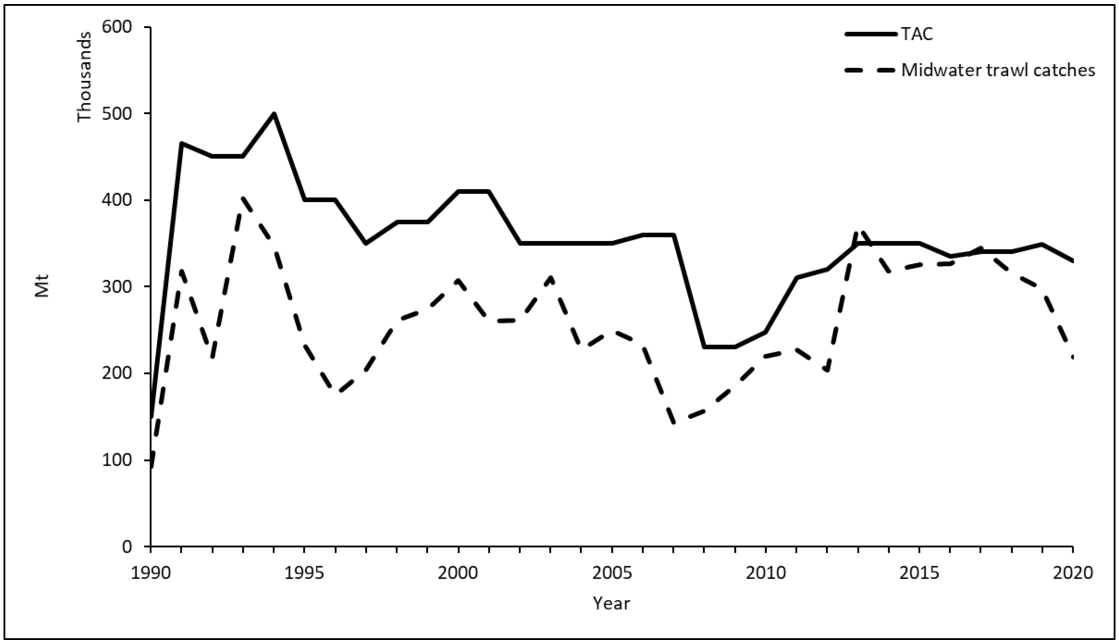

Figure 3. Midwater trawl catches of Cape horse mackerel and TAC

1.2 Rationale

Regulations in Namibia encourage research on marine resources to better understand fish species behaviour, commercial viability, and development activities in connection with the harvesting and protection of marine resources (MFMR, 2000). This study falls under the research and development activities that can support further development of the fisheries management system in Namibia.

The current economic blueprint being implemented in Namibia, the Harambee Prosperity Plan II, calls for MFMR to review the existing regime for the allocation of fishing rights, quotas, and mineral licenses (Office of the President, 2021). The call establishes a review process on the approach to the distribution of fisheries resources in Namibia and several options are up for management considerations. The first appropriate approach is to estimate optimal management plans that will derive maximum economic benefits from fisheries. Surplus production modelling, if correctly applied, can provide guidance to managers on developing management plans for fisheries with selective rebuilding plans that have the best chance to improve the wellbeing of citizens (Larkin, Alvarez, Sylvia, & Harte, 2011).

Cape Horse Mackerel is an important pelagic species in the Namibian waters as it provides affordable protein for human consumption, generates foreign exchange, supports sustainable employment opportunities, and constitutes the largest biomass that largely supports the massive food web, particularly as a feed to hake species, the most valuable fish in Namibia.

Post 2014, the commercial fishery in Namibia is dependent on seven species with three dominant stocks being: Hake (*Merluccius capensis and M. paradoxus*), Cape Horse Mackerel (*Trachurus Capensis*), and Monkfish (*Lophius spp.*) following the collapse of the Pilchard (*Sardinops sagax*), which is the third major commercial species. Some analyses have shown that Pilchard, which collapsed in 2014, used to support 20%-25% of the density for young Hake (Wilhelm, et al., 2015). It is possible that hake is feeding on cape horse mackerel more than usual as a substitute for pilchard.

Overall, this study aims to raise awareness among fisheries managers regarding considerations of economic dimensions in decision-making on Cape Horse Mackerel fisheries in Namibia.

1.3 Research objectives

The objective of this study is to determine optimal yield and stock development of the Cape horse mackerel fisheries in Namibia by applying a bioeconomic model which considers biological and economic characteristics and provides suggestions for management. Specific research objectives are:

- Establish economic benefits from fish production using maximum sustainable yield, and maximum economic yield reference points
- Examine trends and causality in Cape horse mackerel fisheries
- Support sustainable measures for management considerations

2 LITERATURE REVIEW

Surplus production analysis provides a means for measuring net benefits from fisheries resources by comparing gains and loss of biomass and exploitation levels of the stock in a data scarce system (Pedersen & Berg, 2017). A loss of environmental resources becomes an economic problem because important economic activities are lost and livelihoods disappear (FAO, 2003). Each management option on the use of environmental resources has an implication of economic gains or loss so it is important that these potential gains and losses are appropriately assessed. An important component of surplus production analysis is that it informs the basis of optimal biomass, harvest, fishing effort and the maximum benefits that can be derived from fishing activities and therefore, can be a powerful tool to improve management and the sustainable use of healthy fish stocks.

Bioeconomic analysis represents an impartial standardised model of individual species or multispecies and the interactions between fishing effort and fish stock. The model does not explain the performance of individual fisheries or the interactions between fisheries operations in an ecosystem (Arnason, Kobayashi, & de Fontaubert, 2017). However, it is an important analysis as it depicts the trade-offs and potential benefits possible through fishery management reforms.

Analysts argue that bioeconomic modelling expands recognition to a modern Ecosystem Based Fisheries Management (EBFM) and that benefits can be attained through the maximisation of economic yields as a strategic management objective (Pascoe, Kahui, Hutton, & Dichmont, 2016).

2.1 Biology of the Cape horse mackerel

Cape horse mackerel is species of the genus *Trachurus* and a member of the Carangidae family of the Perciformes order (MacKenzie, et al., 2004). Members of this genus are distinguished from the other members of the Carangidae family by the presence of scutes covering their lateral lines. Cape horse mackerel, *T. capensis* (Castelnau, 1861), is one of two species of horse mackerel found in the northern Benguela off the coast of Namibia. The other species is the Cunene horse mackerel, *T. trecae* (Cadenat, 1949), found mainly in southern Angola and occasionally extending into the northern Namibian shelf area during the summer months. Cape horse mackerel is regarded as a non-migratory resident of the cool Benguela current region from south of the Lüderitz upwelling cell up to the Angola-Benguela Front, with the bulk of its distribution from 25°00`S, north of the upwelling cell, to 17°15`S. In the Namibian waters the adult stock occurs in extensive shoals of variable densities, with a general increase in abundance from south to the north. The species is epipelagic as juveniles, becoming mesopelagic with age where it spends a large part of its pre-adult and adult life. At the end of their lifespan the older adult fish adopt a semi to exclusively demersal lifestyle and they tend to migrate southward and disperse in waters south of 25°S where they are mainly detected in demersal trawls. Cape horse mackerel is a batch spawner, spawning mainly during the warm summer months. The species exhibits male: female ratios of 1:1, and reproductive maturity is attained at about the age of two years (NatMIRC, 2021).

Prior to the country's independence in 1990, stock biomass was estimated using Virtual Population Analysis by scientists of the International Commission of Southeast Atlantic Fisheries (ICSEAF) (MFMR, 2004). During 1991-2001, acoustic surveys formed the basis of assessment of the resource. The surveys were carried out by the R.V. Dr. Fridtjof Nansen between 1991 and 1998 and the R.V. Welwitchia, between 1999 and 2001. Cape horse mackerel was surveyed as a by-product of sardine-directed surveys between 1990 and 1994 and therefore, the surveys did not cover the entire distribution area of the Cape horse mackerel.

Cape horse mackerel-directed surveys commenced with winter surveys by the R.V. Dr Fridtjof Nansen from 1995 to 1998, and then, the R.V. Welwitchia, took over from the Nansen between 1999 and 2014. Thereafter, these surveys have been conducted by board the RV Mirabilis which replaced the RV Welwitchia. The survey strategy on the Dr Fridtjof Nansen surveys was a combination of parallel transects, laid down perpendicular to the coastline and targeted the adult/midwater horse mackerel in the offshore area, and a zig-zag setup for inshore area to target pelagic aggregations of juvenile/pelagic horse mackerel. The survey strategy on the RV Welwitchia, was exclusively parallel transects placed parallel with the longitudes, and covered the entire distribution of the resource (NatMIRC, 2021).

Biomass estimates obtained from acoustic surveys are not absolute indicators of stock size, however the trend is reliable as the survey design has been consistent since 1999 (Figure 4). Biomass estimates of horse mackerel indicates that the stock level fluctuated between 0.8 and 1.8

million tonnes prior to 2005, after which the estimates declined to the lowest estimates of approximately 0.5 million tonnes in 2006 and 2007. The high variability in stock estimates is a result of the species aggregating behaviour, whereby they tend to aggregate more during warmer periods when the formation of thermal fronts concentrates nutrients along those thermal gradients. Planktonic life forms concentrate along the fronts and in turn attract large concentrations of secondary consumers up the food chain (Robinson, Sponaugle, Luo, Gleiber, & Cowen, 2021).

Biomass estimates are carried out annually on Cape horse mackerel, however due to technical problems, the survey did not take place in 2008, 2020 and 2021. Nonetheless, fishing activity continued during the same periods.

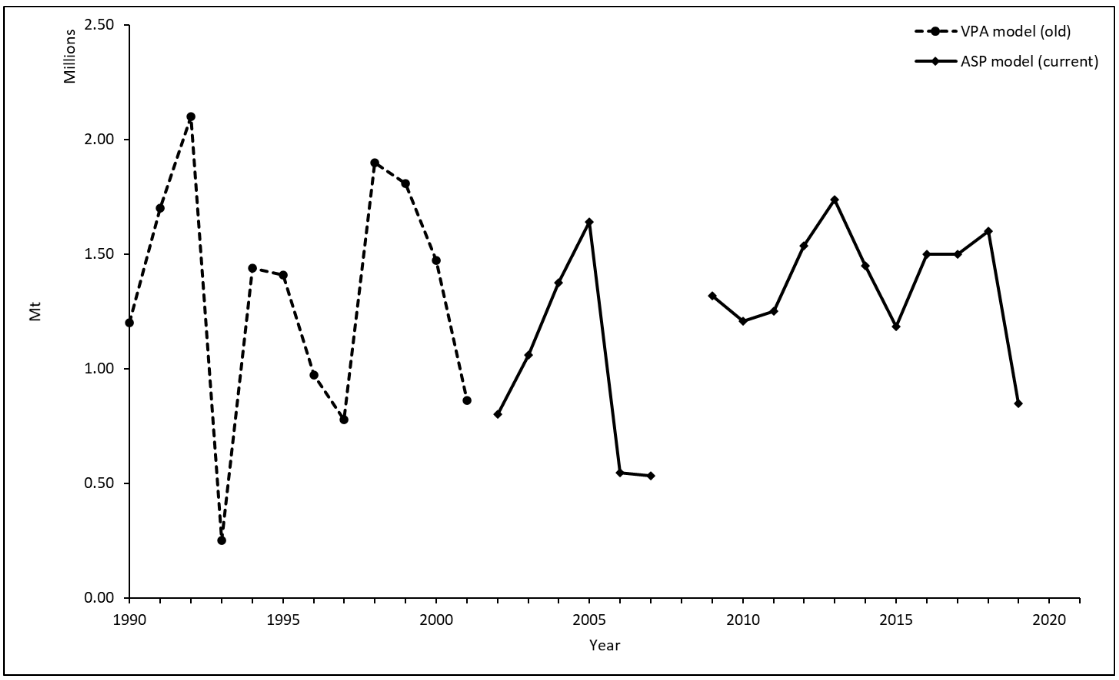

Figure 4. Cape horse mackerel biomass estimates from surveys (MFMR, 2021).

The status of Cape horse mackerel resource is assessed using an Age Structured Production Model (ASPM). Input data consists of total catches, catch at age matrices from biomass surveys and landings, abundance estimates (survey and commercial), weight-at-age, selectivity-at-age, and maturity-at-age (NatMIRC, 2021). Overall, resource assessments guide the estimation of TAC using MSY reference points.

2.2 The Cape horse mackerel fishery

The Cape horse mackerel fishery is characterised by onshore and offshore processing activities. The following subsections give a description on Cape horse mackerel in terms of production, fishing effort, export markets, and ex-vessel prices.

2.2.1 Cape horse mackerel production

Cape horse mackerel have been allocated to midwater trawlers and purse seine fleets between 1990-2020 (Figure 5). Midwater trawlers target adult fish which are frozen whole for direct human consumption, with fishmeal produced as a by-product from damaged fish at a conversion factor of 1:4.25. Purse seine fleets targeted juveniles for fish oil processing between 1995-2013. Analysis has proven that juvenile allocation is unsustainable as it leads to a reduction in overall stock, recruitment of the stock, and overall profitability of the fishery for adult horse mackerel (Mukumangeni & Viium, 2006). Fishing allocation for juvenile fish was discontinued in 2013. Therefore, Cape horse mackerel referred to in this study analysis and discussions focus on allocation to midwater trawlers.

There are two places where fish is processed in Namibia: at Walvis Bay on the western coastal area and in Lüderitz at the southwestern coastal area. The Cape horse mackerel is exclusively landed in Walvis Bay due to a lower cost of doing business for fishing companies. The bulk of the catches are processed at sea and a small portion is landed as wet fish for processing on land since the introduction of onshore value added product programme on Cape horse mackerel in the 5th National Development Plan (NDP5) (NPC, 2017). Onshore value addition was introduced after a successful piloting of the programme commenced in 2014.

All catches are required to be recorded upon landings, inclusive of bycatch. The regulations have a strong harvest rule against discards and encourage fishing companies to declare and land bycatch. On average, less than 1,000MT of Cape horse mackerel are landed by hake fleet trawlers as bycatch per year.

From 1990, the catch size increased sharply until 1994 and fluctuated the years after due to fishing conditions and reduction in TAC (Figure 5). Catches below the TAC could mean a good stock recovery and rebuilding of fish stocks in the long run. Over-catches were recorded in 2013 and were deducted from the following year's quota. The decline in the past years have resulted from unresponsive allocation.

Generally, midwater trawl catches have been below the TAC with exception of 1994, 2002 and 2003 where catches were above the TAC. Since independence in 1990, highest catches of 474,611Mt was recorded in 1993, a year before Namibia gained full control over Walvis Bay, the coastal town where major fisheries activities take place. In 1994, existing user rights were discontinued, and new user rights were granted in accordance with adoption of a new management system.

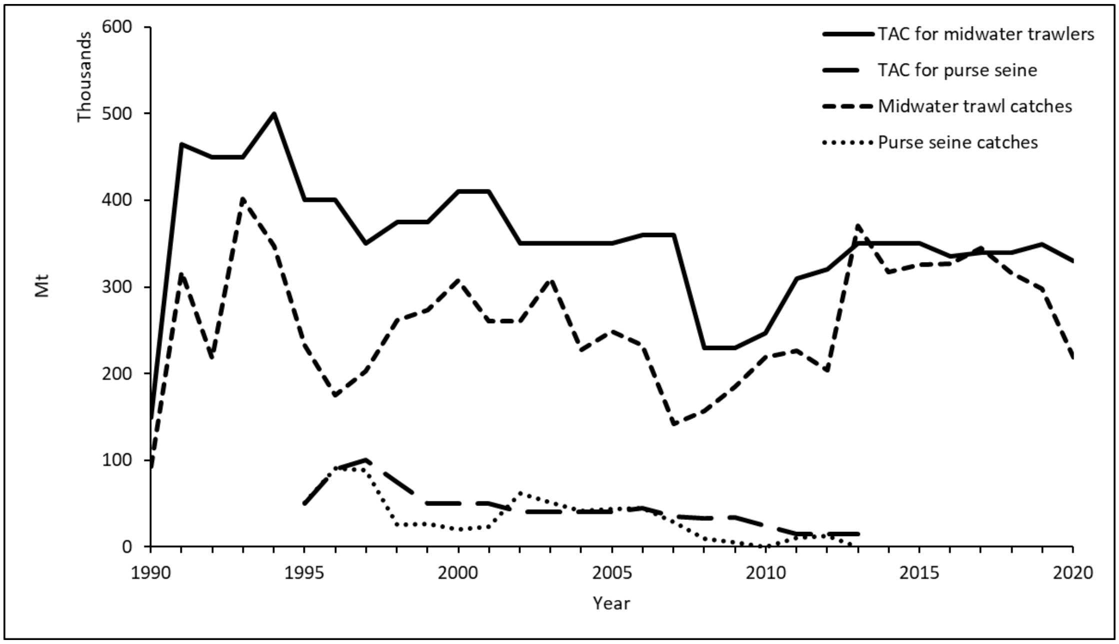

Figure 5. Midwater trawl and purse seine catches against TAC (MFMR, 2020).

2.2.2 Fishing fleet and fishing effort

Cape horse mackerel is a mesopelagic species harvested by midwater trawlers targeting adult fish beyond 200 m isobath throughout the year. The area along the shoreline to the 200 m depth contour is a marine protected area and no commercial fishing is allowed to take place in order to protect the spawning stock and juvenile fish found along the coast. Some trawlers are fully or partly locally owned and some trawlers are foreign, chartered through legally binding agreements.

Fishing effort is the total amount of fishing activity carried out on a fishing ground over a given period and is comprised of several factors (FAO, 2003). First, technological interactions such as type of fishing gear, and fish finding devices makes it easier for the crew members to fish and navigate around fishing grounds respectively. Second, the construction of the vessel determines its ability to access different fishing grounds, handle larger fish volumes, and operate during different weather conditions. Third, the level of skills and knowledge of crew members to operate the vessel in an effective and efficient way. These dynamic factors contribute to the amount of fishing effort for a particular vessel which makes it difficult to estimate and therefore, no unique universal measure of fishing effort is established (Arnason, Kelleher, & Willmann, 2008). Overall, increasing demand for fish in new and old markets is the key driver of increases in fishing effort (Anderson & Seijo, 2010).

Catch per unit of fishing effort (CPUE) is applied as aggregate catch per trawling hour for each year from 1990-2020 (Figure 6). From 1990-2008, CPUE was stable around 5.1-9.0 metric tonnes per hour and increased sharply to 17.1 and 23.4 metric tonnes per hour in 2009 and 2010 respectively. This depicts high catches per trawling hour and could be subject to several factors such as change in improvement of fishing effort, or stock size or prolonged aggregate fish behaviour due to availability of food between in the reference periods. Then, CPUE declined and attained equilibrium catch per hour trawled between 7.2-19.4 tonnes (2011-2020).

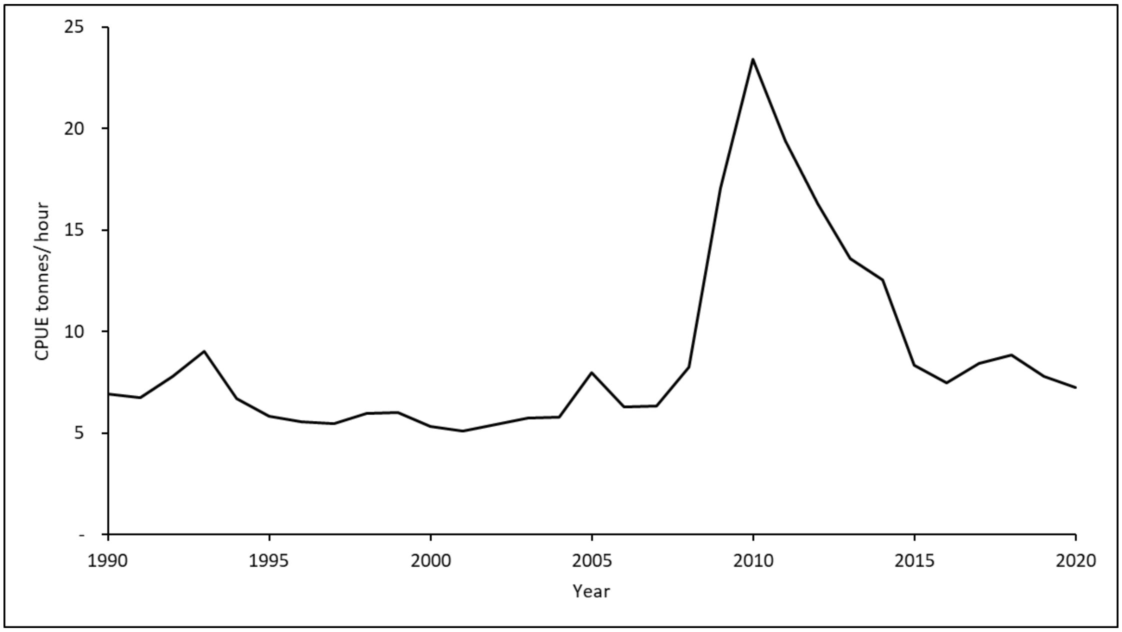

Figure 6. CPUE – Average CPUE of horse mackerel, measured as catch per hour trawled.

2.2.3 Export destinations

Cape horse mackerel is a low value commodity that is often traded in traditional markets and in low- and middle-income markets in southern Africa and in smaller proportions to the rest of Africa. Cape horse mackerel is largely exported to SADC regional markets using road transport with freezer trucks. Based on 2020 export data, the value for Cape horse mackerel trade stands at USD 178 million (NamRA, 2021). The largest export destination is the Democratic Republic of Congo with over 42% market share, followed by Zambia with over 21% market share and South Africa with 14% market share.

2.2.4 Ex-vessel prices

The price of whole Cape horse mackerel was relatively stable with minimal fluctuations of USD 0.04/kg to USD 0.16/kg between 1990 to 2004. Thereafter, average ex-vessel prices increased and ranged from USD 0.14/kg to USD 0.60/kg (2013-2019) before reaching a peak of USD 0.88/kg in 2020 (Figure 7). Cape horse mackerel remain a low value commodity due to a lack of demand from high income markets and minimum value-added processing on the fish as over 84% of catches is processed at sea (freezer) in whole fish round form (79%) and fishmeal (5%) between 2017 - 2021.

Fishmeal fetches a higher price per kilogram on the market compared to whole round fish, however, the demand for Cape horse mackerel for human consumption is greater than that for fishmeal. Nowadays, fishmeal is mainly produced as a result of damaged fish from trawling and processing. Fishing companies invest in reducing damage on catches and hence, lower volumes of fishmeal are produced.

Ex-vessel prices of fishmeal remained relatively stable in the range of USD 0.19/kg to USD 0.21/kg between 1990 to 2004. The trend of price fluctuations is similar to that of whole round fish where the price increased and ranged from USD 0.19/kg to USD 0.98/kg.

The largest export destination for Cape horse mackerel remains DRC, which has a gross national income of USD 550 per capita and is thus classified as a low-income export market (World Bank, 2021).

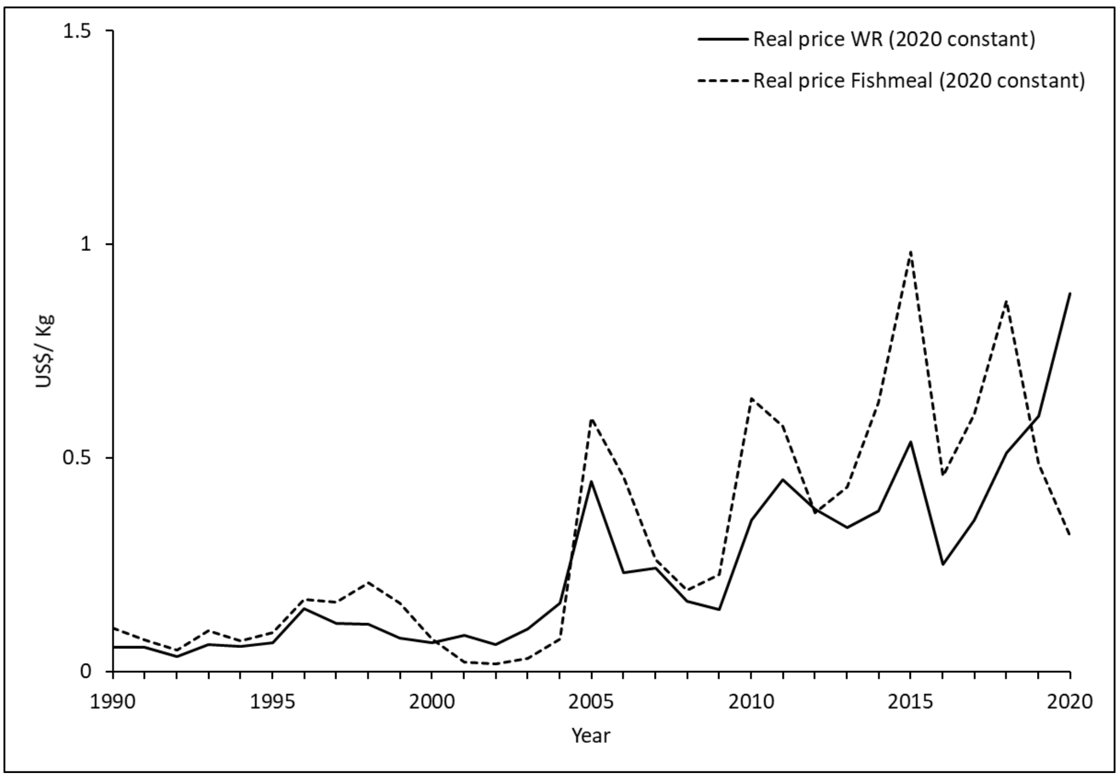

Figure 7. Average ex-vessel prices for Cape horse mackerel per kilogram, adjusted for inflation to prices in 2020 (MFMR, 2021).

2.3 Fisheries management in Namibia

Article 100 of the Namibian Constitution gives sovereign power for all natural resources below and above the surface on land, continental shelf and within the territorial waters (EEZ) to the state and therefore, fisheries resources belong to the Namibian nation and are governed by the national government.

Cape horse mackerel, together with other marine species such as hake, were discovered during the 1950s and 1960s by foreign distant trawler fleets (MFMR, 2004). After independence in 1990, Namibia adopted a user rights and quota management system as a solution to the problem of open access fishing and to improve economic benefits from fisheries for Namibians. The introduction of the user rights and quota management system has successfully protected marine resources and ensured maximum yields from fish stocks and income. To that end, Namibia developed the Marine Resources Act, No. 27 in 2000, Regulations relating to the exploitation of Marine Resources in 2001 and the Marine Resources Policy in 2004 to regulate the utilisation of marine resources within the territorial marine waters. At the same time, a Namibianisation policy in fisheries was passed into law which is aimed to empower and improve Namibian's participation in fisheries operations.

2.3.1 User rights and quota management system

The Cape horse mackerel is managed through TAC output measures. The National Marine Information and Resources Centre (NatMIRC) of the Directorate of Resource Management conducts scientific assessments annually to determine the stock sizes and distribution of different species and recommends TAC, using Maximum Sustainable Yield (MSY)as a reference point, for the next harvesting season. The TAC recommendation is presented together with analysis on socio economic performance of the species carried out by the Directorate of Policy, Planning and Economics to the Marine Resources Advisory Council (MRAC). MRAC members are appointed to represent fisheries stakeholder groups. The council members give full consideration to the biological status of the stock based on best scientific evidence available and socio-economic performance of the sector and provide a recommendation of the TAC to the Minister who then tables it in cabinet for approval. After cabinet approval of the TAC, the Minister allocates quotas to user rights holders based on Section 33 of the Marine Resources Act, No. 27 of 2000. The MRAC members are available to advise on all fisheries related matters on which the Minister might require advice as the need arises.

2.3.2 Monitoring, control and surveillance

Fishing activities are monitored by the Directorate of Operations in collaboration with the Fisheries Observer Agency (FOA). Fisheries observers are placed on board each time a vessel goes out fishing. In addition, the agency utilises a vessel monitoring system (VMS) and conducts regular ocean patrols by boats and air surveillance. The beaches are patrolled by manned vehicles and target mainly artisanal and recreational fishers.

By law, fishing vessels are required to be registered and are issued a licence by the local authorities before accessing fishing grounds and all catches must be recorded. Should a company record higher catches than allocated quota, the excess catch will be deducted from the next season's quota allocation. The catch records are utilised in stock assessments modelling which determines the TAC for the next season.

2.3.3 Resource rents

Fishing companies pay resource rents to the Namibian government. The resources rent system is based on several contributions, including direct cost recovery fees for the fisheries management system. The direct fees are charged as a percentage of the landed value and depends on whether the fish was landed frozen or fresh, processed on land or processed at sea. In addition, fees are further grouped into three categories based on whether the vessel is Namibian, Namibian-based, or foreign (MFMR, 2017).

On average, the fees for landing fresh fish or fish to be processed on land utilising a Namibian vessel are lower than landing frozen fish or fish processed at sea from a Namibian-based or foreign vessel. This is to promote maximum employment, production, and purchasing power for Namibian citizens.

The Namibian system charges quota fees, fund levies, and observer fees on a basis of quota allocation and harvest to encourage optimum utilisation of fisheries resources and charges a deterrence fee for bycatch (MFMR, 2017). Furthermore, a vessel licence fee is paid together with application to access fishing grounds.

In its simplest definition, landed value is a pre-determined value for harvesting each species per Kg and it is updated over time in consultation with fisheries stakeholders and the Ministry of Finance. The current landed value for Cape horse mackerel is USD 0.60/kg. On top of the fees described above, fishing companies are obliged to pay 32% corporate tax and 15% value added tax on net income and many other fees and duties for services rendered to them.

3 METHODS

To estimate surplus production in the Cape horse mackerel fishery within the Namibian EEZ, this study applies the Gordon-Schaefer (1954) bioeconomic static model as a reference to estimate parameters assuming equilibrium conditions. Surplus production model analysis is an appropriate tool to use when catch, effort and biomass data are available, as is the case with the Namibian Cape horse mackerel fishery.

The bioeconomic model integrates biological and economic data from a single species to explain stock, catch and effort dynamics which can be used to ensure optimal management of the stock over time (Larkin, Alvarez, Sylvia, & Harte, 2011). Overall, the model estimates the bioeconomic impacts derived from the fisheries management system. The model is run with an objective function in relation to the fishing effort over time and a maximum level of effort is determined by introducing the cost structure and value of harvest.

Fisheries bioeconomics, if correctly applied, is a useful tool in the development of practical management policies and regulations of fishing activities. This comes at a time when developing countries such as Namibia are exploring approaches to maximise benefits from fisheries resources. A stated objective of the current management system is rebuilding stock. This model is important in determining a fishing effort level that will maximise economic yield in the long run, but rebuilding stock can only take place when growth in stock biomass is greater than natural and harvesting mortality. Rebuilding Cape horse mackerel stock will take time since the stock itself is limited in its reproduction and growth capacity within its environment. Estimating stock rebuilding dimensions requires extensive analysis which is not covered in this study due to limited scope and timeframe.

This study applies a simplified approach to the Gordon-Schaefer (1954) bioeconomic model using the best available data in line with theories, concepts and rationalisations published in the *Economic Justification of Fisheries Reform* (Arnason, Kelleher, & Willmann, 2008) and *Fundamentals of Fisheries Bioeconomics of Fisheries Management* (Anderson & Seijo, 2010).

3.1 Data sources and data quality

This study applies bioeconomic analysis using annual time series biology data sourced from the NatMIRC (Directorate of Resource Management), and economic data from the Directorate of Policy, Planning and Economics as collated from monthly, quarterly, and annual surveys. The same data is used in the compilation of national fish capital accounts; however, data treatment might differ between modelling assessments. In addition, foreign currency exchange rates and consumer price indices (CPI) to respectively estimate price in USD and apply price deflator was sourced from the Bank of Namibia. The following is the description of the data used and is in accordance with fishing and biological calendar for Cape horse mackerel that runs for a whole calendar year:

3.1.1 Biological data

Biomass estimates from Cape horse mackerel targeted surveys date back to 1995 and are derived from annual stock surveys. Biomass estimates obtained from surveys are not absolute indicators of stock size, however the trend is reliable as the survey design has been consistent since 1999.

3.1.2 Economics data

Fish catches are entered into a log sheet for every fish trip and reconciled with quota allocation. Of late, the number of fishing days has been reduced due to several factors. First, improved fishing skills and technology that lead to easier navigation around fishing grounds. Second, continued demand for better-quality seafood has driven fast processing soon after the fish is caught to supply the market. Catch data is used in socioeconomic and scientific assessments of the fishery.

Nominal ex-vessel prices per metric tonne were obtained from the economic model generated by MFMR. The model is updated with price data from bi-annual price surveys completed by fishing companies targeting Cape horse mackerel. The price is converted from local currency into USD and indexed to constant Consumer Price (CPI) at 2020 prices obtained from the Bank of Namibia and Namibia Statistics Agency which makes levels of 2020 real economic prices comparable for to prices in the past.

There is limited cost data available for fishing fleets. Cape horse mackerel is harvested by several fishing companies who on average operate two or more fleets. Ex-vessel cost is estimated per vessel for one company and aggregated to effort in 2020. The data is extracted from the annual income and expenditure survey (AIES) in local currency and converted to USD (Appendix 1). The harvest cost was compared to the long run average cost of Icelandic pelagic fleets and an error of low-cost capital was detected for operating a trawler in Namibia. Therefore, the cost of the Namibian pelagic fleet was adjusted by 35% upwards to account for the low cost of capital.

3.2 Equations

3.2.1 Maximum sustainable yield (YMSY)

Maximum sustainable yield is achieved at the level where equilibrium fishing effort produces maximum growth of biomass and is estimated in Table 1.

Table 1. Yield and effort estimation for maximum sustainable yield reference point.

Model	$\boldsymbol{Y_{MSY}}$	$\boldsymbol{E_{MSY}}$
Verhulst-Schaefer	$= \frac{a^2}{4b} = \frac{r\kappa}{4} = aE_{MSY} + bE_{MSY}^2$	$= -\frac{a}{2b} = \frac{r}{2\theta}$

3.2.2 Bioeconomic equilibrium yield (YBE)

Bioeconomic equilibrium is achieved when marginal cost (MC) is equal to marginal revenue (MR) and yield and effort are estimated in Table 2.

Table 2. Yield and effort estimation for bioeconomic yield reference point.

Model	$\boldsymbol{Y_{BE}}$	$\boldsymbol{E_{BE}}$
Verhulst-Schaefer	$= \frac{c^2 - pca}{p^2 b} = \frac{rc}{p\theta}\left(1 - \frac{c}{p\theta\kappa}\right)$	$= \frac{c - pa}{pb} = \frac{r}{\theta}\left(1 - \frac{c}{p\theta}\kappa\right)$

3.2.3 Maximum economic yield (YMEY)

Maximum economic yield is achieved at the level where equilibrium fishing effort produces the highest monetary gain and is estimated in Table 3.

Table 3. Yield and effort estimation for maximum economic yield reference point.

Model	$\boldsymbol{Y_{MEY}}$	$\boldsymbol{E_{MEY}}$
Verhulst-Schaefer	$= \frac{c^2 - p^2a^2}{4p^2 b} = \frac{r(p^2\theta^2\kappa^2 - c^2)}{4p^2\theta^2\kappa} = aE_{MEY} + bE_{MEY}^2$	$= \frac{pa - c}{2pb}$

4 RESULTS

4.1 Fishing effort and catch per unit effort – CPUE

Catch per unit of fishing effort (CPUE) is applied as aggregate catch per trawling hours each year from 1990-2020 (Figure 4). Catch data per trawling hours is available from daily log sheets since 1990. Therefore, CPUE is developed for each year by estimating catch and the total number of trawling hours. Fishing effort, on the horizontal axis, is assumed to be total duration of trawling hours and catch-per-unit-effort, on the vertical axis, is the average catch per hour (Figure 8 and Figure 9. The data trend suggests high CPUE can be attained with fewer fishing hours as the fishing operations become more efficient. Fishing companies maximise revenues and profits using maximum output approach from less effort which results in higher economic yields from fisheries and government can benefit from high resource rents if applied correctly.

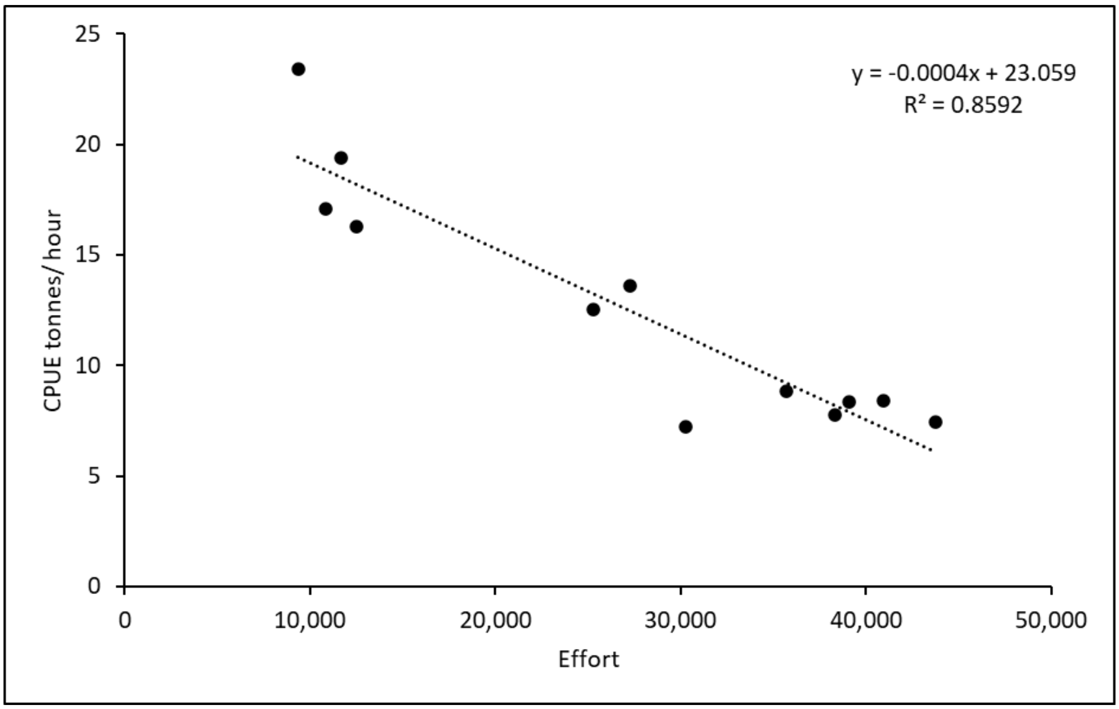

Figure 8. CPUE of 2009-2020, measured as catch per hour trawled.

The development of CPUE from 1990-2020 shows a lower fit of data in the model (R^2 = 0.52) and could have been caused by different transitions in methodologies and process of managing the stock over time (Figure 9). Nevertheless, estimation of the model with data points from 2009-2020 shows a similar modelling result as the longer time series data however, with a better data fit (R^2 = 0.86). Therefore, this model applies most recent data estimates from 2009-2020.

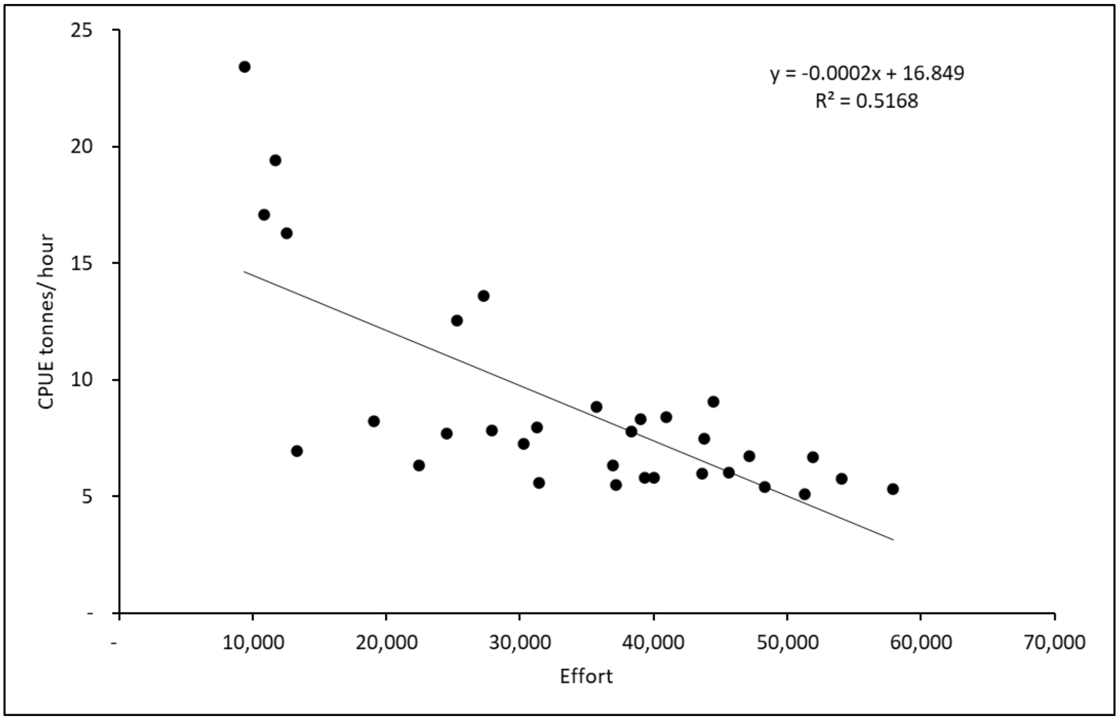

Figure 9. CPUE of 1990-2020, measured as catch per hour trawled.

4.2 Biological estimates of the Cape horse mackerel

The model applies the Pearl-Verhulst logistic growth function (Schaefer) to estimate the relationship between biomass and biomass growth as a linear function derived from the growth equation:

$$F(X_t) = 0.58X_t\left(1 - \frac{X_t}{2{,}365{,}811}\right) \tag{23}$$

Table 4. Estimating r, and κ parameters.

Parameters	Pearl-Verhulst model
r	0.58
κ	2,365,811

Stock biomass depends on the intrinsic growth of the stock *r* estimated to be 0.58 and a carrying capacity κ of 2.3 million metric tonnes of fish (Figure 10). It is assumed that the maximum growth of the stock will reach an equilibrium state (MSY) at 342,115Mt and 1,182,905Mt carrying capacity (κ/2).

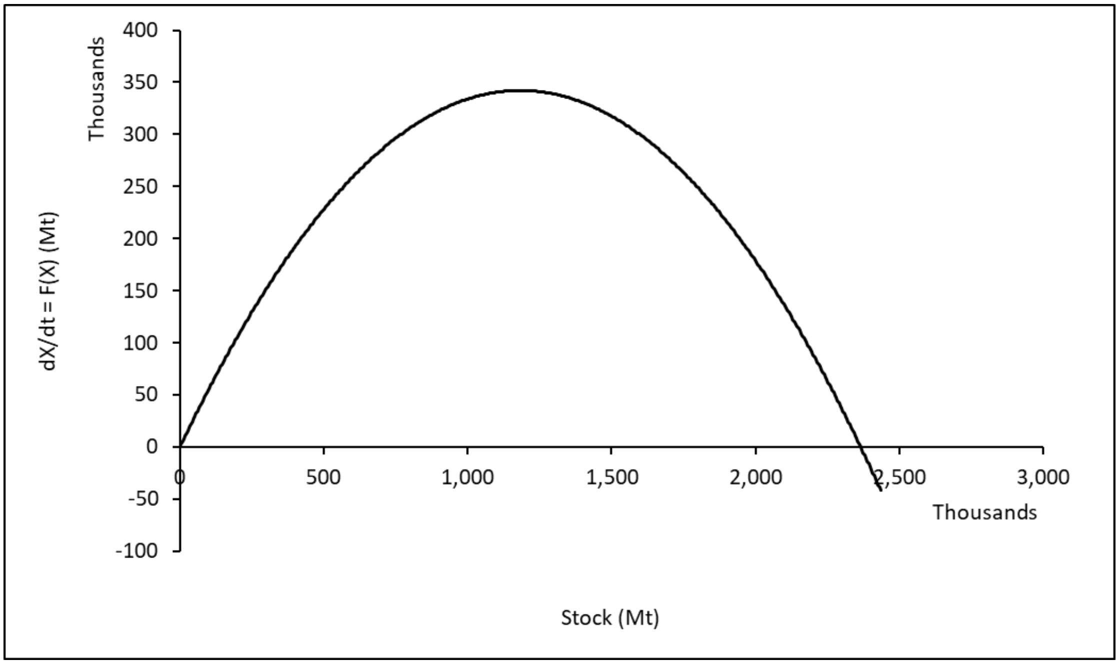

Figure 10. Biomass growth and stock size of Cape horse mackerel.

The Schaefer logistic growth model predicts the fluctuations of biomass due to growth and harvest (Figure 11). Biomass estimates from the logistic model show an overestimation of the stock when compared to the biomass estimates from stock surveys due to a lack of incorporation of environmental factors that are considered in stock surveys. Therefore, estimating biomass from a standardised logistic growth model may be unreliable unless a dynamic model is applied to include environmental factors in the assessments. No stock surveys were carried out on Cape horse mackerel in 2020 and 2021 due to technical challenges, however, the logistic growth model predicts an increase in biomass to 1.5 million and 1.6 million metric tonnes respectively.

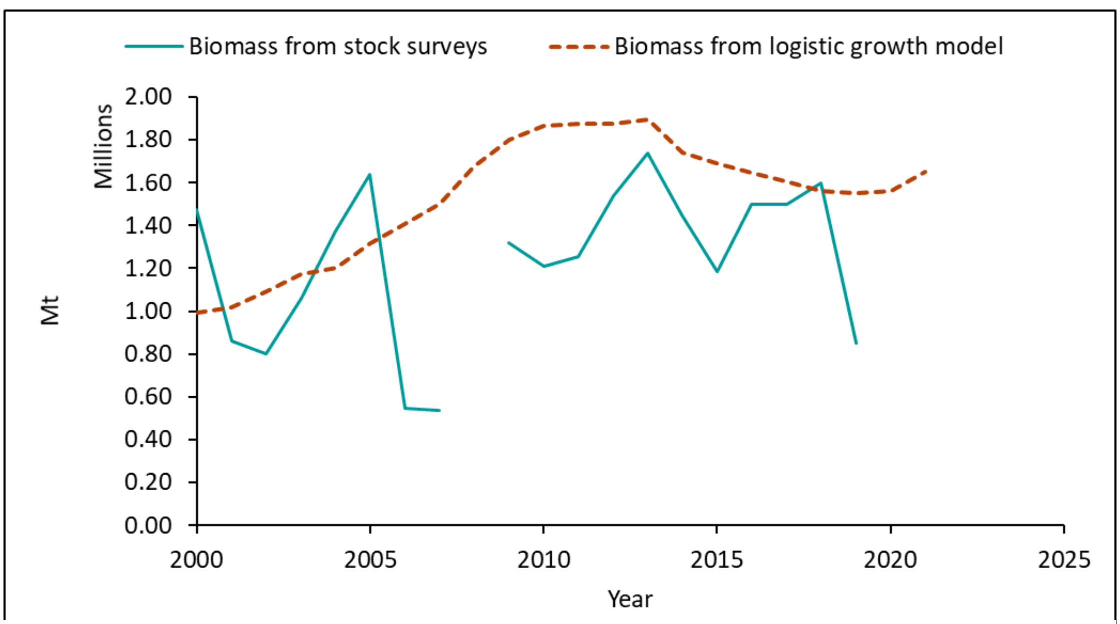

Figure 11. Biomass estimates of horse mackerel from acoustic surveys and the logistic growth model.

4.3 Estimation of harvest function

The harvest function, also known as the yield function, predicts the production curve based on effort and stock biomass, estimated as:

$$H_t = 0.000009.75XE \tag{24}$$

The catchability parameter indicates a relationship between effort and harvest. The data on harvest shows high effort is exerted during summer months through the end of August, which is attributed to high aggregating behaviour simulated by availability of food. The results derived from the model show that an increase in effort by one unit affects the harvest by less than 0.001%. This can imply that the cause of variation is in stock size and less on effort because there have not been many changes in the type of fleets targeting Cape horse mackerel. Also, the trend observed from the catch data plotted against time supports this (Figure 12).

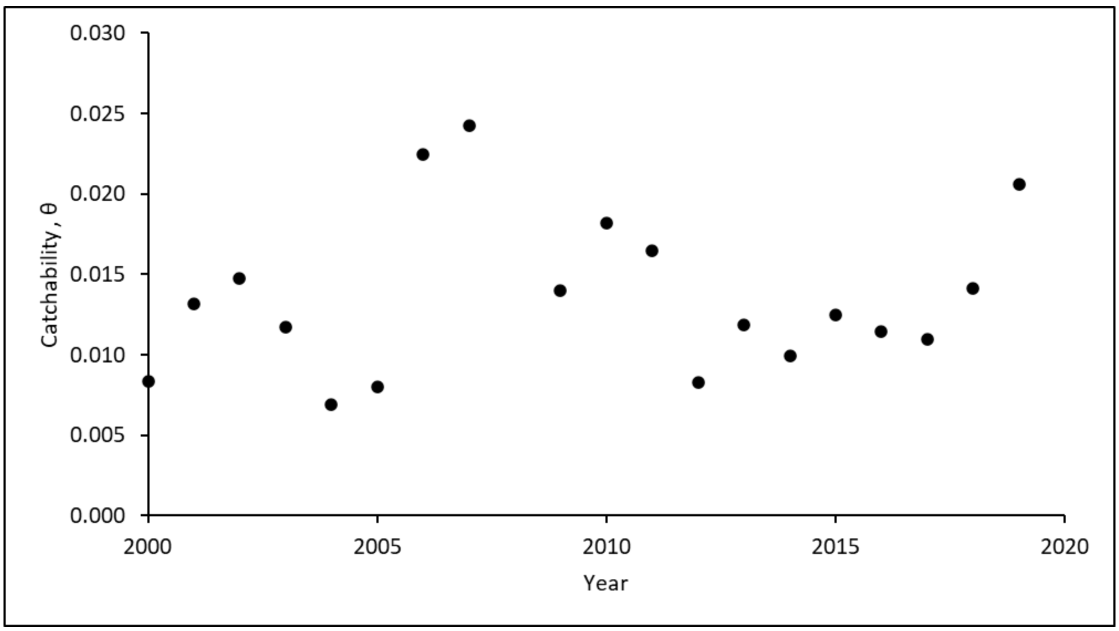

Figure 12. Catchability parameter.

Table 2 summarises the estimation of ordinary least squares (OLS) regression of the harvest function. The regression (R^2 = 0.8591505) of the best fit line explains 86% of variation for harvesting Cape horse mackerel with a standard deviation of 0.0069. The coefficient *b* which depicts the degree of schooling behaviour of the stock (Arnason, Kobayashi, & de Fontaubert, 2017). The schooling parameter is estimated to be -0.000389 which resembles a high degree of aggregation behaviour of Cape horse mackerel.

Table 5. Estimation parameters of the harvest function.

Regression Statistics								
Multiple R	0.9269037							
R Square	0.8591505							
Adjusted R Square	0.8450656							
Standard Error	2.1433861							
Observations	12							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	280.23016	280.23016	60.997787	1.452E-05			
Residual	10	45.941038	4.5941038					
Total	11	326.1712						
	Coefficients	Standard *Error*	t *Stat*	P-value	Lower *95%*	Upper *95%*	Lower *95,0%*	Upper *95,0%*
Intercept	23.058777	1.4828521	15.550288	2.472E-08	19.754776	26.362777	19.754776	26.362777
X Variable 1	-0.000389	4.975E-05	-7.810108	1.452E-05	-0.000499	-0.000278	-0.000499	-0.000278

4.3.1 Cape horse mackerel production yield curve

The production yield curve, a polynomial concave, shows the long term relationship between harvest (measured in tonnes) and the level of fishing effort applied (defined here as trawling hours) (Figure 13). The equilibrium yield increases as more effort is applied, until it reaches the highest point, referred to as MSY, where additional effort applied results in lower yield until the stock is depleted. Maximum sustainable yield (Y_{MSY}) of Cape horse mackerel is estimated to be achieved at a harvest of 342,115Mt by a corresponding effort of 29,673 trawl hours E_{MSY}. In 2020, a total of 219,028Mt of Cape horse mackerel were harvested at an effort level of 30,276. Catch is below estimated stock growth at MSY and MEY level by 36% and 33% respectively, whilst effort is above with 2% and 29% for the same levels. Hypothetically, the estimated biomass contained in the carrying capacity of the environment can be depleted by effort level over 60,000. However, this is not likely to happen in the current fisheries management system as fishing activities become uneconomical.

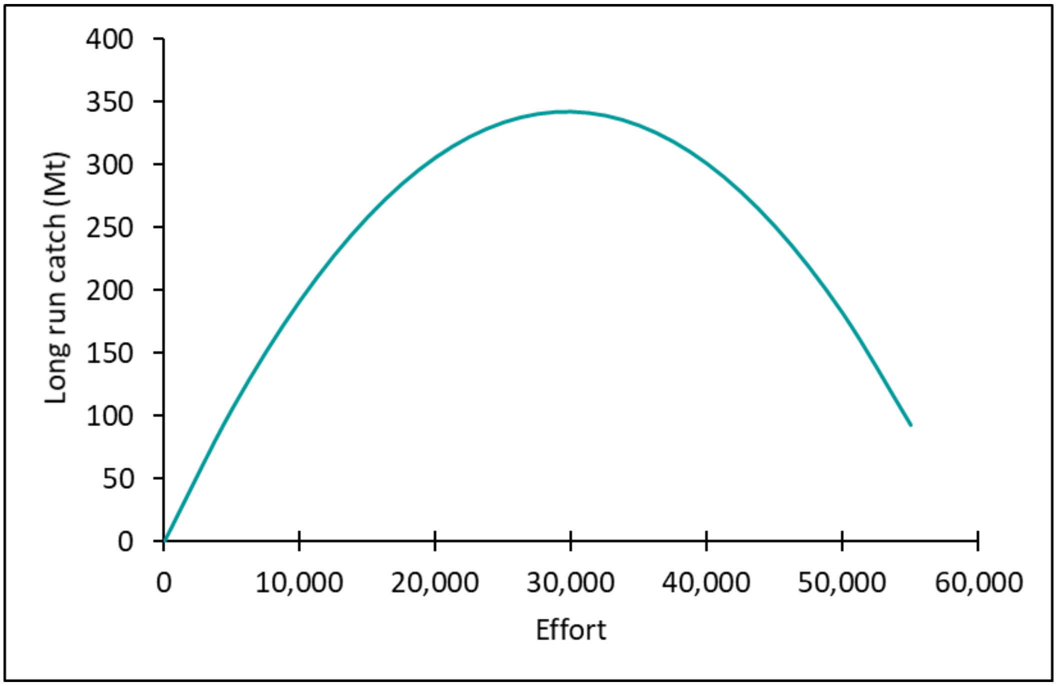

Figure 13. Cape horse mackerel production curve.

When the value of production is known, a polynomial total revenue can be created (Figure 14). This model predicts that maximum economic yield is achieved at an effort lower than maximum sustainable yield, estimated as:

$$TR_t = 884(23.05888E - 0.000388E^2) \quad (25)$$

Results of the model suggest profits of USD 175,698,106 and USD 188,981,801 will be achieved at MSY and MEY respectively. The bioeconomic equilibrium yield will be achieved at 46,910 trawling hours.

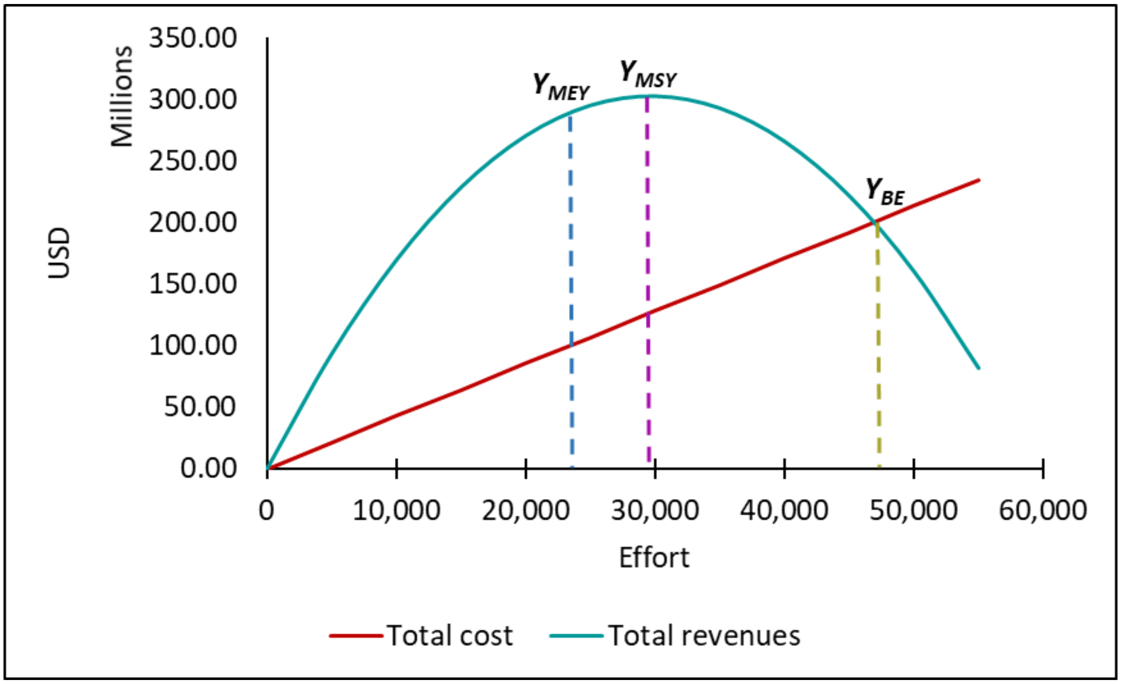

Figure 14. Total revenue and cost in equilibrium.

4.4 Optimal sustainable yield for the Cape horse mackerel projection

Optimal management policy for Cape horse mackerel biomass in equilibrium state is estimated to be around 1.2 million MT to 327,091Mt for the years 2022 to 2050 (Figure 15).

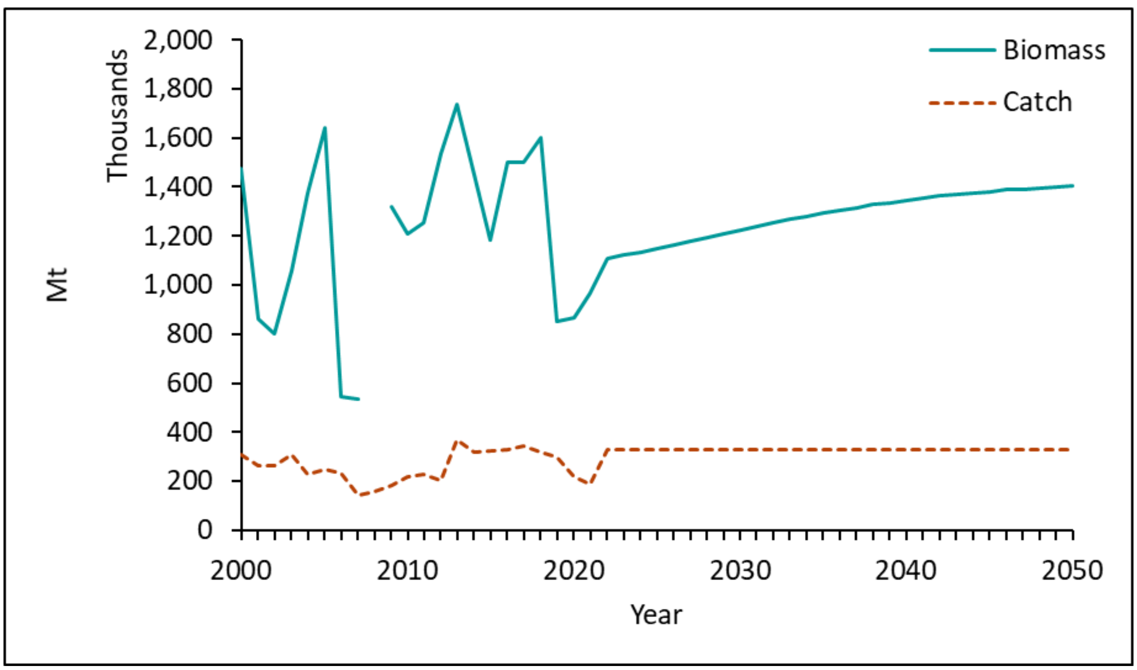

Figure 15. Optimal policy management projection.

Table 6 below summarises the estimation of parameters from the growth function, harvest function and economic functions.

Table 6. Parameter estimation for the bioeconomic model.

	Symbol	**Value** ***E***
Biological parameters		
Intrinsic growth rate	r	0.58
Carrying capacity	κ	2,365,811
Economic parameters		
Price of fish per metric ton in USD	P	884
Cost per unit of effort in USD	C_E	5,323,065
Catchability coefficient	Θ	9.74667E-06
Equilibrium values		
Maximum sustainable yield	Y_{MSY}	342,115
Bioeconomic equilibrium yield	Y_{BE}	226,681
Maximum economic yield	Y_{MEY}	327,091
Stock at maximum sustainable yield	X_{MSY}	1,182,905
Stock at bioeconomic equilibrium yield	X_{BE}	495,788
Stock at maximum economic yield	X_{MEY}	1,430,800
Effort at maximum sustainable yield	E_{MSY}	29,673
Effort at bioeconomic equilibrium yield	E_{BE}	46,910
Effort at maximum economic yield	E_{MEY}	23,455
Profits at maximum sustainable yield in USD		175,698,106
Profits at maximum economic yield in USD		188,981,801

5 DISCUSSION

Results from the model depict an abundant stock of Cape horse mackerel with regular fluctuations in biomass estimates. The stock shows a potential for good growth in less than 10 years under a rebuilding management plan. Good growth in stock may be attributed to favourable environmental factors of the Benguela upwelling and management protection measures such as the 200m contour marine protected area along the coast which protects spawning stock and juvenile fish.

The bioeconomic model applies effort as a critical factor in overall parameter estimations and therefore an accurate effort estimation is necessary for a reliable model. In this study, effort is assumed to be the total duration of active fishing by trawlers targeting Cape horse mackerel each season. CPUE is calculated as catch per hour. Estimated CPUE declined by 7% from 7.8 t/hr in 2019 to 7.2 t/hr in 2020. The decline is likely due to an exit of some trawlers during 2020 and an unresponsive allocation of the quota for the remaining fishing companies.

The model suggests that effort level exerted in 2020 could achieve a maximum economic yield in an efficient quota share system. In recent years, the Ministry has been allocating the Cape horse mackerel quota in portions, often at the beginning of the first quarter and in the middle to end of the second quarter per season, which results in poor planning by fishing companies due to uncertainty of receiving an allocation, leading to low catches at the end of the year. On the other hand, low catch is good for stock growth in the long run which can lead to an increase in future catch and revenues.

Cape horse mackerel catch was below the MSY and MEY levels in 2020 and effort was above the estimated corresponding effort at the same levels. This means that low income and resources rents were generated due to low production prompted by an ineffective quota allocation.

Theories and concepts of the bioeconomic model predict adjustments of effort that can maximise economic profits from fisheries over time and can be achieved mainly by improving effort. Improving effort requires fishing companies to move towards the use of the latest technology and away from human labour in order to meet demand. This is different from current fishery practices in Namibia. The government is promoting employment creation through onshore value addition initiatives mainly by rewarding more quota allocation to fishing companies with more Namibian employment. Furthermore, improvement in effort requires equal advances in regulations to ensure it does not negatively affect fish population growth in the long run.

Other socioeconomic factors considered by the fisheries management system in fishing allocation are statutory payments, Namibian ownership share in fishing operations, contribution to food security, investment, corporate social responsibilities, local procurement of goods and services, regional development, and onshore value addition initiatives. These impacts on fisheries are not defined in the bioeconomic model concepts and will require extensive research to evaluate the effect on the fishery.

The allocation of additional user rights with a relatively similar stock size impacts fishing effort and diminishes per capita share, leading to lower resource rents. In addition, each user right holder is required to perform investments in fisheries in order to qualify for a long term period of the right.

Cape horse mackerel is a low-priced commodity and that makes it hard to process high end products or products for high end fish markets. With limited potential to process value added products, employment creation in the Cape horse mackerel fishery will be more challenging than with high valued commercial species such as hake. Therefore, there is a need to realize the maximum employment creation in the fishery to maximise economic benefits.

The model derives a development path in equilibrium of profits to be made for each TAC set (Figure 16). The curve suggests that there is not a wide difference between estimated levels of maximum economic yield and maximum sustainable yield and overfishing catches will lead to a sudden fall in profits.

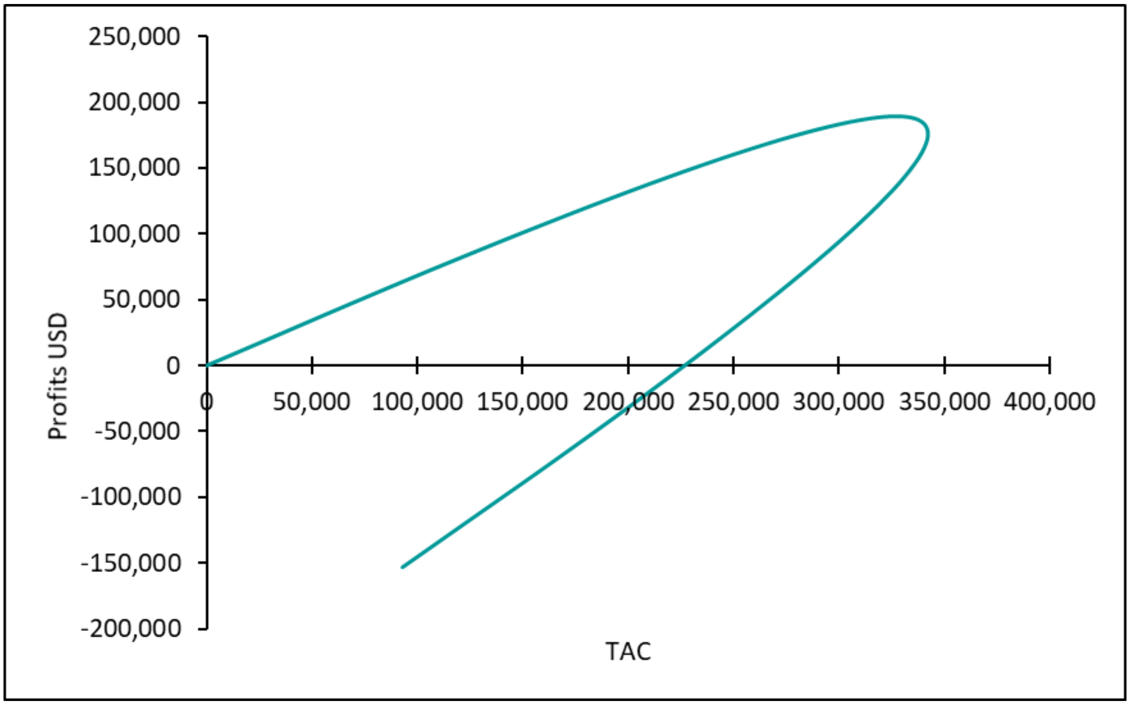

Figure 16. Parameter estimation for the bioeconomic model.

Maximising economic profits can be a good option for Cape horse mackerel management. The excess profits generated in the MEY harvest rule can be directly or indirectly diverted through an appropriate resource rents system to support secondary industries of affected communities such as provision of study grants, infrastructure development, grants for entrepreneurship etc., that can achieve similar socioeconomic benefits for the Namibian people.

5.1 Study limitations

A complete empirical cost assessment of fishing effort for all midwater trawlers is unavailable. Therefore, this study applied the best cost data available from one fishing company and applied it to the total number of vessels in the fishery. The cost of operating a midwater trawler was further observed to be very low when compared to that of Icelandic pelagic fleets and was adjusted up to a long term cost by 35%.

This study aimed at integrating economic and biological data to establish maximum sustainable yield and maximum economic yield of the Cape horse mackerel using the Gordon-Schafer bioeconomic modelling analysis. The results support the theories and concepts of the model as established, the estimations of key reference points in equilibrium conditions have supported the theories and predictions in the real fisheries management practices in Namibia.

Exploitation level at maximum economic yield is lower than the level of effort at maximum sustainable yield and therefore, implementing the MEY harvest rule requires an exit plan for some fishing companies. Overall, there are several key reforms to be achieved for management considerations regarding MEY harvesting to make it work more effectively:

i. Political will to exploit fisheries resources at maximum economic yield and effort.
ii. Prioritisation of stock assessment to estimate biomass on a yearly basis.
iii. Permit longer terms of fishing for user rights. This will allow user right holders to forgo short lived benefits for longer sustainable benefits.
iv. Effective allocation of fishing quotas which allow for effective planning and transferability amongst Namibians that can maximise benefits from fisheries.
v. Set a limit quota concentration to avoid skewed market power. Market power can lead to several factors i.e., control of fishing, prices, market manipulation.

The use of bioeconomic modelling informs fisheries management to determine optimal fleet sizes and fishing effort to give Namibia an advantage in maximising potential benefits from Cape horse mackerel resources. However, bioeconomic analysis is fundamentally driven by effort parameters and therefore, further research may be required to develop a consensus of accurate effort measures and other dynamic factors for the Cape horse mackerel stock fishery in Namibia.

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APPENDICES

Appendix 1 Offshore Direct expenditure: Annual Income and Expenditure Survey (AIES)

Personnel
Salaries & Emoluments
Employee Contr. To Social Welfare
Consumables
Inputs To Processing
Utilities
Electricity, Water, Gas
Materials
Parts: Repairs & Maintenance
Ice
Bait
Detergents & Cleaning Materials
Packaging Material
Fees
Quota Fees
Fund Levies
Vessel License Fees
By-Catch Fees
Observer Fees
Harbour Fees
Processing Fees
Unloading Fees and Transhipment Expenses
Price Variance
Cost Of Goods Sold
Communication Costs
Protective Clothing
Safety Equipment
HACCP
Credit Guarantee Insurance
Documentation & Handling
Purchases Of Quota
Fuel & Lubrication
Vessel Repairs & Maintenance
Vessels Insurance
Vessel Charter Fees
Rent Equipment on Vessels
Depreciation
Fishing Gear
Food & Rations/Crew Provisions
Technical Liquids
Licences and permits
Cleaning Expenses
Inspection Fees

Appendix 2 Biological growth function calculations

A2.1 The Schaefer logistic growth model

The biological growth model is based upon the Pearl-Verhulst equation of population dynamics of fish stock and can be expressed as:

$$\frac{dX}{dt} = F(X_t) \tag{1}$$

Where,

$\frac{dX}{dt}$ represent change in stock per unit of time

$F(X_t)$ represents biological growth of stock

t represents time

$$F(X_t) = rX_t\left(1 - \frac{X_t}{\kappa}\right) \tag{2}$$

Where,

X is the stock size measured in terms of tons of biomass

r is the intrinsic growth rate, the rate at which the stock will grow overtime

κ is the carrying capacity of the environment, the biggest size of stock that can be sustained by the environment

Equation 2 generates a bell-shaped polynomial concave of the long-term production function of a fishery, where $F(X_t)$ corresponds to a yield for any given level of effort applied to the stock at equilibrium, known as sustainable yield. The yield in equilibrium will increase with effort until the highest point of the bellcurve, where the gradient of the slope is zero, which is referred to as the maximum sustainable yield (MSY). The yield in equilibrium will then continuously decrease until stock reaches zero when more effort is applied, reaching carrying capacity of the environment.

To predict maximum growth of the stock, where the gradient of the slope is zero, we set the derivative of equation 2 to zero and solve for r and κ, expressed as:

$$r - \frac{2rX}{\kappa} = 0 \tag{3}$$

Solving for X obtains maximum sustainable yield of a fishery that is equal to the maximum growth of the stock, expressed as:

$$X_{MSY} = \frac{\kappa}{2} \tag{4}$$

A2.2 The harvest function

When fish exploitation takes place, the biological growth model is altered to:

$$\frac{dX}{dt} = F(X) - H_t \qquad (5)$$

A sustainable stock level is sustained when the rate of harvest is equal to the rate of reproduction and growth of the recruits. Therefore, the stock remains in a constant state, expressed as:

$$F(X) = H_t \qquad (6)$$

The yield function, also known as the production or harvest function, is assumed to be equal to demand rate depending on amount of fishing and size of the stock, expressed as:

$$H_t = \theta X^a E^b \qquad (7)$$

Where,

E is fishing effort

X is the stock size measured in terms of tons of biomass

θ is catchability coefficient, the level of technology that is used to harvest fish

a, b are positive constants of the function, where b is the degree of schooling behaviour of the fish

In a case where a, b is 1, equation 8 is simplified to:

$$H_t = \theta XE \qquad (8)$$

CPUE is equivalent to θX, and solving for effort, E equals to:

$$E = \frac{H_t}{\theta X} \qquad (9)$$

Solving for catchability coefficient, θ equals to:

$$\theta = \frac{H_t}{XE} \qquad (10)$$

Fishing effort E, depending on fishing gears, is the man-made capital of fisheries system, exploiting with the expectation to supply fish (demand of fish) to the markets and provide returns to trawler owners.

Therefore, equation 7 is expanded to:

$$rX_t\left(1-\frac{X_t}{\kappa}\right)=\theta XE \tag{11}$$

Solving for X obtains,

$$X=\kappa-\frac{\kappa\theta E}{r} \tag{12}$$

Equation 12 is known as the population equilibrium curve and refers to that, changes in fish stock is inversely related to effort in equilibrium. As more fishing effort is applied, harvest removes stock growth until it reaches 0 at maximum carrying capacity, κ, in the absence of any form of rules and regulations. A simplified yield function (equation 7) will obtain the sustainable yield function, depending on fishing effort, expressed as:

$$H_t=aE-bE^2 \tag{13}$$

Where solving for *a* and *b* equals to:

$$a=\theta\kappa \tag{14}$$

$$b=-\frac{\theta^2\kappa^2}{r} \tag{15}$$

Solving for κ and r, obtains

$$\kappa=\frac{a}{\theta} \tag{16}$$

$$r=-\frac{\theta^2\kappa^2}{b} \tag{17}$$

A2.3 Economics

This section monetises the sustainable yield function to generate total revenues and total cost of fishery production at any given level of effort. This illustrates changes in cost and revenues along with changes in effort and stock over time:

Total sustainable revenues:

$$TR_t=p\ (H_t)$$

$$TR_t=\ p(aE-bE^2) \tag{18}$$

$$TC_t=c\ (E_t) \tag{19}$$

Where

TR_t is total revenue over time

TC_t is total cost over time

p is the constant price per unit of stock

c is the constant cost per unit of effort

Commercial fishing takes place primarily to maximise profits for fishing company owners. Maximising profits requires fishing companies to know the value that customers are willing to pay for the fish and cost of input production. With that in mind, fishing companies continuously seek to maximise output from limited materials available to bring the fish to the market which ultimately translates to fishing effort. Therefore, companies settle for the level of fishing effort *E* that gives high sustainable net returns, and the greatest difference between price and cost, known as the maximum economic yield.

Total net returns can be expressed as:

$$NR_E = pH(E) - c(E) \tag{20}$$

$$= p(aE - bE^2) - cE$$

$$= paE + pbE^2 - cE$$

$$= (pa - c)E + pbE^2$$

$$\Pi'(E) = pa - c + 2\text{pbE} = 0$$

$$pa - c = -2pbE \tag{21}$$

$$E_{MEY} = \frac{pa - c}{2pb} \tag{22}$$