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Shifts in composition of fish species of fishery in Lake Naivasha, Kenya: Trend implications for fishing effort, yields and revenue

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Abstract

Assessing fisheries resource composition and exploitation trends is vital for the sustainable management of fish stocks. Accordingly, the present study analysed datasets of fish catches and market values from 1991 to 2019, and from 2004 to 2019, respectively, to determine shifts and trends in fish species composition, fishing effort, fish yield and revenue. The annual percentage weight composition and relative biomass of different fish species in the lake were calculated over the study period. Fishery time series data comprised fishing effort, fish yield, catch per unit effort (CPUE), revenue and revenue per unit effort (RPUE). Moving average (MA) trends at 5-year intervals were plotted and the Mann–Kendall (MK) method applied to detect trends at the 95% confidence limit. The results identified shifts in fish species composition during various periods, with Nile tilapia *Oreochromis niloticus* comprising 94% of the total weight of fish landed in 2019, with an overall mean relative biomass of 4221.4 ± 2229.7 kg/km^2. The mean total fish catch (1683.5 ± 420 ton/year), CPUE (10.6 ± 2.0 ton/boat/year) and modal effort (176 boats) were highest from 2014 to 2019 period. The fishery revenue increased in 2019 (US$ 4,096,490) with a RPUE of US$ 22,263.5/boat/year. The fishing effort, fish yields, CPUE, revenue and RPUE trends increased significantly ($p < .01$), likely being related to the shifts in species composition. Lake Naivasha is a learning model for improving fisheries management and yields through stock enhancement interventions. Nevertheless, the increasing level of fishing effort warrants a precautionary approach to ensure sustainability of the fishery resource.

KEYWORDS

catch composition, CPUE, fishery, RPUE, stock enhancement

1 | INTRODUCTION

Fishery resources are an essential component of the socioeconomic development of many countries, especially developing countries, because they provide a source of nutrition and food security, employment and livelihood opportunities for the local communities (Welcomme et al., 2010; Youn et al., 2014). Inland waters are endowed with high (>12,700) fish species diversity (Funge-Smith, 2018), supporting local livelihoods and food security in many nations. Globally, inland water fish captures have exhibited a steady yearly increase, with over 12 million tonnes reported in 2018 (FAO, 2020). The FAO indicated that nations endowed with important water bodies and river basins have inland captures more concentrated than marine captures. Of the total global inland capture fishery production, Asia accounted for over 55%, while Africa accounted for 25%, including Kenya's contribution of one per cent (FAO, 2020). Despite the importance of inland water fisheries, overfishing in these areas occurs because of poor reporting and the complex pressures influencing fishery exploitation and management (Allan et al., 2005). Fish capture decreases likely happens with increasing fishing intensities that remove larger and slower-growing fish, thereby causing considerable shifts in the species composition of target fishery resources (Allan et al., 2005; Molfese et al., 2014; Welcomme, 1985). Because fishing exerts selective pressures on the target species, leading to traits of early maturity or reduced sizes at the age of maturity (Funge-Smith, 2018), increasing fishing efforts and a shift to new target species can be an indicator of historical responses to overfishing (Molfese et al., 2014; Roberts, 2007).

Lake Naivasha is one of the vital inland fishery waters in Kenya. The lake is typically shallow, with an average depth ranging from 3 to 6 m, and a surface area varying between 110 and 160 km^2 during the drought and wet spells respectively (Harper, 1992; Harper et al., 1990; Litterick et al., 1979). The ecosystem is a national resource because of the unique faunal and floral biodiversity found within the basin. The lake has a high potential for human economic activities, including farming, tourism, fisheries and geothermal energy production, among other entrepreneurial ventures. The multiplicity of stakeholder interests and conflicts in the use of its resource led to the lake's designation as a Ramsar wetland in 1995 (Ramsar, 2019). Accordingly, there are various management interventions contemplated and enforced to restore the integrity of Lake Naivasha ecosystem since 1996. The interventions the stakeholders' endorsed management plan with a primary objective of managing the current human activities in order to facilitate the conservation and sustainable use of the lake's freshwater resources (Becht et al., 2005). One of the secondary objectives envisioned in the plan is to promote and encourage growth of the lake's contribution to the local and national economy.

An artisanal fishery of Lake Naivasha supports a local economy, including the livelihoods of more than 4000 people that depend on the resource (Obegi et al., 2020). The fishery has evolved through various development phases in both fish yield and exploitation levels (Hickley et al., 2002; Muchiri & Hickley, 1991). All the target fish species were either intentionally or accidentally introduced (Muchiri & Hickley, 1991; Njiru et al., 2017). These include the large-mouth bass *Micropterus salmoides* Lacépède, blue-bellied tilapia *Oreochromis leucostictus* (Trewevas), red-bellied tilapia *Coptodon zillii* (Gervais), common carp *Cyprinus carpio* (Linnaeus), the Nile tilapia *Oreochromis niloticus* (Linnaeus) and African sharp-tooth catfish *Clarias gariepinus* (Burchell). Lake Naivasha had only three finfish species (*M. salmoides*; *O. leucostictus*; *C. zillii*) since the 1960s that supported an active fishery for over four decades. A crustacean species, *Procambarus clarkii* Girard (Louisiana red swamp crayfish), also comprised a significant part of the fishery resource until the end of 1990s. Its population abundance was subsequently decimated, however, with a decreased contribution in commercial landings because of periodic changes in their habitat conditions (Harper et al., 2002; Smart et al., 2002). The three finfish species and crayfish were among the first intentional introductions in various periods for diversification of the fishery and ecological purposes (Muchiri & Hickley, 1991; Njiru et al., 2017). Common carp were discovered within the lake basin in 2002 (Hickley et al., 2004). The carp was thought to have escaped from aquaculture farms in the catchment (Njiru et al., 2017), becoming the most important target commercial species in Lake Naivasha, with its catch increasing from less than one per cent (0.9 tonnes) in 2002 to more than 95 per cent (133.4 tonnes) in 2006. As recent as 2011, *O. niloticus* was re-introduced in Lake Naivasha through a Government of Kenhya initiative to enhance tilapia stocks following the collapse of cichlid species fishery in the early 2000s (Hickley et al., 2015). Introduction of *C. gariepinus*, however, was inadvertent because its source is still unknown, although the species is also suspected to have escaped from aquaculture farms and entering the lake through its inflow rivers (Njiru et al., 2017). Since small catches of the African catfish were first reported with the catches of *O. niloticus* in 2012 (Hickley et al., 2015; Njiru et al., 2017), it is also possible that the species' fingerings may have been introduced along with those of *O. niloticus*.

Before a commercial fishery in Lake Naivasha began in 1959, the fish resource was under the protection of the Kenya government, with a limited number of permits provided for recreational fishing purposes (Muchiri & Hickley, 1991). Since the onset of open access to the fish resource, the lake's fishery has been highly dynamic over time, with notable fluctuations in the abundance of fish resources, fishing efforts and total yearly catches, leading to an overfishing situation (Hickley et al., 2002; Njiru et al., 2017; Waithaka et al., 2019). Earlier studies (Siddiqui, 1977, 1979) reported some changes in fish species composition, and a challenge of low diversity of the target commercial fishery species, being attributed to the high predation and changes in ecological conditions of the Lake Naivasha fishery environment. This literature corroborated previous observations that the lake had a higher potential for fish yield based on its morphoedaphic characteristics (Henderson & Welcomme, 1974) and the Melack (1976) primary production indices. Furthermore, Henderson and Welcomme (1974) compared the number of fishers among thirty-eight tropical freshwater lakes globally, finding that 18 (47%) of the lakes had more than one fisher/km^2, while Lake Naivasha had less than 0.7 fishers/km^2. Based on these findings, Siddiqui (1977) suggested the need for stocking of additional fish species in the lake for both diversification of the ecosystem and enhancement of commercial catches. A follow-up study also recommended a need to consider the addition of new fish species in Lake Naivasha, but only after thorough feasibility appraisals of each of the candidate species were conducted (Muchiri et al., 1995). The same study examined the feeding regimes of the various fish species, relative to the potential food supply within Lake Naivasha, to address the question of whether or not there were underutilised food resources in the lake. Their study identified four vacant niches, in terms of food and space, for the potential additional introduction of fish species, including bottom feeders, zooplanktivores, phytoplanktivores and piscivores.

Other studies also described the dynamic fishery environment, the resource itself and the mode of its exploitation in Lake Naivasha. Hickley et al. (2002), for example, identified and discussed three development phases of the lake's fishery, including an initial alternate sequence of high and low catches (1959–1973), a stability period (1974–1988) and an underperforming fishery marked with low fishery yields, culminating in its collapse in 2001. Related studies attributed the underperforming phase to excessive resource exploitation and habitat degradation in the lake (Hickley & Harper, 2002; Hickley, Muchiri, Britton, et al., 2004). According to Hickley et al. (2002), the potential annual yield of Lake Naivasha fishery is higher (900 ton/year) than the overall maximum sustainable yield (MSY) estimated using the time series data of catch per unit effort (CPUE). Thus, the Hickley et al. study reinforced the earlier proposal of introducing additional candidate fish species in Lake Naivasha (Muchiri et al., 1995; Siddiqui, 1977). Later studies (Aloo et al., 2013; Hickley et al., 2015; Hickley, Muchiri, Britton, et al., 2004; Njiru et al., 2017; Ojuok et al., 2007) reported an alteration of the fish community structure with new fish species populations established in the lake between 2002 and 2011. The studies identified common carp, Nile tilapia and the African catfish as the most recent entrants into the Lake Naivasha fishery.

Introduction of the new fish species may have elicited an increased resource exploitation level, with an increasing number of fishing boats and capacity (Njiru et al., 2017; Obegi et al., 2020; Waithaka et al., 2019). This situation suggests the need for an in-depth assessment of the changes in fishery resources composition and exploitation levels for sustainable conservation and wise use of the Lake Naivasha fish stocks. Trend analyses of historical fisheries data are particularly important aspects of a continual stock monitoring in order to provide insights into the present status of a fishery resource and forecast of the plausible future trajectories with various management actions for the lake. Accordingly, in view of the new species introductions into Lake Naivasha over time, the present study was conducted to evaluate the alterations in fish species composition and their implications for the annual fishing effort, fish yield and revenue trends, as a means of guiding sustainable fishery management.

2 | MATERIALS AND METHODS

2.1 | Study area

Lake Naivasha is a freshwater body located on the floor of the eastern African Rift Valley in Kenya (0°45′S, 36°26′E) at an altitude of about 1890 m above sea level. It covers an average surface area of 145 km^2, being the second lake in Kenya to be designated a Ramsar status after Lake Nakuru. Although a network of rivers and ephemeral streams maintain the lake ecosystem, the most significant inflow (90%) is from the Malewa River, with surface runoff and underground recharge accounting for the remainder of the lake's recharge. Its freshness is attributed to the underground seepage from its basin since it lacks any known surface outlets. Agricultural farms, hotels and urban human settlements are among the most notable socioeconomic operations around Lake Naivasha. There are four designated fish landing sites around the lake (Figure 1; Table 1) where the staff of the Fisheries Department (FD) and Kenya Marine and Fisheries Research Institute (KMFRI) record daily fish landings, the number of fishing boats and the approximate market value of fish caught per boat. Although fishing operations in Lake Naivasha are conducted by a regulated number of boats, each expected to deploy a maximum limit of ten multifilament gillnets, enforcement of this limit is often difficult. The daily fisheries datasets are compiled into monthly and annual reports from which time series information can be obtained.

2.2 | Fisheries data analysis

The present study used secondary data on fishing efforts, fish catches by species and their respective market value from 1991 to 2019. Annual datasets were obtained from the FD, with only the exploited finfish species being examined. Data on fish stock enhancement through restocking *O. niloticus* in Lake Naivasha were obtained from the annual fisheries reports available from the FD. Fish catch composition over the period was calculated using the percentage weight of the various fish species landed, with the relative annual biomass of each fish species calculated as follows:

$$\text{Relative fish biomass} = \frac{\text{Annual total catch of fish species (kg)}}{\text{Average Lake surface area (km}^2\text{)}} \tag{1}$$

The lake's fishery production trends were analysed using time series data of the total catches, fishing effort and catch per unit effort (CPUE) from 1991 to 2019. The fishing effort was standardised as the total number of licenced fishing boats, with the assumption that each boat used the same number of crew, gears and hours of fishing hours in the lake. The CPUE index was the total annual catches, divided by the yearly total number of licenced fishing boats (Hickley et al., 2002; Muchiri & Hickley, 1991). Fish yields and CPUE data were regressed, respectively, against the fishing effort data, with Pearson's linear correlation function used to test the significance association at a 95% confidence level. Fish market data available from the FD comprised the wholesale value of the total catch per fish species per year. Upon weighing and selling to the fish traders operating within the town of Naivasha and other neighbouring urban markets, each boat owner or fishing crew declares the wholesale value of their fish catches to fisheries officials at the land sites. Thus, the datasets of fish value between 2004 and 2019 provided the yearly revenue and RPUE trends, with the RPUE index calculated as the quotient of the total annual income and the corresponding fishing effort during that period.

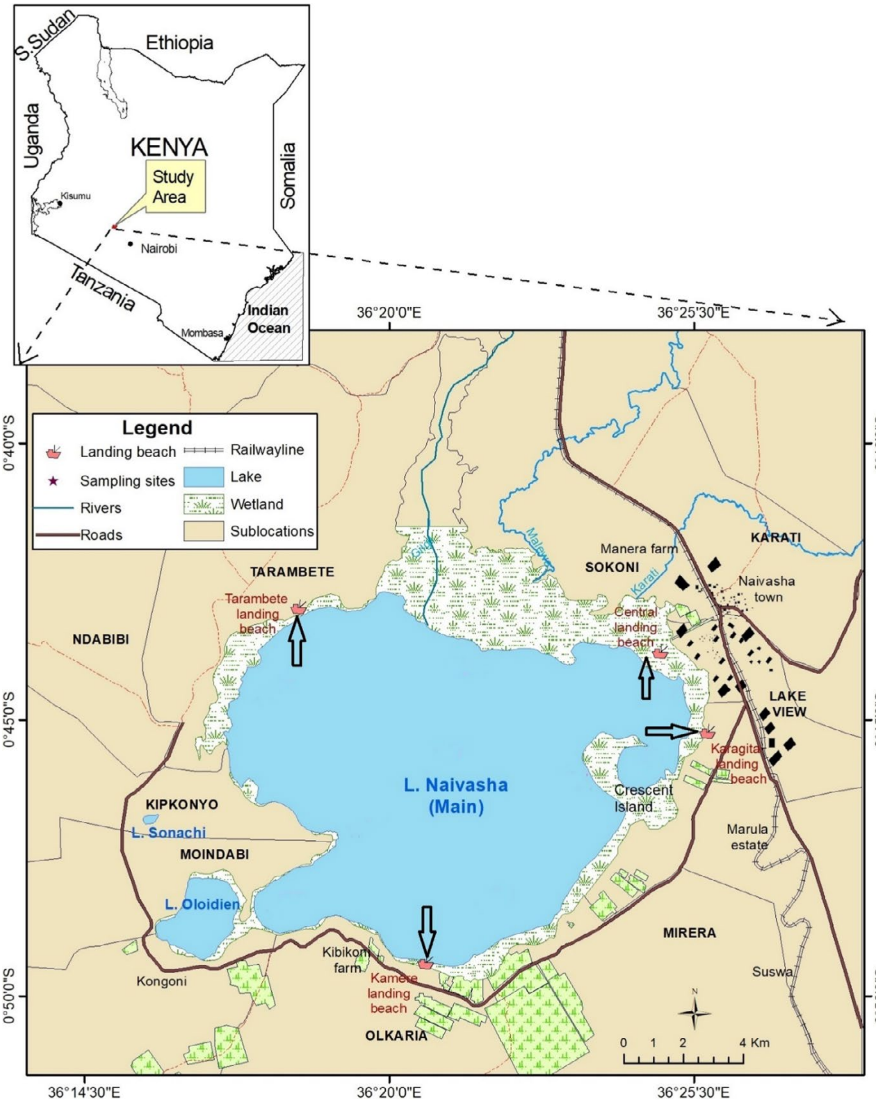

FIGURE 1 Map of Kenya indicating location of Lake Naivasha and current fish landing sites

TABLE 1 Location (geographical coordinates) of four fish landing site around Lake Naivasha

	Geographical coordinates	
Landing site	**Latitude (Y)**	**Longitude (X)**
Central landing beach	−0.71860	36.42059
Karagita landing beach	−0.76247	36.42708
Kamere landing beach	−0.81596	36.32398
Tarambete landing beach	−0.72305	36.30228

The fishery production and revenue trends were examined by plotting data of the annual yield and effort values against the respective years and superimposing the computerised moving average (MA) trend line function at a 5-year interval within the dataset period. Using the Mann–Kendall (MK) trend test method (Kendall, 1975; Mann, 1945), the present study examined the trends at the 95% level of significance. Ahmad et al. (2015) provided the detailed mathematical equations that derived the MK statistic (S), the variance of S (SE) and the standardised test statistic (Z).

3 | RESULTS

3.1 | Fish resource composition

The results of catch composition analysis by weight in Lake Naivasha depicted phases of various fish species dominance between 1991 and 2019 (Figure 2). Notably, *M. salmoides* and *O. leucostictus* were dominant (66% and 34%, respectively) in 1991, *O. leucostictus* (96%) in 2000, *C. carpio* (100%) in 2009 and *O. niloticus* (94%) in 2019. The common carp population was successfully established in Lake Naivasha basin after the species appeared in the reported catches since 2003. Catching the carp included its varieties, namely the mirror carp and leather carp, which were observed in relatively small, but varying, quantities over time. By late 2000s, the carp population was abundantly distributed in the lake, having decimated the production of the *M. salmoides* and the two cichlids. However, *O. niloticus* dominates in the present fishery phase after its restocking in the lake between 2011 and 2019 (Table 2). Although the African catfish appeared in the fishery after introduction of the Nile tilapia, the former accounted for only one per cent of the total fish catch composition in 2019.

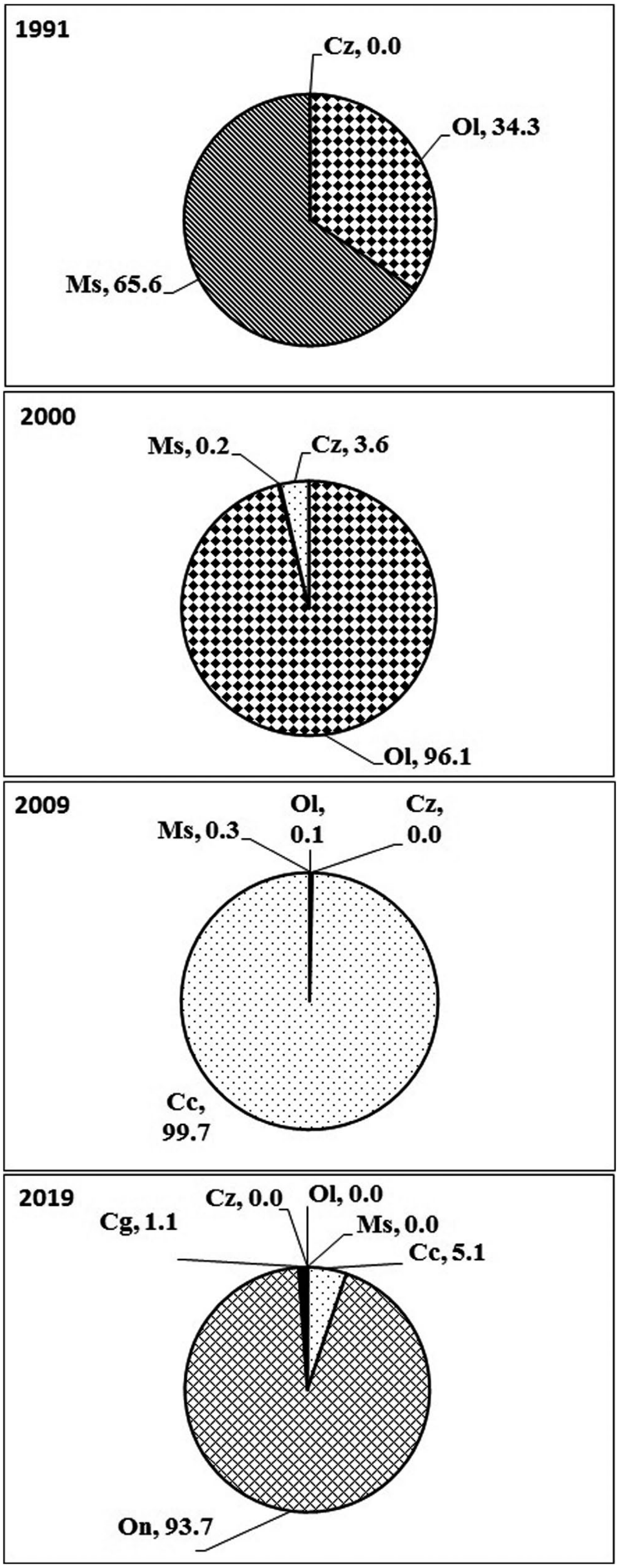

FIGURE 2 Composition (by weight) of target fish species in Lake Naivasha from 1991 to 2019 (datasets are in intervals of about 9–10 years; numbers indicate percentages; Cc, *Cyprinus carpio*; Cg, *Clarias gariepinus*; Cz, *Coptodon zillii*; Ms, *Micropterus salmoides*; Ol, *Oreochromis leucostictus*; On, *Oreochromis niloticus*)

TABLE 2 History of recent stock enhancement by restocking of *Oreochromis niloticus* in Lake Naivasha between 2011 and 2019 (*Data source*: Directorate of Fisheries Department (Naivasha Station) Nakuru County)

Period	Number of fingerings	Responsible
2011	535,000	NGoK
2012–2016	ND	ND
2017	69,500	NGoK
2018	73,000	NGoK & CGoN
2019	45,000	CGoK

Abbreviations: CGoN, County Government of Nakuru; ND, no data; NGoK, National Government of Kenya.

3.2 | Relative biomass of fish species

The relative biomass of different target fish species in Lake Naivasha (Figure 3) exhibited high annual fluctuations. The biomass of *O. leucostictus, M. salmoides and C. zillii* (Figure 3a–c), which were the dominant fishery resource before the entry of *C. carpio* and *O. niloticus* in 2003 and 2015, respectively, declined over this period. Shortly after the introduction of the common carp and Nile tilapia, however, their respective relative biomass steadily increased in the lake (Figure 3d,e), followed by the African catfish (Figure 3f). The mean relative biomass of exploited fish species in the fishery (Table 3) varied widely, with *O. niloticus* (4221.4 kg/km^2) and *C. carpio* (2371.6 kg/km^2) being the most abundant resource.

3.3 | Fishing effort, catch and CPUE

The fisheries data indicated wide fluctuations in annual fish landings, fishing effort and the CPUE index (Figure 4a–c, respectively). A summarised comparison of fish yield, effort and CPUE in Lake Naivasha during different fishing phases, and for the entire period from 1991 to 2019, is presented in Table 4. Although the fish yield fluctuated in a declining trend from 1991 to 2019, a slight recovery was observed in 1999 following the previous year's long *El-nino* rain phenomenon (Figure 4a). The mean fish yield was 185.5 ton/year, with the CPUE being 3.3 ton/boat/year. Although the fishing boats was relatively controlled from 1992 to 1997, a sharp increase in effort occurred between 1998 and 2000, preceding the fishery collapse in 2001 (Figure 4b). The fishery management in Naivasha subsequently instituted controlled measures from 2002 to 2013, maintaining the maximum fishing effort at 50 boats. During this period, the fish stocks began to recover, with a slight improvement in the mean yield (198.7 ton/year) and CPUE (4.2 ton/boat/year). A further rising trend in the CPUE was evident from 2014 to 2019 (Figure 4c), with the mean fish yield and corresponding CPUE being 1683.5 ton/year and 10.6 ton/boat/year respectively. This later phase of the fishery depicted growth with a modal fishing effort of

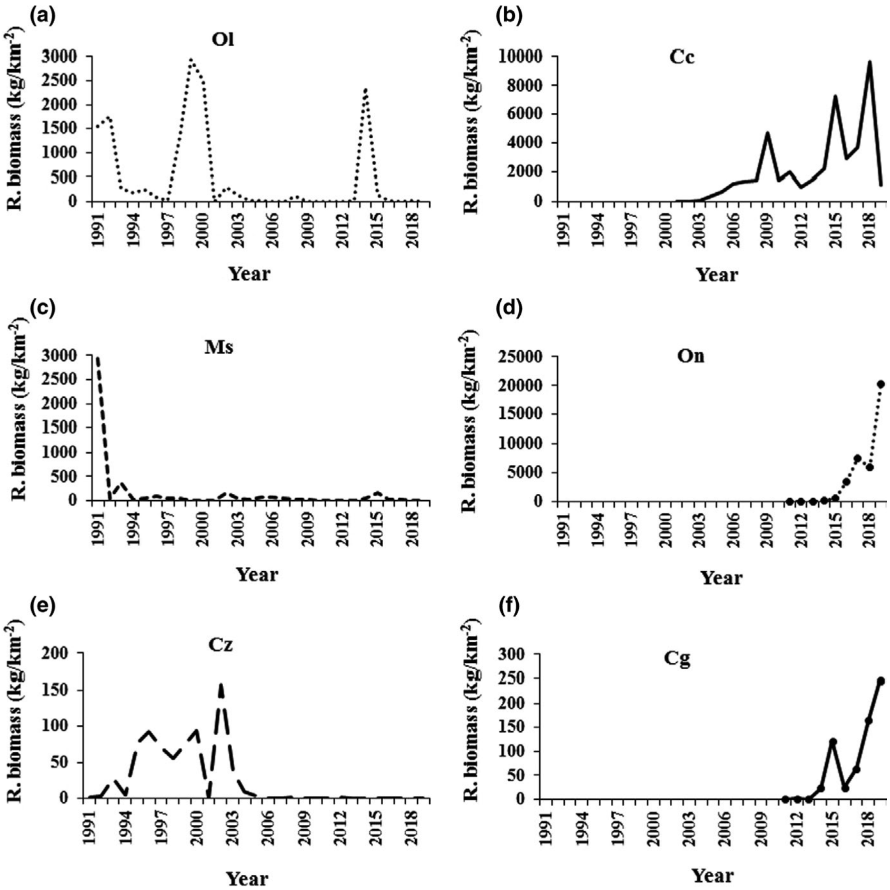

FIGURE 3 Changes in relative biomass of six target fish species in Lake Naivasha fishery from 1991 to 2019 ((a) Ol, *Oreochromis leucostictus*; (b) Ms, *Micropterus salmoides*; (c) Cz, *Coptodon zillii*; (d) Cc, *Cyprinus carpio*; (e) On, *Oreochromis niloticus*; (f) Cg, *Clarias gariepinus*)

TABLE 3 Mean relative biomass (weight per surface area) of different target fish resource in Lake Naivasha between 1991 and 2019 (average surface area of Lake Naivasha (145 km^2) was used; SE, standard error)

Species	Minimum-maximum (kg/km^2)	Mean relative biomass ± SE (kg/km^2)
Oreochromis leucostictus	0.11–2952.9	502.4 ± 167.1
Micropterus salmoides	1.09–2952.0	154.3 ± 104.6
Coptodon zillii	0–157.7	25.6 ± 7.8
Cyprinus carpio	0–9668.3	2371.5 ± 602.3
Oreochromis niloticus	0–20,342.8	4221.4 ± 2229.7
Clarias gariepinus	0–247.3	72.0 ± 29.4

176 boats. The increased fishing effort was linearly correlated with an increasing fish yield ($r^2 = .685$; $p < .001$) and CPUE ($r^2 = .410$; $p < .05$). Upward trends in fish yield, fishing effort and CPUE were detectable and statistically significant.

3.4 | Revenue and RPUE

The annual total revenue corresponding to fishing intensity gradually increased from US$ 22,589.2 to 4,096,490 per annum between 2004 and 2019, with a RPUE index ranging from US$ 627.9 to 22,263.5/boat/year (Figure 5a,b). The median yearly fishery revenue was US$ 150,280.8, with a corresponding median RPUE of US$ 3005.6/boat/year. There was a strong positive and significant correlation ($r^2 = .726$; $p < .001$) between the fishing effort levels and the annual revenue from the fishery resource, with increasing trends of revenue from the fishery resource and RPUE being statistically significant (Table 5).

4 | DISCUSSION

Analysis of historical data of fish species composition provides new insights for fisheries resource management in Lake Naivasha. The artisanal fishery of the lake is artificial with a naturalised stock whose population size has changed over time. *M. salmoides*, *O. leucostictus* and *C. zillii* were the only commercial finfish species targeted for the gillnet fishery until 2002. However, the bass could also be caught by rod and line for limited recreational fishing (Hickley et al., 2002; Muchiri et al., 1995). The results of the present study indicate a recent modification in fish species composition following the introduction of *C. carpio*, *O. niloticus* and *C. gariepinus*. Both the common carp and the African catfish are a result of their inadvertent introduction into the Lake Naivasha basin (Njiru et al., 2017). Likely attributable to the subsequent changes resulting from this introduction, the main fishery indicator species of the lake are currently *M. salmoides*, *O. leucostictus*, *C. carpio* and *O. niloticus* (Figure 2). The current fish species composition is likely to meet the objective of earlier recommendations for introducing additional species to diversify both the fish resource and their functions in the lake ecosystem (Muchiri et al., 1994; Siddiqui, 1977). The initially low diversity of the target fishery resource and unstable conditions, such as lake level variations affecting the ecology of the lake, were blamed for the observed high fluctuations and declining trends of fish production in Lake Naivasha since the 1970s to 2000 (Hickley, Muchiri, Boar, et al., 2004; Muchiri & Hickley, 1991; Siddique, 1977).

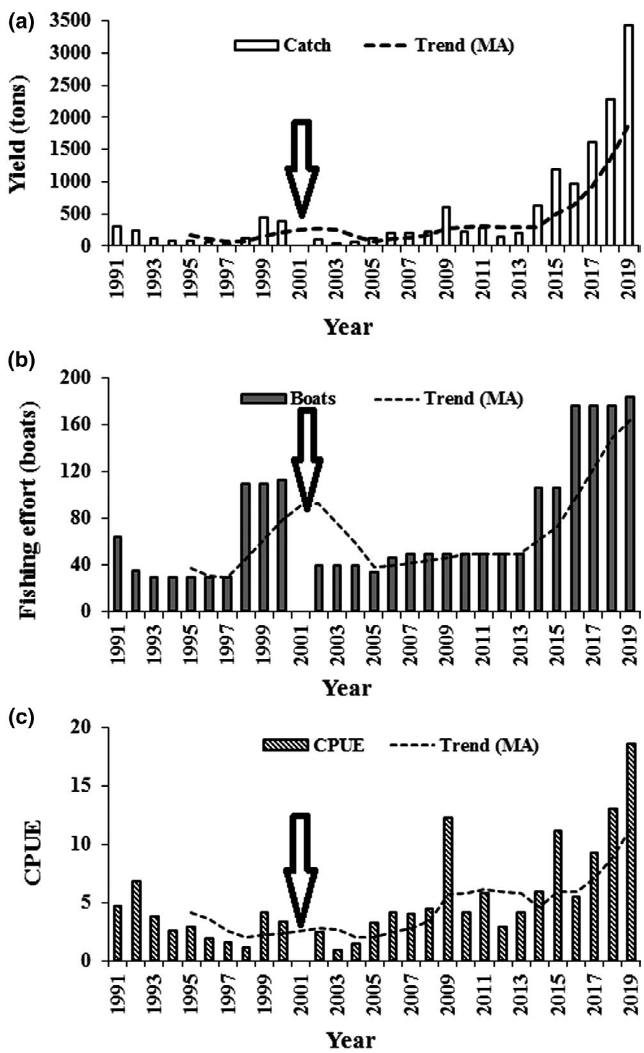

FIGURE 4 Fishery production and exploitation trends in Lake Naivasha from 1991 to 2019 ((a) fish yield; (b) fishing effort: (c) CPUE; trend lines are moving average (MA) in five-year intervals; arrows indicate period of fishery collapse and fishing ban in 2001)

The relative biomass of various fish species in Lake Naivasha provides an insight into changes of their respective resource abundance over time. Except for fluctuations in annual fish yield from 1991 to 2003, *O. leucostictus* was the major stock biomass in the Lake Naivasha fishery before the entry of *C. carpio*, *O. niloticus* and *C. gariepinus*. Muchiri et al. (1995) previously reported the persistence of the *O. leucostictus* population under ecologically stressful conditions and fishing pressures. Since the introduction of *C. carpio*, *O. niloticus* and *C. gariepinus*, however, their relative superiority in stock biomass has been evident in recent years. In comparison, these three species have advantageous reproductive strategies, with a high fecundity and wide range of adaptive capacity in various freshwater conditions. They grow faster and attain larger sizes with relatively higher fertility (Hossain et al., 2016). The fecundity of *C. carpio* increases with its body size and age, for example, and it can produce between 500,000 and three million eggs per spawning period (Smith, 2004). Under suitable conditions for survival of its larvae, the species may reproduce more than once per year, although the timing, frequency and period of spawning, including growth and size at first maturity, can all change with prevailing temperature conditions (Alikunhi, 1966; Smith & Walker, 2004). Common carp also can survive under a wide range of water quality conditions, including very low water temperatures or even low concentrations and/or super-saturation of dissolved oxygen (Banarescu & Coad, 1991; Tessema et al., 2020). Because of its advantaged reproductive and adaptive strategies, the carp population may have decimated bass and cichlid catches, thereby dominating the commercial fish landings (Aloo et al., 2013; Britton et al., 2007; Ojuok et al., 2007; Oyugi, 2012). On the other hand, *O. niloticus* has a capacity for early maturation and prolific breeding with large numbers of fingerings (Shoko et al., 2015).

The annual levels of fishing effort, fish catches and CPUE fluctuated highly between 1991 and 2019. In the earlier part of the period, until the early 2000s, the fishery was markedly in a low performing state (Hickley et al., 2002), being constrained by limited numbers of target fish species, fluctuation in fishing efforts and weak

TABLE 4 Comparison of fishing effort, fish yield and CPUE of Lake Naivasha at different time intervals between 1991 and 2019 (*N* = dataset number of years)

Period	*N*	Range	Modal effort (boats/year)	Mean fish yield (ton/year)	Mean CPUE (ton/boat/year)
1991–1999	10	29–113	29	185.5 ± 46.2	3.3 ± 0.5
2002–2013	12	34–50	50	198.7 ± 42.9	4.2 ± 0.8
2014–2019	6	106–184	176	1683.5 ± 420.0	10.6 ± 2.0
1991–2019	28	29–184	50	512.1 ± 146.4	5.2 ± 0.8

management of the fishery resource. During the three years preceding collapse of the fishery and imposition of a fishing ban in 2001, for example, the number of licenced fishing boats had increased fourfold from twenty-nine boats in 1991. The boats also contained an unknown number of fishing nets and fishing crew members. Improved catches and CPUE from 2003 onwards, however, highlights the effects of four measures taken within fisheries management efforts to mitigate the decreasing trends. The first action was a drastic reduction of fishing effort from 113 at that time, to less than 50 boats with a maximum of 10 fishing nets (2.5 m wide × 100 m long) of >4-inch mesh size and operated by three crew members per boat (Kundu et al., 2010). Along with the reduced fishing effort, an annual closed season was introduced from June to September to allow for fish recruitment and stock replenishment. These management decisions are reviewed periodically and supported with research monitoring results shared among local stakeholders in a consultative process.

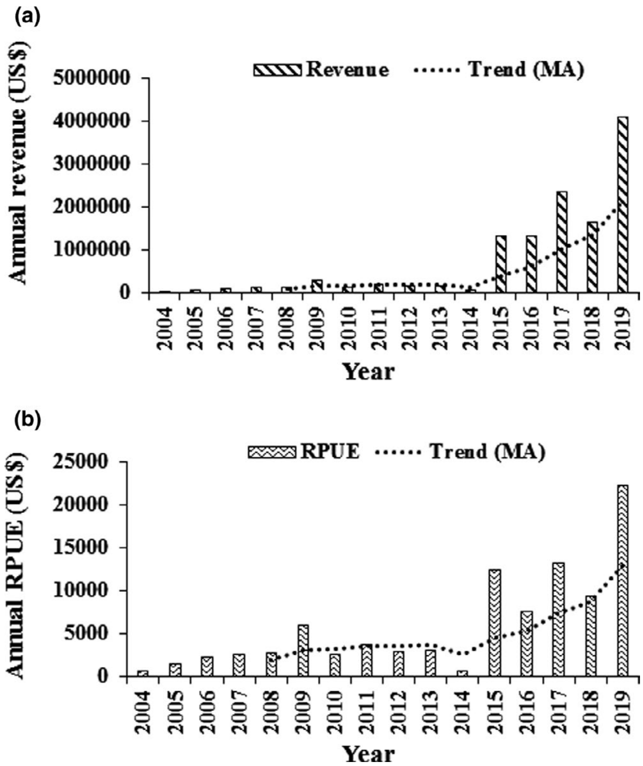

FIGURE 5 Trends in (a) fishing effort (marked line) and total revenue (bars); (b) corresponding RPUE from 2004 to 2019

The second management action entailed a participatory community approach (co-management concept) whereby fishers formed a democratically elected leadership known as beach management units (BMUs). The fisheries department staff facilitated this capacity, empowering four BMU establishments around the lake in 2008. The BMUs currently provide support in fisheries governance issues through fishery regulations and limitations that influence management decisions regarding the number of fishing boats, nets, fishing grounds and periods (Waithaka, Boera, et al., 2020). The co-management controls and guidelines in Lake Naivasha have not only enhanced resource management, but also positively influenced the relationship between the fishers and fish traders and, therefore, the market value of fish along the supply chain (Kundu et al., 2010; Waithaka, Boera, et al., 2020). The third action involved delineation and protection of critical fish breeding areas for sustainable fisheries reproduction and yields (Yongo et al., 2013). There are currently four sites (Crescent Island, Malewa river mouth, Korongo and Oserian bays) that are marked and protected for fish spawning. The fourth action was a stakeholder consultative decision to re-introduce *O. niloticus* into Lake Naivasha to support an exploitable fishery. The Nile tilapia was first introduced into Lake Naivasha in 1967 to diversify and reinvigorate the fishery, which was dwindling at that time, although this species disappeared in 1971 (Gozlan et al., 2010; Njiru et al., 2017). The Nile tilapia was later re-introduced several times in the lake (Table 2) between 2011 and 2019 (Government of Kenya, 2011; Waithaka et al., 2020).

Comparing actual fish catches with theoretical yield models (e.g. Hickley, Muchiri, Boar, et al., 2004; Muchiri et al., 1994), Lake Naivasha has the potential for higher fish production than the quantity being realised at present. Henderson and Welcomme (1974), for example, used a morphoedaphic index model to assess the Lake Naivasha fishery. Melack (1976) used primary production values in a model to estimate the potential yield of the lake. Muchiri and Hickley (1991) later used historical catch and effort datasets to estimate the maximum sustainable yield for the Lake Naivasha fishery. These models predicted potential production ranging from 495 to 5649 ton/year. The present study demonstrated a consistent increase in annual fish catches from 623 to 3424 tonnes, with a mean yield of 1683.5 ton/year between 2014 and 2019 (Table 4). These results are well within the theoretical yield estimates, suggesting that fish stocks in Lake Naivasha, if well managed, are likely to sustain a healthy fishery. Apart from the effect of fishing effort variations,

TABLE 5 Results of the Mann–Kendall test on fishery trends in Lake Naivasha (fishing effort, yield, CPUE (dataset 1991–2019); revenue and RPUE (dataset 2004–2019); MK statistic and *p* values in bolded fonts)

Variable	Minimum value	Maximum value	MK test statistic (*S*)	Variance of *S* (SE)	Normalised test statistic (*Z*)	Probability (*p* value)	Trend at 95% level of significance
Fishing effort (boats)	29	184	**205**	50.6	4.03	**<.001**	Increase
Yield (ton)	38	3424	**167**	34.18	4.86	**<.001**	Increase
CPUE (ton/boat)	1.1	18.6	**160**	50.6	3.14	**<.01**	Increase
Revenue (US$)	25,589	4,096,490	**88**	22.21	3.92	**<.001**	Increase
RPUE (US$/boat)	628	22,264	**80**	22.21	3.56	**<.001**	Increase

researchers such as Bandara and Amarasinghe (2017) and Patrick (2016) have reported relationships between fish biomass and water level fluctuations in lakes and reservoirs. Gownaris et al. (2018) also reported seasonal water level fluctuations correlate positively with primary production and biomass of aquatic organisms. Recent trends of water level fluctuations in Lake Naivasha basin since 2010 have been determined, being consistent with climate change and variability of rainfall patterns in the catchment area (Nyokabi et al., 2021). This situation may have influenced favourable habitat conditions for the three fish species (*C. carpio*, *O. niloticus* and *C. gariepinus*) presently dominating in the fish catches.

Fish stock enhancement in Lake Naivasha has facilitated the increasing trends in fishing effort, annual catch and revenue (Table 5), all likely being driven by the human population increase, and the fish market dynamics, around the lake. An increase in the fishing effort is intricately related to the number of people without formal education, and who easily find employment for their livelihoods from the fishing industry (Waithaka et al., 2019). Furthermore, there are ready market destinations in the surrounding urban (Nakuru, Nyahururu, Narok and Nairobi city) that exert high demands for fish, causing pressure on the resource. The present study, assuming a lake surface area of 145 km^2, determined the current effort of 184 boats has a fishing intensity of >3.8 fisher/km^2. This magnitude of fishing pressure is more than fivefold the estimated pressure (<0.7 fishers/km^2) observed by Muchiri and Hickley (1991). It also is more than threefold the number of fishing boats (50) recommended for a sustainable fishery under natural recruitment conditions (Hickley et al., 2002; Kundu et al., 2010; Muchiri & Hickley, 1991). Because of the urge to sustain the local livelihoods and employment found within the fisheries sector, the County Government of Nakuru has continued to provide subsidised fish fingerings for annual restocking of *O. niloticus* in Lake Naivasha. Thus, it is not surprising that a steady rise in catches, fishing effort and CPUE (Figure 4), including and revenue and RPUE (Figure 5), coincides with the restocking of *O. niloticus* at various times between 2011 and 2019. Nile tilapia is a superior fisheries species, accounting for about 80% of Kenya's freshwater fish production and also being one of the most favoured aquaculture candidates because of its high demand in the markets (KMFRI, 2017). Keyombe et al. (2018) have attributed the introduction of *O. niloticus* to the improved income of fishers in Lake Naivasha, thereby demonstrating the need for high compliance to fisheries regulations for sustainable exploitation of the species.

Stock enhancement is an emerging field of fisheries management with a potential to improve inland fisheries production and create opportunities for many local livelihoods (Malony et al., 2005). Lake Naivasha is a moderately small, shallow water body, being a good example in Kenya wherein the introduction of different fish species has manipulated the fishery resource. Fish stocking interventions focussing on meeting human food and nutritional requirements are among the reasons for fish stock enhancements (Welcomme & Bartley, 1998). The current Lake Naivasha fishery exhibits some characteristics of enhanced stock that comprise a combination of wild and culture-based types (De Silva & Funge-Smith, 2005). It is considered wild because the lake is large enough, because it can support an open-access nature of its fishery and because some fish species are self-recruiting with no property rights to their stocks. Nevertheless, regular restocking of *O. niloticus* is the primary mechanism of sustaining the current fish production, typifying a culture-based type of fishery that relies on fingerings purchased from aquaculture hatcheries owned by other organizations. Honma (1980) noted that culture-based fisheries increase fish yields in natural environments by managing a part of the life history of certain species and introducing their seed into the open waters. Thorpe (1980) also described the process of culture-based fishery to entail the release of juvenile fish, usually produced in hatcheries, into open waters where they grow on natural food until they mature for harvesting. Pushpalatha and Chandrasoma (2010) reported a 263% increase in fish yield under culture-based fishery practices in small-to-large perennial and seasonal reservoirs in Sri Lanka. By comparing the mean annual Lake Naivasha fish yield at various time intervals (Table 4), the present study found a colossal increase (747%) of fish production between 2014 and 2019. The present study attributes the present phenomenal increase in fish yield to changes in fish species and restocking of *O. niloticus* in the lake. It also may demonstrate the potential of enhancing fish production through culture-based fishery approach.

5 | CONCLUSIONS AND RECOMMENDATIONS

The target fishery resources of Lake Naivasha have been significantly modified and exhibit a potential of enhancing higher production and revenue for the local community. Lake Naivasha, therefore, is a learning model for improving fisheries management and fish yield through stock enhancement interventions. It presents a situation of trying to balance stock exploitation levels and sustainable livelihoods and food security concerns. If successful, this approach can be applied in other fishery impoverished inland waters for which issues of biodiversity and conservation impacts have been assessed and mitigated. The trend of increasing fishing effort, fish yields and income for fishers are associated with new species introductions. The increasing fishing effort trend, however, which already exceeds the recommended levels by three-fold, is likely to put pressure on *O. niloticus* and *C. carpio*, thereby negatively impacting the fishery yield and revenue trends. Although the findings of the present study demonstrate the potential of enhancing fish stock for a culture-based fishery in the lake, precautionary approaches directed to addressing the increasing level of fishing effort should be adopted to ensure the sustainability of the fish resource. Furthermore, the present study recommends a clear institutional and policy framework for the restocking program. It should also consider the imminent risks of accidental introductions of untargeted species that may cause unknown ecological impacts in the ecosystem. Overall, therefore, close monitoring of all fish stock enhancement programs is warranted to mitigate undesired impacts on the targeted fisheries.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at Kenya Marine and Fisheries Research Institute in Naivasha.

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