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Original Article

Simulating Mesh-size and Selection Pattern Impacts on the Lake Turkana Fisheries Sustainability in Kenya

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ABSTRACT

The study compared impacts of different gear mesh sizes and landing sizes (L_{cap}) through gillnet and knife-edge selection patterns on Tilapia and Nile perch of Lake Turkana. The results will help contribute to the debate on whether to capture large and protect small fish or vice versa. R simulation employing the 1934 Thompson and Bell's model for data-deficient stocks was used to simulate fish cohorts using secondary input data for the two species. Gillnet selection pattern with recommended mesh size (127 mm) produced an 80% increase in Tilapia YPR while ESS and SPR ratios reduced by 12.5%. and 14.3% respectively when fishing mortality (F) was tripled to 3.0. Nile perch's YPR increased by 90% while ESS and SPR dropped by 70 and 75% each when F increased to 0.8. Tilapia YPR maximized by reducing mesh size to 101.6 mm at F=2, and maintained ESS and SPR at 20% each, while the Nile perch YPR dropped by 20% and 66.7% respectively at F=1.0. Small mesh-sized (<40 mm) gears had no effect on Tilapia's ESS and SPR but produced the lowest YPR ratios. The 152.4 mm mesh for Nile perch produced a 25% YPR increase and maintained optimal ESS and SPR at F=0.5. Knife-edge selection pattern utilizing 127 mm, 20 cm L_{cap} and F=1.5, produced 50% YPR, ESS, and SPR for Tilapia, and maintained at F=3.0. Large-sized Nile perch using 152.4 mm gear resulted in about 40% YPR of the stock. Reduction of L_{cap} using 127 mm gear, produced a 75% increase in YPR. ESS and SPR depicted Nile perch collapse at F>0.65. Mesh size and selection pattern impacts are dependent on F. Small mesh gillnets are not damaging if F is controlled and caution should be taken with them in a knife-edge selection. This study recommends 101.6 mm and 152.4 mm mesh sizes for Tilapia and Nile perch respectively in Lake Turkana.

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INTRODUCTION

Gear mesh-size influences fish exploitation rate and pattern in any fishery through selection (Vasilakopoulos *et al.*, 2011). Therefore, selection refers to the gear capacity to target and catch only certain species while allowing others to evade capture (Cooper, 2016). Though fishing gears are naturally selective, most fisheries worldwide, desire the most selective gears for harvesting fish at sizes that do not jeopardize their natural populations. According to Petersen’s (1984) principle of fish growth, fish must be captured once the growth potential has been determined to prevent the possibility of growth overfishing (Cushing, 1976). Fulton (1890) and Holt (1891) stated that the capture of young fish impairs fish population’s reproductive capabilities and suggested that fish breed once before capture (Kolding & van Zwieten, 2014; Vasilakopoulos *et al.*, 2011). Thus, in most fisheries, mesh-size and minimum landing size rules have been used to control gear selection to preserve small and immature fish while targeting large-sized fish.

Some scientists (*see*, Garcia *et al.*, 2012; Gomes, 2018; Gwinn *et al.*, 2013) are skeptical about preserving young juvenile fish and argued that it neither prevents the fishery from reaching its full potential nor safeguards it from depletion when bigger, more fertile fish are unreasonably removed (Wallace & Fletcher, 1997). They believe that the capture of large-sized fish shortens the stock’s size structure, amplifies variations in abundance and unstable stockpiles (Law *et al.*, 2015; Wolff *et al.*, 2015), which could be permanent because of the evolutionary implications of fishing, and hinders fish population restoration, resulting in recruitment overfishing. They pointed out that, safeguarding large-sized, old, mature spawners, enhances spawning biomass, increases the development of high-quality offspring, and provides a reserve buffer for severe environmental circumstances (Ottersen *et al.*, 2006; Wolff *et al.*, 2015). This divergence of opinion regarding the sizes of fish to capture for sustainability is a worldwide concern in fisheries management yet resolved, thus an uncertain future regarding the continued preservation of young fish.

To date, despite the uncertain benefits of preserving young fish, Africa’s majority of lake fisheries are open access and managed using common mesh-size, fishing gear, and minimum landing size limitations, with minimal routine monitoring (Kolding & Van Zwieten, 2011). A usual cause for conflict between fisheries authorities and fishermen whereby, with total disregard for recommended size limits, fishermen adjust their gear mesh sizes to suit the prevailing abundance and seasonality (Kolding & van Zwieten, 2011; Muhoozi, 2002; Ogutu-Ohwayo, 1990). In Uganda, Nile perch gillnet mesh size (203mm) in Lake Victoria declined from 45% in 1989 to 2.7% in 2000 (Taabu *et al.*, 2004). Also, outlawed, less selective fishing gear like beach and purse seines as well as trawl nets, in some lakes are still prominently used, with most of their catches being small fish. Therefore, these points to a likely mismatch between management rules and the prevailing stock status over time that calls for a rethink of the prevailing regulations, and a research gap on linking the current stock levels to appropriate exploitation rates and patterns via revised gear mesh sizes.

Lake Turkana, the world's largest desert lake, is reported to be an underutilized of Kenyan major lakes (Muška *et al.,* 2012). Despite a 30,000 metric tons potential (Keyombe *et al.,* 2022). However, the current production and effort trends as well as booming fish trade in all its key landing ports of Lowarengak, Kalokol, and Loiyangalani, coupled with serious climate impacts in the region which has affected the rate of water influx from rivers (a key influence to the lake fishery), points to the need for precautionary approaches, thus, the significance of understanding the fishing gear mesh-size effects on the sustainability of its fish populations, at least owing to lake's nature of being the main source of livelihood for the destitute pastoral populace around it. Despite research by Longora (2017) at the Ferguson gulf, on the effects of artisanal fisheries on fish community structure and water quality, and that by Olilo *et al*. (2020) on gillnet fishing impacts on stock structure conducted on the river mouths along the western shore of the lake and the Omo River delta, there is a paucity of research into effects of gear mesh-sizes and selection patterns on the sustainability of the lake's fish populations.

Therefore, the current study explored the effects of different gear mesh sizes and selection patterns on the sustainability of the fish population of Lake Turkana in Kenya, focusing on key commercial Nile perch and Tilapia fisheries. The study compared different gear mesh sizes and landing sizes (L_{cap}) through gillnet and knife-edge selection patterns respectively, to determine the performance of small mesh sizes against recommended mesh sizes as well as contribute to the debate on whether to capture large and protect small fish or vice versa. The R language simulation technique employing the broadly utilized Thompson and Bell (1934) model, essential in data-deficient stocks was used to simulate the fish cohorts using secondary sourced input data for the two study species. The study objectives were fulfilled by comparing stock production and biomass indices i.e., Yield Per Recruit (YPR), Stock Potential Ratio (SPR) (Powers, 2015), and Escapement Spawning Stock (ESS) referred to as the remaining spawners (Wolff *et al.,* 2015), throughout the cohort's lifespan with and without fishing.

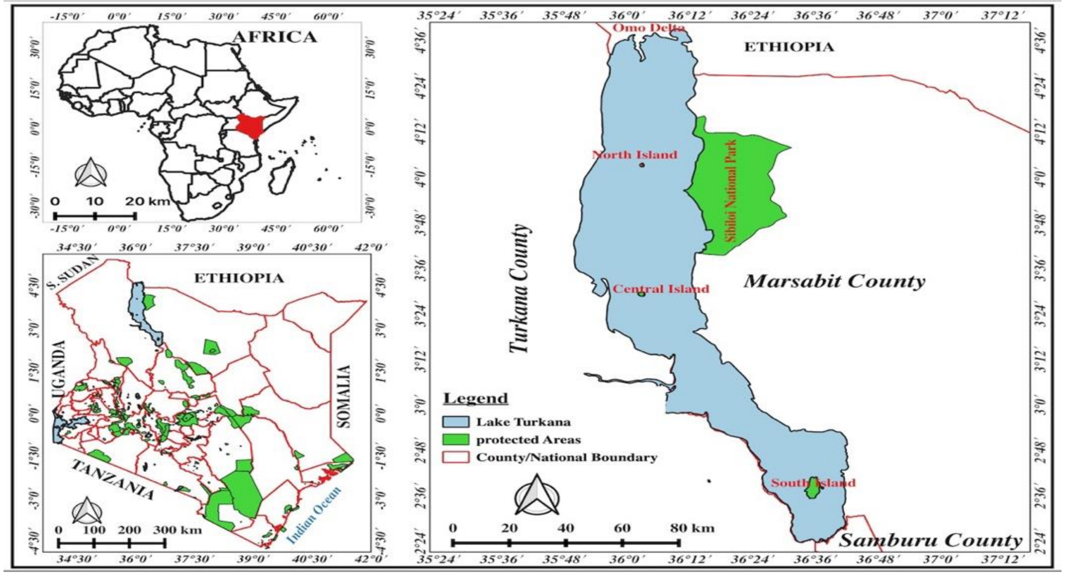
MATERIALS AND METHODS

Description of the Study Site

Lake Turkana formerly known as Lake Rudolf is situated in northwestern Kenya (Hopson, 1982) between 2° 27' S and 4° 40' N extending 265Km long and 30Km wide (Mwikya, 2005). It is a closed basin along the Great Rift Valley's eastern branch, at 365 m asl (Ojwang *et al.,* 2018). The lake is transboundary, shared internationally to the north by the Dassenach (South Omo) woreda in southern Ethiopia, and in Kenya by Marsabit, Turkana, and Samburu counties to the east, west, and south (*Figure 1*) respectively. It is a transboundary resource with its northern end extending across the Omo Wetland, the lake's most productive area (Keyombe *et al.,* 2022).

Lake Turkana's surface size of 7560 Km^2 is described as the largest permanent desert lake in the world and the fourth largest in Africa (Gownaris *et al.,* 2017). It is a chloro-carbonate alkaline lake and the largest in the Kenya network of Rift Valley lakes (BirdLife International, 2022). It receives over 90% of annual water inflow from river Omo, which carries about 14% of Ethiopia's total runoff (Avery, 2013), and about 10% from river Kerio, and river Turkwel with seasonal additional water inflow from other ephemeral rivers, streams, and distributaries.

Figure 1: The study area location



Biological diversity and Fisheries

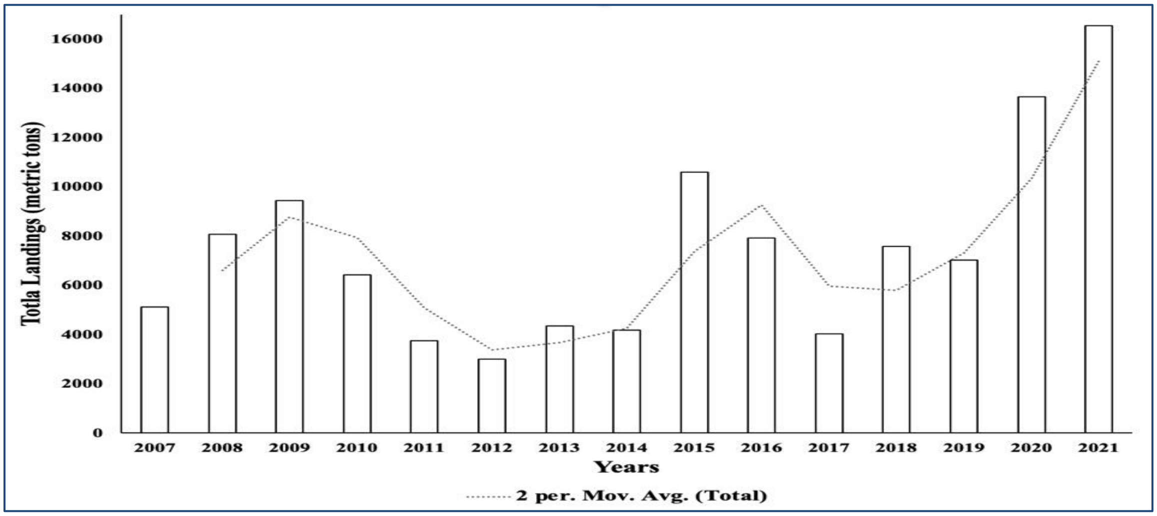
Lake Turkana is endowed with a biodiversity of flora and fauna. The flora is mostly grass tussocks, thinly scattered bushes, and short trees. *Acacia tortilis*, *A. nubica*, *Balanites aegyptiaca*, and *Boswellia hildebrandtii* are the most common trees (Hopson, 1982).

The lake's fauna includes endemic freshwater turtles and one of the large populations (about 14,000 in 1968) of *Crocodylus niloticus* (Modha, 1967). 84 shorebird species, comprising 34 Palearctic migrants, the wintering *Calidris minuta*, *Ardea goliath*, and regionally endangered species which breed on Central Island, inhabit this significant waterbird habitat. (BirdLife International, 2022).

Lake Turkana's ichthyofauna originated from the Nile system and has about 60 freshwater fish species (FishBase, 2022; Muška *et al.*, 2012) of which 10 are endemic and 12 are considered of high economic value; *Alestes spp,* Catfish (*Clarias gariepinus), Hydrocynus forskalii*, *Distichodus niloticus*, Tilapia (*Oreochromis niloticus*), *Labeo horie*, *Bagrus spp*, Nile perch (*Lates niloticus*), *Barbus spp*, *Synodontis schall* and *Citharinus spp* (State Department of Fisheries, 2014). The other species are not fished because they are either too small to support commercial fishing or their biology, stock levels, ecological roles, market availability and/or acceptable exploitation strategies have not yet been established (Keyombe, 2017). The fishery is typified by boom-and-bust cycles in fish landings due to oscillations in lake levels caused by climatic conditions, particularly precipitation, which causes the filling and emptying of Ferguson's gulf (Kenya Fisheries Service, 2019).

It provides the next highest landings of Kenya's freshwater fish, following Lake Victoria, and is home to around 7000 fishermen and 6500 dealers (Kenya Fisheries Service, 2019). The lake's annual fish production has fluctuated between 3,000 and 10,000 metric tons since 2007 (*Figure 2*) but the last two years show increasing production close to the 1976 historical peak (17,950 metric tons) (Keyombe *et al*., 2022).

Figure 2: Total annual landings for Lake Turkana fisheries



***Data source**: Kenya annual Fisheries Statistical Bulletins.*

From 1963 until the early 1970s, fishing efforts in Lake Turkana significantly decreased, although between 1976 and 1982, intermittent rises occurred (Hopson, 1982; Kolding, 1987, 1989). Fishing gears used include gillnets, seine nets, longlines, and hooks while crafts are dominated by foot fishers, rafts (*Ng'ataadei*), and wooden boats (Keyombe, 2017). Any mesh below 5 inches (extended diagonal) is banned in Lake Turkana (Olilo *et al.*, 2020). Gillnets with 1-inch mesh are commonly utilized in the lake.

Study Species Description

O. niloticus, one of Lake Turkana's three Tilapia species (along with *T. zillii* and *S. galilaeus*), is endemic and prefers shallow, quiet, vegetated lake edges. It is abundant within 5 m of the lake's depth contour in sheltered areas like Fergusson gulf on the west bank (Hopson, 1982; Kolding, 1993; Rabuor *et al.*, 1998). It grows quickly and lives for 10 years (Global Invasive Species Database, 2022). The average age at Lake Turkana is predicted to be 9, whereas that of Victoria is 12 years (Moreau *et al.*, 1986; Njiru *et al.,* 2006). Various studies indicate that the total length (TL) of the Lake Turkana population is decreasing; from 65cm (Moreau *et al.*, 1986), to 61cm (Kolding, 1993), 29.7cm (Moreau *et al.*, 1995), to 21.3cm (Ishikawa *et al.,* 2013). Length at first maturity (L_{50}) has reduced by 13cm since 1982 (Kolding, 1993).

The perch fishes of Lake Turkana include the Nile perch (*Lates niloticus*) and the long-spine perch (*L. longispinis*) (FishBase, 2022). Unlike the relatively smaller, deep-water long-spine perch, the Nile perch is a slow-growing predator mostly favoring the nearshore areas in the lake (Hopson, 1982). The largest documented in Lake Turkana weighed 200 kg and measured 200 cm TL (Kolding, 1987). Females are often the largest, reaching an $L\infty$ of 190 cm TL, compare to 145 cm TL for males; they demonstrate negative allometry growth (Hopson, 1982).

Nile perch and Tilapia have consistently dominated the entire annual fisheries production in Lake Turkana (*Figure 3*) (Kenya Fisheries Service, 2019).

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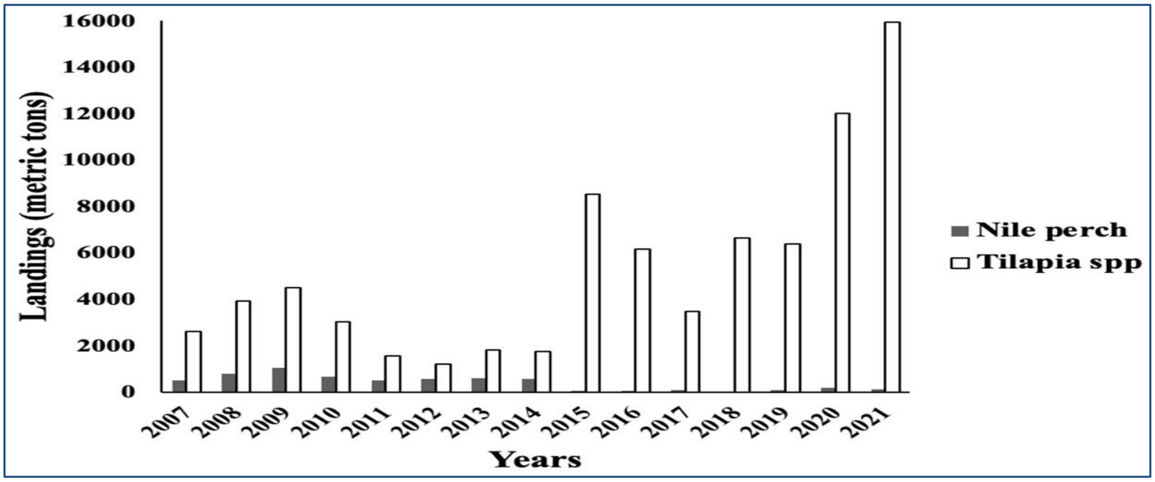
Figure 3: Annual landings for Lake Turkana Nile perch and Tilapia fisheries.



Data source: *Kenya annual Fisheries Statistical Bulletins.*

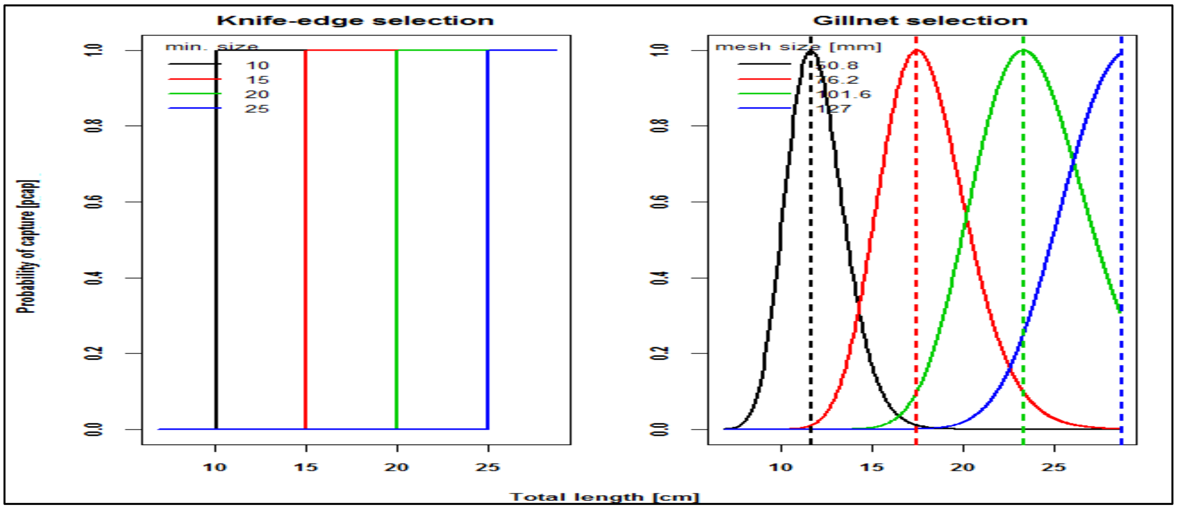
Study Data, Model, and Simulation

The study utilized secondary unpublished data sourced from Kenya Marine Research Institute (KMFRI), Turkana station. The data was from a survey on fish abundance distribution in the lake and was collected from major fishing locations in all sectors of the lake (Northern, central, Ferguson gulf, and the southern sector as well as river mouths). The length-weight and catch data were utilized here to compute some model input parameters (*Table 1*). Other literature information from Hopson (1982), Moreau *et al*. (1986), Kolding (1987, 1989, 1993), and Rabuor *et al*. (1998) was utilized where appropriate.

The fisheries dynamics package (fishdynR) (Taylor, 2022) in R version 4 (R core team, 2022) was utilized for simulating the fishing regime of Tilapia and Nile perch using a modified version of Thompson and Bell's 1934 model (Wolff et al., 2015). Different mesh sizes of gillnets were evaluated with the recommended mesh size of 127 mm. The model simulations tracked cohorts of fish from their initial (t_{cap}) to the maximum (t_{max}) age at capture, while assuming t_{max} as years at which 95 percent of $L\infty$ is reached (Taylor, 1958).

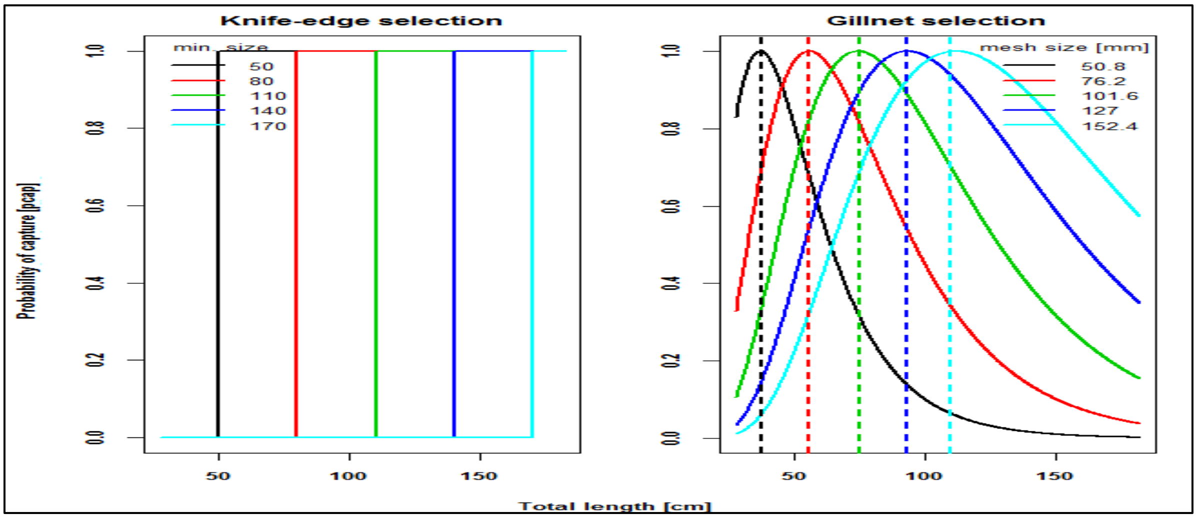
First, it was assumed that the fish cohort's vulnerability to capture rises with age, from t_{cap} to t_{max}., using the unimodal gillnet selection function, which displays the maximum probability of capture (p_{cap}) at L_{cap} and lowers p_{cap} values for fish that are smaller and larger than Lcap (*Figures 4 & 5*).

Figure 4: Tilapia probability of capture (p_{cap}) for different selection and gear mesh sizes.



The fish amount captured by gears at every age of the cohort was contingent on p_{cap} and applied fishing effort. The cohort's p_{cap} values were higher at and above the L_{cap} when a knife-edge selection was assumed; therefore, all fish above L_{cap} were equally susceptible to being caught *(Figures 4 & 5)*.

Figure 5: Nile perch likelihood of capture (p_{cap}) for different gear mesh sizes.



In this investigation, fishing mortality (F) and effort (E) was directly correlated. Using the fishing gear selection equation, the impact of F was adjusted by multiplying it by p_{cap} ranging between 0 and 1. It was possible to predict the fish quantity captured by gillnets at each age, notwithstanding the selection curves' variation, under the assumption that natural mortality (M) for capture-vulnerable sizes was constant. The model determined the variations in capture from the fisheries throughout the cohort's life. In addition, it enabled fish abundance estimation above the L_{50} also referred to as ESS. In addition, the model evaluated the influence of varied F and L_{cap} scenarios on SPR, which is suggestive of the stocks' potential to replenish themselves as fishing continues. Using Pauly's (1980) empirical equation, t_o was calculated (*Equation 1*).

$$t_o = e^{-(0.3922-0.275*\log(L\infty)-1.038*\log K)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [1]$$

The 1997 model for a lognormal distribution by Millar and Holst was used for L_{cap} estimation and

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fitting selection curves to the simulated cohort data. The standard deviation (σ) and mean (µ) were used as input prerequisites. Computation of the model's input selection parameters was performed using Mood *et al.* (1974) formulae.

$$\mu = \ln\left(\frac{m}{\sqrt{(1+v/m^2)}}\right) \ldots\ldots [2]$$

$$\sigma = \sqrt{ln(1+v/m^2)} \ldots\ldots [3]$$

$$\mathrm{L}_{cap} = \frac{1}{Li} * e\left(\mu 1 + \log\left(\frac{mj}{m1}\right) - \frac{\sigma^2}{2} - \frac{\left(logLi - \mu 1 - \log\left(\frac{mj}{m1}\right))\hat{}2\right)}{2\sigma^2}\right) \ldots\ldots [4]$$

where L_i is the median length for the ith size category in gillnet j's capture, m_j is gillnet j's mesh size, m1 represents gillnets smallest mesh size, while µ and σ represent mean and standard deviation respectively (*see Table 1*).

Table 1: Simulation inputs for Tilapia and Nile perch cohorts' fishing regimes.

	Tilapia	**Source**	**Nile Perch**	**Source**
K (yr^{-1})	0.44	Moreau *et al.*, 1986	0.2	Moreau *et al.*, 1986
L∞ (Cm)	29.7	Hopson, 1982	190	Hopson, 1982
$\boldsymbol{\alpha}$	0.2104	Equation. 5	0.007	Hopson, 1982; Hughes, 1992
$\boldsymbol{\beta}$	2.3024	Equation. 5	3.13	Hopson, 1982; Hughes, 1992
L_{50} (cm)	18.6	Trewavas, 1983	65	Hopson, 1982
µ	2.4739	Equation. 6	3.8309	Equation. 6
$\boldsymbol{\sigma}$	0.1339	Equation. 7	0.4614	Equation. 7
w (cm)	3.27	KMFRI, unp.	20.9	KMFRI, unp.
m1(mm)	50.8	KMFRI, unp.	50.8	KMFRI, unp.
M(yr^{-1})	1.03	Moreau *et al.*, 1986	0.5	Moreau *et al.*, 1986

Mortality

Tilapia and Nile perch had total mortality rates (Z) of 1.28 and 1.60, respectively (Moreau *et al.*, 1986). The natural mortality (M) rates were calculated using equation 5 and assumed constant for the sizes susceptible to fishing over the simulation run time.

$$M = (L\infty^{-0.718}) * 12.96 \ldots\ldots [5]$$

This gave Tilapia 1.03 yr^{-1} and Nile perch 0.5 yr^{-1} M values.

F was calculated using equation 6 for each studied species.

$$F = Z - M \ldots\ldots [6]$$

F and L_{cap} combinations were utilized in simulating one cohort for both Tilapia and Nile perch to t_{max}. Using a matrix of 30 iterative simulations, F was modelled over the limit equivalent to t_{cap} and t_{max}.

Growth Parameters

The Von Bertalanffy's growth function (*equation 7*) was utilized in estimating somatic growth in fish size:

$$L_t = \left(1 - e^{(-K*(t-t_o))}\right) * L\infty \ldots\ldots [7]$$

L∞ represents the fish's asymptotic size, L_t is the age t's total length (cm), K (yr^{-1}) is Von Bertalanffy growth index, and t_o fish age at zero length.

The Length-Weight Relationship (LWR) power function was utilized for fish biomass (g) estimation (*see equation 8*).

$$W_t = \alpha * L_t^{\beta} \ldots\ldots [8]$$

α and β represent the LWR linear regression equation constants.

Cohort Size, Capture Rate, and Yield at Age

At ages prior to t_{cap} when F=0, it was assumed that the cohort numbers comply with a negative exponential function whose slope is solely influenced by M.

$$N_{to} = R_{to} \ldots\ldots\ldots\ldots\ldots\ldots [9]$$

$$N_{t1} = N_{to} * e^{(-M*(t_1 - t_\circ))} \ldots\ldots\ldots\ldots\ldots\ldots [10]$$

Where N_{to} is the initial number of recruits (R_{to}) at time t = 0, while N_{t1} represents the fish quantity after a unit of time without fishing.

By introducing fishing on the cohort population, the negative exponential functions' slope is thus given by the sum of the scaled F and M.

$$N_{t2} = N_{t1} * e^{(-(M+F*p_{capt})*(t_1 - t_\circ)))} \ldots\ldots\ldots\ldots [11]$$

p_{capt} represents the cohort's capture vulnerability at time t, whereas N_{t1} and N_{t2} are cohort numbers at time t1 and t2 respectively.

Cohort catch (C_t) and yield (Y_t) at respective ages were determined by estimating their population number depreciation owing to fishing mortality:

$$C_{t1} = N_{to} * \left(1 - e^{-(F*pp_{capt})*(t_1 - t_\circ))}\right) \ldots\ldots\ldots\ldots\ldots [12]$$

$$Y_t = C_t * W_t \ldots\ldots\ldots\ldots\ldots\ldots [13]$$

The YPR of the cohorts was calculated by adding cumulatively, all Y_t throughout the cohort lifespan divided by the total initial cohort population (N_{to}).

$$\mathrm{YPR} = \sum_{t=0}^{tmax}(Y_t) / N_{to} \ldots\ldots\ldots\ldots\ldots\ldots [14]$$

Stock Biomass and Production Indices

The biomass of the cohort population at t (B_t) age, was computed by multiplying its population (in numbers) and mass (g) at time t.

$$B_t = N_t * W_t \ldots\ldots\ldots\ldots\ldots\ldots [15]$$

To assess the impact of fish capture on the reproductive potential of the cohorts' populations, the maturity likelihood (pMAT_t) was estimated using the logistic regression outlined by Heino *et al.* (2002).

$$\delta = \frac{w}{\log it\ pu - log\ it\ pi} \ldots\ldots\ldots\ldots\ldots\ldots [16]$$

$$\mathrm{pMAT}_t = \frac{1}{\left(1 + \frac{e^{-(Lt-L50)}}{\delta}\right)} \ldots\ldots\ldots\ldots\ldots\ldots [17]$$

where δ represents the transformation slope of a cohort from immature to mature, as indicated by the breadth, w (*see equation 16*), ranging from the lower to higher likelihood boundaries, p_i=0.25 and p_u=0.75. The spawning biomass, (SB_t), was computed as the population's percentage of matured biomass (B_t):

$$SB_t = B_t * \mathrm{pMAT}_t \ldots\ldots\ldots\ldots\ldots\ldots [18]$$

The ESS was computed as the sum of SB_t across all population ages.

$$ESS_t = \left(\sum_{t=0}^{tmax} SB_t\right) / \mathrm{t}_{incr} \ldots\ldots\ldots\ldots\ldots\ldots [19]$$

The time step (t_{incr}) was utilized to model F for which increments in time diverged from those of M and K. SPR ration was computed between unexploited and exploited biomass of the spawning stock per recruit or $SSBR_{uf}$ and $SSBR_f$, respectively.

$$SSBR_{tf} = \left(\sum_{t=0}^{tmax} SB_{tf}\right) / N_{tf} \ldots\ldots\ldots\ldots\ldots\ldots [20]$$

$$SSBR_{tuf} = \left(\sum_{t=0}^{tmax} SB_{tuf}\right) / N_{tuf} \ldots\ldots\ldots\ldots\ldots\ldots [21]$$

$$SPR_t = \left(\sum_{t=0}^{tmax} SSBR_{tf}\right) / \left(\sum_{t=0}^{tmax} SSBR_{tuf}\right) \ldots\ldots\ldots\ldots\ldots\ldots [22]$$

Where the spawning biomass and cohort numbers for exploited and unexploited populations at time t are represented as SB_{tf}, SB_{tuf}, N_{tf}, and N_{tuf} respectively.

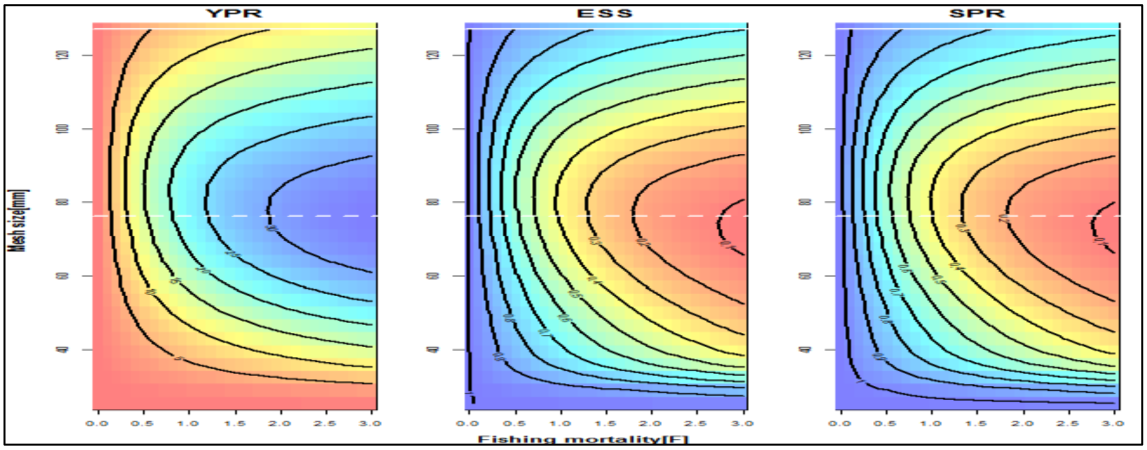
RESULTS

Gillnet Selection

Comparing the performance of different gear mesh sizes on a gillnet selection pattern revealed high dependence on the fishing intensity applied for Tilapia exploitation in Lake Turkana (*Figure 6*). The fishing gear of recommended mesh size (127 mm, white solid line) produced an 80% increase in

YPR with increasing fishing mortality (F) from 1.0 to 3.0. Similarly, the ratio of mega spawners (ESS) and the stocks' SPR reduced by 12.5%. and 14.3% respectively. However, at F less than unity, gears of the recommended mesh size and those with very small mesh sizes (<40 mm) performed alike. They both saw minimal (<5.5) YPR and maximum ESS and SPR ranging from 0.75 to 1.0 with reducing F values. On the contrary, gears with very small mesh sizes (<40 mm) did not depict any difference in YPR, ESS, and SPR ratios irrespective of increases in F values as well as decreases in mesh sizes, thus producing the lowest YPR (<5.5), 0.8 ESS and maximum (1.0) SPR. Gears with intermediate mesh sizes, ranging from 50 to 100 mm, produced the highest indices for YPR and lowest for both ESS and SPR, with increasing F. Notably, the gear with 76.2 mm mesh size (white dashed line) produced maximized YPR and optimal ESS and SPR at F=2.0.

Figure 6: Tilapia fishery yield and spawning stock explorations from gillnet selection.



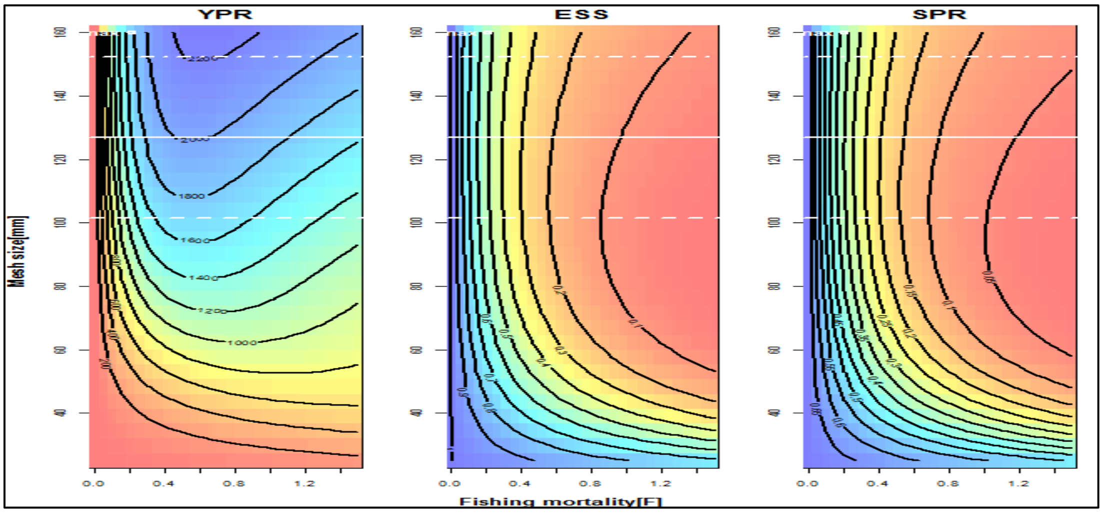
Key: *Color scheme: Brick red to dark blue represent low and high indices respectively. Horizontal lines: White solid and dashed represent 127 and 76.2 mm respectively.*

With the gillnet selection pattern of fishing, Nile perch fishing gears of recommended mesh sizes (middle solid line) produced maximum YPR at F=0.8 (*Figure 7)*. The stocks' YPR depicted a 90% increase when F increased from 0.1 to 0.8 and a 20% drop when F increased from 0.8 to 1.8. The gear mesh-size optimized Nile perch ESS (0.3) and SPR (0.25) at F=0.5 and 0.4 respectively. Increasing F values from 0.1 to 0.5 saw a 70% decline in Nile perch ESS. However, with a similar increase in F, SPR dropped by 75%. The Nile perch stock SPR and ESS showed evidence of a collapse at F>1.2 and F>1.0 respectively.

Increasing gear mesh size to 152.4 mm (top dot-dashed line) from 127 mm, resulted in a 25% increase in the Nile perch YPR, maximized at F between 0.6 to 0.8, while a mesh-size reduction from 127 mm to 101.6 mm (lower dashed line) saw a 20% drop in the stock's YPR, maximized between 0.4 to 1.0 F. The optimal ESS (0.3) and SPR (0.25) indices at F=0.5 and 0.4 respectively, showed no changes when fishing gear mesh sizes were increased from 127 mm to 152.4 mm or dropped to 101.6 mm. However, increasing mesh size to 152.4 mm and F from 0.5 to 1.3 resulted in a 66.7% decline of ESS from the optimal index, as well as a collapsed stock at F>1.3. Also, the SPR ratio dropped by 80% when F ranged from 0.4 to 1.6. Notably, a similar reduction in ESS and SPR was realized at F=1.0 when the mesh size was reduced from 127 to 101.6 mm.

Fishing with small mesh-sized gears (<40 mm) provided a constant mean decline of 85% Nile perch YPR with increasing F values, from that produced by the recommended gear mesh size. However, these gears maintained high ESS values with a 20% drop from maximum (1.0) at F=1 and only a 10% further decline at F>1, thus maintaining the ESS at 70% of the initial stock biomass. Despite high F. The SPR also dropped by 35% when fishing was capped at F=1 but further declined by 23.1% to maintain a 50% SPR despite the increase in F beyond 1.4.

Figure 7: Nile perch fishery yield and spawning stock explorations from gillnet selection.



Key*: Color scheme: Brick red to dark blue represent low and high indices respectively. Horizontal white lines: dashed solid, and Top dot-dashed are 101.6, 127, and 152.4 mm mesh sizes, respectively.*

Knife-edge Selection

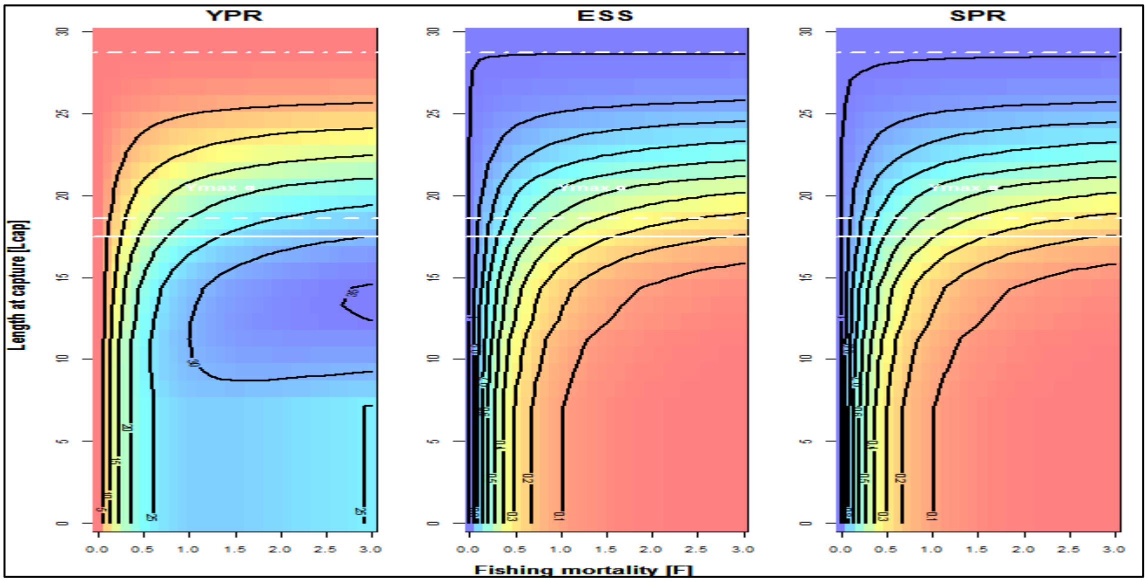
Fish capture by the knife-edge selection pattern utilizing the recommended mesh-size targeted Tilapia 28.5 cm total length (TL) at capture (L_{cap}) (*Figure 8*). At this L_{cap}, Tilapia fishery YPR was minimal (<5) irrespective of the increase in F from 0.1 to 3.0. The stocks' ESS and SPR were maximized (1.0) irrespective of the F value applied in the fishery. However, 50% YPR, ESS, and SPR for Tilapia was realized at 20 cm L_{cap} and F>1.5.

Reduced L_{cap} of 18.5 cm produced by 101.6 mm mesh size resulted in an 80% increase in YPR, and a 70% decline in both ESS and SPR, with increasing F from 0.1 to 3.0.

Further reduced L_{cap} for Tilapia of 17.5 cm was captured by 76.2 mm gear mesh size and this resulted in an 83.3% increase in YPR and an 80% decline in ESS and SPR when fishing was increased from F 0.1 to 3.0.

Targeting small tilapia with reducing L_{cap} below L_{50} (solid line), from 18cm to 9cm at F above 1.0 to 3.0, showed maximized YPR with very low (<0.1) ESS and SPR. However, targeting 15cm L_{cap} tilapia at F above 1.0 depicted a collapse of ESS and SPR but high YPR, though a 16.7% YPR reduction at L_{cap} lower than 8cm and fishing at F above 0.5 to 3.0 was realized.

Figure 8: Tilapia fishery yield and spawning stock explorations from Knife-edge selection

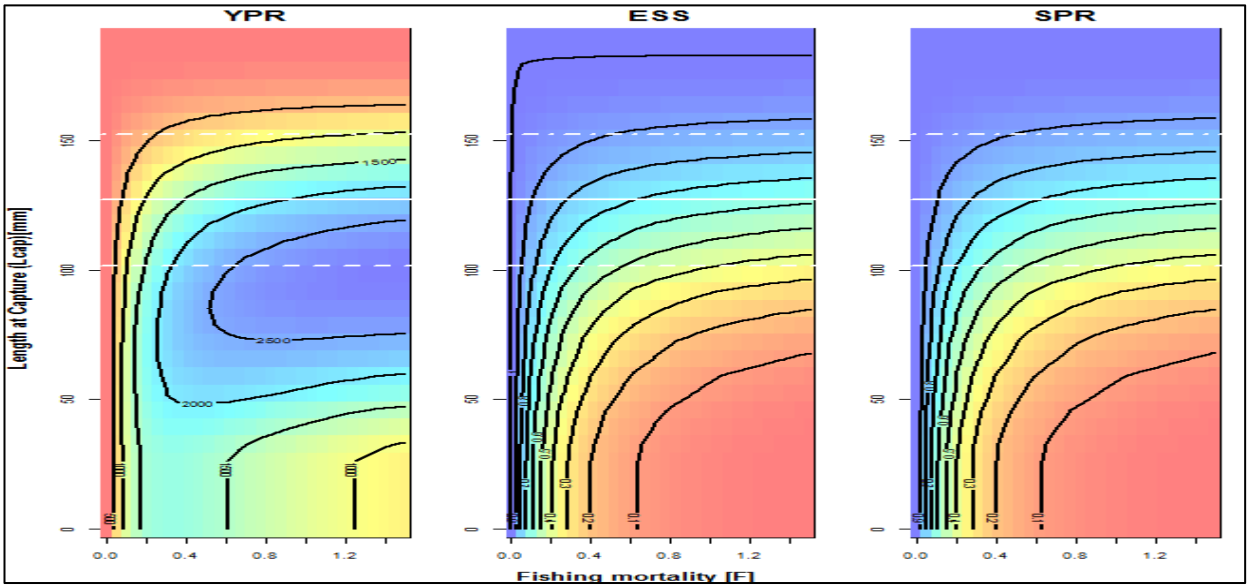


***Key**: Color scheme: Brick red to dark blue represent low and high indices respectively. Horizontal lines: solid, dashed, and Top dot-dashed, are L_{cap} for maximum P_{cap} of 76.2, 101.6, and 127 mm mesh sizes, respectively.*

Therefore, fishing of small sizes of tilapia using non-selective small, meshed gears may not be detrimental provided the exploitation rate (F) is maintained at levels below 1.0. Fishing at an F value of 0.5 will maintain Tilapia ESS and SPR at 30% each, with optimal stock biomass limits.

Resulting trends for YPR, ESS, and SPR indices for Nile perch stock explorations (*Figure 9*), were like those obtained for Tilapia (*Figure 8*) while exercising a knife-edge selection pattern, despite minor changes in isolines. Targeting large-sized Nile perch using 152.4 mm gear resulted in the production of about 40% YPR of the stock while maximizing ESS and SPR at over 75% and 95% respectively. Reduction of L_{cap} using 127 mm gears, depicted a 75% increase in YPR and a 40% reduction of ESS and SPR for Nile perch with increasing F from 0.1 to 1.6. Further capture of smaller L_{cap} sizes using 101.6 mm gears resulted in Maximized YPR at F>0.5 with over 80% while showing a 65% reduction in ESS and SPR with increased F at 1.6. The capture of Nile perch smaller than L_{opt} (65 cm) using non-selective small, meshed gears (<101.6 mm) showed maintenance of high YPR irrespective of increasing F, while ESS and SPR depicted stock collapse at F=0.65. Nonetheless, the fisheries of both species may endure provided fish capture levels are lower and controlled at F<0.5, whereby the stock population ESS and SPR are within the optimal values of approximately 30%.

Figure 9: Nile perch fishery yield and spawning stock explorations from Knife-edge selection



***Key**: Color scheme: Brick red to dark blue represent low and high indices respectively. Horizontal lines: Top dot-dashed, solid, and solid are L_{cap} for maximum P_{cap} of 152.4, 127, and 101.6 mm mesh sizes, respectively.*

DISCUSSION

As projected, F intensity influences mesh sizes and selection pattern impacts on fish populations. Employing fishing gear with different mesh sizes has varying effects on fish populations in Lake Turkana. Fishing gears with mesh diameters between 45 mm and 127 mm, show moderate exploitation impact across both huge, adult, and small, immature fish. Unlike fishing gears with small mesh sizes (<45 mm), recommended gear mesh size performed sustainably for Tilapia capture by ensuring increasing YPR and 70% stock ESS and SPR irrespective of increasing in F. This was attributed to the reduced ability of small meshes in entangling fish with large sized heads or gills in a gillnet selection pattern of fishing, resulting to them catching a few hence a lower simulated YPR and maximized ESS and SPR.

The gillnet mesh size of 101.6 mm for Tilapia balances the fishing pressure among juvenile fish and the spawning population. The 127 mm recommended gear mesh size on the other, provides a broad susceptibility range and increases P_{cap} on big mature fish whose reproductive capabilities the fish population requires to avoid recruitment overfishing. However, Gear mesh sizes smaller than 45 mm and larger than 127mm, given any level of F values, produced maximized SPR and ESS as well as a very low YPR for Tilapia. Considering that most mature tilapia, for example, had L_{cap} sizes that are both large enough to prevent capture from mesh sizes less than 45 mm and smaller to be caught by mesh sizes above 127 mm. Therefore, gillnets with a mesh size smaller than 45 mm and those larger than 127 mm may appear harmful for maintaining the viability with greater fishing strains (F > 1) of the tilapia fishery than 101.6 mm (*Figure 4*).

By using gillnets with a large mesh size of at least 80 mm, Nile perch YPR is maximized (*Figure 6*). This is explained by the Nile perch's ability to achieve a massive body at much shorter lengths than L_{50}. Thus, compared to gillnets with large mesh sizes, entanglement is decreased by small mesh gillnets. When fishing for small fish with lower L_{cap} or mesh sizes of 60 mm, ESS and SPR are maximized. This is because, given the enormous Nile perch bodies, large-mesh gillnets present significant P_{cap} on practically all brooders and developing tiny fish. The maintenance of F values that offer SPR and ESS at levels sufficient for restocking the population in terms of reproduction would be necessary for the fishery to continue to exist.

Gillnets with a mesh size greater than 45 mm and 127 mm with F values that produce the 40% SPR, and ESS may be responsible for the persistence of the Nile perch and tilapia fisheries in Lake Turkana. The SPR in most well-managed fisheries typically ranges between 20 to 40%. (Powers, 2015). When recruitment is low, as a limit reference point (LRP), an ESS of 40% is regarded as safe (Caddy, 1998). However, when recruitment is robust, lower ESS between 20 and 25 percent of the expected size of the virgin breeding population, or F of 1.4 to 1.6, are safe LRP (Basson *et al.*, 1996).

The study found that targeting small fish may not be as harmful as always believed, with controlled exploitation. This finding is supported by that of Wolff *et al*. (2015) thus, maintaining a high population of mega spawners (MS), herein referred to as ESS, would improve population replenishment and enhance sustainability while providing an optimal YPR. Law *et al.* (2015) modelling results also concur with this finding by positing that biomass fluctuations have a larger amplitude when fishing focuses on giant fish as opposed to juveniles. Focusing capture primarily on big fish can destabilize populations and enhance size and age structure truncation (Borrell, 2013). Importantly, this may not hold in a knife-edge selection pattern, because fishing using gears like purse seines, beach seines, and trawling nets which capture unselectively or pose little selection, results in low ESS. These gears are known for ecosystem disturbance, because they capture fish beyond their L_{cap}, preventing spawning individuals from escaping capture and cushion stock collapse resulting from the combined use of small gear mesh sizes and increased exploitation pressure (Wolff *et al.*, 2015).

In terms of the sustainability of Tilapia fisheries and possible economic viability of the yields from the currently recommended mesh size (127 mm), this study's findings are comparable to those of Olilo *et al.* (2020), though the 101.6 mm mesh in this study produced higher YPR with constant 40% ESS and SPR irrespective of F level than with the 127 mm., which optimized YPR only at F >1.5 However, this study findings on Nile perch YPR decrease with increasing mesh-sizes to 127 mm and increasing with larger meshes, reflects a meeting point between the two studies. In their study, they proposed mesh sizes over 127 mm for Tilapia, *Labeo horie*, and Nile perch for sustainability and fish stock replenishment (Olilo *et al.*, 2020).

The study results differed with Vasilakopoulos *et al.* (2011) which projected that a high percentage of fishing mortality of juvenile fish showed a negative influence on stock status, thus supporting the "spawn-at-least-once" idea. They further argued that stock status falls below cautious limits when immature fish mortality surpasses half that of mature fish. Though, Vasilakopoulos *et al.* (2016) expounded that, productivity is determined by biological characteristics, while SSB by extortion method (i.e., selectivity and rate of exploitation), thus harvesting fish, a year or more after they mature ensures high sustainable harvests only at low stock degradation, they blamed significant selection of juvenile for untapped capability for improved optimal landings among 31 north Atlantic stocks, highlighting the necessity of safeguarding small fish.

Debates on the optimal size of fish to be captured in a fishery without affecting its long-term viability are varied. In their Yield Per Recruit (YPR) model Beverton and Holt (1957) demonstrated that delaying the fish age of capture to an optimal level maximizes the theoretical potential yield of the fishery. Others proposed optimal selectivity methods that would focus more effort on little fish, even if it meant collecting more juveniles while allowing large, aging fish to survive (Caddy & Seijo, 2002). They suggest that the presence of big fecund fish in the stock helps to avert the possibility of recruitment overfishing due to strong gear selection. Garcia *et al.* (2012) and Law *et al.* (2015) support a balanced harvest plan as it guarantees that fishing mortality is adjusted to account for each age/size class of biomasses and that young ones are captured frequently as compared to huge or big individuals. The benefits of protecting the younger generation are unclear, as shown by these many points of view, and they may change depending on different techniques of fishing applied.

Reality is much more intricate than the models, which have their constraints, thus interpretation of this study results that are pegged on a theoretical simulation of a pseudo-cohort are only illustrative and not necessarily precise. It may have benefitted much from an exploratory study. However, this study provides a baseline reference and fills a knowledge gap and contributes to the current debate on whether to continue the capture of mature, fecund big-sized individuals and preserve young juveniles or vice versa.

CONCLUSION

Small mesh gillnets are not damaging if F is controlled and may promote long-term catches from the fisheries. Caution should be taken when such gears are used for seining and trawl fishing (Knife-edge selection). Recommended gear mesh-size, is sustainable though produces minimal YPR and very ESS and SPR compared to the 101.6 mm gear that produces high YPR while maintaining ESS and SPR at 40% of the stock irrespective of an increase in F. This study recommends mesh sizes below the currently permitted size (127 mm) up to 100 mm (about 4 inches) to be able to maintain a viable YPR and with resulting stock ESS and SPR capped at 40% irrespective of F value, since controlling F in Lake Turkana is challenging.

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