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A Holistic Bioeconomic Assessment of the Lake Koka Fishery (Ethiopia): Implications for Management and Livelihood

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Abstract

The fishery resource in Lake Koka is very important for food and nutrition security, and livelihoods of many riparian communities. Proper resource utilization is very essential to sustain the benefits of this natural capital for the present and future generations. So far little is known about the state of the fishery in Lake Koka. Therefore, the study aims at combining stock assessment of fishery target species of the Lake Koka with an economic analysis to find out if current exploitation levels are biologically and economically sustainable or need adjustment. Biomass dynamic models (equilibrium and non-equilibrium), bioeconomic model and the Thompson and Bell model were applied to estimate reference points related to Maximum Sustainable Yield (MSY), Maximum Economic Yield (MEY) and their corresponding efforts (f_{MSY} & f_{MEY}). While the reference points estimated using the length-based Thompson and Bell predictive model were not significantly different from the non-equilibrium model, the former model provided a more flexible estimate than the other models. As none of the models tested suggested overfishing of the target resources, I conclude that the general state of the Lake Koka fishery is healthy, but see scope for improvement in terms of socioeconomic benefits if the current minimum length of capture were increased toward the length of capture at MEY.

Keywords: Biomass dynamic model, fisheries management, length-based analytical model, reference points, small-scale fishery, stock assessment.

Introduction

Many coastal and riparian populations, particularly in developing countries, are highly dependent on fisheries for their food supply and livelihoods. This small-scale fishery is characterized as artisanal – which is generally assumed to be both cleaner and more efficient than industrial fisheries (UNEP, 2005). However, given climate change, human population growth and limited alternative livelihoods, artisanal fisheries could also cause overfishing and may pose a significant impact on the ecosystem as a whole, unless the resource is managed properly based on scientific advice. Evidences show that the global capture fishery production has been declining since the late 1980s, and many fish stocks are believed to be overfished and some even to have collapsed (Pauly, 1998; FAO, 2010). It is therefore, essential to assess and manage resources to maximize the benefits to both the present and future generations. The issue of sustainability has been advocated by many national and international organizations, and maximum sustainable yield (MSY) has become the agreed upon management target of the United Nations Convention for the Law of the Sea (UNCLOS, 1982). FAO further formulated the code of conduct in the mid 1990s, where it is stated in Article 7 that “States and all those engaged in fisheries management should adopt measures based on the best scientific evidence available and be designed to ensure the long-term sustainability of fishery resources at levels which promote the objective of their optimum utilization and maintain their availability for present and future generations” (FAO, 1995).

However, some scientists and economists argued that MSY and its corresponding level of effort (f_{MSY}) should not be used as a management target as the fishery-induced mortality would already be too high at this level of fishing, and as the concept of MSY neglected entirely the cost of production. It thus advised that fisheries management should take into account both the state of exploited stocks and the cost of exploitation. For this reason, maximum economic yield (MEY) and its corresponding level of effort (f_{MEY}) were put forward as management target. The present study therefore aims at finding out if, under the current level of exploitation, the target fish stocks in Lake Koka are sustainably fished based on those reference points. Two alternative methods have often been used for assessing the dynamic response of fish populations to exploitation: (1) biomass dynamic models, and (2) analytical age/length-structured models (Hilborn & Walters, 1992). I thus want to explore this question using both approaches, and adding on top an integrated bioeconomic analysis for the calculation of the biological and bioeconomic reference points for the Lake Koka fishery.

Materials and Methods

Description of study area

The tropical Lake Koka is located in the Ethiopian Rift Valley (08°23’22” N; 39°05’15” E) at an altitude of 1590 m above sea level, which is about 90 km southeast of Addis Ababa. It has a surface area of about 255 km^2 with a maximum and mean depth of 14 m and 9 m, respectively (LFDP, 1997). Water in- and outflow of the lake is mainly regulated by the River Awash. In addition, the River Mojo may also contribute to the inflow during the rainy season. Lake Koka is among the most important lakes for the Ethiopian fishery and contributes about 7% to the total fish supply in the country (Gashaw Tesfaye & Wolff, 2014). Its fishery is mainly artisanal and the target fish species include Nile tilapia (*Oreochromis niloticus L.*), African catfish (*Clarias gariepinus B.*), common carp (*Cyprinus carpio L.*), and barbs (*Labeobarbus intermedius R.*). The common fishing gears used in Lake Koka include beach seines, gillnets, and long lines (Gashaw Tesfaye & Wolff, 2015).The different gears have different catch efficiencies and modes of operation. Effort therefore needs to be standardized and/or a common measure of effort like boat fishing days (e.g. Puga et al., 2005), number of fishermen or man days (e.g. King, 2007) should be used. Here I used boat days as a common measure of effort for all gears.

Source of data and data analysis

Time series catch and effort data (from 2002 – 2012) and length frequency data (from 2007 – 2012) were obtained from the National Fisheries and Aquatic life Research Center. Economic data (fish price and cost of fishing) were collected during a field work conducted from October 2012 – March 2013 from key informants such as heads of the fishery associations, senior fishermen and the local fishery expert (Table 1). For stock assessment, biomass dynamic models (equilibrium and non-equilibrium) and the Thompson and Bell Y/R model were applied to estimate reference points related to Maximum Sustainable Yield (MSY) and the corresponding effort (f_{MSY}). Bioeconomic analysis gave estimates of Maximum Economic Yield (MEY) and the corresponding effort (f_{MEY}). Using the results of a cohort analysis (CA) from Gashaw Tesfaye (2016) as an input for the Thompson and Bell model, I also predicted the effect of different management measures on future yields, value of the catch and stock biomass levels.

Bioeconomic model

The bio-economic model was used to analyze the revenue, costs of effort and profits or resource rent of the fishery. The required input parameters include price of fish per kilogram and unit cost of fishing (Table 1). Then, the total revenue (*TR*) at the given effort from the fishery was computed following Flaaten (2011) as the product of the total quantity harvested and mean price of fish per kilogram. The price of fish varies along the different market channels, but here I considered only the price of fish at landing sites where the fishermen directly sale their harvest to consumers or other market actors. The mean annual price of fish adjusted for inflation was used for this analysis. I further computed the average revenue per unit of effort (*AR*) and the marginal revenue (*MR*), which shows the change in total revenue due to a small change in effort and is calculated as:

$$MR_{(f)} = \Delta TR_{(f)} \big/ \Delta f \quad (1)$$

For the cost analysis, each additional unit cost of effort is assumed to be constant and the fishing crafts are assumed to be homogenous as almost all the fishermen use small wooden boats (1.4 m wide by 4 m long on average). As I did to the total revenue of the fishery, total cost (*TC*) is also expressed in a simple function of effort and computed as a product of the unit cost of effort and the total effort. To determine the maximum economic yield (*MEY*) and its corresponding effort (f_{MEY}), I then calculated the average cost (*AC*) of effort as the total cost divided by effort, and the marginal cost (*MC*) which shows the change in total cost as a result of a small change in effort was calculated in analogy to equation (14) as:

$$MC_{(f)} = \Delta TC_{(f)} \big/ \Delta f \qquad (2)$$

The equilibrium profits also called resource rent (π) from the fishery can be described as both as a function of stock size and effort (Foley *et al.*, 2012). So, rent (π) from the fishery expressed as a function of effort was computed as:

$$\pi_{(f)} = TR_{(f)} - TC_{(f)} \qquad (3)$$

According to Gordon (1954) and Flaaten (2011) rent or profit can be maximized as:

$$\frac{\Delta \pi_{(f)}}{\Delta f} = \frac{\Delta TR_{(f)}}{\Delta f} - \frac{\Delta TC_{(f)}}{\Delta f} \qquad (4)$$

Thus, the maximum economic yield, *MEY* appears at a point where *MR* equates *MC*, and the corresponding effort of *MEY* is considered as f_{MEY}.

Results

Fish catch trends

The catch trend analysis showed an interannual fluctuation of the overall yield with a peak reaching 841 t in 2007 and a downward trend (negative slope) afterwards (Fig. 1 A). The mean annual catch composition also varied slightly over the decade and the contributions of *O. niloticus, C. gariepinus, C. carpio* and *L. intermedius* ranged from 31 – 47 % (mean = 40 %), 37 – 49 % (mean = 42 %), 13 – 19 % (mean = 16 %), and only 1 – 4 % (mean = 2 %), respectively (Fig. 1 A). All the landed catches were mainly fished with gillnets, beach seines and longlines, whereby 60% of the landings came from beach seines, 23% from gillnet and the remaining 17% from longline fisheries. The catches of longlines were solely comprised by *C. gariepinus*, whereas beach seines and gillnets were unselective toward these target species. Fishing effort increased from 9016 boat days in 2003 to 30805 boat days in 2007 which also resulted in a general increase in yield until 2007, but gradually decreases as the CPUE did. Overall the total landings seem stable following the historical peak in 2007 and fluctuated annually between 483 t and 644 t (Fig. 1 A).

Table 1: Fishing costs for target species in Lake Koka (the local currency was converted into US $ using the mean exchange rate: 1 $ = 12.616 Birr)

No.	Description of cost components	US $	Remark
1	***Fixed cost (FC)***		
	Average price of a boat	317.06	
	Average price of a standard beach seine (BS)	396.32	
	Depreciation (D) for capital assets	217.98	D equals capital cost of boat plus BS
	Capital cost for a boat = cost of a boat/6yrs	118.90	Life span of a wooden boat = 6 years
	Capital cost for a BS= cost of a BS/4yrs	99.08	The mean life span of a BS = 4 years
	Interest on investment	49.94	Interest on investment refers cost of a loan or opportunity cost on own capital. I assumed 50 % capital comes on loan (rate = 9 %) and 50 % from saving (rate =5 %)
	Total	267.91	D + interest on investment
2	***Variable (operating) costs***		
2.1	Beach seine (BS) operating cost		
	BS maintenance (3 %)	11.89	
	Opportunity cost of labor for BS fishery: 63.41 Birr*12 m *3 persons	2282.76	
	Subtotal	2294.71	
2.2	Gillnet (GN) & Longlines (LL) operating cost		The GN & LL data are aggregated together as they often used the same boat
	Price of a standard GN	63.41	
	GN maintenance (10 %)	6.34	
	Price of a standard LL	39.63	
	LL maintenance (10 %)	3.96	
	Opportunity cost of labor for GN & LL fishery: $ 63.41 Birr*12 m*2 person	1521.84	
	Subtotal	1635.22	
2.3	Boat repair (3 %)	9.51	
2.4	Miscellaneous (e.g. plastic bags, sacks, etc)	15.85	
	Total	3955.29	
3	*Unit cost of fishing per year* [a]	4179.61	
4	***Cost of fishing per unit of boat day*** [b, c]	**14.79**	

[a] Unit cost of fishing per year for *O. niloticus, C. carpio and L. intermedius;* note that it excludes the cost of longlines and their maintenance cost.

[b] Unit cost of fishing per boat day for *O. niloticus, C. carpio and L. intermedius* calculated as annual unit cost of fishing divided by 282 days, which is the mean annual fishing days calculated from the annual catch records.

[c] The unit cost of fishing for *C. gariepinus* equals $ 4223.21/year or $ 14.95/boat day as it includes the cost of longlines and their maintenance costs.

Biomass dynamics under equilibrium condition

Application of the different biomass dynamic models gave slightly different estimates of MSY and f_{MSY} values. Using the aggregated catch (all species combined) and effort data, the Schaefer model estimated MSY of 702 t/year and corresponding f_{MSY} at 21423 boat days, while the Fox model estimated a slightly lower MSY of 670 t/year but higher f_{MSY} value at 24917 boat days (Fig 1 B). However, the Fox model gave a better fit than the Schaefer model. The results also suggested that the observed mean annual yield (602 t) and level of fishing effort (18272 boat days) did not exceed these management reference points obtained using both models except in few occasions (e.g. 2006 – 2007) indicating overfishing was not occurring and it rather suggested that there is a slight room for expansion of exploitation as the overall mean yield and effort was still below these calculated reference points.

Similarly the two surplus production models (Schaefer and Fox) fitted for the different fish species separately gave different estimates of MSY and f_{MSY} values except for *C. carpio* and *L. intermedius* whose MSY estimates were very similar (Fig. 1 C and D). Both models estimated significantly higher MSY for *O. niloticus* and *C. gariepinus* than for *C. carpio* and *L. intermedius* but the Fox model gave a better fit for all species. Nevertheless, the level of effort required to sustainably exploit the two large species (*C. gariepinus* and *C. carpio*) was not significantly different (Fig. 1 C and D).

Bioeconomic analysis

As the Fox model gave a better fit to the data, further bioeconomic analysis using this model showed that the estimated MEY and f_{MEY} value of all target species combined were 618 t (valued as $ 685901) and 16200 boat days, respectively (corresponding to the point where the marginal revenue equates to the marginal cost, Fig. 1 B). It should also be noted that these values are smaller than the commonly used management reference points MSY and the corresponding effort (f_{MSY}). In addition, the results revealed that the total cost ($ 242172) at this level of effort (f_{MEY}) was less than half of the total revenue (Fig. 1 B) suggesting that the overall Lake Koka fishery was very profitable during the period considered. Moreover, the open access equilibrium or breakeven point occurs at the point where the average revenue equates the average and marginal cost, and the effort at this point (f_{OA}) is still higher than the value of f_{MSY}.

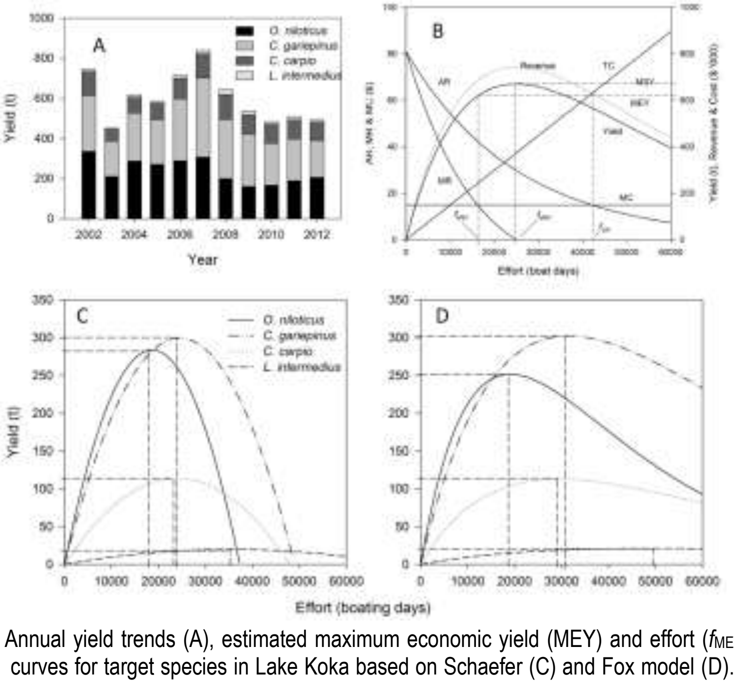

Fig. 1. Annual yield trends (A), estimated maximum economic yield (MEY) and effort (f_{MEY}) levels (B), sustainable yield curves for target species in Lake Koka based on Schaefer (C) and Fox model (D). The dashed lines indicate the estimated MSY, MEY, f_{MSY} and f_{MEY} values for targeted fish stocks s. Abbreviations: f_{OA} = effort at open access equilibrium, AR = average revenue, MR = marginal revenue, TC = total cost and MC = marginal cost.

Looking at the economics by species separately also gave different estimates of MEY and f_{MEY} values. For instance, the estimated MEY and f_{MEY} for *O. niloticus* were 217 t (valued as $ 343959) and 10500 boat days, and for *C. gariepinus* 185 t (valued as $ 204908) and 9600 boat days, respectively. In addition, the total costs of the two species (*O. niloticus* and *C. gariepinus*) were less than the total revenue suggesting that the fishermen earn resource rent from their fishery. Whereas the estimated MSY and f_{MSY} for *C. carpio* were 113 t (valued as $ 98467) and 29378 boat days, and for *L. intermedius* were only 21 t (valued as $ 18565) and 49336 boat days, respectively. However, the total cost of both species (*C. carpio* and *L. intermedius*) outweighed the total revenue suggesting that their fishery would not be profitable, if the fishermen were only targeting these two species.

Time- series fitting under non-equilibrium condition

The estimated MSY and f_{MSY} were 211 t and 12654 boat days for *O. niloticus*, 266 t and 20953 boat days for *C. gariepinus*, 104 t and 24357 boat days for *C. carpio*, and 30 t and 62047 boat days for *L. intermedius*, respectively. These results suggested that unlike the commonly used biomass dynamic model under equilibrium condition, the time-series fitting using the non-equilibrium condition gave a more conservative estimate of MSY and f_{MSY} values for all species except *L. intermedius*. Nevertheless, the overall mean annual catch was still lower than the estimated maximum yield using the biomass dynamic model that assumed non-equilibrium condition suggesting not overfishing yet, but the result indicated a state of full exploitation.

Thompson and Bell predicted yield

Simulation results of target species explored using the Thompson and Bell prediction model with different F-factors below and above the present *F* level indicated that the present *F* level (F- factor = 1) doesn't seem to provide optimum yield for all target fish species considered (Fig.2 left). It allowed the exploitation of about 55 % of the virgin biomass (B_o) for *O. niloticus*, 47 % for *C. carpio*, and 53% for *C. gariepinus*. In addition, it was revealed that in all cases the MSY would not be realized within a realistic range of *F* values and hence, the $F_{0.1}$ was calculated. Accordingly, the estimated MSY for *O. niloticus*, *C. carpio*, and *C. gariepinus* were 250, 121 and 282 t with F-factor that equates $F_{0.1}$ at 1.2, 1.8 and 1.6, respectively, suggesting a need to increase the present *F* value by 20 %, 80 % and 60 %, respectively (Fig. 2 left). However, the F-factor that give the maximum economic value for *O. niloticus*, *C. carpio* and *C. gariepinus* were estimated at 1.0, 1.4 and 1.0, respectively, suggesting that economically, the current exploitation of *O. niloticus* and *C. gariepinus* had already reached optimum level, while the *C. carpio* exploitation level could be increased by 40%. At these levels of *F*, the predicted MEY and values for *O. niloticus*, *C. carpio* and *C. gariepinus* were about 239 t and $ 169000, 112 t and $ 144000, and 242 t and $ 728000, respectively.

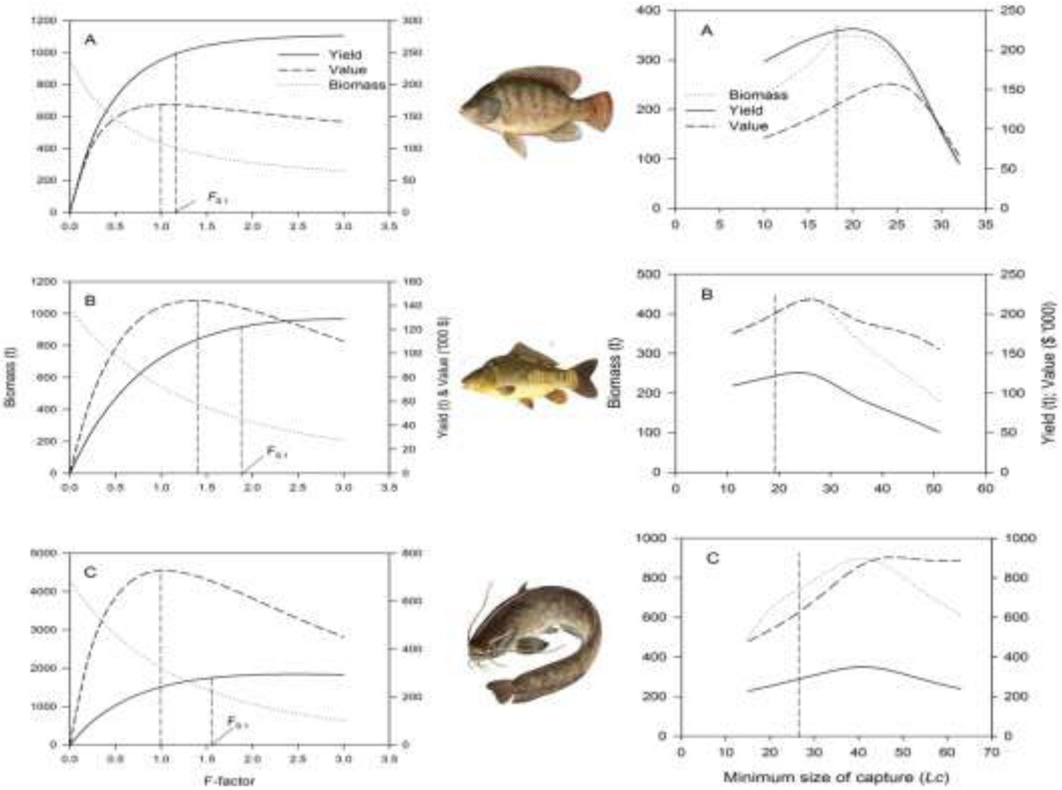

Fig. 2. Predicted biomass, yield and values for target species: a) *O. niloticus*, b) *C. carpio* and c) *C. gariepinus* in Lake Koka using different F-factors (left) and minimum length of capture (*Lc*) (right). The vertical dash lines show the current level of F-factor and level of $F_{0.1}$ (left), and the current *Lc* (right).

A similar simulation run, keeping the present *F* constant but changing the minimum size of capture (*Lc*) for these target species, indicated that the present size of capture doesn't seem to provide the optimum yield either, for all the three target fish species considered (Fig. 2 right). It is also revealed that reducing the minimum size of capture (e.g. by reducing mesh size) would not increase yield and economic value of the fish catch either. Instead, the optimum size of capture and the sizes that give the maximum economic yield were estimated at 20 and 24 cm for *O. niloticus*, 23 and 27 cm for *C. carpio* and 39 and 45 cm for *C. gariepinus*, which are both above the present minimum size of capture (Fig. 2 right). The corresponding MSY and B_{MSY} values were 227 and 349 t for *O. niloticus*, 126 and 438 t for *C. carpio*, and 348 and 893 t for *C. gariepinus*, while the predicted MEY values were about $ 157000, 218000 and 900000, respectively.

Discussion

Assessing the states of fish stocks is essential for the elaboration of measures for their sustainable use. Underexploitation may result in loss of potential socioeconomic benefits (e.g. Hilborn & Walters, 1992; Anderson et al., 2012), whereas overexploitation negatively impacts both the socioeconomic benefits and the sustainability of the stock per se, and might eventually lead to stock collapse and destabilization of the entire ecosystem.

Inter-annual catch fluctuations in longer time series have been used to describe the state of the fishery particularly when only catch data are available. For instance, the fraction of the catch relative to the historical maximum has been widely used as a catch-based measure of fishery status (Froese & Kesner-Reyes, 2002; Worm et al., 2006; Pauly, 2007). A fishery may thus be classified as underdeveloped, when the catch level corresponded to < 10 % of the historical peak, and developing if it was 10 – 50 % of the maximum reached. However, it is considered fully exploited, when the catch oscillated above 50 %, but it is considered as overfished, when the catch falls down to 10 – 50 % of the maximum and collapsed when it falls below the 10% level following the maximum recorded. Accordingly, the state of Lake Koka fishery can be qualified as full exploitation, as catch levels never fall below 50 % of the historical peak in the time series (Fig. 1 A). This general observation is substantiated by the reference point estimates of our study which suggest that none of the target species has yet been overfished (Figs. 1 and 2).

The most popular fisheries objectives commonly found in fisheries legislation and international agreements include: (a) maximization of biological production (referred as MSY), (b) economic efficiency or resource rent (referred as MEY), (c) social benefits like employment, income distribution and food supply, and (d) avoidance of conflicts (Mardle et al., 2002; Hilborn, 2007). However, these objectives are at times contradicting each other and become difficult to achieve all simultaneously. For instance, considering MSY rather than MEY as a management target would increase production or catch volume and might seem favourable, if the management objective is maximization of biological production and increasing food supply for the fishermen and the society rather than achieving economic efficiency. Nevertheless, a reduction in fishing effort to achieve MEY is considered a better management target than MSY (e.g. Gordon, 1954; Clark, 2006). It increases the benefit –to-cost ratio of the fishermen and leads to a decrease in fishing intensity and- mortality (Fig. 1 B - D). This allows for a more rational maximization of long-term profits and conservation of the target fish resources.

The results of both the equilibrium and non-equilibrium models clearly showed that *L. intermedius*, while of lowest importance of all target stocks in terms of catch volume and economic value, would require a high level of effort to exploit it at its MSY level (Fig. 1 D). Since its contribution only represents < 5 % to the total landings (Fig. 1 A), it doesn’t seem feasible and rational to go for its maximization since at this high fishing effort the other valuable species would be heavily overexploited with the consequences of huge economic losses and stock collapse. The crucial question then arises, how all target resources of a multispecies or mixed fishery could be harvested at their level of MSY simultaneously, knowing that the different target species have different level of f_{MSY} as shown in Fig. 1 C & D. As suggested above, the harvest management may focus on the levels of effort that allow for a sustainable and more profitable harvest of the most productive target species (e.g. *O. niloticus* and *C. gariepinus*) than the less productive ones (e.g. *L. intermedius*). The resulting underexploitation of *L. intermedius* would lead to an increase in its abundance, and since it is an important prey species for *C. gariepinus*, this species would benefit. In addition, the *O. niloticus* population and fishery should also benefit through the resulting reduction in predation pressure as Elias Dadebo et al. (2014)

reported that *O. niloticus* and *L. intermedius* are known to be two common prey species for *C. gariepinus* in Lake Koka and other freshwater systems. In fact, the balanced harvest strategy considered as a new paradigm shift in fisheries management (e.g. Garcia et al., 2012; Law et al., 2013; Kolding & van Zwieten, 2014) is also favouring fisheries harvest intensity to be proportional to the productivity of target resources.

In addition, the biomass dynamic model that assumes non-equilibrium condition shows that the three most productive species (*O. niloticus, C. gariepinus* and *C. carpio*) are not in a state of overfishing and of the three species, *C. carpio* shows room for expansion of exploitation, which is in agreement with the models that assume equilibrium condition including our analytical length-based simulation model (Fig. 2). The only exception is that the non-equilibrium model gave a higher estimate of MSY than the equilibrium models for *L. intermedius*. While both models assume catch per unit effort (CPUE) as an abundance index, it is not clear what causes this difference.

Our findings suggest that none of the current minimum size of capture for the different target species provide the MSY and MEY (Fig. 2 right). Instead, yield and economic benefit for the target species would be maximized, if the mesh size of the nets and hook sizes of longlines were increased, which is in agreement with cohort analysis results reported by Gashaw Tesfaye (2016) and the stock assessment study by Gashaw Tesfaye and Wolff (2015). In addition, our simulation results clearly show that reducing the current minimum size of capture (Lc) will neither maximize yield nor economic benefits (Fig. 2 right). Our result also suggests that the value of Lc that gives the maximum yield (referred here as length of capture at MSY – L_{MSY}) in all the three target species (Fig. 2 right) is always < the size at first maturity (L_{m}) values for the respective species (see Gashaw Tesfaye et al. (2016) for L_{m} values). This also holds true for the Lc values that give the maximum economic benefit (referred here as length of capture at MEY – L_{MEY}), but this size is always > L_{MSY} and closer to $L_{\mathrm{m.}}$ Therefore, as sizes close to the L_{m} values proved to offer the highest economic benefit without significantly reducing the overall yield, targeting this size (L_{MEY}) seems the best approach. This is contrary to those who recommend harvesting at the optimum length of capture (L_{opt}) – which is usually greater than L_{m} (e.g. Froese, 2004). But Wolff et al. (2015) showed that harvesting these target species with small mesh gillnets at sizes < their L_{m} value would cause less impact on the remaining spawning stocks than using larger mesh sizes which would target sizes above L_{m} values.

But, what if effort was controlled only and use of current gear was just maintained? Our simulation model suggests that the current level of F (F-factor = 1) offers suboptimal yield for all target species, which necessitates increase in effort levels. However, looking at from an economic perspective, all the target species except *C. carpio* are indeed efficiently exploited (Fig. 2 left) suggesting that increasing the current level of F with increasing in fishing effort is not a good option at least for *O. niloticus* and *C. gariepinus,* which is in agreement with the result of the non-equilibrium model.

In conclusion, although our result on *L. intermedius* is not conclusive and calls for further research, all our model results show that currently the state of the Lake Koka fishery seems healthy. However, if the fisheries manger still wish for optimization of resource exploitation and sustain the socioeconomic benefits (such as nutrition and food security, cash income, sustainable livelihoods and poverty alleviation), modifying the current *Lc* value towards the L_{MEY} value seems the best option rather than effort manipulation, which is practically impossible to implement such measures in small-scale fisheries like Lake Koka due to lack of alternative means of livelihoods.

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