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Impact of anthropogenic pollution and artisanal fishing on the population of Tilapia spp. *Oreochromis niloticus* and *Oreochromis amphimelas* in Lake Manyara, northern Tanzania

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Abstract Lakes are among the main sources of protein and livelihood to huge communities of rural people, and some of them house endemic fish species. The livelihood of about 200,000 rural people depends on Lake Manyara resources which also houses a population of the endemic and endangered fish, the Manyara Tilapia (*Oreochromis amphimelas*). Despite this importance, fishery in the lake is nearly under open access and it is not known how this has affected fish stocks. The lake is also under strong influence from overgrazing and poor farming practices in the highlands and adjacent areas which are polluting the lake. However, it is also not known how this has affected the growth and survival of fish in the lake. We assessed the impact of artisanal fishing and anthropogenic pollution on the stock of Manyara Tilapia and Nile Tilapia in Lake Manyara. We found that fish stocks in the lake are under heavy fishing pressure. Nearly all harvested Nile Tilapia were immature, and the majority of Manyara Tilapia were first time spawners caught at the length of their first maturity. This prevented the fishes from spawning at least once in their lifetime. Anthropogenic pollution has also hypereutrophied the lake and degraded the ecological quality for growth of Tilapia fish. Therefore, urgent site-specific mitigation measures and conservation actions are required to safeguard community livelihood and continued existence of the endangered Manyara Tilapia.

Keywords Eutrophication · Fish · Nile · Tilapia · Small scale · Habitat degradation

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Introduction

Inland fishery is estimated to employ about 19 million fishermen globally with 97% of them living in developing countries (Sonneveld et al., 2019). In these countries, the fishery is also an important source of protein to over millions of rural populations (Basurto

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et al., 2017; de Graaf et al., 2012) who are often poor and undernourished (Magqina et al., 2020; Simmance et al., 2022). This fishery is typically artisanal and is mainly for subsistence with less commercial importance at national level. Owing to this, the fishery has received less government priority and is poorly managed in many countries, with many of the lakes being exploited under nearly open access (Allan et al., 2005; Arthur, 2020; Sonneveld et al., 2019). The few available studies report that this has culminated into decline of fish stocks in some lakes due to overexploitation by the poor rural people who over-depend on the lakes for their livelihood (Allan et al., 2005; Sonneveld et al., 2019; Welcomme et al., 2010). Despite that, the effects of artisanal fishery on fish populations in many lakes in developing countries, Africa in particular, are still not known. This situation threatens fishery productivity and sustainability for many lakes, and the benefits it delivers to the surrounding communities. Furthermore, some lakes host endemic fish species, some of which are endangered and need special conservation attention. Overfishing can push their populations to the edge of extinction, and if not halted to total extinction (Allan et al., 2005; Bayona, 2006).

Decline of fish populations in overexploited water bodies is further intensified by diffuse pollution from anthropogenic sources (Allan et al., 2005; Arthur, 2020). Pollution of aquatic habitats particularly via runoffs from agricultural and grazing lands is known to deteriorate ecological habitats for fish species, and thus interfere with their reproductive success and survival (Donohue and Molinos, 2009; Henley et al., 2000). Despite that, regular assessment of water condition in the lakes for optimal survival of fishes is not a priority in many countries and has led to a serious lack of information on the quality of ecological habitats for fish including endangered species. Assessing fish ecological habitat degradation and its drivers in lakes is important to come up with fisheries management strategies that combine socio-economic activities with biodiversity conservation. This is particularly relevant in areas where human population and the accompanying environmental degradation are increasing.

Lake Manyara is a small inland lake in northern Tanzania. In addition to two fish species (Nile Tilapia: *Oreochromis niloticus*, and African catfish: *Clarias gariepinus*) harbored by the lake, the lake is also a home for the endemic but endangered fish Manyara Tilapia (*Oreochromis amphimelas*). Manyara Tilapia was inscribed in the IUCN red list of threatened species in 2006 because of driving forces, namely overfishing, extreme drought, and habitat degradation (Bayona, 2006). There is huge artisanal fishery on the lake where main catches are Nile Tilapia and Manyara Tilapia with Manyara Tilapia contributing largest portion of the total landings. Artisanal fishery supports the life of about 200,000 villagers who subsist on the lake (URT, 2013). Since 1970 abundance of fish in Lake Manyara have been declining, thus threatening livelihood of local communities and long-term existence of the endangered Tilapia. Overdependence on fishing by villagers and the nearly open access nature of the fishery imparted high fishing pressure on the lake with consequent decline in all fish catch from 1,800 tons in 1970 to 0.5 tons in 1990 (Bayona, 2006). More importantly, 33 years have lapsed since the last estimation of fish catch from Lake Manyara, hence the current stock of Nile Tilapia, and that of the endangered Tilapia is unknown. Moreover, the effect of artisanal fishing on the population of Manyara Tilapia and Nile Tilapia has never been investigated and is also not known. In addition, overgrazing around the lake and poor cultivation practices involving clearing of vegetation cover around riparian zone of rivers pouring into Lake Manyara have caused soil erosion and subsequent sedimentation into the lake. This is thought to cause ecological habitat degradation which could be limiting abundance of Nile Tilapia and Manyara Tilapia (Bayona, 2006). However, this also has never been investigated. Assessing the impact of artisanal fishing and degradation of ecological habitat on the population of Manyara Tilapia and Nile Tilapia is important in order to understand conservation needs for the endangered Tilapia and for maximization of fish yield from Lake Manyara. This will safeguard the population of Manyara Tilapia and ensure its long-term existence while improving income and food security for local populations.

Prolonged overexploitation of fisheries resources is known to deplete fish populations. It is also known to selectively remove large individuals that fetch high market prices while leaving behind small-sized individuals. If overexploitation is not halted, the fish population structure may become dominated by small individuals (Ben-Hasan et al., 2021; Hutchings and

Reynolds, 2004; Magqina et al., 2021). We therefore hypothesized (H_1) that the population of Manyara Tilapia and Nile Tilapia in Lake Manyara was dominated by small, bodied fishes due to overfishing. Likewise, pollution of aquatic habitats is known to lower fish populations. Elevated sedimentation is known to interfere with fish reproduction and breathing by smothering breeding grounds and causing gill inflammation with eventual fish death by clogging fish gills (Ardjosoediro and Ramnarine, 2002). Excessive input of organic carbon can cause hypoxic condition with subsequent fish kills. We thus hypothesized (H_2) that lake pollution by rivers and surface runoff from agricultural and grazing lands is lowering population of Manyara Tilapia and Nile Tilapia. This study therefore intended to: (1) estimate the stock size of Manyara Tilapia and Nile Tilapia in Lake Manyara, (2) assess the impact of artisanal fishery on the population structure of Manyara Tilapia and Nile Tilapia in Lake Manyara, and (3) assess the quality of the ecological habitat for the growth and survival of these fish in Lake Manyara.

Materials and methods

Study area

Lake Manyara is a shallow small lake extending from 3°25'–3°48'S, and 35°44'–35°53'E and is located at 960 m asl in the Lake Manyara Basin (LMB) in northern Tanzania (Fig. 1). The lake is located within the East African Rift Valley and covers an area of 470km^2 and has an average depth of 2.3 m. The water of Lake Manyara is saline-alkaline with a high concentration of dissolved salt and pH values exceeding 9.5. The lake is a closed basin with no natural outlet, and there are number of rivers, namely Mtowambu, Simba, Kirurumo, Msasa, Endabashi, Lyambi, Magara, and Makuyuni, which pour fresh water into the lake thus diluting its sodic water. The lake is recognized as Important Bird and Biodiversity Area as it provides breeding and feeding ground for nearly two million lesser flamingos (*Phoenicopterus minor*), and thousands of Pelicans (*Pelecanus rufescens*), and Yellow billed stork (*Mycteria ibis*). Other bird species present in small numbers are Marabou stork (*Leptoptilos crumeniferus*) and gray heron (*Ardea cinerea*) (BirdLife International, 2021). The lake also houses a population of one endemic and endangered fish species the Manyara Tilapia (*Oreochromis amphimelas*) in addition to other two common fish species (Nile Tilapia: *Oreochromis niloticus*, and African catfish: *Clarias gariepinus*). These fish often tend to aggregate in river mouths where water is less saline. There is an artisanal fishery which huge population of about 200,000 residents in surrounding villages heavily depend upon for their livelihood. Bad grazing and cultivation practices in areas around the lake and rivers has cleared off vegetation cover of the riparian zone (AWF 2003; Nonga et al., 2010). Soil erosion on these bare lands has caused deposition of sediments in the lake and thus thought to cause habitat degradation for Nile Tilapia and the endangered Manyara Tilapia (AWF, 2003; Nonga et al., 2010). The climate of the region is tropical semiarid with an average annual temperature and rainfall of 22 °C and 700 mm respectively. The region has a bimodal rainfall pattern with a short rainy season from the end of November to end of December and a long rainy season from March to May. Levels of water in the lake fluctuate with rainfall.

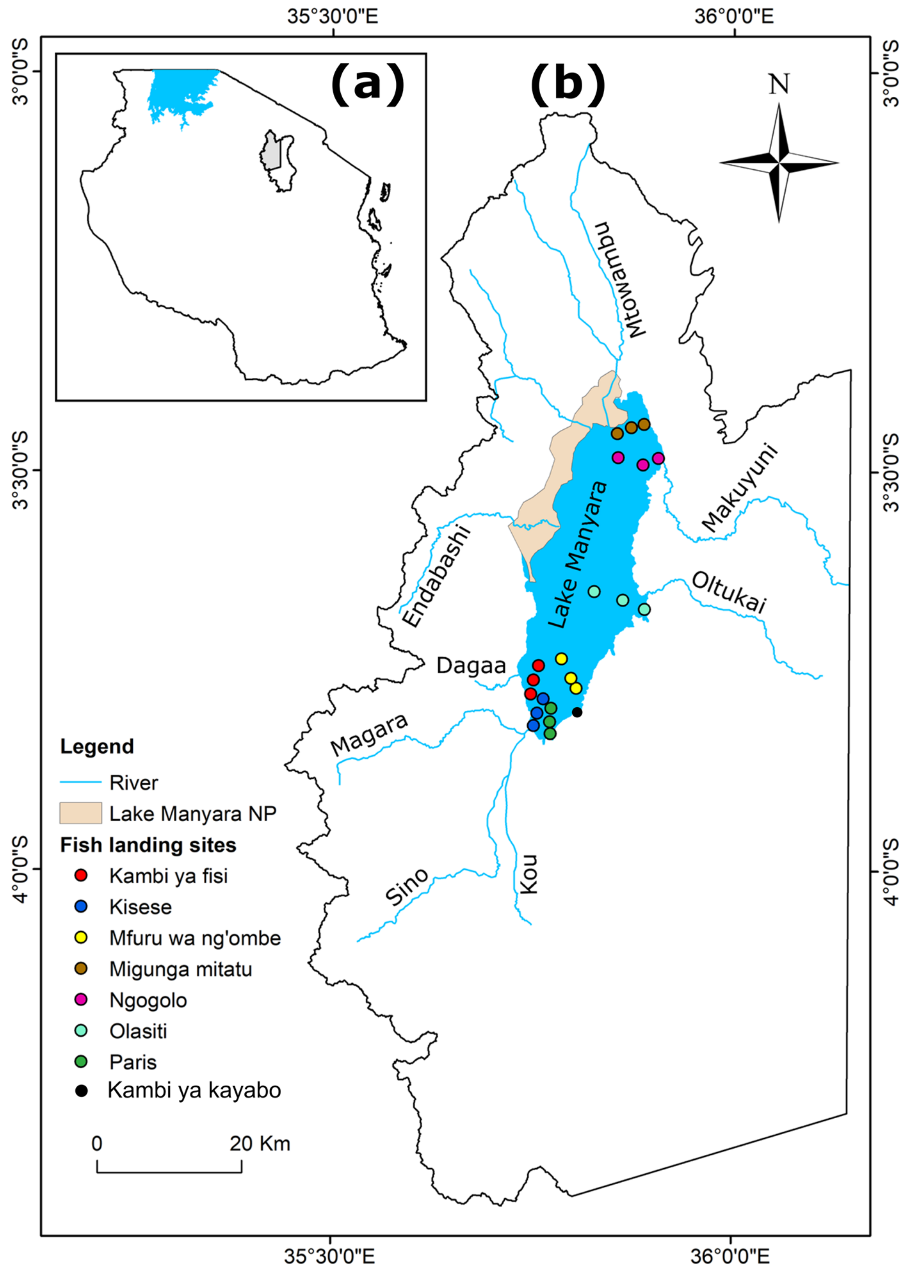
Data collection

Sampling for data collection was done for one month during the dry season from September 29 to October 30, 2021. The lake has a total of 15 fish active landing sites (fishing camps). To ease study implementation, the entire lake was divided into seven zones each comprised of two fish landing sites which were geographically located close to each other (Table S1). In each zone, one representative site was randomly selected and visited for three consecutive days for data collection. The first visit was for landing/catch estimation, second visit for measuring fish length, and third visit for measuring habitat condition variables. We also randomly selected three representative fishing boats from each zone for data collection.

Collection of fisheries related data

Catch per unit effort (CPUE) technique was employed to estimate stock size of Tilapia fishes in Lake Manyara. CPUE index is gear specific and is considered proportional to the stock of the fish species that a particular gear can catch (Kantoussan et al., 2014; Maunder et al., 2006). Upon landing on the shore,

Fig. 1 Map of the study area showing (**a**) map of Tanzania with the Lake Manyara sub-basin (gray color) inserted in the Lake Manyara Basin (LMB), and (**b**) Lake Manyara and the visited fish landing sites on the shore of Lake Manyara. NP = National Park. The three cycles on each landing site show locations where water was sampled, and depth measurement taken



all the fish in the boats were immediately counted and the records logged into the field logbooks. In the case of a small catch, the whole catch was counted, and when necessary, the large catch was sub-sampled, and a multiplicative factor was applied to estimate the total catch. Catch weight was measured using a 20-L bucket which was assumed to be equivalent to 20 kg. This bucket is the catch measurement tool fishermen use at Lake Manyara. A number of fishermen and fishing boats were also counted on each camp and gear types identified and enumerated. To obtain fish length, some fish (about 200 fish) in each boat were randomly sub-sampled and their standard lengths (SL) measured using a ruler. Unit effort was defined as a fishing trip per boat per day and catch by the number of fishes landed on the shore per boat per fishing trip. Only catches using gill nets and beach seines which were the dominant gears were considered. One special landing site "Kambi ya kayabo" was included as the eighth site for assessing the stock of Manyara Tilapia. At this site, all landed catches were Manyara Tilapia and were caught by beach seine.

Assessment of the quality of ecological habitat for Tilapia fishes in Lake Manyara

Ecological habitat condition for Tilapia fishes was assessed through in situ measurement of turbidity, chlorophyll-a (ChloA), level of salinity and average depth as proxies for habitat condition. Other variables which were measured were total dissolved solids (TDS), electrical conductivity, and phycocyanin. Using selected boats in each zone, researchers sailed with fishermen into the lake for in situ measurements during day hours. Measurements were taken at three different points in the lake which were at 150 m interval offshore. Tilapia fishes are microphagous, and concentration of chlorophyll-a in water can indicate the level of planktonic algae which are food resources for the fish. High levels of turbidity caused by sedimentation may clog fish gills and cause fish death (Ardjosoediro and Ramnarine, 2002) and may also bury fish eggs, thus interfering with reproductive success of the fish. Excessive nutrient input may cause algae blooms which when they die off may throw the lake into anoxic condition which is dangerous to fish survival (Henley et al., 2000). Turbidity (FAU), pH, conductivity (µs/cm), TDS (mg/l), and salinity (PSU) were measured by a portable multiparameter meter (HACH-DR 900, China), chlorophyll-a (µg/l) and phycocyanin (µg/l) by a fluorometer (AquaFluor-Turner designs, Model 8000-010, USA) and average water depth (cm) by a calibrated stick.

Integrated sample of lake water (taken at the surface and at 0.5 m depth) was also collected in a1L plastic bottle at each point where in situ measurements were taken and stored in a cool box containing ice packs and later transferred to a field refrigerator for storage at −20 °C. All samples were later transported to the laboratory at the Nelson Mandela African Institution of Science and Technology (NM-AIST) for storage where water samples were further stored at -20° C until analysis. In the laboratory, water was thawed and then nitrate (NO_3) (mg/l), ammonia (NH_3) (mg/l), and total phosphorus (TP) (mg/l) were analyzed by a spectrophotometer (HACH-DR 900, China) by following manufacturer protocols. The PhosVer3 Acid Persulfate Digestion method (0.06–3.5 mg/l) was used to measure the concentration of total phosphorus. The high-range Cadmium Reduction method (0.3–30 mg/l) was used to measure concentrations of nitrate. The indophenol method (0.01–0.50 mg/l) was used to measure the concentration of ammonia. The same integrated water sample was also used to measure turbidity and concentration of chlorophyll-a. Locations of landing sites on the shore of Lake Manyara, and where water and physicochemical variables were sampled and measured, were recorded using the Geographical Positioning System (GPS) device (Garmin, etrex 30).

Statistical analysis

Data were analyzed and graphs plotted using the R platform version 3.6.2 (R Core Team, 2019). Similarity between landing sites in the sizes of landed fishes was visualized by the ordination technique the Non-Metric Multidimensional scaling (NMDS). Differences between landing sites in the catch per unit effort (CPUE) of a boat and differences between landing sites in the level of physicochemical variables were assessed using one-way ANOVA for variables which conformed to assumptions of normality and homoscedasticity, and Kruskal–Wallis test for those which did not even after necessary transformations. Tukey honest significant difference (Tukey HSD) or Dunn post hoc tests were performed to confirm these differences. Correlations between environmental variables were assessed using Pearson correlation and visualized using the principal component analysis technique (PCA). Unit fishing effort of a boat was defined as a go and return fishing trip by a single boat. CPUE of a boat was calculated as the number of fish caught in a single go and return fishing trip by a single boat. Unit fishing effort for the entire lake was defined as the total number of fishing boats in a single go and return fishing trip. Catch per unit effort for the entire lake was calculated as.

$$CPUE = \sum_{i}^{k} N * n$$

where CPUE = catch per unit effort of the lake, N = mean CPUE of a boat at landing site (i), n = number of fishing boats at a landing site (i), N*n = CPUE of a landing site (i), and letters (i) to (k) = landing site (i) to (k).

Trophic state of Lake Manyara was determined by comparing levels of three physicochemical variables (water turbidity, total phosphorus, and chlorophyll-a) with their established international standards from the Organization for Economic Co-operation and Development (OECD) which are normally used for classification of trophic states of water bodies (Vollenweider and Kerekes, 1982). Conversion of the measured turbidity levels from Formazin Attenuation Units (FAU) to Secchi depth (m) was achieved through adoption of a conversion equation developed by the US Army Engineer Research and Development Center (ERDC) which is: $Y = 2.0777 * Xe - 0.489$, where Y = Secchi depth (m), and X = water turbidity (FAU or NTU or FTU) (Xu et al., 2019).

The quality of ecological habitat for optimal survival of Tilapia fish in Lake Manyara was assessed by comparing levels of the four measured physicochemical variables (water turbidity, ammonia, conductivity, and pH) with the corresponding levels for optimal growth of Nile Tilapia in earthen ponds (Ardjosoediro and Ramnarine, 2002; Makori et al., 2017). We chose earthen ponds because of their high resemblance to lake habitats. Similar data for Manyara Tilapia were not available. Results were considered statistically significant when p values were less than or equal to 0.05.

Results

We visited eight landing sites which are Kambi ya fisi, Kisese, Parisi, Kambi ya kayabo, Mfuru wa ng'ombe, Olasiti, Ngogolo, and Migunga mitatu. At these sites, we counted a total of 738 fishing boats, 1200 fishermen, and 2905 other people who were engaging in fisheries related businesses (Table S2). The main fishing gear on each landing site was gillnet; however, beach seines and very few longlines and basket traps were also present. Gillnets were 529, beach seines were 131, and basket traps were 30 (Table S3). Gillnets were of both cotton (fiber) and nylon (plastic) twine or materials. However, nylon nets were very few. Fishermen normally set and haul their nets once a day either early in the morning at dawn or in the afternoon at 15h and each boat landed fish once a day.

Manyara Tilapia

Fishermen at Lake Manyara caught fish at variable lengths. The average length at capture for Manyara Tilapia was 10.37 cm. The length frequency distribution of Manyara Tilapia shows that 30.2% of caught fish were in the length 2–7.5 cm, length class 7.6–10.5 cm (63.3%) dominated the catch, and fish in the length class 10.6–22.5 cm (6.5%) were rare (Fig. 2a). The maximum length of caught Manyara Tilapia was 21 cm and was the length of two individuals caught at Ngogolo landing site. Fish in the length class 2–7.5 cm were mostly caught at Olasiti, Paris, and Kambi ya kayabo landing sites (Fig. 3a). These sites used a combination of beach seines (8 mm stretched mesh) and small meshed gill nets (38 mm). Kambi ya kayabo used solely beach seine. In addition, Olasiti, Paris, and Kambi ya kayabo landed +81% higher number of fish per boat per trip (CPUE of a boat) than other landing sites ($F = 19.84$, $df = 7$, $p < 0.001$) (Fig. 4a; Table 1). Fish in the length class 7.6–10.5 cm were mostly caught at Kisese, Kambi ya fisi, Migunga mitatu, and Mfuru wa ng'ombe landing sites which use 45 mm to 63.5 mm mesh gillnets. Ngogolo was the only landing site which captured large fish (SL: 14.5–21 cm) and fishermen there use large size mesh nets (63.5 mm). The estimated annual catch or landing of Manyara Tilapia in Lake Manyara was 10,000 metric tons caught at CPUE of 27.79 metric tons/day (Table 1).

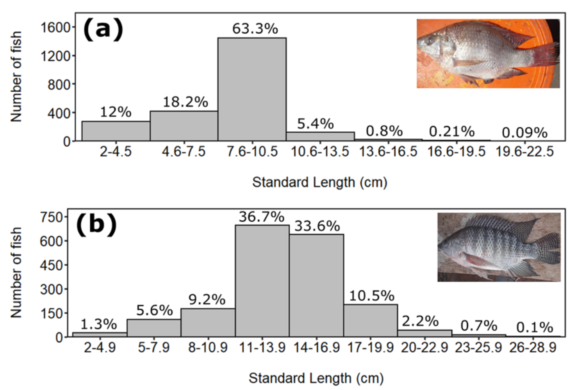


Fig. 2 Length frequency distributions of sampled (**a**) Manyara Tilapia, (**b**) Nile Tilapia from Lake Manyara in Tanzania in 2021

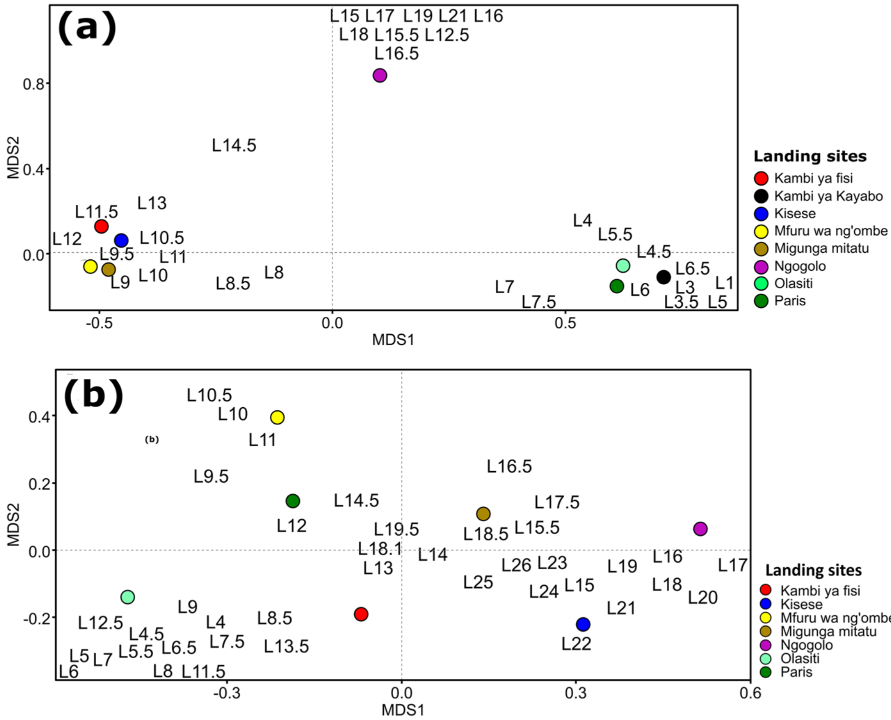


Fig. 3 NMDS analysis showing grouping of landing sites which were highly similar in the standard lengths of landed (**a**) Manyara Tilapia, (**b**) Nile Tilapia from Lake Manyara in Tanzania in 2021. The letter "L" followed by a number represents the standard length of the fish

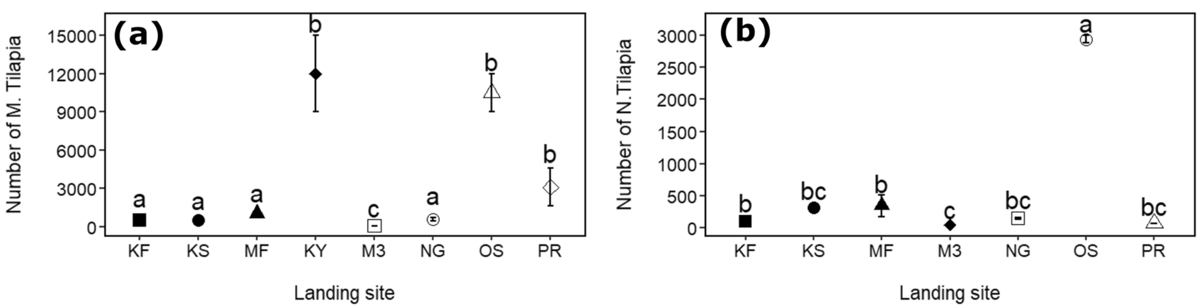


Fig. 4 Catch per unit effort of a boat (number of fishes/fishing trip of a boat) in 2021 for (**a**) Manyara Tilapia, (**b**) Nile Tilapia in Lake Manyara in Tanzania. KF = Kambi ya fisi, KS = Kisese, MF = Mfuru wa ng'ombe, KY = Kambi ya kayabo, M3 = Migunga mitatu, NG = Ngogolo, OS = Olasiti, PR = Parisi. Letters represent significant differences

Nile Tilapia

The average length at capture for Nile Tilapia was 13.77 cm. Fish with length 11–16.9 cm (70.3%) dominated the catch, while those with length 20–28.9 cm (3%) were rare (Fig. 2b). The maximum length of Manyara Tilapia was 26 cm which was the length of two individuals caught at Kisese landing site. Lager fish with length 13–26 cm were caught at Kisese, Ngogolo, Migunga mitatu, and Kambi ya fisi landing sites using 45–76 mm stretched mesh gillnets (Fig. 3b). Olasiti caught smaller fish with length 4–11 cm using beach seines and 38 mm mesh gillnets, and it was the landing site that landed + 48% higher number of fish per boat per trip (CPUE of a boat) than other landing sites ($F = 12.82$, $df = 6$, $p = 0.0002$) (Fig. 4b, Table 2). Mfuru wa ng'ombe and Paris caught smaller fish of intermediate length 9.5–12 cm using 45 mm mesh gillnets. The estimated annual landing of Nile Tilapia in Lake Manyara is 8046 metric tons caught at CPUE of 22.35 metric tons/day (Table 2).

Table 1 CPUE of a boat per day and CPUE of a camp per day for Manyara Tilapia in Lake Manyara in Tanzania in 2021

Sn	Landing site	Number of boats	Mean number of M. Tilapia/boat/day	Total number of M. Tilapia/day	Mean weight (T) of M. Tilapia/boat/day	Total weight (T) of M. Tilapia/day
1	Kambi ya fisi	30	500	15,000	0.033	0.99
2	Kisese	100	473	47,333	0.03	3
3	Mfuru wa ng'ombe	120	1,033	124,000	0.06	7.2
4	Kambi ya Kayabo	22	12,000	264,000	0.08	1.76
5	Migunga Mitatu	126	66	8,316	0.004	0.58
6	Ngogolo	146	567	82,733	0.03	4.38
7	Olasiti	98	10,500	1,029,000[1]	0.08	7.84
8	Parisi	76	3,100	235,600	0.027	2.03
	Total	738	28,239	1,807,230	0.344	27.79

Table 2 CPUE of a boat per day and CPUE per day per camp for Nile Tilapia in Lake Manyara in Tanzania in 2021

Sn	Landing site	Number of boats	Mean number of N. Tilapia/boat/day	Total number of N. Tilapia/day	Mean weight (T) of N. Tilapia/boat/day	Total weight (T) of N. Tilapia/day
1	Kambi ya fisi	30	97.33	2,920	0.033	0.99
2	Kisese	100	309.33	30,933	0.073	7.33
3	Mfuru wa ng'ombe	120	345	41,400	0.033	3.99
4	Migunga Mitatu	126	39	4,914	0.01	1.46
5	Ngogolo	146	148.5	21,681	0.04	5.84
6	Olasiti	98	2,940	288,120	0.02	1.96
7	Parisi	76	70	5,320	0.01	0.76
	Total	738	3,949	396,068	0.22	22.35

Levels of physicochemical variables and their correlations

Mean values of physicochemical variables in Lake Manyara at each landing site are presented in Table S4. Mean pH, turbidity, TDS, salinity, and conductivity were higher at Olasiti and Ngogolo landing sites and lower at Kambi ya fisi and Kisese landing sites (all $p<0.05$). Mean phycocyanin was higher at Kisese and lower at Ngogolo landing sites ($F=4.08$, $df=6$, $p=0.014$). Mean levels of NO_3, NH_3, TP, chlorophyll-a, and lake depth were not significantly different between landing sites (all $p>0.05$) (Fig. S1). Despite that, mean levels of NO_3 tended to be higher at Kambi ya fisi, Kisese na Mfuru wa ng'ombe landing sites, while that of NH_3 and chlorophyll-a tended to be higher at Olasiti and Ngogolo landing sites. We also observed a strong positive correlation between levels of turbidity and NH_3 ($r=0.75$, $t=4.94$, $df=19$, $p<0.001$), TDS and salinity ($r=0.99$, $t=135.93$, $df=19$, $p<0.001$), TDS and NH_3 ($r=0.57$, $t=3.03$, $df=19$, $p=0.007$), salinity and NH_3 ($r=0.6$, $t=2.91$, $df=19$, $p=0.008$), and a strong negative correlation between levels of NO_3 and pH ($r=-0.82$, $t=-6.28$, $df=19$, $p<0.001$) (Fig. 5). The correlations between other environmental variables were weak ($r\leq0.5$) as indicated in Table S5. Based on the OECD international standards for trophic states of water bodies, the hypereutrophic lake has Secchi disk transparency depth of less than 0.7 m, concentration of total phosphorus above 0.1 mg/l, and concentration of chlorophyll-a above 25 µg/l (Vollenweider and Kerekes, 1982). The corresponding levels of turbidity (Secchi depth: 0.26 m), total phosphorus (4.9 mg/l), and chlorophyll-a (349.8 µg/l) measured in Lake Manyara fall in the range of these internationally established standards (Table 3). From their field study, Ardjosoediro and Ramnarine (2002) and Makori et al. (2017)

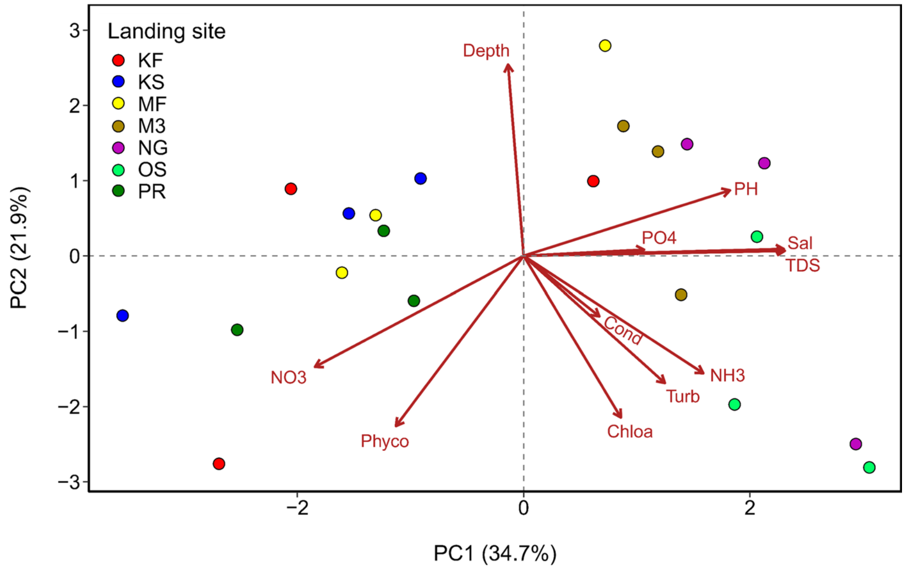


Fig. 5 PCA showing correlations between levels of environmental variables along their concentration gradients in Lake Manyara. Sal = salinity, Phyco = phycocyanin, Cond = conductivity, Turb = Turbidity,ChloA = chlorophyll-a, KF = Kambi ya fisi, KS = Kisese, MF = Mfuru wa ng'ombe, KY = Kambi ya kayabo, M3 = Migunga mitatu, NG = Ngogolo, OS = Olasiti, PR = Parisi

Table 3 Levels of physicochemical variables in Lake Manyara (mean ± se) in Tanzania in 2021

Variable	Mean ± se[a]	Maximum[a]	Minimum[a]	Optimum condition for growth of Nile Tilapia	Standards for hypereutrophic water[c]
Depth (cm)	237.1 ± 23	462	67		
Secchi depth (m)	0.26 ± 0.01[b]	150	36	0.13–0.18[d]	< 0.7 m
pH	9.5 ± 0.1	9.9	8.1	6.5–9[e]	
Salinity (PSU)	2.2 ± 0.03	2.4	2.1		
TDS (mg/l)	2111.9 ± 25.1	2291	1908		
Conductivity (µs/cm)	4128.9 ± 99.3	4586	2403	100–2000[e]	
TP (mg/l)	4.9 ± 0.2	6.4	1.5		> 0.1 mg/l
NO_3 (mg/l)	21.9 ± 3.9	76.5	7.6		
NH_3 (mg/l)	0.1 ± 0.02	0.4	0.02	0.02–0.05[e]	
Chlorophyll-a (µg/l)	349.8 ± 13.1	565.4	294.8		> 25 µg/l
Phycocyanin (µg/l)	9.5 ± 0.2	10.7	8.2		

[a]This study

[b]Equivalent to turbidity 76.6 ± 6.2 (FAU) measured in the current study

[c]Vollenweider and Kerekes (1982)

[d]Ardjosoediro and Ramnarine (2002)

[e]Makori et al. (2017)

reported that the optimal conditions for Nile Tilapia growth in earthen pond environment are pH (6.5–9), turbidity (0.13–0.18 m), electrical conductivity (100–2000 µs/cm), and ammonia (0.02–0.05 mg/l). The measured physicochemical levels in Lake Manyara exceed these optimal conditions for growth of Nile Tilapia except for turbidity (Table 3).

Discussion

We explored how artisanal fishing and anthropogenic pollution have affected the population of Tilapia fishes in Lake Manyara. Contrary to our expectation, we found that total fish catch from Lake Manyara has increased by 18 thousand-fold since the last catch estimation in 1990. Despite this, Tilapia fishes are under heavy fishing pressure which has already depleted large fish in the lake. Ecological habitat for healthy survival of Tilapia is also degraded which jeopardizes long time existence of these fish in the lake.

Nile Tilapia and Manyara Tilapia were the main catches from Lake Manyara with Manyara Tilapia being more dominant in the catch than Nile Tilapia. The estimated annual total catch for Tilapia fishes was 18 thousand-fold higher than the 0.5 metric tons in 1990 (Bayona, 2006), suggesting that fish populations in Lake Manyara have increased by 18 thousand-fold. Bayona (2006) ascribed the low fish catch in 1990 to lake drying which was the result of severe drought that struck the region in 1982 and nearly wiped-out fish populations in Lake Manyara. However, for the previous 33 years no drying episodes have been observed on the lake, the scenario which managed Tilapia populations due to their high fecundity to recover from few remnant individuals in parts of the lake which did not dry.

Despite the increase in population size of fish in Lake Manyara, their stocks show signs of being overfished (Lappalainen et al., 2016). During this study 30.2% and 97% of caught Manyara Tilapia and Nile Tilapia were juveniles of length 2 cm to 7.5 cm and 2 cm to 19.9 cm, respectively, and are attributed to the dominant use of beach seines and gillnets which predominantly remove immatures. Bayona (2006) reports the length at first maturity for Manyara Tilapia to be from 9 to 10.5 cm, Froese and Pauly (2022) reports 8 cm and above, and Trewavas (1983) reports 7.5 cm. Muluye et al. (2016) report the length at first maturity for Nile Tilapia in Lake Awassa Ethiopia to be from 20.3 to 20.8 cm, and Tefera et al. (2019) report 21 cm in Lake Tana Ethiopia. Our observed length at capture from 2 cm to 7.5 cm for Manyara Tilapia and from 2 to 19.9 cm for Nile Tilapia were below the lengths at first maturity for Manyara Tilapia and Nile Tilapia, indicating that these fish are at risk from recruitment overfishing if fishing mortality will continue to remain high (Froese, 2004).

Catching of immature Manyara Tilapia happened dominantly at Olasiti, Paris, and Kambi ya kayabo landing sites where use of beach seines (8 mm stretched mesh) and small mesh gillnets (38 mm) was dominant. These were also the sites where the observed CPUE (in terms of number of fish) per boat for Manyara Tilapia was threefold to tenfold higher compared to other sites. In fact, this CPUE was raised by higher number of immatures in the catch which stresses how effective and destructive beach seines and small mesh gillnets (38 mm) are in catching juveniles. Furthermore, nearly all caught Nile Tilapias were immature and were caught at all landing sites using 45–63 mm mesh gillnets. However, at Olasiti the landing site with higher CPUE (in terms of number of fish) per boat fishers use smaller mesh nets (38 mm) which caught much younger Nile tilapia fish. Generally, older fish are now depleted in the catches from Lake Manyara. We observed only 6.5% of older Manyara Tilapia (SL:10.6–22.6 cm), and 3% of older Nile Tilapia (SL: 20–28.9 cm), which indicates that majority of fish in Lake Manyara are experiencing growth overfishing because they are caught before they have realized their full growth potential.

The average length at capture of Manyara Tilapia of 10.3 cm and domination (63.3%) of Manyara Tilapia of length from 7.6 to 10.5 cm in the catch indicates that majority of Manyara Tilapia are caught at the length of their first maturity which is the time they start to spawn for the first time. This was mostly observed at Kambi ya fisi, Kisese, Ngogolo, and Migunga mitatu landing sites which uses gillnets with 38–45 mm mesh size. For sustainable fishing, length at first maturity of fish is considered as the minimum harvestable size of a given fish species (Muluye et al., 2016). Catching fish at lengths above the length at first maturity is a common principle and practice for sustainable fishing, because it allows fish to spawn at least once and replace themselves in the population (Montanm̃o and Morales, 2013; Tefera et al., 2019). Prolonged excessive removal of spawning stock may prevent population replenishment and hence successive recruitments. This may lead to the collapse of productive fishery like this of Manyara Tilapia, which is not only dangerous for the livelihood of communities around the lake, but also for the continued existence of the endangered Manyara Tilapia. The infamous collapse of the population of Atlantic cod in Canada (*Gadus Muhua*) is a classic example of the effect of prolonged overexploitation of fish stocks. The cod population in Canada was once the most abundant cod stock in the world and in the early 1960s it numbered almost two billion breeding individuals. Up to 2000, this cod stock declined by 97%

and catch rates by 99.9% since 1983 (Hutchings and Reynolds, 2004).

Despite causing diminution of fish stocks, overfishing in Lake Manyara has an extra concern as the lake is housing the endangered species which is endemic to five small lakes in northern Tanzania including Lake Manyara (Bayona, 2006). Manyara Tilapia was inscribed in the IUCN red list of endangered species due to heavy overfishing pressure using small mesh gillnets. However, up to now this factor has not been reversed, instead it keeps increasing due to lack of compliance to existing fisheries laws and regulations. Although local authorities have imposed a closed season of five months from October to February each year for fish in Lake Manyara to breed and rebuild their stocks, there is still no evidence of positive feedback of lake closure on the stock size of Tilapia fish, because lake closing is not properly implemented. Most of the time the lake is not closed during the closed season, and if it does fish poaching remains high (Mataba pers communication with locals). Lack of positive feedback of the closed season on fish stocks is also attributed to mismatch between closing season and fish breeding season. For example, Trewavas (1983) observed that the breeding season of Manyara Tilapia in Lake Manyara is from April to June.

Moreover, during open season fishing in Lake Manyara is nearly unregulated. Fishing licenses are issued without limit for revenue maximization, the act which incite overfishing. Fishermen are also still fishing using small mesh gillnets, and to maximize catches they have introduced beach seine which was not there before. As an outcome, and despite lake closure adult Tilapia fish are depleted in the lake which suggests that the length of lake closure (five months) could be too short for Tilapias to grow to harvestable size (age just above the age at first maturity). For example, the time Nile Tilapia spends growing to the age at first maturity is reported to vary from 5.6 to 10 months (Duponchelle and Panfili, 1998). Although beach seines are known to be indiscriminate and destructive, catching mostly juveniles, we lack evidence of its effect on fish stocks in Lake Manyara, and we did not quantify it during this study.

Income poverty and lack of conservation awareness is another driver of overfishing in Lake Manyara. Communities of nearly 200,000 residents over-depend on the lake for their subsistence. This is because fishing is a source of cheap income and protein compared to agriculture and livestock keeping. The LMB where Lake Manyara is located is also famous for its lucrative wildlife-based tourism, an opportunity which is well taped by a tiny number of villagers. To benefit from tourism, villagers often sell locally made artifacts and carvings as souvenirs and others serve as tour guides. However, these activities demand appropriate knowledge and skills which most poor villagers lack. Wider dissemination of conservation education coupled with supporting villagers to engage in other income generating activities such as fish culture to supplement fish catches would reduce fishing pressure in Lake Manyara and help conserve the endangered species. Studies shows that environmental or conservation education interventions are a keyway to increase the local population's knowledge on their environment and encourage positive attitudes and habits to preserve the environment and wildlife on a local and global scale (Chanvin et al., 2023). In Indonesia for example, conservation education provided by the Tangkoko Conservation Education program (TCE) to school pupils and to local populations around the Tangkoko reserve and in North Sulawesi area for conservation of the critically endangered and endemic crested macaques monkeys (*Macaca nigra*), increased their awareness and knowledge on wildlife conservation, and changed their behavior and attitudes toward wildlife, the thing which eased management of macaque primates (Chanvin et al., 2023).

Higher turbidity at Olasiti and Ngogolo landing sites is attributed to differential reginal land degradation around landing sites. During this study, we observed areas around Kambi ya fisi, and Kisese landing sites where turbidity was lowest were uncultivated lands covered with vegetation, while large areas around Olasiti and Ngogolo landing sites were bare grazing lands which escalate soil erosion and sediment deposition in the lake. In contrast, lower levels of TDS, conductivity, and salinity at Kambi ya fisi, and Kisese landing sites could perhaps be due to dilution of lake water by the inflowing year-round river Magara. The levels of these water chemical parameters were higher at Olasiti landing site possibly because of lack of fresh water from the temporary Oltukai river which was already dry at the time of sampling.

Although we did not determine the constituents of turbidity in the lake, the strong positive correlation between levels of turbidity and NH_3 suggests that lake turbidity could be largely constituted by organic matter which were undergoing decomposition by microbes. Ammonia is the immediate by-product of microbial organic matter decomposition, and once it is formed in oxic environment, it is immediately oxidized to nitrate (Kalff, 2001). The observed higher negative correlation between levels of nitrate and pH indicates that active nitrification was taking place in the lake. Nitrification is usually accompanied by the fall of system pH because oxidation of one mole of ammonium yields two moles of hydrogen ions and one mole of nitrite ion. Eventually, accumulation of the formed hydrogen ions leads to lowered pH, and nitrite ions are oxidized to nitrate (Nkotagu, 1996; Murray et al., 1974). Higher correlations between levels of NH_3 with both levels of TDS and salinity indicate that dissolved HN_3 (i.e., NH_4^+) is a constituent of TDS, the surrogate of salinity in the lake.

Levels of physicochemical variables such as water turbidity, total phosphorus, and phytoplankton chlorophyll-a were also higher than the OECD established standard indicators for hypereutrophic state of water bodies (Vollenweider and Kerekes, 1982). This suggests that water in Lake Manyara is hypereutrophic and could be limiting reproductive success and growth of Tilapia fish in Lake Manyara. This was confirmed by higher levels of pH, electrical conductivity, and ammonia, than the reported optimal levels for reproduction and survival of Nile Tilapia (Ardjosoediro and Ramnarine, 2002; Makori et al., 2017). This could be a sign that ecological habitat for optimal growth of Nile Tilapia in Lake Manyara is already degraded. Since Nile Tilapia and Manyara Tilapia are congeners, this finding could also be true for Manyara Tilapia which we lack data for comparison. Despite the obvious sign for ecological habitat degradation, Tilapia fish continue to exist in Lake Manyara in good abundance perhaps because their tolerance limit to extreme physicochemical variables is not exceeded yet. Tilapias are known for their tolerance to higher conductivity (up to 5000 µS/cm: Makori et al., 2017), ammonia (up to 0.1 mg/l: Makori et al., 2017), salinity (up to 24ppt: El-Leithy et al., 2019), and turbidity (up to 100 mg/l: Ardjosoediro and Ramnarine, 2002). The recorded physicochemical variables do not exceed these levels. Since habitat condition in Lake Manyara shows sign of degradation, it could also be possible that Tilapia fish in the lake are existing at suboptimal growth rate; however, we lack direct evidence. Extremely high levels of physicochemical variables in water bodies are known to affect fish populations negatively (Henley et al., 2000). Higher levels of turbidity can burry fish eggs and clog fish gills leading to gill inflammation and poor ventilation and eventual death (Ardjosoediro and Ramnarine, 2002; Henley et al., 2000), higher levels of nutrients can promote excessive algae growth some of which are toxic to fish, and algae blooms can also lead to oxygen depletion when they die and decompose which may kill fish at a concentration 0.3–0.8 m/l of dissolved oxygen (Makori et al., 2017).

Extreme eutrophication in Lake Manyara is attributed to land degradation around LMB via deforestation, overgrazing, and poor cultivation practices such as shifting cultivation and cultivation on slopping lands which have turned vegetated soils into bare lands. This has enhanced soil erosion with subsequent sediment and nutrients addition into the lake by rivers and surface runoff (Wynants et al., 2018, 2020). During our study, we observed large herds of cattle, vast bare lands, and large farms around the lake. Climate change predictions for the region predict an increase in rainfall from 0.15 to 0.45 mm/day by 2040 (Luhunga et al., 2018). This scenario may enhance lake pollution if appropriate mitigation measures will not be taken in time. Vegetation restoration through afforestation, and refraining from shifting cultivation, cultivation on slopping lands, and overgrazing can reverse the situation.

In conclusion, the population structure of Tilapia fish in Lake Manyara is dominated by small-sized individuals after depletion of large fish in the lake because of overfishing. These results support directly our first hypothesis. If this overfishing will continue unabated the stock of Tilapia fish in lake Manyara will eventually collapse and lead to loss of important source of livelihood and income to the surrounding poor rural communities. Collapse of fish stocks may also lead to extinction of the endangered Manyara Tilapia in lake Manyara. Adherence to sustainable fishing practices such as compliance to, and enforcement of, the existing national fisheries regulations and bylaws is recommended for sustainable fishing in Lake Manyara. For example, Tanzania fisheries regulations prohibit use of beach seine, and gill net with mesh size less than 76 mm. Strengthening enforcement of these regulations will ensure protection of

Manyara Tilapia and sustainable fishing in the lake. Also, Manyara Tilapia lacks legal protection in the country. This is because fisheries laws and regulations in Tanzania do not list Manyara Tilapia as an endangered species. Tanzania fisheries regulations protect endangered species by prohibiting catching of these species. Tanzania fisheries regulations therefore need revision to include other endangered species such as Manyara Tilapia for their protection. Compliance to fisheries regulations and bylaws can be strengthened by participatory community fisheries management through establishment and empowerment of beach management units coupled with provision of sustainable fisheries and conservation education to create conservation awareness in the community.

Also, the ecological habitat condition for the growth and survival of Tilapia fish in the lake is in a deteriorated state due to poor land use practices. This might be interfering with the survival of fish in the lake. This result supports our second hypothesis and can be resolved by complying to sustainable land use and soil conservation practices so as to reduce sedimentation and pollution in the lake. Compliance to sustainable land use and soil conservation practices can be enhanced by dissemination of education on proper farming and soil conservation practices to raise awareness among community members.

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Declarations

Conflict of interest We are declaring that we authors do not have any competing nor conflicting interests.

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