Applicable statistical model to assess the status of the Namibian orange roughy (*Hoplostethus atlanticus*)

Vasana Tutjavi

Ministry of Fisheries and Marine Resources, National Marine Information and Research Centre

P O Box 912, Swakopmund, Namibia

v_tutjavi@yahoo.com / vtutjavi@mfmr.gov.na

Supervisors:
Kristján Kristinsson
kristjan.kristinsson@hafogvatn.is
Klara Jakobsdóttir
klara.jakobsdottir@hafogvatn.is

ABSTRACT

A common objective of marine fishery management is to estimate stock sizes and harvesting levels that produce maximum sustainable yields. Relatively little is known about the status of the Namibian orange roughy stock in terms of current biomass levels. This document presents an assessment of the Namibian orange roughy at different aggregating grounds by using the Schaefer surplus production model. Exploration of the Namibian orange roughy began in 1994, but the first Total Allowable Catch was allocated in 1997. Swept-areas and acoustic surveys were conducted from 1997-2007. No fishing or surveys were conducted between 2008 and 2015. However, surveys to assess the possible recovery of orange roughy stocks were resumed in 2016. The annual catches from 1994-2007, survey indices from 1997-2016 and catch-per-unit efforts from 1994-2007 were used as model inputs. The model estimated the biomass to be at very low levels, although there are slight increases at Johnies and Frankies aggregations. Model outputs indicate that the Maximum Sustainable Yield was 661 t at Johnies, 168 t at Frankies and 296 t at Rix in 2016. The replacement yields were 0.366 at Johnies, 0.074 at Frankies and 0.00 at Rix. The stock depletions were 17% at Johnies, 13% at Frankies and 11% at Rix relative to the initial biomass (B$_0$). There are no signs of recoveries at Rix and Hotspot aggregations. Orange roughy species is highly vulnerable to overfishing and can only sustain low rates of fishing. The biomass is still low at all the aggregations, therefore harvesting may not be viable for the time being.

Keywords: Orange roughy, Namibia, Schaefer surplus production model, biomass, aggregating grounds, overfishing

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ACRONYMS

TAC: Total Allowable Catches
QMA: Quota Management Area
CPUE: Catch-Per-Unit-Effort
ICES: International Council for the Exploration of the Sea
FAO: Food and Agricultural Organisation

1   INTRODUCTION

1.1   The orange roughy (*Hoplostethus atlanticus*)

Orange roughy (*Hoplostethus atlanticus*) is a deep-water, bathypelagic species that belongs to the family Trachichthyidae. It occurs at depths from 400 to 1100 m but is most abundant between 400 and 800 m. Orange roughy generally stays within 50 -100 m of the seafloor and does not undertake extensive vertical migrations (Branch, 2001). It is found in the waters around New Zealand and south of Australia, south of Madagascar in the Indian Ocean, off Walvis Bay (Namibia), in the North-East Atlantic and in the Eastern Pacific off Chile (Branch, 2001). The species forms single-species aggregations on hard grounds such as seamounts and canyons where water movement and mixing is high, ensuring dense spawning and prey concentrations. Spawning occurs between June and August, peaking in July and this seems to be consistent between years and among different populations in the southern hemisphere (Ministry of Fisheries and Marine Resources, 2017).

Orange roughy feeds mainly on prawns, fish, and squid and it has an exceptional lifespan as it is thought to live up to over 100 years. It has a slow growth rate (K = 0.055–0.070 years), low natural mortality (M = 0.045–0.064 year) and reaches maturity at the age of 20-30 years. Fecundity is low and the eggs are large (Branch, 2001). On average, female fish carry approximately 40,000 to 60,000 eggs. Fertilization takes place in the water column; the eggs stay planktonic and hatch after 10-20 days near the bottom (Ministry of Primary Industries, 2008).

1.2   Namibian marine fisheries

Namibia is situated in southern Africa and its entire western border is on the Atlantic Ocean. It covers a total area of 825,615 km^2 with a coastline of 1,572 km. Namibia has one of the most productive fishing grounds in the world because of the upwelling of cold nutrient-rich water off the Namibian coast that supports abundant fish life. The fishing sector is one of the economic pillars in the economic growth of Namibia. It plays an important role in supporting the policies and aspirations of the government in terms of employment, value addition, export, investment and social contribution (Ministry of Fisheries and Marine Resources, 2012). Namibian fisheries resources faced over-exploitation and illegal or non-controlled fishing, but this changed in the 1990s as the fisheries management improved when the Ministry of Fisheries and Marine Resources was established after independence in 1990 (Kashindi, 1999).

Namibia's marine fisheries consist of the demersal trawl fishery, which mainly targets hake (*Mercluccius capensis* and *Merluccius paradoxus*) and Devil anglerfish (*Lophius vomerinus*), a midwater trawl fishery targeting adult horse mackerel (*Trachurus capensis*), and a purse seine fishery targeting sardine (*Sardinella sardinops*) and juvenile horse mackerel. There are also large pelagic fisheries targeting, tunas, swordfish, large pelagic sharks, and the rock lobster and deep-sea red crab fisheries (FAO, 2015).

Exploratory fishing in the Namibian waters on orange roughy started in 1994. By 1996, four main aggregating areas, namely Hotspot, Johnies, Rix and Frankies were discovered (Figure 1).
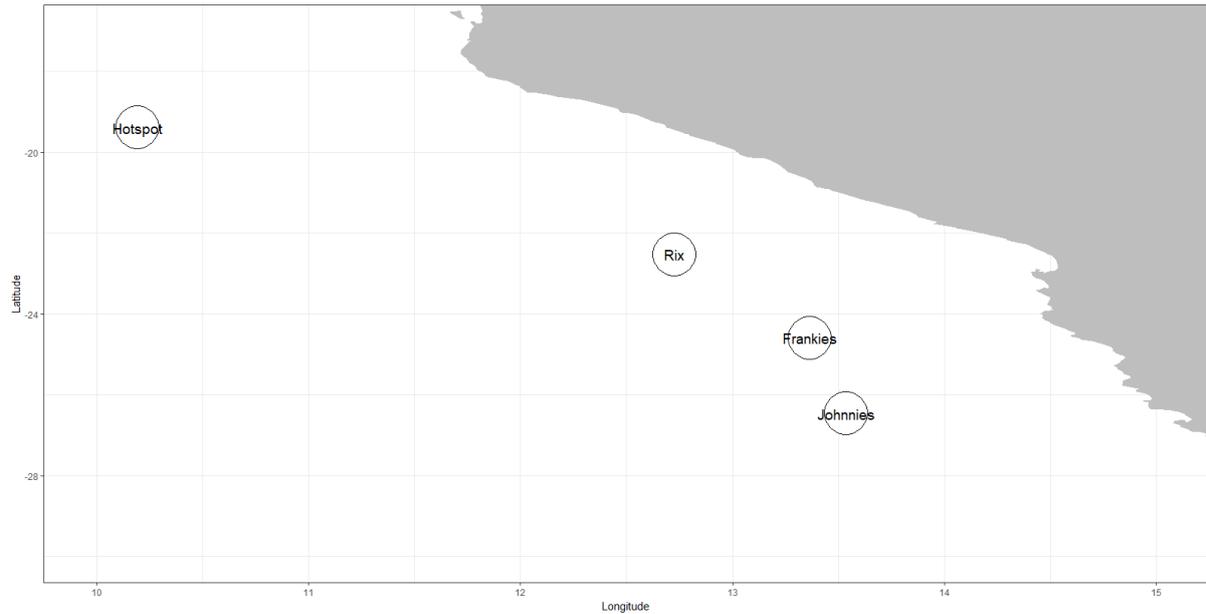
Figure 1. Orange roughy main aggregation areas along the Namibian Coast

Each aggregation is treated as a separate Quota Management Areas (QMA). The first Total Allowable Catch (TAC) of 12,000 tonnes was allocated in 1997, and five bottom trawlers were licenced to fish orange roughy (Ministry of Fisheries and Marine Resources, 2017). The highest catch of 18,000 tonnes was recorded in 1997 but dropped by over 90% to 1,600 tonnes in 2000. Landings decreased rapidly after 2000 and only 288 tonnes were landed in the last fishing season (2007/2008). Since the 1998/1999 fishing season, the fishery never landed the allocated TAC, which indicates that the TAC allocations were high in relation to the stock biomass (Figure 2). In 2008, the Ministry of Fisheries and Marine Resources and the industry made a joint decision to impose a three-year moratorium. However, no fishing has been allowed since the moratorium was imposed in 2008 (Ministry of Fisheries and Marine Resources, 2017).
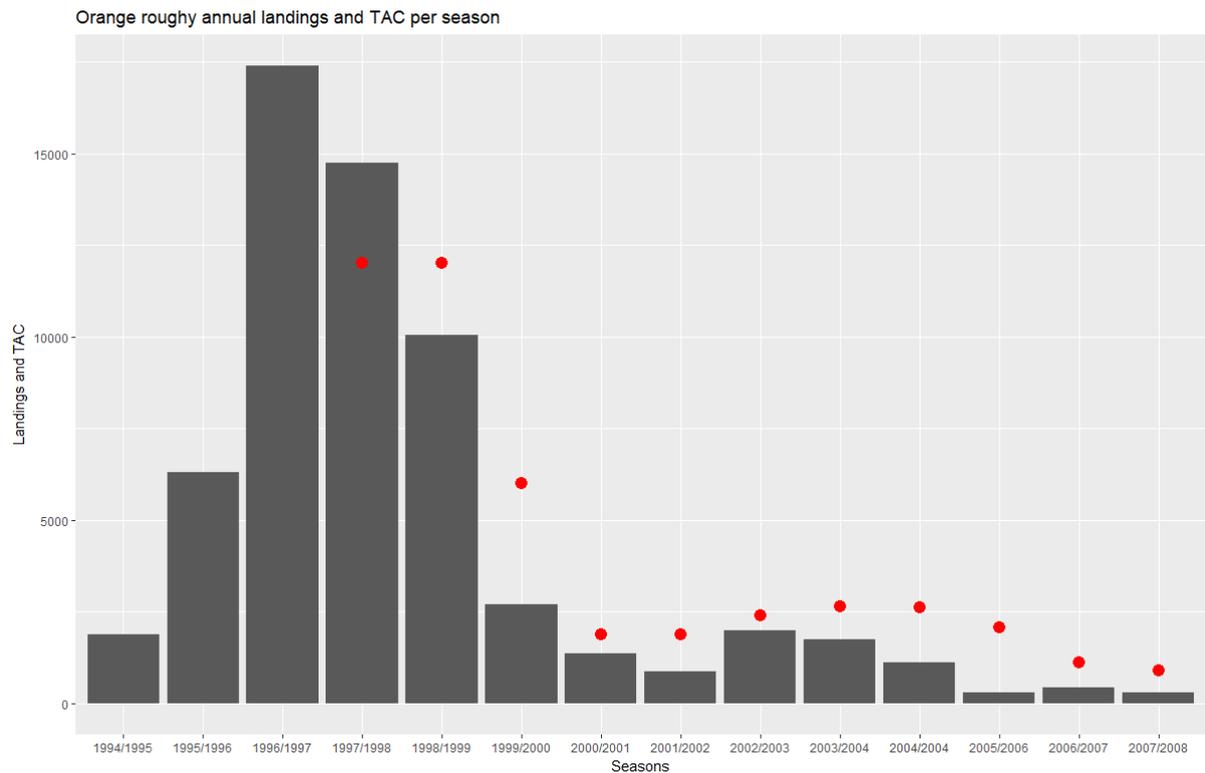
Figure 2. Total landings (bars) and TAC allocations (points) in the fishing seasons 1994/1995-2007/2008 (Ministry of Fisheries and Marine Resources, 2015).

To conduct a formal stock assessment, it is necessary to model the dynamic behaviour of the exploited stock. One objective of stock assessment is to describe how the stock responds to different fishing pressures. This makes it possible to assess the productivity of exploited stocks. This project attempted to find an applicable statistical model to be used to assess the status of Namibian orange roughy at the four aggregating grounds.

1.3   Project rationale

In the beginning of the orange roughy fishery in Namibia, there was a lack of expertise on the species biology and its reaction to fishing. An age-structured production model has been used to assess the status of Orange roughy in the Namibian waters 1997-2008 (Brandao & Butterworth, 2007). The stock has not been assessed and no surveys have been conducted since 2008 because of the moratorium. The Namibian government wants to assess the status of the orange roughy stocks at the main aggregating grounds and this project aims to identify applicable statistical model/s. Scientific surveys on orange roughy resumed in 2016, hence there is a need to statistically analyse the state of the stocks for sustainable management.

2   PROJECT OBJECTIVES

2.1   General objective

The overall objective of this study was to find an applicable statistical model to assess the status of orange roughy at the aggregating grounds in the Namibian waters by analysing available data from Namibia.

2.2   Specific objectives

- ➢   To estimate orange roughy biomass indices time-series by using data from the swept-area and acoustic surveys conducted from 1997-2016.
- ➢   To identify and explore applicable statistical models that can be used to assess the status of the orange roughy stocks in the Namibian waters.

3   LITERATURE REVIEW

3.1   Global orange roughy fisheries and management

Commercial fisheries of orange roughy have developed in the areas around New Zealand, off Namibia, Australia, Chile, in the North East Atlantic and the southern Indian Ocean. It is caught almost entirely in bottom trawls. Commercial fishing started in 1978 on the Chatham Rise off New Zealand, and later off south-eastern Australia in 1989. In New Zealand, the catches increased steadily from 1984 to 1988. The fisheries in the North-East Atlantic and off Namibia started in the late 1980s and early 1990s, and in the Pacific off Chile in 1998 and the south-western Indian Ocean in 1999 (Branch, 2001). In the North-East Atlantic, major fishing took place in the French and Irish waters. In French waters, the highest catches of 3000 t were recorded in 1992. In Irish waters, the landings peaked in 2000 when 5000 t were landed. Currently, there are no directed fisheries for orange roughy in the North-East Atlantic due to depleted stocks. Low by-catches are still observed in the French mixed deep-water trawl fisheries. Limited data are available to assess the status of the stocks, and there are no sufficient monitoring programmes to monitor the recovery of the stocks (ICES, 2012).

In general, various orange roughy fisheries experienced a sharp increase in catches after the discovery and subsequent decline after just a few years of fishing, which led to the closing of fisheries and/or fishing grounds in some cases. Unfished populations of long-lived species such as orange roughy are usually characterized by a large biomass of mainly older fish (Beamish & Leaman, 1984). This means that recruitment of new individuals into maturity is relatively low compared to the number and biomass of older adults (Heppell *et al.*, 2005). Fishing on such populations leads to the reduction of the age group of adult stock and possibly diminish its reproductive value (Beamish & Leaman, 1984). Low recruitment to the matured or adult group often results in rapid population collapse due to fishing. Disturbance of spawning populations and delayed maturity, further intensify overexploitation. This results in slow recovery times for populations and in some cases, permanent loss of aggregations (Heppell, Heppell, Read, & Crowder, 2005). The long life-span makes it difficult for traditional stock

assessment methods to assess species such as orange roughy. Management strategies are mostly based on fishing mortality, and these might be inappropriate for these species because the delayed maturity and longevity makes an accurate assessment of fishing mortality nearly impossible (Heppell *et al*., 2005).

New Zealand is a major contributor to the orange roughy global total catches. The global annual catches started to decrease in the 1990s, and most stocks have been overfished and reduced to below the long-term sustainable yields (Branch, 2001). The Australian orange roughy was estimated to be around 10% of the virgin biomass by 2008, which placed this species on Australia's endangered species list. The Australian fishery was closed for commercial fishing in 2006 (with the exception of the Cascade Plateau Zone), due to low stock levels. A research quota of 200 t is allocated each year to collect scientific information to keep track of the status of the stock in the Australian waters (Upston, *et al*., 2014).

Quota management systems are widely used to manage the orange roughy stocks. It is used in the largest fishery found off New Zealand with many fishing or/and aggregating grounds. Due to the aggregating behavior, the areas of concentrations or fishing grounds are managed independently but assessed with similar models and assumptions (Branch, 2001). Common management measure used in most marine fisheries is to fish down populations to maximum sustainable levels. However, this measure can be challenging to achieve and has caused overfishing of orange roughy in some parts the world. The closing of some fishing grounds and reducing the catch limits and effort to allow stocks to rebuild are some of the control measures that are being used by countries like New Zealand and Australia (Ministry of Primary Industries, 2016).

New Zealand, one of the more successful nations in orange roughy fishery, applies a precautionary approach in its fishery management on orange roughy, i.e., limiting fishing effort and implementing rotational closure of aggregations. As an assessment tool, an age-structured, single-sex, and single-area production model is being used in New Zealand for all stocks, whereby fish numbers are categorised by age and maturity stages within models. One of the reasons for the success of New Zealand's stock assessment is the fact that they are effectively able to age orange roughy and use the age-frequencies in the Bayesian age-structured assessment model. This model requires age frequency data to determine recruitment patterns. In recent years, CPUE indices have not been used in the assessments of orange roughy in New Zealand. This is because it was found to be inappropriate as the fishing effort generally focus on a small area where the fish aggregates. The use of CPUE as an indicator of stock size may, therefore, lead to overestimation of stock size and to high quota (Ministry of Primary Industries, 2014). Fishing vessels may also target a spawning aggregation so the CPUE is unlikely to reflect the level of spawning biomass but rather how the aggregation is fished, i.e., around the edges of the seamount or targeting the highest aggregation (Ministry of Primary Industries, 2014). In New Zealand, acoustic survey data on spawning plumes are now being used to estimate relative biomass indices (Ministry of Primary Industries, 2014).

3.2 Earlier assessments of the Namibian orange roughy

Scientists from the Namibian Ministry of Fisheries and Marine Resources and senior managers from the fishing industry formed a working group in 1995. This group was formed to establish and execute strategies to manage orange roughy because there was a lack of data and well-

trained deep-water biologists. Its main objective was to "promote the rational development of the Namibian deep-water fisheries, and furthermore to ensure the long-term sustainable utilisation of the stocks exploited through proactive research and co-management strategies" (Boyer *et al.*, 2001). Since this was a developing fishery, the TAC policy was based on the experiences of the orange roughy fisheries in New Zealand and Australia. In these developed fisheries, a precautionary approach, which entails catching cautionary target biomass levels and effort restrictions, are used in orange roughy fisheries management (Kashindi, 1999). The Namibian management goal was to fish the spawning biomass down to 50% of its virgin biomass. Despite fishing effort limitations and other aspects of the precautionary approach, the first stock assessments were overly optimistic, and the biomass declined to 10-50% of virgin biomass in just six years (Branch, 2001).

Orange roughy is a long-lived, slow-growing and late-maturing fish species. It also has relatively low productivity. This means that it provides low sustainable yield and is highly vulnerable to overfishing. Due to great depths and difficulty in catching this species, there was little knowledge about biology, and thus no thorough stock assessments were done on the Namibian orange roughy, which made the management of the fishery challenging. Overfishing, while the fishery was still developing shows, that the biomass and catch time-series of abundance were too short for conventional stock assessment methods to be reliable (McAllister & Kirchner, 2001).

Scientific surveys are one of the most important tools in fisheries management because they provide estimates of trends in absolute biomass or relative index of abundance. The surveys also provide other biological information such as length frequencies and size at maturity. Analyses of catch-per-unit-effort (CPUE) are sometimes used to provide relative indices of abundance when scientific survey series are not available (Ministry of Primary Industries, 2014). Commercial trawl analyses have been used for orange roughy in New Zealand, but also in Australia and Namibia. They are only used as relative estimates of abundance, primarily because the interaction between orange roughy and trawling gear is poorly understood. Bias-corrected swept-area estimates of abundance from commercial trawl data have not provided good absolute estimates for orange roughy (Branch, 2001).

Orange roughy stock is assessed separately for each fishing ground in Namibia. In the beginning, the absolute abundance of orange roughy off Namibia was estimated from commercial catch data because the scientific surveys had not started. This method converted the commercial catch data to swept-area estimates using the wingspread of the nets, the bottom distance of the tows, and post-stratified estimates of the area of the aggregations based on catch locations. Uncertain catchability, the directed (non-random) nature of tows, and uncertainty in how to define the area occupied by the aggregations introduced major biases. When combined with the subsequent catch history it was clear that the biomass estimates using this swept-area method were many times too high, resulting in excess optimism about the future of the fishery. Scientific surveys started in the third year of fishing, which may have been a little late because, in a developing fishery, early survey series are essential as trends only become apparent after several years (Branch, 2001).

For a species that forms dense aggregations, acoustic surveys could be a good method to provide a relative index of abundance. However, many factors make their conversion to absolute abundance challenging. Some challenges are the interference when obtaining individual estimates of target strength, which arises due to the lipid but not gas-filled swim bladders and undetectable fish within acoustic dead-zones, which is a major problem when estimating the biomass of orange roughy (Branch, 2001). No estimates of target strength are

available for Namibian orange roughy, so the target strength estimates obtained for the New Zealand and Australian stocks were used for the analyses of the Namibian surveys, after adjustment for the smaller average size of Namibian orange roughy (Branch, 2001).

The stock assessments were done using Bayesian age-structured production model. This model used a maximum penalised likelihood approach which uses all available indices of abundance and reflects the proportion of stock present at the fishing aggregation each year (Brandao & Butterworth, 2007).

3.3   Production models

Population sizes, growth rates, immigration and emigration rates, age and size structures and spatial distribution are some of the distinct properties of biological populations. Changes to these properties affect the dynamics of populations over time. These aspects are used in mathematical equations to model biological populations in an attempt to provide an abstract representation of population dynamics (Haddon, 2011).

Schaefer surplus production model is one of the simplest analytical methods available for fish stock assessment. Population dynamics at different levels of population size is measured in terms of surplus production, which is a net production of recruitment and growth over natural mortality (Prager, 1994). The Schaefer surplus production model is fairly simple to run because it pools the overall aspects of production, i.e., recruitment, growth, and mortality into a one-production function. The model ignores the age, sexual and size differences as it considers the stock as homogeneous. This means that the minimum required data to estimate the parameters are catch time-series and indices of relative abundances (Haddon, 2011). The most commonly used indices of abundance are CPUE, swept-area, and acoustic surveys. Time series of catches, which is a sequence of yields produced by the available biomass, are important data for fisheries stock assessments. Annual stock productivity has a strong effect on biomass dynamics. For simple stock assessment purposes, if two of the three variables, i.e., productivity, yield, and biomass are known, the third one can be estimated by using production models such as Schaefer's (Froese *et al.*, 2017). Despite the prevalence of length and age-structured production models, surplus-production models continue to be useful for analyses of population dynamics. These models are important particularly when there is a lack of ageing data, and thus age-structured models cannot be applied. Surplus production models may be used as alternatives or complement to age-structured models to provide another view of the data and the fisheries (Prager, 1994).

Accurate data are needed for studies on how the stock responds to fishing. Poor data collection makes stock assessment difficult, unreliable or even impossible. Thus, essential data are needed to model stock dynamics. More complicated and data-demanding age-structured models that analyse cohorts and catch-at-age and size-based models may be used. It is always ideal for biologists to collect enough data required to produce an age-structured model in preference to the simpler data requirements of a Schaefer surplus production model. However, the Schaefer surplus production model may produce results just as meaningful and, in some cases, better for management than those produced by age-structured models (Haddon, 2011). The importance of any model is strongly related to how representative the available data are for a harvested fish stock and whether the index of relative abundance provides a clear index of stock size.

4   METHODOLOGY

4.1   Biomass estimates

Data used to obtain estimate of biomass time series was collected during annual swept-area and acoustic surveys (supported by targeted trawling) 1997-2007 and 2016. The fishing vessel Southern Aquarius was used to conduct swept-areas and acoustic surveys in 1997-2007. In 2016, FV Pemba Bay carried out the surveys. The vessels deployed a standard commercial deep-water net and gear. The net is based on the standard New Zealand 'Arrow' rough bottom trawl, with cut-away lower wings. Sweep and bridle lengths were 100 m and 50 m respectively. A 'rock-hopper' footrope was used with 21 rock-hoppers. The net had a 5-6 m headline height when towed at an average speed of about 3.5 knots, and wingspread was estimated at 15 m (Ministry of Fisheries and Marine Resources, 2017).

Stratified random swept-area random trawling was done at fishing ground Johnies and acoustic and target trawls at fishing grounds Hotspot, Rix and Frankies (Figure 1). Since the moratorium on the orange roughy in 2008, no survey was conducted in 2008-2015. Surveys resumed in July 2016 to get an indication of the possible recovery of the stock. Swept-area trawl surveys were only conducted at Johnies because this ground is suitable for bottom trawling, whereas bottom conditions are rough at Rix, Frankies, and Hotspot. At each station, catches were sorted by species. For orange roughy length, weight, sex and gonad maturity data were collected. The swept-areas were divided into strata according to depth. The survey design was the same every year for comparison purposes. The duration of each trawl was 30 minutes on the bottom. Between 100 and 200 orange roughy were collected at each tow station to obtain biological samples. Standard length was measured, and the total weight of orange roughy was taken from the final factory number in cases where not all the fish were sampled (Ministry of Fisheries and Marine Resources, 2017).

Acoustic surveys were conducted at fishing ground Frankies annually 1997-2007. There was no acoustic survey at Johnies in 1999-2003, Rix in 1999-2002 and 2004. Hotspot ground only has data for two years, 2007 and 2016, hence no model predicted biomass indices were analysed for this ground. The surveys used equally spaced east-west transects. The interval between transects was one nautical mile for all coverages. Survey depths ranged between 400 and 1000 meters. The vessels were equipped with a Simrad EK60 (MK II) split beam echo sounder, operating at 38 kHz and echo sounder settings were kept the same as during previous surveys. The sounder on the *M.V. Pemba Bay* was interfaced to ECHOLOG for data logging and processing and ECHOVIEW was used for the acoustic data processing.

4.2   Data analyses

4.2.1   Biomass estimates

Biomass indices were calculated for the survey area from random trawl data using standard swept-area methodology. Biomass, and its standard error was calculated using the following formulae:

$$B = \sum (X_i a_i) / cb$$

$$S_B = \sqrt{(\sum s_i^2 a_i^2)} / c^2 b^2$$

where B is biomass (tonnes), X_i is the mean catch rate (kg*NM^{-1}) in stratum i, a_i is the area of stratum i (NM^2), b is the width swept by the trawl gear (0.0081 NM), c is the catchability coefficient (an estimate of the proportion of fish available to be caught by the net), S_B is the

standard error of the biomass, and s_i is the standard error of X_i. The coefficient of variation was calculated by using the formula:

$$cv = S_B / B$$

No correction was made for possible herding by the trawl gear or escape of fish from the path of the trawl. It is assumed that all fish in the water column above the trawl path are caught by the gear (i.e. $c = 1$). The effective area of bottom swept by the trawl (b) was taken as the distance between the wing-ends (15 meters) and times tow distance (Ministry of Fisheries and Marine Resources, 2017). Due to the unavailability of raw data from the acoustics surveys, the acoustic indices as relative of abundance were obtained from previous reports. Data cleaning, organisation and statistical analyses were done in MS Excel, MS Access and the statistical software R and R studio.

4.3 Schaefer Surplus Production Model fit

The Schaefer surplus production model was used to assess the status of orange roughy stock at the four fishing grounds in the Namibian waters. This model relates to the production from a stock beyond that required to replace losses due to fishing mortality. Thus, the production from the model is the sum of new recruitment and the growth individuals already in the population minus catch (Haddon, 2011). Given a known stock biomass, the total production can be predicted by;

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$$

Where B_{t+1} is the biomass in the subsequent year, B_t is the current stock biomass, r is the intrinsic population growth rate, K is the maximum population size for the growth to be positive and C_t is the catch in year t. Both r and K are parameters of the logistic equation.

Assuming lognormal uncertainty, the objective function is;

$$-\log L = [0.5n\log(2\pi)] + \sum \log \sigma_i + \sum\left(\frac{y_i - \mu_i}{2\sigma_i^2}\right)^2$$

Where y_i is the observed survey index and μ_i the predicted index. The data come with nominal coefficients of variation that describe the uncertainty about the observed biomass indices. These are not used as absolute σt in the objective function, but rather as relative coefficients ϵt that are multiplied with an estimated scaler r to predict σt. Parameters of r and K were manually estimated and adjusted until the best fits between the observed and predicted abundance were achieved. The initial value of biomass in 1994 for Johnies and Hotspot, and 1995 for Frankies and Rix (first years of fishing) and the observed catches were used as model inputs. The biomass for subsequent years was then estimated using the log likelihood of the Schaefer surplus production equation for a given set of r and K parameters. As a slow growing species and given that the biomass decreased from the beginning of the time series, r parameter was estimated to be less than 0.15 for all the fishing grounds. This parameter describes a stock with very low productivity such as orange roughy. The most probable value of K was determined from a linear regression fitted to log (K) as a function of log (r) (Froese et al., 2017). Survey and standardized CPUE as indices of abundance were used as relative to the stock biomass by using catchability coefficient (q). The expected biomass for each year was then used to produce

a series of predicted survey indices by multiplying expected biomass with a catchability coefficient (q);

$$I_t = qB_t$$

The optimisation function in R was then run to minimize the sum of squares to obtain the best parameter estimates of r, K, B_0 and q. The production function entails that the maximum production occurs at K/2 (Magnusson, 2012). Irrespective of the stock size, it should be possible to take the excess production above the equilibrium line of replacement and leave the stock in the condition it was before production and harvesting. A clear management strategy of this model is to bring the stock to a size that would maximize the surplus production and hence the potential yield. This supports the intuition that it is necessary to fish a stock down in size so that it becomes more productive (Haddon, 2011).

Surplus production model assumes that:
- The relative index of abundance is proportional to the true abundance
- The stock responds instantly to fishing mortality
- The stock is self-contained
- Any loss is mortality
- No interspecific interaction occurs
- The environment is constant
- Fishing is density-independent

Biomass projections were performed based on historical catches fitted to the Schaefer surplus production model, using zero catch scenario from 2008.

5   RESULTS AND DISCUSSION

5.1   Biomass estimates

At Johnies, the survey biomass index was estimated to be 57650 t in 1997 and decreased sharply to 6980 t in 1998, a reduction of 88% (Figure 3). The biomass remained low from 1999 to 2007, however higher estimates where obtained in 2016 compared to 1998-2000 and 2003-2007. This is a sign of population recovery possibly because of the moratorium. The biomass index was 29567 t in 1997 at Frankies but dropped to 8478 t in the second year of the survey. There was an increase in 2002 (25839 t), but from 2003, the biomass started to decrease again with the lowest estimate of 2264 t in 2007. The 2016 survey index was at 10331 t, which was higher than the indices in years 2003-2007. The biomass at Rix fishing ground has been decreasing since the beginning of the surveys. Since 2004, Rix fishing ground has been closed for fishing, but the last survey estimate remained lower than all the previous years, which indicate that the population has not recovered.
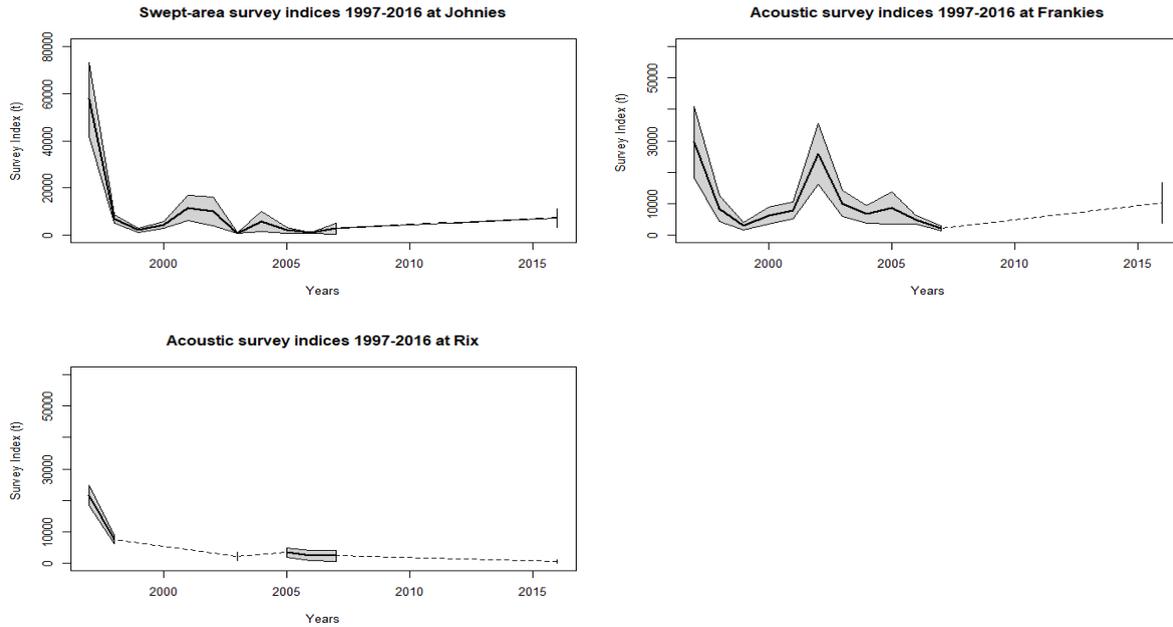
Figure 3. Survey indices at three Namibian fishing grounds for orange roughy in 1997-2016. The shaded area represents the coefficient of variance over the years.

The total annual catches per fishing ground were high in the 1990s but decreased in the last years of fishing. The catches were decreasing as the fishing years progressed as it is shown on the catch per ground spatial map (Figure 4).
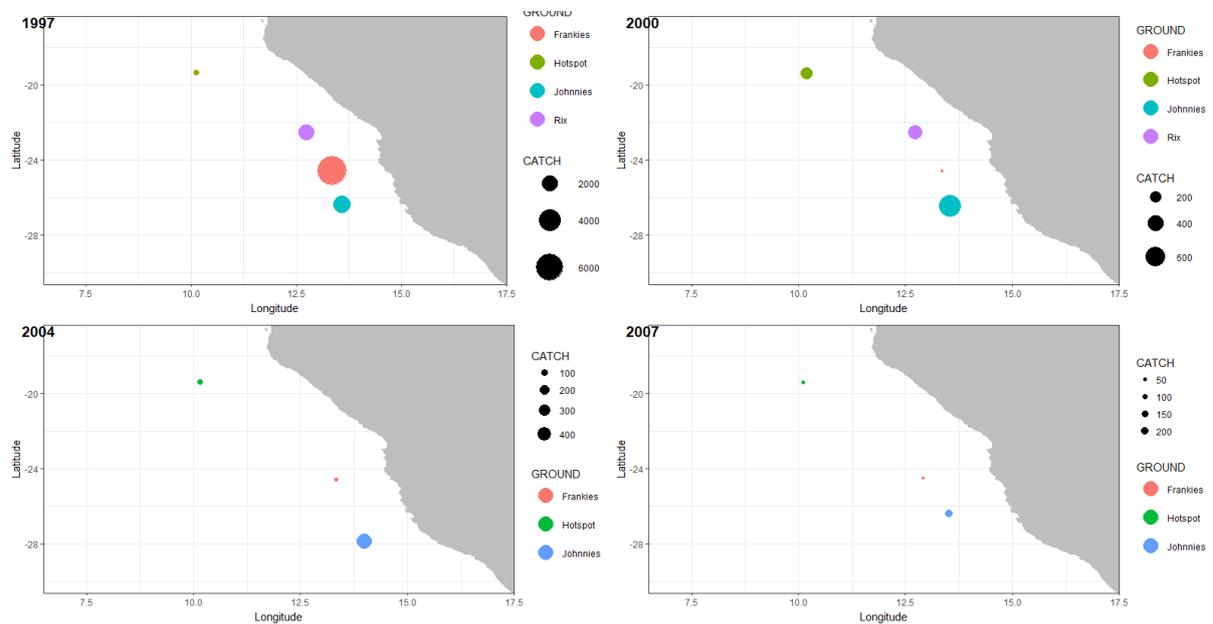
Figure 4. Spatial distribution of total catches at the four Orange roughy aggregations off Namibian coast for 1997, 2000, 2004 and 2007.

5.2 Schaefer surplus production model fitted to the survey indices and annual catches

The survey index in 1997 was high compared to all the other years, and the Schaefer surplus production model does not provide a particularly good fit to the observed index at Johnies aggregation (Figure 5). However, the model seems to fit the last few years of the survey indices. The model estimates that at Johnies, the survey index in 2016 was 4776 t, which is 17% of the estimated index biomass in 1994. The model estimates 661 t biomass at Maximum Sustainable Yield with 366 t replacement yield. (Table 1) This indicates that the stock has a very low productivity and has been heavily fished down in the first years of fishing. Thus there has been relatively low recovery.

High catches (7539 t) were observed in 1997, which was possibly because this was the first year of TAC allocations and the allocated TAC was among the highest during the fishing period (Branch, 2001). The total catches decreased sharply from 1997 to the closure of the fishery in 2007. The model estimated the biomass to be recovering slightly from around 2011/2012 (Figure 5). This is possibly because there has been no orange roughy fishing from 2008.
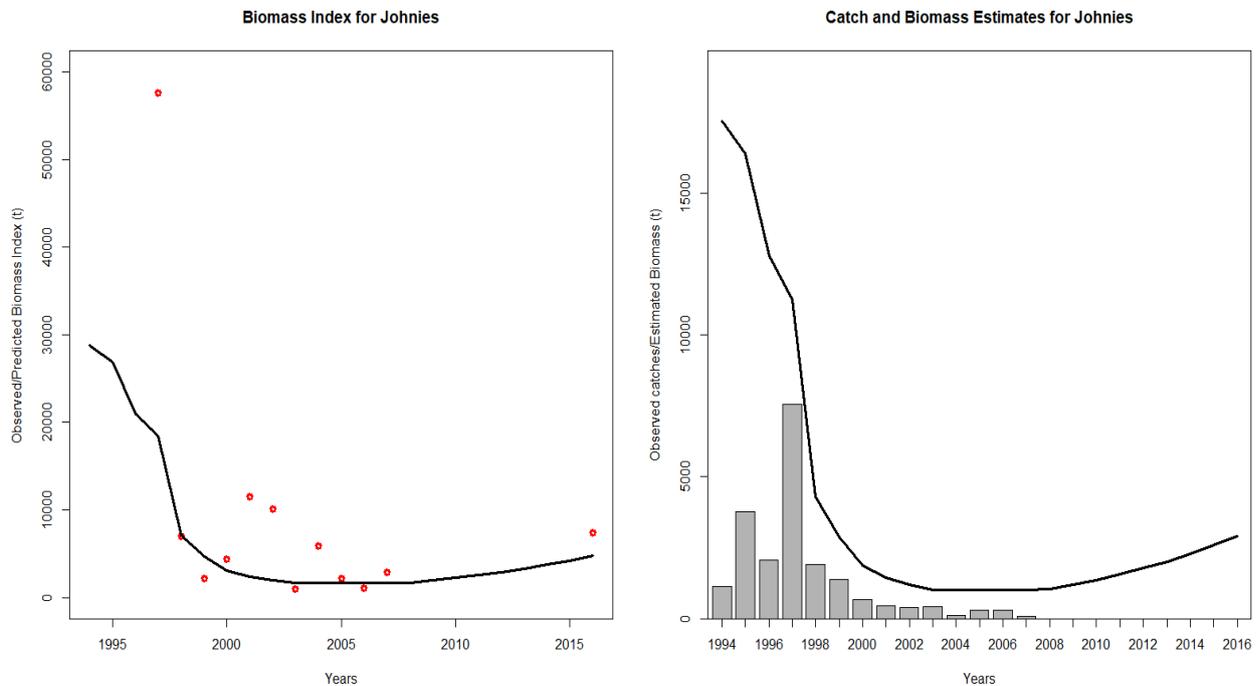
Figure 5. Left panel: Observed indices from swept-area surveys (dots) and model estimated relative indices of abundance (line). Right panel: Annual catches (bars) and model estimated biomass at Johnies aggregation (1994-2016).

The Schaefer surplus production model did not fit the observed survey indices at Frankies for most of the years. The model estimated 76273 t survey index in 1995, but decreased sharply to very low levels in 1997. The biomass was estimated to remain very low for the following years, however, it had recovered slightly after the closure of the fishery. The model estimated the population's intrinsic growth rate (r parameter) to be low (0.06), and this means that the biomass is recovering very slowly.

The model estimated a biomass of 1543 t in 2016, which is 13% of the estimated biomass in 1995 (Figure 6). The estimated biomass at MSY is 168 t with 74 t replacement yield (Table 1). High catches were recorded in the first three years of the fishing but decreased from 4817 t in 1997 to only 24 t in 2007.
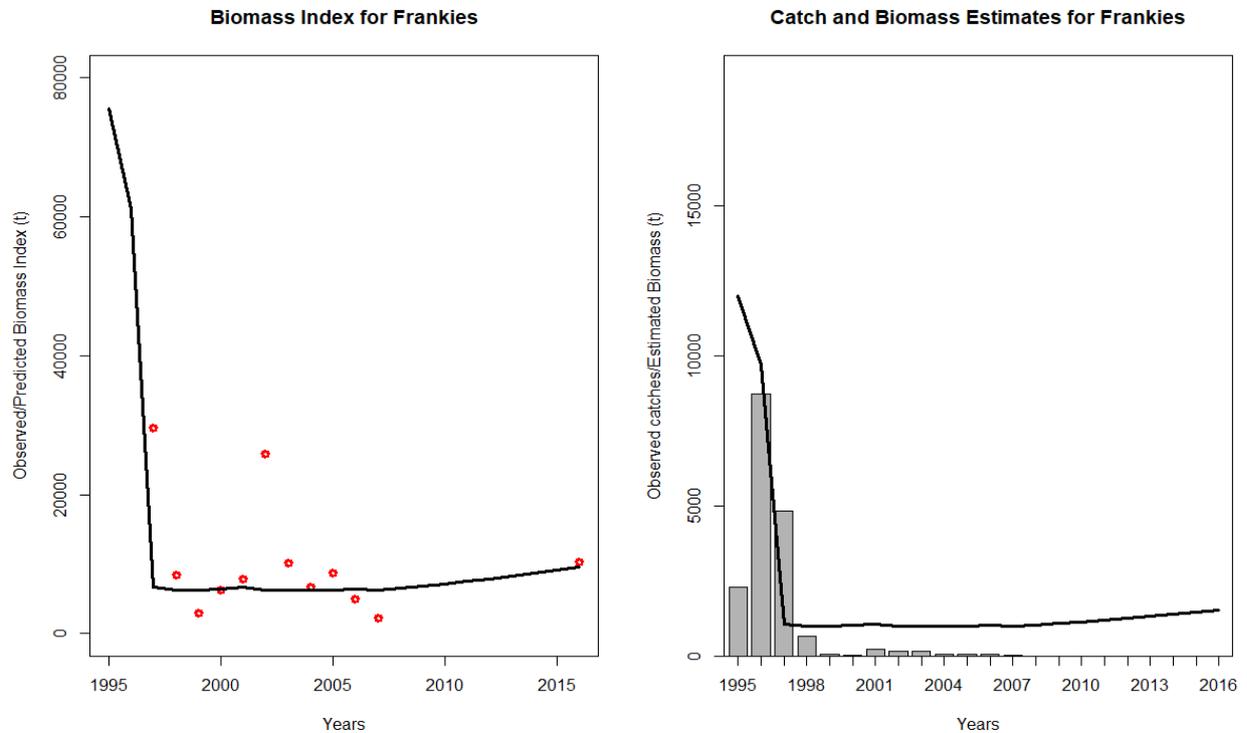
Figure 6. Left panel: Observed indices from hydro-acoustic (dots) and model estimated relative indices of abundance (line). Right panel: Annual catches (bars) and model estimated biomass at Frankies aggregation (1995-2016).

The Schaefer surplus production model estimated the biomass at Rix to be 9447 t in 1995 but decreased sharply to very low levels in 1999. The biomass remained very low since 1999, and this led to the closure of fishing activities at Rix from 2004. Catches of 3836 t and 3921 t were recorded in 1997 and 1998 respectively, but decreased sharply to 444 t in 1999. The model estimated very low biomass since 1999, and it does not show recovery (Figure 7). This is because the model estimated a 0 intrinsic growth rate (r parameter), which means that there has been no population growth at this aggregation.

The biomass at MSY is predicted to be 296 t, however, the replacement yield was predicted to be 0 (Table 1).
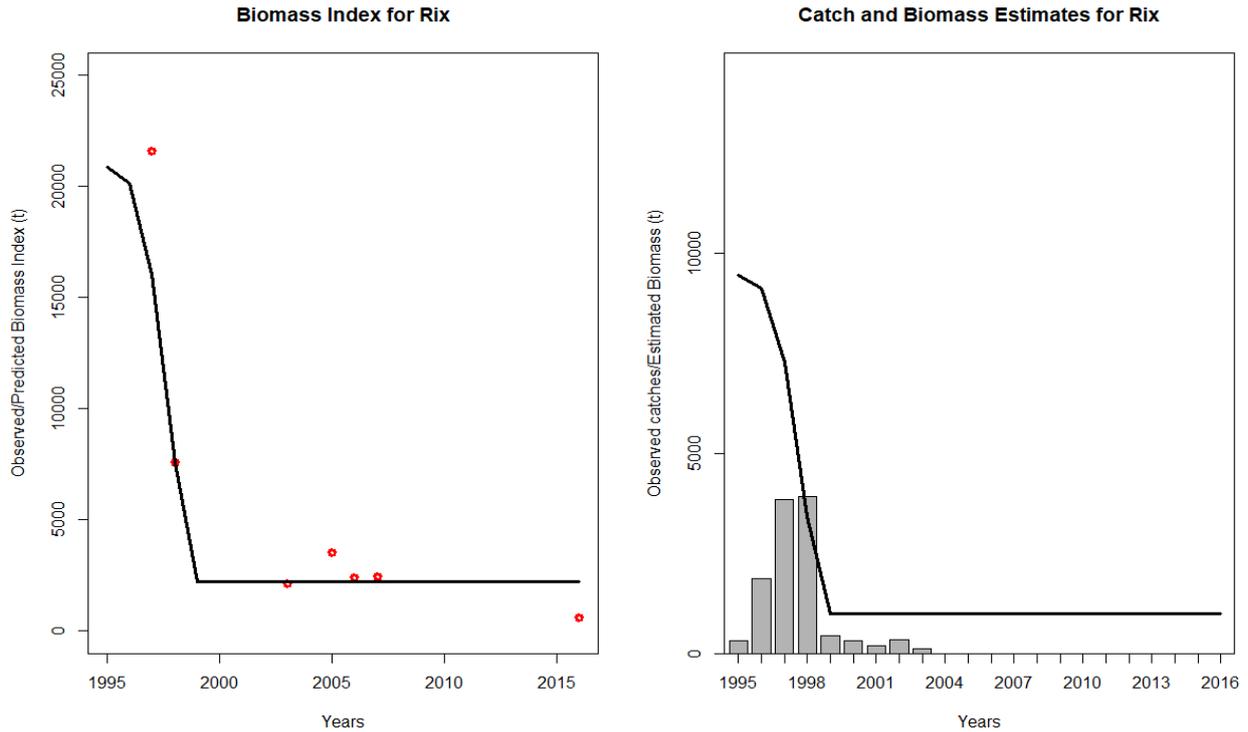
Figure 7. Left panel: Observed indices from hydro-acoustic (dots) and model estimated relative indices of abundance (line). Right panel: Annual catches (bars) and model estimated biomass at Rix aggregation (1995-2016).

Table 1. Estimates obtained when the Schaefer surplus production model was fit to the available indices of Namibian orange roughy for the Johnies, Frankies and Rix aggregations. The estimates shown are for the pre-exploitation orange roughy abundance (B_0), the current stock biomass (B_{2016}) and stock depletion (B_{2006}/B_0), the maximum sustainable yield (MSY), Replacement yield (SY_curr) and the negative of the log likelihood. Biomass units are tonnes.

Parameter estimates	Johnies	Frankies	Rix
B0	17531	11986	9447
B2016	2907.4	1542.9	1000
B2016/B0	0.17	0.13	0.11
MSY	661	168	296
SY_curr	0.366	0.074	0.00
r	0.15	0.06	0.00
K	17.53	12.0	9.4
q	1.64	6.31	2.21
neglogL	15.7362	11.46	3.72

As for Hotspot aggregation, the catches decreased since the first year of fishing. Annual catches of 2169 t were recorded in 1994 but in the last year of fishing, only 22 t of orange roughy was landed from Hotspot aggregation. Using catch data, the model estimated very low biomass since 1998 and it does not show recovery (Figure 8).

Catch and Biomass Estimates for Hotspot
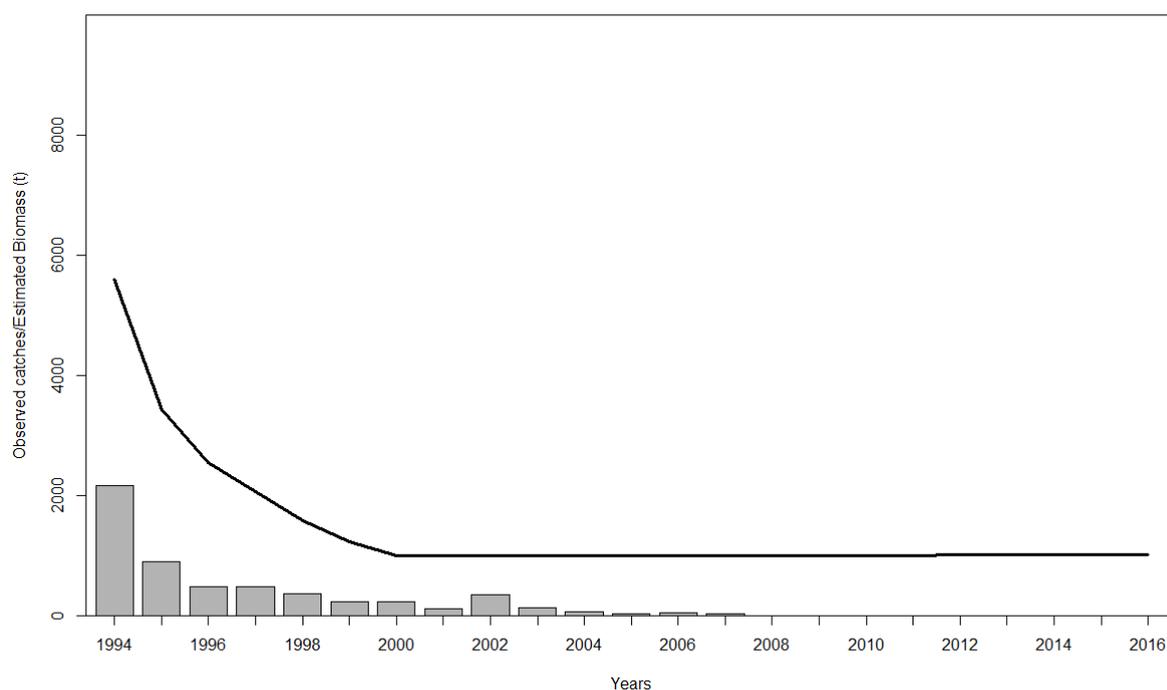
Figure 8. Annual catches (bars) and model estimated biomass at Hotspot aggregation (1994-2016).

5.3 Schaefer surplus production and age-structured production models' outputs

5.3.1 Johnies and Frankies surveys and CPUE indices

The Schaefer surplus production model and the age-structured production model used in the past did not produce similar outputs by using swept-area survey indices as relative of abundance at Johnies aggregation. The surplus production model estimated a biomass of 18454 t for 1997, whereas the age-structured production model estimated a high biomass of 22951 t for the same year. The age-structured production model estimated the biomass to be 6461 t in 2007 at Johnies but the surplus production estimate is 1643 t (Figure 9). Figure 9 also indicates that the Schaefer surplus production model fits the observed CPUE well, except for the first three years of fishing, but the age-structured production model did not fit the observed index of 1994, 2001 and 2002.

As for Frankies aggregation, the Schaefer surplus production model and the age-structured production model did not produce similar outputs when the acoustic survey indices were fit to the models. The Schaefer surplus production model did not fit the observed data very well compared to the age-structured production model and this model predicted that the biomass was low since 1997. The Schaefer surplus production model predicted that the biomass was 6696 t whereas the age-structured model estimated the biomass of 18743 t in 1997 (Figure 9). The age-structured production model predicted that the biomass was fluctuating with the observed indices. In 2007, the Schaefer surplus production model predicted a high biomass from the survey indices (6307 t) compared to the age-structured production model which

predicted the biomass to be 3532 t. The surplus production model provided a good fit to the observed CPUE indices than the age-structured production model. However, both models did not fit the observed values of the first few years.
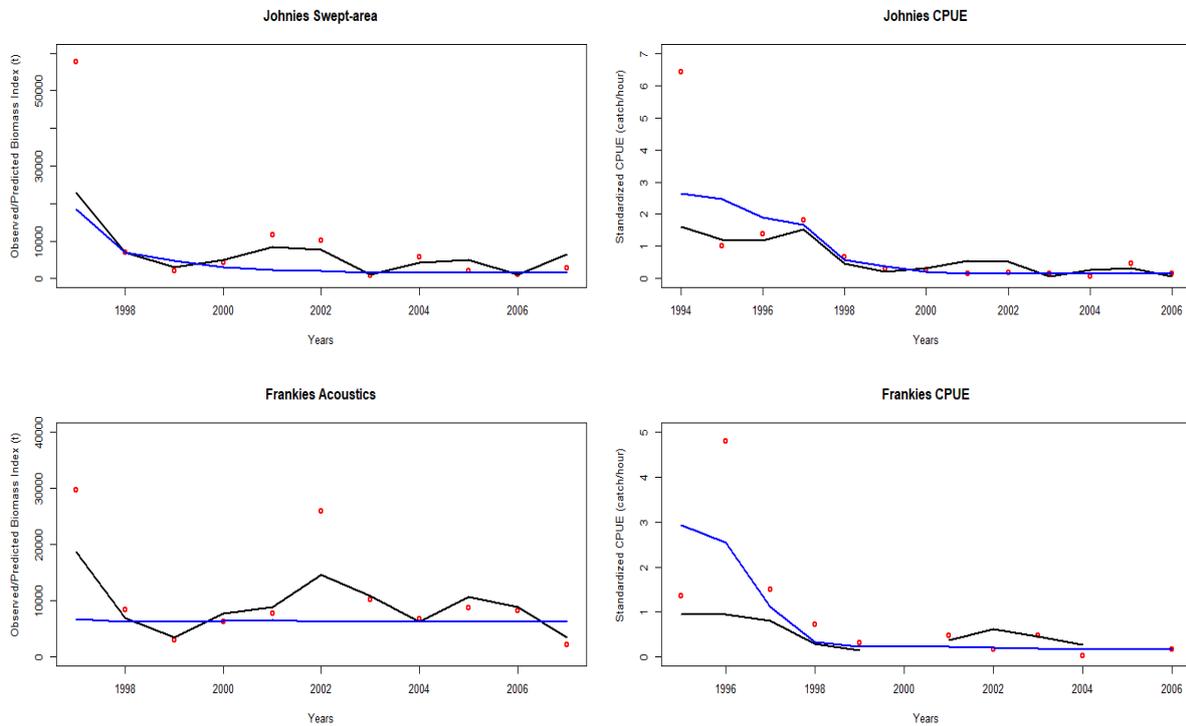
Figure 9. Survey predictions fit to the observed biomass and standardized CPUE indices (red dots) using age-structured production model (black lines) and Schaefer surplus production model (blue lines) for Johnies and Frankies aggregations (1994-2007).

5.3.2 *Rix surveys and CPUE and Hotspot CPUE indices*

Rix ground has been closed for commercial fishing since 2004 in an attempt to allow the fish to recover and manage the orange roughy stocks on a rotational closure basis. Both models produced almost similar outputs from the acoustic survey indices for Rix aggregation. The Schaefer surplus production model predicted that the biomass was 16047 t whereas the age-structured production predicted a biomass of 17291 t in 1997, and in 2007 the age-structured production model predicted a biomass of 2146 t whereas the Schaefer surplus production model predicted 2209 t. The Schaefer surplus production model did not fit the observed CPUE indices for Rix aggregation compared to the age-structured production model. As for Hotspot aggregation, both models fit the observed CPUE indices. However, the surplus model did not provide a good fit for the first three years (Figure 10).
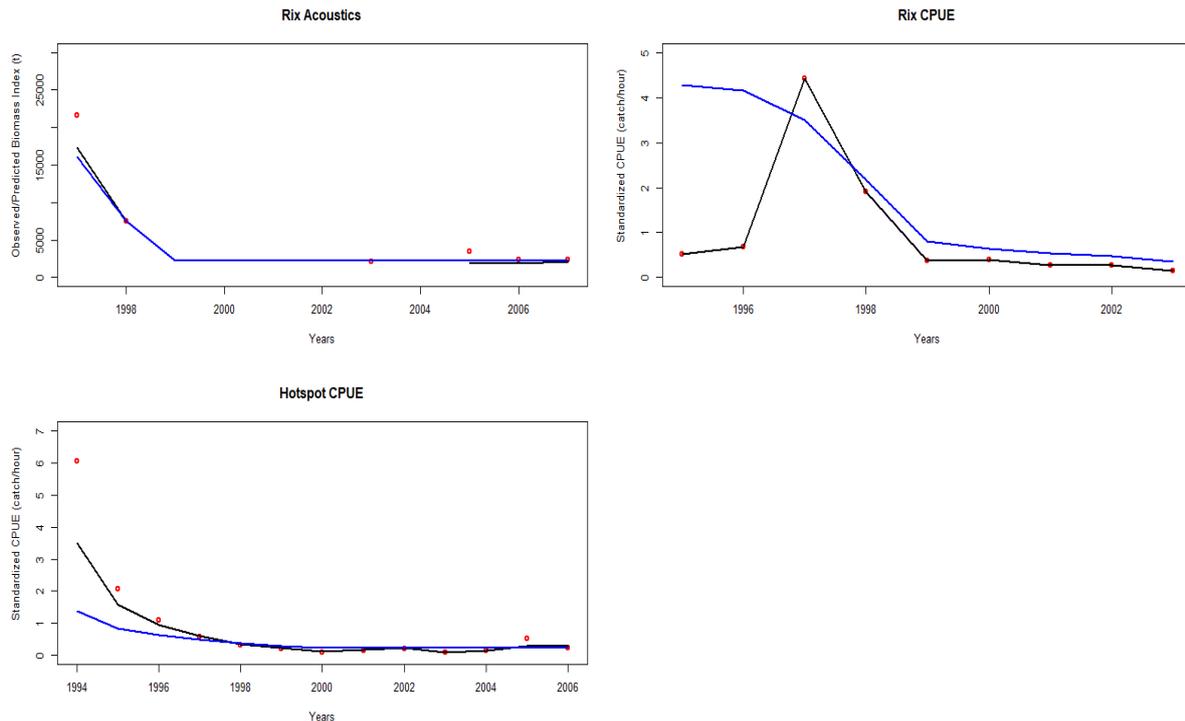
Figure 10. Survey predictions fitted to the observed biomass and standardized CPUE indices (red dots) using age-structured production model (black lines) and Schaefer surplus production model (blue lines) for Rix and Hotspot aggregations.

5.4   Biomass projections

Estimates for the Schaefer surplus production model biomass were fitted to the catch data and projected to 2030, using zero catch scenarios from 2008 (Johnies, Frankies and Hotspot aggregations) and 2004 (Rix aggregation). The stock at Johnies aggregation was depleted in 2003. However, it started to recover slowly from 2010. It is estimated that by 2020 and 2030, there will be 4586 t and 10718 t of orange roughy biomass at Johnies aggregation. The model indicates that Frankies aggregation was depleted in 1998, the stock is recovering slowly since 2015 (1446 t). According to the model, the stock at Frankies aggregation will only recover to 1830 t in 2020 and 2846 t in 2030. The model indicates that Rix and Hotspot aggregations were depleted in 1999 and 2000 respectively, and these two grounds are not showing signs of stock recovery for the projected period (Figure 11).

Predicted biomass
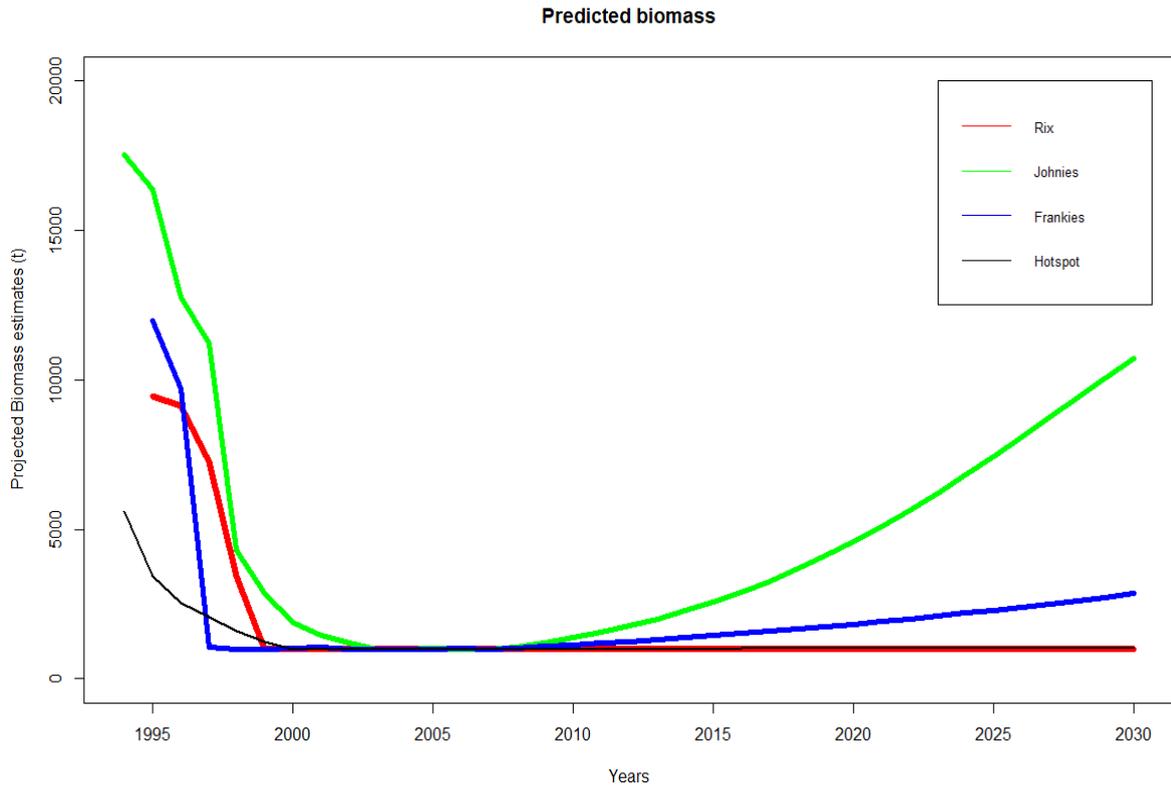
Figure 11. Schaefer surplus production model estimates of orange roughy stocks fitted to the catch data for the four aggregations projected to 2030

6   RECOMMENDATIONS AND CONCLUSIONS

Globally, orange roughy has not been fished for a long time, and the majority of identified stocks have been depleted. This makes the uncertainty of whether an orange roughy fishery can be sustainable over a long-term to remain in the fishing industries. Populations of long-lived species such as orange roughy recover very slowly after overexploitation because of low recruitment to matured or adult stocks. Late maturity (recruitment to adult stock), longevity (requires long time data series) and lack of comprehensive data sets of orange roughy makes stock assessment of this species challenging. Due to its low productivity and slow growth rates, orange roughy can only sustain low rates of harvesting. These together with aggregating behaviour, high longevity, and late maturity make this species vulnerable to overfishing.

Even in the absence of fishing for the past 10 years, orange roughy stocks are still estimated to be very low at all the aggregation sites in the Namibian waters, thus commercial fishing may not be viable for the time being. Scientific surveys should continue in order to add more points to the indices of relative abundance. Biological data such as the percentages of spawning biomass and size and age structures would give clearer indications on the current condition of the populations. This data should be analysed in order to provide more information on the productivity (recruitment) and status of the stocks for informed recommendations on the management of the Namibian orange roughy stocks.

The Schaefer surplus productions model is useful in the assessment of stocks for which there is limited data available. However, its simplifying assumptions implies that any conclusions drawn from its outputs should be treated with caution. Given the constraints of only considering total stock biomass, this model can provide insights into the relative performance of the stock through time.

Although the project confirms that the orange roughy stocks have been depleted at the four grounds in Namibia, there are signs of recoveries at Johnies and Frankies aggregations. The model estimated that there are no stock recoveries at Rix and Hotspot fishing grounds. The Schaefer production model did not produce similar outputs to the previously used age-structured production model because the parameter estimations and model designs were not the same.

ACKNOWLEDGEMENTS

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APPENDICES

Appendix 1. Annual catches, relative abundance indices in tonnes and standardized CPUEs used in the Schaefer surplus production model.

	Catches	Acoustic survey Index	*Acoustic CV*	Swept-area Index	*Swept-area CV*	CPUE
Hotspot						
1994	2169					6.038
1995	897					2.067
1996	477					1.094
1997	482					0.584
1998	358					0.314
1999	226					0.208
2000	224					0.089
2001	106					0.162
2002	336					0.201
2003	129					0.089
2004	52					0.155
2005	30					0.52
2006	39					0.242
2007	22	4 965	*0.71*			0.241
2016	0	3452	*0.43*			
	Catches	Acoustic survey	*Acoustic CV*	Swept-area	*Swept-area CV*	CPUE
Johnies						
1994	1145					6.411
1995	3773					1.006
1996	2062					1.382
1997	7539	55757	*0.28*	57650	*0.27*	1.827

	Catches	Acoustic survey	Acoustic CV	Swept-area	Swept-area CV	CPUE
1998	1917	6267	*0.48*	6980	*0.25*	0.662
1999	1367			2137	*0.4*	0.296
2000	667			4365	*0.35*	0.256
2001	452			11544	*0.46*	0.142
2002	376			10148	*0.59*	0.179
2003	430			943	*0.18*	0.151
2004	123	5865		5865	*0.73*	0.067
2005	298	2132		2132	*0.64*	0.456
2006	311	1117	*0.16*	1117	*0.16*	0.166
2007	93	2910	*0.79*	2910	*0.79*	0.116
2016	0	7351	*0.53*	7351	*0.53*	
	Catches	**Acoustic survey**	*Acoustic CV*	**Swept-area**	*Swept-area CV*	**CPUE**
Frankies						
1995	2291					1.354
1996	8736					4.797
1997	4817	29567	*0.38*	30995	*0.37*	1.499
1998	650	8478	*0.49*	2400	*0.6*	0.715
1999	40	2934	*0.38*	3055	*0.35*	0.325
2000	11	6294	*0.44*			0.173
2001	214	7805	*0.34*			0.474
2002	155	25839	*0.37*			0.167
2003	158	10126	*0.41*			0.474
2004	51	6720	*0.41*			0.024
2005	4.4	8667	*0.59*			0.173
2006	65	4914	*0.27*			0.171
2007	24	2264	*0.35*			0.135
2016	0	10331	*0.62*			
Rix	**Catches**	**Acoustic survey**	*Acoustic CV*	**Swept-area**	*Swept-area CV*	**CPUE**
1995	323					0.518
1996	1861					0.676
1997	3836	21579	*0.15*			4.415
1998	3921	7572	*0.19*			1.914
1999	444			1006	*0.59*	0.379
2000	307					0.393
2001	183					0.28
2002	350					0.282
2003	124	2133	*0.63*			0.144
2004	0					NA
2005	0	3514	*0.43*			NA
2006	0	2422	*0.64*			NA
2007	0	2439	*0.73*			NA
2016	0	618	*0.67*			NA