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MODELLING AND FORWARD PROJECTIONS OF NILE PERCH, *Lates niloticus*, STOCK IN LAKE VICTORIA USING GADGET FRAMEWORK

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ABSTRACT

A Globally applicable Area Disaggregated Ecosystem Toolbox (Gadget) was used to generate population and stock assessment models for Nile perch, *Lates niloticus* in Lake Victoria. Two model runs were conducted. Growth parameters generated from the first run $L_\infty = 255$ cm, $K = 0.069$, $t_0 = -0.25$ and $L_\infty = 198$ cm, $K = 0.1$, $t_0 = 0.8$ for the commercial and survey fleets respectively, fitted well with data. These parameters were there fore fixed in the final model run. Sizes at 50% maturity (Lm50) were 61.34 and 70.37 cm while the adult sex ratio was 2:1 for males and females respectively. Model fit to length disaggregated, CPUE and acoustic survey indices showed strong positive correlation. Two selection patterns were evident in the commercial fleet in the periods prior and after 2002 with the latter exhibiting higher mean length. Population estimates show a biomass that decreased sharply in the late 1980s with rapid increase in fishing mortality. Cathes on the other hand increased exponentially from 1968 and then levelled off after 1990. The current fishing mortality of 0.53 gives a per recruit yield of 1.38 kg, which is lower than it could have been at $F_{max} = 0.33$ that results in 1.45 kg. The current fishing mortality is almost double the optimum. The estimated yield at $F_{0.1} = 0.21$ is 1.37 kg. Forward prediction based on different exploitation strategies show that the current fishing mortality or any increase in the same will lead to decline in biomass and catches in the long run. A fishing mortality F_{max} that optimizes yield with significantly less effort is therefore recommended for the species in Lake Victoria.

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1 INTRODUCTION

1.1 Background

Lake Victoria, with a surface area of 68,000 km^2, is the largest tropical and second largest freshwater lake in the world (Greenwood 2006). The Lake's waters straddles three countries (Kenya, Uganda and Tanzania) and supports Africa's largest fishery (Geheb *et al*. 2007) Estimates indicate that riparian states earn US$ 500 - US$ 550 million annually from fish catches from the lake (Manyala and Ojuok 2007).

Sustainability of Lake Victoria's fish yields is a major concern given the modification of its fishery and water quality since the 1960s (Witte *et al.* 2000). Before 1954, the lake's ecology was characterised by enormous biodiversity. It was inhabited by over 500 species of fish (Graham 1929) dominated by cichlids (genus *Haplochromis*), which accounted for more than 80% of the fish biomass (Kudhongania and Cordone 1974). During that time, the local fishers were fishing for subsistence, with surplus for internal markets (Pringle 2005). In the 1950-1960s, new tilapine species (*Oreochromis leucostictus, Tilapia zillii, T. rendalli, O. niloticus O. mossambicus*) and the predacious Nile perch (*Lates niloticus*) were introduced in the lake, an event which altered the existing diverse fish assemblage (Balirwa *et al.* 2003, Balirwa 1992, Coulter *et al*. 1986).

The introduction of the Nile perch had a major impact on the *Haplochromis* stocks, which it favoured as prey, affecting both their abundance and diversity. The latter's contribution to biomass was reduced to less than 1% (Witte *et al*. 1992). Up to 65% of *Haplochromis* species are thought to have been lost, an event which may well represent the largest species extinction amongst vertebrates in the 20th century (Goldschmidt *et al*. 1993, Kaufman and Cohen 1993, Kaufman 1992, Kitchell and Schindler 1997). Reduction of *Haplochromis* stocks eased the competition pressure on the diminutive endemic silver cyprinid *Rastrineobola argentea* (Dagaa) populations, which in turn flourished developing into huge shoals (Goudswaard *et al*. 2011, Pringle 2005, Witte *et al*. 1992).

Currently only 3 species (*L. niloticus, O. niloticus* and *R. argentea*) are exploited on a commercial scale. The introduced species revolutionized the fishery from mere subsistence to highly commercial making it one of the world's most productive inland fishery with a Nile perch boom in the 1980s (Kayanda *et al*. 2009). Production increased from below 50,000 tonnes in 1980 to over 300,000 tonnes in the year 1990. In the subsequent years, production dropped to about 250,000 tonnes.

1.2 Statement of the problem

Nile perch from Lake Victoria provides important export earnings for riparian states (Manyala and Ojuok, 2007). However concerns about over-exploitation of the stock have been raised. Recent studies have shown signs of overfishing, such as a decline in biomass, catch rates and a decrease in the size at first maturity (Kayanda *et al*. 2009, Njiru *et al.* 2009, Taabu 2004). Although, several surveys aimed at monitoring Nile perch stocks, have been conducted in the lake, lack of funds has often resulted in inconsistencies in data collection (Cowx and Knaap 2003). In addition, little effort has been made to link the several data sets collected to model the trends of Nile perch stock over a long period of time. There is also a big knowledge gap of the relationships between recruitment and spawning stock biomass for the species in the lake. Lack of such knowledge raises concern of the current management measures, including the slot size of 50-85 cm (Njiru *et al*. 2009) that primarily targets only the spawning proportion of the stock. The question of how much fish stocks are there in the lake still lingers. How much should be exploited is not clear to stakeholders (Cowx and Knaap 2003).

1.3 Significance of the study

Several attempts have been made to estimate fish biomass in Lake Victoria using fishery independent methods (acoustic surveys, trawl surveys and other forms of experimental fishing). Frame surveys and catch assessment surveys have also been on-going in Lake Victoria – in essence providing catch and effort information of the major commercial species. The present study critically evaluates available data sets from catch statistics, frame surveys and experimental fishing and ultimately utilizes useful datasets to evaluate the trends and develops a population model for Nile perch in Lake Victoria. The development of the Nile perch stock (present and future) is illustrated, which can assist fisheries managers to evaluate and revise current regulations in place. The study also estimates sustainable yield harvest levels for the species.

1.4 Scope of the study

The study investigates the status and trends of Nile perch stocks in Lake Victoria. Biological parameters for the species are obtained from lake-wide survey data. A **G**lobally applicable **A**rea **D**isaggregated **G**eneral **E**cosystem **T**oolbox, Gadget, computer program (Begley 2005) was used to generate models to simulate Nile perch stock, compare the models to real data, perform forward projections, as well as predicting yield based on different exploitation strategies.

1.5 Objectives of the Study

The overall objective was to assess the status and model past and future Nile perch stock in Lake Victoria.

1.5.1 Specific objectives

- To simulate and model the Nile perch stock in Lake Victoria and establish its trends.
- To establish recruitment and fishing mortality trends for Nile perch in Lake Victoria.
- To estimate the sustainable harvest rates for Nile perch in Lake Victoria.
- To simulate plausible trends of the Nile perch stock in Lake Victoria for the next 20 years using the Gadget framework and evaluate the effects of different harvest strategies.

2 LITERATURE REVIEW

2.1 Introduction

The genesis of Nile perch in Lake Victoria dates back to early in the 20th century. A few decades after John Speke's 'discovery' of the lake in 1858, British colonialists started to exploit the lake's watershed. They cleared the surrounding natural vegetation, denuding forests and draining swamps (Balirwa *et al*. 2003), to start cash crop plantations which have grown in size and number over the years. Agricultural chemicals, applied on these plantations are washed into rivers during the rainy season, and end up in the lake, providing nutrients for massive algal blooms. The plantations attracted migrant workers who settled in the area. As the population grew and fishing methods advanced, overfishing became a problem and catch sizes began to drop. By the 1950s, popular species, such as ngege (*Oreochromis esculentus*), had diminished so severely (Witte *et al*. 1992). At that time the lake was however still teeming with small sized bony haplochromine cichlids (Kitchell and Schindler 1997). To remedy the situation, British officials thought introducing new fish in the lake (Graham 1929, Lowe-McConnell 1987, Welcomme 1967). Nile perch was presumed to be a solution to boost stocks as well convert the small sized cichlids into bigger attractive flesh (Witte *et al.* 1999).

Arguments on possible impacts of new species on the ecosystem started some decades before the actual introduction. As debate was going on, secret introductions had begun in 1954 (Goudswaard *et al*. 2008). Subsequent official introductions followed afterwards at different sites around the lake and its catchment. At the beginning, the new species constituted only a small percentage of the lake's fish biomass, which was dominated by haplochromine cichlids (Witte *et al*. 1992). It took over 20 years for Nile perch to establish itself as an exploitable stock (Njiru *et al*. 2009). Up until the late 1970s, the biomass composition of the lake remained relatively constant, but in 1980, a survey of the lake revealed an abrupt and unexpected change: a total reverse in biomass composition. Cichlid numbers had fallen drastically, comprising only 1 per cent of fish weight, while those of the Nile perch had suddenly jumped to constitute 80 percent. It is thought that over 200 species of the former fish fauna had disappeared (Kitchell and Schindler 1997, Witte *et al*. 1992). Although not foreseen, the collapse of the haplochromine cichlids was inevitable since they were the preferred prey of the new predator. The devastation on biodiversity wrought by Nile perch has made it to be considered one of the world's 100 worst invasive species by the International Union for Conservation of Nature (IUCN) World Conservation Union Invasive Species Specialist Group (Kitchell and Schindler 1997).

2.2 Biology and ecology

Nile perch is silver in colour with a blue tinge. It has a distinctive dark-black eye, with a bright-yellow outer ring. The fierce predator is Africa's largest freshwater fish, reaching up to 200 cm meters in length and weighing up to 200 kg (Kaufman 1992). Mature fish average 55–137 cm, although many fish are caught before they can grow this large. Nile perch occupy all habitats of the lake where oxygen is sufficient (Feroese and Pauly 2012, Kitchell and Schindler 1997, Ogutu-Ohwayo and Hecky 1991). The species is highly valued in both commercial and recreational fisheries. It is widely distributed in Africa, occurring in the Congo, Niger, Volta and Senegal Rivers, and in Lakes Chad and Turkana, and throughout the

Nile system as far as Lake Albert but was prevented from reaching Lake Victoria by the Murchison Falls (Njiru *et al*. 2009).

The species exhibits ontogenic shift. Young perch feed on zooplankton and then shift to fresh water shrip, *Caridina nilotica*. Adults consume fish, haplochromines being their most prefered prey (Mkumbo and Ligtvoet 1992). Size at first maturity has been changing over the years. It was estimated for males and females at 50 - 54 cm and 90 - 99 cm respectively between 1988 and 1992. Earlier studies in the Winam gulf between 1979 and 1983 estimated the sizes at 74 and 100 cm for males and females respectively. The sizes were later observed to decrease to 55 and 85 cm for males and females respectively between 1985 and 1989. Latest studies undertaken in Kenyan waters between 2004 and 2005 estimated size at first maturity at 54 and 62 cm for males and females respectively (Ojwang *et al*. 2011). In Tanzania, the size at first maturity for males and females in Mwanza Gulf (1988 - 1989) was at 60 cm and 110 cm TL respectively (Mkumbo and Ligtvoet 1992). Later (1998/2001), the size at first maturity showed a decrease where males and females matured at 54 and 76 cm TL respectively (Mkumbo 2002). The decreases in maturity size have been generally attributed to increase in fishing pressure, changes in food availability and the lake environment.

Nile perch takes 1.6 and 2.5 years to mature for males and females respectively. Females are extraordinarily fecund producing between 1,136,000 to 17,336,000 eggs for individuals of sizes 94.5 to 153.0 cm TL (Mkumbo 2002).

2.3 Nile perch fishery

At present the Nile perch fishery is largely artisanal. The only trawlers present belong to research institutes. Small-scale fishing boats are propelled either by sails, paddles or outboard engines. One to three fishermen use a boat. The fish is caught with mainly gill nets and hand lines and long lines. Those caught by gill net are usually dead when the nets are lifted. The fish are kept in the boat sometimes with or without protection from the sun or on ice and taken to landing sites, mostly beaches, where they are weighed and purchased by company buyers using insulated boats or vans with ice. Some of the catch is bought by local fish traders who are predominantly women (Reynolds *et al*. 1988).

Nile perch bought at the beach by women is usually cut into large pieces and smoke-dried for sale in distant places. The fish bought by companies is taken after one to three days to a processing plant where the fish is filleted and the fillets are exported either fresh by air or frozen by boat. Local people around Lake Victoria prefer to eat tilapia, rather than Nile perch, but in West Africa and also in Sudan and Egypt, as well as in Israel it is highly appreciated. In recent years the value of Nile perch exports from Lake Victoria reached almost 500 million USD per year (Manyala and Ojuok 2007).

The yield of fillets from a whole ungutted fish is about 30 percent. The remainder is head, skin, guts, bones and fins plus meat attached to the frame. The frames used to be smoke-dried for local consumption, while heads and skins were used as fuel under frying pans to collect oil from the guts. Nowadays the companies process the filleting waste to fish meal. However, the swim bladder is dried and sold to traders for export to south-east Asia where they are used as food. Nile perch flesh has a high content of omega-3 fatty acids (Werimo 1998).

From the time of its introduction until about 1980 Nile perch were of little economic importance but the population explosion that occurred from 1980 onwards led to a huge increase in yields, which peaked at over 300,000 t in 1990. Catches declined after that but now appear to have stabilized around 250,000 t per annum. The bi-annual lake-wide frame surveys that have been carried out since 2000 provide data on trends in fishing effort which has increased since 2000 but by varying degrees in each country (Ikwaput-Nyeko *et al.* 2009)

2.4 Nile perch slot size

Studies carried out between 1998 and 2000 suggested that the capture of fish between 50 and 85 cm TL could be permitted and slot sizes of 50 to 85 cm TL were gazetted by the countries around the lake with enforcement starting in mid-2000s (Njiru *et al.* 2009). The slot size is based on the premise that Nile perch ≤ 50 cm TL feed predominantly on the shrimp *C. nilotica*, thus converting invertebrates into fish flesh while larger fish are predominantly piscivorous, feeding mainly on the cyprinid *R. argentea*, juvenile Nile perch, Nile tilapia, and haplochromines, which is both destructive to the lake's biodiversity and energetically wasteful. Harvesting Nile perch ≥ 50 cm TL could also lead to the recovery of the haplochromines, thus enhancing the productivity of the fisheries, especially in deep waters where only the pelagic *R. argentea* occurs at present. Female Nile perch grow to a larger size and mature later than males and up to 2006 males and females reached 50% maturity at 54-64 and 62-85 cm TL respectively. The sex ratio changed with size because males were smaller than females and most fish > 80 cm were females (Njiru *et al.* 2009) but the removal of large fish by the fishery has resulted in a more or less equal sex ratio in the 40-60 cm size range (LVFO, unpublished data). Thus, the slot size of 50 to 85 cm TL sought to protect immature fish, harvest mature individuals and at the same time protect the larger females, which would be expected to replenish the stocks.

2.5 Stock assessment in Lake Victoria

Ecosystem monitoring is becoming increasingly important. However in Lake Victoria, data collection is always characterized by inconsistencies (Cowx and Knaap 2003). Data collected often lacks critical components necessary for meaningful stock assessment using many available methods. Reliable quantitative measures of abundance or age structure do not exist for the Nile perch in Lake Victoria (Cowx and Knaap 2003, Kitchell and Schindler 1997). The only lake-wide fish biomass monitoring attempts were done using acoustics under the Lake Victoria Research Project, LVRP (1999-2002) and Implementation of a Fisheries Management Plan, IFMP (2005-2010) projects (Kayanda *et al*. 2009). Only one acoustic survey has been conducted under the East Africa Commission partner fund in 2011. These projects were short term with a time lapse between them causing a data gap. It is therefore hard to predict long-term stock trends using the generated information. The Gadget modelling framework, has in part been developed to undertake analyses in data poor situations using formal statistical approaches (Begley 2005).

2.6 Gadget

The Gadget is a complicated statistical model that can utilise many different types of fisheries data, using appropriate assumptions on each dataset (Begley 2005, Taylor *et al.* 2007). The idea is to model the actual data collected in as raw a form as possible. Gadget generates a corresponding fitted dataset for each type of observed data available. It then allows direct comparisons between the modelled population and the observed population. As a result, whether each model component provides an adequate description of the corresponding dataset can be evaluated. The describtion of Gadget from Begley (2005) hereafter is summarized.

2.6.1 *Arrangement of a Gadget run*

Data and simulation model are separate within Gadget (Figure 1). Simulation starts with a given set of parameters values and functions producing a modelled population with modelled surveys and catches. These are then compared against available data to produce a weighted likelihood score. Finally, the best set of parameter values are obtained using optimization routines described in details in section 2.6.5.

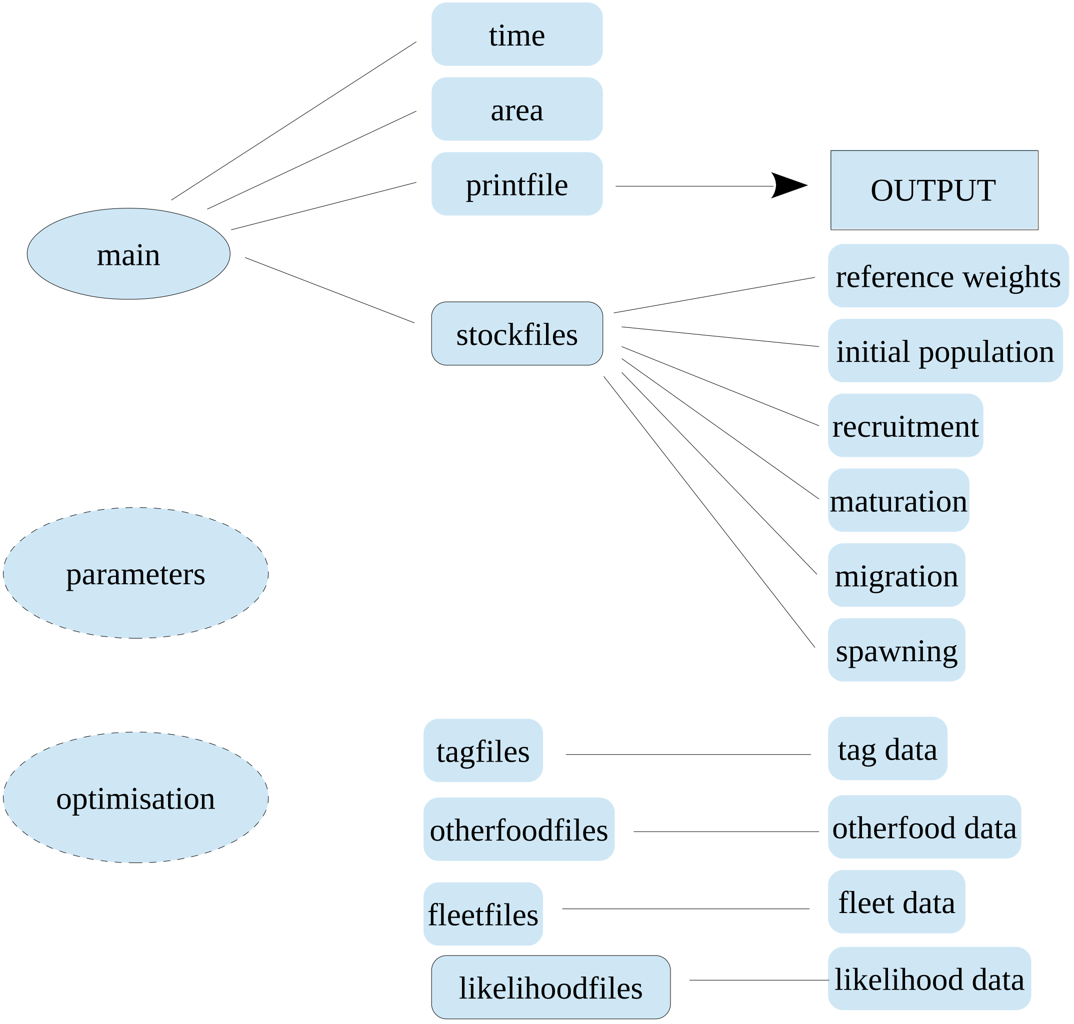

Figure 1. Schematic representation of a Gadget model adapted from Begley (2005).

2.6.2 *Growth*

Growth is modelled by calculating the mean growth for each length group following a Von Bertalanffy (1938) growth equation:

$$\frac{dL}{dt} = K\left(L_\infty - L(t)\right), \quad t \in R^+$$

and

$$L(t) = L_\infty(1 - e^{Kt}), \quad t \in R^+$$

where L is the length at time t, L_∞ the asymptotical maximum length, and K the growth rate. Note that R^+denotes the real positive numbers.

Then the length distributions are updated according to the calculated mean growth by allowing some portion of the fish to have no growth, a proportion to grow by one length group and a proportion two length groups etc. How these proportions are selected affects the spread of the length distributions but these two equations must be satisfied (Stefansson 2001):

$$\sum p_{il} = 1$$

and

$$\sum ip_{il} = \mu_l$$

where μ is the calculated mean growth and p_{il} is the proportion of fish in length group l growing i length groups.

The probability p in the binomial distribution comes from a beta distribution described by α and β (Stefansson 2001). As in all discrete probability distributions the condition $\sum p_{il} = 1$ is automatically satisfied. The mean of the distribution is given by:

$$\mu_l = \frac{n\alpha}{\alpha + \beta} = \sum_{i=0}^{n} p_{il} i$$

For a given value of β, a value of α is selected so that $\mu_l = G_l$ where G_l is the calculated mean growth from the parametric growth equation. β, which can either be estimated or specified in the input files, affects the spread of the length distribution.

2.6.3 Fleets

A submodel in Gadget simulates the fleet, which can be treated as a simplified predator with size preference.

To estimate catch in numbers by age and length the modelled CPUE for the fleet is calculated:

$$CPUE_{mod} = \sum_{prey} \sum_{l} S_{prey,l} N_{prey,l} W_{prey,l}$$

where $S_{prey,l}$ is the selection of prey length l, $N_{prey,l}$ is the number of fish and $W_{prey,l}$ is the mean weight of prey of length l. The total catch of each length group of each prey is then estimated by:

$$C_{prey,l} = C \frac{S_{prey,l} N_{prey,l} W_{prey,l}}{CPUE_{mod}}$$

where $C_{prey,l}$ is the amount caught by the predator of length-group l of prey and C is the total amount caught by the fleet, either specified or calculated from $C = E \times CPUE_{mod}$, where E is the specified effort.

2.6.4 Likelihood Data

The second step in Gadget is to compare the simulated system with the available real data, to make the model statistically testable. These data are termed “likelihood data” and each dataset used is assigned to a “likelihood component”, specifying the statistical relationship to be used when comparing simulation results with the observed data (Taylor *et al*. 2007). The data used as likelihood components depend on data availability and the aim of the model. Datasets, from both commercial fisheries and scientific surveys (e.g. length distributions, age–length keys, and survey abundance indices are used in the model (Taylor *et al*. 2007). The model combines a wide selection of the available data using a maximum likelihood approach to find the best fit to a weighted sum of the data-sets.

2.6.5 Optimization

The last step in the Gadget approach is the estimation of parameters using one or more algorithms to optimize parameter values iteratively, i.e. those that give the lowest negative log-likelihood score. The model has three alternative optimizing algorithms: simulated annealing (Corana *et al.* 1987), Hooke and Jeeves algorithm (Hooke and Jeeves 1961) and one based on the Boyden-Fletcher-Goldfarb-Shanno algorithm (BFGS). The overall negative log-likelihood score gives a measure of how well the simulated model fits the data.

Simulated annealing

The simulated annealing algorithm is a way of finding optimum solutions to problems, which have a large set of possible solutions. It is a good tool for complex nonlinear optimization problems (Ram *et al.* 1996). Often the solution space of an optimization problem has many local minima. A simple local search algorithm proceeds by choosing random initial solution and generating a neighbour from that solution. The neighbouring solution is accepted if it is a cost decreasing transition. Such a simple algorithm has the drawback of often converging to a local minimum. The simulated annealing algorithm, though by itself it is a local search algorithm, avoids getting trapped in a local minimum by also accepting cost increasing neighbours with some probability.

Hooke and Jeeves

This is a direct search method where no derivatives are required (Hooke and Jeeves 1961). It is a simple and fast optimizing method, but somewhat unreliable. From the initial starting point the algorithm takes a step in various directions, and conducts a new model run. If the new likelihood score is better than the old one then the algorithm uses the new point as its best guess. The search proceeds in series of these steps, each step slightly smaller than the previous one. When the algorithm finds a point that cannot be improved by a small step in any direction then it accepts this point as being the solution and exits. It can be seen that this renders the scheme vulnerable to producing local solutions, accepting a local dip as being the solution even if a better solution exists elsewhere, beyond a local hill that the algorithm cannot see past (Begley 2005).

BFGS

BFGS is considered to be the most effective quasi-Newton method. It uses information about the gradient of the function at the current point to calculate the best direction to look for a better point. Using this information it can iteratively calculate a better approximation to the inverse Hessian matrix. A necessary condition for optimality is that the gradient be zero. In comparison with the two other algorithms implemented in Gadget, BFGS is very local search compared to simulated annealing and more computationally intensive than the Hooke and Jeeves. However, the gradient search in BFGS is more accurate than the step-wise search of Hooke and Jeeves and may therefore give a more accurate estimation of the optimum (Begley 2005).

Gadget can use all three algorithms in a single optimization run, utilising the strengths of all. Simulated annealing is used first to attempt to reach the general area of a solution, followed by Hooke and Jeeves to rapidly home in on the local solution and finally BFGS is used for fine-tuning the optimization. This procedure is repeated several times to attempt to avoid converging to a local optimum (Begley 2005).

2.6.6 Likelihood weighting

Results from an optimizing run using the inverse sum of squares (SS) are compared with those from the iterative reweighting scheme (Taylor *et al*. 2007). The reweighting scheme requires a separate optimizing run for each likelihood component. Optimization in the iterative reweighting scheme involves the sequential use of Simulated Annealing and Hooke and Jeeves to estimate the weights. For the subsequent parameter estimation runs, optimization consists of two optimization runs, each a combination of Simulated Annealing followed by Hooke and Jeeves. The aim of the first run is to move the parameters into the vicinity of the solution and the second is a more precise run. The two-run approach also allows for a second global search (Simulated Annealing) if the first optimization moved the solution into a local minimum (Taylor *et al*. 2007). The iterative re-weighting is implemented in the R statistical language using the rgadget package (Elvarsson *et al.* 2011).

3 MATERIALS AND METHODS

3.1 Study area

This study focuses on the Nile perch fishery in Lake Victoria (Figure 2). The lake occupies a wide depression near the equator between the Western and Eastern Rift Valleys. It has a maximum depth of 84 m and an average depth of 40 m (United Nations 1999).

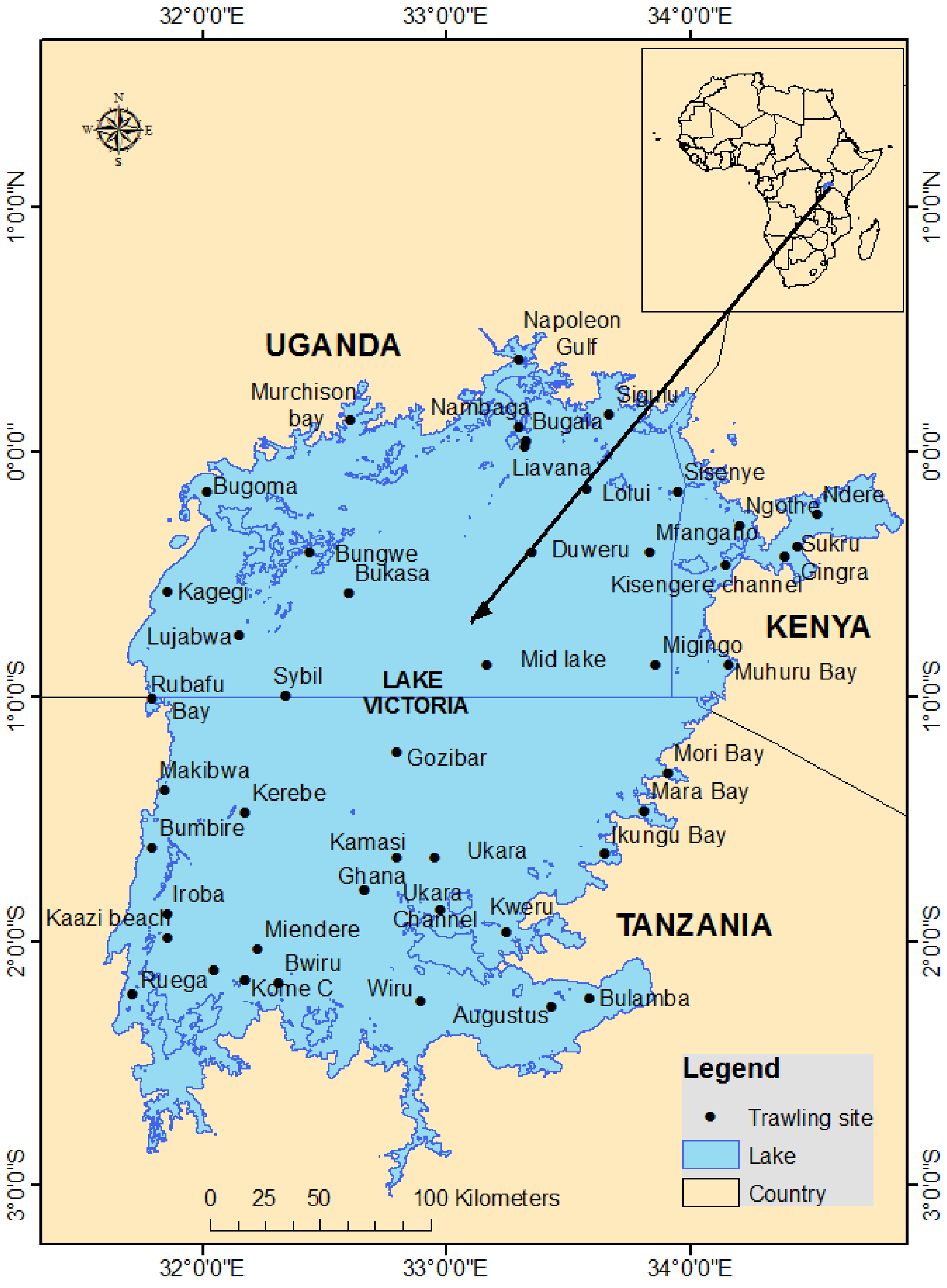

Figure 2. Map of Lake Victoria, showing different sampling points during regional acoustic and trawl surveys.

Its catchment area covers 184,000 km^2 and has a shoreline of 4,828 km with islands constituting 3.7% of this length (Hickling 1961). Lake Victoria is known for its abundance of fish (mainly Nile perch), which are exported by local fisherman. This study utilizes both fishery independent and dependent data sets to assess the development the Nile perch stock in Lake Victoria using the Gadget framework.

3.2 Data and file arrangement in Gadget

As illustrated in section 2.6.1 data and simulation model are separate within Gadget. Data used in the present study included: annual commercial landings, length distributions and age-length keys from catch and trawl surveys, catch per unit effort (CPUE) and acoustic biomass indices. These were stored in the data files folder in Gadget. The apportionment of data into different length, age, and area groups was defined in the aggregation files of the Gadget model. Initial numbers of each age group, annual recruitment, length-weight reference data and time differentiated selection pattern functions were input the initial file of the model. The type and selection pattern function of each fleet were defined in the fleet file whereas the likelihood file was used to define the various likelihood components that were used to calculate the "goodness of fit" of the Gadget model to the available data using optimization routines. The type of optimization, number of iterations and criteria of accepting optimum values were defined in option information file of the model. All the information and list the files that define the stock to be used in the model were summarized in the stock file. The links to other files that make up the Gadget model were contained in the main file. Simulations were started with the given set of parameters values and functions.

3.3 Gadget input data

3.3.1 Commercial catches data

Anual commercial landings for Nile perch from Lake Victoria are shown in Table 1. The division of landings in quarterly three month steps was based on availabe monthly catch statistics that were analyzed to check seasonal variabilty in landings within the year. The determined proportions for each time step were then used to apportion catch for the entire data accordingly. The assumption here was that seasonal variability of catch within the year was similar across all the years.

There is scarcity of monthly length measurements of Nile perch from commercial catch in Lake Victoria. The biannual catch assessment surveys are usually conducted only in two months (February and August) of the year and therefore cannot give a reflection of length distribution of catch throughout the year. The limited length distributions are collected by research institutes of the riparian states. Data that were input into the Nile perch model are shown in Table 2. These were also divided into quarterly three month steps for each year. Additionally, catch per unit data for commercial fleet from 1968 to 1996 were also input into the model to be used as an index of abundance.

Table 1. Commercial catches in tonnes in three-month steps and years.

Year	Step 1	Step 2	Step 3	Step 4	Total
1968	9585	9275	8831	8109	35800
1969	11727	11347	10804	9921	43800
1970	11352	10985	10459	9604	42400
1971	13146	12720	12111	11122	49100
1972	16065	15544	14800	13591	60000
1973	19813	19171	18253	16762	74000
1974	19735	19096	18182	16696	73709
1975	18549	17948	17089	15693	69279
1976	15869	15355	14620	13426	59271
1977	21446	20751	19758	18143	80098
1978	21205	20518	19535	17939	79197
1979	21773	21068	20059	18420	81321
1980	20552	19886	18934	17387	76760
1981	25999	25157	23953	21996	97104
1982	35536	34385	32739	30064	132723
1983	44895	43441	41361	37982	167680
1984	51353	49690	47311	43446	191800
1985	47431	45895	43698	40127	177151
1986	53410	51680	49206	45186	199481
1987	72310	69967	66618	61175	270070
1988	86928	84113	80086	73543	324670
1989	90989	88041	83826	76978	339834
1990	99474	96252	91644	84156	371526
1991	69488	67237	64018	58788	259532
1992	82358	79690	75875	69676	307599
1993	94097	91049	86690	79607	351443
1994	88052	85200	81121	74494	328867
1995	94012	90967	86612	79536	351128
1996	80205	77607	73892	67855	299559
1997	84945	82193	78258	71865	317261
1998	87141	84318	80282	73722	325463
1999	78239	75705	72081	66192	292217
2000	76862	74372	70812	65026	287072
2001	70528	68243	64976	59668	263415
2002	64561	62470	59479	54620	241130
2003	71348	69037	65732	60362	266479
2004	83546	80840	76970	70681	312036
2005	94206	91155	86791	79700	351851
2006	81808	79158	75369	69211	305546
2007	78374	75835	72204	66305	292718
2008	74493	72080	68629	63022	278223
2009	73823	71432	68012	62456	275723
2010	68810	66581	63393	58214	256998
2011	66581	63393	58214	58214	246402

3.3.2 Survey data

Length distributions were obtained from lake wide trawl surveys (2005-2011) conducted in the month of August. The lengths were clustered into three length groups (Table 3). Most of the catch in the surveys belonged the length group 1.

Biannual acoustic biomass index data for the period 1999-2002 and 2005-2011 were also used as a tuning series in the gadget model. The biannual surveys have usaully been counducted in the months of February and August. Lake Victoria does have a season of deep vertical mixing when the lake becomes isothermal. During June and July the established thermocline breaks down under the seasonal onset of the south-east trade winds and for a brief period at the end of July the main body of the lake becomes isothermal with respect to depth (Talling 1966). The thermocline most often occurs at 30-40 m depth. Complete mixing occurs once a year. The acoustic surveys were designed to capture fish densities during the mixed (August) and thermo-stratified (February) periods.

Table 2. Number of commercial length measurements in quarterly three-month steps used as input data into the Gadget model.

Year	**Step**			
	1	2	3	4
1999				5145
2000	3102	5397	9650	5184
2001	6150			
2011	1168	1220	1165	1094

Table 3. Number of fish in the different length groups from the August 2005-2011 trawl surveys in Lake Victoria.

Year	**Length group**		
	1 (0 to 10 cm)	2 (10 to 30 cm)	3 (30 to 150 cm)
2005	18711	2611	176
2006	5118	1403	61
2007	23482	2001	96
2008	12876	1837	101
2009	25962	2376	94
2010	10934	1124	60
2011	11129	2181	38

3.4 Model assumptions

Due to the lack of age data for Nile perch in Lake Victoria, growth is assumed to be constant through time. It was estimated during the first run but it was fixed in the final model run. After the initial run, additional likelihood components i.e mean lengths at age and standard deviation for both commercial and survey fleets were introduced. The likelihood components were estimated by fitting a von Bertalanffy growth curve to the available data. Mean lengths at age were assumed to have a CV of 15% resulting in a standard deviation of 15% of the predicted mean length at age. These estimates are shown in Figures 3 and 4. Growth parameters for both fleets were estimated using a non linear regression model (von Bertalanffy).

The estimated paramters were L_∞ = 255 cm, K = 0.069, t_0 = -0.25 and L_∞ = 198 cm, K = 0.1, t_0 = 0.8 for the commercial and survey fleets respectively. In both cases the predicted models fitted well with to data. As already mentioned these growth parameters were fixed in the final model run. Also fixed was the recruitment length (8.3 cm) and standard deviation (9.6 cm). In the final run the mean length at age likelihood components were omitted.

During the initial first run recruitment was estimated annually. The output estimates were highly variable characterized with patchy large cohorts alternating with periods of almost no recruitment. To overcome this challenge, recruitment was estimated in three year blocks (one parameter for every three cohorts) from 1968 to 2000 in the final run. In the last 10 years it was estimated annually because of availability of survey data. The model runs were started from the `params.start` files (Appendices 1 and 2).

3.5 Model settings

3.5.1 Aggregation of data

The Nile perch model runs from 1968 to 2011 in quarterly time-steps. The model simulates the Nile perch population from age 1 (recruitment) to age 14, which is considered to be a plus group. The length range considered is 11–149 cm, aggregated in 1 cm intervals. Survey data was grouped in 3 length groups of 0 – 10, 10 – 30 and 30 -149 cm (Figure 5). All data were considered to be from one area group in the model.

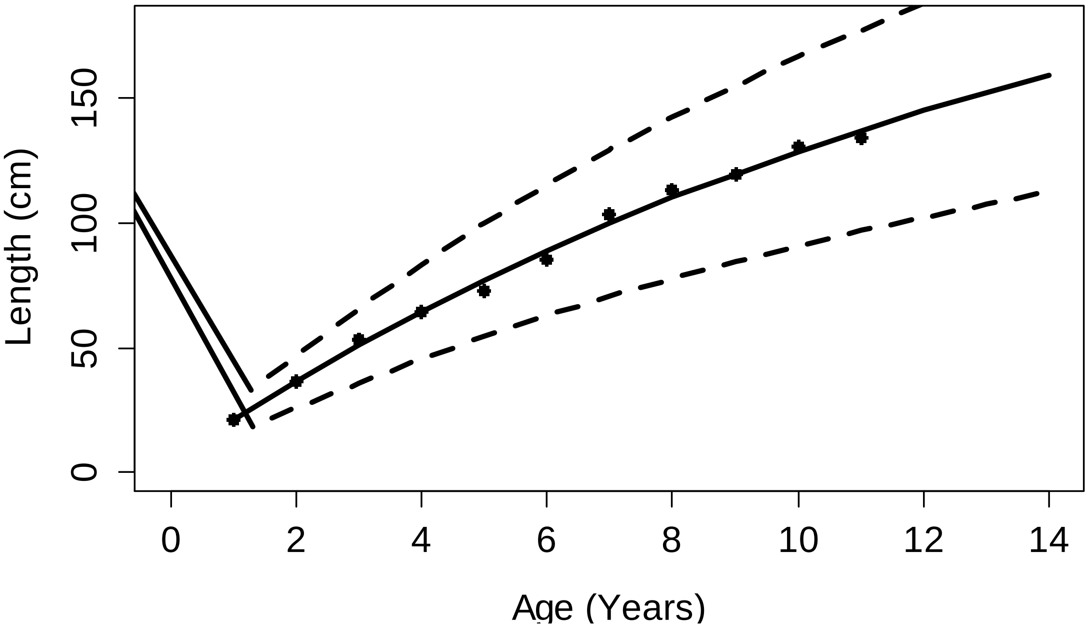

Figure 3. Mean length by age (solid line) and 95% CI (dashed line) and actual data (dots) for commercial landings data used as components in the likelihood function.

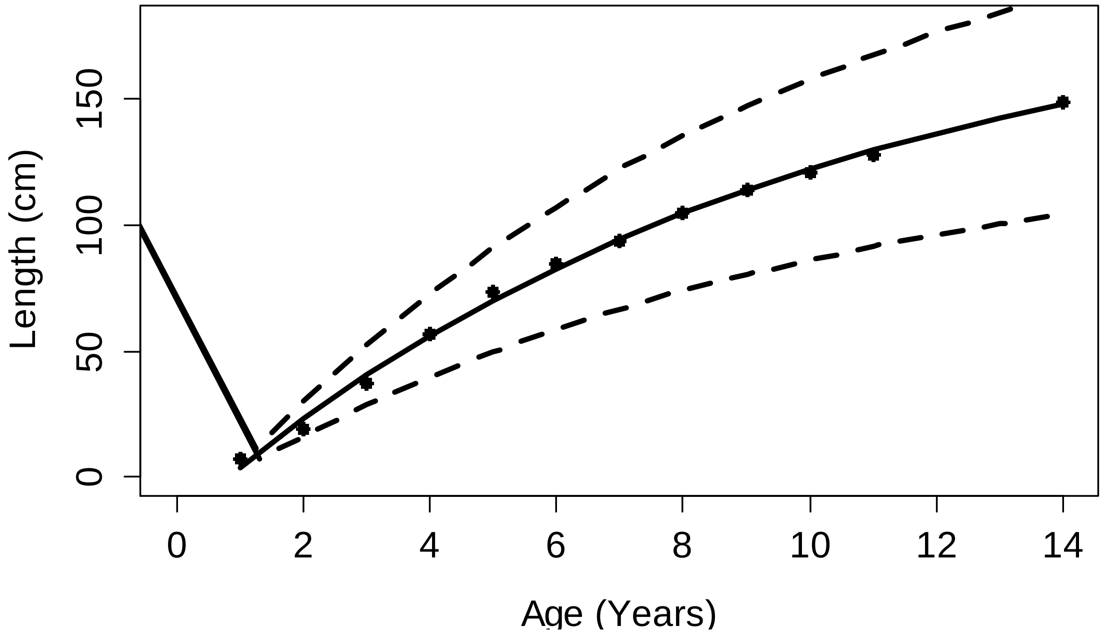

Figure 4. Mean length by age (solid line) and 95% CI (dashed line) and actual data (dots) for survey data used as components in the likelihood function.

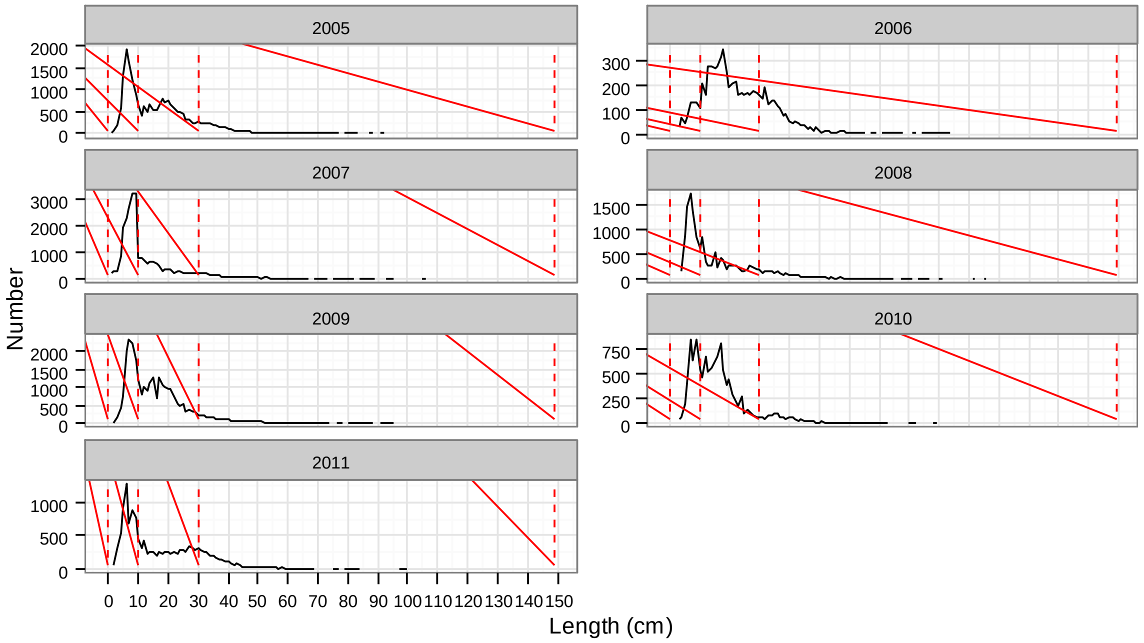

Figure 5. Length distributions from the August (2005–2011) lake-wide trawl surveys. The vertical lines indicate the length-groups within which the data are aggregated to calculate survey indices.

3.5.2 Growth

The length at recruitment (age 1) is not estimated but fixed and mean growth is assumed to follow the Von Bertalanffy (1938) equation (see section 2.6.2 , Figures 3 and 4).

3.5.3 Natural mortality

After repeated initial simulation runs with different values, a natural mortality of 0.28 for all age groups was considered fit for the Nile perch model.

3.5.4 Recruitment

To develop the stock over time, Gadget requires the addition of the youngest modelled age group. One way to do this is to add recruits annually into the youngest age group of the stock. The Gadget model calculated this recruitment for each year from 1968 to 2011. From 2012 to 2030, recruitment was set as the average recruitment in 2009 to 2011.

3.5.5 Fleets and selection

The commercial catch was modelled as one fleet, with two different selection patterns in the periods prior and after 2002. In the stated year, there was a shift in the exploitaion strategy in due to introduction of size restrictions (slot size) of landed fish. The preference of the fleet for prey from a specific length group L was implemented in the model with a suitability function (selectivity pattern of the fleet). In this case, the selectivity pattern of the commercial fleet follows an exponential L_{50} suitability function, defined by the following equation:

$$Sp_{,p}(L) = \frac{1}{1 + e^{-4\alpha(L - L_{50})}}$$

where L_{50} is the length where fish have reached 50% selectivity, and α is a slope constant to be estimated. This selectivity pattern varies between seasons and is estimated by the model.

For the survey fleet selectivity pattern was assumed to follow the Andersen suitability function (bell-shaped). This is function is dependent on the ratio of the predator length as given by the following equation:

$$S(l,L) = \begin{cases} p_0 + p_2 e^{-\frac{\left(\ln\frac{L}{l} - p_1\right)^2}{p_4}} & \text{if} \ln\frac{L}{l} \leq p_1 \\ p_0 + p_2 e^{-\frac{\left(\ln\frac{L}{l} - p_1\right)^2}{p_4}} & \text{if} \ln\frac{L}{l} \geq p_1 \end{cases}$$

The log of the ratio of the predator / prey length is bounded to ensure that the suitability function is always well defined (Begley 2005).

3.6 Objective function

Data used in the objective function to be minimized (to generate corresponding fitted datasets) were as follows:

a) Length distributions from the commercial catches and surveys using sum of squares.
b) Age-length keys from surveys and commercial catches using sum of squares.
c) Length disaggregated survey indices in 1cm length groups using log-normal errors.
d) Biannual acoustic survey biomass indices using log-normal errors.
e). Annual CPUE index using log-normal errors.
f) Mean length at age and standard deviation from survey (not used in final run but corresponding parameters fixed).
g) Understocking, i.e. to small biomass to cover the specified catch in tonnes and bounds, i.e. to keep minimization routines within the specified bounds.

The total objective function to be minimized is a weighted sum of the different components. The optimization was started with simulated annealing to make the results less sensitive to the initial values and then the optimization changed to Hooke and Jeeves when the optimum is approached and then finally the BFGS is run for fine-tuning. The optimization procedures are described in detail in section 2.6.5.

3.6.1 Weights on likehood components

An rgadget package (Elvarsson *et al*. 2011) was used iteratively reweight each component seperately. This was done in order to determine the lowest possible value for each likelihood component. Optimization in the iterative reweighting scheme involved use of Simulated Annealing and Hooke and Jeeves to estimate the weights.The dermined likelihood weights were then fine tune using expert knowledge for the final run (Table 4).

Table 4. Likelihood components and likelihood weights for the Nile perch model.

Likelihood type	Likelihood component	Likelihood weight
Penalty	Bounds	10.00
Understocking	Understocking	1.00
Survey Indices	si2039	15.00
	si4069	20.00
	si70110	3.00
	febSur.lik	1.00
	augSur.lik	18.00
	cpue.lik	2.00
Catch distribution	ldist.catch	50.00
	ldist.survey	116.00
	alkeys.catch	50.00
	alkeys.survey	27.00

3.7 Maturity estimates

Data for maturity analyses was derived from the 2011 trawl survey. Length at maturity for both males and females was estimated by a Generalized Linear Model GLM, (logistic regression) with the proportion mature as the dependent variable and length as an independent variable. This was done using the statistical computing language and environment R 2.15.0 (R Development Core Team 2012). A binomial distribution (0 = immature, 1 = mature) with log odds (logit) link was used for the GLM.

3.8 Yield and spawning biomass per recruit

Yield-per-recruit models are often used to provide management guidance for the efficient use of a fish cohort and to estimate the biological reference points, such as $F_{0.1}$ or F_{Max}. Although model parameters are usually age-specific, these parameters are thought to be more likely related to length than age (Chen 1997). In this study, length-structured yield per recruit (YpR) and spawning biomass per recruit (SSB/R) curves were estimated within gadget using different selection patterns i.e. before and after introduction of slot size restrictions.

4 RESULTS

4.1 Gadget fit to data

The model fit corresponded well with the length dis-aggregated survey indices especially for length groups 1 and 2 (Figure 6). It also fitted well to observed data of all length groups from trawl surveys. The indices flactuate over the years but the general trend is level. In all the instances, there was postive correlation between the observed and predicted indices i.e showing similar trends. From the model setting (Figure 5) it can be seen that length groups one and two represent cohorts hence the better predictions than the third length group which is a combination of several cohorts. Likewise the predicted CPUE indices compared well with data showing a strong positive correlation coefficient (Figure 7). This was particularly so during the early years of the fishery. The index was low before 1977. Afterwards, it increased steadily and then slowed in 1992. The predicted and observed acoustic survey indices (February and August) showed similar trends (Figures 8 and 9). Both acoustic indices show a general decline of biomass over time.

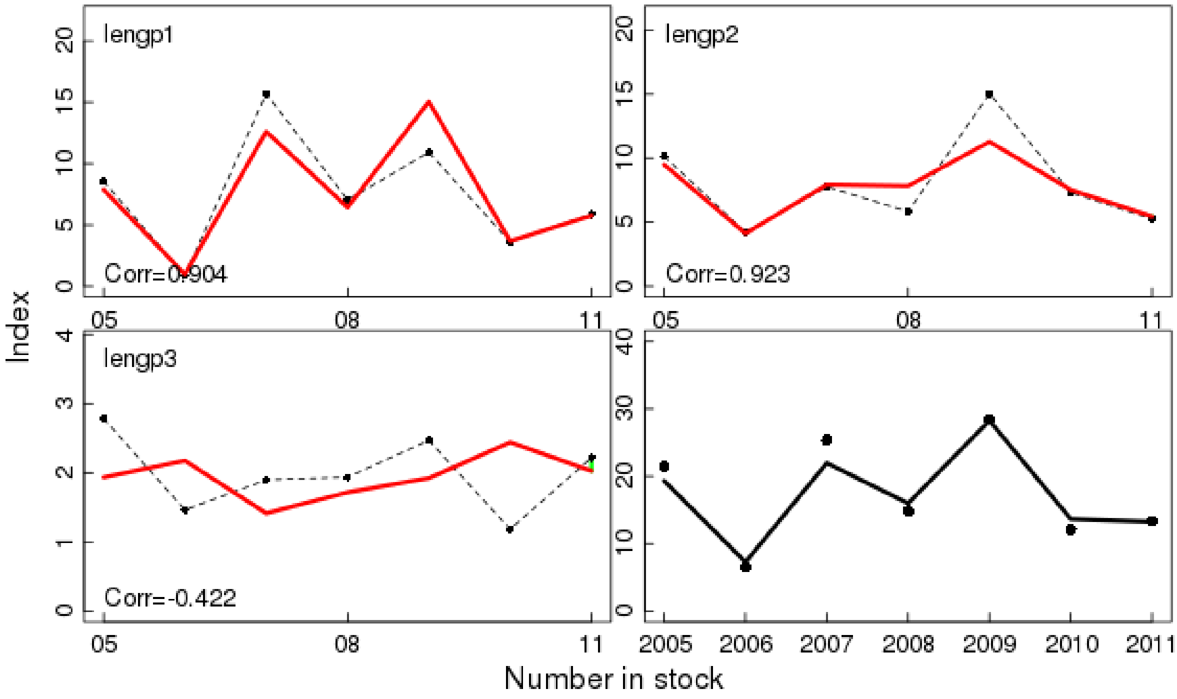

Figure 6. Gadget model fit to length dis-aggregated indices from trawl surveys in Lake Victoria. The red and black dotted lines represent predicted and observed indices respectively. The fourth subplot shows the overall model fit (black line) to all length group indices.

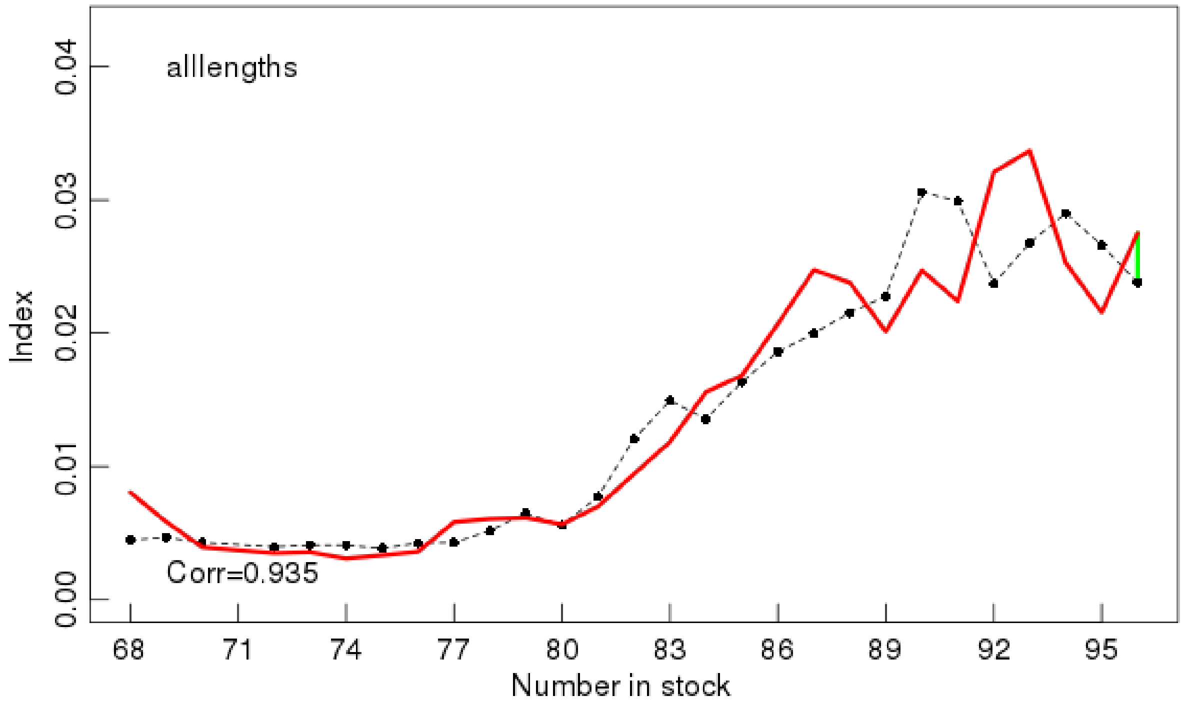

Figure 7. Gadget model fit to CPUE survey indices data for Nile perch from Lake Victoria.

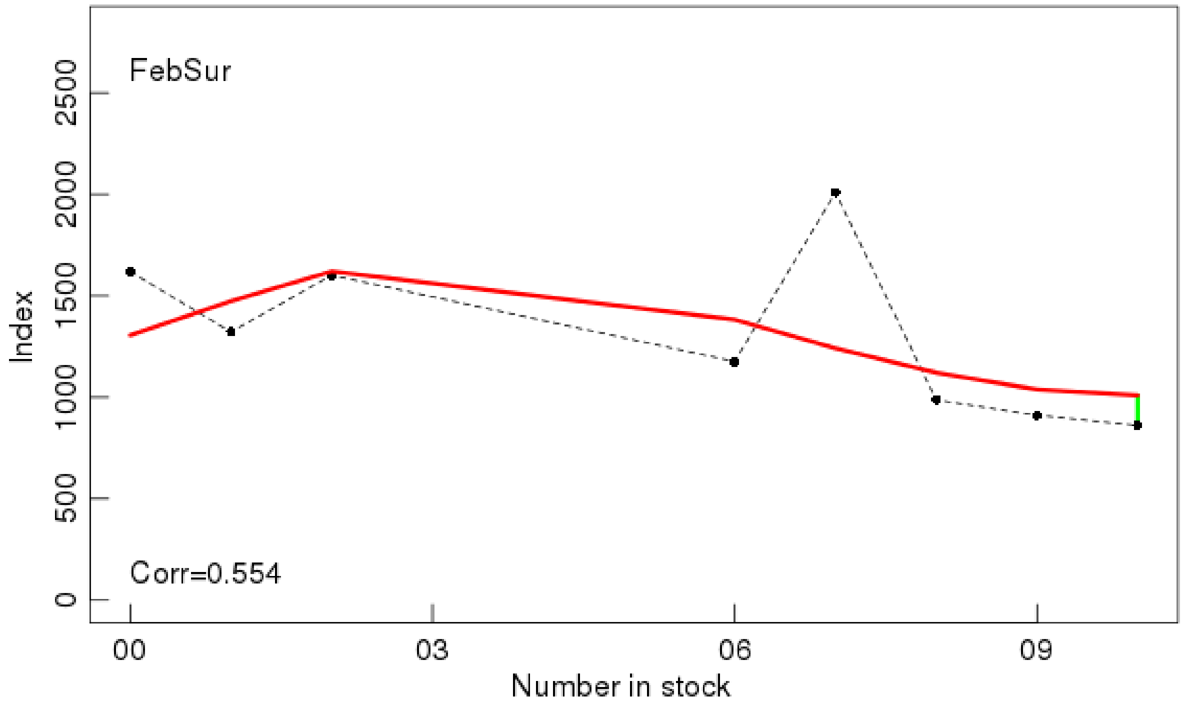

Figure 8: Gadget model fit to February acoustic survey indices data for Nile perch from Lake Victoria.

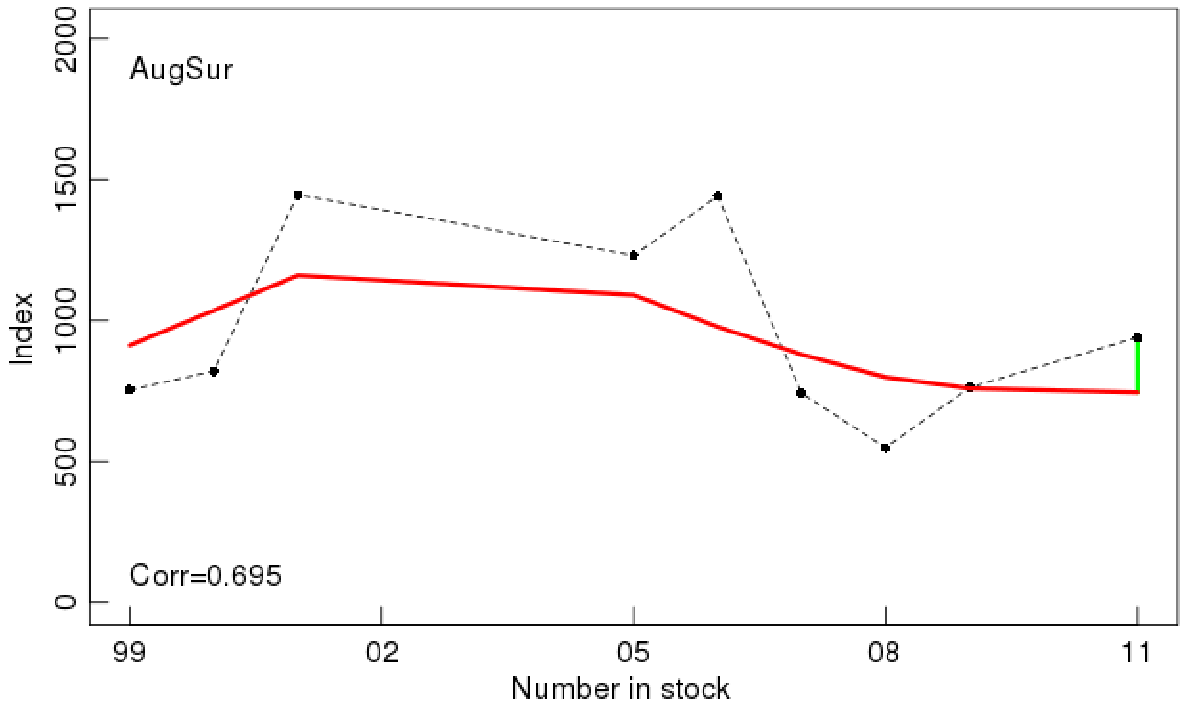

Figure 9. Gadget model fit to August acoustic survey indices data for Nile perch from Lake Victoria.

4.1.1 *Commercial catches*

The model fit to the only available data is shown in Figure 10. It fits well to data with a different pattern for the year 2011. This is attributable to the change in selecetion of the commercial fleet in recent years following the implementation of the slot size.

4.1.2 *Surveys*

The model fit follows the pattern of observed survey length distributions (Figure 11). The size distribution was highly skewed to the left indicating either a selection biased towards small sized fish or dominance of the small size classes in the population.

4.2 Estimates

4.2.1 *Selectivity*

Two distinct selection patterns were evident in the commercial fleet. The probability of 50% capture (L_{50}) was 25.88 and 50.00 cm before and after the introduction of slot size respectively. For the survey fleet probability of capture was very high for the small individuals as opposed to the large ones (Figure 12).

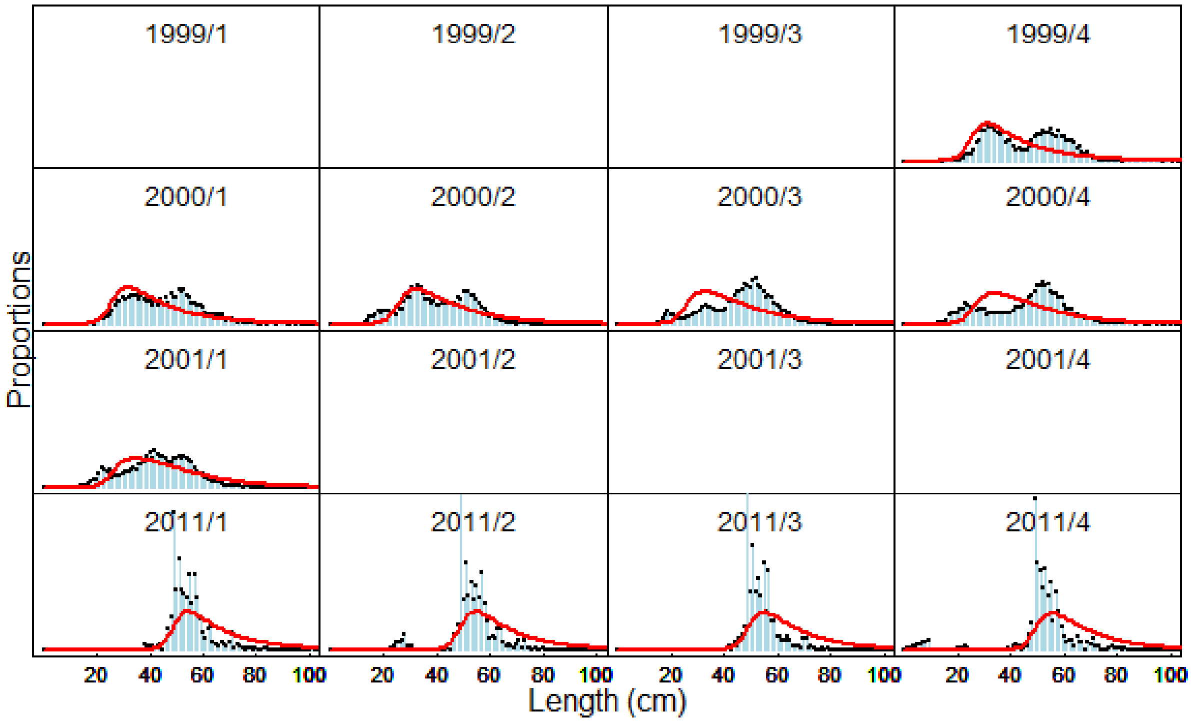

Figure 10. Gadget model fit to quarterly three-month step length distributions of Nile perch from commercial catches in Lake Victoria. The red line and bars represent the predicted length distributions.

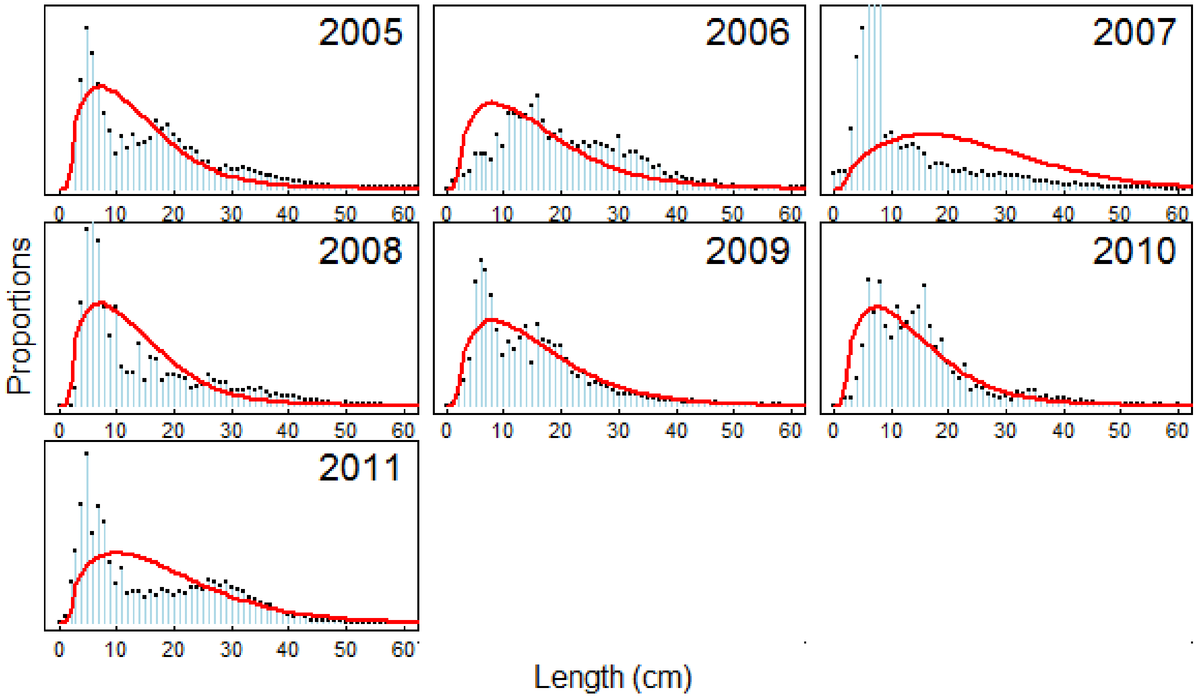

Figure 11. Gadget model fit to Nile perch length distributions of survey data from Lake Victoria. The red line and bars represent the predicted length distributions.

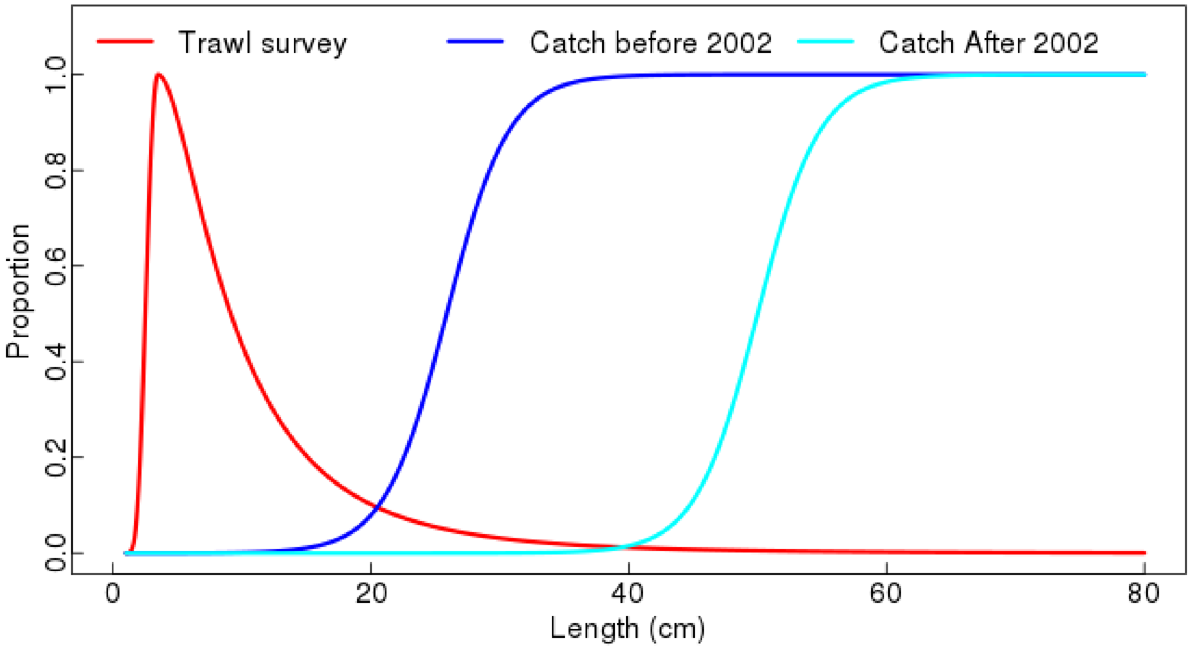

Figure 12. Fleet selection curves for Nile perch in Lake Victoria. Selection patterns for commercial fleet before and after introduction of slot size restrictions are illustrated.

4.2.2 Maturity estimates

Size at 50% maturity (Lm50) was 61.34 and 70.37 cm while adult sex ratio was 2:1 for males and females respectively (Figure 13). The maturity ogive for males was used to define the Spawning Stock Biomass (SSB) for the model.

4.2.3 Population

Figure 14 depicts trends of population parameters (landings, recruitment, fishing mortality, and biomass) estimates for Nile perch in Lake Victoria. Biomass increased rapidly from 1968 to 1975. It remained high through out the 1980s. At the begining fishing mortality was low. The fishing mortality started to increase as from 1980. A concurrent increase in in catch was witnessed reaching a record high in 1990. After this period, total biomass reduced steadily with increasing fishing mortality. By 1999, total biomass had dipped to an all time low. This was reflected in cathes two years later with a dip in 2001-2002. Fishing mortality increased more than two fold four years prior to turn of the mellinum. Fishing mortality reduced considerably between 1999 and 2002. The drop in fishing mortality concided with the European Union ban (EU) on Nile perch from Lake Victoria. After 2002, biomass slighly increased until 2006 when the trends changed again.

The unprecedented decline in Nile perch biomass coincided with sweeping changes in its population structure. Spawning stock biomass (SSB) which constituted 90% of total biomass in 1980 reduced steadily until 1999 where it was still over 50%. It reduced drastically after the year 2000, accounting for only 22% in the year 2011. This development occurred during the implementation of the slot size (50 – 85 cm) and after the ban on trawling in the lake.

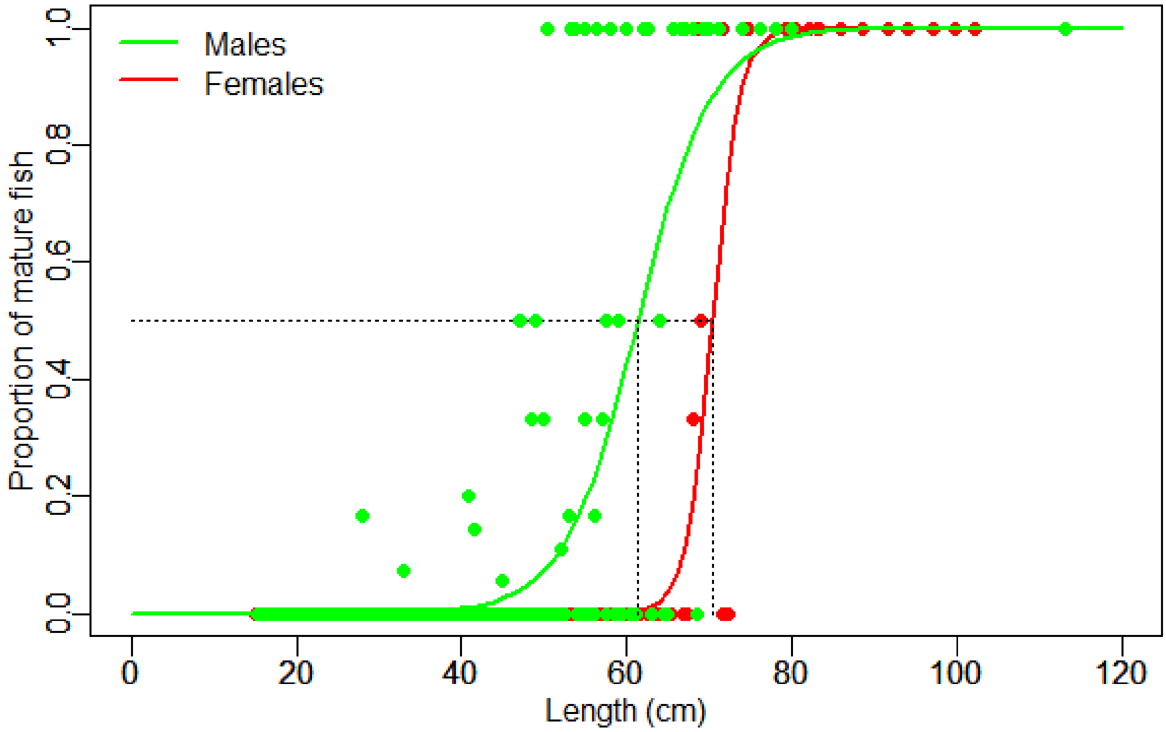

Figure 13. Logistic ogives fitted to percentage of sexually mature Nile perch males and females from Lake Victoria.

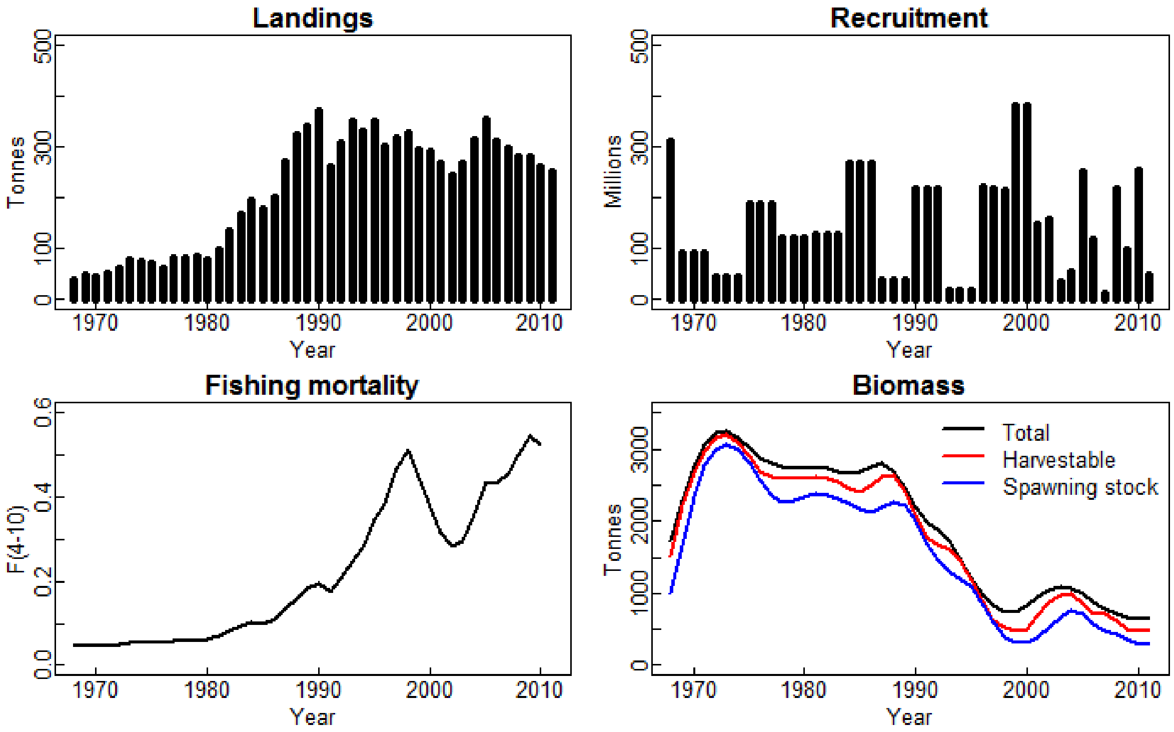

Figure 14. Population parameters trends of Nile perch in Lake Victoria as estimated by Gadget.

4.2.4 Yield and spawning biomass per recruit

The effect of different fishing mortalities on yield using the current selection patterns of commercial fleet is shown in Figure 15. It is apparent that the current fishing mortality of 0.53 results in yield per recruit (YpR) of 1.38 kg which is lower than it could have been at F_{max} =0.33 that results in YpR. 1.45 kg. The current fishing mortality is almost double the optimum. It is estimated that a fishing mortality of $F_{0.1}$ = 0.21 will result in a YpR of 1.37 kg. At the current fishing mortality level, SSB/R is almost half what it could be at F_{max}. If fishing was further reduced to $F_{0.1,}$ SSB/R will increase considerably. The YpR and SSB/R curves for the fleet selection before the introduction of slot size are shown Figure 16. The effect of fleet selection pattern on YpR and SSB/R curves is depicted in Figure 17. It is evident that the current selection pattern results in higher YpR and SSB/R.

4.2.1 Forward projections

Assuming a constant recruitment of 5.48 (average of the last four years), projections show that the current fishing mortality will lead to further decline of biomass. Increasing the effort (to $F_{0.7}$, $F_{1.0}$ or $F_{2.0}$) will further reduce biomass (Figure 18). In the short term, raising fishing mortality will result to an increase in catch, followed by a sharp decline before stabilizing at much lower level (Figure 19). On the other hand, biomass will increase by almost two fold in less than a decade if fishing mortality was to be reduced to F_{max}. Reducing fishing mortality to $F_{0.1}$ will further increase biomass. Reduction of fishing mortality to either reference points will see an immediate reduction of catches in the short term. Afterwards the catch increases, stabilizing at a much higher level. Predictions based F_{max} results in the highest catch levels.

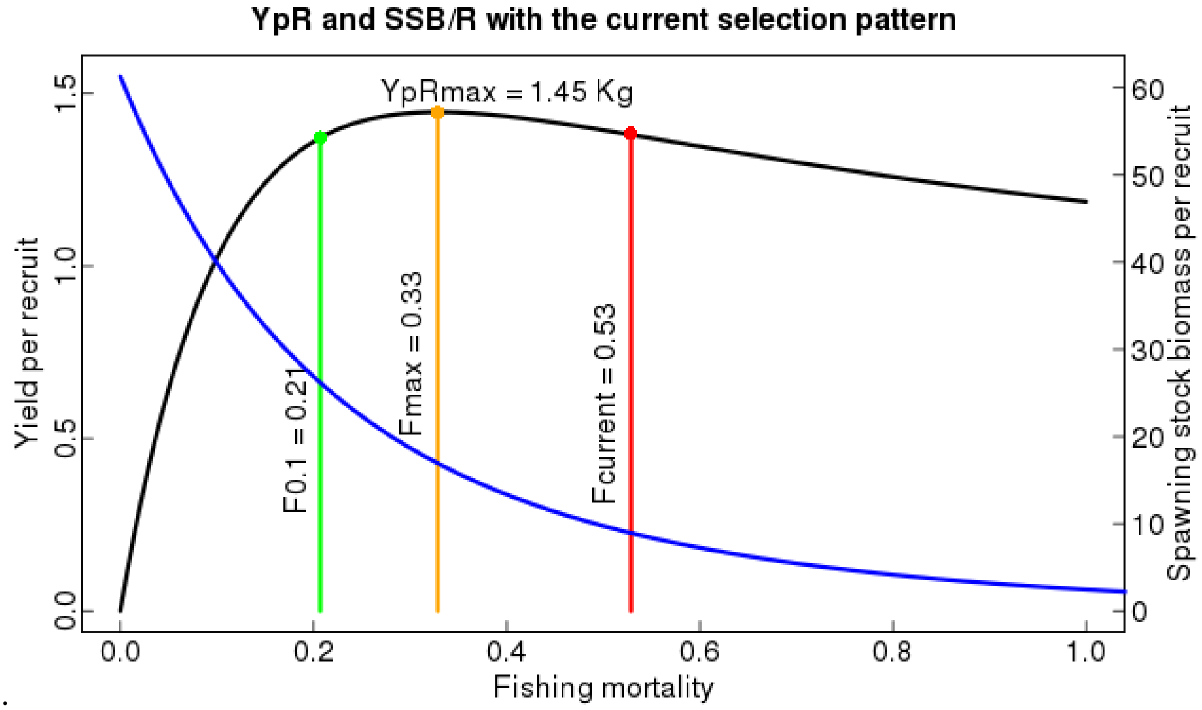

Figure 15. Yield per recruit analysis for Nile perch in Lake Victoria given the current fleet selection at different fishing mortalities. The blue line represents the spawning stock biomass per recruit.

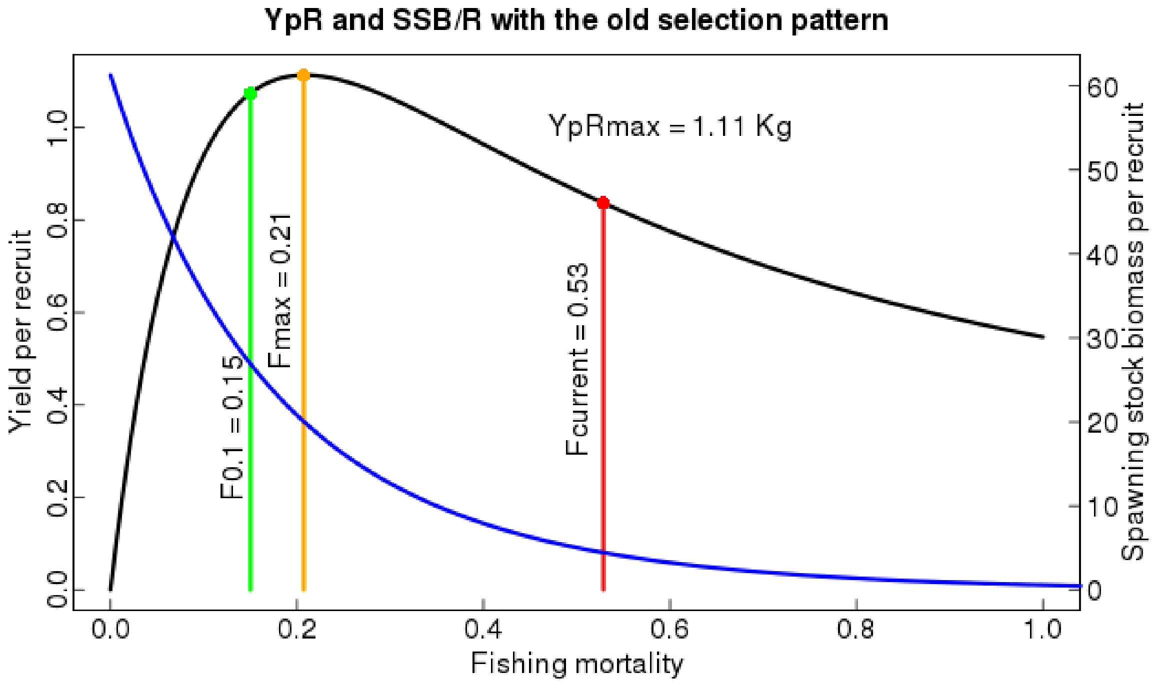

Figure 16. Yield per recruit analysis for Nile perch in Lake Victoria using fleet selection before the introduction of slot size at different fishing mortalities. The blue line represents the spawning stock biomass per recruit.

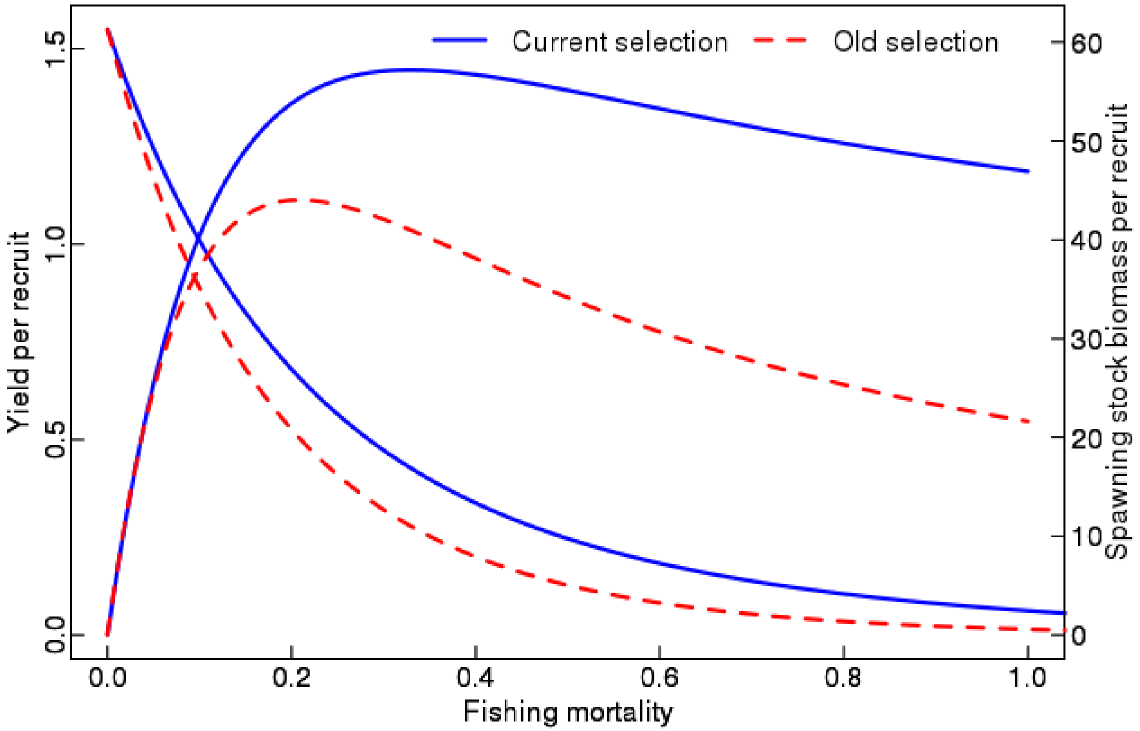

Figure 17. Yield and spawning stock biomass per recruit analyses for Nile perch in Lake Victoria using the current and old fleet selection patterns.

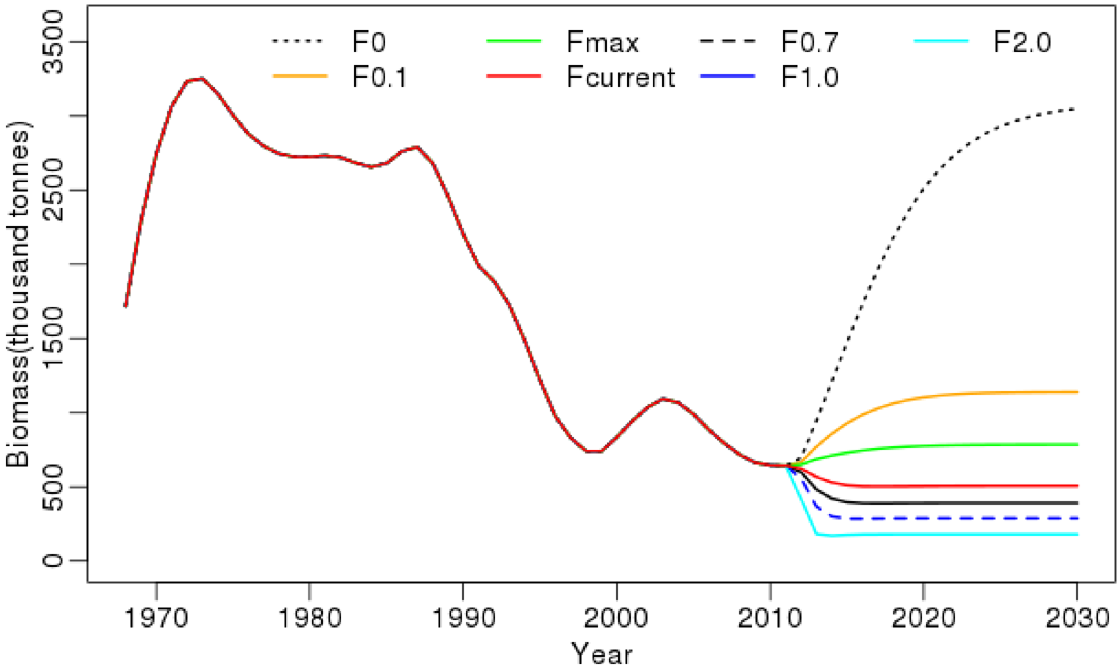

Figure 18. Forward projections of Nile perch biomass in Lake Victoria based on different fishing mortality levels.

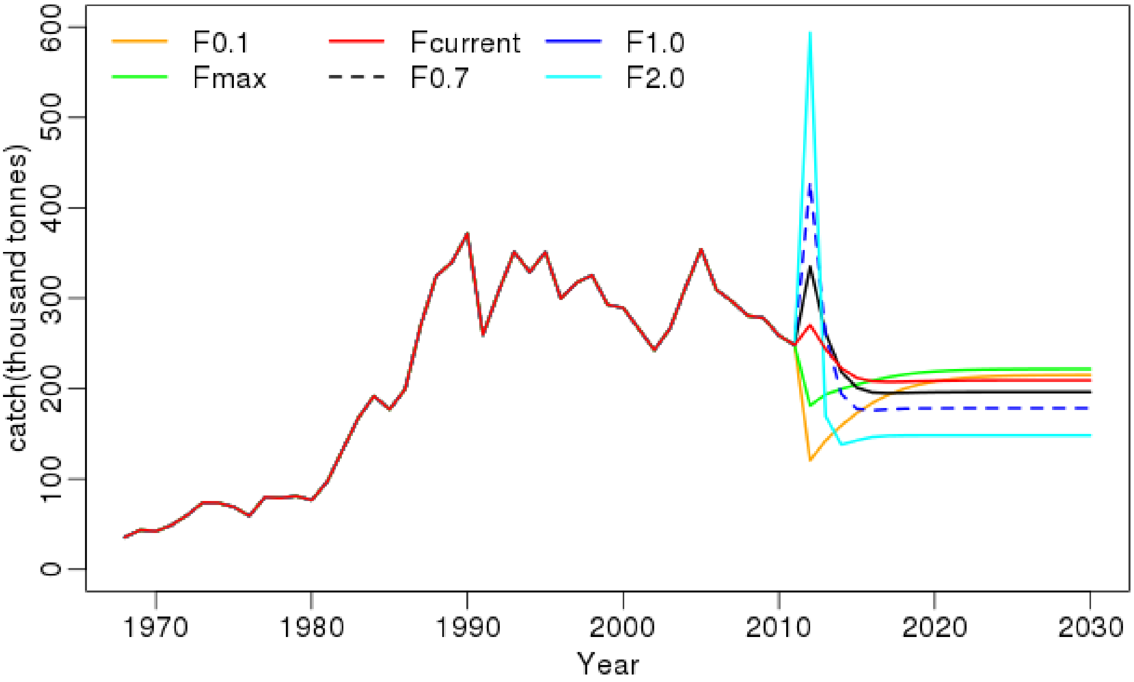

Figure 19. Catch predictions for Nile perch of in Lake Victoria based on different fishing mortality levels.

5 DISCUSSION

The present study used Gadget to generate a population model for Nile perch in Lake Victoria. There were minimal inconsistencies between the simulation models and real data confirming the reliability of the developed model. It therefore presented a unique opportunity into exploring the development of the species stock over the years as well as modelling future trends. Gadget has been successfully used previously to assess fish stocks and population dynamics in Icelandic waters, the Barents Sea, the North Sea and the Irish and Celtic Seas (Begley 2005). The model was run with a set of assumptions. Due to lack of age-structured data, growth was assumed to be constant through time. Initially, growth parameters were estimated by fitting a von Bertalanffy growth curve to the available data, assuming mean lengths at age have a CV of 15%. Recruitment was also estimated in 3-year blocks from 1968 to 2000. This was because of the high variability in recruitment exhibited between successive years in the initial run. It was however estimated annually as from the year 2000 due to the availability of survey data in recent years. The weights of likelihood components used in the Nile perch model were assigned using expert knowledge. These were allocated based their temporal and spatial spans. The effect of environmental change on the stock was not incorporated in the model predictions.

Findings on growth of the species indicate that it is long lived, attaining size at 50% maturity (Lm50) during third and fourth years of growth for males and females respectively. Males dominate the adult sex ratio. This might be a consequence of applying disproportionate pressure on females which generally grow to bigger sizes than males (Njiru *et al*. 2009). Selection bias of fleet against one sex might alter the population structure of the species which could have adverse effect on the sustainability of a fishery (Kendall *et al*. 2009, Rodhouse 1998). Disturbing the natural sex ratio may compromise the reproductive potential of a fishery. As noted by Rochet (1998), rigorous studies on the effects of different exploitation strategies on the population should be incorporated into stock assessments. Such studies are necessary to guide management and exploitation of Nile perch in Lake Victoria. There is limited information on aging of the species due to lack of studies on hard body parts such as otoliths (Taabu 2004). Even so, the estimated age parameters were in agreement with those documented in Kitchell and Schindler (1997) and hence satisfactory for the stock assessment model employed in this study. The computed Growth parameters L_∞ and K were comparable with those estimated in other studies (Ojwang *et al*. 2011).

Although there is scarcity of survey data, available survey indices spanned most of the Nile perch post introduction era. All the modelled indices mimicked data really well with minimal discrepancies. CPUE index gave the best fit to data and also covered most the study period. Landings from the commercial fleet reflect the change of selection pattern following the introduction of the slot size restrictions. The inception restrictions lead to landing of bigger sized fish. All available length distributions from trawl surveys are from the period after the inception of the slot size regulation. These distributions show a population dominated by small sized individuals a probable indication of growth overfishing.

The resultant model indicates that Nile perch biomass increased after its introduction into the lake, peaking prior to 1980. Trawl surveys conducted during that period showed that the species comprised more than 80% of total catch (Goudswaard *et al*. 2011), a totally different scenario from years earlier when it accounted for 1% of total biomass (Kudhongania and Cordone 1974). The peak, which was about three million tonnes probably, represented unsustainable accumulated stock. Biomass growth levelled off and then started to decline, even though fishing mortality was very low at the time. Afterwards, with development of the fishery, fishing mortality increased exponentially. Even so, biomass remained relatively high and constant until about 1989 when a rapid decline in biomass was witnessed. At this point probably the maximum sustainable yield (MSY) had been exceeded. The stocks continued on the downward trend until they were at the lowest in the years 1999 - 2000. Worried by the declining catch rates, riparian states, through the Lake Victoria Fisheries Organizations put in place management measures to save the Nile perch. Trawling was banned (Mbuga and Getabu 1998) and slot size restrictions were introduced (Njiru *et al*. 2009). There was an immediate reduction of fishing mortality and biomass increased. The effect was however short-lived as the trends reversed after 2005. The introduction of the stated management measures had enormous effects the population structure of the species. Spawning stock biomass reduced drastically. From the findings of this study it can be seen that selection pattern changed considerably as from 2002, after which bigger fish in the population were targeted. Size selective removal of bigger fish from the population could have led to the reduction of the spawning stock. This could have far reaching effects on the future fishery as its renewal potential is consistently reduced.

YpR analysis can be used to test alternative management strategies when historical information on recruitment for the fish population being studied is limited (Chen *et al*. 1998) like in Lake Victoria. A YpR model assesses changes in cohort biomass by balancing the growth in weight of its individuals against loss in biomass due to mortality. In this study, it was used to determine fishing rate F_{max} that optimizes yield per recruit for the current and old selection patterns as well as the yield at a precautionary approach by maintaining fishing mortality at $F_{0.1}$. According to Cadima (2003) the ultimate goal of fisheries management is to have a fishing level that allows bigger catches in weight while at the same time ensuring conservation of the stocks. He argues that extreme values of biomass or fishing level have catastrophic effects on self-rejuvenation of the stock. In the Nile perch case in Lake Victoria the estimated current fishing mortality is way beyond the optimum levels while standing stock is relatively low. In such situation any deliberate attempt to decrease fishing mortality will result in better YpR and increase the standing stock as well as the SSB/R. To achieve maximum YpR, for the Nile perch in Lake Victoria, fishing mortality should be reduced by almost 40%. Operating beyond F_{max} is quite precarious and may lead to undesired outcomes like growth overfishing might manifest. Another advantage of F_{max} reference point is that it yields near maximum yield per recruit with significantly less effort (Cadima 2003). The current selection pattern (slot size) results at higher YpR and SSB/R than the old one. Raising the slot size will further increase the YpR and SSB/R.

Future simulations of stock status and catch were done at different fishing mortalities assuming constant recruitment. If the current levels were maintained, both biomass and catches would decrease and stabilize at lower levels in the long term. The same scenario could be observed but with more severity if effort would be increased. Deceptively there will be an initial increase in total landings before plunging below the current levels. This of course will decrease catch per unit effort and reduce yield per recruit as observed earlier. Consequently, there will be less and less returns from the fishery with time. On the other hand, if fishing was to be conducted at F_{max} or $F_{0.1}$ the stocks will rejuvenate with the latter leading to a much higher standing stock in the long term. At $F_{0.1}$ biomass will increase more than two times in less than eight years. Taking such an option has severe consequences on catch in the short term. The landings will drop by near half before steadily picking up. At the surface it might look that this will lead to loss of revenue from the fishery. Realistically, the concealed benefits are much more than of the contrary options. Reducing fishing mortality to from the current to F_{max} will in the long term end up with more yields with much less effort. The catch per unit effort will increase making the fishery much profitable.

Currently there are gear restrictions and slot size enforcement in the Nile perch fishery (Njiru *et al*. 2009). As observed from the fishery development trends these efforts have not reduced the fishing mortality significantly. The introduction of slot size and banning of trawler in the lake reduced fishing mortality initially, but shortly afterwards it increased again. These size and gear restrictions don’t limit the amount of fish caught i.e. there no limits on the total intensity of use of the allowable gears fishers use to catch fish. Like any other fishery Nile perch in Lake Victoria are limited, and failure to control fishing mortality will lead to the stock collapse.

6 CONCLUSIONS AND RECOMMENDATIONS

The present study demonstrates the ability of Gadget to handle diverse data sets to generate biologically sound and realistic fish population models. The present study used the available data from Lake Victoria to model historical trends as well predict future stocks at different exploitation levels. The simulated model fitted well with survey indices. It is therefore recommended that fishery dependent and independent data collection be continued for future stock assessments.

Results showed that the introduction of the slot size regulation impacted on the selectivity of the commercial fleet. Although it resulted in the increase mean size of land fish, it has not resulted in neither in increase in total landing nor biomass. A drastic decrease of the spawning stock proportion was witnessed after the slot size regulation was established. The effect of the regulation on the population structure needs further investigation.

The modelled population show that stocks were remarkably high prior to the 1990s. Afterwards, they exhibited a sharp decline hitting a record low in the 2000. Since then stocks have recovered. The drop in biomass was not reflected in catches, which were maintained by increasing fishing mortality.

Yield per recruit results show that the current fishing mortality of 0.53 is way beyond the optimum for maximum yield $F_{max} = 0.21$. Consequently, the exploitation level is quite inefficient. To attain an optimum yield, it is recommended to reduce the fishing mortality to F_{max}.

Future predictions show a further decline in biomass and catch if the current fishing levels were to be maintained. Any increase in fishing mortality exacerbates the situation. However reduction of mortality to either F_{max} or $F_{0.1}$ will improve stocks and catch in the long term, with the latter predicting higher benefits.

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To God be the Glory

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APPENDICES

Appendix 1: Input parameters for the first run of the Nile perch Gadget model

Linf	250	200	300	0
k	66.898616	0.1	120	0
bbeta	0.016427495	0.001	25	0
ic02	13.084849	0.001	25	1
ic03	23.710678	0.001	25	1
ic04	13.387414	0.001	25	1
ic05	1.2965187	0.001	25	1
ic06	15.286001	0.001	25	1
ic07	7.453283	1e-05	25	1
ic08	1.5271348	1e-05	25	1
ic09	19.651214	1e-06	25	1
ic10	18.153823	1e-06	25	1
ic11	22.126796	0.001	25	1
ic12	22.543954	0.001	25	1
ic13	5.8517649	0.001	25	1
ic14	20.919769	0.001	25	1
rec1968	10.035731	0.004	15	1
recl	8.2868068	0.5	40	0
recsdev	9.6203135	0.01	10	0
rec1969	6.967805	0.004	15	1
rec1970	1.8450302	0.004	15	1
rec1971	1.6895353	0.004	15	1
rec1972	7.912188	0.004	15	1
rec1973	3.1400767	0.004	15	1
rec1974	4.0155836	0.004	15	1
rec1975	6.6040312	0.004	15	1
rec1976	7.2738682	0.004	15	1
rec1977	5.4711805	0.004	15	1
rec1978	3.0805226	0.004	15	1
rec1979	9.0099927	0.004	15	1
rec1980	10.23778	0.004	15	1
rec1981	12.442316	0.004	15	1
rec1982	10.134402	0.001	15	1
rec1983	14.621659	0.004	15	1
rec1984	11.53597	0.004	15	1
rec1985	12.557784	0.004	15	1
rec1986	7.2424823	0.004	15	1
rec1987	9.1552863	0.004	15	1
rec1988	1.2364904	0.004	15	1
rec1989	0.527988	0.004	15	1
rec1990	4.6124844	0.004	15	1
rec1991	2.0037178	0.004	15	1
rec1992	5.6658926	0.004	15	1
rec1993	3.0152703	0.004	15	1
rec1994	3.4739762	0.004	15	1
rec1995	9.1795756	0.004	15	1
rec1996	4.9641056	0.004	15	1
rec1997	7.3392386	0.004	15	1
rec1998	10.256506	0.004	15	1
rec1999	14.999792	0.004	15	1
rec2000	14.999276	0.004	15	1

rec2001	4.6254606	0.004	15	1
rec2002	0.2804184	0.004	15	1
rec2003	14.999744	0.004	15	1
rec2004	9.4990879	0.004	15	1
rec2005	1.7408638	0.004	15	1
rec2006	5.6817692	0.004	15	1
rec2007	8.9383036	0.004	15	1
rec2008	6.9995403	0.004	15	1
rec2009	11.464076	0.004	15	1
rec2010	3.7095485	0.004	15	1
rec2011	4.3448248	0.004	15	1
alphacomm	0.062066008	0.03	10	1
L50comm	39.967253	20	60	1
p0sur	0	0	1	0
p1sur	3.371053	0	10	1
p2sur	1	0	2	0
p3sur	0.18784166	0	10	1
p4sur	1.8921864	0	10	1

Appendix 2: Input parameters for the second run of the Nile perch Gadget model

switch	value	lower	upper	optimize
Linf	250	200	300	0
k	66.898616	0.1	120	0
bbeta	0.016427495	0.001	25	0
ic02	3.3508127	0.001	25	1
ic03	24.999829	0.0001	25	1
ic04	24.999366	0.0001	25	1
rec196870	4.1524484	0.01	20	1
recl	10.340967	0.5	40	1
recsdev	9.6378179	0.01	10	1
rec197173	1.9808256	0.01	20	1
rec197476	8.8404501	0.01	20	1
rec197779	5.7120389	0.01	20	1
rec198082	6.0095562	0.01	20	1
rec198385	12.844039	0.01	20	1
rec198688	1.6798194	0.01	20	1
rec198991	10.666596	0.01	20	1
rec199294	0.79255231	0.01	20	1
rec199597	11.114823	0.01	20	1
rec1998	19.999407	0.01	20	1
rec1999	19.865392	0.01	20	1
rec2000	7.4389735	0.01	20	1
rec2001	7.7240495	0.01	20	1
rec2002	1.5215892	0.01	20	1
rec2003	2.4676871	0.01	20	1
rec2004	12.390066	0.01	20	1
rec2005	5.8277729	0.01	20	1
rec2006	0.36554038	0.01	20	1
rec2007	10.741768	0.01	20	1
rec2008	4.739927	0.01	20	1
rec2009	12.513097	0.01	20	1
rec2010	2.1944715	0.01	20	1
rec2011	4.7357698	0.01	20	1
alphacomm	0.10428441	0.1	1	1
comm1968L50	25.878557	20	60	1
comm2002L50	50.001002	50	80	1
p0sur	0	0	1	0
p1sur	3.0603457	0	10	1
p2sur	1	0	2	0
p3sur	0.15914125	0	10	1
p4sur	1.3338938	0	10	1
aFebSur	0.75088086	0.1	1	1
lFebSur	1.3330385	0	10	1

aAugSur	0.73569235	0.1	1	1
lAugSur	0.0002195832	0	10	1
acpue	1	-9999	9999	0
lcpue	1	-9999	9999	0